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

https://github.com/andreatramacere/adiabatic_exp_radio_gamma_delay

https://jetset.readthedocs.io/en/1.2.2/

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A&A 658, A173 (2022)
https://doi.org/10.1051/0004-6361/202142003

Astronomy & Astrophysics

Radio-γ-ray response in blazars as a signature of adiabatic blob expansion

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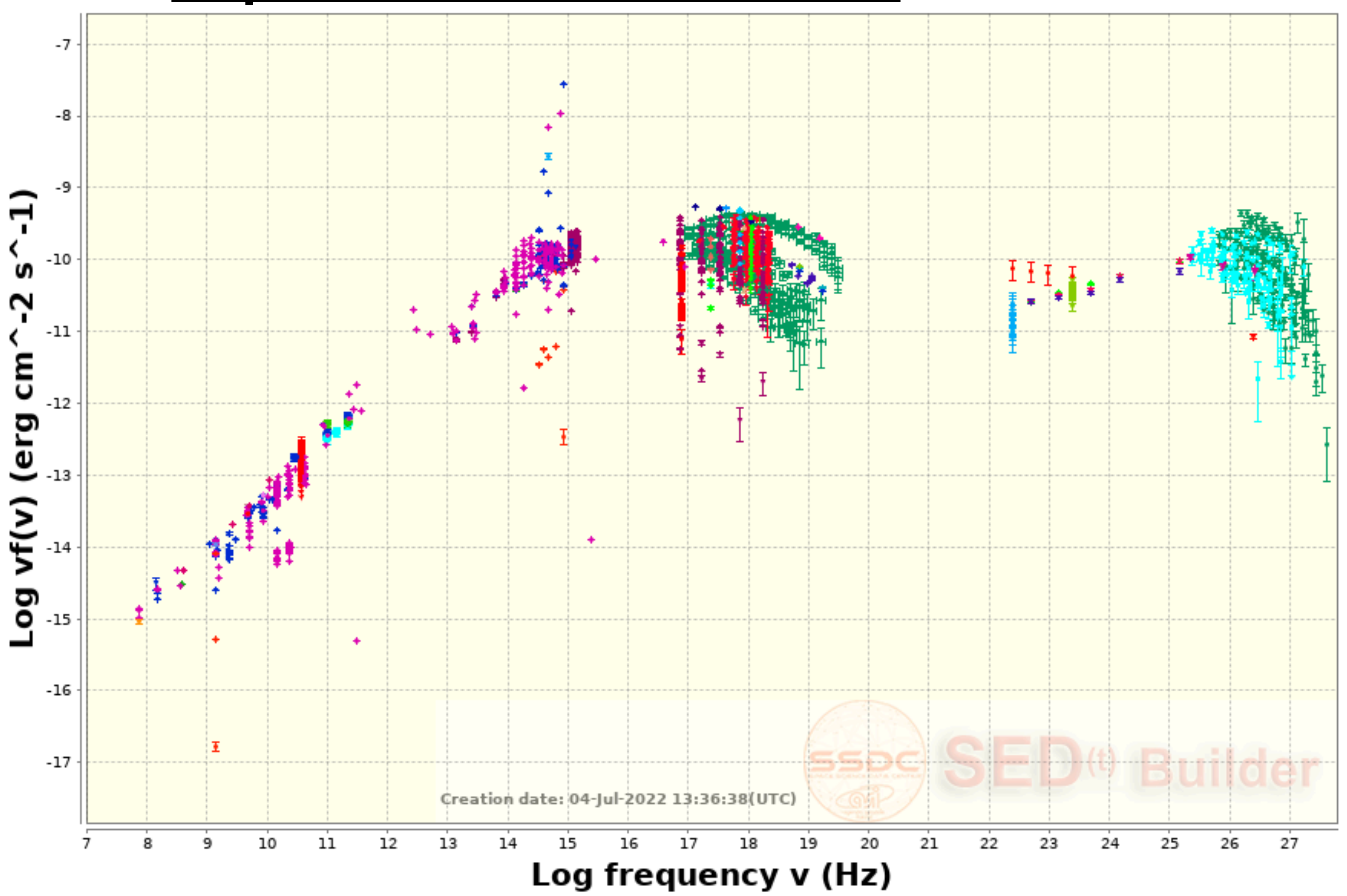
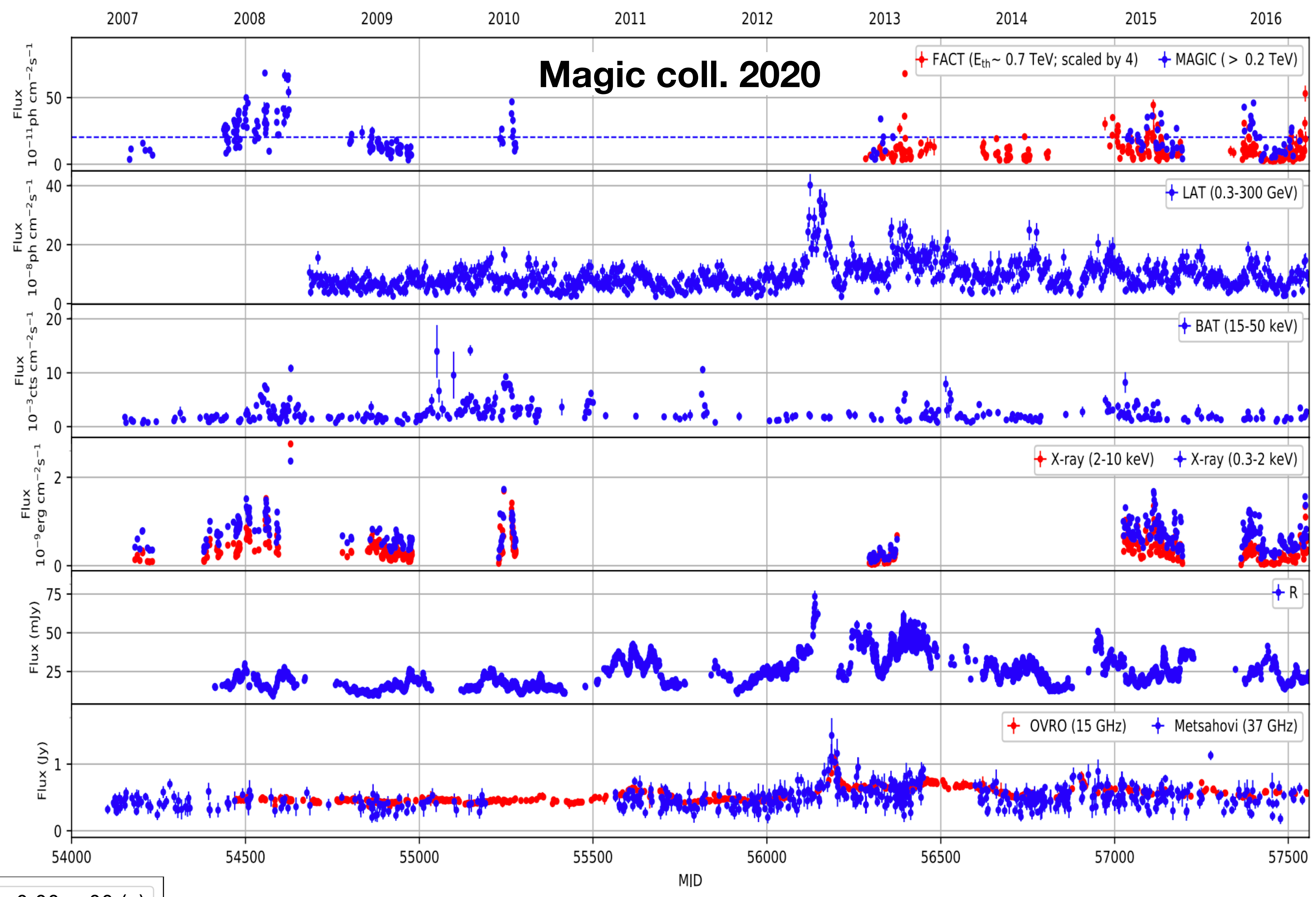
variability: acc. and cooling (lags,hyst. cycle etc…)

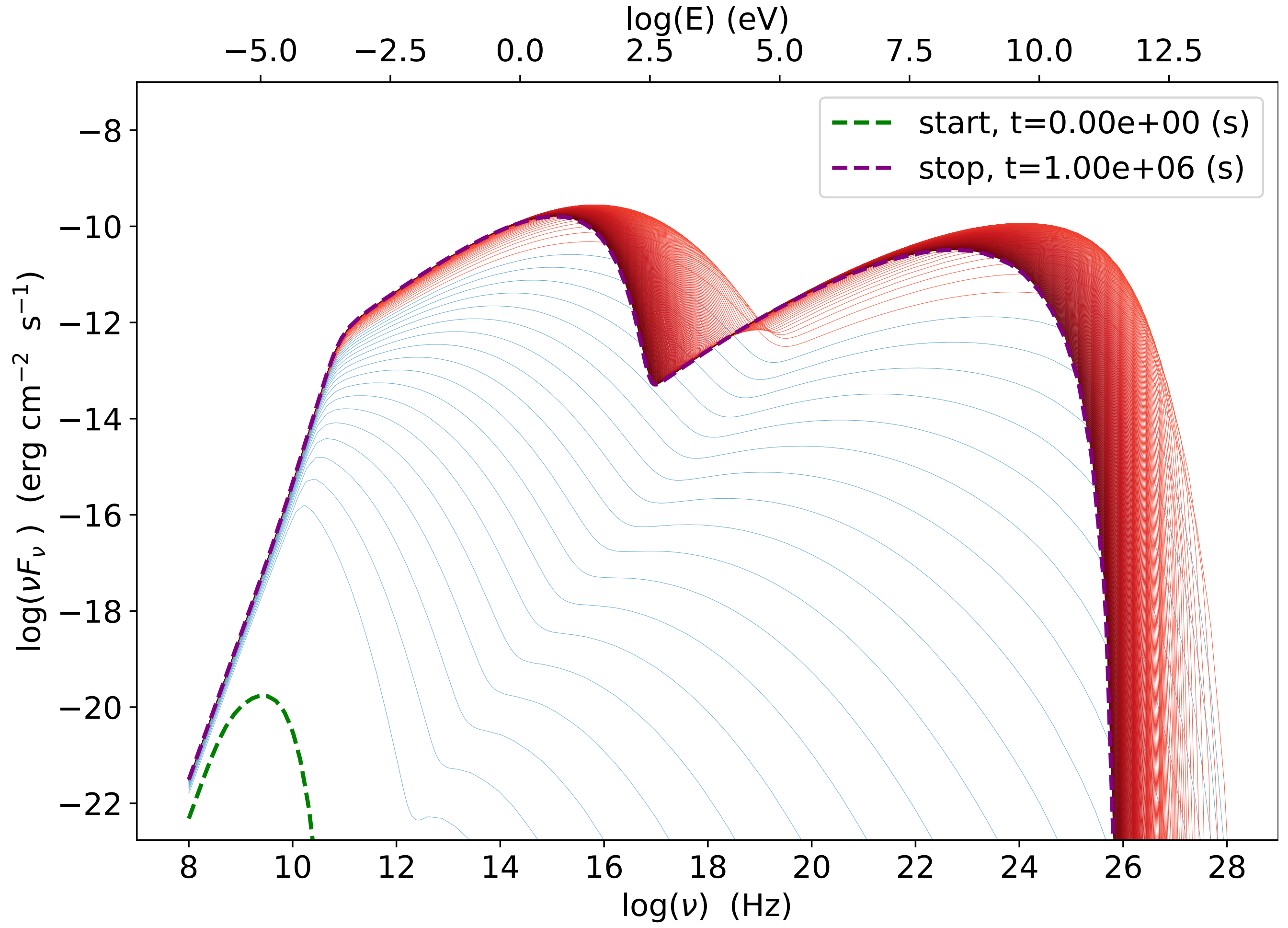
https://tools.ssdc.asi.it/SED Mrk 421



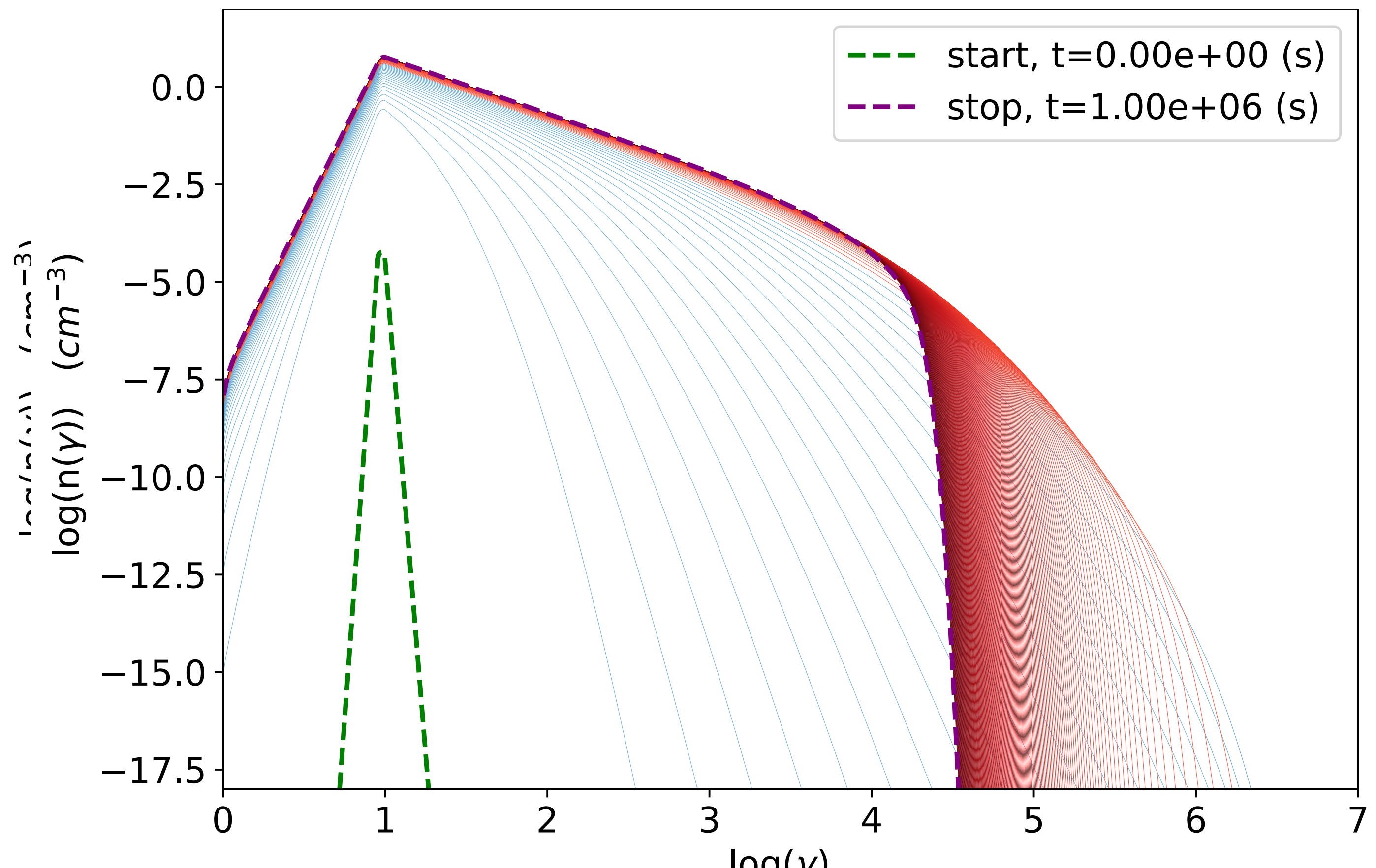
t_{var} depends on $t_{acc,inj.}$ and properties of radiative process plus geometry



Acc+cooling
Tramacere+ 2022,2011



FI+FII



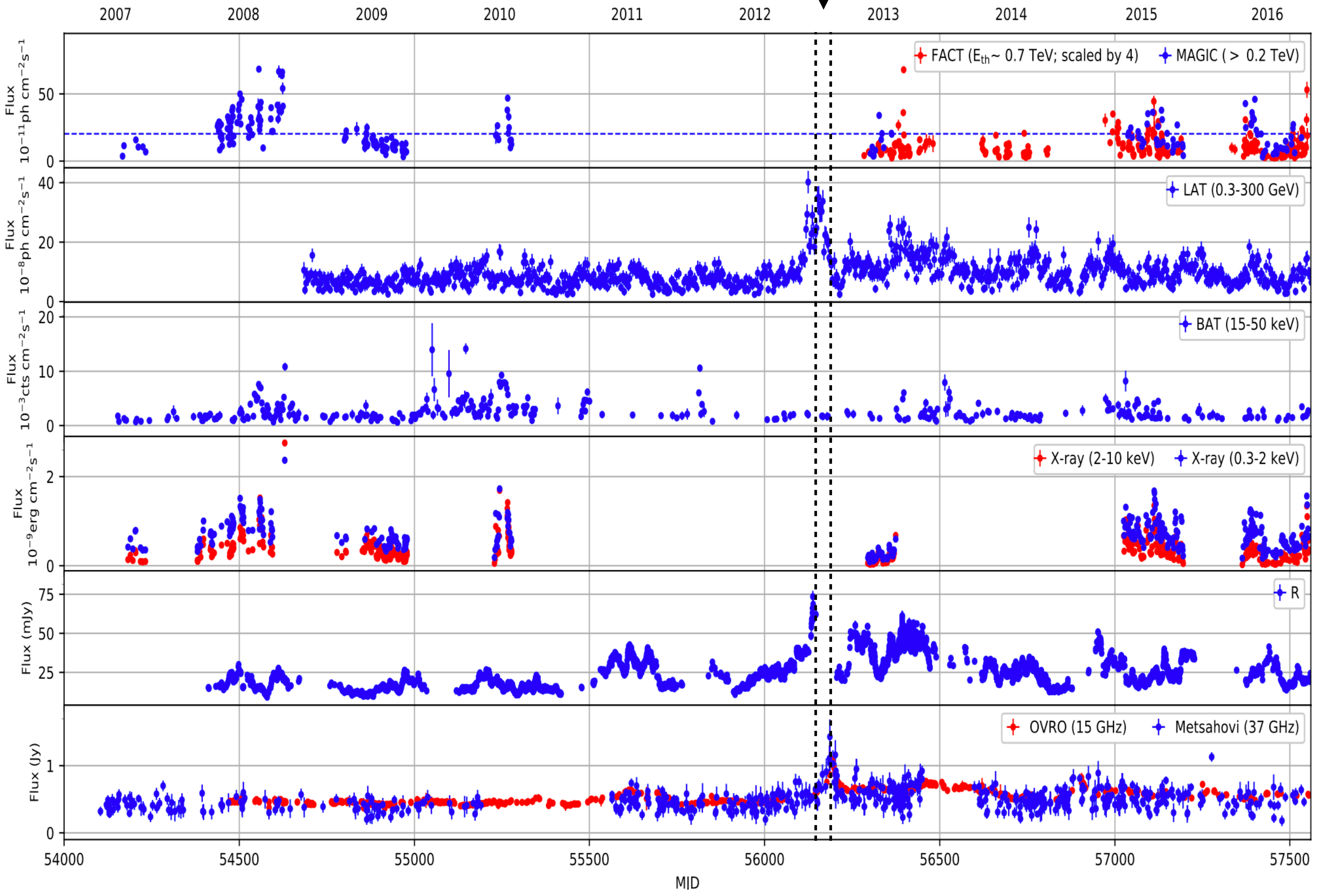
delays on weeks to years timescales

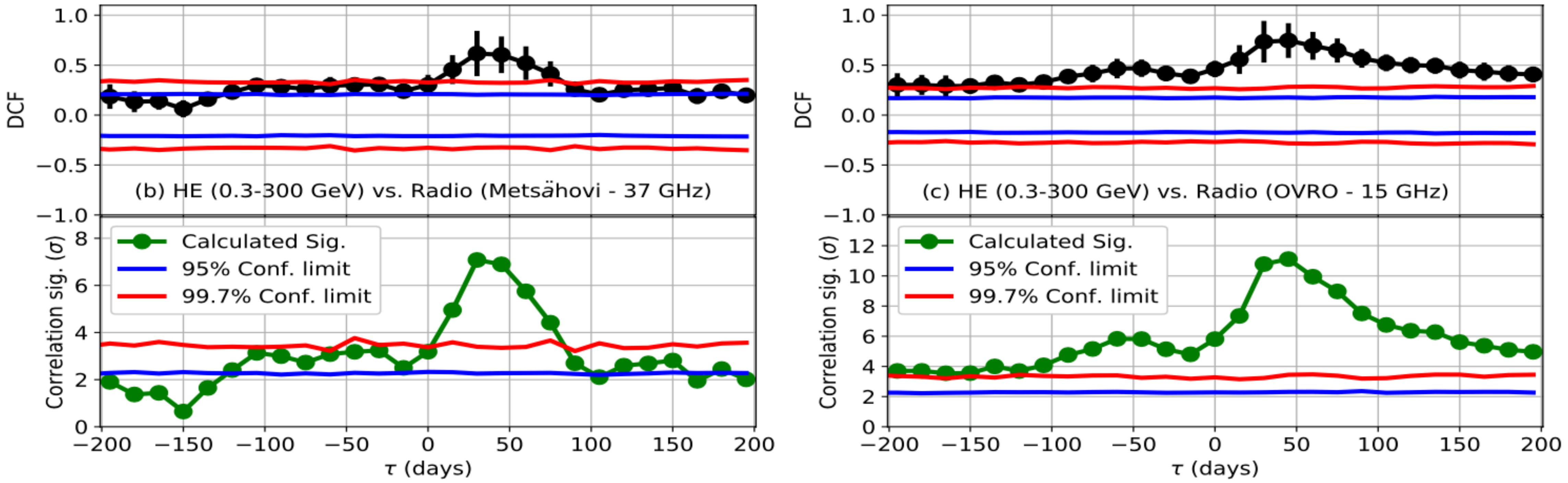
MW variability and correlation studies of Mrk 421 during historically low X-ray and γ-ray activity in 2015-2016

Radio-γ delay in Mrk 421 (months)

~ 2 months

Magic coll. 2020



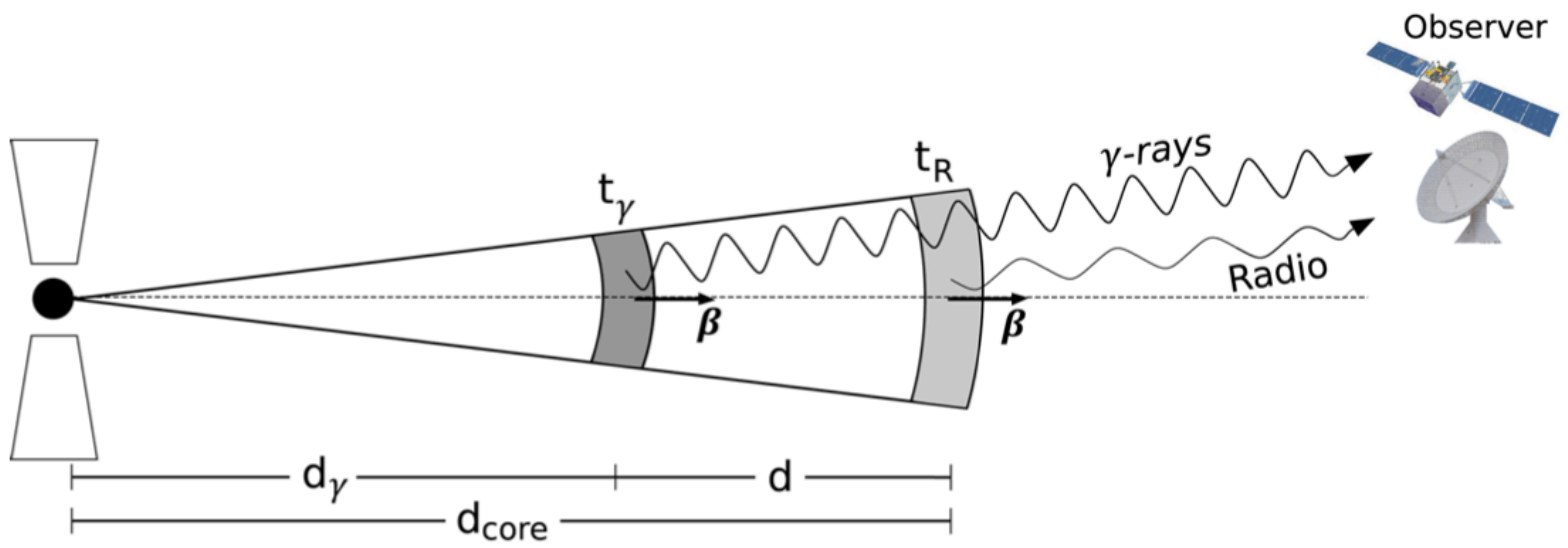


Radio-γ delay ~ 1/ν

what we want to test

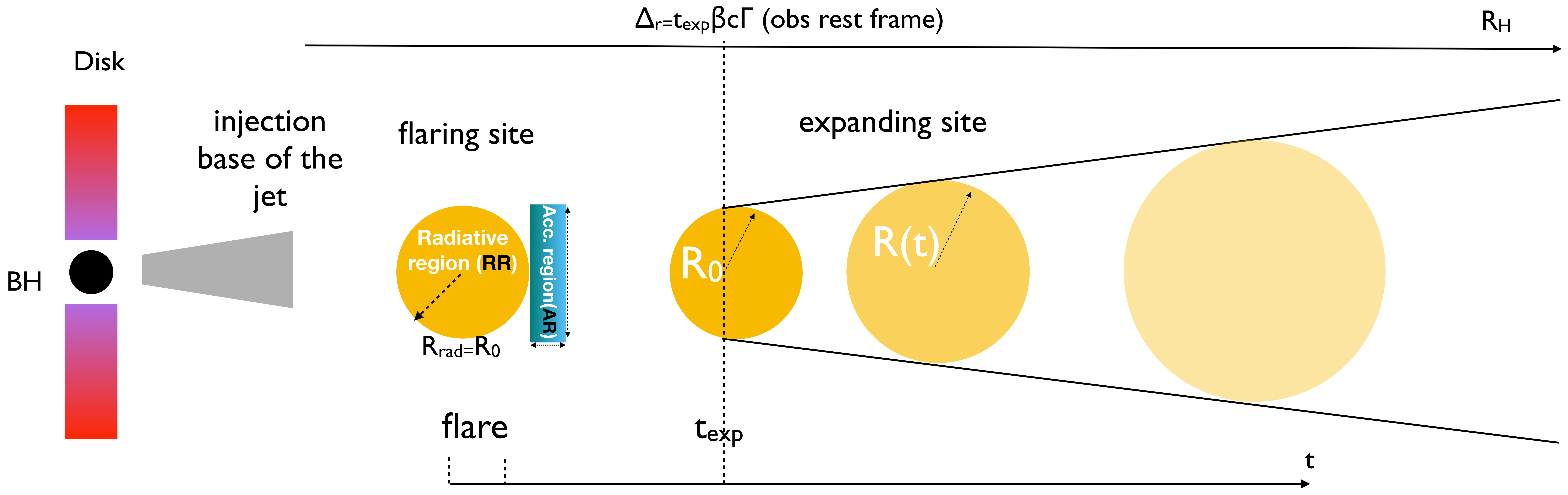
- Observed lags are not compatible with cooling, acc., crossing (unless strong fine tuning)
- Explanations based on reacceleration, would be challenging due to MW observations

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



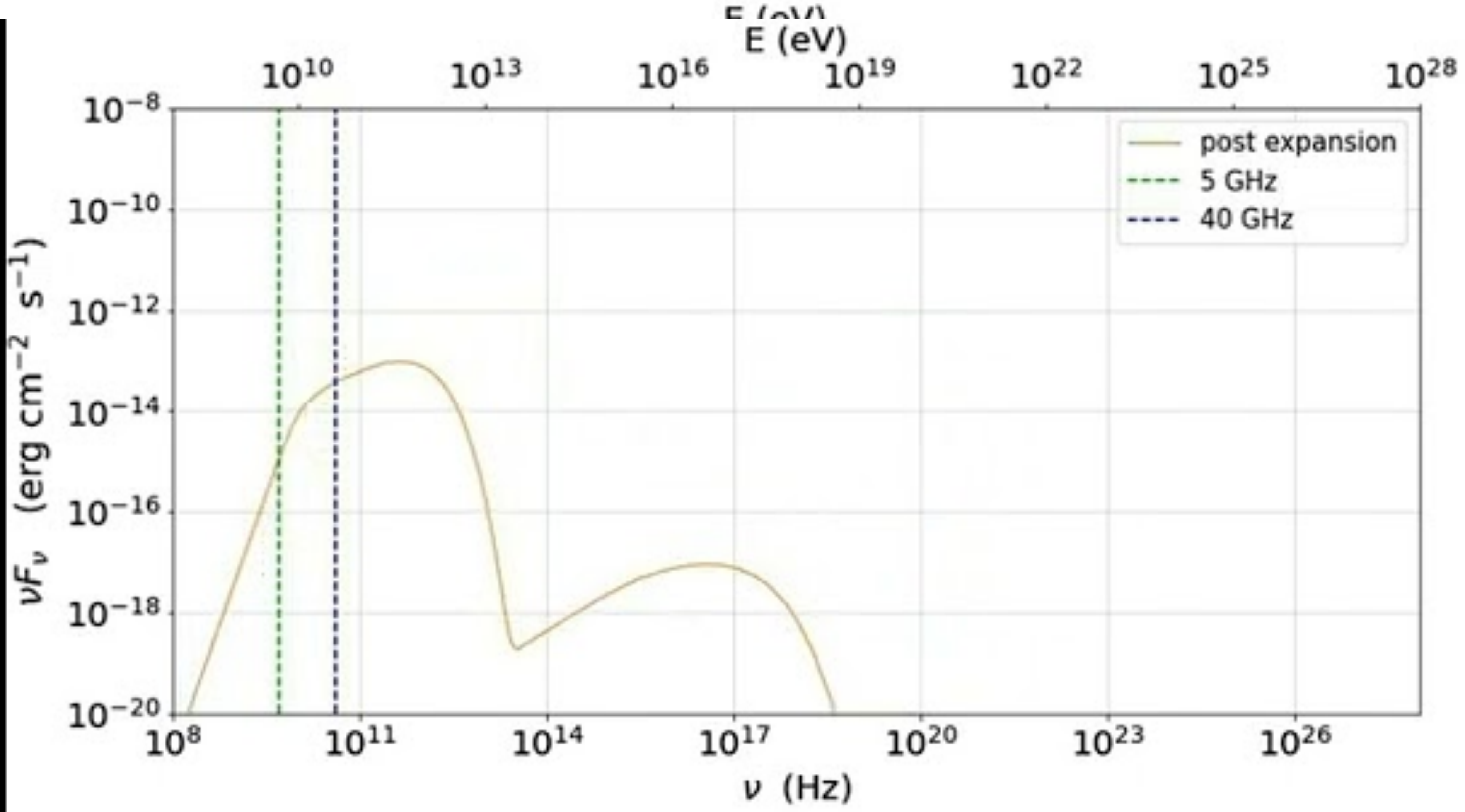
W. Max-Moerbeck+ 2014
B. Pushkarev+ 2010
McCray,R. 1968

self-consistent approach

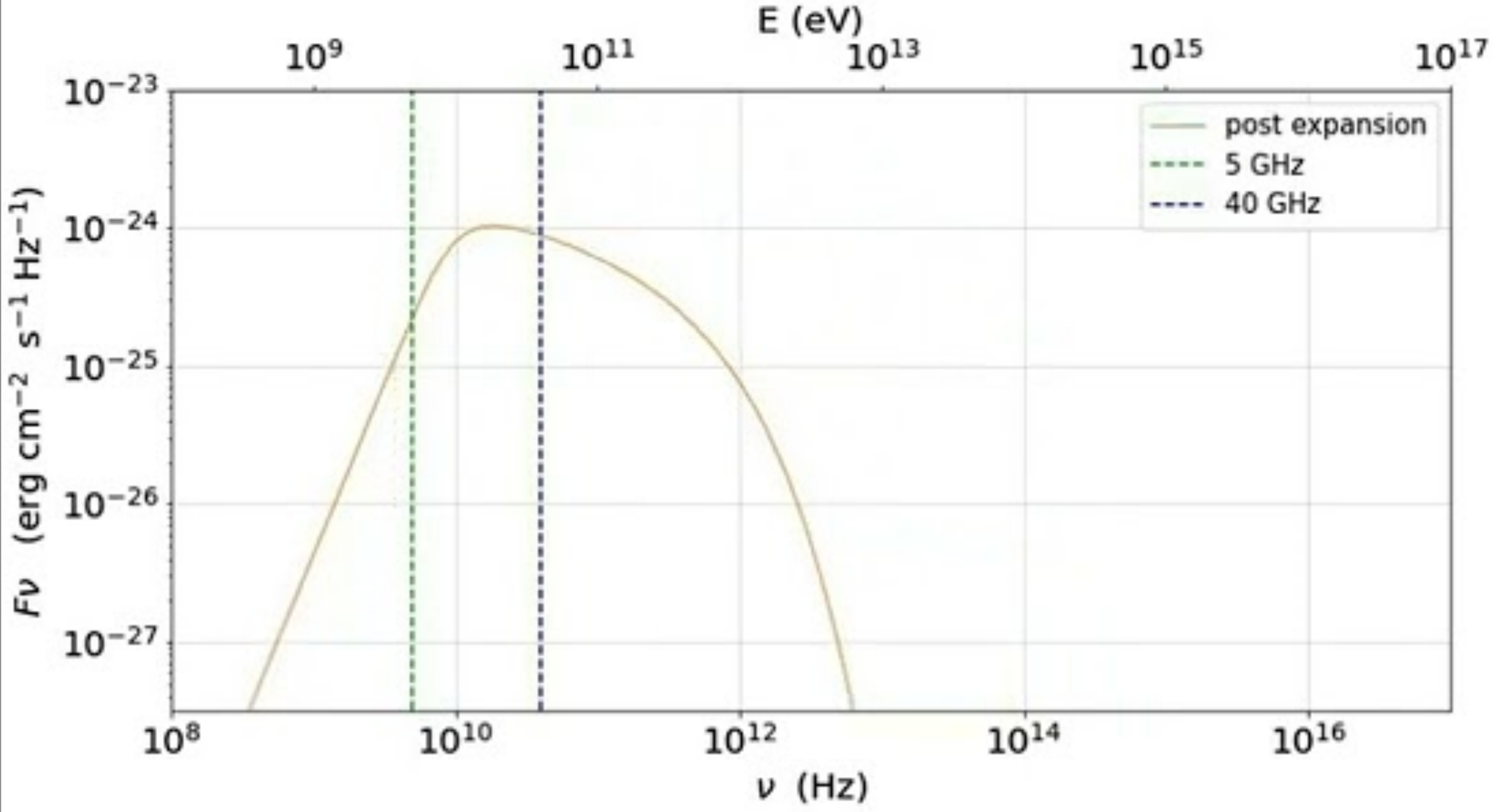


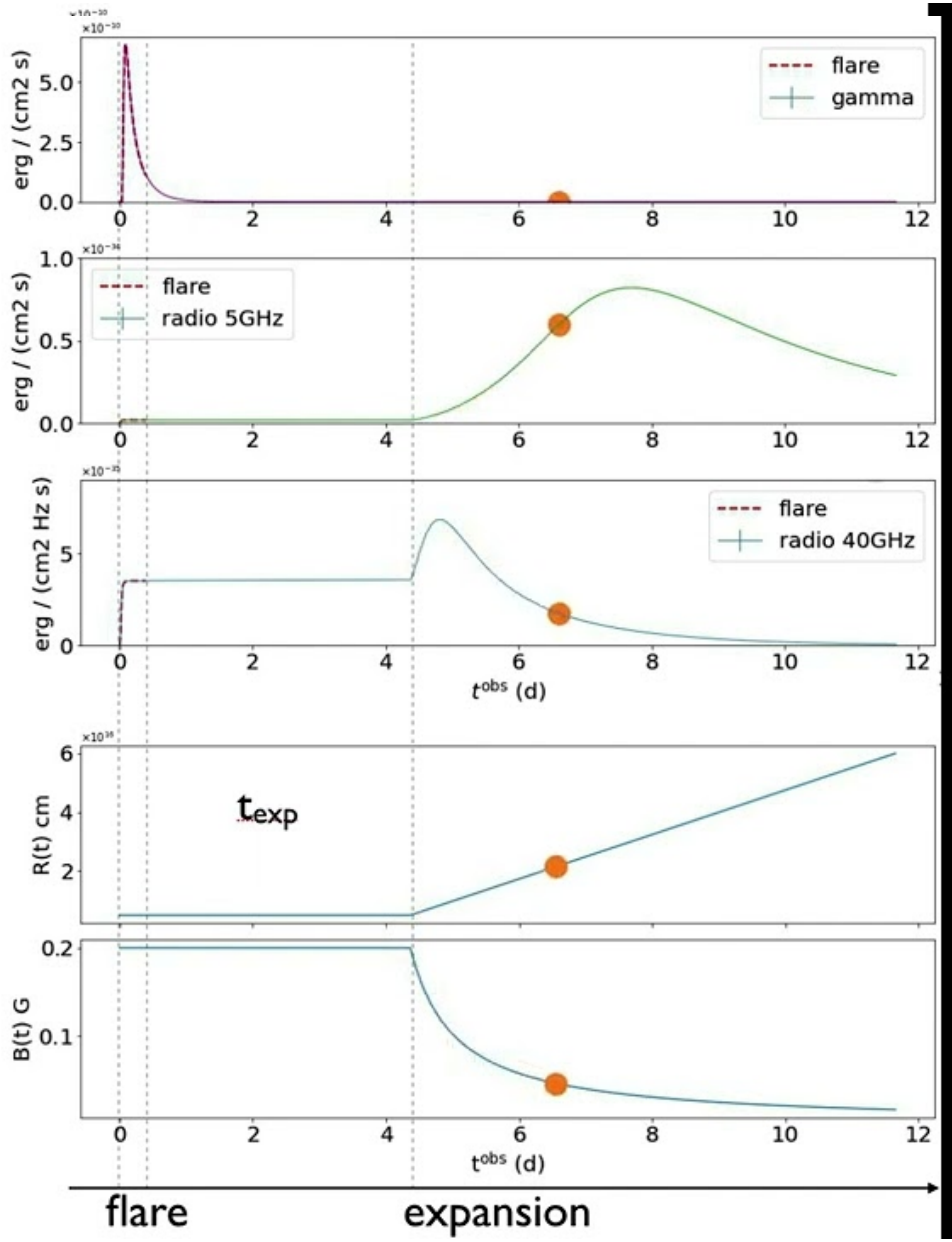
Numerical solution of FP equation taking into account:

- **FI+FII(first order and stochastic acceleration)**
- **Radiative cooling: Sync+IC(SSC)**
- **Adiabatic expansion/cooling**



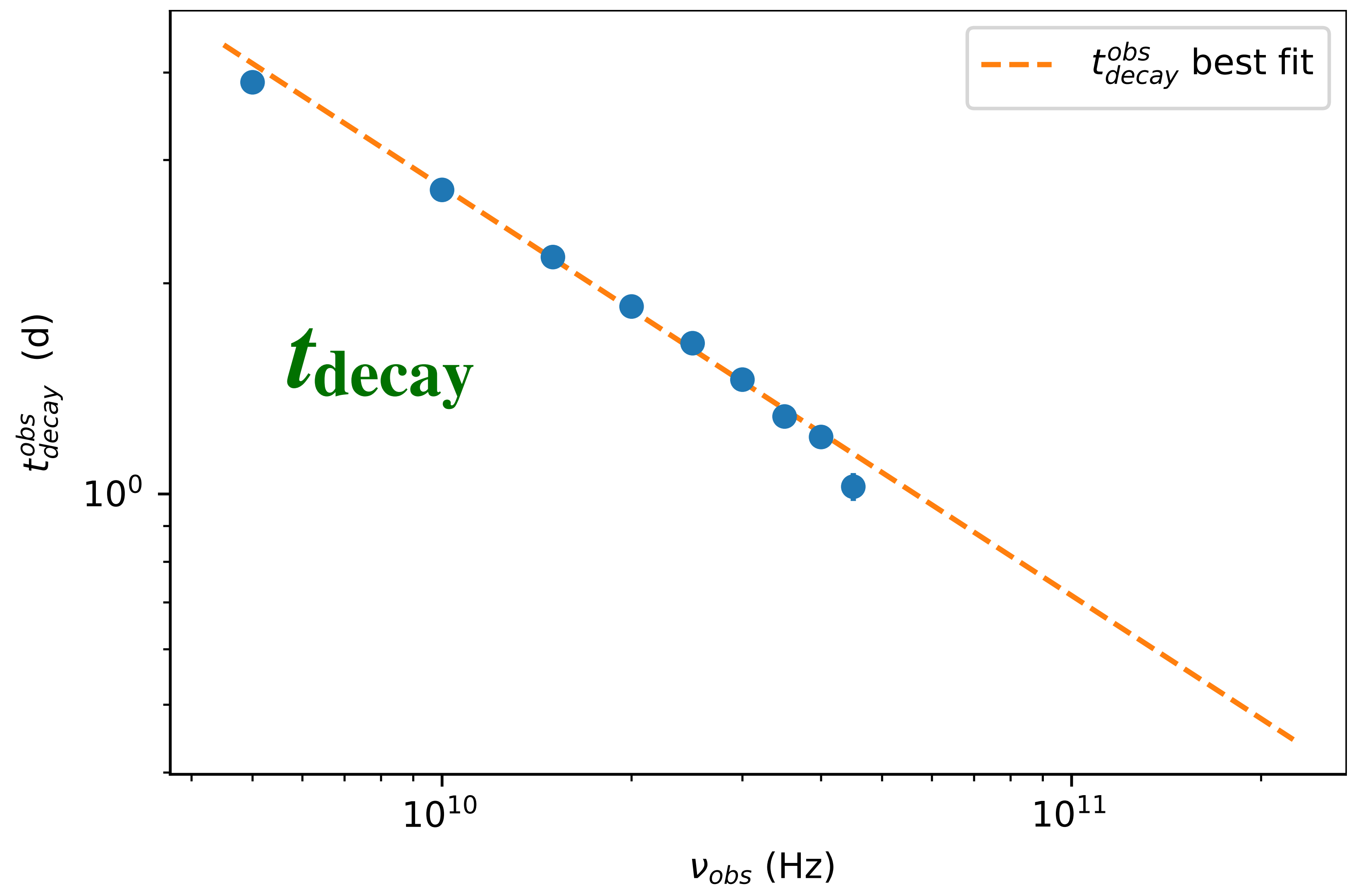
- duration~$3\mathrm{x}10^{7}$ s (blob frame)~ 11 d obs
- t_{exp}=$1\mathrm{x}10^{7}$ s
- β_{exp}=0.1c

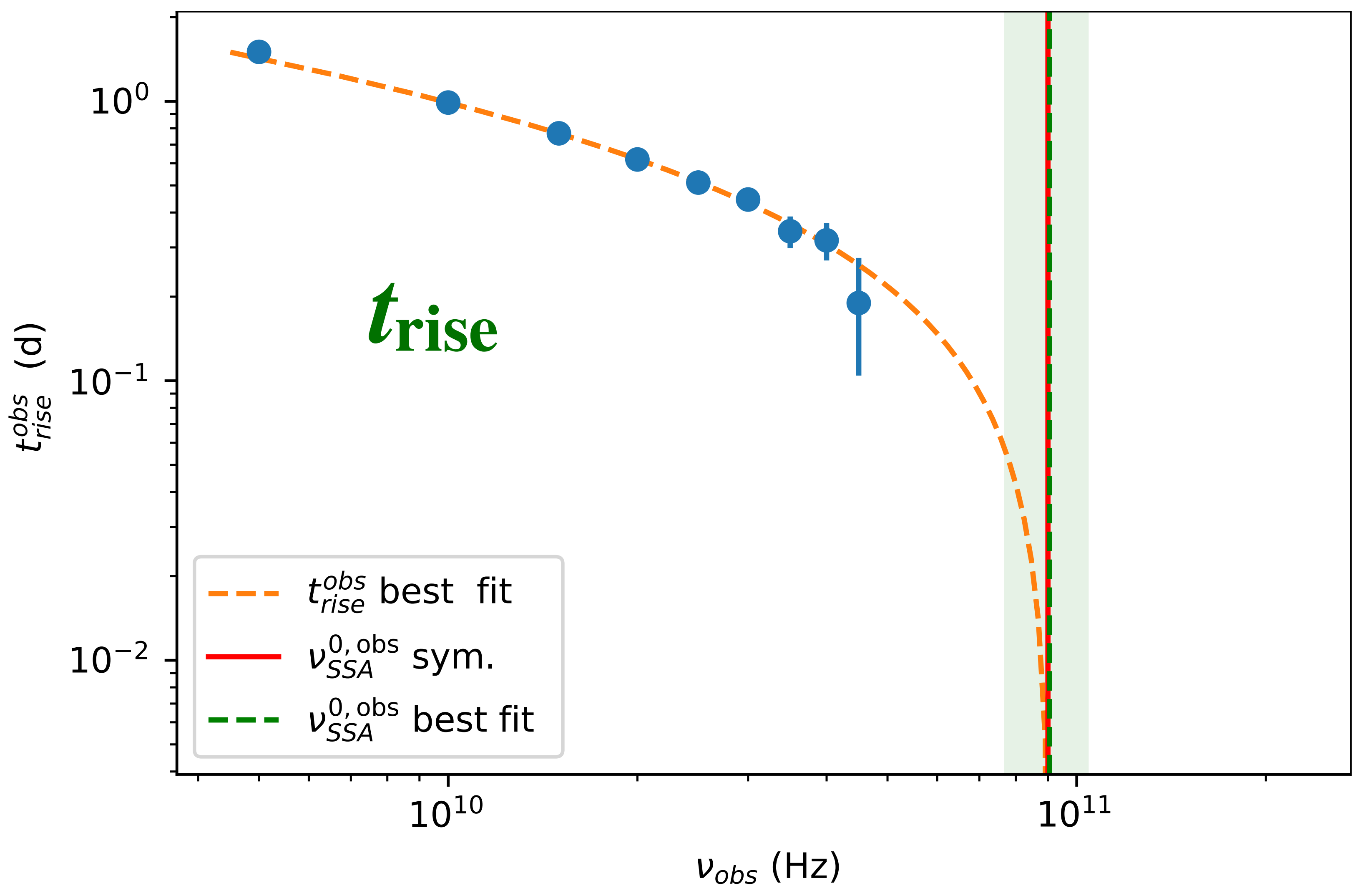




phenomenological trends ν_{obs}

Tramacere+ 2022

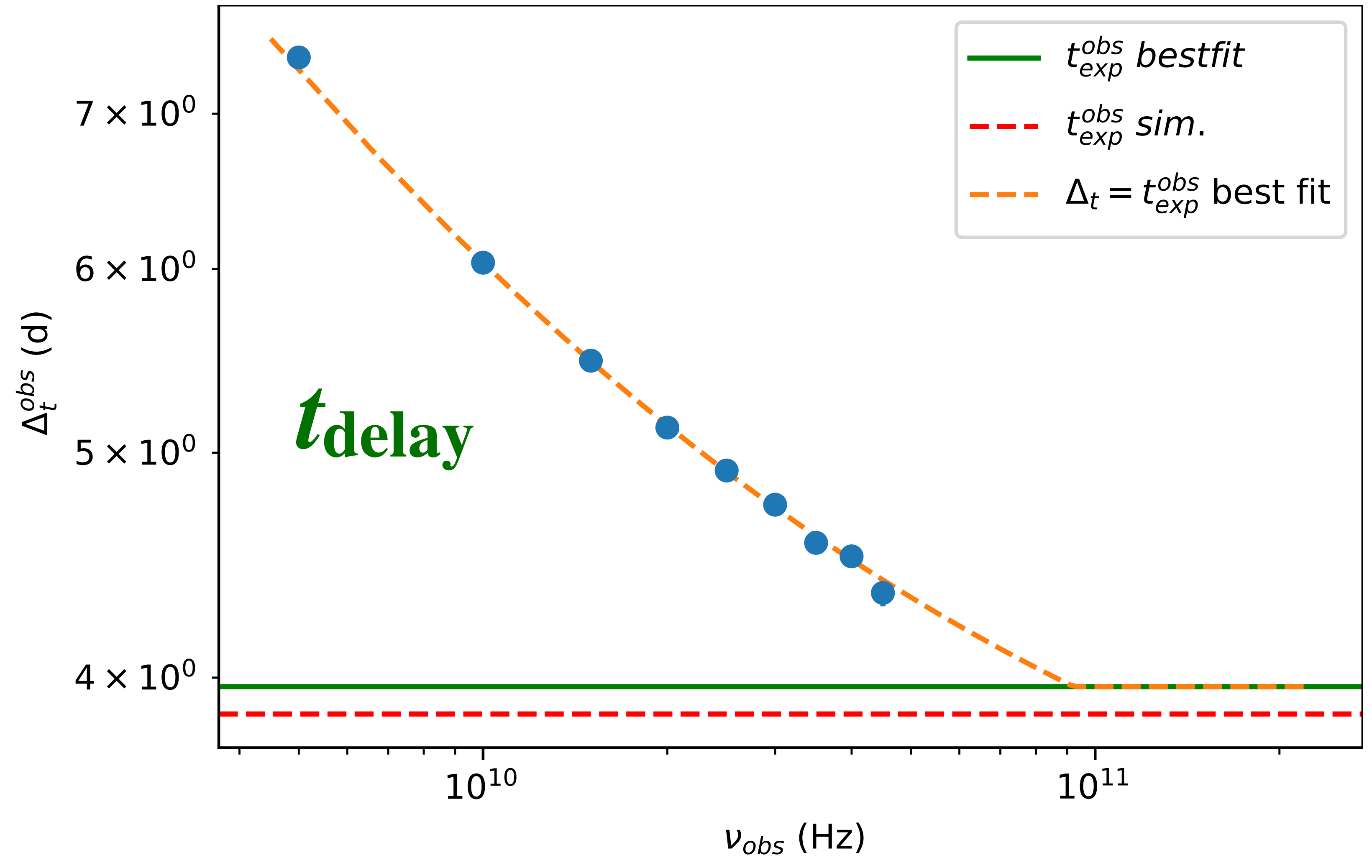




β_{exp}=[0.1]

● results from simulations

- - - phenomenological trend



$t_{[rise,\,decay,\,delay]}=f(m_B, \beta_{exp}, \nu_{ssa}, B, R, p)$

link the observables to physics

$t_{[rise,\,decay,\,delay]}\sim$ $\nu^0_{SSA}/\nu^{obs}_{SSA}$

$1/\beta_{exp}$

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

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

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

m_B=[1,2] (tor., pol.)

how to extract physics from the data?

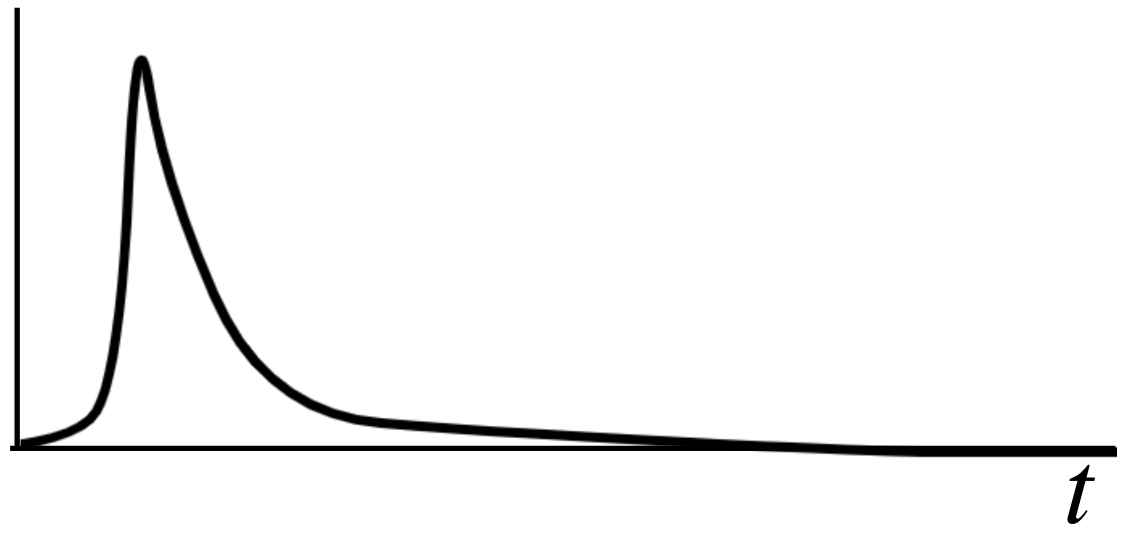
✓ **Numerical self-consistent simulations reproduce the radio-gamma delay due to adiabatic expansion!**

✓**phenomenological trends, derived for adiabatic expansion match numerical simulation!**

let’s extract some physics from the data!

single flare fit or….

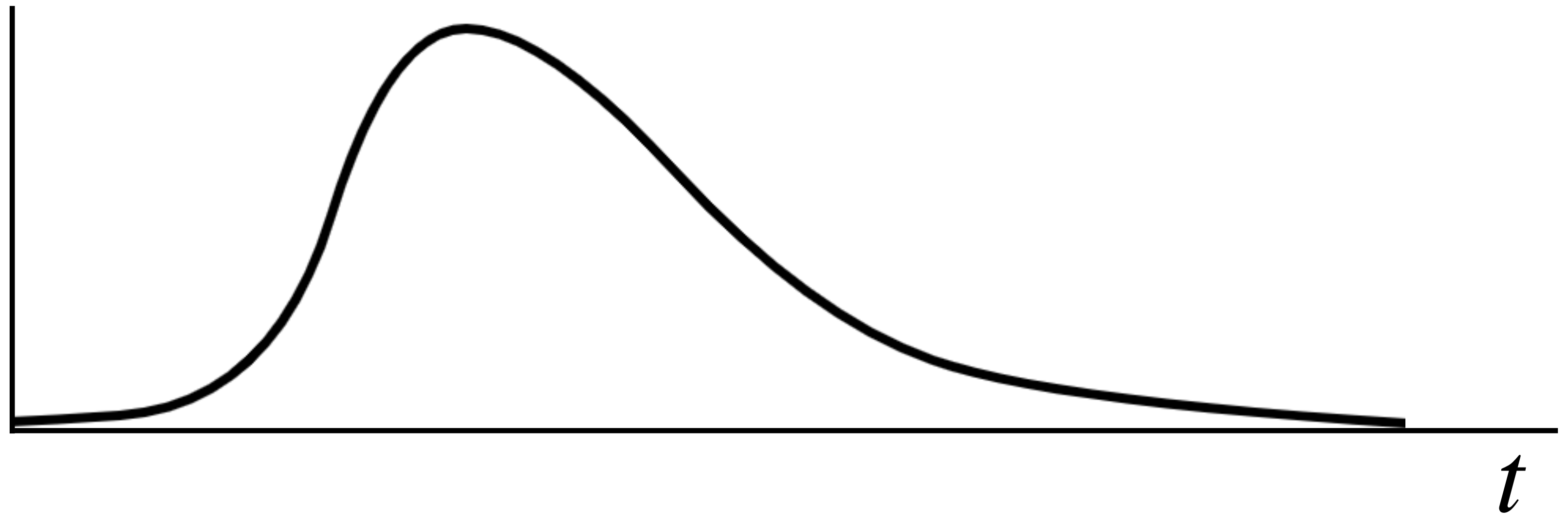
Radio-γ response



$l_\gamma(t)$

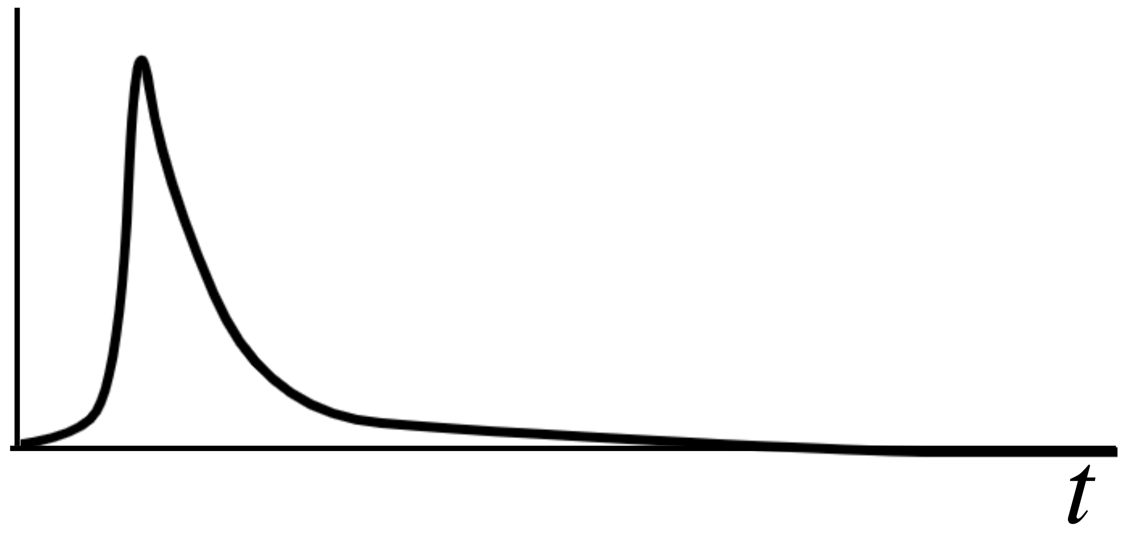
phenomenology links the observables to physics

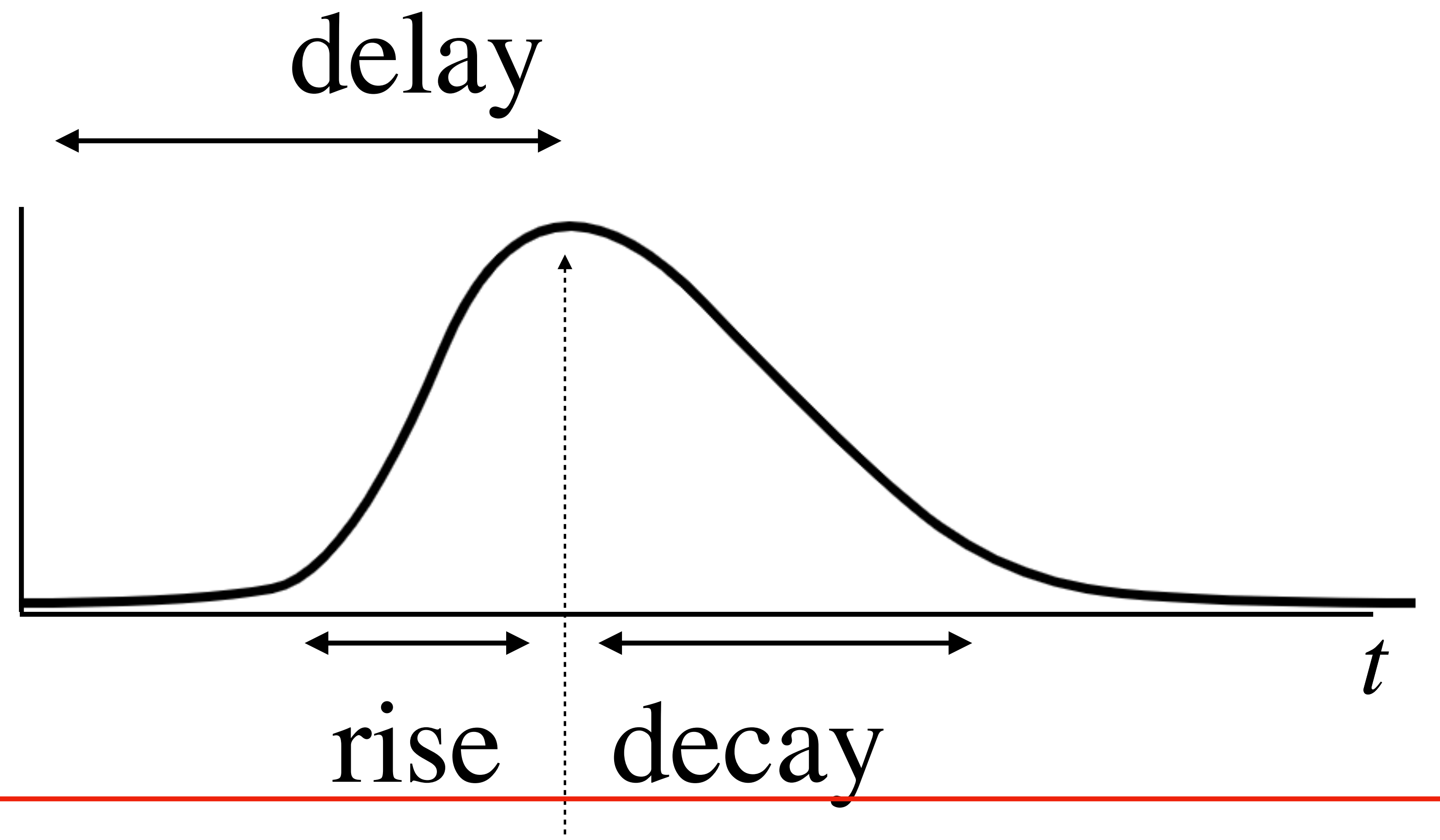
t

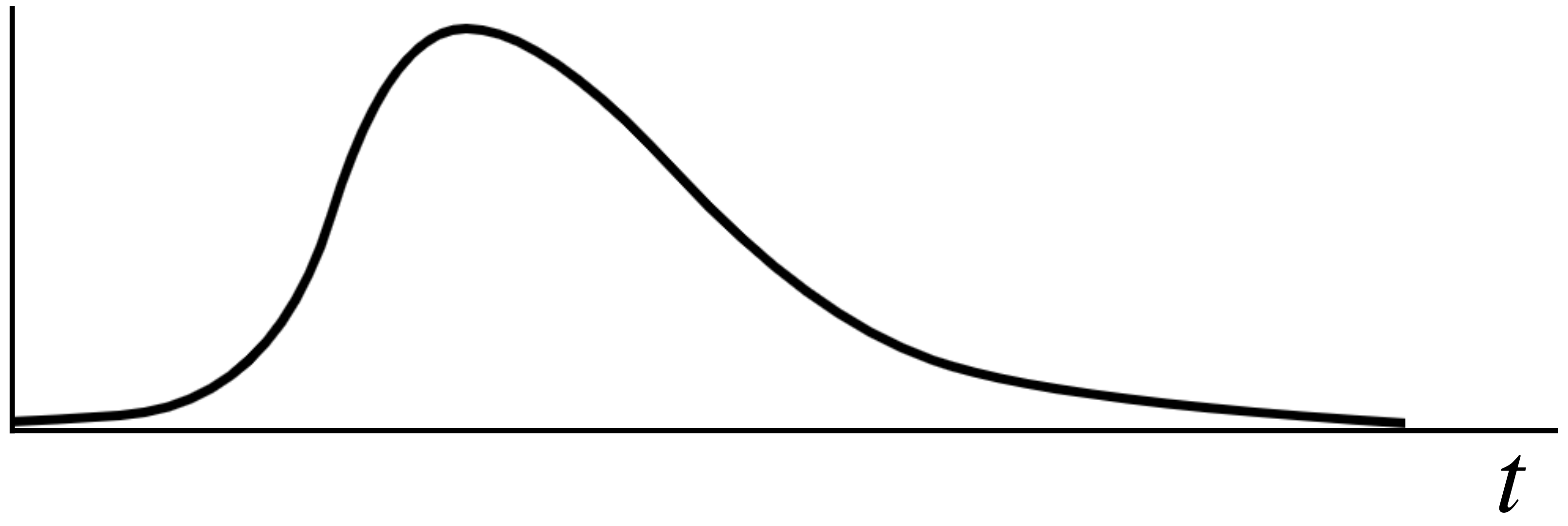


$l_R(t)$

Radio-γ response



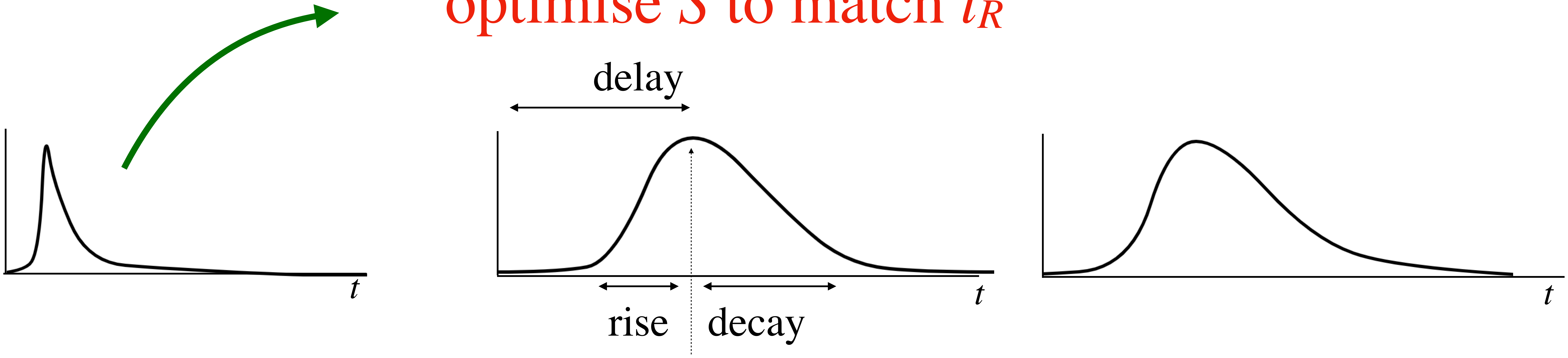




$$l_{\gamma}(t) \quad * \quad S(t, t_{rise}, t_{decay}, t_{delay}) \quad = \quad l_{R}(t)$$

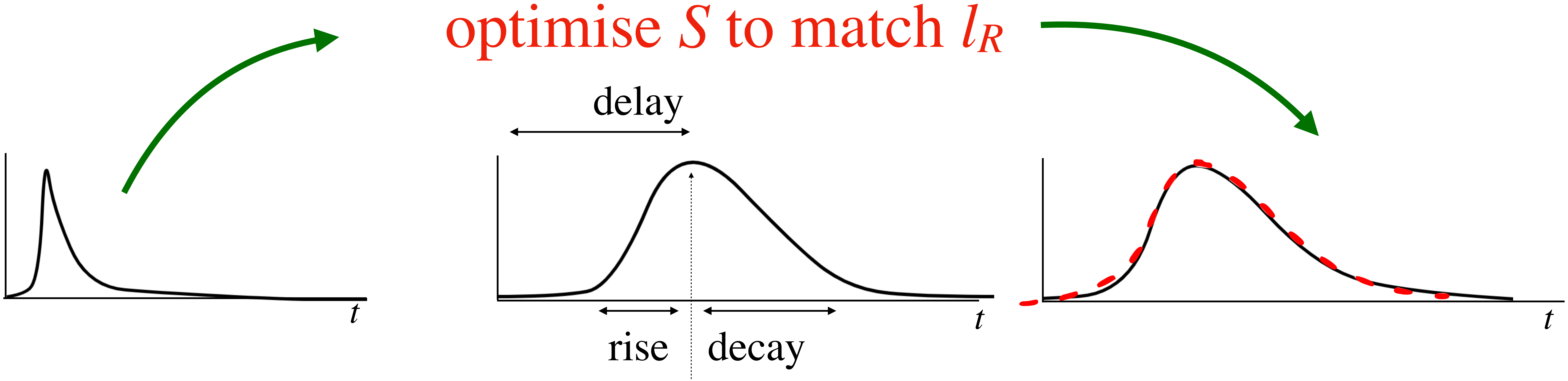
Radio-γ response

optimise S to match l_R



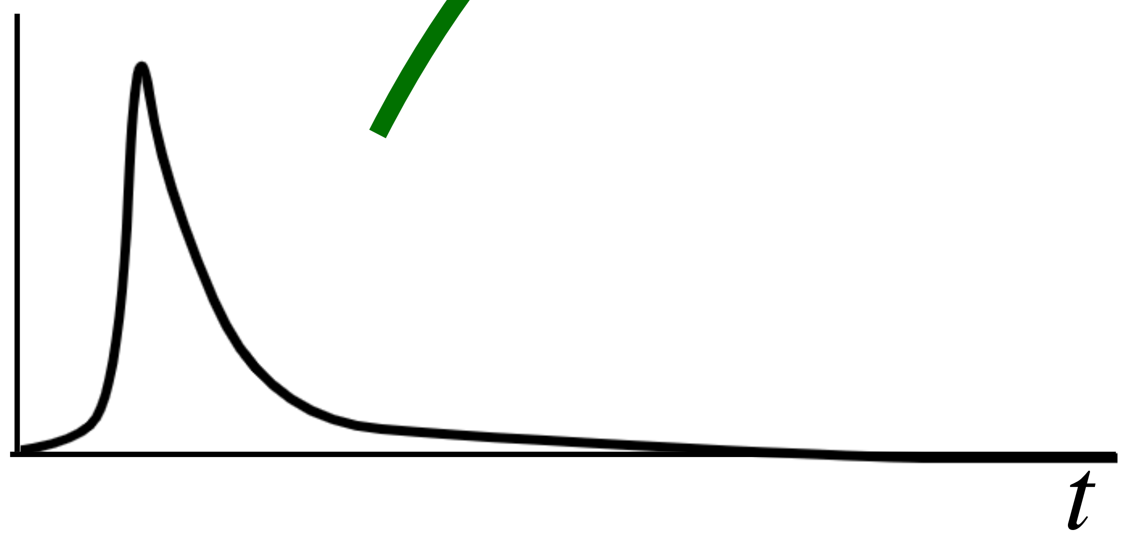
$$l_\gamma(t) \quad * \quad S(t, t_{rise}, t_{decay}, t_{delay}) \quad = \quad l_R(t)$$

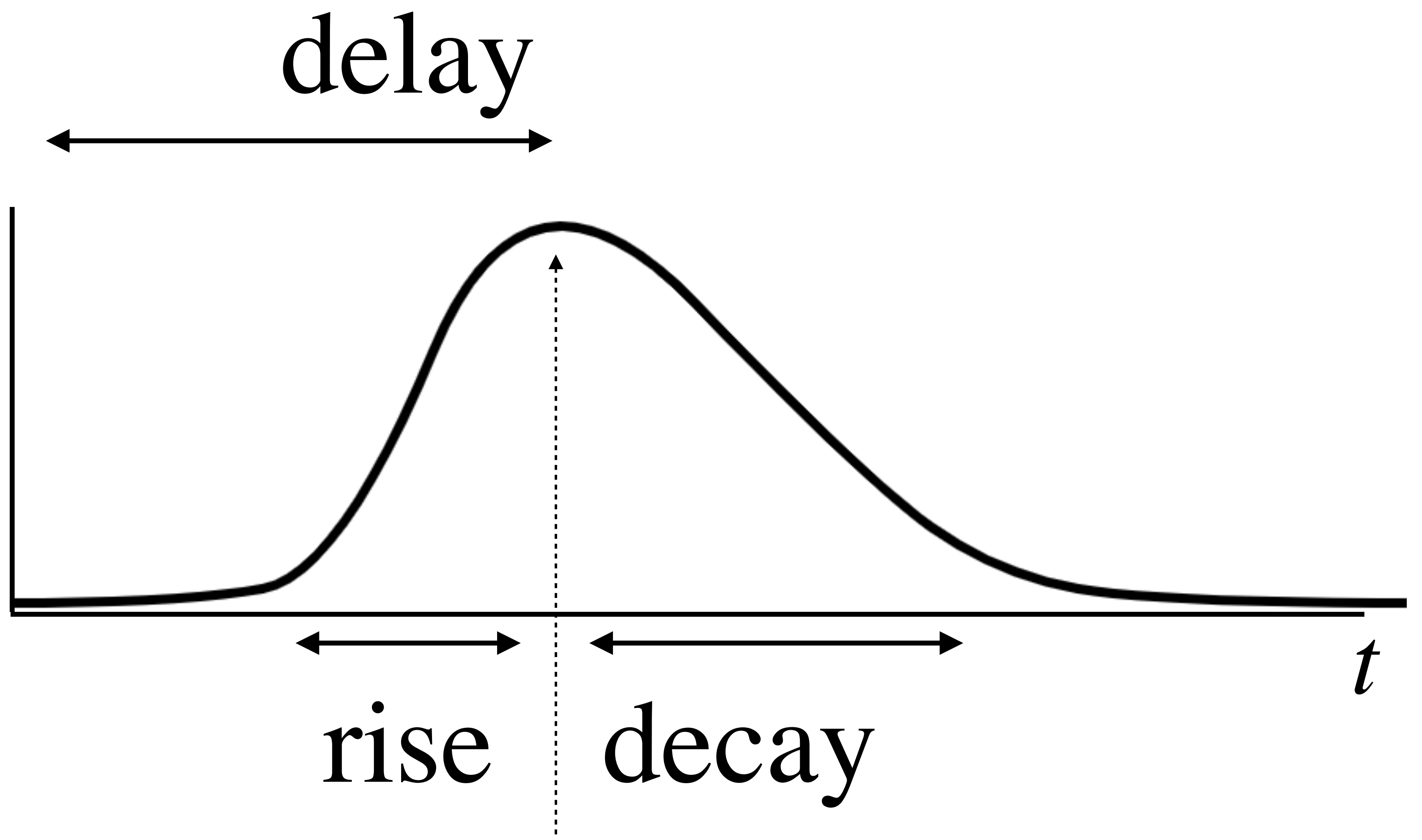
Radio-γ response

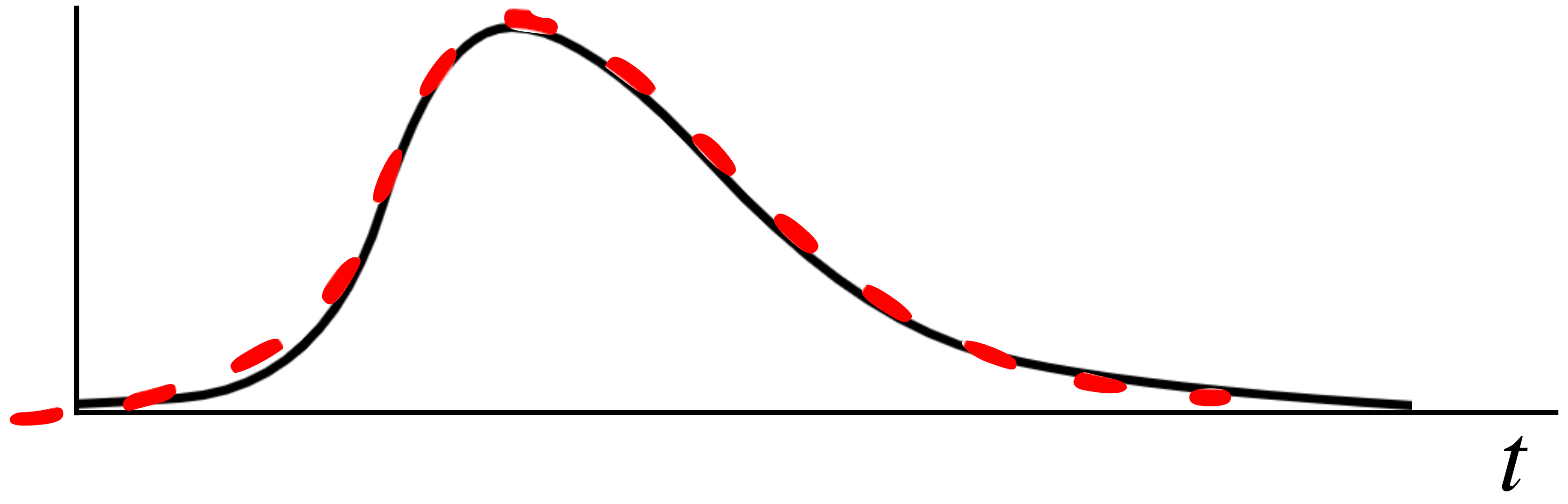


$$l_\gamma(t) \ast S(t, t_{rise}, t_{decay}, t_{delay}) = l_R(t)$$

optimise S to match l_R







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

phenomenology:

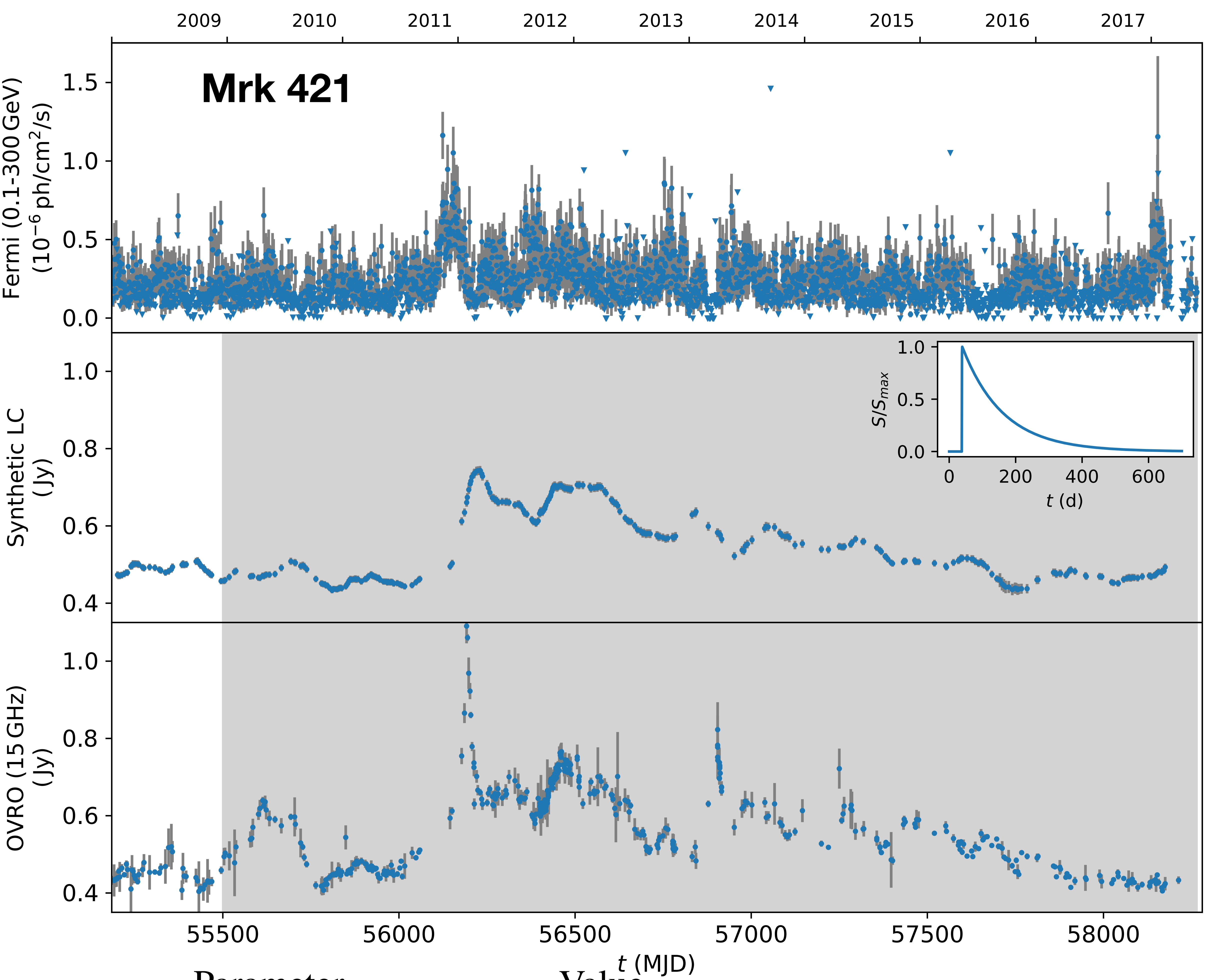
observables -> physics

$$t_{[\mathrm{rise,\ decay,\ delay}]} = f(m_B, \beta_{exp}, \nu_{ssa}, B, R, p)$$

Radio-γ response

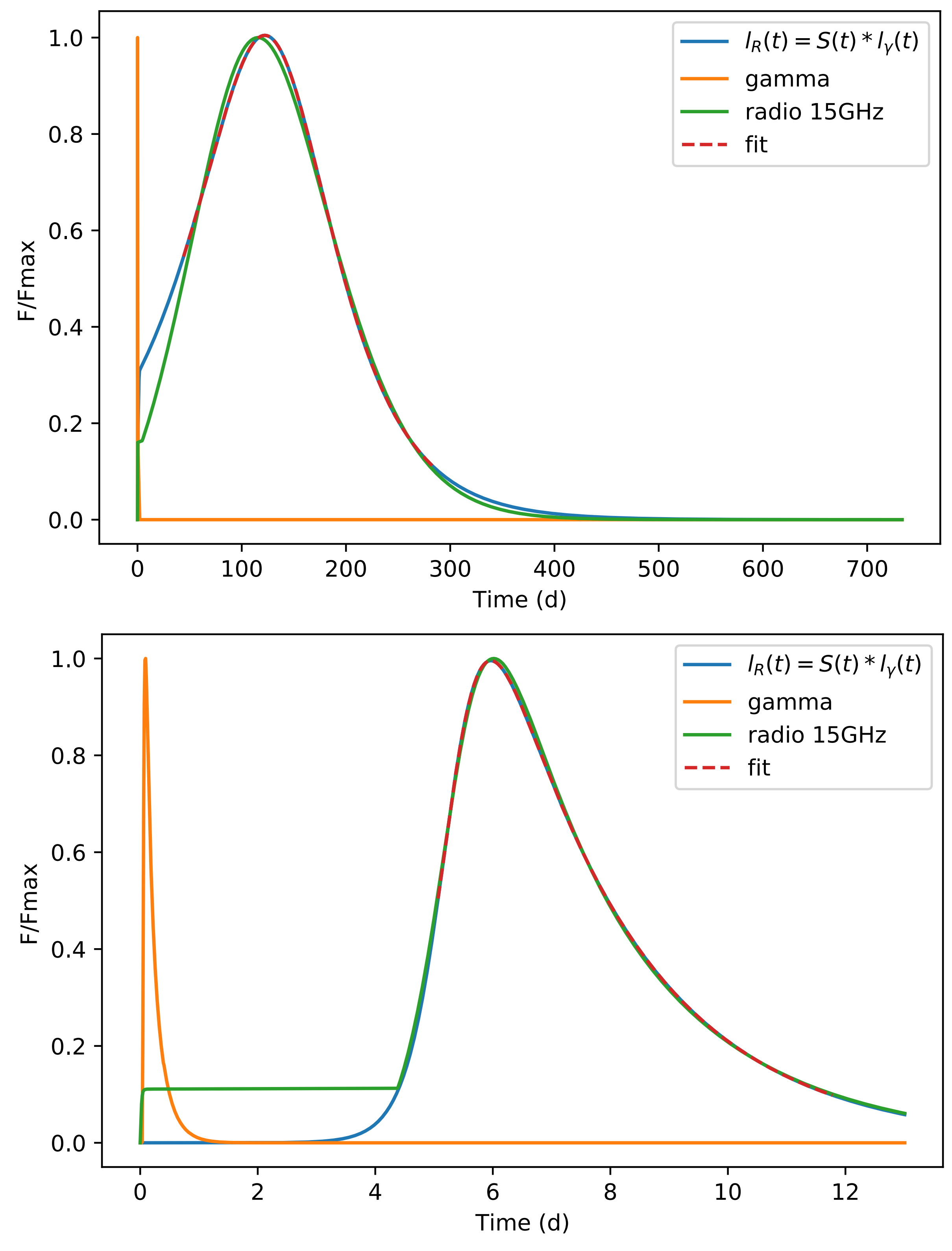
Tramacere+ 2022

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

Numerical simulation



exp-logistic

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

t^{obs}_{decay}

t^{obs}_{rise}

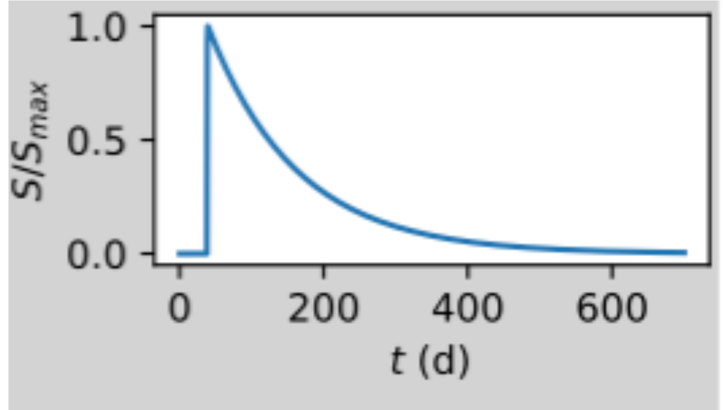
$\Delta t^{obs}_{\nu^{0,obs}_{SSA} \to \nu^{*,obs}_{SSA}}$

MCMC sampling

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

$$t_{[\rm rise,\, decay,\, delay]} = f(m_B,\, \beta_{exp},\, \nu_{ssa},\ B,\, R,\, p)$$

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



conv. analysis best fit values

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

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MCMC validation with real data

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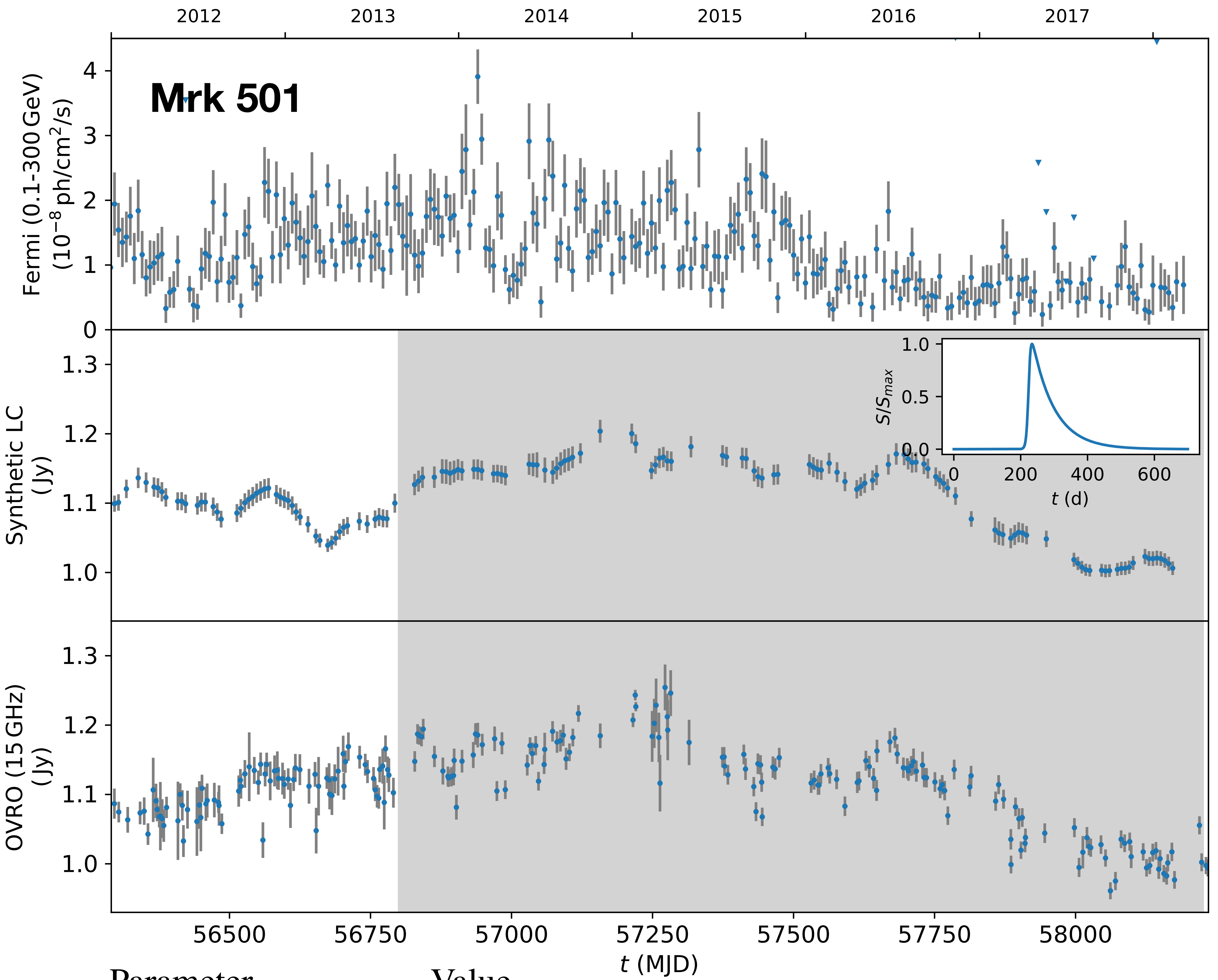
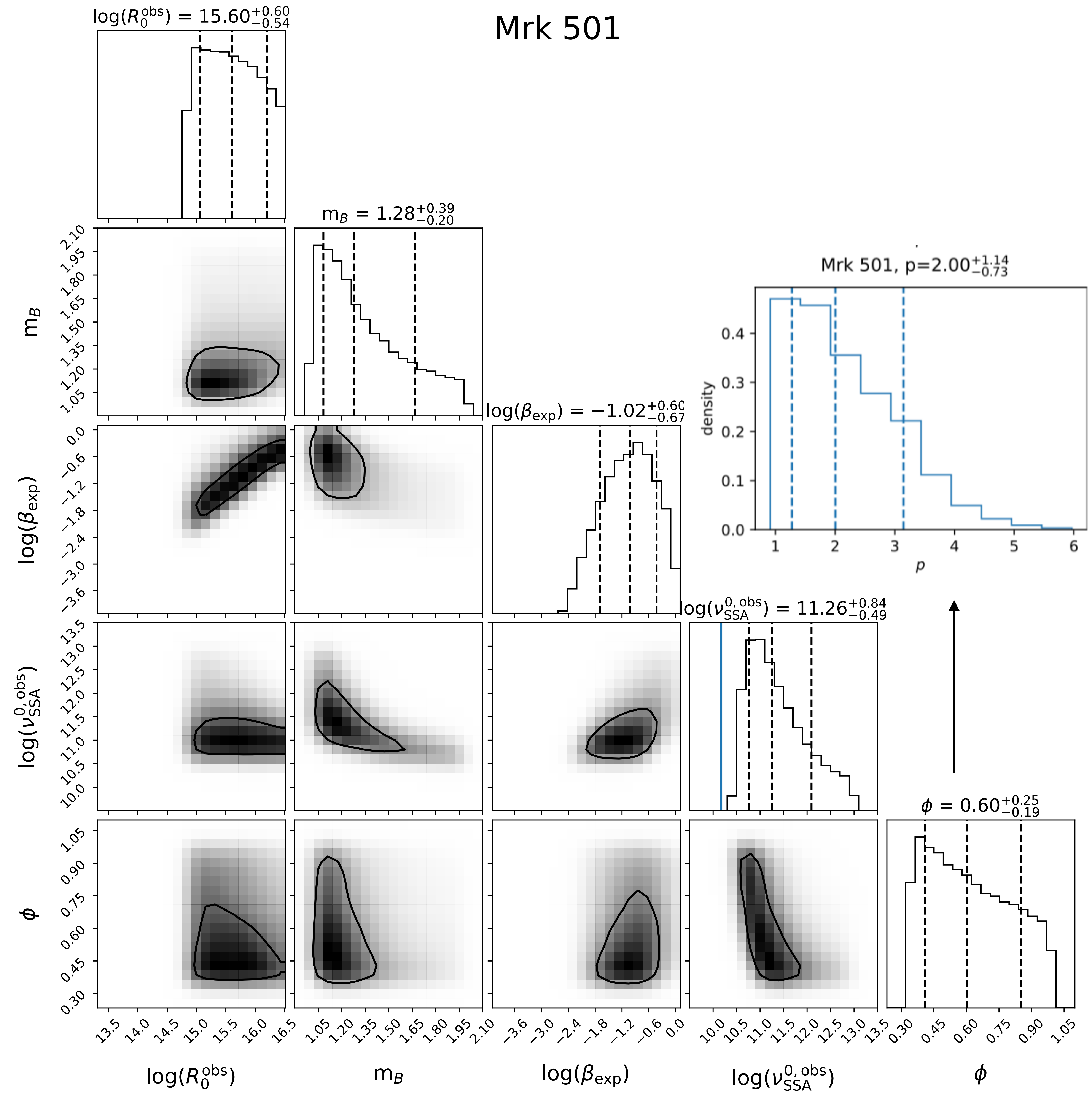


Parameter	Value
A	$166^{+5}_{3} \times 10^4$ Jy cm^2 s/ph
t_{rise}	12^{+4}_{-4} days
t_{decay}	$73^{+3.6}_{-3.6}$ days
Δt	234^{+10}_{-10} days
$F_{background}$	$0.915^{+0.004}_{-0.004}$ Jy



Conclusions

- Radio-gamma delays on weeks to year timescales can be self consistently reproduced by adiabatic blob expansion (consistent with Potter 2018, Boula 2022)

- 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

- Next: Plugging a realistic jet model with parabolic-to-conical transition, plus EC and crossing time effect, and application to a large sample of BL Lacs and FSRQs

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

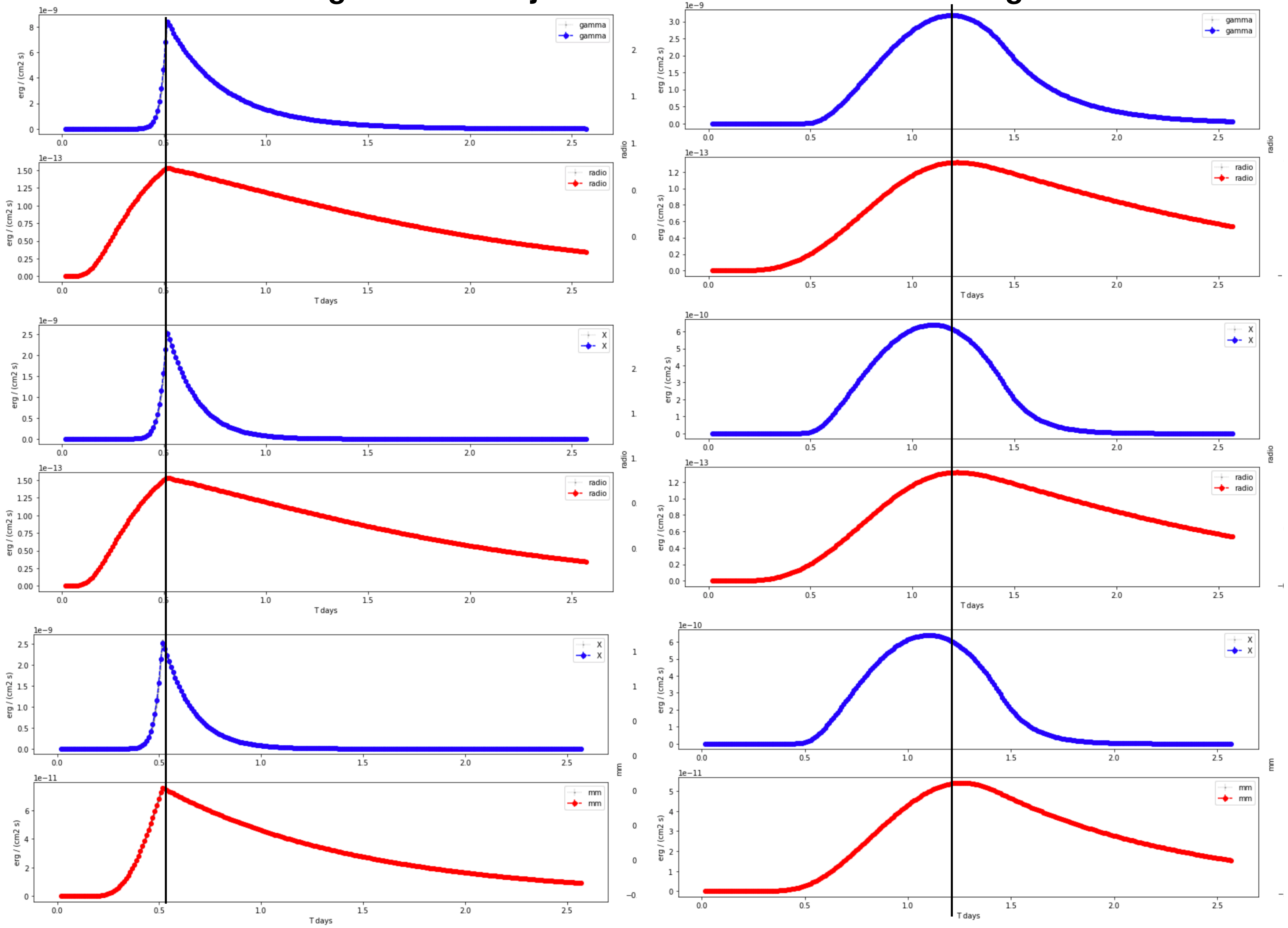
https://github.com/andreatramacere/adiabatic_exp_radio_gamma_delay

https://jetset.readthedocs.io/en/1.2.2/

backup slides

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

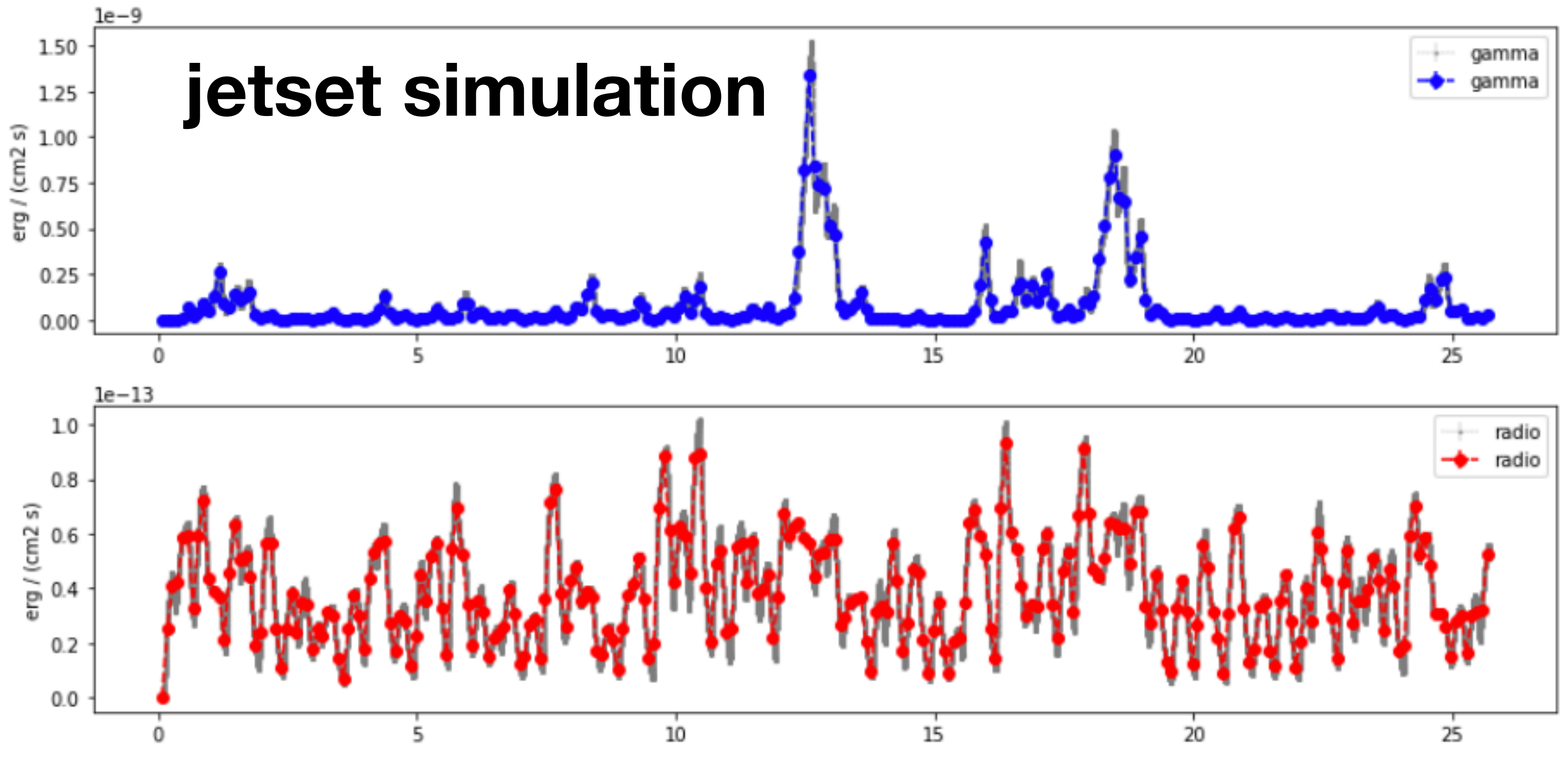
no crossing time   jetset simulation   with crossing time

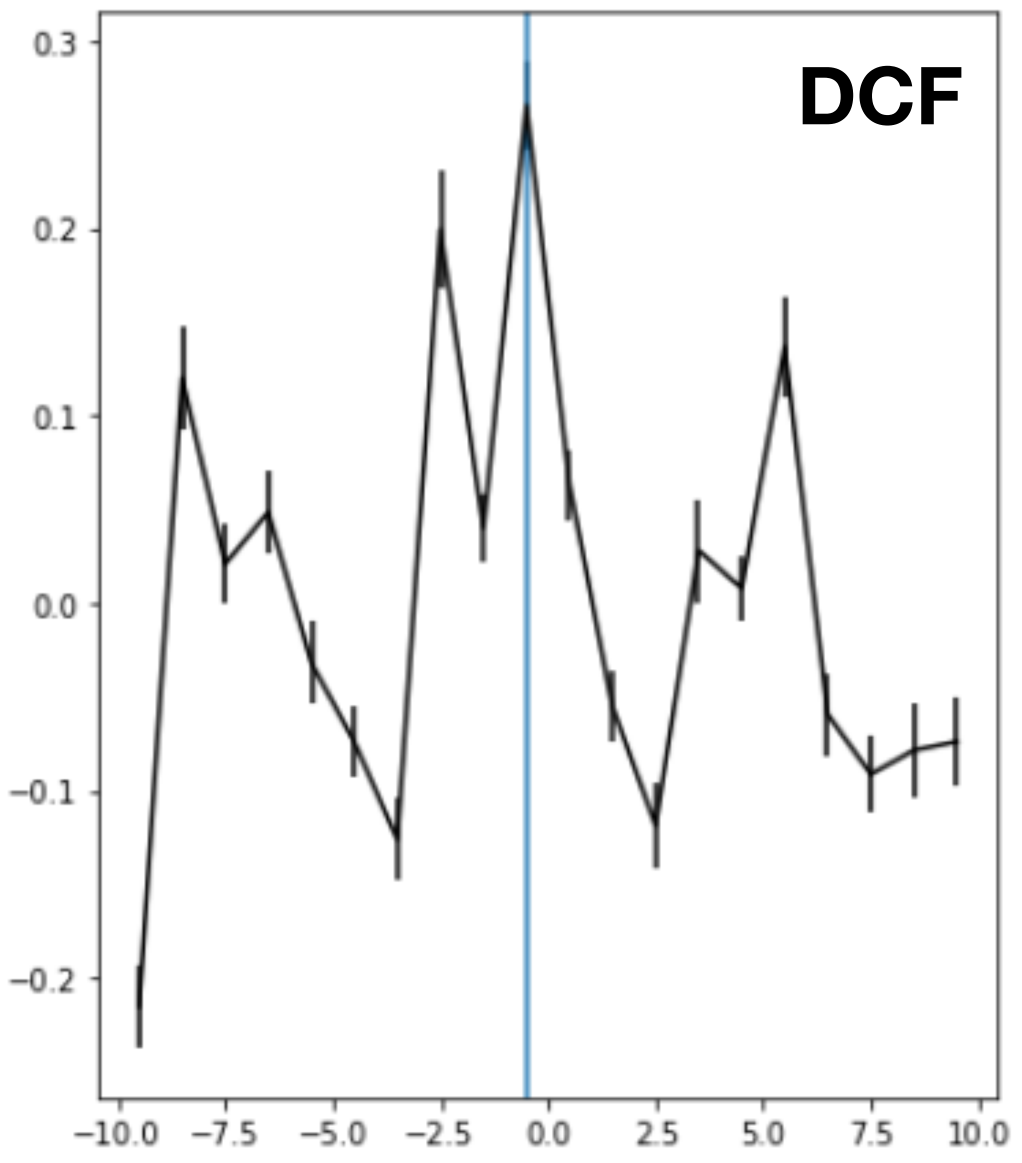


hours to days

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

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



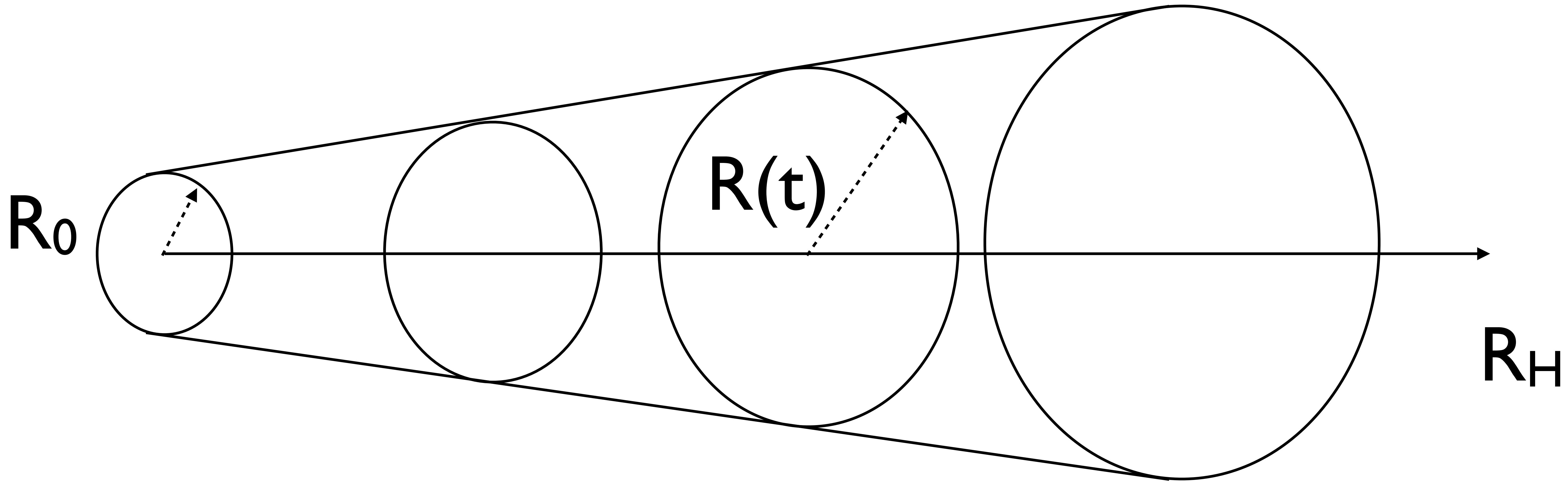


blob expansion

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

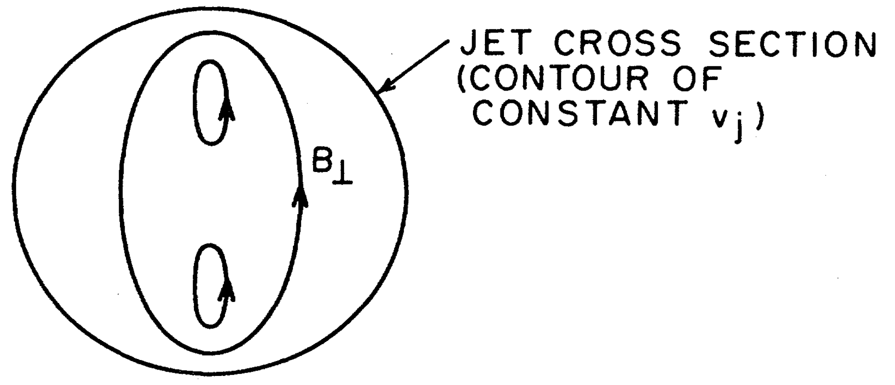
$$R(t) = R_0 + \beta_{\rm exp} c(t - t_{exp}) H(t - t_{exp})$$

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



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

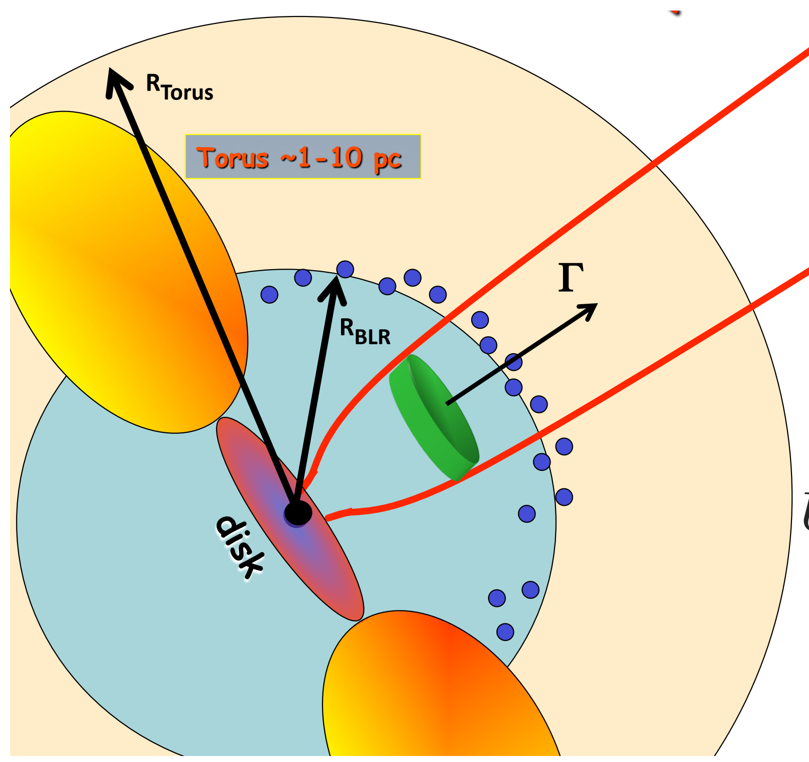
- $B|| \alpha R^{-2}$ (poloidal) m_B=2
- $B \perp \alpha R^{-1}$ (toroidal) m_B=1
- for initial mixed configuration, **and no velocity gradient**, B⊥ will dominate with $m_B \sim m_R$



Blazars in a nutshell

FSRQs
HERGs

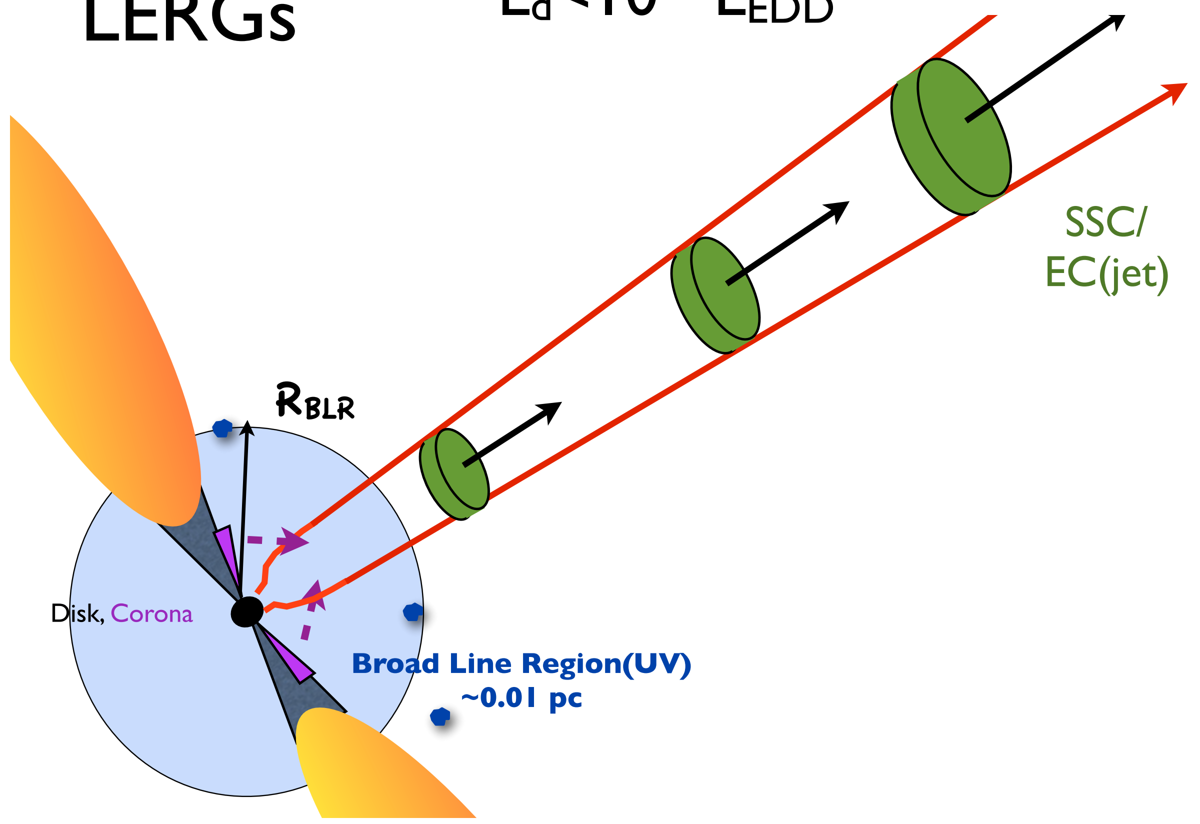
rad eff.
$L_d > 10^{-2} L_{EDD}$

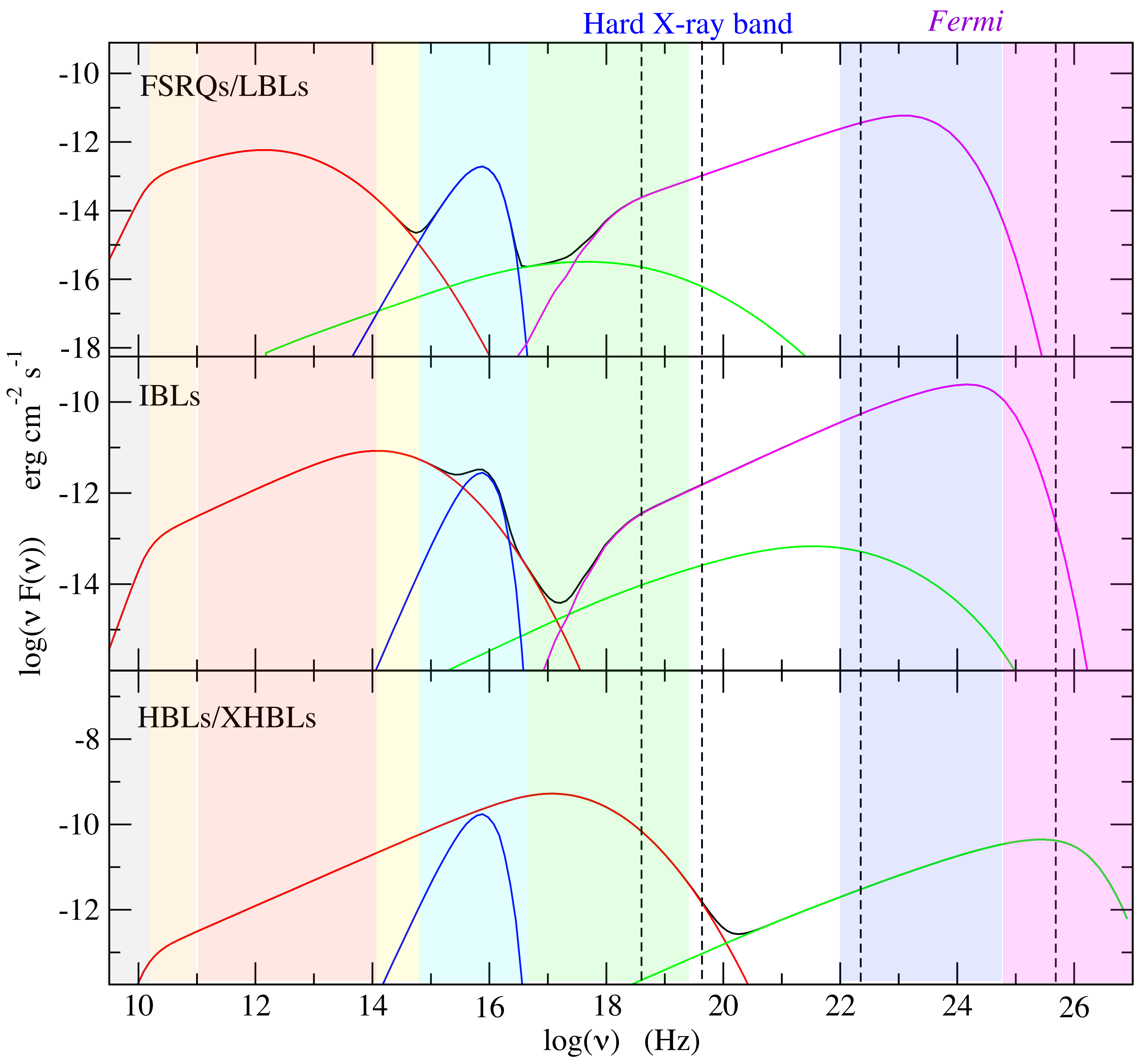


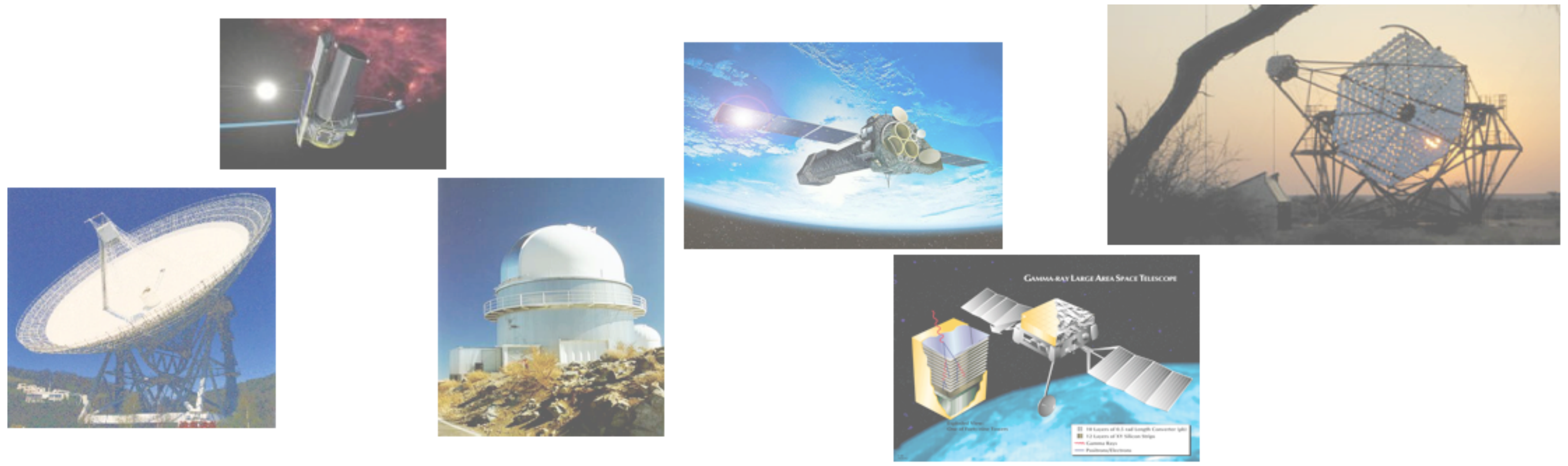
$$U_{ext} \simeq \frac{L_d}{R^2_{ext}\, c}$$
$$R_{ext} \simeq L_d^{1/2}$$

BL Lacs
LERGs

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



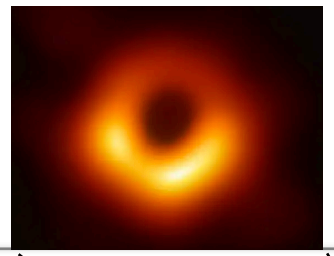




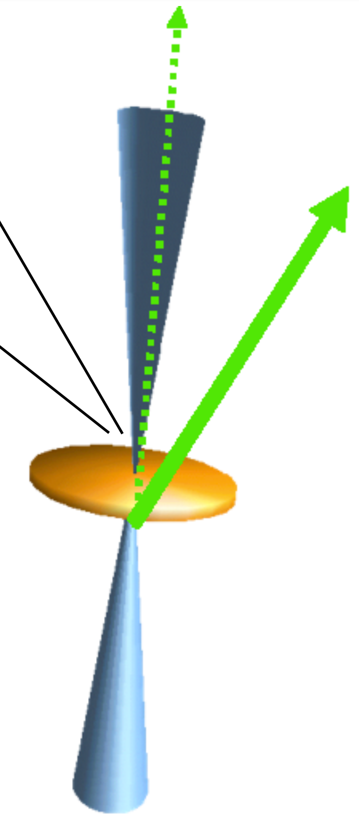
phenomenology

model fit

simulations

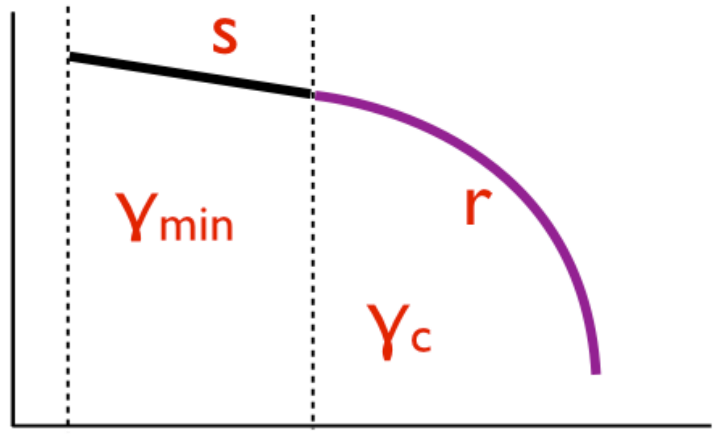


jet/disk



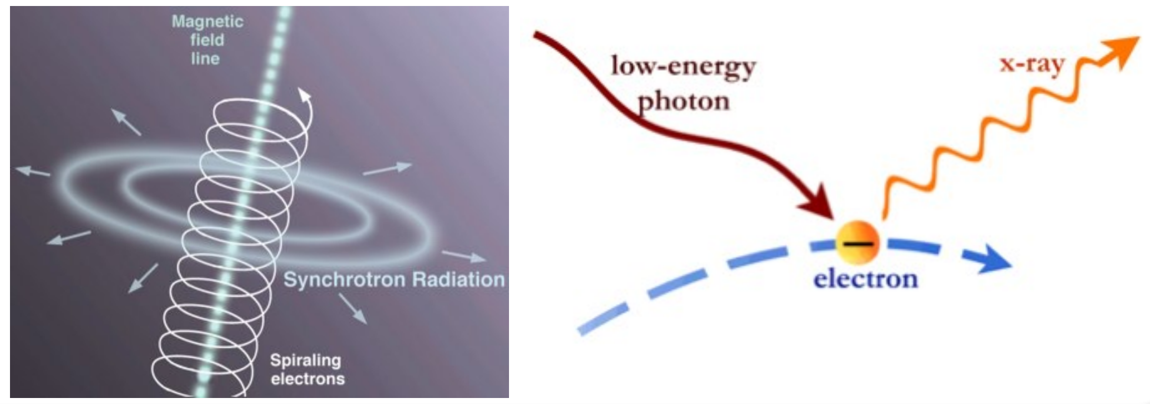
+

acc.

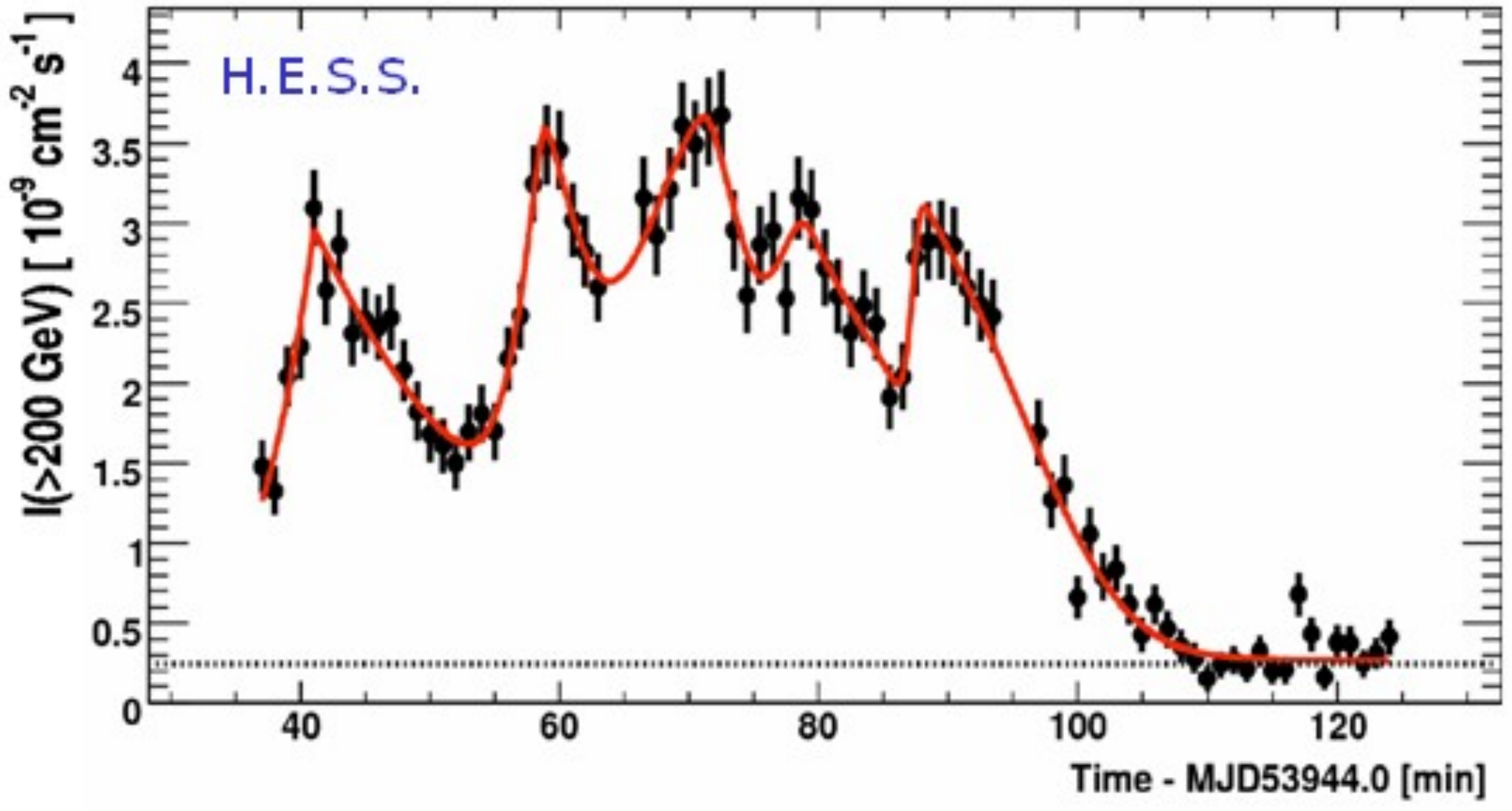


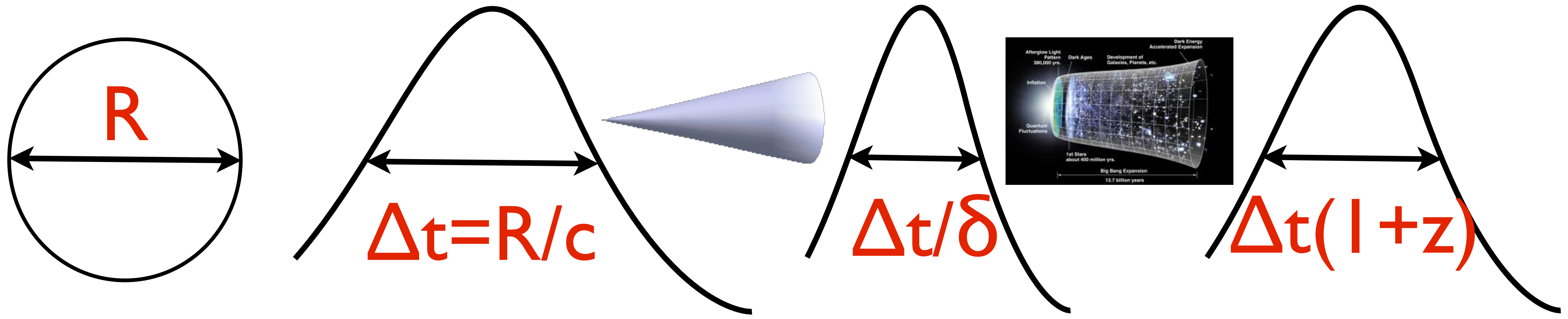
+

em.

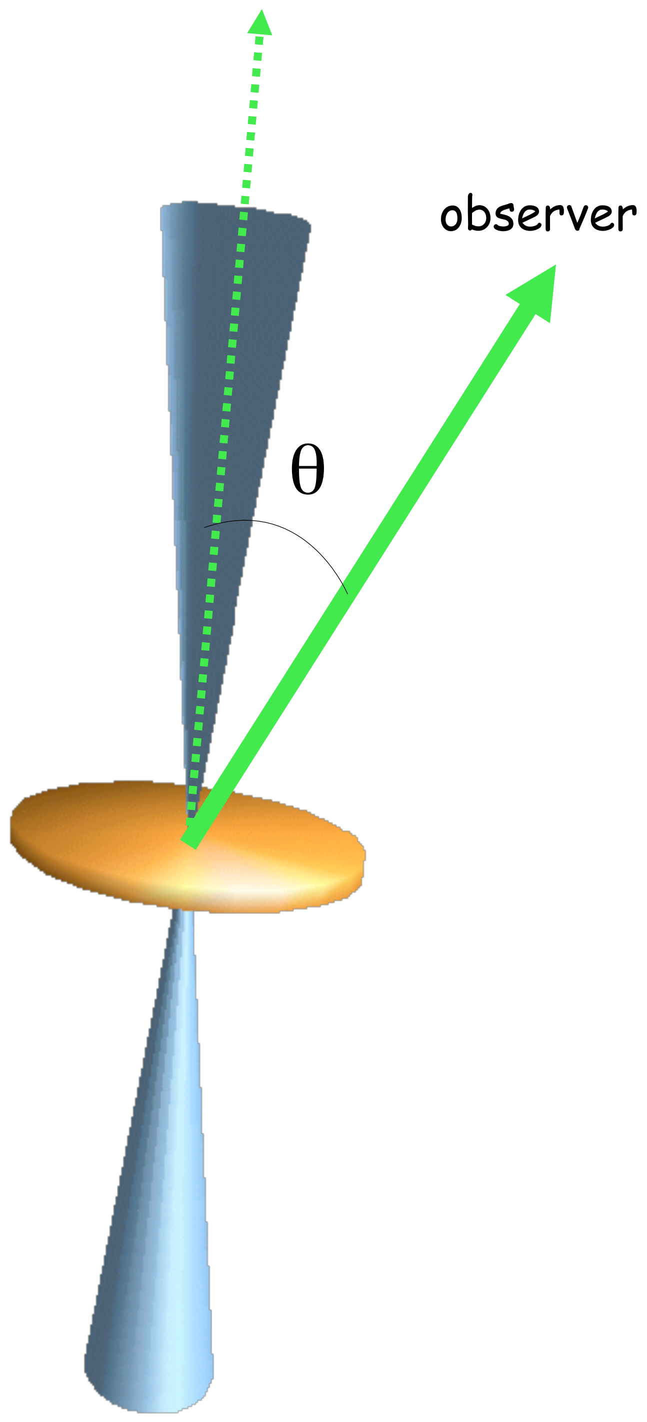


Beamed Emission (achromatic var.)





R<= c Δtδ/(1+z)

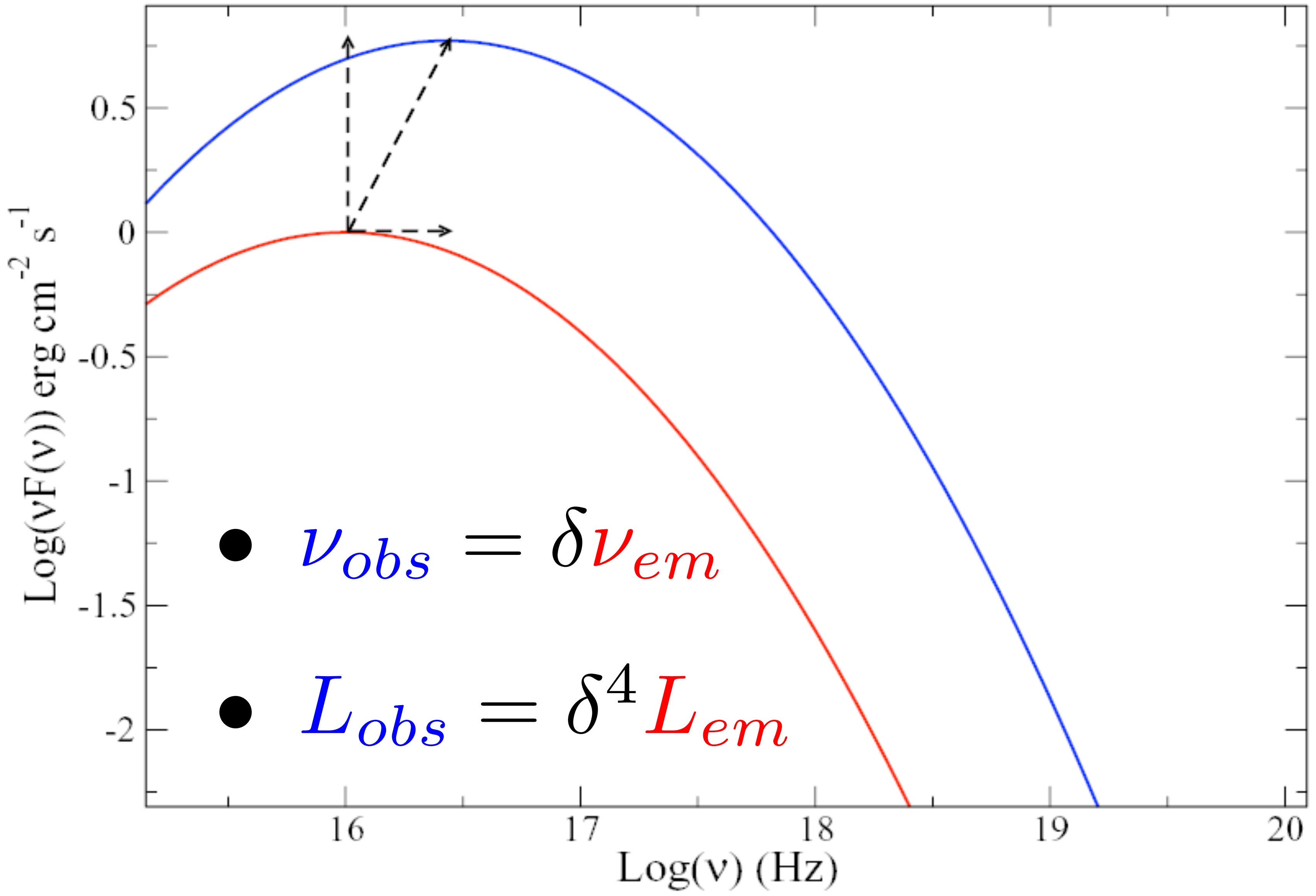


rest frame :
isotropic emission

Observer frame: beamed

Beaming factor:

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



- $\nu_{obs} = \delta \nu_{em}$
- $L_{obs} = \delta^4 L_{em}$

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.

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

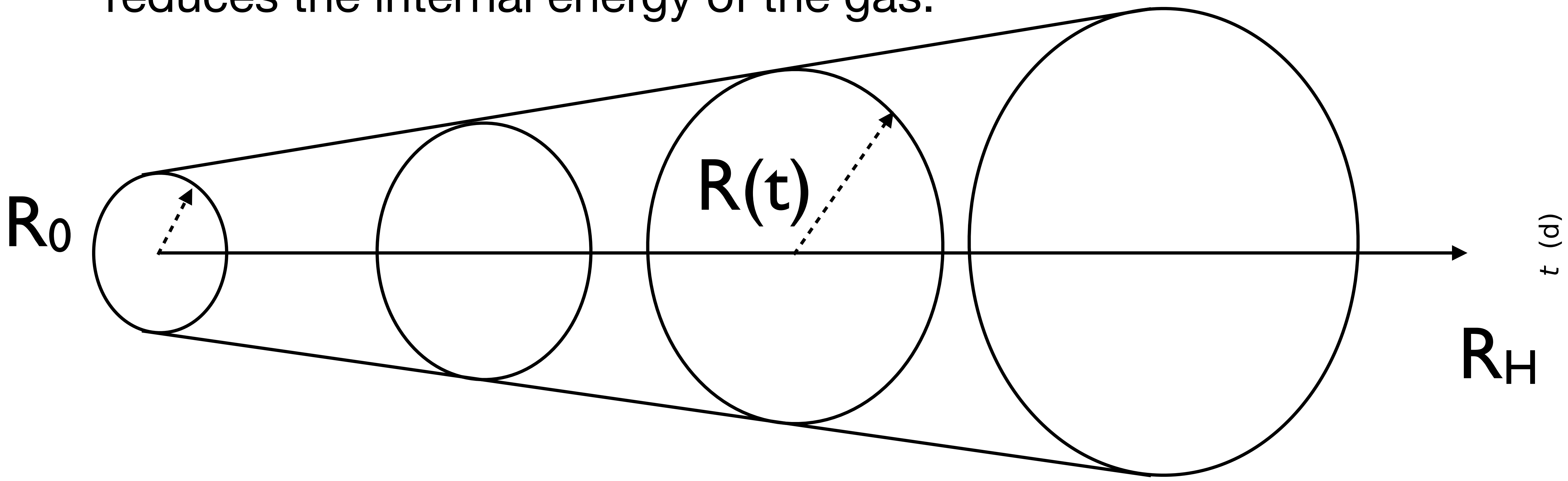
$$|\dot{\gamma}_{IC}(t)| = \frac{4\sigma_T c}{3 m_e c^2} \gamma^2 \int f_{KN}(4\gamma\epsilon_0)\epsilon_0 n_{ph}(\epsilon_0, t) d\epsilon_0$$

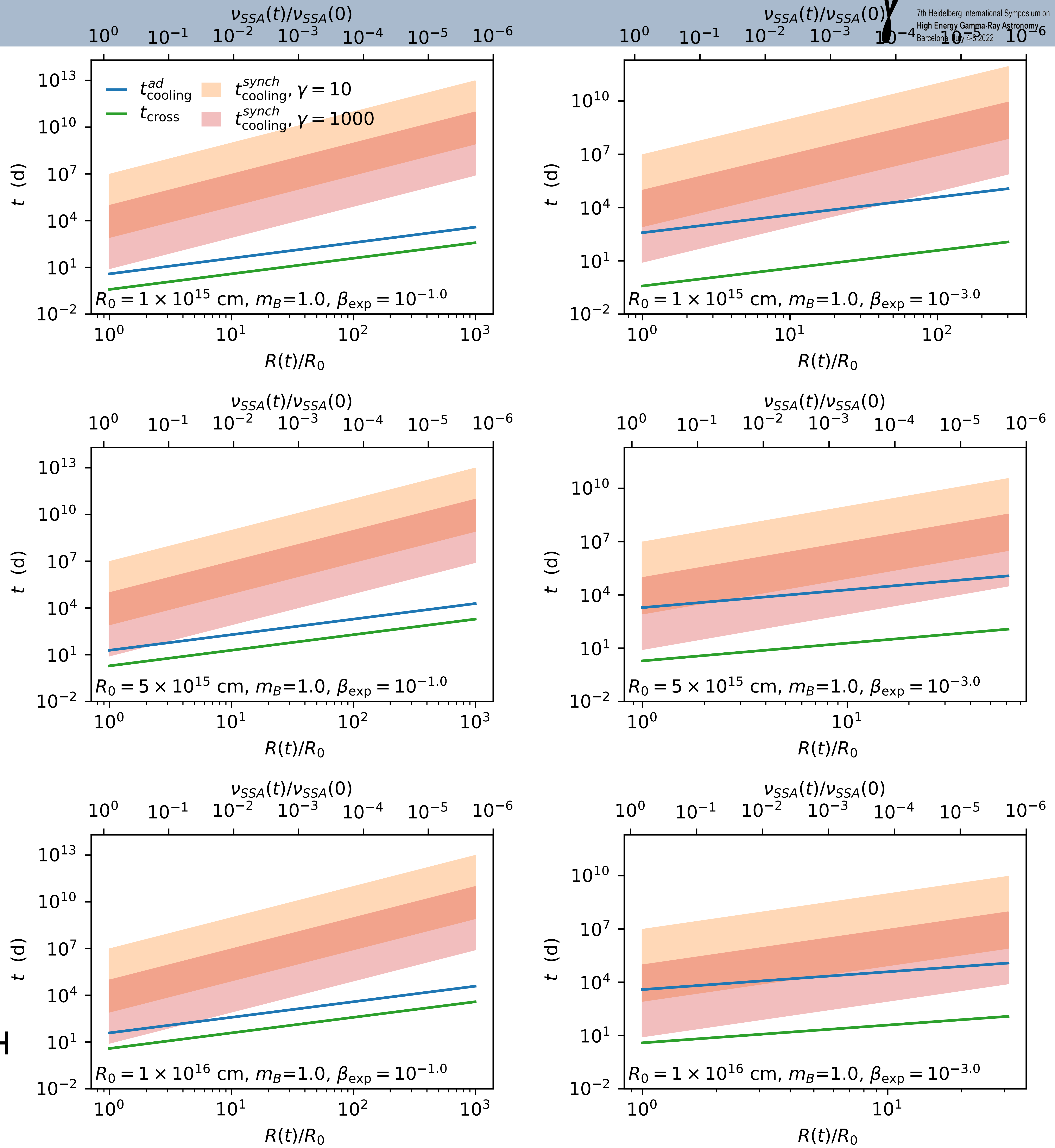
$$= C_0 \gamma^2 F_{KN}(\gamma, t)$$

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

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)

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

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

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

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

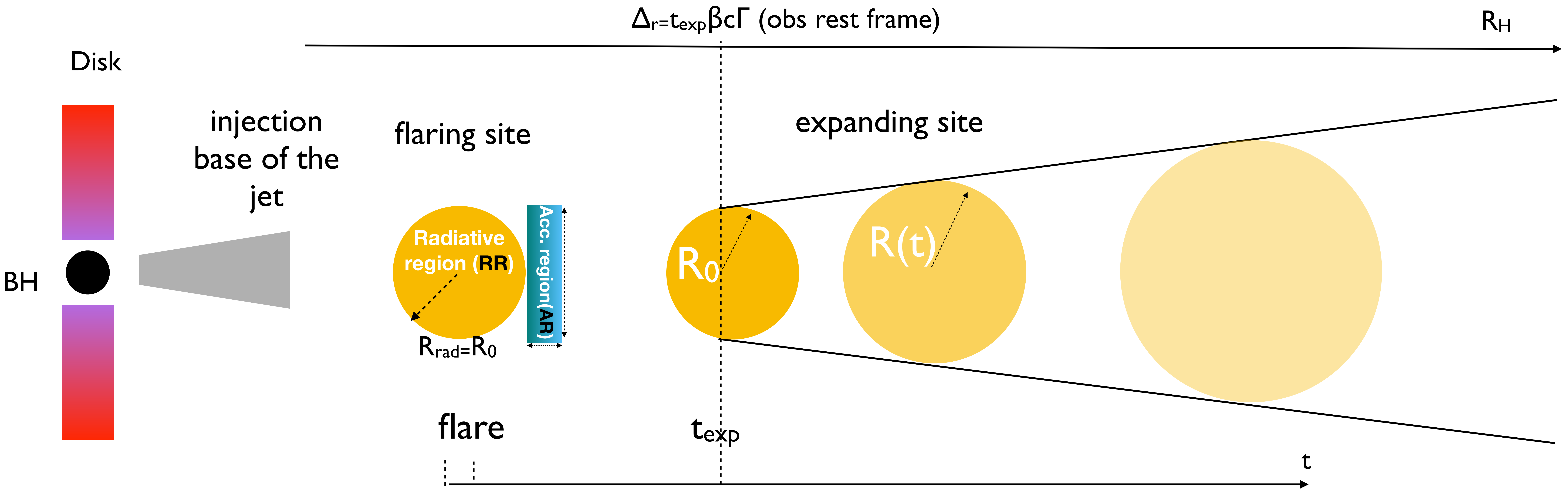
$$T_{ad} = \frac{1}{3}\frac{R(t)}{\beta_{\exp}c} \quad \text{(Gould 1975)}$$

Turbulent magnetic field → momentum diffusion term

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

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

self-consistent approach



- Acc. region+Rad. region
- SSC scenario (*R*,*B* similar to those observed in HBLs from MW model fitting)
- Particles are confined in Rad. region
- we limit to m_B=1, beaming factor constant across the jet
- we ignore crossing time (<<other time scales in the expanding site)

deriving phenomenological trends

synch self. abs

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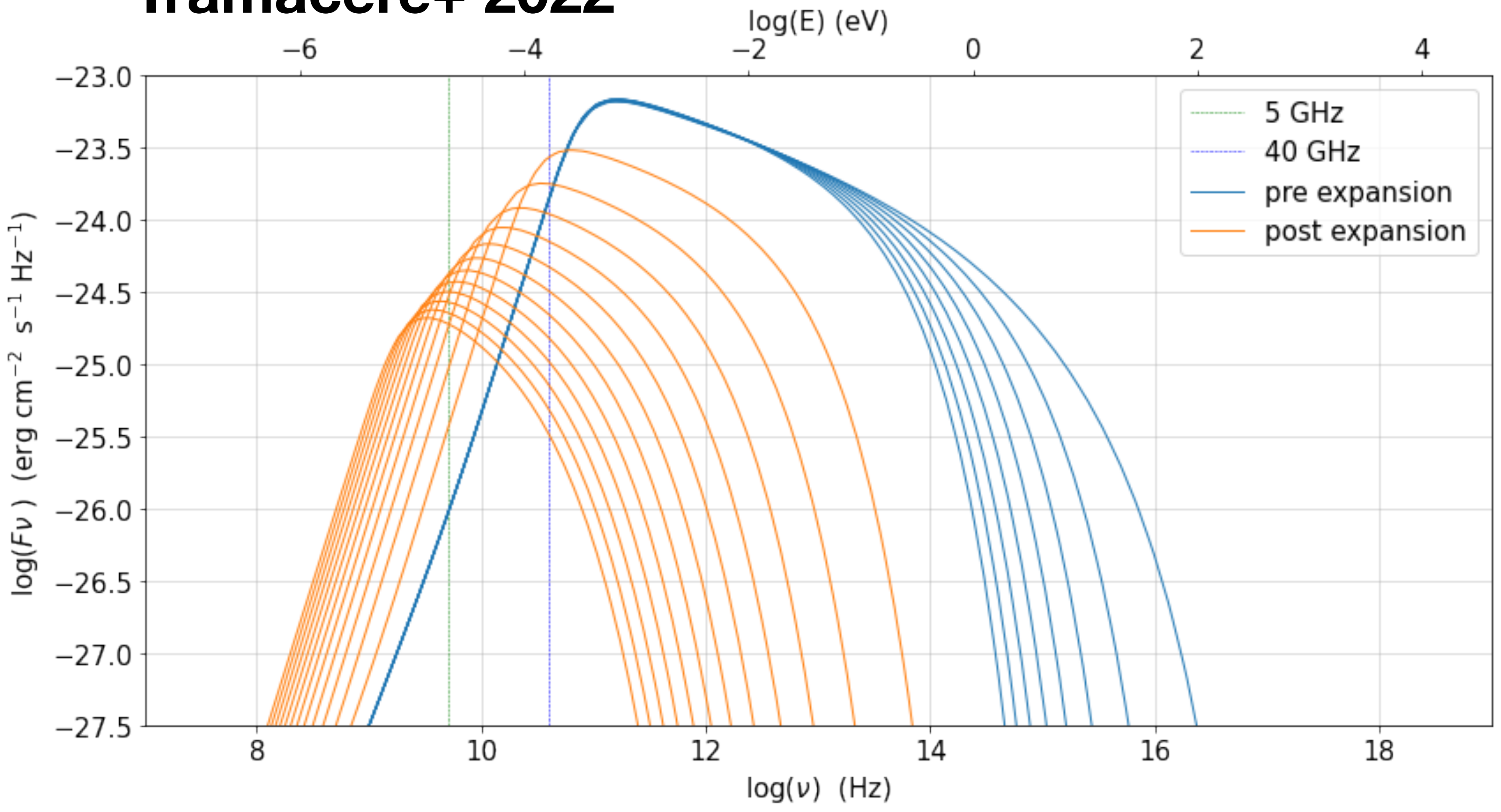
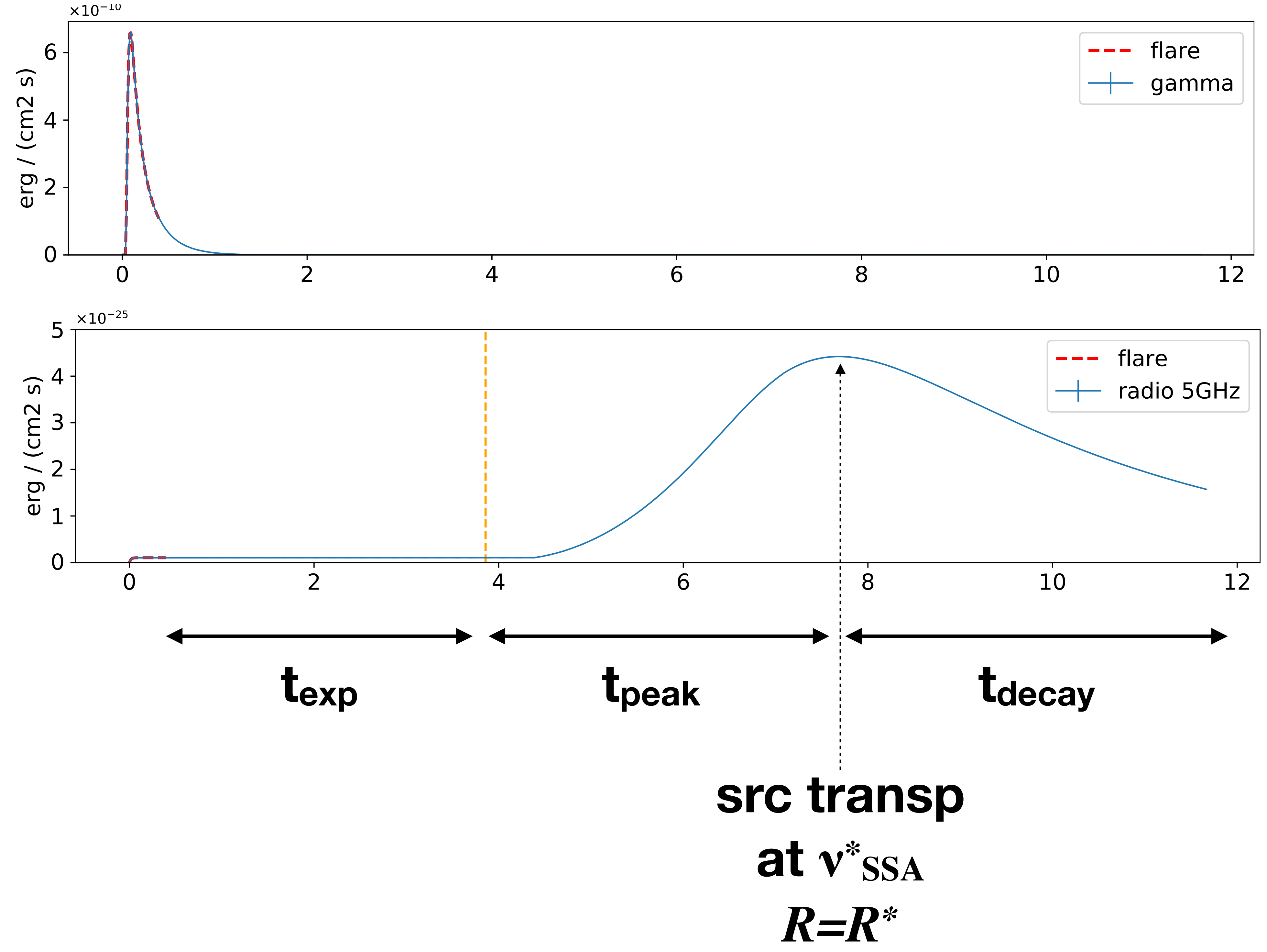
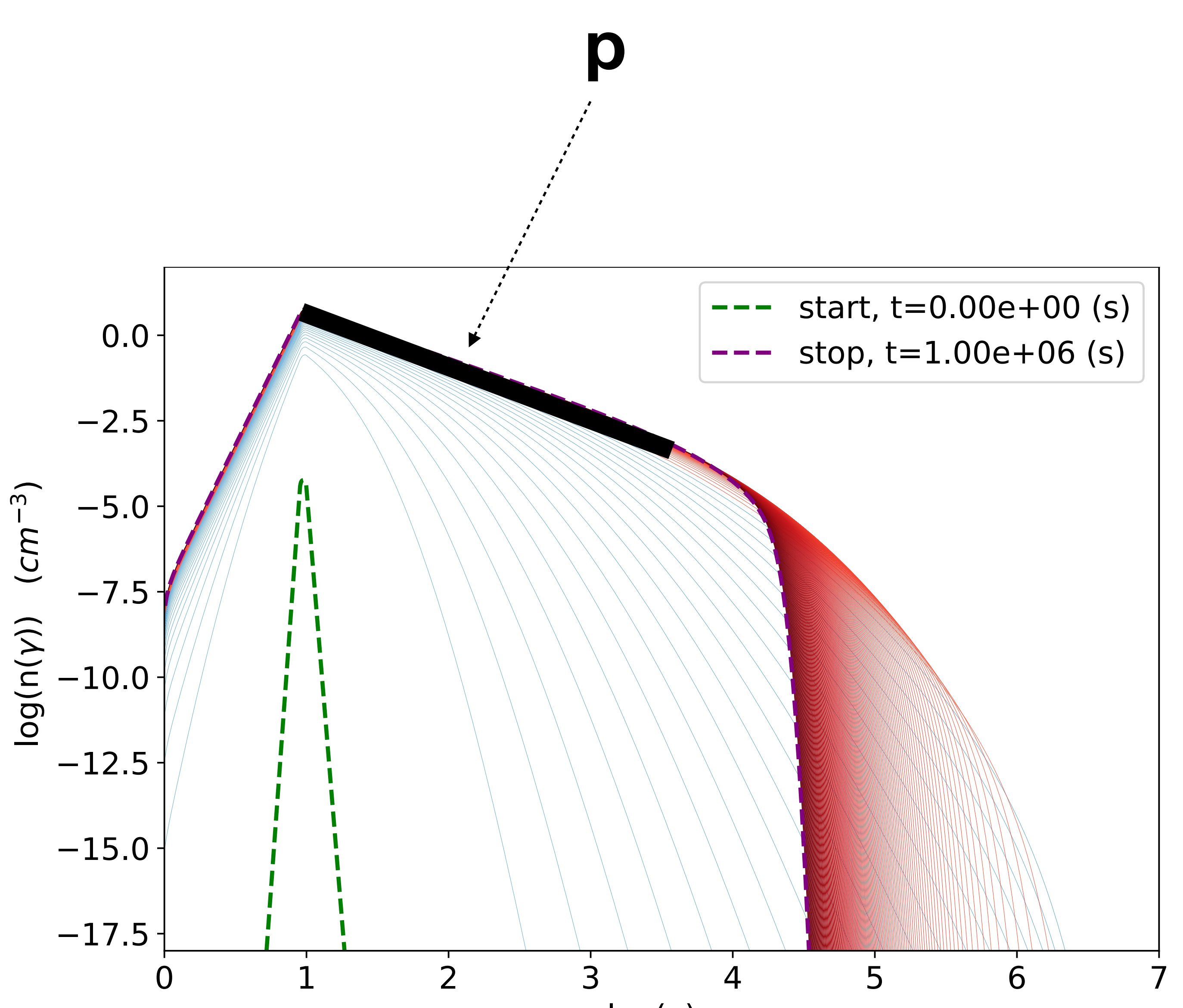




Rybicki&Lightman (1985) standard synchrotron theory

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



synch self. abs

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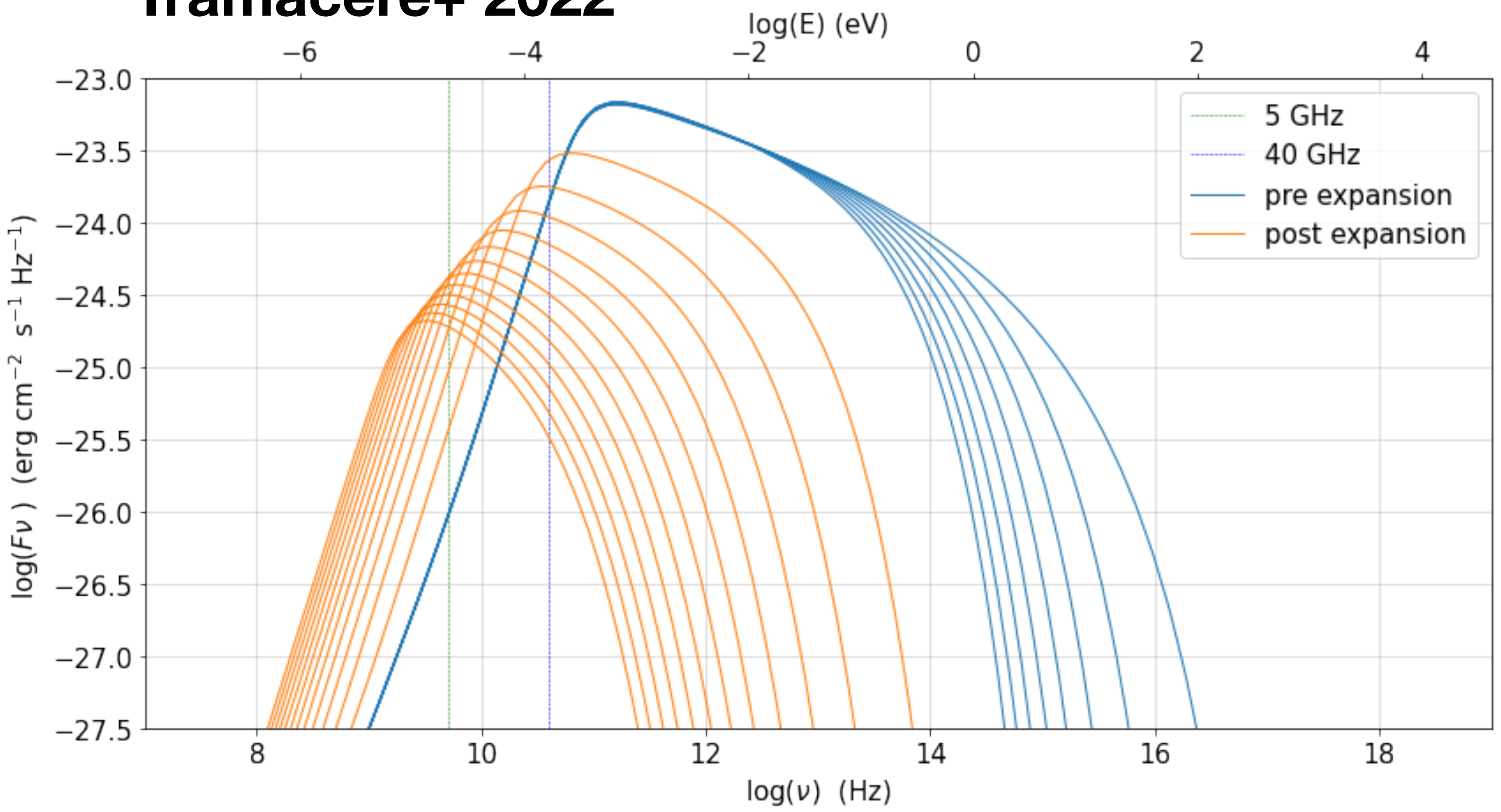
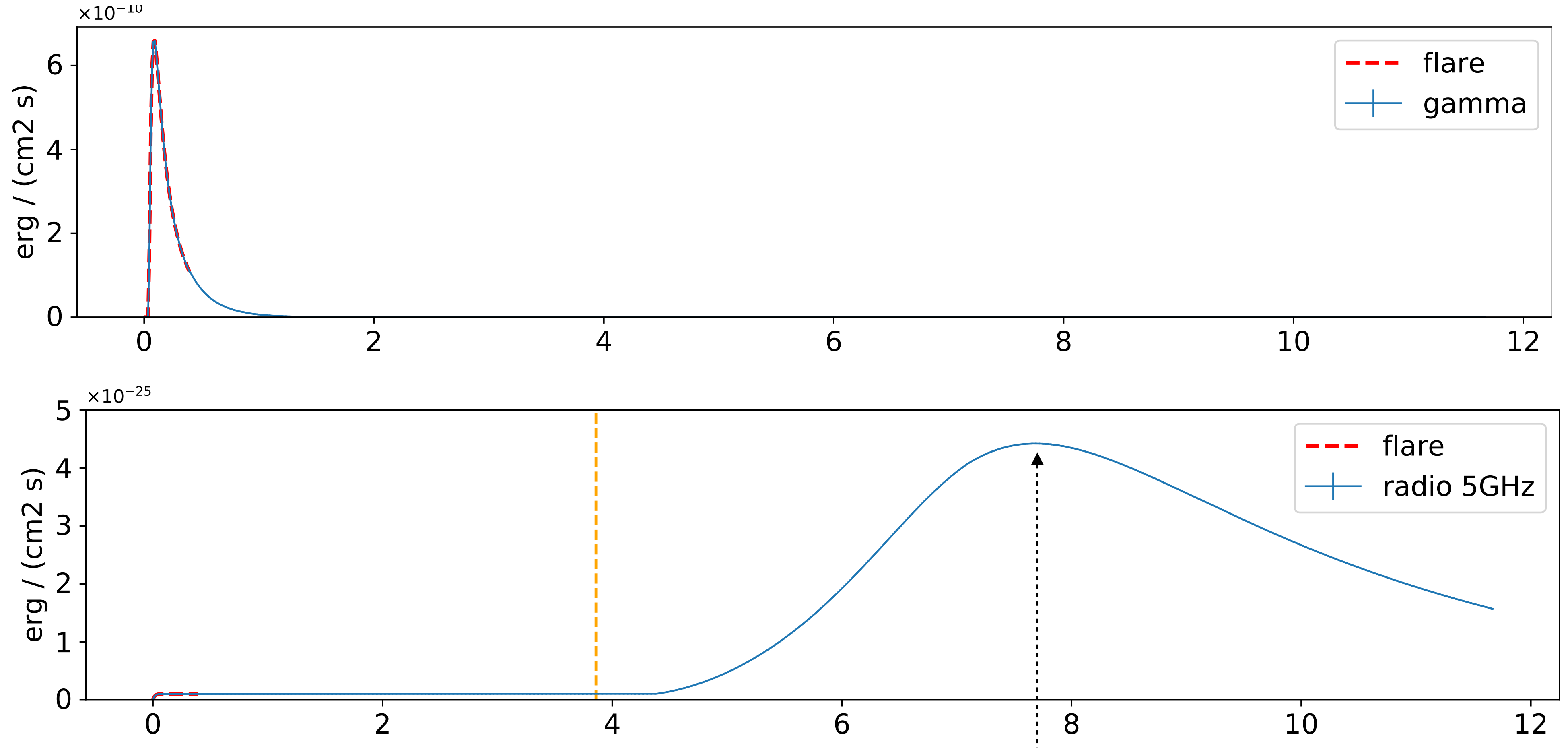




t_{exp} t_{peak} t_{decay}

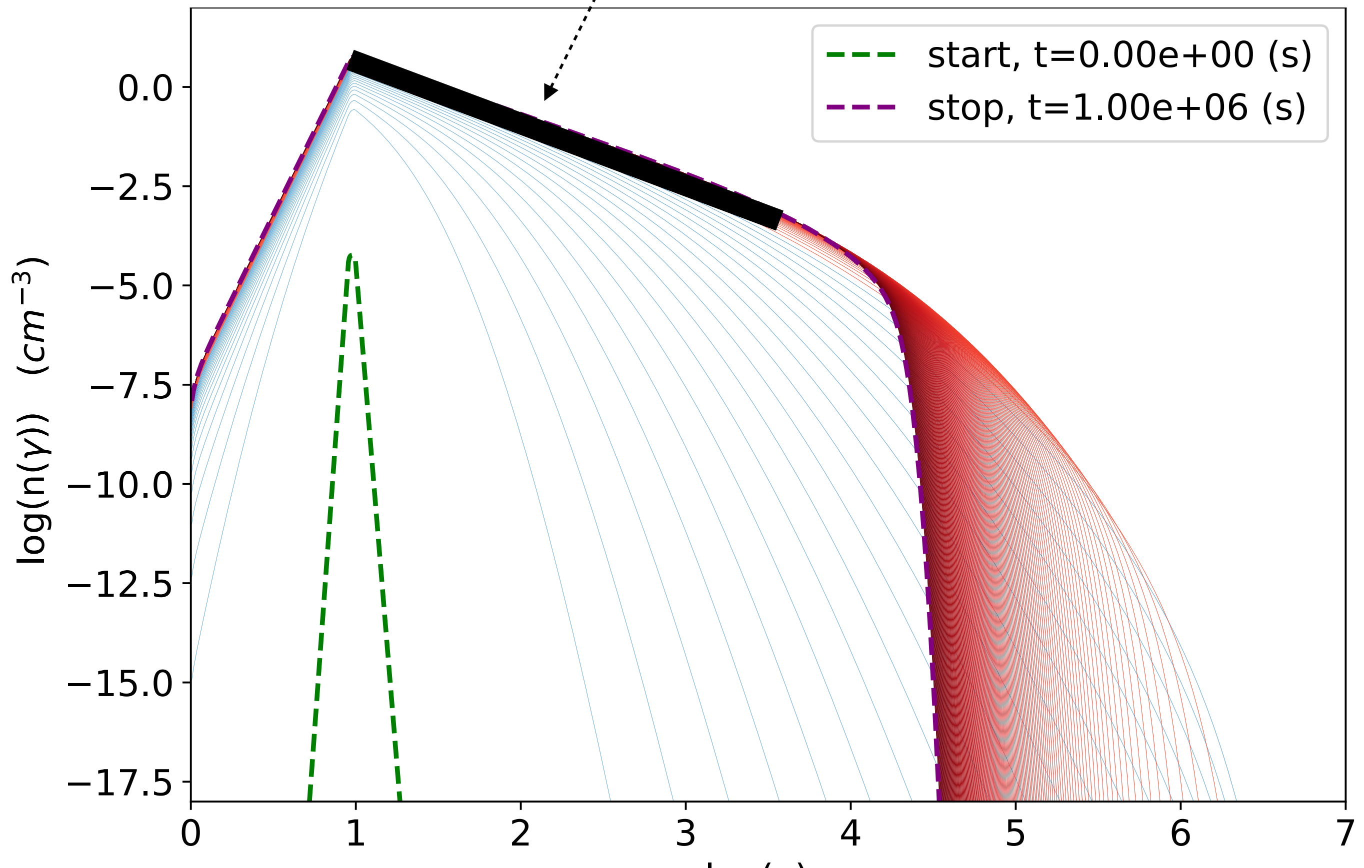
src transp
at ν^*_{SSA}
R=R*

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

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

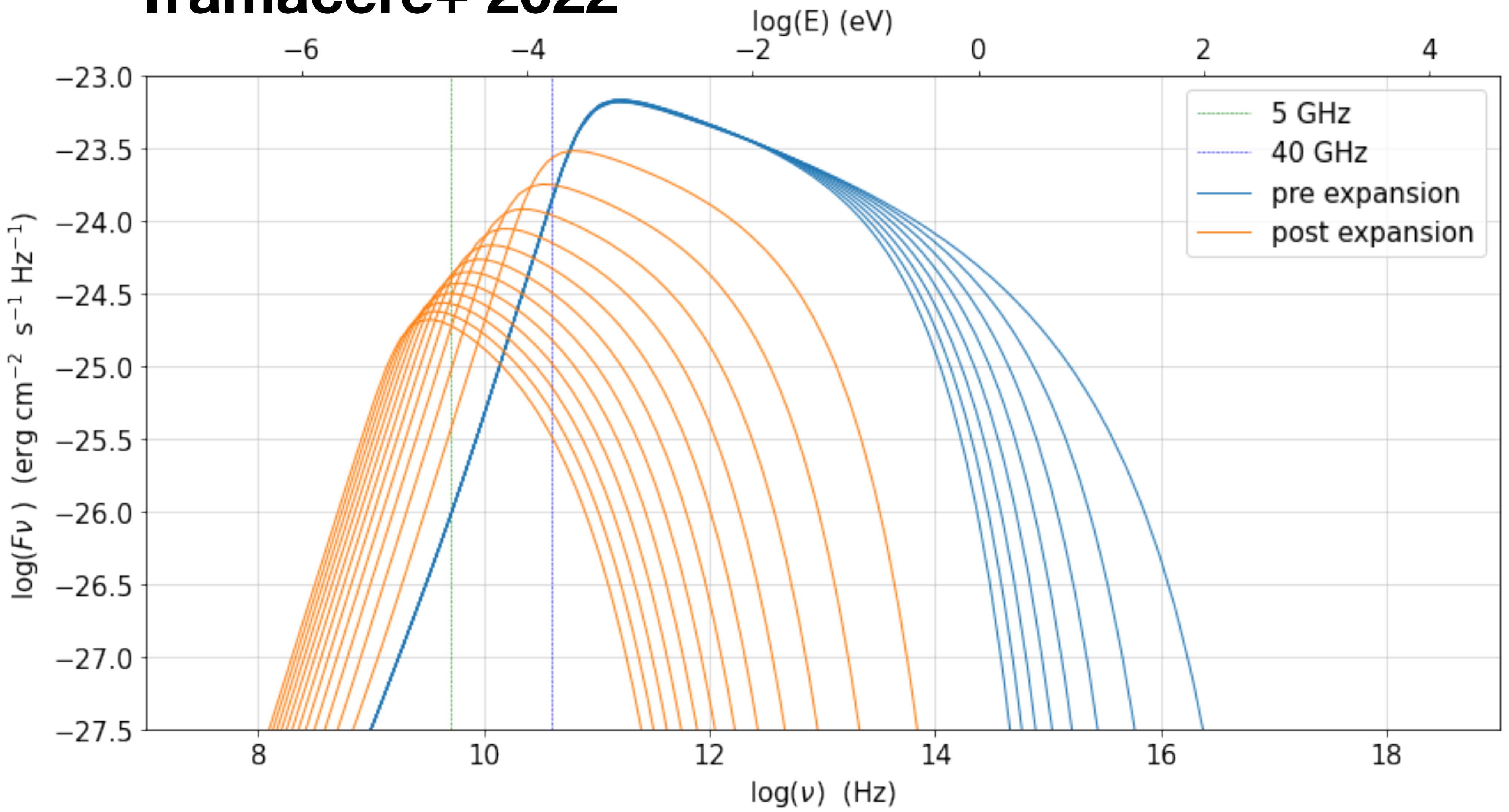
$$B(t) = B_0\left(\frac{R_0}{R(t)}\right)^{m_B}$$

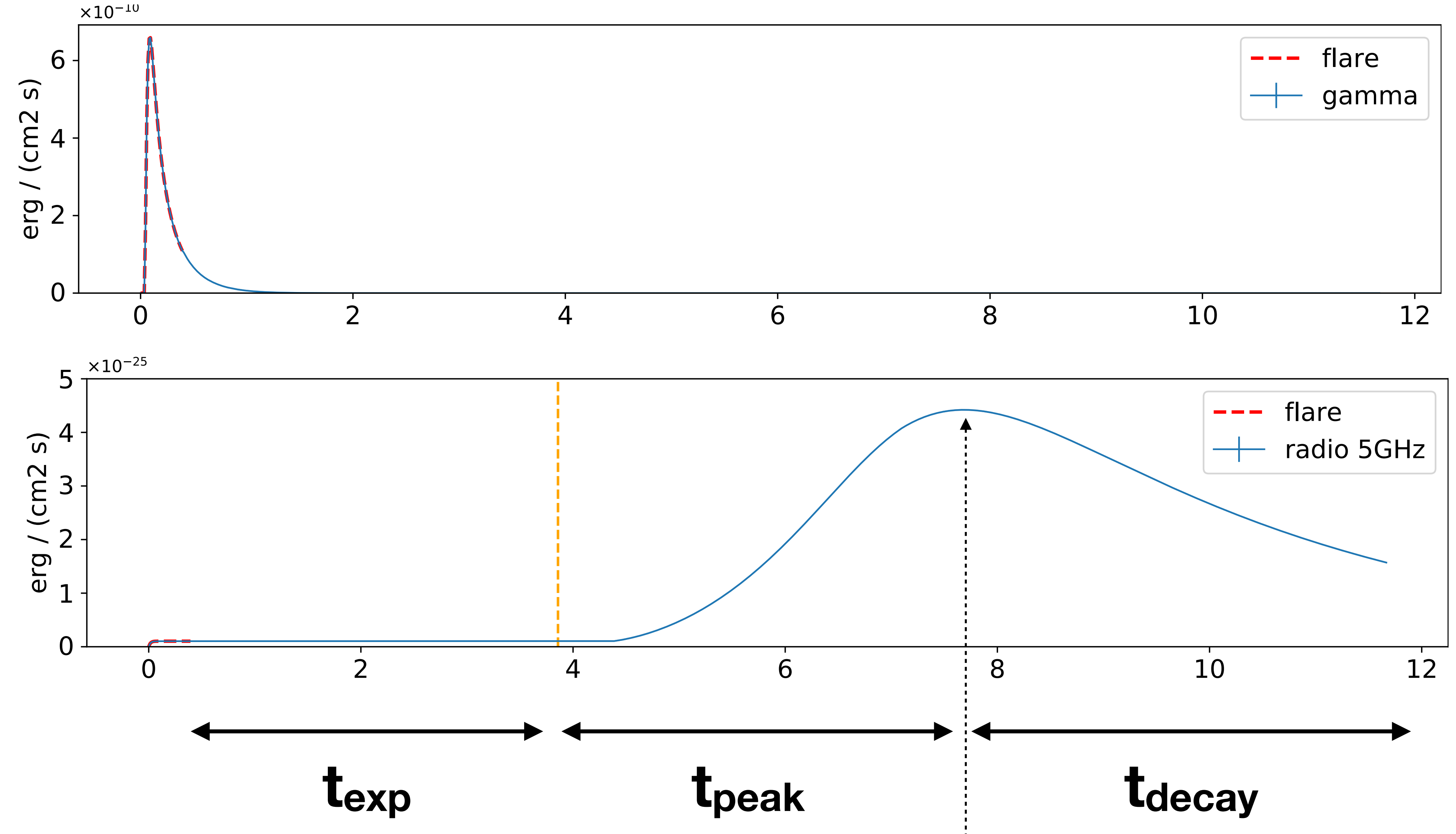
p



synch self. abs

Tramacere+ 2022





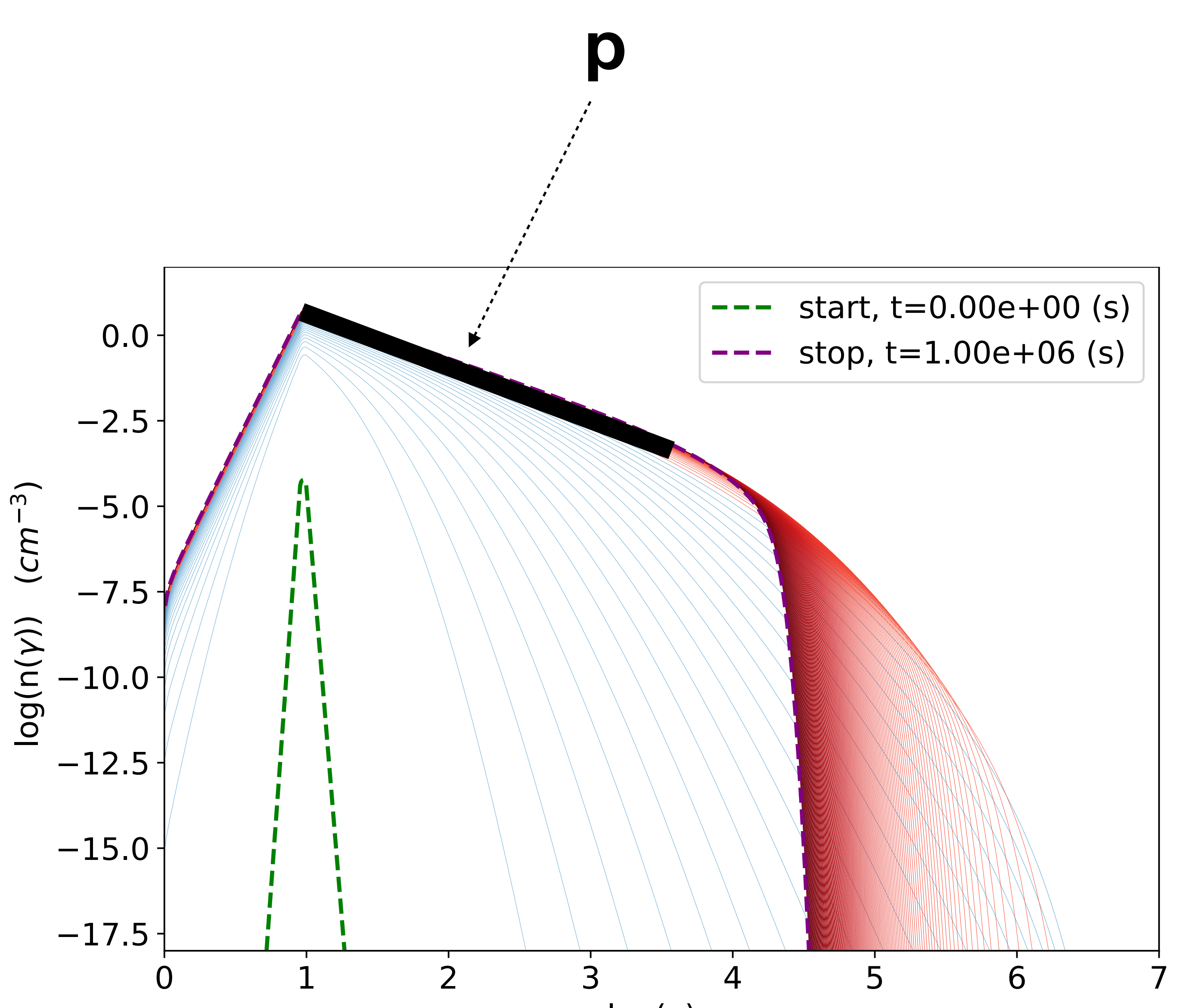
src transp
at ν^*_{SSA}
$R=R^*$

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

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

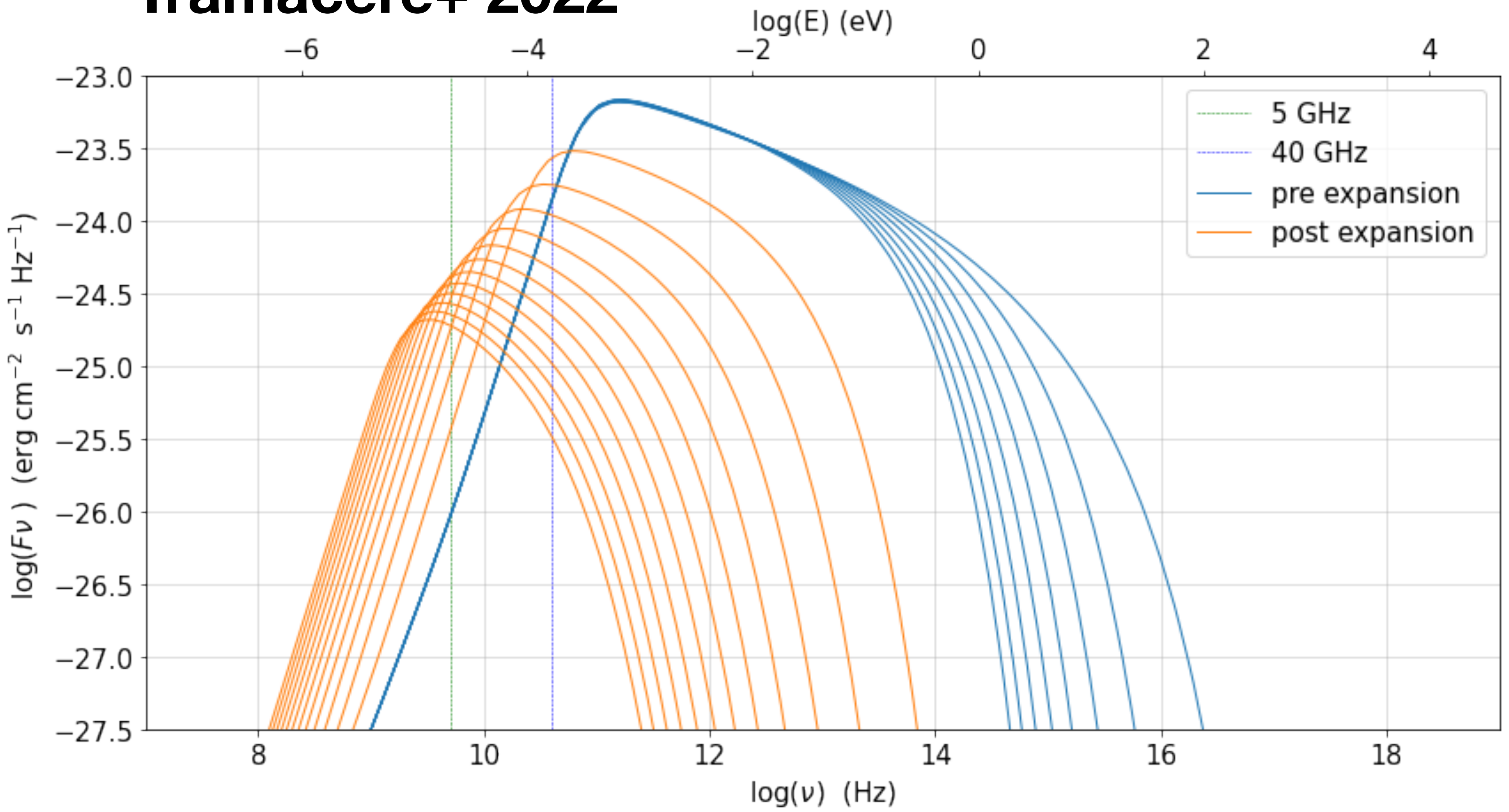
$$B(t) = B_0\left(\frac{R_0}{R(t)}\right)^{m_B}$$

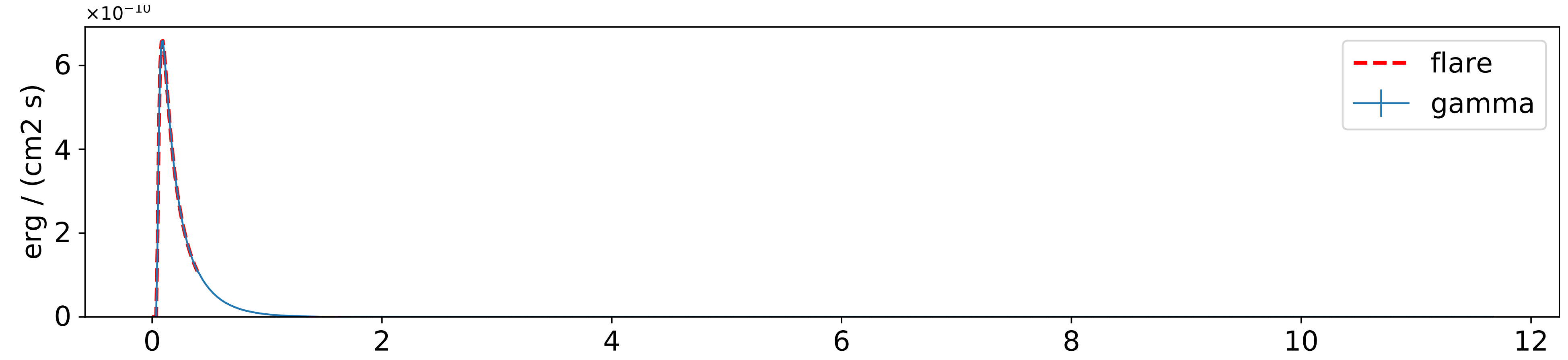
$$\frac{\nu^*_{\rm SSA}}{\nu^0_{\rm SSA}} = \left[\left(\frac{B^*}{B_0}\right)^{\frac{p+2}{2}}\left(\frac{R_0}{R^*}\right)^2\right]^{\frac{2}{p+4}} = \left[\frac{R_0}{R^*}\right]^{\frac{m_B(p+2)+4}{p+4}}$$

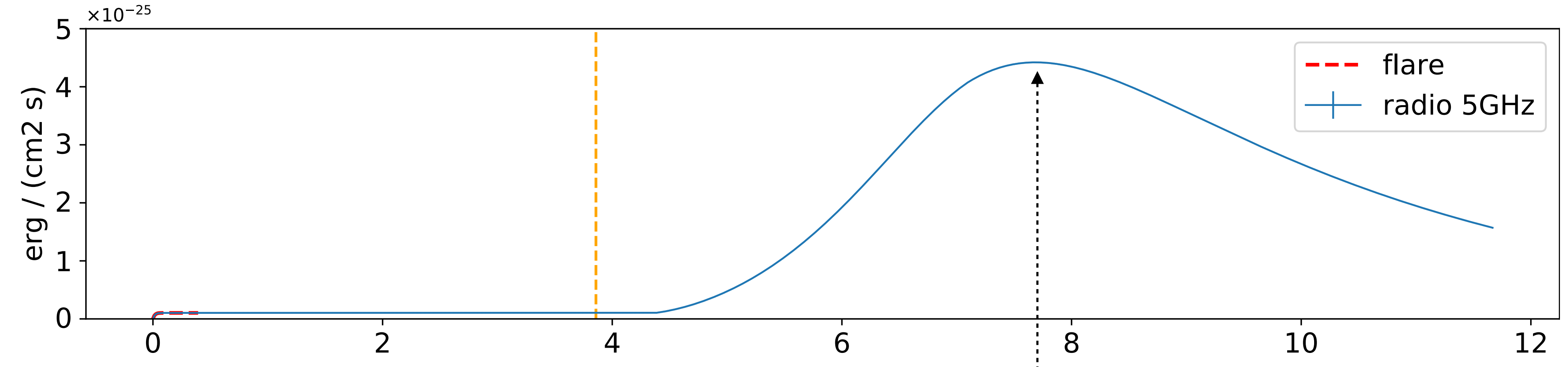


synch self. abs

Tramacere+ 2022







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

src transp
at ν^*_{SSA}
R=R*

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

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

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

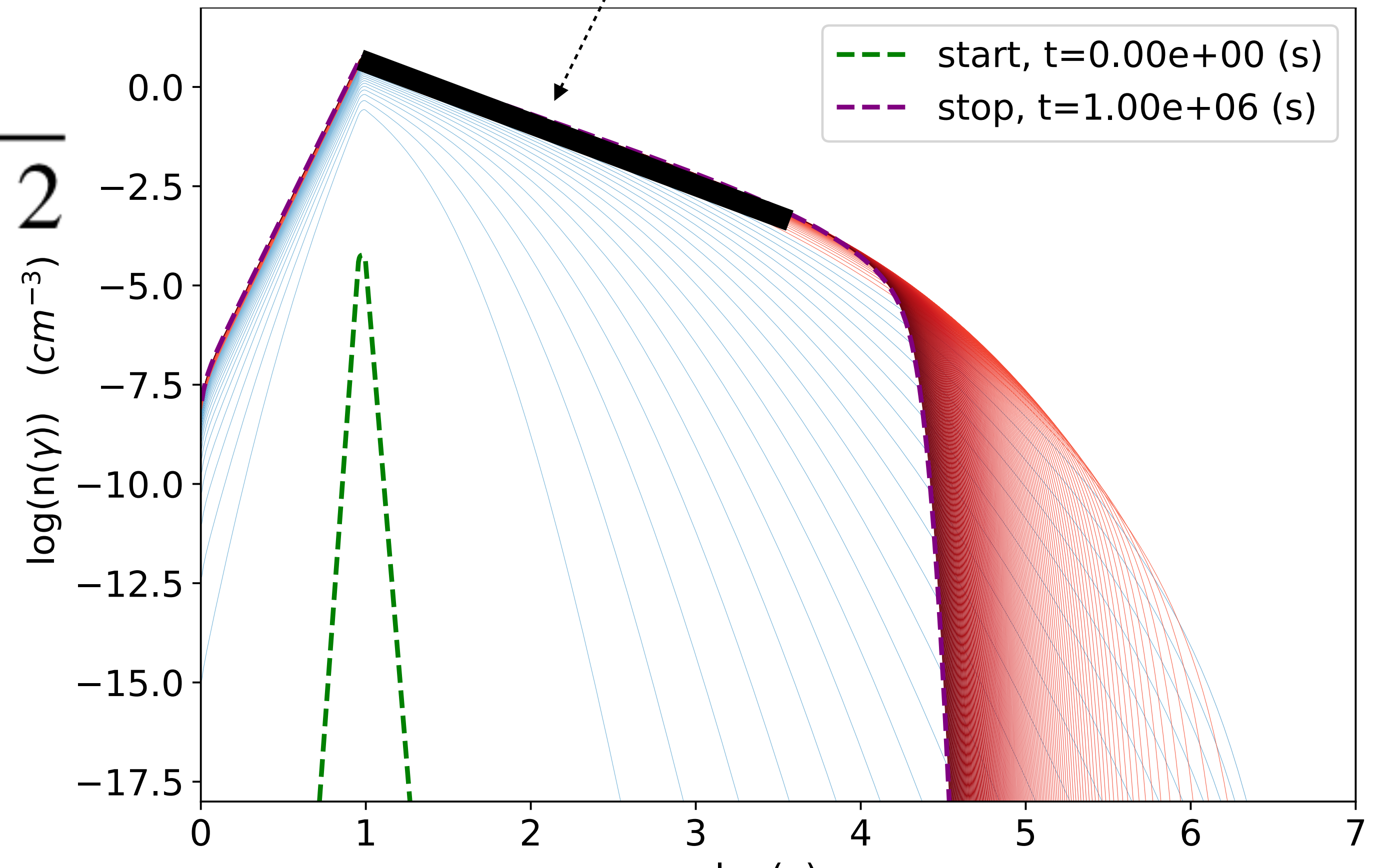
$$\frac{\nu^*_{\rm SSA}}{\nu^0_{\rm SSA}} = \Big[\Big(\frac{B^*}{B_0}\Big)^{\frac{p+2}{2}}\Big(\frac{R_0}{R^*}\Big)^2\Big]^{\frac{2}{p+4}} = \Big[\frac{R_0}{R^*}\Big]^{\frac{m_B(p+2)+4}{p+4}}$$

invert

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

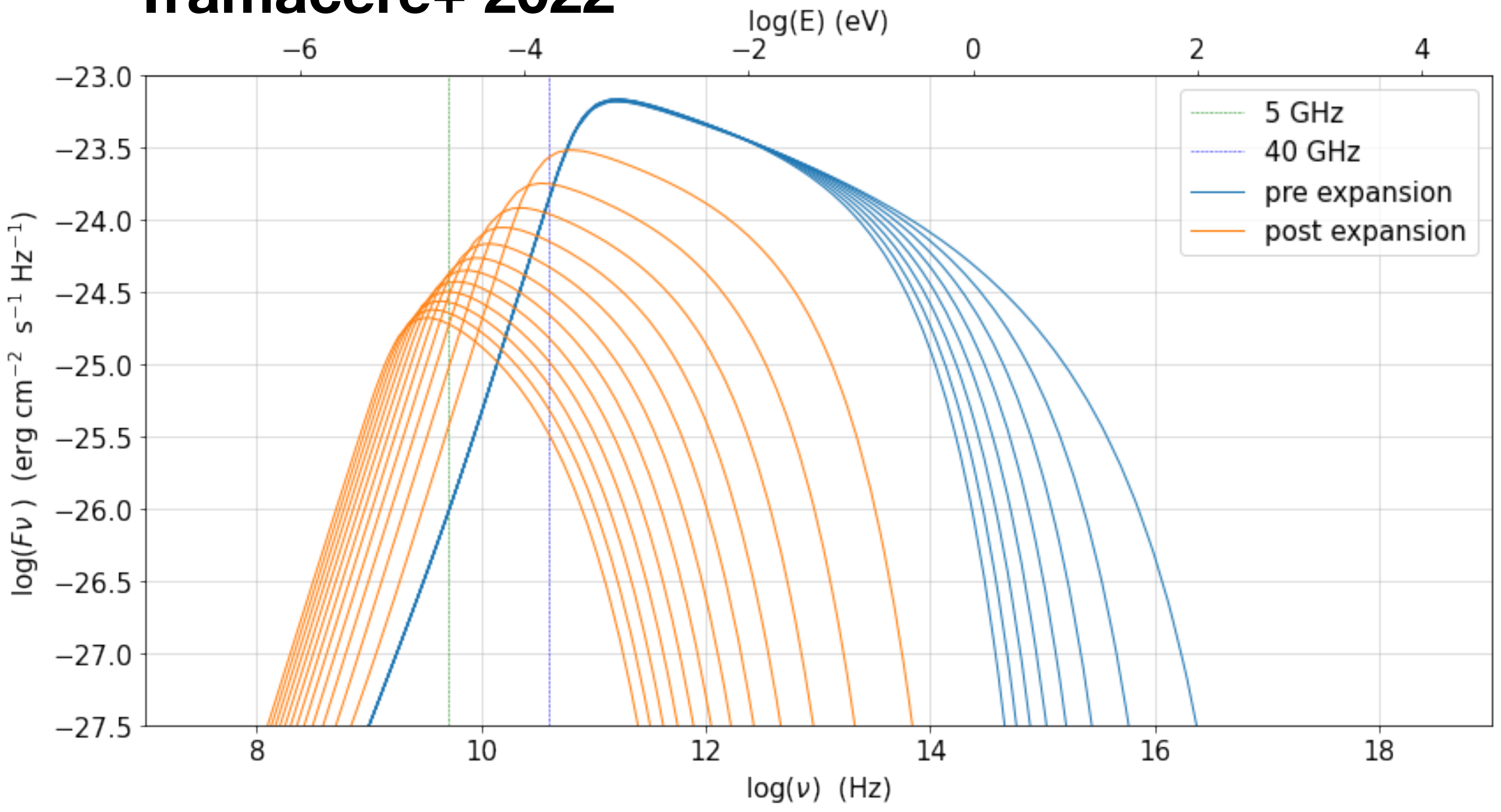
$$\psi = \frac{p+4}{m_B(p+2)-2}$$

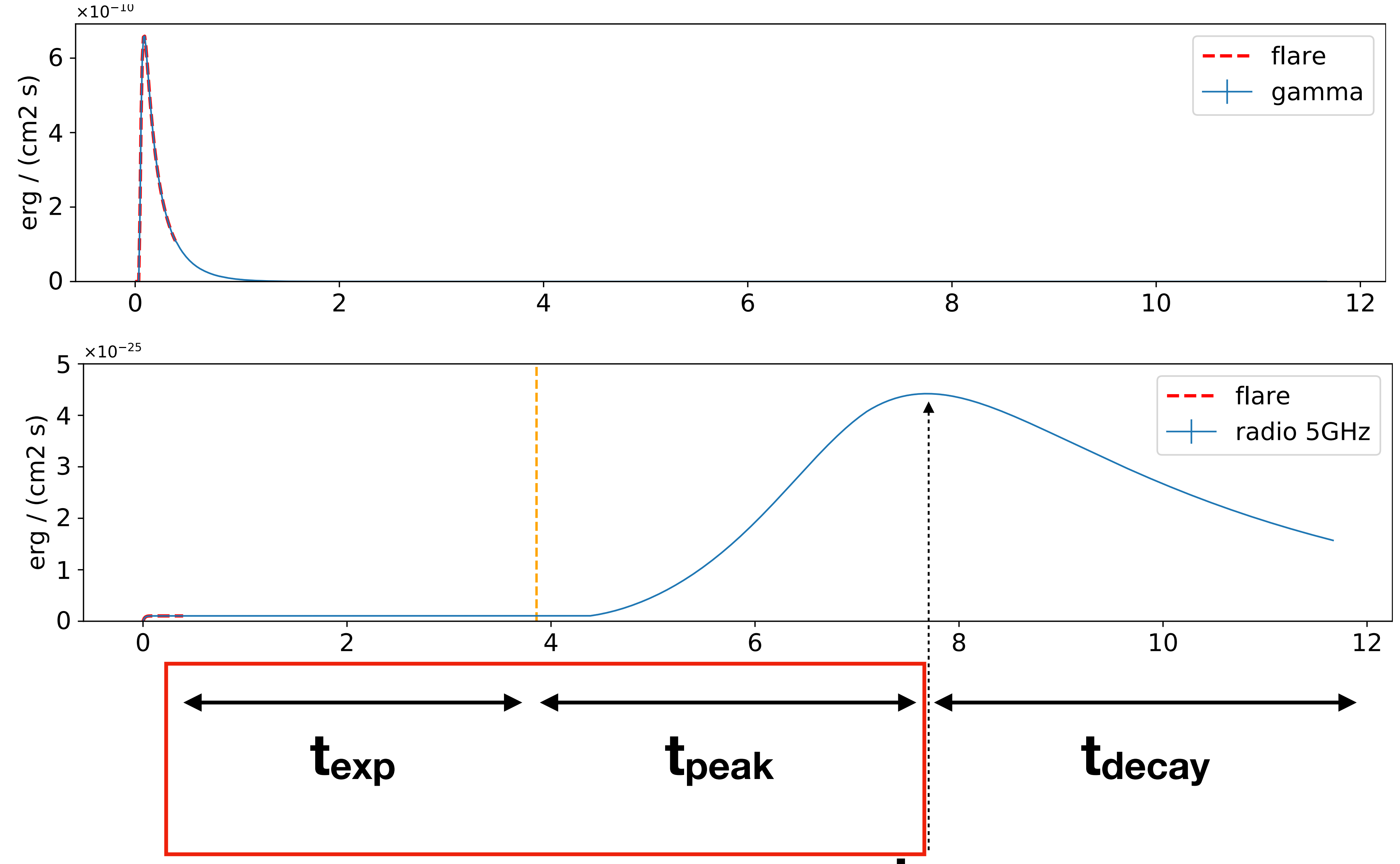
p



breaking down the process

Tramacere+ 2022





src transp
at ν^*_{SSA}
R=R*

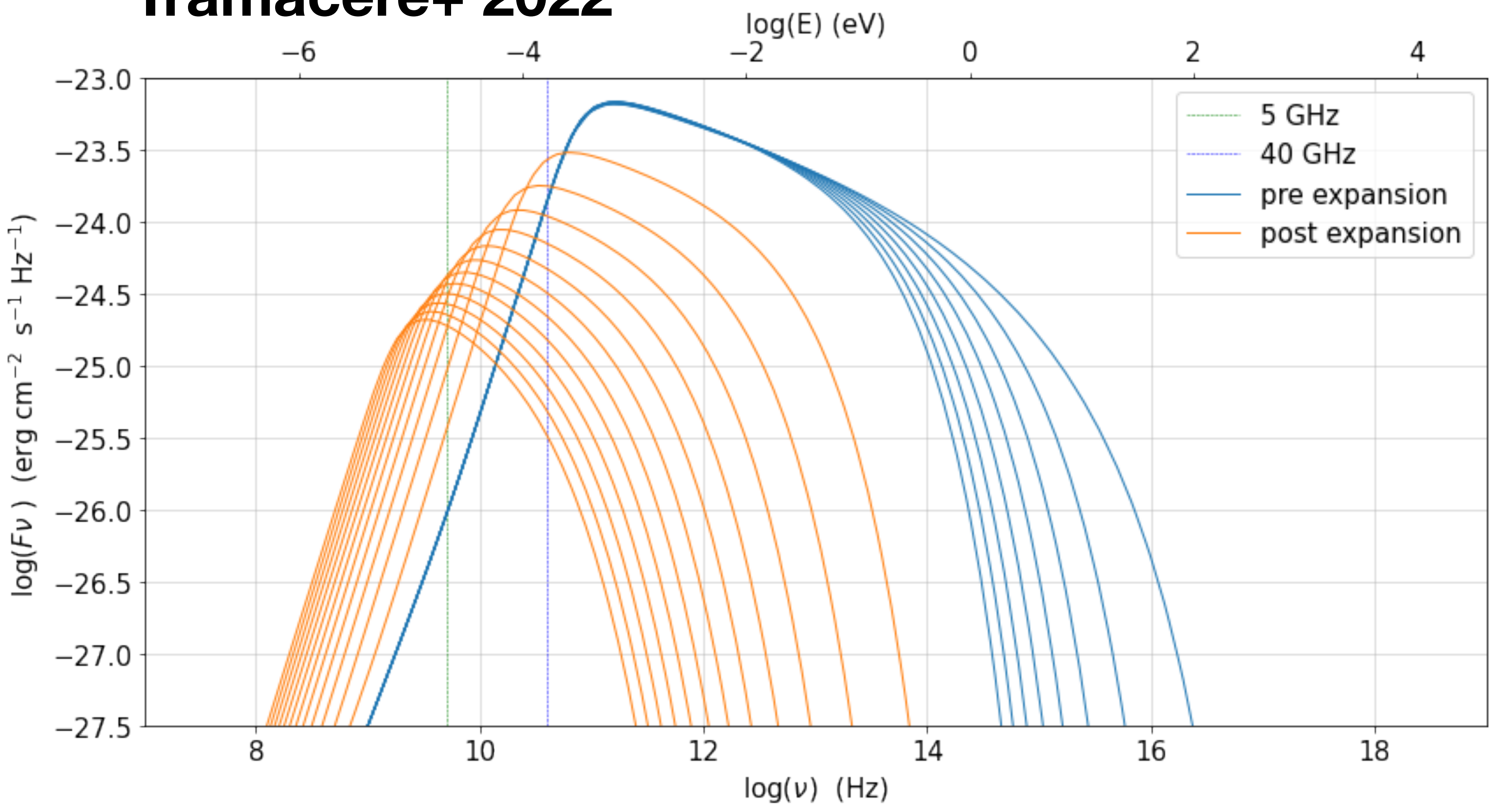
$$\Delta t_{\nu^0_{\rm SSA}\rightarrow\nu^*_{\rm SSA}} = t_{\rm exp} + t_{\rm peak}$$

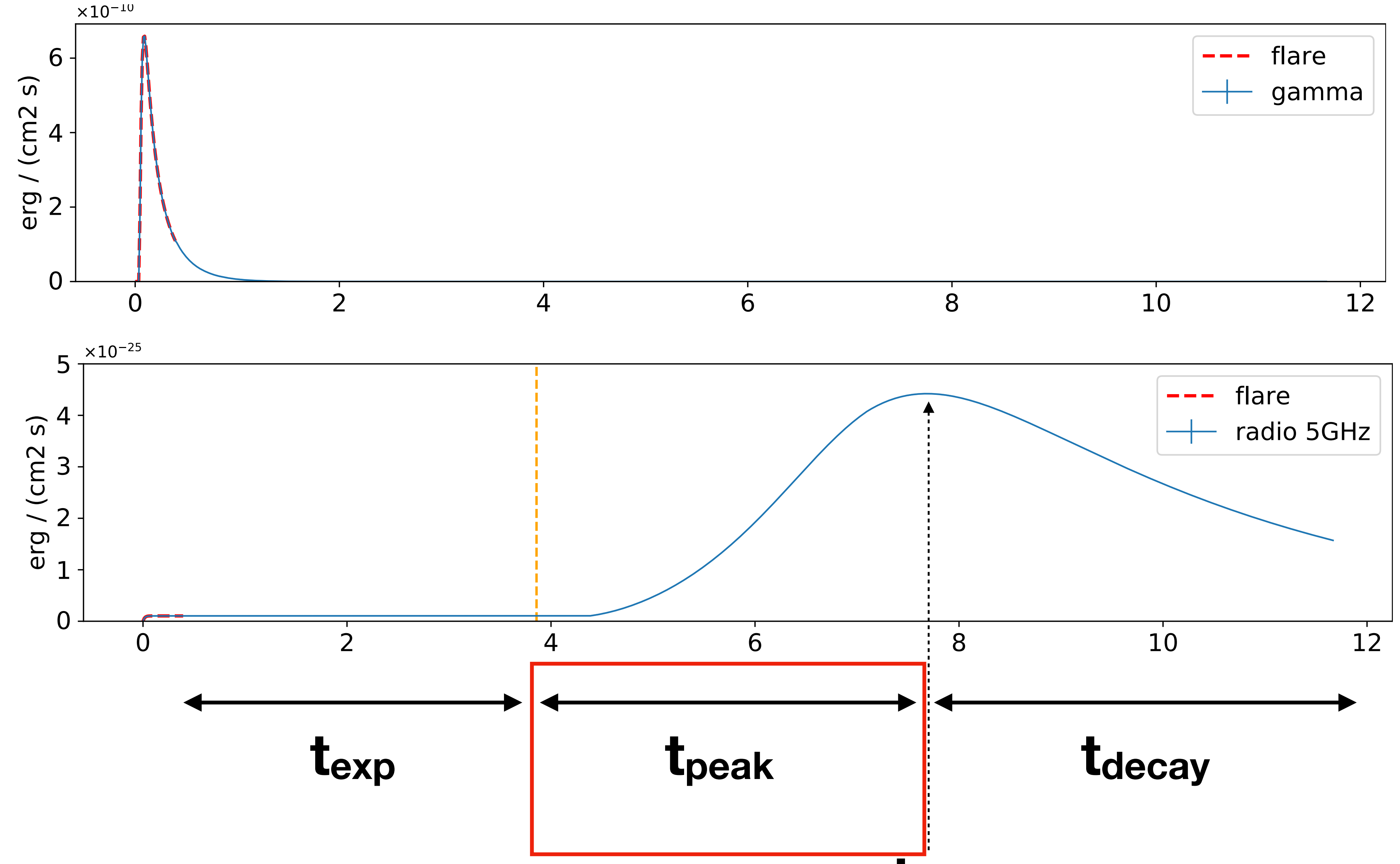
$$R^* = R_0\left(\frac{\nu^0_{SSA}}{\nu^*_{SSA}}\right)^{\psi}$$

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

breaking down the process

Tramacere+ 2022





src transp at ν^*_{SSA}

R=R*

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

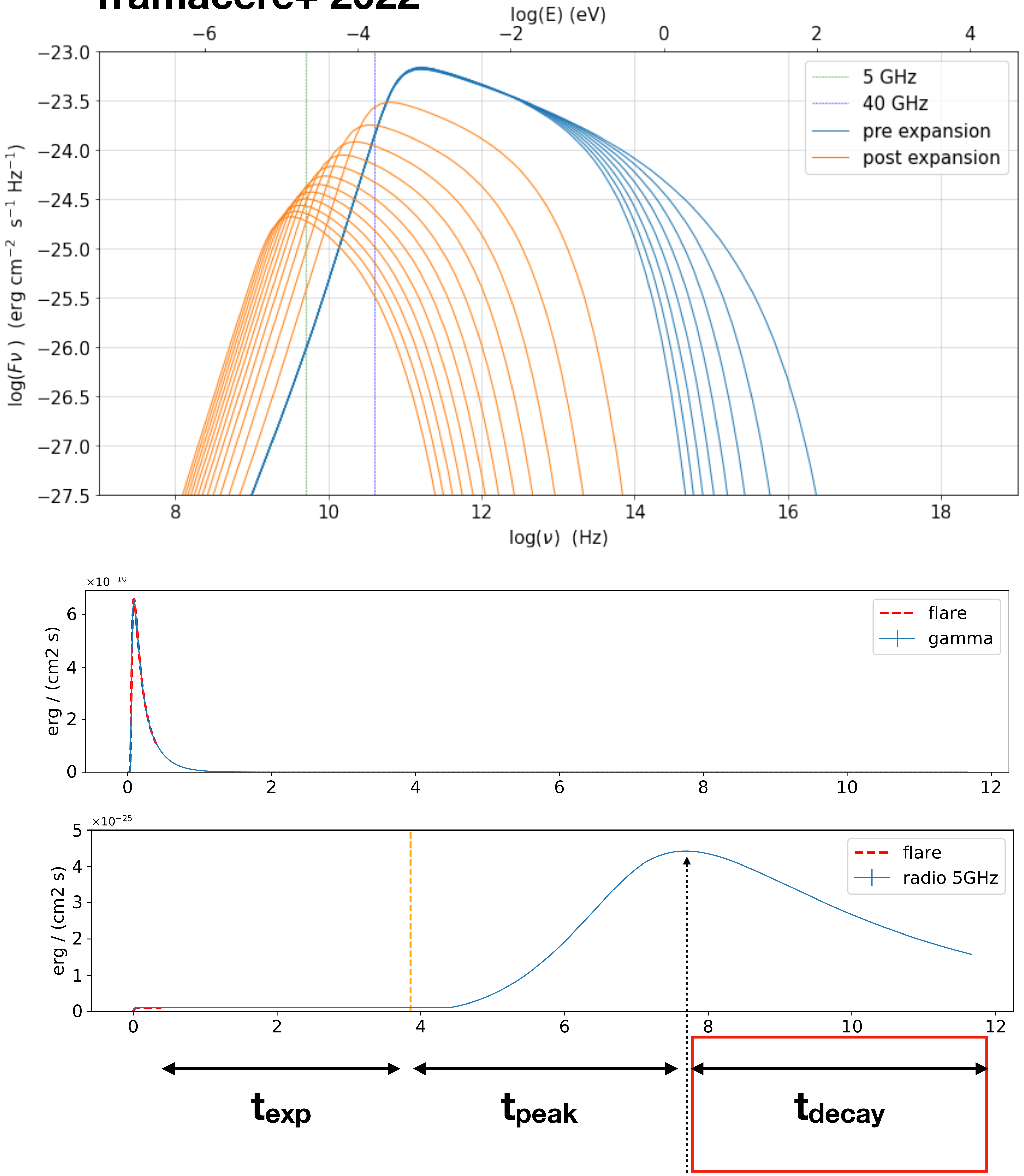
$$t_{\rm peak} = \Delta t_{R_0\rightarrow R^*} = \frac{R^* - R_0}{\beta_{\rm exp} c} = \frac{R_0}{\beta_{\rm exp} c}\left[\left(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\right)^{\psi} - 1\right]$$

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

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

breaking down the process

Tramacere+ 2022



src transp
at ν^*_{SSA}
R=R*

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

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

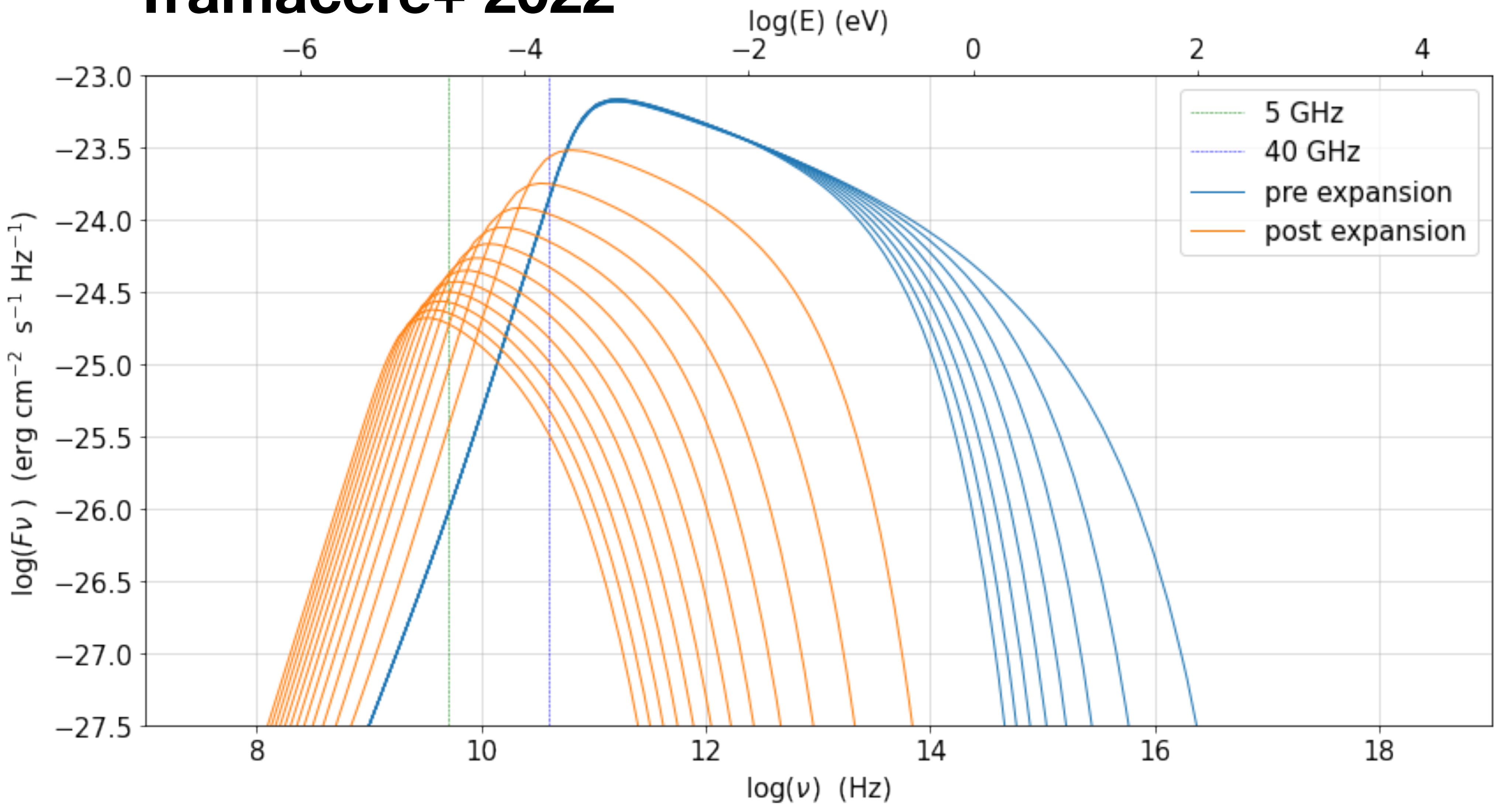
$$t_{decay} \dashrightarrow t^{ad}_{\rm decay}(t^*) \propto \frac{R^*}{\beta_{\rm exp}c} = \frac{R_0}{\beta_{\rm exp}c}\left(\frac{\nu^0_{\rm SSA}}{\nu^*_{\rm SSA}}\right)^{\psi}$$

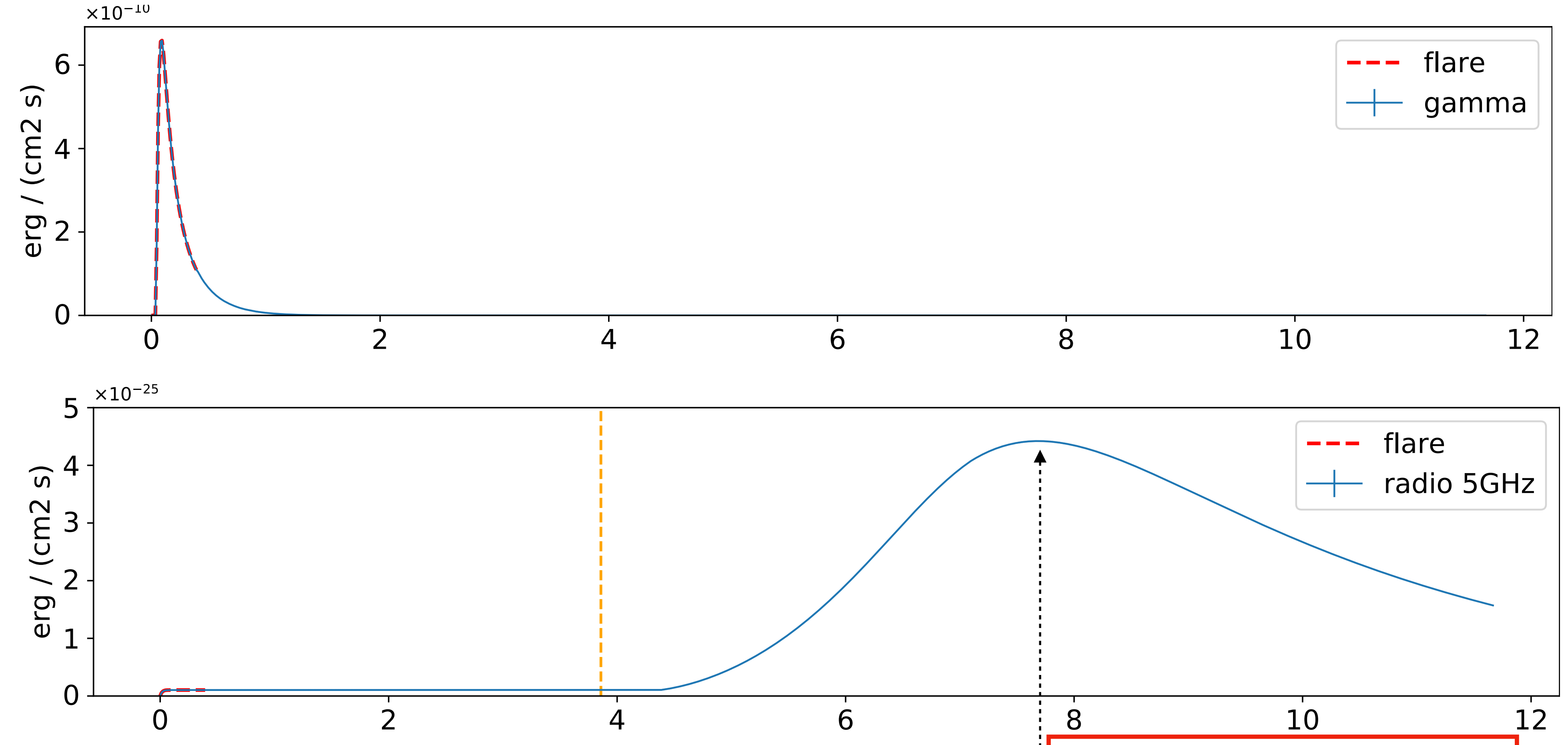
$$R^* = R_0\left(\frac{\nu^0_{SSA}}{\nu^*_{SSA}}\right)^{\psi}$$

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

breaking down the process

Tramacere+ 2022





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

src transp at ν^*_{SSA}

R=R*

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

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

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

t_{decay} → **radiative**

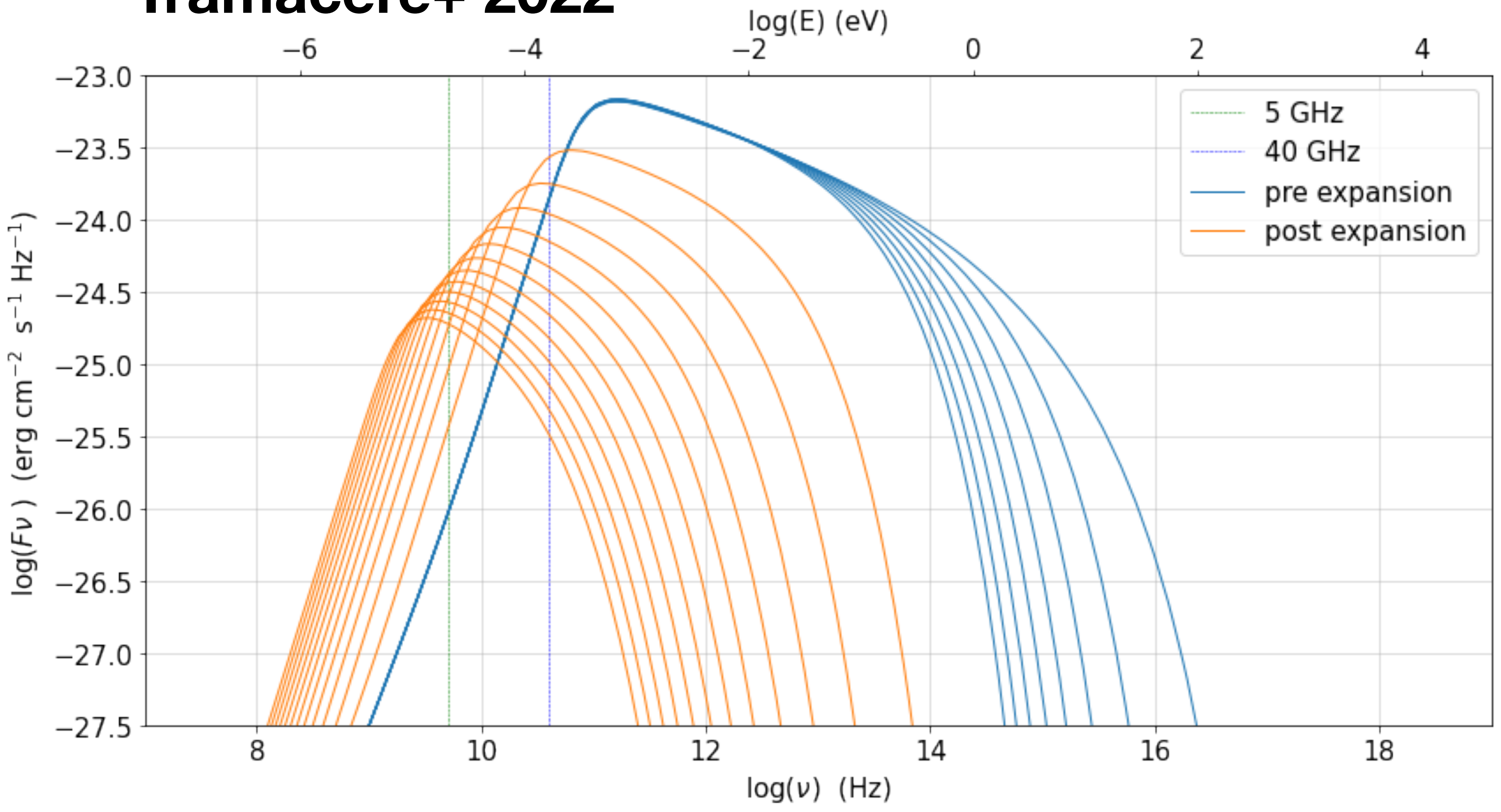
$$t_{\rm decay}^{geom}(t^*) \propto \frac{F_{\nu_{\rm SSA}}(t^*)}{\dot{F}_{\nu_{\rm SSA}}(t^*)} \propto \frac{R^*}{m_B \beta_{\rm exp} c} = \frac{t_{\rm decay}^{ad}(t^*)}{m_B}$$

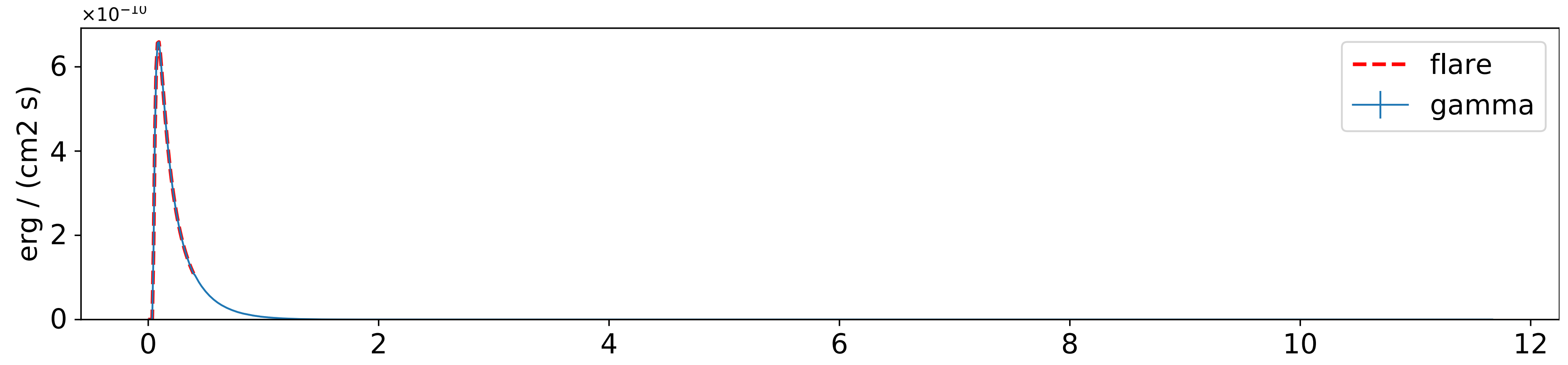
$$R^* = R_0 \left(\frac{\nu^0_{SSA}}{\nu^*_{SSA}} \right)^{\psi}$$

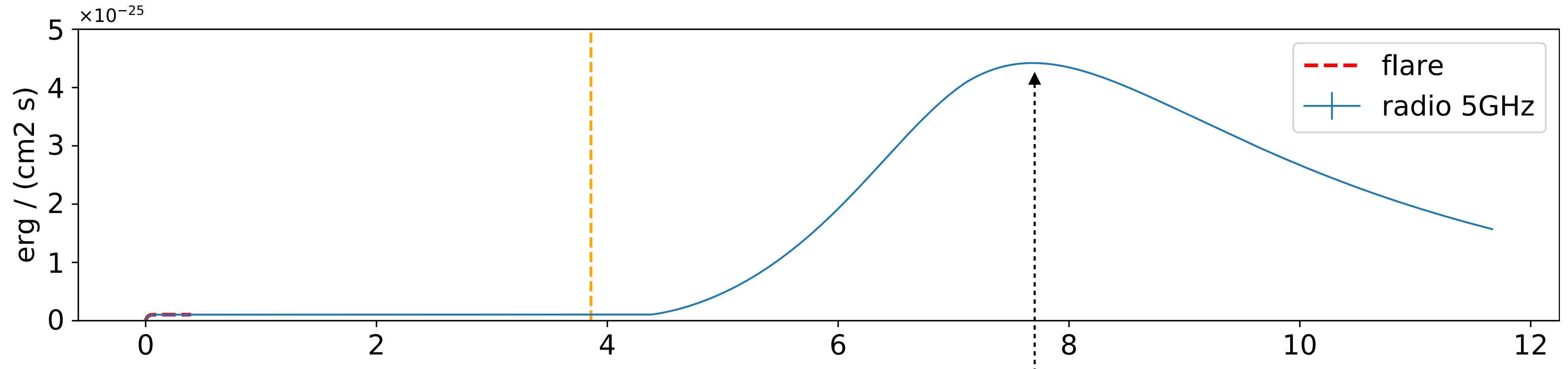
$$\psi = \frac{p+4}{m_B(p+2) - 2}$$

trends in the obs. frame

Tramacere+ 2022







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

src transp at ν^*_{SSA}

R=R*

Tramacere+ 2022

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

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

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

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

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

$$\delta = \frac{1}{\Gamma(1-\beta_\Gamma\cos(\theta))} \qquad \nu^{\rm obs} = \nu\frac{\delta}{z+1}$$

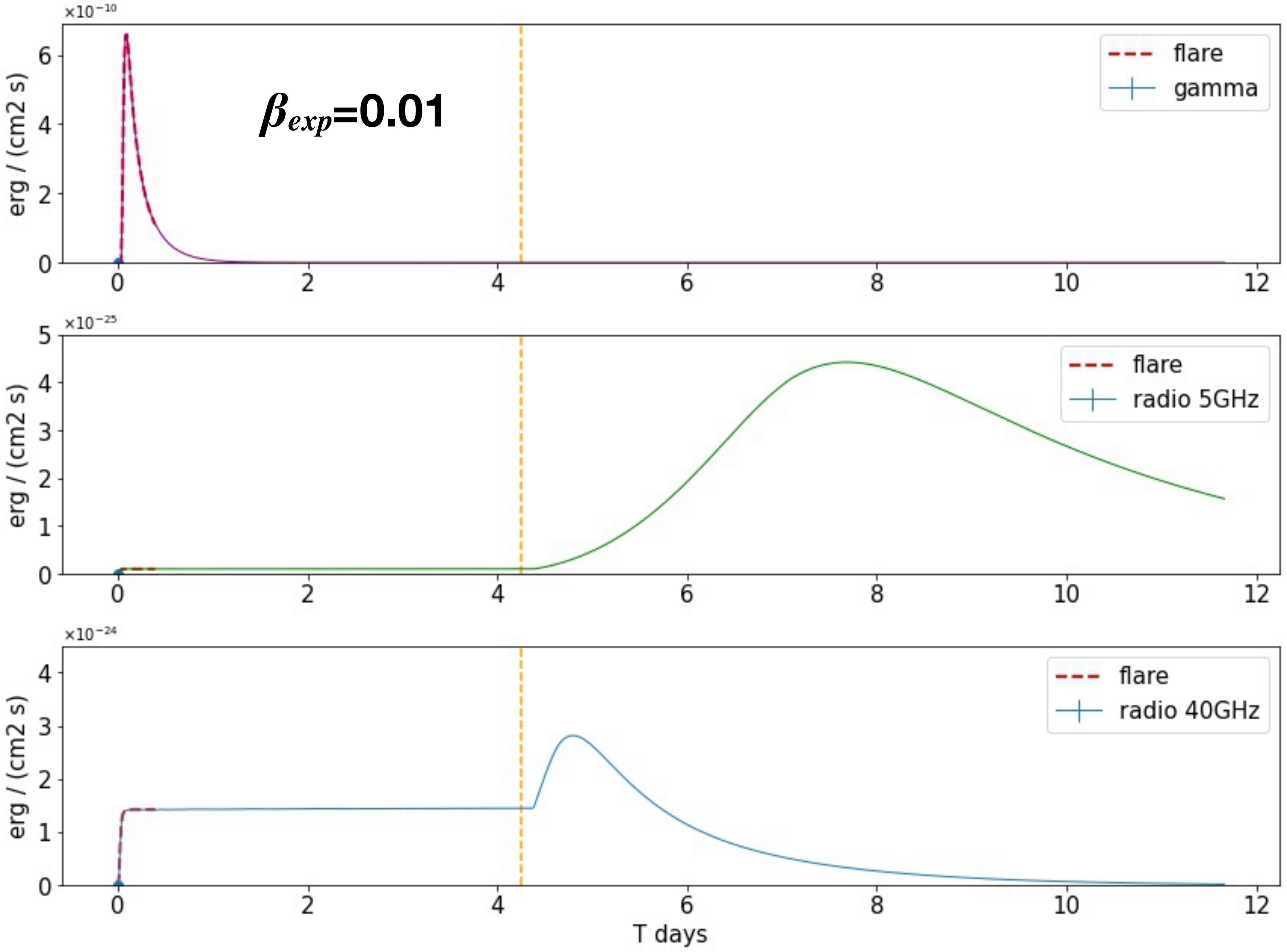
$$t^{\rm obs}_{var} = \frac{(1+z)R_0}{\delta c}$$

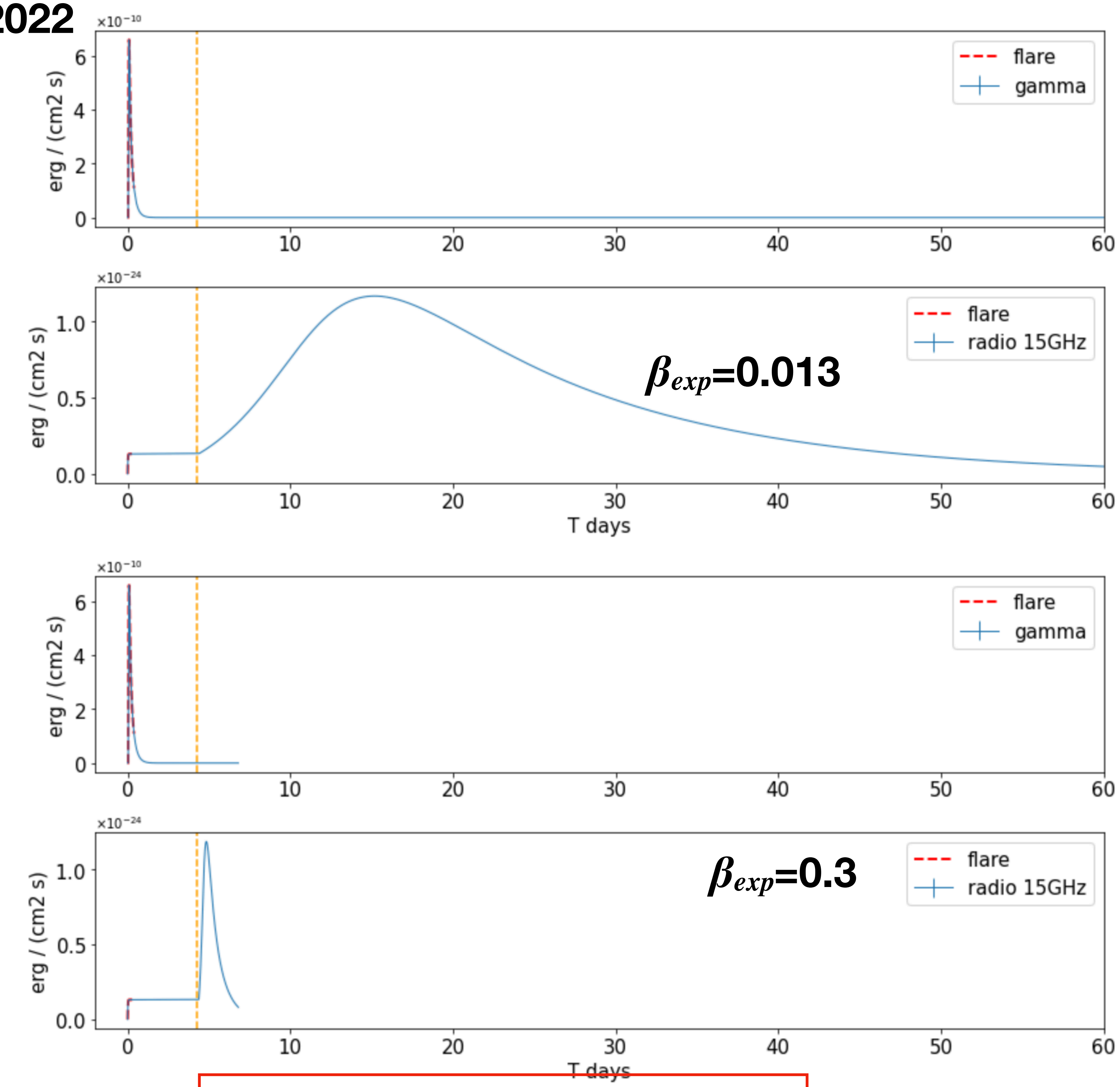
$$R^0_{\rm obs} = R_0\,\frac{1+z}{\delta}$$

$$\Delta_r = \Gamma\Delta t_{\nu^0_{\rm SSA}\to\nu^*_{\rm SSA}}\beta_\Gamma c = \frac{\delta\Gamma\beta_\Gamma c\Delta t^{\rm obs}_{\nu^{0,\rm obs}_{\rm SSA}}}{1+z}$$

trends vs ν^*_{SSA}. trends vs β_{exp}

Tramacere+ 2022





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

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

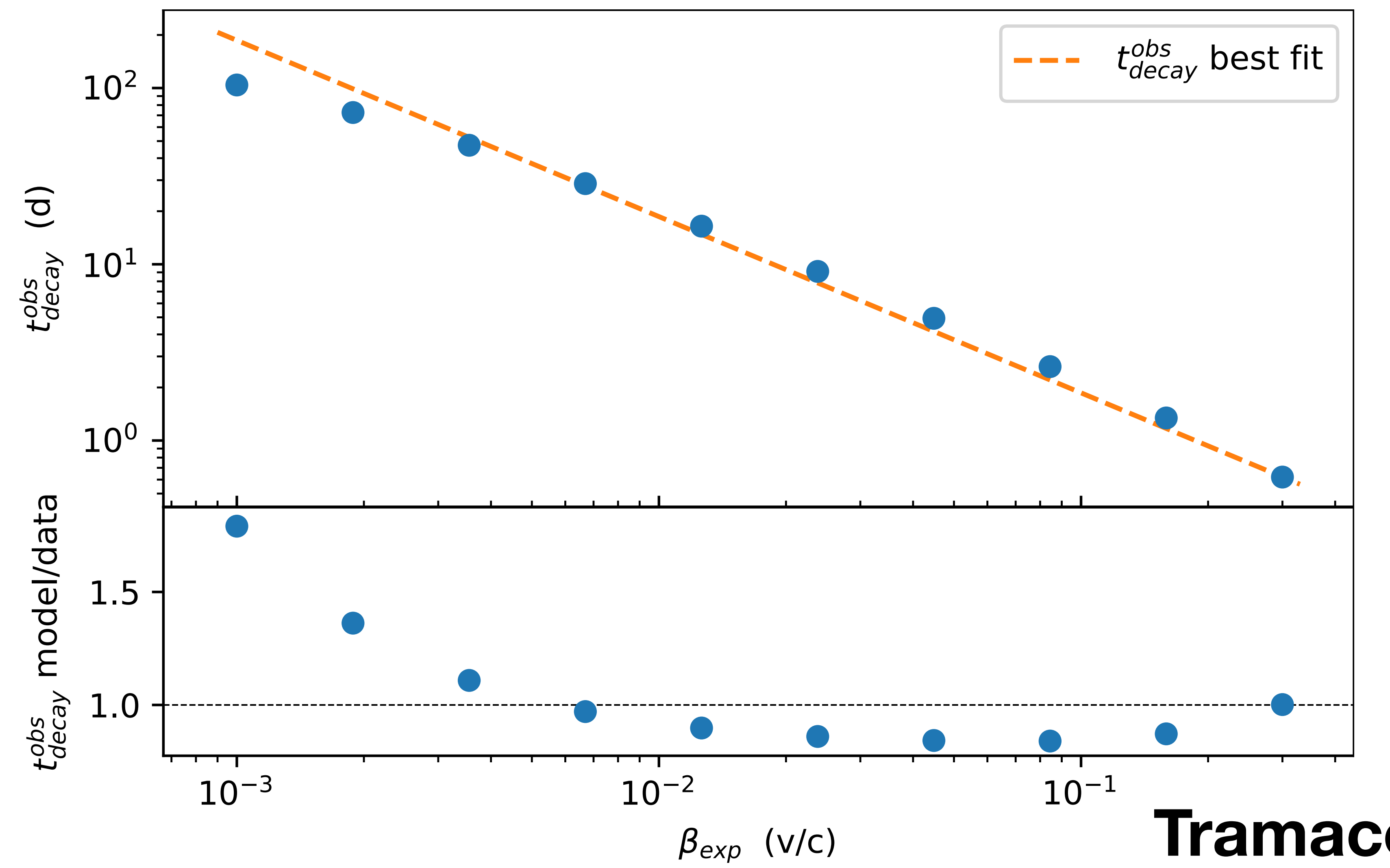
$\Delta t \sim t_{exp} + t_r$

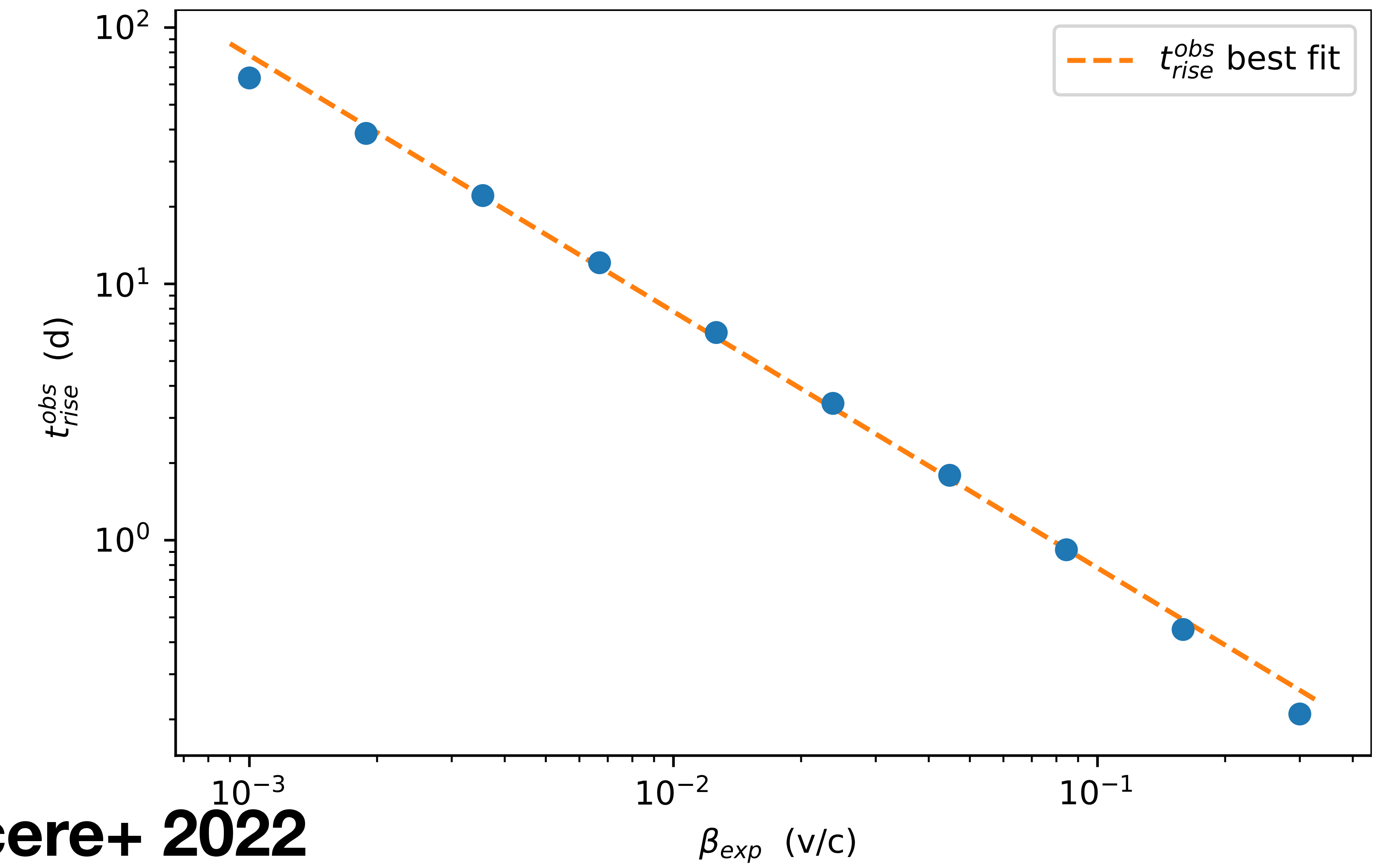
$t_r \sim 1/\beta_{exp}$

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

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

trends vs β_{exp}





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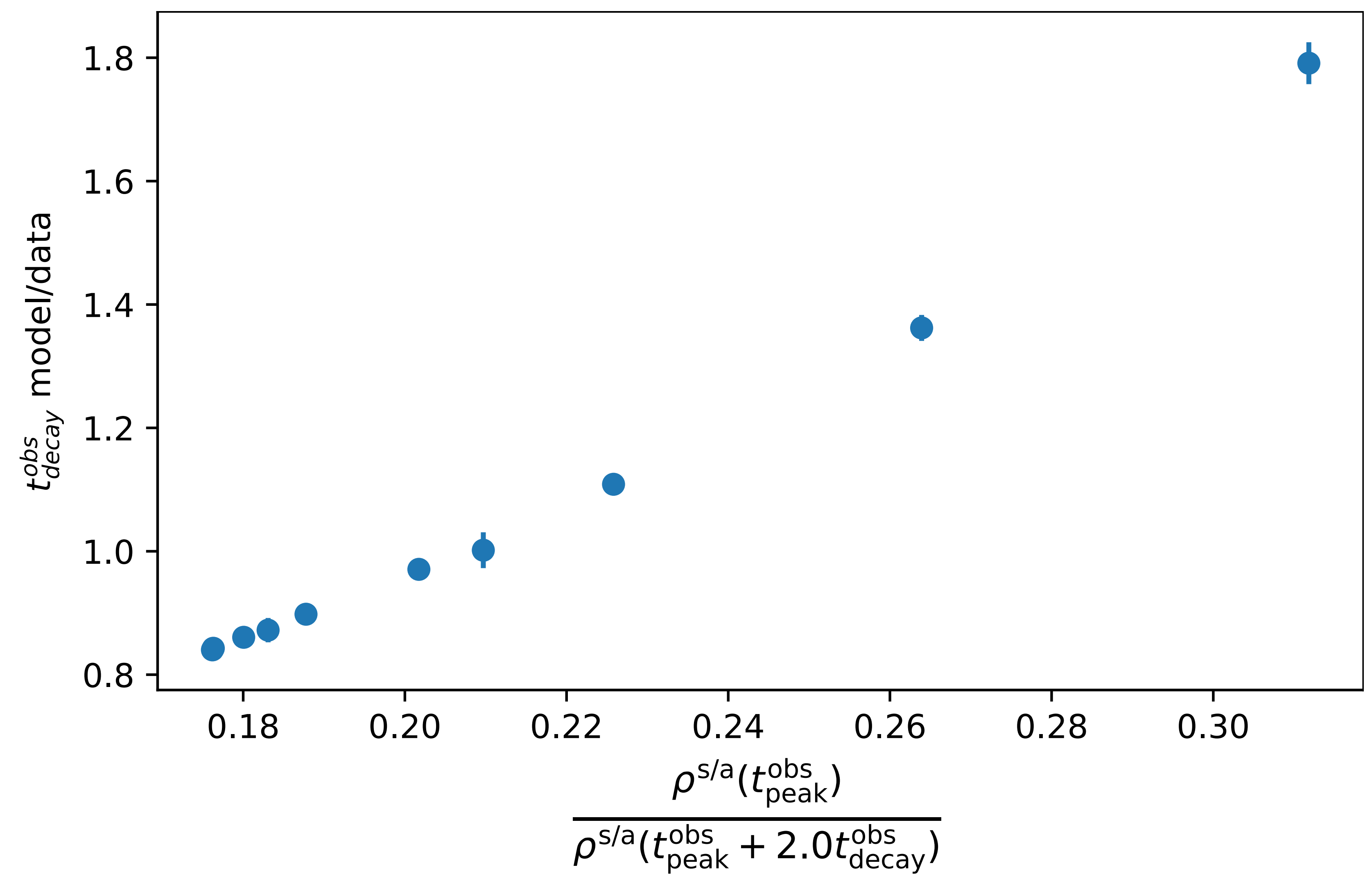
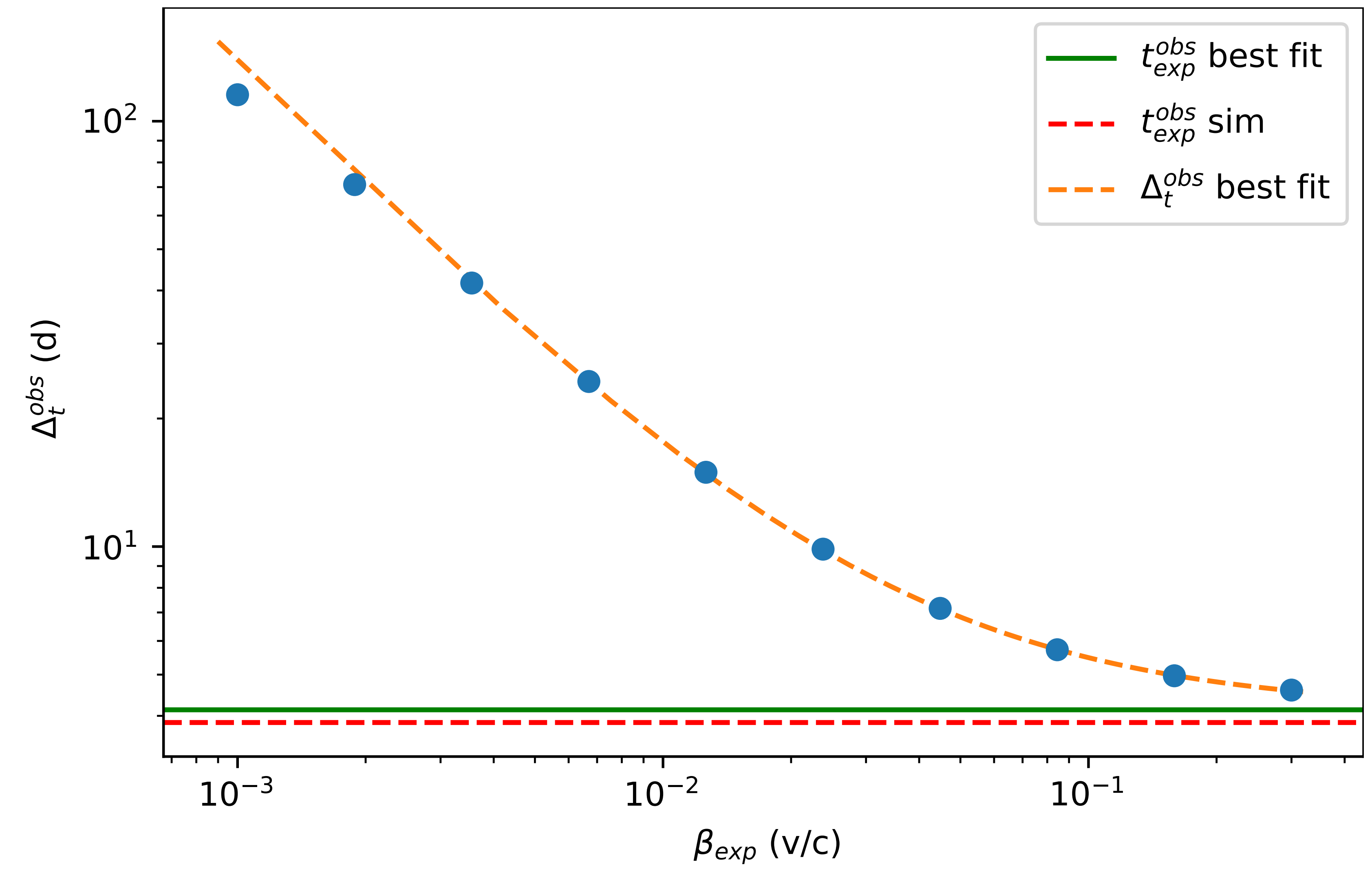




β_{exp}=[0.001-0.3]

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

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

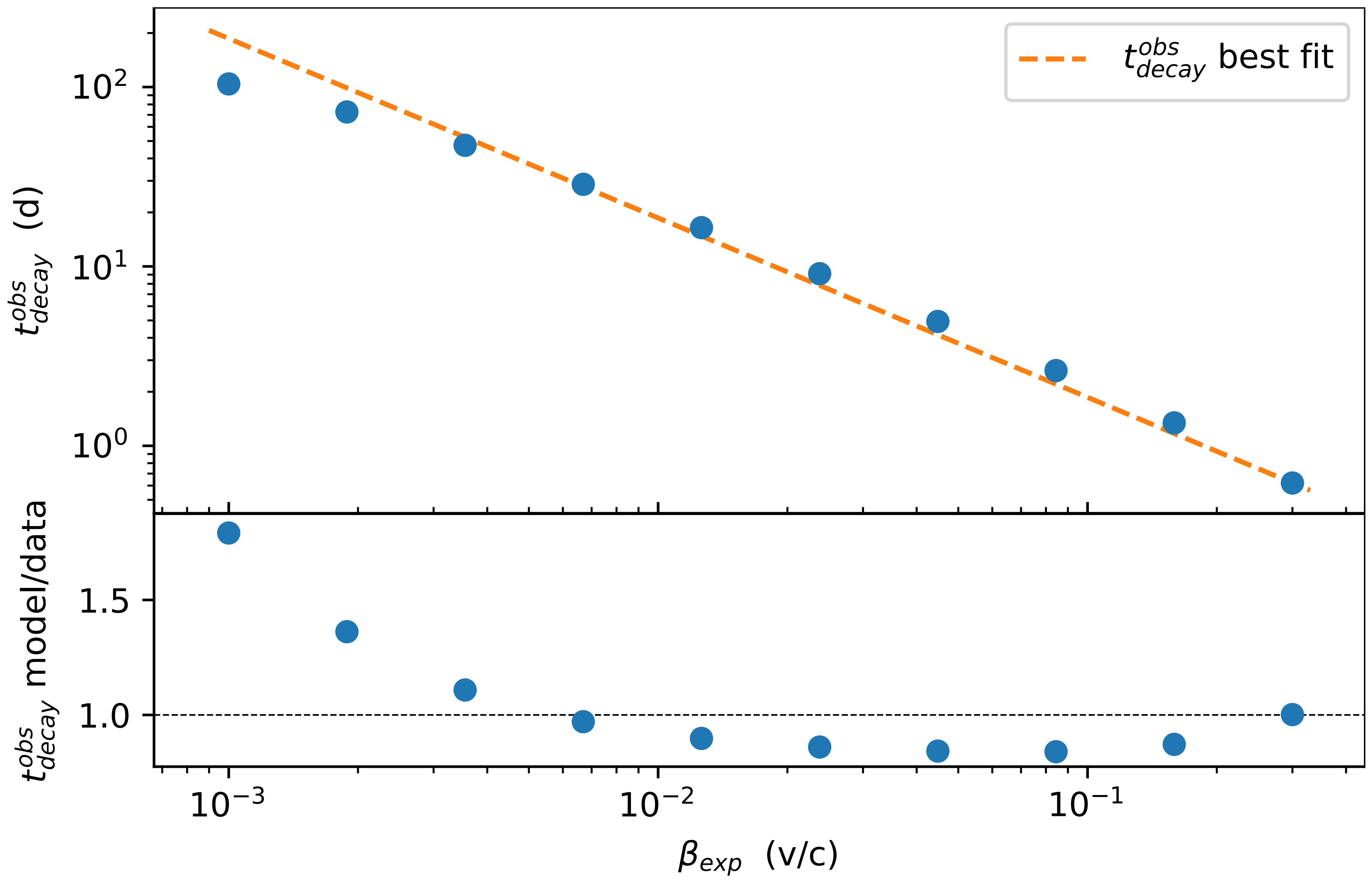
$$\Delta t^{\rm obs} = t^{\rm obs}_{\rm exp} + t^{\rm obs}_{\rm peak} = t^{\rm obs}_{\rm exp} + \frac{R^{\rm obs}_0}{\beta_{\rm exp} c}\Big[\Big(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\Big)^{\phi} - 1\Big].$$

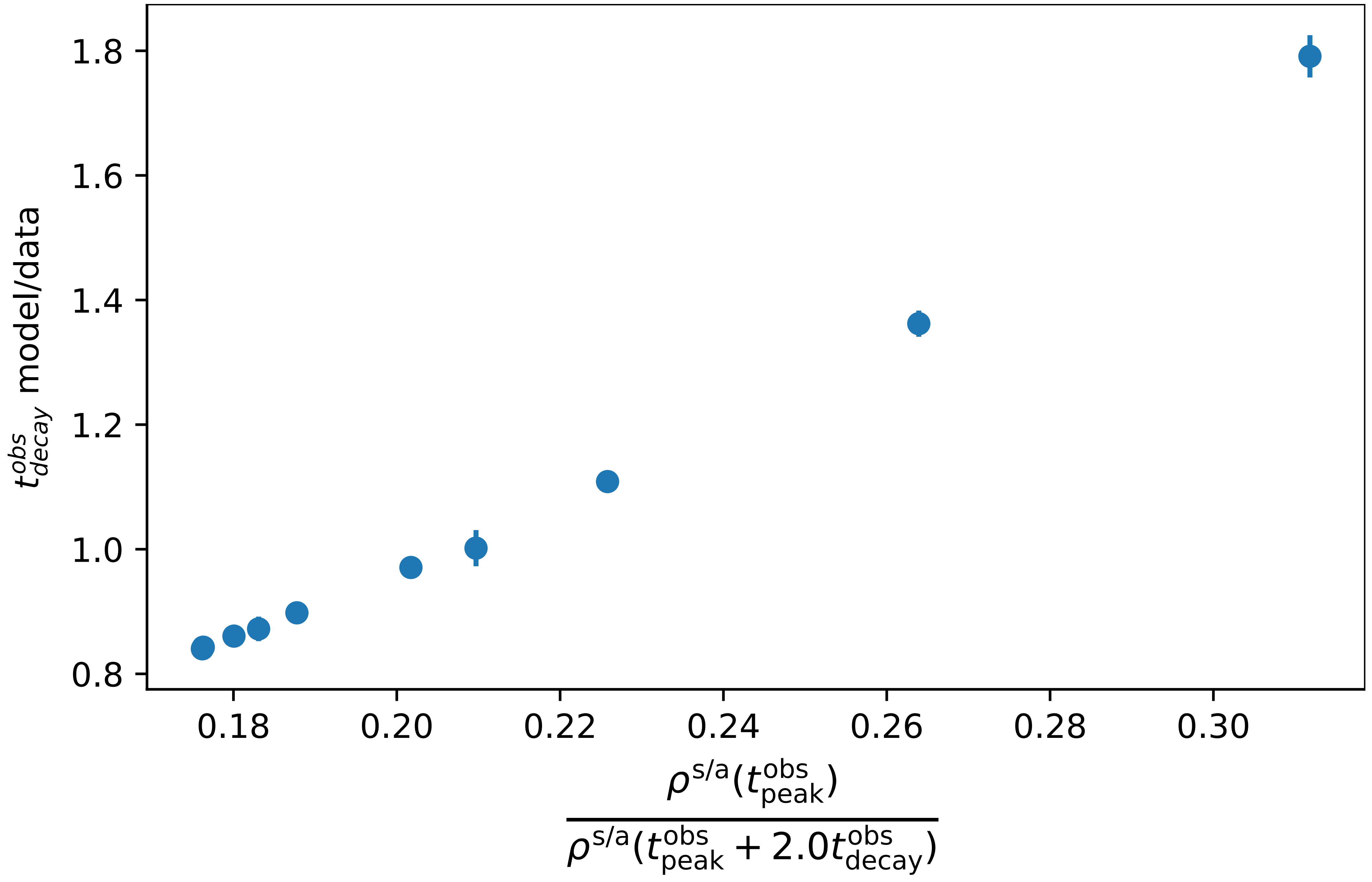
		actual values		values from β trend best fit		
		blob	obs	$t^{\rm obs}_{\rm rise}$	$t^{\rm obs}_{\rm decay}$	$\Delta t^{\rm obs}$
R_0	cm	5×10^{15}	1.66×10^{14}	$(1.9 \pm 0.5) \times 10^{14}$	$(1.7 \pm 0.1) \times 10^{14}$	$(1.8 \pm 0.1) \times 10^{14}$
$\nu^0_{\rm SSA}$	GHz	3	90	110 ± 40	100 ± 10	100 ± 5
$t_{\rm exp}$	s	1×10^7	3.3×10^5			$(3.57 \pm 0.01) \times 10^5$
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 β_{exp}

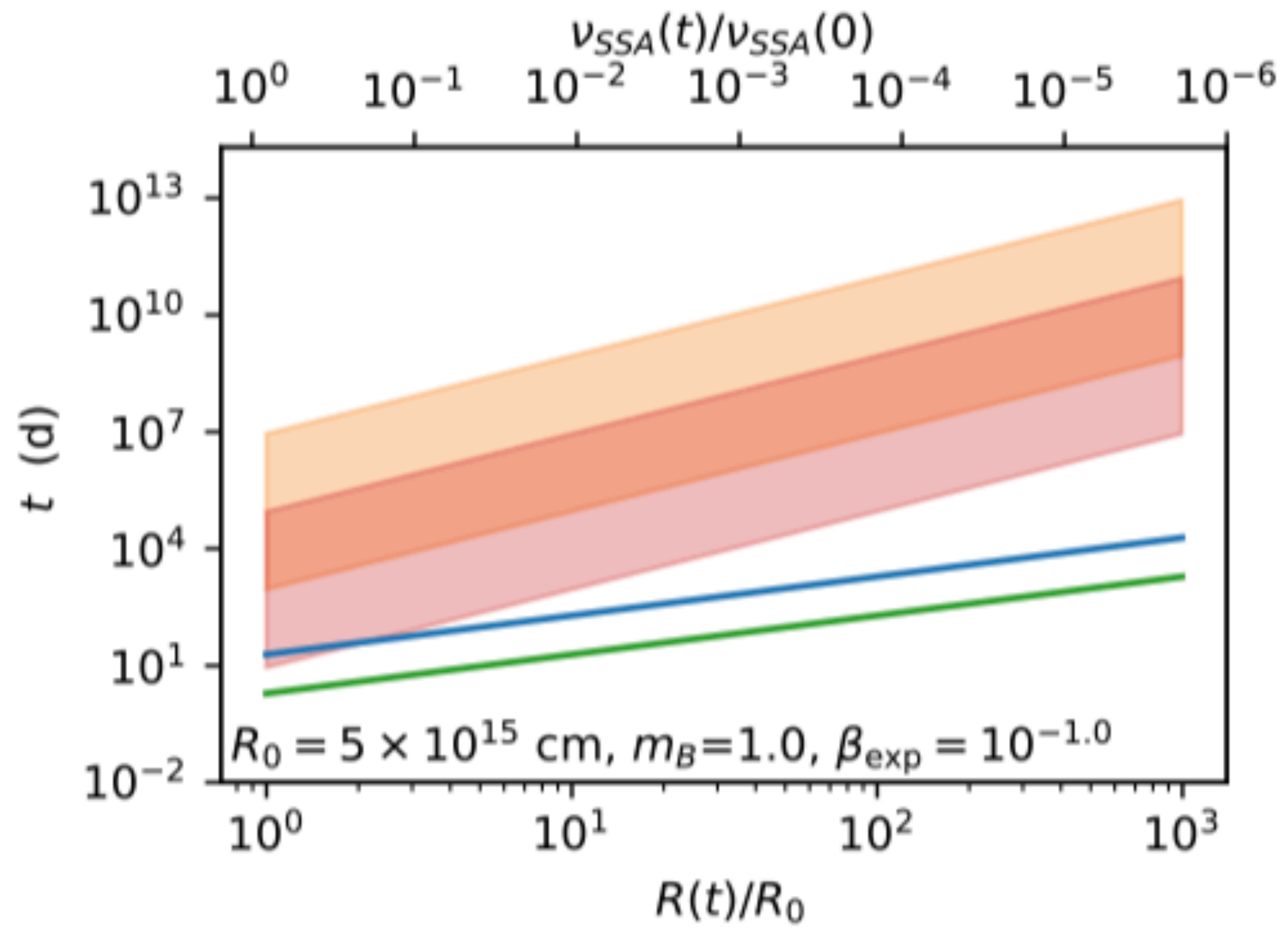
2022
7th Heidelberg International Symposium on
High Energy Gamma-Ray Astronomy
Barcelona, July 4-8 2022

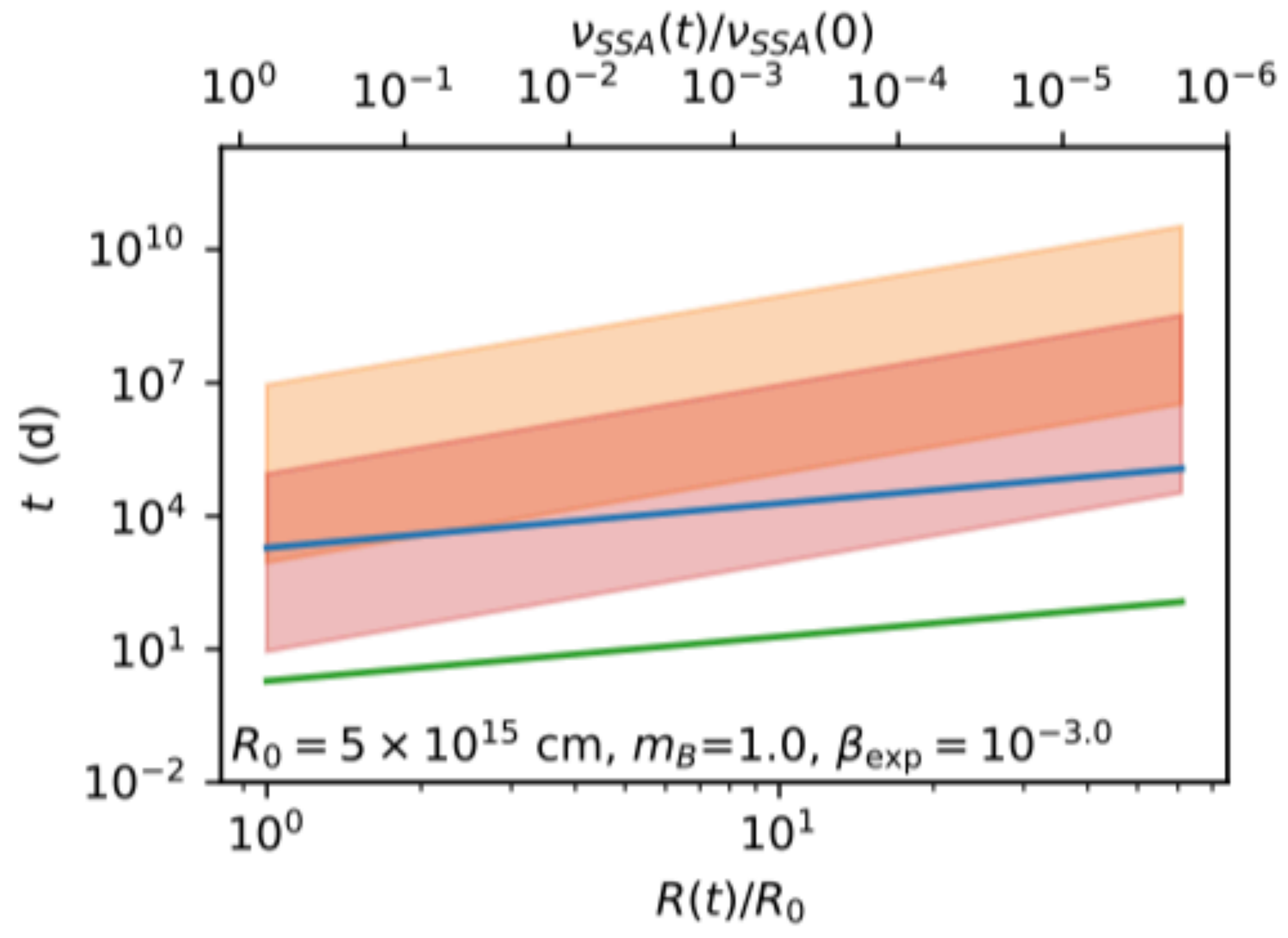
Tramacere+ 2022





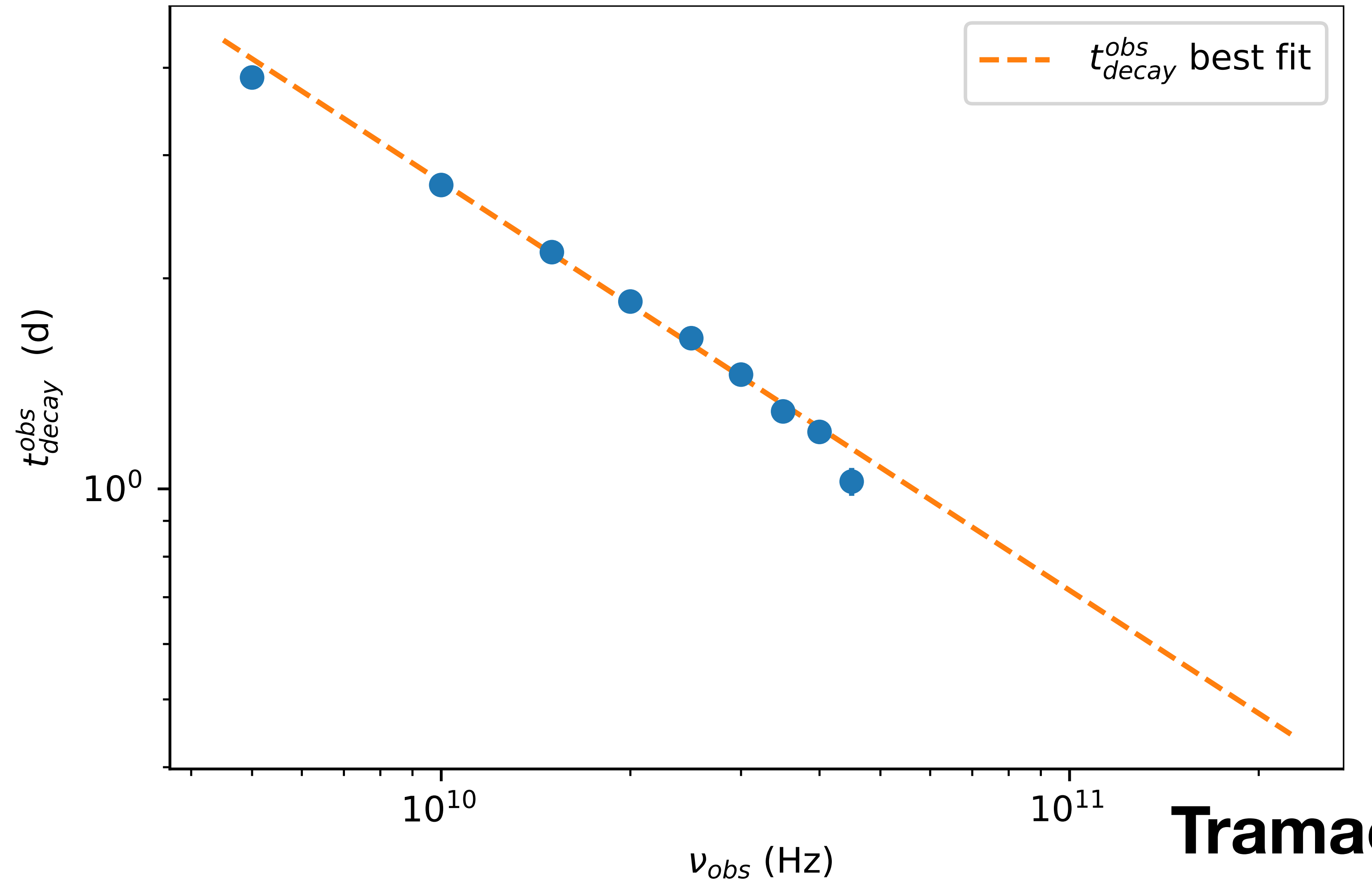
β_{exp}=[0.001-0.3]

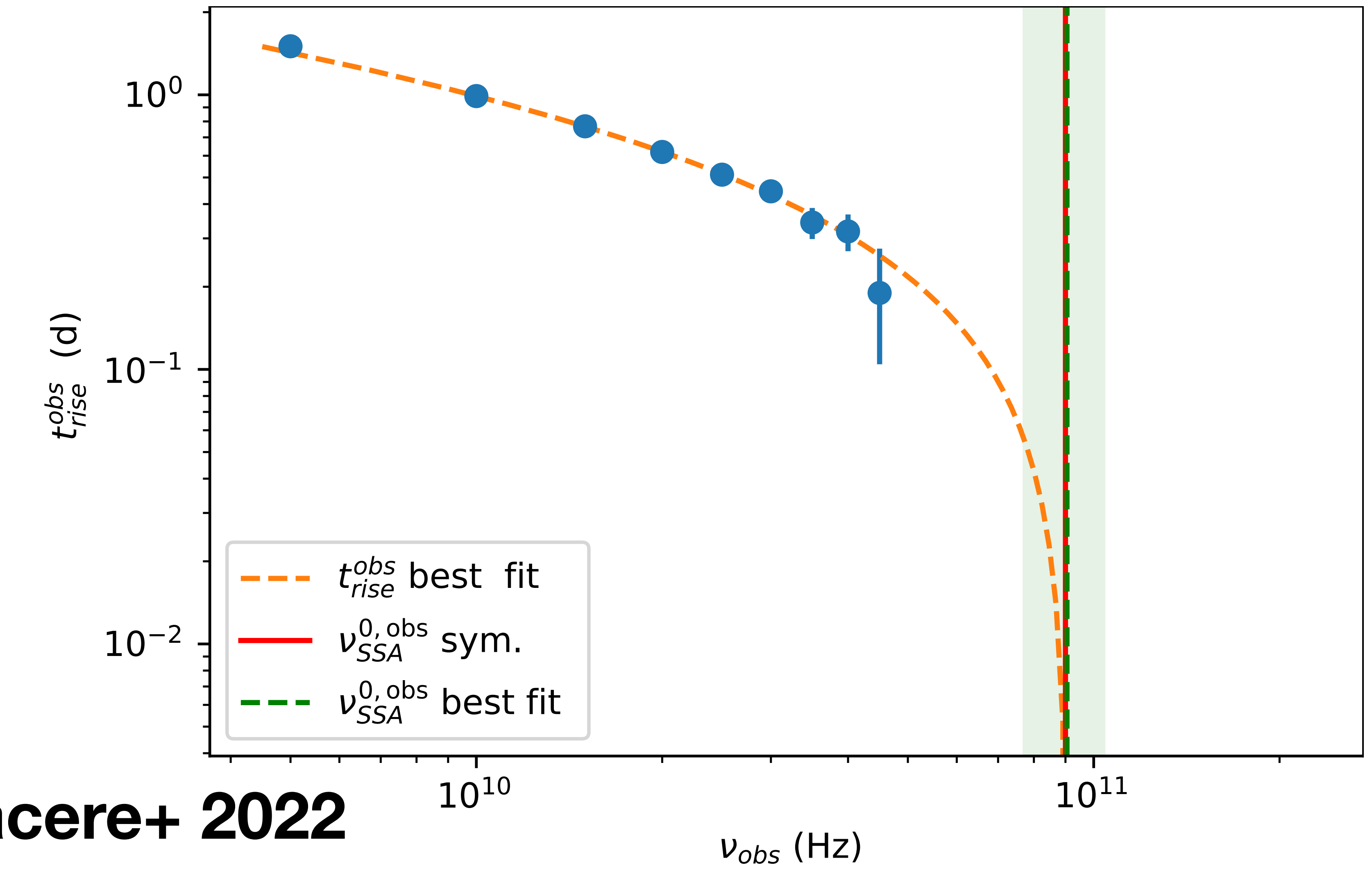




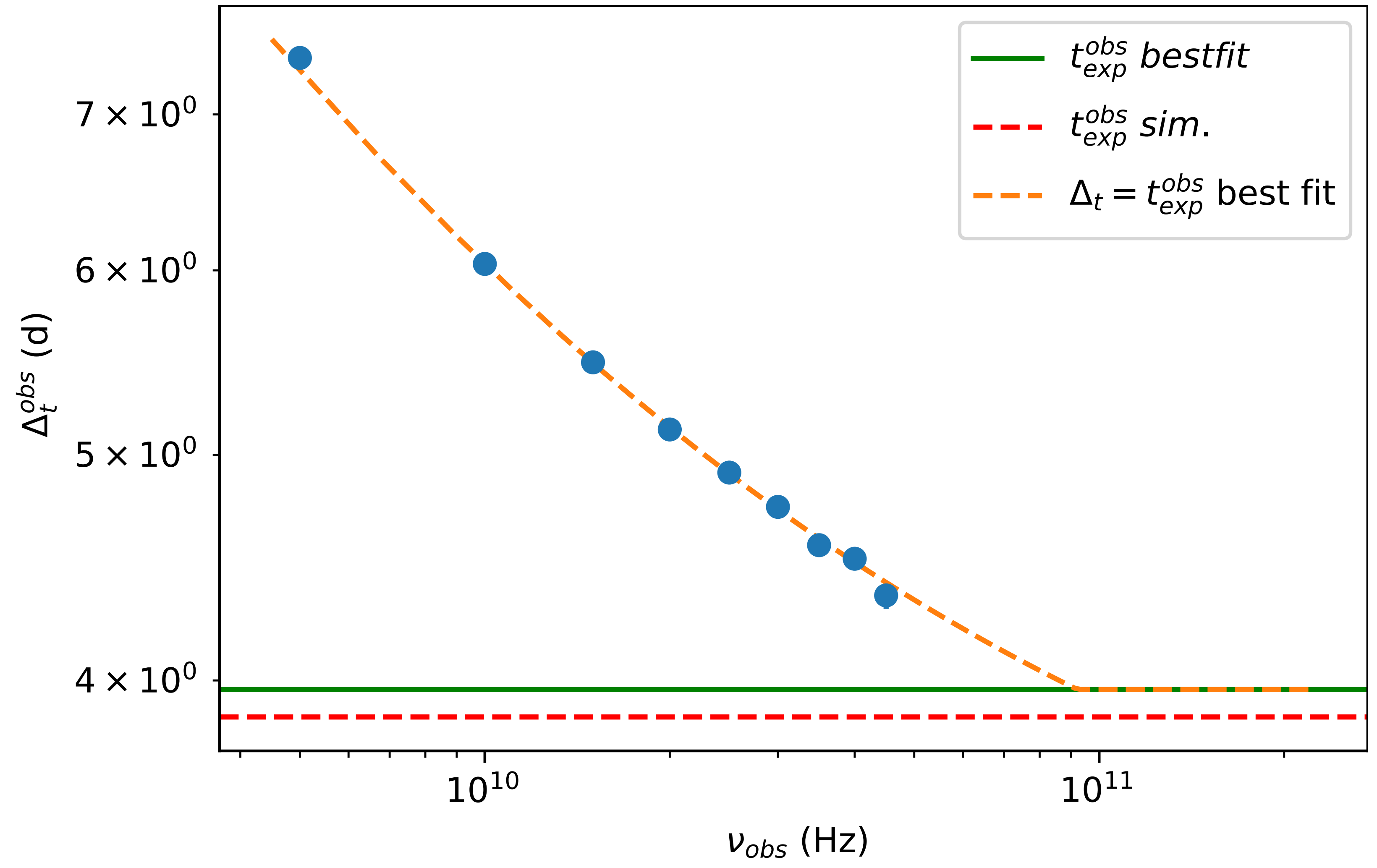
trends vs ν_{obs}

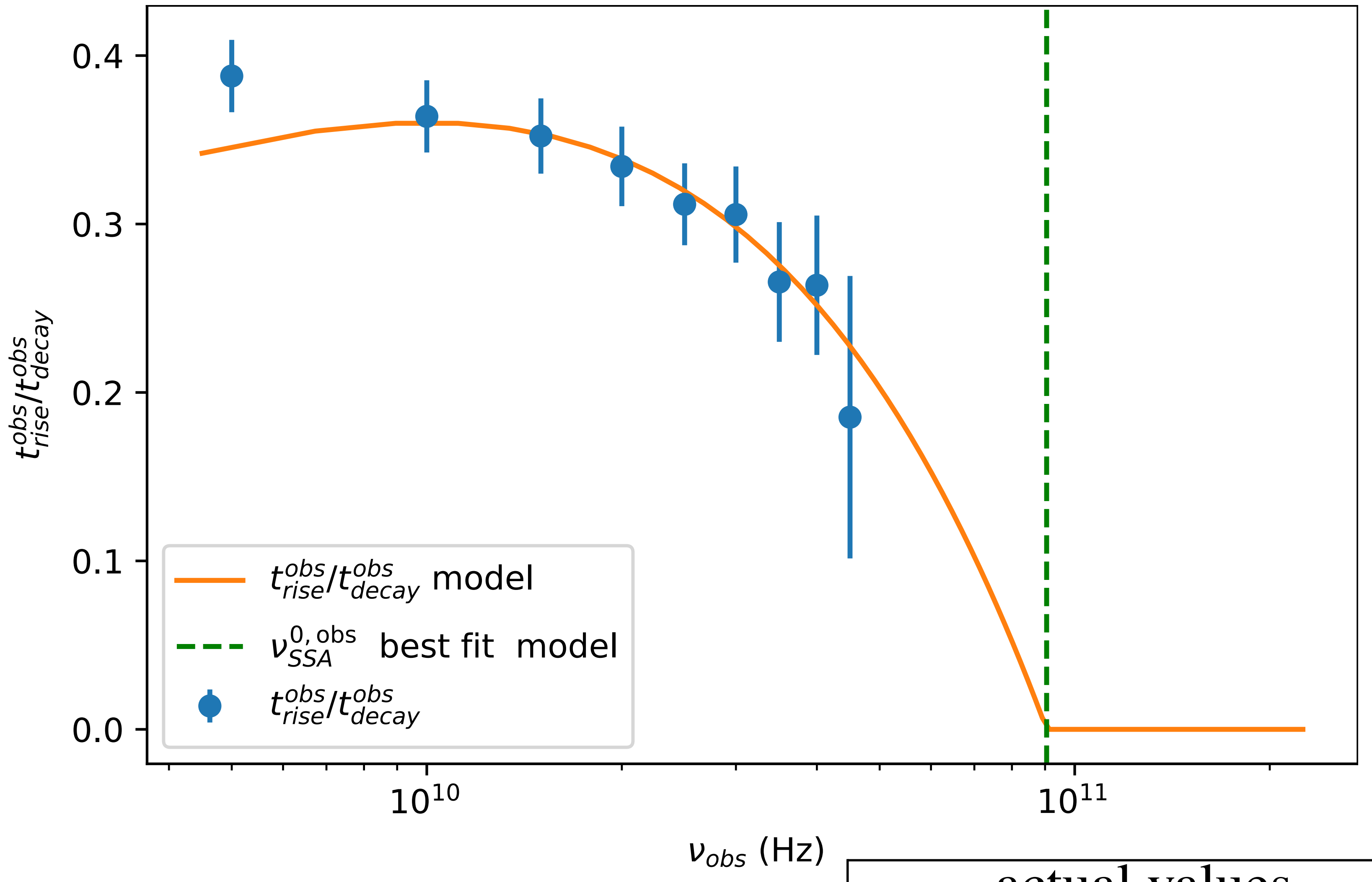
γ 2022 — 7th Heidelberg International Symposium on High Energy Gamma-Ray Astronomy, Barcelona, July 4-8 2022





Tramacere+ 2022





β_{exp}=[0.1]

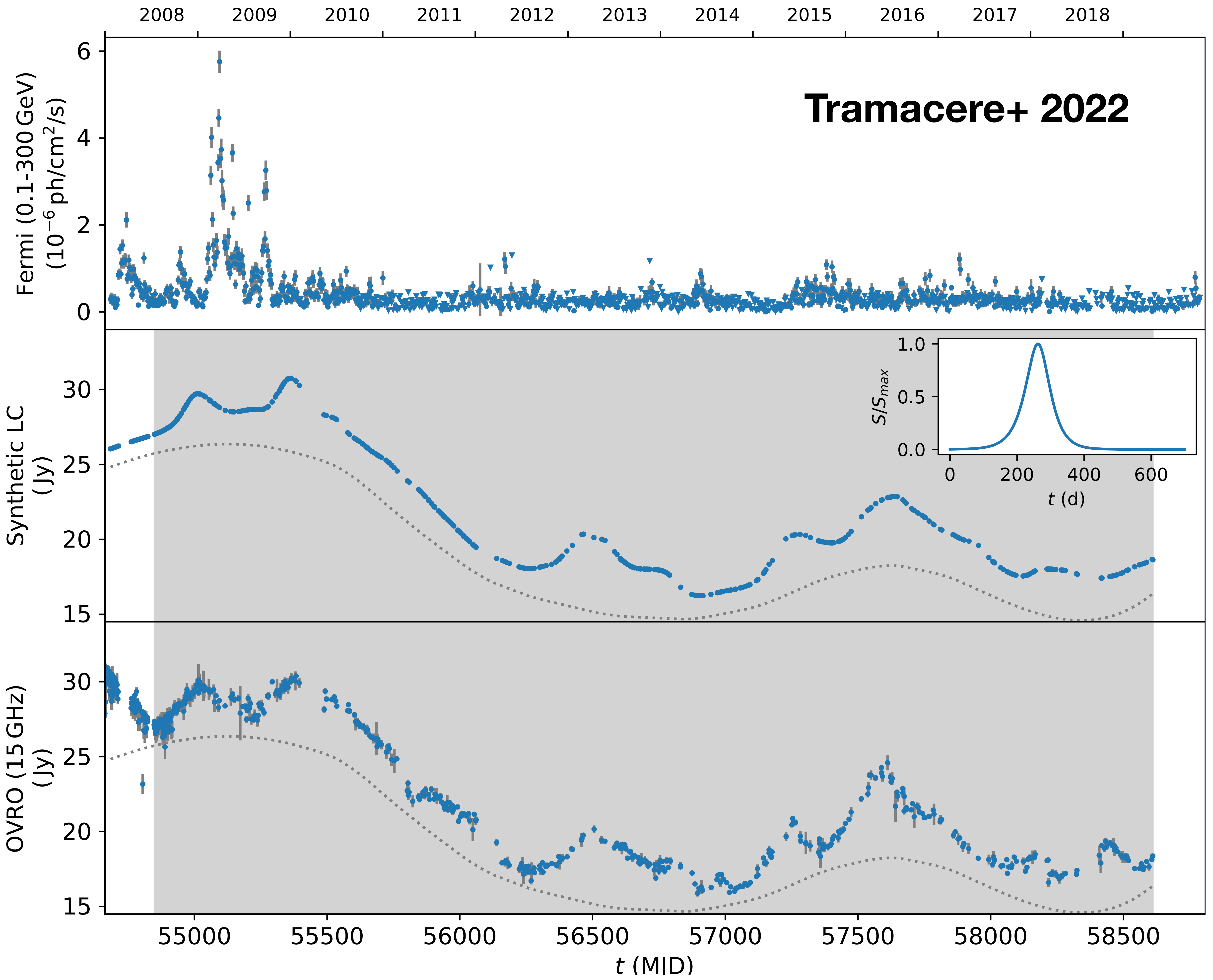
$$t^{\rm obs}_{\rm decay} = \frac{R^{\rm obs}_0}{m_B\beta_{\rm exp}c}\left(\frac{\nu^{0,\rm obs}_{\rm SSA}}{\nu^{*,\rm obs}_{\rm SSA}}\right)^{\phi}$$

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

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

		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}	$(2.4\pm1.0)\times10^{14}$	$(1.7\pm0.2)\times10^{14}$	$(1.6\pm0.1)\times10^{14}$
$\nu^0_{\rm SSA}$	GHz	3	90	90 ± 10	100 ± 20	90 ± 10
$t_{\rm exp}$	s	1×10^7	3.3×10^5			$(3.4\pm0.1)\times10^5$
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

comparison with observed data



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Period, MJD	Value
54684-54890	1.07 ± 0.11
54890-55340	0.69 ± 0.04
55340-56125	1.39 ± 0.08
56125-56530	5.31 ± 0.16
56530-56920	0.46 ± 0.15
56920-57250	5.3 ± 0.4
57250-57710	2.71 ± 0.12
57710-57910	0.88 ± 0.17
57910-58110	3.5 ± 0.3
58110-58610	2.4 ± 0.3

Parameter	Value
A_0	$174^{+12}_{-11} \times 10^3$ Jy cm^2 s/ph
t_{rise}	37^{+2}_{-2} days
t_{decay}	69^{+3}_{-3} days
Δt	276^{+10}_{-10} days

MCMC sampling

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

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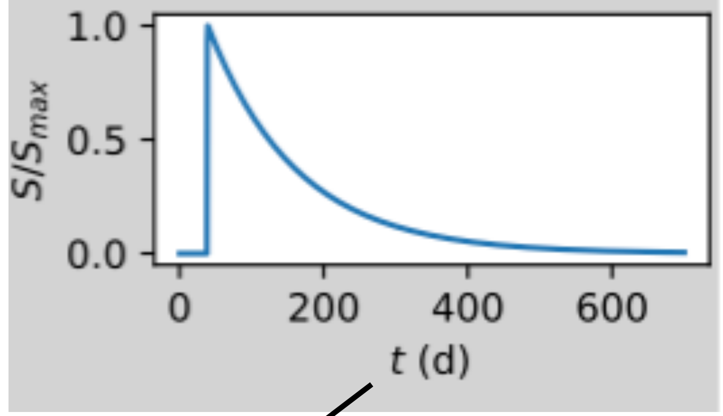
$$\mathcal{L} \propto \sum_{i=[1,2,3]} -\frac{1}{2}\frac{(x_i-\mu_i)^2}{2\sigma_i^2} - \frac{1}{2}\ln(\sigma_i^2)$$



conv analysis best fit values

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

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

$$m_B \in [1,2]$$
$$\nu^{0,\rm obs}_{\rm SSA} \in [10, 10^4]\ \rm GHz$$
$$\phi \in [1/3, 1]$$
$$t^{\rm var}_{\gamma} \in [0.25, 14]\ \text{days}$$

$$R^0_{\rm obs} = R_0\frac{1+z}{\delta} \qquad R_0^{\rm obs} \in [6.5\times10^{13}, 3.6\times10^{17}]\ \rm cm$$

MCMC validation with simulations

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

red dashed line simualtion values

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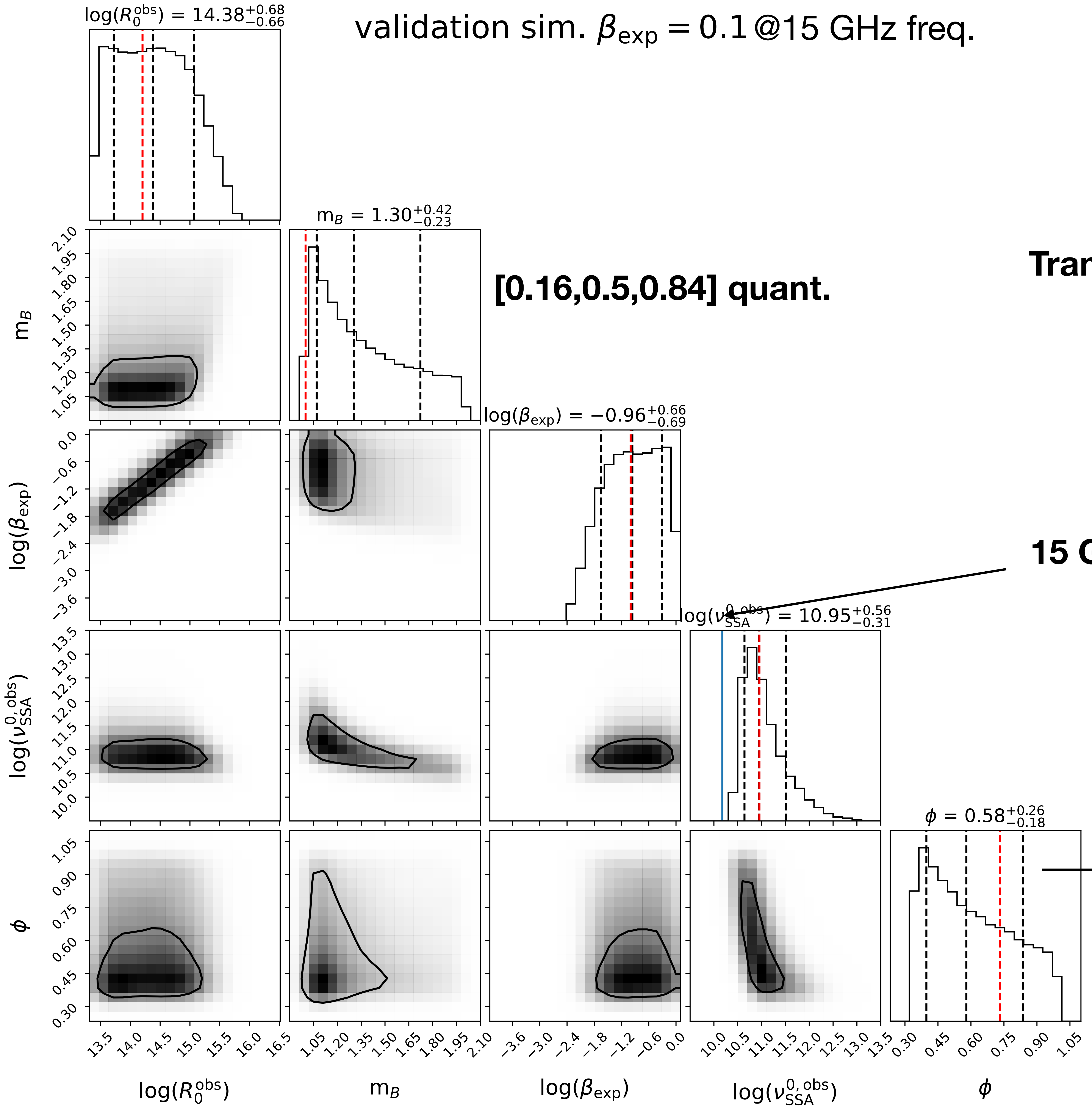
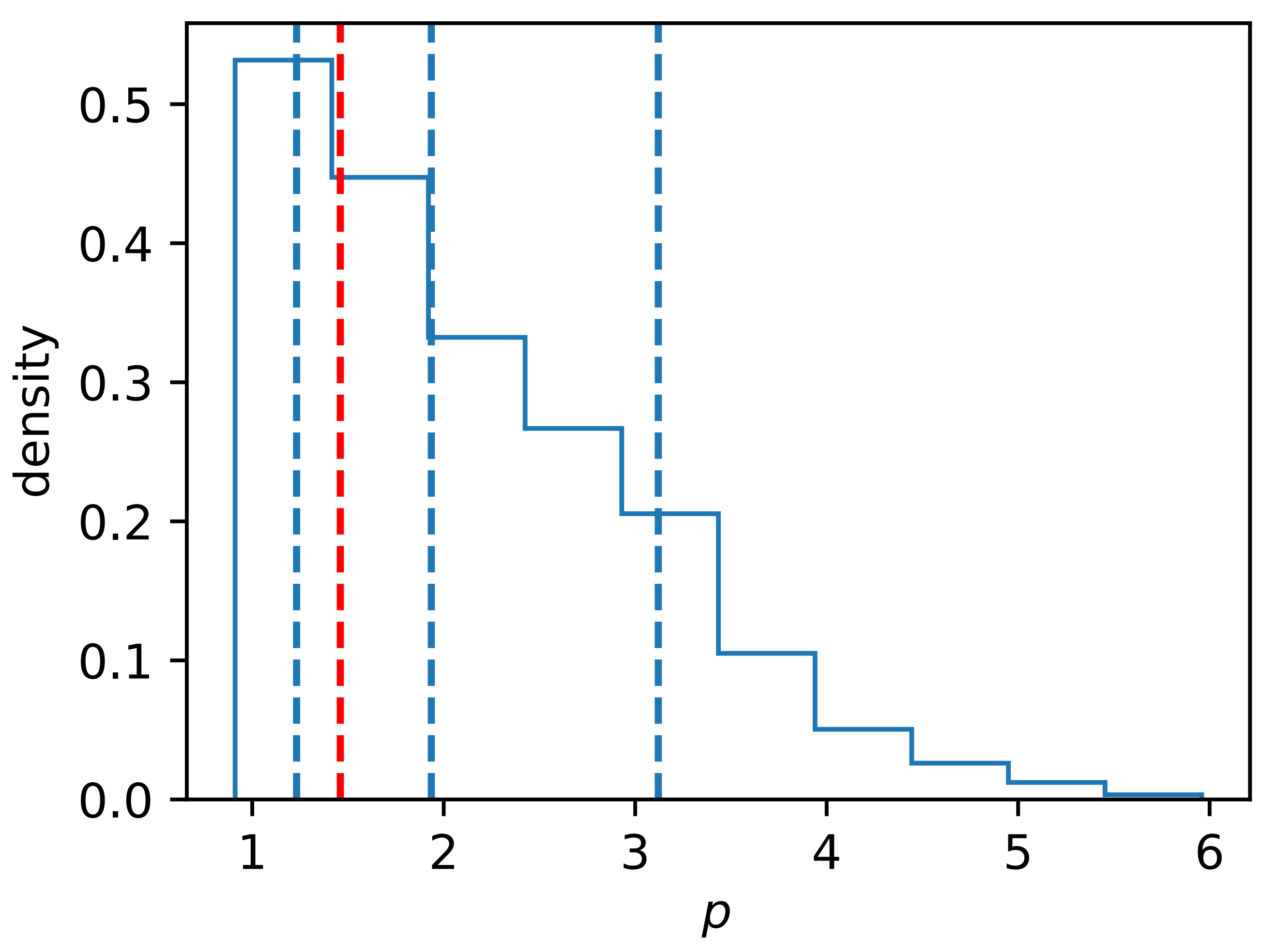
[0.16,0.5,0.84] quant.

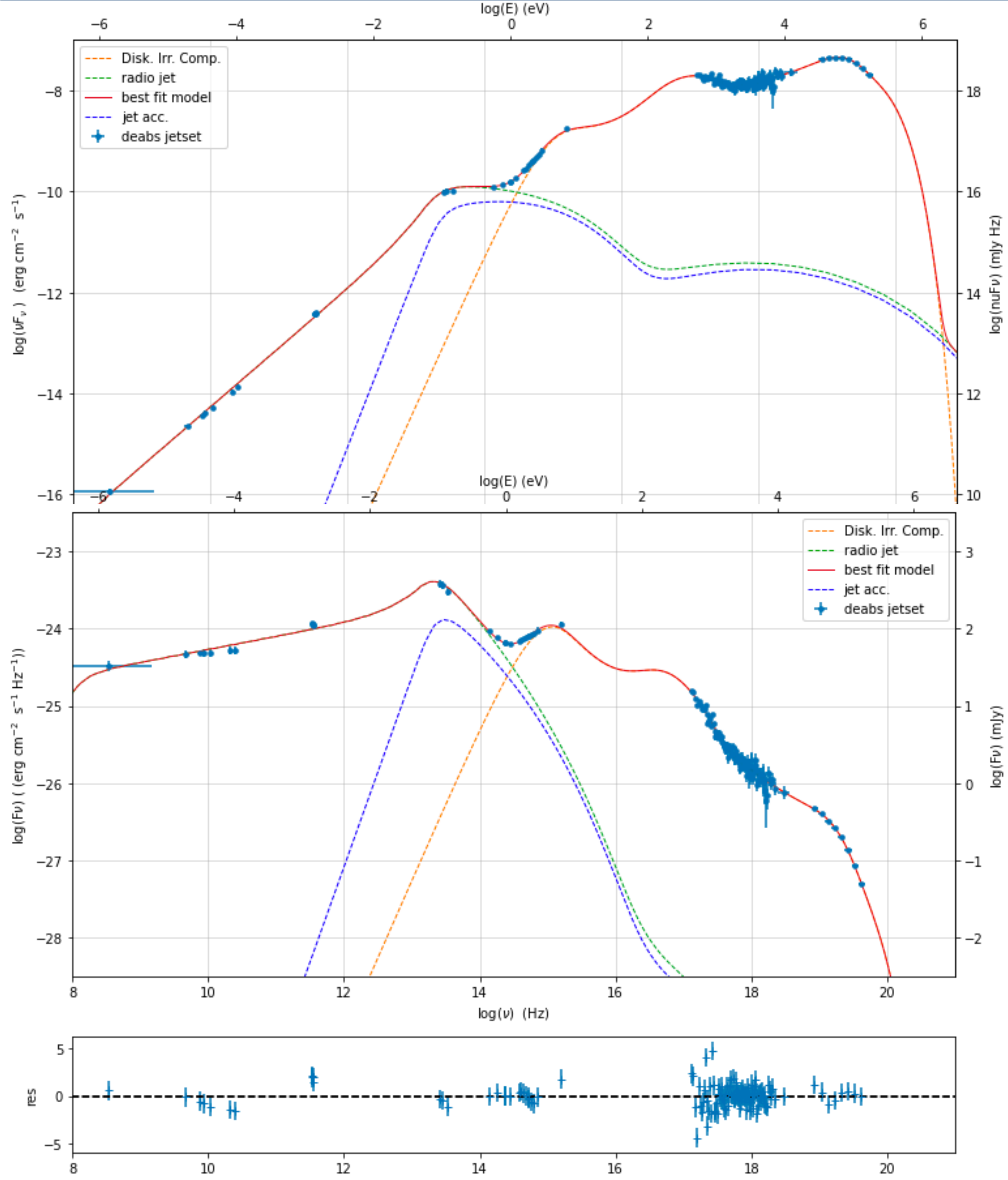
15 GHz freq.



validation sim. $\beta_{\rm exp} = 0.1$, p=$1.94^{+1.19}_{-0.70}$



connection with MQ:



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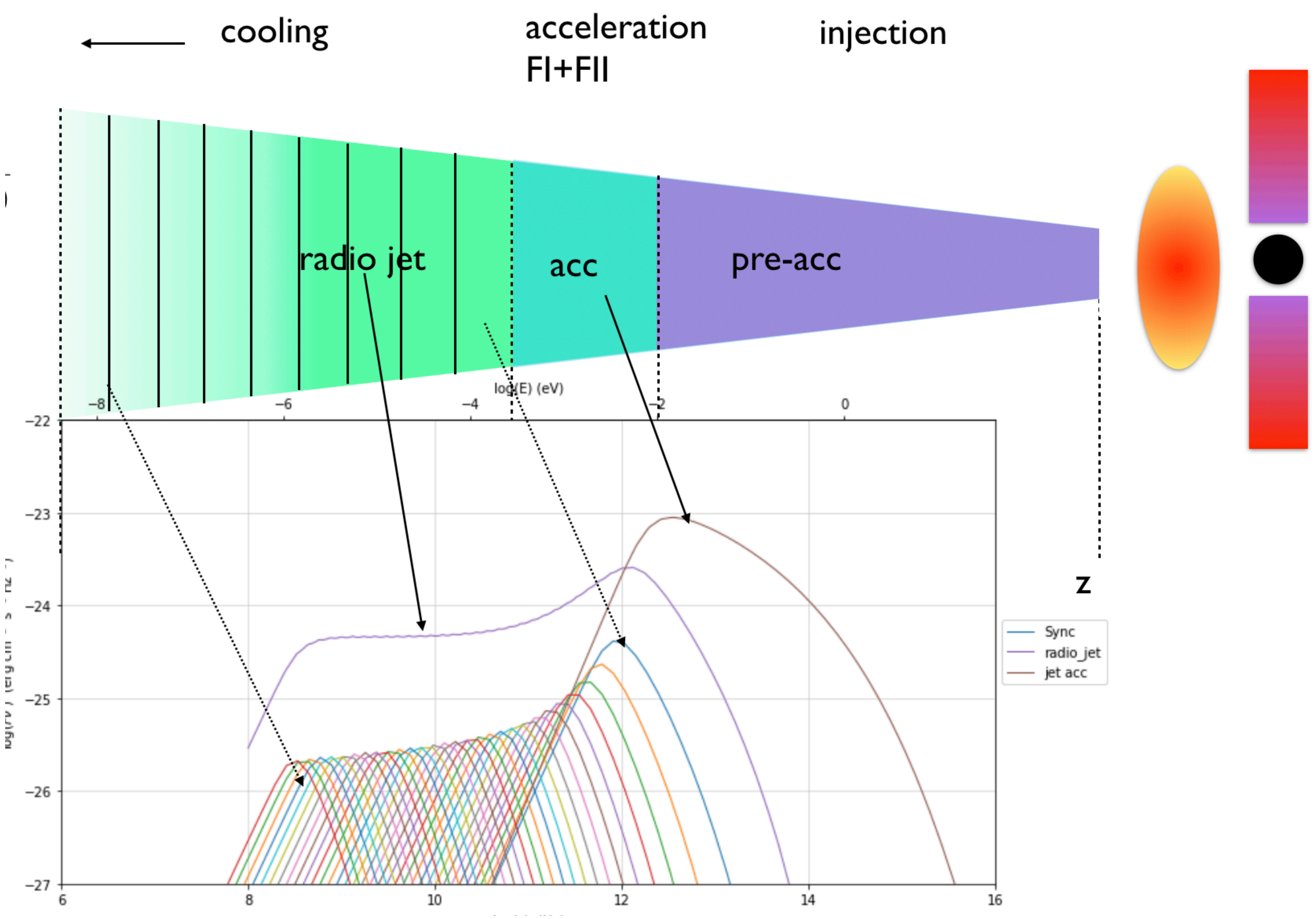

Response

Analytical

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

Numerical

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

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

adb./rad. cooling competition

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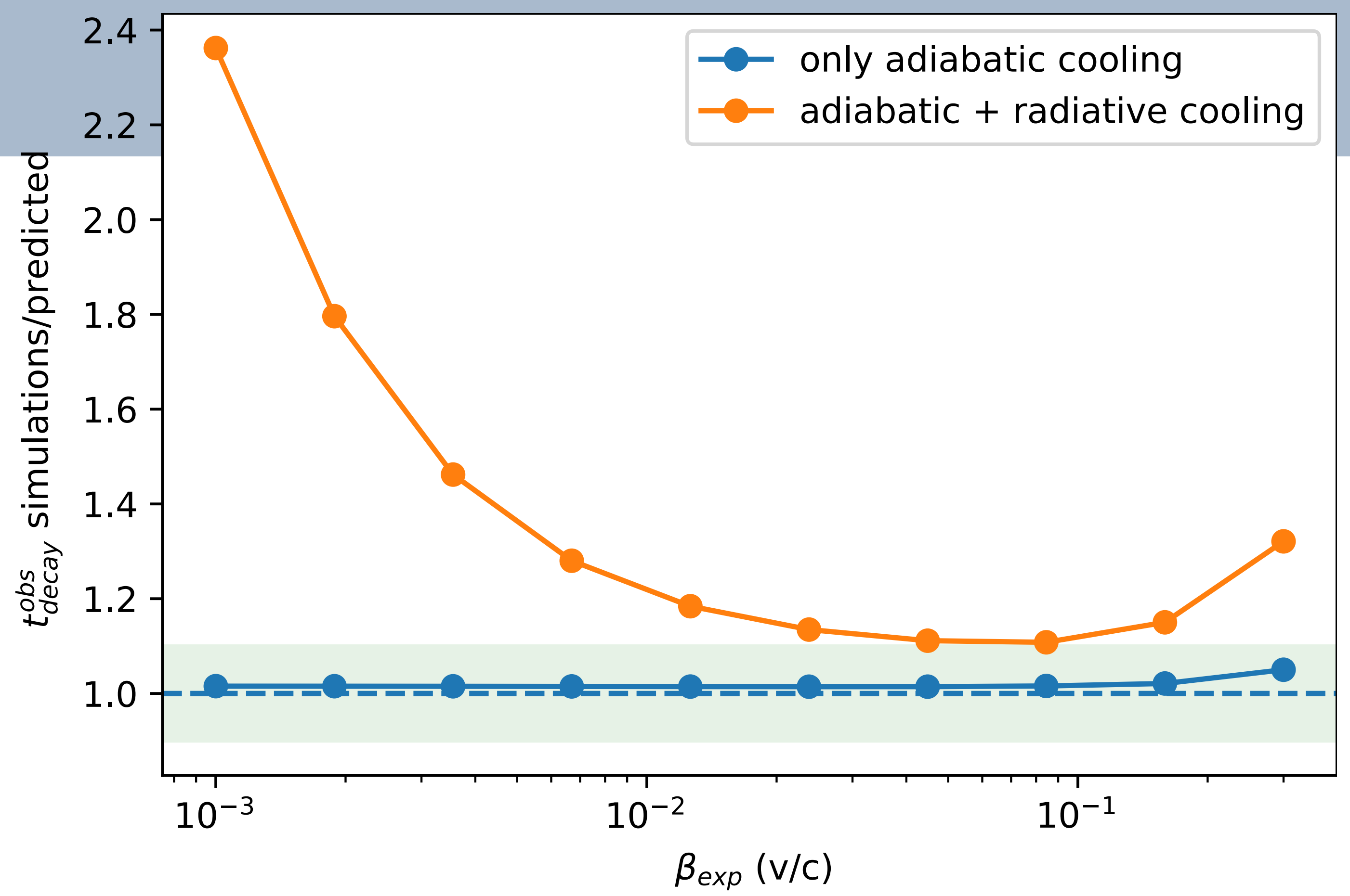

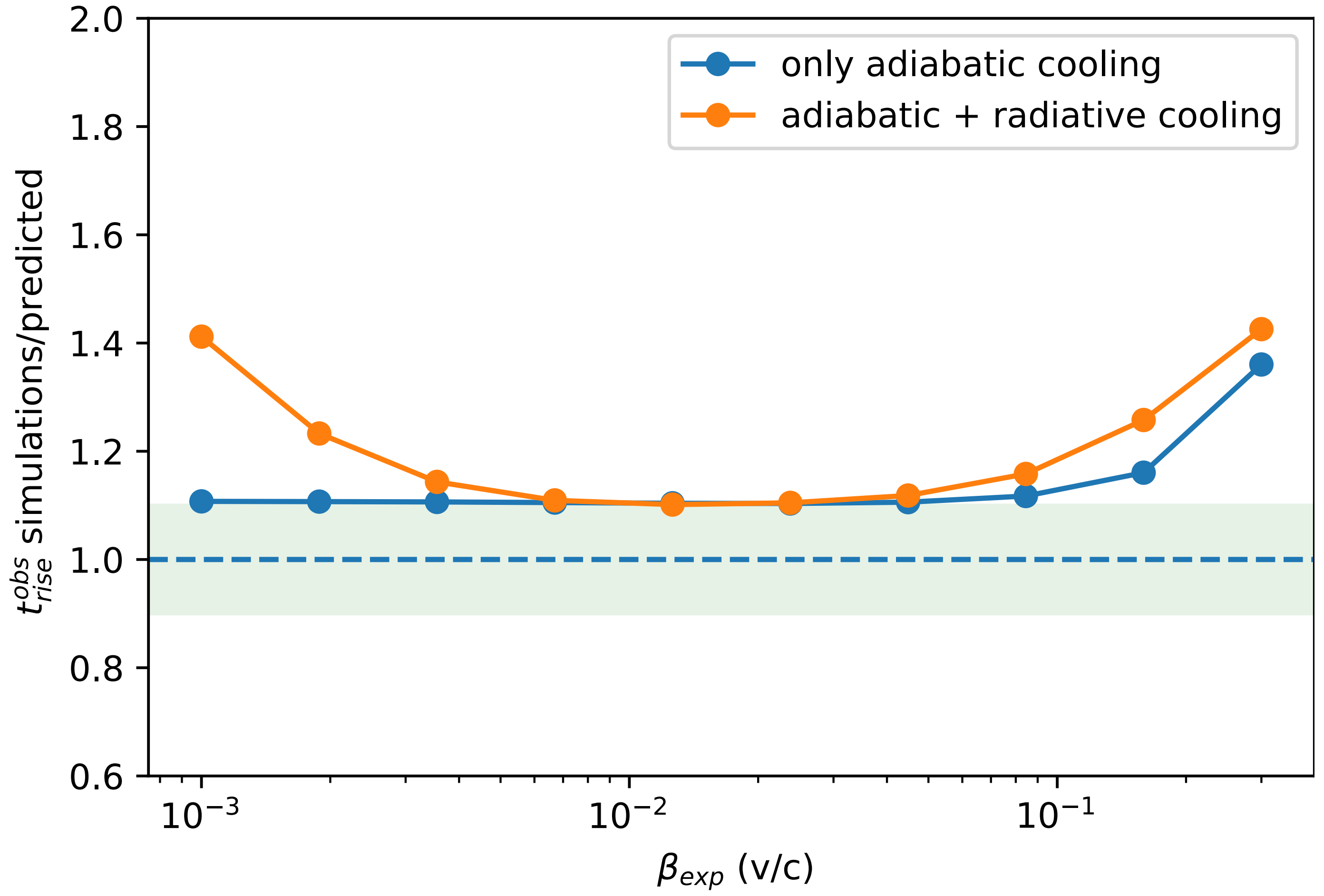

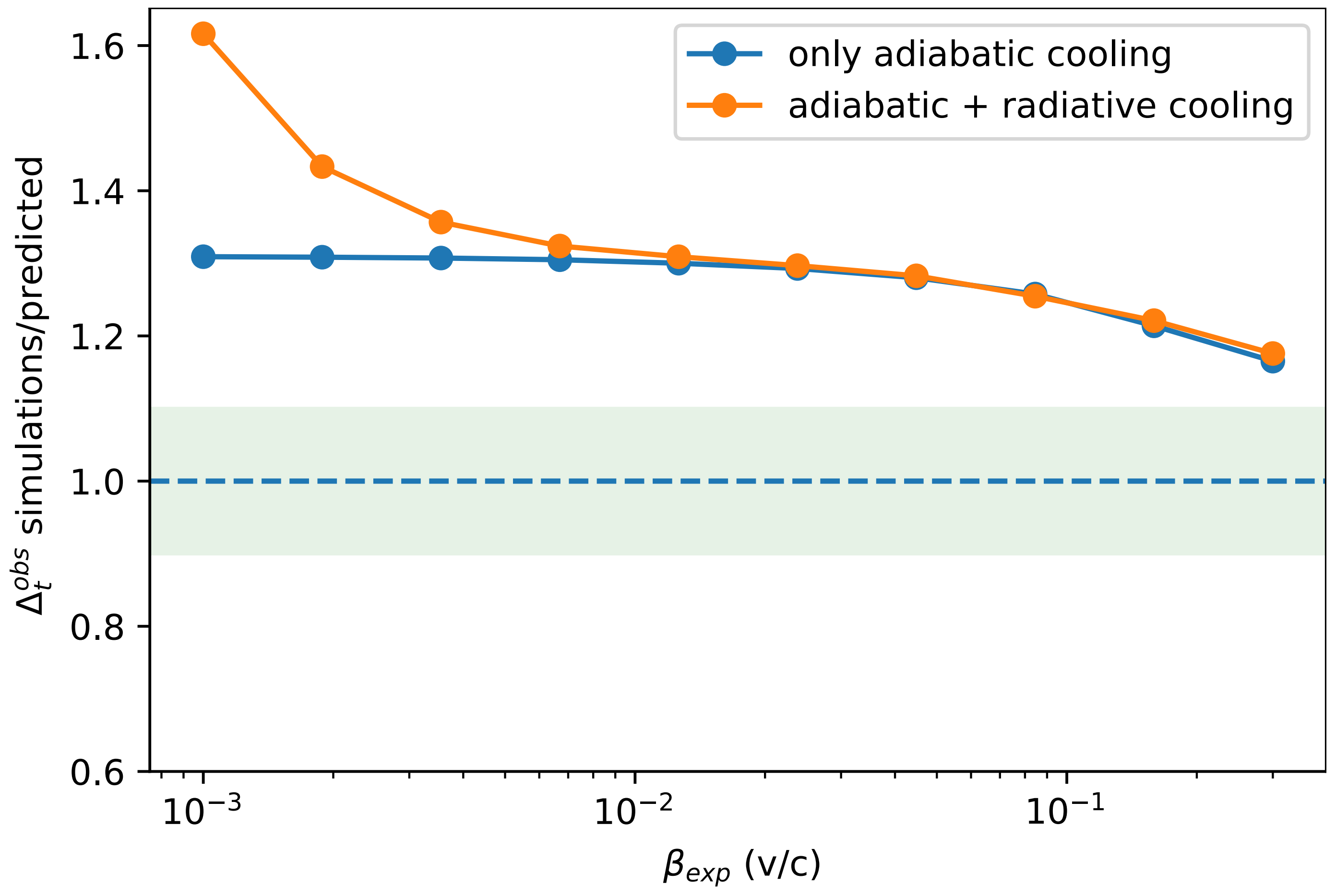

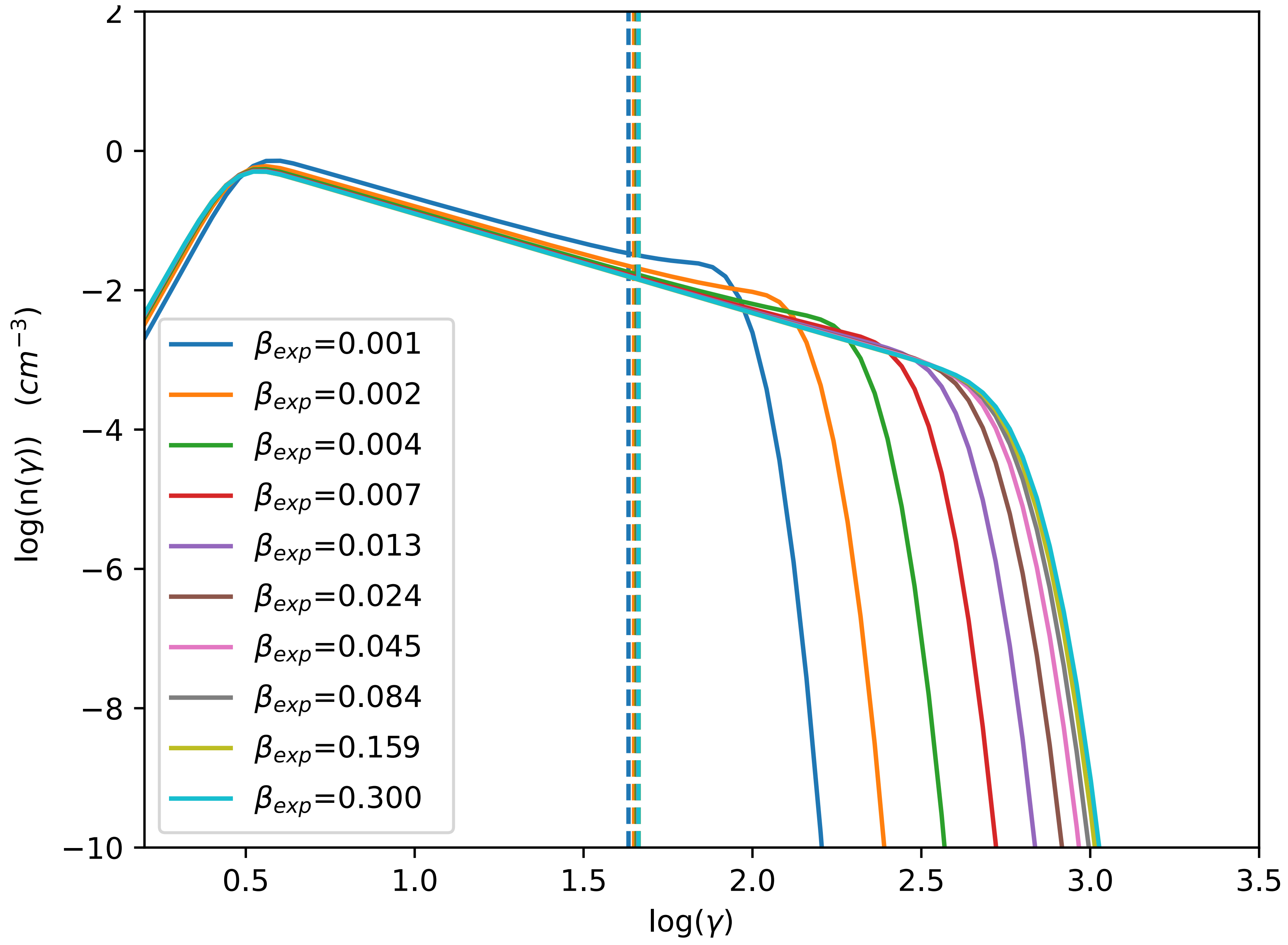

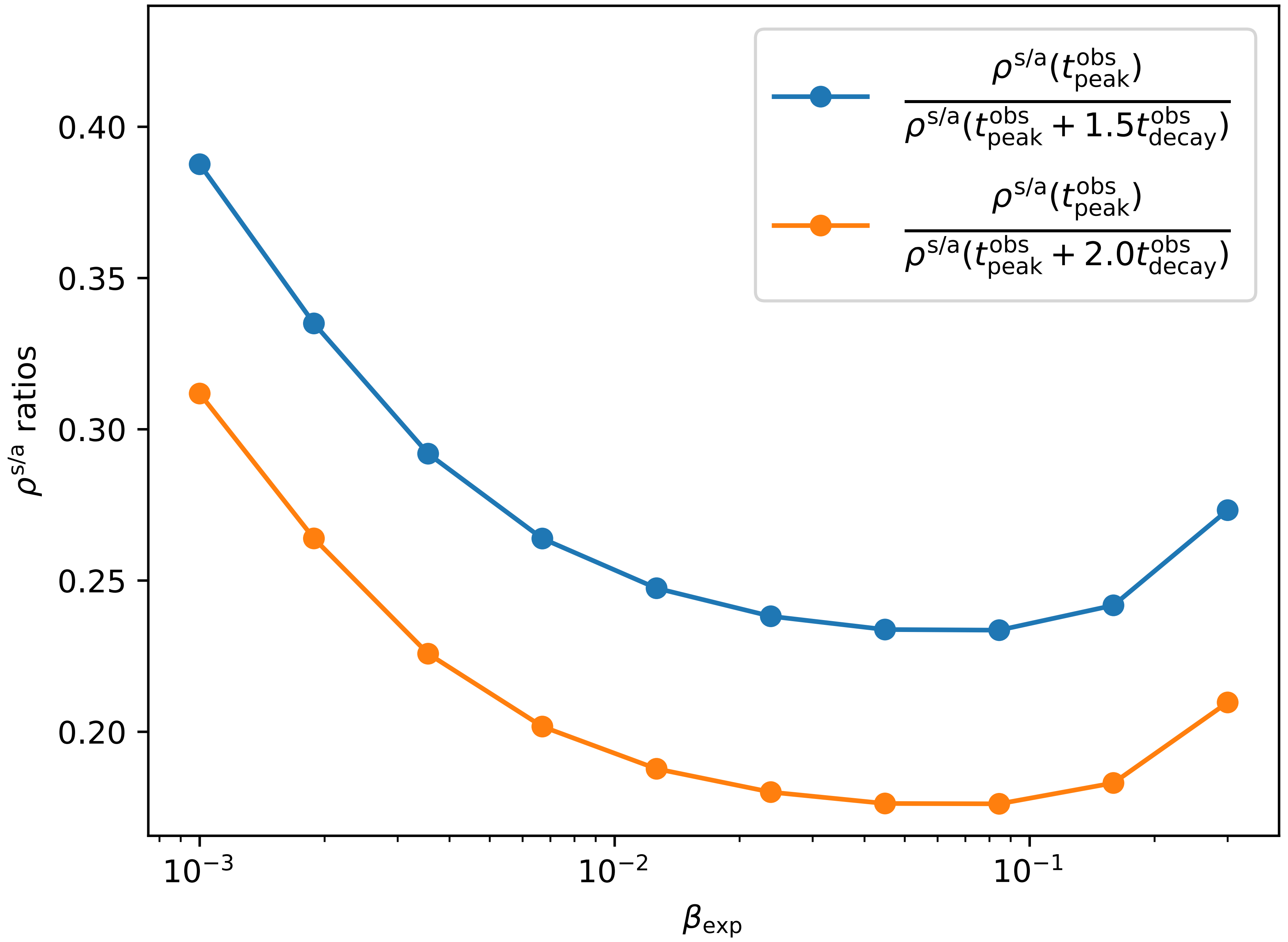

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