Time dependent particle injection to investigate the local source behaviour of flaring AGN

CRPropa Workshop 2023

L. Schlegel, J. Becker Tjus, M. Schroller, L. Merten, J. Dörner, E. Kun

Time dependent particle injection to investigate the local source behaviour of flaring AGN - current status

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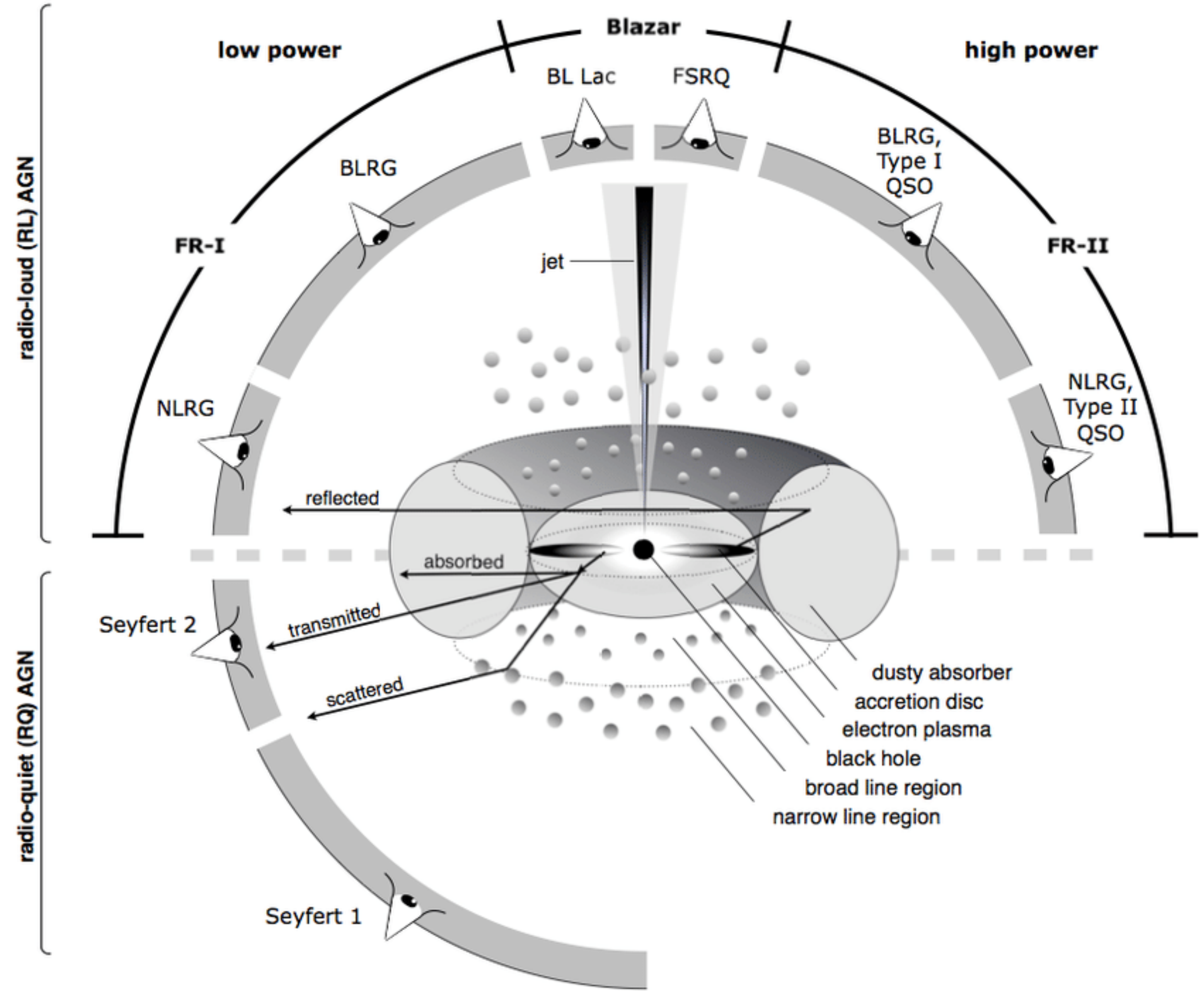
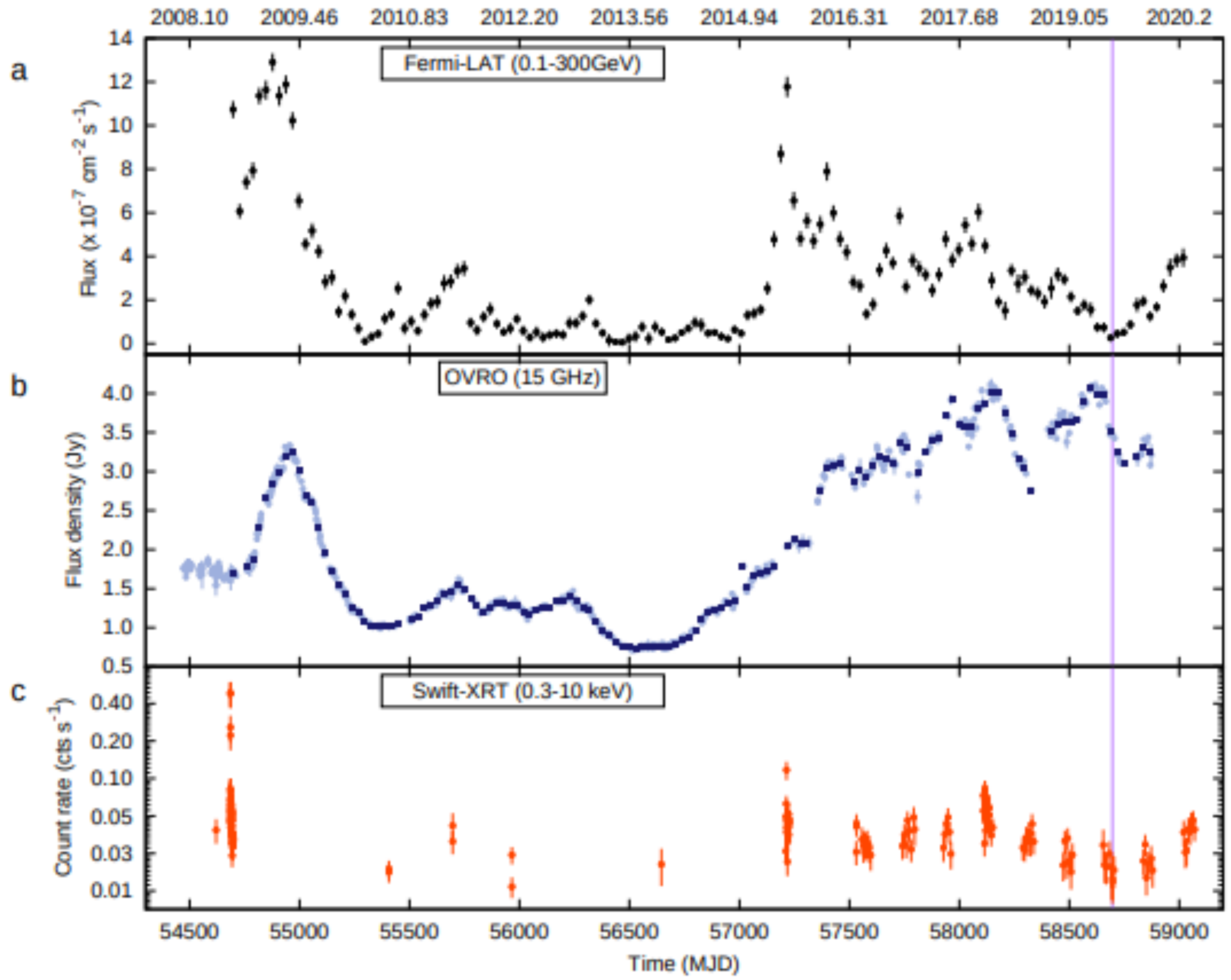
Introduction

Motivation



(Beckmann, Shrader 2012)



(Kun et al, 2021)

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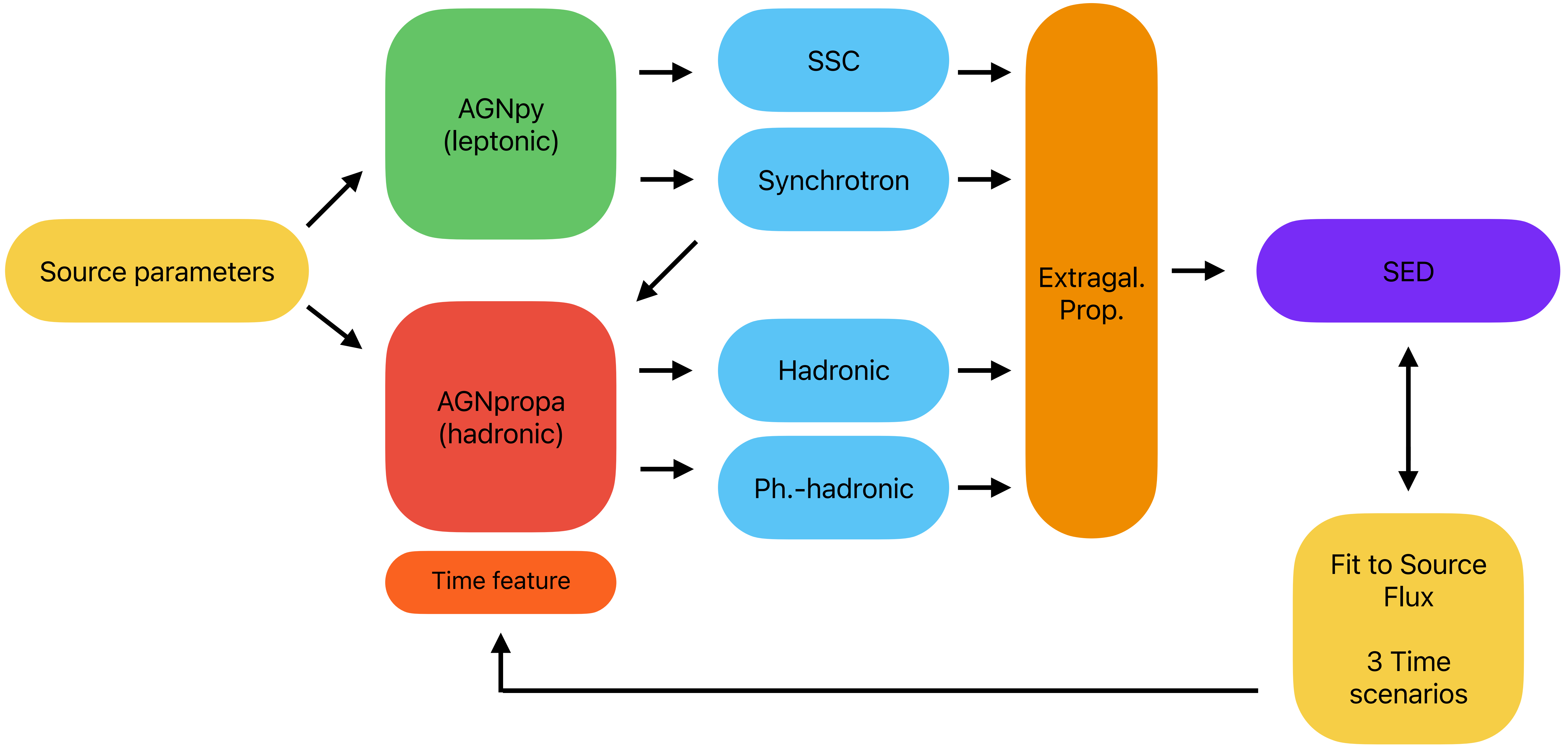
Project overview

Time dependent SED modeling

- Leptohadronic **SED modeling**.
- Using AGNpy + (AGN)CRPropa.
- Using **time dependent particle injection** to model flares also in time domain accurately.
- In the application, at later stage three different time-scenarios and the correlated SEDs are going to be tested for the source TxS0506+056.



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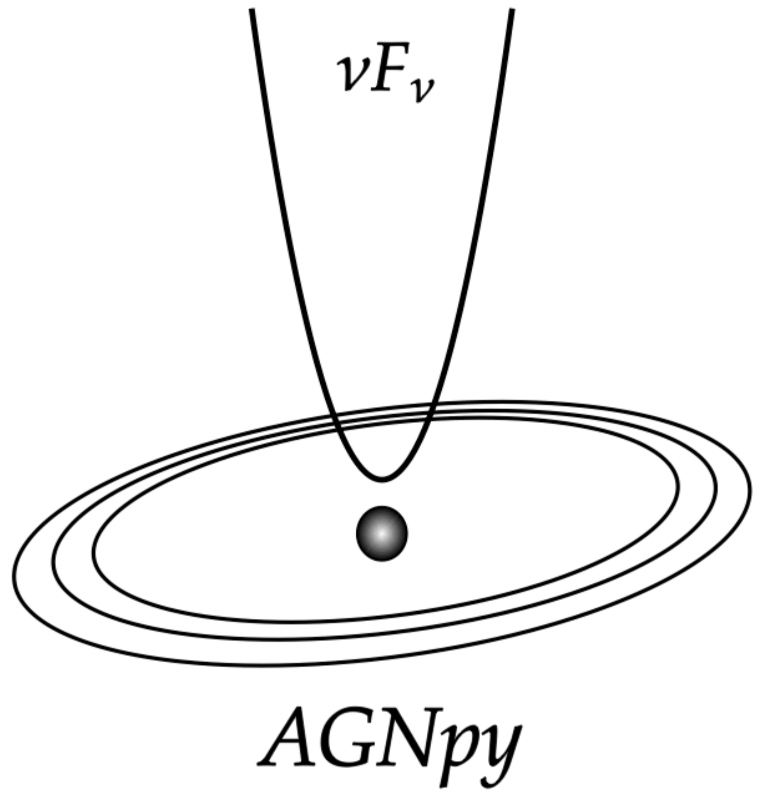
Numerical codes

AGNpy to model leptonic AGN Emission

- AGNpy (Nigro et al. 2022) provides a python steerable framework for the calc. of leptonic emission processes of relativistic blobs in AGN jets.
- After (Dermer, Menon 2009) the leptonic modeling of Synchrotron and SSC can be described by

- $$f_{\epsilon}^{\mathrm{syn}} = \frac{\delta_{\mathrm{D}}^4 \epsilon' J'_{\mathrm{syn}}(\epsilon')}{4\pi d_L^2} = \frac{\sqrt{3}\delta_{\mathrm{D}}^4 \epsilon' e^3 B}{4\pi h} \int_1^{\infty} d\gamma' \; N'_e(\gamma') \; R(x)$$

- $$f_{\epsilon_s}^{\mathrm{SSC}} = \frac{9}{16} \frac{(1+z)^2 \sigma_{\mathrm{T}} \epsilon_s'^2}{\pi \delta_{\mathrm{D}}^2 c^2 t_{v,\mathrm{min}}^2} \int_0^{\infty} d\epsilon' \frac{f_{\epsilon}^{\mathrm{syn}}}{\epsilon'^3} \int_{\gamma'_{\mathrm{min}}}^{\gamma'_{\mathrm{max}}} d\gamma' \frac{N'_e(\gamma')}{\gamma'^2} F_{\mathrm{C}}(q, \Gamma).$$



(https://agnpy.readthedocs.io/en/latest/index.html)

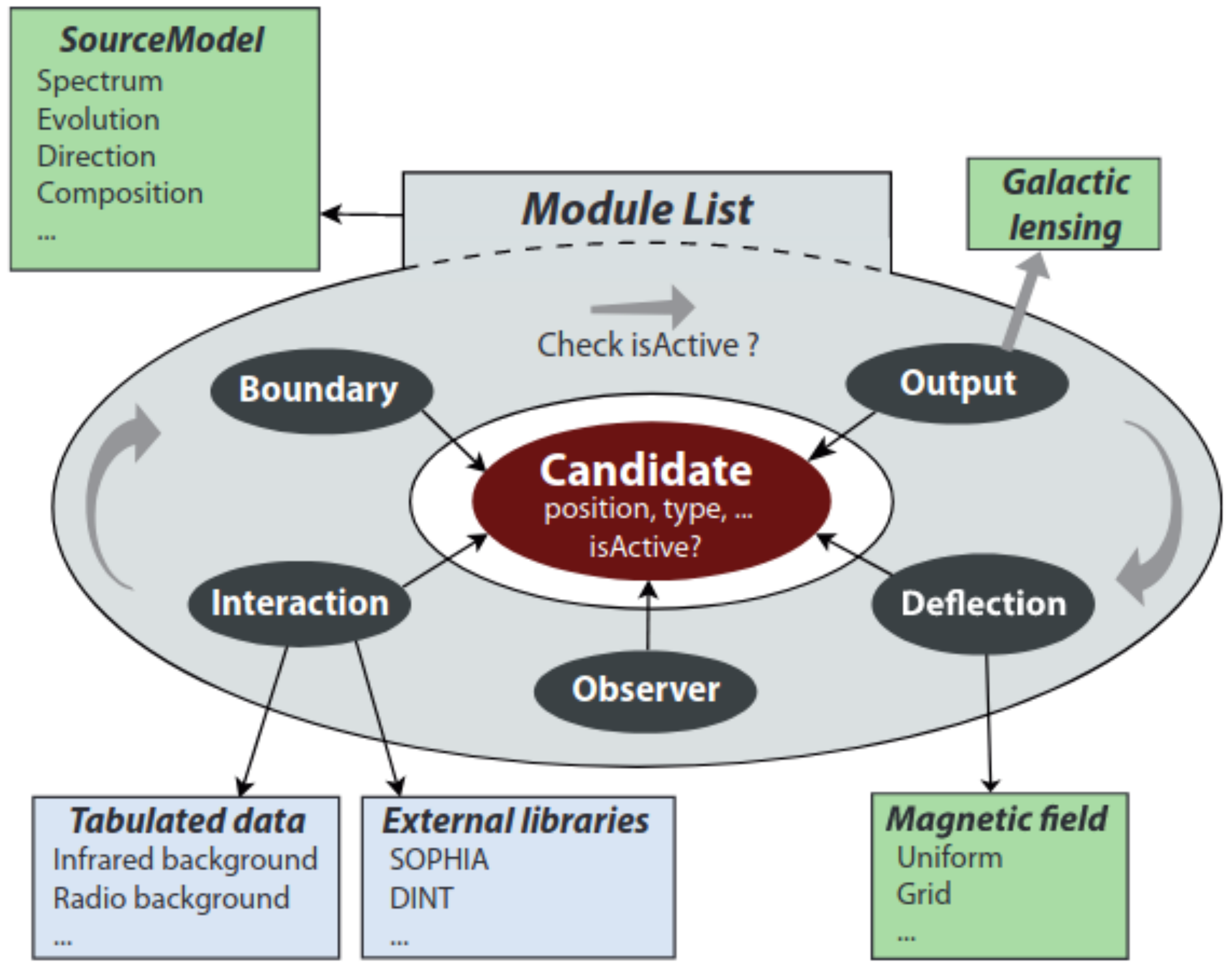
Numerical codes

AGNpropa to model hadronic AGN Emission

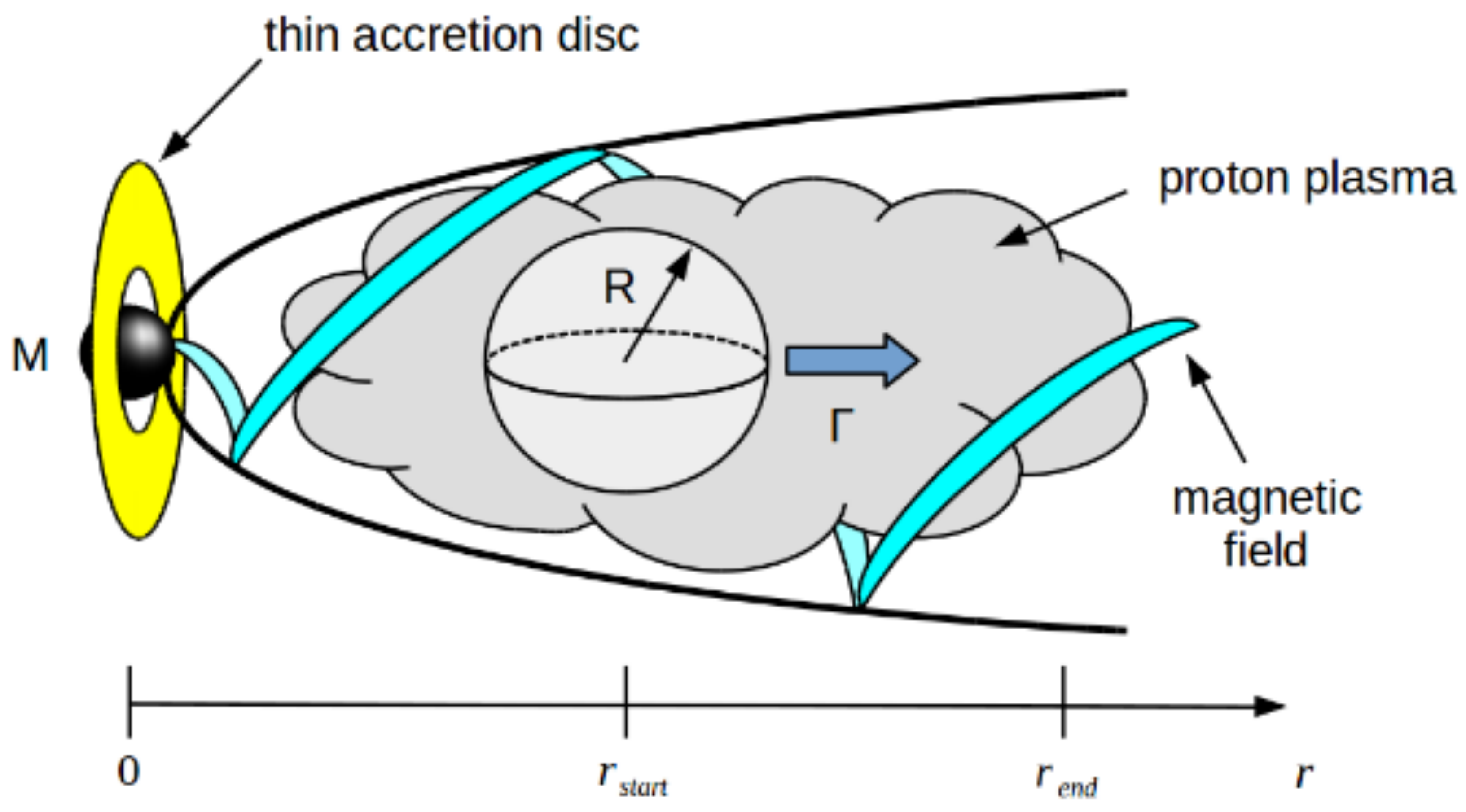
CRPropa 3

Jet model

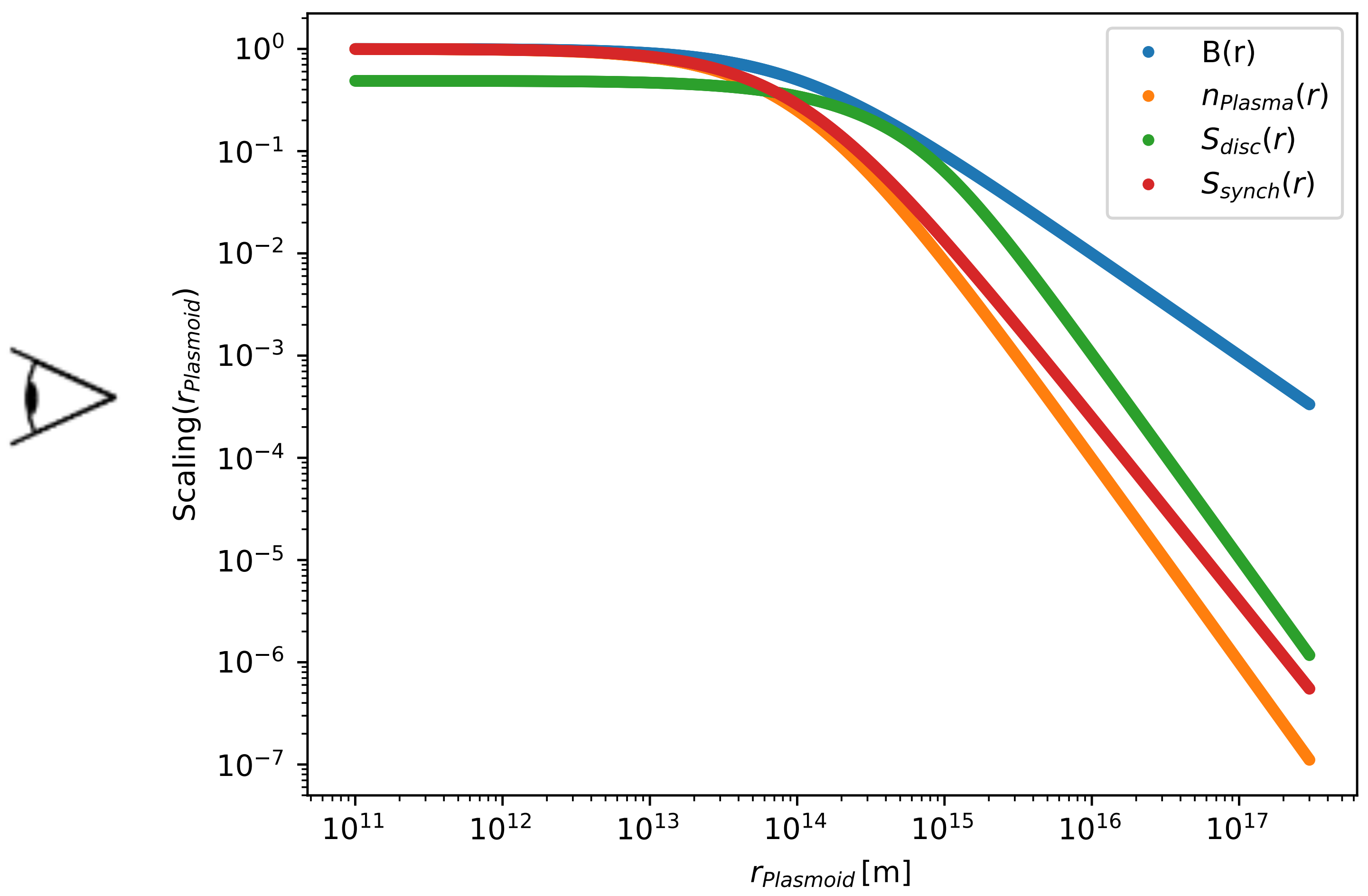
Scalings
+ Modifications



(Alves Batista et al. 2016)



(Hörbe et al. 2020)



(After Hörbe et al. 2020)

Local source model

Blazar-Jet

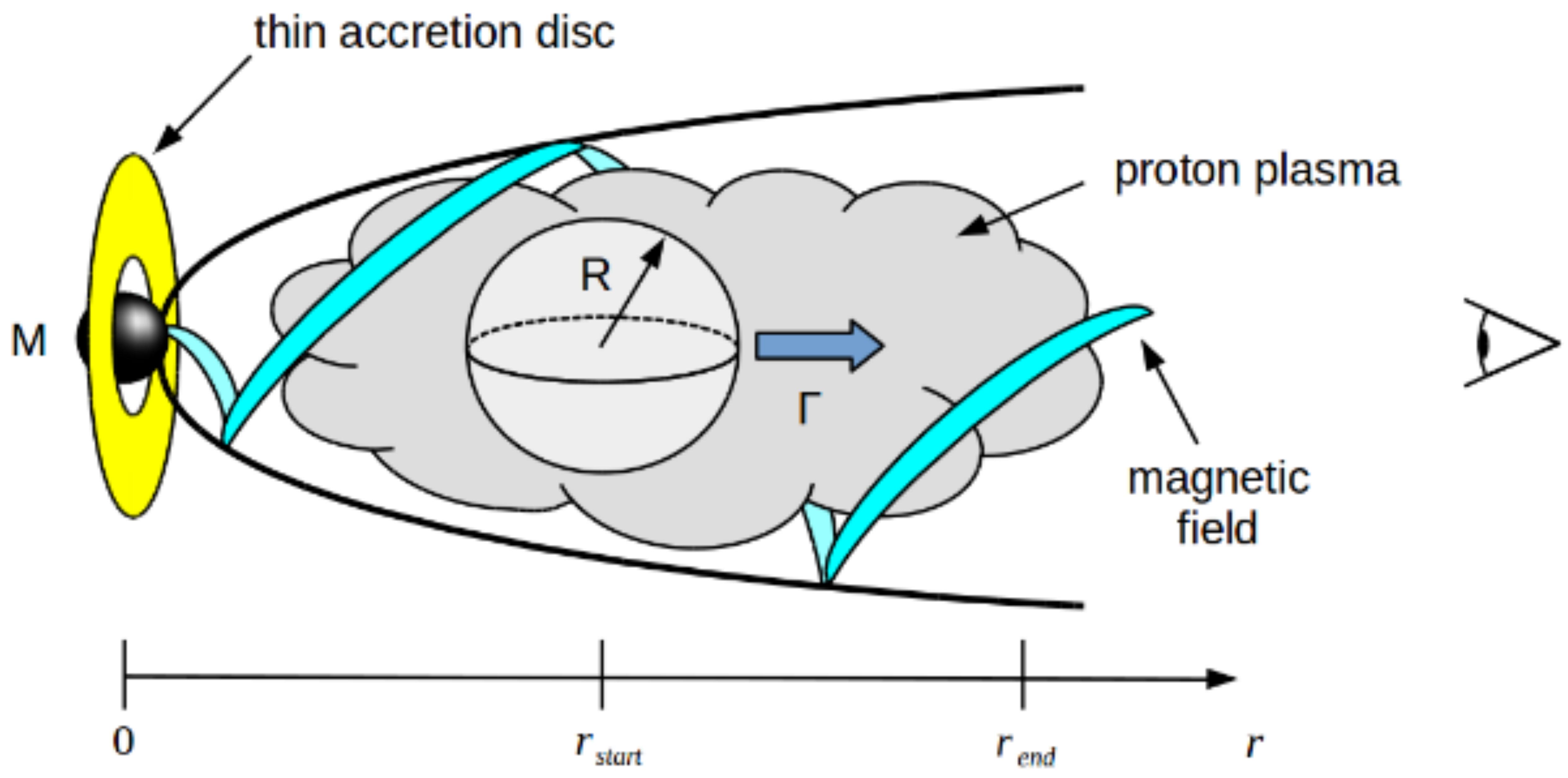
The local source model developed by **(Hörbe et al. 2020)** consists of

Relativistic plasmoid of primaries travelling along jet axis.

Turbulent magnetic field leading to diffusion.

Local target fields (Proton plasma, Accretion disc field, Synchrotron radiation field).

Relevant **interaction processes**:



(Hörbe et al. 2020)

1) Synchrotron radiation of primaries

2) EM-Pair Production: $\gamma + \gamma \rightarrow e^+ + e^-$

3) Photohadronic: $p/n + \gamma \rightarrow \pi^{0/\pm} + X$

4) Hadronic: $p + p \rightarrow \pi^{0/\pm} + X$

Local source model

Scaling functions

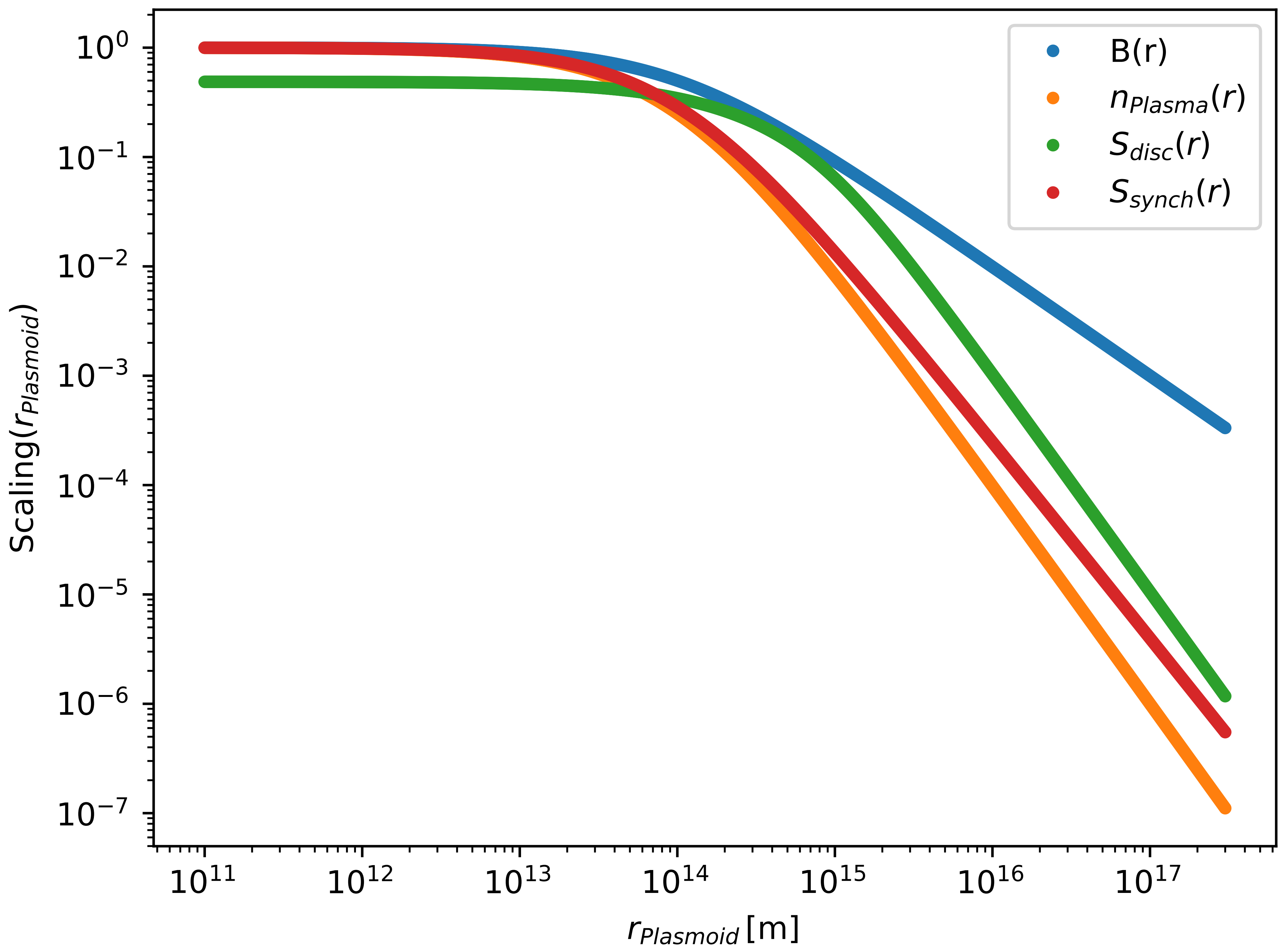
With the **separation-ansatz** $n_\gamma(\epsilon_\gamma, r) = n_{\gamma,0} \cdot S(r)$ the target fields densities can be implemented as (spatial) fields and (temporal) scalings, that allow the modelation of the **changing environment during propagation** along the jet-axis.

From geometric considerations the scalings read **(Hörbe et al. 2020)**

$$B(r) \propto r^{-1} \qquad n_{Plasma}(r) \propto r^{-2}$$

$$S_{disc}(r) \propto \ln \frac{R_{acc}^2 + r^2}{(3R_s)^2 + r^2} \qquad S_{synch}(r) \propto r^{-\left(\frac{1+\alpha_e}{2}\right)}$$

For each case the Lorentz-trafo has to be considered.

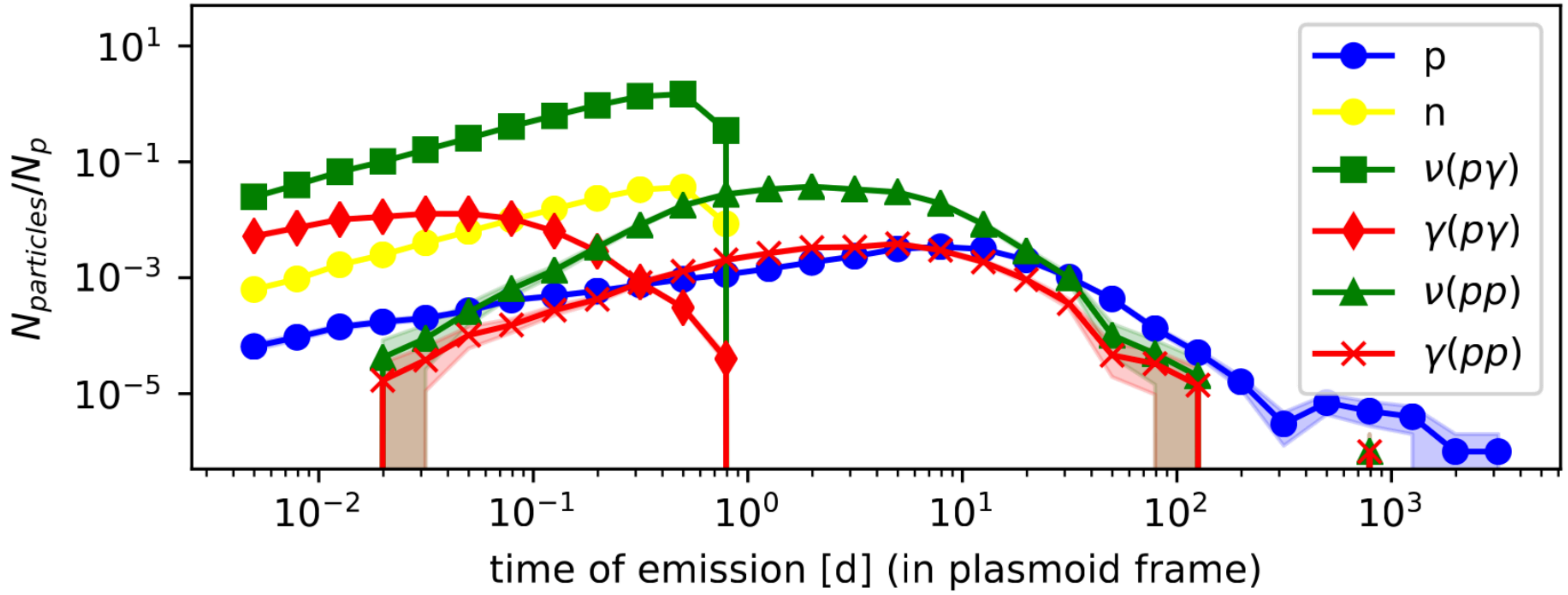


(After Hörbe et al. 2020)

Local source model

Multimessenger results from the AGN model

- **Reproduction** of the results from (Hörbe et al. 2020).
- The time-evolution of the flares shows **steep increases** (around 1 day) and **long decreases** (up to 0.3 years).
- Timescales of flares regarding the increase-time and symmetry **typically too short compared to observed flares**.



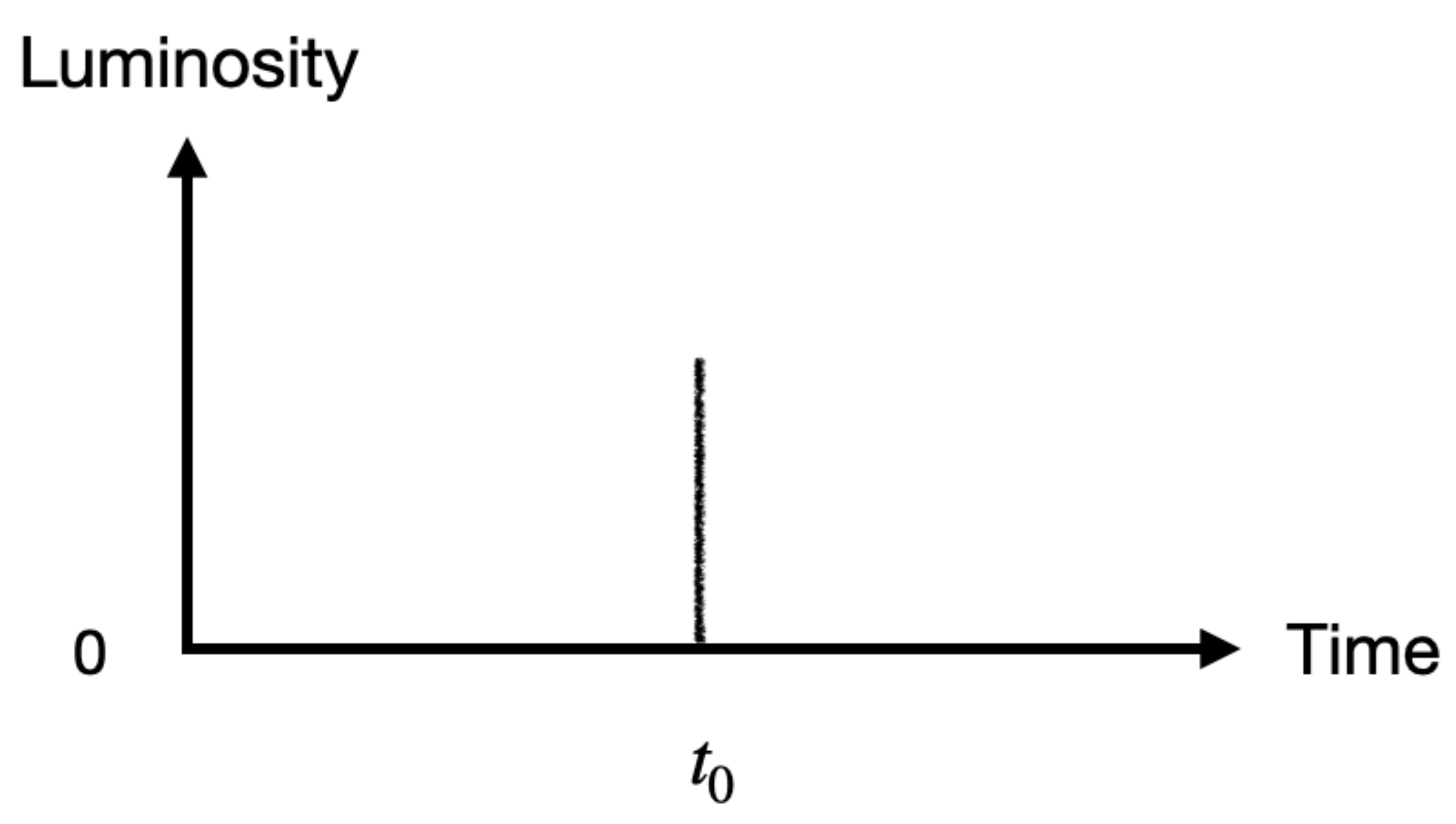
- **Multi-Messenger information (p,n, ν,γ) is shown in temporal evolution.**
- **Each messengers is tagged by interaction.**
- **ν-flare visible, corresponding to minimum in γ-flux.**

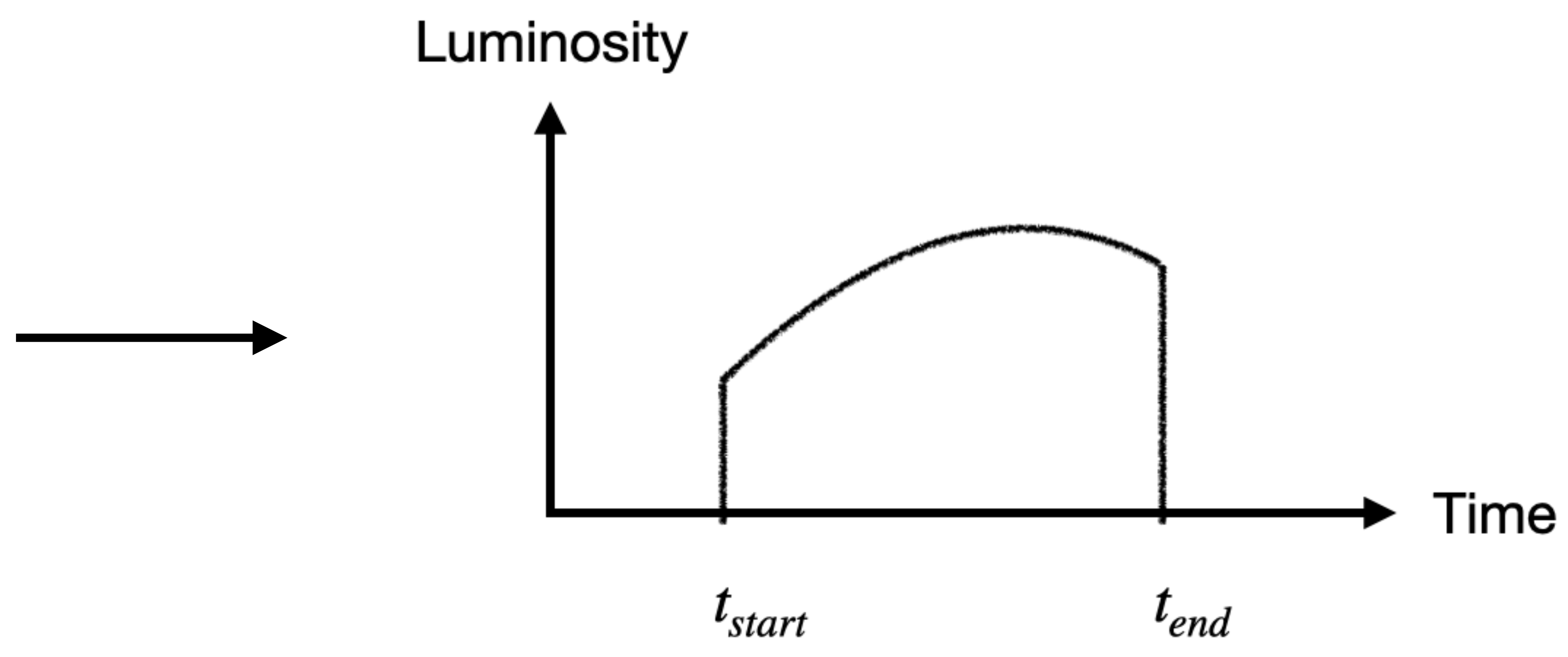
(After Hörbe et al. 2020)

Modifications

Time dependent particle injection

- Most codes assume instantaneous primary injection in time.
- Generally, **arbitrary source injection-times** would demand for: $S(t) = S_0 \cdot \delta(t - t_0) \rightarrow S(t) = S_0 \cdot f(t)$
- This can be **realized by setting the primaries trajectory-length** l_{traj} upon injection via MC-Sampling from the PDF $f(t)$, describing a luminosity profile.





Modifications

Time dependent particle injection

- To distribute particles injection times according to a certain luminosity profile, **Monte-Carlo Sampling** is used.

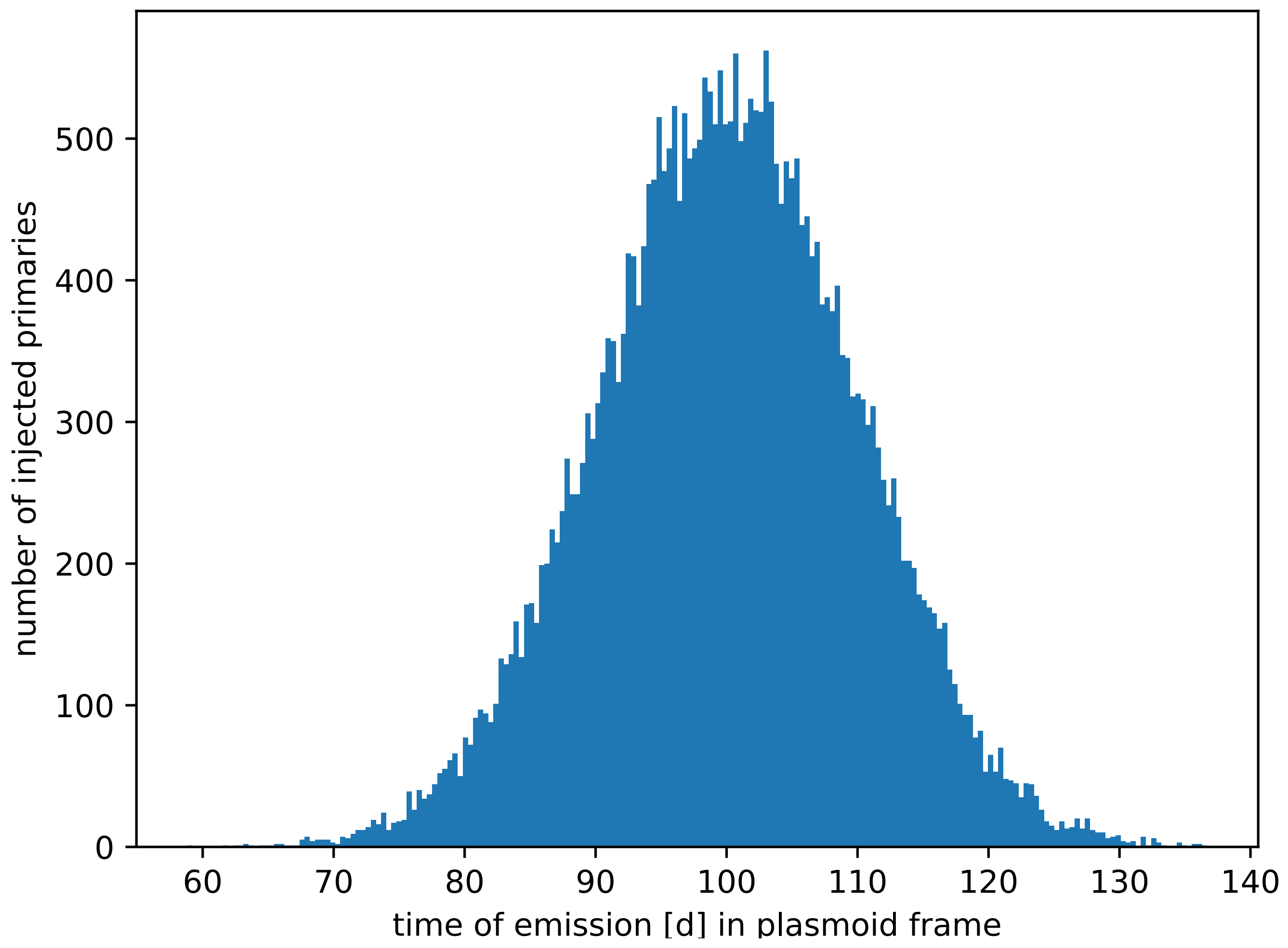
$$CDF(x) = \int_{-\infty}^{x} dx' pdf(x') \qquad r = cdf^{-1}(u)\,, u \in [0,1)$$

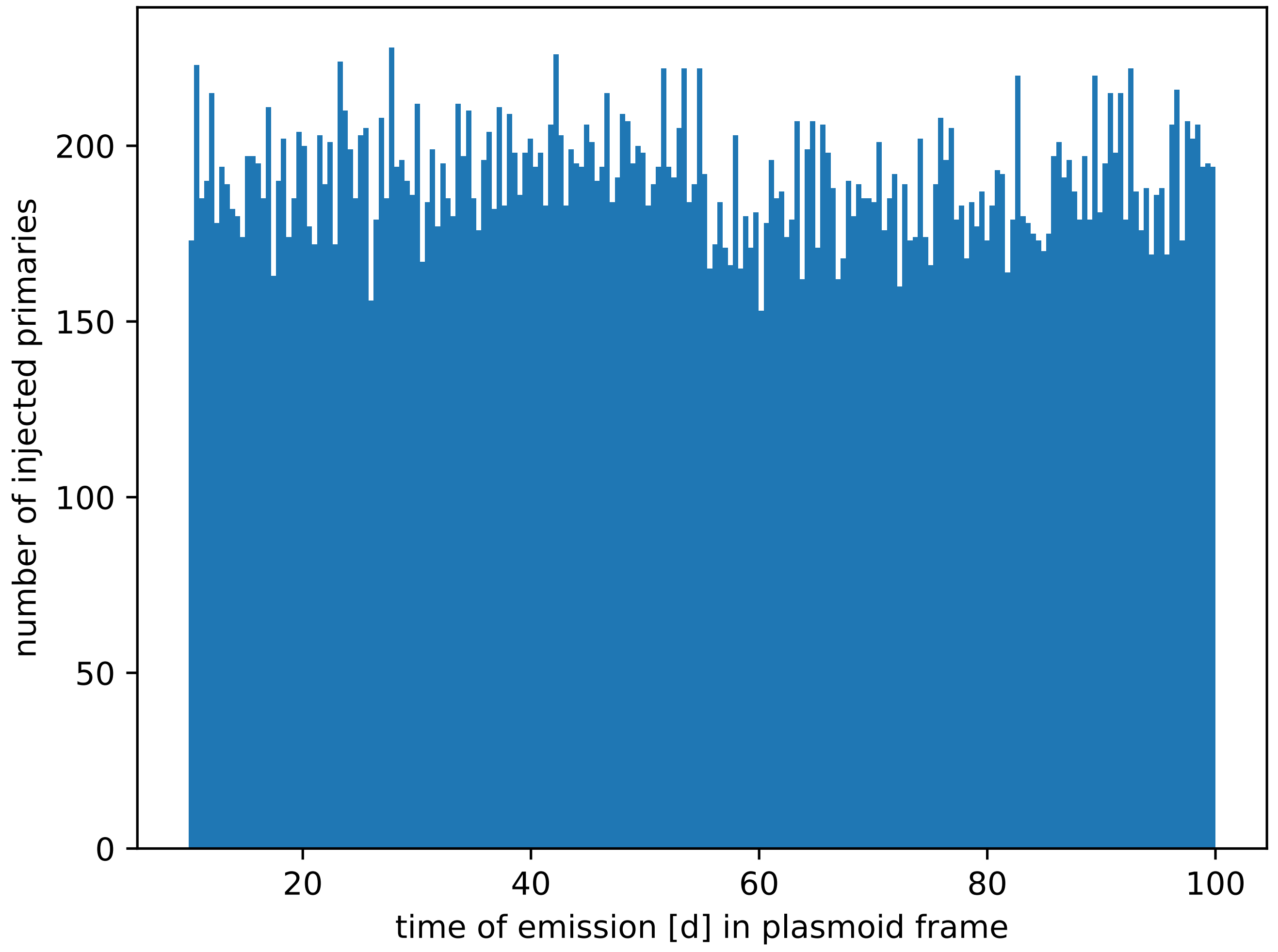
- For the **exemplary case of the normal distribution** we get:

$$PDF(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp^{-\left(\frac{x-\mu}{\sigma}\right)^2 \cdot \frac{1}{2}} \qquad CDF(x) = \frac{1}{2}\left(1 + erf\left(\frac{x-\mu}{\sqrt{2}\sigma}\right)\right)$$

$$x = \sqrt{2} \cdot \sigma \cdot erf^{-1}\left(2 \cdot CDF(x) - 1\right) + \mu$$

- Implemented both in AGNPropa source code and as a Python-Plugin, **for now two profiles are available**.
- $f_{box}(t) = \Theta(t - t_{start})\Theta(t_{end} - t) \qquad f_{normal} = G(\mu, \sigma)$

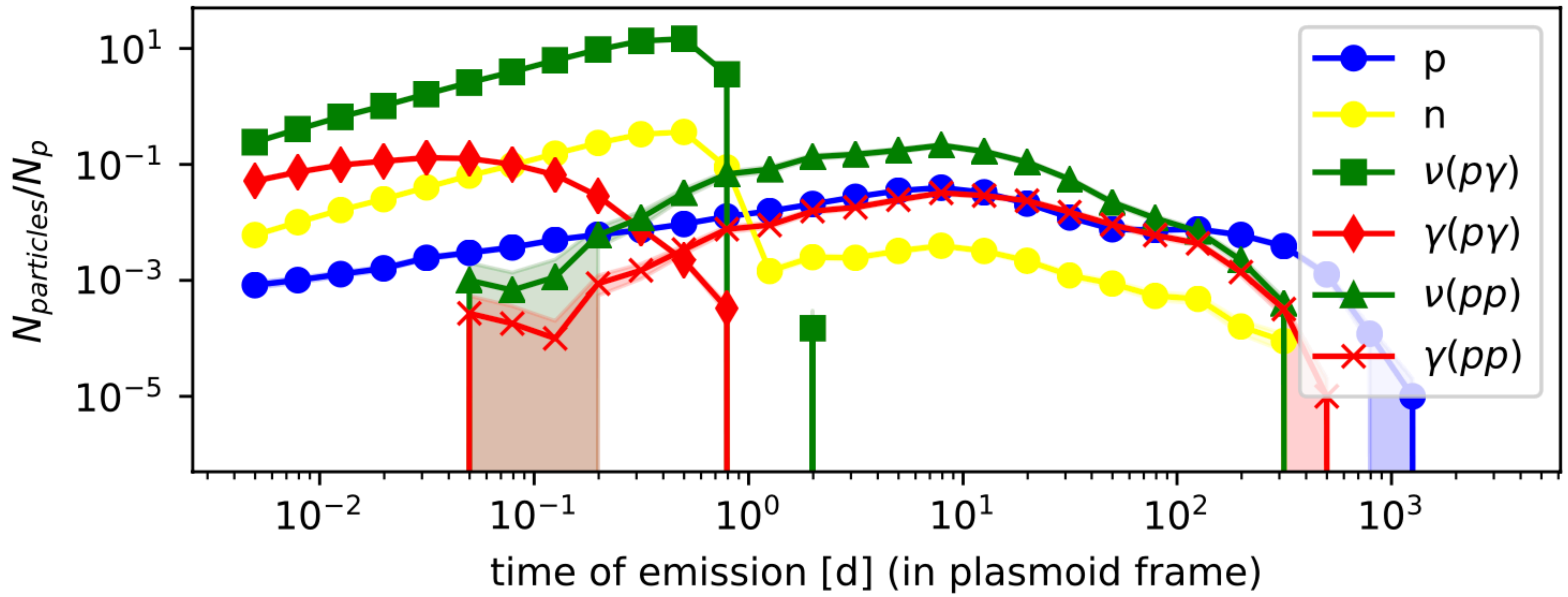




Modifications

Time dependent particle injection

- Exemplary demonstration using AGN model setting similar to **(Hörbe et al. 2020).**
- Plot shows temporal evolution of all messengers for **Burst-injection** $f_{burst}(t) = \delta(t - 0\,\mathrm{s})$

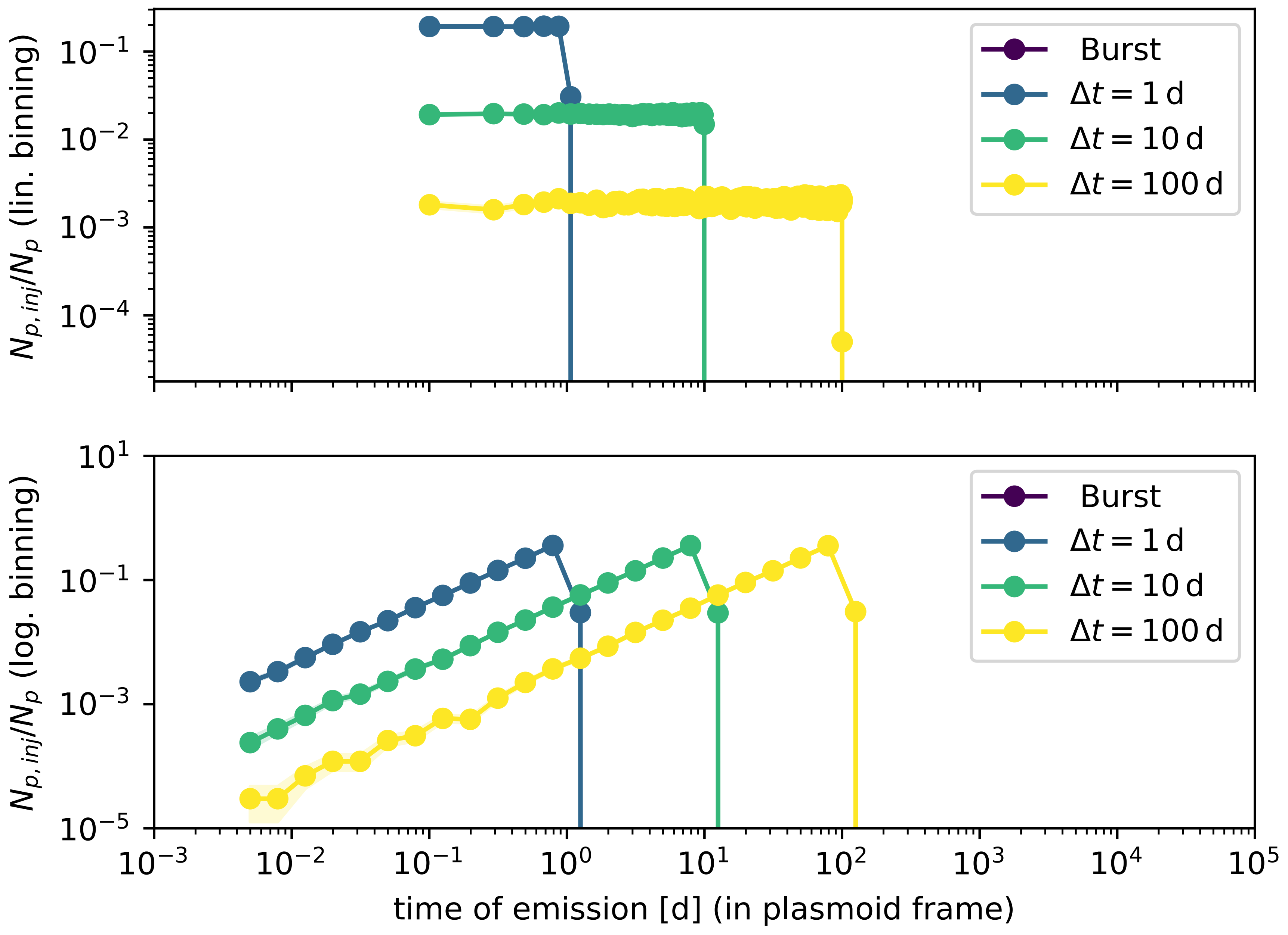


Modifications

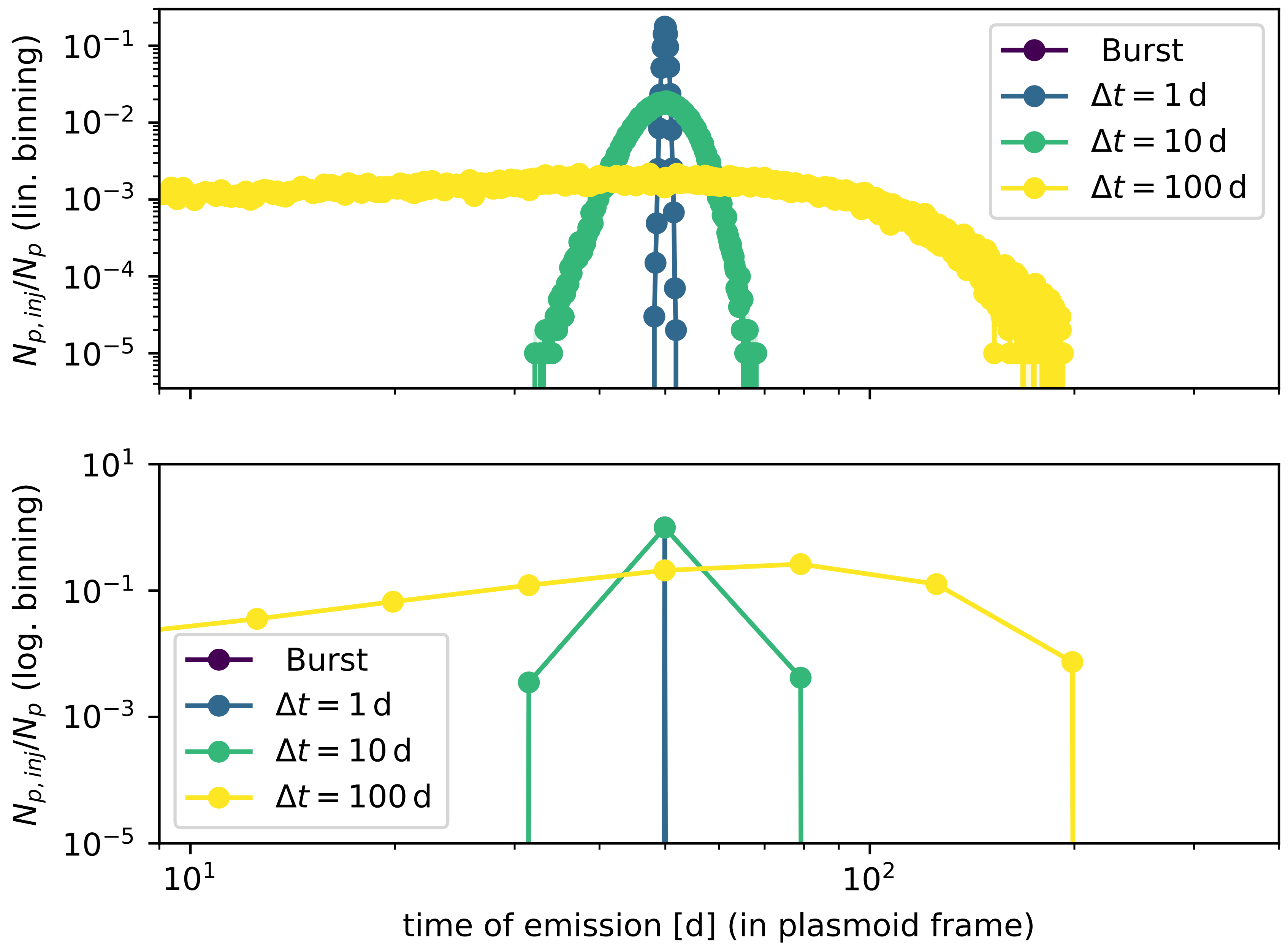
Time dependent particle injection

- Exemplary demonstration using AGN model setting similar to **(Hörbe et al. 2020).**
- **Left** shows timeprofile for **Box-injection**, **right** shows time-profile for **Gaussian-injection**. Emitted energy is kept constant.

$$f_{box}(t) = \Theta(t - 0\,\mathrm{s})\Theta(\Delta t - t)$$



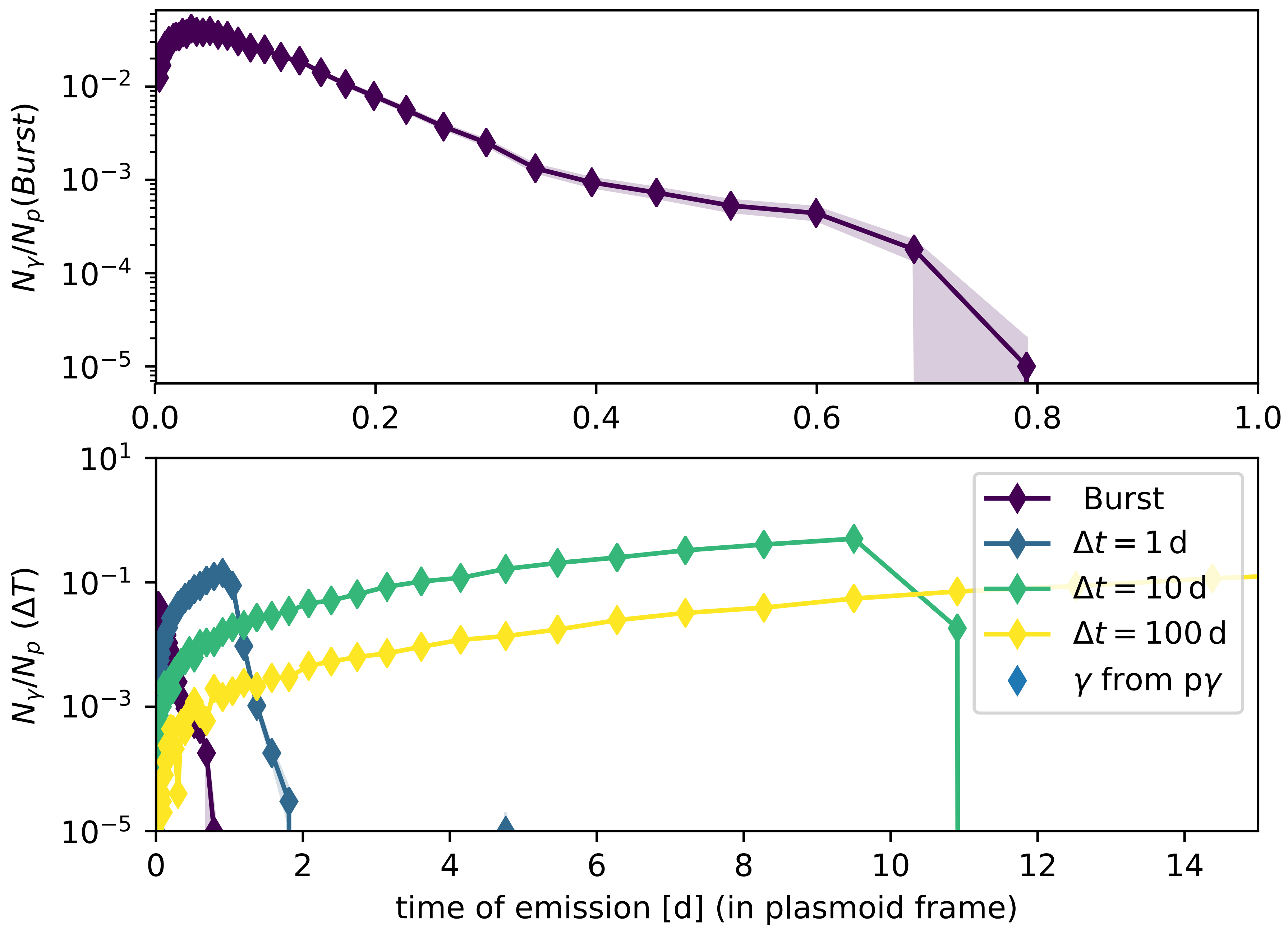
$$f_{normal} = G(50\,\mathrm{d}, \sigma(FWHM = \Delta t))$$

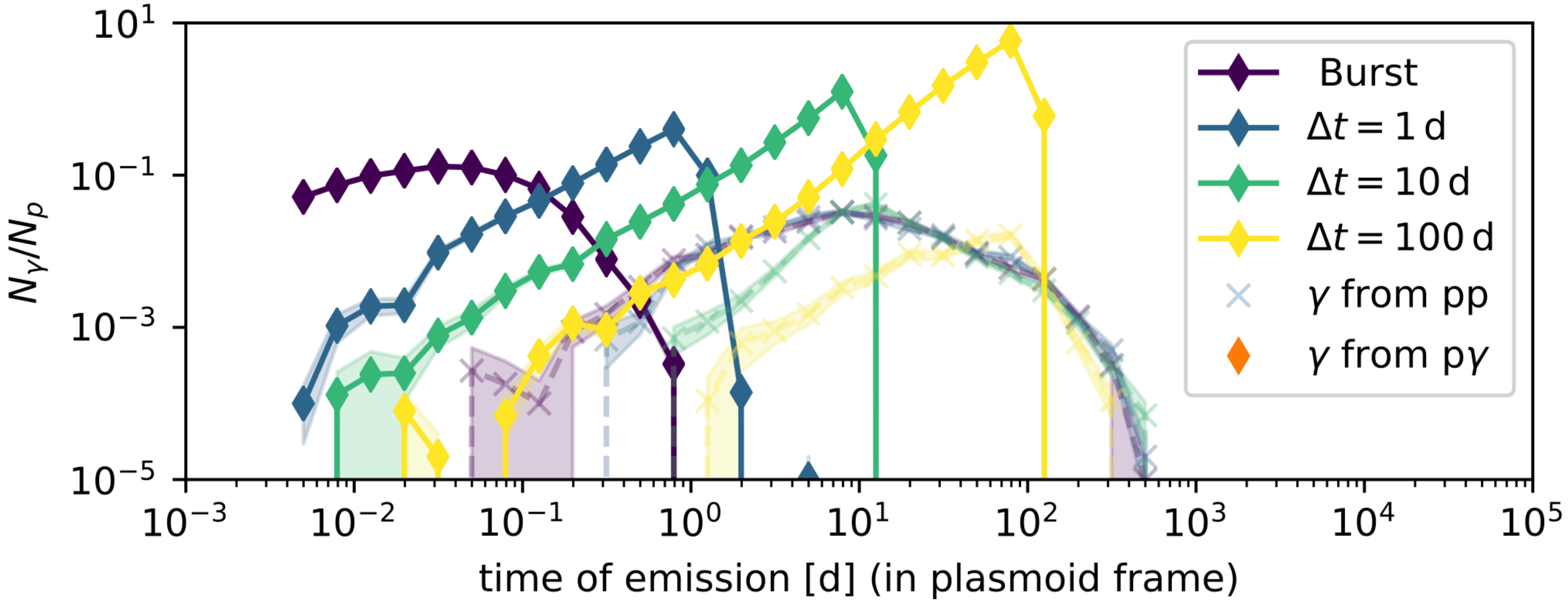


Modifications

Time dependent particle injection

- Exemplary demonstration using AGN model setting similar to **(Hörbe et al. 2020).**
- Plots shows temporal evolution only of γ-flux (pp (left), pp+pγ (right)) for **finite Box-injection** for different times.



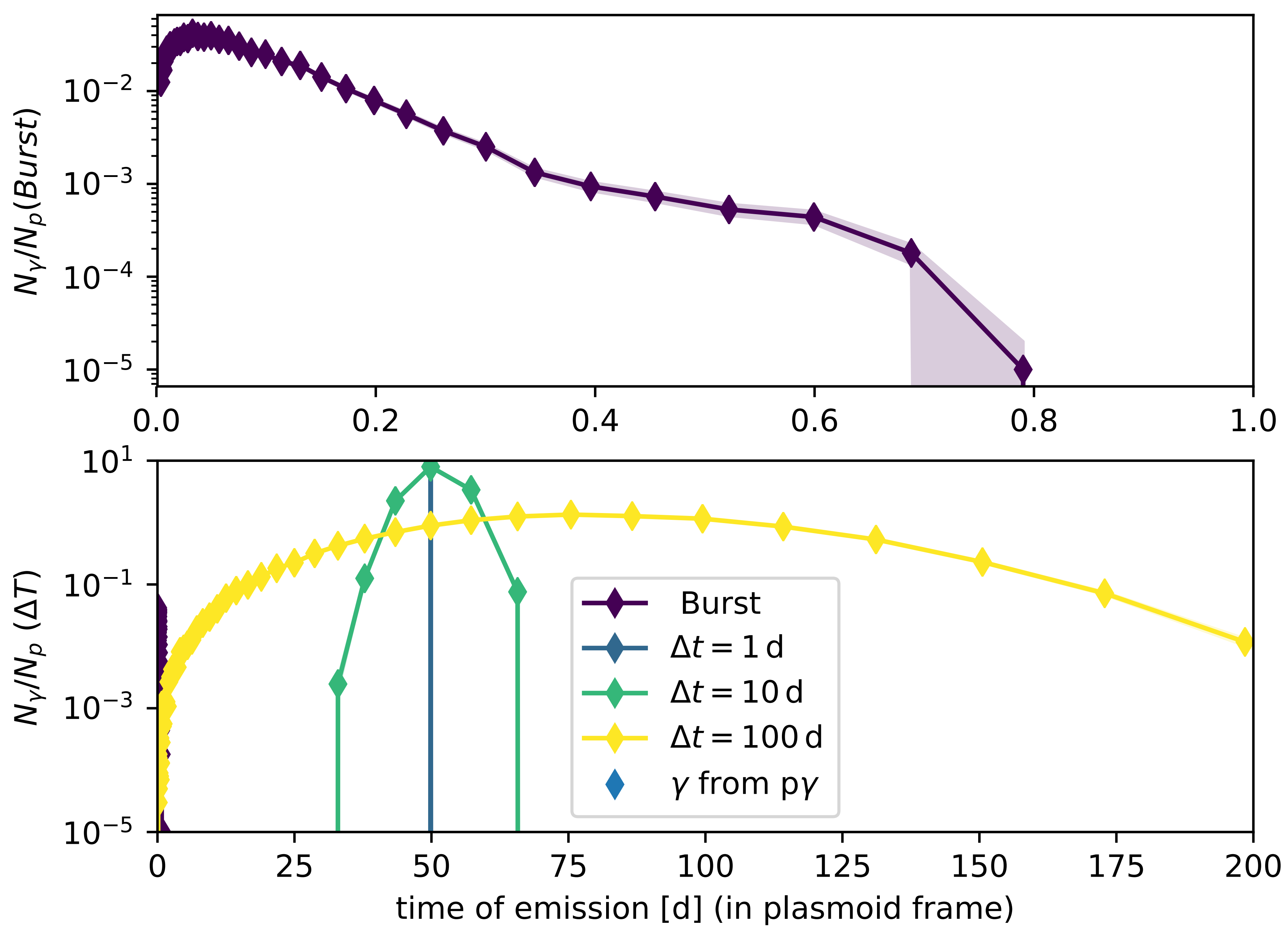


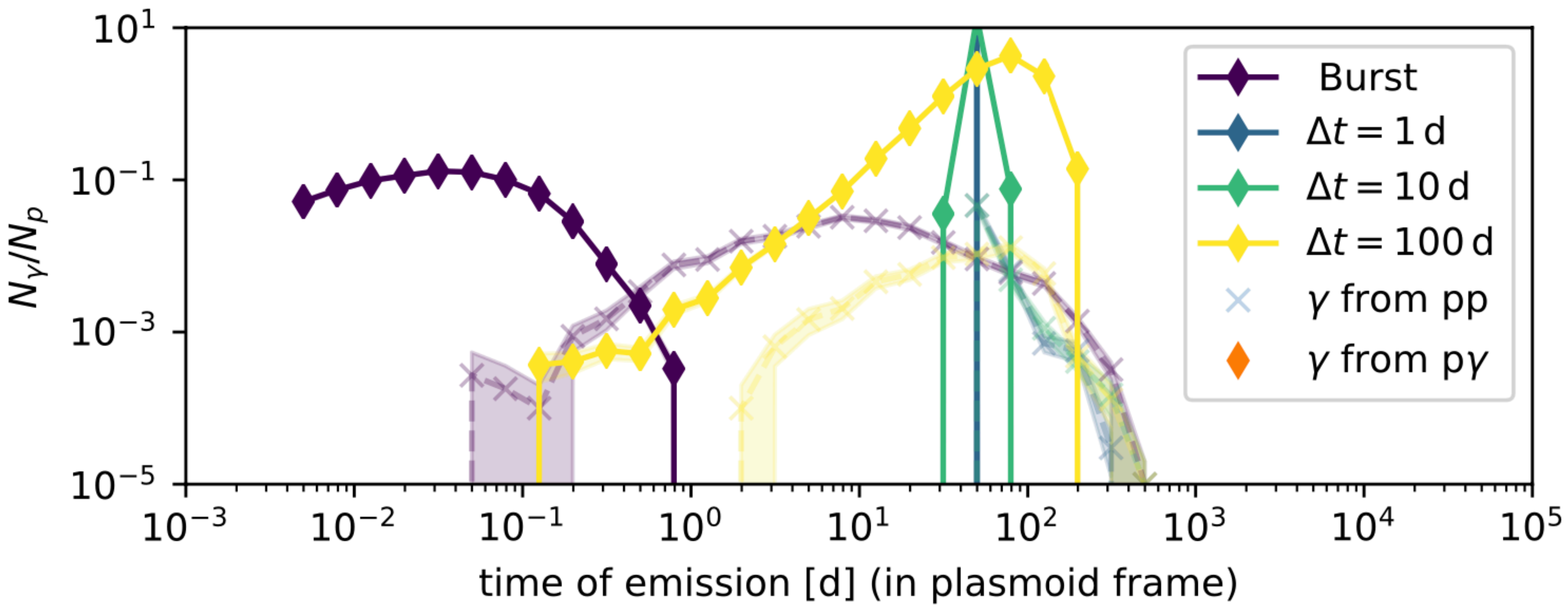
$$f_{box}(t) = \Theta(t - 0\,\mathrm{s})\Theta(\Delta t - t)$$

Modifications

Time dependent particle injection

- Exemplary demonstration using AGN model setting similar to **(Hörbe et al. 2020).**
- Plots shows temporal evolution only of γ-flux (pp (left), pp+pγ (right)) for **finite Gaussian-injection** for different times.



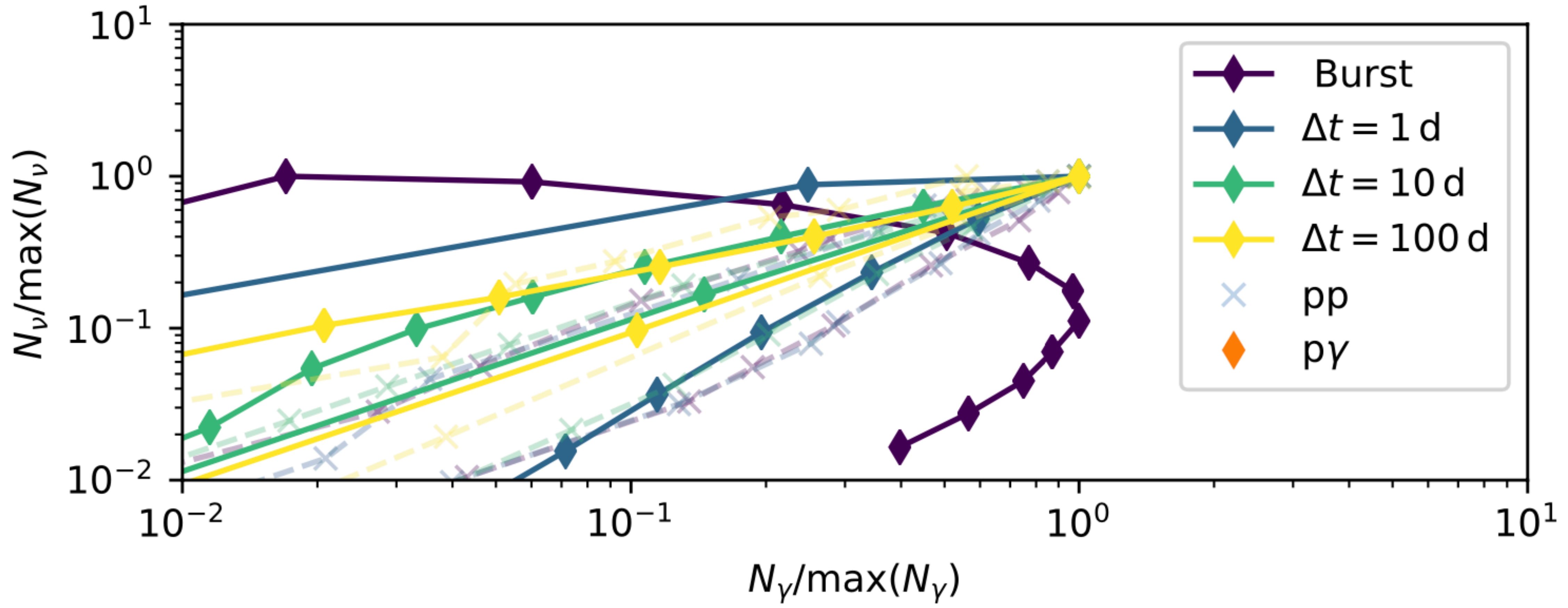


$$f_{normal} = G(50\,\mathrm{d}, \sigma(FWHM = \Delta t))$$

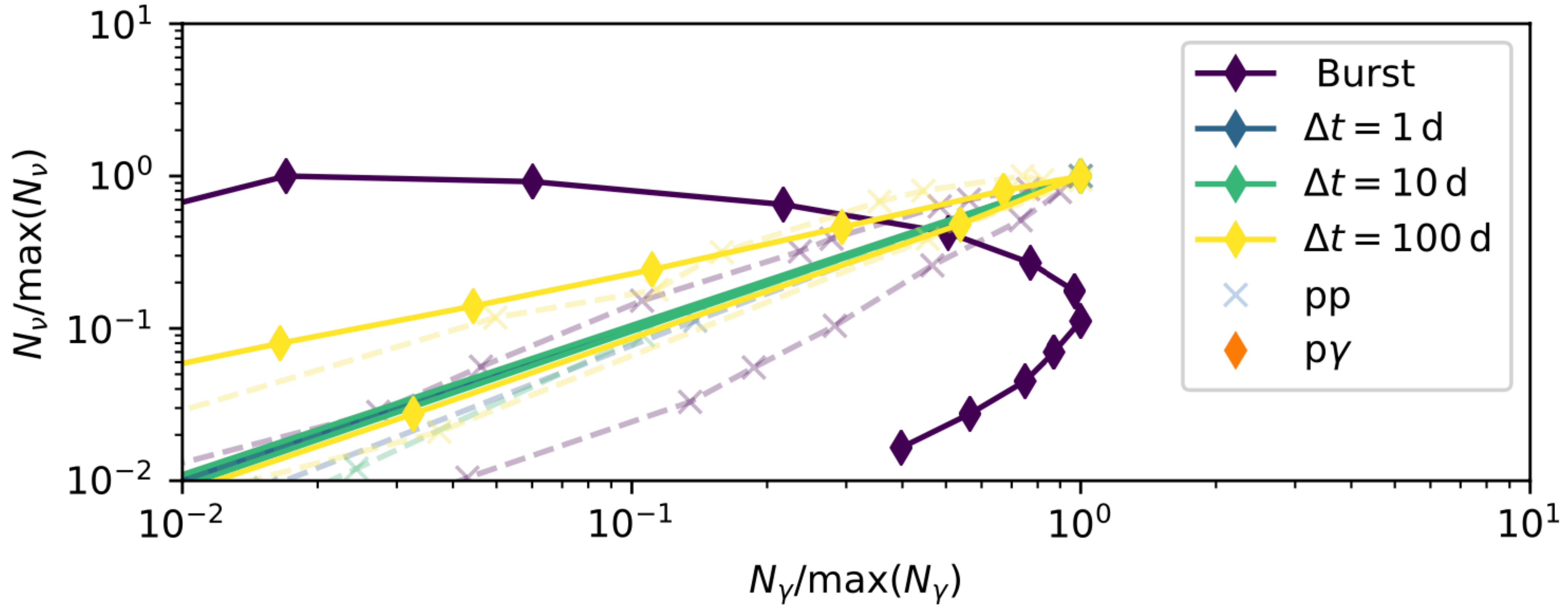
Modifications

Time dependent particle injection

- **Left** shows temporal correlation of normalized ν and γ fluxes for Burst- and **finite Box-injection** for different times.
- **Right** shows temporal correlation of normalized ν and γ fluxes for Burst- and **finite Gaussian-injection** for different times.
- **Stronger temporal correlation** between ν and γ fluxes **for larger injection times**.



$$f_{box}(t) = \Theta(t - 0\,\mathrm{s})\Theta(\Delta t - t)$$



$$f_{normal} = G(50\,\mathrm{d}, \sigma(FWHM = \Delta t))$$

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Modifications
Low-energy extension

- CRPropa is designed for **highly-relativistic energies only, implying** $v = c$ and in consequence $d = c \cdot t$ can always be assumed. Furthermore, **interactions are highly boosted** in the lab-frame.

- To model the low-energy part of the SED below the rest-mass of the primaries, a low-energy extension is necessary.

- **Two modification** were made, the **PropagationCK-module** was adapted to calculate the Lorentz-force with the relativistic β and a proper time was introduced in the **Candidate-object**.

- The Lorentz-force implementation with $\overrightarrow{u}$ denoting the normalized direction of the velocity $\overrightarrow{v} = v \cdot \overrightarrow{u}$ reads

- $\frac{d\overrightarrow{u}}{dt} \cdot c = \frac{q \cdot c^2}{E} \cdot c \cdot \overrightarrow{u} \times \overrightarrow{B} \rightarrow \frac{d\overrightarrow{u}}{dt} \cdot c \cdot \beta = \frac{q \cdot c^2}{E} \cdot c \cdot \beta \cdot \overrightarrow{u} \times \overrightarrow{B}$

- with the relativistic factor $\beta = \frac{v}{v} = \sqrt{1 - \frac{1}{\left(\frac{E_{kin}}{mc^2} + 1\right)^2}}$

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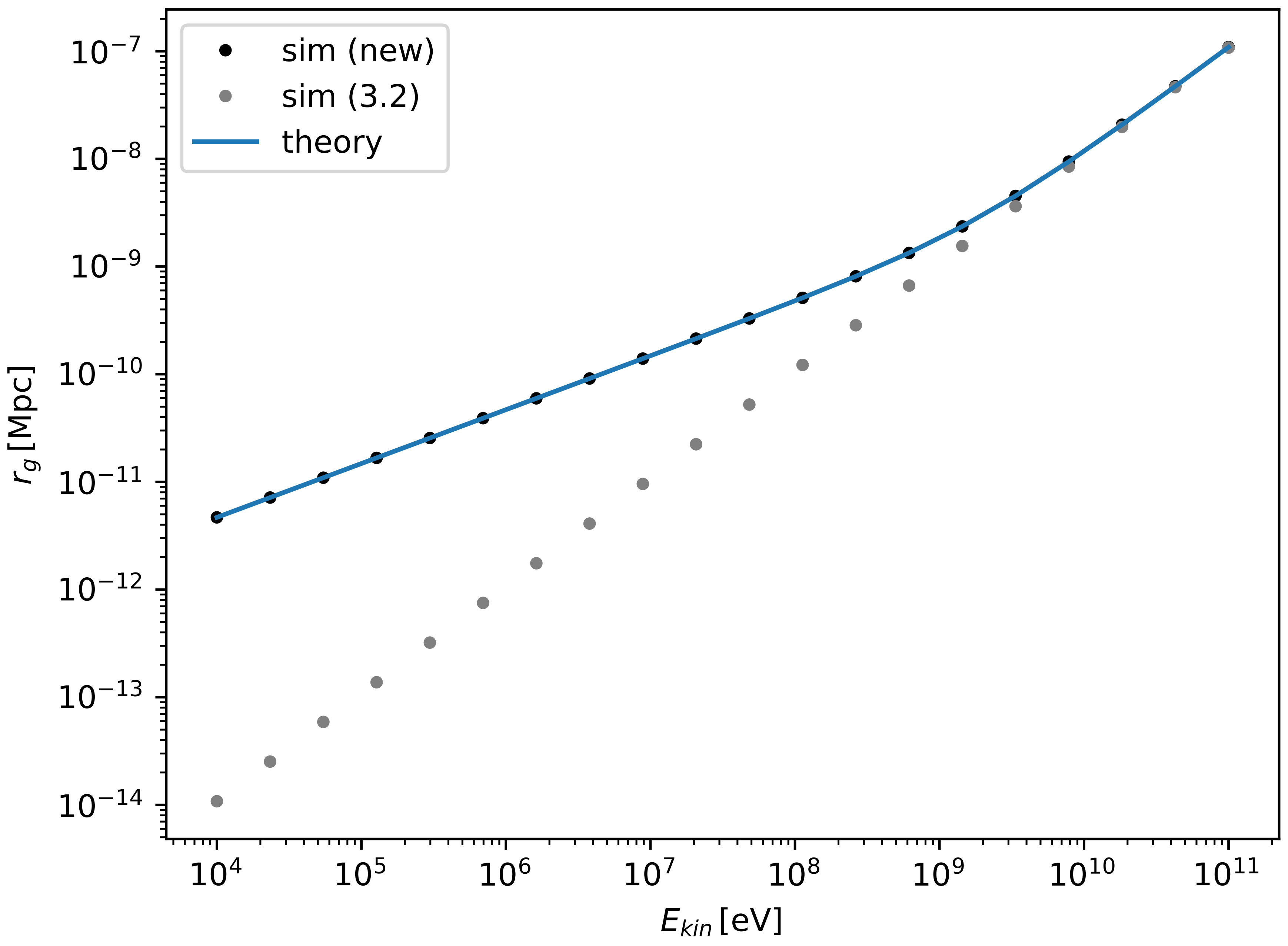
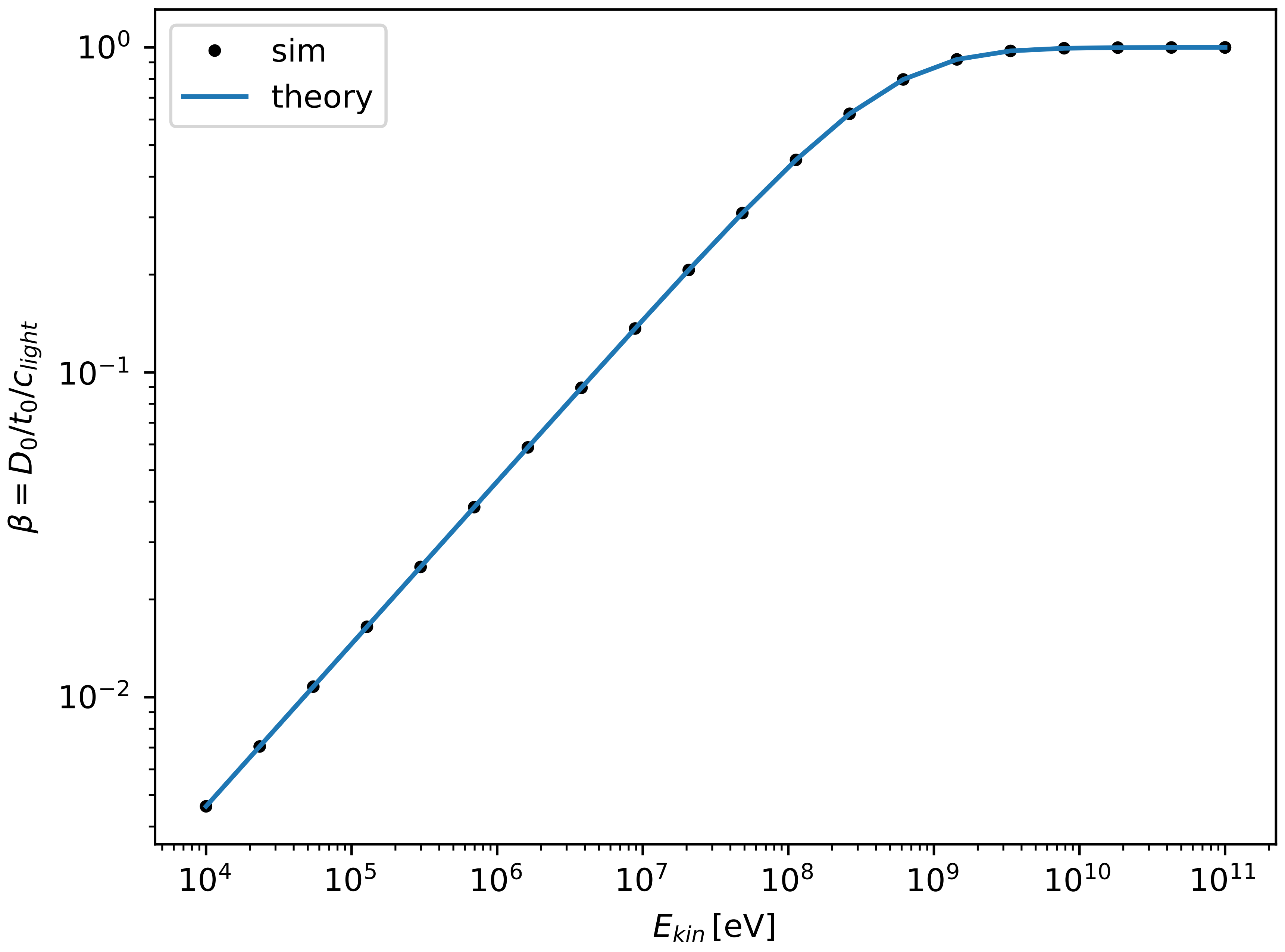
Modifications

Low-energy extension

- In a **minimal test-setup**, a single proton is propagated in an isotropic magnetic field $\overrightarrow{B} = B \cdot \overrightarrow{e_z}$ a trajectory length $D = 2 \cdot \pi \cdot r_g$ for different energies in the range $[10^4, 10^{11}]\,\mathrm{eV}$. The relativistic gyroradius reads $r_g = \frac{\gamma m v_\perp}{qB}$.





Propagation chain

From source to signal

- The local source results need to be propagated further till they reach the observer.
- The in-jet-propagation is for now neglected.
- The transformation into the observer-frame reads $\epsilon = \frac{\epsilon' \cdot \delta(\Gamma_j)}{(1+z)}$ and $D = \frac{D'}{\Gamma_j}$.

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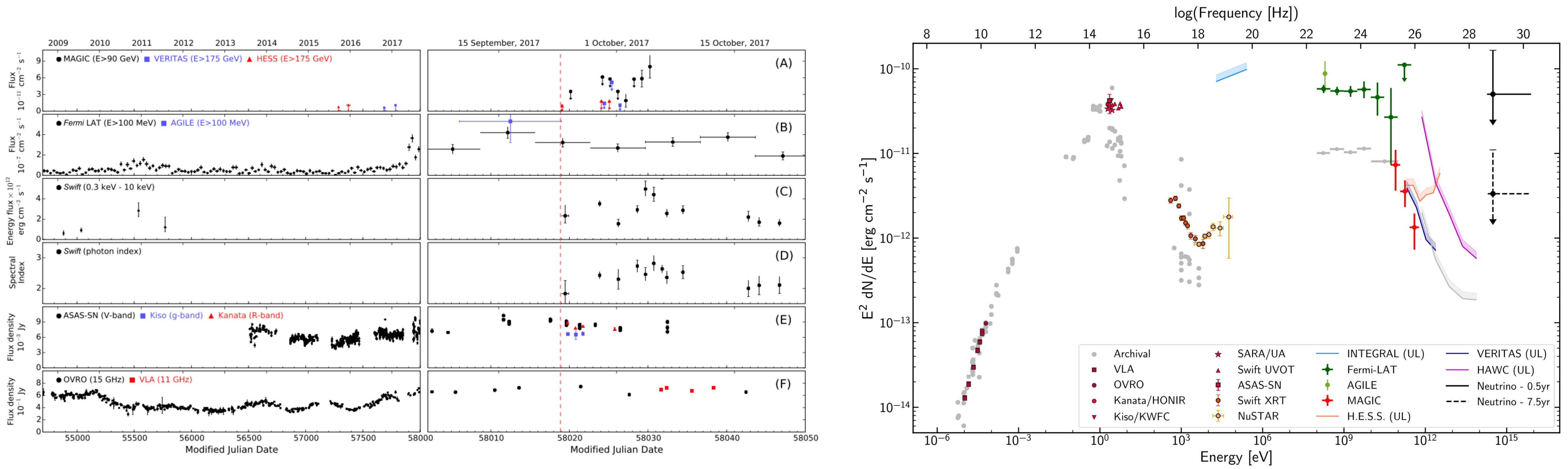
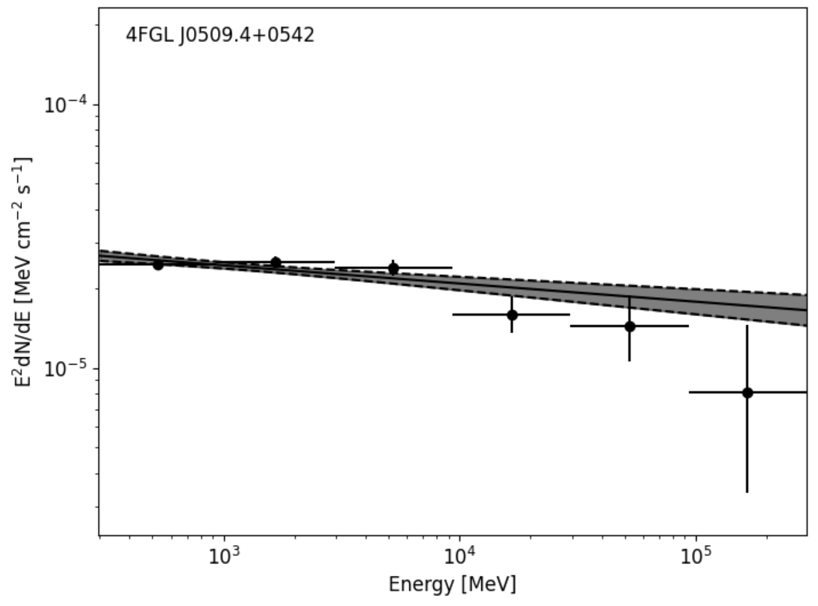
Outlook

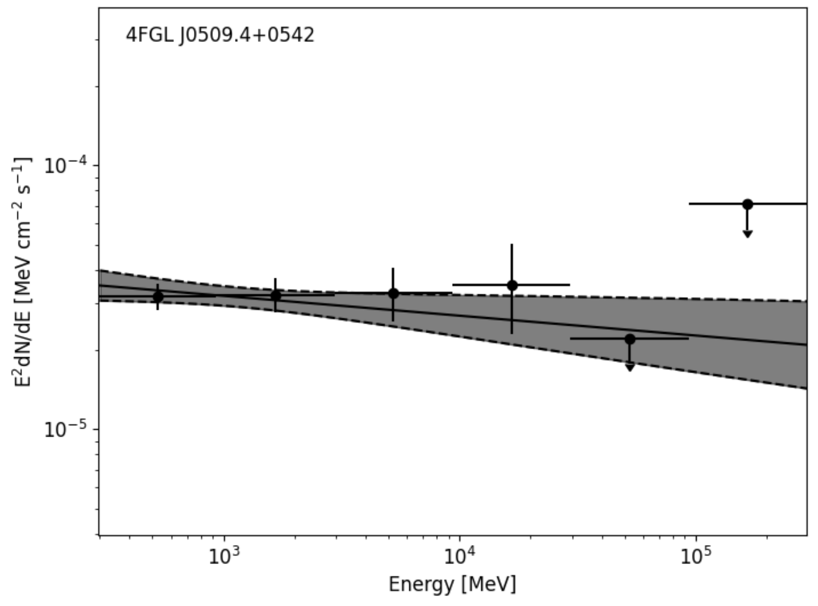
Application to the TxS0506+056 2017 gamma ray flare



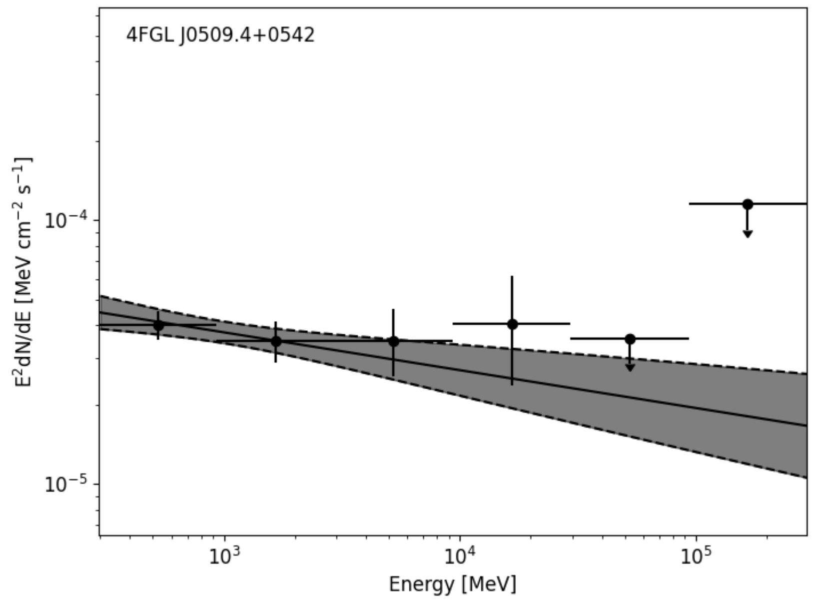
(The IceCube Collaboration et al. 2018)



a) One year centered around the neutrino.

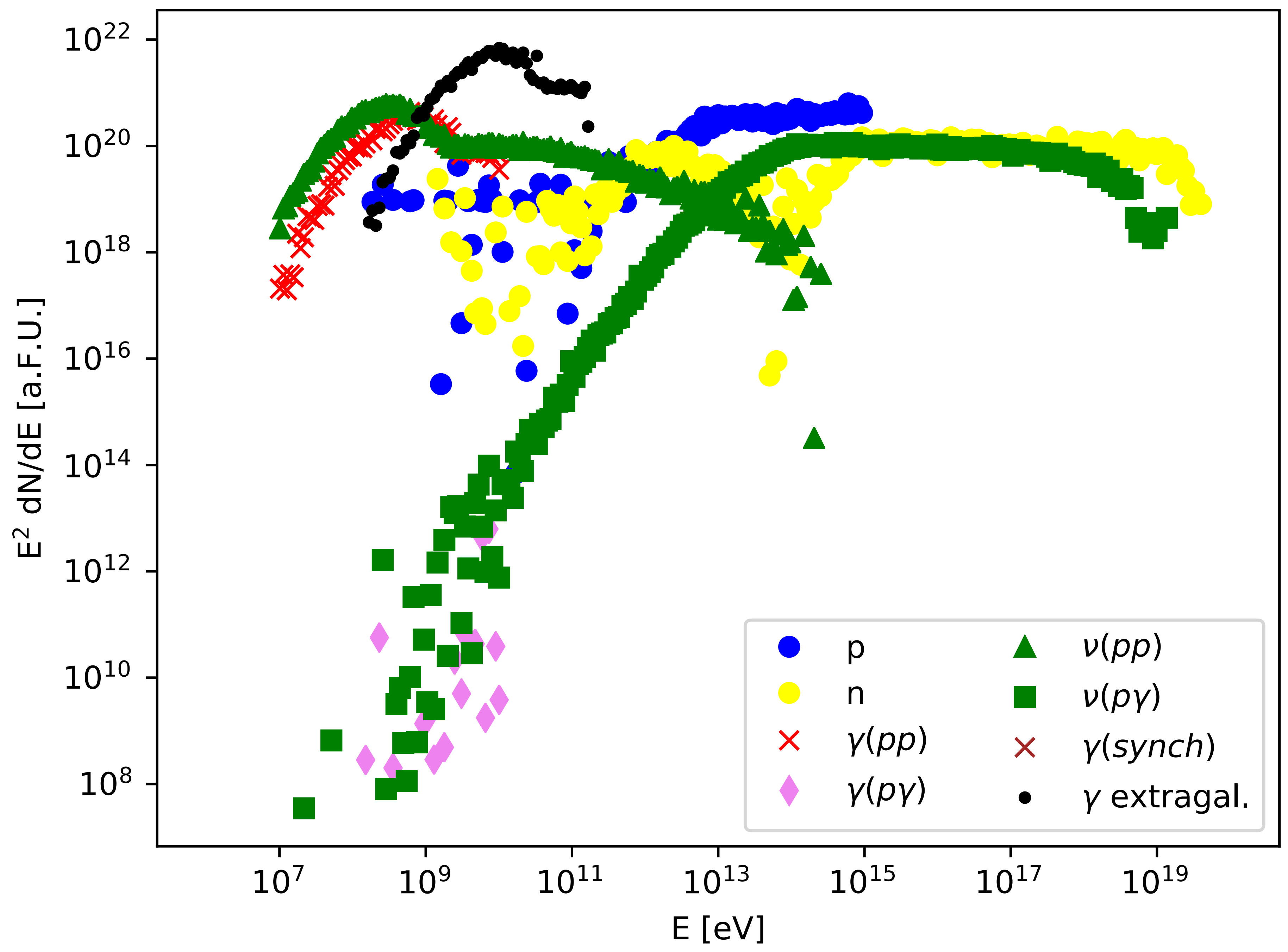


b) Local flare of 25 days.



c) 14 days centered around the neutrino.

(SEDs provided by Emma Kun)



(prelim modeling, not possible as is)

Summary and Outlook

From AGN simulations to flares of finite source lifetime

- A **feature for time dependent particle injection** was implemented in our local code AGNpropa and is, with a python-plugin, also usable with CRPropa 3.2.
- A **low-energy extension** to correctly propagate particles with kinetic energy below their rest-mass was implemented in our local code AGNpropa, an implementation in CRPropa 3.2 would be possible.
- The **basic propagation chain** (in-source, extragalactic, Trafo to observer frame) is implemented for the (AGN)CRPropa part.
- Currently, working on the SED modeling for the TxS0506+056 source.
- In a next step, a fit of the normalization of the gamma-flux to the lightcurve/SED enables prediction of the neutrino-flux.
- In a next step, in the scope of the MICRO-project, the proton- and neutron-escape-spectrum during the flare will be calculated as an estimate for possible CR emission of flaring AGN.

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