Effects of non-continuous losses during inverse Compton cooling in blazars

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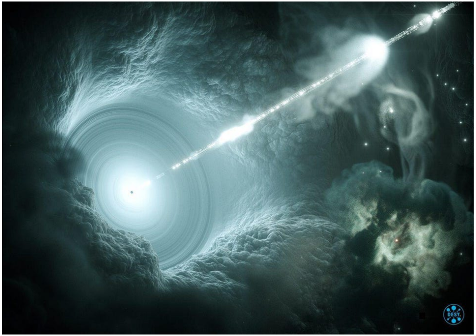

Tenth International Fermi Symposium – October 9-15, 2022

Outline

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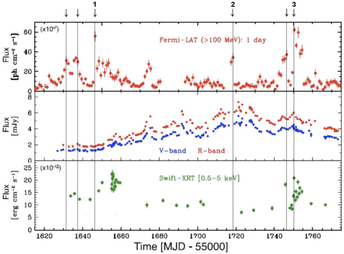
Blazars – radio-loud AGN with a jet aligned with the line of sight

- non-thermal emission from radio to γ-rays
- two-bump SED
- highly variable!
  - **flares**: flux $\nearrow$ by factor $\sim$**10** over time-scale *minutes* – *weeks*
  - **high states**: time-scale *weeks* – *years*



3C 279

Blazars: emission origin

Origin of low-energy bump: e^- synchrotron in extended jet $+$ host galaxy (optical)

Origin of γ-ray emission

Leptonic

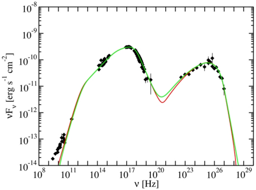
Inverse Compton

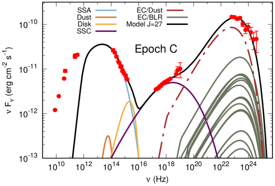
Synchrotron Self-Compton
BL Lac

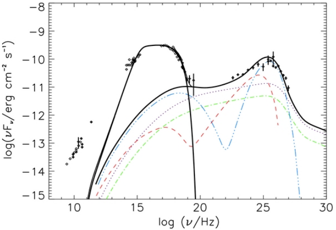
External Compton
FSRQ

Hadronic

- proton synchrotron
- p-γ interactions
- p-p interactions







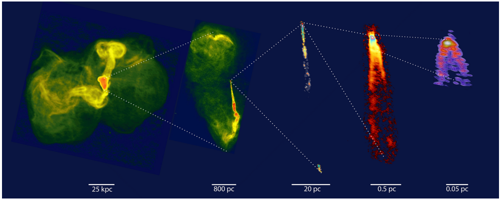
Why study blazars?

Probing AGN jets physics

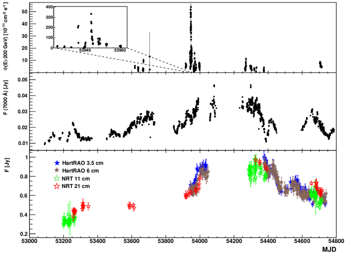
– matter content $(e^- e^+ \; or \; e^- p)$
– origin of γ-ray emission (*leptonic? hadronic?*)
– VHE γ-ray production site
– **nature of flares and high states**

- **Blazar flares carry information about violent physical processes in jets**
  – details of particle acceleration and cooling mechanisms

- **Study method**: physical modeling of varying MWL emission



FR I radio galaxy M87



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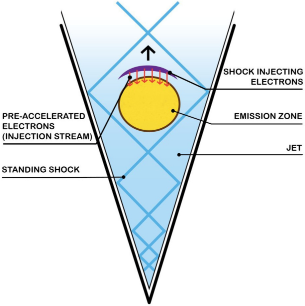
Outline

Fundamental assumptions:

- VHE γ-ray production site: **blob-in-jet** (e.g. Katarzynski et al., 2001)
- Purely **leptonic** blob ($e^- e^+$)
- High-energy plasma particles



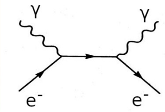
Physical processes:

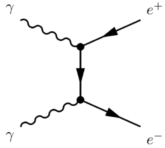
- particle injection
- stochastic (*Fermi-II*) or/and shock (*Fermi-I*) acceleration
- escape
- synchrotron and **IC cooling** (continuous case: $\Delta E_e / E_e \ll 1$)

$$\boxed{\frac{\partial N_e}{\partial t} = \frac{\partial}{\partial \gamma}\left(\left[\underbrace{b_{\text{cool}}\gamma^2}_{\text{cooling}} - \underbrace{a\gamma}_{\text{Fermi-I}} - \underbrace{2D_0\gamma}_{\substack{\text{Fermi-II} \\ \text{(system. en. gain)}}}\right] N_e\right) + \underbrace{\frac{\partial}{\partial \gamma}\left(D_0\gamma^2 \frac{\partial N_e}{\partial \gamma}\right)}_{\substack{\text{Fermi-II} \\ \text{(diffusion in momentum space)}}} - \underbrace{\frac{N_e}{t_{\text{esc}}}}_{\text{escape}} + \underbrace{Q_{\text{inj}}}_{\text{injection}}}$$

Radiative processes:

- **Synchrotron emission**
  $+$ self-absorption
- **Synchrotron Self-Compton (SSC) / external Compton (EC)**
  $+$ absorption on EBL





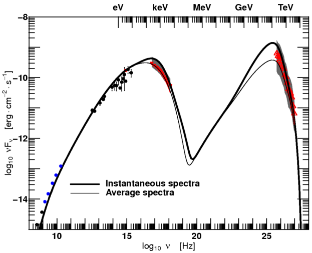
Transformation to observer's frame:

$$\nu = \frac{\delta_\mathrm{b}}{1+z}\,\nu'$$

$$I_\nu(\nu) = \delta_\mathrm{b}^3\, I_{\nu'}(\nu')$$

– Associated SED is computed for electron spectrum at each time step

– Light curves $\Rightarrow$ $\int$ of SEDs



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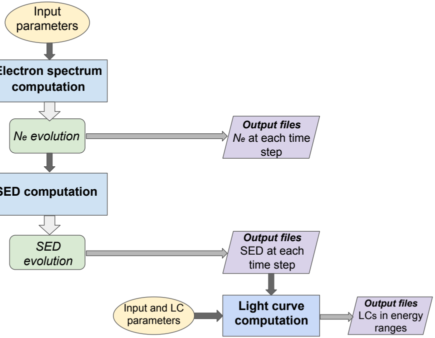
EMBLEM code

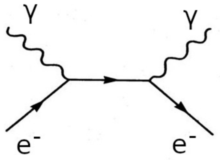
EMBLEM – Evolutionary Modeling of BLob EMission



- Time-dependent leptonic code (SSC/EC) for flare modeling (Dmytriiev et al., 2021)
- Self-consistent connection of the blazar low state with the high one
- Flares arise as a perturbation of low state
- Kinetic equation is solved with Chang & Cooper 1970 numerical scheme
- Initial code: BL Lac objects. **Extended to FSRQs recently!**

Inverse Compton cooling in blazars

>> Cooling is important process damping a flare



IC cooling is significant in blazars with high $U_{\rm rad}$ (FSRQ)

$\rightarrow$ leads to *softer spectra* and *lower* ν *of SED peaks*

– **Thomson regime**: $\Delta E_e/E_e \ll 1, \quad E_{\rm IC} = \gamma^2 \epsilon_s \quad \rightarrow \quad \boxed{\gamma \frac{\epsilon_s}{m_e c^2} \ll 1}$

$\sigma \sim \sigma_{\rm T}$

continuous losses

– **Klein-Nishina (KN) regime**: $\Delta E_e/E_e \sim 1, \quad E_{\rm IC} \sim E_e \sim \gamma m_e c^2 \quad \rightarrow \quad \boxed{\gamma \frac{\epsilon_s}{m_e c^2} \sim 1}$

$\sigma \approx \frac{3}{8}\sigma_{\rm T}\frac{\ln(4\chi)}{\chi}, \quad \chi = \gamma\frac{\epsilon_s}{m_e c^2} \quad \Rightarrow$ cross-section quickly drops with energy

jumps in energy: NON-continuous losses!

! The *Fokker-Plank* (kinetic) equation is derived assuming $\Delta E_e / E_e \ll 1$!

▷ KN effects are common in blazars!

- Most authors use **continuous** description of IC cooling in **KN regime** in the kinetic equation:

$$\dot{\gamma}_{\mathrm{cool,IC}} = -b_{\mathrm{cool,IC}}(N_e, U_{\mathrm{rad}})\,\gamma^2$$

while KN effects have a **non-continuous** nature and *cannot* be handled by that term

- A continuous approximation by Moderski et al. (2005) is designed to reasonably treat KN effects:

$$\dot{\gamma}_{\mathrm{cool,IC}} = -\frac{4\sigma_{\mathrm{T}}}{3m_e c}\gamma^2 \int_{\epsilon'_{\mathrm{min}}}^{\epsilon'_{\mathrm{max}}} f_{\mathrm{KN}}(4\gamma\epsilon')\,u'_{\mathrm{rad}}(\epsilon')\,d\epsilon'$$

$$f_{\mathrm{KN}}(x) = \begin{cases} (1+x)^{-1.5}, & \text{for } x < 10^4 \\ \frac{9}{2x^2}\left(\ln(x) - \frac{11}{6}\right) & \text{for } x \geq 10^4 \end{cases}$$

Inverse Compton cooling: NON-continuous case

The proper *transport equation* to treat large jumps of e^- in energy (Zdziarski 1988):

$$\boxed{\frac{\partial N_e(\gamma,t)}{\partial t} = -N_e(\gamma,t)\int_1^{\gamma} C(\gamma,\gamma')d\gamma' + \int_{\gamma}^{\infty} N(\gamma',t)C(\gamma',\gamma)d\gamma' - \frac{N_e(\gamma,t)}{t_{\rm esc}} + Q_{\rm inj}(\gamma,t)}$$

downscattering from γ to lower LF   downscattering from higher LF to γ

with $C(\gamma,\gamma') = \int_{E_*/\gamma}^{\infty} dx\, n_0(x)\, \frac{3\sigma_T c}{4E\gamma}\left[r + (2-r)\frac{E_*}{E} - 2\left(\frac{E_*}{E}\right)^2 - \frac{2E_*}{E}\ln\frac{E}{E_*}\right] \rightarrow$ Compton kernel by Jones (1968)

$$x = \frac{\epsilon_s}{m_e c^2}, \quad E = \gamma x, \quad E_* = \frac{1}{4}(\gamma/\gamma' - 1), \quad E > E_*, \quad r = \frac{1}{2}(\gamma/\gamma' + \gamma'/\gamma)$$

- A transient Fermi-I/II (re-)acceleration term can be added

>> The full kinetic equation becomes **integro-differential** equation !

Goals and methods of this project

? **How does non-continuous cooling change blazar N_e and SED** ?

Goals:

- Test the limits of the continuous-loss approach:
  When does the non-continuous cooling becomes important for typical physical conditions in blazars?
- Explore the effect of non-continuous cooling in the context of blazar variability and its impact on the *electron spectrum* and *SED*

Methods:

- We extend the `EMBLEM` code by including non-continuous cooling terms
- We numerically solve the *integro-differential equation* by iteration technique

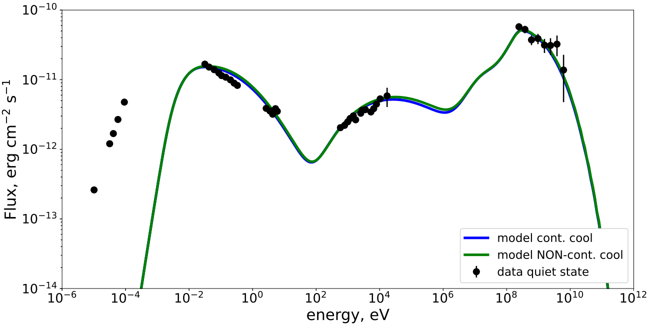
Application:

- **FSRQ**: strong IC cooling $\rightarrow$ **we choose 3C 279**
- Model 3C 279 flares in a simple way *with and without* inclusion of the effect

Outline

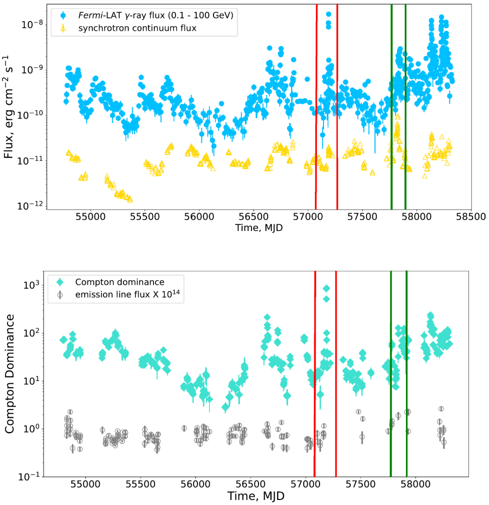
First we model the low state of 3C 279 (data: Hayashida et al. (2012))

- One-zone leptonic EC
- Steady state arises as a result of competition between injection, escape and cooling
- Cooling: synchrotron and IC
- *Injection spectrum*: **log-parabola** (e.g. Dermer et al. (2014))
- *External photon fields*: **BLR** (single Ly α emission line) and **dusty torus** (e.g. Hayashida et al. (2012))



$B = 1$ G, $\delta = 30$, $R_b = 5 \times 10^{15}$ cm, $L_{\rm disk} = 0.6 \times 10^{46}$ erg/s, $f_{\rm BLR,DT} = 0.1$, $t_{\rm esc} = 1\,R_b/c$

Two extreme flares of FSRQ 3C 279



Dmytriiev et al. (2023) (in prep.)

Flare 1: June 2015

- *Fermi*-LAT γ-ray flux $\sim \mathbf{10^{-8}}$ **erg cm^{-2} s^{-1}** **(historical maximum!)**
- Optical synchrotron flux (at $\lambda \approx 6000$ Å) $\sim (1-2) \times 10^{-11}$ erg cm^{-2} s^{-1}
- Compton dominance (CD) $\sim$ **500 – 800** **(!)**

Flare 2: April 2017

- *Fermi*-LAT γ-ray flux $\sim 3 \times 10^{-9}$ erg cm^{-2} s^{-1}
- Optical synchrotron flux (at $\lambda \approx 6000$ Å) $\sim \mathbf{10^{-10}}$ **erg cm^{-2} s^{-1}** **(historical maximum!)**
- Compton dominance (CD) ~ 30

Modeling the two extreme flares of 3C 279

Flare 1 (brightest γ-ray)

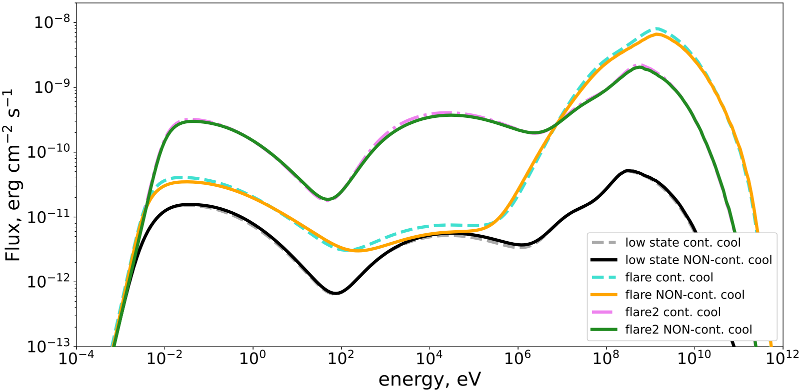
- Simple one-zone model
- Increase of **Doppler factor δ**
- Decrease of **magnetic field B**

$\delta = 83,\ B = 0.3$ G

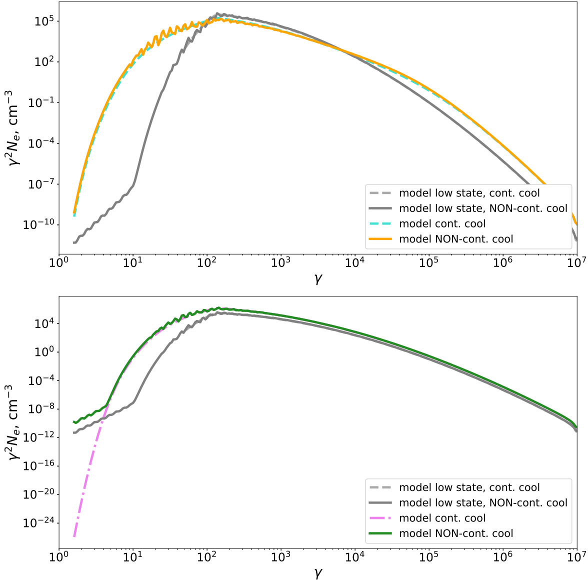
Flare 2 (brightest optical)

- Simple one-zone model
- Increase in the **injection rate** (normalization/density)
- Increase of **Doppler factor δ**

$\delta = 45,\ n_e$ X 6



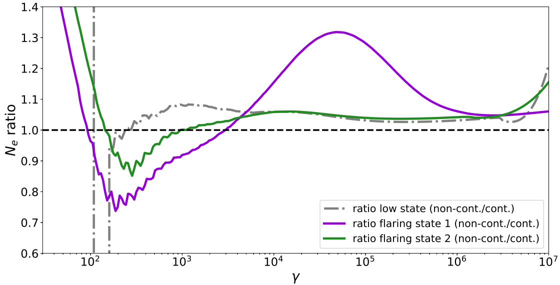
Electron spectra: low and flaring states



Difference in electron spectrum and SED

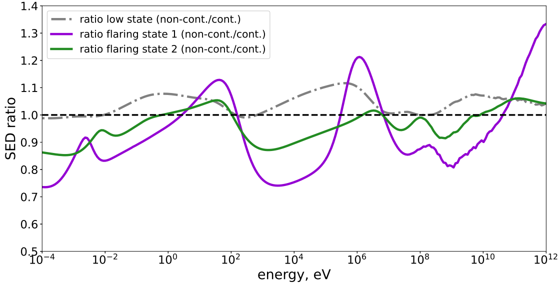
Ratio of **electron spectra**

$$\frac{N_e \text{ with full cooling term}}{N_e \text{ with continuous approx}}$$



Ratio of **SED**

$$\frac{\text{SED with full cooling term}}{\text{SED with continuous approx}}$$



Outline

Summary

- We have considered the effect of **non-continuous IC cooling** in the context of blazar variability (with an emphasis on FSRQ)

- The *continuous-loss* approximation is quite reasonable for low states of blazars with the difference < 10 %

- The **non-continuous cooling** effects become quite important (difference up to $\sim$ **35%**) during **flaring states** with *high Compton dominance*:

  – At **low Lorentz factors** past the *cooling break*: a large number of electrons "miss" this area as they experience jumps to very low γ

  $\rightarrow$ **spectral softening**

  – At **medium-to-high Lorentz factors** far beyond the *Klein-Nishina transition*: the continuous approximation **overestimates** the cooling effect

  $\rightarrow$ **spectral hardening**

Outlook

- **What makes blazar jets cool?**

  More profoundly explore the effect in terms of different flare scenarios

  > shock/stochastic **re-acceleration**

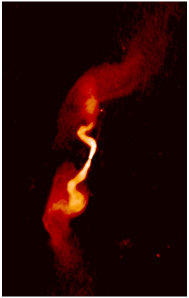
- Detailed physical modeling of blazar flares with the inclusion of *non-continuous cooling* effect

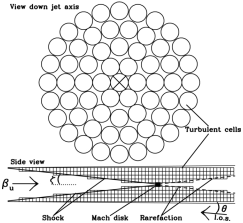
- Consider the effect within the framework of theory/simulations of **stochastic particle acceleration** (non-continuous acceleration + cooling)

Thank you for your attention!

Back-up slides

- Transient turbulence around the emitting zone
  (Dmytriiev et al., 2019, 2020)
- EXHALE jet
  Lepto-hadronic cascade developing throughout the entire jet
  (Zacharias et al., 2022)
- Synchrotron mirror model (orphan flares)
  (Böttcher 2021) (Oberholzer 2021)
- Ablation of a gas cloud (Zacharias et al. 2017)
- Transient acceleration processes within em. zone:
  shock, Fermi-II (turbulence), magnetic reconnection
  (e.g. Marscher & Gear 1985 ; Tramacere et al. 2011 ; Giannios et al. 2009)
- Particle injection flash
  (e.g. Mastichiadis & Kirk 1997)
- Doppler factor increase due to jet bending or helicity
  (Abdo et al. 2010a ; Villata & Raiteri 1999)
- Large-scale turbulence in the jet
  (e.g. Li et al., 2018)
- Acceleration + plasma compression (+ turbulence)
  (Marscher (2014))





Numerical implementation: integration

The Compton kernel $C(\gamma, \gamma')$ has a peculiar point when $\gamma \approx \gamma'$ (small losses)

$\rightarrow$ Separate the continuous-loss part, $\gamma/(1+\delta) \leq \gamma' \leq \gamma(1+\delta)$, $\delta \ll 1$ and decompose into Taylor series around $\gamma \approx \gamma'$:

$$-N_e(\gamma, t) \int_1^{\gamma} C(\gamma, \gamma') d\gamma' + \int_{\gamma}^{\infty} N(\gamma', t) C(\gamma', \gamma) d\gamma' =$$

$$-N_e(\gamma, t) \int_1^{\gamma/(1+\delta)} C(\gamma, \gamma') d\gamma' + \int_{\gamma(1+\delta)}^{\infty} N(\gamma', t) C(\gamma', \gamma) d\gamma' +$$

non-cont. scatter. from γ to lower LF   non-cont. scatter. from higher LF to γ

$$+ \frac{\partial}{\partial \gamma} \left[N_e(\gamma, t) \int_{\gamma/(1+\delta)}^{\gamma} C(\gamma, \gamma')(\gamma - \gamma') d\gamma' \right]$$

continuous cooling losses

The continuous term $\frac{\partial}{\partial \gamma}[N_e \dot{\gamma}]$ is integrated analytically, $g = \min(\delta/s, 1)$, $s = 4x\gamma$:

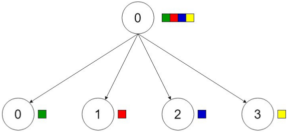
$$\dot{\gamma} = \int_{\gamma/(1+\delta)}^{\gamma} C(\gamma, \gamma')(\gamma - \gamma') d\gamma' = \int_0^{\infty} dx\, n_0(x) \sigma_T c s g^2 \left[\frac{3}{2} + \frac{g}{3} + 2g \ln g - \frac{3}{2} g^2 - 9sg \left(\frac{1}{3} + \frac{g}{8} + \frac{g}{2} \ln g - \frac{2}{5} g^2 \right) \right]$$

Numerical implementation: parallelization

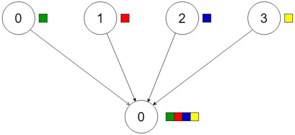
- One simulation run (without non-continuous cooling): $\sim$ 10-15 min
- One simulation run (WITH non-continuous cooling): $\sim$ **40-50 hours !!!**

$\Rightarrow$ **Parallelization is required!**

We use the `MPI4PY` module in Python Anaconda to perform *parallel computation* over the Lorentz factor grid



MPI_Scatter

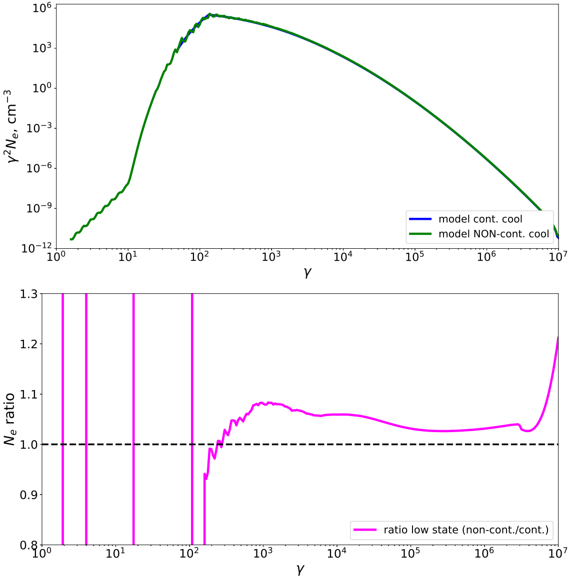


MPI_Gather

– The Lorentz factor grid array is split into blocks, simultaneously processed on separate cores

– NWU/CSR cluster = **128 cores!!!** $\rightarrow$ **1 simulation run: $\sim$ 45 min - 1 hour**

Electron spectrum ratio (low state)



SED ratio (low state)