What makes blazar jets cool?

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Outline

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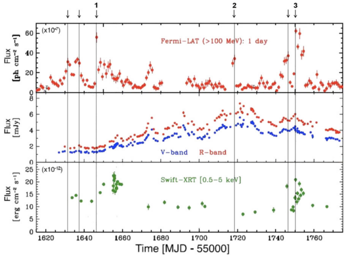
1. Blazars: Introduction
2. Ongoing projects
3. Testing leptonic scenario for 3C 279
4. Characterizing magnetic field geometry in blazar jets
5. Blazar flares: cooling modeling
   - Kinetic approach and EMBLEM code
   - Process under study: inverse Compton cooling
   - Modeling approach
   - Results
6. Summary and outlook

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

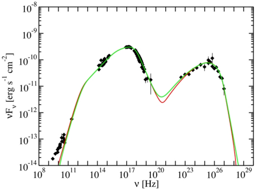
↙ ↘

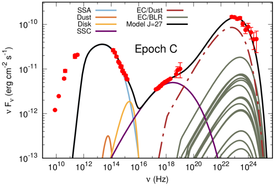
Synchrotron Self-Compton
BL Lac

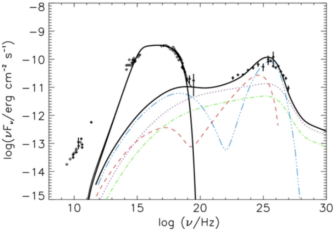
External Compton
FSRQ

Hadronic

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







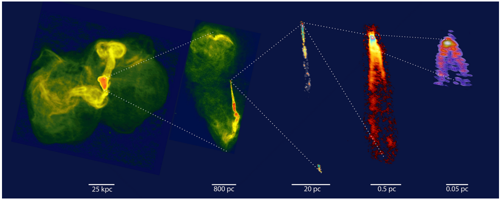
Why study blazars?

Probing AGN jets physics

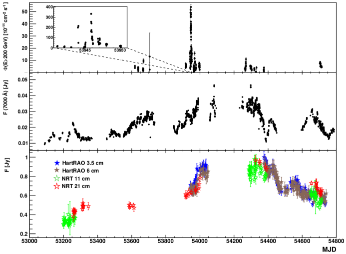
- matter content ($e^- e^+$ *or* $e^- p$)
- origin of γ-ray emission (*leptonic? hadronic?*)
- VHE γ-ray production site
- **nature of flares and high states**

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

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



FR I radio galaxy M87



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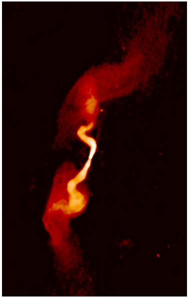
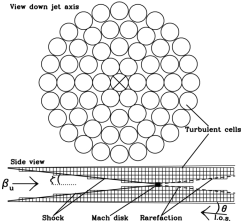
Nature of blazar flaring activity. Origin: jet

- 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))





Outline

Projects currently in development

- Testing leptonic scenario for the FSRQ 3C 279 (M. Böttcher, T.O. Machipi)
- Characterizing magnetic field geometry in blazar jets (M. Böttcher, H. Schutte)
- **Testing the limits of continuous-loss approximation for particle cooling in blazar jets** (M. Böttcher)
- Periodic unicorns: long-term periodicity of blazar γ-ray emission (N. Żywucka, M. Kreter, D. Dorner, M. Tarnopolski, M. Böttcher, et al.)
- Sgr A* flares modeling (N. Aimar, F. Vincent, A. Zech, et al.)
  $\Rightarrow$ **completed! Paper to be submitted in July**

– Too many projects... –

Outline

Project 1: Testing leptonic scenario for 3C 279

Studied object: Flat Spectrum Radio Quasar (FSRQ) **3C 279**

$\rightarrow$ SED of the sauce can be well fit with both *leptonic* and *hadronic* models

Tested hypothesis: γ-ray emission arises from IC upscattering of **soft photons from BLR** by high energy e^- in the compact region of the jet (blob)

Expectation: Correlation between the luminosity of optical emission lines (originating in the BLR) and the γ-ray (Compton) dominance

$$CD = \frac{F_{\rm IC}}{F_{\rm syn}} \propto \frac{N_e U_{\rm rad,BLR}}{N_e U_B} \propto \frac{U_{\rm rad,BLR}}{U_B}$$

Methods:

– use the Fermi-LAT γ-ray long-term light curve

– measure the optical emission lines luminosity vs time

– measure the optical synchrotron flux vs time

Optical data

- **Steward Observatory monitoring program:**
  - Optical spectra of 3C 279 ($\sim$ 400 spectra)
  - 10 years data (with a slightly irregular sampling)
- **We use optical spectra to:**
  - Measure optical emission line luminosity
  - Estimate synchrotron flux

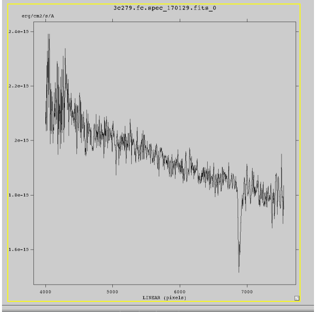
Figure: Steward Observatory

- Continuum: **Power Law**

$$F_\lambda = A_c \left(\frac{\lambda}{\lambda_0} \right)^{-p}$$

- Emission line: Mg II (2798 $\mathring{A}$ / 4298 $\mathring{A}$)
Gaussian

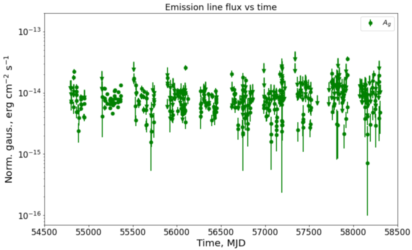
$$F(\lambda|\mu, \sigma) = \frac{A_g}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\lambda - \lambda_\mu)^2}{2\sigma^2} \right)$$

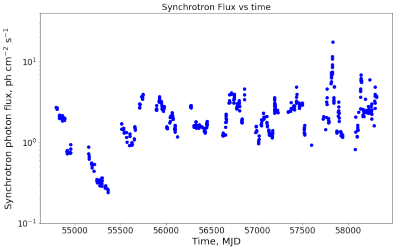


Total Model = Power law + Gaussian

Fitting the optical data

- We fit $\sim$ 400 optical spectra (10 years span) $\Rightarrow$
  $\Rightarrow$ **retrieve emission line luminosity depending on time**
- If line not detected $\rightarrow$ Upper Limit for line luminosity
- Compute the optical synchrotron flux (t) by integrating the continuum model

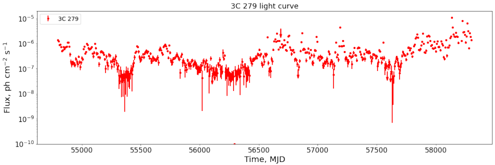




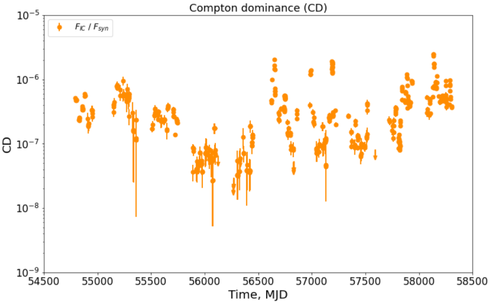
Compute the CD light curve:

- Extract the long-term 10-year Fermi LC
  (binned likelihood analysis with *Fermitools*)
- Approximate the Compton Dominance as the ratio of Fermi γ-ray flux to the optical synchrotron flux

Fermi-LAT LC

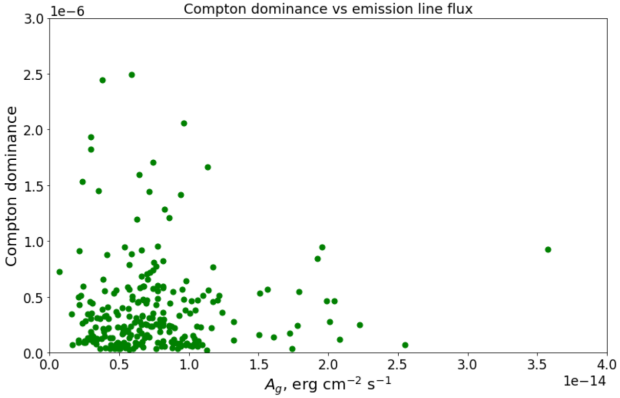


Compton ratio LC



Correlation of line luminosity vs Compton Dominance: simultaneous measurements

We plot **emission line flux** vs **Compton dominance** for simulatnaous measurements (scatter plot)

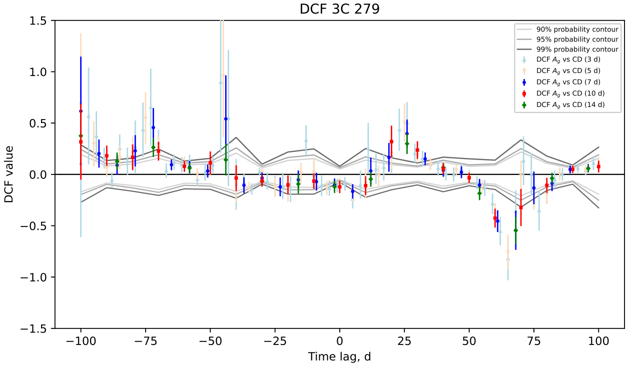


No correlation whatsoever!!

PRELIMILARY!

Test the leptonic scenario: a time lag?

- Cross-correlate light curves of **CD** with the **emission line luminosity** using the *discrete correlation function (DCF) analysis* (Edelson & Krolik 1988)
- Time lags in the DCF can constrain the location of γ-ray emission zone in the jet (if correlation found)



PRELIMILARY!

> **The Compton dominance responds to the changes in emission line luminosity with a delay**

Two putative peaks in the DCF:

- $\boldsymbol{\Delta t \sim 25}$ **d**: positive correlation, DCF ~ 0.5
  - corresponds to the light travel time from BLR to γ-ray production site
  - we assume the emitting zone is within the BLR (the most efficient scattering)
    - $\Rightarrow$ The emitting zone is $\sim 2 \times 10^{16}$ cm inside the BLRs inner boundary
  - The BLR size is estimated to be 2×10^{17} cm (Böttcher & Els, 2016)
    - $\Rightarrow$ The emitting zone is relatively close to the BLR inner boundary
- $\boldsymbol{\Delta t \sim 60}$ **d**: negative correlation, DCF ~ 0.7
  - Light travel effects cannot explain this time lag
  - $\Rightarrow$ *Time-scale of accretion disk duty cycle?*

– First author paper almost finished – To be submitted in ~~June~~ July

Outline

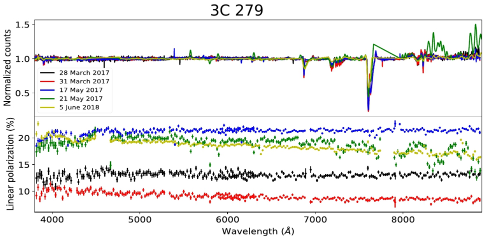
Project 2: Magnetic field geometry in blazar emission zone

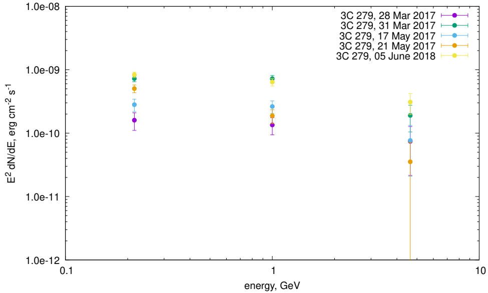
Lead author: H. Schutte

- Blazars emit non-thermal *highly polarized* synchrotron emisssion
- Dusty torus, BLR, accretion disk emission is thermal and non-polarized
- *Polarimetry* measurements of blazar emission allows to characterize the *magnetic field structure* in these sources (ordered/chaotic)
- **South African Large Telescope (SALT)** Large Science Program “Observing the Transient Universe”: ToO spectrapolarimetry observations of blazars

Project 2: Magnetic field geometry in blazar emission zone

- SALT observed FSRQs **3C 279** and **3C 273**
- Polarization degree decreases towards longer wavelengths for some observations
- **Model**: shock acceleration + magnetic field compression and gradual restoration of its configuration behind the shock
- Multi-wavelength approach is crucial: Fermi-LAT γ-ray spectra would allow to constrain theoretical models
- **Method:** physical modeling of spectrapolarimetry data and Fermi-LAT γ-ray spectra





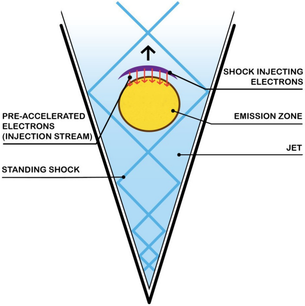
Outline

Testing the limits of continuous-loss approximation for inverse Compton cooling in blazars

Flare modeling: time-dependent kinetic approach

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



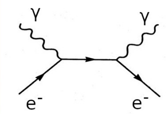
Physical processes:

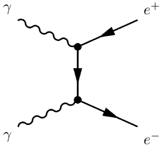
- particle injection
- stochastic (*Fermi-II*) or/and shock (*Fermi-I*) acceleration
- escape
- synchrotron and **IC cooling**
  (continuous case: $\Delta E_e / E_e \ll 1$)

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

Radiative processes:

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





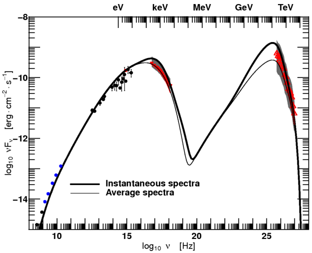
Transformation to observer's frame:

$$\nu = \frac{\delta_b}{1+z}\,\nu'$$

$$I_\nu(\nu) = \delta_b^3\, I_{\nu'}(\nu')$$

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

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



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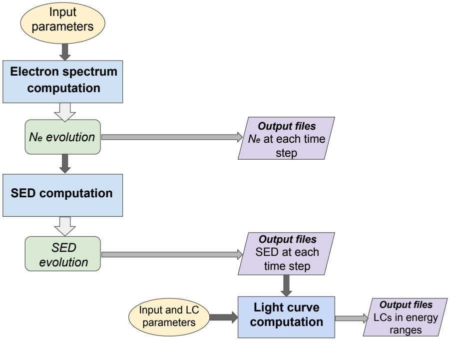
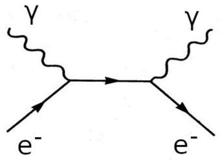
EMBLEM – Evolutionary Modeling of BLob EMission



- Time-dependent leptonic SSC code 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 via re-acceleration process
- Kinetic equation is solved with Chang & Cooper 1970 numerical scheme
- Currently the code application limited to **BL Lac objects** ; plan to extend to FSRQs

>> Cooling is important process damping a flare



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

- **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!

Inverse Compton cooling: contniouous apprxomiation

! 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:

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

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:

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

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

Inverse Compton cooling: NON-continuous case

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

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

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)

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

- 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 accurate is the continuous-loss approximation for IC cooling ?

Goals:

- Test the limits of the continuous-loss approach:
  when does the non-continuous cooling becomes important?
- Investigate the effect of non-continuous cooling
  on blazar 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:

- We model simple blazar flares with different physical parameters
- Compare results of the two approaches

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, $\gamma/(1+\delta) \le \gamma' \le \gamma(1+\delta)$, $\delta \ll 1$ 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

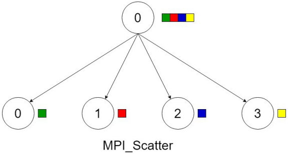
The continuous term $\frac{\partial}{\partial\gamma}[N_e\dot{\gamma}]$ is integrated analytically, $g = \min(\delta/s,1)$, $s = 4x\gamma$:

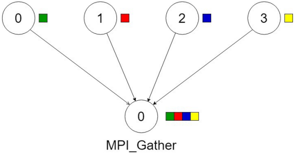
$$\dot{\gamma} = \int_{\gamma/(1+\delta)}^{\gamma} C(\gamma,\gamma')(\gamma-\gamma')d\gamma' = \int_0^{\infty} dx\, n_0(x)\sigma_T c s g^2\left[\frac{3}{2}+\frac{g}{3}+2g\ln g-\frac{3}{2}g^2-9sg\left(\frac{1}{3}+\frac{g}{8}+\frac{g}{2}\ln g-\frac{2}{5}g^2\right)\right]$$

- One simulation run (without non-continuous cooling): $\sim$ 5 min
- One simulation run (WITH non-continuous cooling): $\sim$ **40 hours !!!**

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

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

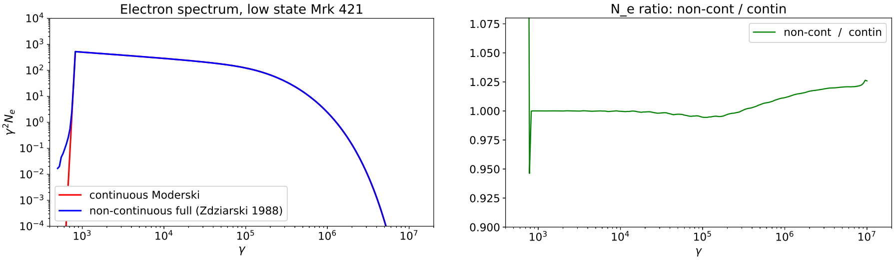




– The Lorentz factor grid array is split into blocks, simultaneously processed on separate cores

– Markus/James cluster = **128 cores!!!** $\rightarrow$ **1 simulation run: $\sim$ 30 min**

We explore the **non-continuous IC cooling** contribution to the *low state* of the BL Lac object Mrk 421

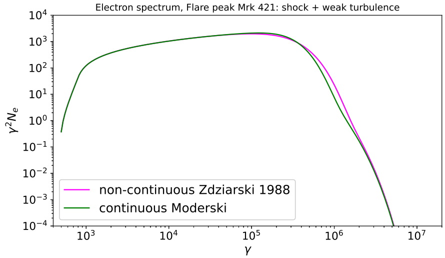


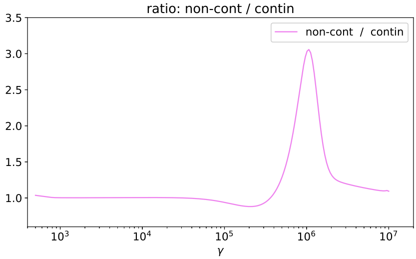
⇒ **The effect is below 3% and thus negligible for a low state**

Non-continuous cooling effect: HIGH state (shock + turbulence)

Now we check the impact of **non-continuous IC cooling** on the *flaring state* of the BL Lac object Mrk 421:

>> initiate a flare with a **shock** (1.65 R/c) and moderate **turbulence** (5 R/c)



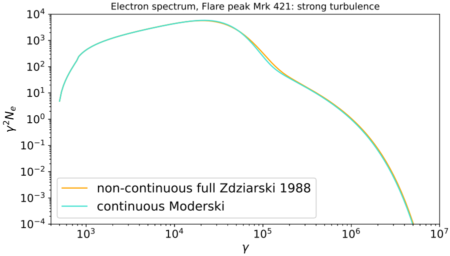


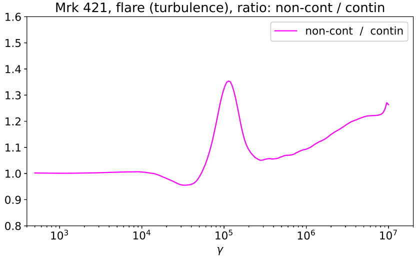
⇒ **The electron spectrum is smoother due to non-continuous losses**

⇒ **The effect can lead up to factor ~ 3 difference at high Lorentz factors!**

Non-continuous cooling effect: HIGH state (strong turbulence)

>> initiate a flare with a **strong turbulence**

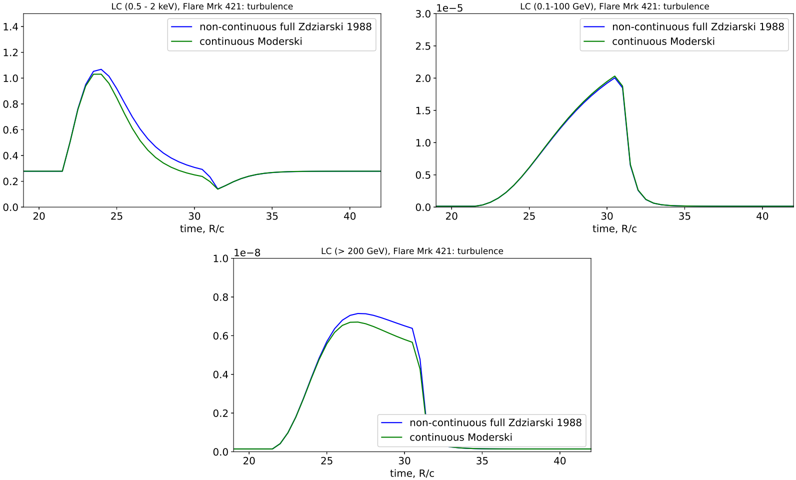




⇒ **The effect is less pronounced due to the re-distribution of e^- in energy**

⇒ **Still leads to ~ 40% difference at medium-to-high Lorentz factors!**

Light curves: HIGH state (strong turbulence)



⇒ **The effect is not visible at GeV energies. Manifests more in X-rays and VHE**

Outline

A very nice summary

- We have extended the EMBLEM code by adding the effect of **non-continuous IC cooling**
- The parallelization of the integro-differential equation solver enables to speed up computation significantly
- The Moderski et al. (2005) *continuous-loss* approximation is reasonable for low states of BL Lac objects
- This approximation is also quite accurate for *Thomson regime* and *deep Klein-Nishina* regime, however has *low accuracy* for **transition domain**
- The **non-continuous effect** seems to be rather *pronounced* even in BL Lac objects (but only during very strong flaring states)

A very ambitious outlook

- We aim to explore this effect in **FSRQs flares** (e.g. 3C 279) $\rightarrow$ work in progress!
  - We added external photon fields from the BLR into the code
  - *Very simplified model*: Ly α line Doppler-boosted into the blob frame
  - Done rough modeling of the low state
  - Testing flare scenarios going on right now $\rightarrow$ interesting results coming soon!
- Study of parameter space: **under which physical conditions in jets the effect manifest the most?**
- ..... lots of other ideas are coming! ....
- Two publications:
  - (1) Theory and parameter space study
  - (2) Full physical modeling of a few blazar flares with inclusion of the effect

Thank you for your attention!