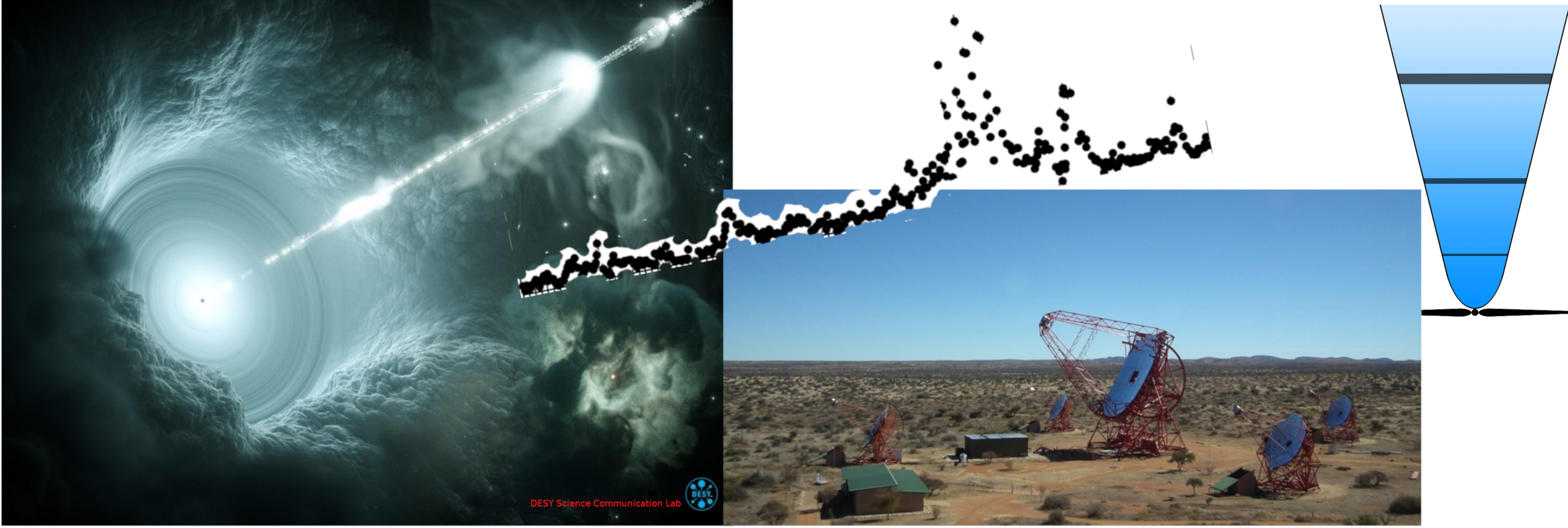

OneHaLe: a One-zone Hadro-Leptonic code

Michael Zacharias

Workshop on Numerical Multi-messenger Modeling

Paris, France

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Table of Content

OneHaLe is. . .

```
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Example of the parameter input file.

Gory details:

- Zacharias, M., 2021, Physics, 3, 1098
- Zacharias, M., et al., 2022, MNRAS, 512, 3948

. . . a time-depdendent, parallelized, hadro-leptonic, one-zone C code

. . . very flexible to accommodate various kinds of variability

. . . in each time step solves the Fokker-Planck equation for every particle species using the Chang&Cooper routine, the radiation transport equation, and obtains the neutrino output

. . . Pion and Muon evolution explicitly calculated (following Hümmer+10)

. . . includes external photon fields: accretion disk, BLR, DT, CMB

. . . particle-photon interactions involve internal and external photon fields

. . . tests suggests good agreement with the “Hadronic Code Comparison” project

Fokker-Planck equation

$$\frac{\partial n_i(\chi,t)}{\partial t} = Q_i(\chi) + \frac{\partial}{\partial \chi}\left[\frac{\chi^2}{(a+2)t_{\rm acc}}\frac{\partial n_i(\chi,t)}{\partial \chi}\right] - \frac{\partial}{\partial \chi}(\dot{\chi}_i n_i(\chi,t)) - \frac{n_i(\chi,t)}{t_{\rm esc}} - \frac{n_i(\chi,t)}{\gamma t^*_{i,\rm decay}}$$

with normalized momentum $\chi = \gamma\beta$.

Particle injection
Acceleration processes
Cooling processes
Particle escape
Particle decay

Fokker-Planck equation

$$\frac{\partial n_i(\chi,t)}{\partial t} = Q_i(\chi) + \frac{\partial}{\partial \chi}\left[\frac{\chi^2}{(a+2)t_{\rm acc}}\frac{\partial n_i(\chi,t)}{\partial \chi}\right] - \frac{\partial}{\partial \chi}\left(\dot{\chi}_i n_i(\chi,t)\right) - \frac{n_i(\chi,t)}{t_{\rm esc}} - \frac{n_i(\chi,t)}{\gamma t^*_{i,\rm decay}}$$

with normalized momentum $\chi = \gamma\beta$.

Particle injection

- Primary proton and electron (incl. positrons) distributions are injected in each time step according to
  $Q_i(\chi) = q_{0,i}\gamma^{-s}$
  between a minimum and maximum Lorentz factor and $q_{0,i}$ depending on input parameters
- Charged pion injection following Hümmer+10
- Muon injection from pion decay
- Secondary electron injection from muon decay, Bethe-Heitler pair production and γ-γ pair production

Acceleration processes

Cooling processes

Particle escape

Particle decay

Fokker-Planck equation

$$\frac{\partial n_i(\chi,t)}{\partial t} = Q_i(\chi) + \frac{\partial}{\partial \chi}\left[\frac{\chi^2}{(a+2)t_{\mathrm{acc}}}\frac{\partial n_i(\chi,t)}{\partial \chi}\right] - \frac{\partial}{\partial \chi}\left(\dot{\chi}_i n_i(\chi,t)\right) - \frac{n_i(\chi,t)}{t_{\mathrm{esc}}} - \frac{n_i(\chi,t)}{\gamma t^*_{i,\mathrm{decay}}}$$

with normalized momentum $\chi = \gamma\beta$.

Particle injection

Acceleration processes

- Fermi I/II, but only as a “re-acceleration”
- Main acceleration through a generic injection term
- t_{acc} is a free parameter

Cooling processes

Particle escape

Particle decay

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Fokker-Planck equation

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with normalized momentum $\chi = \gamma\beta$.

Particle injection

Acceleration processes

Cooling processes

- Protons: synchrotron, adiabatic, p-γ, Bethe-Heitler
- Charged pions / muons: synchrotron, adiabatic
- Electrons: synchrotron, adiabatic, inverse Compton

Particle escape

Particle decay

Fokker-Planck equation

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with normalized momentum $\chi = \gamma\beta$.

Particle injection
Acceleration processes
Cooling processes
Particle escape

- Escape mimics an advective motion of the plasma through the emission region:
  $t_{\mathrm{esc}} = \eta_{\mathrm{esc}} R/c$
  with free parameter $\eta_{\mathrm{esc}} \geq 1$

Particle decay

Fokker-Planck equation

$$\frac{\partial n_i(\chi,t)}{\partial t} = Q_i(\chi) + \frac{\partial}{\partial\chi}\left[\frac{\chi^2}{(a+2)t_{\mathrm{acc}}}\frac{\partial n_i(\chi,t)}{\partial\chi}\right] - \frac{\partial}{\partial\chi}\left(\dot{\chi}_i n_i(\chi,t)\right) - \frac{n_i(\chi,t)}{t_{\mathrm{esc}}} - \frac{n_i(\chi,t)}{\gamma t^*_{i,\mathrm{decay}}}$$

with normalized momentum $\chi = \gamma\beta$.

Particle injection
Acceleration processes
Cooling processes
Particle escape
Particle decay

- For muons and pions only with the decay time given in the proper frame of each particle

Radiation transport equation

$$\frac{\partial n_{\mathrm{ph}}(\nu, t)}{\partial t} = \frac{4\pi}{h\nu} j_\nu(t) - n_{\mathrm{ph}}(\nu, t)\left(\frac{1}{t_{\mathrm{esc,ph}}} + \frac{1}{t_{\mathrm{abs}}}\right)$$

Photon production
Photon escape
Photon absorption processes

Radiation transport equation

$$\frac{\partial n_{\rm ph}(\nu,t)}{\partial t} = \frac{4\pi}{h\nu} j_\nu(t) - n_{\rm ph}(\nu,t)\left(\frac{1}{t_{\rm esc,ph}} + \frac{1}{t_{\rm abs}}\right)$$

Photon production

- Synchrotron (all particles)
- Inverse-Compton (electrons) on all radiation fields (external photon fields: angle-averaged in the comoving frame after boosting + delta-function approximation to one of the integrals for each IC/ext process)
- Neutral pions decay directly to γ's

Photon escape

Photon absorption processes

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Radiation transport equation

$$\frac{\partial n_{\mathrm{ph}}(\nu,t)}{\partial t} = \frac{4\pi}{h\nu} j_\nu(t) - n_{\mathrm{ph}}(\nu,t)\left(\frac{1}{t_{\mathrm{esc,ph}}} + \frac{1}{t_{\mathrm{abs}}}\right)$$

Photon production

Photon escape

- Photons leave the source with average escape time $t_{\mathrm{esc,ph}} = 0.75\,R/c$

Photon absorption processes

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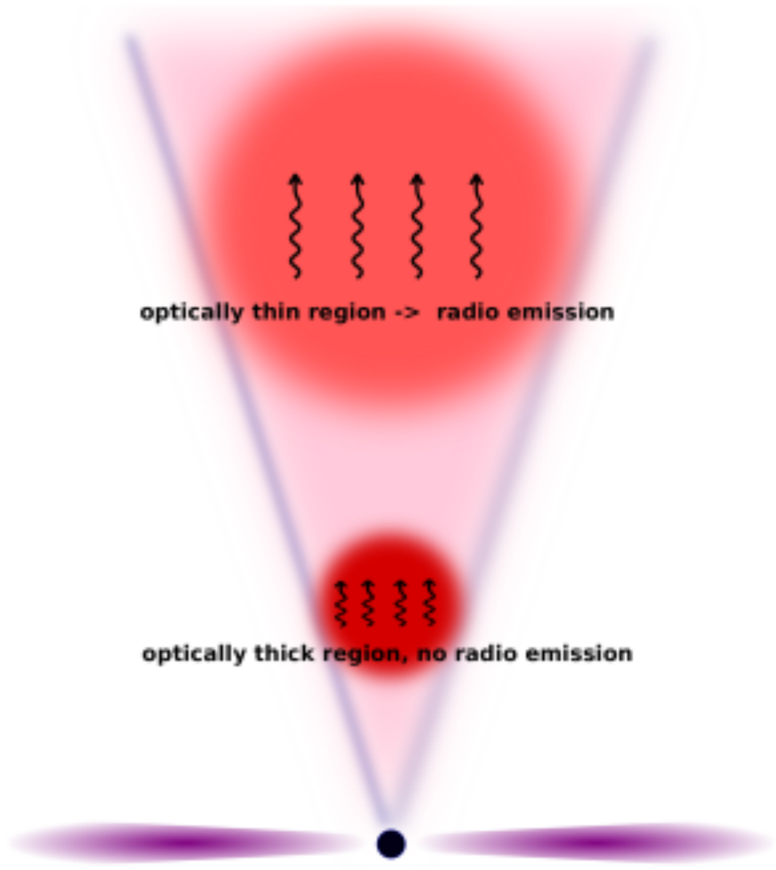
Radiation transport equation

$$\frac{\partial n_{\mathrm{ph}}(\nu,t)}{\partial t} = \frac{4\pi}{h\nu} j_\nu(t) - n_{\mathrm{ph}}(\nu,t)\left(\frac{1}{t_{\mathrm{esc,ph}}} + \frac{1}{t_{\mathrm{abs}}}\right)$$

Photon production
Photon escape
Photon absorption processes

- Bethe-Heitler and γ-γ pair production processes using all photon fields (external ones angle-averaged in the comoving frame after boosting)
- Synchrotron-self absorption
- Photons that left the emission region, are also absorbed in the BLR and DT fields (but no EBL or CMB absorption considered) if applicable

Scientific Example 1: Moving and expanding blob

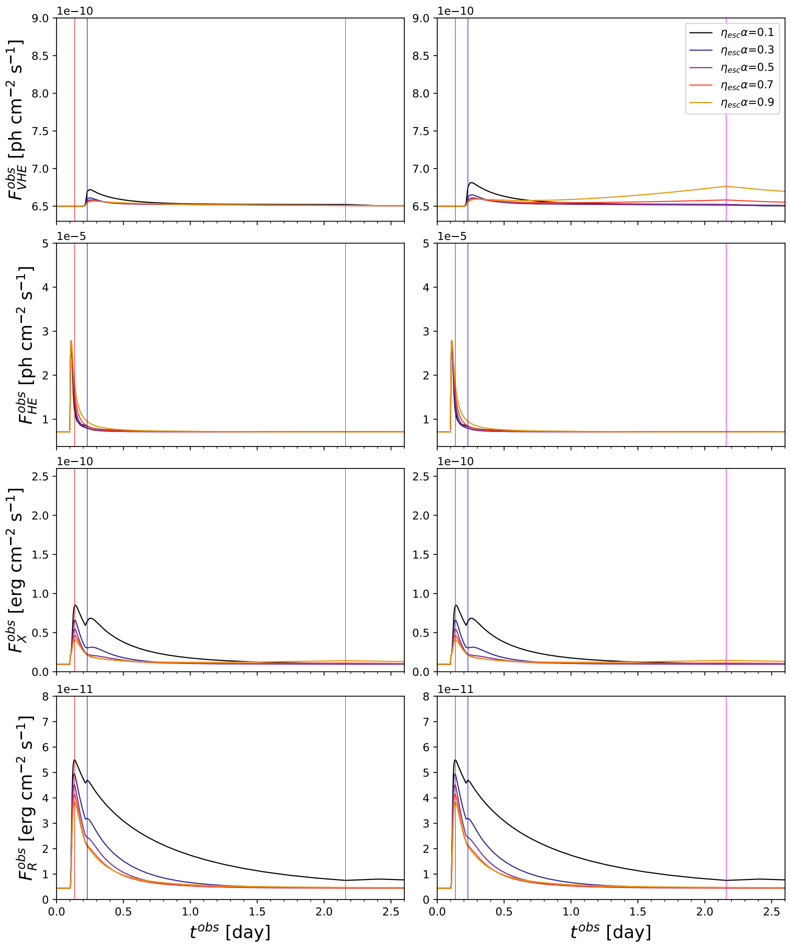


Expansion of blobs in a conical jet

(taken from Boula&Mastichiadis22)

- The blazar one-zone model typically assumes a constant radius of the emission region
- If the emission region moves, the blob should expand adiabatically due to its higher pressure compared to the jet medium
- Expansion: $R(t) = R_0 + \alpha ct$
- Escape of particles: $t_{\rm esc}(t) = \eta_{\rm esc} R(t)/c = t_0 + \eta_{\rm esc}\alpha t$ with $t_0 = \eta_{\rm esc} R_0/c$
- If the blob expands rapidly ($\eta_{\rm esc}\alpha \to 1$), particles are trapped efficiently and particles accumulate
- For constant bulk flow Γ, *time* and *distance from BH* are related linearly $z \propto \beta_\Gamma ct$ (comoving frame!)

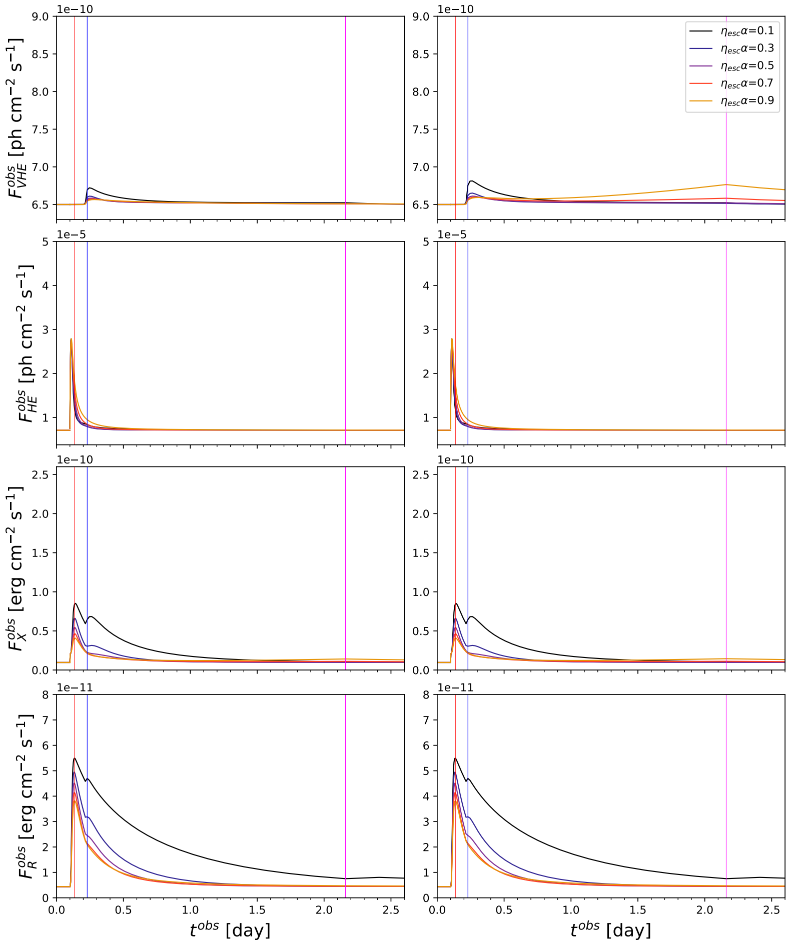
Simulating a cascade based on PKS 1510-089



- Using a parameter set based on PKS 1510-089, an FSRQ at $z = 0.361$ with bright AD, BLR, DT
- Magnetic field evolution: $B(z) = B_0\, R_0/R(z)$ (assuming dominating toroidal structure)
- Curves are shown for increasing opening angles (*dark to light*): $\eta_{\rm esc}\alpha \in [0.1, 0.3, 0.5, 0.7, 0.9]$
- Vertical lines mark: t_0 (red), passing BLR (blue), passing DT (magenta)
- Note: $\Delta t^{\rm obs} = \Delta z'/(\delta\Gamma\beta_\Gamma c)$

Simulations **without** cascade.

Simulations without cascade



VHE emission absorbed within the BLR; shows a secondary bump in hadronic sims for large opening angles at t_{DT}

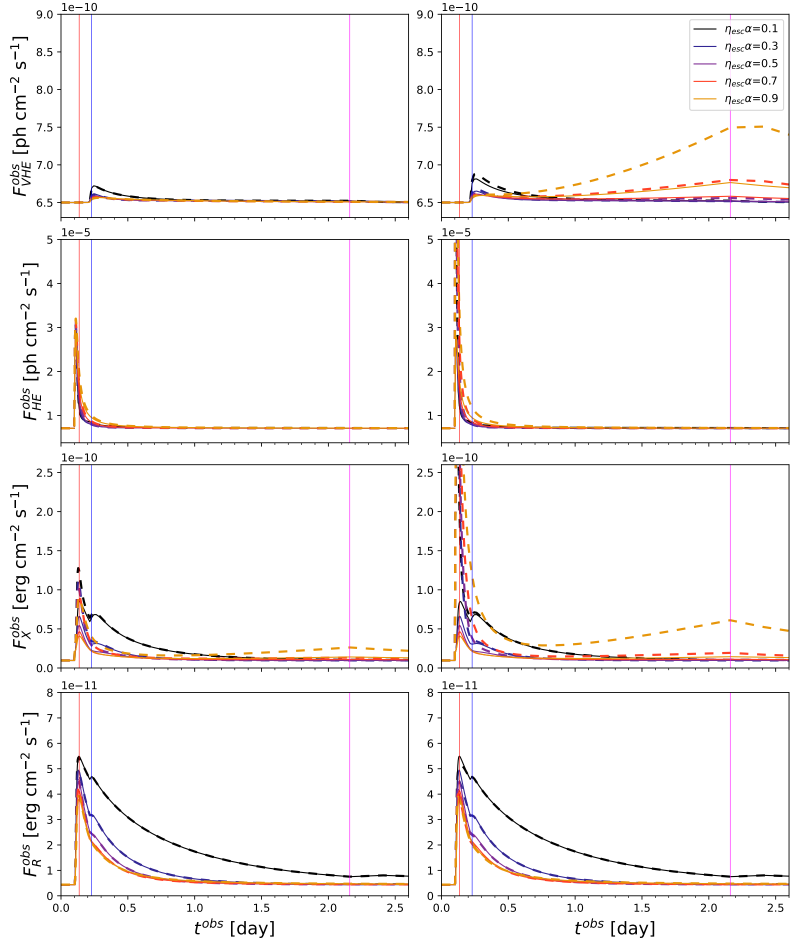
HE shows a quick rise to peak at t_0; flare over at t_{BLR}; minor difference in the decay pattern

X rise a bit slower than HE; secondary peak at t_{BLR} for small opening angles; this influences the decay pattern; very minor secondary flare at t_{DT}

R similar to X-ray

Simulations **without** cascade.

Simulations with cascade



Simulations **with** cascade (*dashed lines*).

VHE similar to sim w/o cascade, but secondary bump in hadronic sims for large opening angles at t_{DT} much stronger

HE leptonic sim similar to w/o cascade except for slightly higher peak flux; much higher peak fluxed (off scale) in hadronic sim, but also quick decline

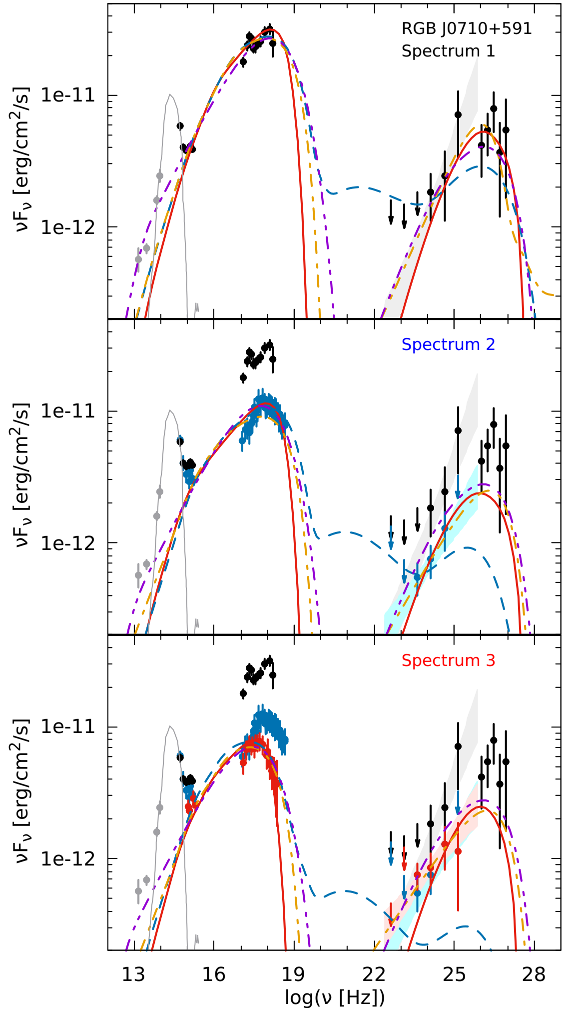
X leptonic sim with higher peak flux, but similar decay pattern except for more pronounced secondary flare at t_{DT} for large opening angles; hadronic sim with much higher peak flux (off scale) and much stronger secondary peak at t_{DT} for large opening angles

R not influenced by the cascade

Gory details:

- Zacharias, M., 2023, A&A, 669, A151

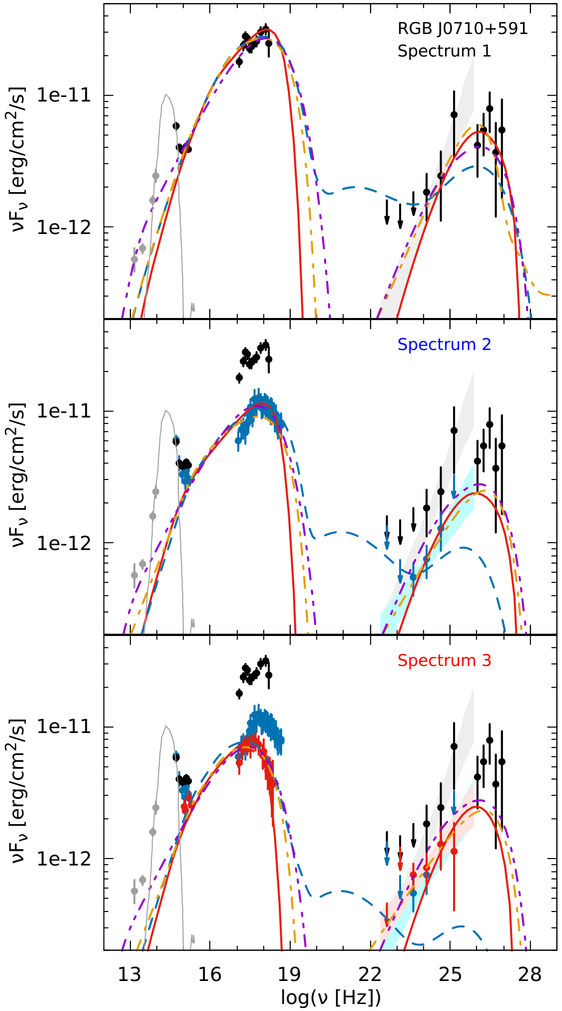
Scientific Example 2: Steady-state modeling of eHBLs



- eHBLs exhibit the most extreme peak frequencies among blazars
- Can exhibit (long-term) variability
- Study to model 4 eHBLs with various models (SSC, *e-p-shock*, LHp, LHπ)
- Used OneHaLe in steady-state for the LH models

Modeling various states of RGB J0710+591

Scientific Example 2: Steady-state modeling of eHBLs



Modeling various states of RGB J0710+591

- SSC, *e-p-shock* and LHp with good fits
- SSC with least power consumption
- *e-p-shock* with best physical setup and good power demand
- LHp with excessive power demand
- LHπ parameters chosen such to suppress SSC, no good fits, excessive power demand
- Interestingly, upper limits on AD suggest that power output of eHBL is above the AD power (irrespective of model)

Gory details:

- Goswami, P., et al., 2024, A&A, 682, A134

Ongoing development

Version 1.1 (current version)

- Available upon reasonable request to me
- hdf5 usage optional (but Bethe-Heitler only with hdf5)
- Output written to individual ascii files
- Variability limited to certain shapes, unless one digs into the code

Ongoing development

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Version 2.0 (in development)

✓ Full hdf5 (output written to single hdf5 file with python script for first look plots and to produce ascii files if wanted)

✓ Variability patterns easy to change for the user

() Include neutrons

() Further user-friendliness improvements

() Upload to GitHub

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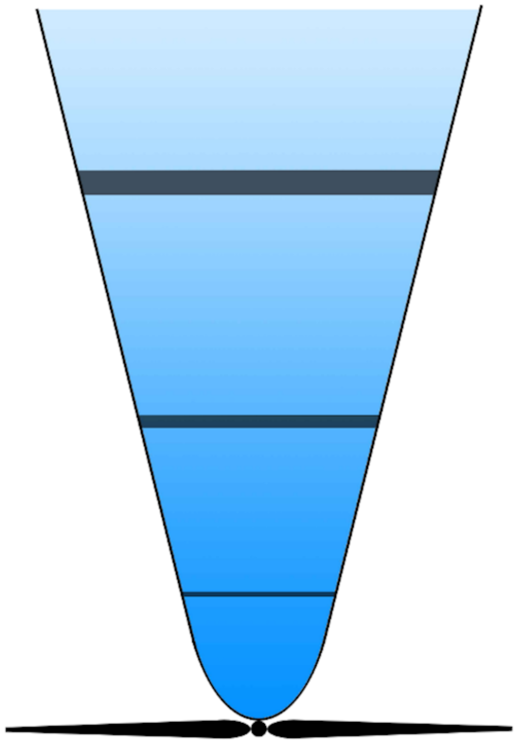
Further plans:

- Tabulate more integrals, remove delta-approximations
- Switch γ-γ pair production cross section from Aharonian+83 to Böttcher&Schlickeiser97
- Allow for restart of sim after certain checkpoints
- Any suggestions?

ExHaLe-jet: An Extended Hadro-Leptonic jet model



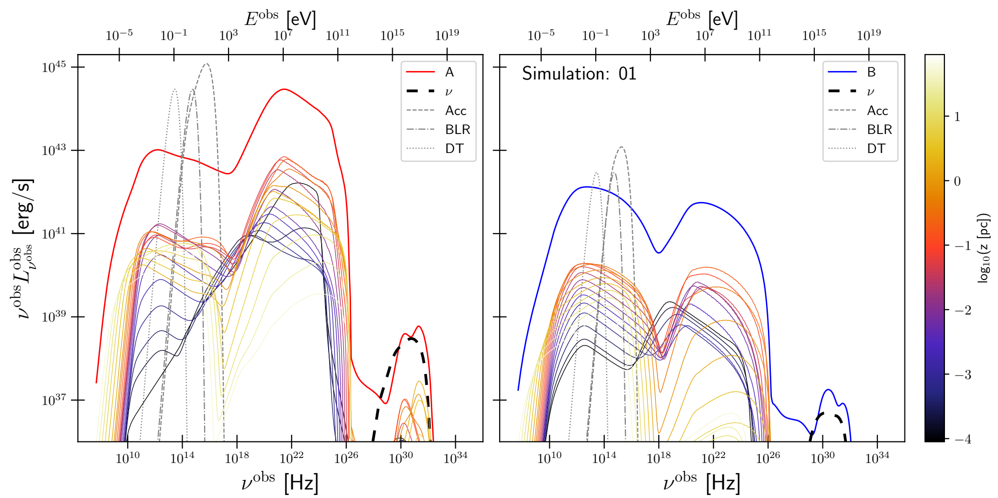
Sketch: jet cut into numerous slices (dark), in which the kinetic equations for each particle species are solved Figure: courtesy of Jonathan Heil

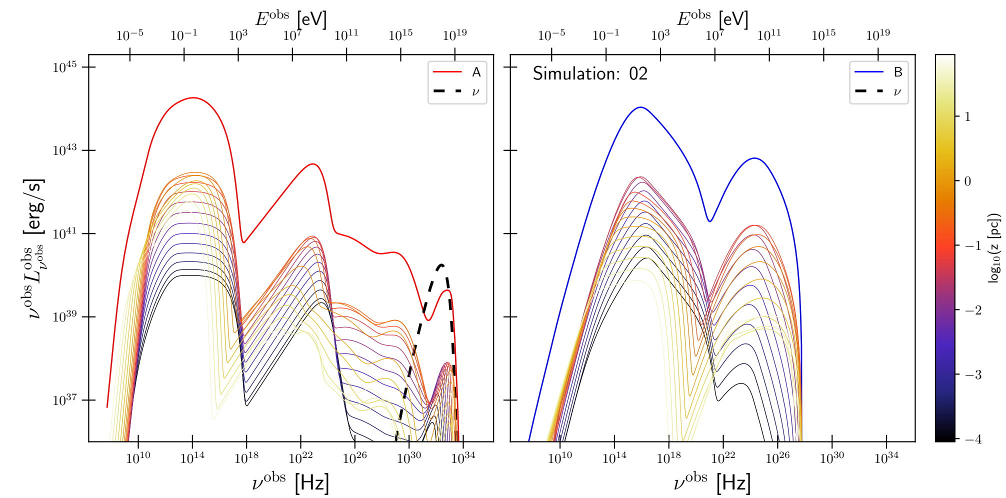
- Core functionality as OneHaLe
- Jet length cut into numerous slices, where kinetic equation is solved for each species
  - Injection of primary proton and electron distribution at the base; evolved self-consistently along the jet
  - Injection of secondaries (pions, muons, pairs) in each slice
  - Pairs propagated along with primaries
  - Radiation and neutrino output for each slice
- Geometry currently fixed as
  - Parabolic acceleration region: $\Gamma_b(z) \propto \sqrt{z}$
  - Conical coasting region $\Gamma_b(z) =$const.
  - Radius: $R(z) \propto \tan\left[0.26/\Gamma_b(z)\right]$
  - Magnetic field derived with Bernoulli equation
- Code not for public use as of now

Gory details:

- Zacharias, M., et al., 2022, MNRAS, 512, 3948

ExHaLe-jet: Total spectra





Strong external fields

- High Compton dominance
- Most flux $\sim z_{acc}$
- Total power sub-Eddington
- Moderate neutrino number

Weak external fields

- Low Compton dominance
- Most flux $\sim z_{acc}$
- Total power sub-Eddington
- Low neutrino number

P-syn solution

- P flux $< 0.5 z_{acc}$
- E flux $< 10 z_{acc}$
- Total power sub-Eddington and p dominated
- High neutrino number

SSC solution

- Low Compton dominance
- Most flux $\sim z_{acc}$
- SSC drops faster than syn
- Total power sub-Eddington and e dominated

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Famous last words…

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- It includes (almost) all relevant processes incl. external photon fields
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- Big THANKS to:
  Anton Dmitriiev, Patrick Kilian, Andreas Zech, Anita Reimer, Catherine Boisson, Markus Böttcher, and the various people who have already used and tested the code

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- Zacharias, M., 2021, Physics, 3, 1098
- Zacharias, M., et al., 2022, MNRAS, 512, 3948

- OneHaLe is a flexible, time-dependent, lepto-hadronic one-zone code
- It includes (almost) all relevant processes incl. external photon fields
- Version 1.1 available upon reasonable request to me
- Version 2.0 in development; will be uploaded to GitHub

- Big THANKS to:
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Thank you for your attention!

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