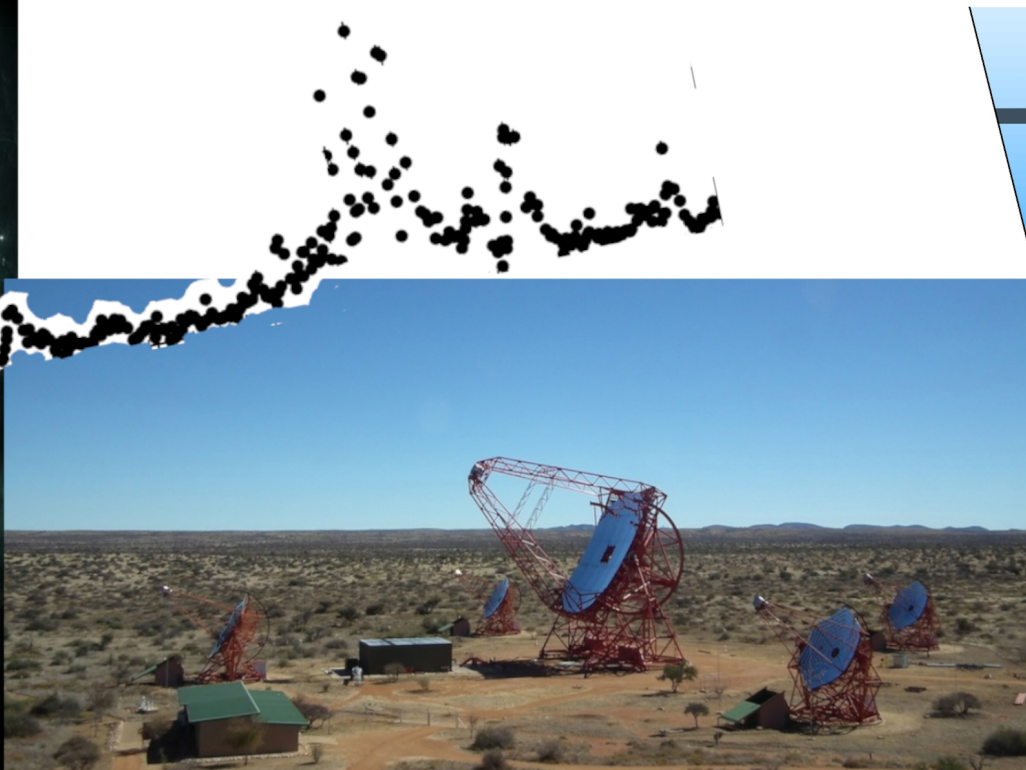
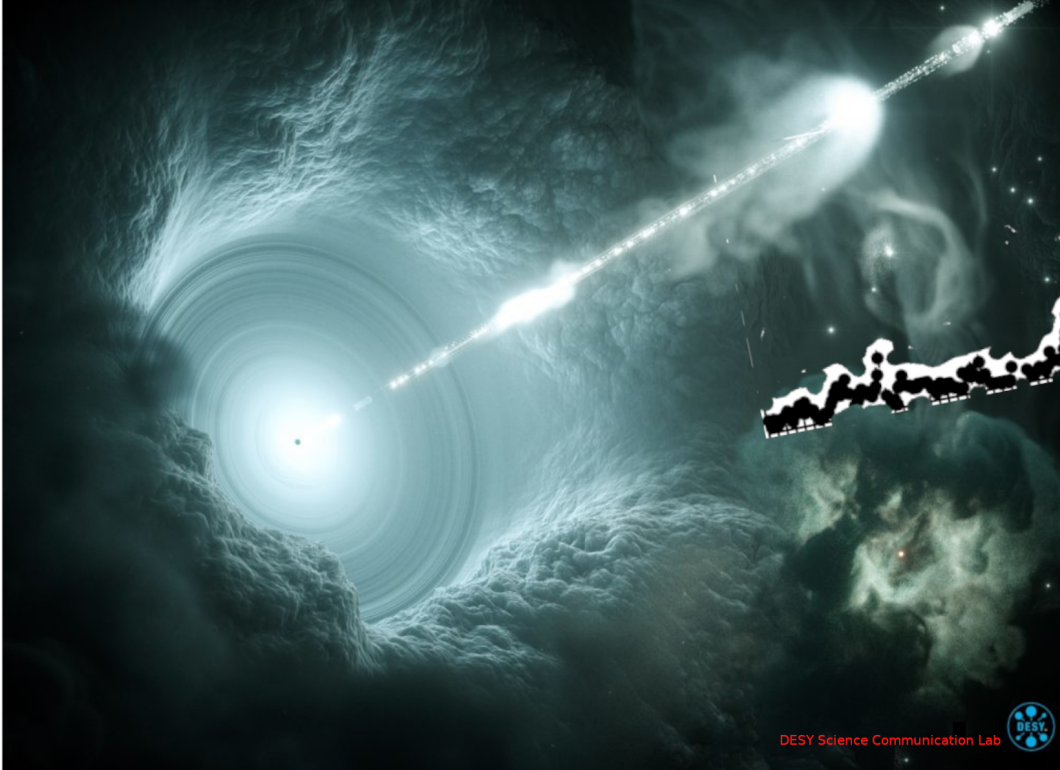


OneHaLe: Towards version 2.0

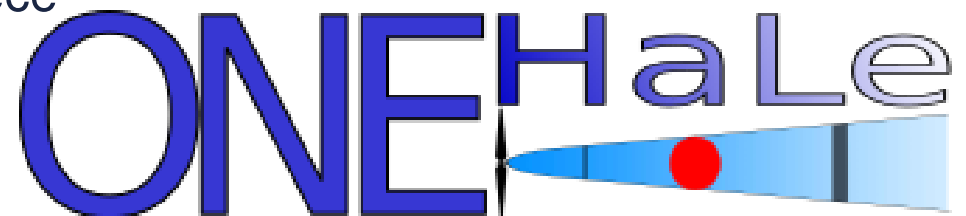
Michael Zacharias

MuMeNTA

Athens, Greece



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OneHaLe currently is...

```
10.0      : Magnetic field of the homogeneous region [G]
1.00e15   : Blob radius [cm]
5.00      : Ratio of the acceleration to escape time scales
0.125     : Redshift to the source
50.0      : Bulk Lorentz factor for the blob
2.00e-2   : Observing angle relative to the axis of the BH jet [rad]
2.00e+0   : Minimum Lorentz factor for the proton injection spectrum
4.00e+10  : Maximum Lorentz factor for the proton injection spectrum
2.30      : Proton injection index
5.00e+41  : Injection luminosity for the proton spectrum [erg s-1]
2.0e+3    : Minimum Lorentz factor for the electron injection spectrum
9.0e+4    : Maximum Lorentz factor for the electron injection spectrum
1.50      : Electron spectral index
3.50e+38  : Injection luminosity for the electron spectrum [erg s-1]
50.0      : Multiplicative factor of the light travel time [eta*R/c]
1.8       : Mass of the supermassive black hole (1.0e+8 Msol)
5.0e-4    : Eddington ratio
1.00e+18  : Initial location of the blob along jet axis [cm]
7.60e+16  : Radius of the BLR [cm]
1.0e+0    : Effective temperature of the BLR [K]
2.30e+24  : Effective luminosity of the BLR [erg/s]
4.20e+18  : Radius of the DT [cm]
5.0e+0    : Effective temperature of the DT [K]
3.0e+24   : Effective luminosity of the DT [erg/s]
0         : Calculate neutrino detection rate using ICeCube effective areas (0=no, 1=yes)
0.0       : Strength of the magnetic field perturbation [G]
0.0e+43   : Strength of the proton injection luminosity perturbation [erg/s]
0.0       : Strength of the acceleration time scale perturbation
0.0e+1    : Strength of the minimum proton Lorentz factor perturbation
0.0e+9    : Strength of the maximum proton Lorentz factor perturbation
0.0e+42   : Strength of the electron injection luminosity perturbation
0.0       : Strength of the proton index perturbation
0.0       : Strength of the electron index perturbation
```

Example of the parameter input file.

Gory details:

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

- ... a time-dependent, parallelized, hadro-leptonic, one-zone C code
- ... can accommodate various kinds of variability
- ... in each time step solves the Fokker-Planck equation for every charged 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

Version 1.2 is available upon reasonable request to the author.

Fokker-Planck equation

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

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

Particle injection

Acceleration processes

Cooling processes

Particle escape

Particle decay

Fokker-Planck equation

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

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

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

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

Fokker-Planck equation

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

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

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

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:

$$t_{\text{esc}} = \eta_{\text{esc}} R/c$$

with free parameter $\eta_{\text{esc}} \geq 1$

Particle decay

Fokker-Planck equation

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

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

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

Photon production

Photon escape

Photon absorption processes

Radiation transport equation

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

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

Radiation transport equation

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

Photon production

Photon escape

- Photons leave the source with average escape time

$$t_{\text{esc,ph}} = 0.75 R/c$$

Photon absorption processes

Radiation transport equation

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

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

Towards version 2.0: Neutrons

$$\frac{\partial n_N(\chi, t)}{\partial t} = Q_N(\chi) - \frac{\partial}{\partial \chi} (\dot{\chi}_N n_N(\chi, t)) - \frac{n_N(\chi, t)}{t_{\text{esc}}} - \frac{n_N(\chi, t)}{\gamma t_{N, \text{decay}}^*}$$

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

Particle injection

No Acceleration processes

Cooling processes

Particle escape

Particle decay

Towards version 2.0: Neutrons

$$\frac{\partial n_N(\chi, t)}{\partial t} = Q_N(\chi) - \frac{\partial}{\partial \chi} (\dot{\chi}_N n_N(\chi, t)) - \frac{n_N(\chi, t)}{t_{\text{esc}}} - \frac{n_N(\chi, t)}{\gamma t_{N, \text{decay}}^*}$$

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

Particle injection

- From p- γ processes (serves as an additional catastrophic loss / escape term for protons!)

No Acceleration processes

Cooling processes

Particle escape

Particle decay

Towards version 2.0: Neutrons

$$\frac{\partial n_N(\chi, t)}{\partial t} = Q_N(\chi) - \frac{\partial}{\partial \chi} (\dot{\chi}_N n_N(\chi, t)) - \frac{n_N(\chi, t)}{t_{\text{esc}}} - \frac{n_N(\chi, t)}{\gamma t_{N, \text{decay}}^*}$$

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

Particle injection

No Acceleration processes

Cooling processes

- n- γ pion production

Particle escape

Particle decay

Towards version 2.0: Neutrons

$$\frac{\partial n_N(\chi, t)}{\partial t} = Q_N(\chi) - \frac{\partial}{\partial \chi} (\dot{\chi}_N n_N(\chi, t)) - \frac{n_N(\chi, t)}{t_{\text{esc}}} - \frac{n_N(\chi, t)}{\gamma t_{N, \text{decay}}^*}$$

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

Particle injection

No Acceleration processes

Cooling processes

Particle escape

- Escape mimics an advective motion of the plasma through the emission region:

$$t_{\text{esc}} = \eta_{\text{esc}} R/c$$

with free parameter $\eta_{\text{esc}} \geq 1$

- Additional term through $n\text{-}\gamma \Rightarrow$ Secondary proton injection

Particle decay

Towards version 2.0: Neutrons

$$\frac{\partial n_N(\chi, t)}{\partial t} = Q_N(\chi) - \frac{\partial}{\partial \chi} (\dot{\chi}_N n_N(\chi, t)) - \frac{n_N(\chi, t)}{t_{\text{esc}}} - \frac{n_N(\chi, t)}{\gamma t_{N,\text{decay}}^*}$$

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

Particle injection

No Acceleration processes

Cooling processes

Particle escape

Particle decay

- Proper decay time: $t_{N,\text{decay}}^* = 878 \text{ s} \Rightarrow$ Secondary proton and electron injection, and neutrino production

Towards version 2.0: User friendliness

- ✓ 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
- ✓ Possibility to change the primary injection function
- ✓ Light curve integration bands can be set

Examples are provided for all these features

It is advisable to know a bit of C coding. . .

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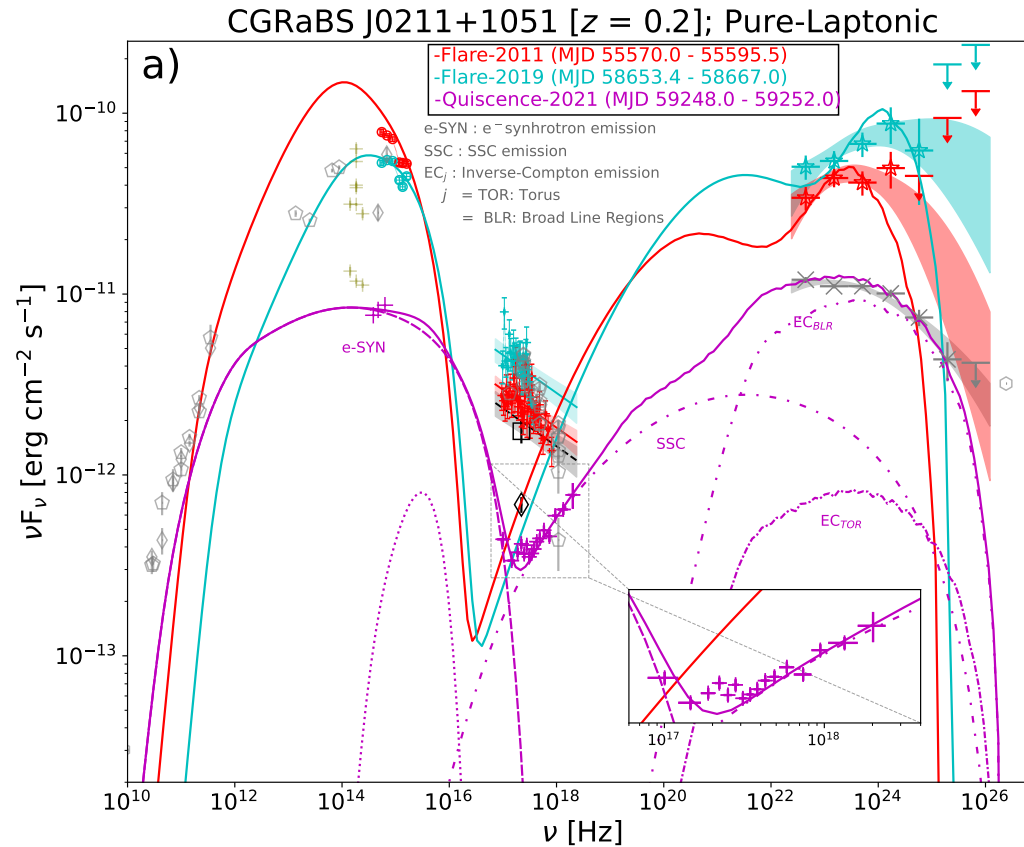
Further plans:

- 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 feature requests?

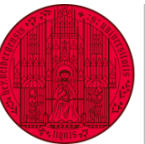
The curious case of CGRaBS J0211+1051

Published in Chandra et al., 2025, ApJ, 995, 145

- CGRaBS is an LBL at $z = 0.20$
- Exhibited flaring states in 2011 (red) and 2019 (cyan)
- Detailed observations of the low state in 2021 (magenta)



Leptonic modeling

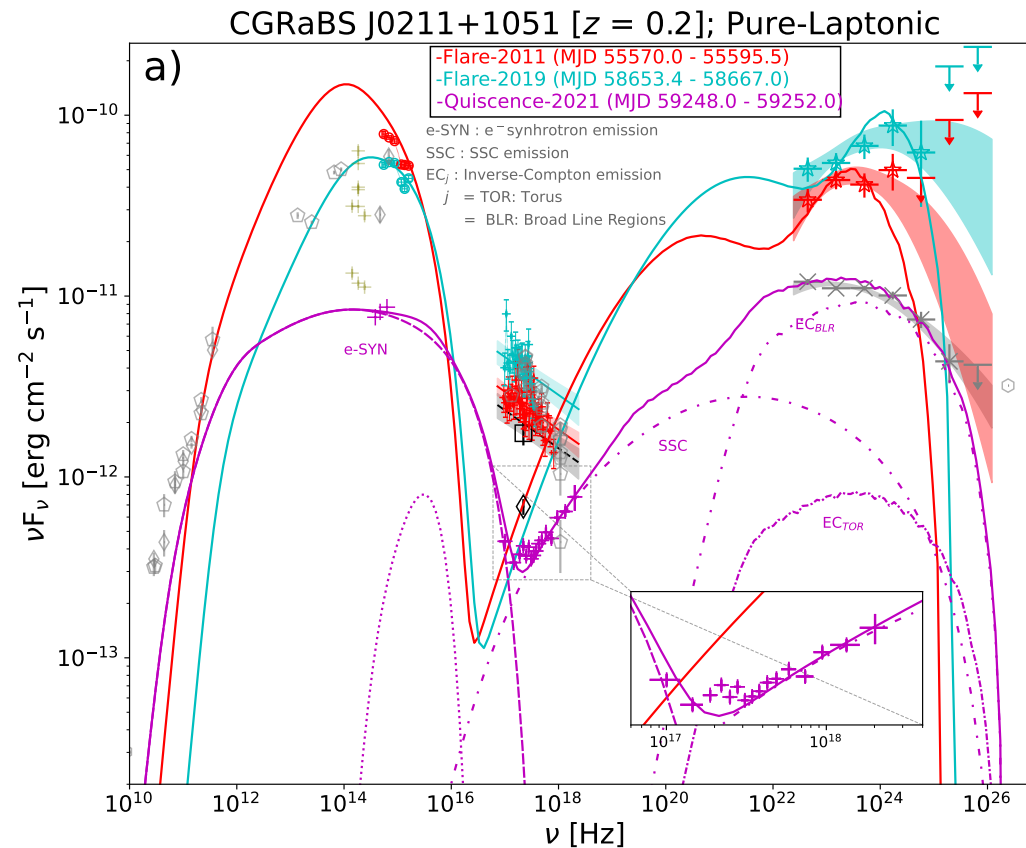


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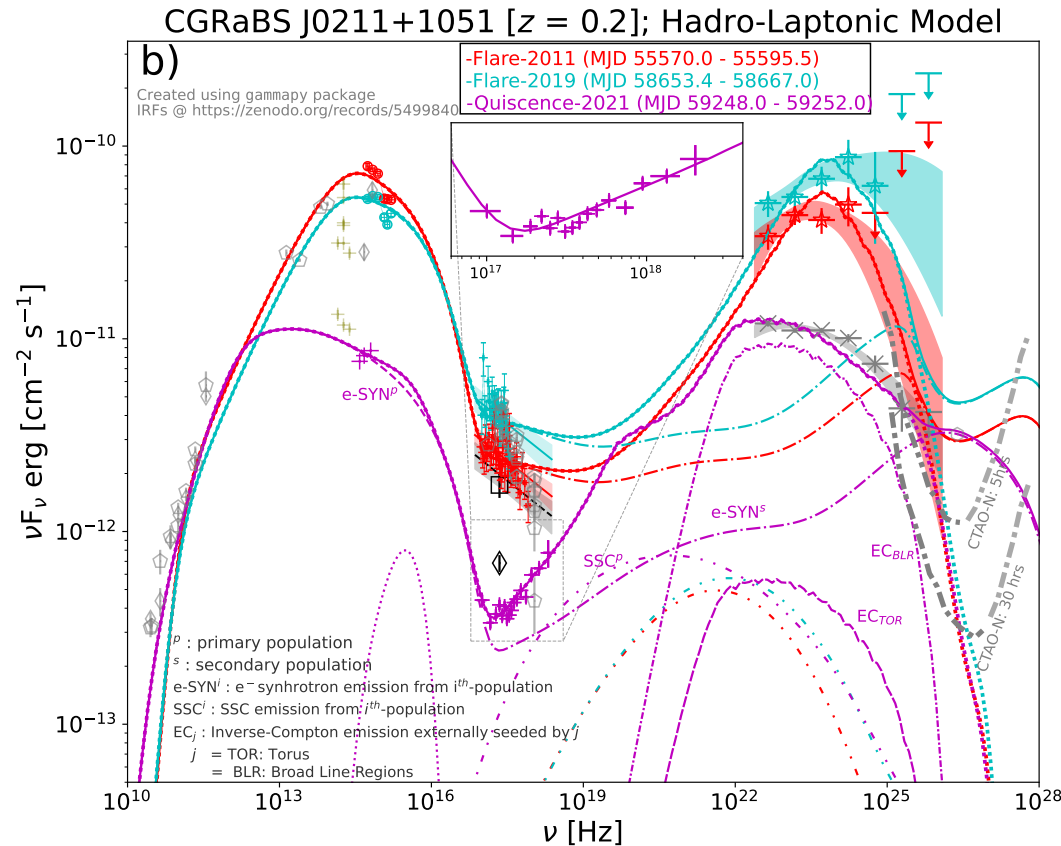


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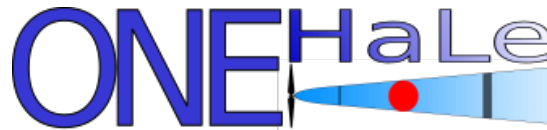


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- Flare characteristics make it impossible to reproduce within leptonic model
- Within a lepto-hadronic setup it works
 - X-rays produced by secondary electrons from $\gamma\gamma$
 - Detection potential at VHE γ rays
 - Detection potential for IceCUBE-Gen2

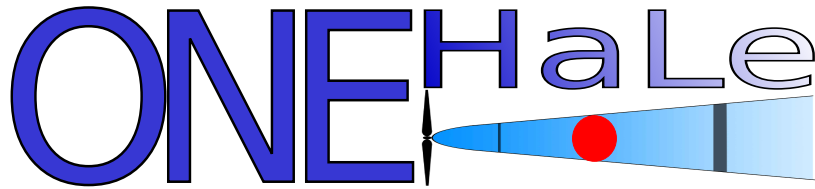
Lepto-hadronic modeling



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Famous last words...

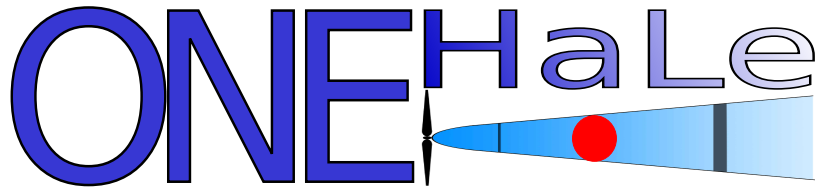


- OneHaLe is a flexible, time-dependent, lepto-hadronic one-zone code
- It includes (almost) all relevant processes incl. external photon fields
- Version 1.2 available upon reasonable request to m.zacharias@lsw.uni-heidelberg.de
- Version 2.0 almost finished; will be uploaded *somewhere soon*

Gory details:

- Zacharias, M., 2021, Physics, 3, 1098
- Zacharias, M., et al., 2022, MNRAS, 512, 3948 (*ExHaLe-jet*)

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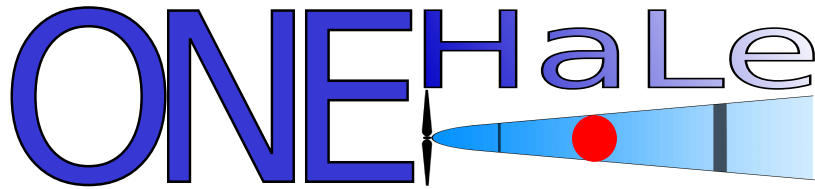


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Thank you for your attention!