Numerical simulations of radiation processes in AGN.

Effect of chemical composition

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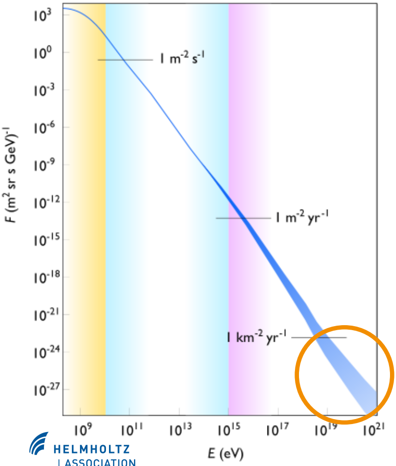
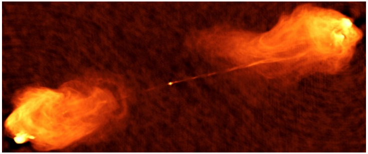
Introduction

- **Question:** origin & composition of Ultra-High Energy Cosmic Rays
- Likely dominated by extra-galactic sources [Allard et al. 2007 astro-ph0512345]
- **Candidate:** Active Galactic Nuclei (AGN)





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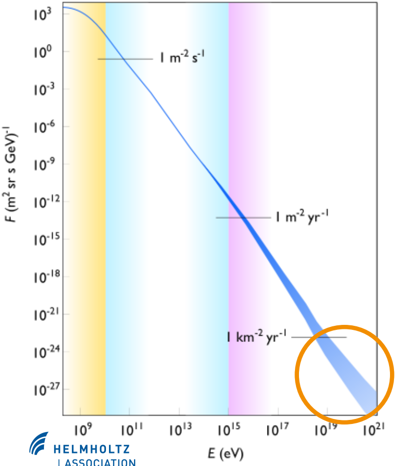
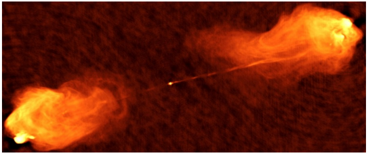
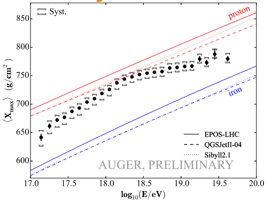




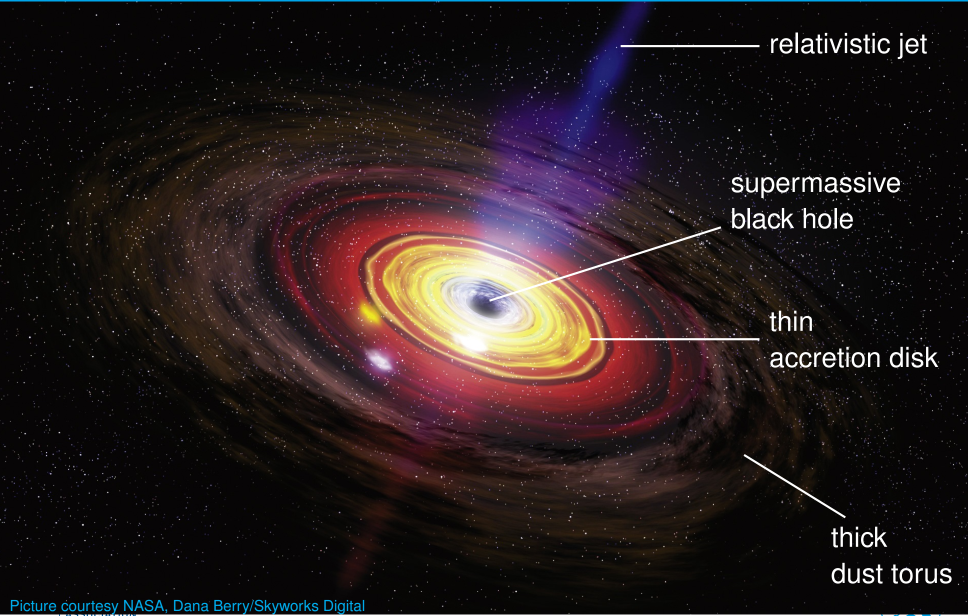
- Numerical model for hadronic interactions
- Predict cosmic-ray (CR) and ν spectra
- **Study effect of heavy elements**

motivation:
experimental data



[Auger Collaboration, ICRC 2015]

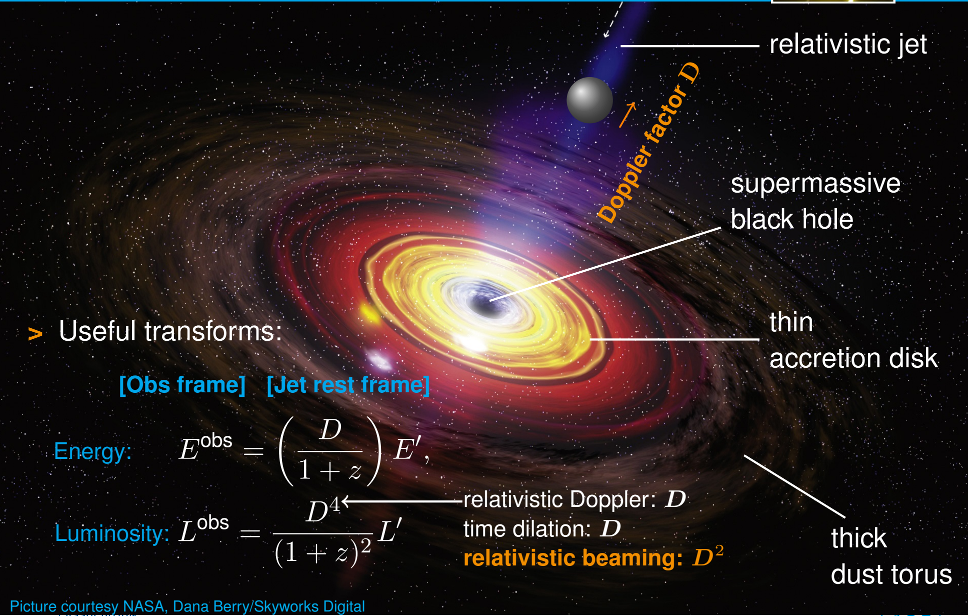
Physical model



Picture courtesy NASA, Dana Berry/Skyworks Digital

Physical model

Blazar



- Useful transforms:

[Obs frame] [Jet rest frame]

Energy: $$E^{\text{obs}} = \left(\frac{D}{1+z}\right) E',$$

Luminosity: $$L^{\text{obs}} = \frac{D^4}{(1+z)^2} L'$$

relativistic Doppler: D
time dilation: D
relativistic beaming: D^2

Picture courtesy NASA, Dana Berry/Skyworks Digital

Physical model

Blazar

- CR acceleration in the jet
- Consider a plasma blob along the jet $\longrightarrow$

  of radius $r = c\, t'_{\text{flare}}$
- ***B*** $\longrightarrow$ **confinement of charged particles**
- $\mathbf{n}, \nu$ **escape directly**
- Useful transforms:

[Obs frame] **[Jet rest frame]**

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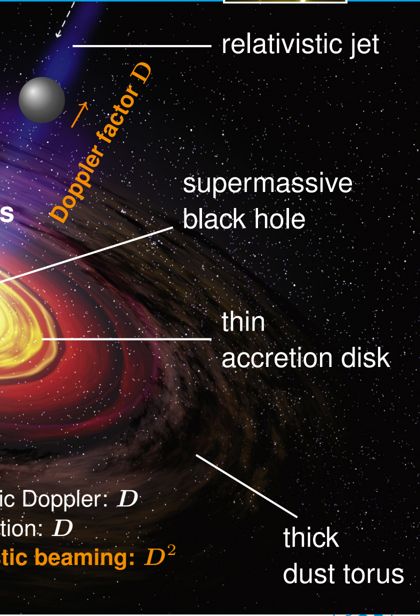

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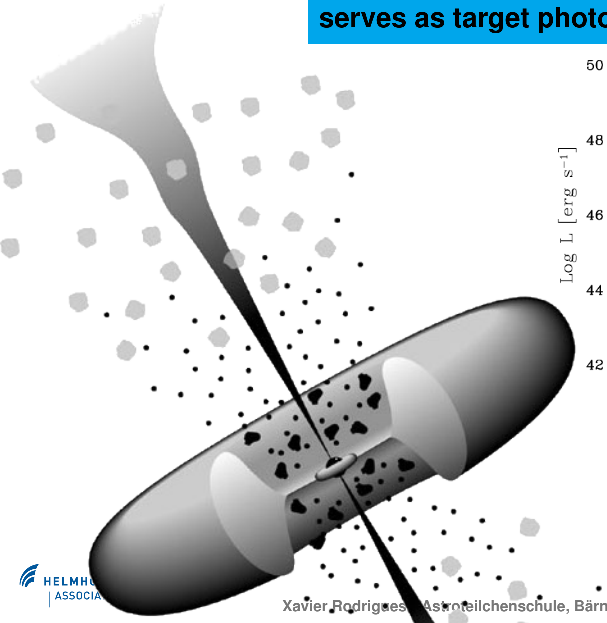
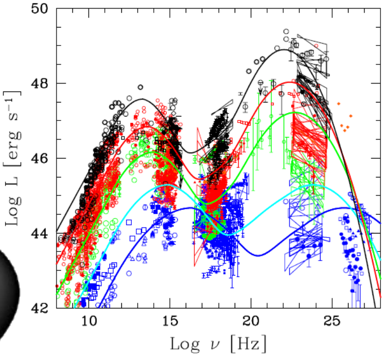
Physical model

Blazar Spectral Energy Distribution (SED)

serves as target photon field for CR interactions





blue: $L_\gamma < 10^{45.5}$ erg/s
green: $L_\gamma < 10^{45.5}$ erg/s
red: $L_\gamma < 10^{47.5}$ erg/s
black: $L_\gamma > 10^{48}$ erg/s
Points: observation. Lines: models
[Ghisellini 2013 arXiv:1309.4772]

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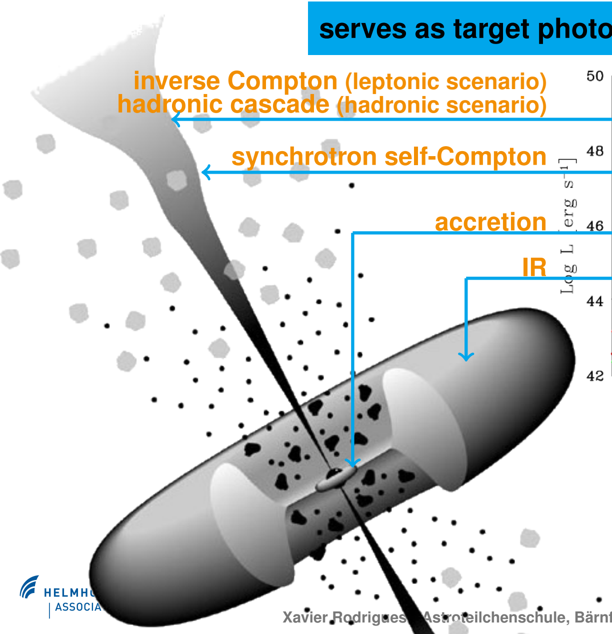

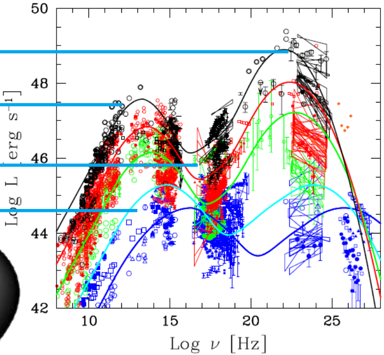

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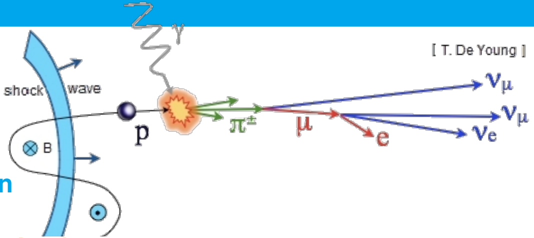
Physical model – hadronic processes



Fermi-shock CR acceleration

↓

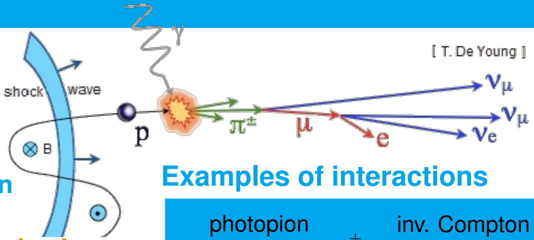
power-law CR injection

$$\frac{dn}{dE} = E^{-\alpha}$$

index α depends on shock compression ratio

(typically $\alpha = 2$)

Physical model – hadronic processes



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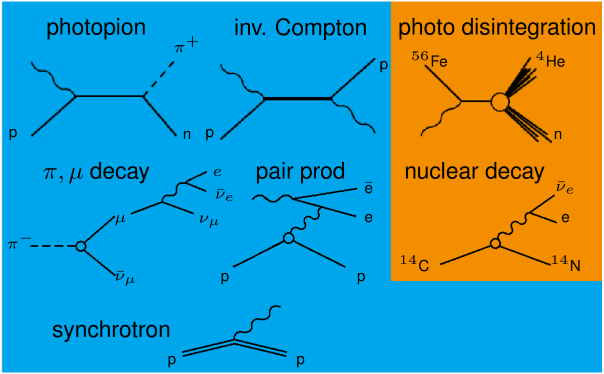
Examples of interactions

If heavier nuclei are present,



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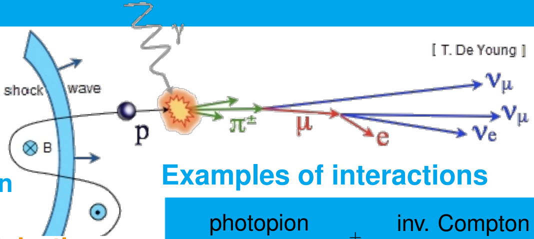

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Acceleration, synchrotron, escape time depend on magnetic field strength

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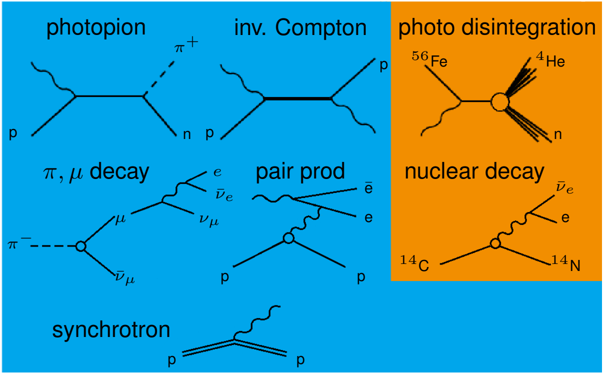

Interaction framework

- **NEUCOSMA** [Bearwald et al, AP 35 (2012) 508-529] numerical framework for nuclear cascades
- Developed for Gamma-Ray Bursts (GRB)$\longrightarrow$ **apply to AGN**
- Numerically solve PDE system (1 eq. per particle species)

$$\frac{\partial N(E)}{\partial t} = \frac{\partial}{\partial E}\left(-b(E)\,N(E)\right) - \frac{N(E)}{t_{\mathrm{esc}}} + Q(E)$$

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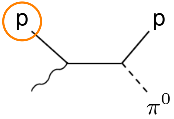

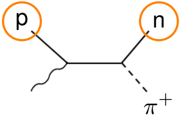

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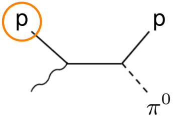
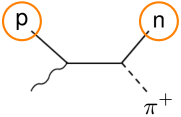
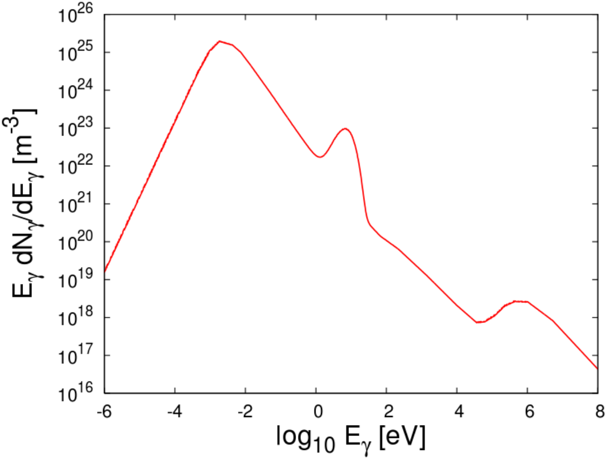
$$\underbrace{\frac{\partial N(E)}{\partial t}}_{==0 \text{ if steady state reached}} = \frac{\partial}{\partial E}\underbrace{\left(-b(E)\,N(E)\right)}_{\text{energy loss}} - \underbrace{\frac{N(E)}{t_{\mathrm{esc}}}}_{\text{particle escape}} + \underbrace{Q(E)}_{\text{particle injection}}$$





Preliminary results

- Input Blazar SED proposed in [Anchordoqui et al., AP 29 (2008) 1-13]



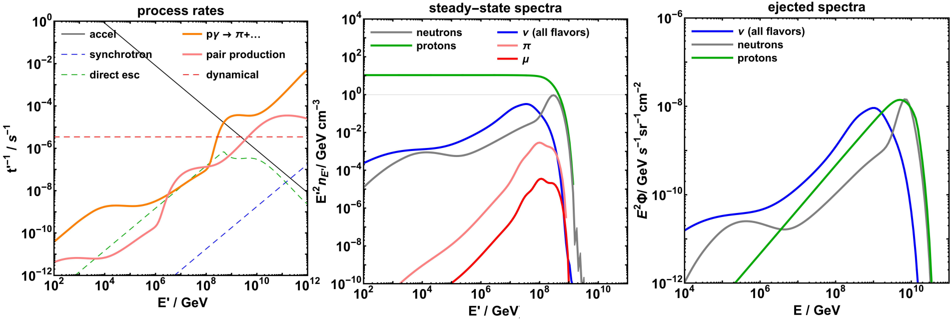
- $L'_\gamma = 10^{45}$erg/s
- $\Gamma = 10^{1.5}$
- $t^{obs}_{\text{flare}} = 10^4$ s

We will also consider

- $z = 0.1$
- $B = 0.9$ G

Preliminary results

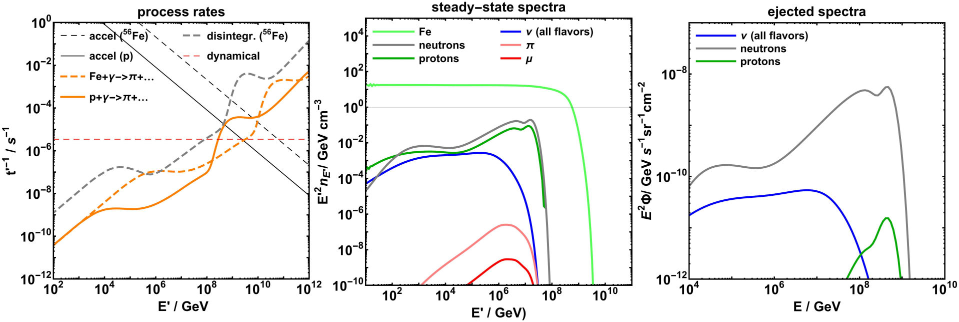
> Pure proton injection:



[X Rodrigues, A Fedynitch, D Boncioli, W Winter – in preparation]

Preliminary results

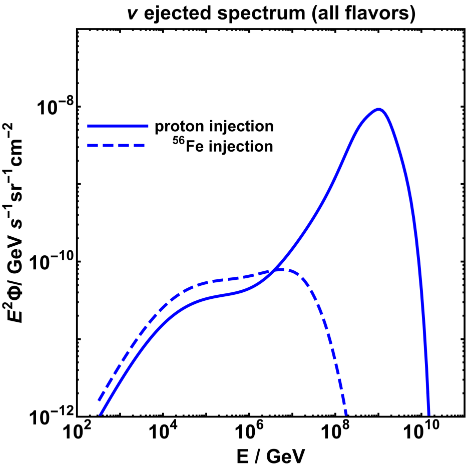
> **Pure iron-56 injection:**



[X Rodrigues, A Fedynitch, D Boncioli, W Winter – in preparation]

Preliminary results

> Comparison of total neutrino spectra



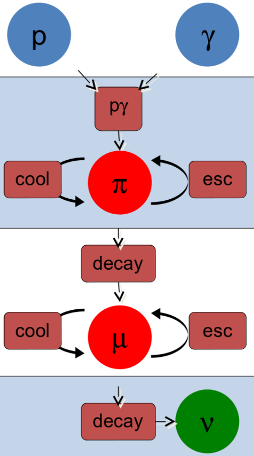
[X Rodrigues, A Fedynitch, D Boncioli, W Winter – in preparation]

Outlook

- Acceleration of heavy nuclei in AGN has a significant effect on the expected ν spectrum
- Currently attempting to reproduce other published results
- **Next step:** probe parameter space, particularly isotopic composition
- **In the future:** consider more sophisticated model to include photon feedback (self-consistent picture of photons–protons–nuclei)

Backup

Example: treatment of $p\gamma \to \pi + \cdots$ in NeuCosmA



Static species
or explicitly time-dependent
-- external input

X

Each variable species corresponds to one differential equation of the form:

Y

$$\frac{\partial N(E)}{\partial t} = \frac{\partial}{\partial E}\left(-b(E)\,N(E)\right) - \frac{N(E)}{t_{\mathrm{esc}}} + Q(E)$$

"Manual" species with injection only
Updated only on request
(e.g. in time-steps, where the data are written into a file)

Z

[W Winter, private note]