Neutrinos and photons as signatures of dissipation close to the photosphere in short GRB jets

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Niels Bohr Institutet

CARLSBERG FOUNDATION

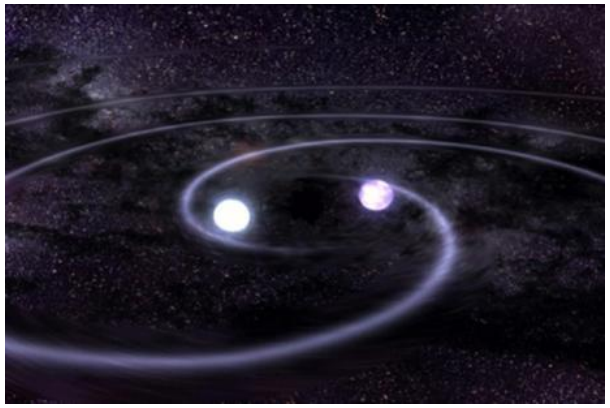
How do energy dissipation and particle acceleration close to the photosphere shape the multi-messenger spectra?

Outline:

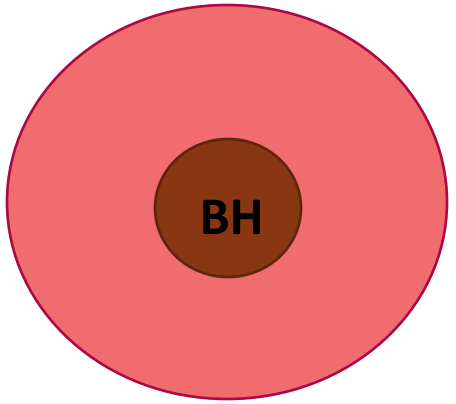
- Short (short) GRB Introduction
- Building a jet model informed by a BNS merger simulation
- Evolution of multi-messenger spectra close to the photosphere
- Summary & Discussion

Short GRB Recap: From Merger to Jet

Compact Binary Merger
(**NS-NS** or BH-NS)



Dynamical
Ejecta



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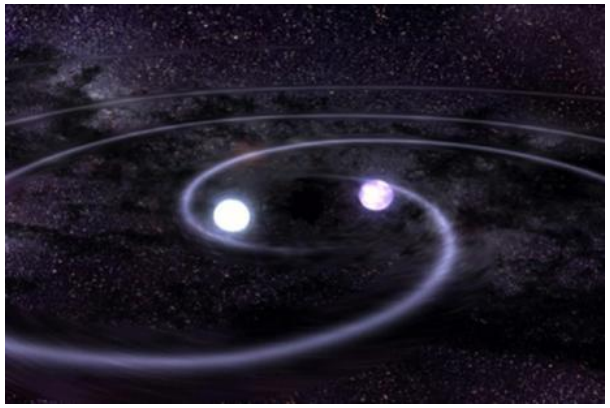

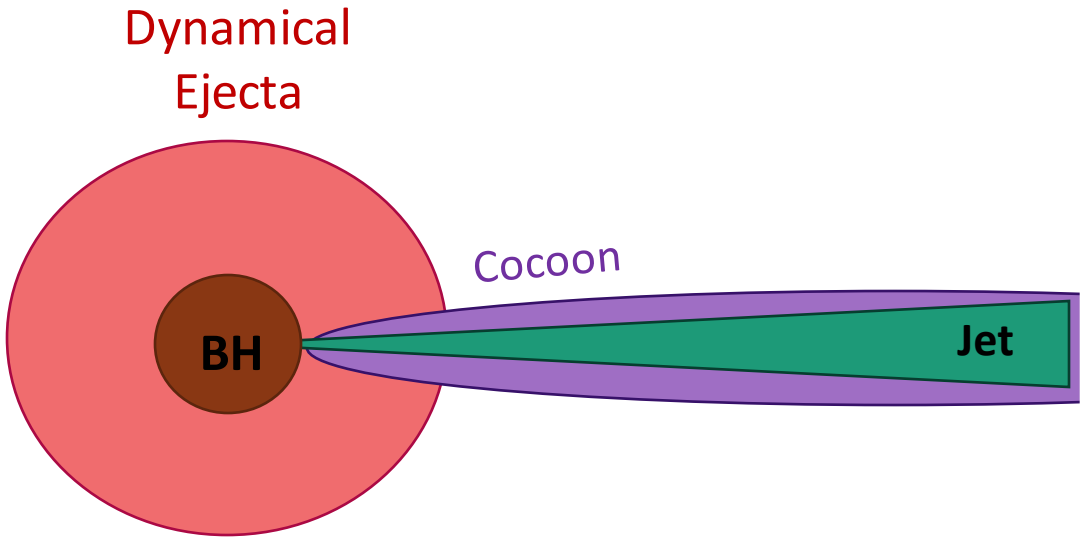

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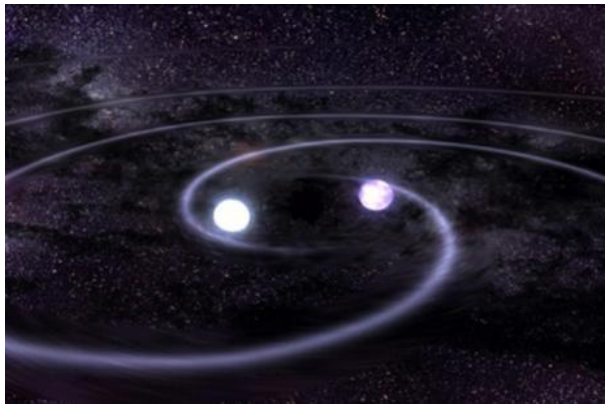

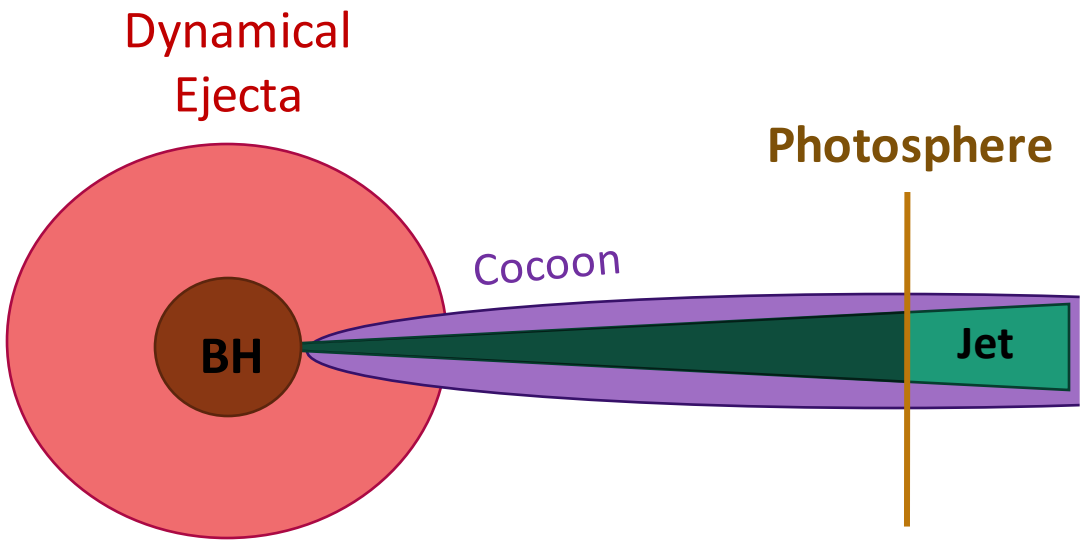

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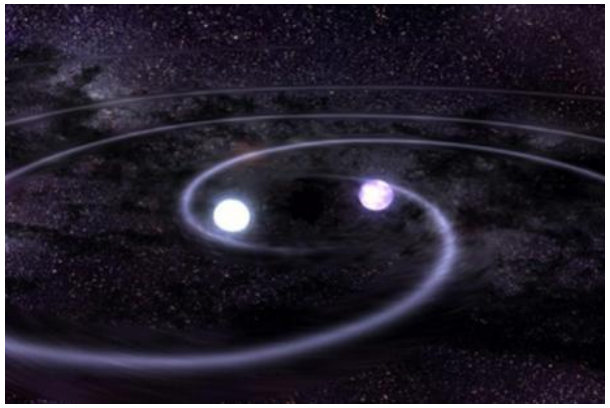
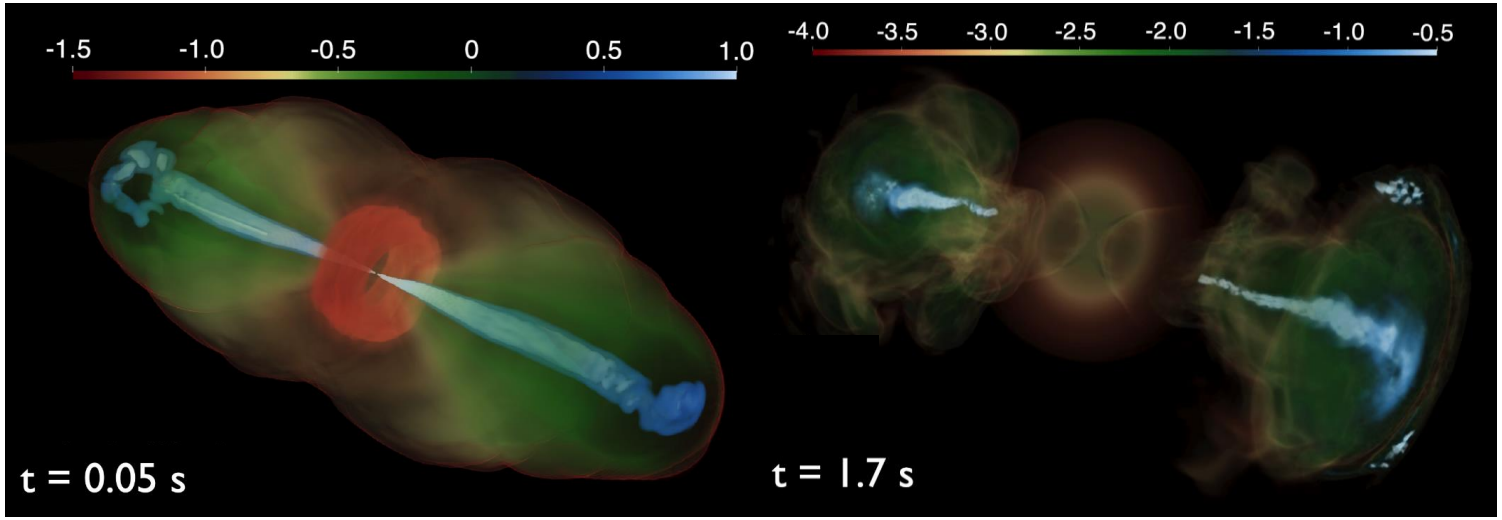


Log(asymptotic proper velocity)

Log(magnetization)

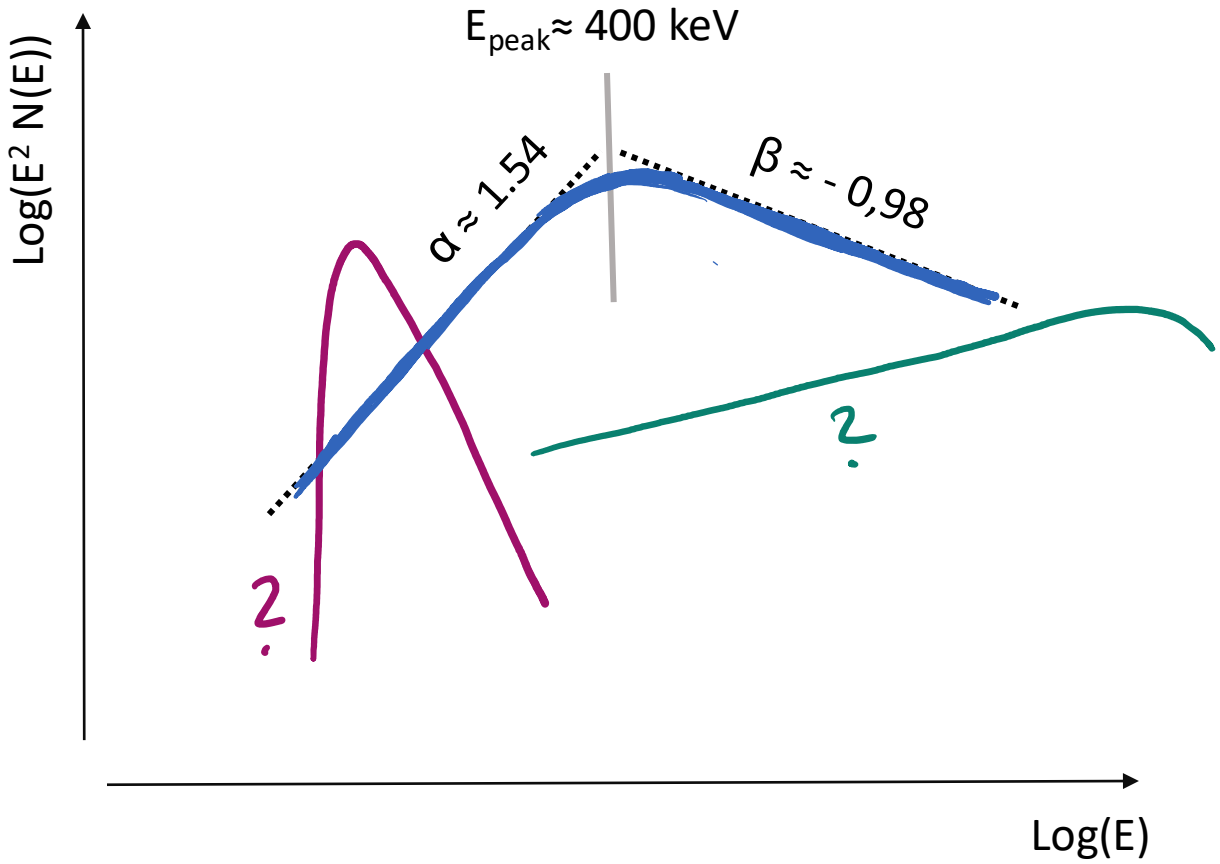


[Breakout from ejecta: 0.37 s]

Gottlieb et al '22

Observed Spectra in Short GRBs

- Smoothly broken power-law ('Band' function)
- Short GRBs: Harder + more narrow spectra than for long GRBs
  [*eg.* Acuner & Ryde '18, Poolakkil et al 2021]
- Photon spectrum origin:
  (a) optically thin regime (synchrotron emission)
  correct peak energies & slope?
  [see Z. Bosnjaks talk]
  (b) optically thick ('photospheric')
  Additional processes for broad specta: rad. mediated shocks/ synchrotron & inverse Compton/ p-n collisions
- -> Connection to jet simulations?
  -> Neutrino signatures?



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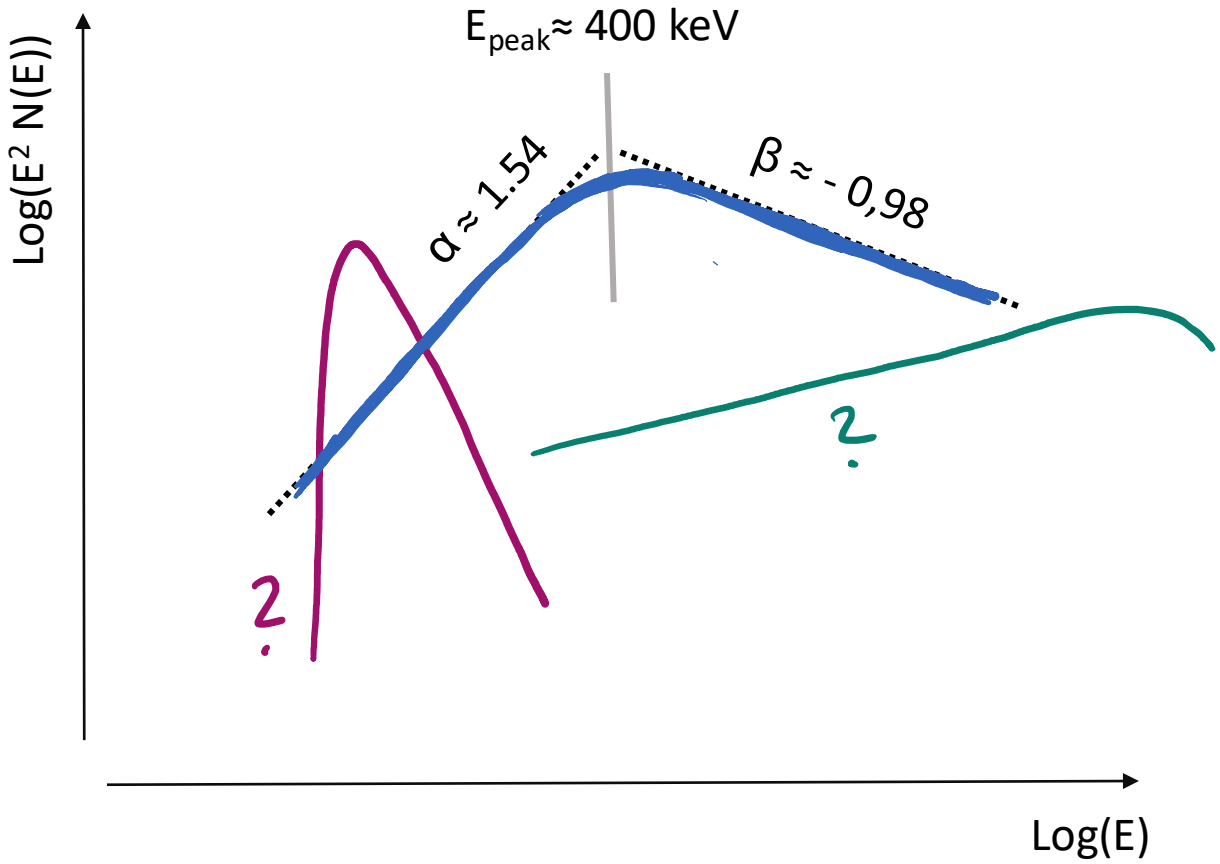
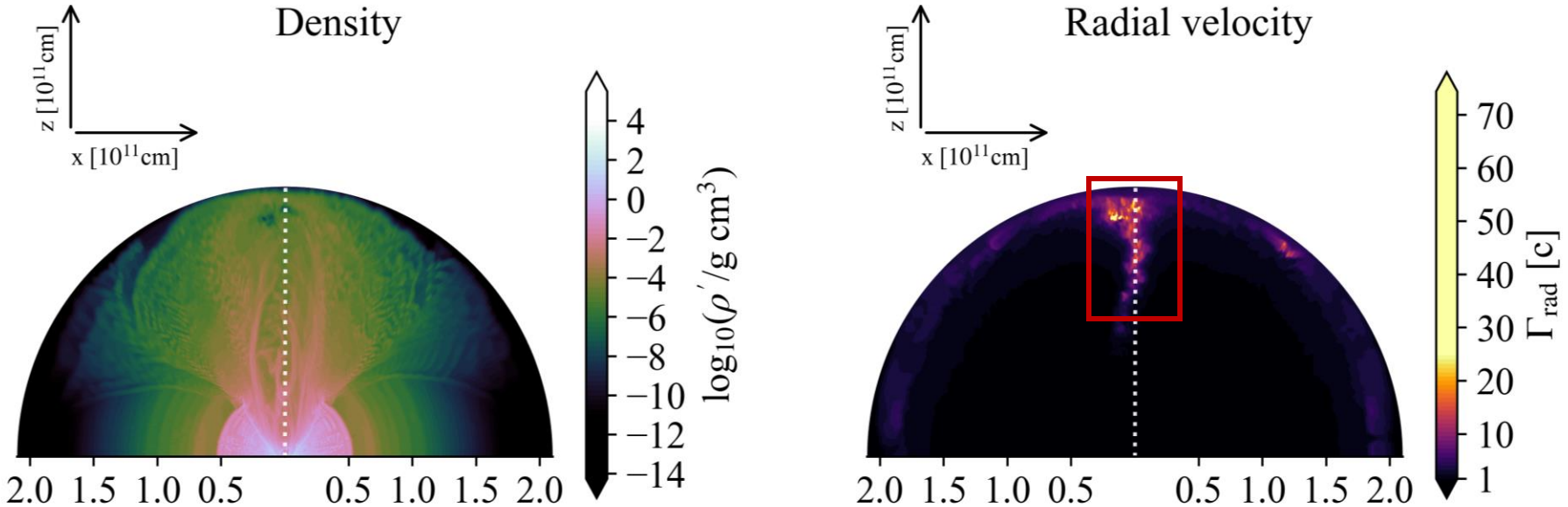


[AR, Irene Tamborra & Ore Gottlieb, arXiv 2309.08667]

A Binary Neutron Star Merger Simulation

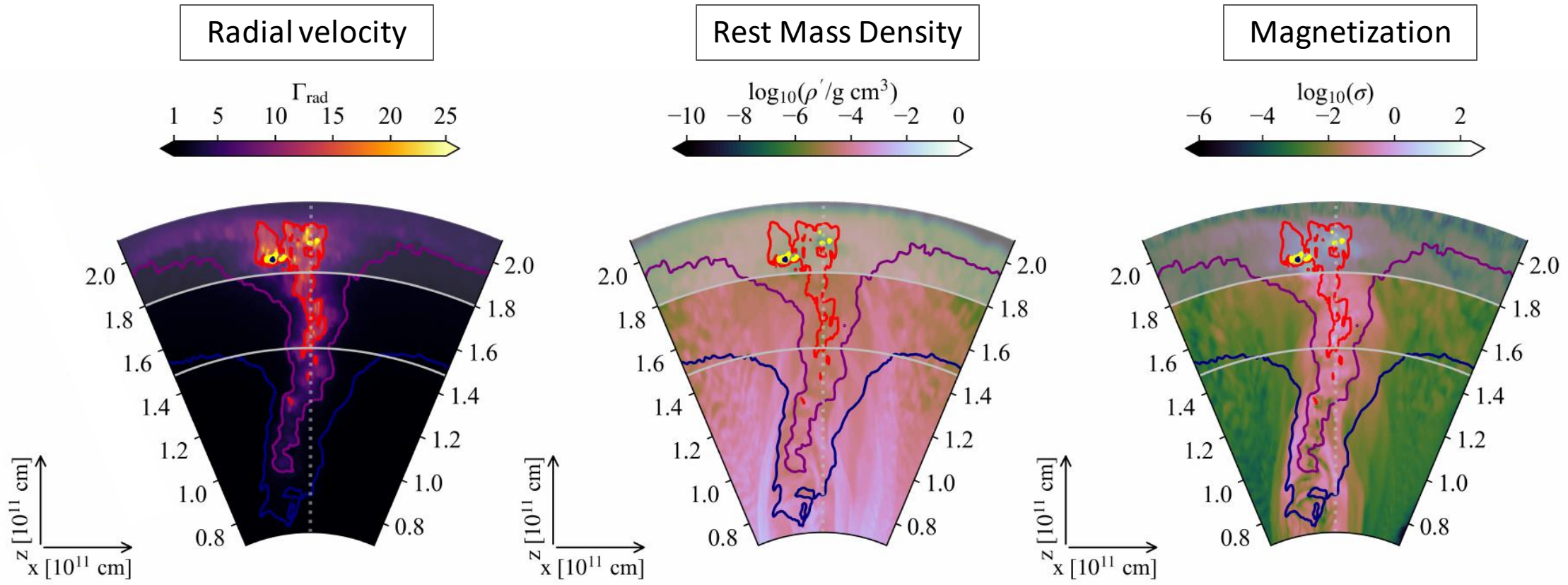
- GR-MHD with H-AMR (Liska et al 2022), ideal EOS
  metastable NS -> **BH** [M_{BH} = 3 M_{sun}] + **Torus** [M_t = 0.2 M_{sun}] + **Ejecta** [M_{ej} = 0.05 M_{sun}]
  More details: Gottlieb et al '22 (simulation α3d5)
- σ_0 = 150, follow for 7 s (up to 10^{11} cm)

Final snapshot, x-z plane



[AR et al, arXiv 2309.08667]

Jet Region: At The Last Snapshot



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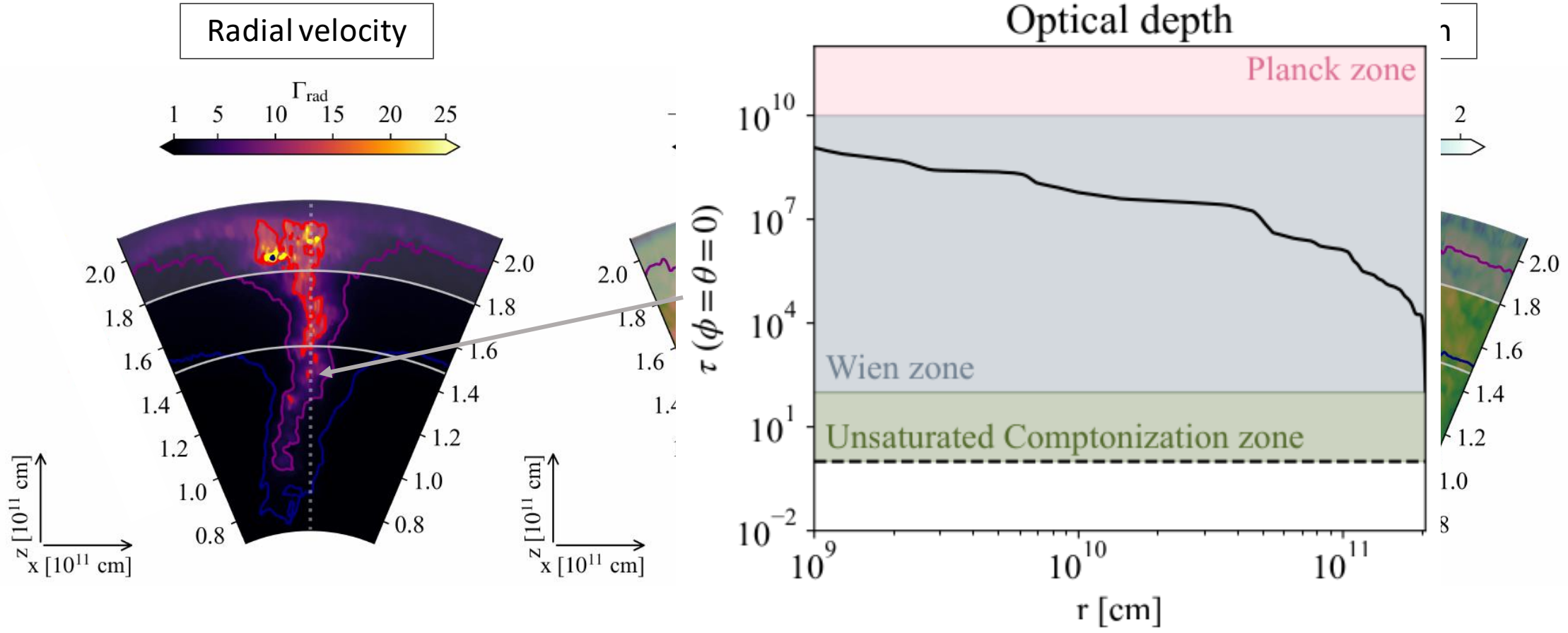

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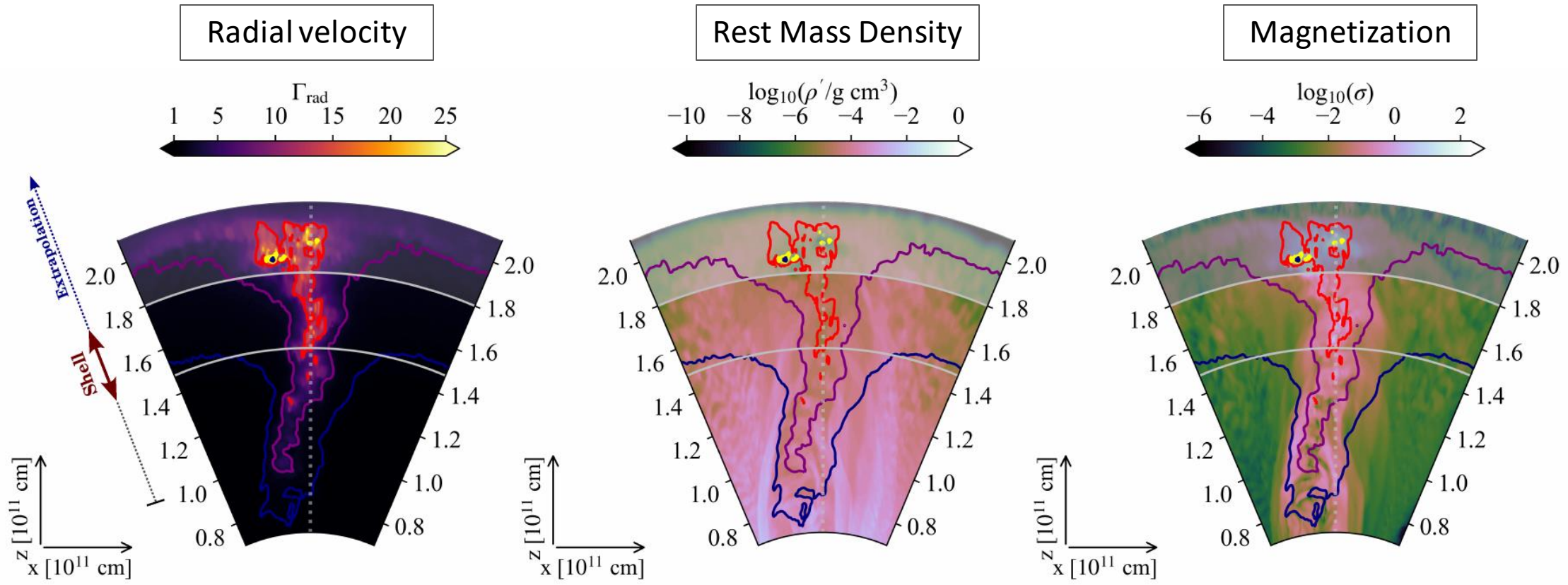

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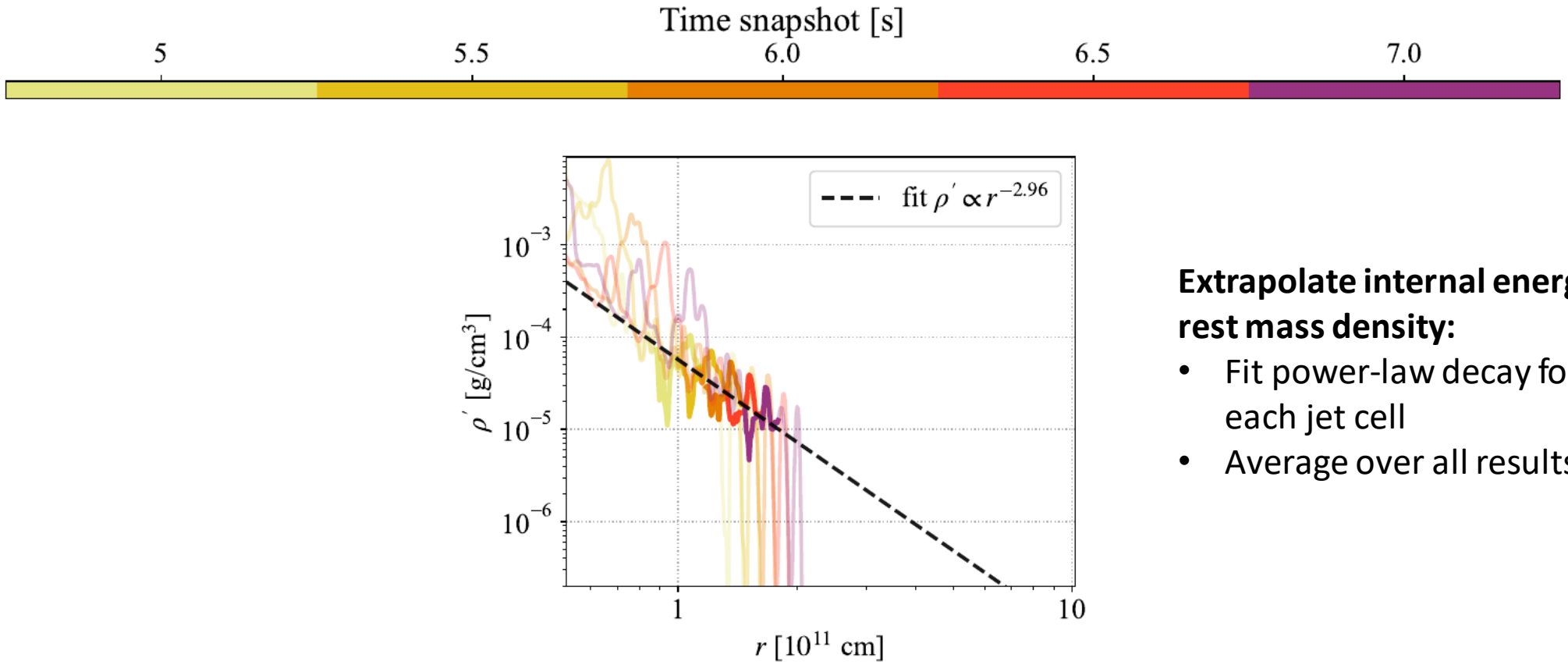
Jet Region: Extrapolation & Energy Dissipation



Extrapolate internal energy & rest mass density:

- Fit power-law decay for each jet cell
- Average over all results

[AR et al, arXiv 2309.08667]

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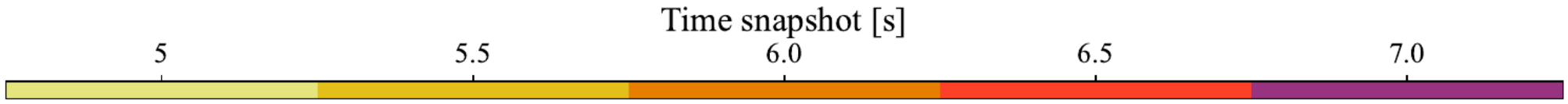
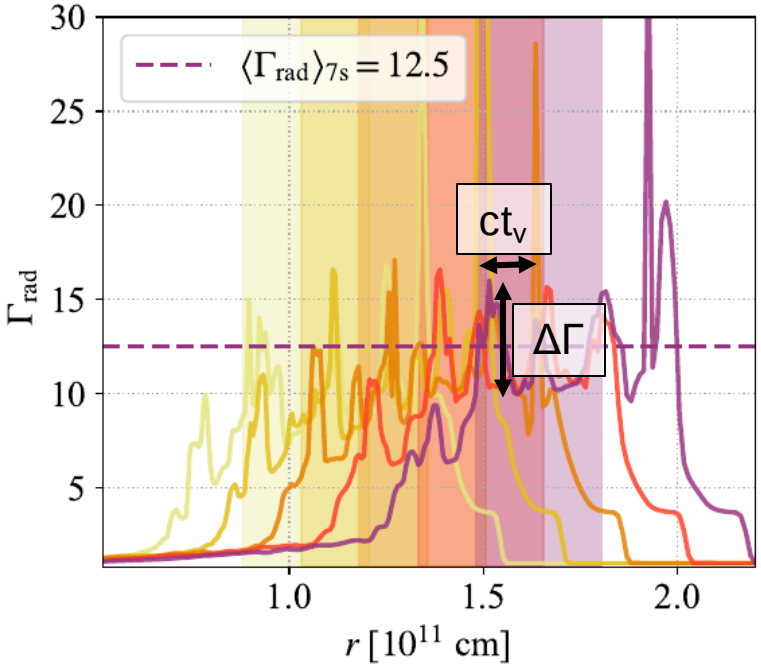
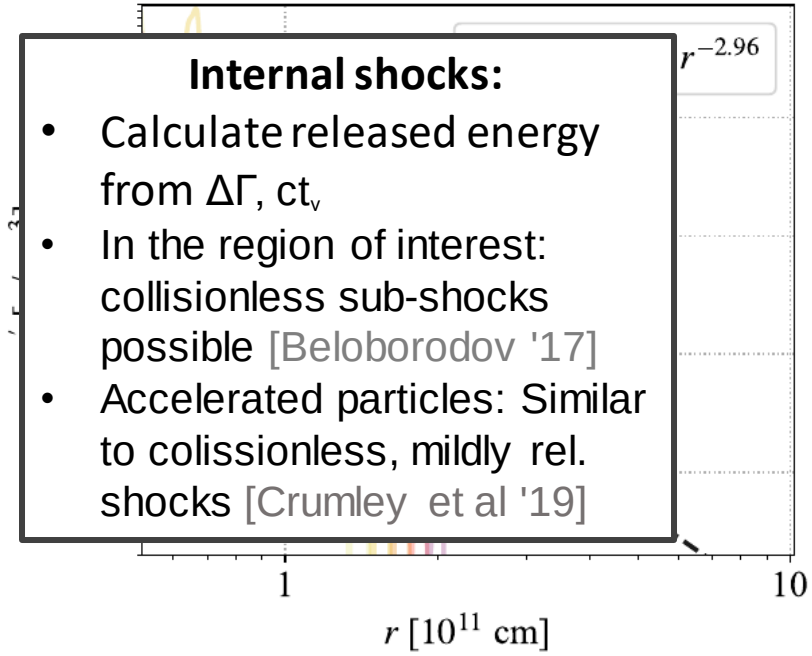




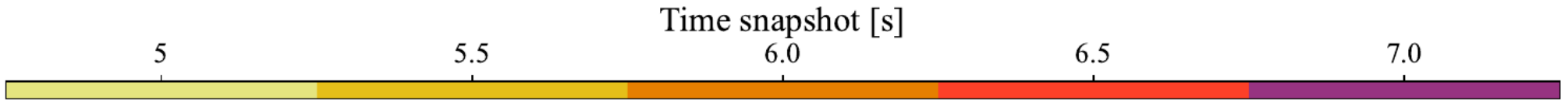


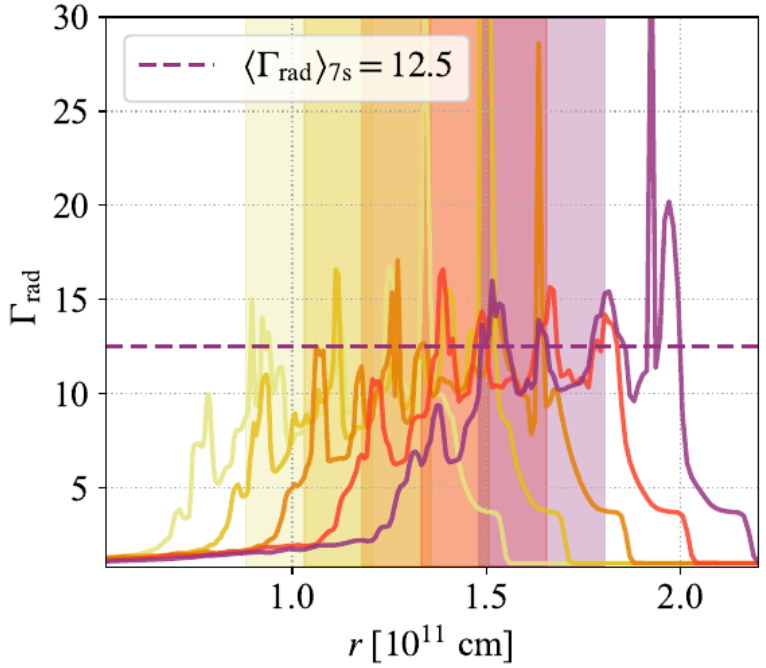
Internal shocks:

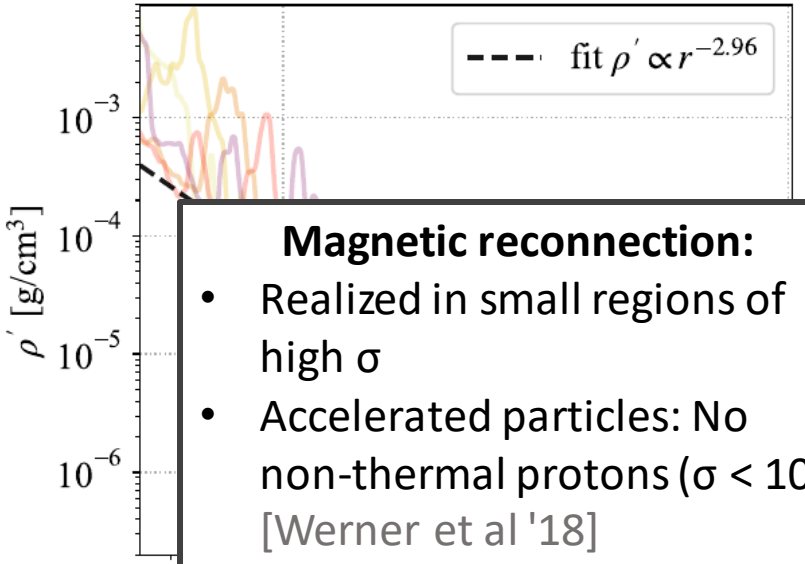
- Calculate released energy from $\Delta\Gamma$, ct_v
- In the region of interest: collisionless sub-shocks possible [Beloborodov '17]
- Accelerated particles: Similar to colissionless, mildly rel. shocks [Crumley et al '19]

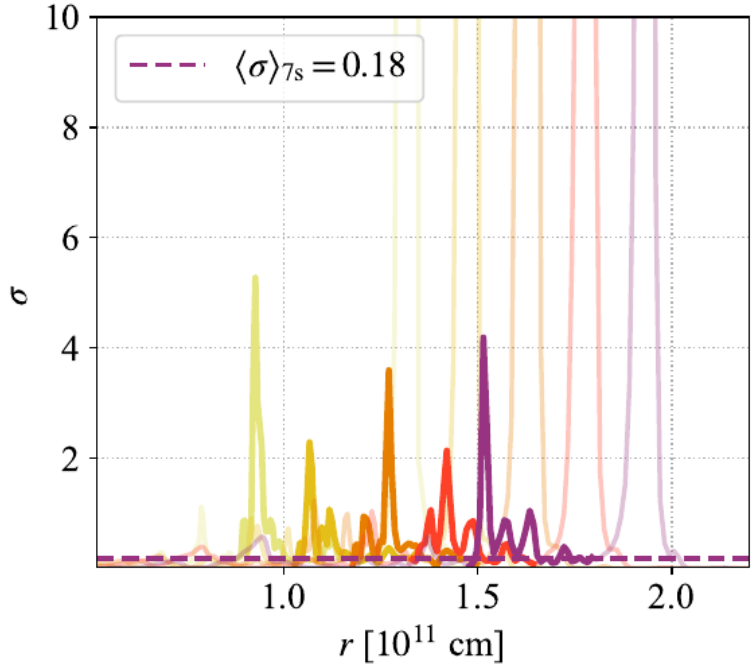
[AR et al, arXiv 2309.08667]

Jet Region: Extrapolation & Energy Dissipation





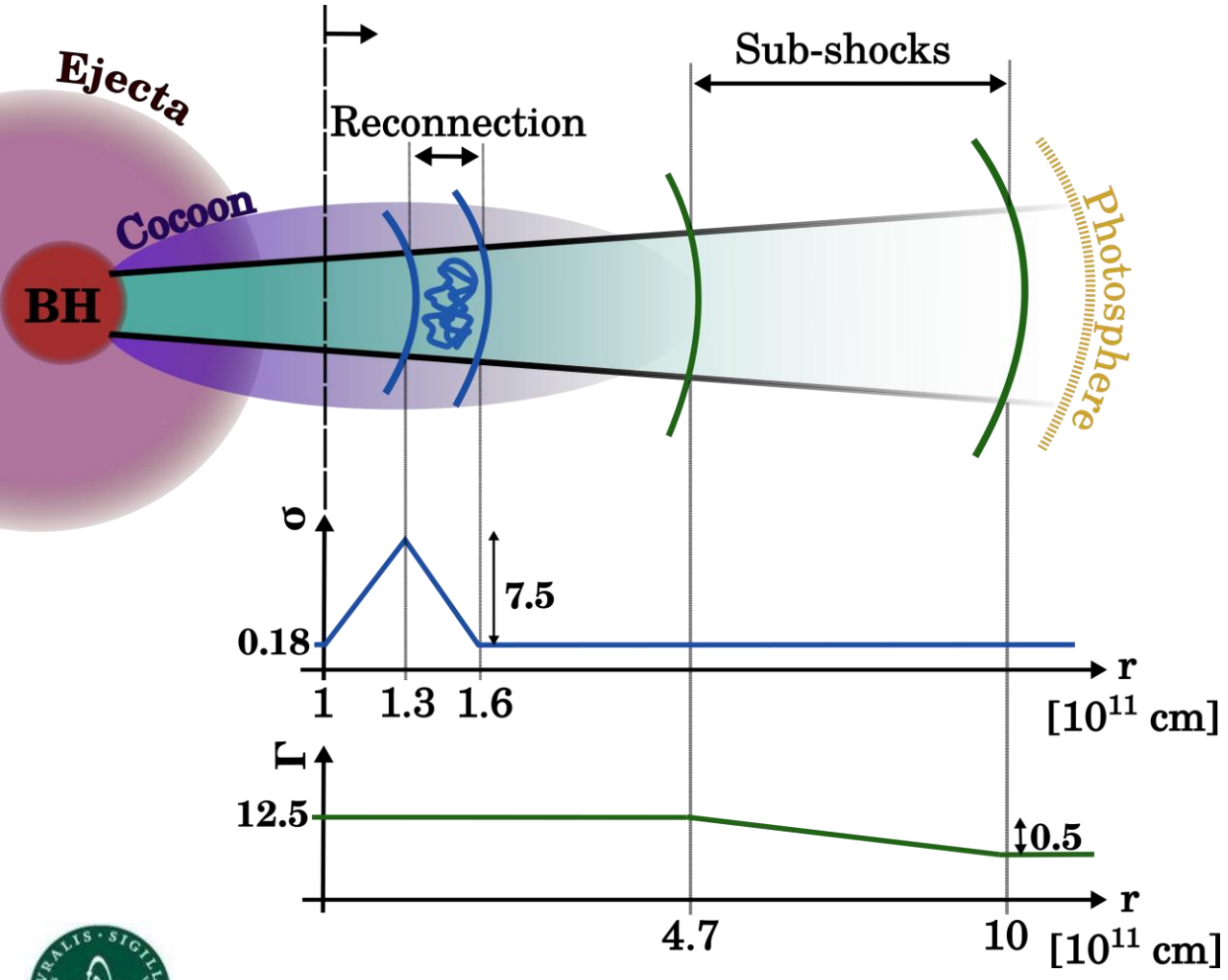




Magnetic reconnection:

- Realized in small regions of high σ
- Accelerated particles: No non-thermal protons (σ < 10) [Werner et al '18]
- Max/min energy scales with σ [eg. Kagan et al '18]

Simplified Jet Model



- Evolution of a homogeneous radiation zone ('shell') between 10^{11} – 10^{12} cm
  Reconnection region [1 – 1.6] x 10^{11} cm
  Expansion region [1.6 – 4.6] x 10^{11} cm
  Sub-shock region [4.6 – 10] x 10^{11} cm

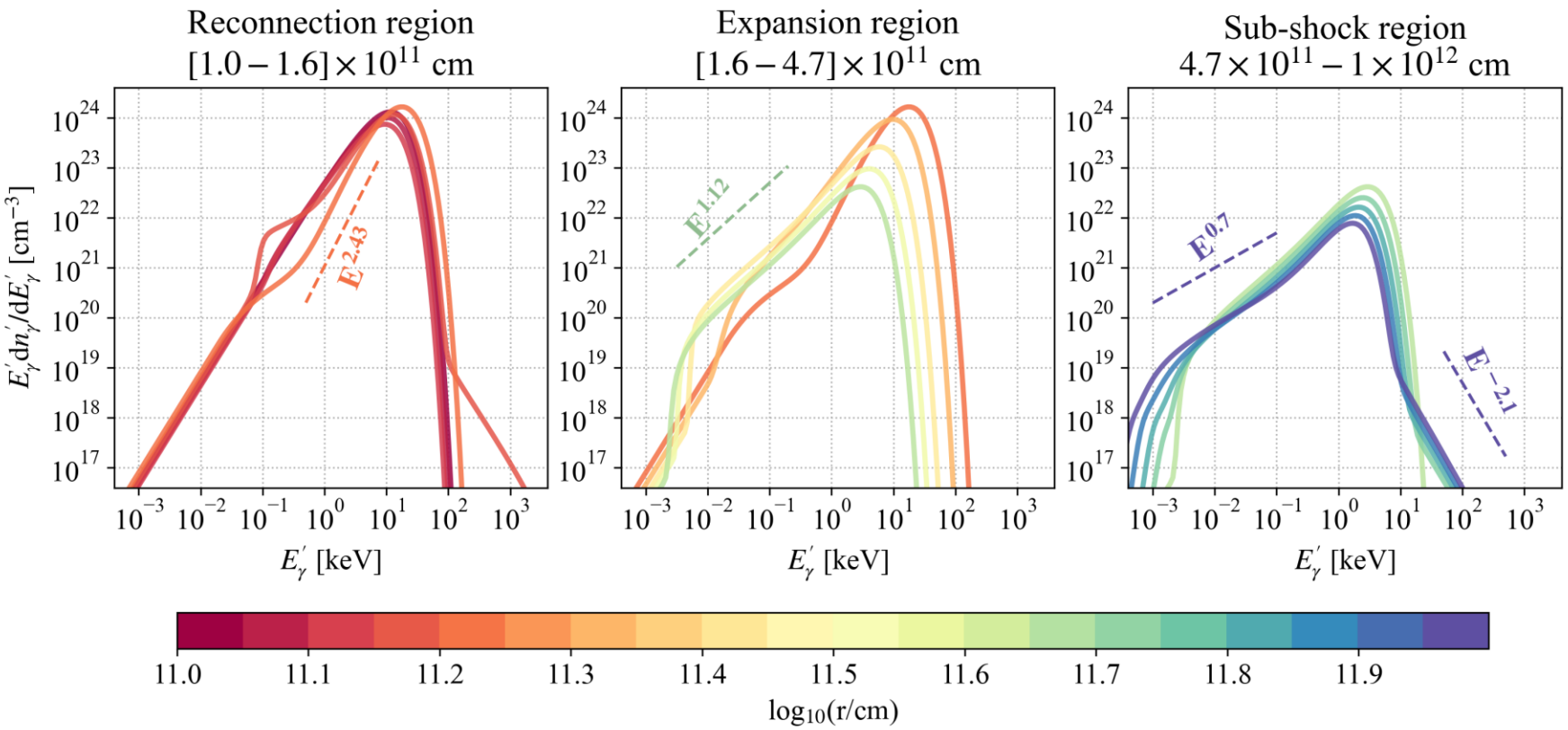
- At each radius:
  solve *coupled PDEs* of photons, thermal electrons, non-thermal electrons, protons, neutrons, pions, muons, neutrinos

$$\delta_t n(x) = \frac{1}{A(x)} \delta_x \left(D(x) \delta_x n(x) + a(x) n(x) \right) + \varepsilon(x) - \alpha(x) n(x) \,,$$

[AM^3 + Comptonization via Kompaneets Kernel + Thermal absorption/emission]

[AR et al, arXiv 2309.08667]

Evolution of Photon Fields



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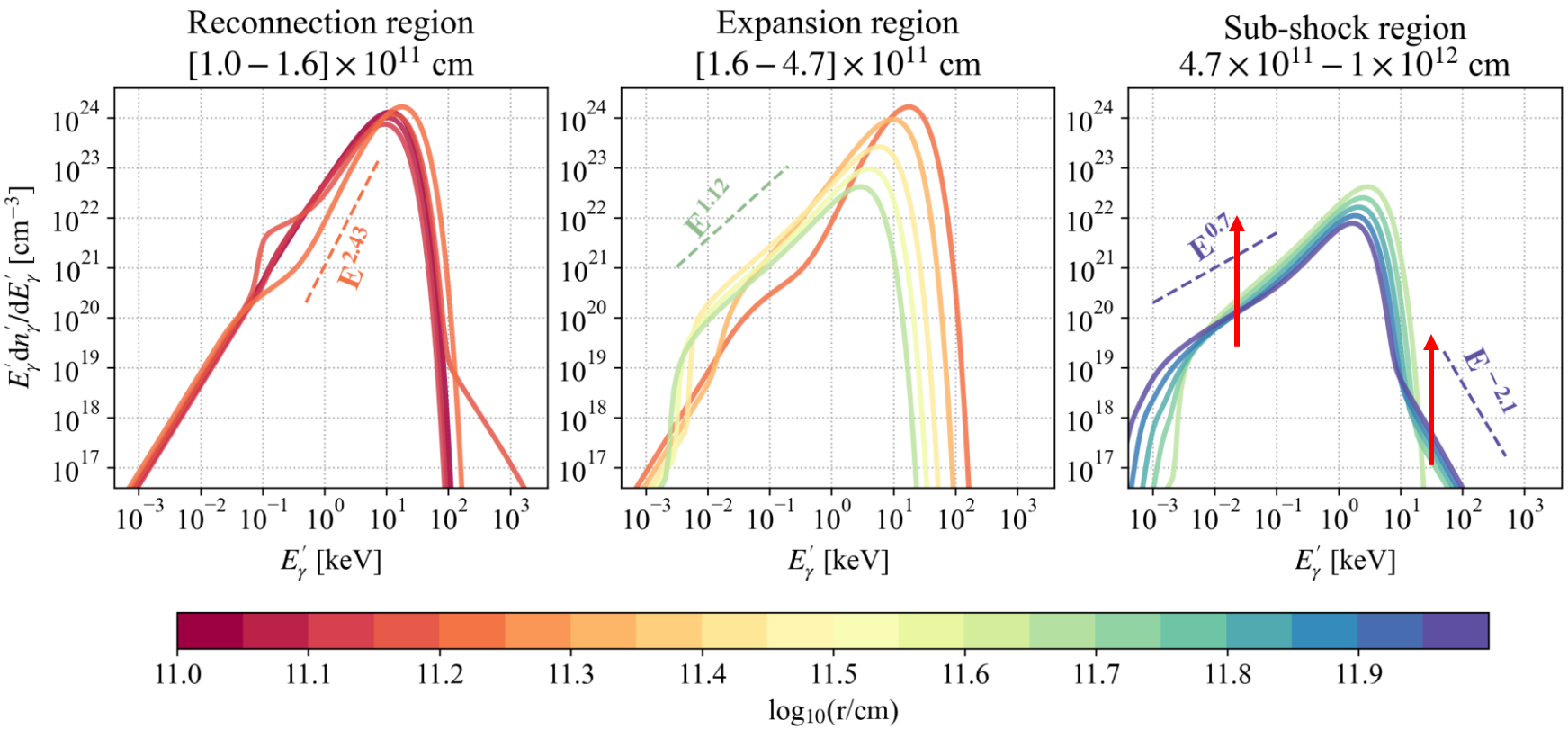
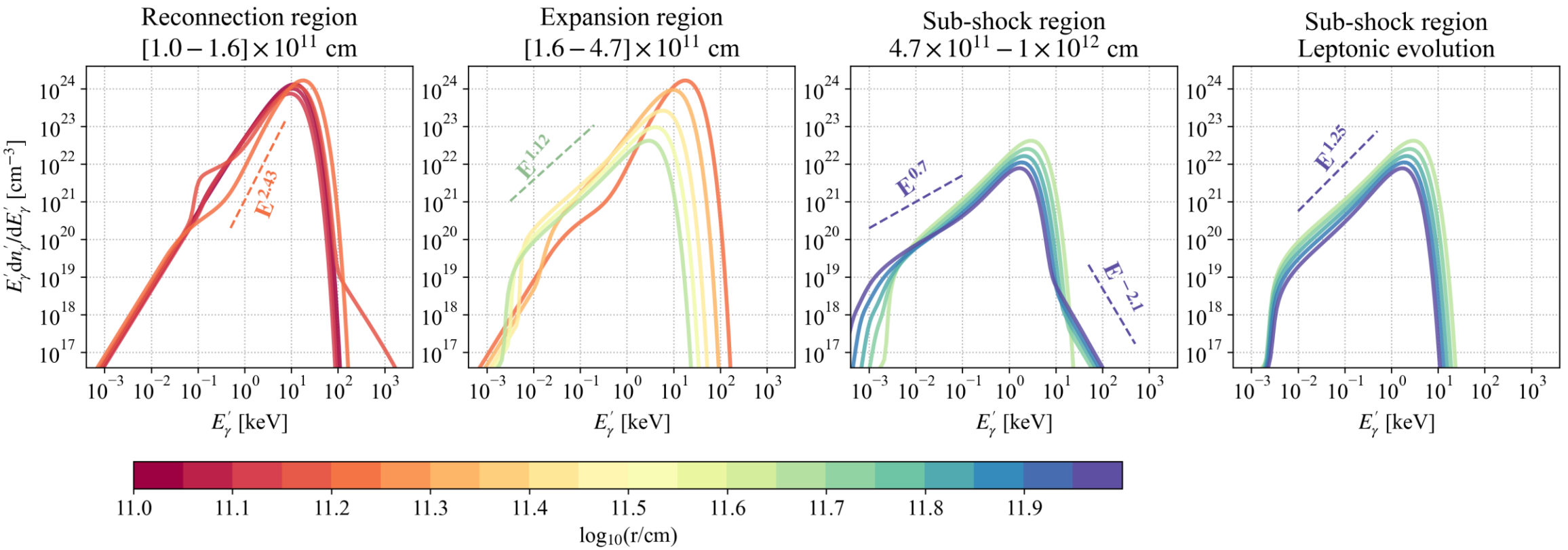


Enhanced dissipation

- wash out thermal relics?
- Softer low-energy slope?

[AR et al, arXiv 2309.08667]

Evolution of Photon Fields



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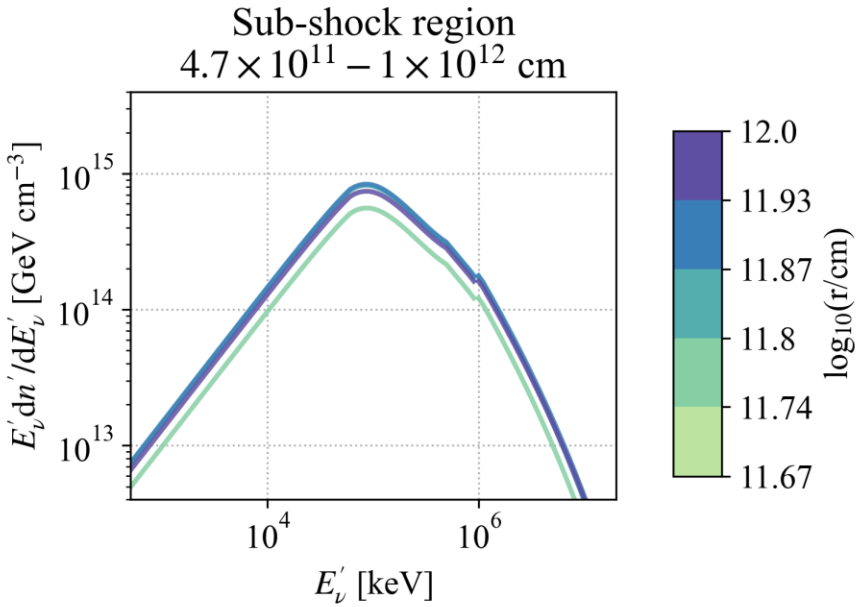
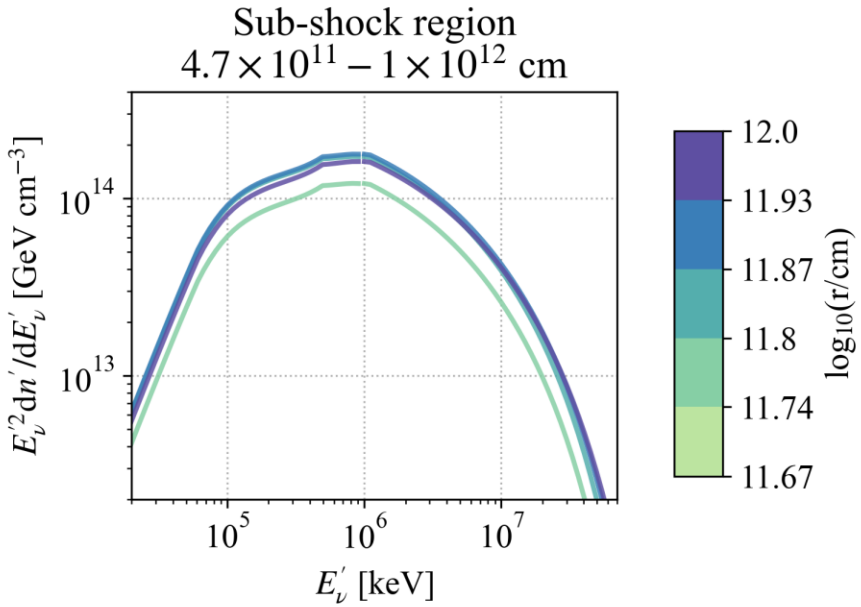
Neutrino Signatures





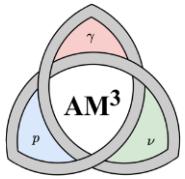
- Neutrinos only in sub-shock region, peak in GeV regime
- Side notes:
  1. No escape considered
  2. Need more studies on sub-shocks and reconnection in collisional plasma!

Summary & Conclusions

- Simplified jet model informed by a BNS merger simulation [10^{11} – 10^{12} cm]
  Reconnection -> Expansion -> (Sub-)shocks

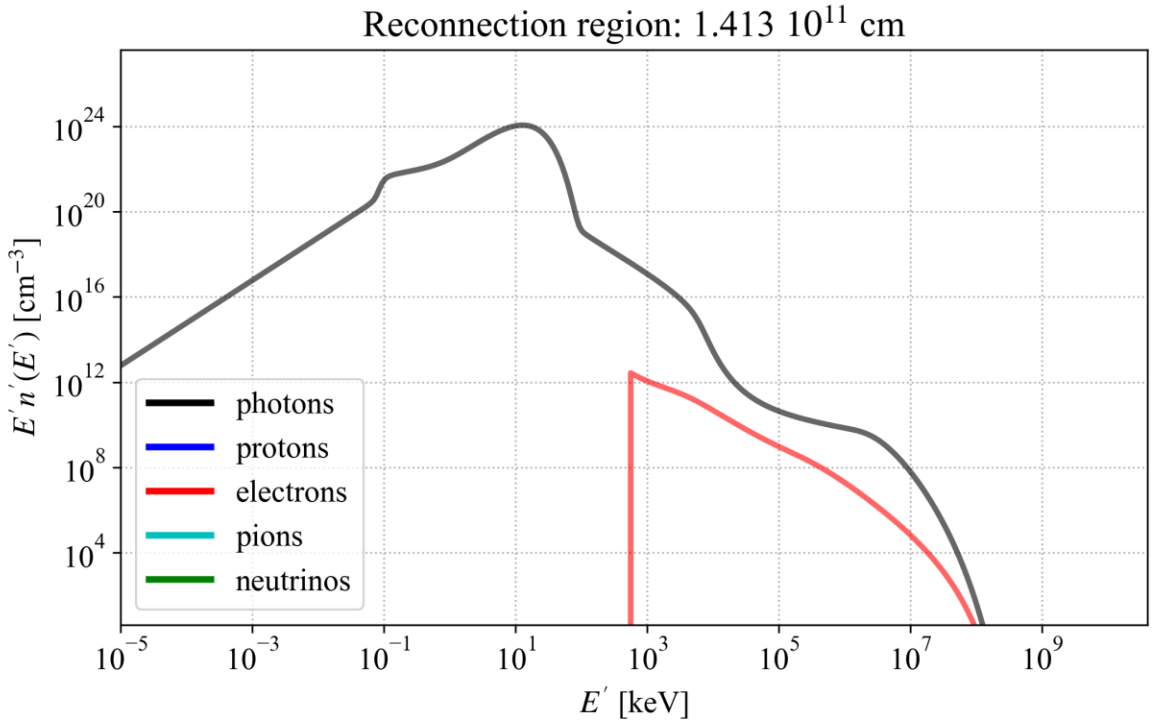
- Proton-induced cascade reshapes the multi-wavelength spectra
- Potentially compatible with observations
- Neutrinos peak at GeV energies

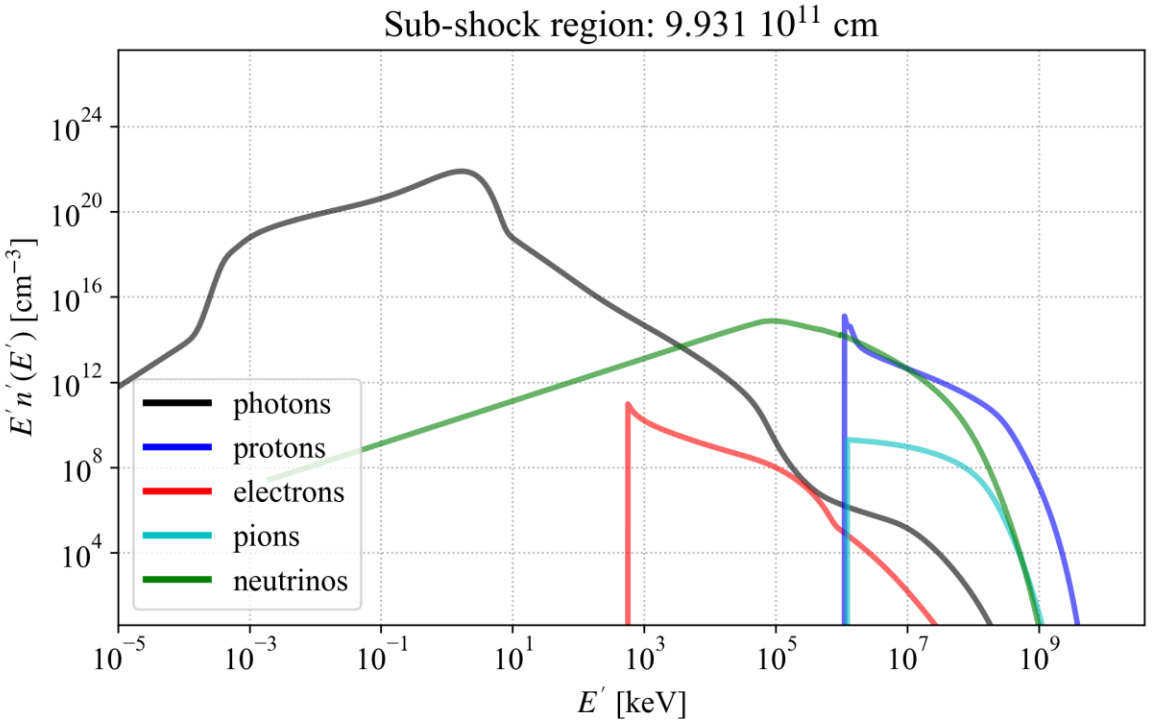
- More realizations to be explored [in preparation]
- AM^3 to be open source soon!



Backup

Particle Spectra





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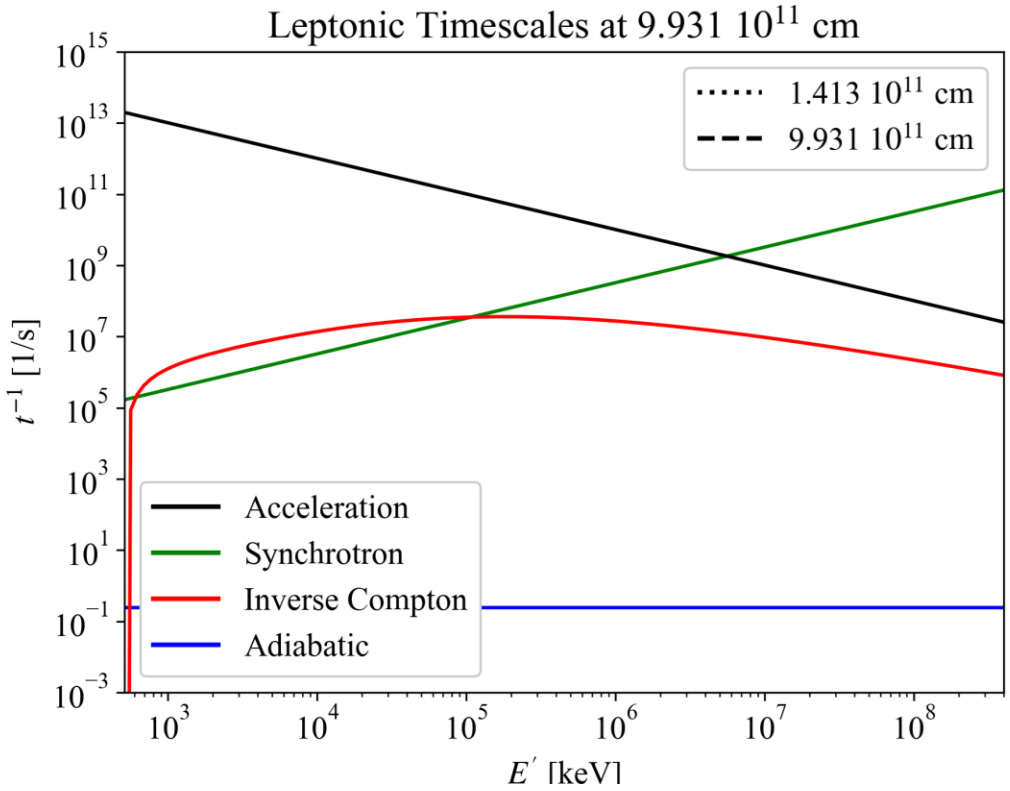
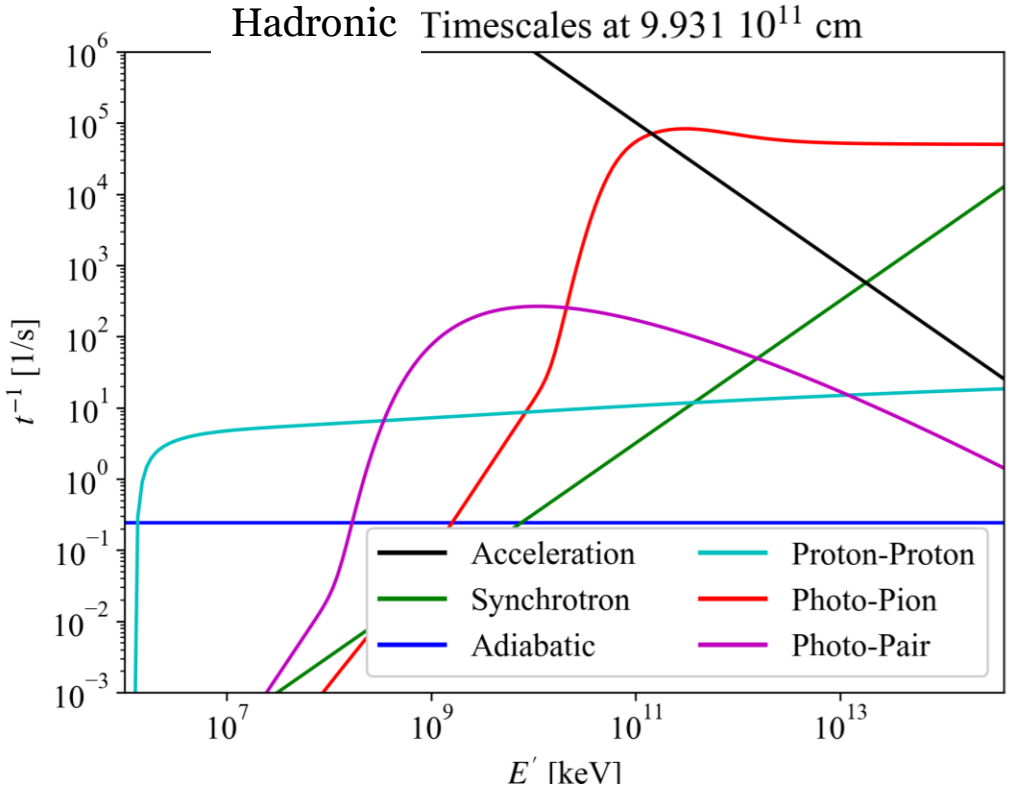
Cooling Timescales: Electrons & Protons





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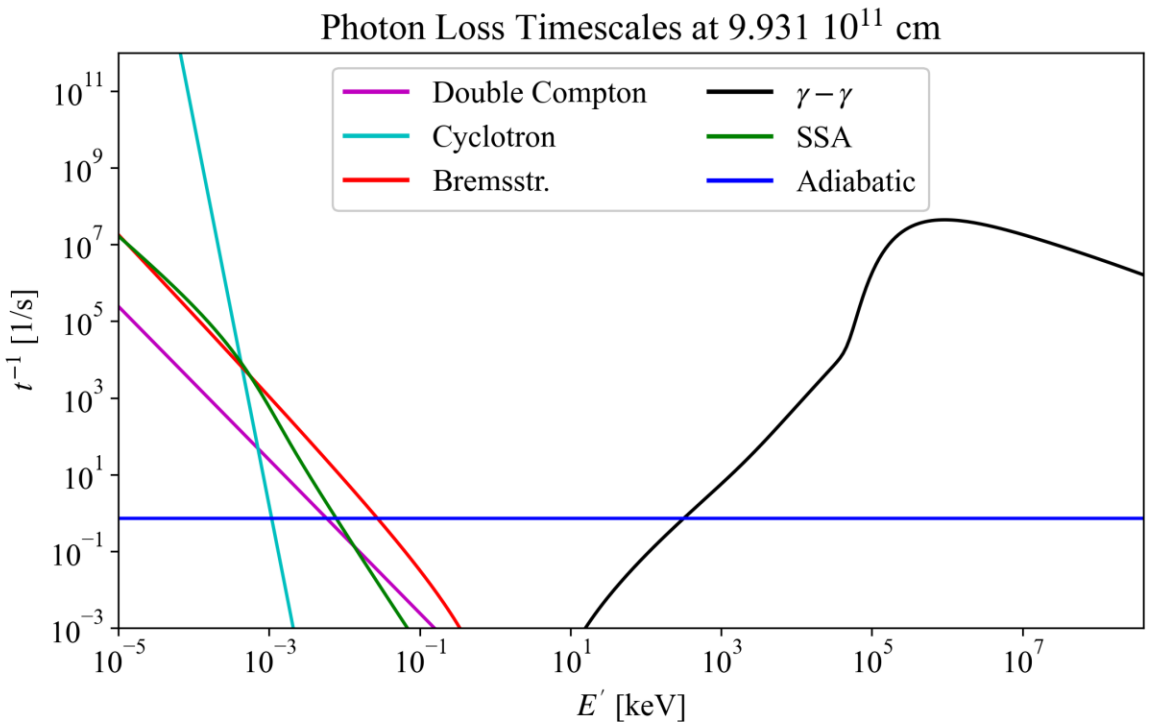
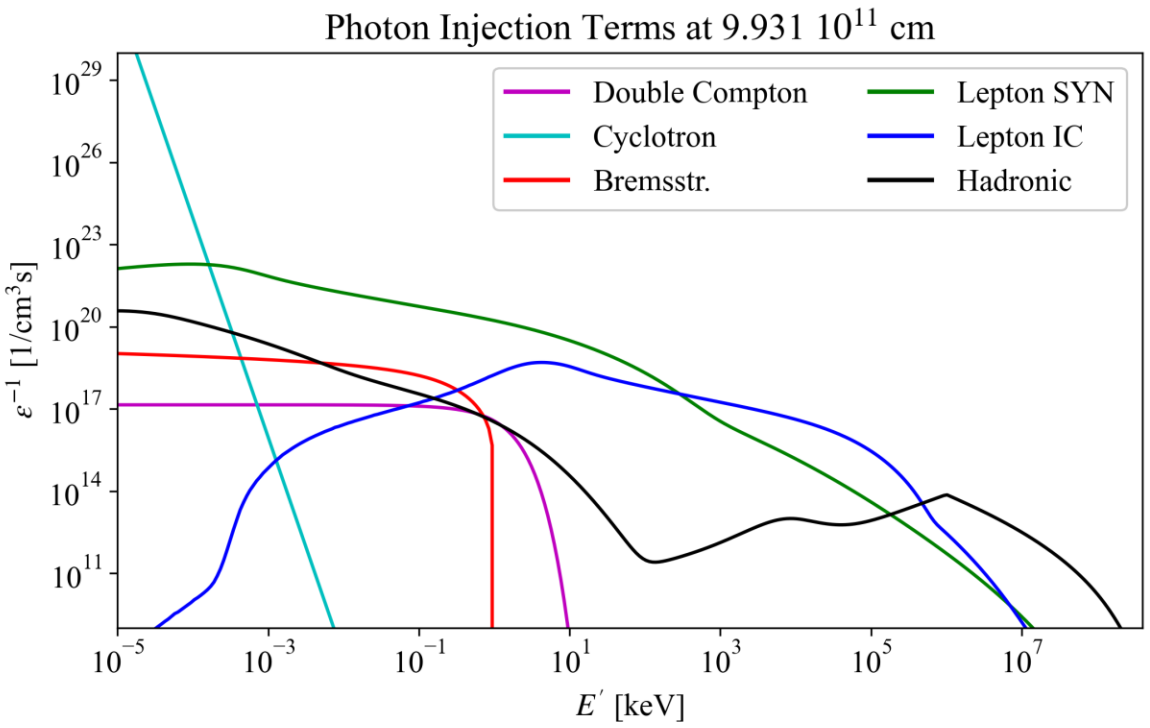
Photon Timescales





Evolution of Jet Characteristic Quantities