The Disconnect Between Radio and Gamma-Ray Emission in Arp 220

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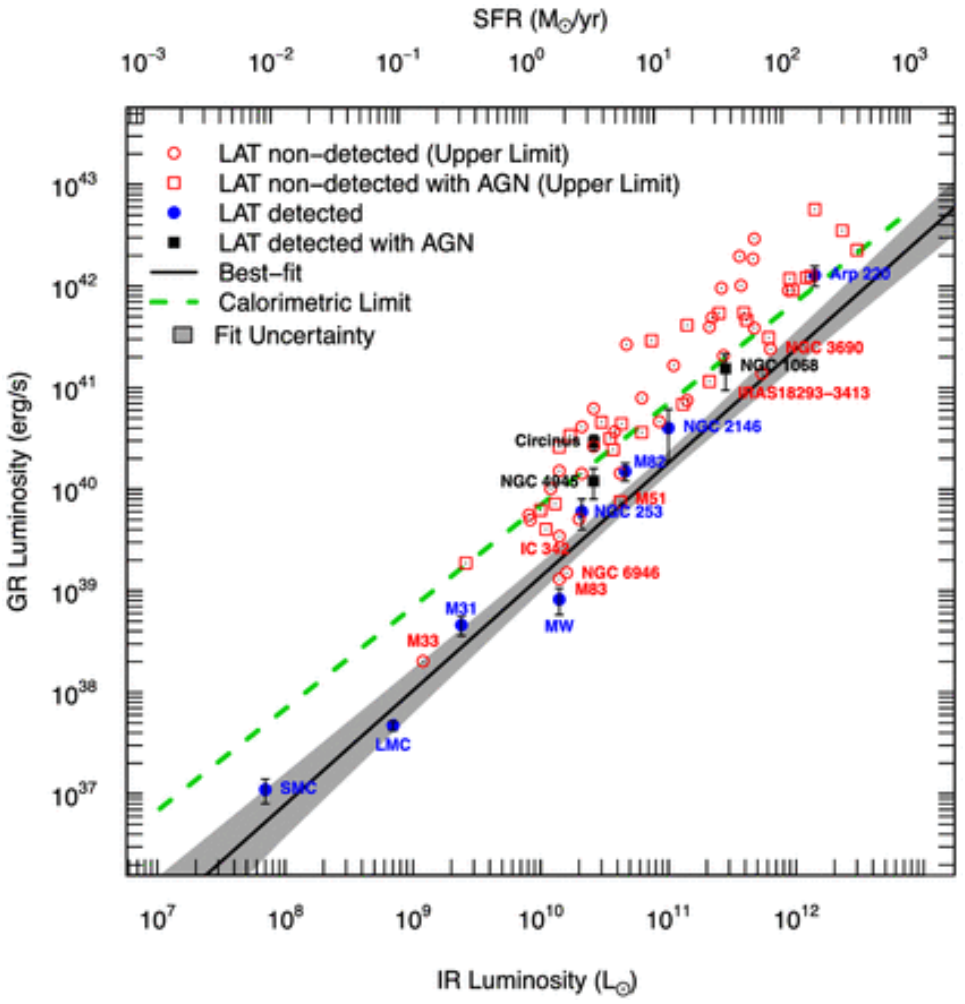
Starburst Galaxies: Gamma-Rays

- Gamma-ray detections:
  - Fermi: M82, NGC 253, NGC 4945⋆, NGC 1068⋆, NGC 2146, Circinus⋆, Arp 220
  - TeV: M82 (Veritas) & NGC 253 (HESS)
- Hard gamma-ray spectral indices.
  - $p \sim 2.3$ -2.4
- Both hadronic & leptonic contributions to total flux.

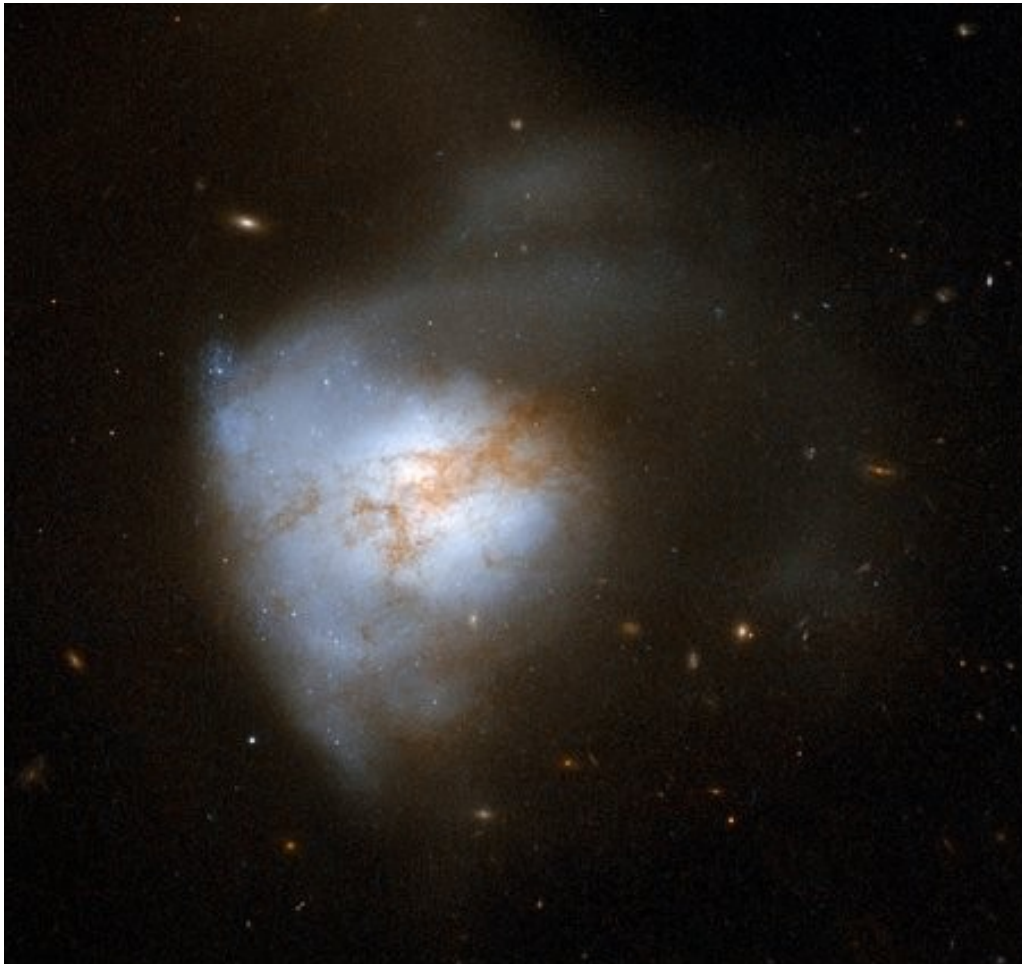
⋆ = Non-Jetted AGN



Rojas-Bravo & Araya 2016, MNRAS, 463

Essential Properties of Arp 220

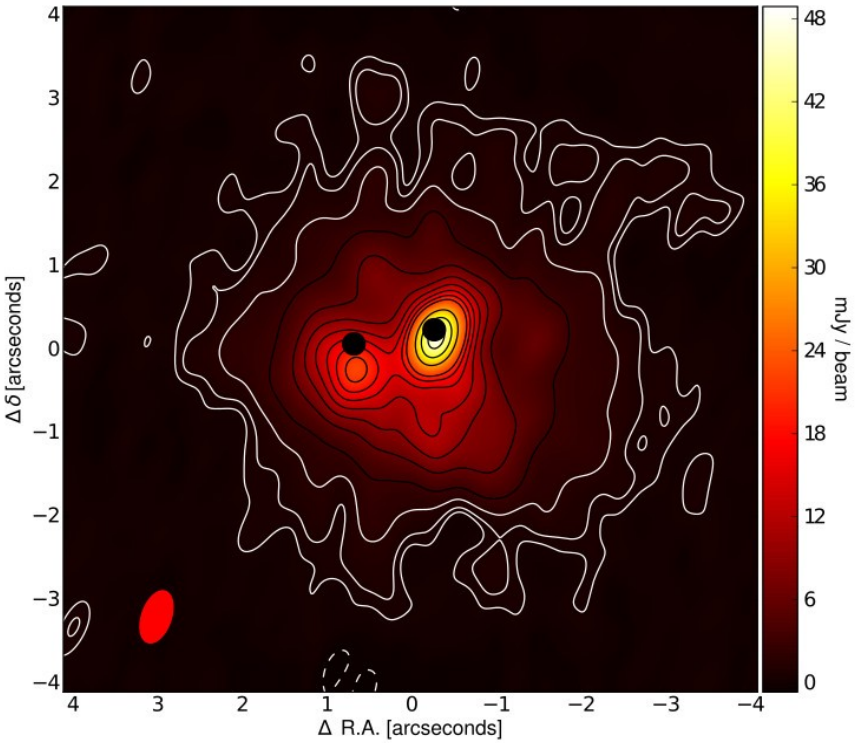
- Closest Ultra-Luminous Infrared Galaxy (ULIRG)
- Late stage merging galaxy
  - Two nuclei separated by ~ 1” ~ 370 pc.
  - Nuclei are embedded in counter-rotating disk
- ISM properties:
  - $L_{FIR} \sim 10^{11.5\text{-}12.5}\ L_{\odot} \sim 10^{45}$ erg/s
  - $M_{H2} \sim 10^{9}\ M_{\odot}$
  - B ~ few mG



HST: Optical + IR

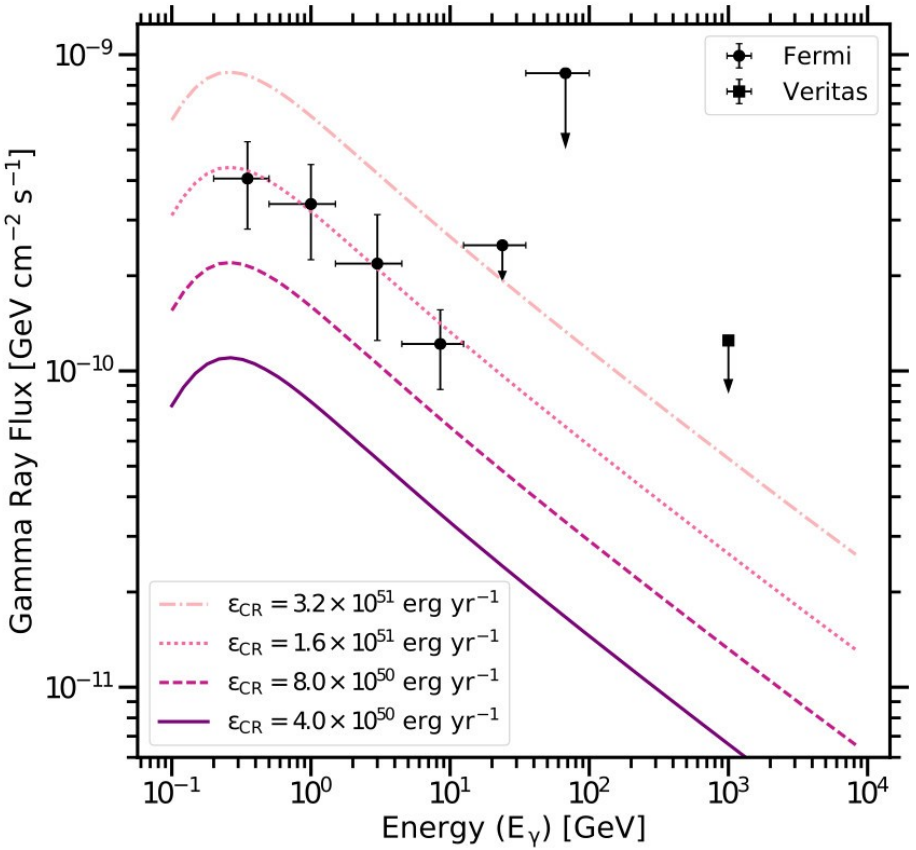
The Central Nuclei of Arp 220

- Power from star formation:
  - SFR ~ 200 $M_\odot$ yr^{-1}
  - SN Rate ~ 2 – 4 yr^{-1}
    - See SNRs with VLBI
- Power from an AGN?
  - Observations of centers hindered by dust obscurration
  - The usual indicators for AGN are not applicable.
    - mm emission lines
    - dust temperature
    - X-rays

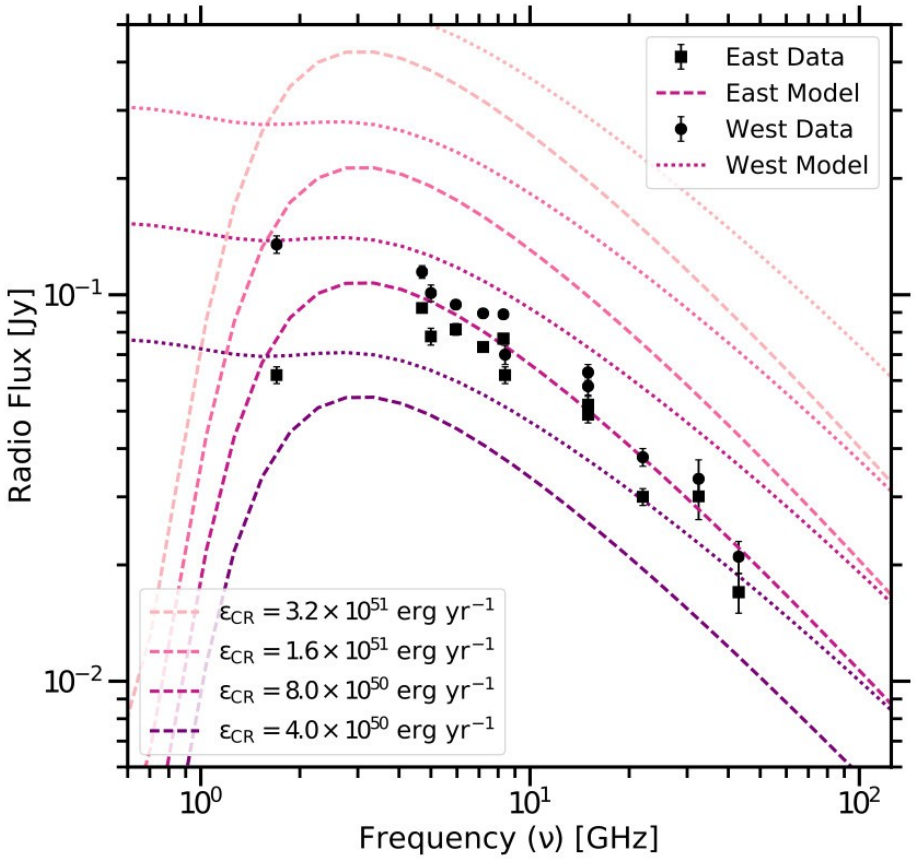


Varenius+ 2016,
A&A, 593, 86
LOFAR 150MHz

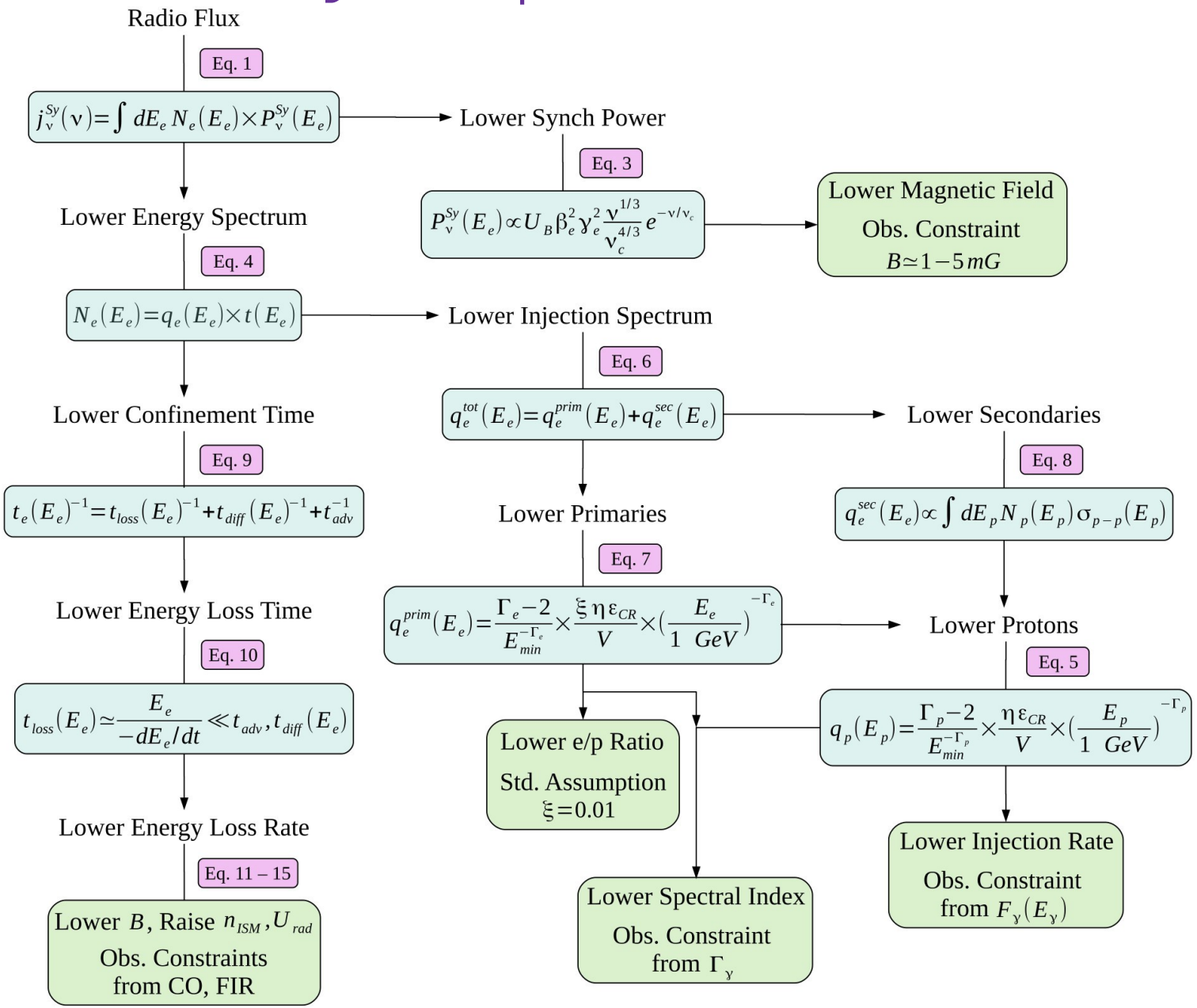
Gamma-Ray + Radio Emission



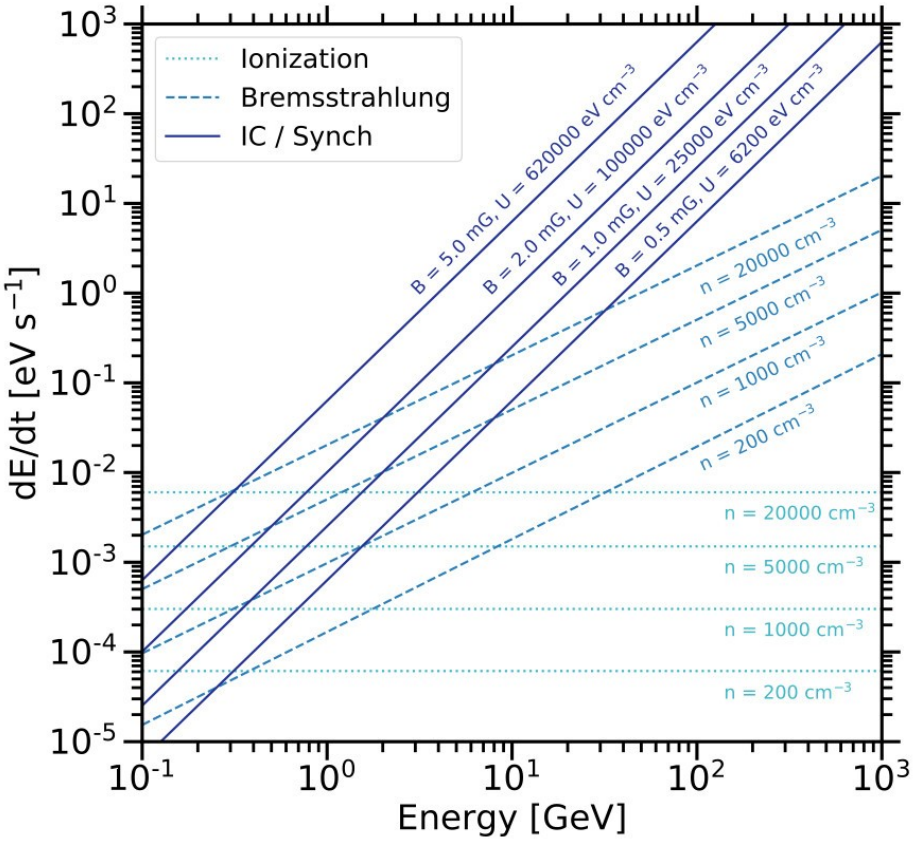
Yoast-Hull & Murray 2018, submitted



Cosmic Ray Leptons



Lepton Energy Losses



Yoast-Hull & Murray 2018, submitted

$$\left(\frac{dE}{dt}\right)_{Ion} = \frac{9}{4} m_e c^3 \sigma_T n_{mol} \left(6.85 + \ln(\gamma_e)\right)$$

$$\left(\frac{dE}{dt}\right)^{ion}_{Br} = \frac{3\alpha}{2\pi} c \sigma_T n_{ion} Z(Z+1) E_e \left(\ln(2\gamma_e)\right)$$

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$$\left(\frac{dE}{dt}\right)_{IC} = \frac{4}{3} c \sigma_T U_{rad} \frac{\gamma_K^2 \gamma_e^2}{\gamma_K^2 + \gamma_e^2}$$

$$\left(\frac{dE}{dt}\right)_{Sy} = \frac{4}{3} c \sigma_T \frac{B^2}{8\pi} \gamma_e^2$$

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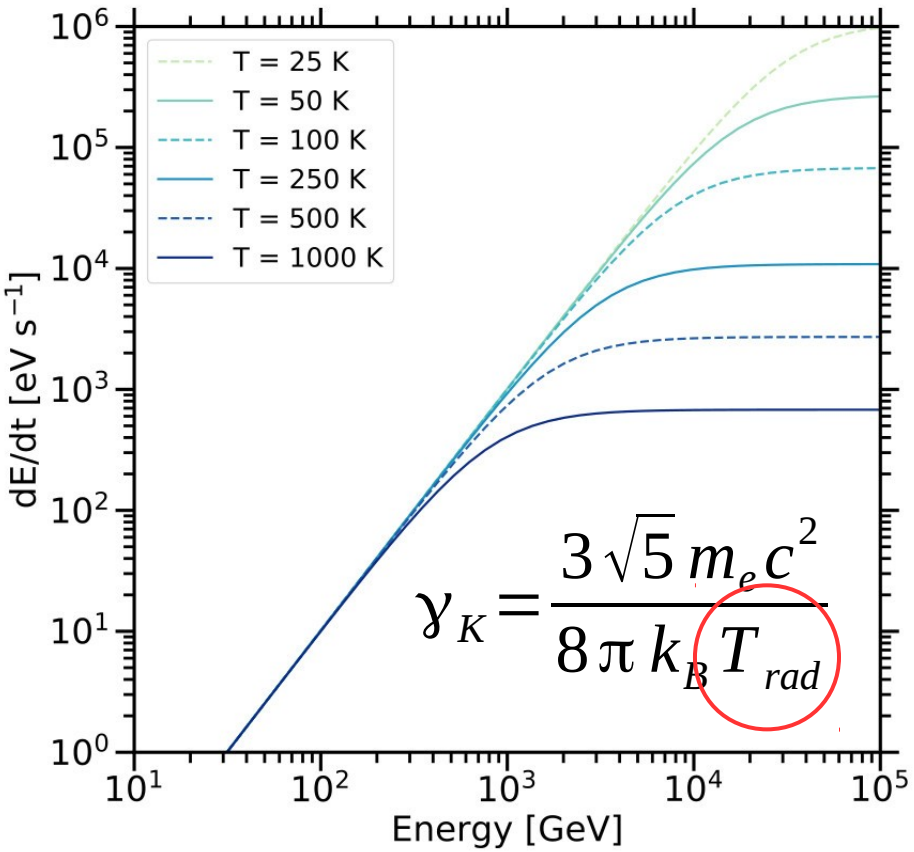

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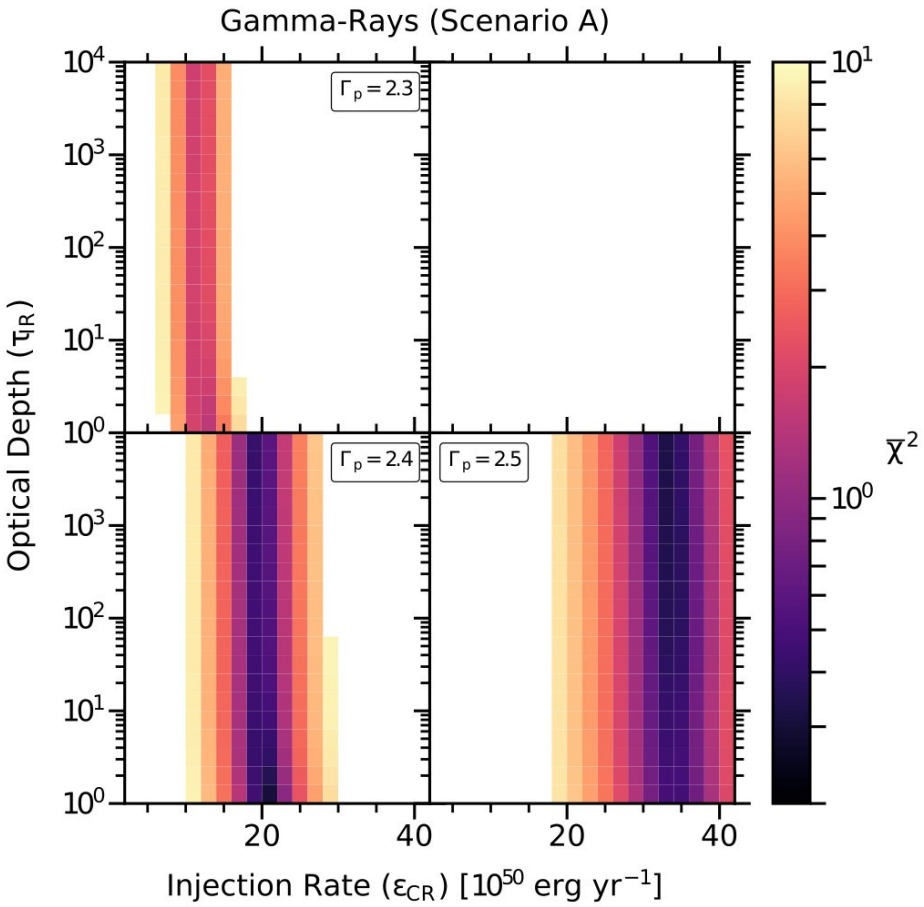
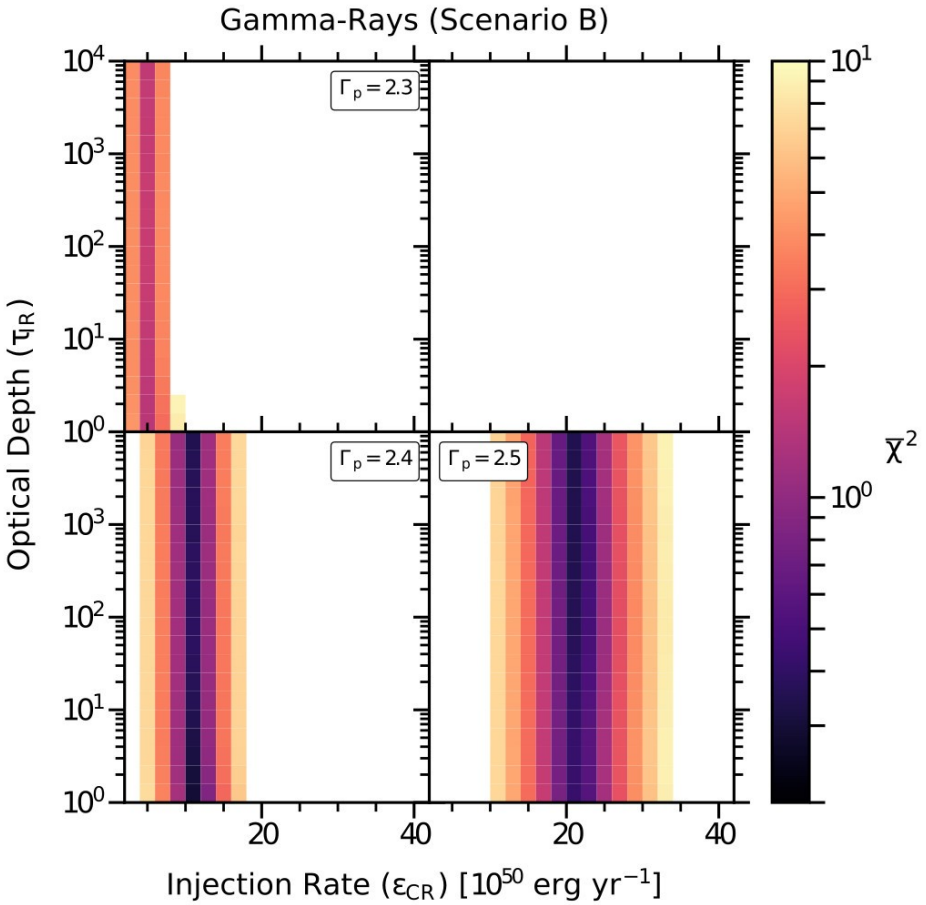
Gamma Ray Contours



Yoast-Hull & Murray 2018, submitted

Scen. A = E + W + CND
Scen. B & C = CND only



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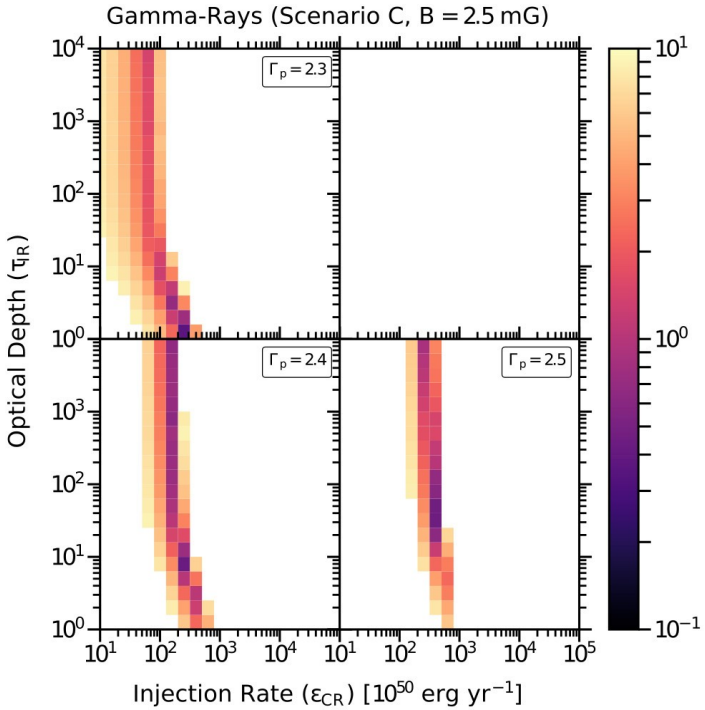
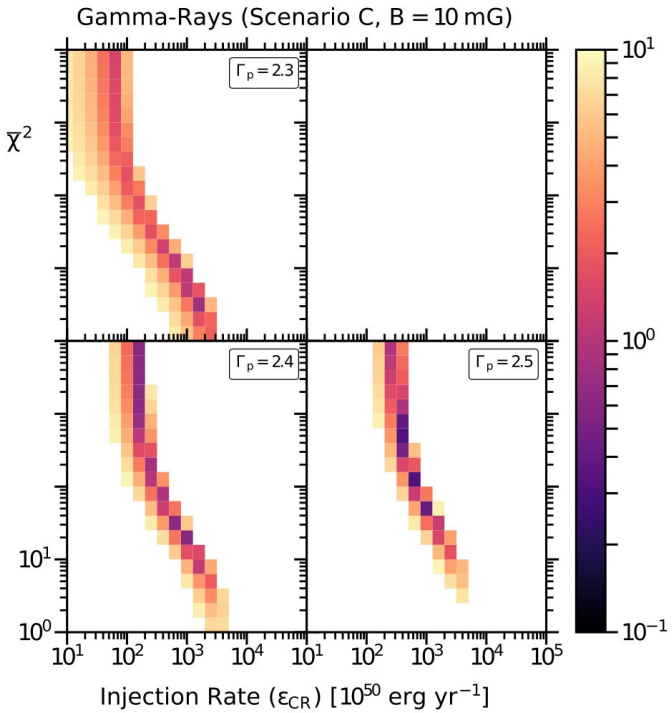


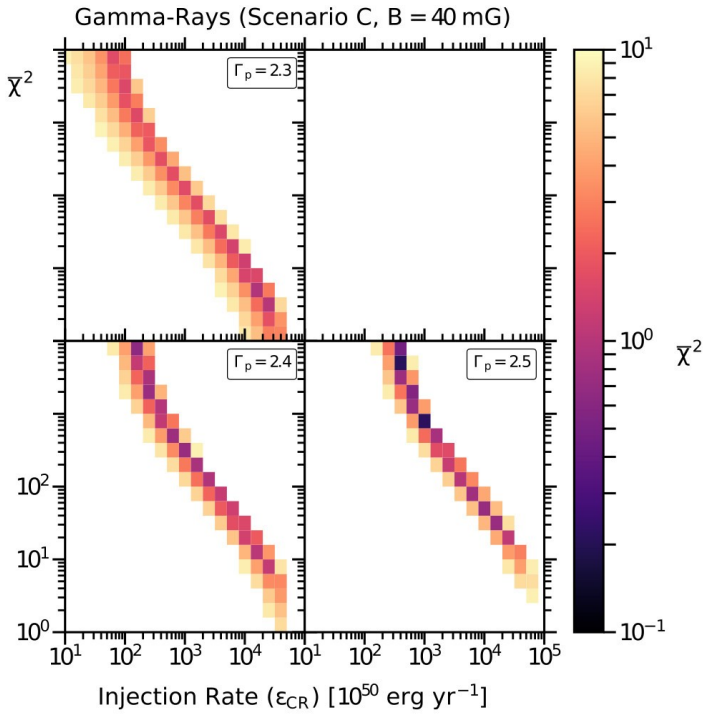
$$U_{rad} = \tau U_{eff}$$
$$T_{rad} = \tau^{1/4} T_{eff}$$

Yoast-Hull & Murray
2018, submitted

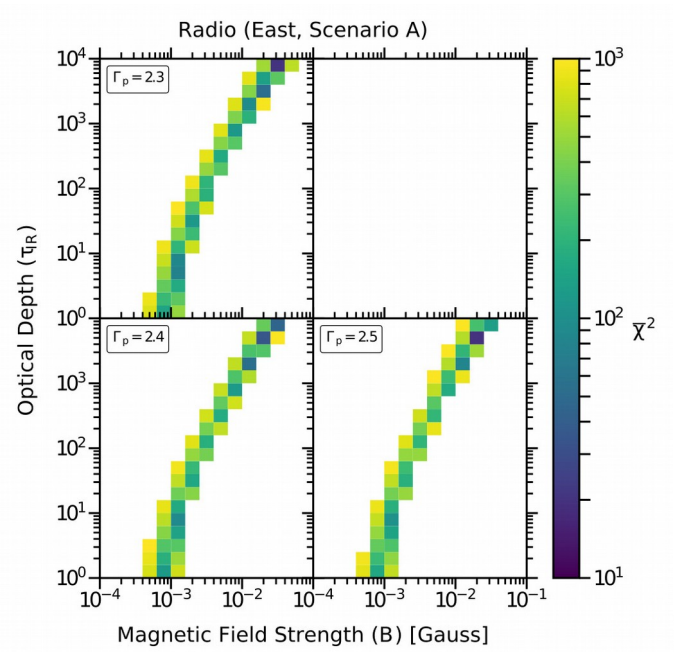


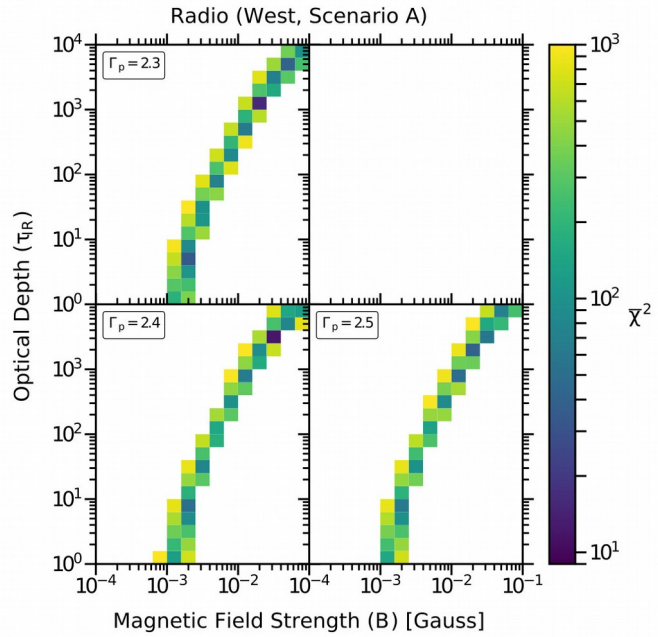
$$q_{IC} \propto \frac{U_{eff}\,\tau^{1/2}}{\left(k_B T_{eff}\right)^2}$$

Scen. A = *p* + *e*-
Scen. B = *p* only
Scen. C = *e*- only



Radio Synchrotron Contours





$$\tau \propto \nu^{1.8}$$

$$\tau_{mm} \simeq 1-5$$

$$\Rightarrow \tau_{60\mu m} \simeq 40-125$$

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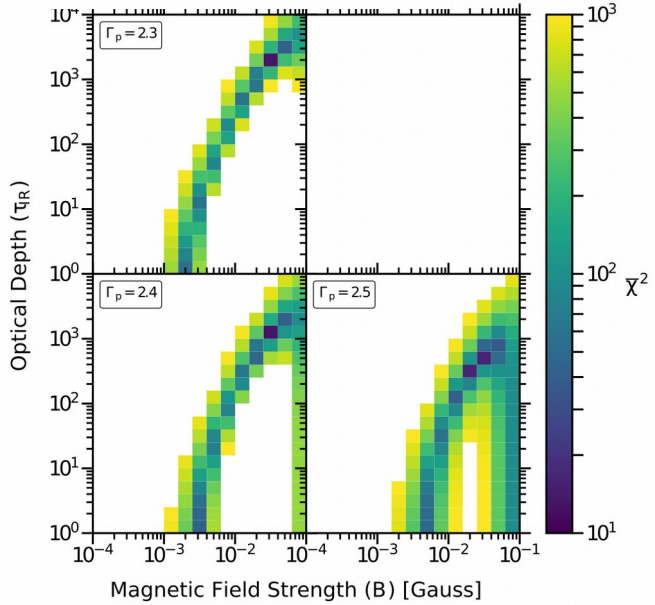

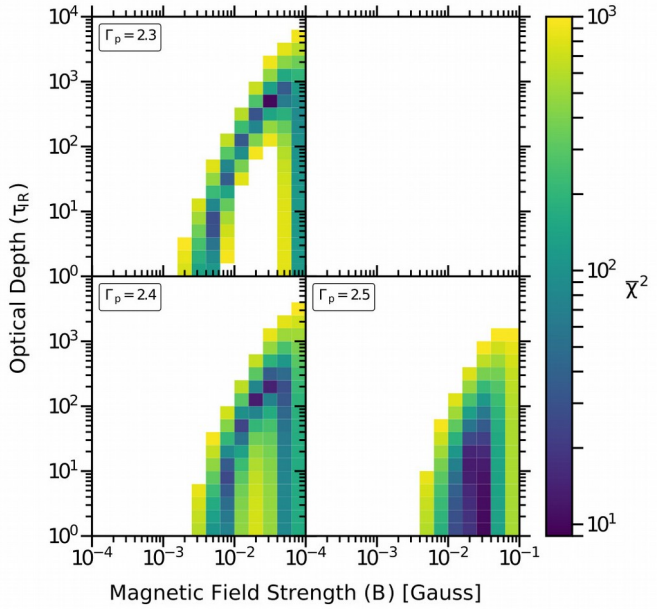

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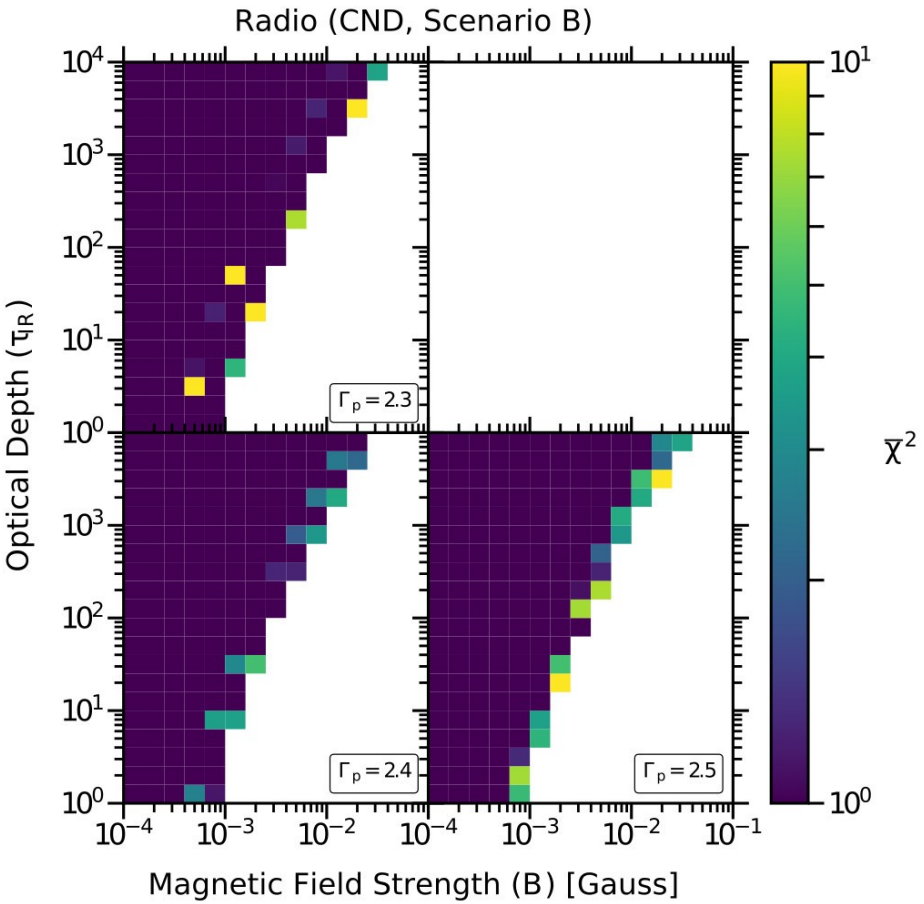

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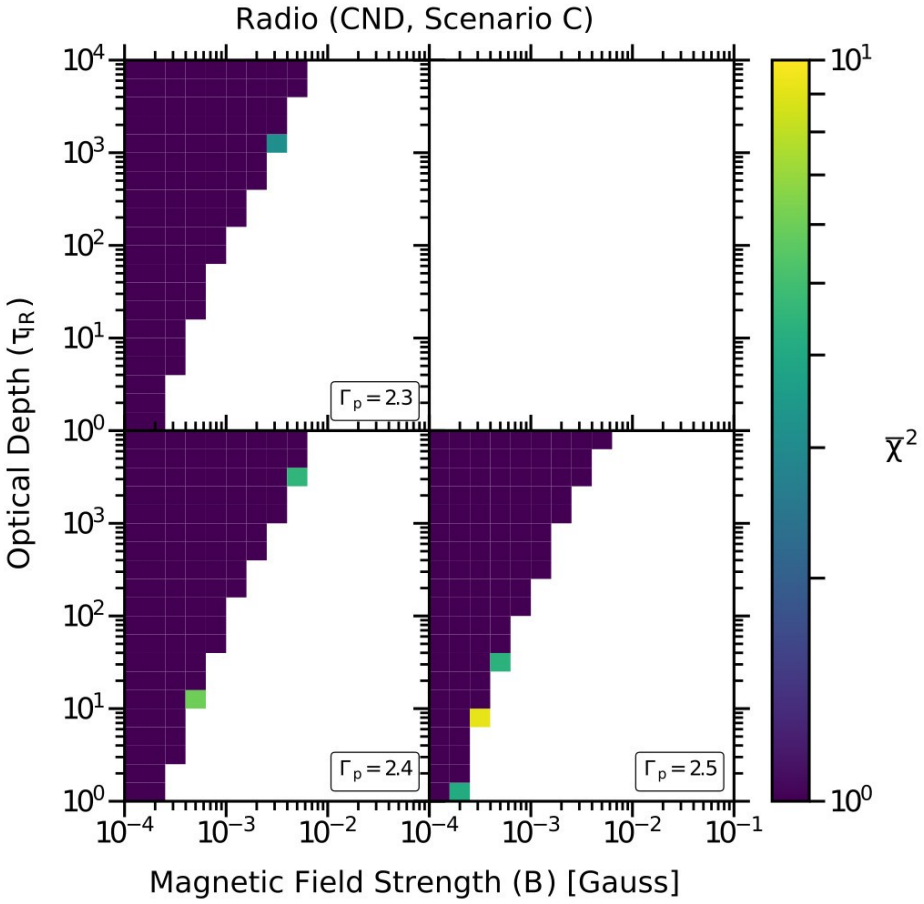

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Other Interactions with Radiation

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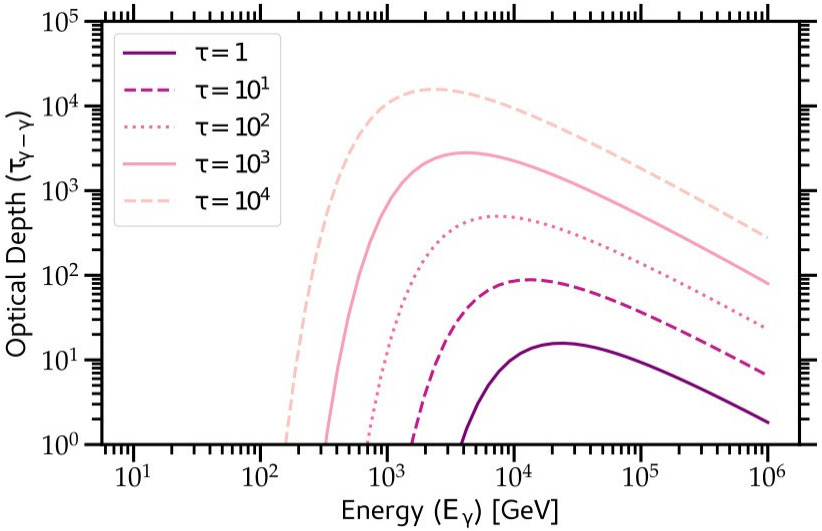

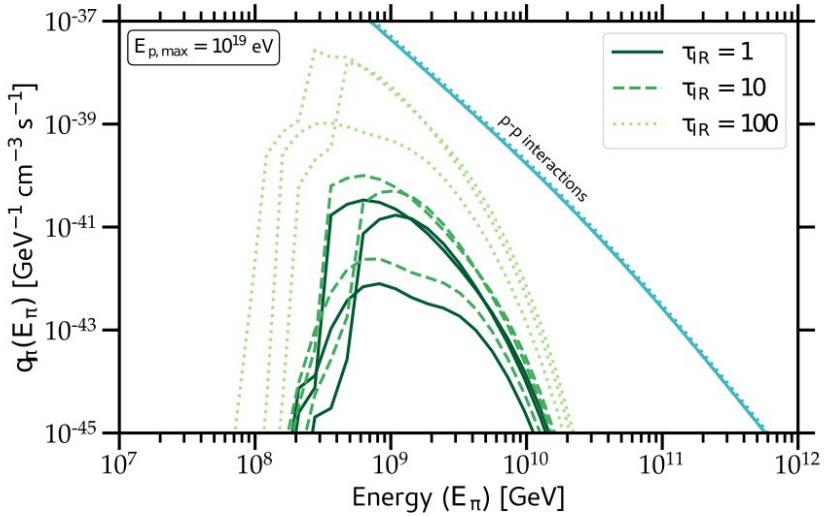

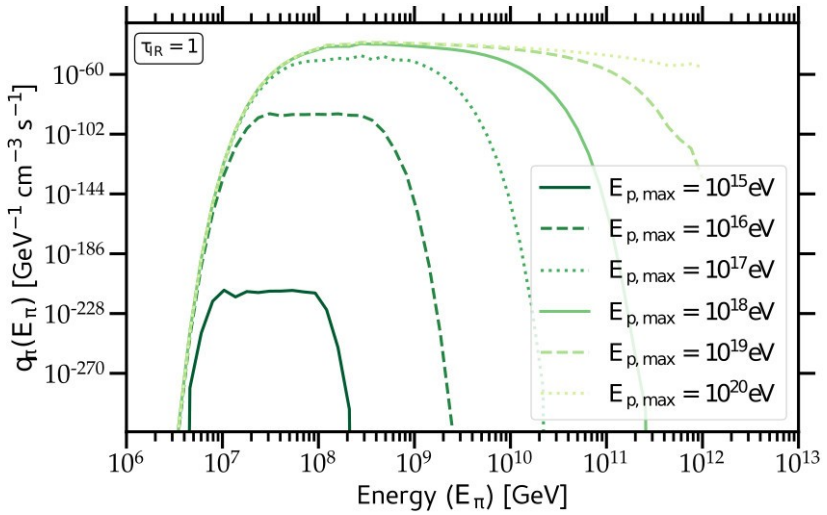

Parametrizations from:
Hümmer+ 2010, ApJ (p-γ)
Dermer & Menon 2009 (γ-γ)

Summary

- Gamma-rays provide critical information about CR proton populations & can be used as **diagnostics for hidden AGN (additional CR populations)**.
- The traditional **radio – gamma-ray connection** breaks down in extreme systems.
  - Accounting for trapped radiation and **optically thick** radiation fields is critical.
- Implications:
  - Possible effect on models for **high-z galaxies**
    - Depends on how “clumpy” star formation is at high-z
  - Potentially higher contribution to background gamma-ray & neutrino fluxes from ultra-luminous infrared (star-forming) galaxies.