Jet Contribution to the γ-ray Flux in NGC 1068

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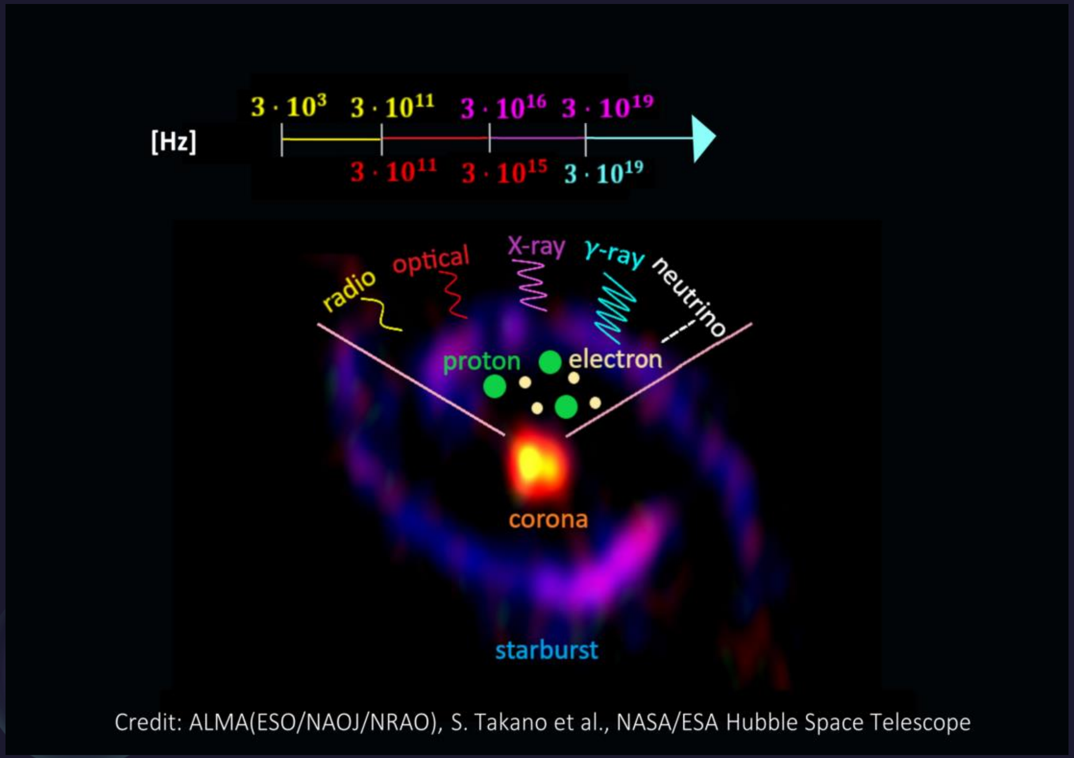
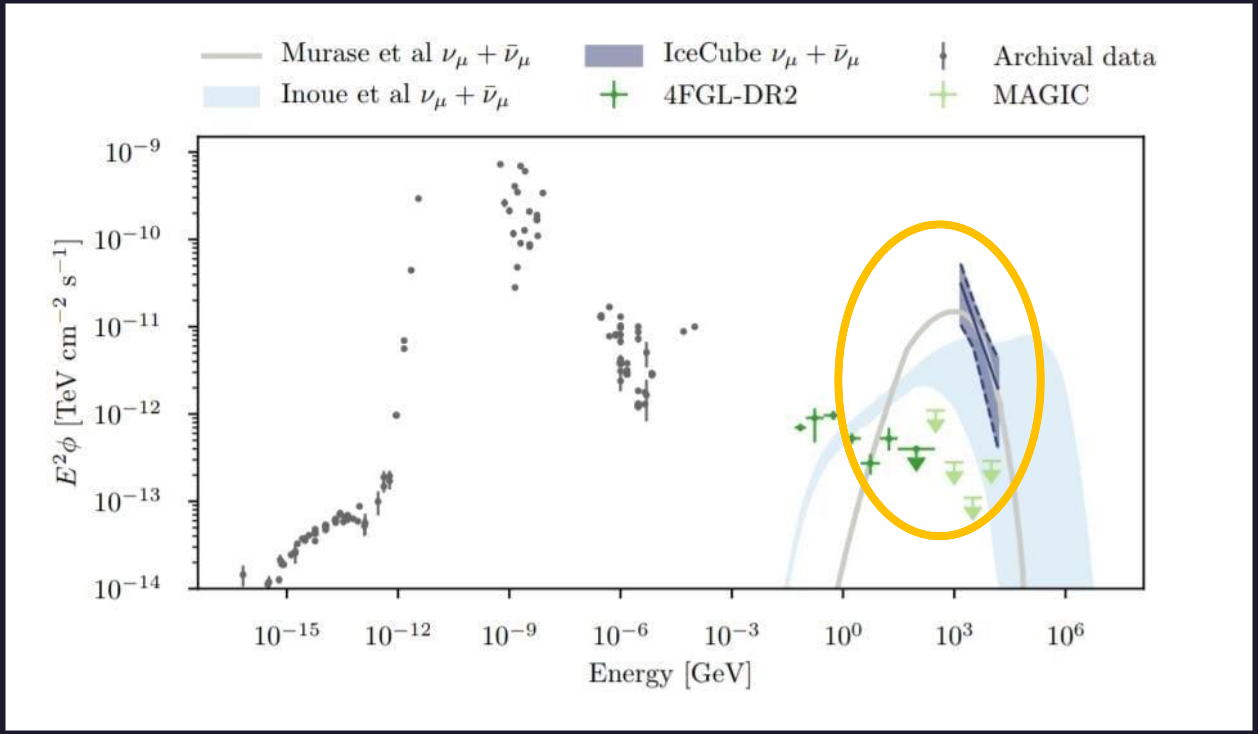
Why are neutrinos important?

- ALMA observations → inner core and outer ring
- For energies between 100 GeV and 10 TeV → significant difference in gamma-ray and neutrino fluxes



Credit: ALMA(ESO/NAOJ/NRAO), S. Takano et al., NASA/ESA Hubble Space Telescope



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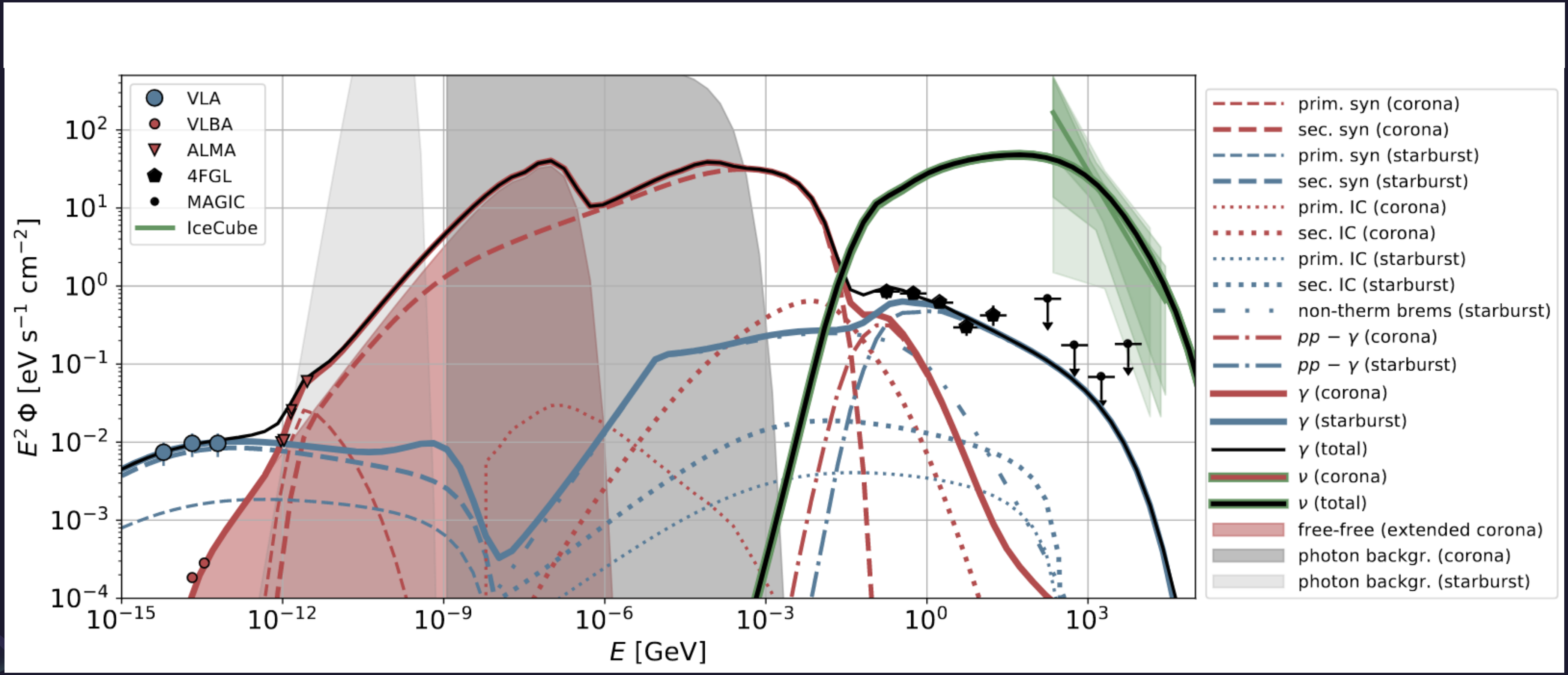
AGN-corona + starburst ring model



Eichmann, …., **Salvatore**, …, 2022

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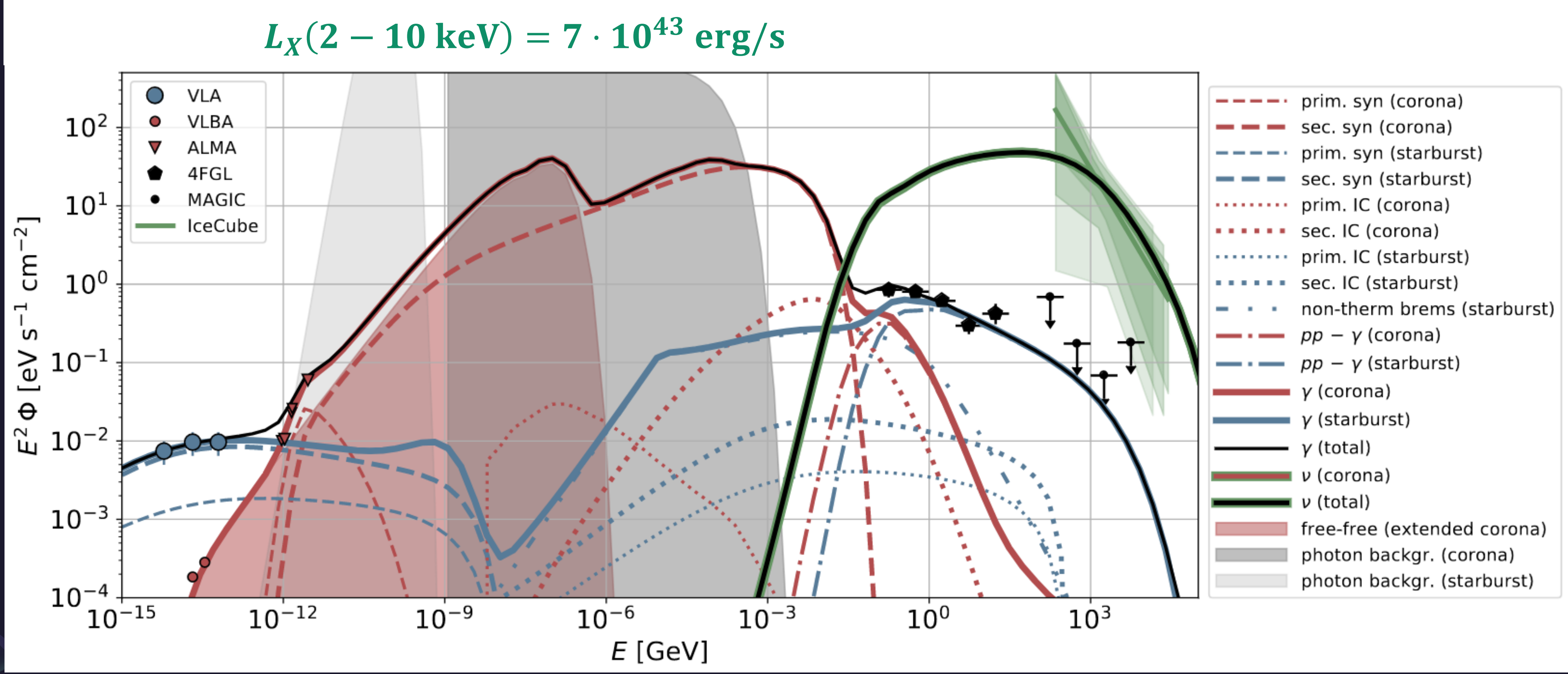

Eichmann, …., **Salvatore**, …, 2022

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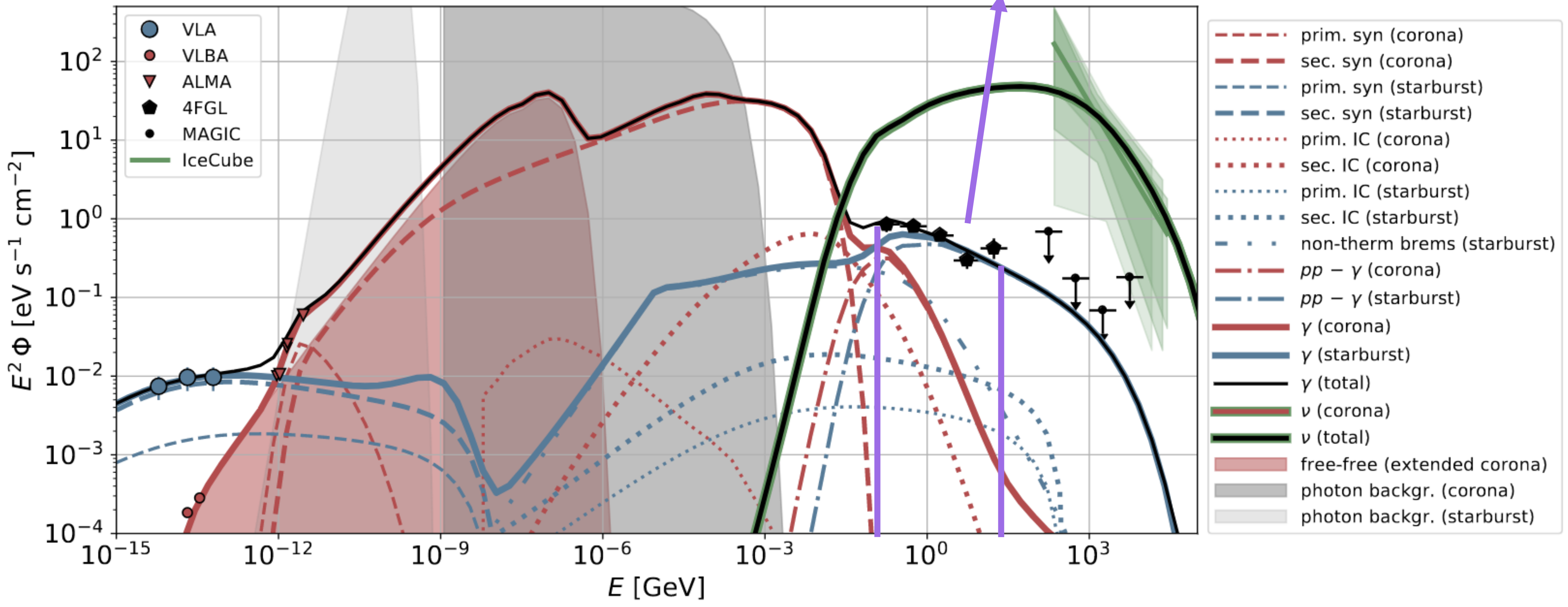
AGN-corona + starburst ring model

$L_X(2-10\ \mathrm{keV}) = 7 \cdot 10^{43}\ \mathrm{erg/s}$ $L_\gamma = 10^{40.92}\ \mathrm{erg/s}$



Eichmann, …., **Salvatore**, …, 2022

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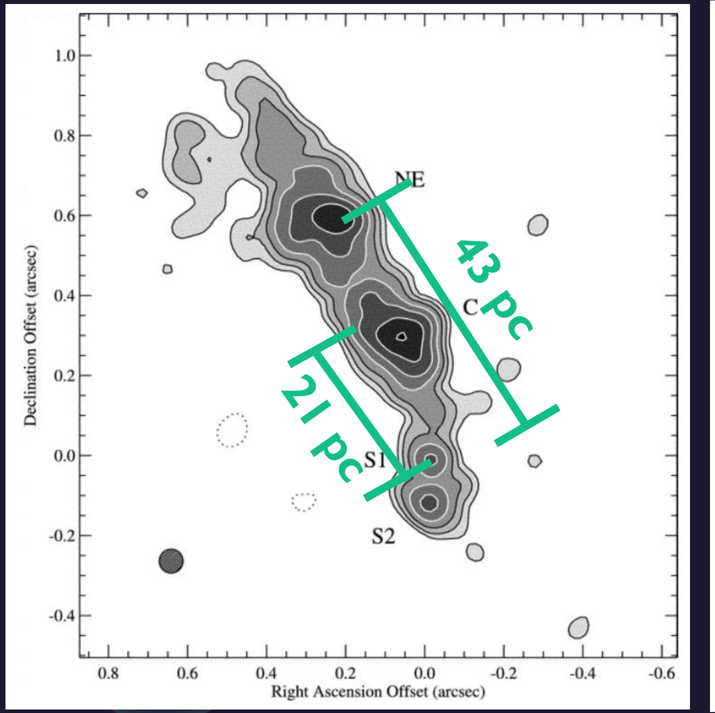
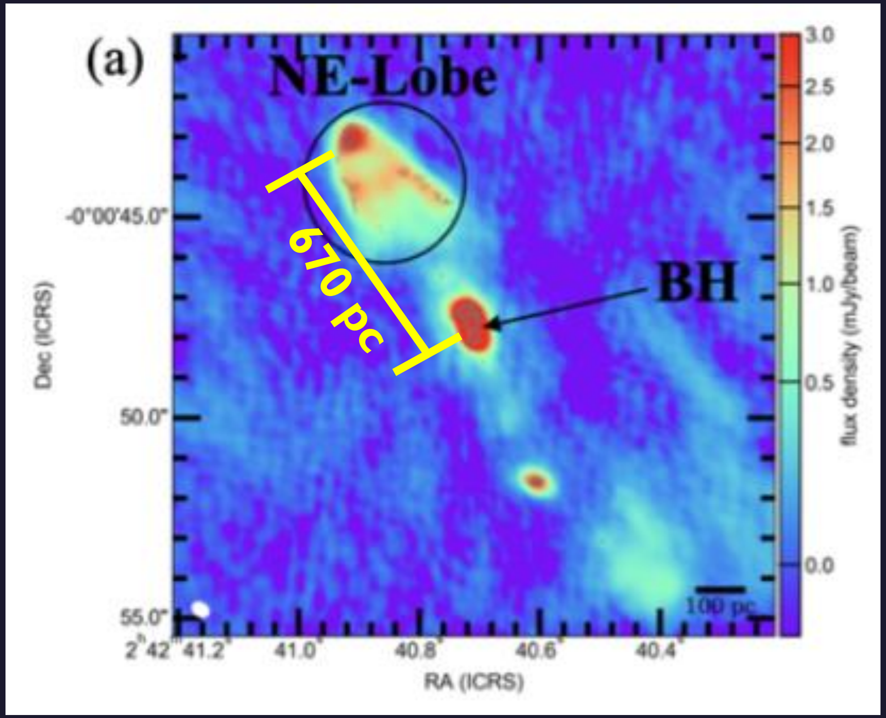
Introducing the jet

Radio data

Gallimore et al., 2004



Michiyama et al., 2022



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Introducing the jet

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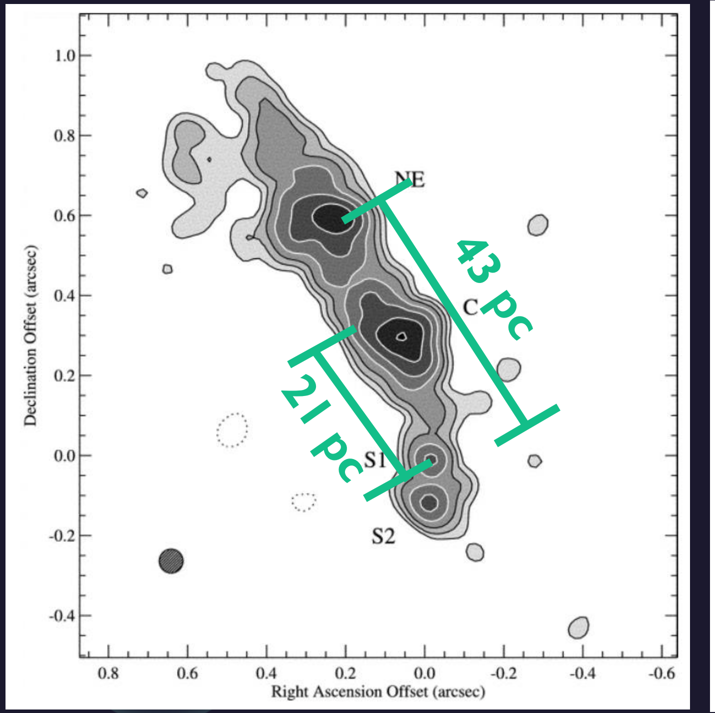

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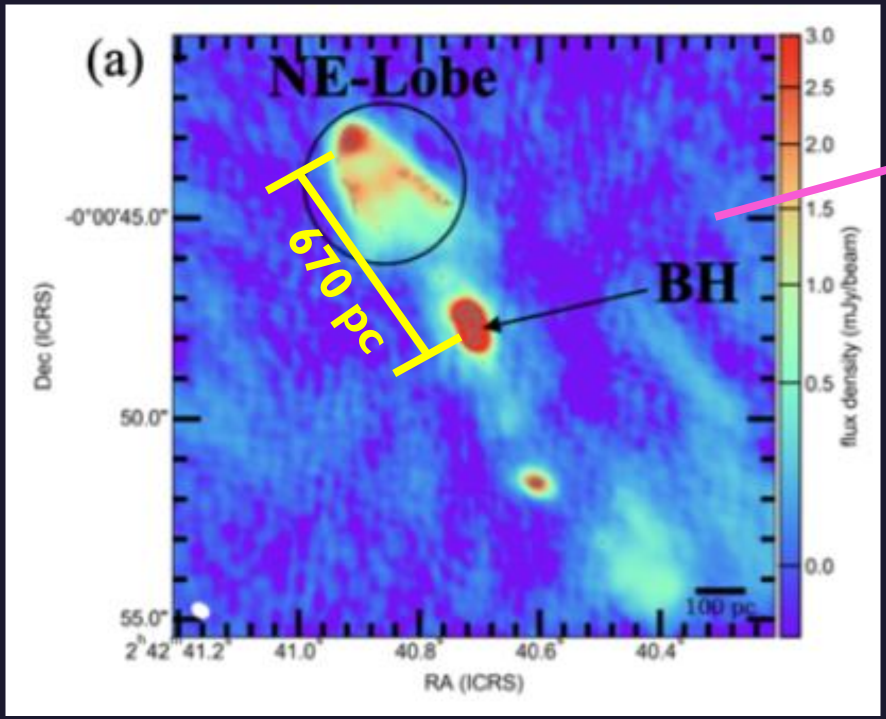

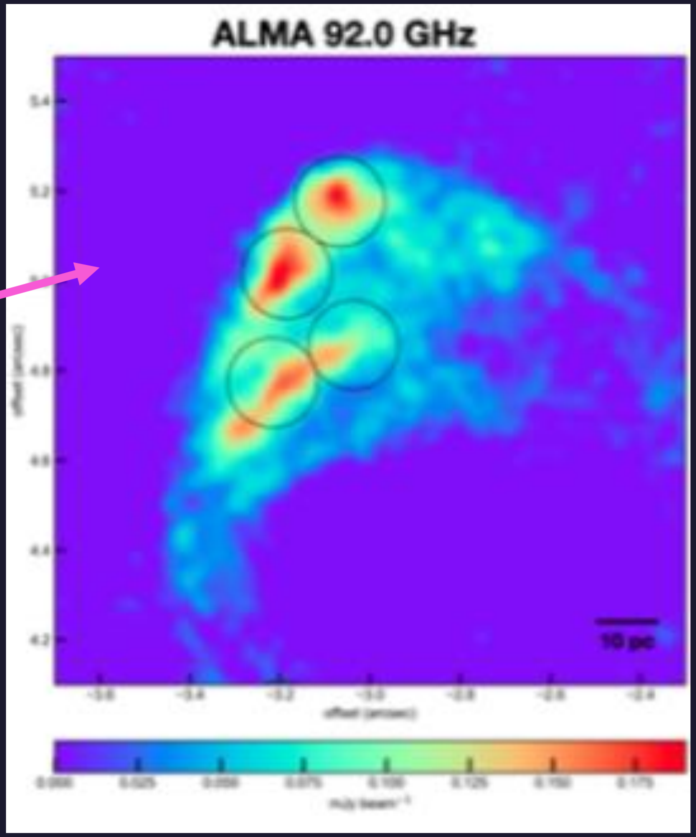

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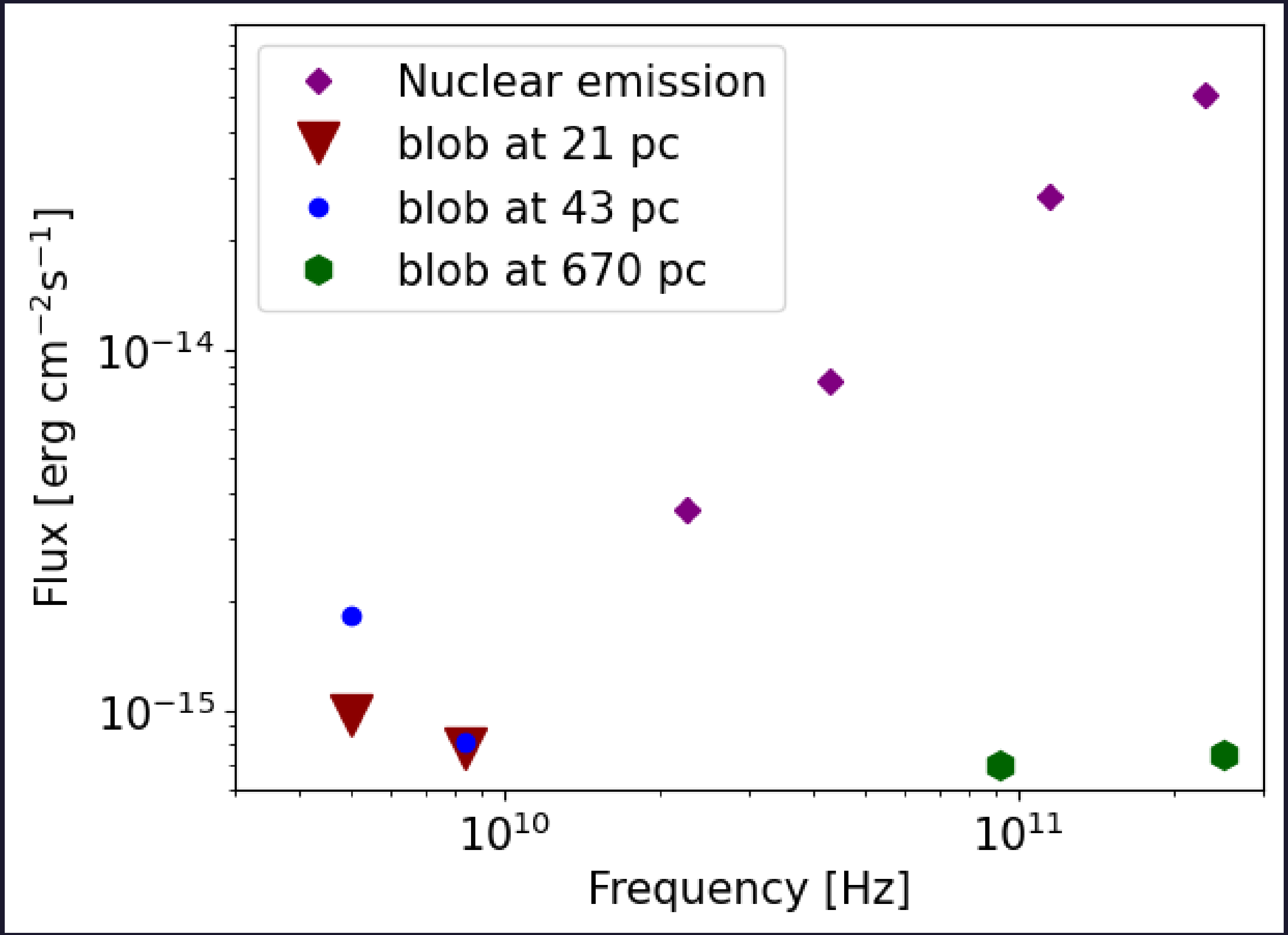

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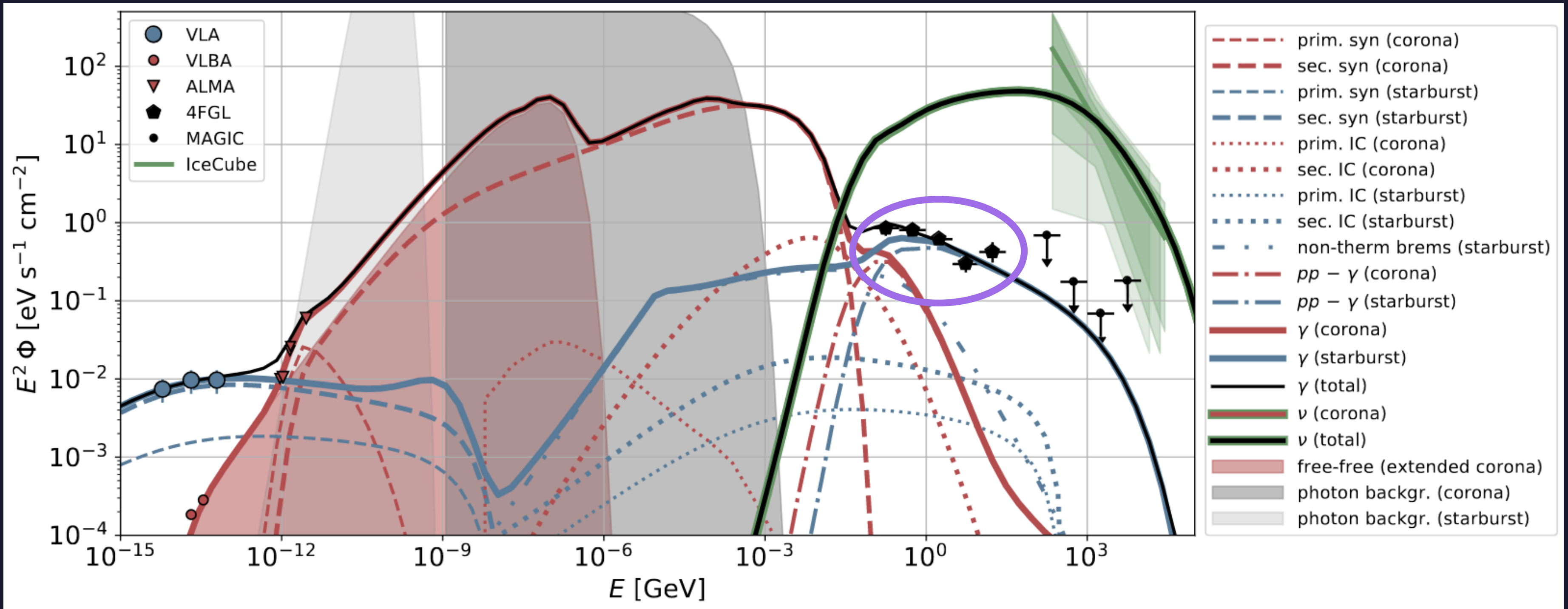
How to produce high energy photons from these blobs?

Possible γ-ray production scenarios:

- Inverse Compton
- $p\gamma$ interactions



Eichmann, …., **Salvatore**, …, 2022

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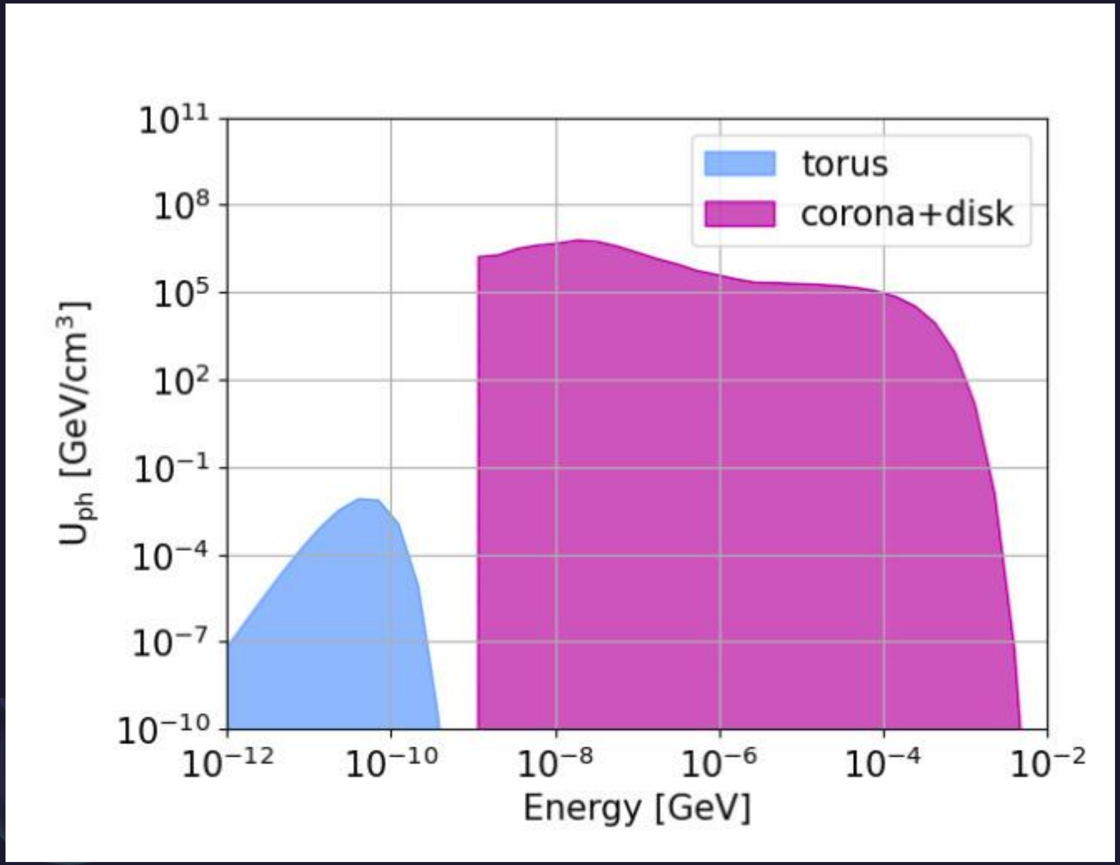
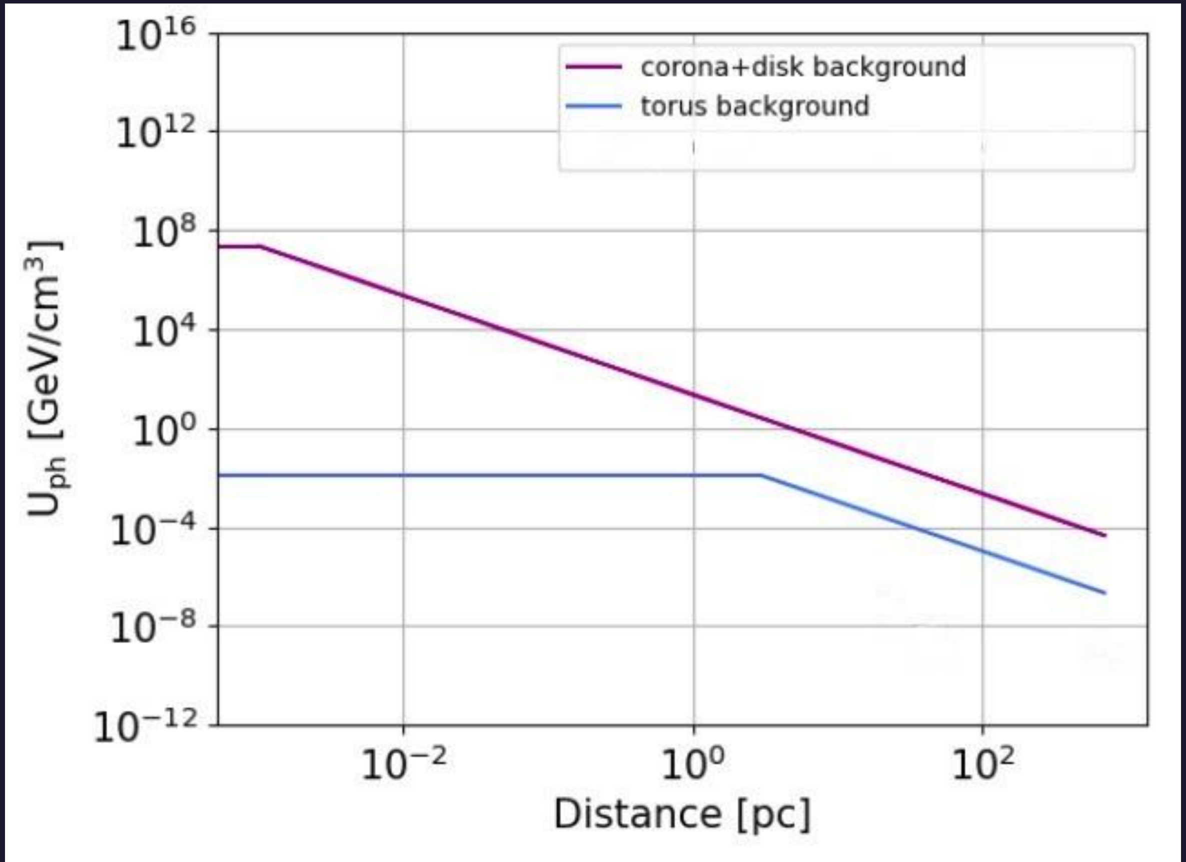
What is the Target Field to Consider?

- X-ray field from the **AGN-corona+disk** or IR field from the **torus**?





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What is the Target Field to Consider?

- X-ray photon field from the AGN-corona: $U_{COR} = \overline{U_{COR}} \left(\frac{d}{r_{COR}}\right)^{-2}$

- Synchrotron photon field: $U_{SYN} = \frac{L_{SYN}}{4\pi r_{blob}^2 c}$

- $L_{SYN} = 4\pi r_{blob}^2 c U_{COR} \left(\frac{d}{r_{COR}}\right)^{-2}$

$L_{SYN}(d = 21 \text{ pc}) = 6.5 \cdot 10^{43} \text{erg/s}$

$L_{SYN}(d = 43 \text{ pc}) = 5.4 \cdot 10^{43} \text{erg/s}$

$L_{SYN}(d = 670 \text{ pc}) = 2.7 \cdot 10^{43} \text{erg/s}$

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$$U_{COR} = \overline{U_{COR}} \left(\frac{d}{r_{COR}}\right)^{-2} \leftarrow U_{RAD}$$

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Production of γ-rays from Inverse Compton

- In the Thomson regime, assuming no absorption process is in action, this relation holds:

$$L_{IC} = L_{SYN} \frac{U_{RAD}}{U_B}$$

- From *(AG Pacholczyk, JA Roberts, 1971)*:

minimum total energy stored in the source → equipartition between particles and magnetic field energies:

$$E_B = \frac{3}{4}(1+k)E_e \longrightarrow B_{min} = (4.5)^{\frac{2}{7}}\,(1+k)^{\frac{2}{7}}\; c_{12}^{\frac{2}{7}}\; r_{blob}^{-\frac{6}{7}}\; L_{SYN}^{\frac{2}{7}}$$

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Production of γ-rays from Inverse Compton

$$L_{IC} = L_{SYN}\,\overline{\boldsymbol{U_{COR}}}\left(\frac{d}{\boldsymbol{r_{COR}}}\right)^{-2}\left(\frac{8\pi}{{B_{min}}^{2}}\right) \sim L_{\gamma} \sim 10^{40.92}\ \mathrm{erg/s}$$

$\mathbf{3.9 \cdot 10^{7}\ GeV/cm^{3}}$ $\mathbf{0.15\ mpc}$

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Production of γ-rays from Inverse Compton

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$\mathbf{U}_{COR}$: $\mathbf{3.9 \cdot 10^7\ GeV/cm^3}$

$\mathbf{r}_{COR}$: $\mathbf{0.15\ mpc}$

- For the blob at $d = 21$ pc: $L_{SYN}(d = 21\ \mathrm{pc}) = 2.0 \cdot 10^{43} \left(\frac{c_{12}}{1.3 \cdot 10^7}\right)^{\frac{4}{3}} \left(\frac{r_{blob}}{2.5\ \mathrm{pc}}\right)^{-4} \left(\frac{1+k}{101}\right)^{\frac{4}{3}}$ erg/s
- For the blob at $d = 43$ pc: $L_{SYN}(d = 43\ \mathrm{pc}) = 1.4 \cdot 10^{41} \left(\frac{c_{12}}{1.3 \cdot 10^7}\right)^{\frac{4}{3}} \left(\frac{r_{blob}}{4.6\ \mathrm{pc}}\right)^{-4} \left(\frac{1+k}{101}\right)^{\frac{4}{3}}$ erg/s
- For the blob at $d = 670$ pc: $L_{SYN}(d = 670\ \mathrm{pc}) \underset{\times 4}{=} 7.5 \cdot 10^{43} \left(\frac{c_{12}}{3.9 \cdot 10^6}\right)^{\frac{4}{3}} \left(\frac{r_{blob}}{5\ \mathrm{pc}}\right)^{-4} \left(\frac{1+k}{101}\right)^{\frac{4}{3}}$ erg/s

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Production of γ-rays from Inverse Compton

$$\rightarrow \quad L_{IC} = L_{SYN}\,\overline{U_{COR}}\left(\frac{d}{r_{COR}}\right)^{-2}\left(\frac{8\pi}{B_{min}{}^{2}}\right) \sim L_{\gamma} \sim 10^{40.92}\ \mathrm{erg/s}$$

$\overline{U_{COR}}$: $3.9 \cdot 10^{7}\ \mathrm{GeV/cm^3}$

r_{COR}: $0.15\ \mathrm{mpc}$

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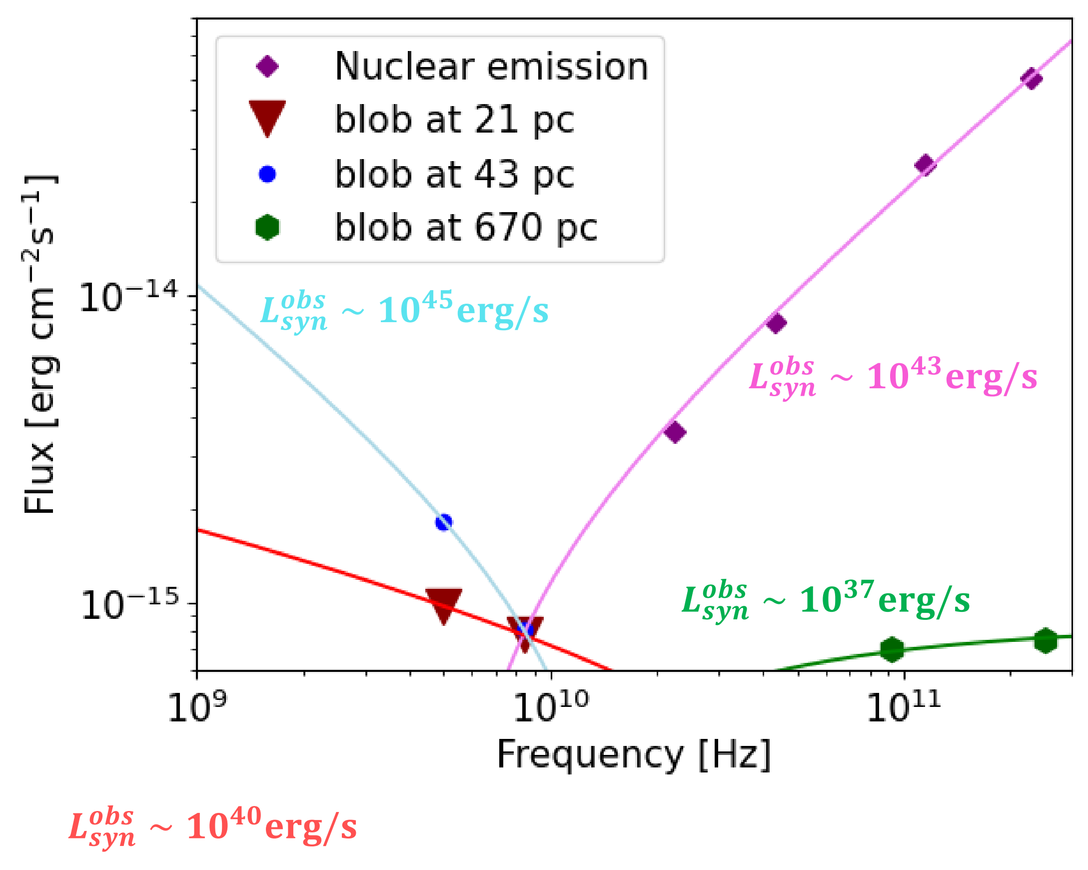

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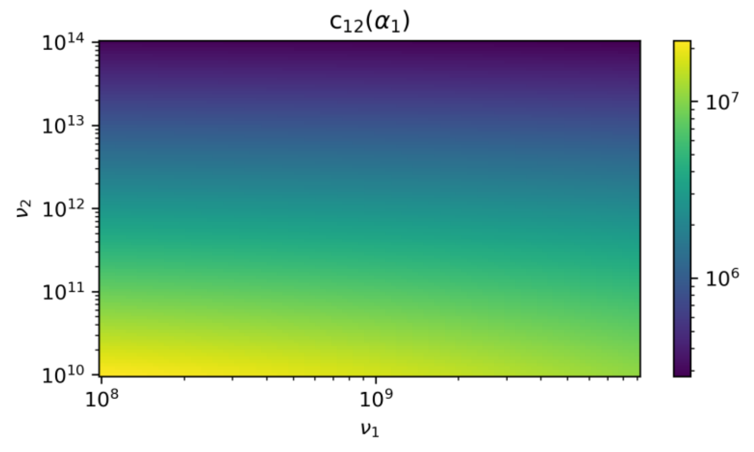
Production of γ-rays from Inverse Compton

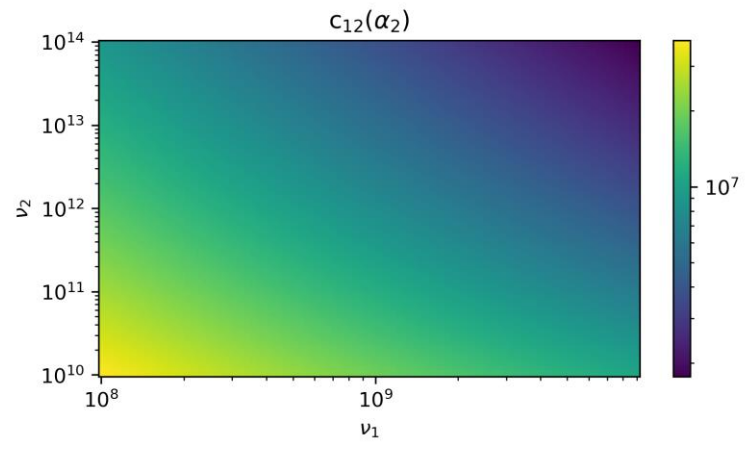
How robust is the dependence on c_{12} ?

$$c_{12} = c_2^{-1} c_1^{\frac{1}{2}} \frac{2\alpha-2}{2\alpha-1} \cdot \frac{\nu_1^{(1-2\alpha)/2} - \nu_2^{(1-2\alpha)/2}}{\nu_1^{1-\alpha} - \nu_2^{1-\alpha}} \left(c_1 = \frac{3e}{4\pi m^3 c^5}, c_2 = \frac{2e^4}{3m^4 c^7}\right)$$

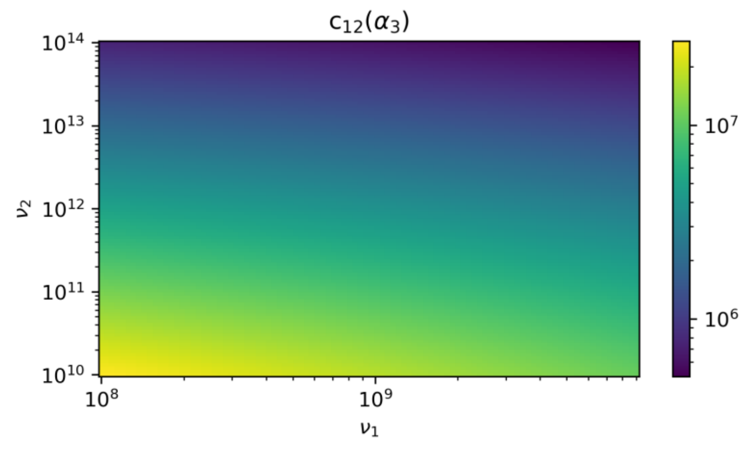
blob at 21 pc



blob at 43 pc



blob at 670 pc



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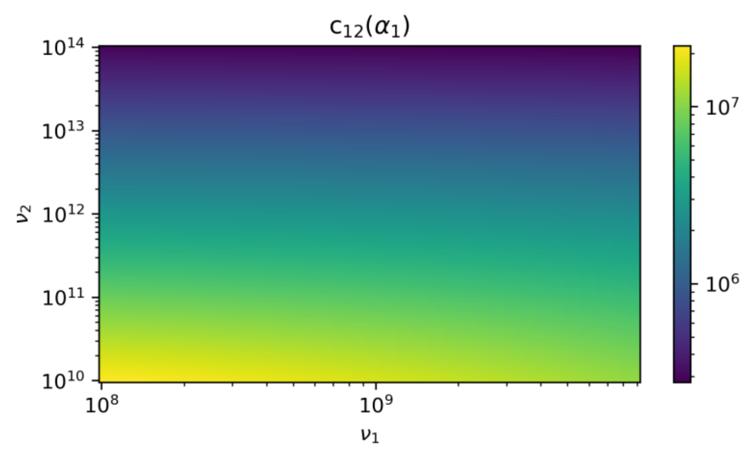
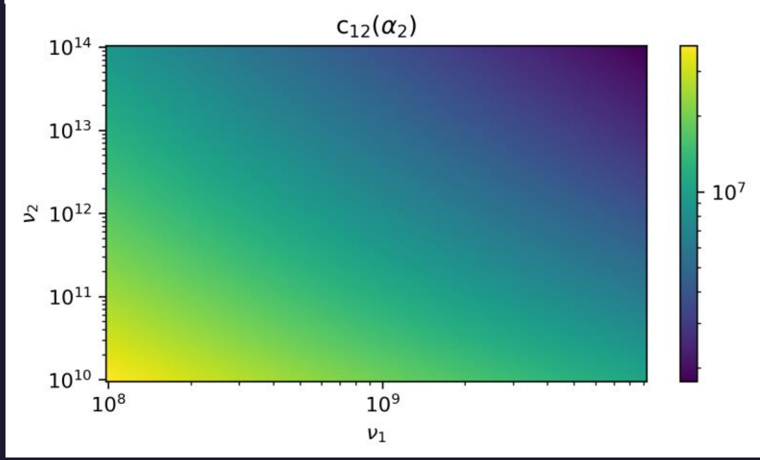
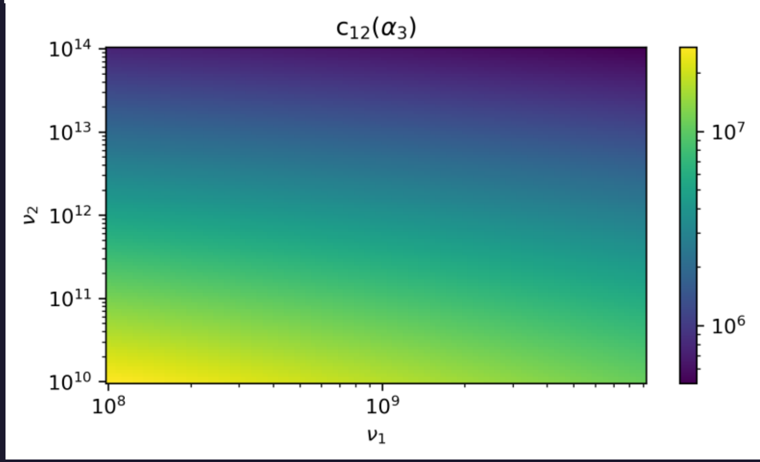
blob at 21 pc



blob at 43 pc



blob at 670 pc



→ $c_{12}^{\frac{4}{3}} \rightarrow \sim 10^8$ - 10^9

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Production of γ-rays from Inverse Compton

How robust is the dependence on ***k*** ?

$$k \simeq \left(\frac{m_p}{m_e}\right)^{\frac{q-1}{2}}$$

- q: spectral index of injected CRs
- If q ranges in $[2, 2.5]$ → k ranges in $\sim [40, 300]$

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Production of γ-rays from Inverse Compton

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→ $\boldsymbol{k^{\frac{4}{3}}} \rightarrow \sim \mathbf{10^{-1}}$ **- 1**

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Production of γ-rays from pγ interaction

$$L_\gamma = \int \mathrm{d}r^3 \int_{E_{\gamma,min}}^{E_{\gamma,max}} \mathrm{d}E_\gamma E_\gamma \sum_i \epsilon^i_{\pi\gamma}(E_\gamma)$$

$$\epsilon^i_{\pi\gamma}(E_\gamma) = \frac{A_i n_\mathrm{p}(\gamma_\mathrm{p})}{\gamma_\mathrm{p}^2} \int_{\frac{\varepsilon'_i}{2\gamma_\mathrm{p}}}^{\infty} \mathrm{d}\varepsilon \frac{n_\mathrm{ph}(\varepsilon)\left(\frac{r_\mathrm{cor}}{d}\right)^2}{\varepsilon^2} f(\gamma_\mathrm{p}, \varepsilon)$$

$$n_\mathrm{p}(\gamma_\mathrm{p}) \equiv \frac{dN}{dV d\gamma_\mathrm{p}} = n_0 \left(\frac{\gamma_\mathrm{p}}{\gamma_{0,\mathrm{p}}}\right)^{-q_\mathrm{p}} \quad \text{for} \quad \gamma_{\mathrm{p,min}} < \gamma_\mathrm{p} < \gamma_{\mathrm{p,max}}$$

$$U_\mathrm{p}^\mathrm{tot} = n_0 \int_{\gamma_\mathrm{p,min}}^{\gamma_\mathrm{p,max}} \mathrm{d}\gamma_\mathrm{p} n_\mathrm{p}(\gamma_\mathrm{p}) \leq \frac{P_\mathrm{jet}}{4\pi r_\mathrm{blob}^2 c E_{0,\mathrm{p}}}$$

$$L_\gamma = V \int_{10^{-1}\mathrm{GeV}}^{10^2\mathrm{GeV}} \mathrm{d}E_\gamma E_\gamma \sum_i \frac{A_i n_0 (\frac{\gamma_\mathrm{p}}{\gamma_{0,\mathrm{p}}})^{-q_\mathrm{p}}}{\gamma_\mathrm{p}^2} \int_{\frac{\varepsilon'_i}{2\gamma_\mathrm{p}}}^{\infty} \mathrm{d}\varepsilon \frac{n_\mathrm{ph}(\varepsilon)\left(\frac{r_\mathrm{cor}}{d}\right)^2}{\varepsilon^2} f(\gamma_\mathrm{p}, \varepsilon)\,.$$

→ $\gamma_{p,\mathrm{max}} \sim 1000$

$P_\mathrm{jet} = 10^{43}$ erg/s.

→ $\ll 10^{40.92}$ erg/s

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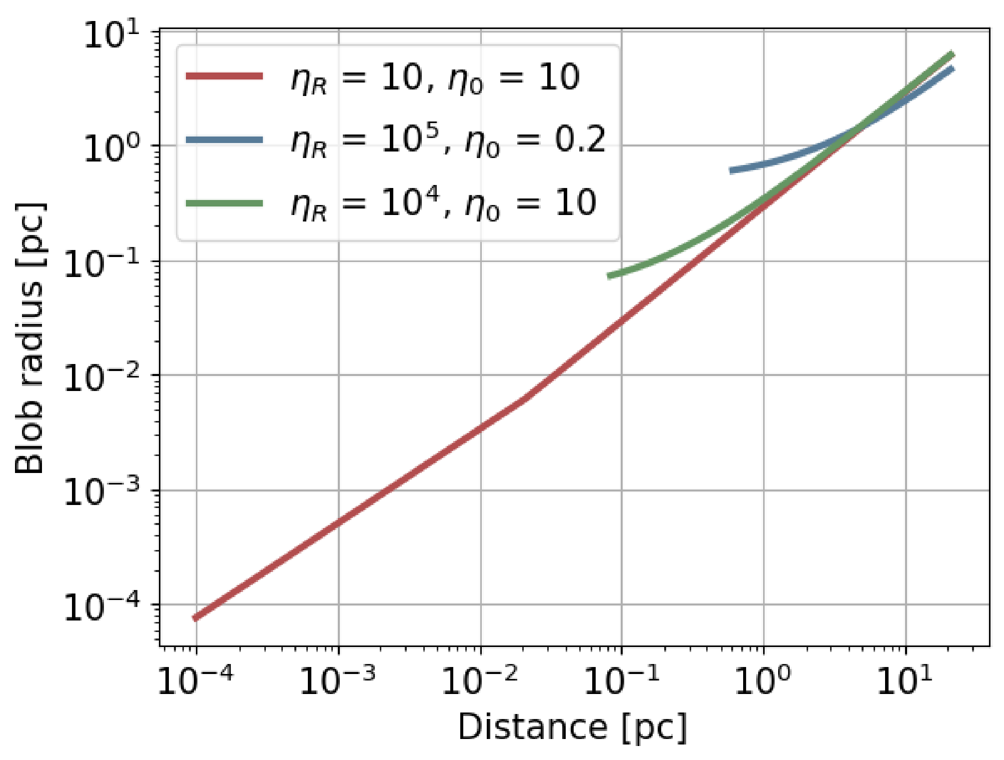
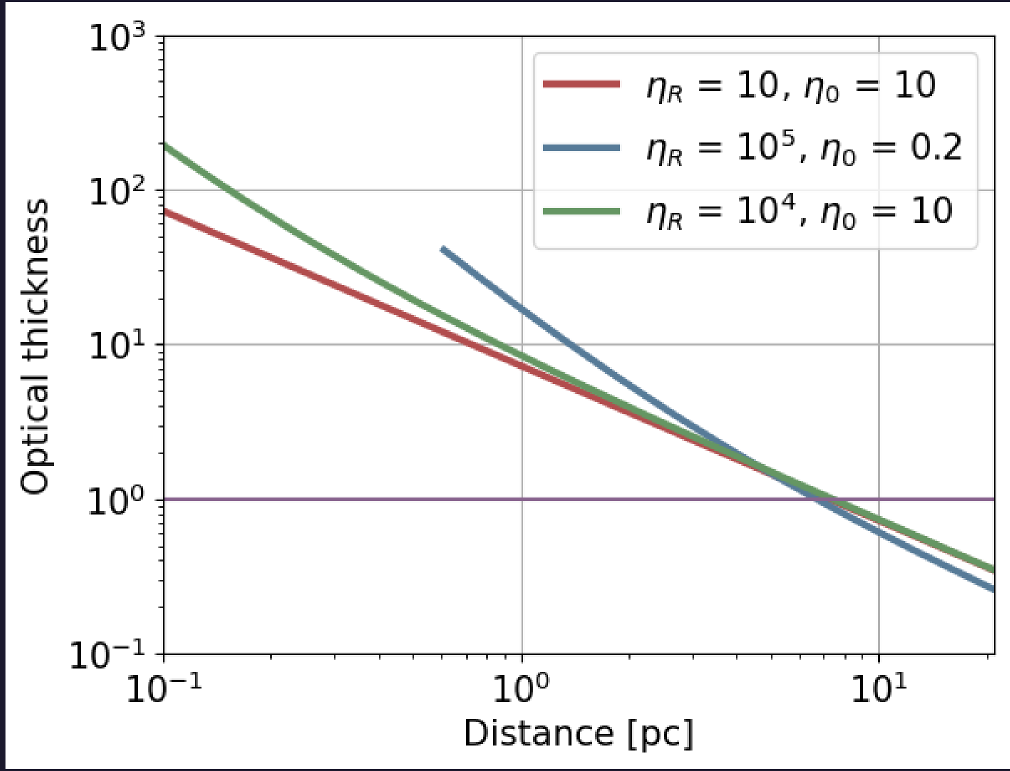
Optical thickness

$r_{\rm blob}(d) = \eta_{\rm R} d_0 + (d - d_0)\tan(\eta_0/\Gamma)$ with $d_0 = 6GM_0/c^2$



$E_\gamma = 10^2$ GeV



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Conclusions

- The gamma-rays could be predicted by the jet component in the leptonic scenario
- Uncertainty on the radio data → uncertainty on the emitted luminosity

In particular: blob radius + spectral index

Lenain et al., 2008: Fermi-LAT gamma-rays predicted by the jet

blob radius of 6 pc ↔ 2.7 pc

background photon field: torus ↔ corona + disk

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