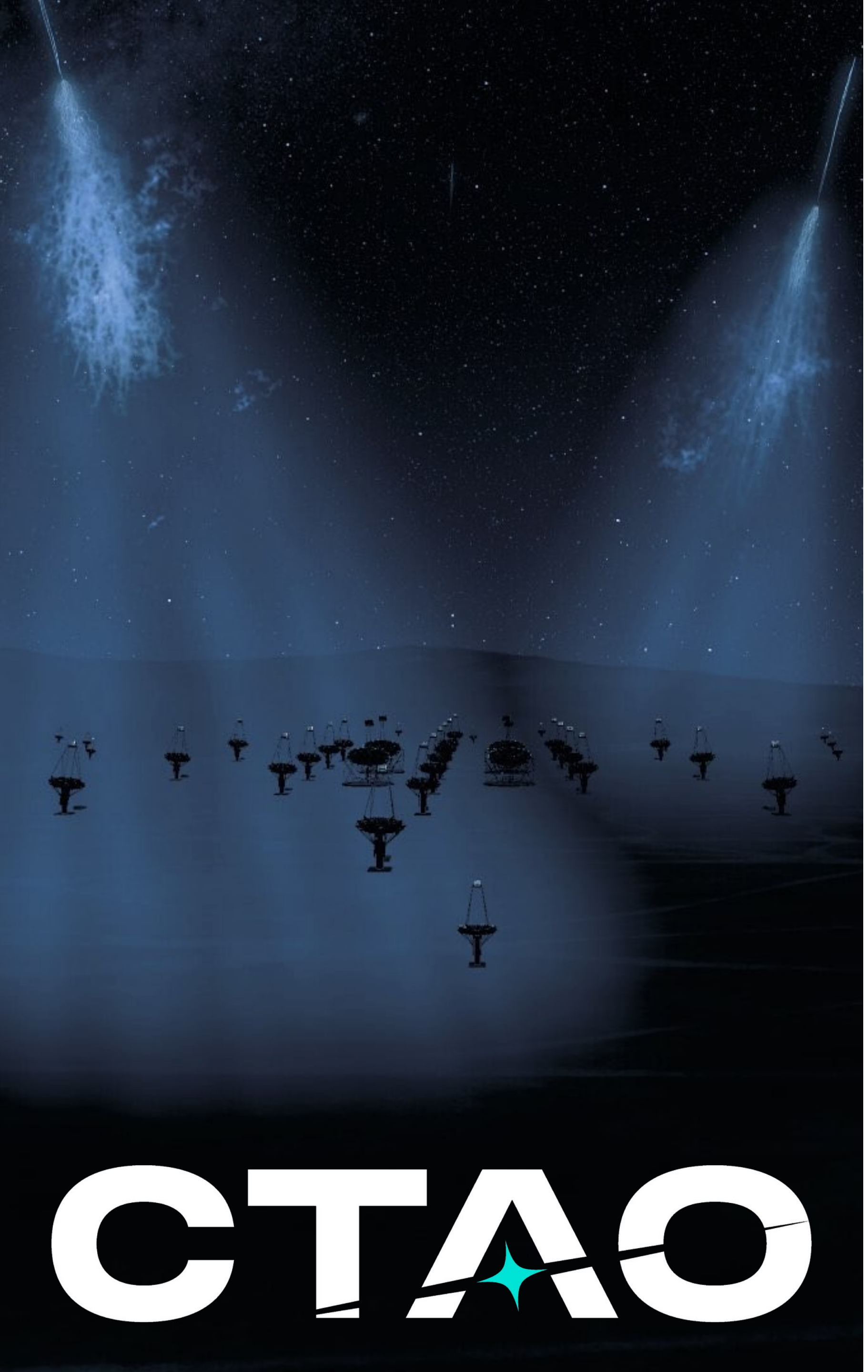

Searching for New Physics with CTAO

Analysis of the MSP and DM GCE

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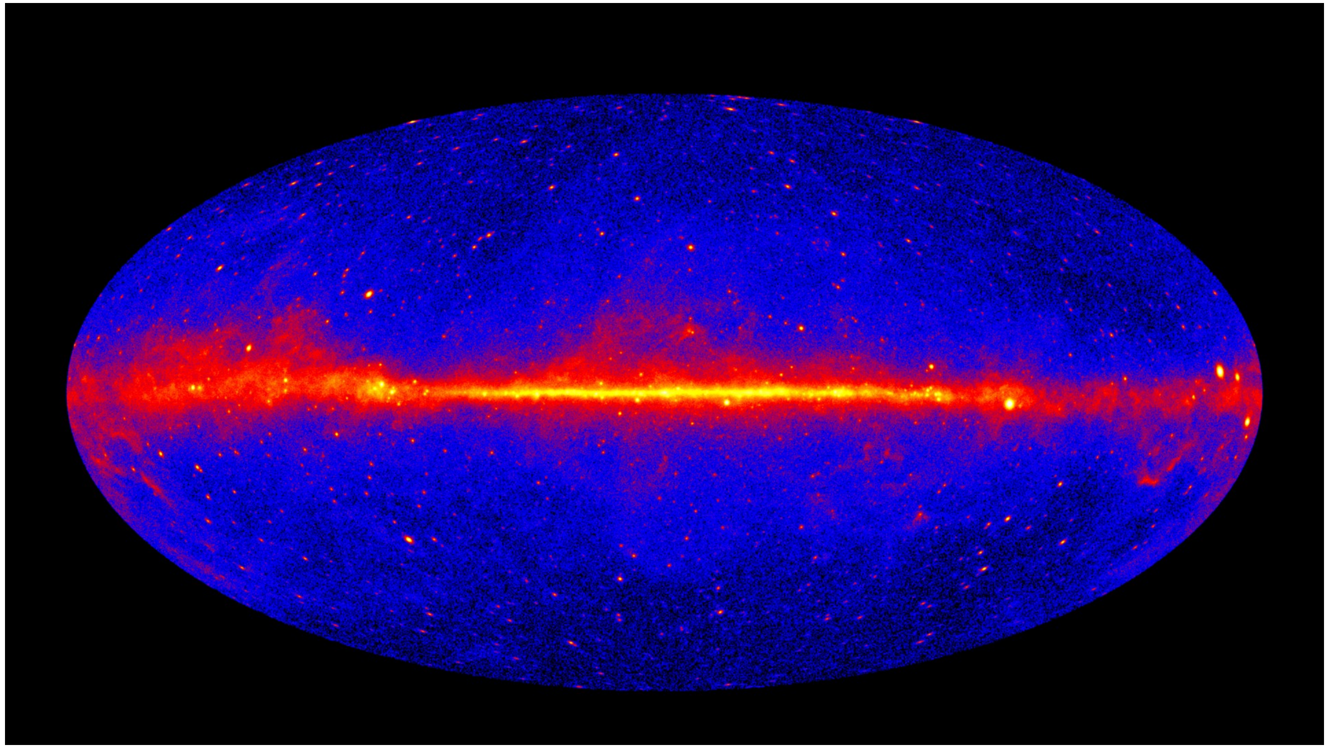
November 13th, 2024

Overview

- Motivations
- Physics Background
- Modelling and Analysis
- Next Steps
- Questions

Motivations

- Galactic Centre Excess (GCE): Unexpectedly high flux of gamma rays from the centre of the Milky Way galaxy.
- May be consistent with either annihilation of dark matter, or an as-yet unresolved population of Millisecond Pulsars (MSPs).
- CTAO can attempt to determine which by looking at TeV gamma ray flux from the galactic centre.
- Hence, we model the gamma ray emission from the MSP source and the Dark Matter source, looking for differences in morphology at high energies.



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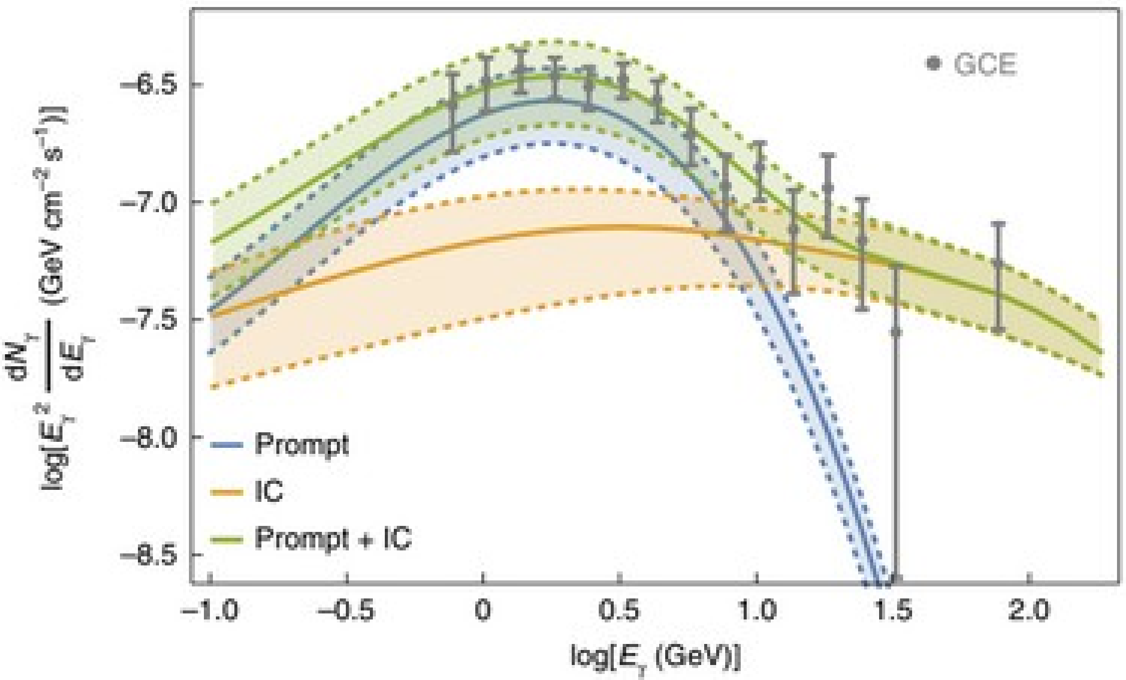
Physics Background

- Previous work by (Gautam et al., 2022):
  - A population of MSPs could explain the Fermi GCE.
  - Predicts that CTAO should be able to resolve a small number of MSPs.
  - Uses “prompt” emission and inverse Compton emission for gamma rays.
    - Prompt component is curvature radiation from electrons and positrons trapped in the MSP’s magnetosphere.
    - About 10% of MSP rotational kinetic energy goes into prompt component.
    - Inverse Compton occurs when relativistic electrons transfer energy to soft photons.

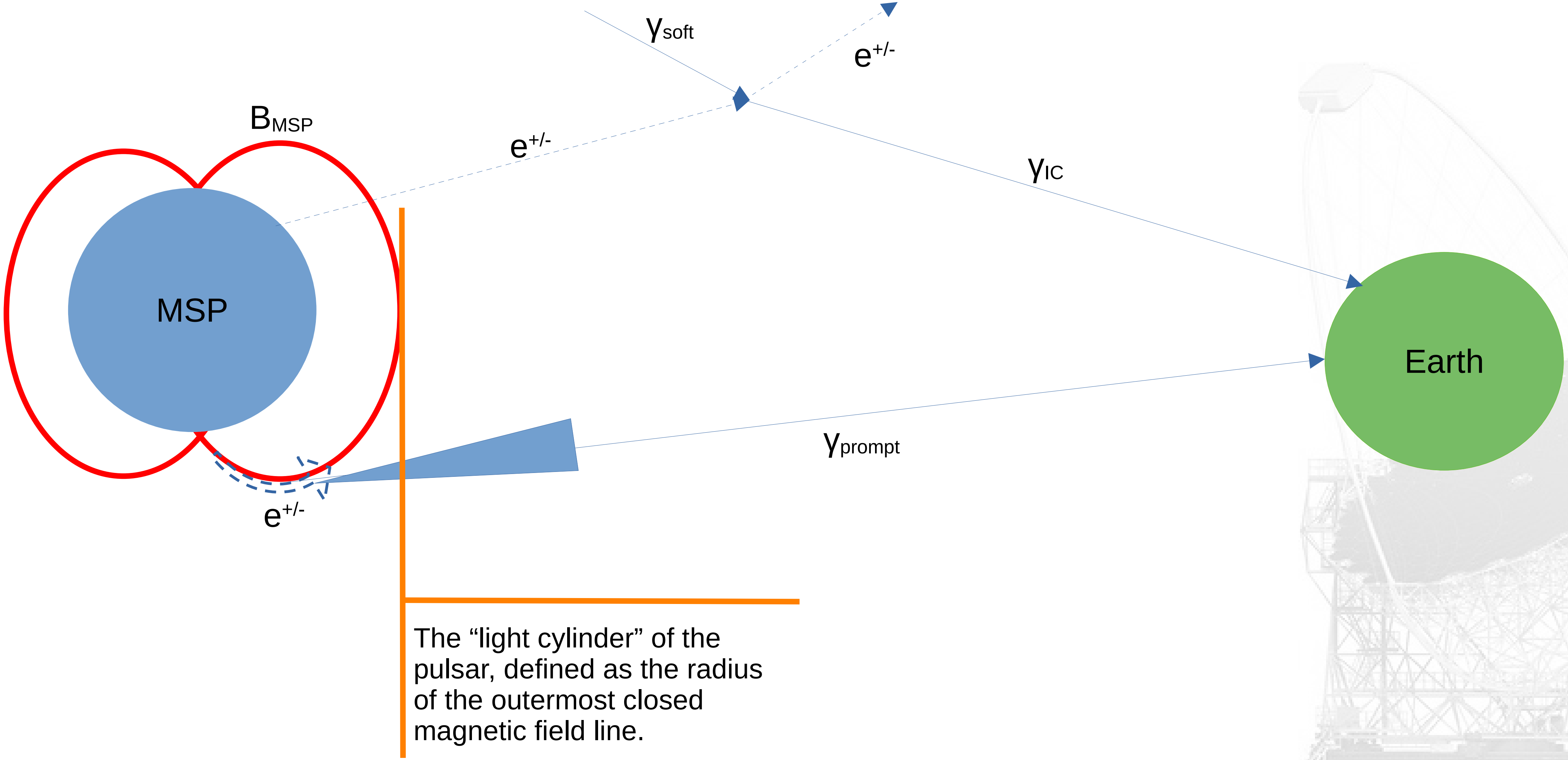


GeV gamma ray spectrum from (Gautam et al., 2022).

The prompt emission of a single MSP is pulsed. The net emission of a population, however, is steady. We only consider the population as a whole, so we neglect the pulsed nature of the prompt component.

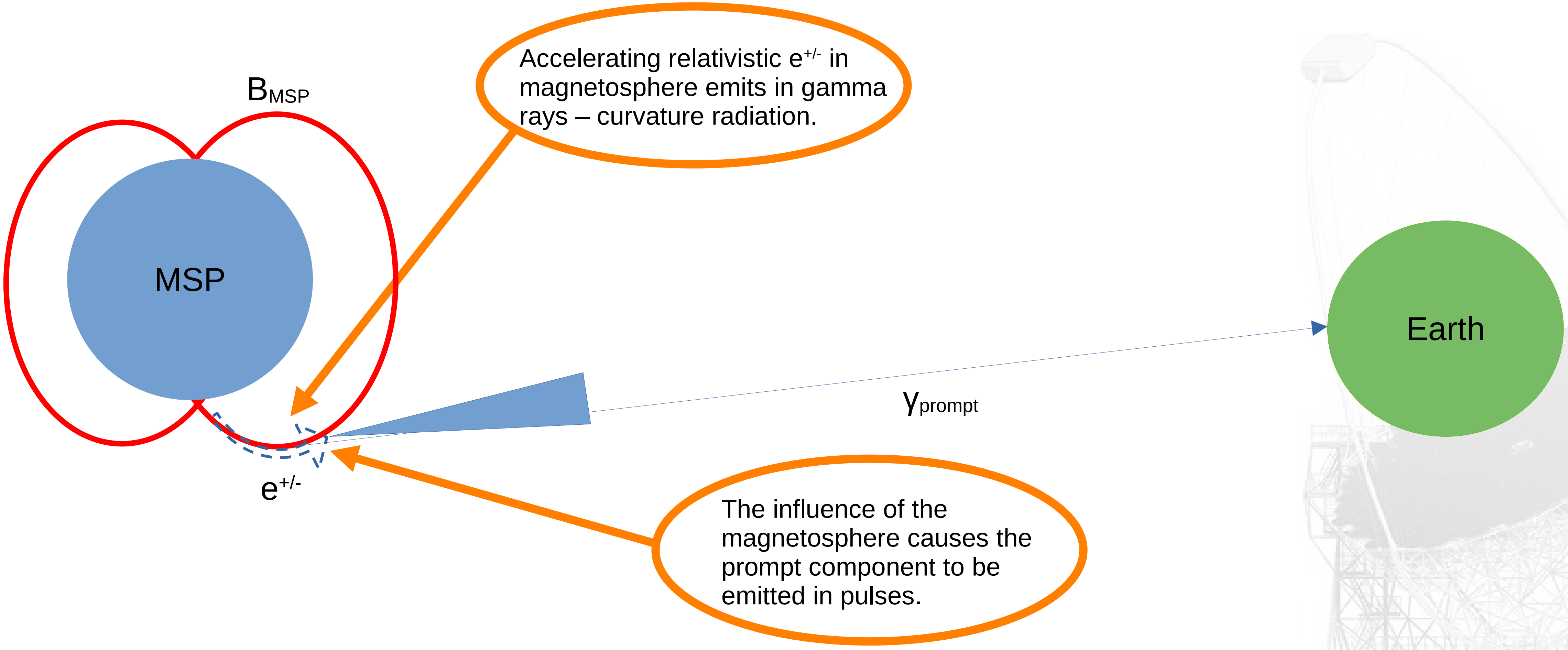
Physics Background

- Emission of gamma rays from an MSP:



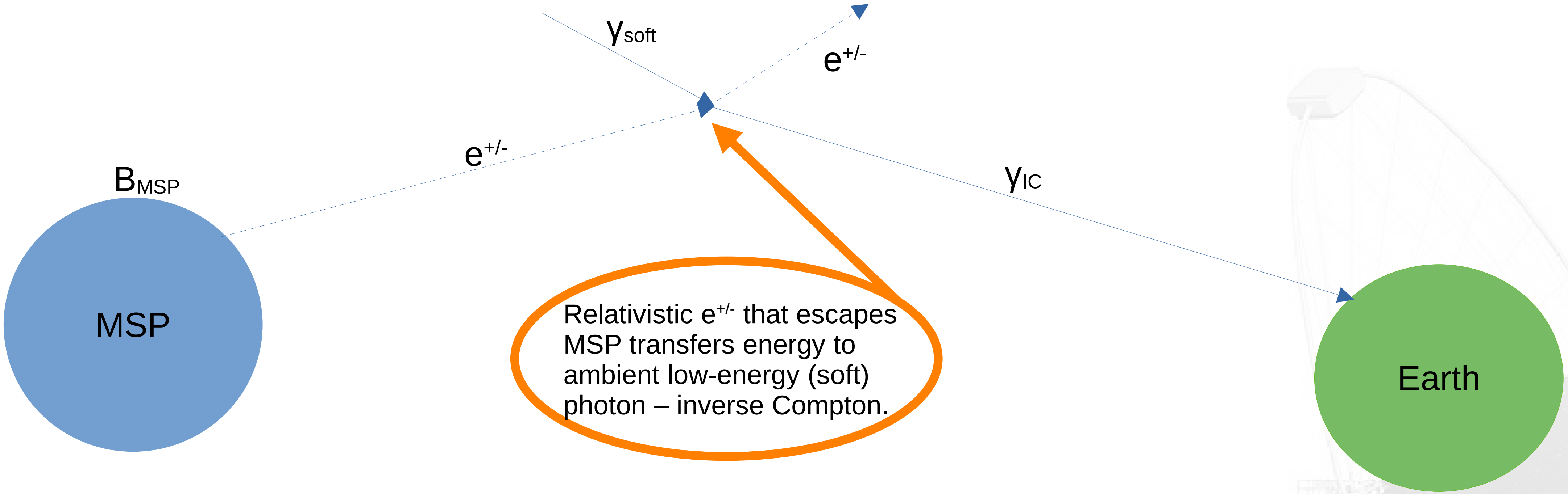
Physics Background

- Prompt emission from an MSP:



Physics Background

- Inverse Compton emission from an MSP:



Physics Background

- What happens when these gamma rays hit the atmosphere?
- Cherenkov radiation:
  - Charge moving through air induces dipoles in surrounding molecules.
  - Dipole radiation interferes destructively unless the moving charge surpasses the local speed of light.

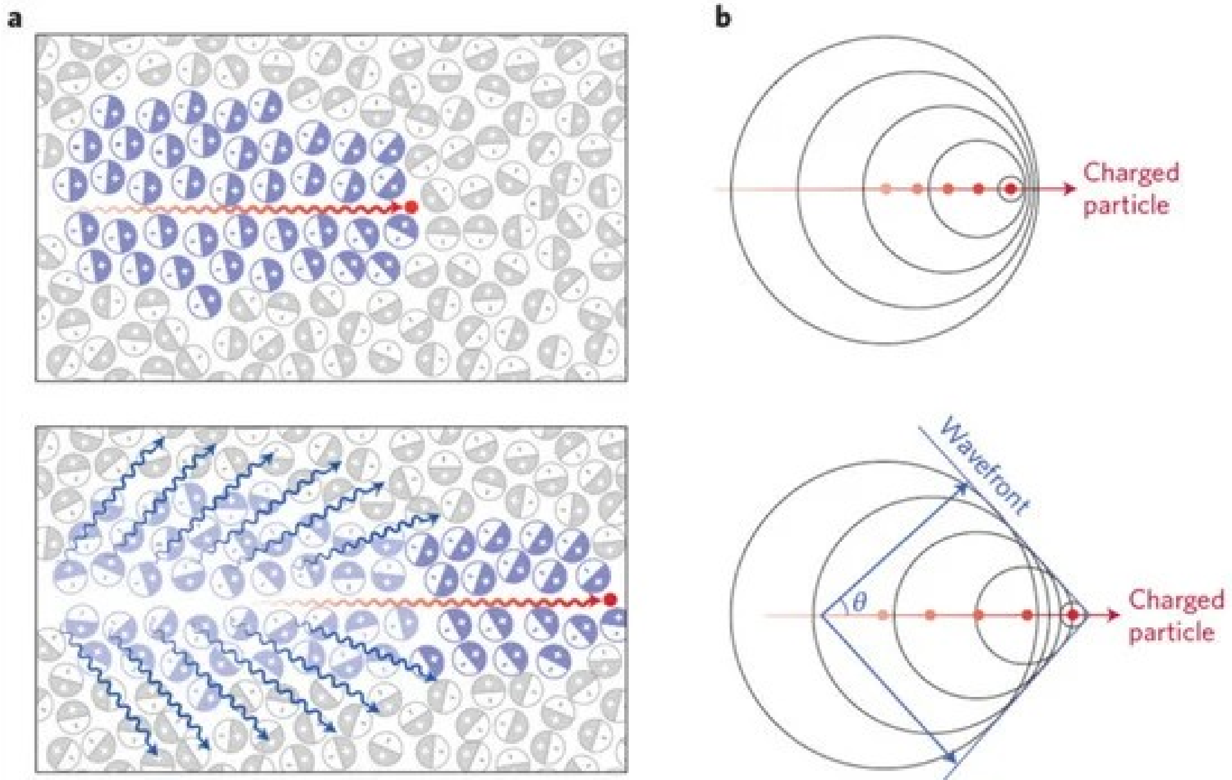
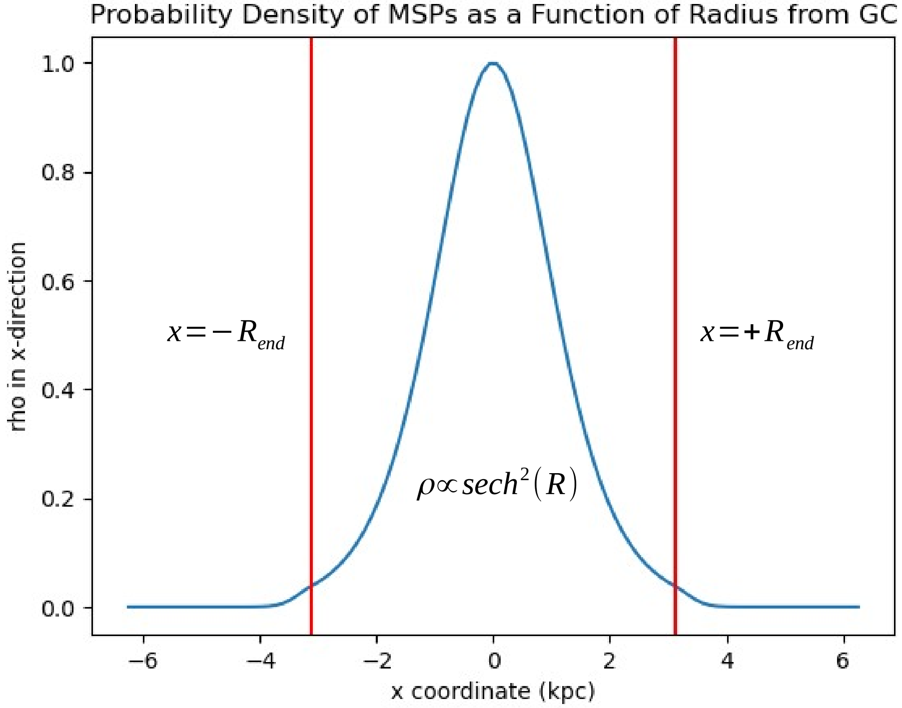


Image credit: Wang X, Li L, Li J, Wang P, Lang J, Yang Y. Cherenkov Luminescence in Tumor Diagnosis and Treatment: A Review. Photonics. 2022; 9(6):390. https://doi.org/10.3390/photonics9060390

Modelling - MSPs

- Several different models may be used, as long as they explain the Fermi GCE.
- Spatial Distribution: (Ploeg et al.,2020)
  - Use a “boxy bulge” probability density.
  - Randomly generate ~130000 MSPs.
  - Randomly assign each MSP a set of properties from a list (luminosity, prompt cutoff energy, spectral index).



- Prompt Emission: (Gautam et al., 2022)
  - Use an ECPL for emission in $TeV^{-1}s^{-1}$.
  - Apply parameters for each MSP individually and sum to obtain total prompt flux.

$$F(E)=K*\left(\left(\frac{E}{1\,GeV}\right)^{-Q}\right)*\exp\left(-\left(\frac{E}{E_{cut}}\right)^{2/3}\right)$$

- Other Emissions:
  - Electron-positron spectrum can be related to prompt spectrum – use for inverse Compton.

Modelling - MSPs

- Boxy Bulge Spatial Distribution: (Freudenreich., 1998),(Ploeg et al., 2020)

$$\rho_{\text{boxy bulge}}(R_s) \propto \text{sech}^2(R_s) \times \begin{cases} 1 & R \leq R_{\text{end}} \\ \exp(-(R - R_{\text{end}})^2/h_{\text{end}}^2) & R > R_{\text{end}} \end{cases}$$

- Where: $R_s^{C_\parallel} = R_\perp^{C_\parallel} + \left(\frac{|z'|}{0.4425\ \text{kpc}}\right)^{C_\parallel}$

- And: $R_\perp^{C_\perp} = \left(\frac{|x'|}{1.696\ \text{kpc}}\right)^{C_\perp} + \left(\frac{|y'|}{0.6426\ \text{kpc}}\right)^{C_\perp}$

- R_{end} = 3.128 kpc; h_{end} = 0.461 kpc; $C_{||}$ = 3.501; $C_{\perp}$ = 1.574. These are best fit values.
- The coordinates (x',y',z') are in the Boxy Bulge frame, which is rotated relative to the galactic centre frame by 13.79^{o} about the z axis, and then 0.023^{o} about the new y axis.
- In the galactic centre frame, Earth is located at ($-R_0$,0,0), where R_0 is approximately 8.3 kpc.

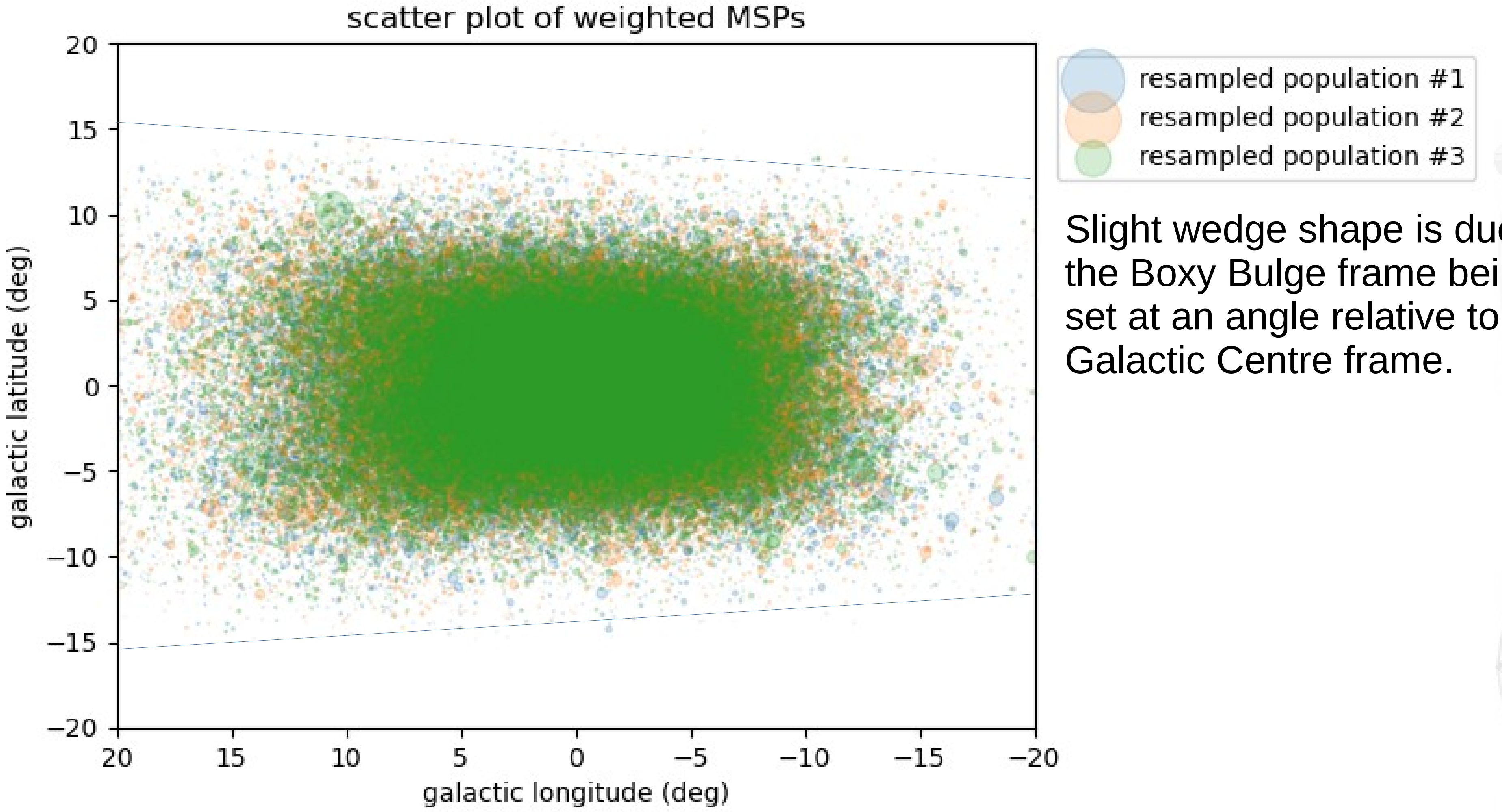
Modelling - MSPs

- Boxy Bulge Spatial Distribution: (Freudenreich., 1998),(Ploeg et al., 2020)

$$\rho_{\text{boxy bulge}}(R_s) \propto \text{sech}^2(R_s) \times \begin{cases} 1 & R \leq R_{\text{end}} \\ \exp(-(R - R_{\text{end}})^2/h_{\text{end}}^2) & R > R_{\text{end}} \end{cases}$$

- Use this distribution to define a probability density, and then apply rejection sampling to get positions of the population:
  - For each coordinate (x,y,z) in the galactic frame, pick a random number in some large range.
  - Transform these coordinates to the Boxy Bulge frame.
  - Generate the rho value for these coordinates. This value will always be in the range [0,1].
  - Treat this as a probability: accept the coordinates if a random number is lower than the rho value. Then generate a new set of coordinates.
  - Repeat until we have ~130000 positions. Obtain longitudes and latitudes using simple geometry.

Modelling - MSPs



Slight wedge shape is due to the Boxy Bulge frame being set at an angle relative to the Galactic Centre frame.

Modelling - MSPs

- From here, associate a given set of three MSP parameters (prompt luminosity, prompt cutoff energy, prompt spectral index) with each position. Generate a prompt spectrum for each:

$$F(E)=K*\left(\left(\frac{E}{1\,GeV}\right)^{-Q_{prompt}}\right)*\exp\left(-\left(\frac{E}{E_{cut}}\right)^{2/3}\right)$$

- Here, Q is the spectral index, and K is a normalisation defined by:

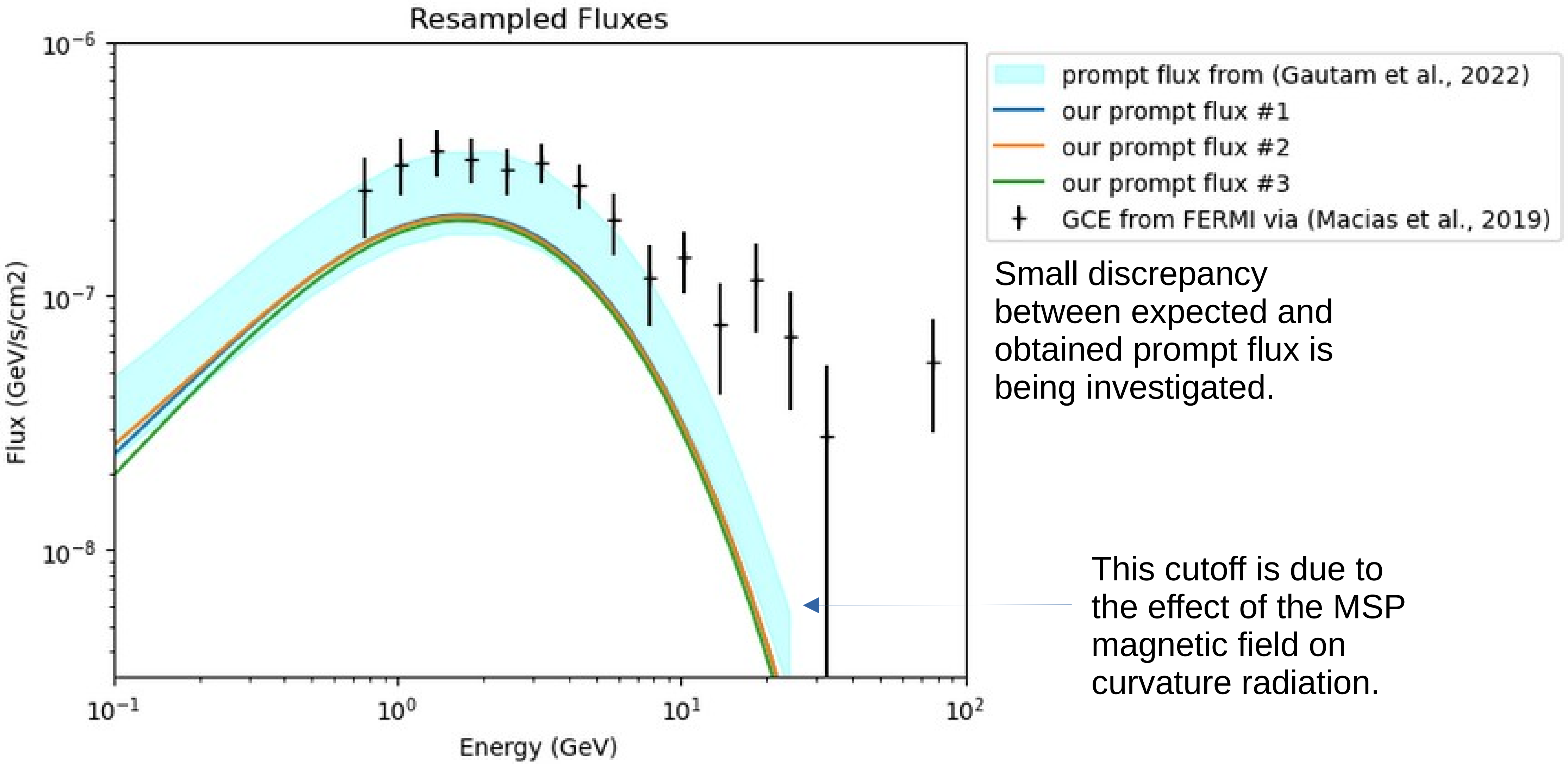
$$K=\frac{L_{prompt}}{4\pi(r_{GC})^2}/X$$

- Where r_{GC} is the distance to Earth in the Galactic Centre frame, and X is given by:

$$X=-\left(\frac{3}{2}\right)\left(\left(\frac{E_{cut}}{1\,GeV}\right)^{2/3}\right)\left(\Gamma\left(3-3\frac{Q_{prompt}}{2}\right)\right)\left(\Gamma^{x}\left(\left(3-3\frac{Q_{prompt}}{2}\right),\left(\frac{E_{max}}{E_{cut}}\right)^{2/3}\right)-\Gamma^{x}\left(\left(3-3\frac{Q_{prompt}}{2}\right),\left(\frac{E_{min}}{E_{cut}}\right)^{2/3}\right)\right)$$

- The symbol Γ^{X} represents the regularised upper incomplete gamma function. The symbol Γ is the normal gamma function.
- The power of (2/3) in the exponential is a phenomenological “beta” factor.

Modelling - MSPs



Small discrepancy between expected and obtained prompt flux is being investigated.

This cutoff is due to the effect of the MSP magnetic field on curvature radiation.

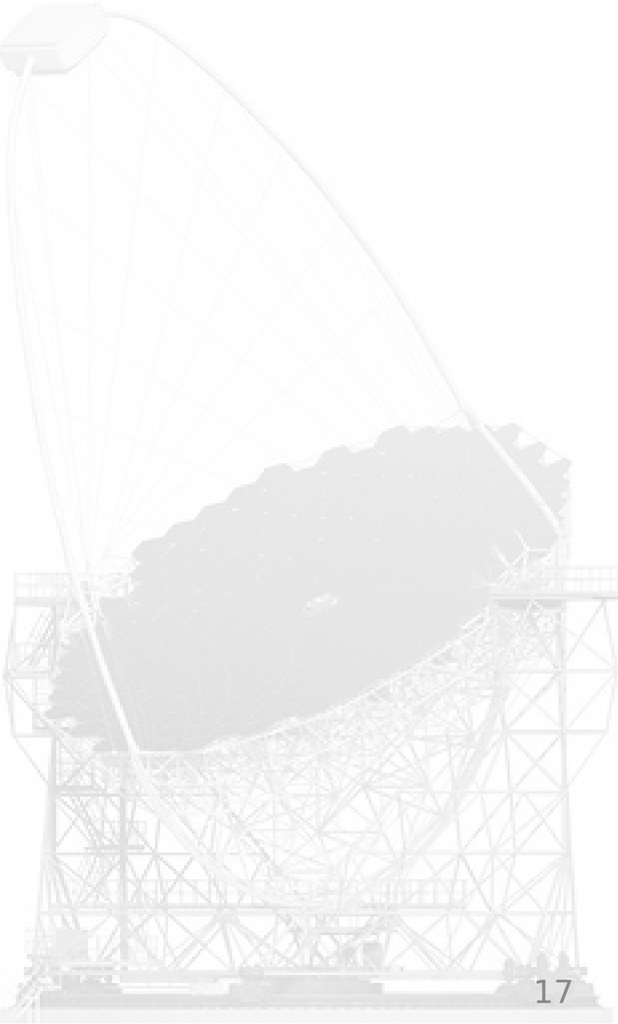
CTAO Analysis - MSPs

- Generate a population of MSPs with associated galactic longitude and latitude, distance, and differential prompt flux.
- Prompt emission parameters (spectral index and cutoff energy) can be related to those of electron-positron pairs:
  - $E_{cut,prompt} = \left(\frac{3\hbar c}{2 r_c}\right)\left(\frac{E_{cut,elec}}{m_e}\right)^3$
  - $Q_{prompt} = \left(\frac{Q_{elec} - 1}{3}\right)$
- Where r_c is the radius of the light-cylinder. This assumes the electron emission has the same form as the prompt emission.
- Multiply by loss times to obtain a steady-state $e^{+/-}$ spectrum for use in determining gamma ray emission from $e^{+/-}$ pairs.
- Apply propagation software to determine the distance travelled before interacting.
  - More energetic $e^{+/-}$ should interact sooner, causing the MSP emission to form clumps at higher energies.
- Flux from interactions then applied to generate a skymap in prompt and inverse Compton gamma rays.

Next Steps

- MSP modelling and analysis is currently underway.
- Spatial distribution sampling has been implemented.
- Prompt emission modelling is functional, inverse Compton is in progress.
- Beyond this, generation of prompt spectral parameters may be improved.
- There is a possibility of simulating dark matter emission after the MSP model is fully implemented.
  - Production of other particles by dark matter could also be considered.
- Compare spatial and spectral morphologies of MSP and dark matter models at various energies.
- Potential to look at radio and x-ray emissions from both MSP and DM sources. Equivalent to including synchrotron emission for MSPs.

Questions?



Backup Slides

- Synchrotron emission from an MSP: