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Extreme Astrophysics
- A “How-To” from a non-Theorist

ANITA Summer School 2023:
Astroparticle Physics and Extreme Transients

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Questions

- Leptonic or hadronic? Spectral distribution?
- Photon fields? Energy density? Temperature?
- Environment? Magnetic field? Number density?

- Distance?
- AGN alignment? Obscured?

- Steady-state sufficient? Time evolution needed (specifically for electrons)?

- Extended sources? Spatial distribution needed?
- Variable sources?

For introduction see Gavin Rowell's lecture (Monday morning)

How-Tos

Programming Tools & Libraries

- python
- astropy
- jupyter notebooks
- Google colab

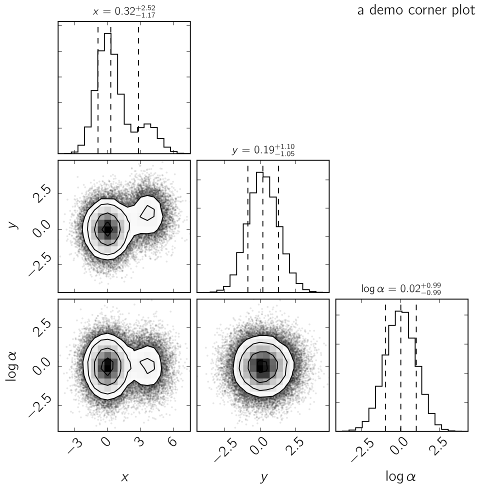
https://colab.research.google.com/

Modelling Tools & Packages

- naima
- Gamera
- agnpy
- gammapy

Statistics

- MCMC fits
- Corner plots and posterior distributions



Software: Naima

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- Python package
- Affiliated with astropy

- Computation of non-thermal radiation from relativistic particle populations
- Fitting models to observational data

- https://naima.readthedocs.io
- https://github.com/zblz/naima

V. Zabalza (2015), *naima: a Python package for inference of relativistic particle energy distributions from observed non-thermal spectra*, Proc. ICRC 2015, arXiv:1509.03319

Particle Populations

- Relativistic **electrons** and / or **protons**
- Typical particle distribution functions:
  - PowerLaw

$$f(E) = A(E/E_0)^{-\alpha}$$

  - ExponentialCutoffPowerLaw

$$f(E) = A(E/E_0)^{-\alpha} \exp(-(E/E_{cutoff})^{\beta})$$

  - LogParabola

$$f(E) = A\left(\frac{E}{E_0}\right)^{-\alpha-\beta\log\left(\frac{E}{E_0}\right)}$$

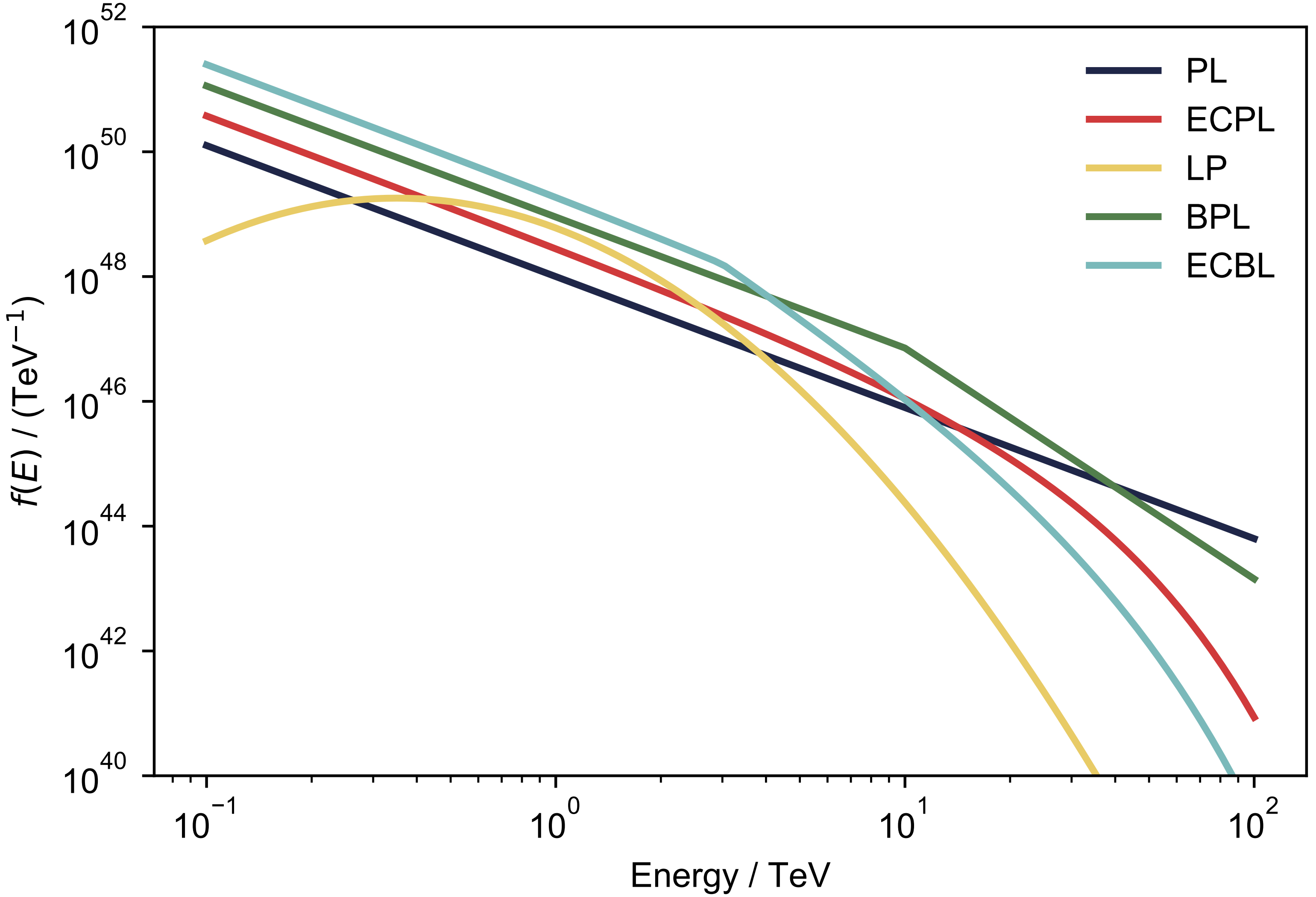
  - BrokenPowerLaw

$$f(E) = \begin{cases} A(E/E_0)^{-\alpha_1} & : E < E_{break} \\ A(E_{break}/E_0)^{\alpha_2-\alpha_1}(E/E_0)^{-\alpha_2} & : E > E_{break} \end{cases}$$

  - ExponentialCutoffBrokenPowerLaw

$$f(E) = \exp(-(E/E_{cutoff})^{\beta}) \begin{cases} A(E/E_0)^{-\alpha_1} & : E < E_{break} \\ A(E_{break}/E_0)^{\alpha_2-\alpha_1}(E/E_0)^{-\alpha_2} & : E > E_{break} \end{cases}$$

Naima: Particle Populations



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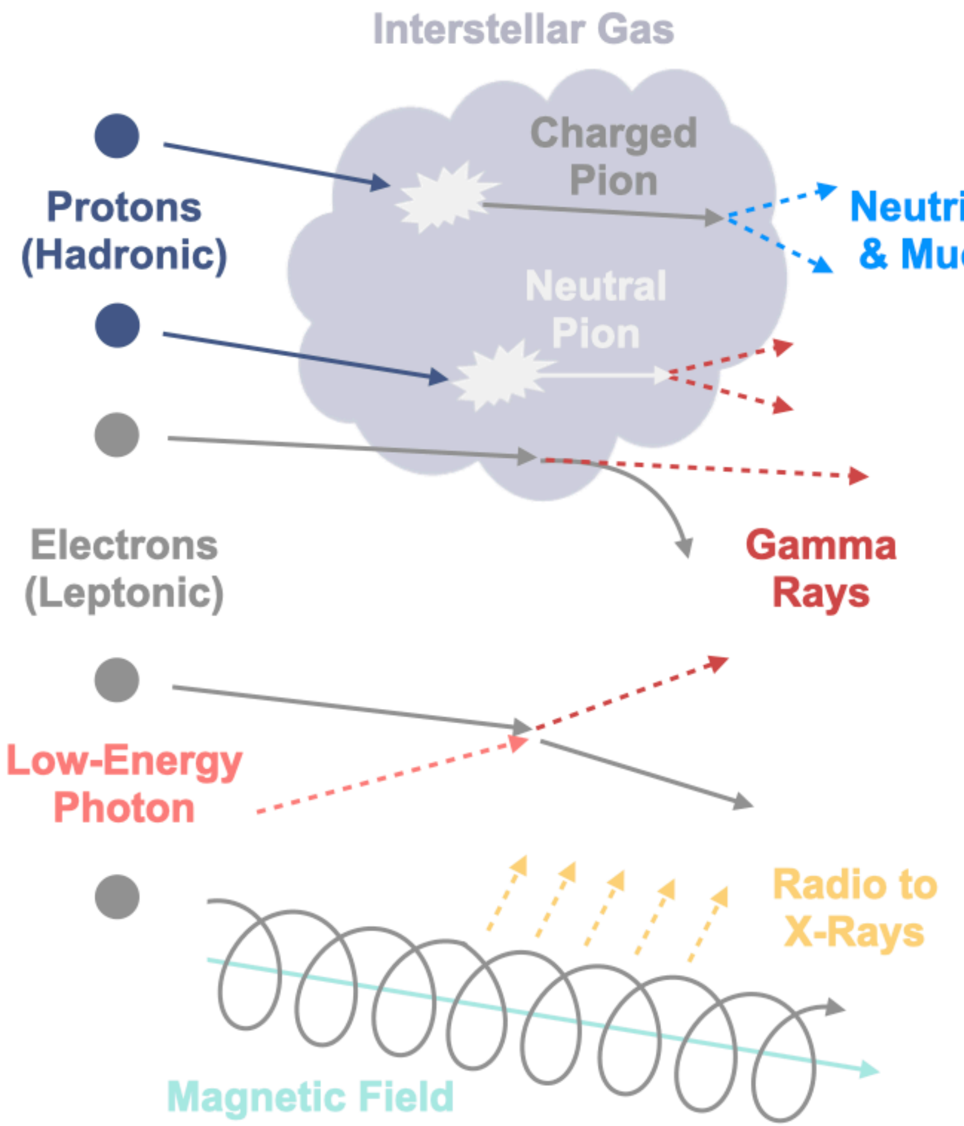
Radiative Models / Processes



Pion Decay

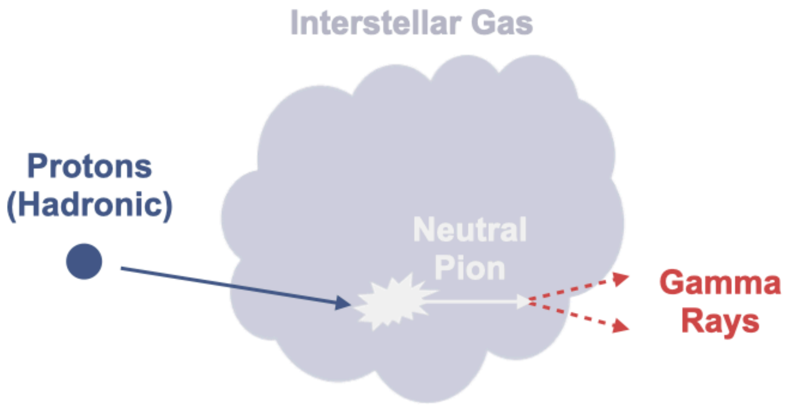
Bremsstrahlung

Inverse Compton

Synchrotron

Pion Decay

- Proton-proton inelastic collisions produce heavy particles, producing many pions, which decay to gamma rays



- Corresponding gamma-ray spectrum:

$$\Phi_\gamma(E_\gamma) = 4\pi n_{\mathrm{H}} \int \frac{d\sigma}{dE_\gamma}(T_p, E_\gamma) J(T_p) dT_p$$

target proton density

gamma-ray differential cross section

proton spectrum

E. Kafexhiu, F. Aharonian, A. Taylor, G. Vila (2014), *Parametrization of gamma-ray production cross-section for pp interactions in a broad proton energy range from the kinematic threshold to PeV energies*, Phys. Rev. D, 90, arXiv:1406.7369.

Pion Decay

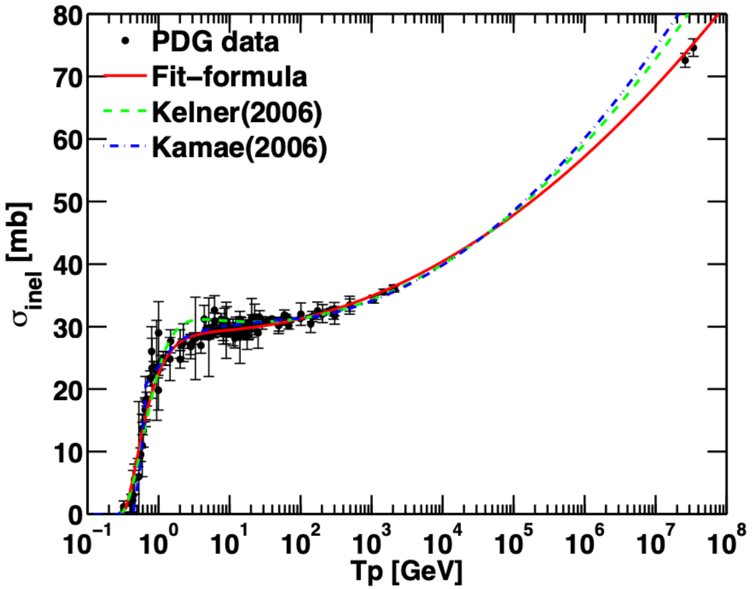
- Parametrisation of gamma-ray differential cross section:

$$\frac{d\sigma}{dE_\gamma}(T_p, E_\gamma) = A_{\max}(T_p) \times F(T_p, E_\gamma)$$

T_p: Proton kinetic energy
$T_p^{th} \approx 0.2797$ GeV

- Dependence on pp inelastic cross section:

$$\sigma_{\text{inel}} = \left[30.7 - 0.96 \log\left(\frac{T_p}{T_p^{\text{th}}}\right) + 0.18 \log^2\left(\frac{T_p}{T_p^{\text{th}}}\right)\right] \times \left[1 - \left(\frac{T_p^{\text{th}}}{T_p}\right)^{1.9}\right]^3 \text{ mb.}$$



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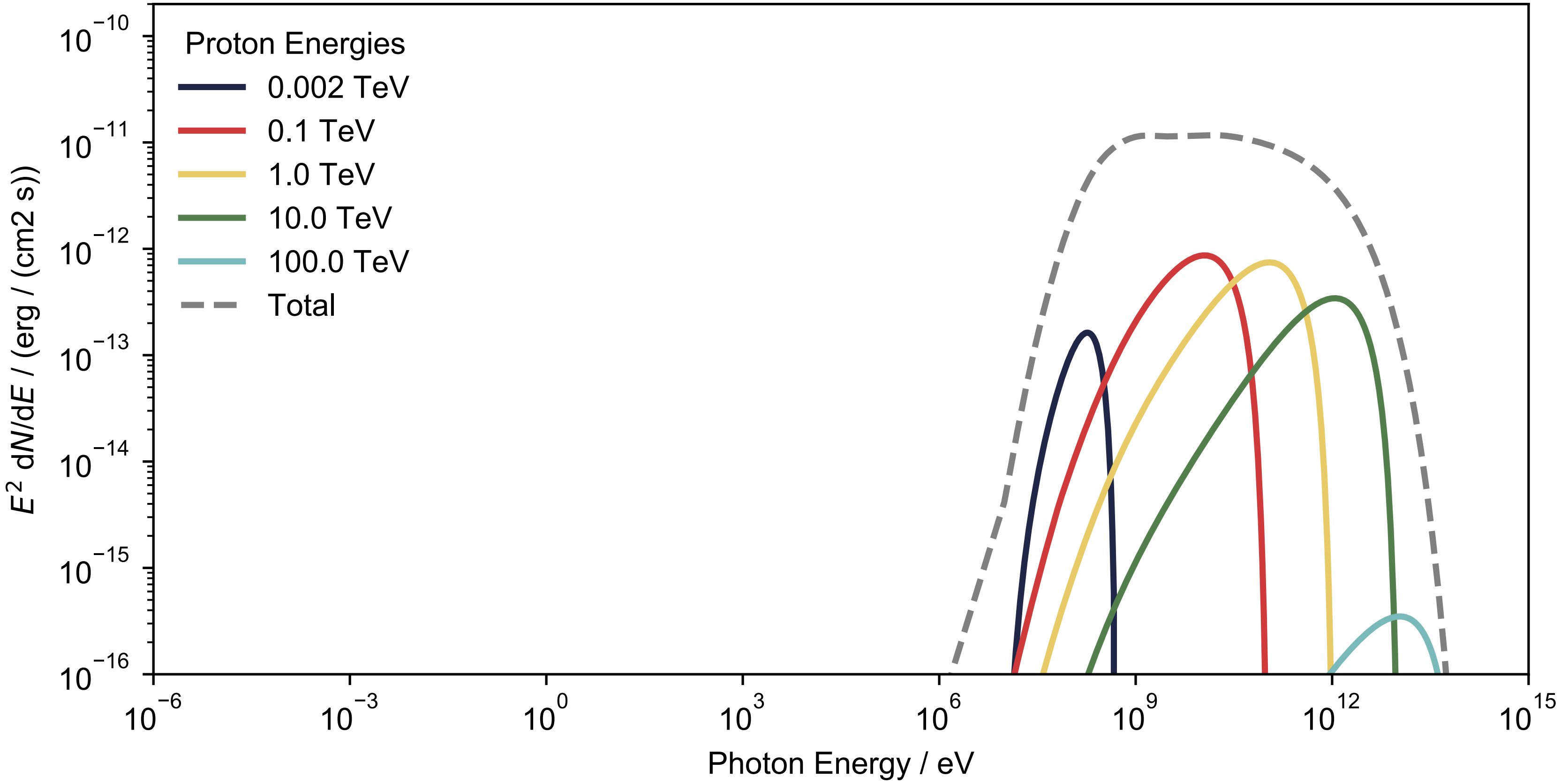
Pion Decay



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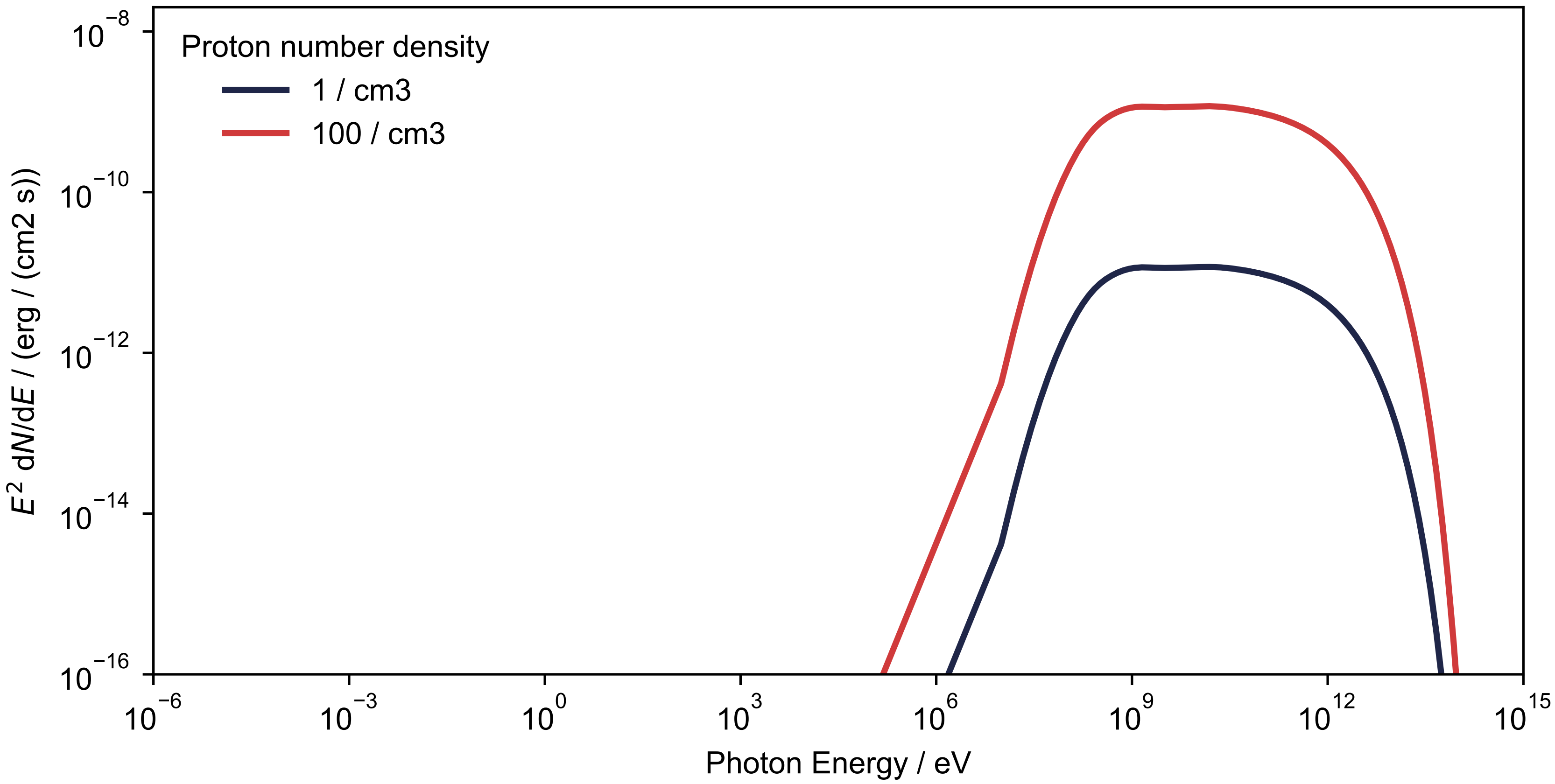
Pion Decay



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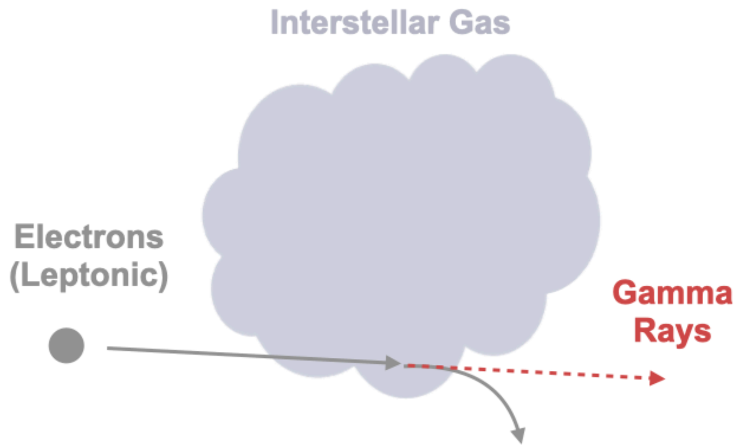
Bremsstrahlung

- Electrons scatter of the ambient interstellar medium, producing Bremsstrahlung



- Corresponding differential photon production rate:

$$\frac{dn_\gamma(E_e,\, \varepsilon_\gamma)}{dt} = v_e \Big[(n_p + 4n_{He})\, \sigma_{e-p}(E_e,\, \varepsilon_\gamma) + n_e \sigma_{e-e}(E_e,\, \varepsilon_\gamma) \Big]$$

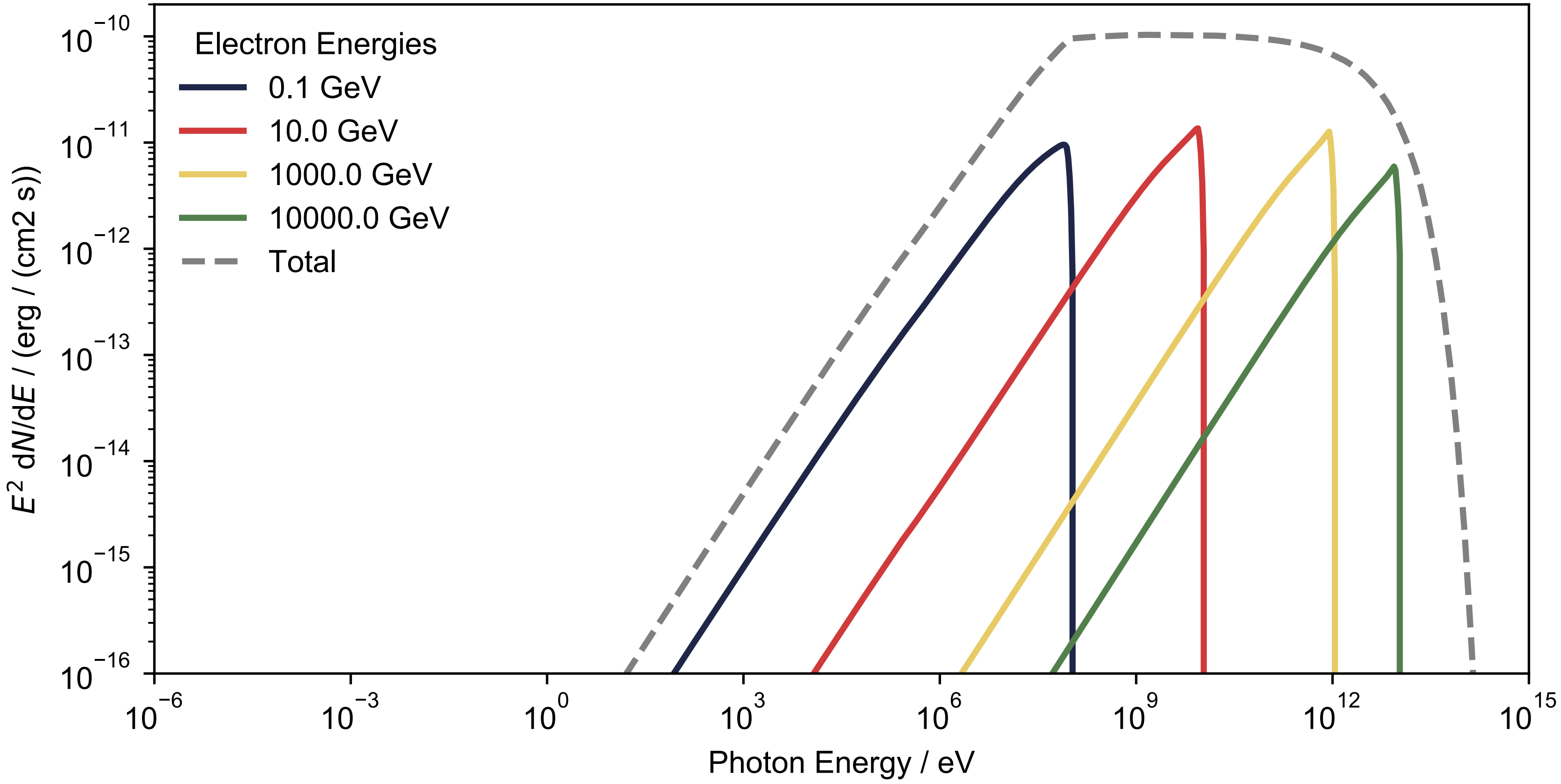
electron-ion cross section

electron-electron cross section

E_e: Electron kinetic energy

M. Baring, D. Ellison, S. Reynolds, I. Grenier, P. Goret (1999), *Radio to gamma-ray emission from shell-type supernova remnants: Predictions from non-linear shock acceleration models*, ApJ, 513, arXiv:9810158.

Bremsstrahlung



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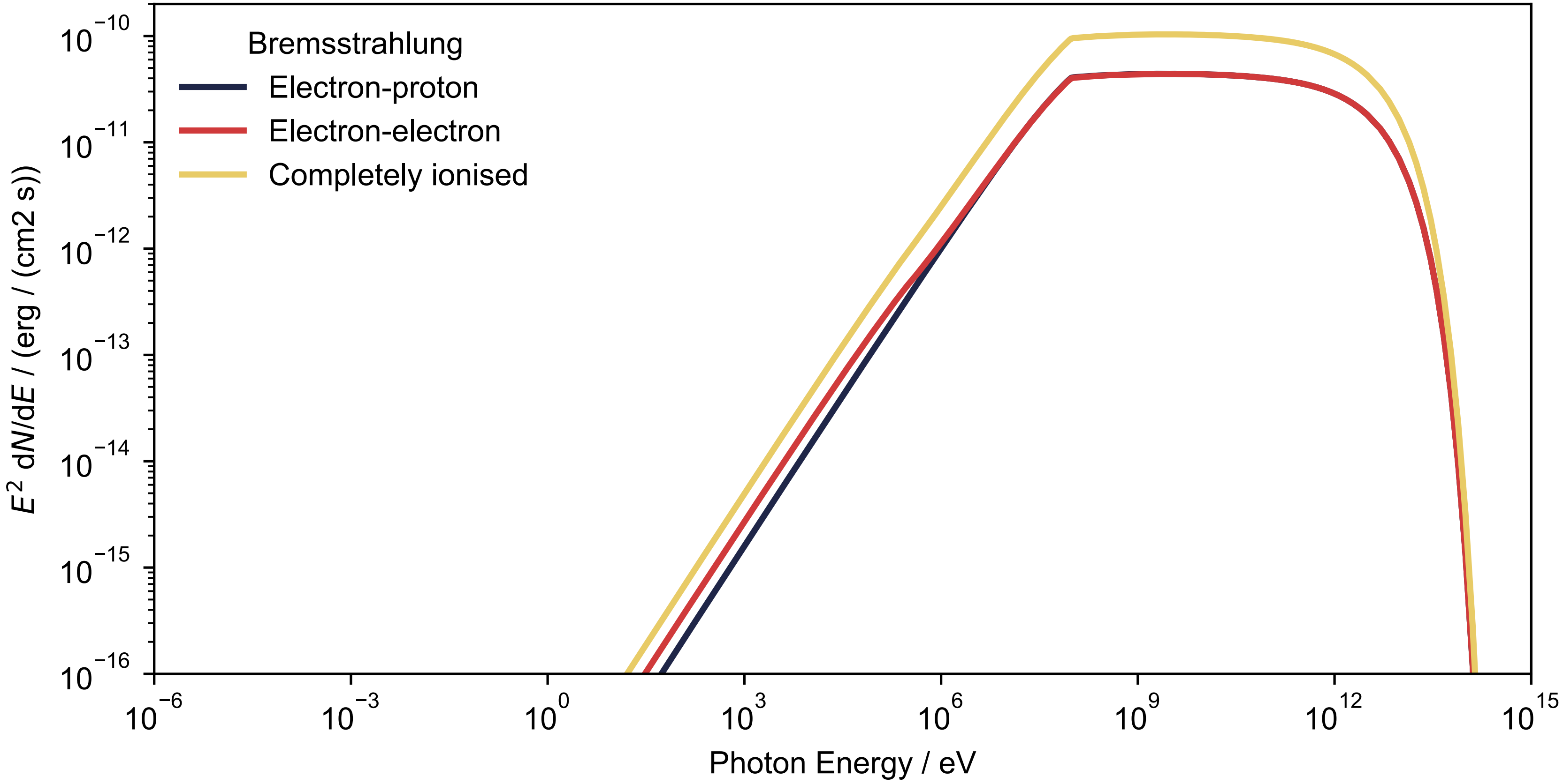
Bremsstrahlung



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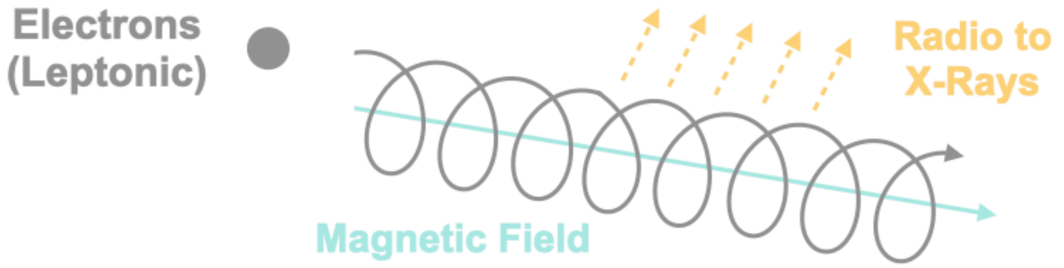
Input: Completely ionised ISM number density. Electron + proton number densities are internally calculated.
Alternatively, weights between electron-electron and electron-proton Bremsstrahlung may be given.

Synchrotron



- Radiation produced by charged particles in presence of magnetic fields

- Random magnetic fields in typical astrophysical environments

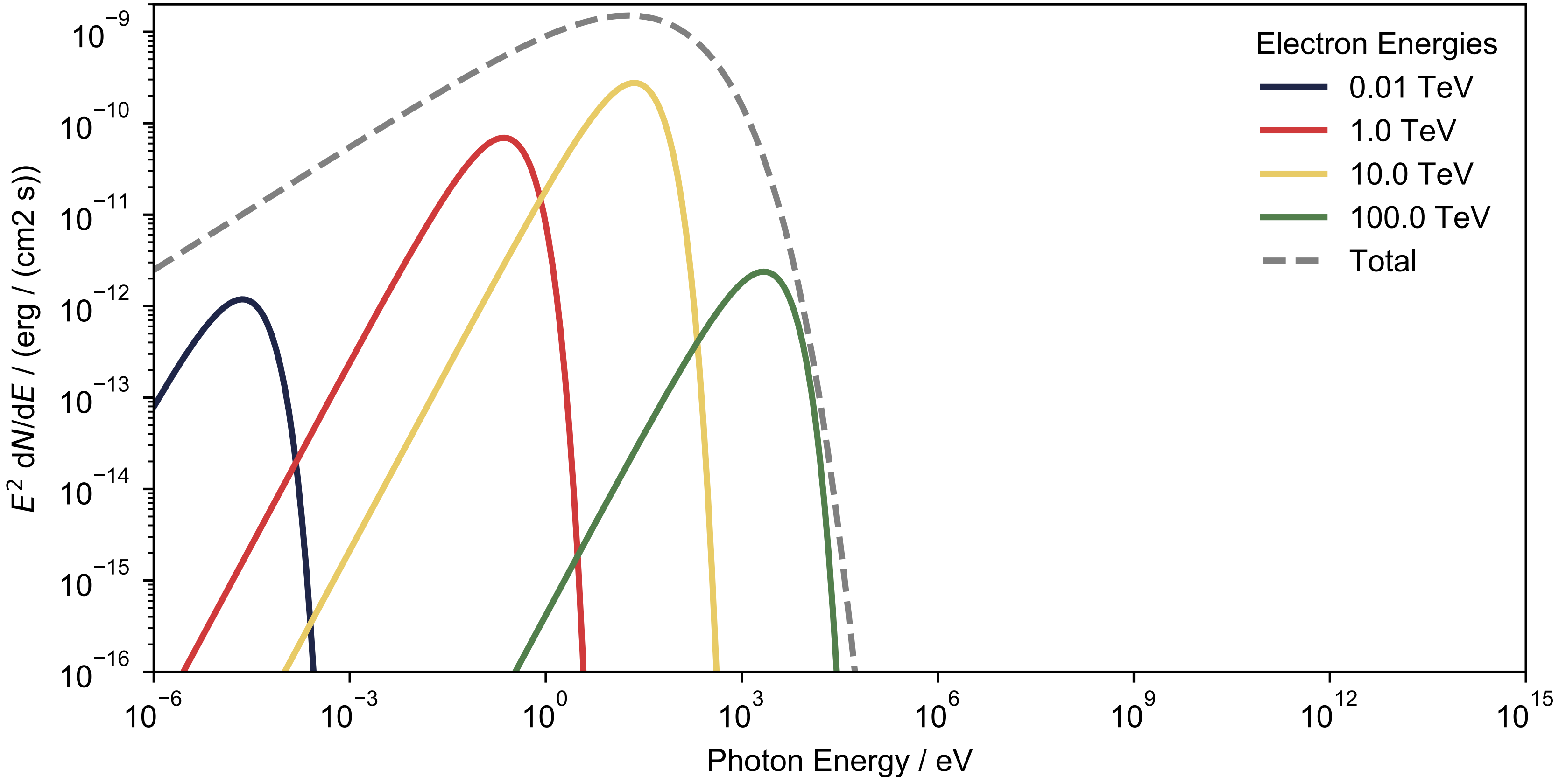
- Corresponding gamma-ray emissivity (averaging distributions over magnetic field directions):

$$\frac{dN_\gamma}{dE_\gamma dt} = \frac{\sqrt{3}}{2\pi} \frac{e^3 B}{m_e c^2 \hbar E_\gamma} F\left(\frac{E_\gamma}{E_c}\right)$$

$$E_c = \frac{3e\hbar B\gamma^2}{2m_e c}$$

F. Aharonian, S. Kelner, A. Prosekin (2010), *Angular, spectral, and time distributions of highest energy protons and associated gamma rays and neutrinos propagating through extragalactic magnetic and radiation fields*, Phys. Rev. D, 82, arXiv:1006.1045.

Synchrotron



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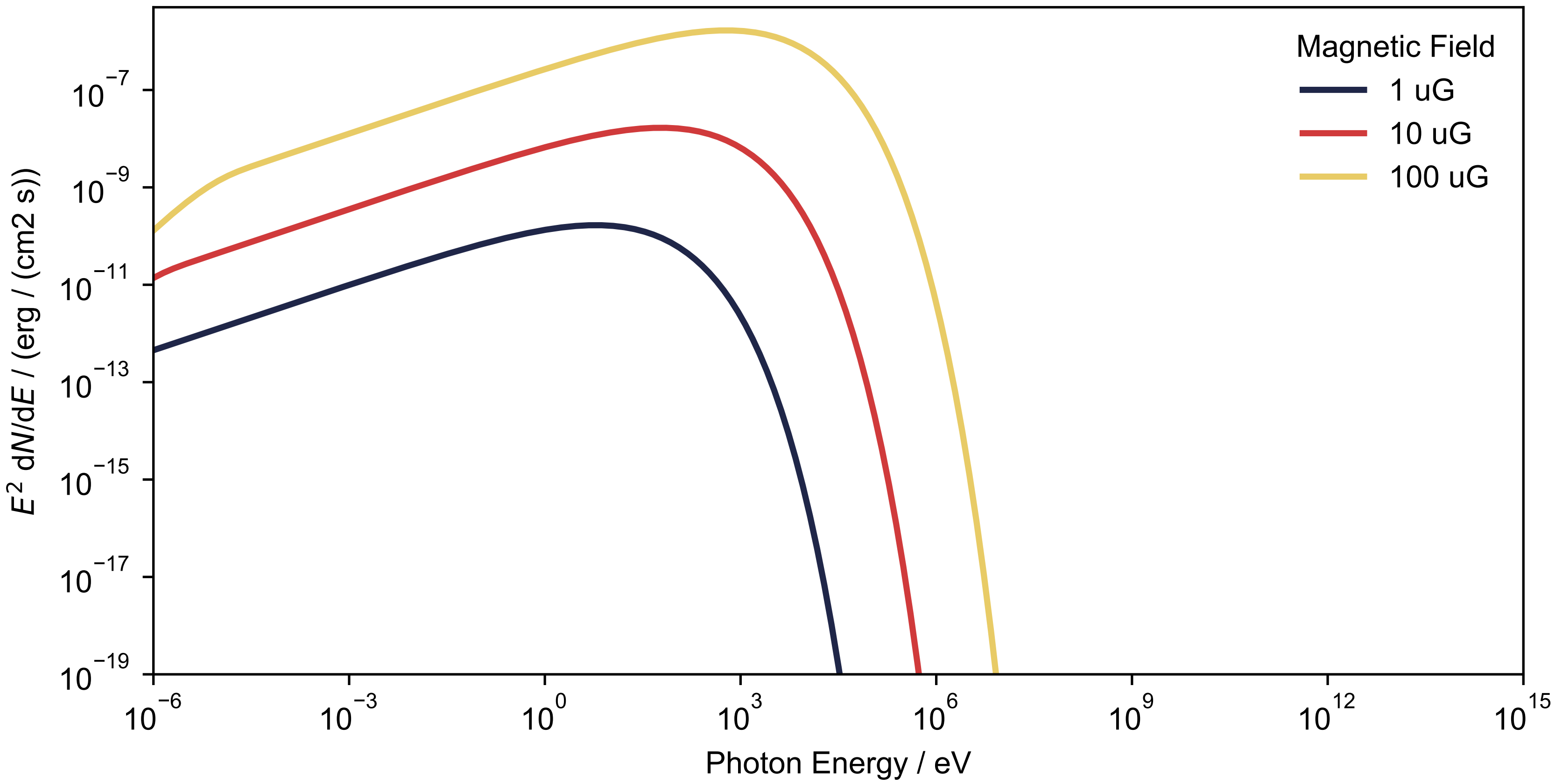
Synchrotron



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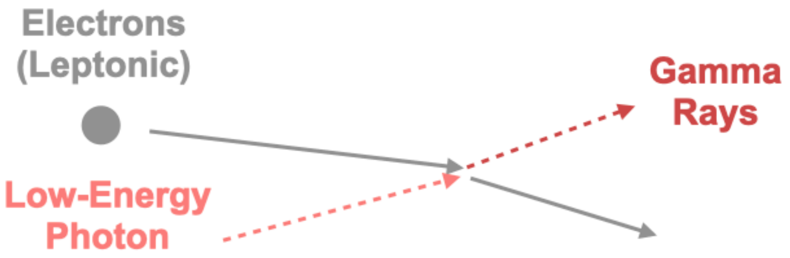
Inverse Compton



- Soft photons (from a seed photon field) scatter off relativistic electrons to produce gamma rays

- Isotropic photon field:

$$\frac{dN_{\rm iso}}{d\omega\, dt} = \frac{2r_o^2 m_{\rm e}^3 c^4 \kappa T^2}{\pi \hbar^3 E^2} \times \left[\frac{z^2}{2(1-z)} F_3(x_0) + F_4(x_0)\right]$$

$$x_0 = \frac{z}{(1-z)t}$$

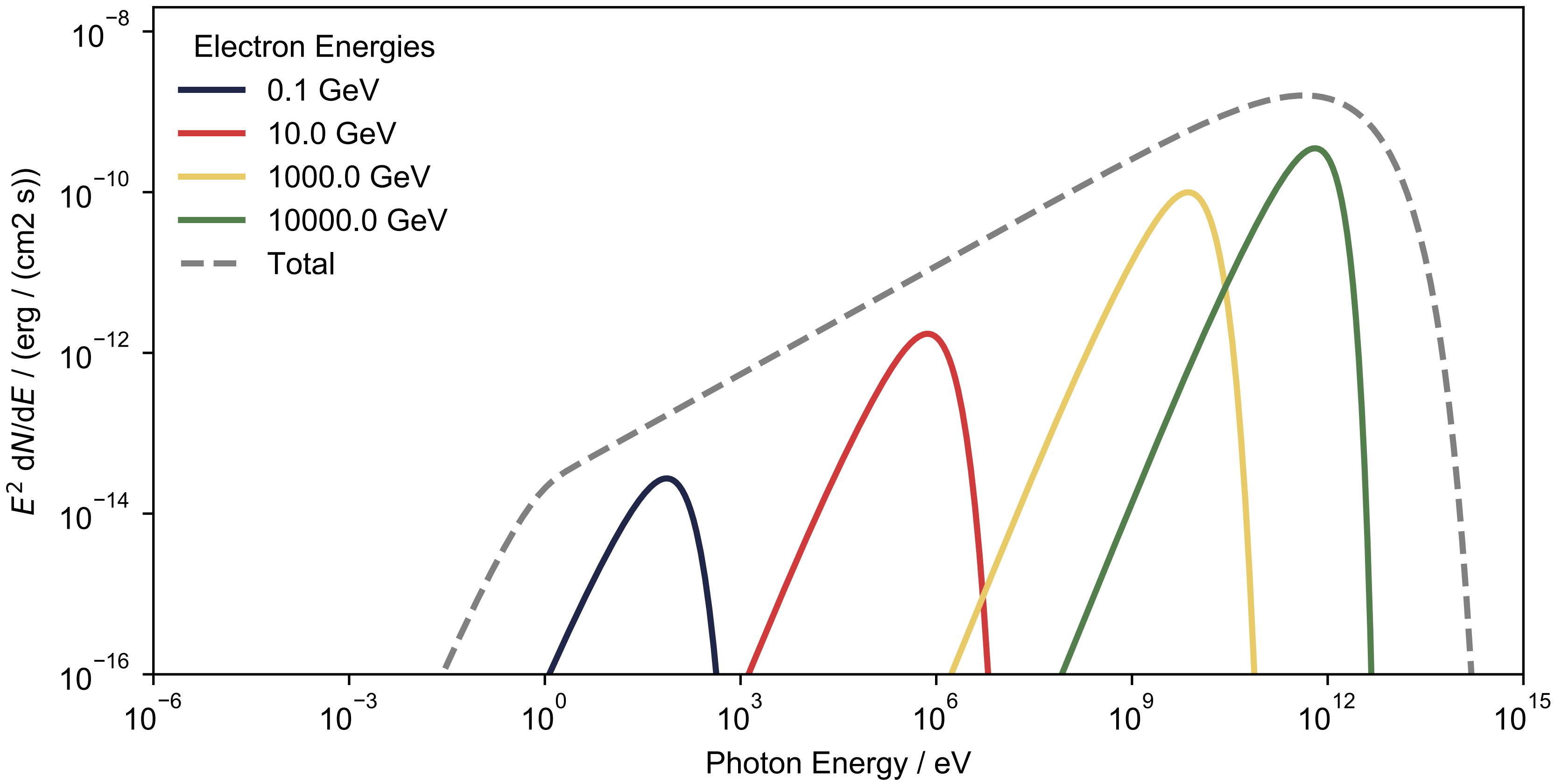
- Anisotropic photon field:

$$\frac{dN_{\rm ani}}{d\omega\, dt} = \frac{2r_o^2 m_{\rm e}^3 c^4 \kappa T^2}{\pi \hbar^3 E^2} \times \left[\frac{z^2}{2(1-z)} F_1(x_0) + F_2(x_0)\right]$$

$$x_0 = \frac{z}{(1-z)t_\theta}$$

D. Khangulyan, F. Aharonian, S. Kelner (2014), *SImple analytical approximations for treatment of inverse Compton scattering of relativisitc electrons in the black-boday radiation field*, ApJ, 783, arXiv:1310.7971.

Inverse Compton



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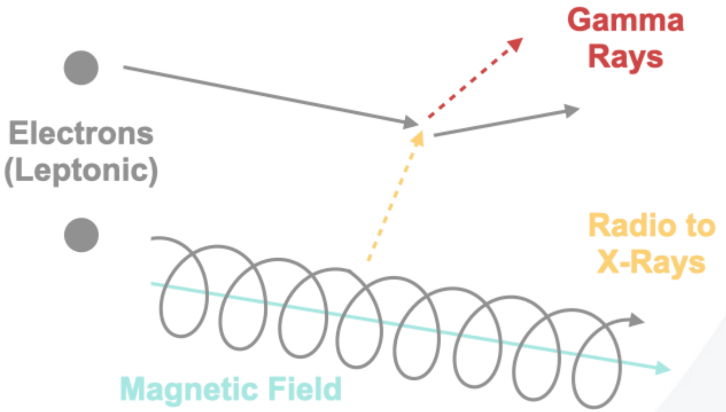
Inverse Compton

- Soft photons (from a seed photon field)
  scatter off relativistic electrons to produce gamma rays

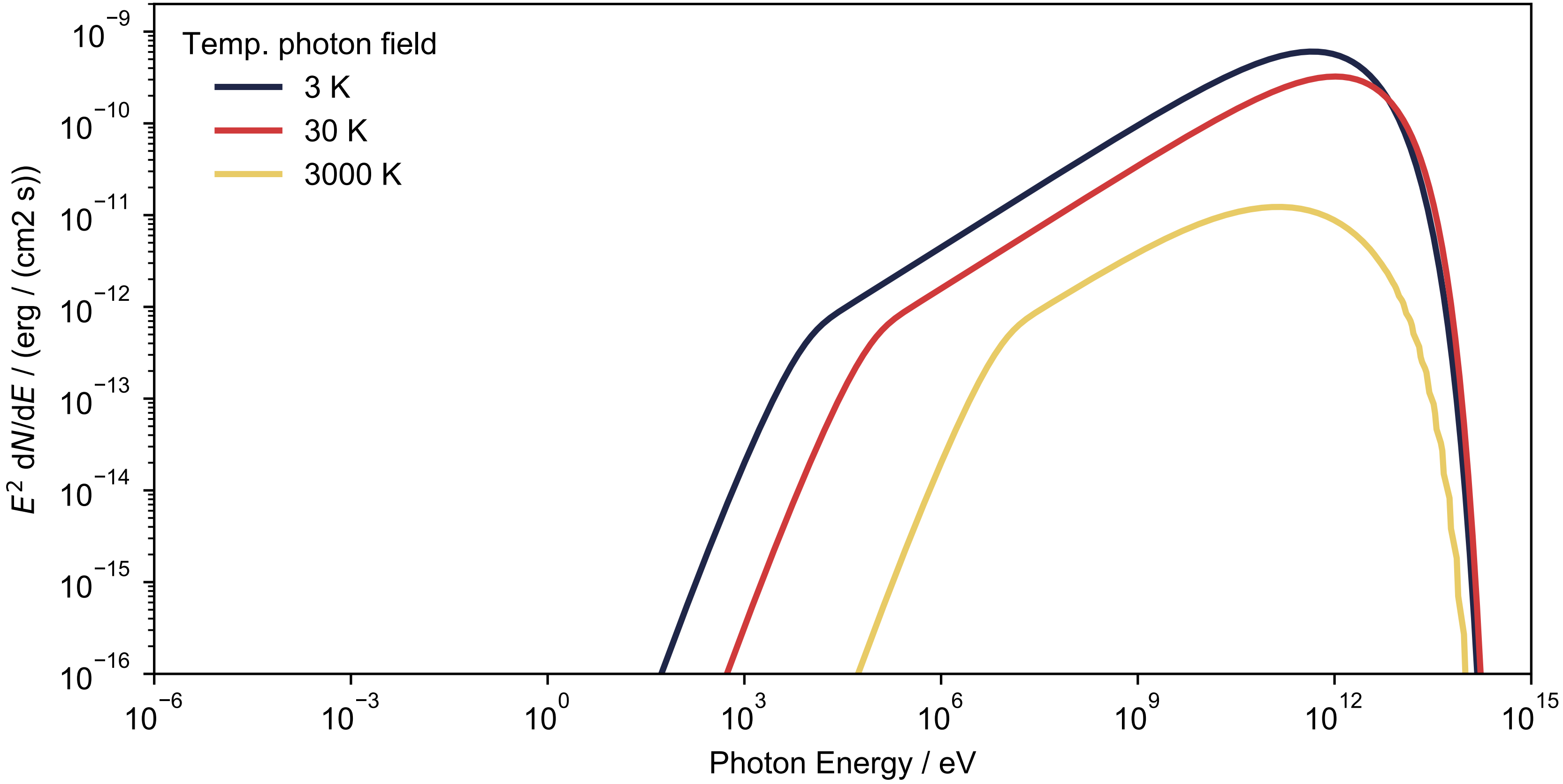
- Dominant Galactic seed photon fields:
  - Cosmic Microwave Background (CMB)
  - Far-infrared dust emission (FIR)
  - Near-infrared stellar emission (NIR)

- Other seed photon fields:
  - Synchrotron emission (SSC: Synchrotron Self Compton)
  - X-ray emitter



D. Khangulyan, F. Aharonian, S. Kelner (2014), *Simple analytical approximations for treatment of inverse Compton scattering of relativistic electrons in the black-body radiation field*, ApJ, 783, arXiv:1310.7971.

Inverse Compton



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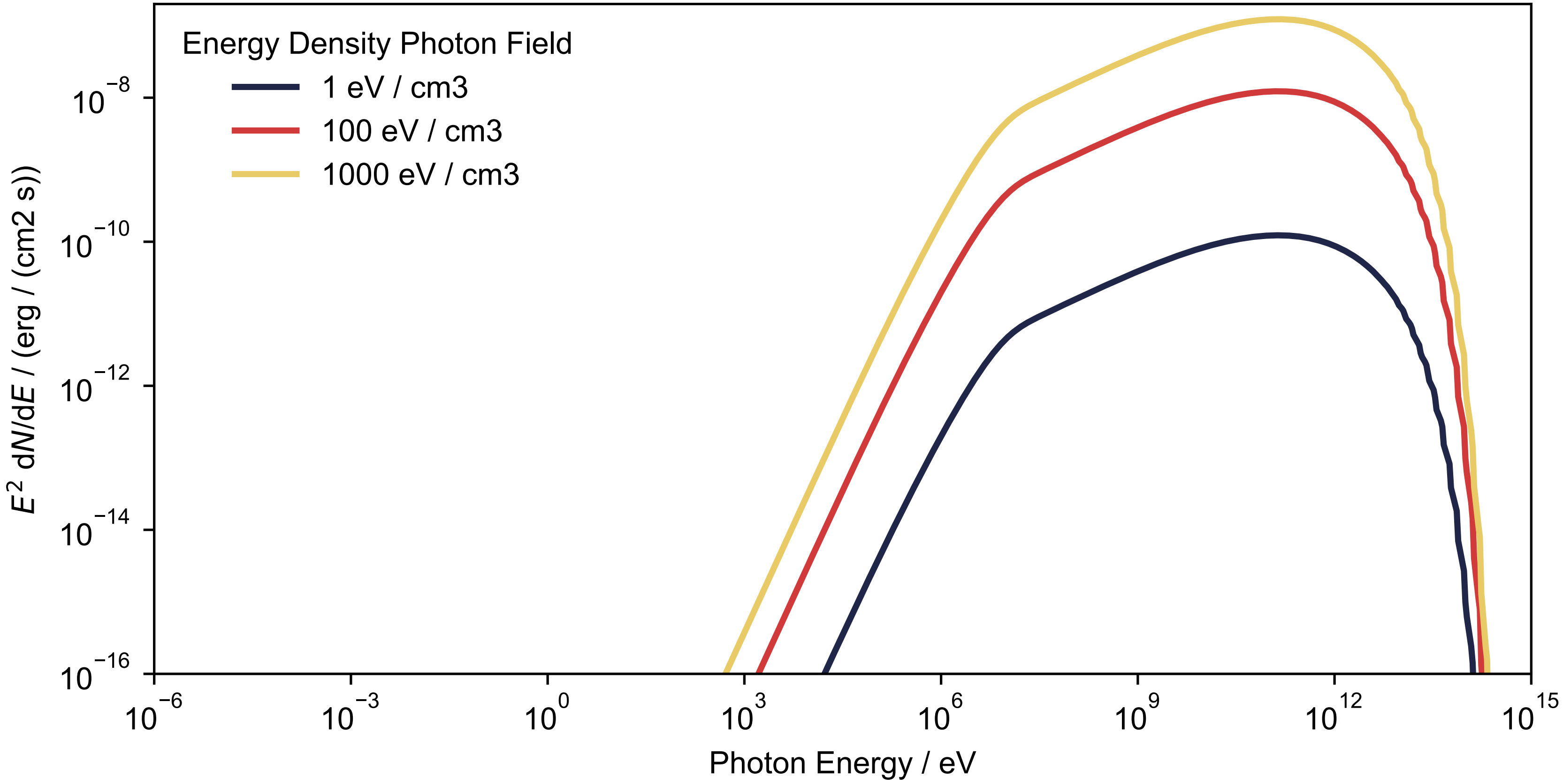
Inverse Compton



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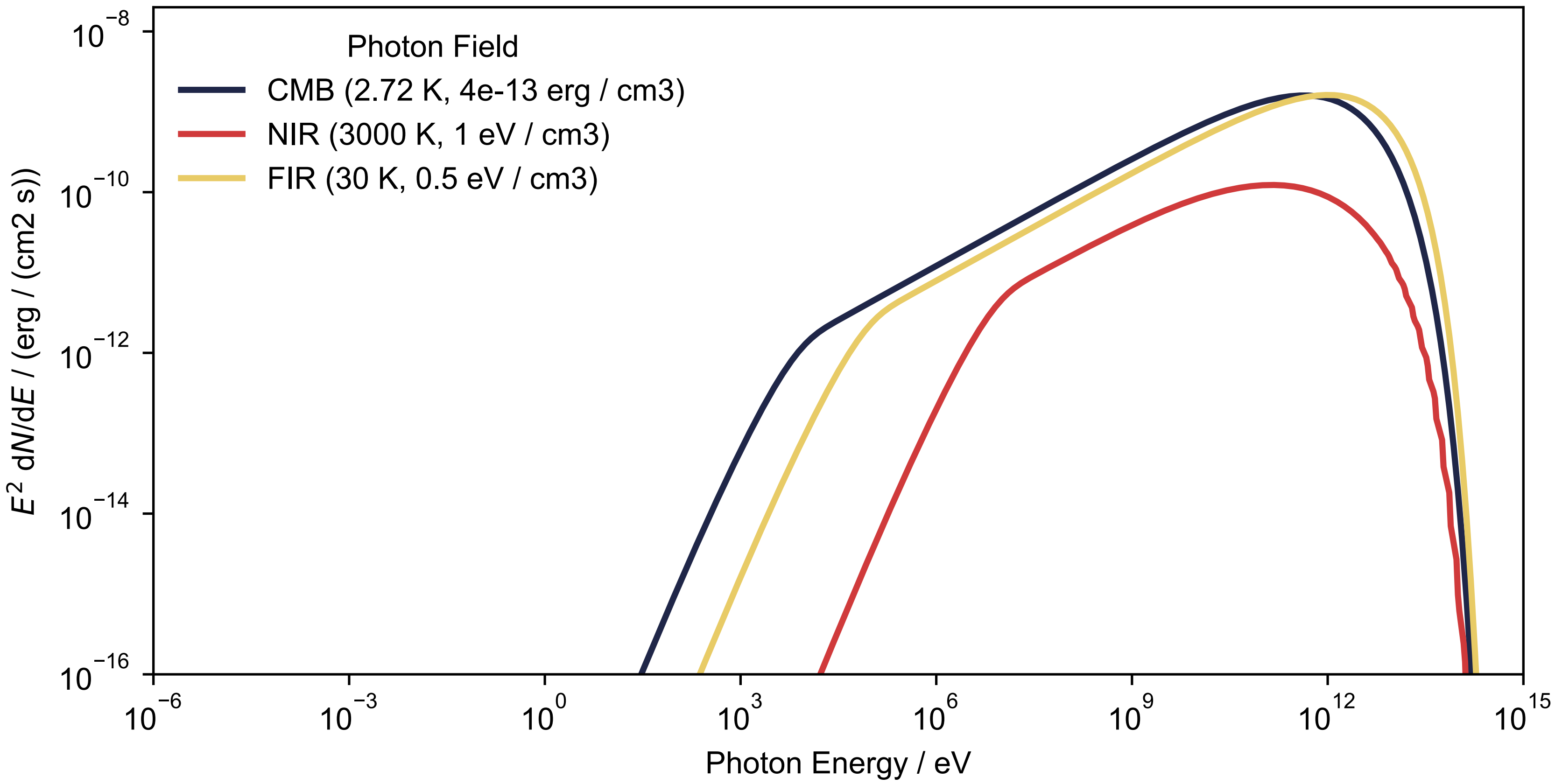
Inverse Compton



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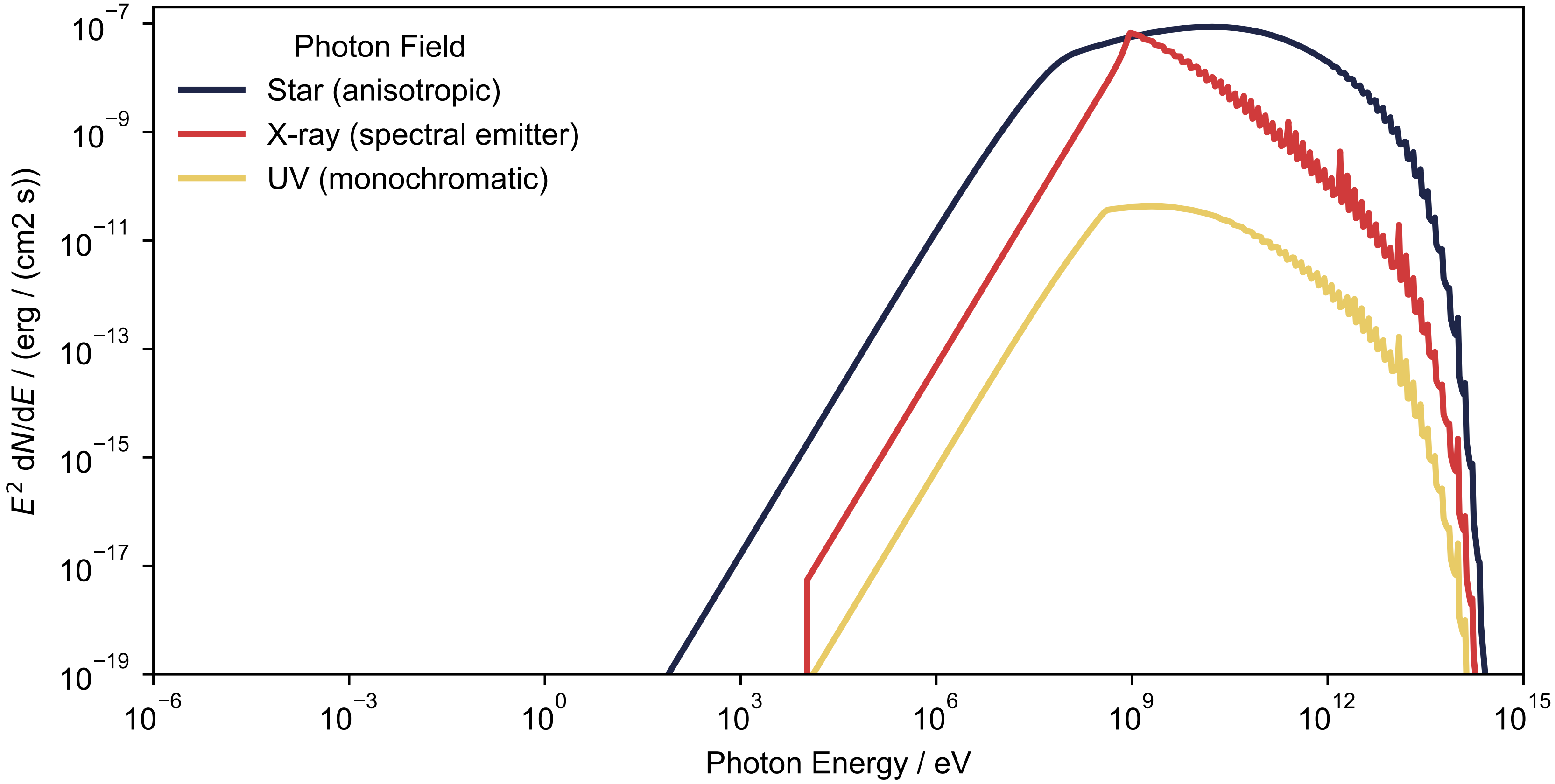
Inverse Compton



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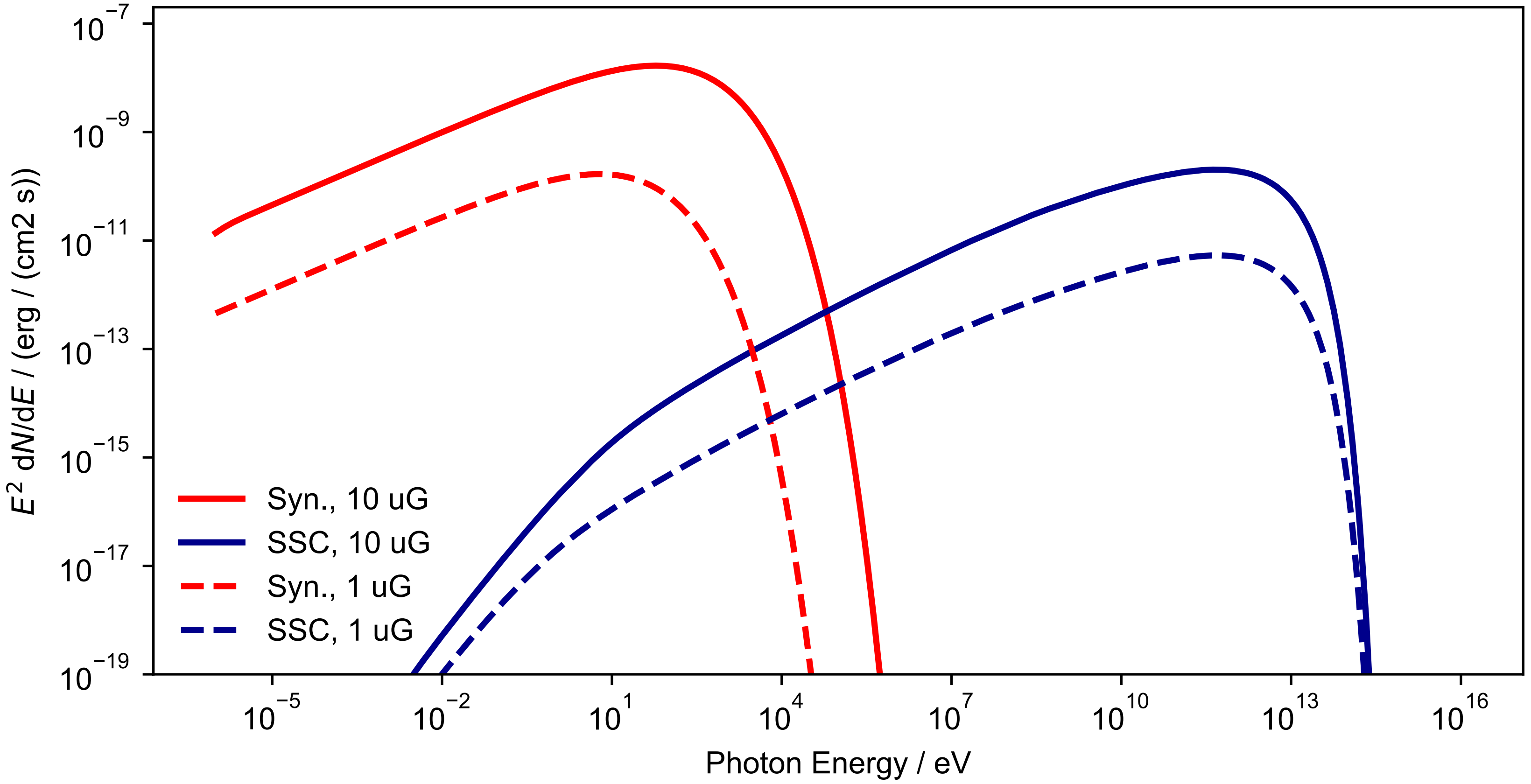
Synchrotron Self Compton



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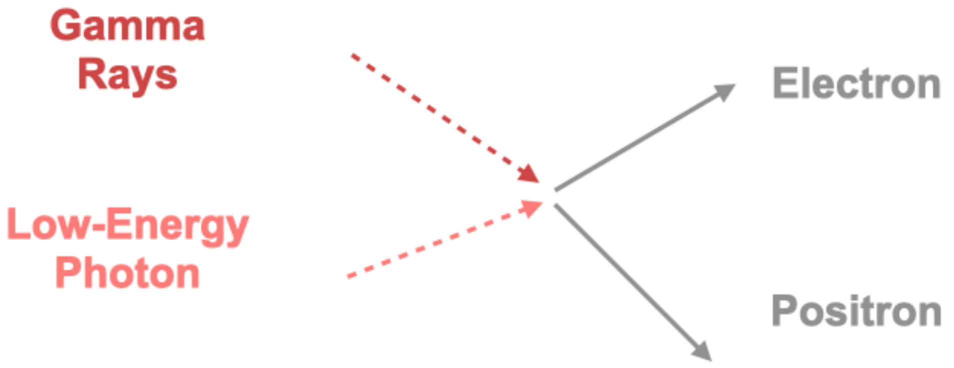
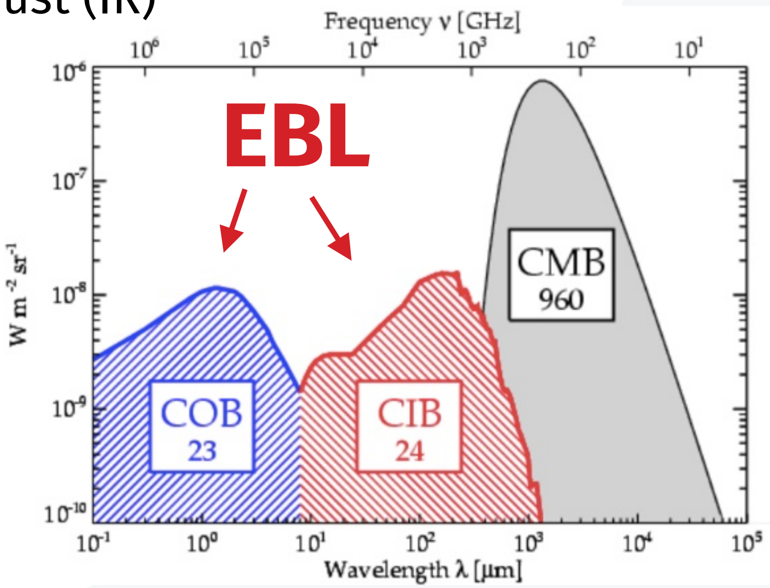
Gamma Gamma Absorption

- High-energy gamma rays can be absorbed by low-energy photons by pair production

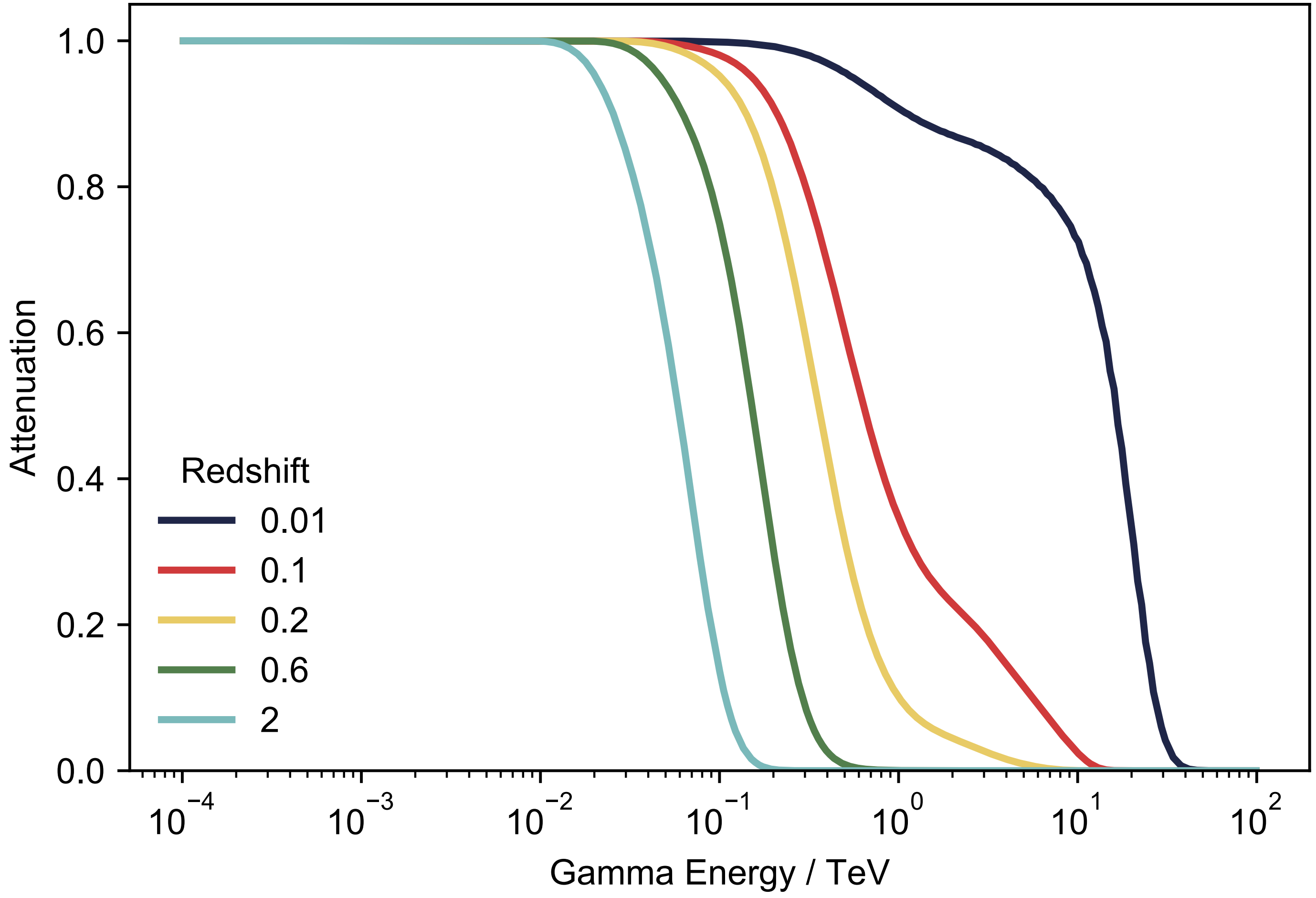


- Absorption depends on energy and path length of the high-energy gamma ray

- Low-energy photon fields:
  - Extragalactic background light (EBL): Starlight (optical + UV + NIR) and light absorbed/re-radiated by dust (IR)
  - Galactic interstellar radiation field (ISRF)
  - Cosmic Microwave Background (CMB)



Extragalactic Background Light Absorption



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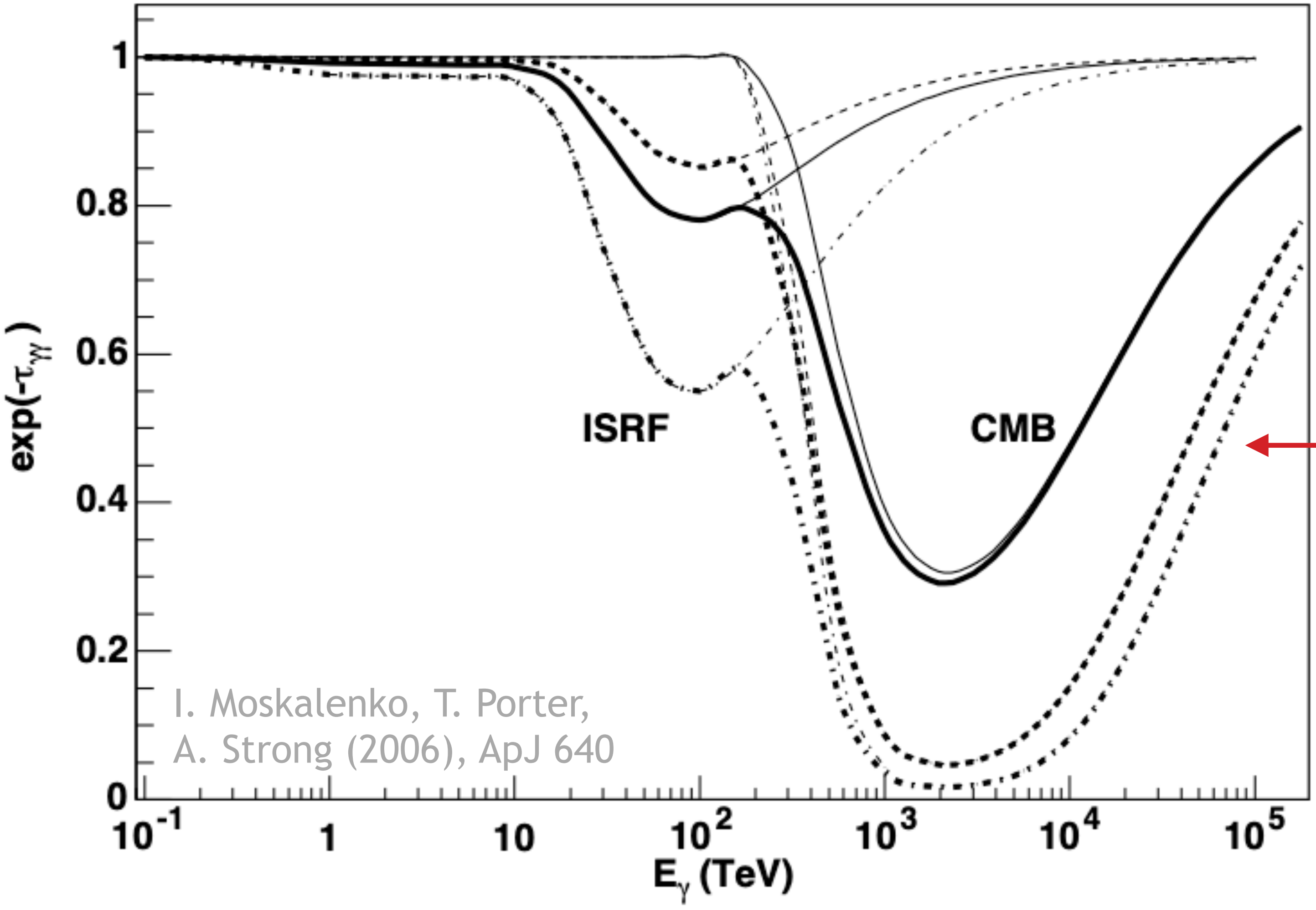
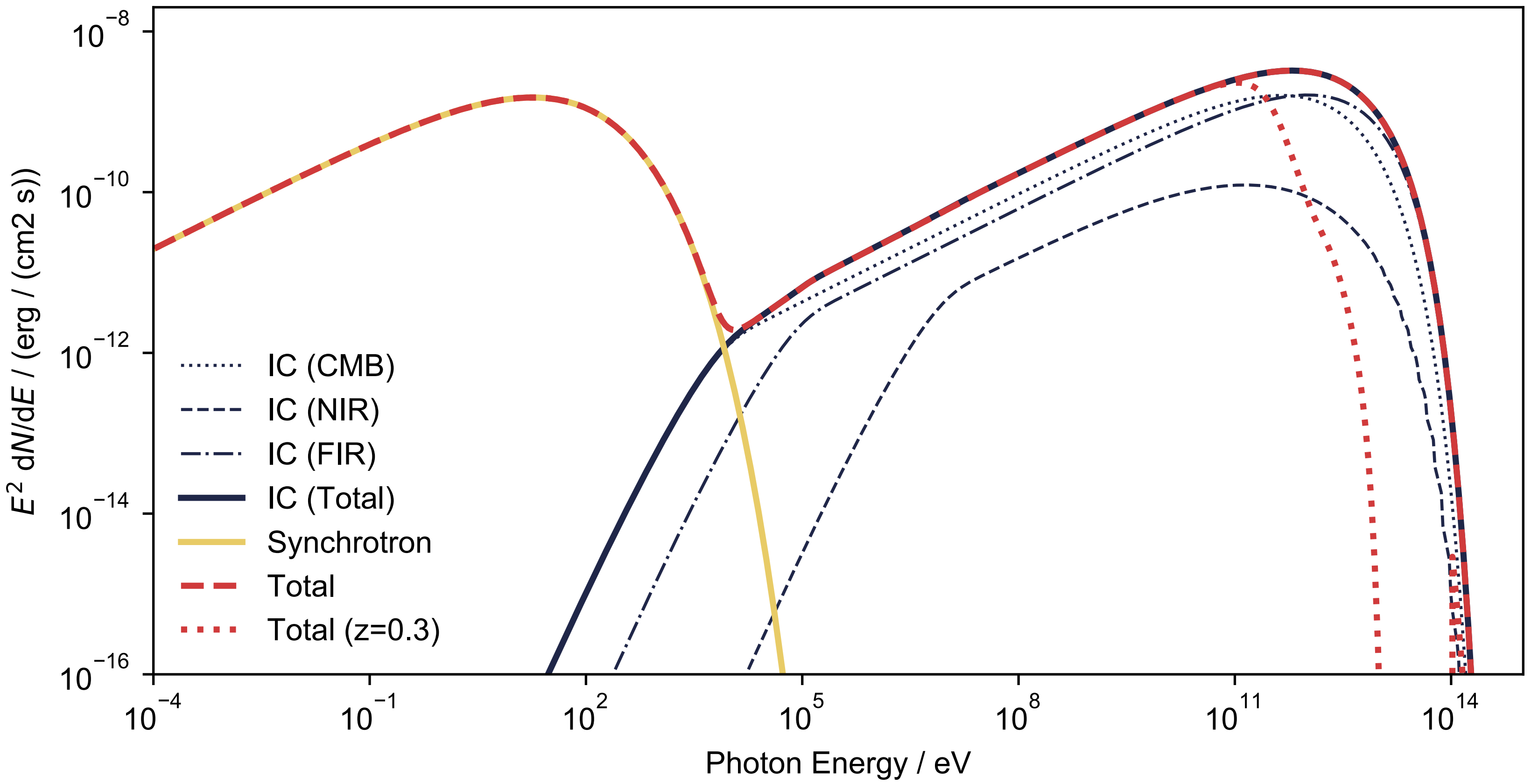
CMB and ISRF Absorption



Galactic Centre
@ 8.5 kpc

Towards
Galactic Centre
@ 28.5 kpc

Combination of Different Models



naima-models.ipynb

HANDS-ON SESSION

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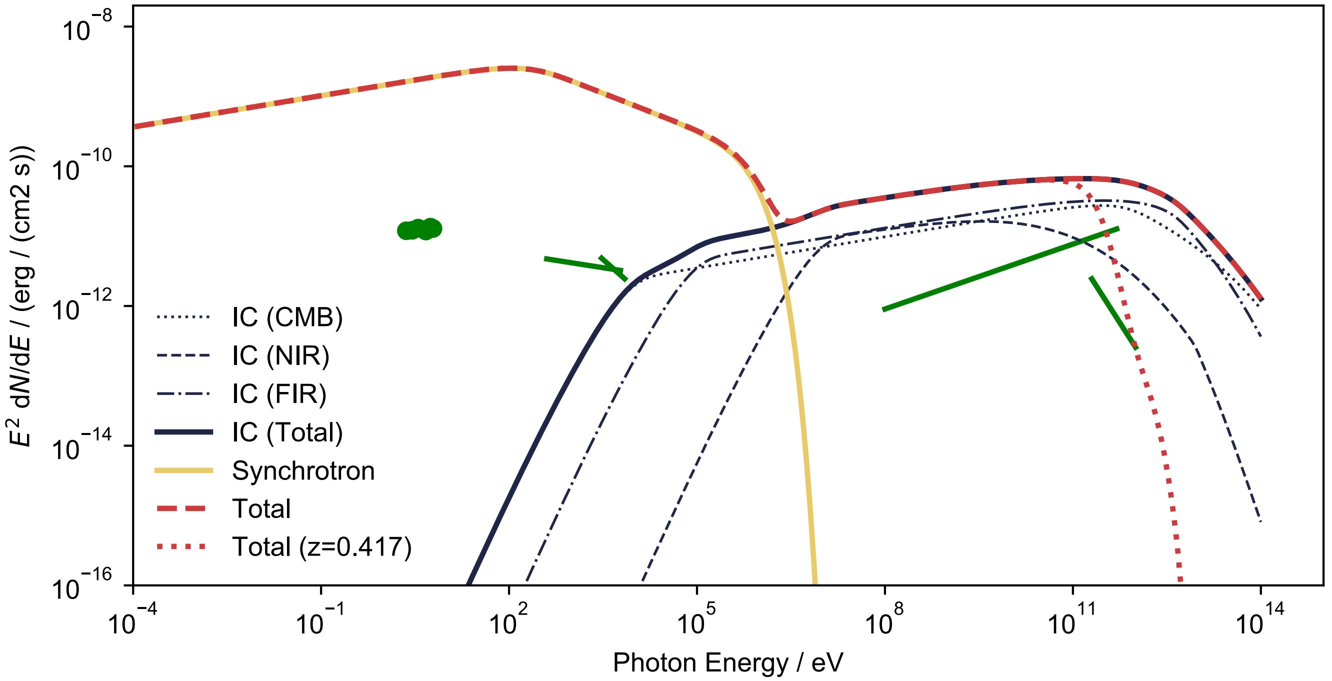
Modelling the AGN 1ES 2344

- Adapt the model parameters to match observations and model
- Add a Bremsstrahlung component

naima-1ES2344 .ipynb

Advanced

- Add a Synchrotron Self Compton component

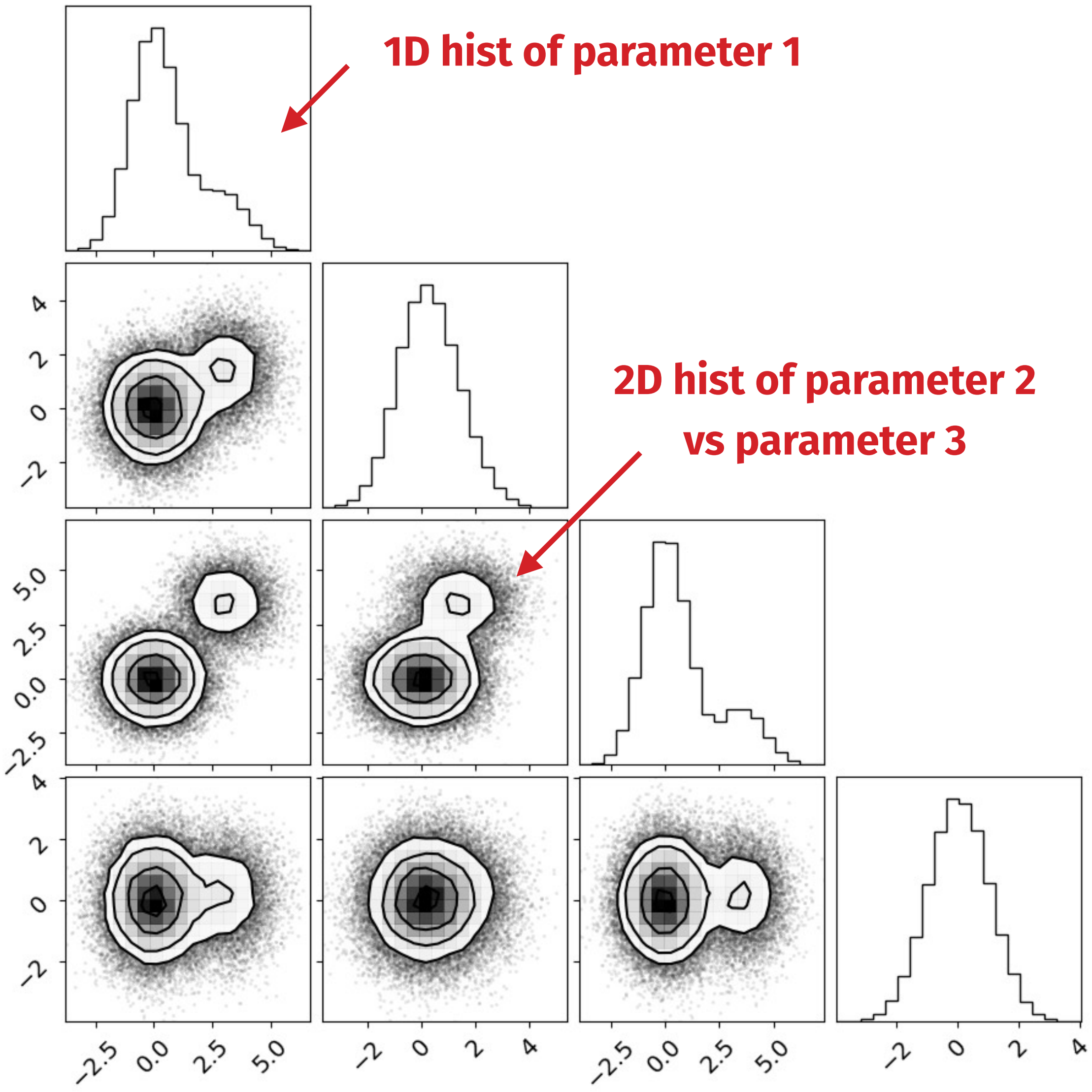


Model Fitting

- Common, but boring: Chi-Square fit

- What are the **multi-dimensional probability distributions** of our model parameters?
- So-called "corner plots" provide
  - Multi-dimensional visualisation
  - 1D histograms of each model parameter
  - 2D histograms of each combination of two model parameters

- Markov Chain Monte Carlo (MCMC) fit (i.e. sampling of model parameters' likelihood distributions)



D. Foreman-Mackey, D. Hogg, D. Lang, J. Goodman (2013), ASP, 125, arXiv:1202.3665.

Markov Chain Monte Carlo (MCMC)

- **Likelihood** of observed data with Gaussian independent uncertainties (E_i, F_i, σ_i,) given a spectral model *S* with parameters *p*

$$\mathcal{L} = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{(S(\vec{p}; E_i) - F_i)^2}{2\sigma_i^2}\right)$$

$$\ln \mathcal{L} \propto \sum_{i=1}^{N} \frac{(S(\vec{p}; E_i) - F_i)^2}{\sigma_i^2}$$

- Define **prior** distributions for model parameters to help sample above Likelihood to obtain **posterior** distributions

- Typical prior distributions:
  - Uniform between two values
  - Normal with mean and standard deviation

MCMC generates **random walk** in parameter space, drawing representative set of samples from distribution

MCMC Sampling

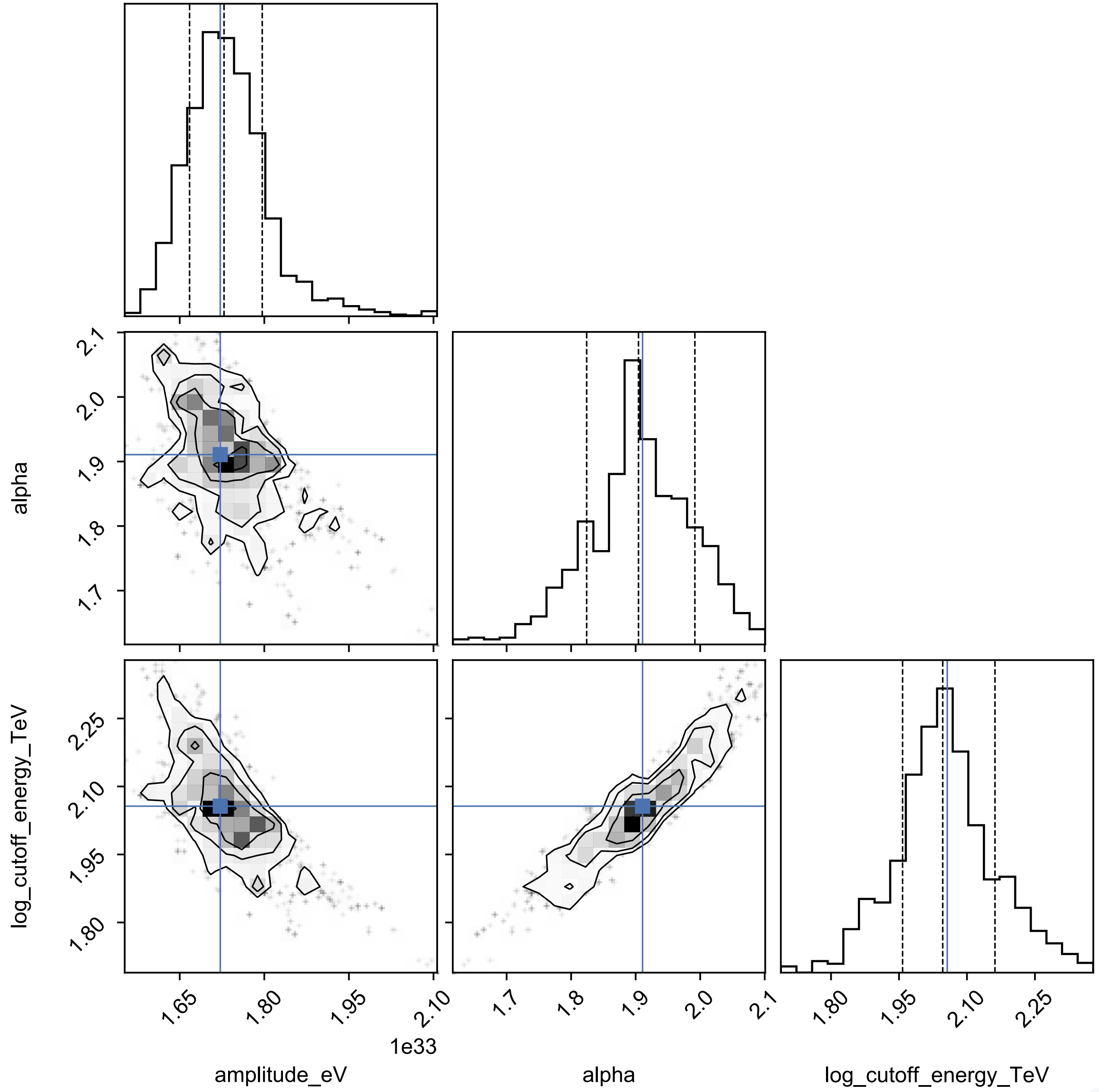
- Initialise walkers (instances of different random walks)
  - Closely (randomly) around maximum likelihood (best)
  - Randomly over parameter space (be careful, needs for sure longer burn-in)

- Burn-in walkers (enter high-likelihood region of parameter space)
  - Throws out first states of Markov chain

- Restart walkers

- Investigate sampling results
  - Posterior distribution (corner plot)
  - View set of high-likelihood models
  - Trace walkers

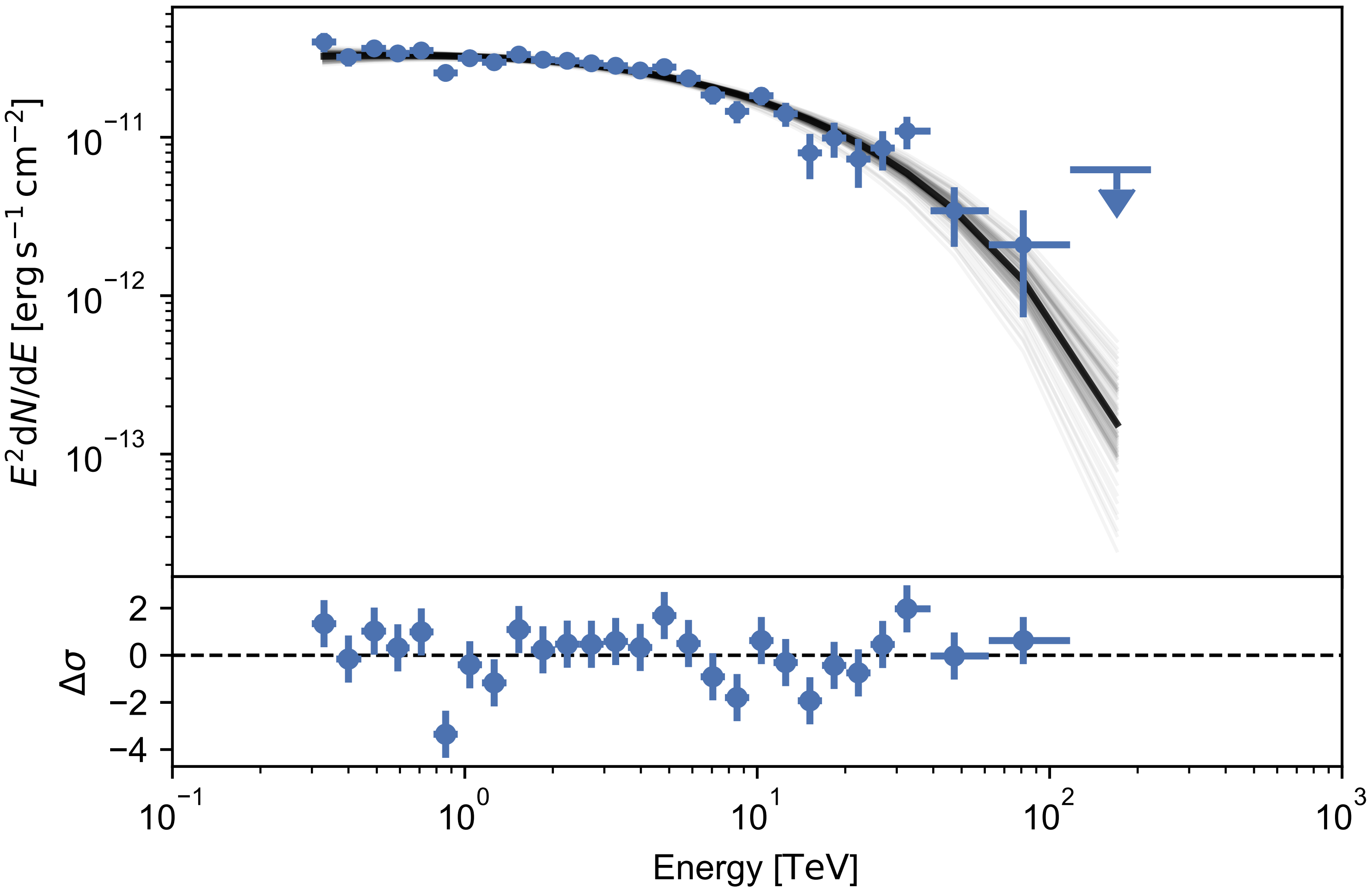
MCMC Sampling



naima-fitting.ipynb

(Note: Limited number of walkers used to reduce runtime)

MCMC Sampling



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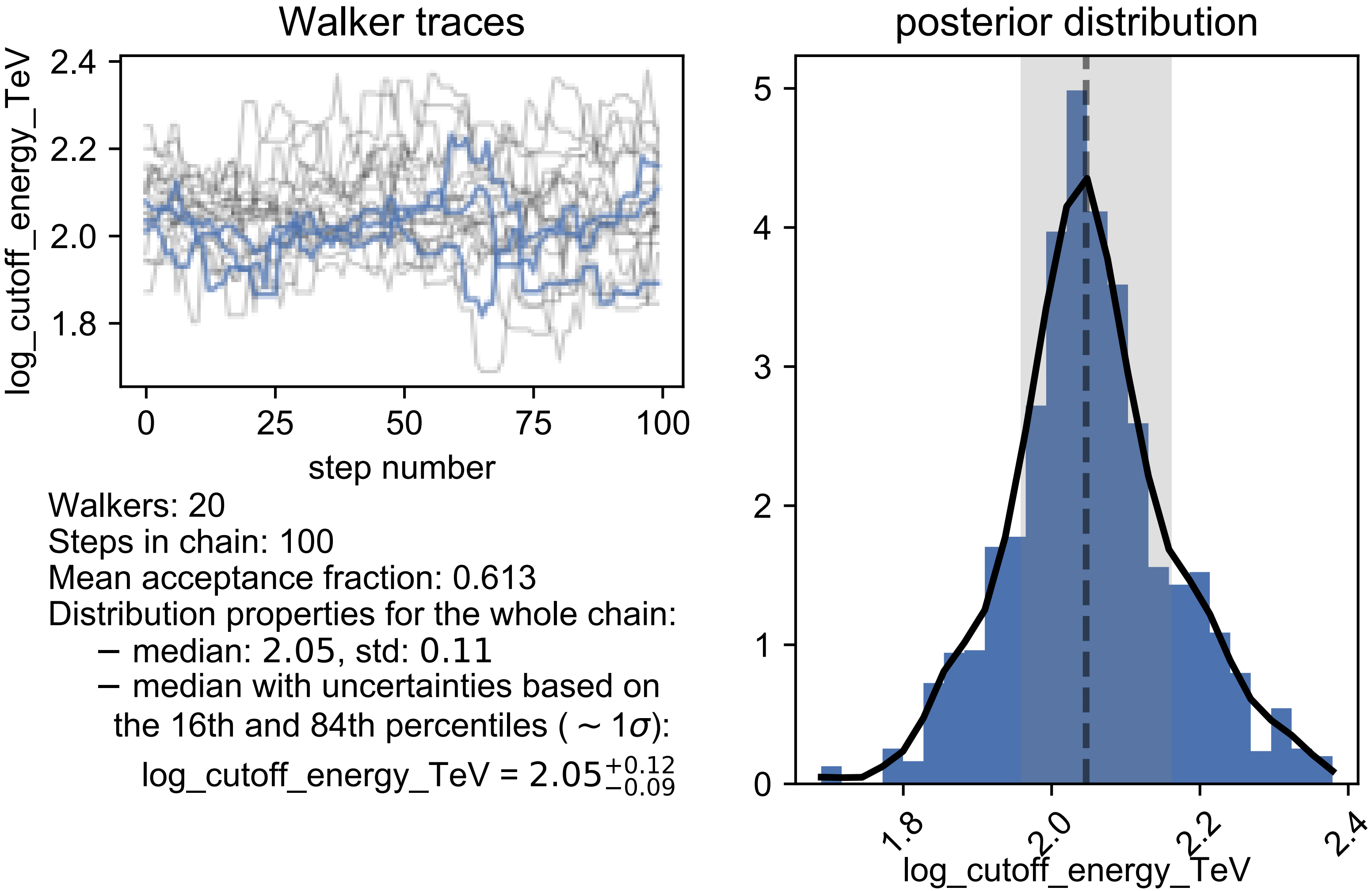
MCMC Sampling



naima-fitting.ipynb

HANDS-ON SESSION

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Simple

- Take the base model and change iteratively each parameter.
  How does each parameter influence the spectrum?
- What's the total proton kinetic energy? Is it realistic for such as source?
- Implement new functions with alternative models, for example using a different distribution of the parent population and / or a different radiative model.
  Determine suitable model parameters by trial and error.

naima-RXJ1713.ipynb

Advanced

- Take one of the above models and perform a MCMC fit.
  Tips (to reduce comp. time):
  - Determine rough parameter ranges for the priors by varying parameters by hand
  - Reduce number of fit parameters (e.g. if the influence of a parameter is marginal, fix the parameter; if two parameters influence spectrum the same, only fit one of them
  - Keep nwalkers, nburn, nrun small (e.g. 10, 50, 10)

Modelling Astrophysical Sources

- So far: Very simple models
- Modelling the processes at work, but:
  - Without spatial and temporal evolution
  - Quite simple assumptions about environment and processes surrounding source

- Motivation naima:
  Understand basics of processes, their settings and their influence on spectrum
  —> Radiative processes, parent population distributions & gamma-gamma absorption
  are the same in more complex models

- Many advanced tools available
  - Gamera
  - agnpy
  - …

Software: Gamera

- C++ library
- (python wrapper available)

- Computation of non-thermal radiation from relativistic particle populations
- Inclusion of spectral evolution of particle population with **time-dependent** injection, energy losses and particle escape (much more realistic!)
- Ability to model **multiple** interacting emission **zones**
- Access to 3D Galactic gas, magnetic field and spiral arm models

- Tutorials available for externally fitting models to observations and including **spatial evolution**

- https://github.com/libgamera/GAMERA

Software: agnpy

- Python package
- Affiliated with astropy

C. Nigro, J. Sitarek, P. Gliwny, D. Sanchez, A. Tramacere, M. Craig (2022), *agnpy: An open-source python package modelling the radiative processes of jetted active galactic nuclei*, A&A 660, arXiv:2112.14573

- Computation of non-thermal radiation from relativistic particle populations
- Ability to model emission regions
- Includes several photon fields for **External Compton** (such as from the broad line region, the dust torus and many more)
- Includes gamma-gamma absorption on line and thermal emitters, on target photon fields, on dust torus, on broad line region etc
- Includes **Doppler boosting**
- **Self-consistent** modelling (considers interplay between acceleration, cooling and escape process)

- https://agnpy.readthedocs.io/

Software: gammapy

- Python package
- Affiliated with astropy

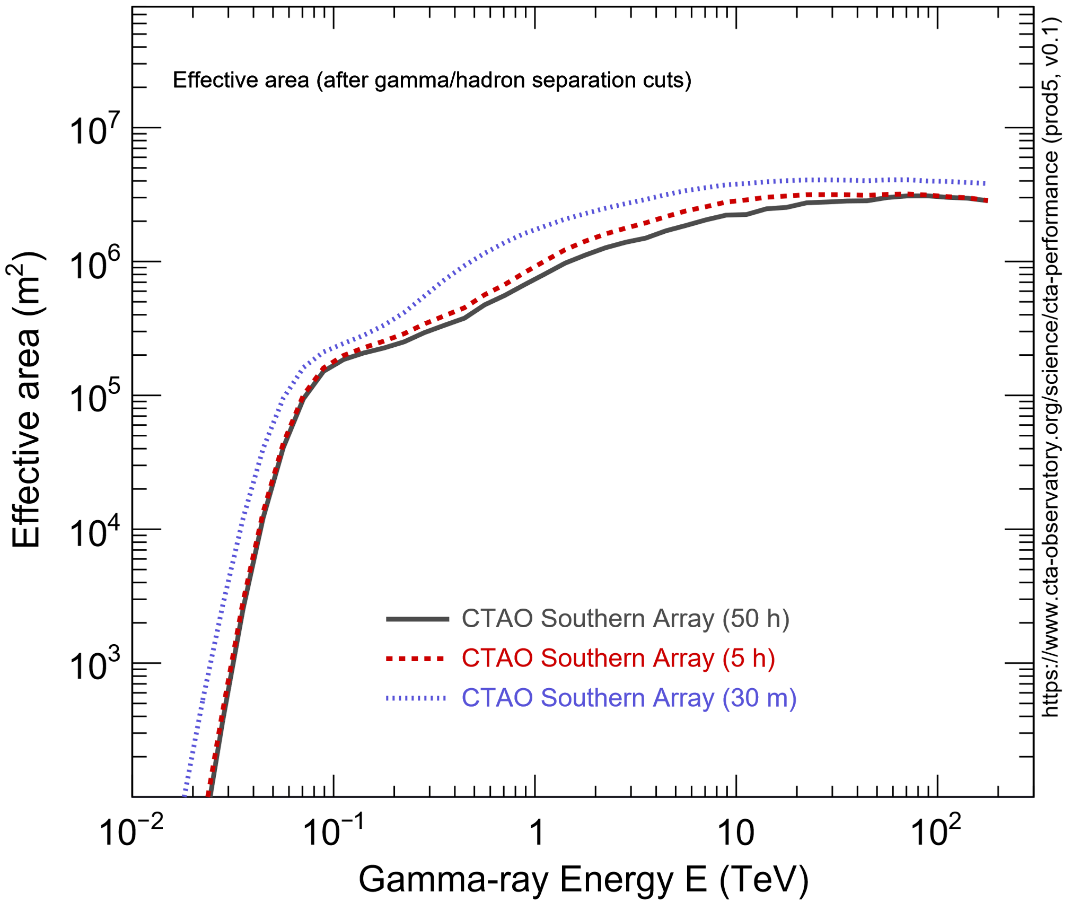
- Core library for Science Analysis tools of CTA
- Widely used in HESS, MAGIC, VERITAS, HAWC

- Derivation of spectra, sky maps and light curves
- Analysis of real and simulated observations
- Allows joint analysis of ob

- https://gammapy.org/
- https://docs.gammapy.org
- https://github.com/gammapy/gammapy

Data Products

- Event lists of gamma-like events
  - Time
  - Estimated event direction
  - Estimated energy
- Instrument Response Functions (IRFs)
  - Effective area
  - Energy dispersion
  - Point spread function



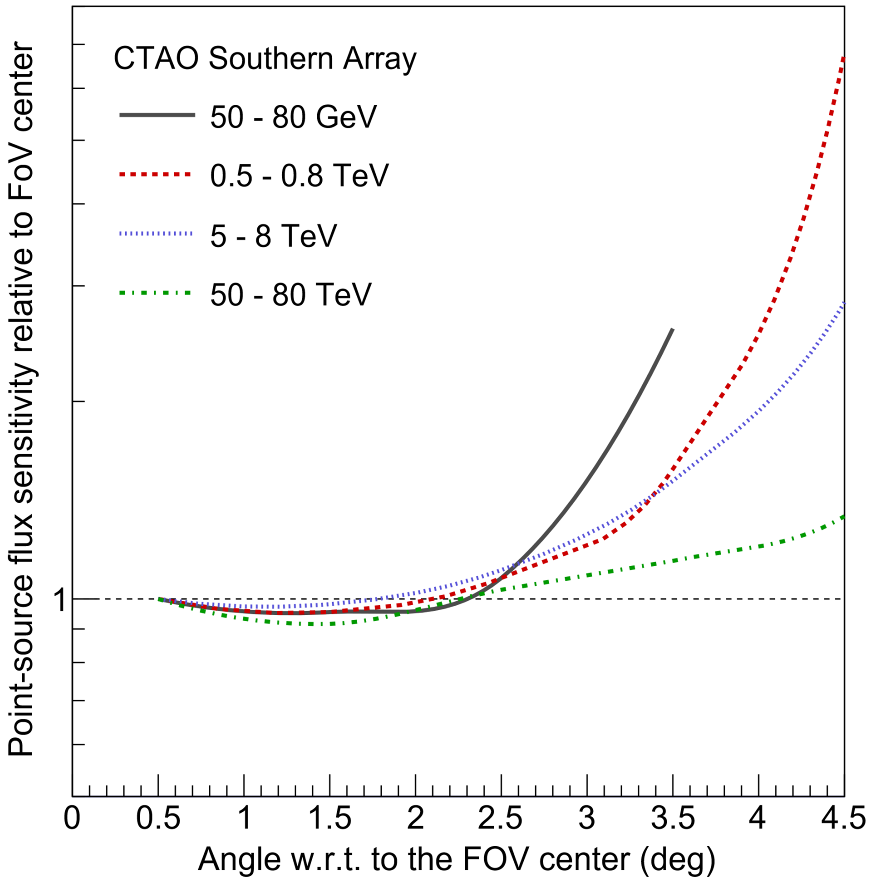
Instrument Response Function needs to be chosen according to observation time

CTA Simulation

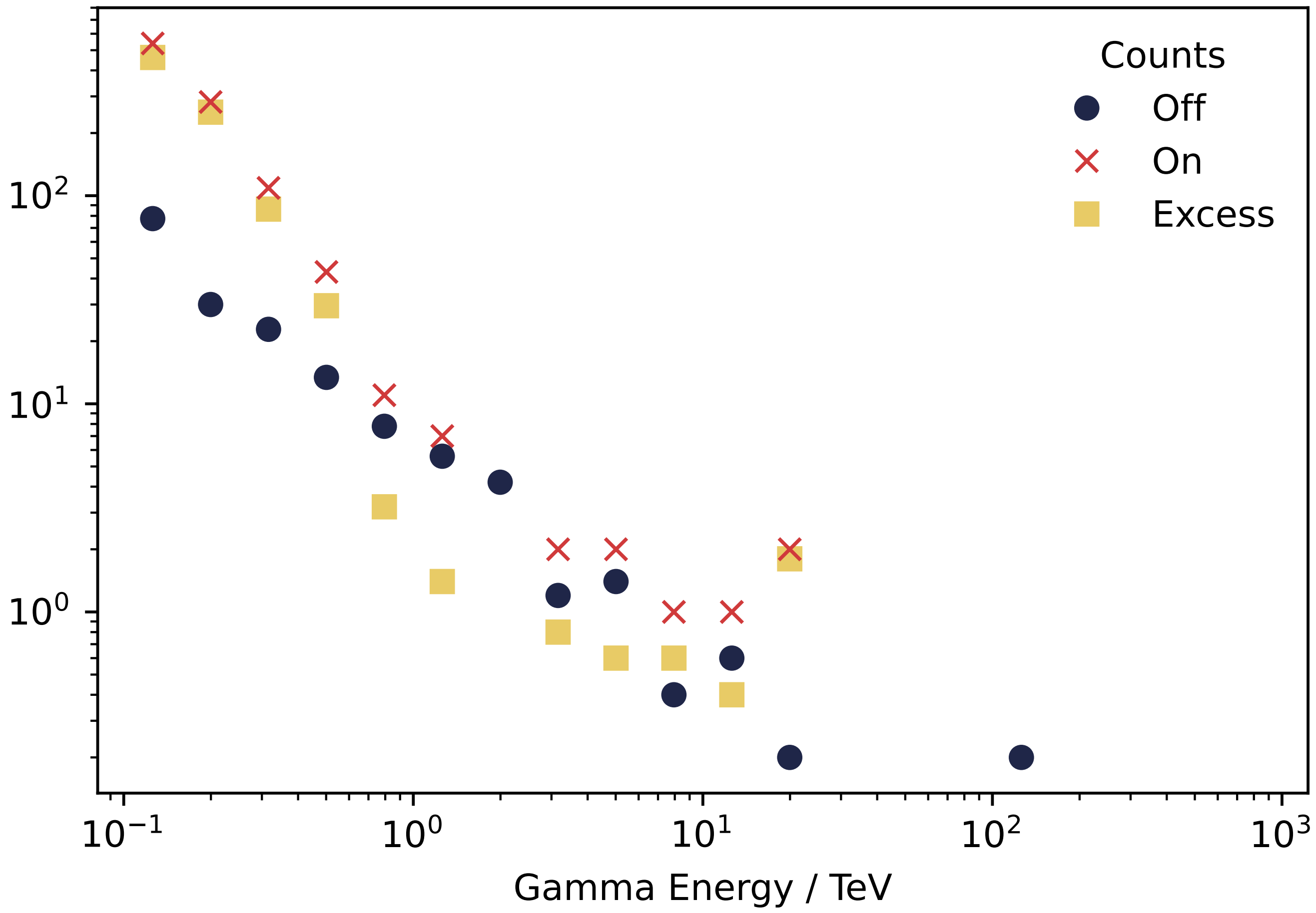
- Spectral models (similar to before)
  - PowerLaw
  - LogParabola
  - [...]
  - EBLAbsorption

- Observation parameters
  - Livetime (exposure)
  - Offset angle

- Analysis parameters
  - IRF
  - Size and number of off regions



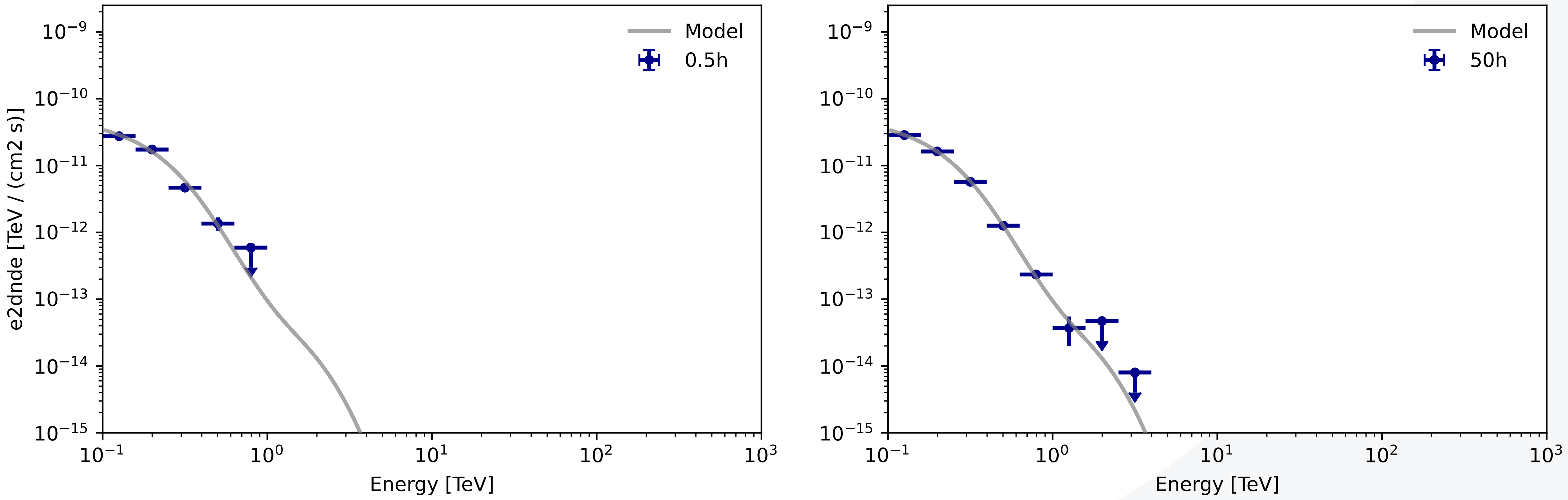
CTA Simulation



gammapy-simulation.ipynb

CTA Simulation

gammapy-simulation.ipynb



HANDS-ON SESSION

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GRB Simulation

- (If you want, pick your own time-dependent GRB spectrum)
- Pick the width of your time bins and choose the appropriate IRF for your choice
- Adapt parameters of your spectrum and time dependence
- Plot excess counts (or excess count rate) vs time (light curve)
- Plot the spectrum for each time bin
- What's the smallest observation time binning you can choose to still get 5 bins in time with > 3 sigma significance?

gammapy-GRB.ipynb

Advanced

- Plot light curve with flux of some energy bin
- In the same plot, plot light curve with flux of different energy bin
- In a new plot, plot light curve with integrated flux
- Compare spectra for different EBL models (interesting for the super bright GRB as its energy seems to violate physics)