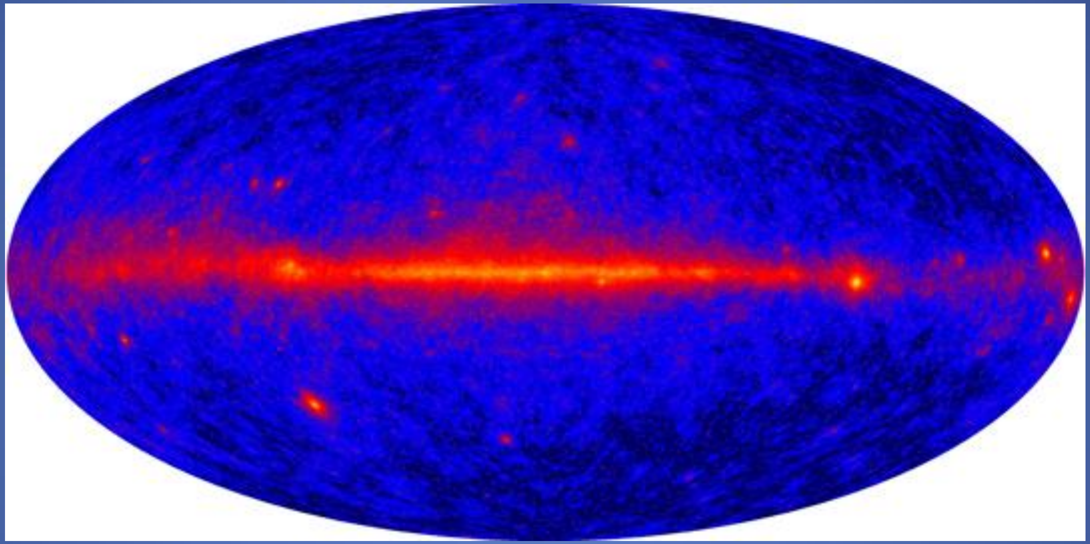
Decomposing the *Fermi* Gamma-Ray Background

Brandon Hensley
California Institute of Technology

Based on Hensley, Pavlidou, & Siegal-Gaskins, in prep.

TeV Particle Astrophysics 2010
July 21, 2010

The Isotropic Gamma Ray Background



Credit: NASA/DOE/International LAT Team

- Large scale isotropic gamma ray flux after point sources have been eliminated

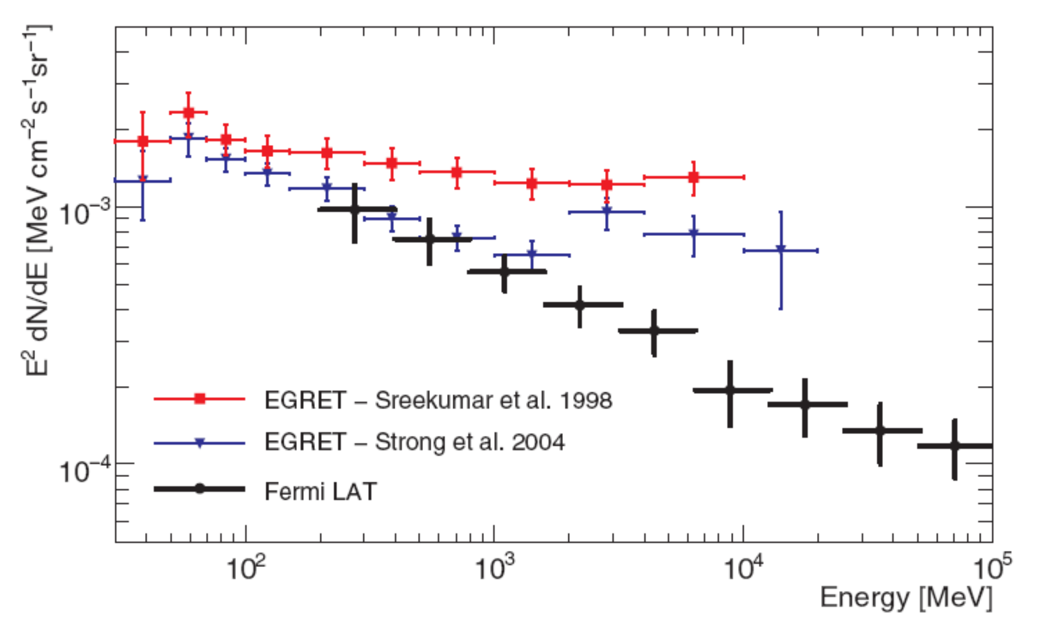
The Fermi Gamma Ray Space Telescope

- Surveys the whole sky once every 3 hours
- 100 Mev - 300 GeV
- Wide field of view: ~2.4 sr
- More precise measurements of the gamma ray background than any previous mission

Credit: http://fermi.gsfc.nasa.gov/

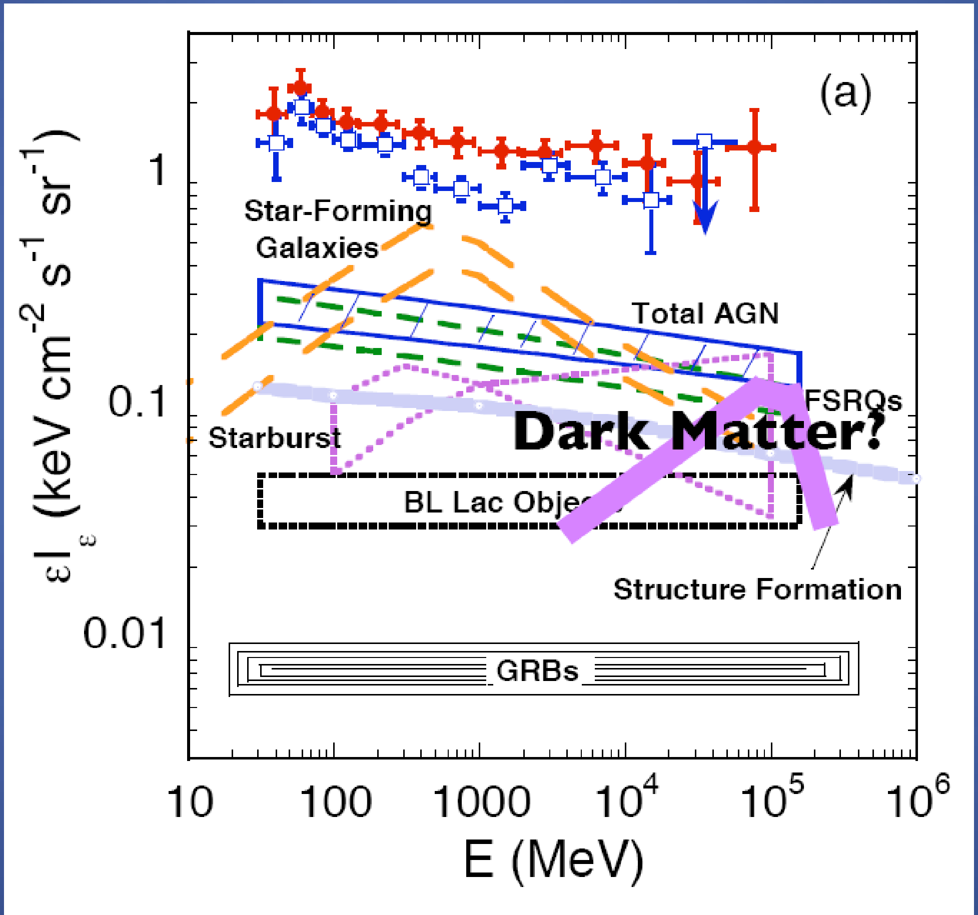
The Fermi Gamma Ray Background

- Sources composing the Fermi Gamma-Ray Background
  - Blazars
  - Star Forming Galaxies
  - Pulsars
  - Dark Matter?
  - Others?



Abdo et al. 2010

Goal:
Separate out the Components



Dermer 2007

Decomposition

- Mathematical techniques to break down the background into its component sources
- Analytic and unique
- Model-independent
- Potentially applicable for a wide variety of sources
- The Key: Anisotropy as a function of energy

Quantifying the Anisotropy

- We use the angular power spectrum of intensity fluctuations *in units of mean intensity (dimensionless)*

$$\delta I(\psi) \equiv \frac{I(\psi) - \langle I \rangle}{\langle I \rangle}$$

$$\delta I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi)$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

- Note: fluctuation power spectra are *independent of intensity normalization*
  - Hence, C_ℓ (E) is *constant* for a single source whose spatial distribution is energy independent

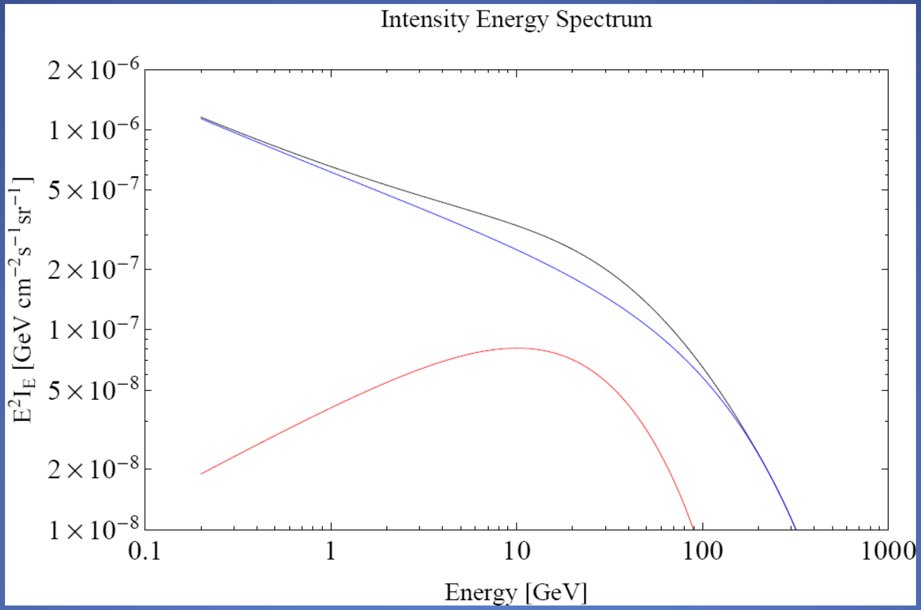
The Anisotropy Energy Spectrum

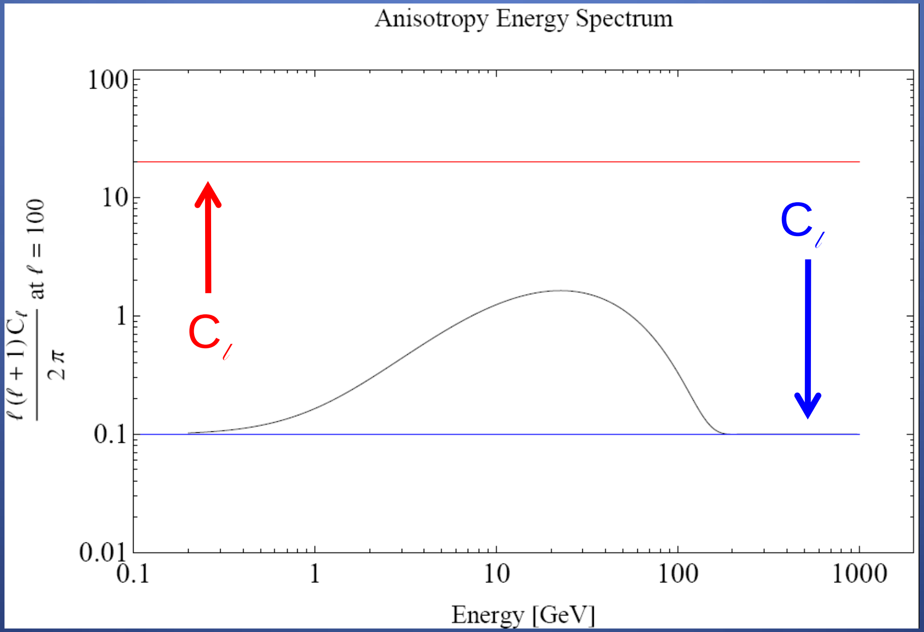
- Anisotropy Energy Spectrum: the angular power spectrum of the total emission at a fixed angular scale (multipole ℓ) as a function of energy
- Total spectrum is computed by

$$C_\ell^{\rm tot}(E) = \left(\frac{I_1(E)}{I_{\rm tot}(E)}\right)^2 C_\ell^1 + \left(\frac{I_2(E)}{I_{\rm tot}(E)}\right)^2 C_\ell^2 + 2\left(\frac{I_1(E)}{I_{\rm tot}(E)}\right)\left(\frac{I_2(E)}{I_{\rm tot}(E)}\right) C_\ell^{1\times 2}$$

  - Note the weighting of each C_ℓ by the fractional intensity squared => total spectrum is energy dependent

Example Spectrum





Goals and Assumptions

- We will assume only two sources are contributing in the energy range considered
  - Three or more sources can be handled with techniques to be discussed
- For each source, C_l independent of energy
  - i.e. spatial distribution is energy independent
- All correlation terms are zero
- The examples that follow are intended to be illustrative of the mathematical techniques, not necessarily realistic scenarios

The Equations

- Total Intensity

$$I_{\text{tot}}(E) = I_1(E) + I_2(E)$$

- Total Anisotropy

$$C_\ell^{\text{tot}}(E) = \left(\frac{I_1(E)}{I_{\text{tot}}(E)}\right)^2 C_\ell^1 + \left(\frac{I_2(E)}{I_{\text{tot}}(E)}\right)^2 C_\ell^2 + 2\left(\frac{I_1(E)}{I_{\text{tot}}(E)}\right)\left(\frac{I_2(E)}{I_{\text{tot}}(E)}\right) C_\ell^{1\times 2}$$

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In Search of C_ℓs

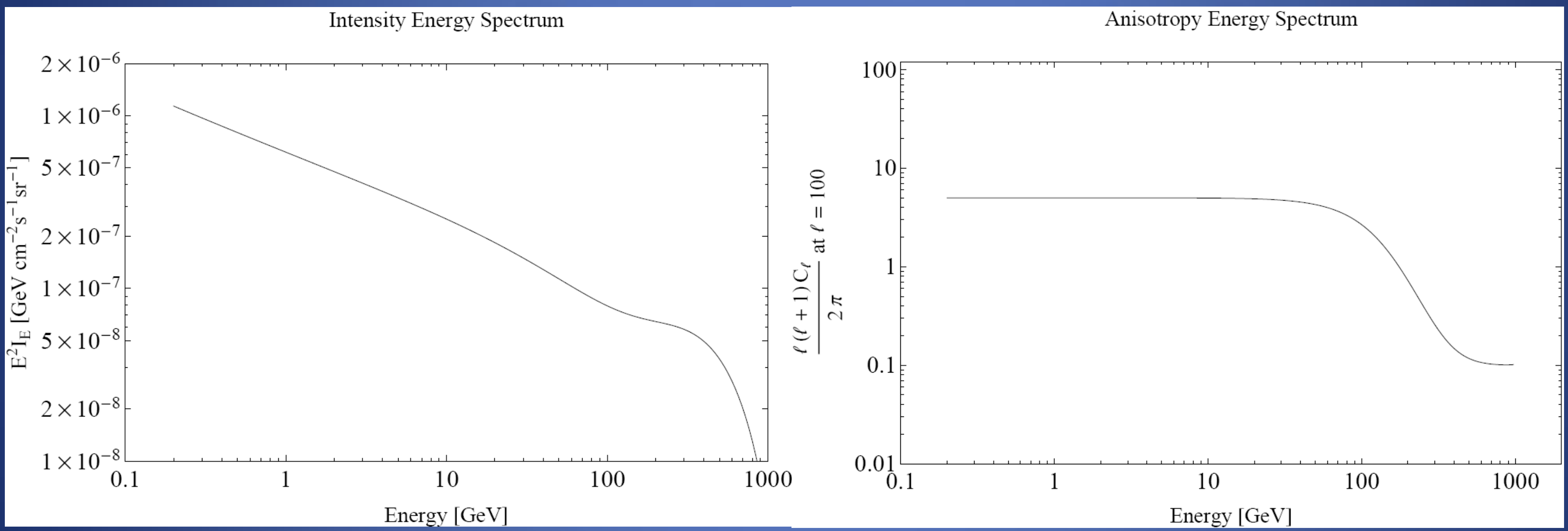
- Equations reduce to finding the C_ℓs of the two source classes

$$I_1 = I_{\rm tot}\left(\frac{C_\ell^2 \pm \sqrt{C_\ell^1 C_\ell^{\rm tot} + C_\ell^2 C_\ell^{\rm tot} - C_\ell^1 C_\ell^2}}{C_\ell^1 + C_\ell^2}\right)$$

$$I_2 = I_{\rm tot}\left(\frac{C_\ell^1 \mp \sqrt{C_\ell^1 C_\ell^{\rm tot} + C_\ell^2 C_\ell^{\rm tot} - C_\ell^1 C_\ell^2}}{C_\ell^1 + C_\ell^2}\right)$$

Plateau

- Transition from one dominant source to another
- Can read off the C_ℓs - then done!



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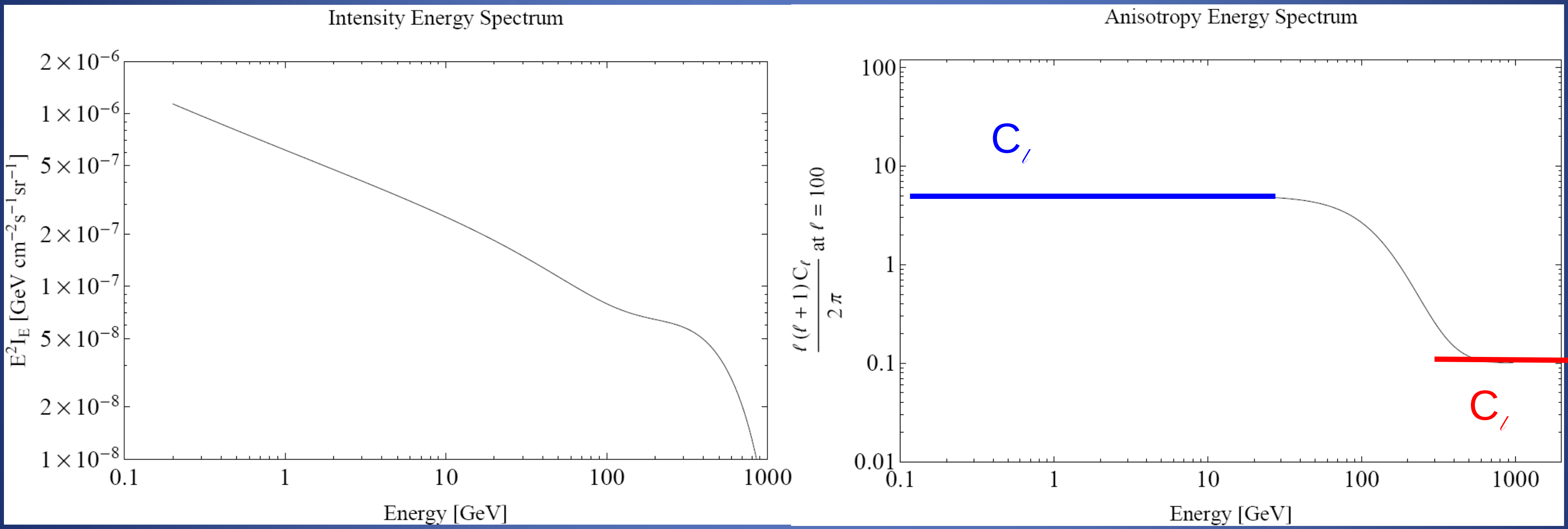

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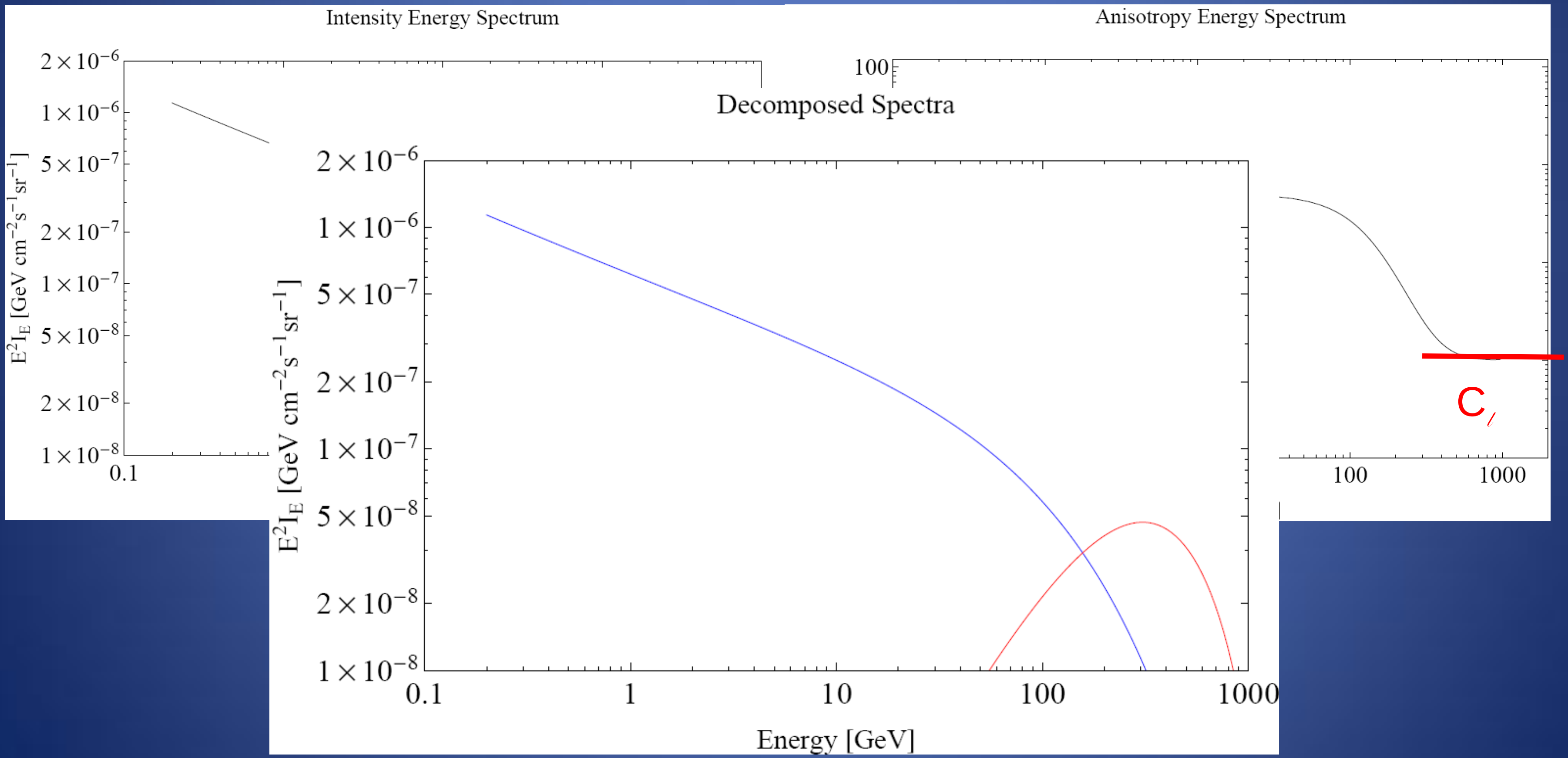
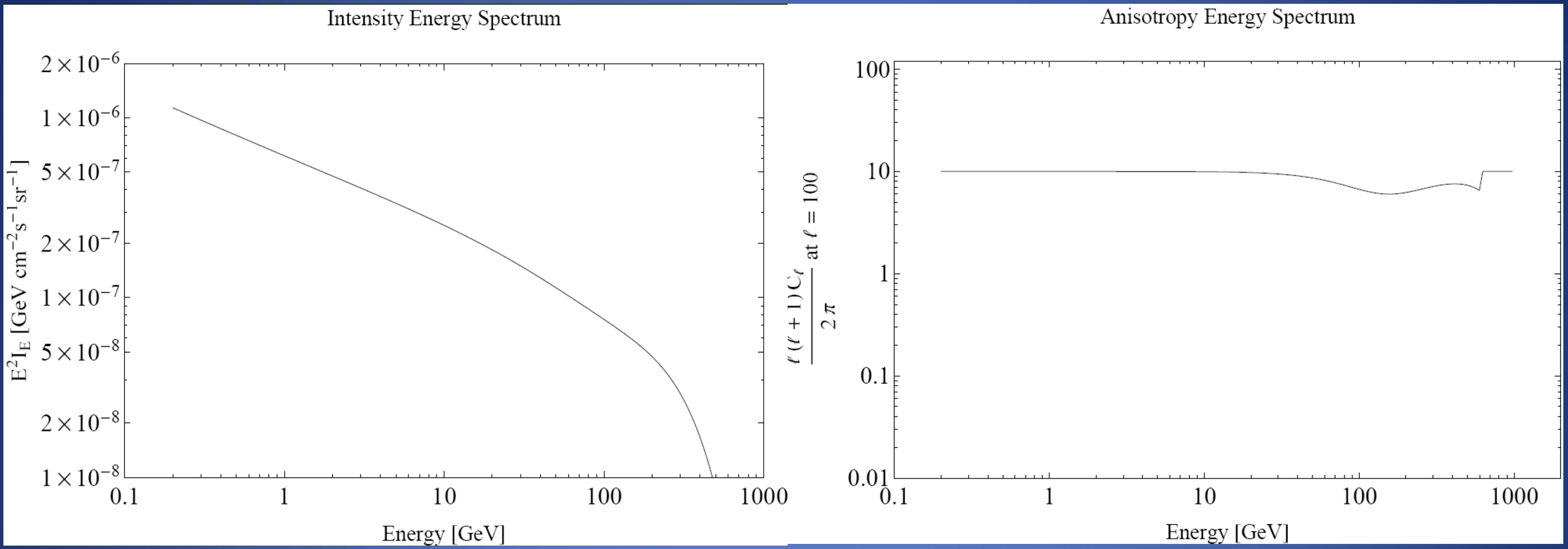


Minimum Example



Minimum

- Two conditions for minima:

$$\left(\frac{I_1(E)}{I_{\rm tot}(E)} - 1\right) C_\ell^2 + \left(\frac{I_1(E)}{I_{\rm tot}(E)}\right) C_\ell^1 = 0$$

And

$$\frac{d}{dE}\frac{I_1(E)}{I_{\rm tot}(E)} = 0$$

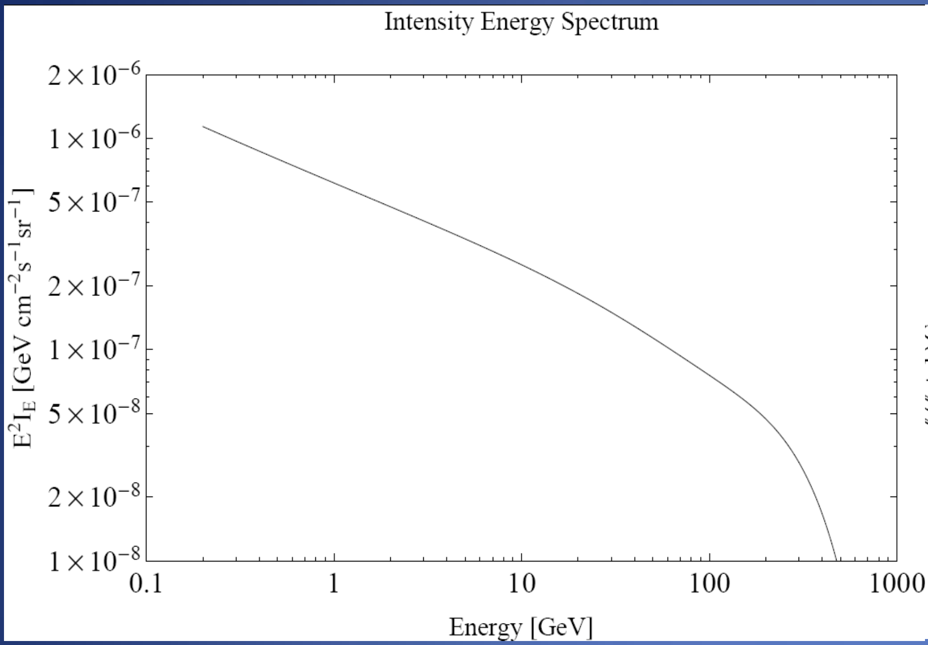
Minimum

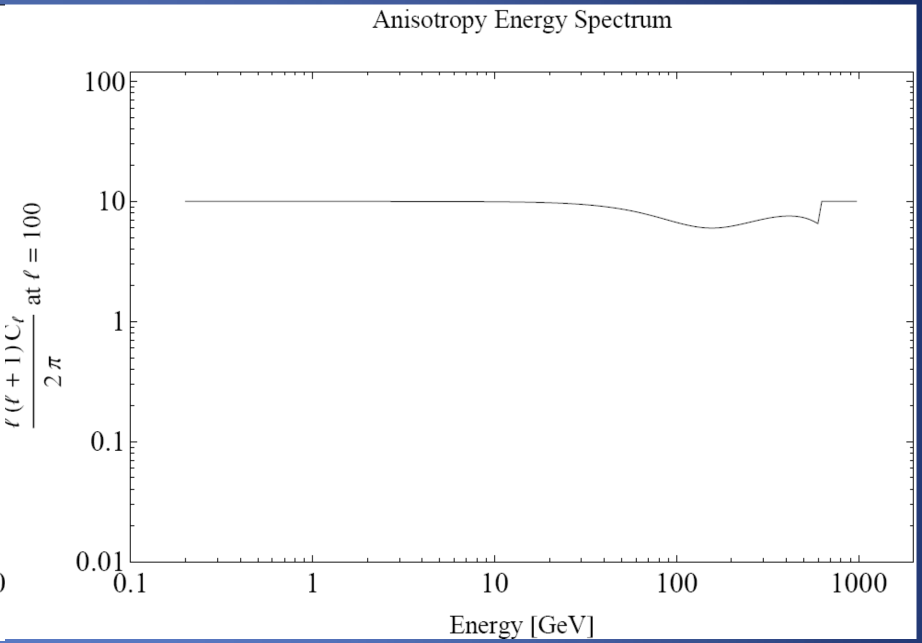
- The first condition yields a relation between the two C_ℓs

$$\left(\frac{I_1(E)}{I_{\rm tot}(E)} - 1\right) C_\ell^2 + \left(\frac{I_1(E)}{I_{\rm tot}(E)}\right) C_\ell^1 = 0$$

- If we know one source dominates at some energy, we can read off its C_ℓ and solve for the other
- The two types of minima can be distinguished in several ways
  - Knowledge about the sources expected to be contributing
  - Computing an anisotropy energy spectrum at a second ℓ

Minimum Example





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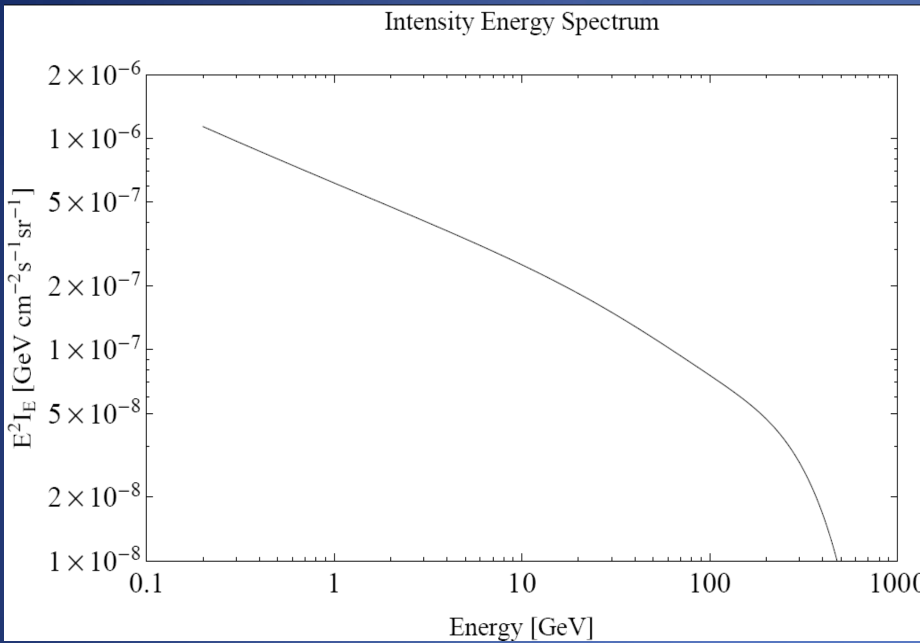
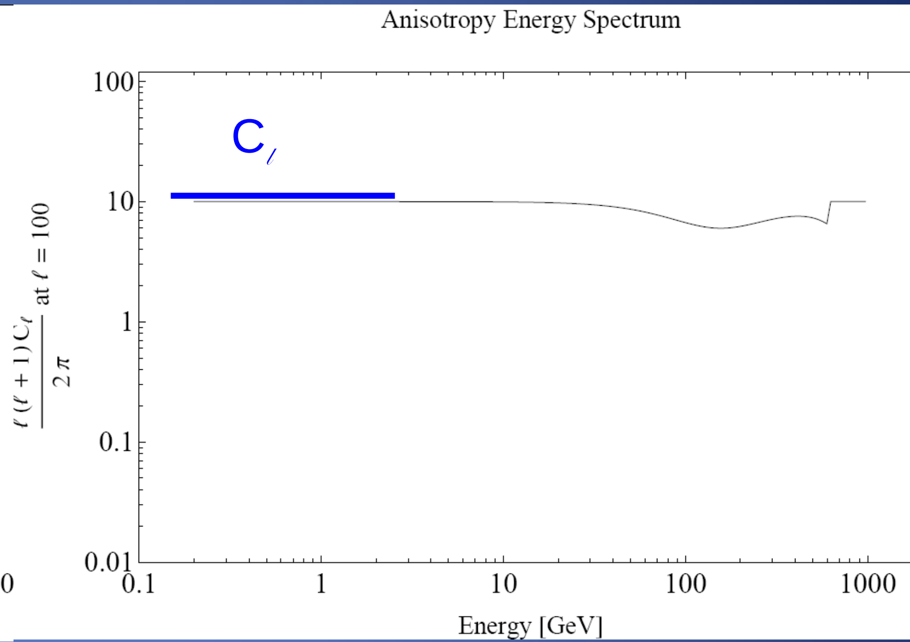
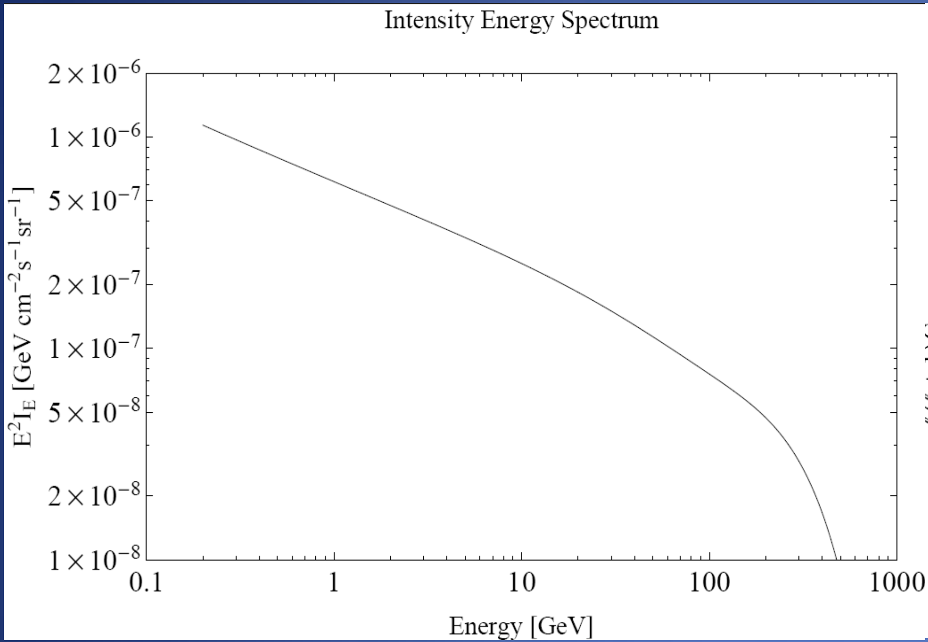
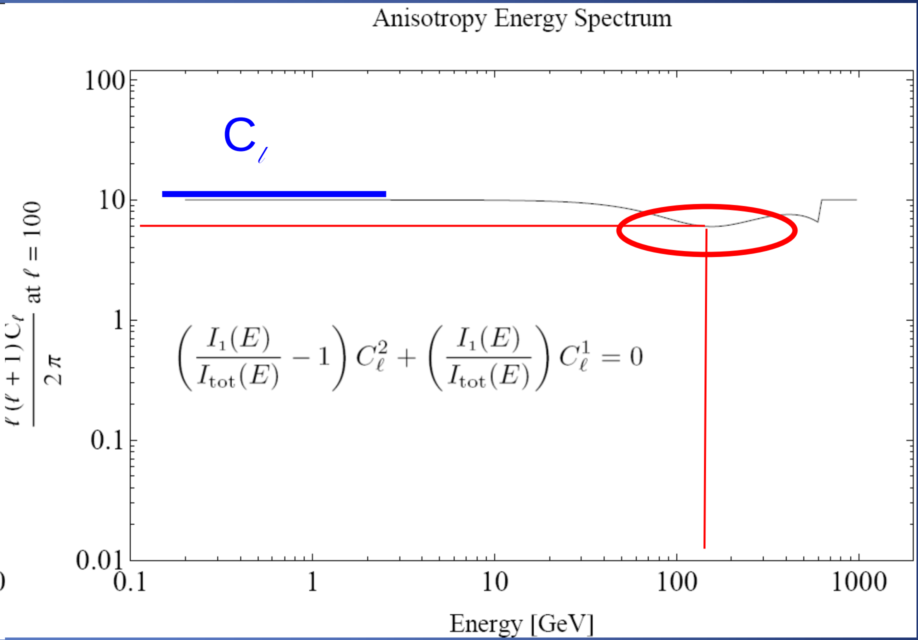


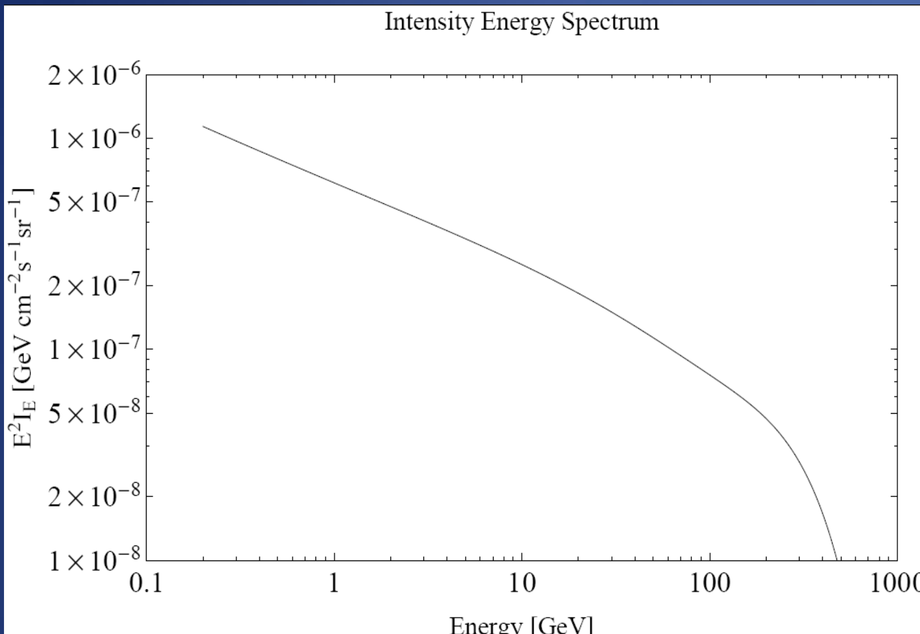


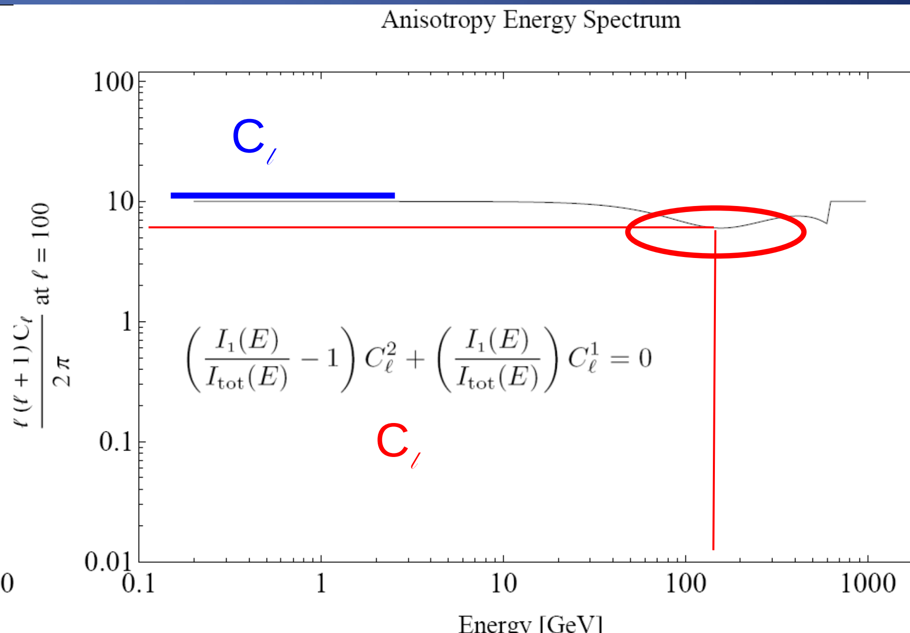
Minimum Example



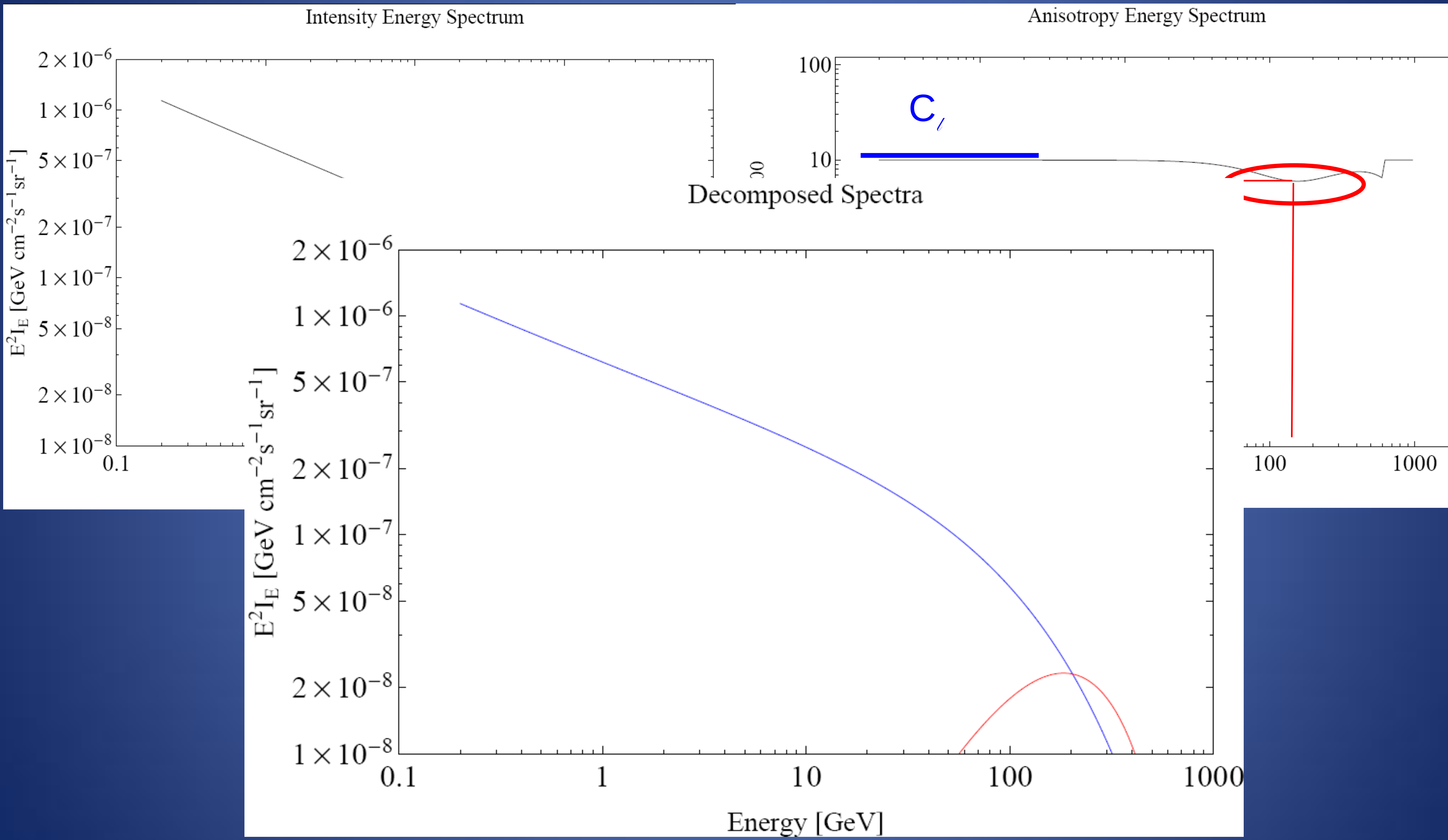


Minimum Example





Minimum Example



Low Anisotropy Subdominant

- Assume Source 1 is dominant over Source 2 in both intensity and anisotropy
- Then we have:

$$C_\ell^{\rm tot} = \left(\frac{I_1}{I_{\rm tot}}\right)^2 C_\ell^1 + \left(\frac{I_2}{I_{\rm tot}}\right)^2 C_\ell^2 \approx \left(\frac{I_1}{I_{\rm tot}}\right)^2 C_\ell^1$$

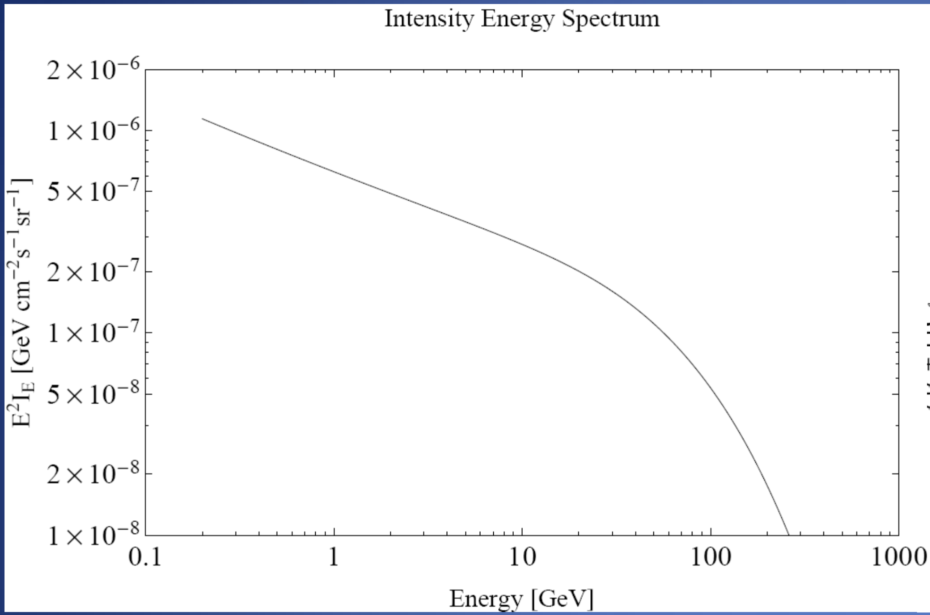
Low Anisotropy Subdominant

- Using this relation, we immediately uncover the intensity spectra

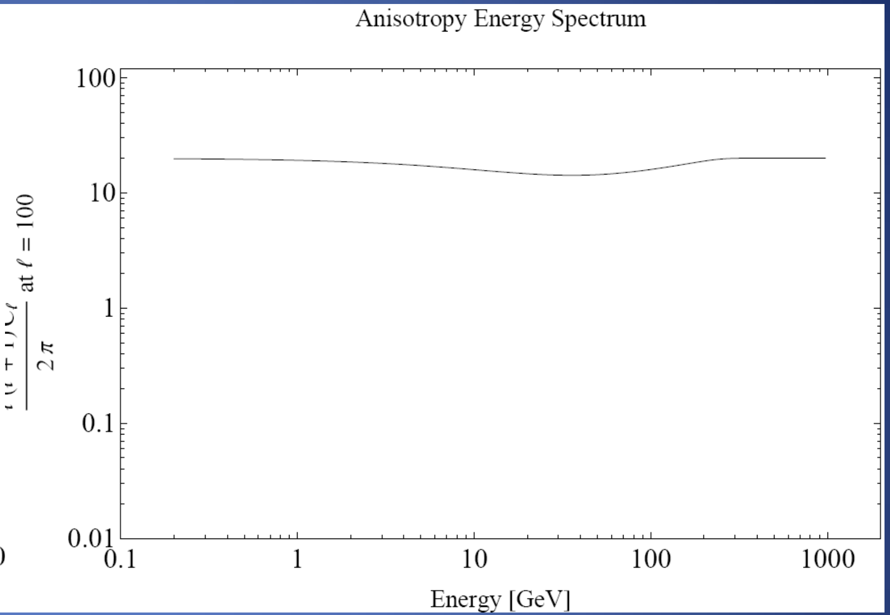
$$I_1 = I_{\rm tot}\sqrt{\frac{C_\ell^{\rm tot}}{C_\ell^1}}$$

$$I_2 = I_{\rm tot}\left(1 - \sqrt{\frac{C_\ell^{\rm tot}}{C_\ell^1}}\right)$$

Example

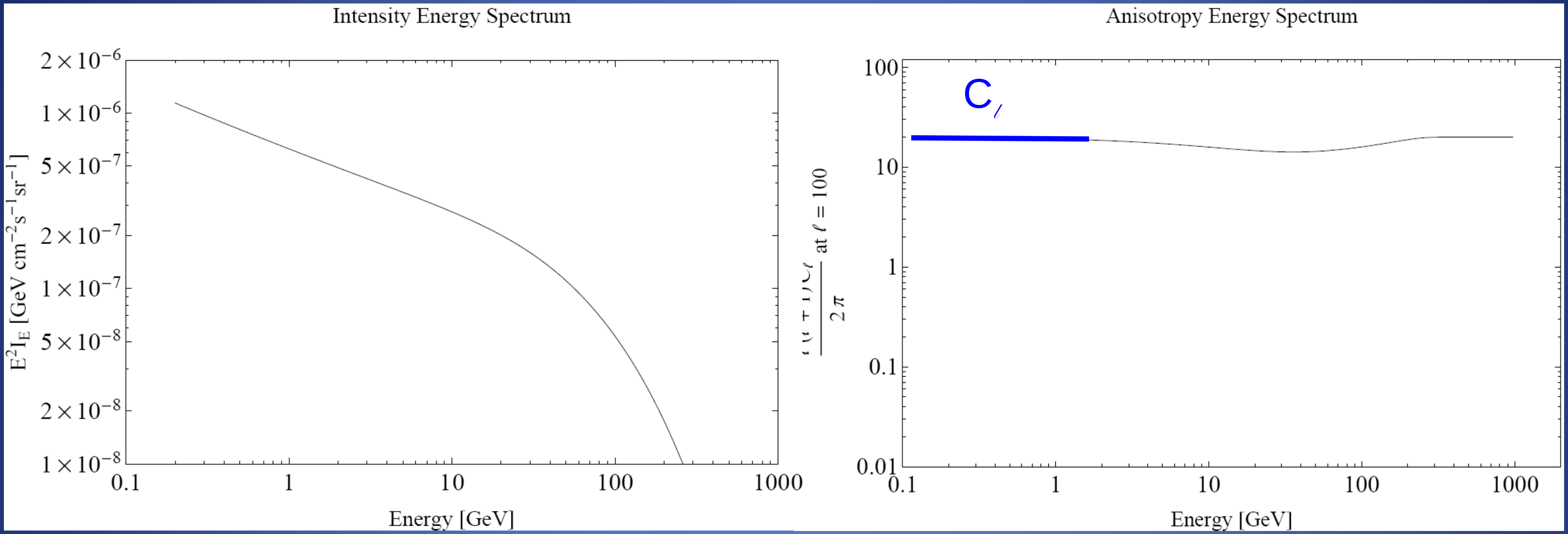


Intensity Energy Spectrum
E^2I_E [GeV cm^-2 s^-1 sr^-1]
2×10^-6
1×10^-6
5×10^-7
2×10^-7
1×10^-7
5×10^-8
2×10^-8
1×10^-8
0.1
1
10
100
1000
Energy [GeV]



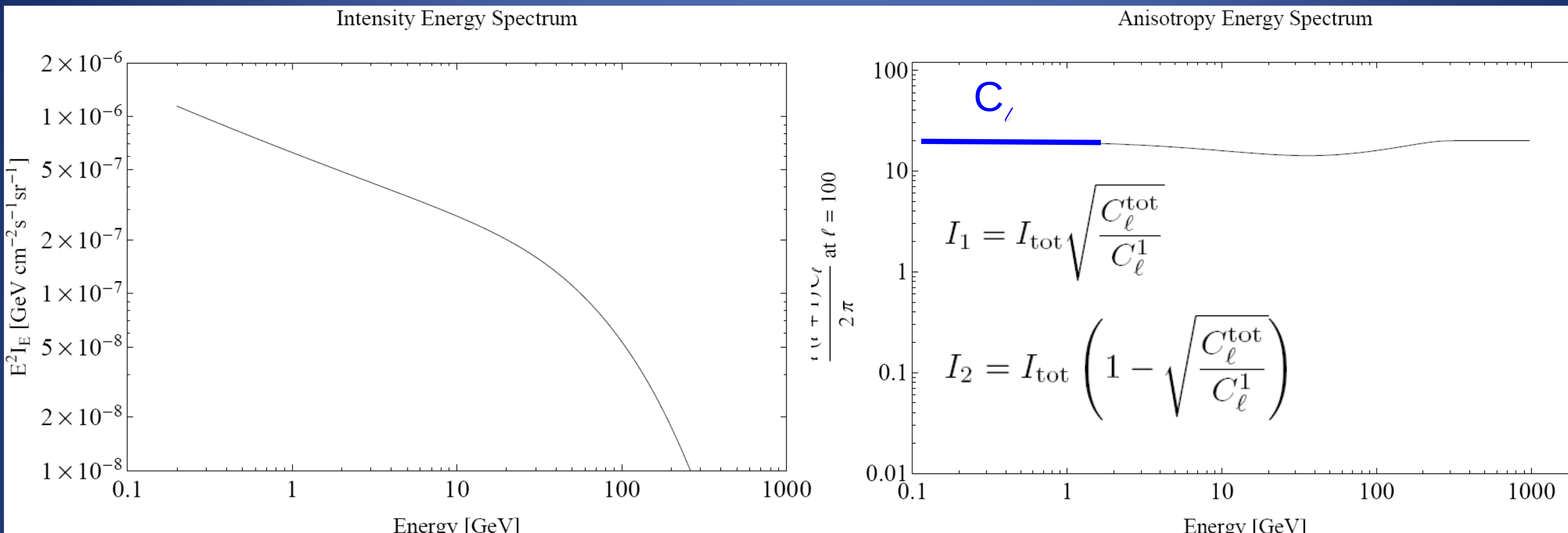
Anisotropy Energy Spectrum
at ℓ = 100
2π
100
10
1
0.1
0.01
0.1
1
10
100
1000
Energy [GeV]

Example

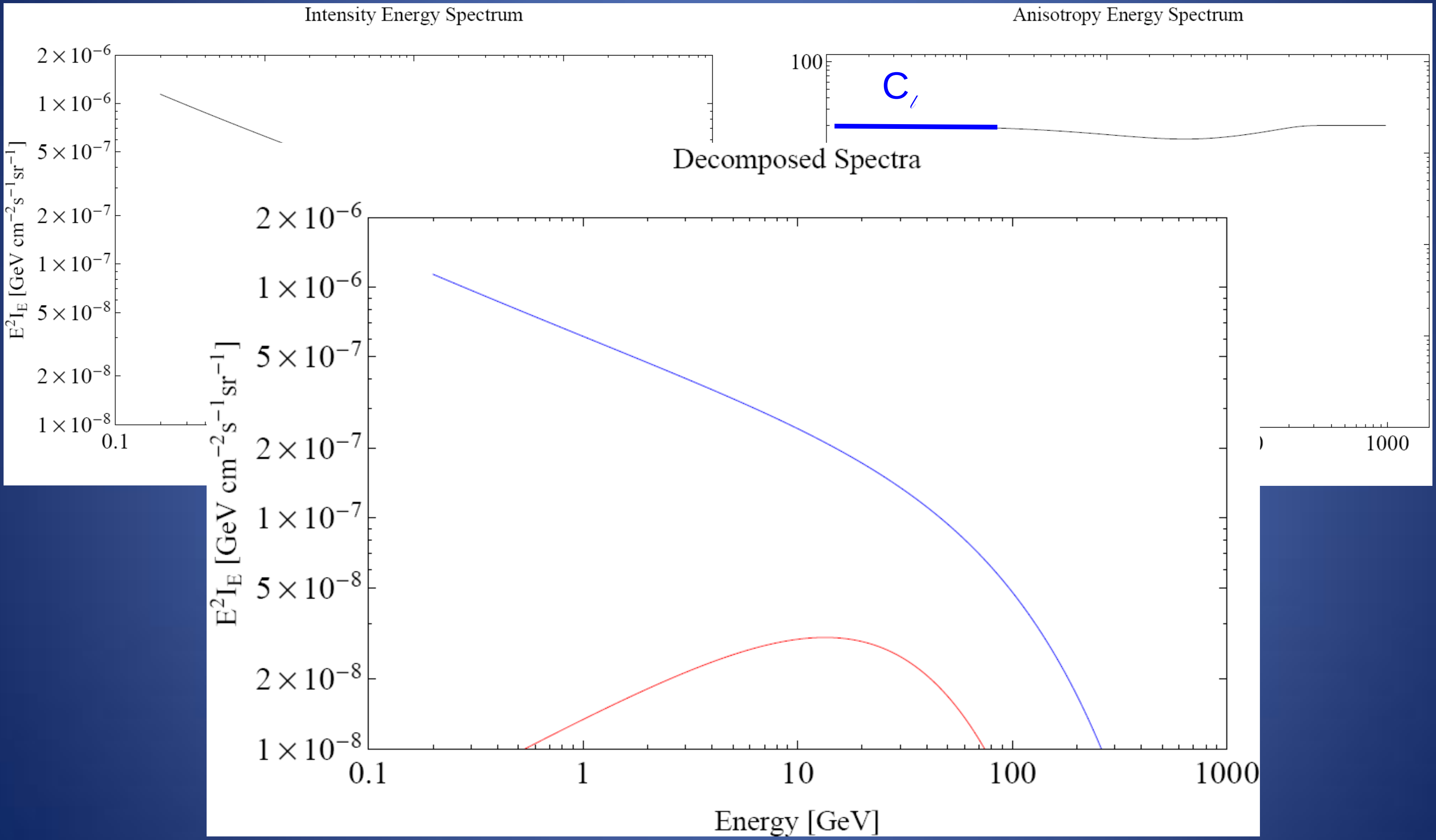


Intensity Energy Spectrum
2×10^{-6}
1×10^{-6}
5×10^{-7}
2×10^{-7}
1×10^{-7}
5×10^{-8}
2×10^{-8}
1×10^{-8}
E^2I_E [GeV cm^{-2}s^{-1}sr^{-1}]
0.1
1
10
100
1000
Energy [GeV]
Anisotropy Energy Spectrum
100
10
1
0.1
0.01
at $\ell = 100$
2π
C_ℓ
0.1
1
10
100
1000
Energy [GeV]

Example


Intensity Energy Spectrum
$E^2 I_E$ [GeV cm^{-2}s^{-1}sr^{-1}]
2×10^{-6}
1×10^{-6}
5×10^{-7}
2×10^{-7}
1×10^{-7}
5×10^{-8}
2×10^{-8}
1×10^{-8}
0.1
1
10
100
1000
Energy [GeV]
Anisotropy Energy Spectrum
at $\ell = 100$
100
10
1
0.1
0.01
C_ℓ
$I_1 = I_{\rm tot}\sqrt{\frac{C_\ell^{\rm tot}}{C_\ell^1}}$
$I_2 = I_{\rm tot}\left(1-\sqrt{\frac{C_\ell^{\rm tot}}{C_\ell^1}}\right)$
0.1
1
10
100
1000
Energy [GeV]

Example



Intensity Energy Spectrum
Anisotropy Energy Spectrum
Decomposed Spectra
$E^2 I_E$ [GeV cm^{-2}s^{-1}sr^{-1}]
Energy [GeV]

High Anisotropy Subdominant

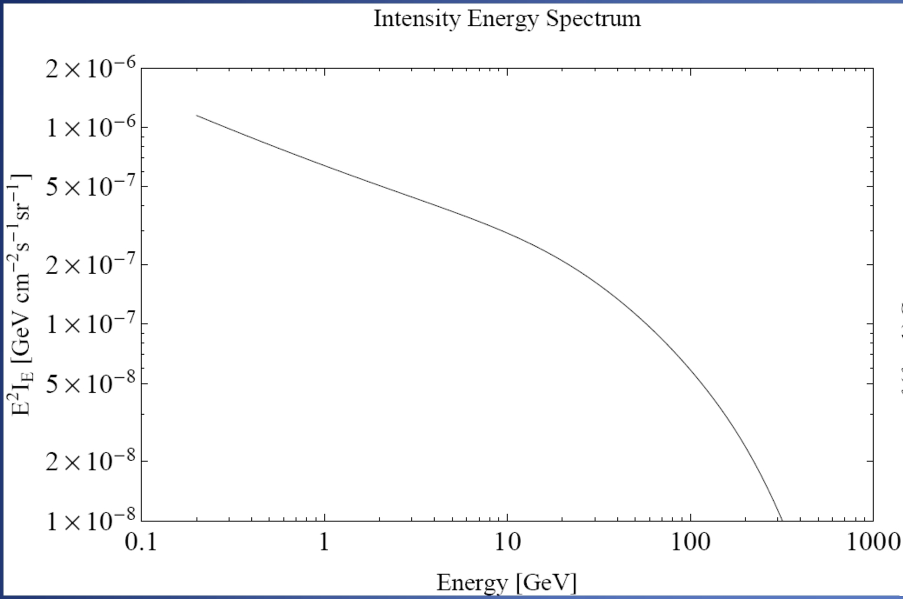
- Now the opposite case: the subdominant source is much more anisotropic than the dominant source

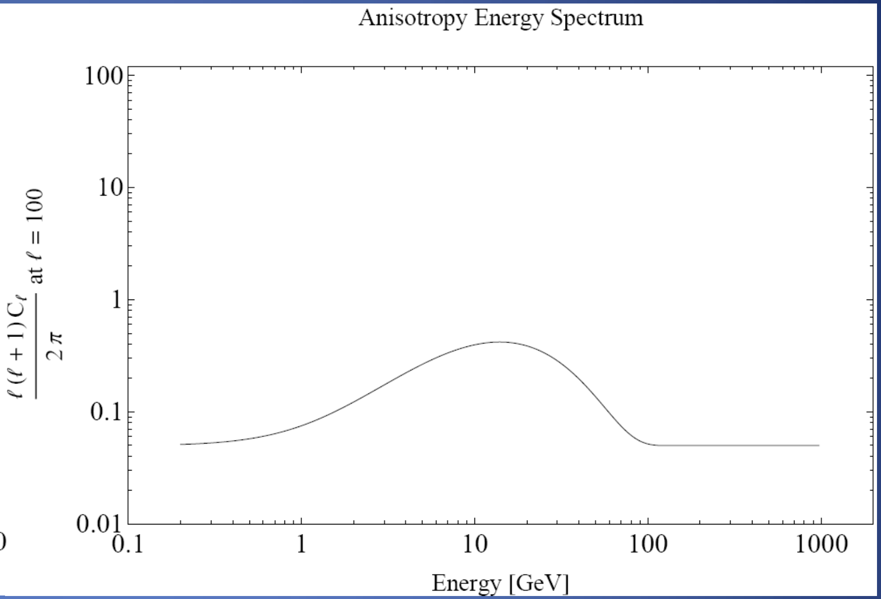
$$C_\ell^1 \ll C_\ell^2 = \Lambda C_\ell^1$$

It can then be shown that

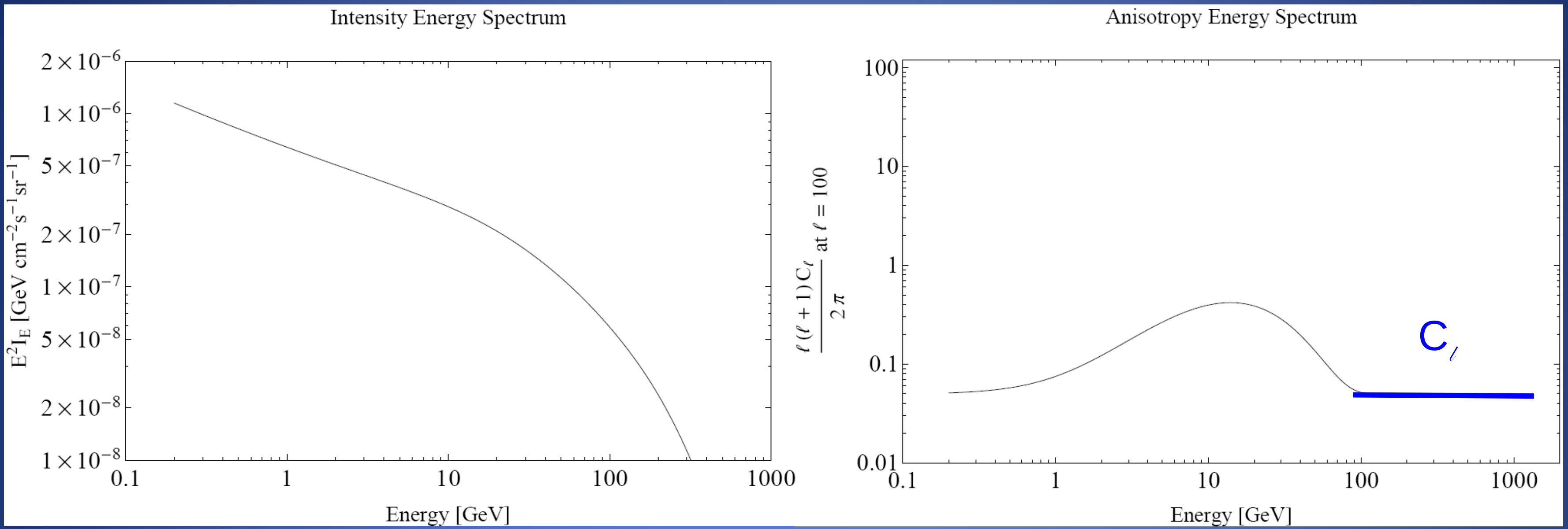
$$I_2(E) \approx \frac{I_{\rm tot}}{\sqrt{1+\Lambda}} \sqrt{\frac{C_\ell^{\rm tot}}{C_\ell^1} - 1}$$

Example

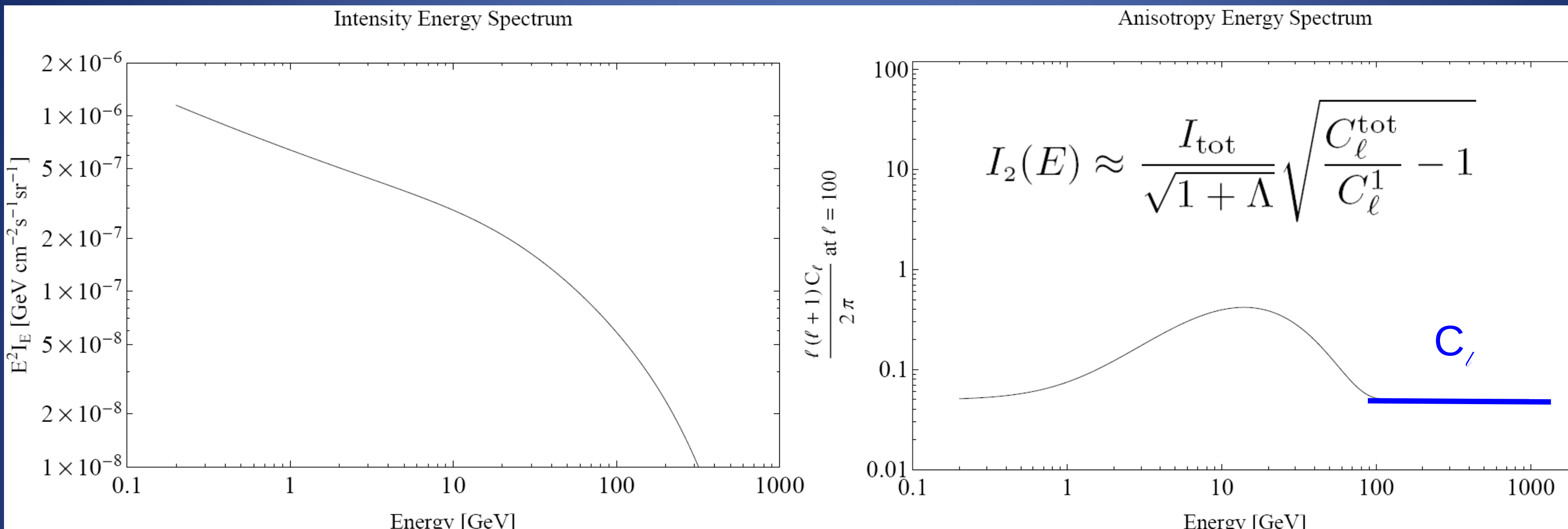

Intensity Energy Spectrum
$E^2 I_E$ [GeV cm^{-2}s^{-1}sr^{-1}]
2×10^{-6}
1×10^{-6}
5×10^{-7}
2×10^{-7}
1×10^{-7}
5×10^{-8}
2×10^{-8}
1×10^{-8}
0.1
1
10
100
1000
Energy [GeV]


Anisotropy Energy Spectrum
$\frac{\ell(\ell+1)C_\ell}{2\pi}$ at $\ell = 100$
100
10
1
0.1
0.01
0.1
1
10
100
1000
Energy [GeV]

Example


Intensity Energy Spectrum
2×10^{-6}
1×10^{-6}
5×10^{-7}
2×10^{-7}
1×10^{-7}
5×10^{-8}
2×10^{-8}
1×10^{-8}
$E^2 I_E$ [GeV cm^{-2}s^{-1}sr^{-1}]
0.1
1
10
100
1000
Energy [GeV]
Anisotropy Energy Spectrum
100
10
1
0.1
0.01
$\frac{\ell(\ell+1)C_\ell}{2\pi}$ at $\ell = 100$
0.1
1
10
100
1000
Energy [GeV]
C_ℓ

Example


Intensity Energy Spectrum
2×10^{-6}
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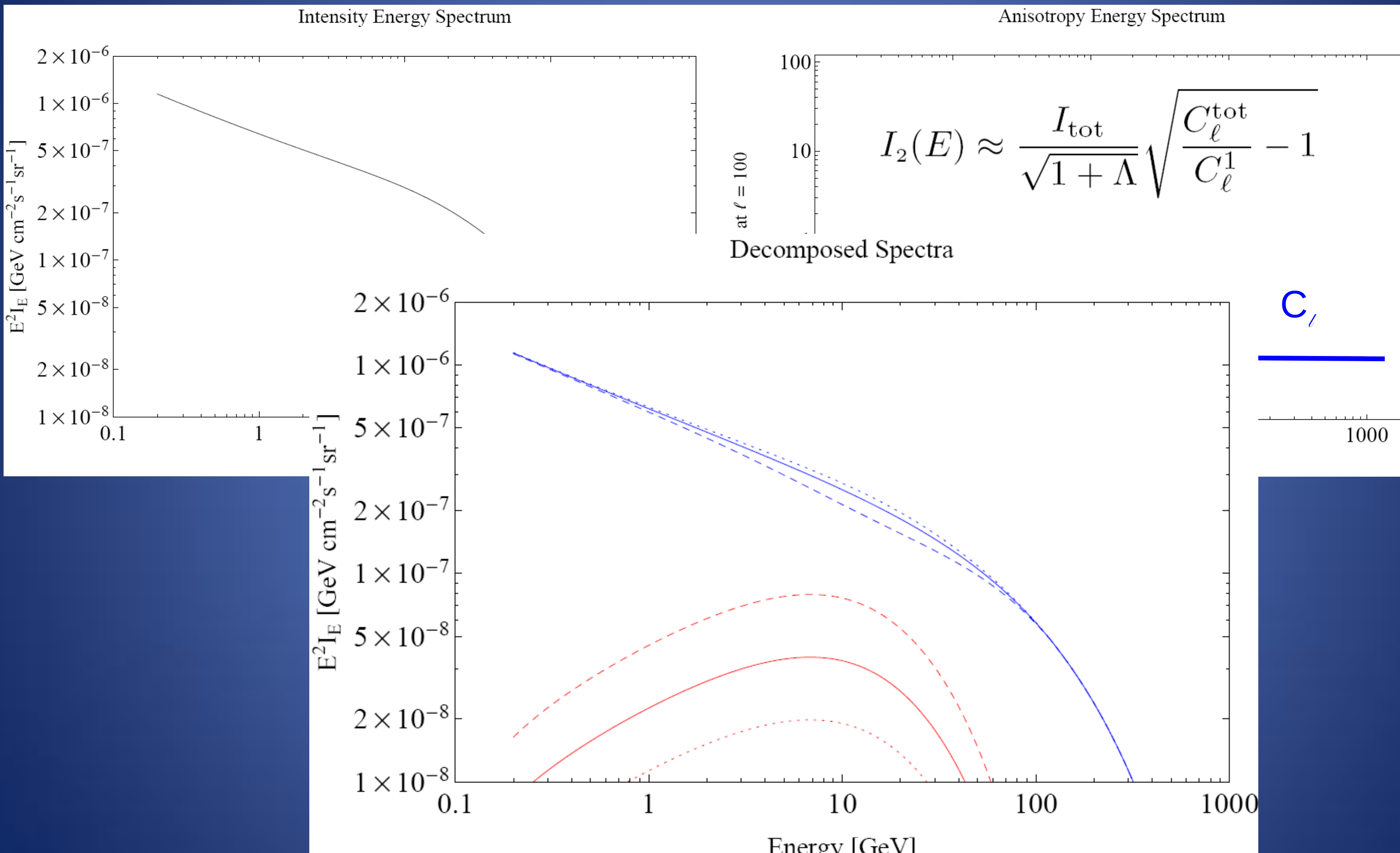
2×10^{-7}
1×10^{-7}
5×10^{-8}
2×10^{-8}
1×10^{-8}
$E^2 I_E$ [GeV cm^{-2}s^{-1}sr^{-1}]
0.1
1
10
100
1000
Energy [GeV]
Anisotropy Energy Spectrum
100
10
1
0.1
0.01
$\frac{\ell(\ell+1)C_\ell}{2\pi}$ at $\ell = 100$
$I_2(E) \approx \frac{I_{\rm tot}}{\sqrt{1+\Lambda}}\sqrt{\frac{C_\ell^{\rm tot}}{C_\ell^1} - 1}$
C_ℓ
0.1
1
10
100
1000
Energy [GeV]

Example


Intensity Energy Spectrum
Anisotropy Energy Spectrum
$I_2(E) \approx \frac{I_{tot}}{\sqrt{1+\Lambda}}\sqrt{\frac{C_\ell^{tot}}{C_\ell^1} - 1}$
Decomposed Spectra
C_ℓ
$E^2 I_E$ [GeV cm^{-2}s^{-1}sr^{-1}]
Energy [GeV]
at ℓ = 100

Multiple ℓ s

- If one or more sources has a C_ℓ that varies with ℓ, then measuring two anisotropy energy spectra can yield a decomposition
- Since the LHS is ℓ - independent, the RHS must be the same measured at any ℓ

$$\frac{df_1(E)}{dE} = \frac{dC_\ell^{\rm tot}(E,\ell)/dE}{2\{f_1(E)[C_\ell^1(\ell)+C_\ell^2(\ell)]-C_\ell^2(\ell)\}}$$

where f indicates fractional intensity

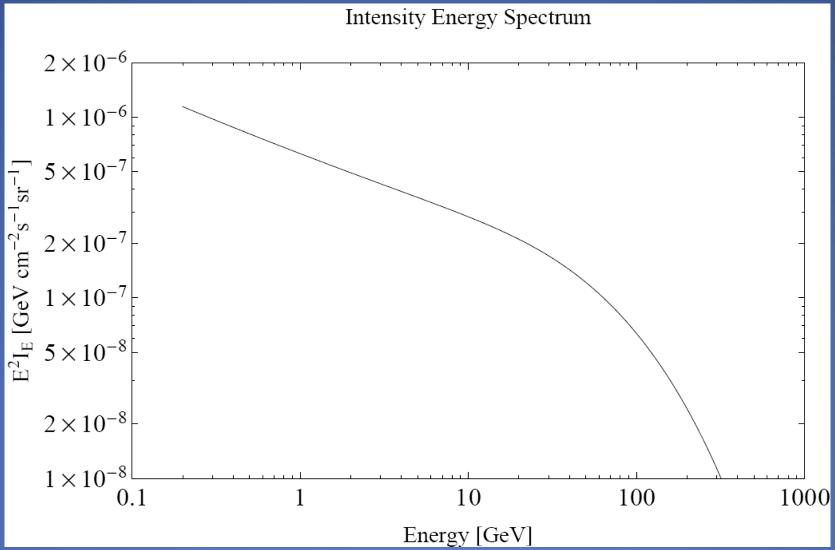
Multiple ℓ s

- We then equate this expression at two values of ℓ
- After a little algebra,

$$I_1 = I_{\text{tot}} \frac{C_{\ell_1}^{\text{tot}} \frac{d}{dE} C_{\ell_2}^{\text{tot}} - C_{\ell_2}^{\text{tot}} \frac{d}{dE} C_{\ell_1}^{\text{tot}}}{C_{\ell_1}^{1} \frac{d}{dE} C_{\ell_2}^{\text{tot}} - C_{\ell_2}^{1} \frac{d}{dE} C_{\ell_1}^{\text{tot}}}$$

where the ℓ subscripts distinguish the two ℓ values used

Example


Intensity Energy Spectrum
$E^2 I_E$ [GeV cm^{-2}s^{-1}sr^{-1}]
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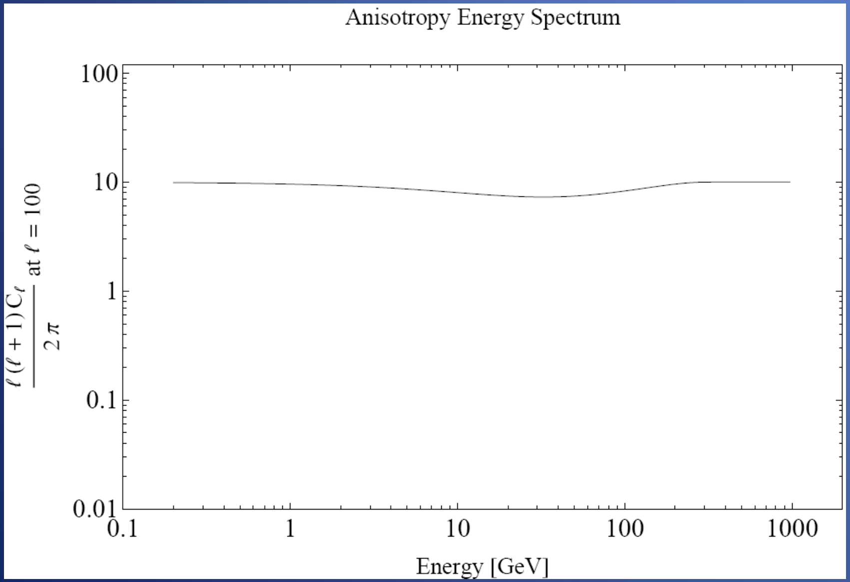
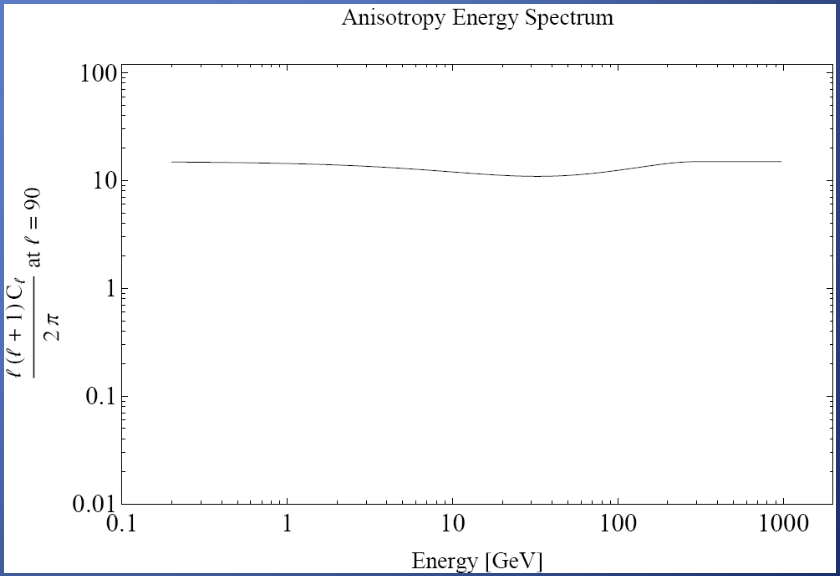
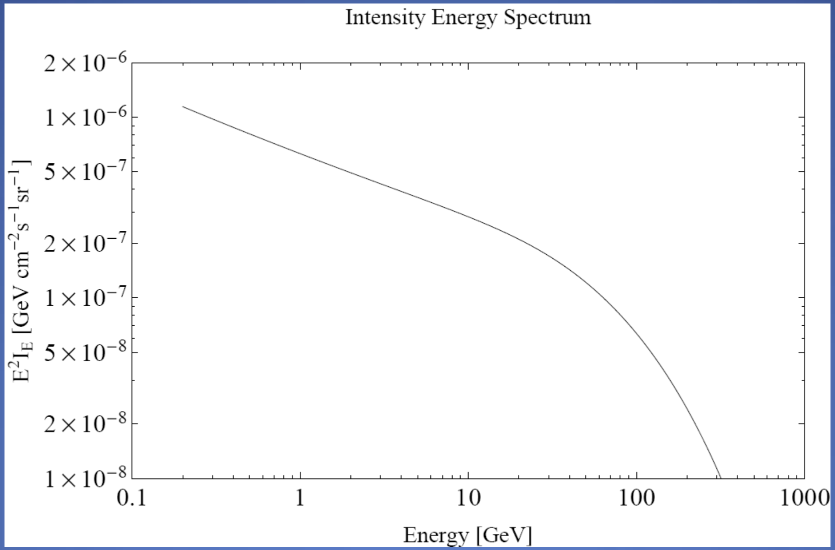
0.1
1
10
100
1000
Energy [GeV]


Anisotropy Energy Spectrum
$\frac{\ell(\ell+1)C_\ell}{2\pi}$ at $\ell = 100$
100
10
1
0.1
0.01
0.1
1
10
100
1000
Energy [GeV]


Anisotropy Energy Spectrum
$\frac{\ell(\ell+1)C_\ell}{2\pi}$ at $\ell = 90$
100
10
1
0.1
0.01
0.1
1
10
100
1000
Energy [GeV]

Example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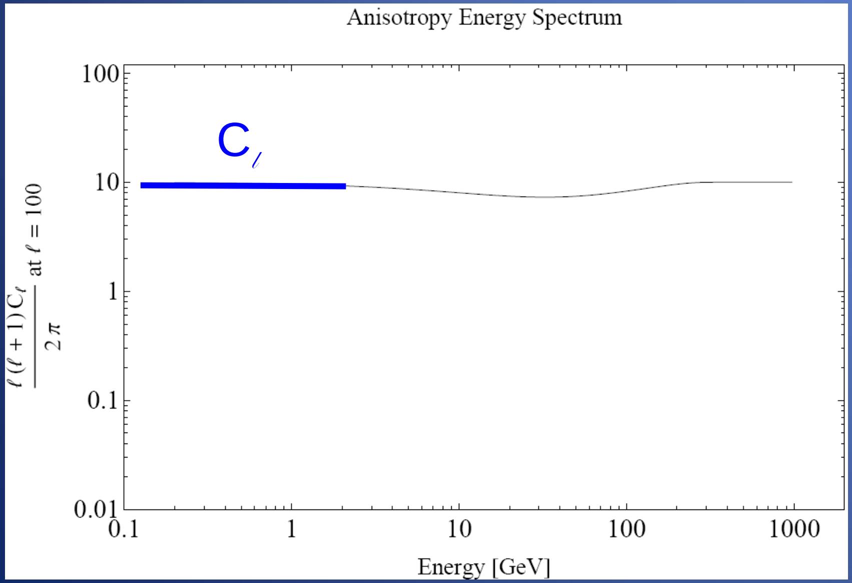
0.1
1
10
100
1000
Energy [GeV]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$\frac{\ell(\ell+1)C_\ell}{2\pi}$ at $\ell = 100$
C_ℓ
100
10
1
0.1
0.01
0.1
1
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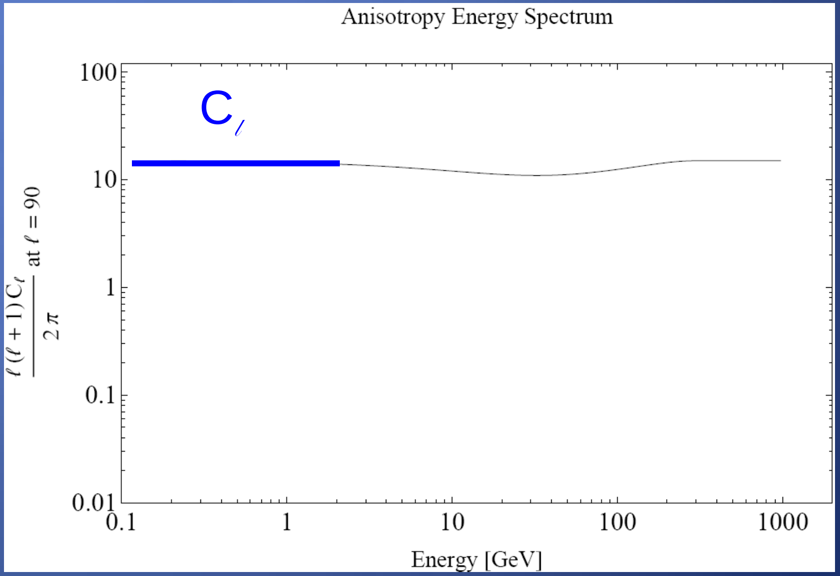
100
1000
Energy [GeV]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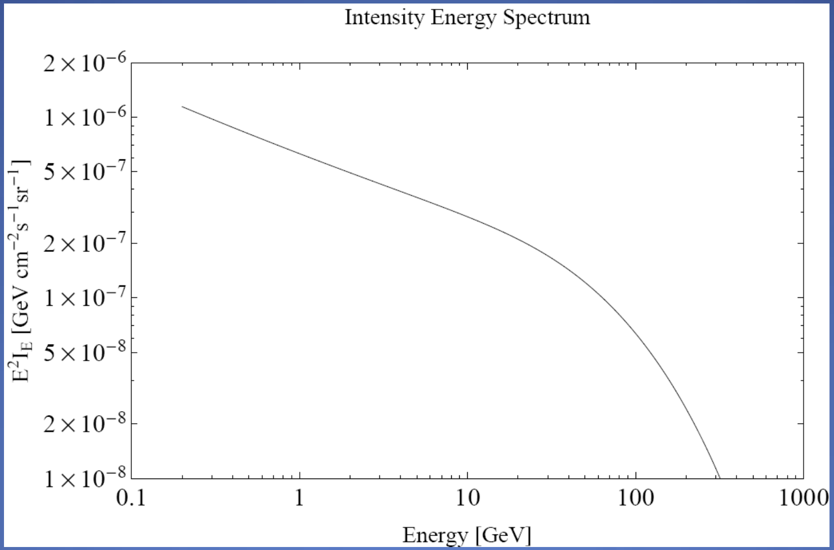
Energy [GeV]

Example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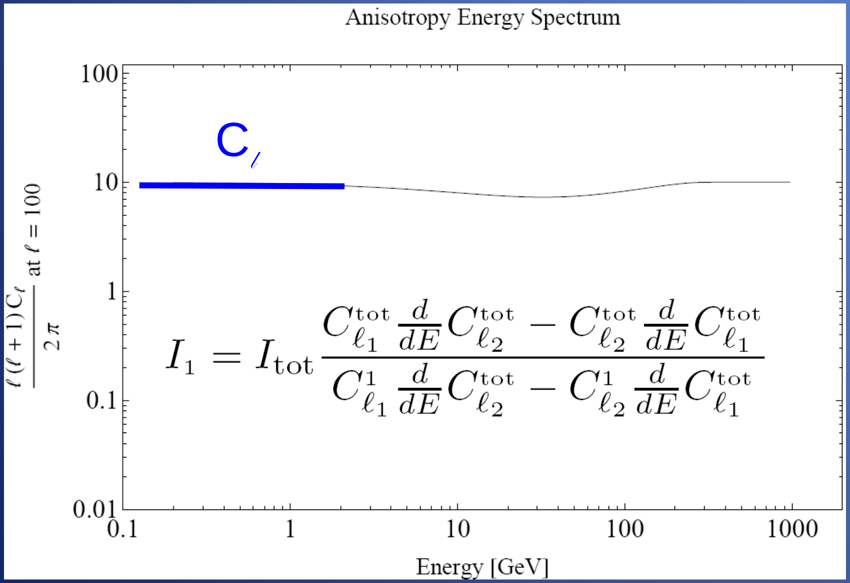
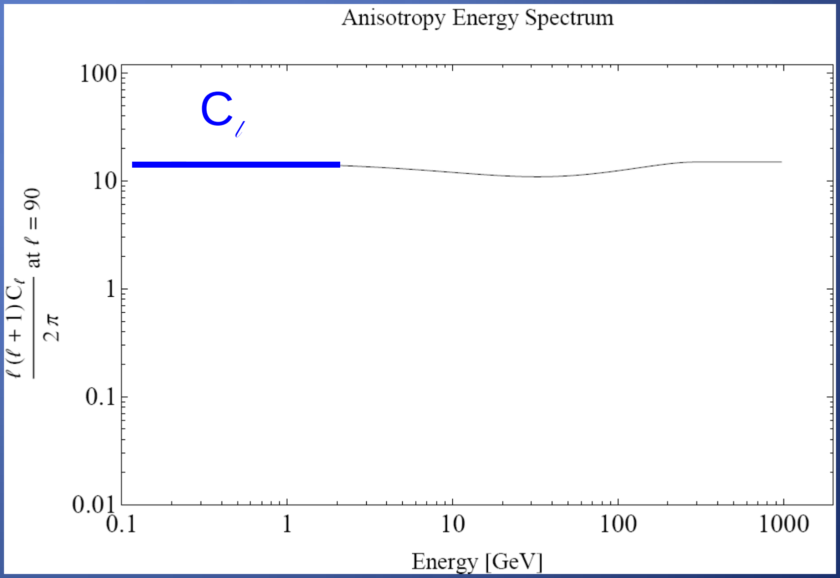
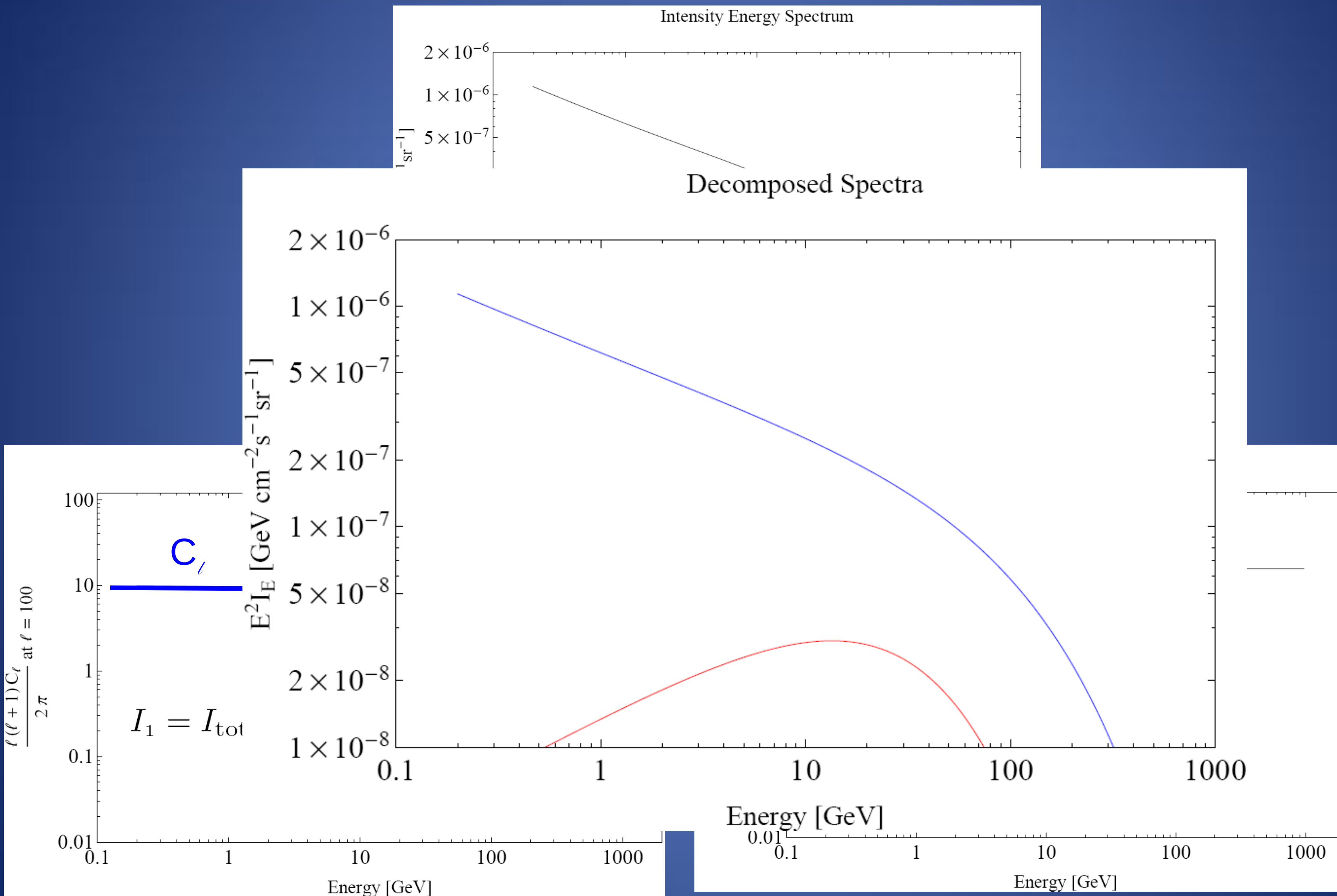
0.1
1
10
100
1000
Energy [GeV]


Anisotropy Energy Spectrum
$\frac{\ell(\ell+1)C_\ell}{2\pi}$ at $\ell = 100$
100
10
1
0.1
0.01
C_ℓ
$I_1 = I_{\rm tot} \frac{C_{\ell_1}^{\rm tot} \frac{d}{dE} C_{\ell_2}^{\rm tot} - C_{\ell_2}^{\rm tot} \frac{d}{dE} C_{\ell_1}^{\rm tot}}{C_{\ell_1}^{1} \frac{d}{dE} C_{\ell_2}^{\rm tot} - C_{\ell_2}^{1} \frac{d}{dE} C_{\ell_1}^{\rm tot}}$
0.1
1
10
100
1000
Energy [GeV]


Anisotropy Energy Spectrum
$\frac{\ell(\ell+1)C_\ell}{2\pi}$ at $\ell = 90$
100
10
1
0.1
0.01
C_ℓ
0.1
1
10
100
1000
Energy [GeV]

Example

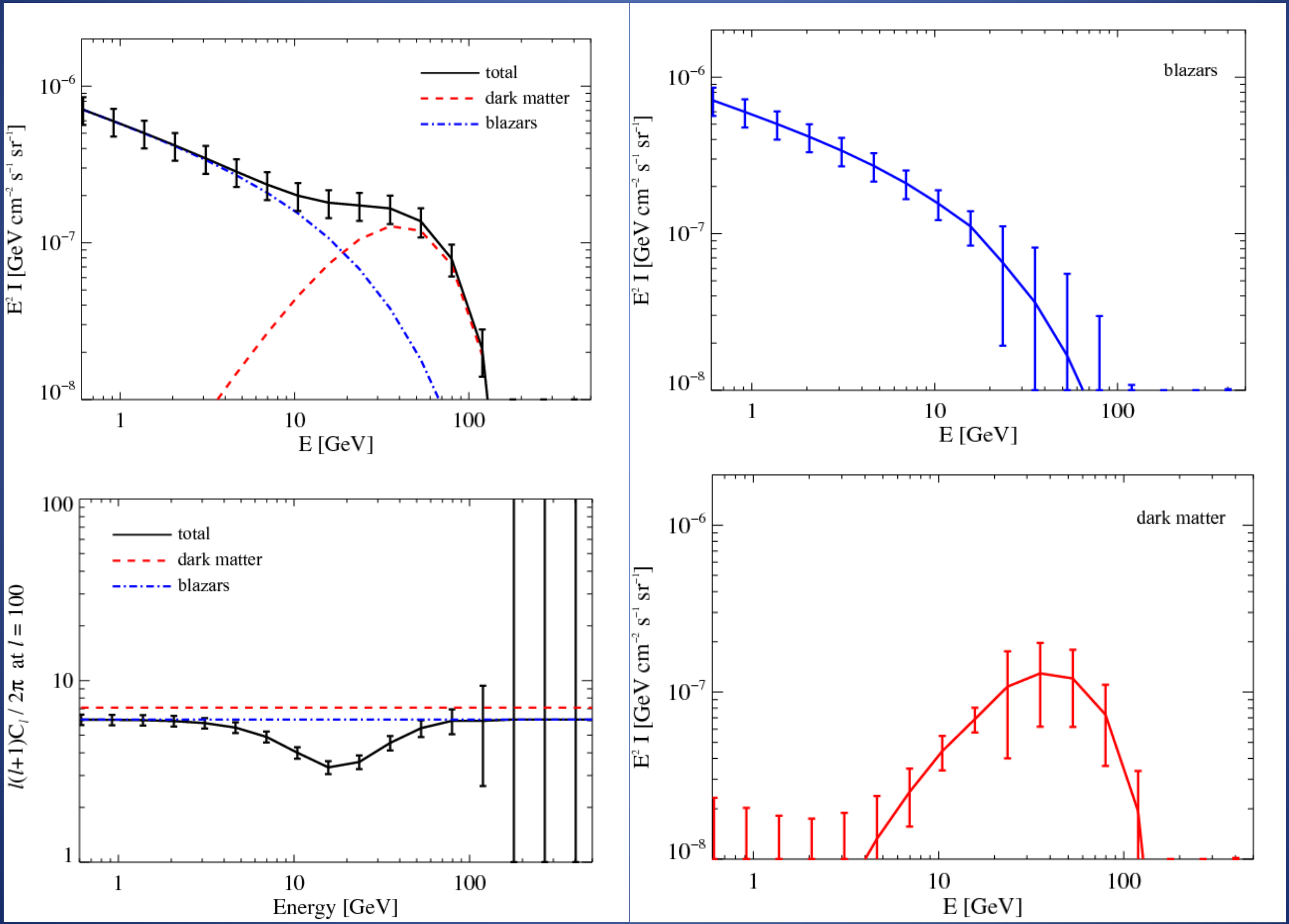


Intensity Energy Spectrum
Decomposed Spectra
2×10^{-6}
1×10^{-6}
5×10^{-7}
2×10^{-7}
1×10^{-7}
5×10^{-8}
2×10^{-8}
1×10^{-8}
$E^2 I_E$ [GeV cm^{-2}s^{-1}sr^{-1}]
0.1
1
10
100
1000
Energy [GeV]
C_ℓ
$\frac{\ell(\ell+1)C_\ell}{2\pi}$ at $\ell = 100$
100
10
1
0.1
0.01
$I_1 = I_{\rm tot}$

Three (or more) Component Case

- Both the total intensity equation and total anisotropy equations are additive
- In a multi-component background, if one source is known completely, i.e. I(E) and C_ℓ, it can be subtracted out
- If the background can be reduced back to two components in this way, all of the methodology can be applied

Example with Error Bars



Summary

- Decomposition techniques cover a wide range of scenarios
  - Transition between two sources (plateau)
  - Sources of comparable anisotropy (minimum)
  - Subdominant sources with very low or very high anisotropy
  - Sources with ℓ-dependent C_ℓs
- Analytic and unique
- Model independent

Notes on Uniqueness

- The choice of signs in the general equation for the intensity spectra is determined by sign of the quantity

$$I_2 C_\ell^2 - I_1 C_\ell^1$$

The sign of this quantity changes at each minimum, necessitating a sign flip in the intensity spectra equations. If there is some energy where only one of the sources is expected to contribute, the proper signs can then be deduced

Notes on Uniqueness

- To distinguish between the two types of minima, one can examine the anisotropy energy spectrum at two different ℓ values. If the location of the minimum changes between the two spectra, then it is a correlation minimum that can be used for decomposition. Otherwise it is an extremum of the fractional intensity.