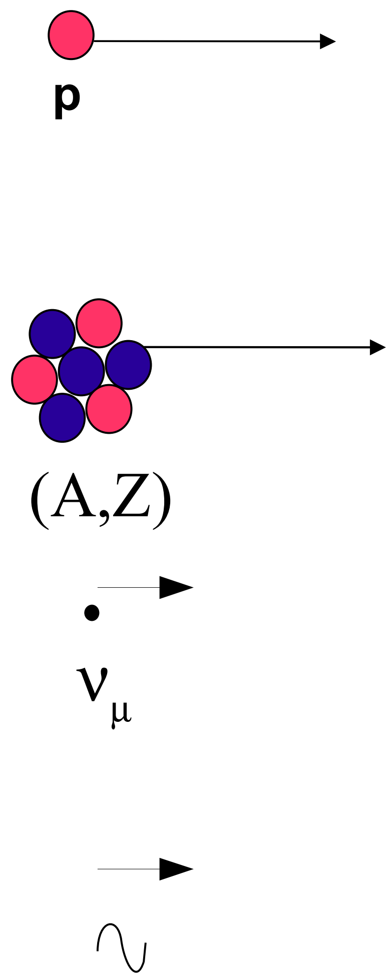
MULTIMESSENGER APPROACH:Using the Different Messengers

PROTONS

NUCLEI

NEUTRINOS

PHOTONS



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LECTURE PLAN:

1) COSMIC RAYS- proton interactions with photons, composition, nuclei interactions with photons, different photon targets

2) NEUTRINOS- presence of GZK-cutoff, photo-pion production mechanism, interaction rate, cosmic ray spectra, source distribution

3) PHOTONS- photon flux production, photon flux attenuation, competition of rates, e/γ cascades

4) MULTIMESSENGER APPROACH (1)- using the different attenuation lengths, homogeneous sources, inhomogeneous sources

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LECTURE PLAN:

1) COSMIC RAYS- proton interactions with photons, composition, nuclei interactions with photons, different photon targets

2) NEUTRINOS- presence of GZK-cutoff, photo-pion production mechanism, interaction rate, cosmic ray spectra, source distribution

3) PHOTONS- photon flux production, photon flux attenuation, competition of rates, e/γ cascades

4) MULTIMESSENGER APPROACH (2)- candidate UHECR source, consistency check of disintegration with neutrino flux calculations

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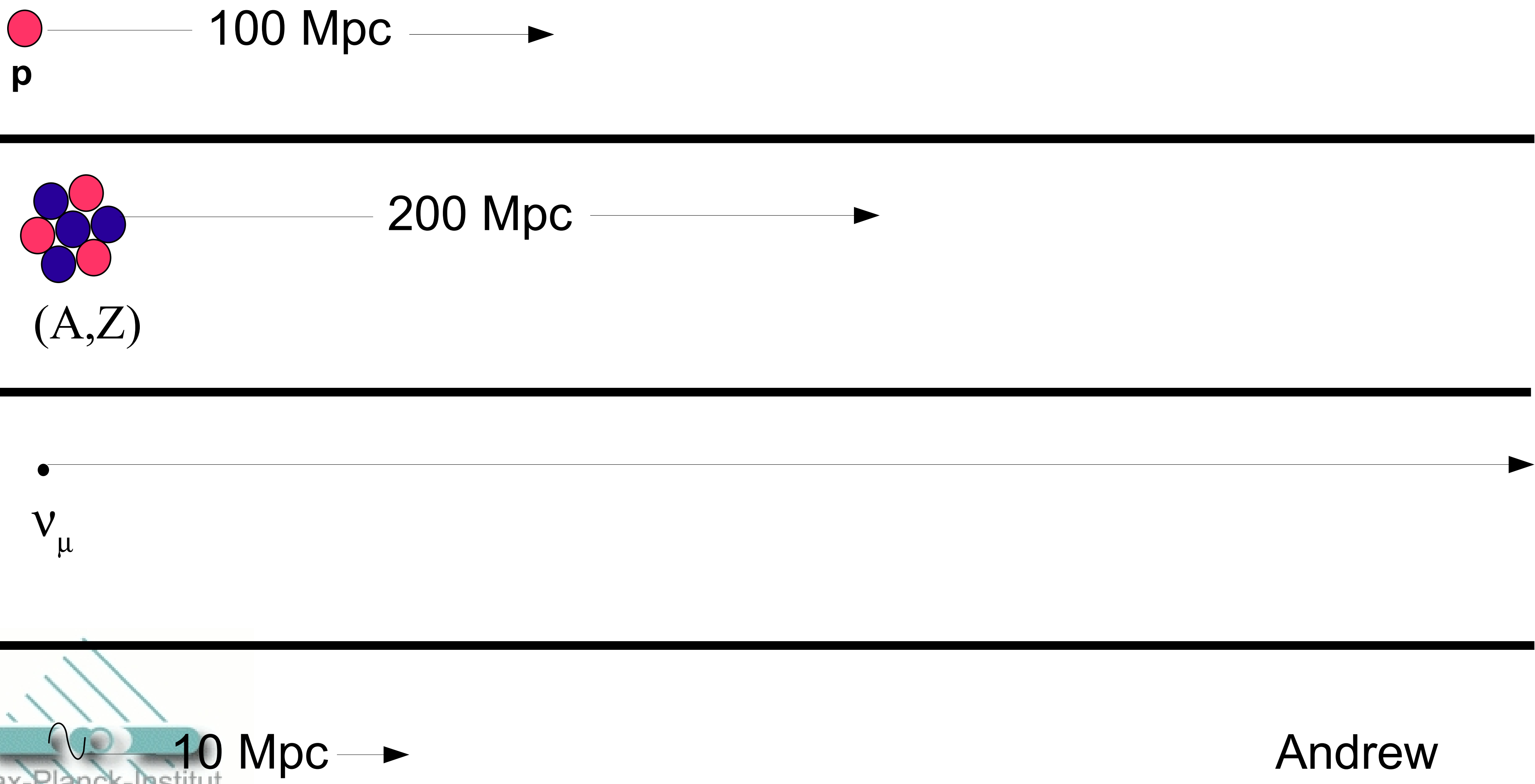
Different Distance Scales

10^{20} eV particles



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Aims- part 1

1) A recap on the interaction rates of protons and photons in the Universe

2) The source distribution typically assumed

3) An analytic description of the of the GZK feature

4) The photon fraction of cosmic rays

5) Different source distributions

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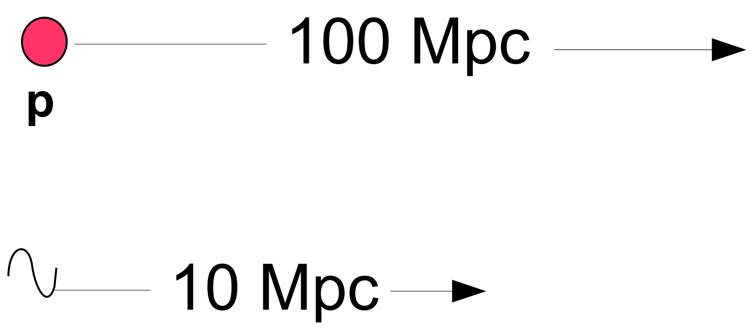
Using the Photons and Protons

10^{20} eV particles



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1) Recapping on the proton and photon interaction rates

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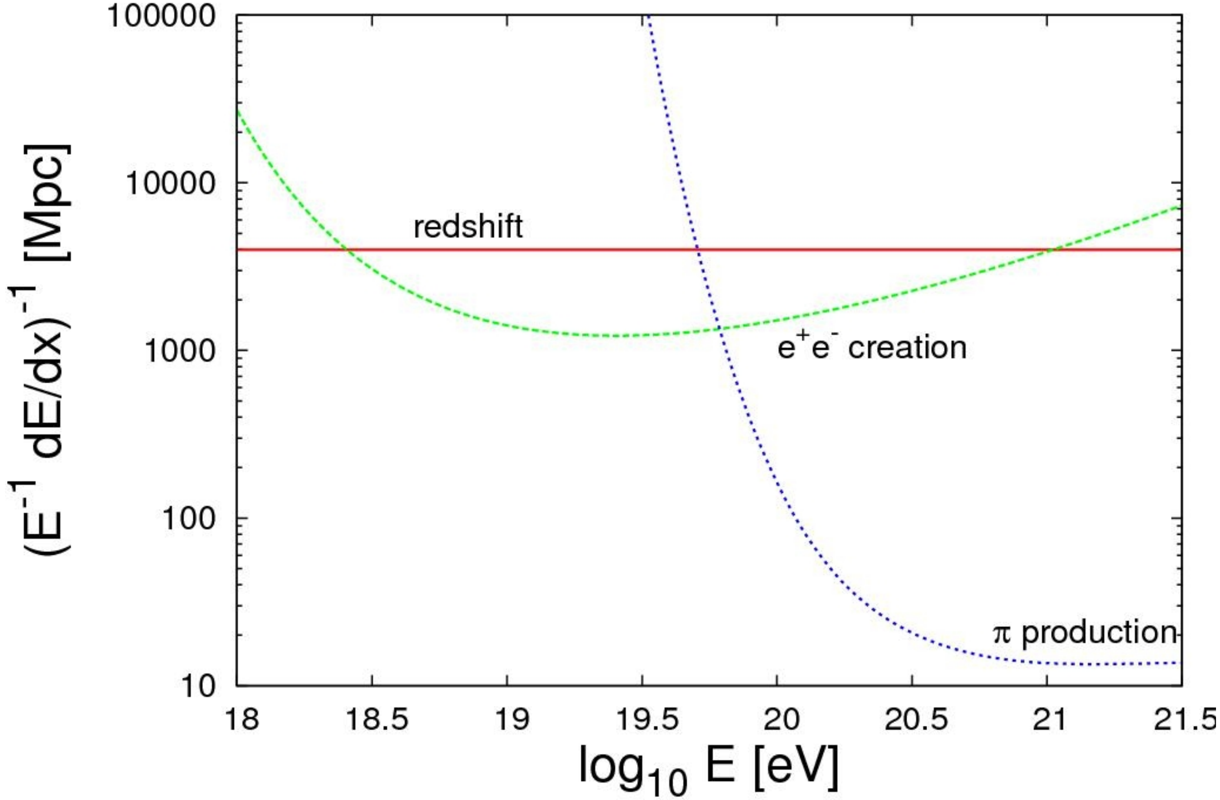
The Impedance of Background Radiation to High Energy Protons



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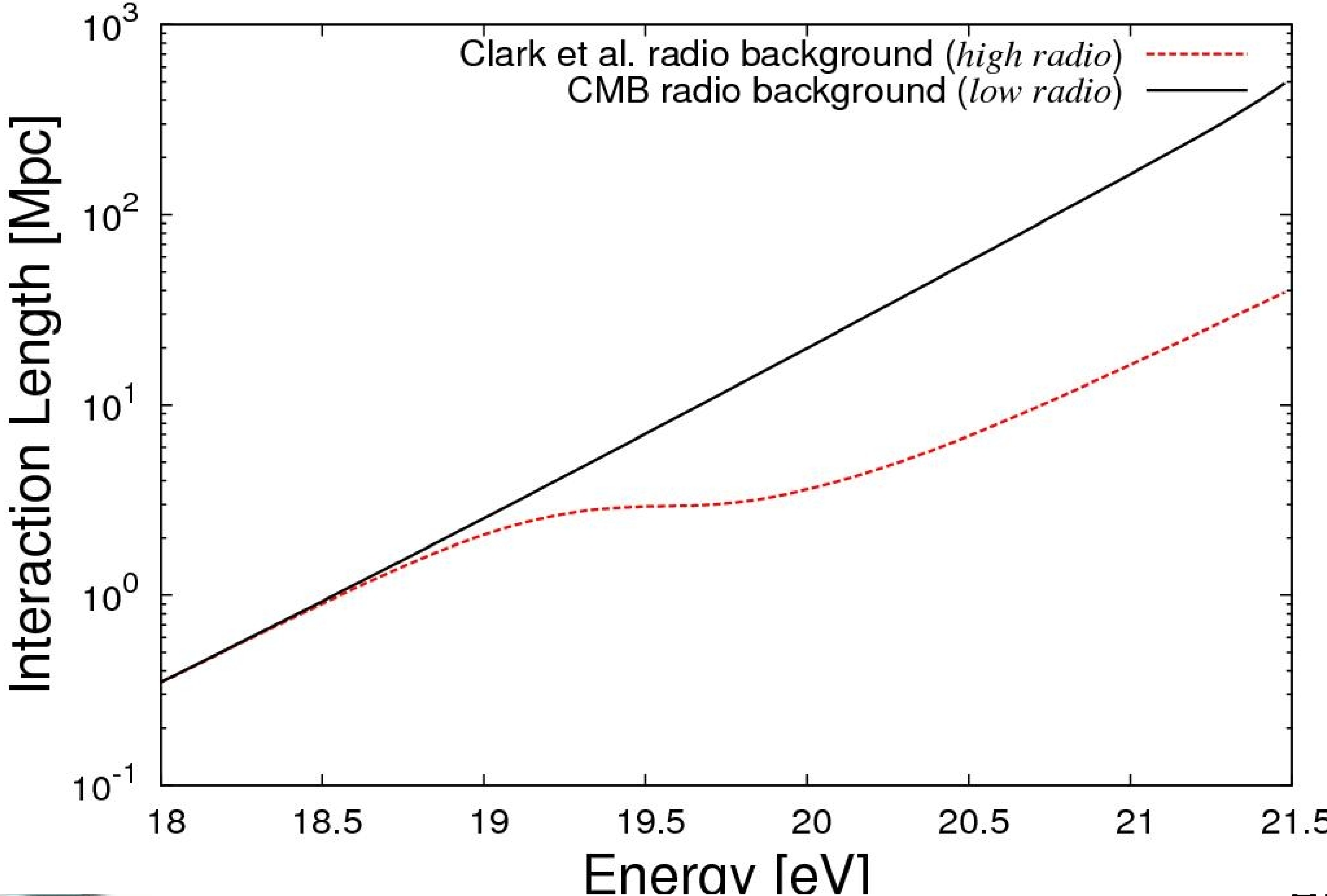
The Impedance of Background Radiation to High Energy Photons



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2) The source distributions typically assumed

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High Energy Cosmic Ray Sources Distribution (Energy and Spatial)

Energy Distribution of Cosmic Rays

– $dN/dE \sim E^{-2}$ motivated by first order Fermi shock acceleration theory

Spatial Distribution of Cosmic Ray Sources

– $dN/dV \sim (1+z)^3$ (z dependence is irrelevant here, only local UHECR contribute due to the distance scales probed)

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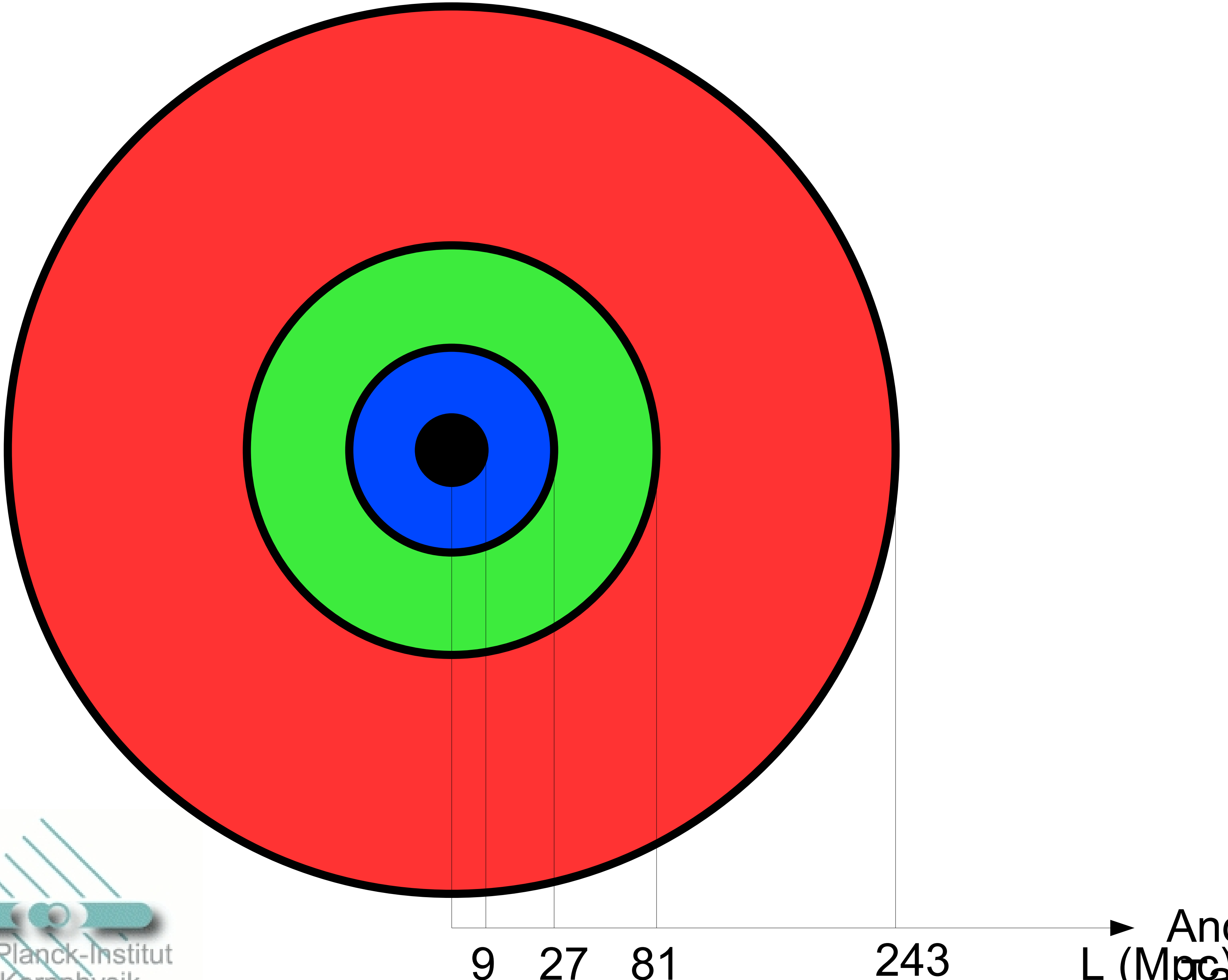
Shells of Source Regions



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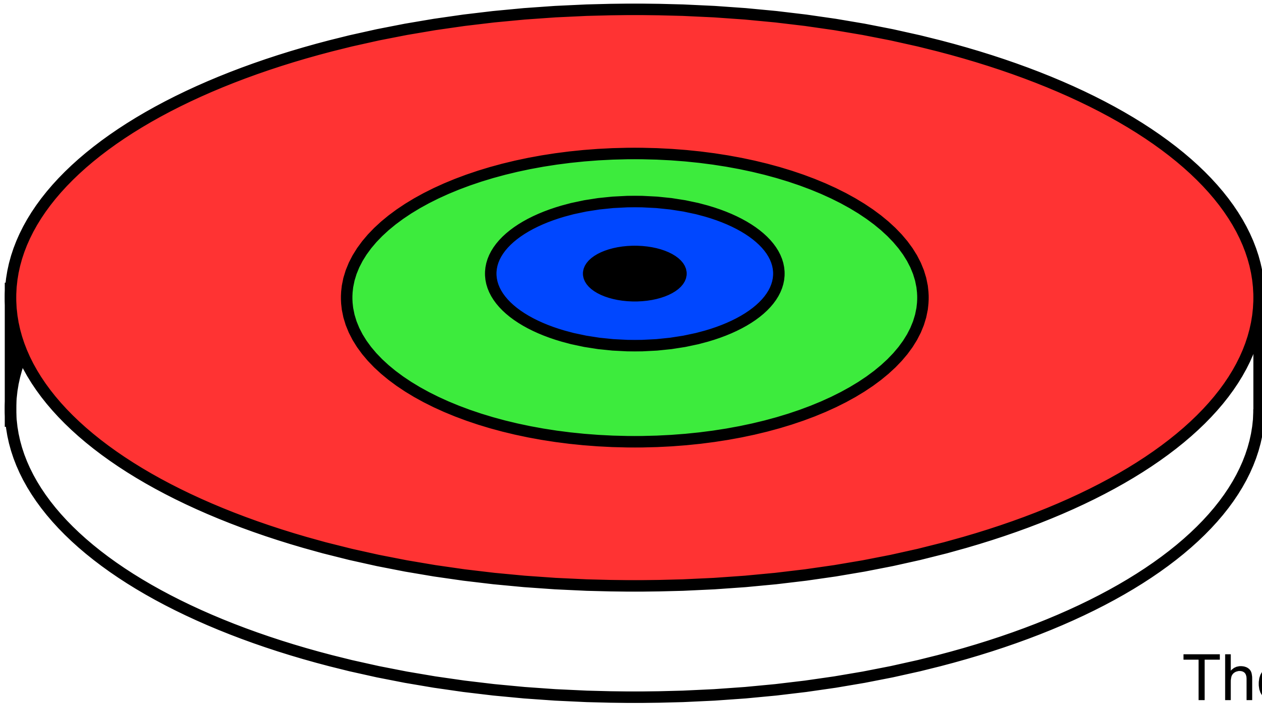
A Homogeneous Source Distribution



The number of sources within a source shell of width dL would be proportional to dL for a local uniform source distribution

The ratio of sources from the different shells-

$$R_{n+1} : R_n = 1 : 0.3$$

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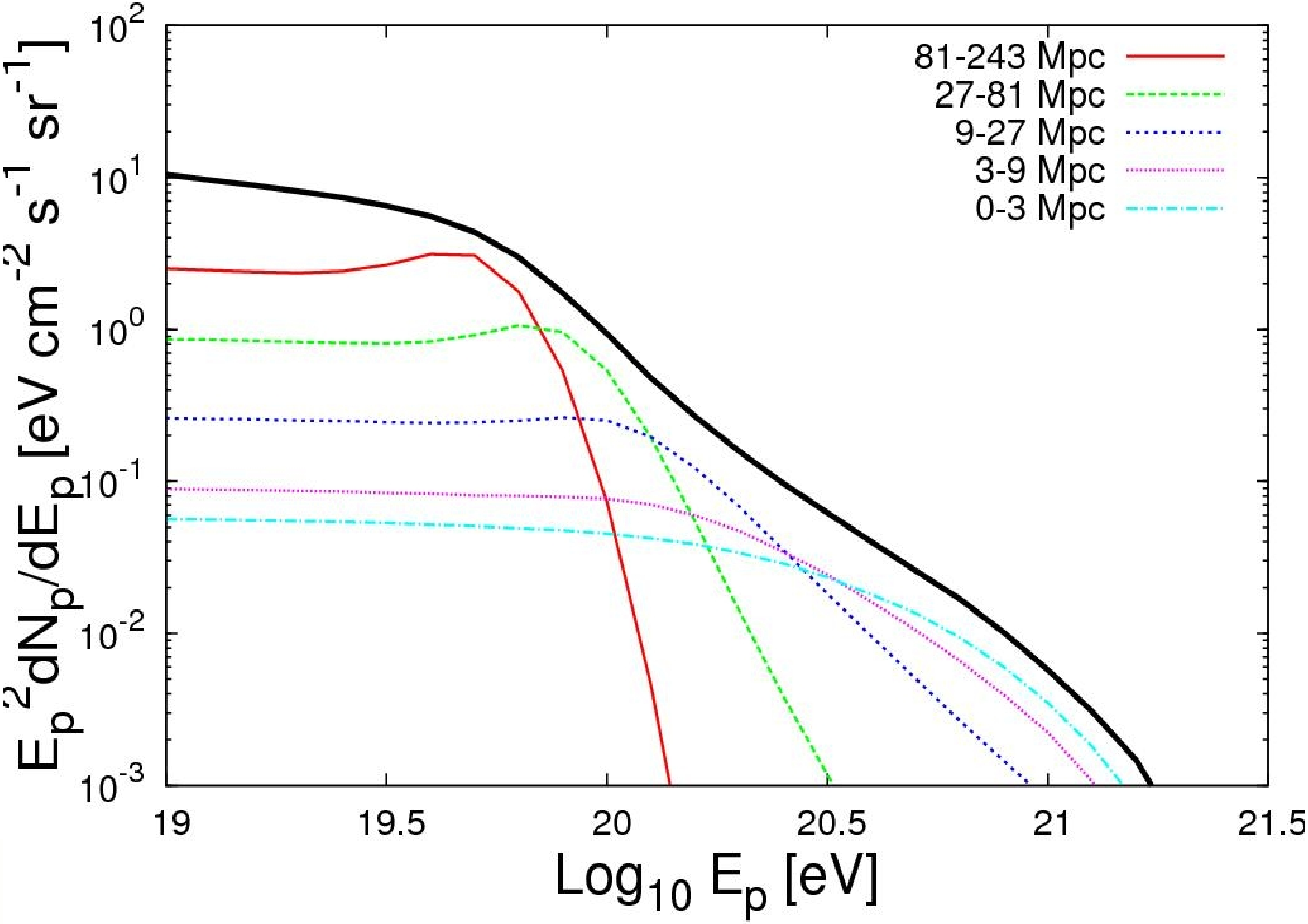
The GZK Feature



Assumptions:

$E_{\max} = 10^{20.5}$ eV

$\alpha = 2.0$

(along with the source distribution mentioned in the previous lecture)

$$\frac{dN}{dE} \propto E^{-\alpha} e^{\frac{-E}{E_{max}}}$$

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3) An analytic description of the GZK feature

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A Simple Analytic Description of the GZK Feature for Protons

$$\frac{N_n(E_p, L)}{N_0(E, 0)} = \Sigma_{m=0}^{n} \frac{l_0 l_m^{n-1}}{\prod_{p=0}^{n} (l_m - l_p)} e^{\frac{-L}{l_m}}$$

$$l(E_p) = \frac{l_0}{e^{-x}(1 - e^{-x})}$$

– where l_0 is 1 Mpc and $x = \frac{10^{20.5} eV}{E_p}$

$$l_m = \frac{l(E_p)}{(1 - K_p)^m}$$

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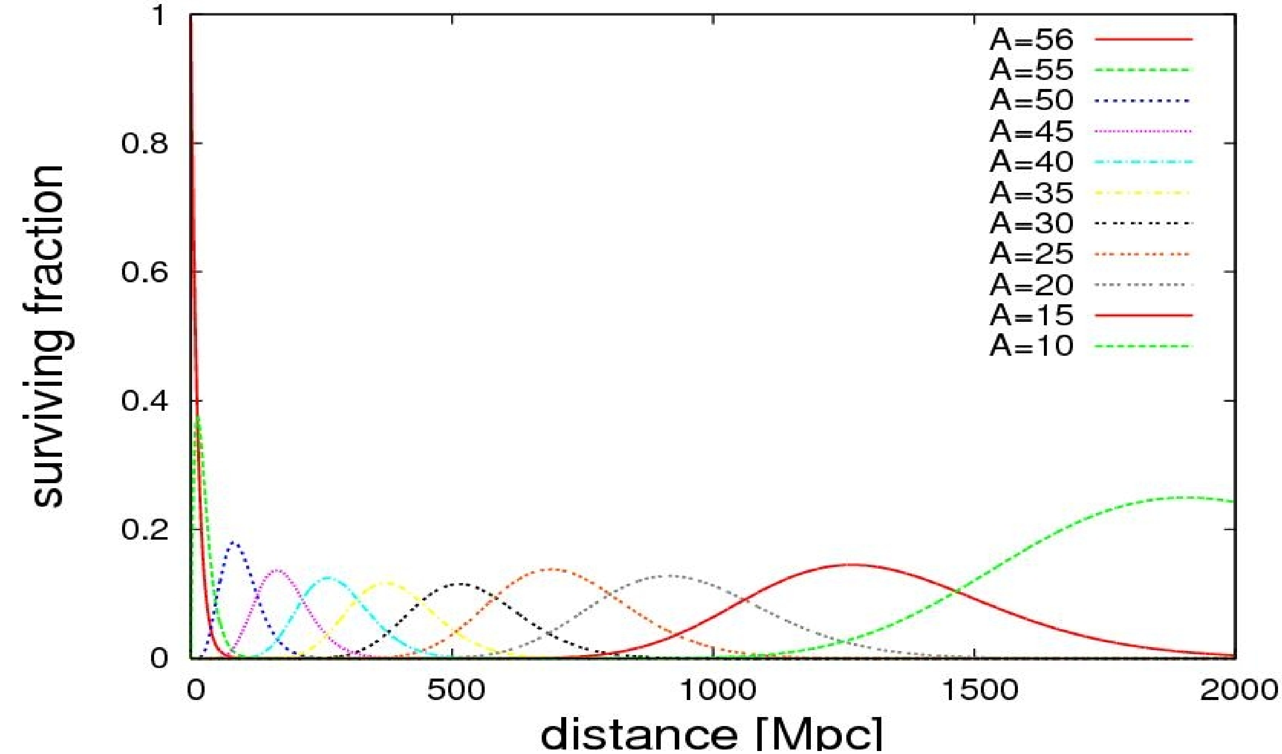
Injecting a 10^{20}eV ~~Fe Nucleus~~ proton and Tracking the Subsequent ~~Nuclei~~ protons



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A Simple Analytic Description of the GZK Feature for Protons

$$\frac{N_n(E_p, L)}{N_0(E, 0)} = \Sigma_{m=0}^{n} \frac{l_0 l_m^{n-1}}{\prod_{p=0}^{n} (l_m - l_p)} e^{\frac{-L}{l_m}}$$

The same expression describes BOTH nuclei and proton attenuation!

$$l(E_p) = \frac{l_0}{e^{-x}(1 - e^{-x})}$$

– where l_0 is 1 Mpc and $x = \frac{10^{20.5} eV}{E_p}$

$$l_m = \frac{l(E_p)}{(1 - K_p)^m}$$

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Using these Distribution Functions to Obtain the Arriving Flux

$$\frac{N_n(E_p, L)}{N_0(E, 0)} = \sum_{m=0}^{n} \frac{l_0 l_m^{n-1}}{\prod_{p=0}^{n} (l_m - l_p)} e^{\frac{-L}{l_m}}$$

$$N_{tot}(E_p, L) = \frac{\sum_{n=0}^{n_{max}} N_n(E_p, L)}{N_0(E, 0)}$$

the source distribution function

$$N_p(E_p) = \int_0^{L'} dL\, f(L)\, N_{tot}(E_p, L)$$

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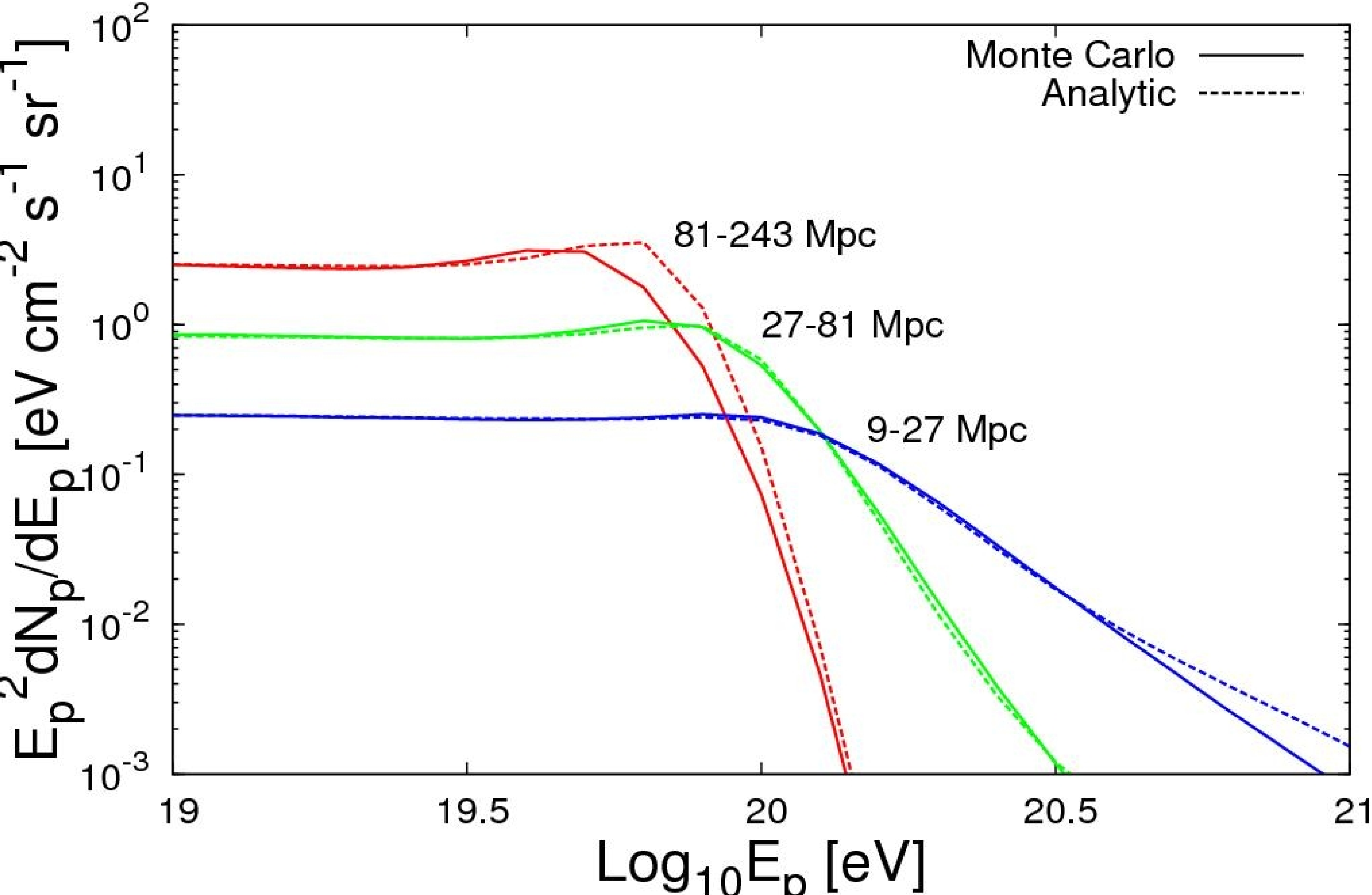
A Comparison of this Description with Monte Carlo



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4) The photon fraction of cosmic rays

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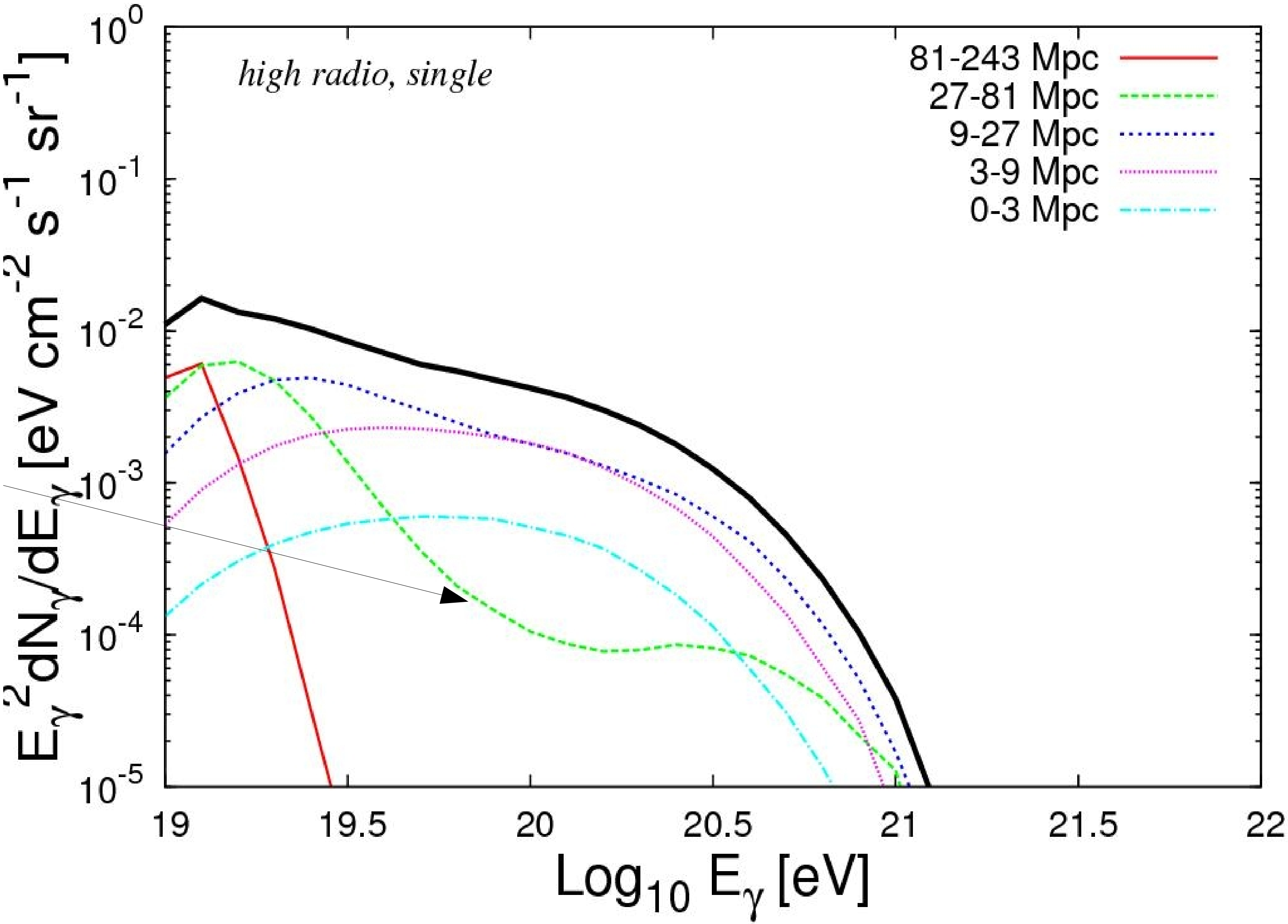
Arriving photon Flux from Different Shells

Dip feature in photon flux from 27-81 Mpc shell



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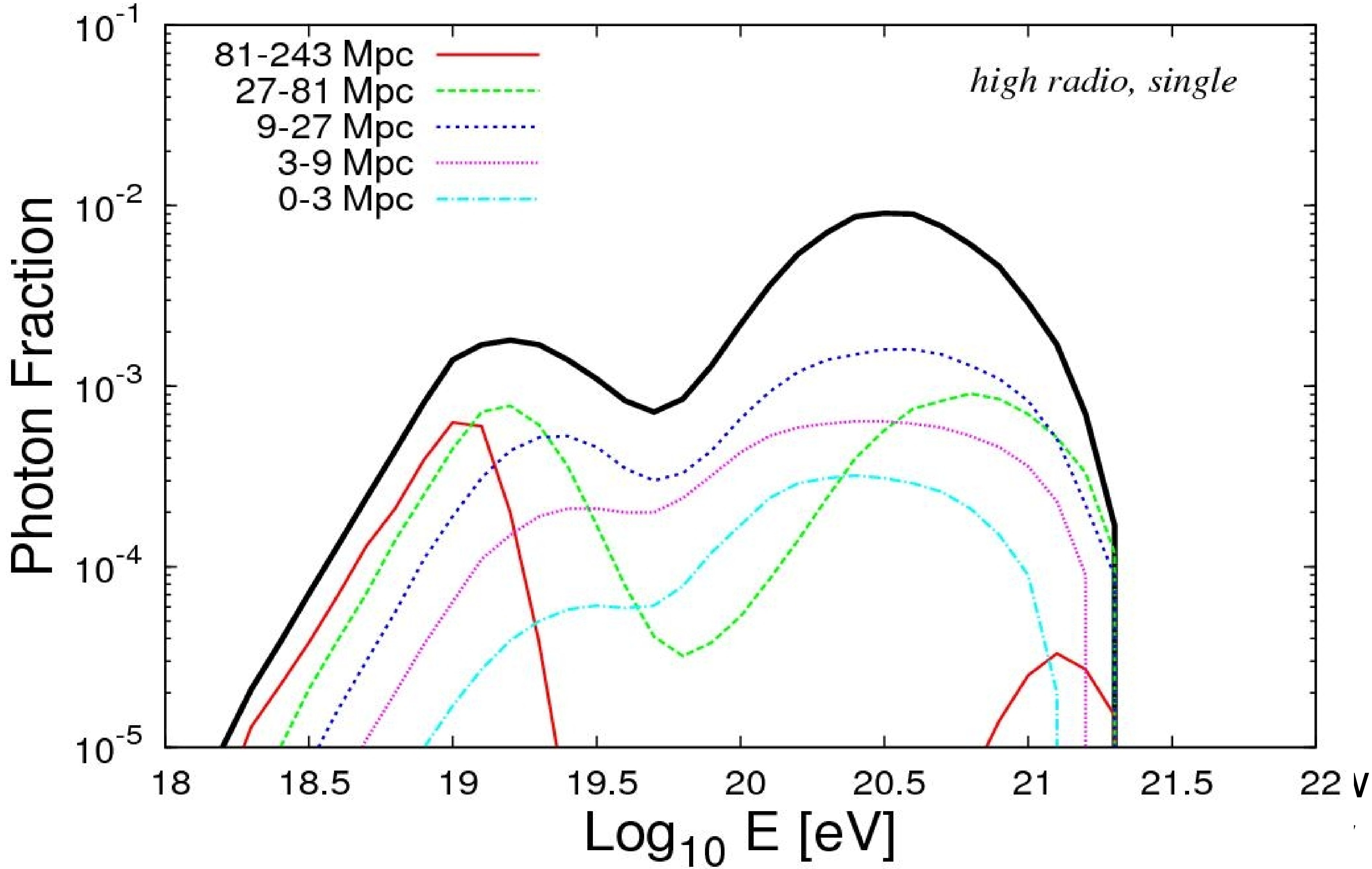
The Photon Fraction



5) Different source distributions

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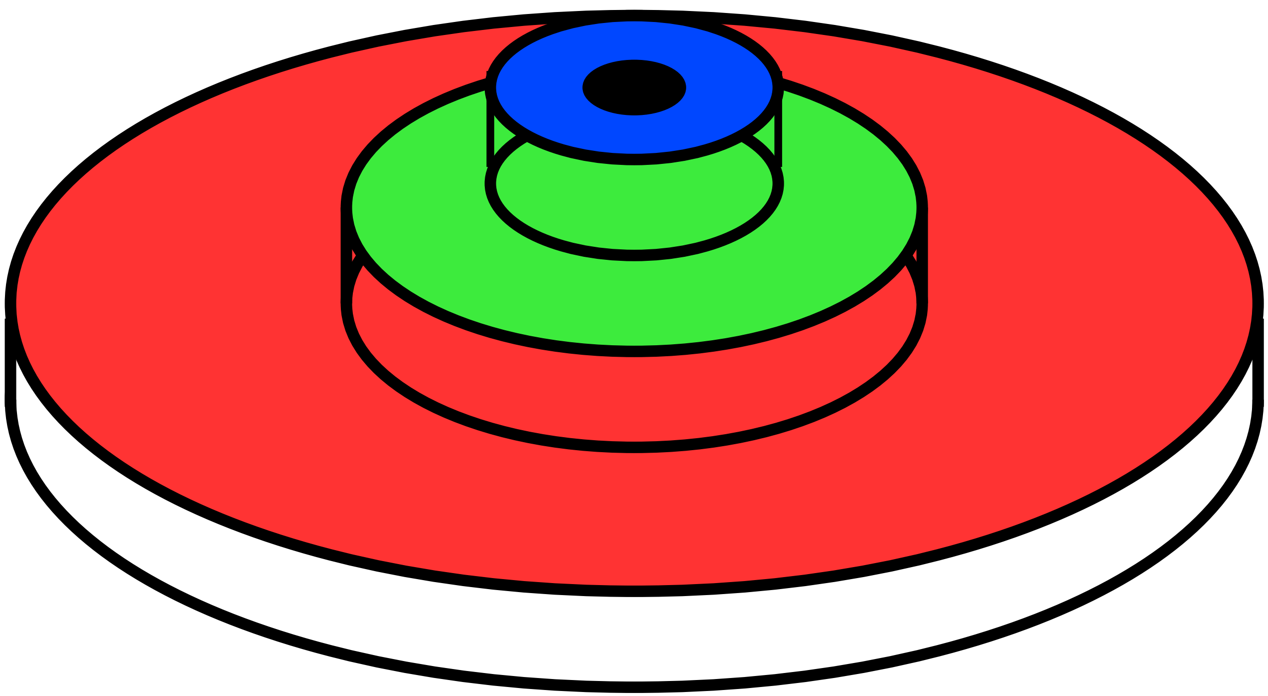
Altering the Source Distribution



Weighting the contribution from the more local sources to create a local overdensity

$$R_{n+1} : R_n = 1 : 0.5 \quad \text{or} \quad R_{n+1} : R_n = 1 : 0.7$$

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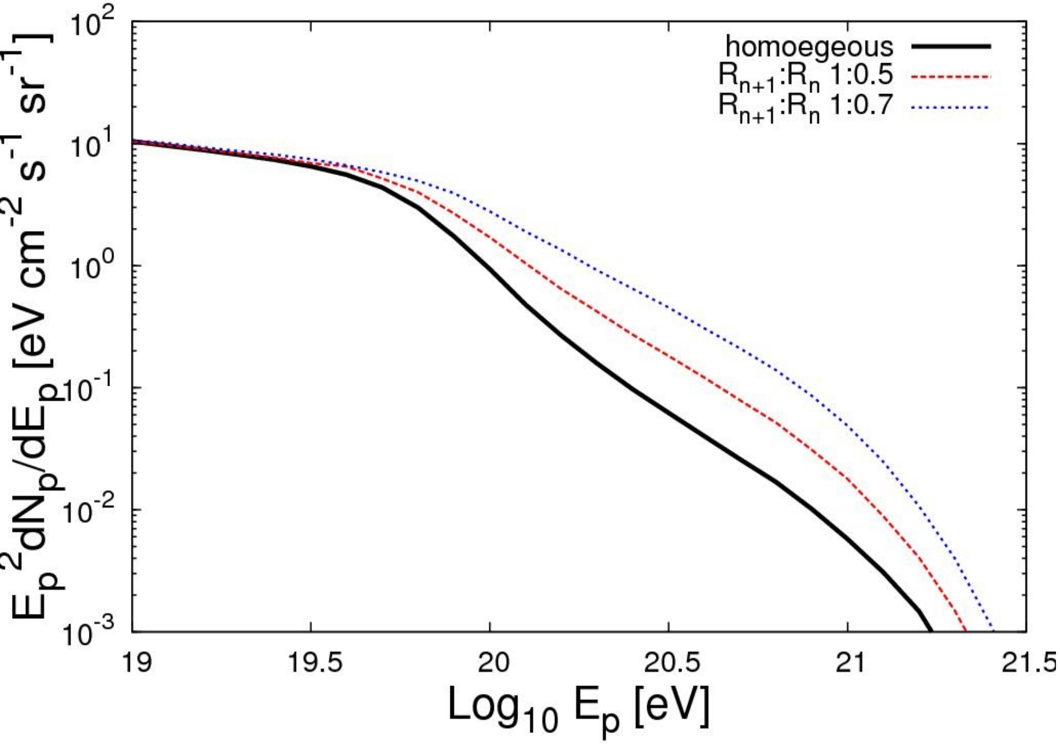
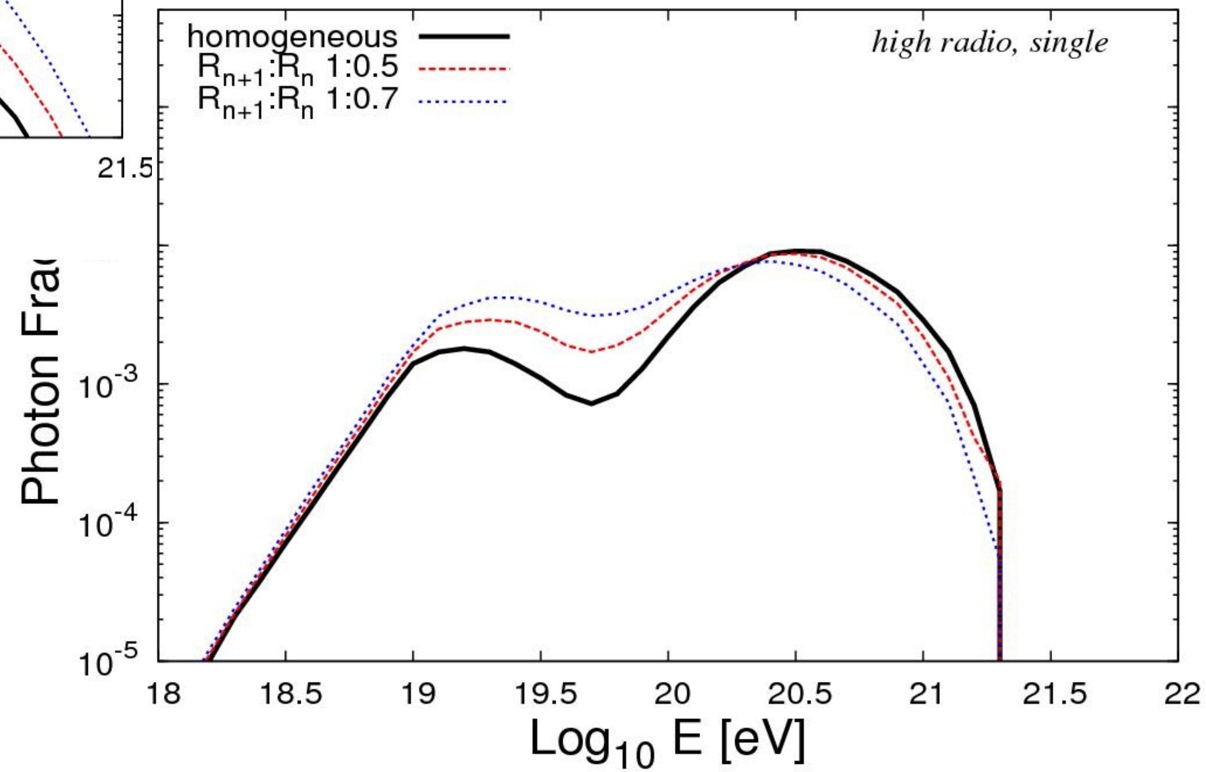
The Local UHECR Source Distribution- overdensity





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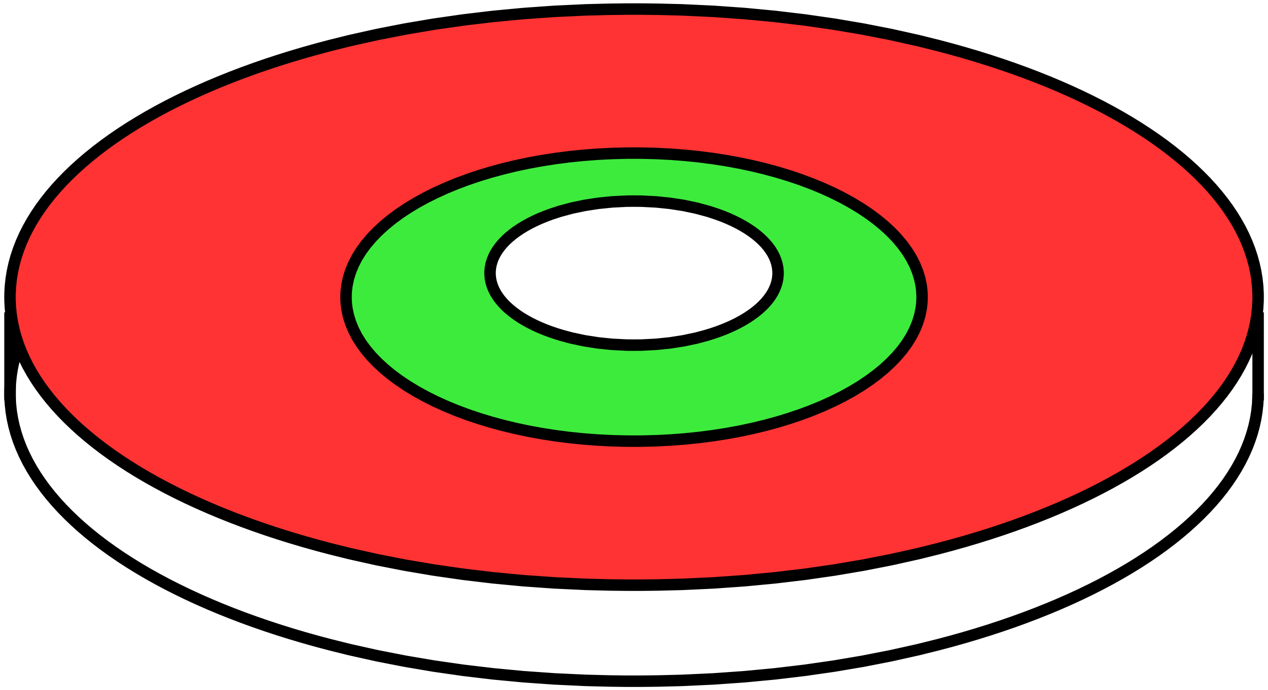
Altering the Source Distribution



Introducing a local void of UHECR sources

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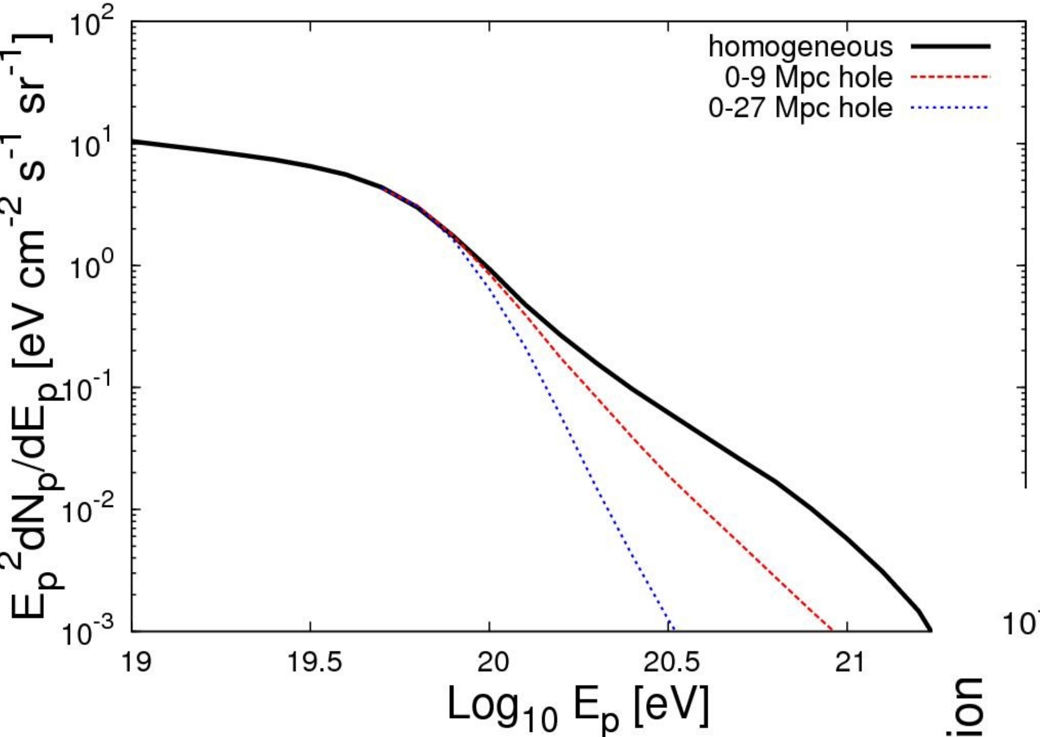
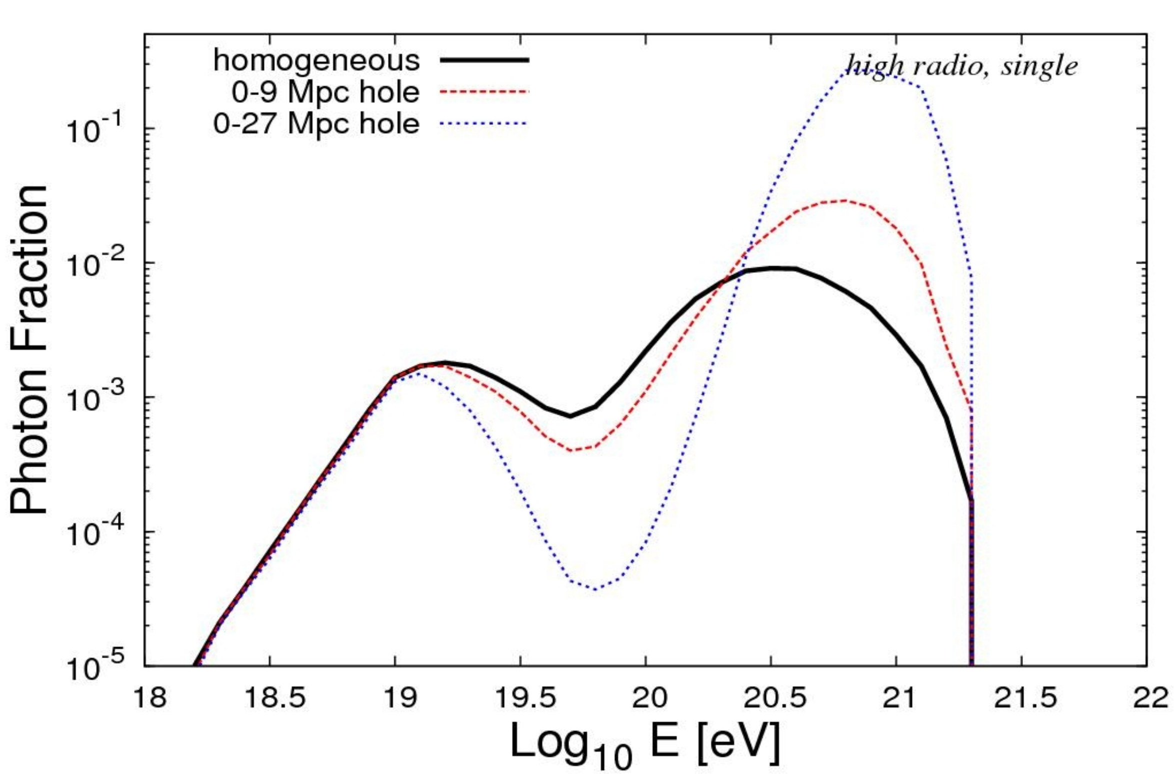
The Local UHECR Source Distribution- underdensity





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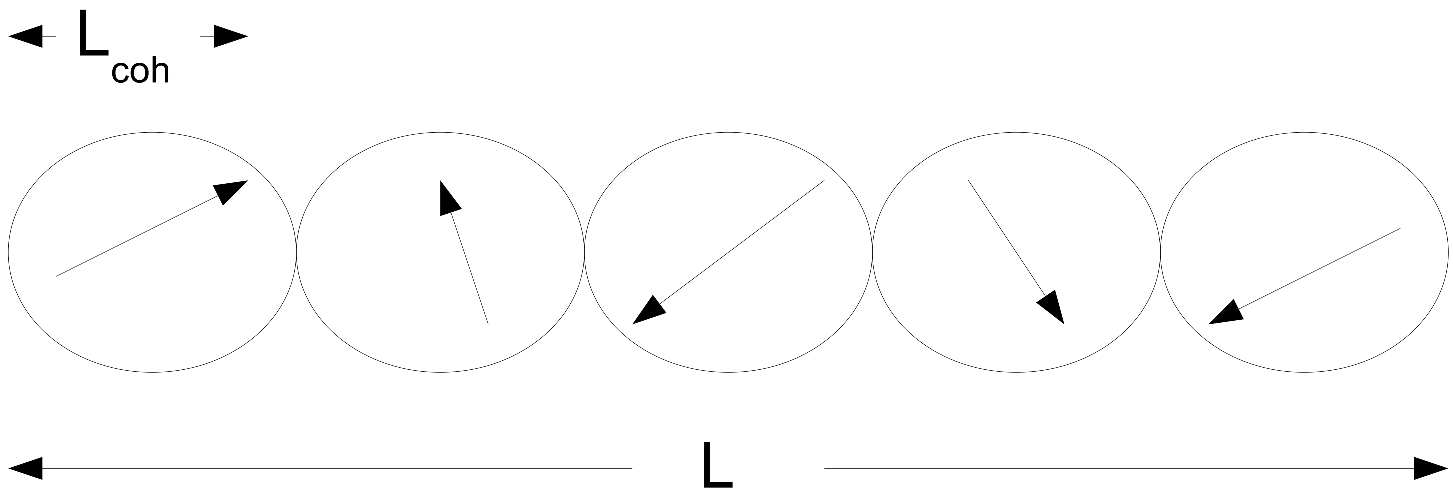
The Effect of Diffusion



For each coherent patch:

$$\alpha = \frac{L_{\rm coh}}{R_{\rm Larmor}}$$

$$\theta(E_p) = \left(\frac{L}{L_{\rm coh}}\right)^{1/2} \alpha$$
$$= \frac{(L\,L_{\rm coh})^{1/2}}{R_{\rm Larmor}}$$

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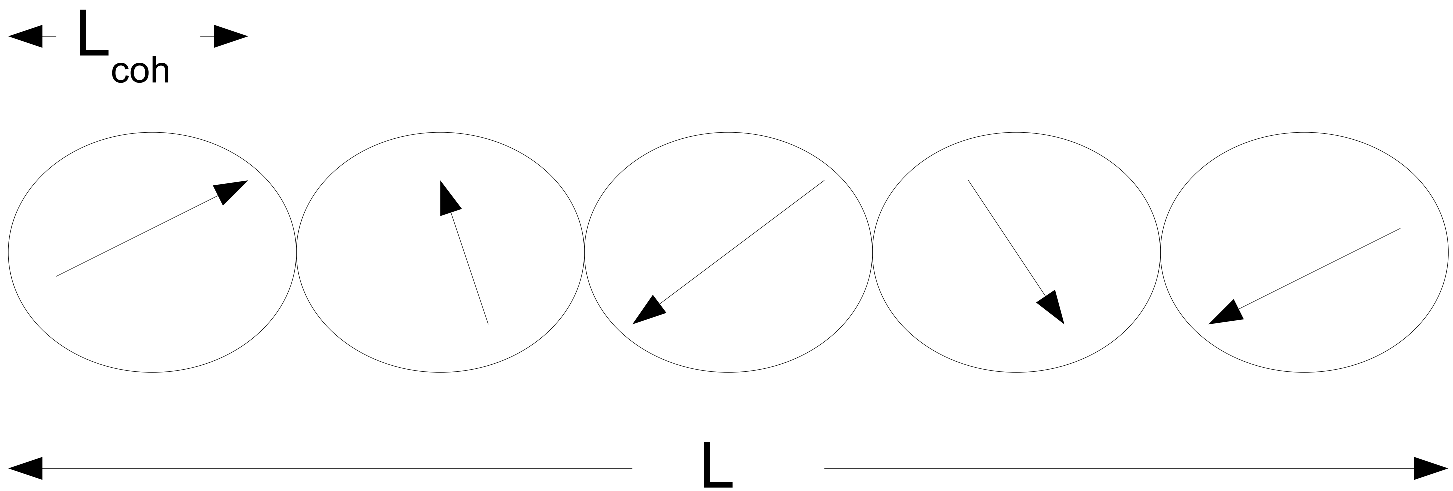
The Effect of Diffusion



$$\theta(E_p) \approx 0.8^\circ \left(\frac{10^{19}}{E_p}\right)\left(\frac{L}{10\,Mpc}\right)^{1/2}\left(\frac{L_{coh}}{1\,Mpc}\right)^{1/2}\left(\frac{B}{0.1\,nG}\right)$$

Diffusion can be expected to increase the path length of the protons more than the photons, reducing the flux contribution from distance sources. The effect diffusion introduces is thus similar to that of a local source overdensity

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Conclusion (1)

The detection of the photon fraction component of UHECR spectrum is a powerful diagnostic tool for:

– verifying the GZK origin of the cut-off/suppression feature in the UHECR spectrum

– (in conjunction with the spectral cut-off) determining the local distribution of UHECR sources

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Aims- part 2

1) Candidate sources of UHECRs to be considered

2) A model for the AGN radiation field

3) A model for the GRB radiation field

4) A model for the Starburst Galaxy radiation field

5) A consistency check of the amount of disintegration expected under the typical optical depth assumption

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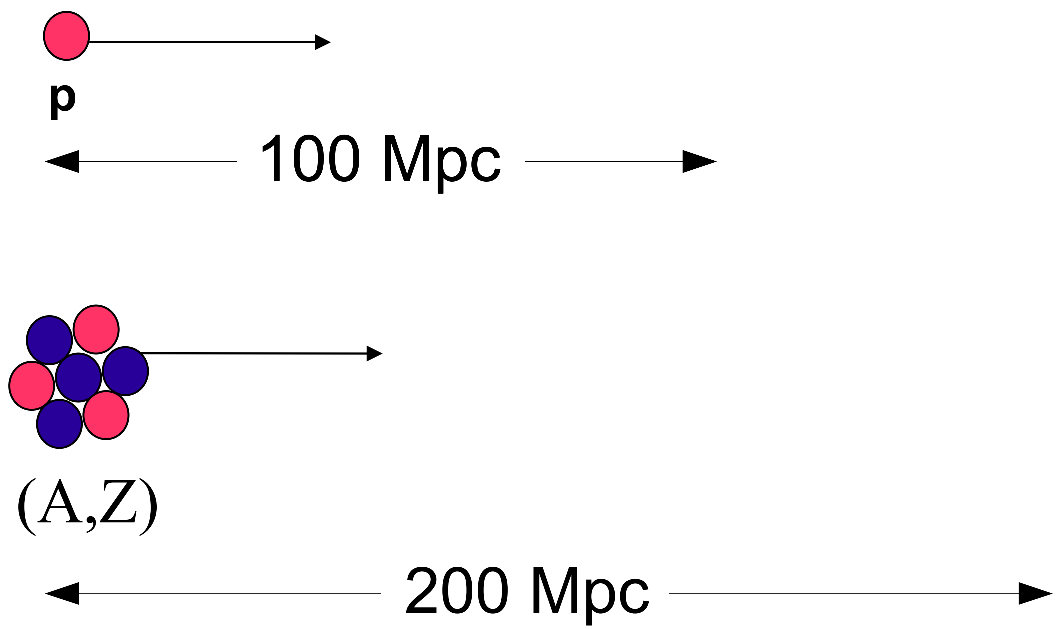
Using the Nuclei to Probe Proton Interactions in the UHECR Source

10^{20} eV particles



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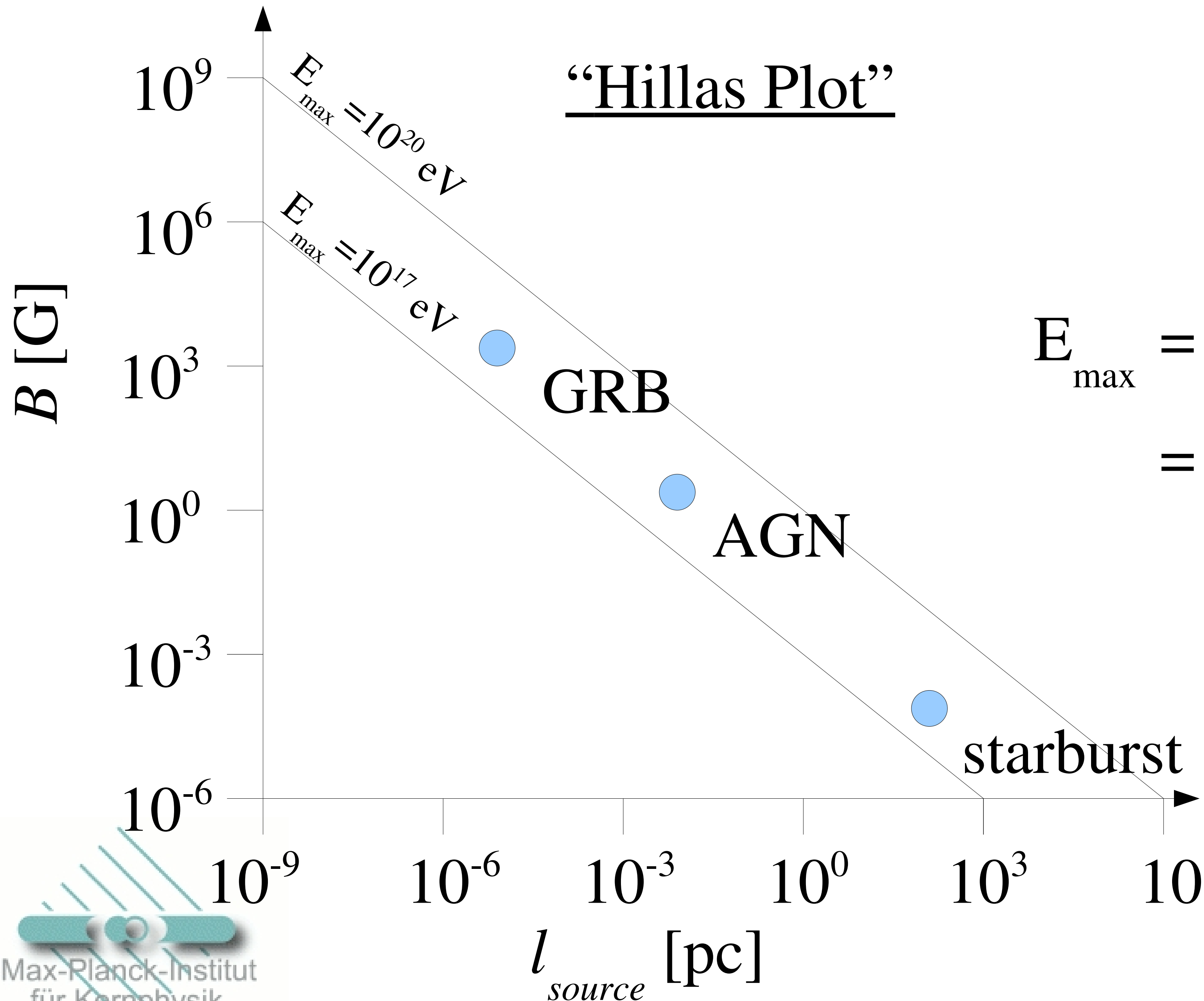
Source Size and B-Field Strength



$$E_{max} = (Bc)R_{Larmor}$$
$$= \beta_{sh}(Bc)\, l_{source}$$

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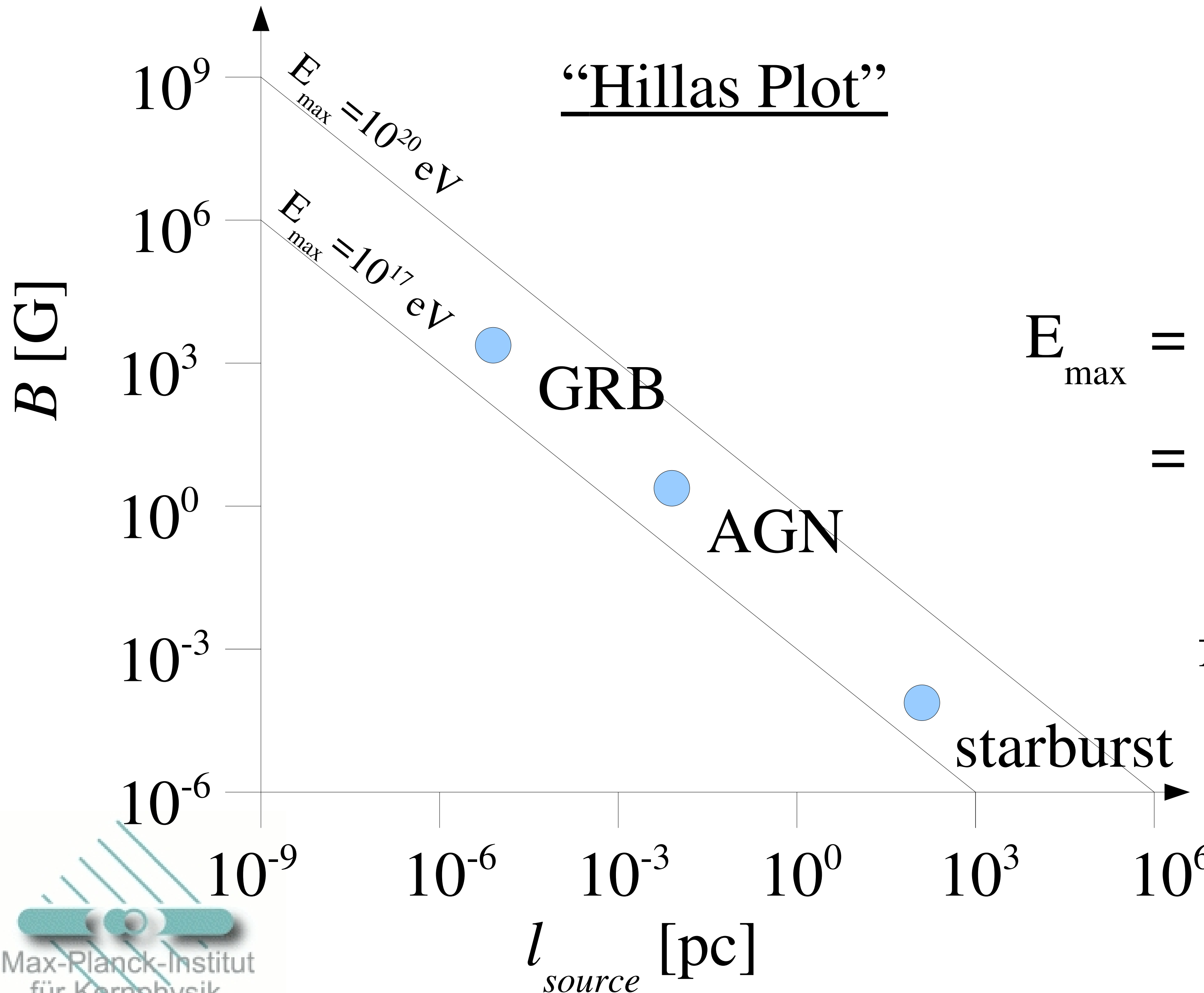
Source Size and B-Field Strength



$$E_{max} = (Bc)R_{Larmor}$$

$$= \beta_{sh}(Bc)\, l_{source}$$

from equating $t_{acc.}$ with $t_{esc.}$

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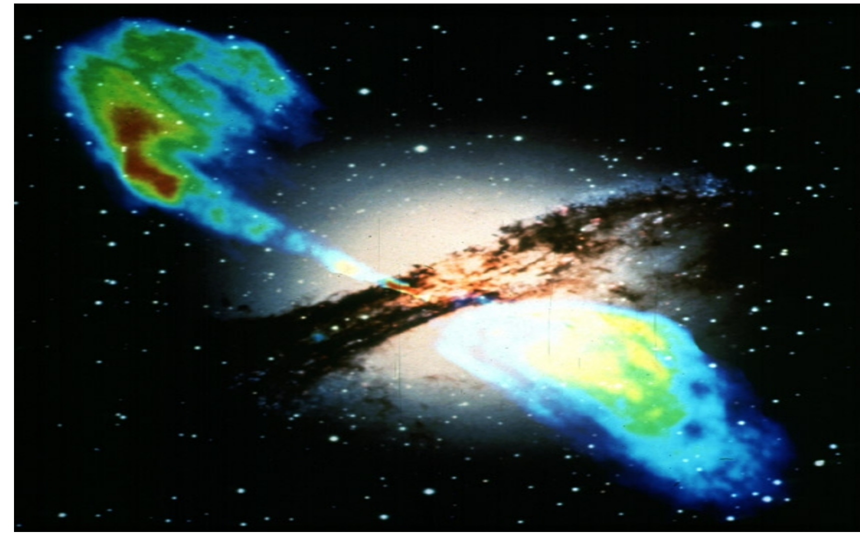
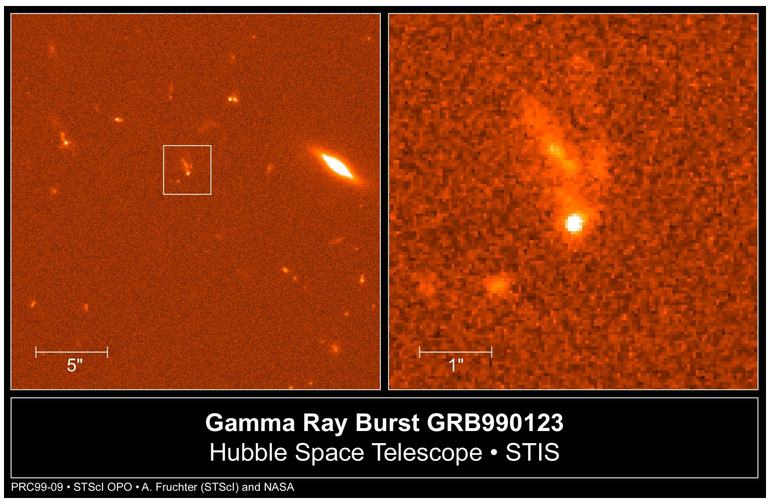
Candidate Sources:

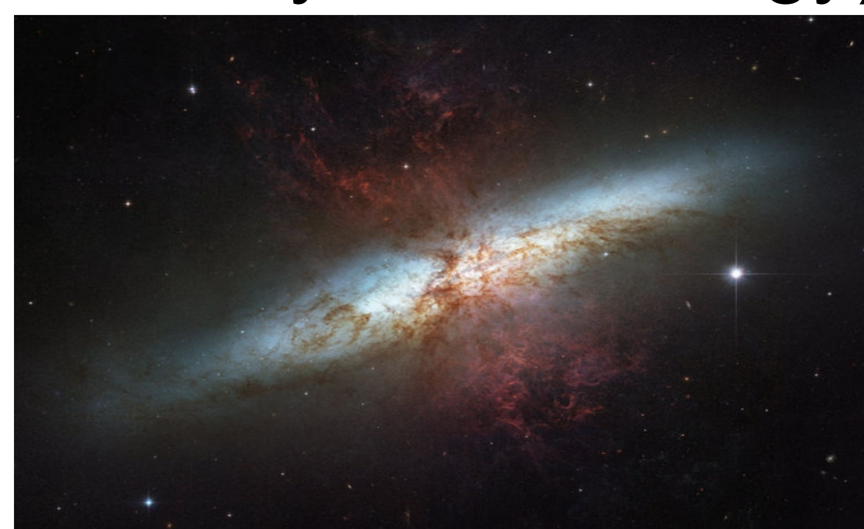
AGN- 10^{44} erg s^{-1}
(luminosity break energy)



GRB- 10^{52} erg s^{-1}
(luminosity break energy)



Starburst- 10^{42} erg s^{-1}
(luminosity break energy)



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Power density of Sources-

Extragalactic Cosmic Rays, $E > 10^{18}$ eV, have an energy density **$\sim 10^{-8}$ eV cm^{-3}** → **10^{-20} erg cm^{-3}**

→ **10^{54} erg Mpc^{-3}**

time$\sim 10^{17}$ s to accumulate

→ **10^{37} erg Mpc^{-3} s^{-1}**

$n \sim 10^{-5}$ Mpc^{-3}

→ **10^{42} erg s^{-1} per source**

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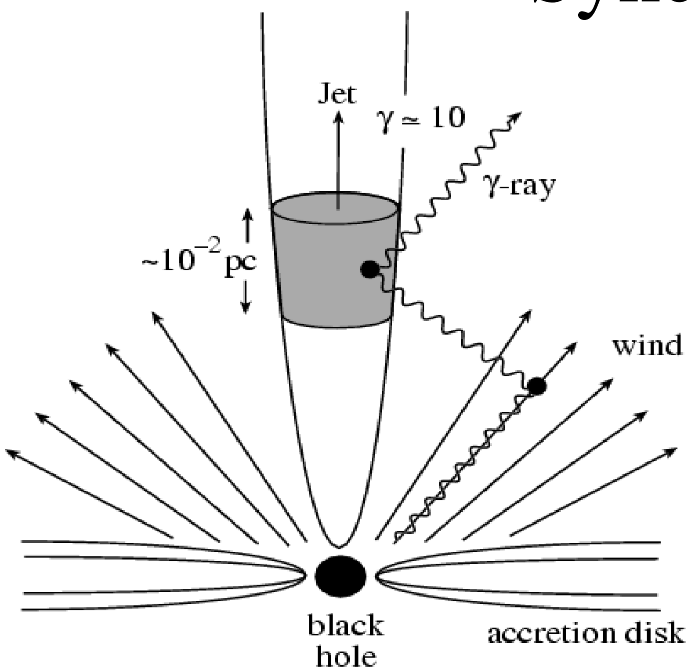
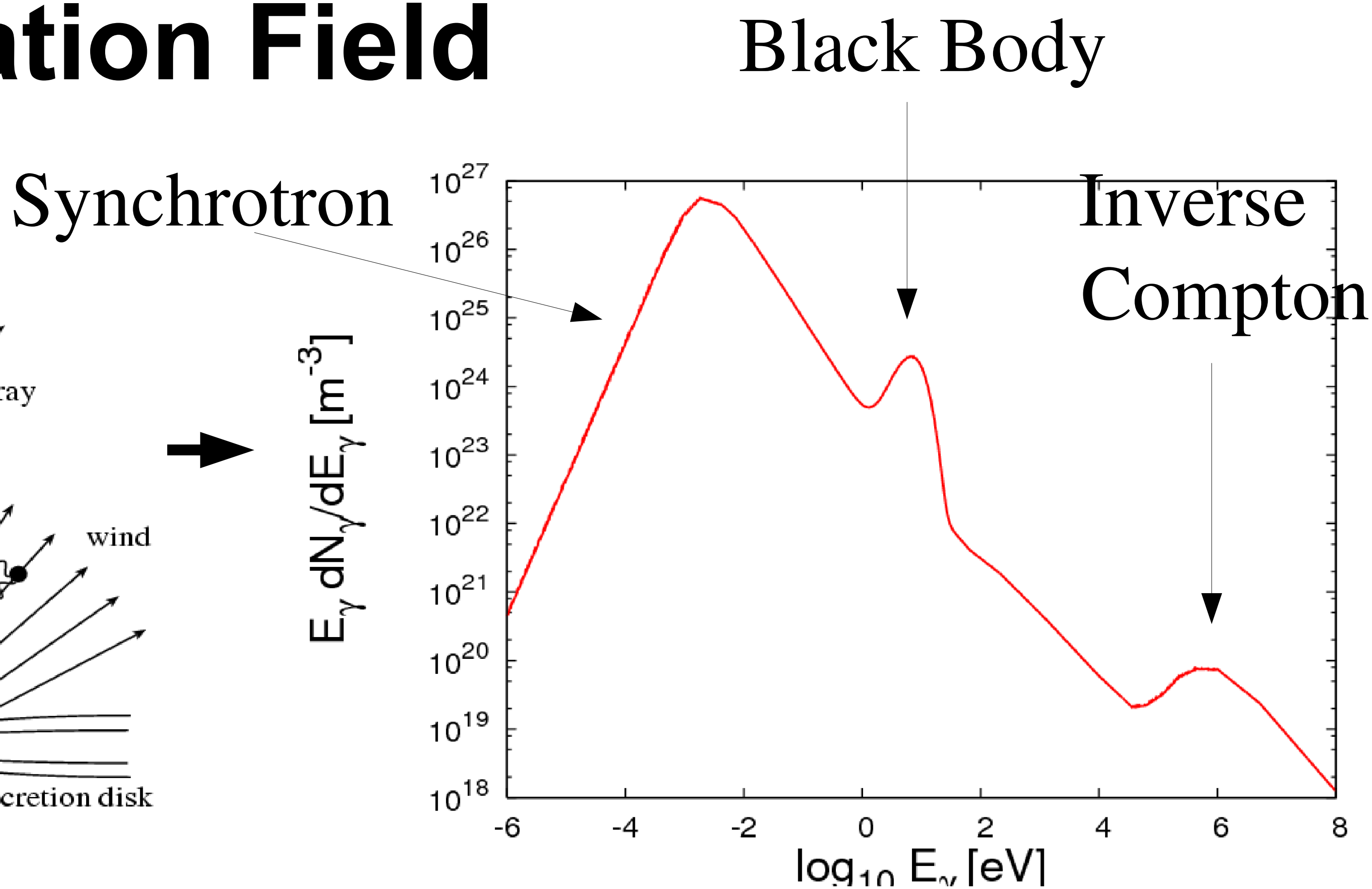
AGN Model and Radiation Field





$\Gamma \sim 30$

$l_{source} = \Gamma c \Delta t = 10^{-2}\,\mathrm{pc}$

$n_\gamma = 10^{16}\ \mathrm{cm}^{-3}$

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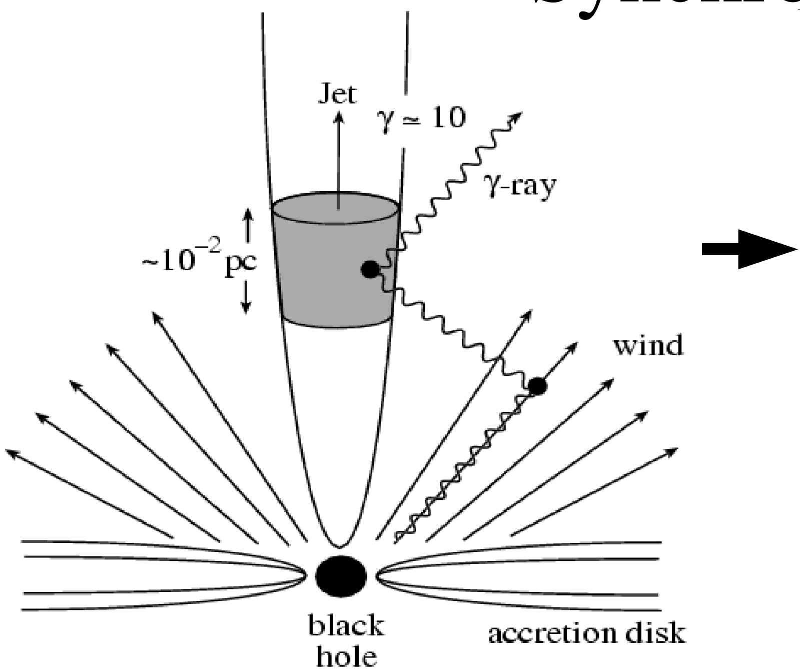
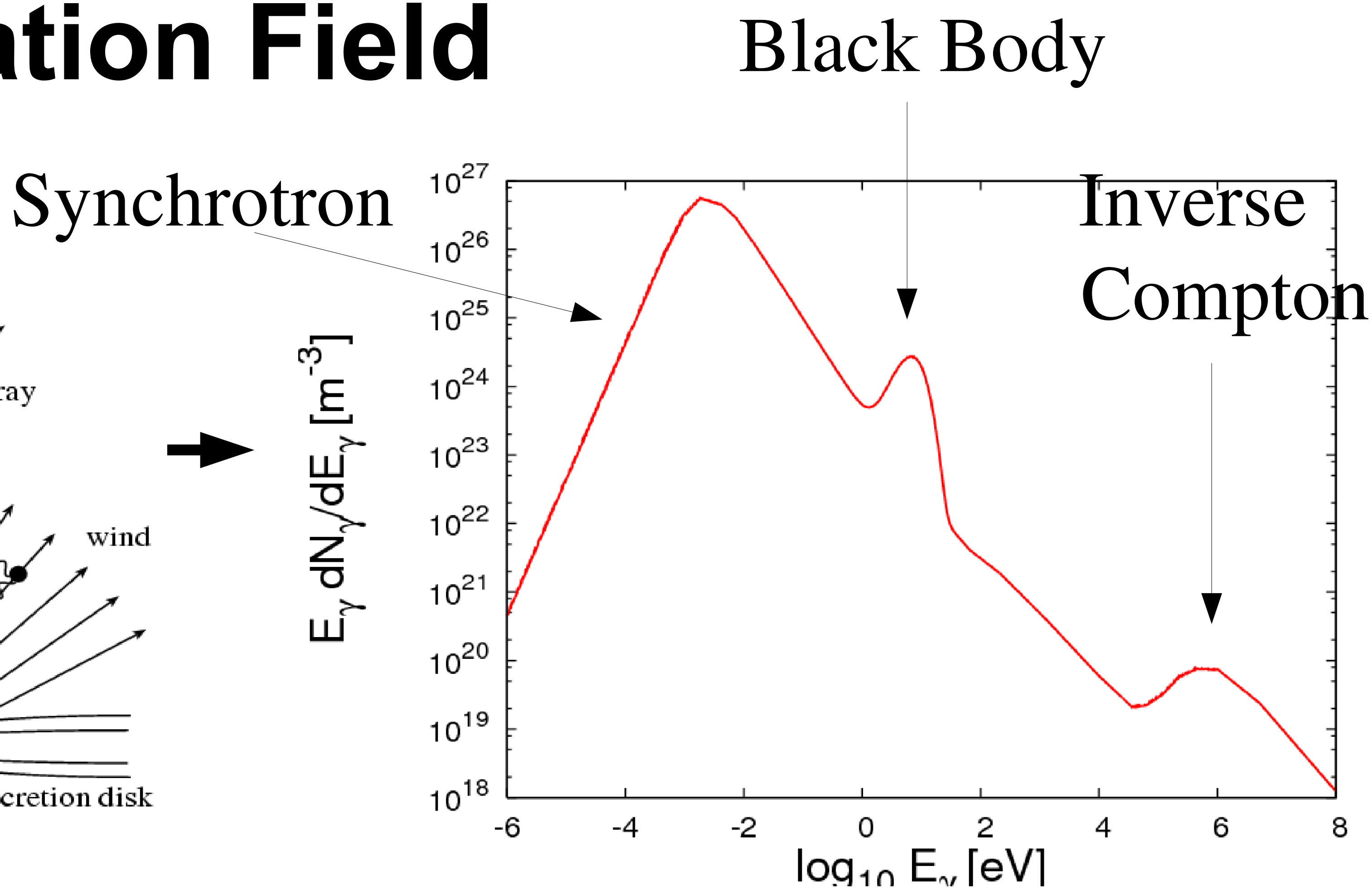
AGN Model and Radiation Field





NB. relativistic sources have smaller n_γ values

NNB. n_γ in plasma frame is ~10^{16} cm^{-3} (about 0.1% of air density in this room)

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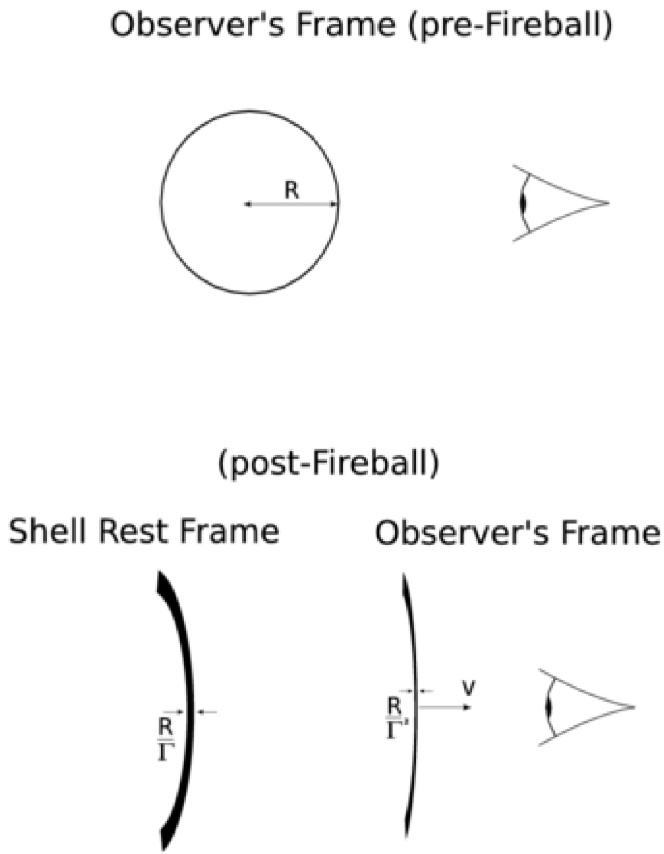
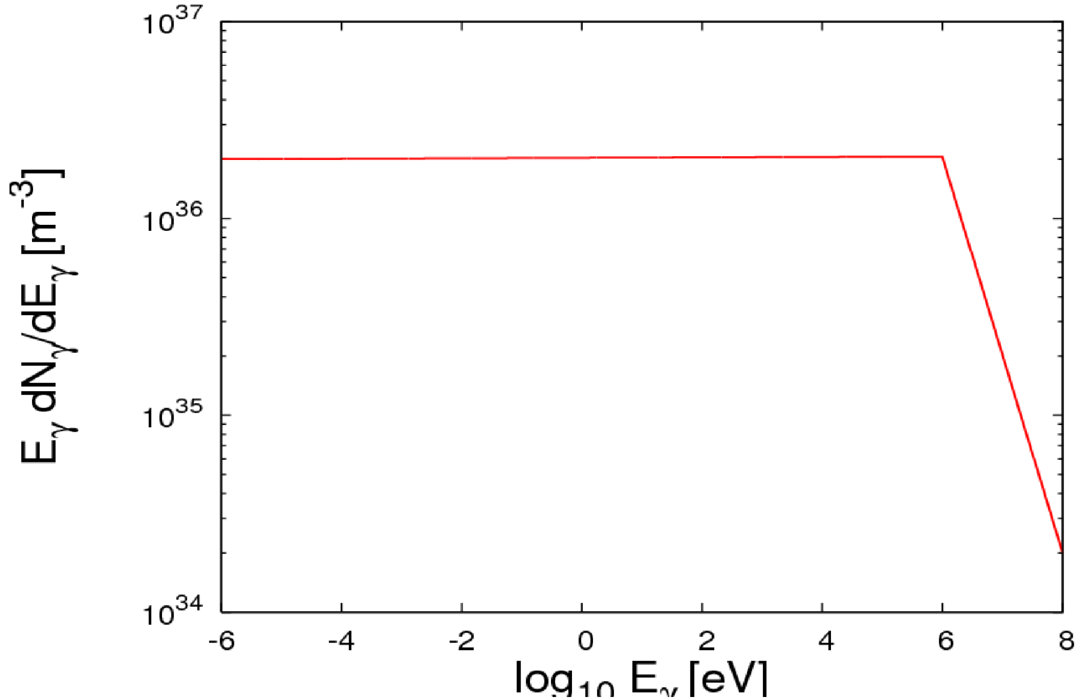
GRB Model and Radiation Field





$dN/dE \,\alpha\, E^{-\beta}$, $\beta=1$, $E <$ MeV

$\beta=2$, $E >$ MeV

$\Gamma \sim 300$

$l_{source} = \Gamma^2 c\Delta t = 10^{-6}$ pc

$n_\gamma = 10^{17}$ cm^{-3}

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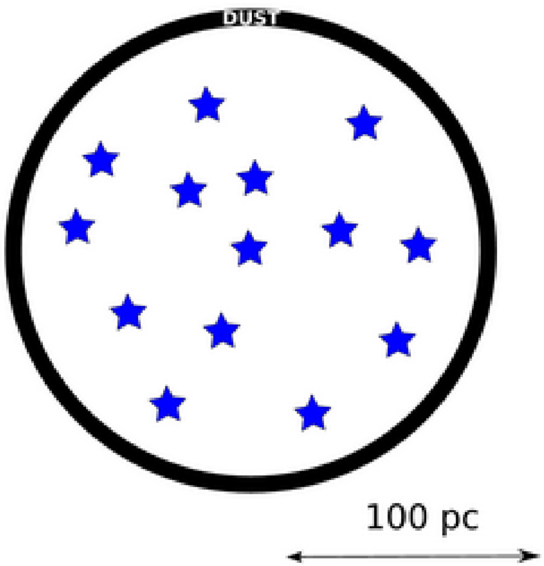
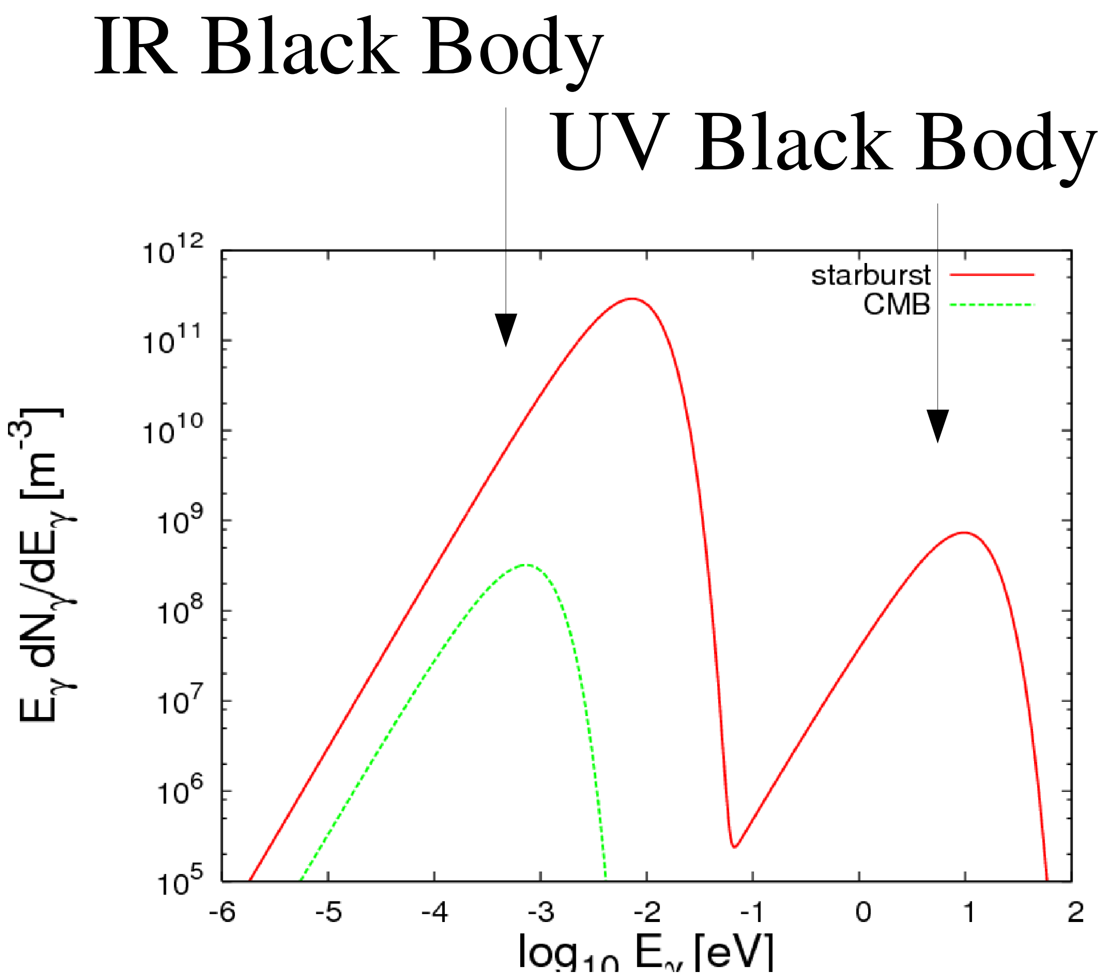
Starburst Galaxy Model and Radiation Field





$$l_{source} = 100\,\mathrm{pc}$$

$$n_\gamma = 10^5\ \mathrm{cm}^{-3}$$

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Assuming Cosmic Rays are Protons ......

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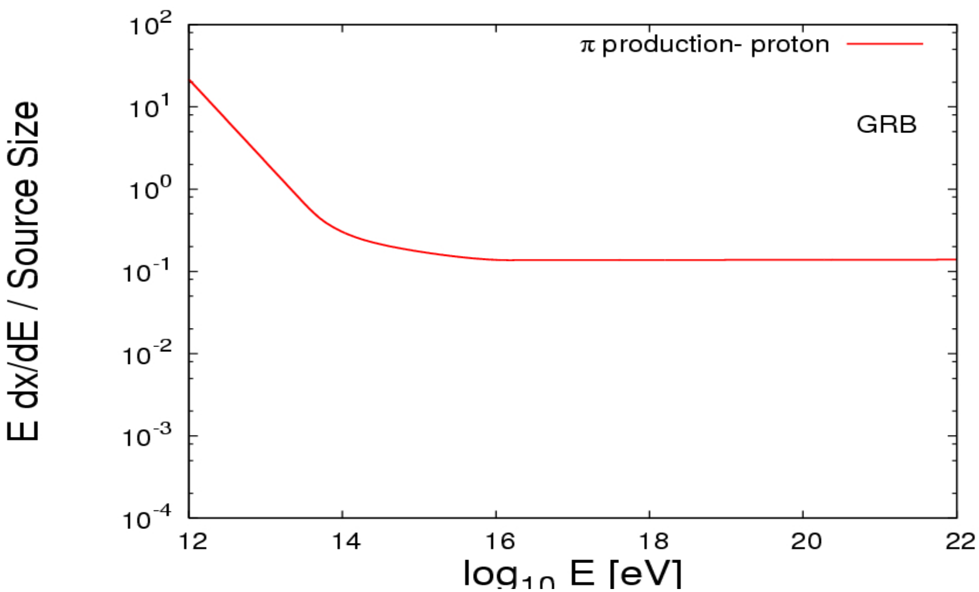
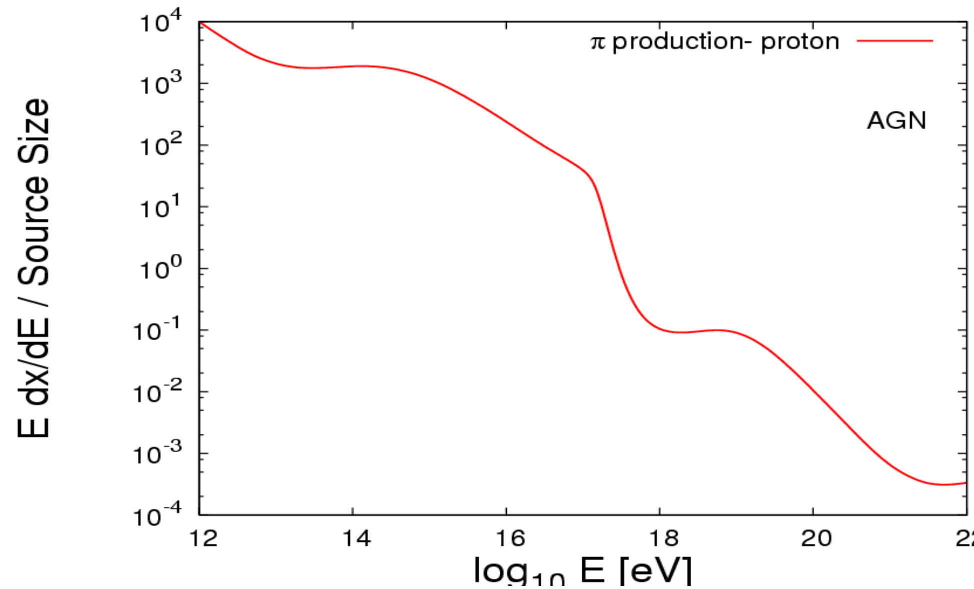
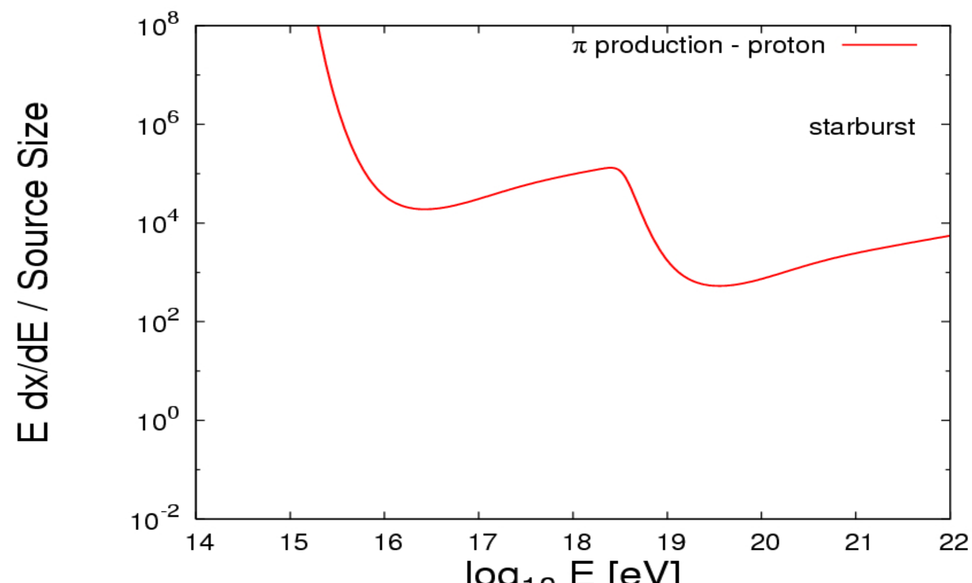
Interactions Rates in Sources- AGN

GRB





Starburst



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Interactions of Cosmic Ray Protons with CMB:

Photo-Pion Production-

$p + \gamma \;\rightarrow\; n + \pi^{+} / p + \pi^{0}$,

$E_{\gamma}^{th} = m_{\pi}(1 + 2m_{\pi}/m_{p}) \sim 145$ MeV

$n \;\rightarrow\; p + e^{-} + \bar{\nu}_{e}$

note- threshold value is in proton rest frame

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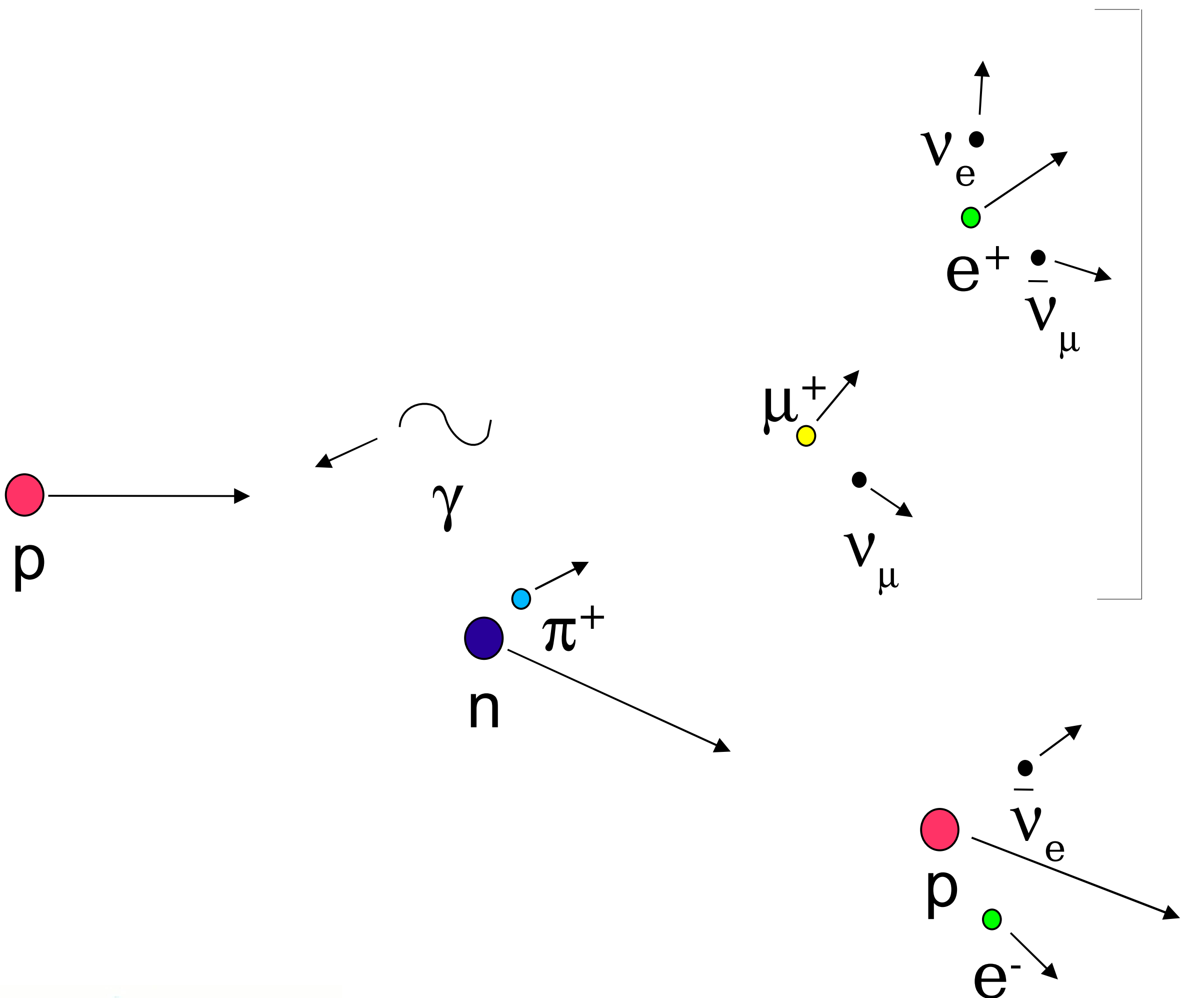
Neutrino Production



note- each ν takes ~0.05 of initial proton energy

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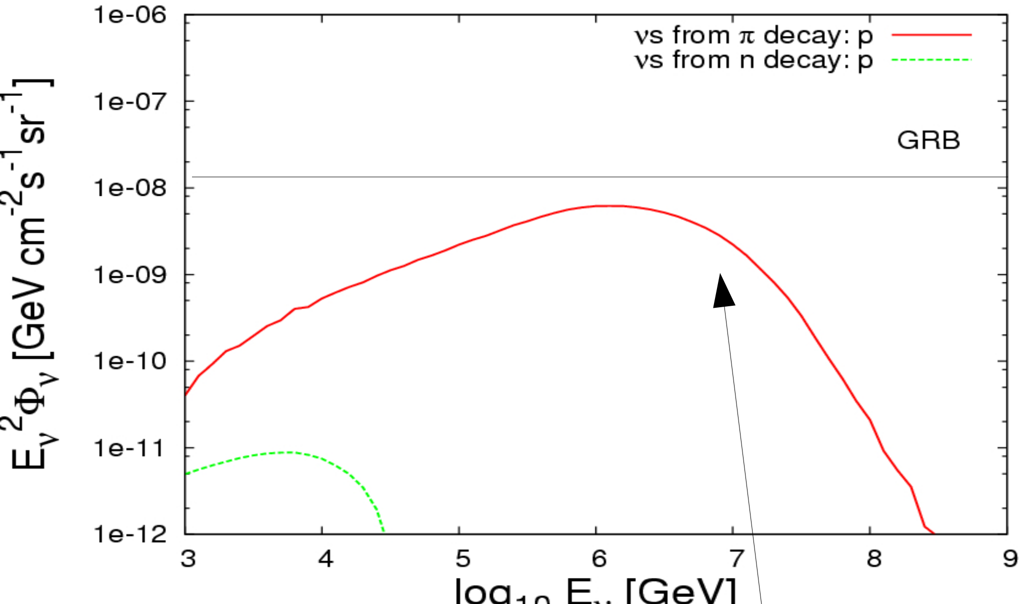
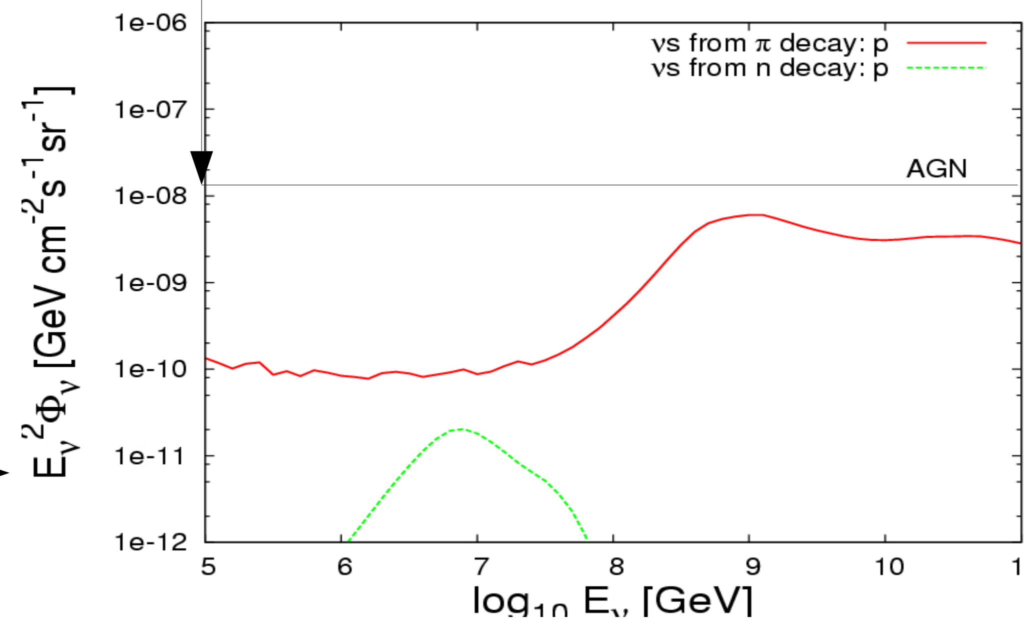
Diffuse Neutrino Fluxes Produced by Candidate Sources



GRB result

π synchrotron radiate

AGN result



$$\Phi_\nu = \int \Phi_\nu \frac{dN}{d\chi} d\chi$$

NB. Starburst flux ~10^{-4} WB bound

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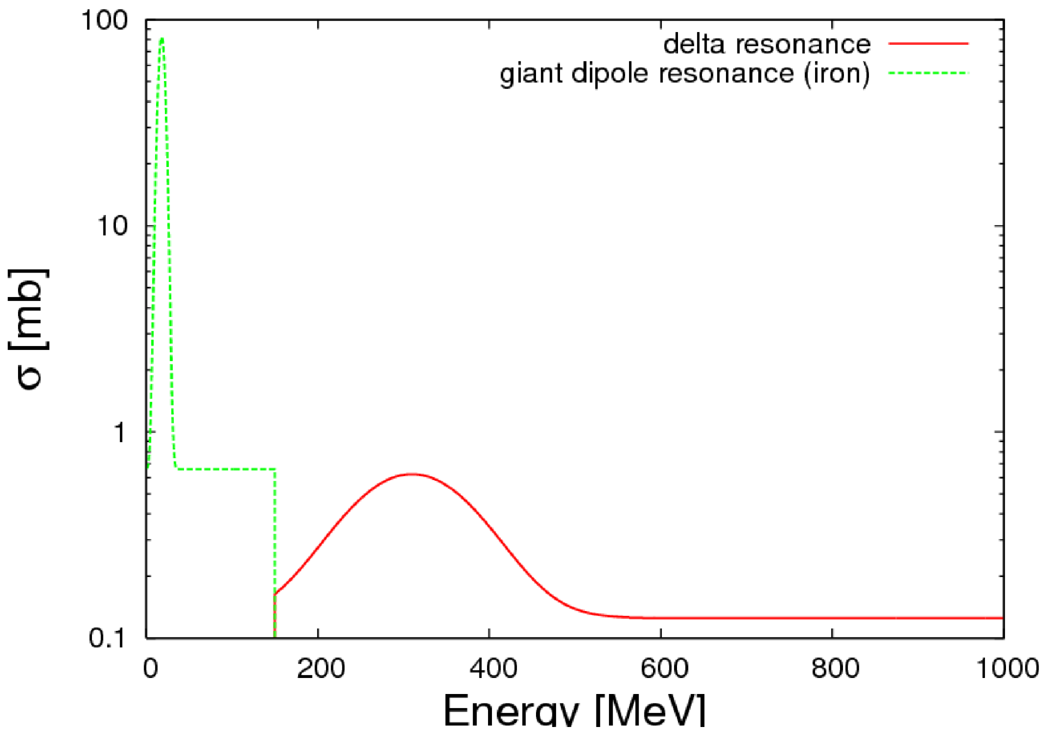
Cosmic Ray Interactions with Radiation



2 cross-sections: pion production

photodisintegration

opacity factor- f_π

$$f_\pi = l_{source} / l_{interaction}$$

$$l_{source} = c\Delta t$$

$$l_{interaction} = 1/(n_\gamma \sigma_\Delta)$$

GRB- $f_\pi^{max} = 0.55$

AGN- $f_\pi^{max} = 550$

Starburst Galaxy- $f_\pi^{max} = 4 \times 10^{-4}$

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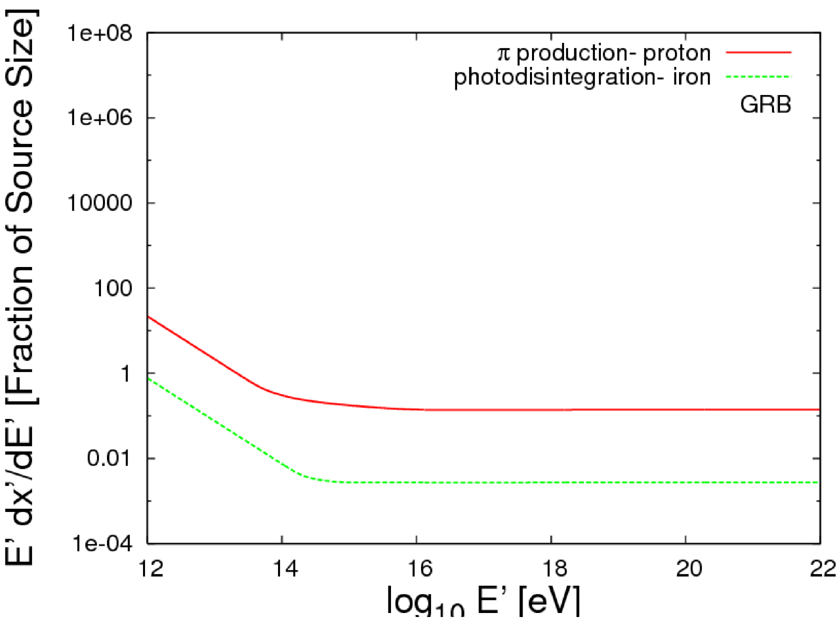
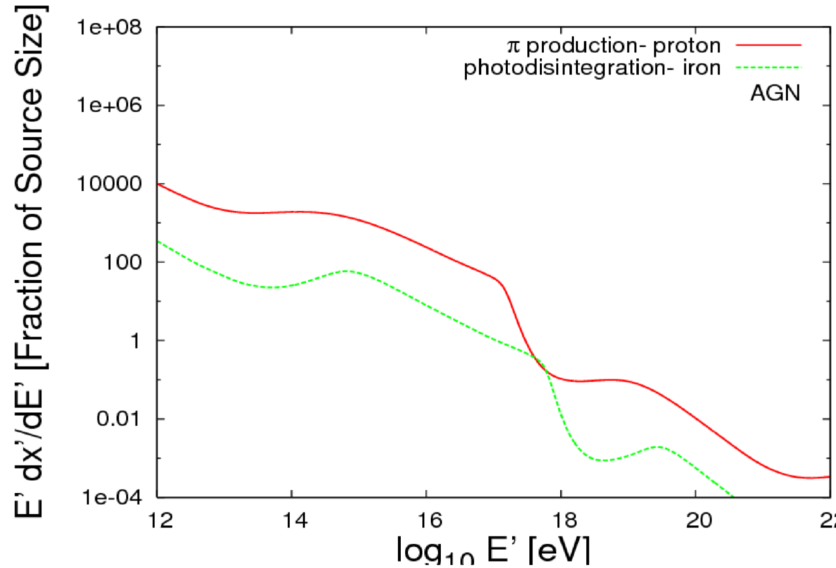
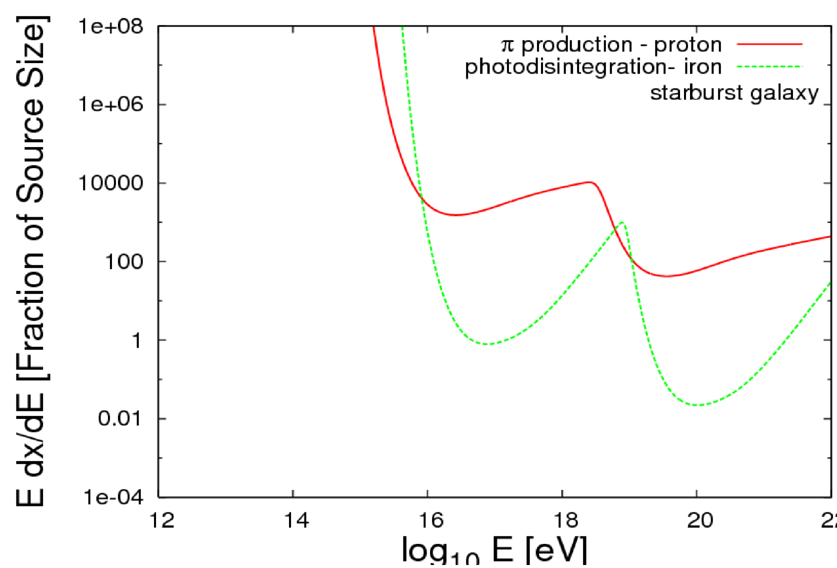
Interactions Rates in Sources- AGN

GRB





Starburst



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Ratio Between Photo-Pion and Photo-Disintegration Rates

From lecture 2:

$$R_{p,\gamma}(\Gamma)=\sigma_{p,\gamma}\int_{\frac{E_{p,\gamma}-\Delta_{p,\gamma}}{2\Gamma}}^{\frac{E_{p,\gamma}+\Delta_{p,\gamma}}{2\Gamma}} d\epsilon_{\gamma}\, n(\epsilon_{\gamma})$$

Applying this to photo-disintegration reactions:

$$R_{A,\gamma}(\Gamma)=\sigma_{A,\gamma}\int_{\frac{E_{A,\gamma}-\Delta_{A,\gamma}}{2\Gamma}}^{\frac{E_{A,\gamma}+\Delta_{A,\gamma}}{2\Gamma}} d\epsilon_{\gamma}\, n(\epsilon_{\gamma})$$

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Ratio Between Photo-Pion and Photo-Disintegration Rates (2)

with,

$$\sigma_{p,\gamma}=0.5\ \text{mb}, E_{p,\gamma}=310\ \text{MeV}, \Delta_{p,\gamma}=100\ \text{MeV}$$

and

$$\sigma_{A_{56},\gamma}=81\ \text{mb}, E_{A_{56},\gamma}=18\ \text{MeV}, \Delta_{A_{56},\gamma}=8\ \text{MeV}$$

therefore

$$R_{A_{56},\gamma}(\Gamma)\approx\frac{\sigma_{A_{56},\gamma}}{\sigma_{p,\gamma}}R_{p,\gamma}(15\Gamma)$$
$$=160\,R_{p,\gamma}(15\Gamma)$$

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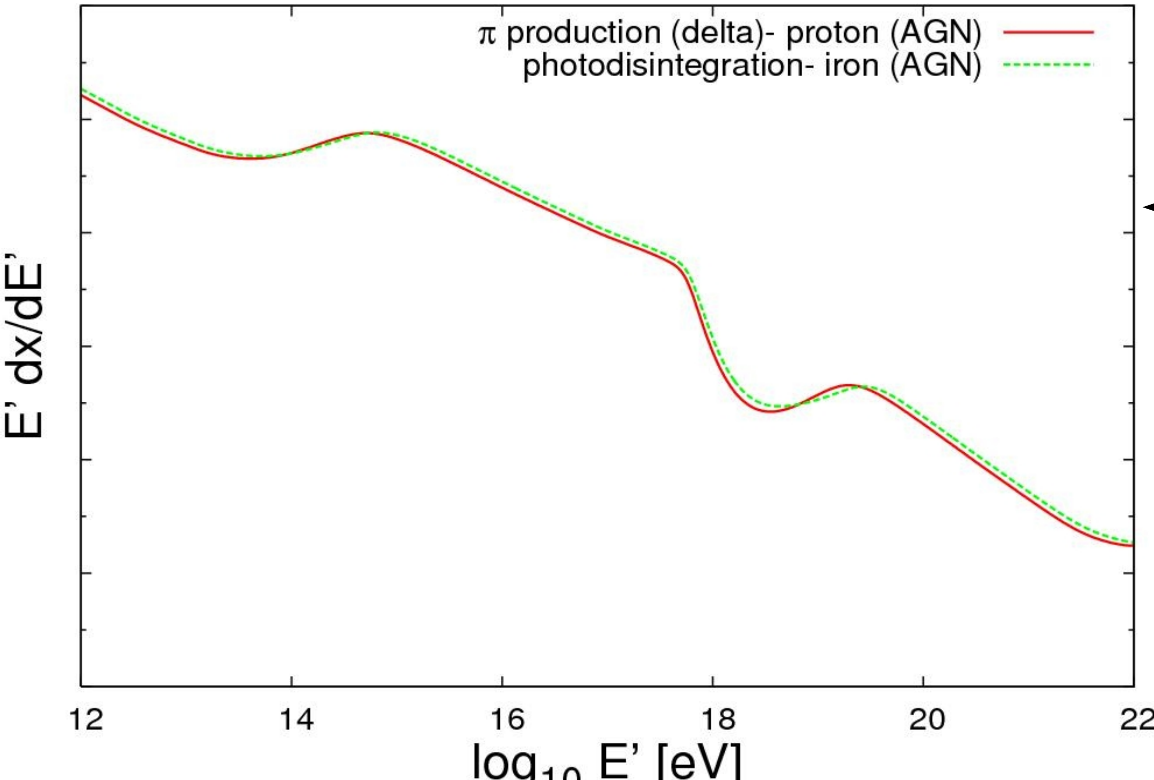
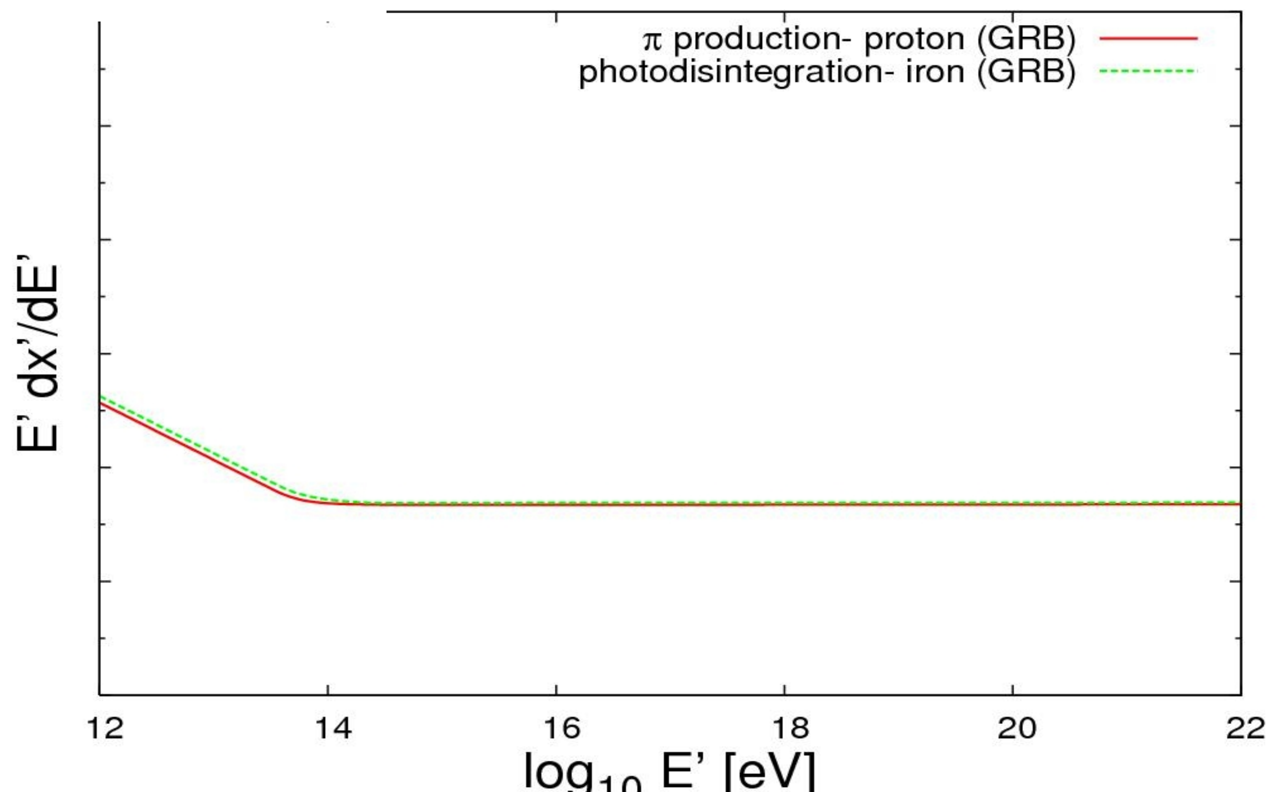


AGN

GRB



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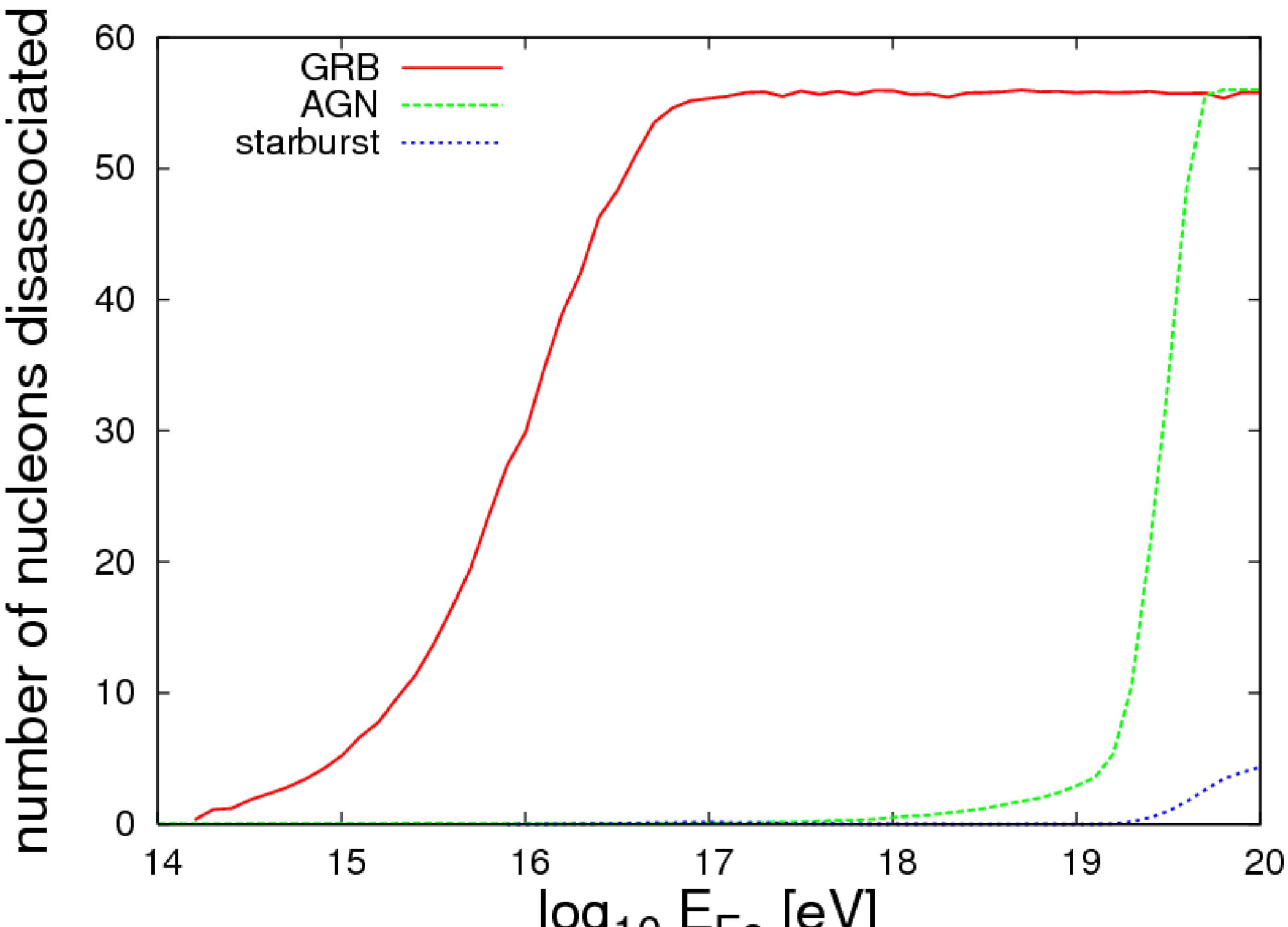
Degree of Photodisintegration in Source Regions



Complete Photodisintegration:

GRB- $E_{Fe}>10^{17}$ eV

AGN- $E_{Fe}>10^{20}$ eV

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Conclusion (2)

- The GRB model with near unity neutrino production opacities leads to complete disintegration of cosmic ray nuclei above 10^{17} eV
- The AGN model with near unity neutrino production opacities leads to complete disintegration of cosmic ray nuclei above 10^{20} eV.
- A consistency check with the typical opacities used in UHECR interaction rate calculations within the source region reveals contradiction with the presence of Fe in the UHECRs for the GRB source model

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Finally

Other messengers carrying useful diagnostic information remain available such as:

– the change in cosmic ray composition with energy

– the neutrino flavour ratios and how they change as a function of energy

.....all you need is imagination (and good physics groundwork)!

SO LONG AND THANKS FOR ALL THE FISH!!!!!!

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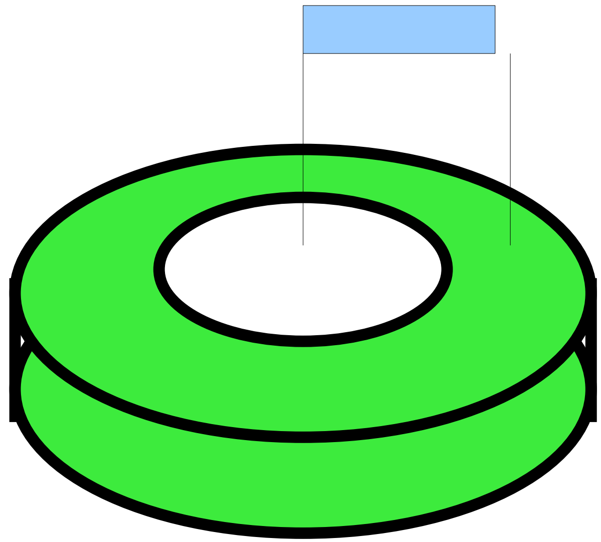
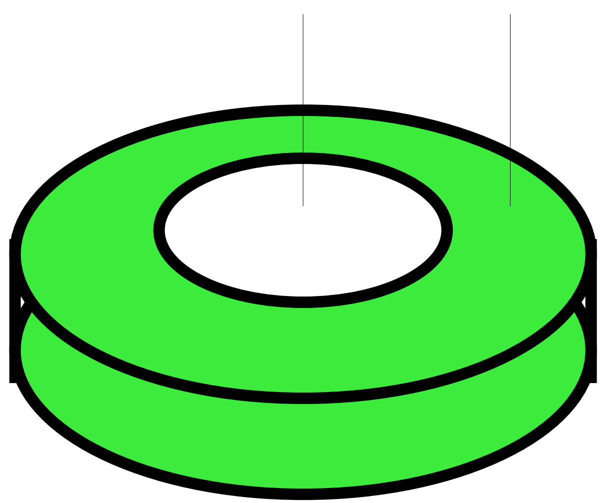
Origin of Dip Feature in Photon Flux

$E_p = 10^{19}$ eV



$E_p = 10^{20}$ eV



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