Astrophysical cosmic rays lecture III Propagation and energy losses

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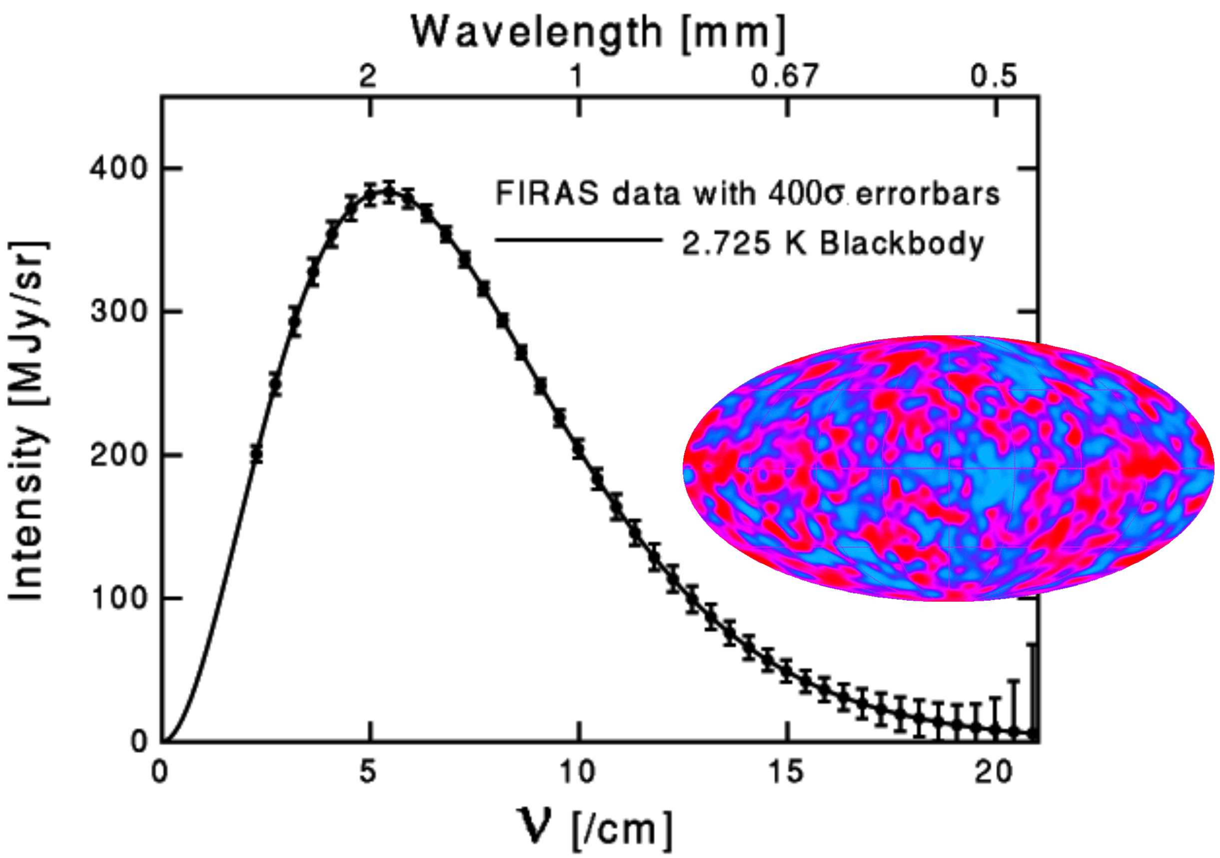
The GZK effect (Greizen-Zatsepin-Kusmin)

- The CMB was discovered in 1965 by Penzias and Wilson when they were operating a telecommunication antenna in New Jersey.

- Since the mid 1950's, the existence of excited states of the proton were experimentally known.

- Already in 1966, Greisen (USA) and Zatsepin & Kuzmin (URSS) used these two pieces of information to study the propagation of ultra-relativistic protons through the cosmos.

The GZK (Greizen-Zatsepin-Kusmin) effect



The universe is filled with an almost isotropic bath of photons with a current temperature:

$$T_{\text{today}} \sim 2.725\,\text{K} \quad \Longrightarrow \quad \overline{E}_\gamma \sim 6.6 \times 10^{-4}\,\text{eV}$$

However in the rest frame of a proton with E ~ 5 x 10^{19} eV:

gamma-ray photon !

head-on collision

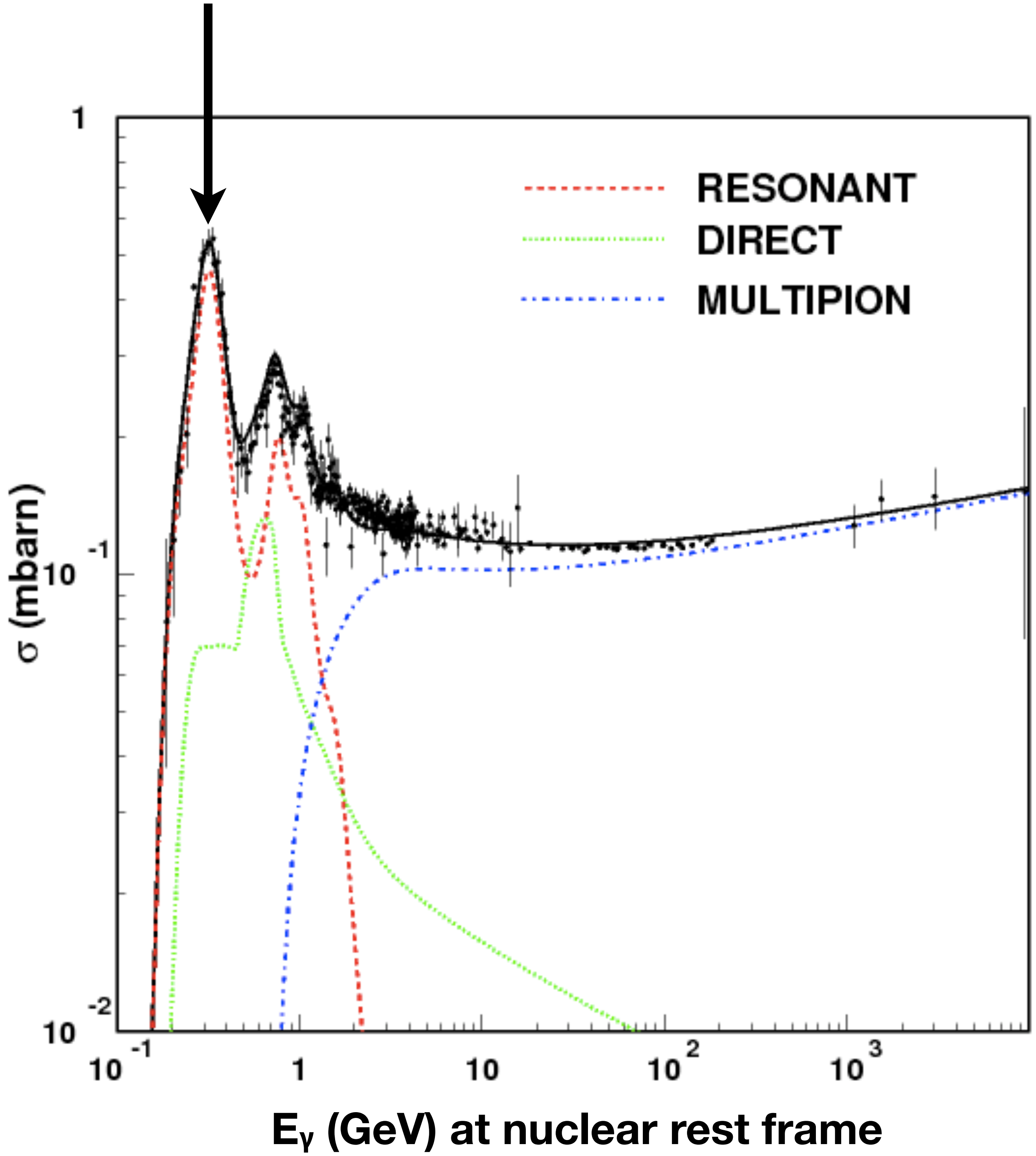
$$\gamma = \frac{E}{m_p c^2} \sim \frac{5 \times 10^{19}\,\text{eV}}{10^9\,\text{eV}} = 5 \times 10^{10} \quad \Rightarrow \quad E'_\gamma \sim 2\gamma \overline{E}_\gamma \sim 66\,\text{MeV}$$

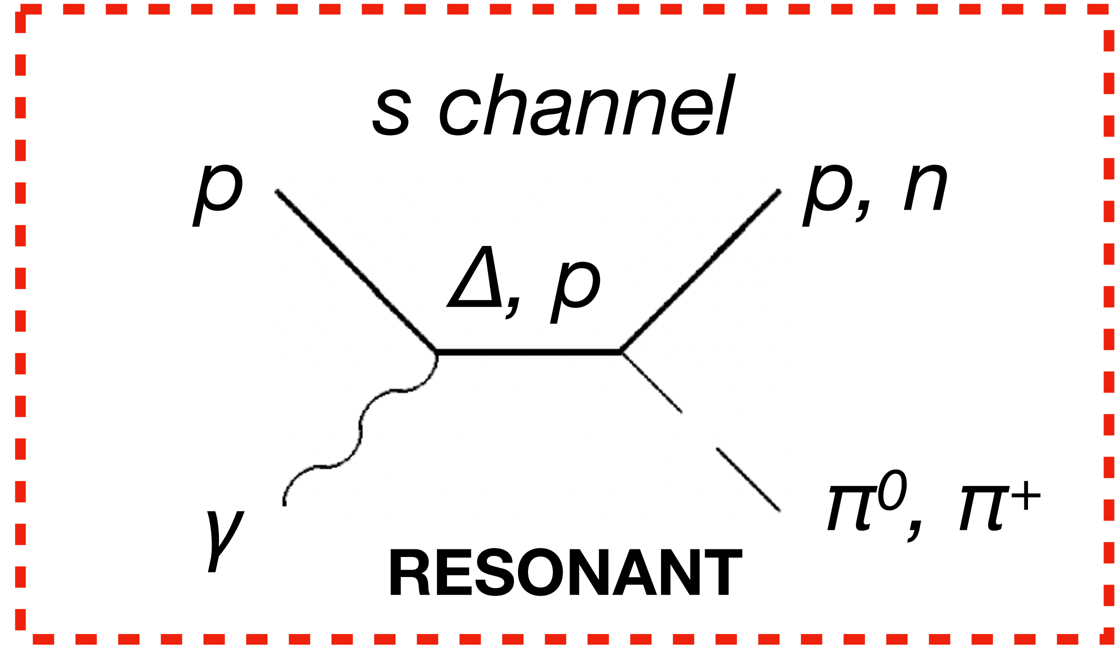
*Greisen, Kenneth (1966). "End to the Cosmic-Ray Spectrum?". Physical Review Letters. **16** (17): 748–750*

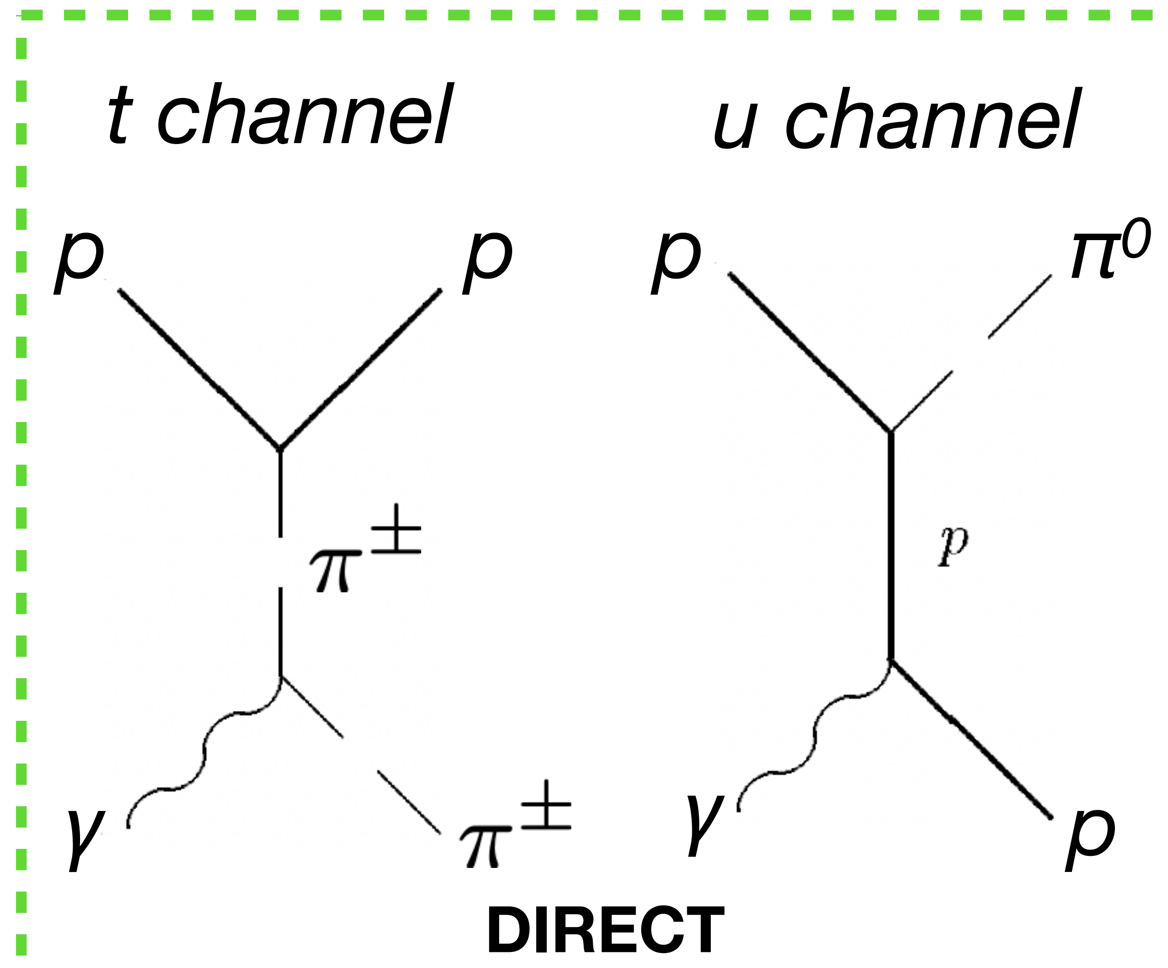
*Zatsepin, G. T.; Kuz'min, V. A. (1966). "Upper Limit of the Spectrum of Cosmic Rays". J. of Exp. and Theor. Phys. Letters. **4**: 78–80.*

The proton-γ cross-section

$\Delta^+(1232)$







1 barn = 10^{-28} m^2 (typical nuclear cross-section)

Proton stochastic energy losses

From the previous plot, we conclude that in the nuclear rest frame (NRF), up to E_γ ~ 400 MeV, the p-γ cross-section is dominated by the following resonant photopion production reactions:

$$p + \gamma_{\rm cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$p + \gamma_{\rm cmb} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

The presence of pions in the final state, lead to the production of secondary photons and neutrinos in the EeV energy range (UHE photons and neutrinos):

$$\pi^0 \rightarrow \gamma\gamma \qquad \pi^+ \rightarrow \mu^+ + \nu_\mu$$ **(cosmogenic photons and neutrinos)**

At each interaction, a considerable fraction of the energy is subtracted from the original proton to account for the pion production. The process is stochastic in nature.

TASK: show that in a frame where the photon has energy Eγ, the threshold proton energy for photopion reactions is given by:

$$E_p = \frac{(m_p c^2 + m_\pi c^2)^2 - m_p^2 c^4}{4E_\gamma}$$

Then calculate the proton energy at this threshold for a photon with an energy equal to the average energy of the CMB Planck distribution today.

Adiabatic energy losses

In this course, I'll define UHECRs as charged particles with energies above 10^{18} eV.

From the thermodynamic point of view, such particles behave just like a gas of photons.

Therefore, they should be affected by the universe expansion just like radiation as we already studied before. In other words, not only their number density should be decreasing, but their individual energies as well.

TASK: working with a collection of mono energetic UHECR propagating in an expanding universe, show that the rate of change of its energy due to the expansion satisfies:

$$\frac{1}{E}\left(\frac{dE}{dt}\right)_{\mathrm{ad}} = -H(t)$$

This energy loss due solely to the expansion is called **adiabatic energy loss**.

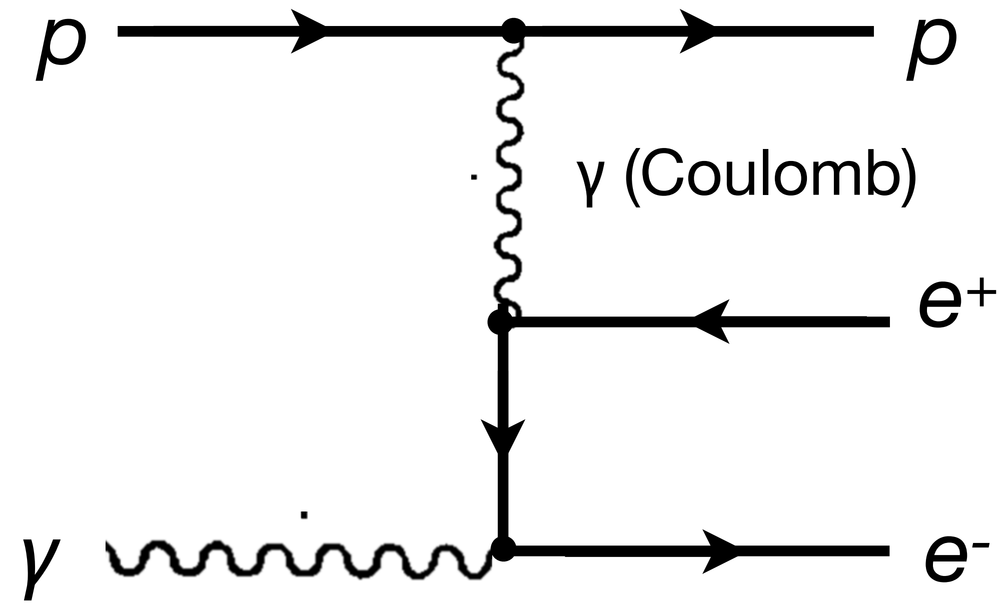
The above energy loss rate allows us to define a redshift-dependent **adiabatic energy loss length**, which at *z=0* is given by:

$$\lambda_{\mathrm{ad}}(z=0) = \frac{c}{H_0} \simeq 4.3\,\mathrm{Gpc}$$

Quasi-continuous energy losses

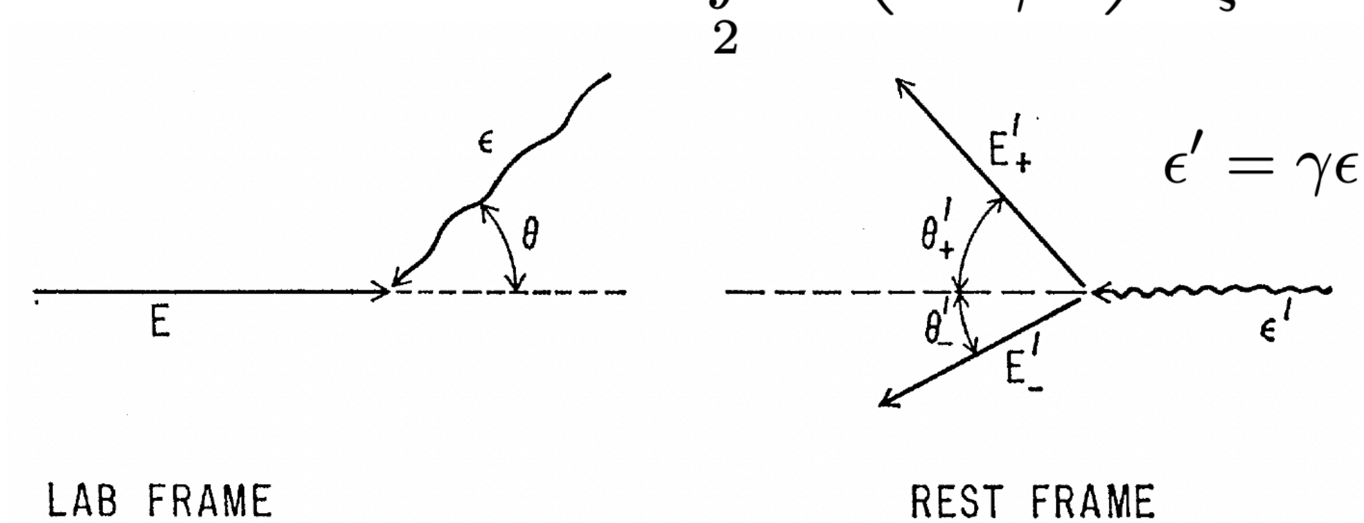
In the presence of the CMB, UHECR proton (or nuclei) can also lose energy through the so called **Bethe-Heitler process** (i.e. photon-induced pair production in the nuclear Coulomb field of the proton):

$$p + \gamma_{\rm cmb} \to p + e^+ + e^-$$

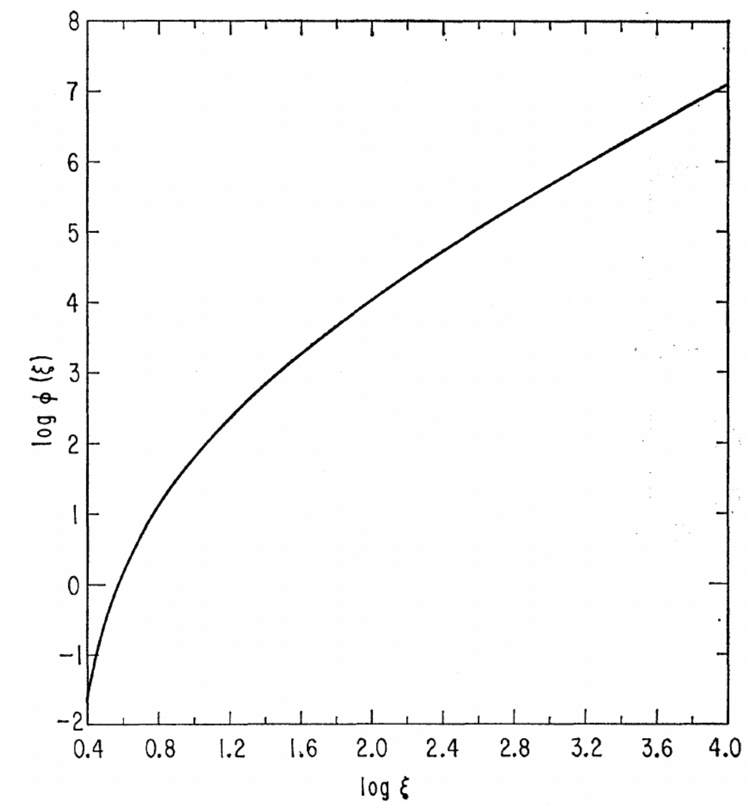


Due to the negligibly small energy subtracted from the proton to create the electron-positron pair, for practical reasons this process can be treated essentially as continuous, or to be more precise: **quasi-continuous**.

$$\frac{dE}{dx} = -\alpha r_0^2 Z^2 m_e^2 c^4 \int_2^\infty n\left(\frac{\xi m_e c^2}{2\gamma}\right)\frac{\phi(\xi)}{\xi^2}d\xi$$



$$\epsilon' = \gamma\epsilon(1+\beta\cos\theta)$$

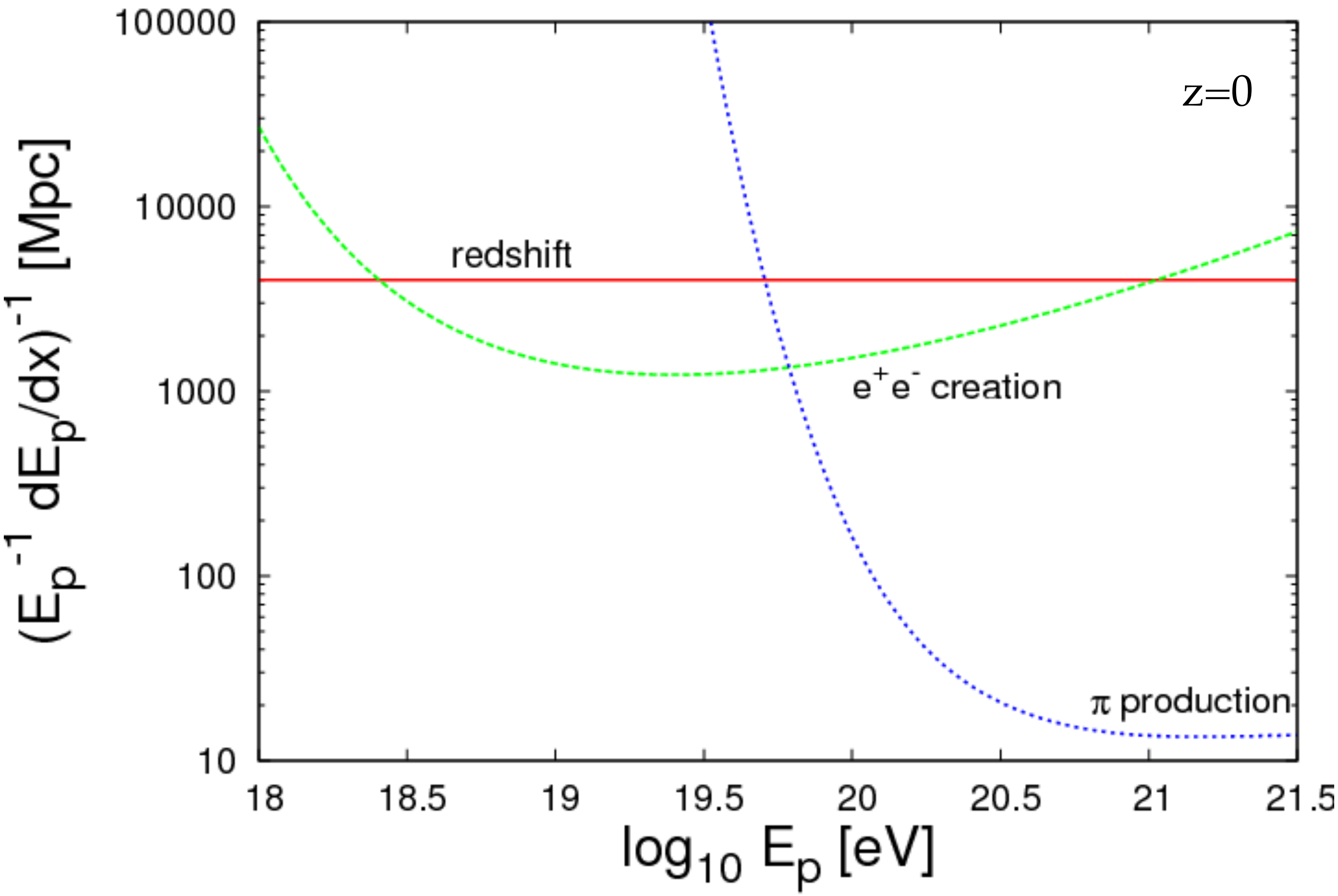


G. R. Blumenthal. *Energy loss of high-energy cosmic rays in pair-producing collisions with ambient photons*. Phys. Rev., D1:1596–1602

Proton energy losses

$1\,\text{parsec (pc)} \simeq 3.3\,\text{light-years (ly)}$

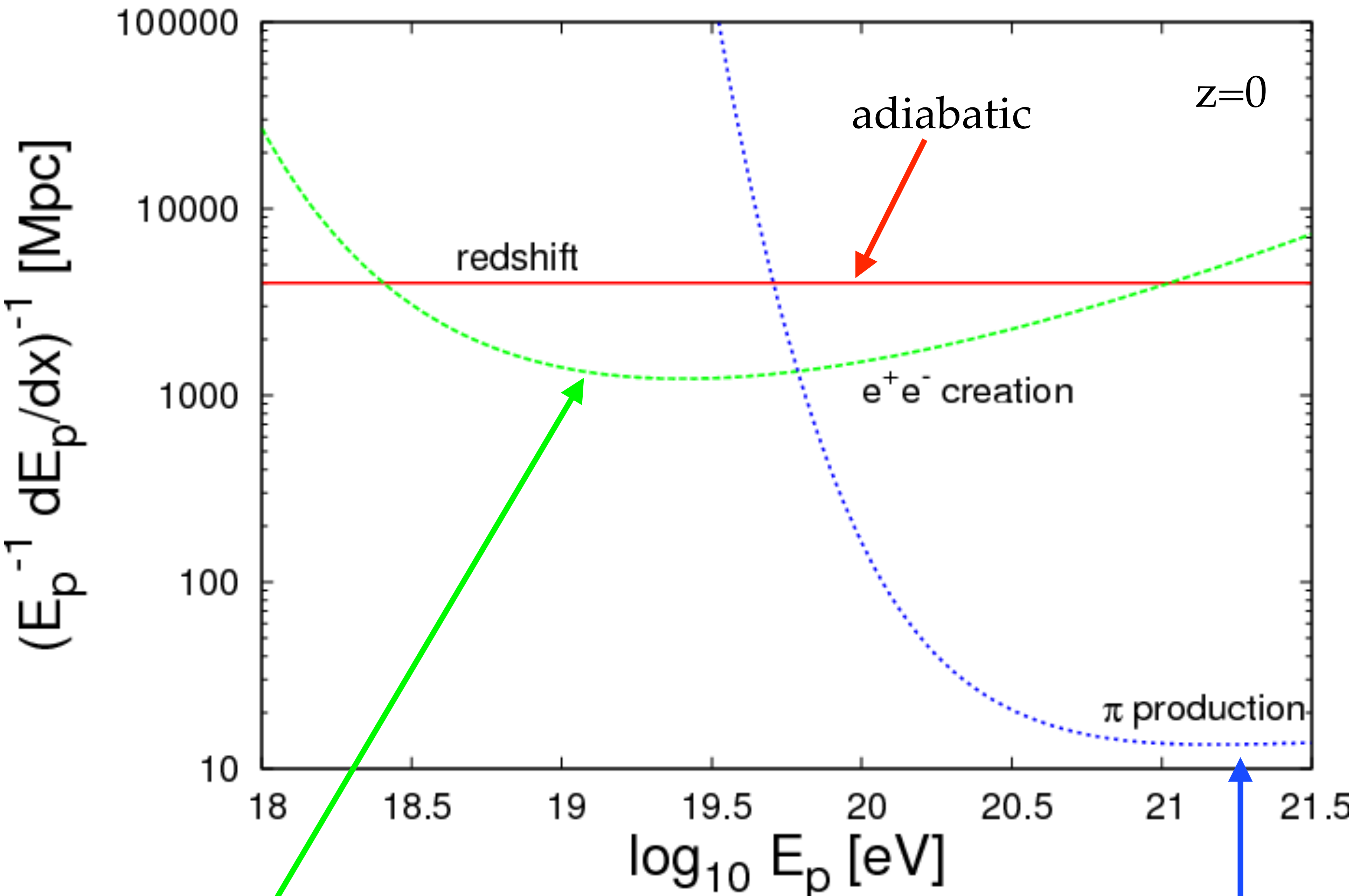
arXiv:0902.3012 [astro-ph.HE]



Proton energy losses

1 parsec (pc) $\simeq$ 3.3 light-years (ly)

arXiv:0902.3012 [astro-ph.HE]

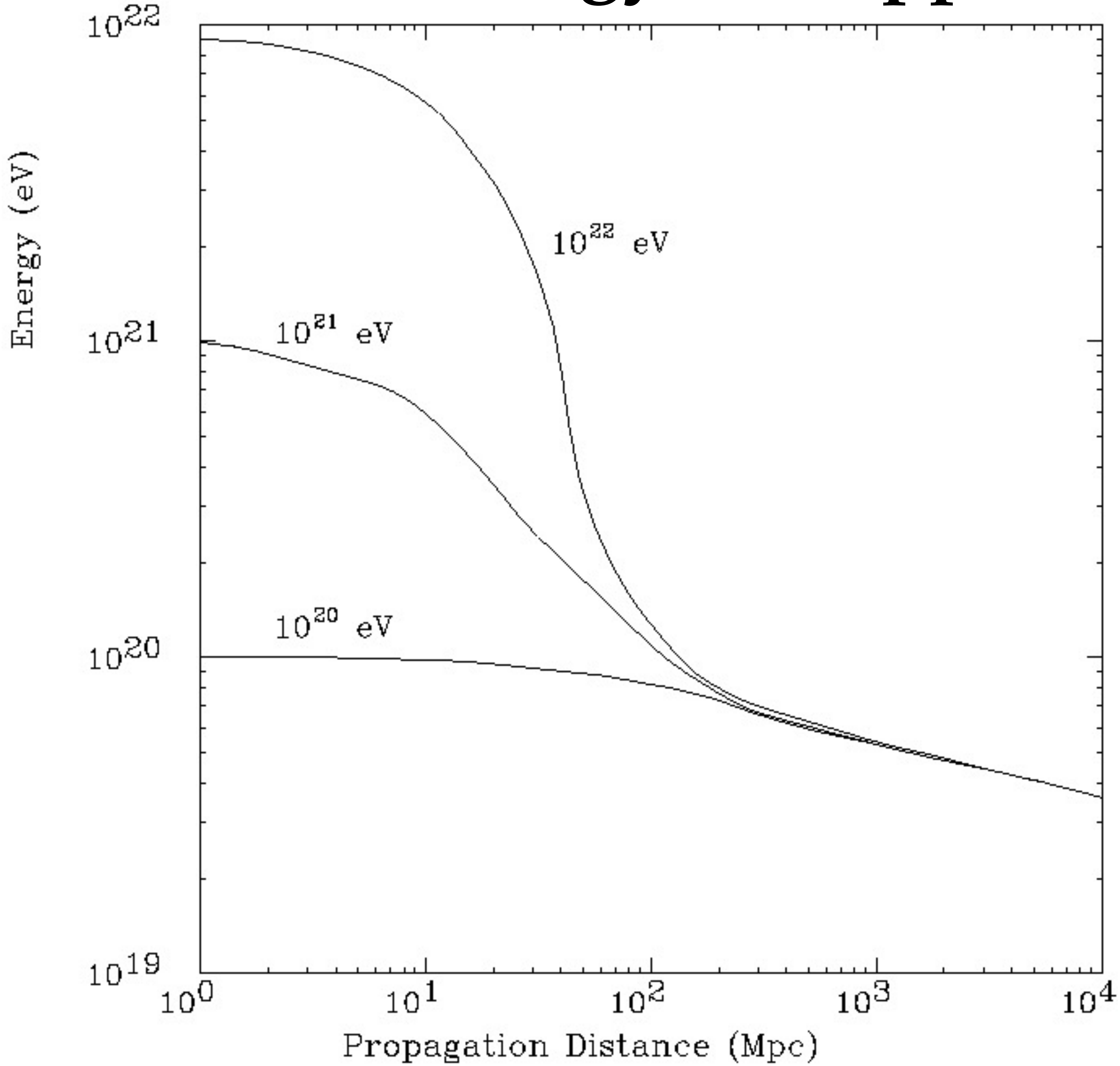


$$p + \gamma_{\rm cmb} \to p + e^+ + e^-$$

$$p + \gamma_{\rm cmb} \to \Delta^+ \to p + \pi^0$$

$$p + \gamma_{\rm cmb} \to \Delta^+ \to n + \pi^+$$

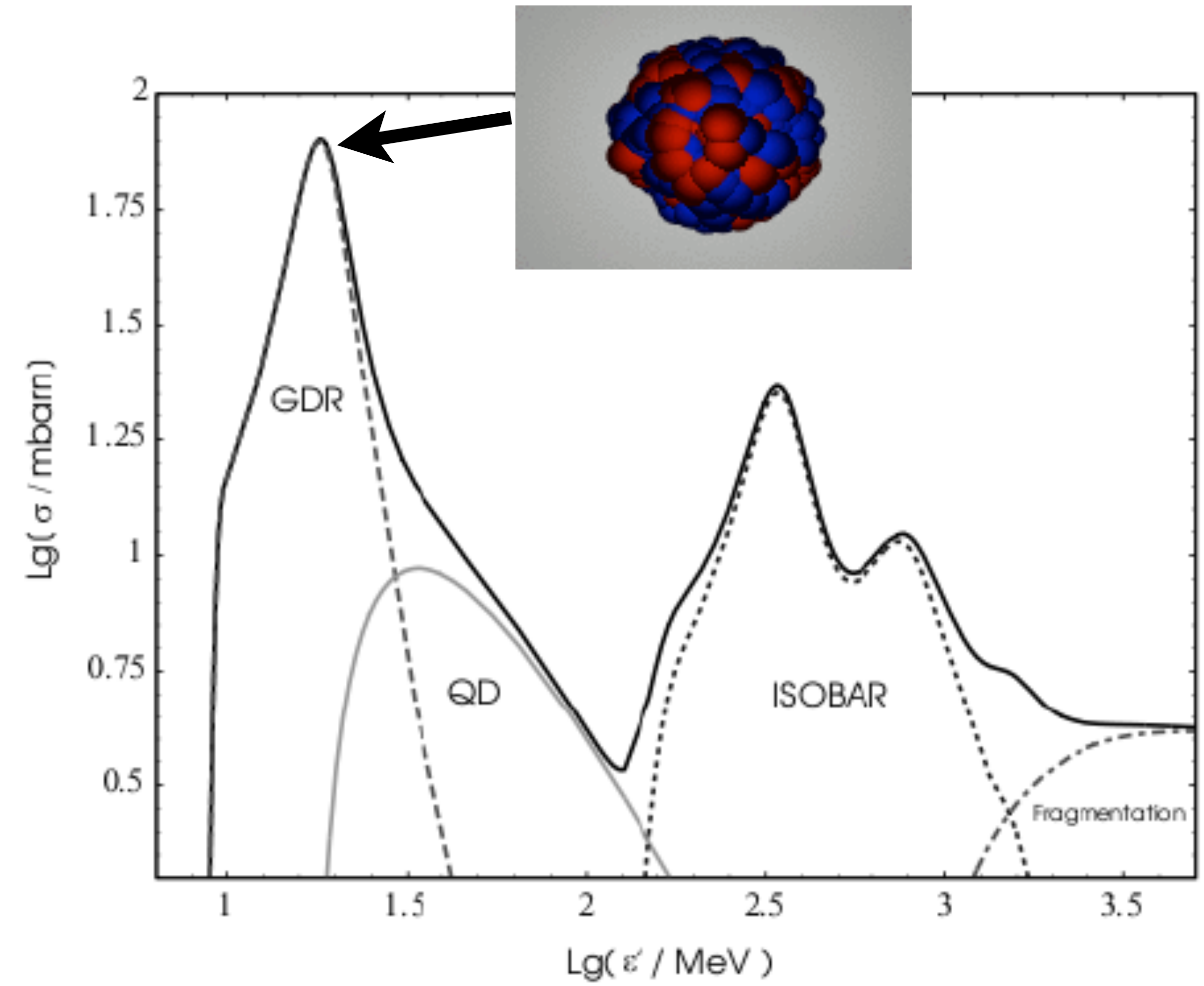
Continuous energy loss approximation



Nuclear photodisintegration

- In the NRF, the nucleus-photon interaction cross-section for tens of MeV photons is dominated by the **Giant Dipole Resonance (GDR).**

- This resonance is characterized by an oscillatory collective mode of the whole nucleus with protons and neutrons in phase opposition (that induces a large nuclear dipole moment).



- The GDR leads to nuclear disintegration with the original nucleus losing, most of the time, one or two nucleons

$$A + \gamma \longrightarrow (A-1) + N, \quad A + \gamma \longrightarrow (A-2) + N$$

$$\epsilon_{\rm GDR} \simeq 80 A^{-1/3} \text{ MeV} \quad \Rightarrow \quad \frac{E_1}{E_2} \simeq \left(\frac{A_1}{A_2}\right)^{2/3}$$

Light nuclei will disintegrate faster than heavy ones

Photon energy per nucleon in NRF

Nuclear photodisintegration

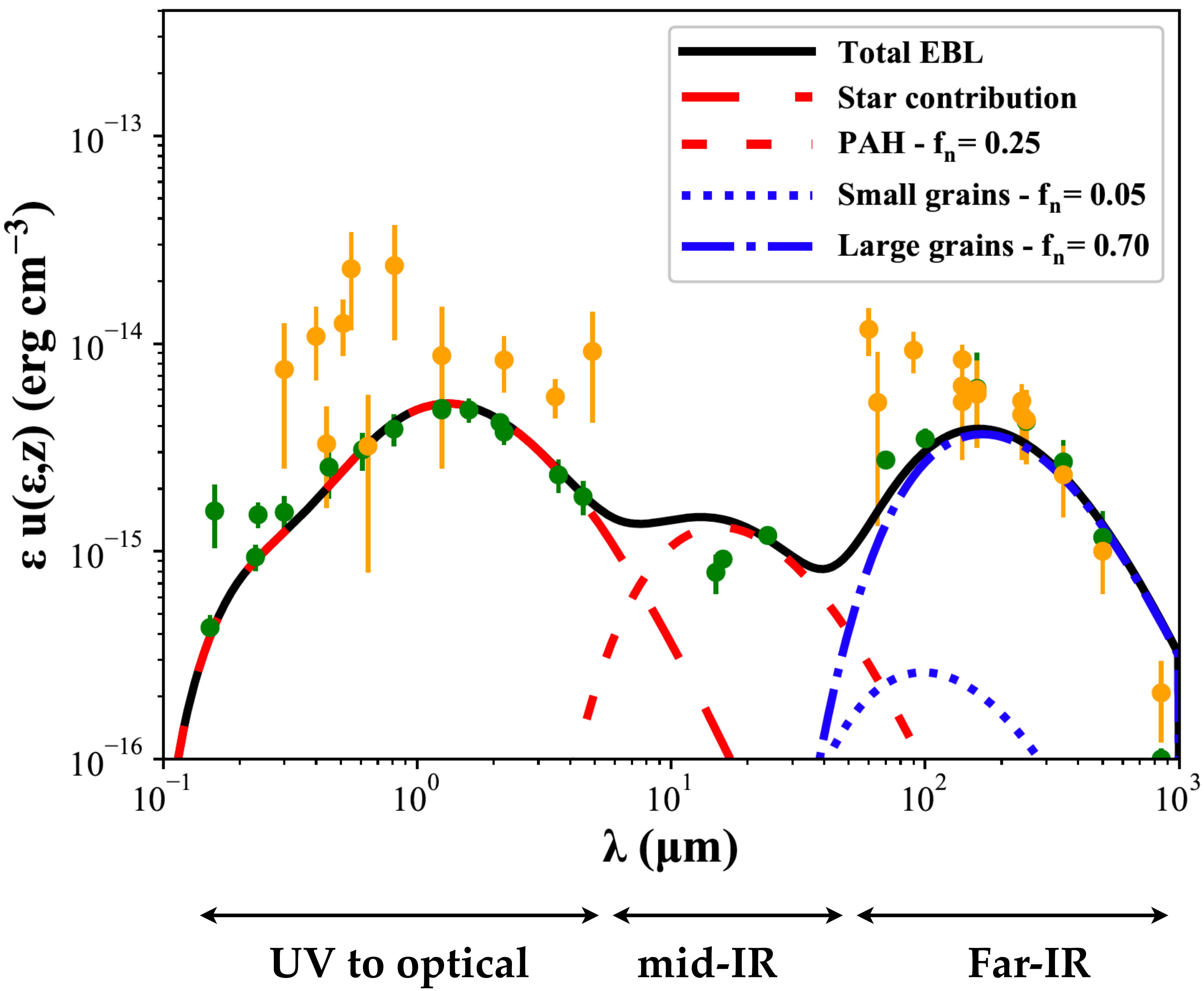
- For nuclei with energy ~10^{19} eV, the resonance has maximum excitation probability for photons with wavelengths in the infrared (IR) region instead of radio or microwave.

TASK: verify the previous statement starting from the photon energy per nucleon in the NRF and calculating its comoving wavelength in the lab. frame (where the nuclei is a UHECR).

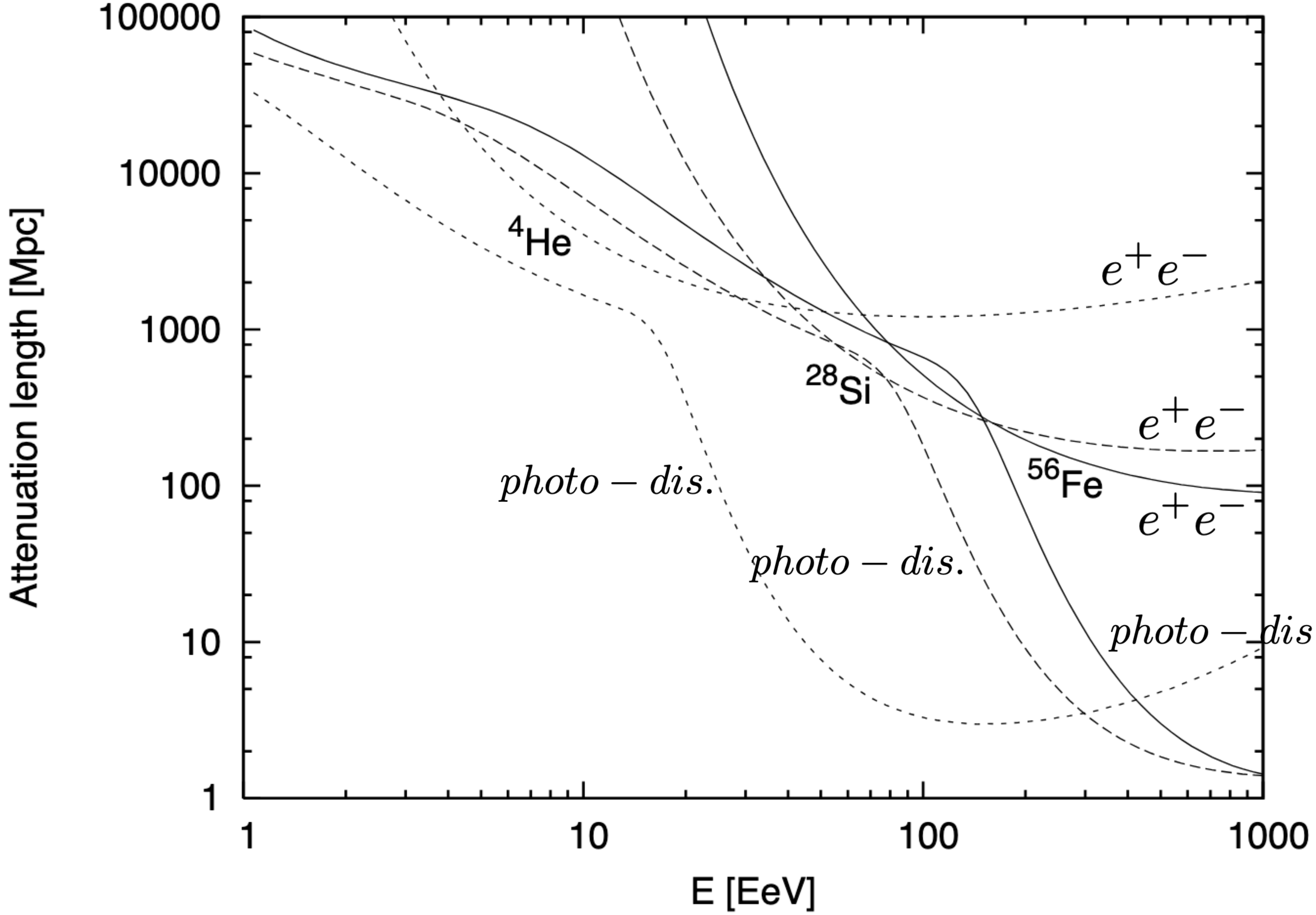
- QUESTION: are there IR emitters scattered through the universe??

YES! Especially dust.

Extragalactic Background Light (EBL)

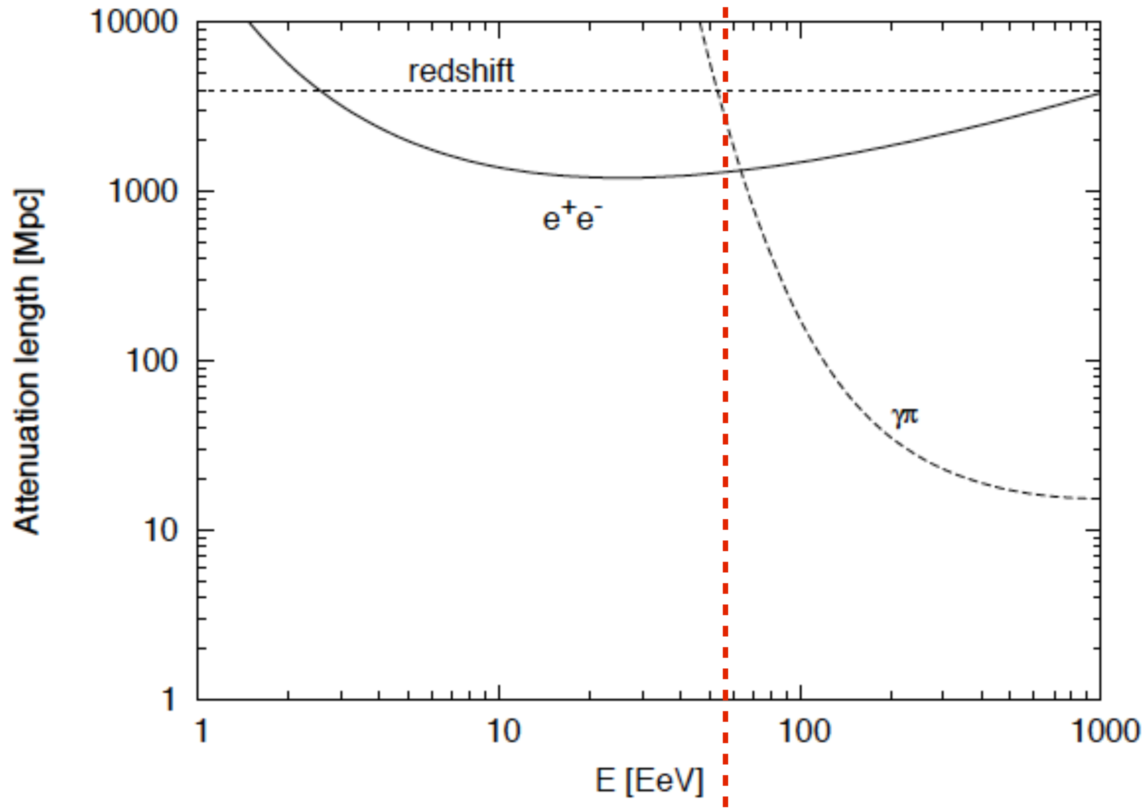


Heavier nuclei energy losses



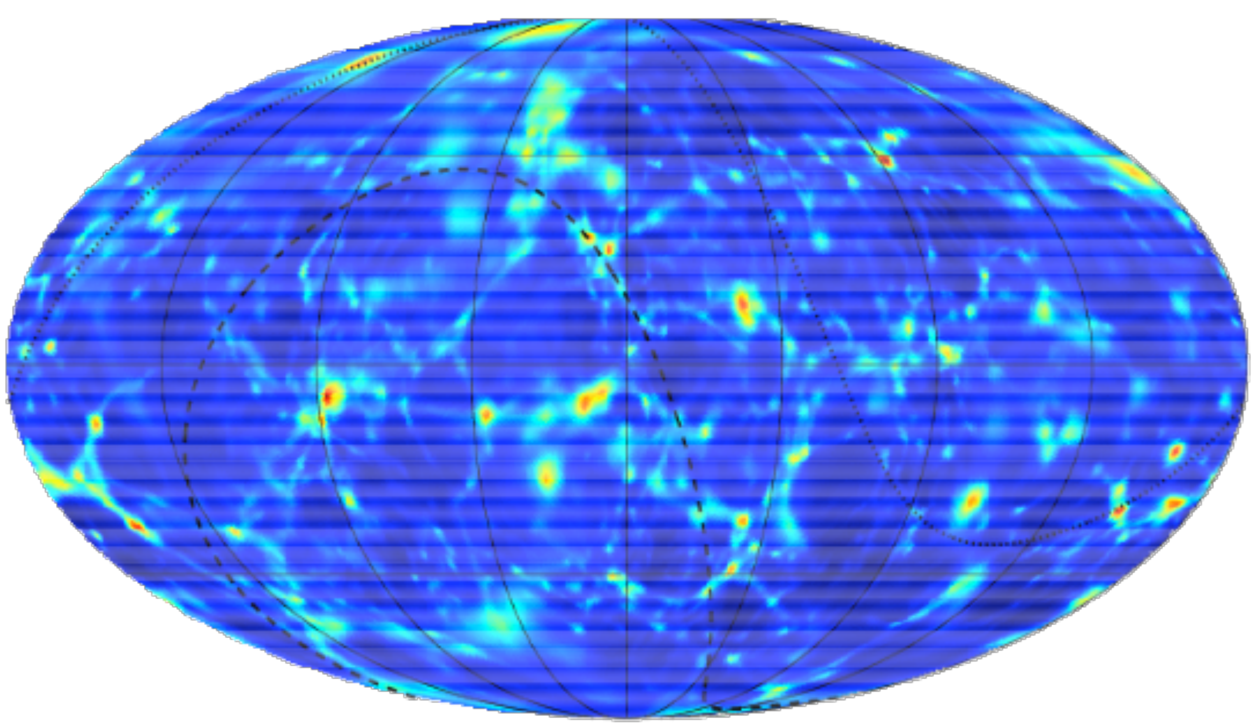
D.Harari, S. Mollerach and E. Roulet, *On the ultrahigh energy cosmic ray horizon*, JCAP **11** (2006), 012

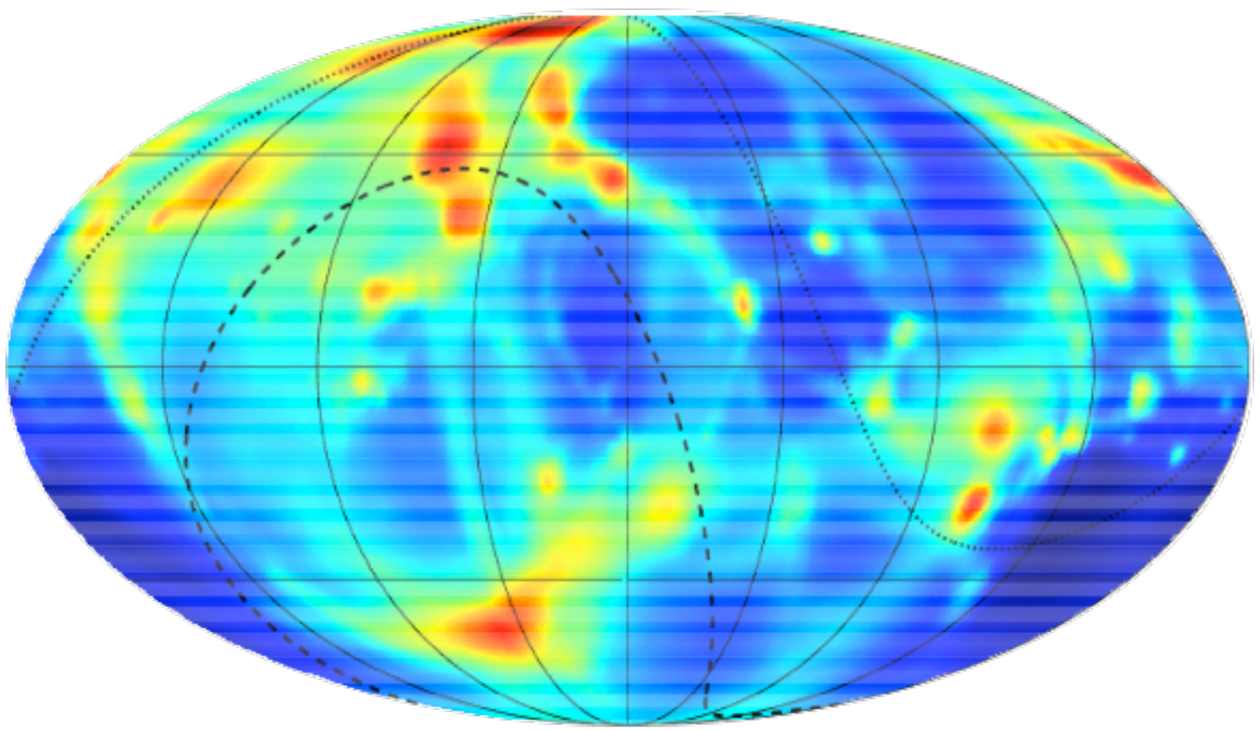
The GZK horizon



The universe seen through cosmic rays should be isotropic at energies below the GZK cutoff...

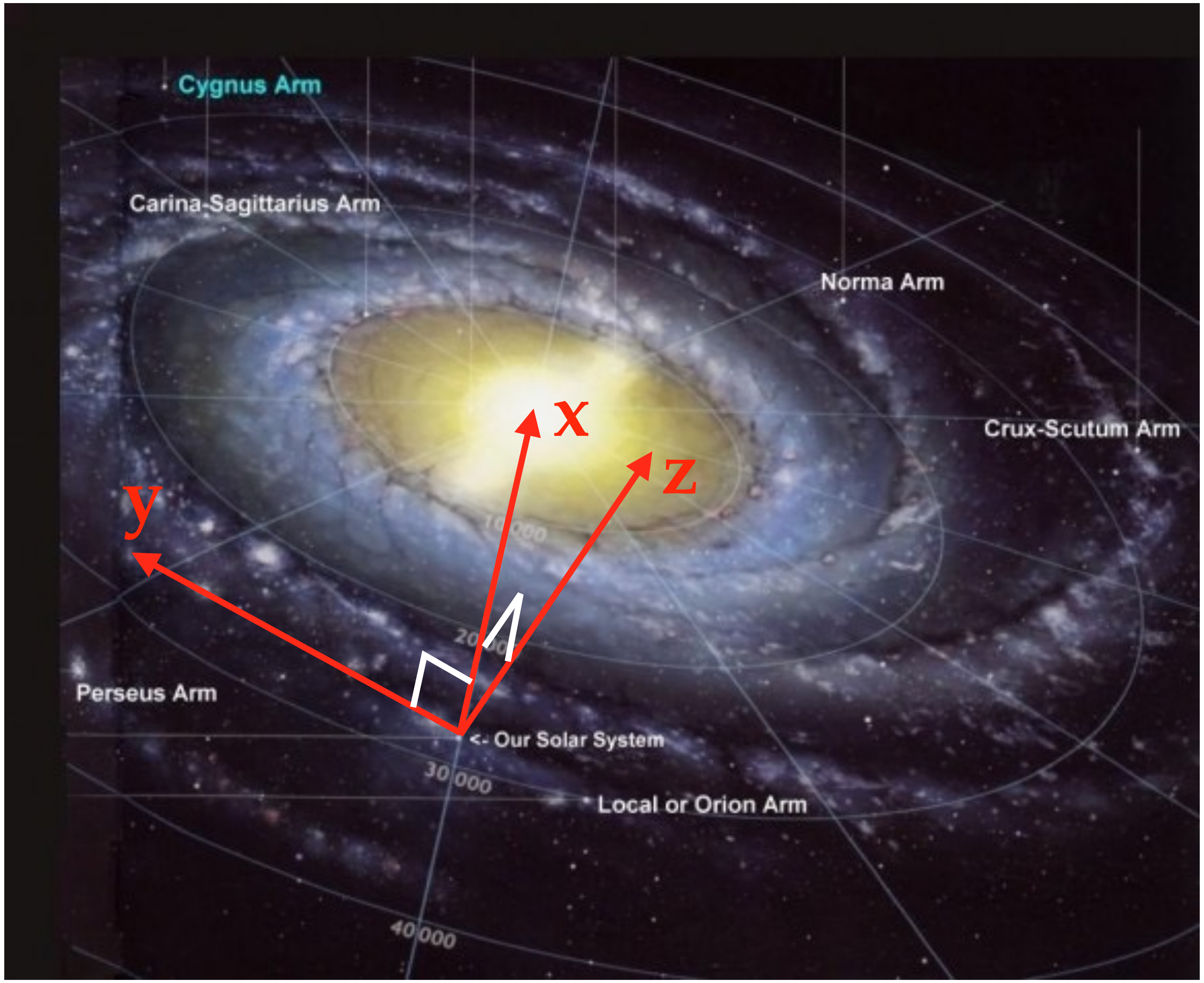
... and become more anisotropic above that energy.



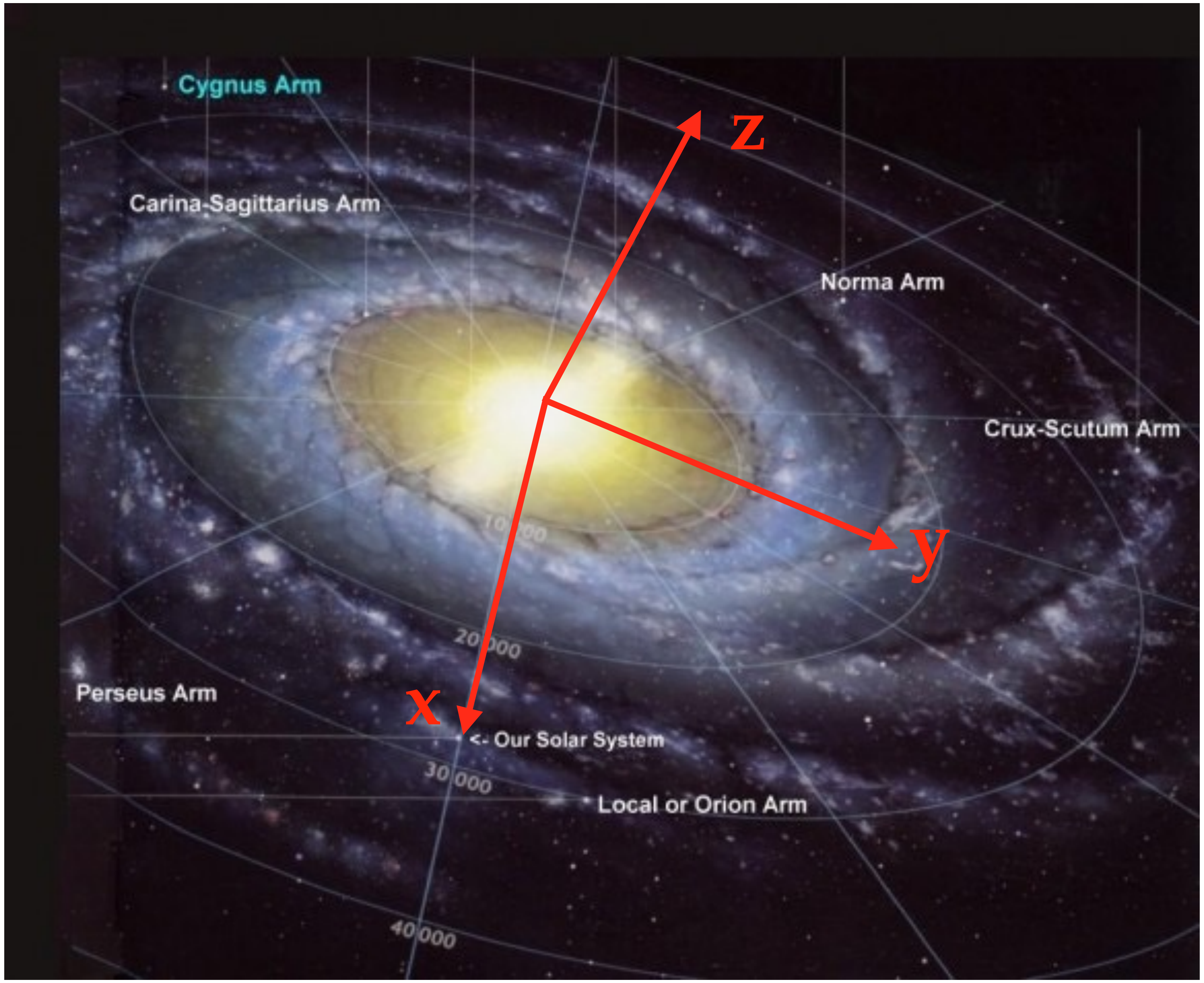


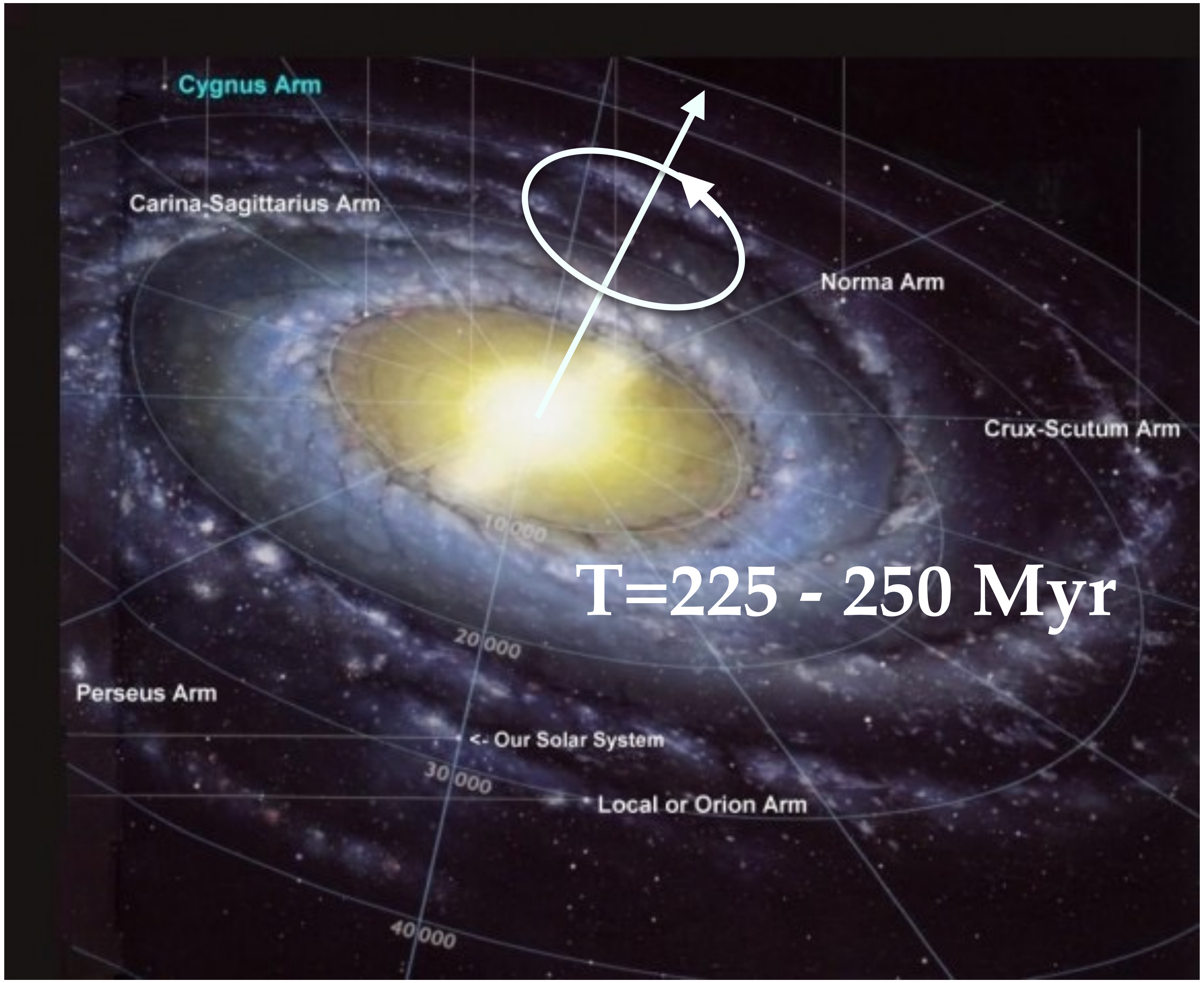
from Kravtsov DM simulations

Galactic coordinate system

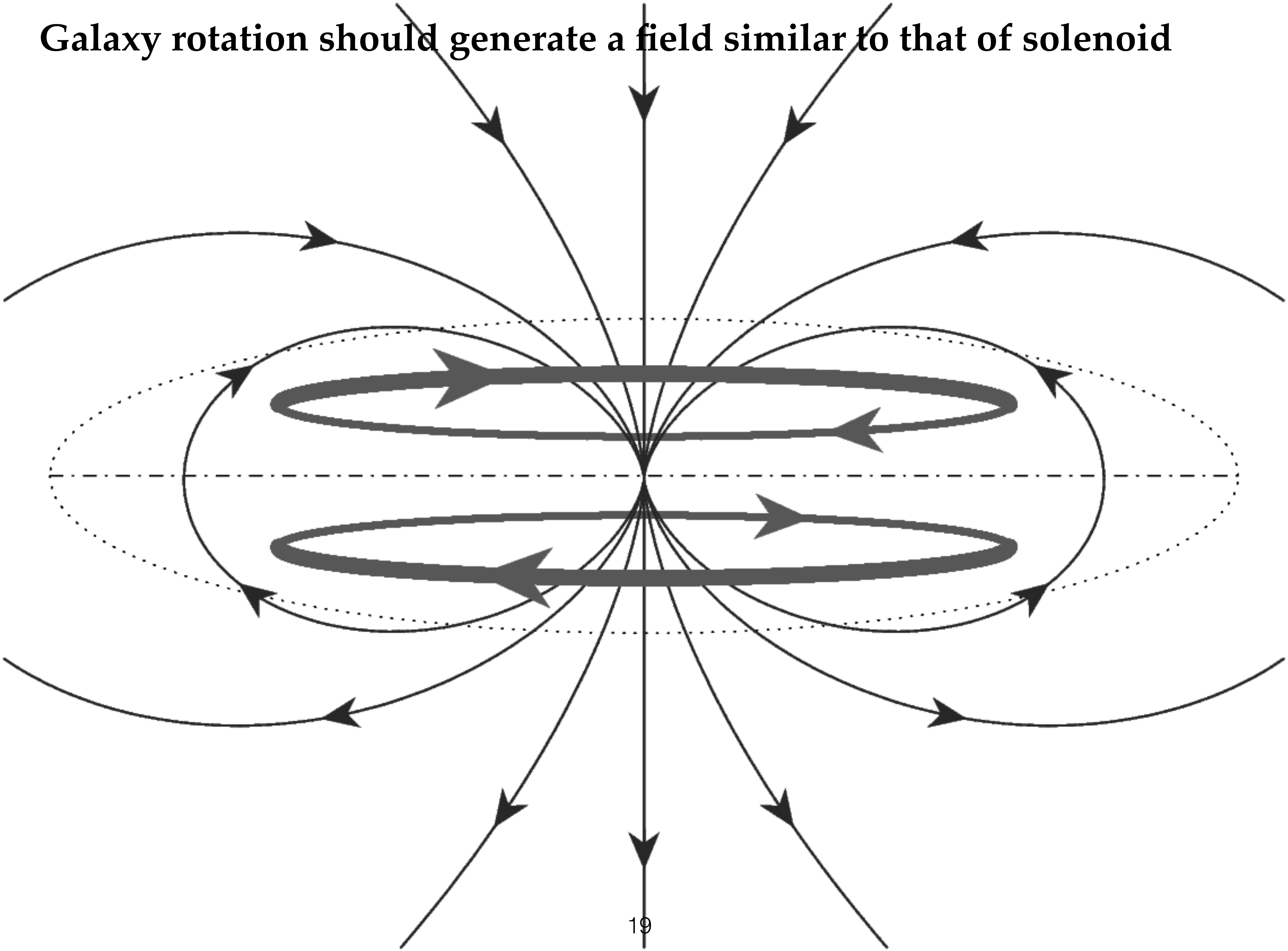


Galactocentric coordinate system




Cygnus Arm
Carina-Sagittarius Arm
Norma Arm
Crux-Scutum Arm
10 000
T=225 - 250 Myr
20 000
Perseus Arm
<- Our Solar System
30 000
Local or Orion Arm
40 000

Galaxy rotation should generate a field similar to that of solenoid



BSS/ASS models

BSS-S

$$B(r,\theta) = \left[\frac{3R}{r}\tanh^3\left(\frac{r}{r_1}\right)\right]\cos\left(\theta - \frac{\pi}{2}\ln\frac{r}{r_0}\right)$$

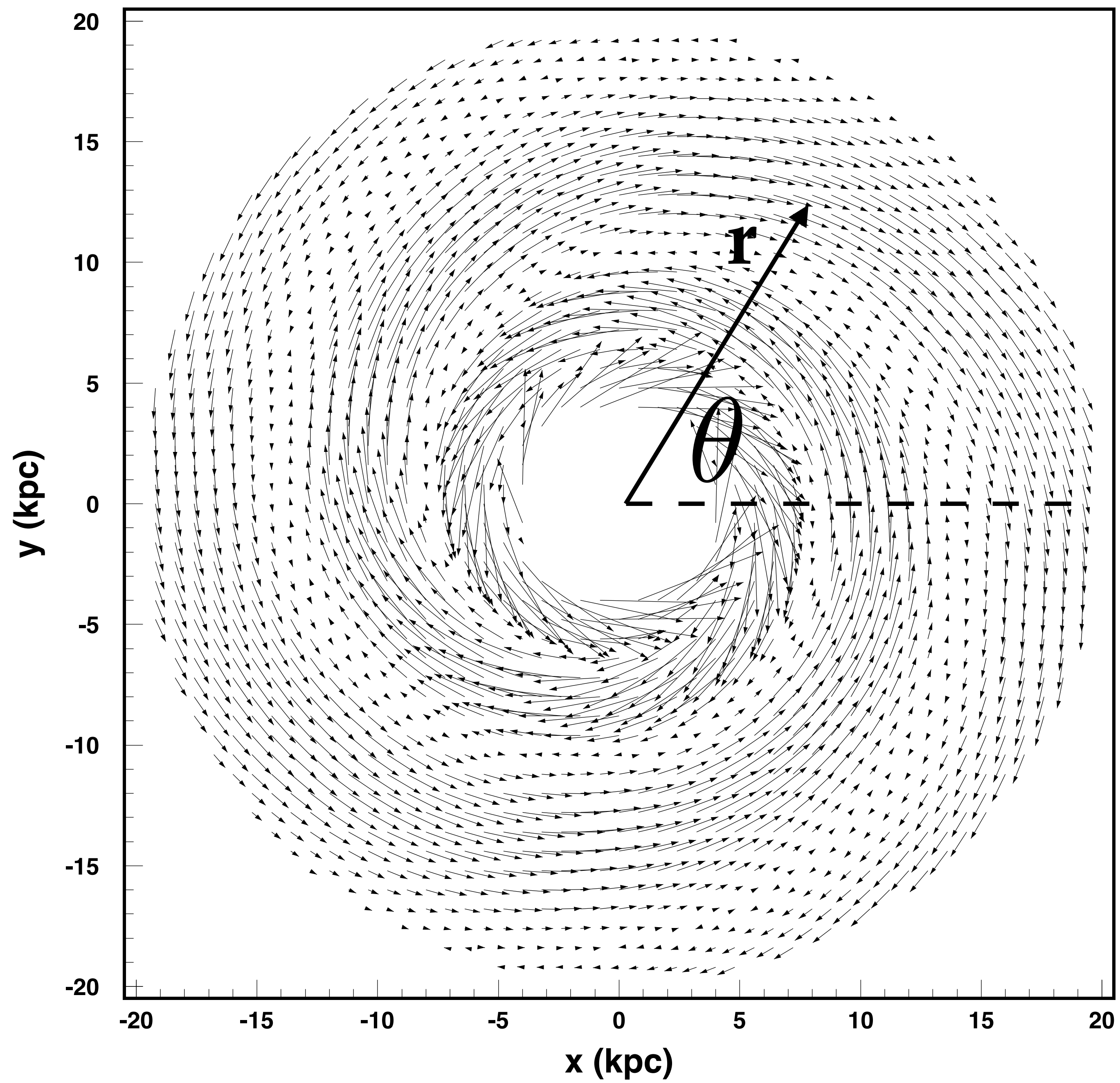
ASS-A

$$B(r,\theta) = \left[\frac{3R}{r}\tanh^3\left(\frac{r}{r_1}\right)\right]\cos^2\left(\theta - \frac{\pi}{2}\ln\frac{r}{r_0}\right)$$

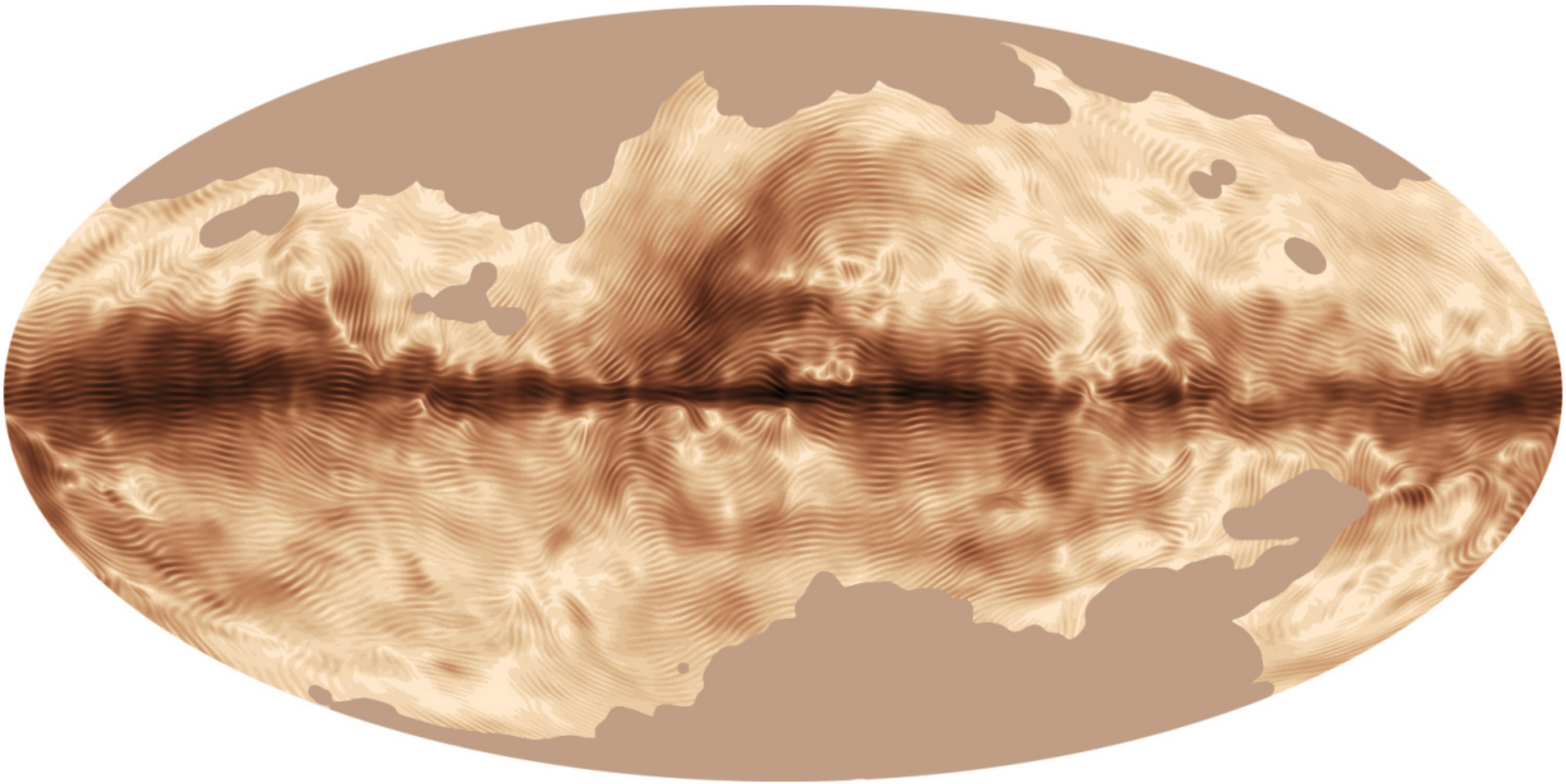
$$B(r,\theta,z) = B(r,\theta)\left[\frac{1}{2\cosh(z/z1)} + \frac{1}{2\cosh(z/z2)}\right]$$

z1=0.3 kpc **r0=10.55 kpc**

z2=2.0 kpc **r1=2 kpc**

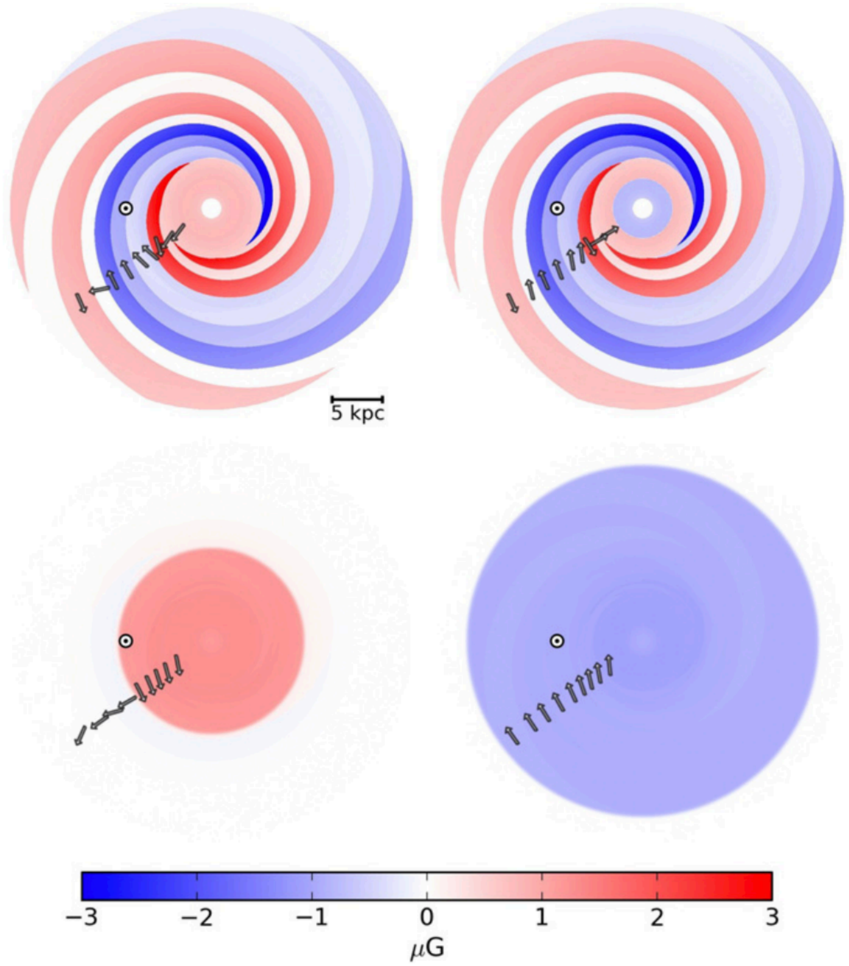


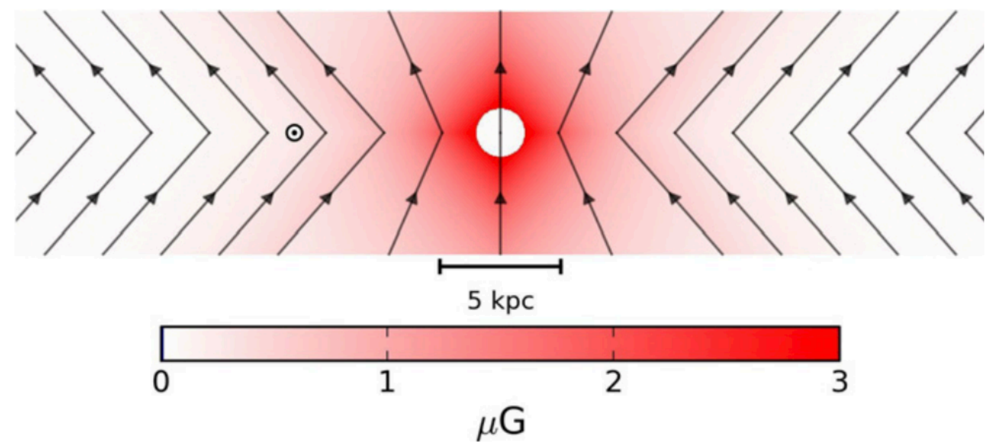
Galactic synchrotron and dust emission



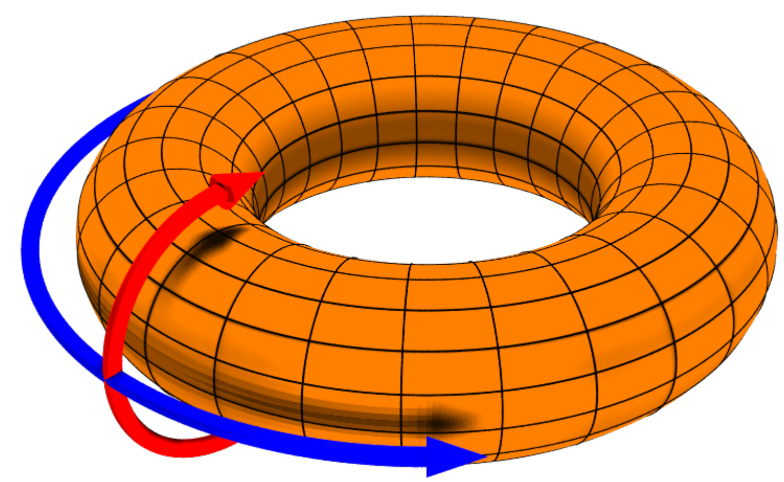
JF12 model

RJ & GF, Ap.J. 757, 14 (2012)



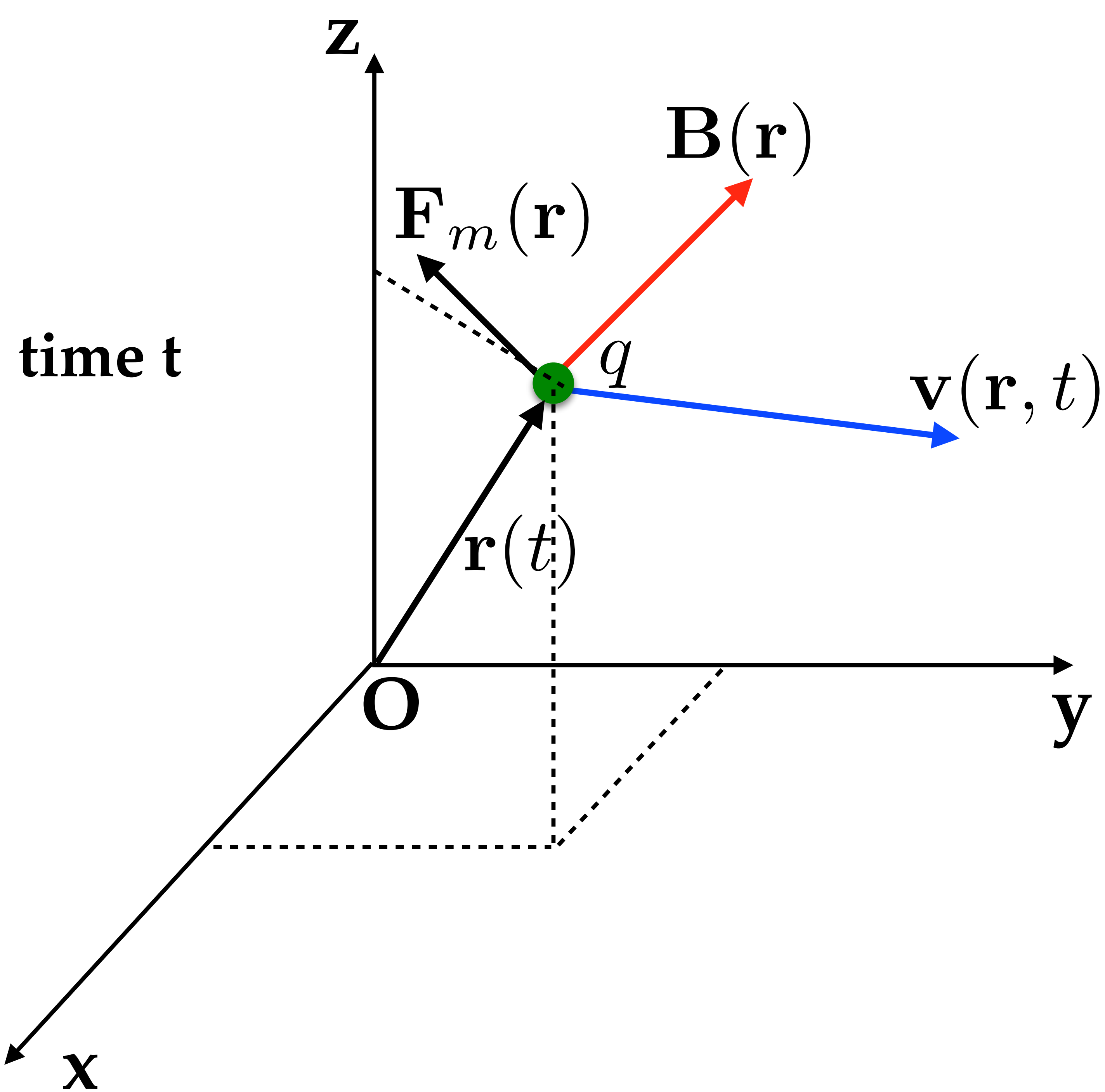


$$\mathrm{DM} = \int_{los} n_e d\ell$$



- **3 components: spiral disk + toroidal at halo + poloidal**
- **Rotation measures** → $\propto \int_{los} d\ell\, n_e(\mathbf{r}) B_{||}(\mathbf{r})$
- **Synchrotron emission (WMAP)** → $\propto \int_{los} d\ell\, n_{cre}(\mathbf{r}) B_{\perp}(\mathbf{r})$

Charged test particles in a magnetic field

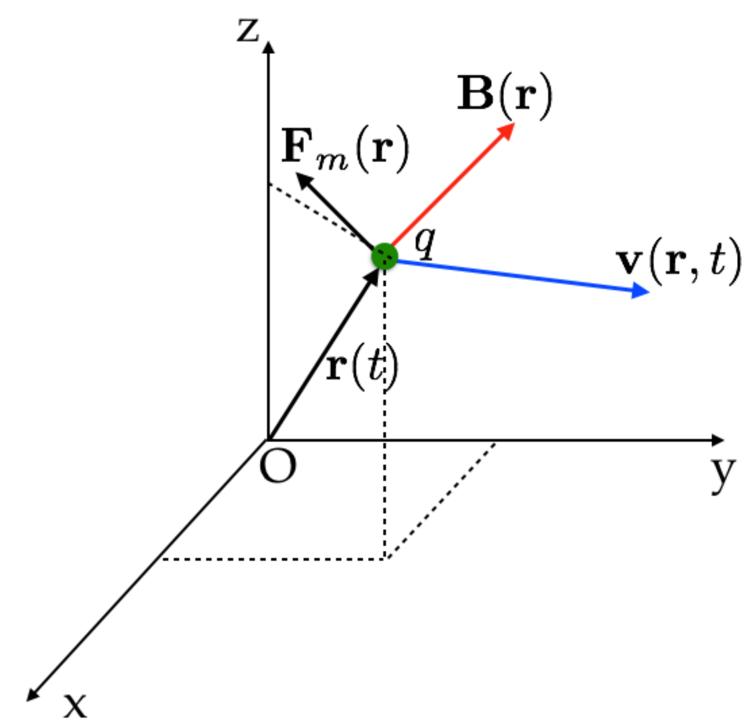


Equations of motion

From the Lorentz force and Newton's 2nd law applied to the relativistic case:

$$\mathbf{F}_m = q\mathbf{v} \times \mathbf{B} = \frac{d\mathbf{p}}{dt} = \frac{d}{dt}(\gamma m_0 \mathbf{v}) = \gamma m_0 \mathbf{a}_{cp} = \gamma m_0 \frac{d^2\mathbf{r}}{dt^2}$$

which represents a system of 3 coupled differential equations:



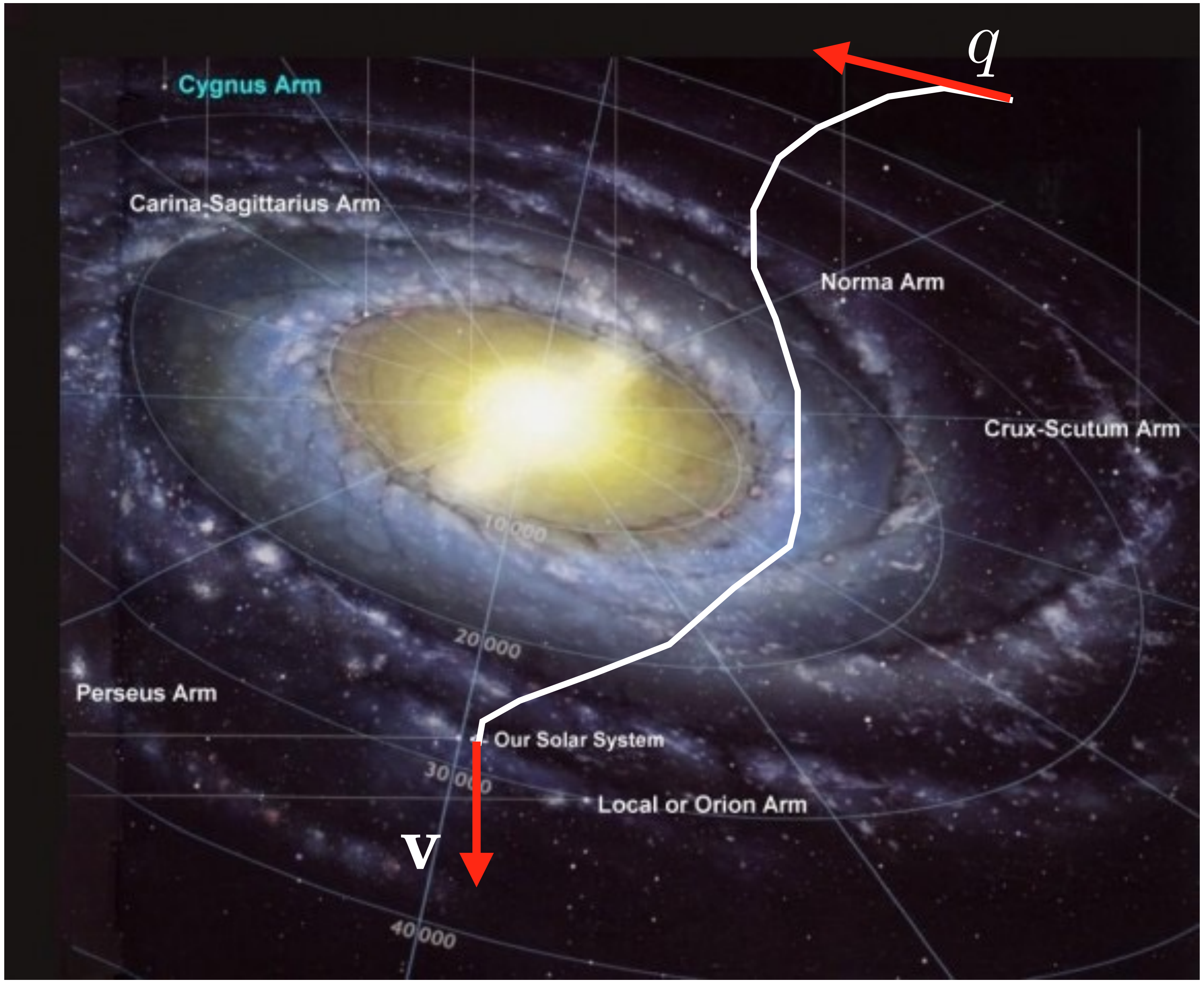
$$\begin{cases} F_x &= q(\dot{y}B_z - \dot{z}B_y) = \gamma m_0 \ddot{x} \\ F_y &= q(\dot{z}B_x - \dot{x}B_z) = \gamma m_0 \ddot{y} \\ F_z &= q(\dot{x}B_y - \dot{y}B_x) = \gamma m_0 \ddot{z} \end{cases}$$

They can be solved numerically (for example, with Runge-Kutta), as long as initial conditions are provided:

$$\begin{aligned} x(t=0) &= x_0 & v_x(t=0) &= v_{x_0} \\ y(t=0) &= y_0 & v_y(t=0) &= v_{y_0} \\ z(t=0) &= z_0 & v_z(t=0) &= v_{z_0} \end{aligned}$$

Backtracking

- Forward tracking of particles from outside the galaxy all the way to Earth encounters a fundamental problem: Earth's volume compared to the galaxy's volume is negligible!



Backtracking

The previous equations are invariant under the combined change:

$$q \longrightarrow -q \qquad \textbf{(particle to antiparticle)}$$

$$t \longrightarrow -t \qquad \textbf{(time reversal)}$$

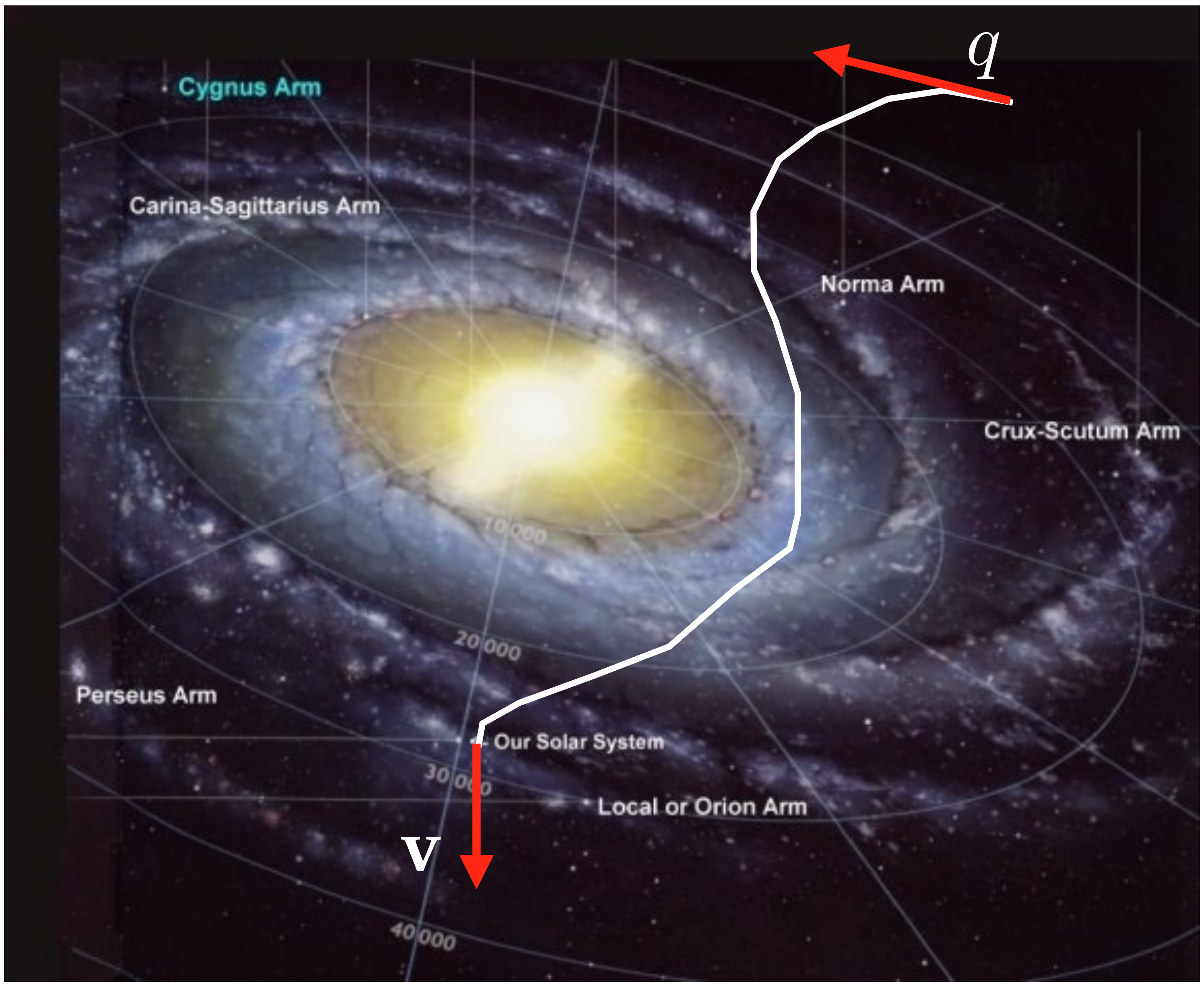
$$\begin{cases} F_x &= q\left(\frac{dy}{dt}B_z - \frac{dz}{dt}B_y\right) = \gamma m_0 \frac{d}{dt}\frac{d}{dt}x \\ F_y &= q\left(\frac{dz}{dt}B_x - \frac{dx}{dt}B_z\right) = \gamma m_0 \frac{d}{dt}\frac{d}{dt}y \\ F_z &= q\left(\frac{dx}{dt}B_y - \frac{dy}{dt}B_z\right) = \gamma m_0 \frac{d}{dt}\frac{d}{dt}z \end{cases}$$

$$|||$$

$$\begin{cases} F_x &= -q\left(\frac{dy}{d(-t)}B_z - \frac{dz}{d(-t)}B_y\right) = \gamma m_0 \frac{d}{d(-t)}\frac{d}{d(-t)}x \\ F_y &= -q\left(\frac{dz}{d(-t)}B_x - \frac{dx}{d(-t)}B_z\right) = \gamma m_0 \frac{d}{d(-t)}\frac{d}{d(-t)}y \\ F_z &= -q\left(\frac{dx}{d(-t)}B_y - \frac{dy}{d(-t)}B_z\right) = \gamma m_0 \frac{d}{d(-t)}\frac{d}{d(-t)}z \end{cases}$$

Backtracking

- Therefore, the track of charged particle arriving at Earth is identical to the that of an antiparticle leaving Earth with a velocity of the same magnitude but opposite to the particle's direction.



Backtracking

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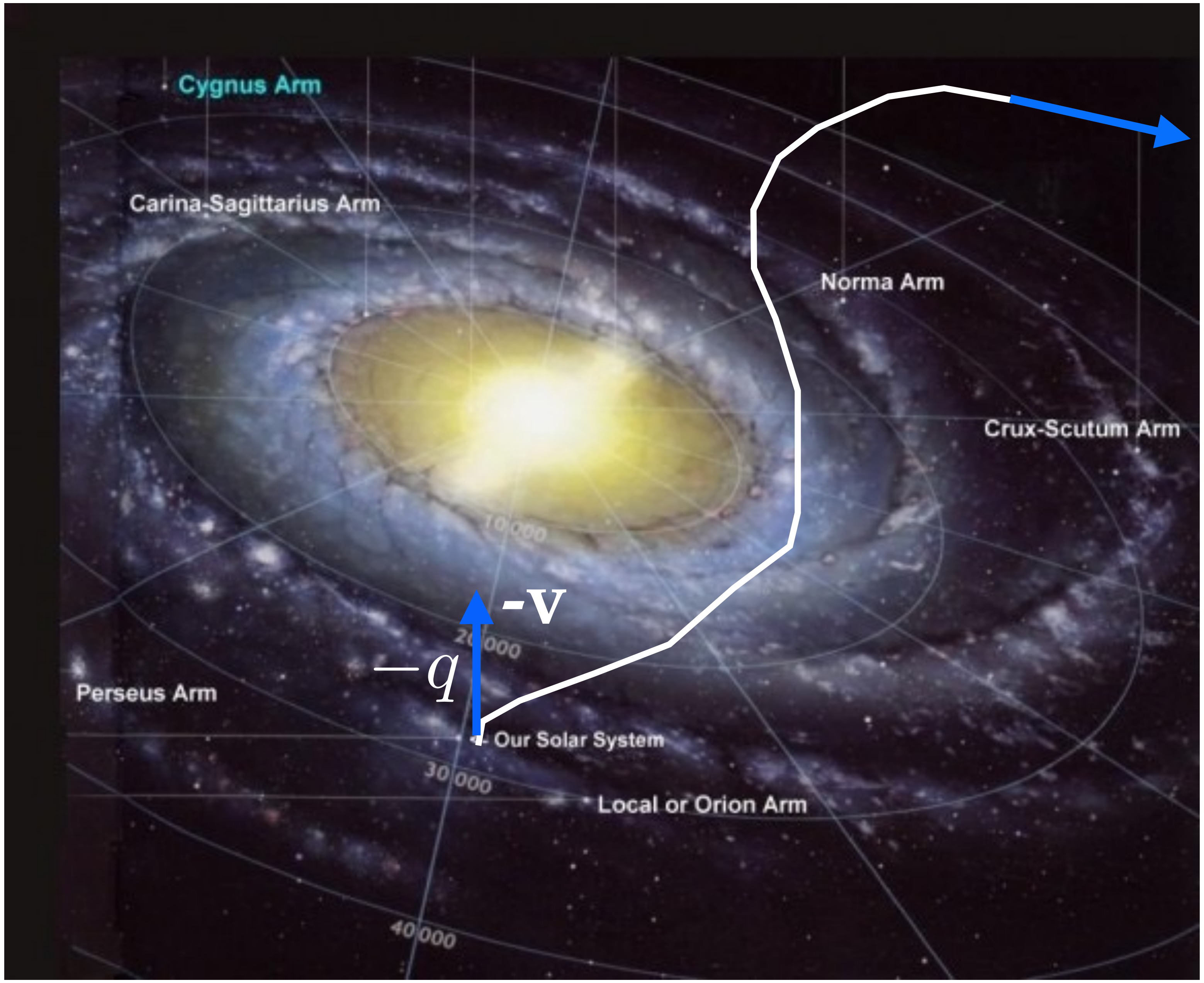
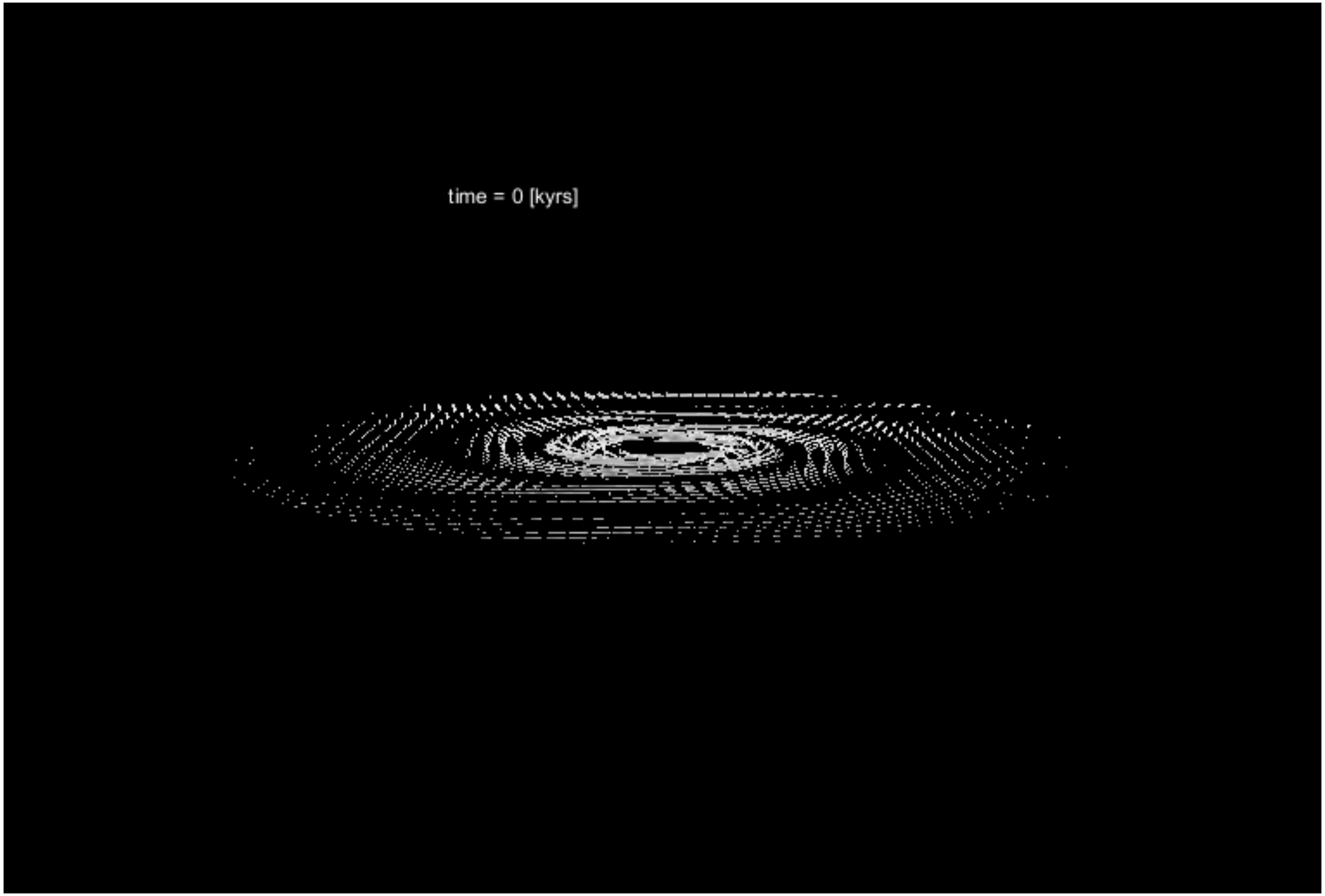
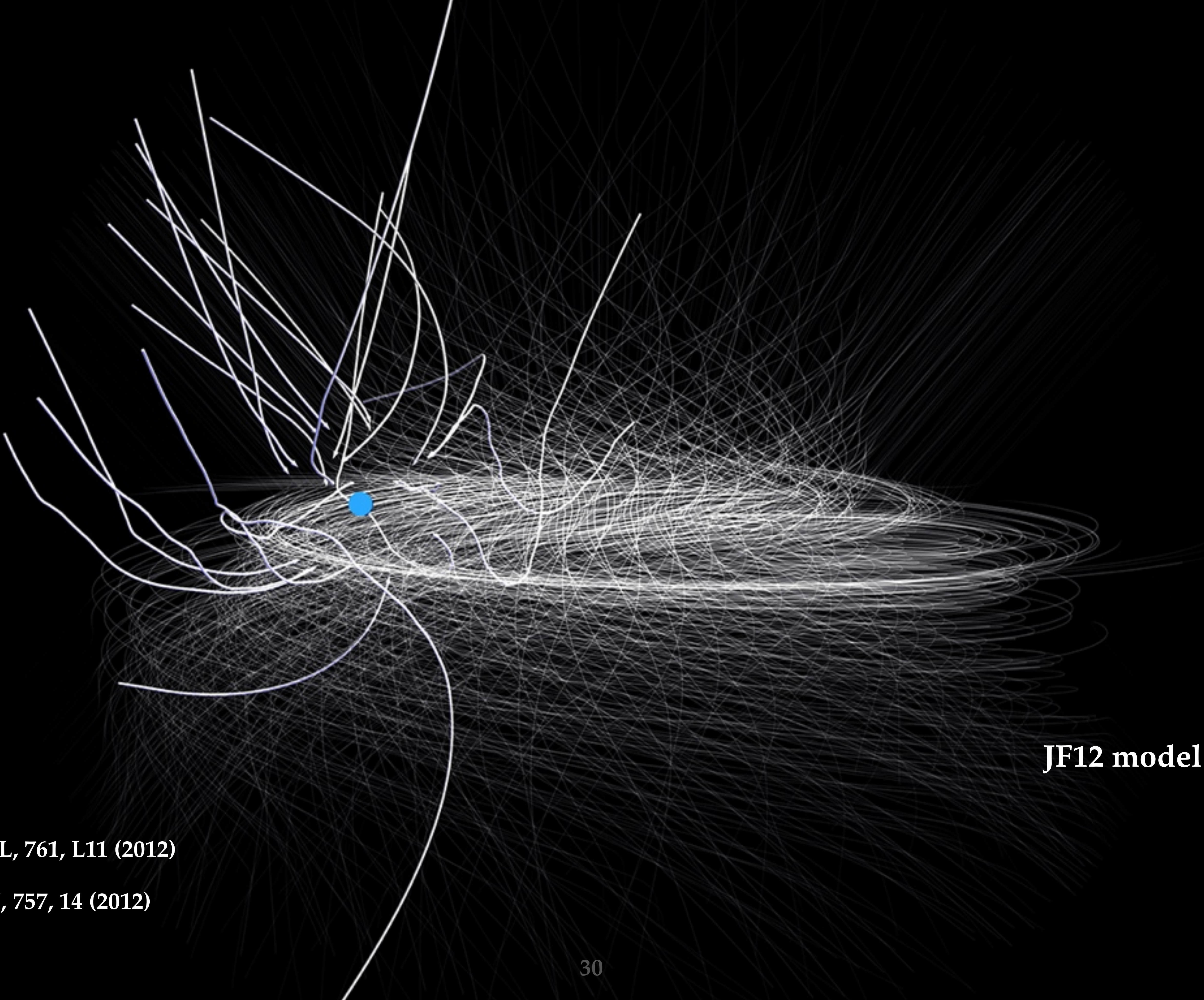


Proton backtracking @ 10^{17} eV



- No dipole term in the magnetic field (pure BSS model)
- 10^{17} eV anti-proton injected from Earth



ApJL, 761, L11 (2012)

ApJ, 757, 14 (2012)

State of the art simulation code

crpropa.desy.de

CRPropa - Cosmic Ray Propagation Framework

CRPropa is a public astrophysical simulation framework for propagating extraterrestrial ultra-high energy particles

CRPROPA3

stable/ release 3.2.1

crpropa-testing_ubuntu22 passing Build Ubuntu 20 crpropa-testing_OSX passing crpropa-example-test passing

issues 21 open pull requests 4 open

DOI 10.1088/1475 arXiv 2208.00107 ascl 2208.016

CRPropa is a publicly available simulation framework to study the propagation of ultra-high-energy nuclei up to iron on their voyage through an (extra)galactic environment. It takes into account: pion production, photodisintegration and energy losses by pair production of all relevant isotopes in the ambient low-energy photon fields as well as nuclear decay. CRPropa can model the deflection in (inter)galactic magnetic fields, the propagation of secondary electromagnetic cascades and neutrinos for a multitude of scenarios for different source distributions and magnetic environments. It enables the user to predict the spectra of UHECR (and of their secondaries), their composition and arrival direction distribution. Additionally, the low-energy Galactic propagation can be simulated by solving the transport equation using stochastic differential equations. CRPropa features a very flexible simulation setup with python steering and shared-memory parallelization.

Interactive Online Demo

You can try out CRPropa online at vispa.physik.rwth-aachen.de. Use the guest login and go to the CRPropa example via "VISPA Cluster" --> "Open Examples".

Installation and Documentation

To install CRPropa, download and unzip either the

- latest release (recommended),
- or current development version.