Dark Matter

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Summer School
on Cosmology
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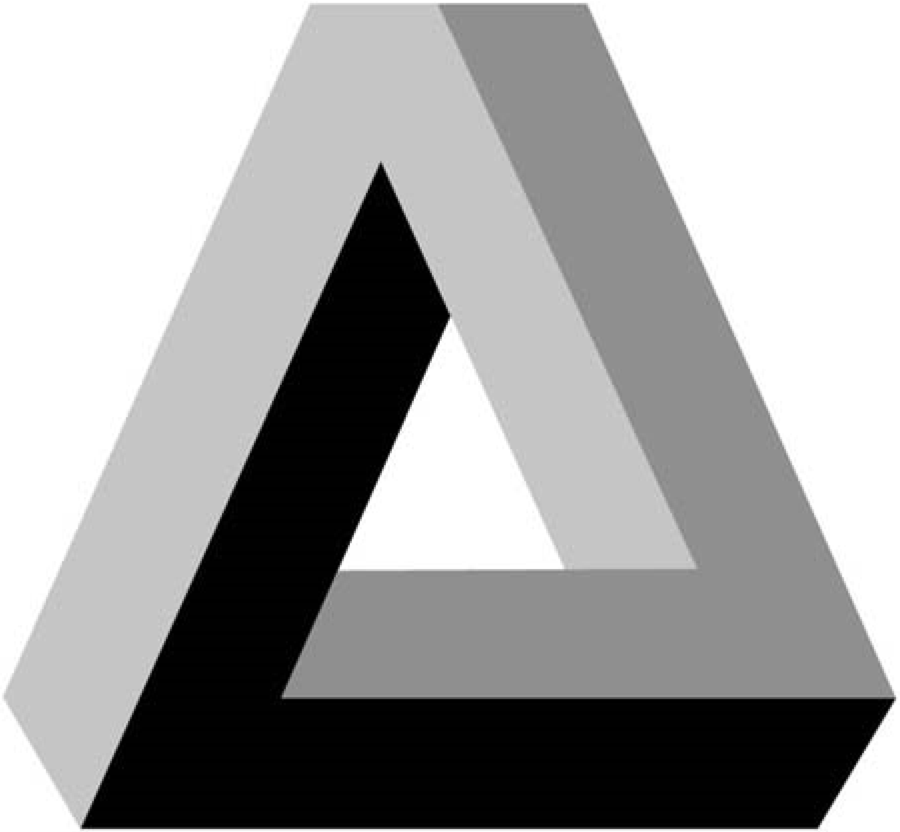
August 2014

Direct detection

DM nucleus → DM nucleus



Indirect detection

DM DM → γ X, e^+e^-... (annihilation)

DM → γ X, e^+X... (decay)

Collider searches

pp → DM X

Direct detection

DM nucleus → DM nucleus

Indirect detection

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pp → DM X

LUX

CMS

ATLAS

MAGIC

Xe
XENON
Dark Matter Project

fermi
Gamma-ray
Space Telescope

PaMeLa

H E S S

Alpha Magnetic Spectrometer
AMS-02
Europe • Asia
North America

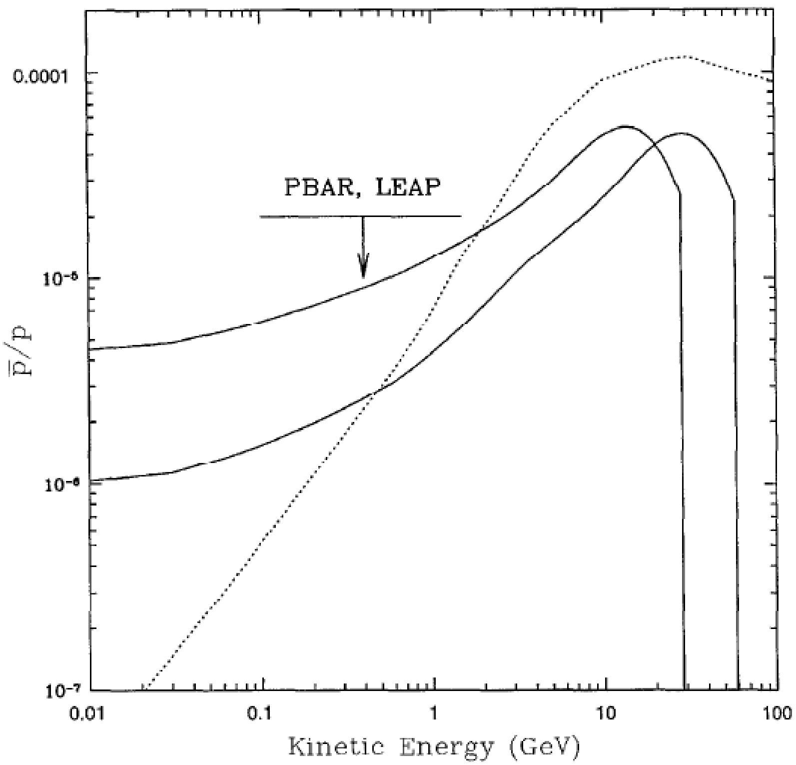
VERITAS

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

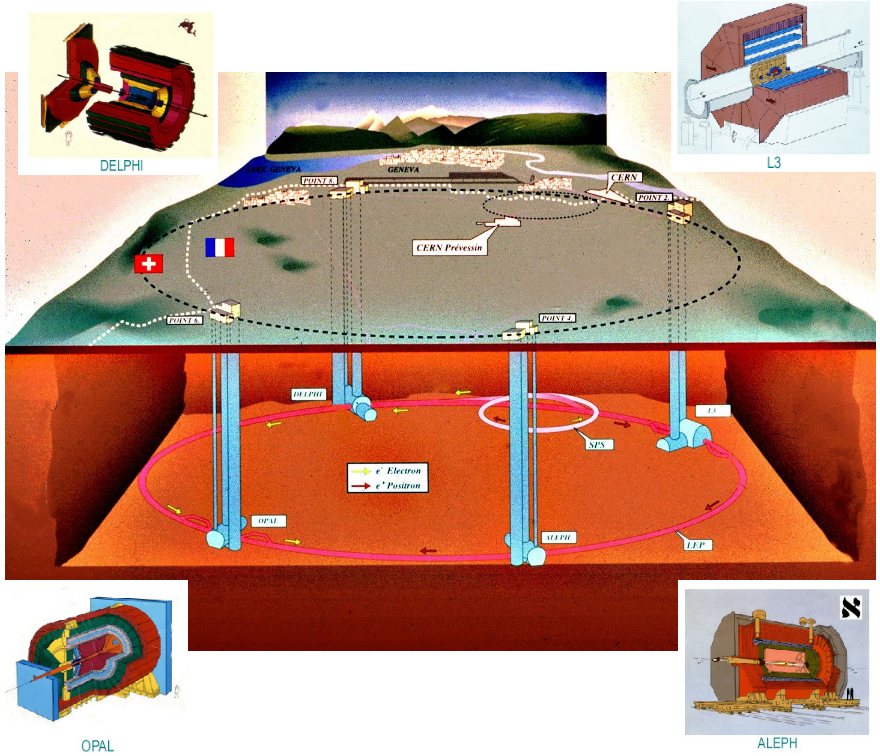
Fifteen years ago...

Cosmic antiprotons

G. Jungman et al. / Physics Reports 267 (1996) 195–373



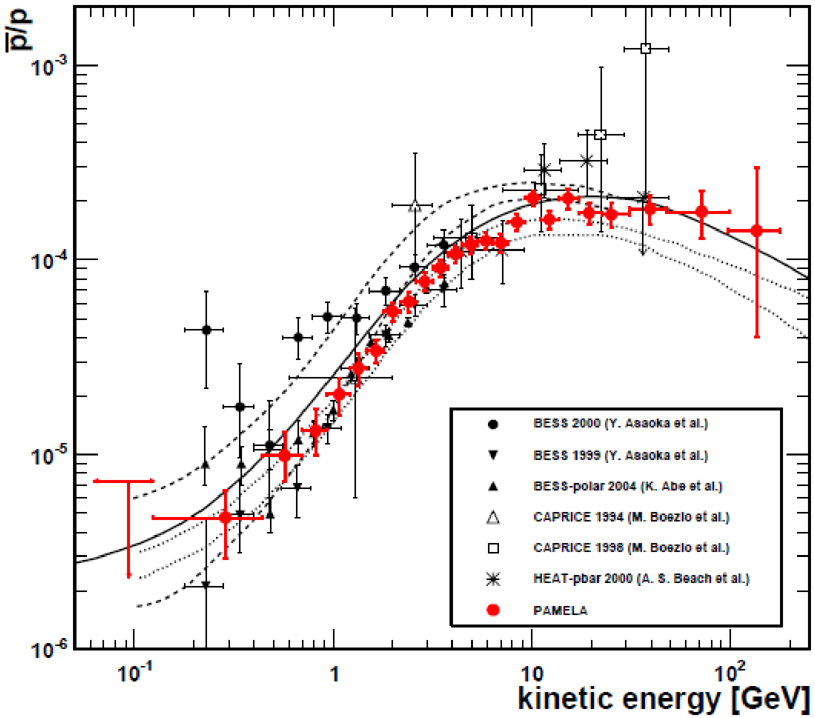
Collider experiments



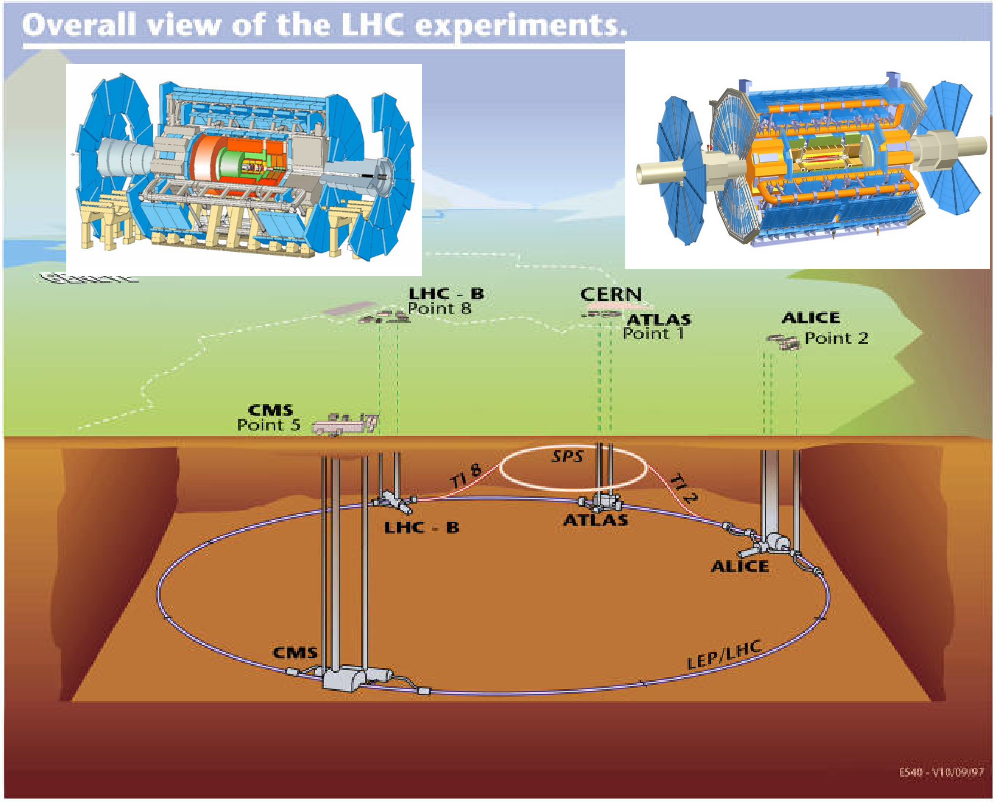
Year	Beam energy [GeV]	Maxi-mum ξ_y	Total lumi-nosity [pb^{-1}]	Average luminosity rate [pb^{-1}/day]
1994	45.6	0.045	64	0.31
1995	45.6 – 70.0	0.050	47	0.23
1996	80.5 – 86.0	0.040	25	0.17
1997	91.0 – 92.0	0.055	75	0.66
1998	94.5	0.075	200	1.16
1999	96.0 – 101.0	0.083	254	1.35
2000*	100.0 – 104.3	0.055	71	0.96

Today

Cosmic antiprotons



Collider experiments

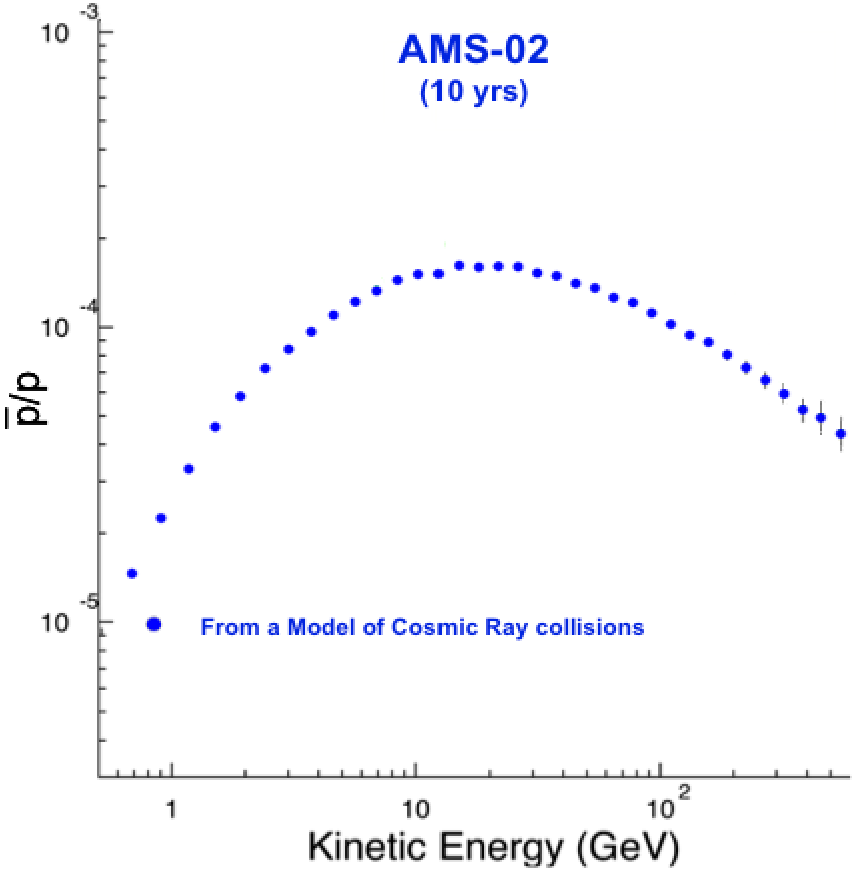


Beam energy: 4000 GeV

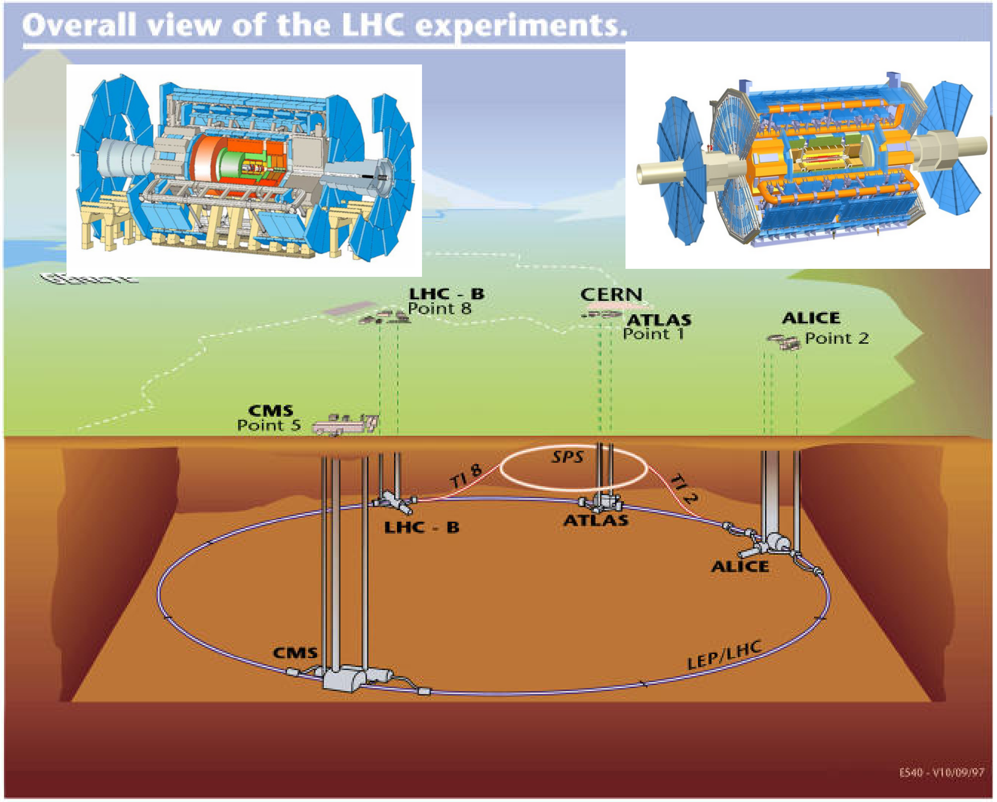
Integrated luminosity: 23.26 fb^{-1}

End of this decade

Cosmic antiprotons



Collider experiments

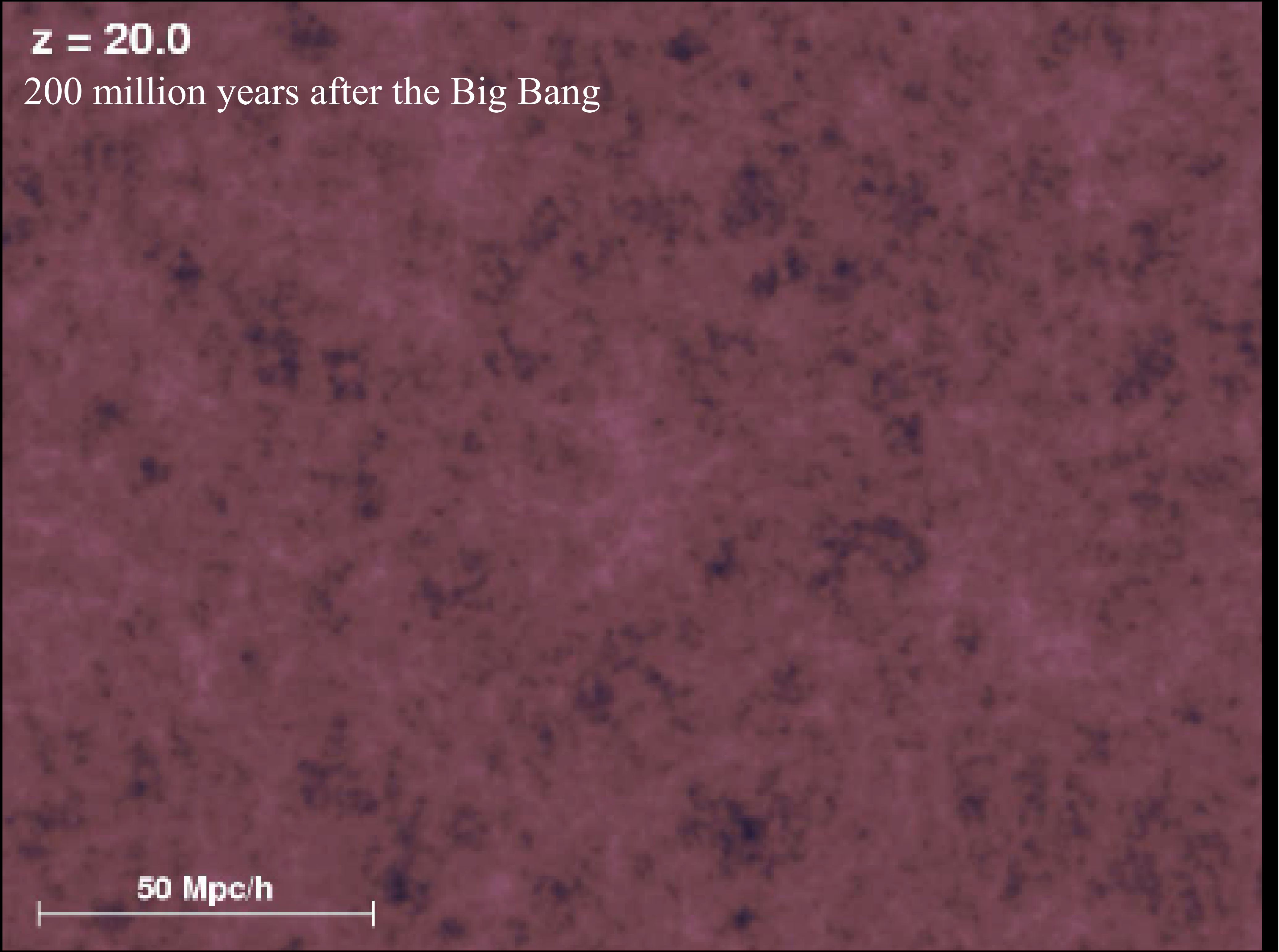


Beam energy: 6500 GeV

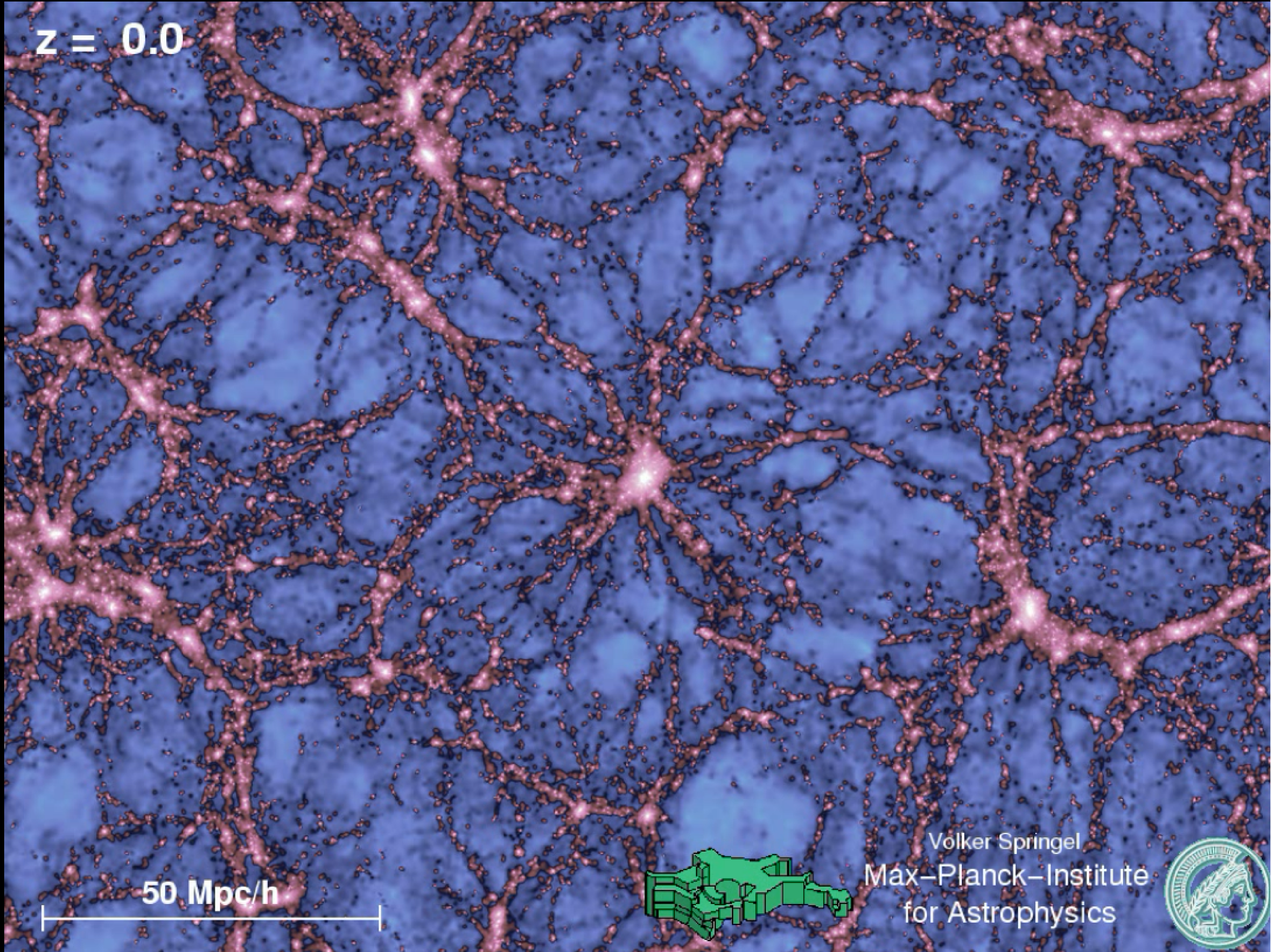
Integrated luminosity: 500 fb^{-1}

Dark matter distribution

The universe 1μs after the Big Bang



200 million years after the Big Bang

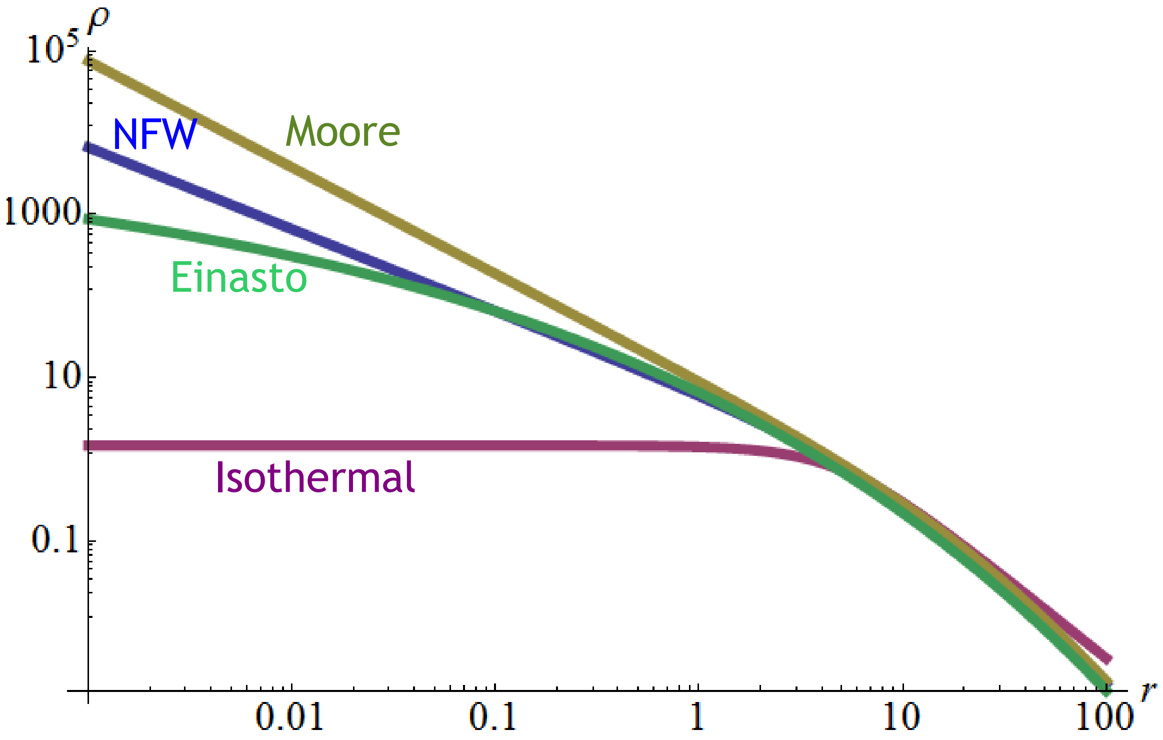


z = 0.0
50 Mpc/h
Volker Springel
Max–Planck–Institute
for Astrophysics

Distance Sun to Milky Way Center ~ 8.5 kpc

Density distribution of dark matter particles:

- Assume spherical symmetry (in a first approximation).
- Radial distribution:



NFW, Isothermal, Moore

$$\rho(r) = \frac{\rho_0}{(r/r_c)^\gamma [1 + (r/r_c)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Halo model	α	β	γ	r_c (kpc)
Navarro, Frenk, White	1	3	1	20
Isothermal	2	2	0	3.5
Moore	1.5	3	1.5	28

Einasto

$$\rho(r) = \rho_0 \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$$

$\alpha = 0.17, \ r_s = 20$ kpc

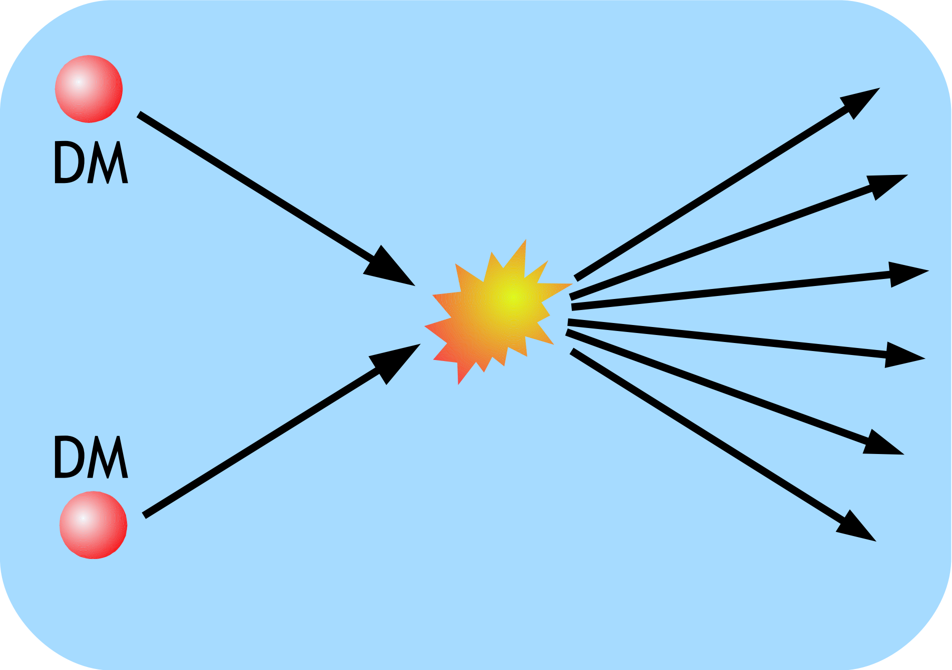
- Normalized such that the local DM density is
  $\rho(r=8.5 \text{ kpc}) = 0.38 \text{ GeV/cm}^3$

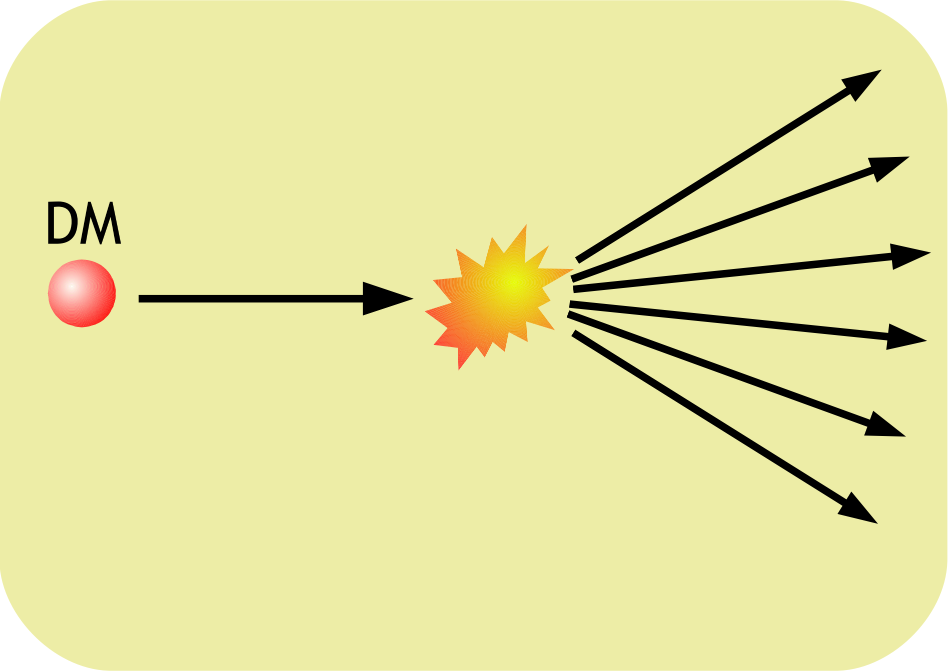
Indirect
Dark Matter
Searches

Indirect dark matter searches

General idea:

1) Dark matter particles annihilate or decay producing a flux of stable particles: photons, electrons, protons, positrons, antiprotons or (anti-)neutrinos.





Indirect dark matter searches

General idea:

1) Dark matter particles annihilate or decay producing a flux of stable particles: photons, electrons, protons, positrons, antiprotons or (anti-)neutrinos.

2) These particles propagate through the galaxy and through the Solar System. Some of them will reach the Earth.

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3) The products of the dark matter annihilations or decays are detected together with other particles produced in astrophysical processes (for example, cosmic ray collisions with nuclei in the interstellar medium). The existence of dark matter can then be inferred if there is a significant excess in the fluxes compared to the expected astrophysical backgrounds.

Indirect dark matter searches

Production
Propagation
Detection

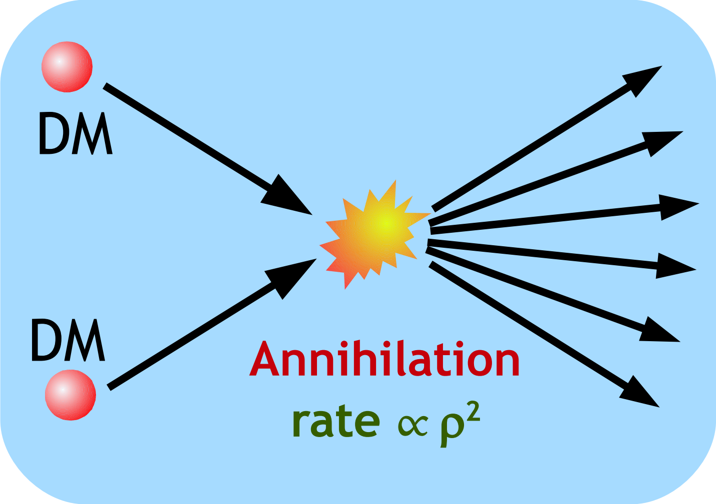
of

Antimatter
Gamma-rays
Neutrinos

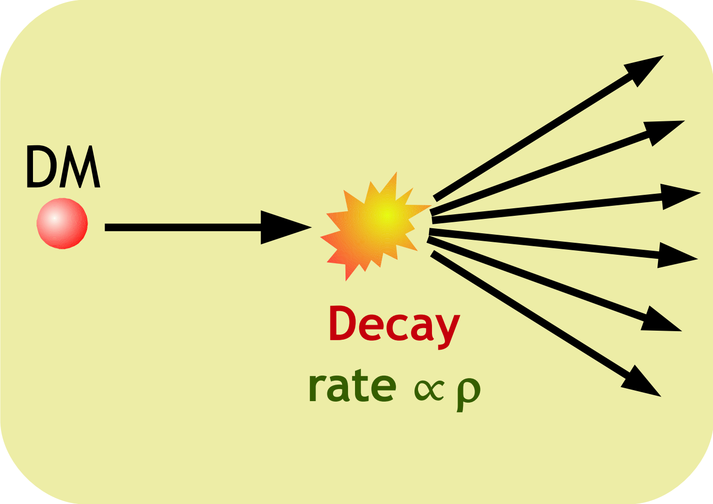
Antimatter

Production

The production is described by the source function: number of particles produced at a given position per unit volume, unit time and unit energy.

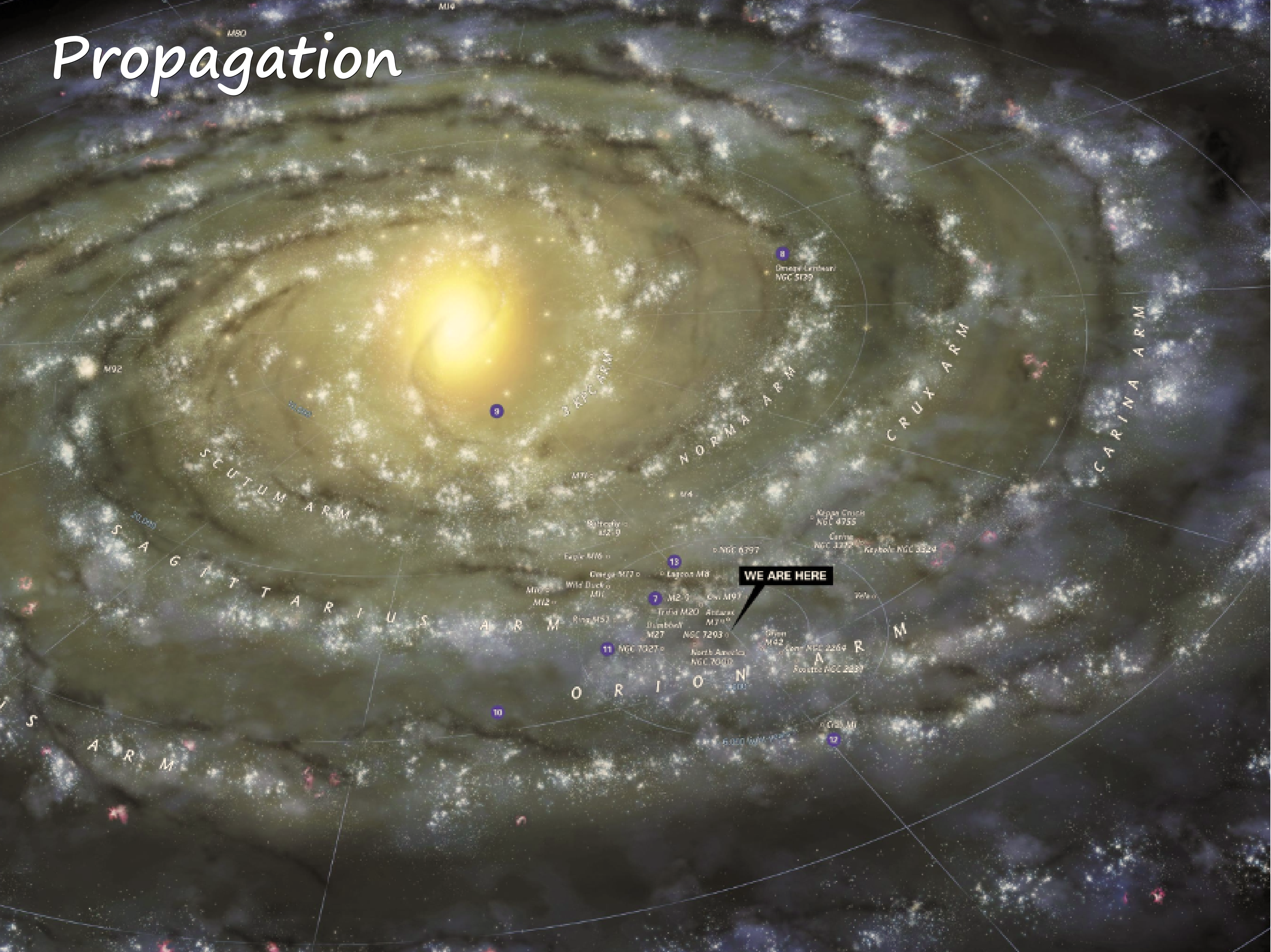


$$Q(E,\vec{r}) = \frac{1}{2}\frac{\rho^2(\vec{r})}{m_{\mathrm{DM}}^2}\langle\sigma v\rangle\frac{dN}{dE}$$

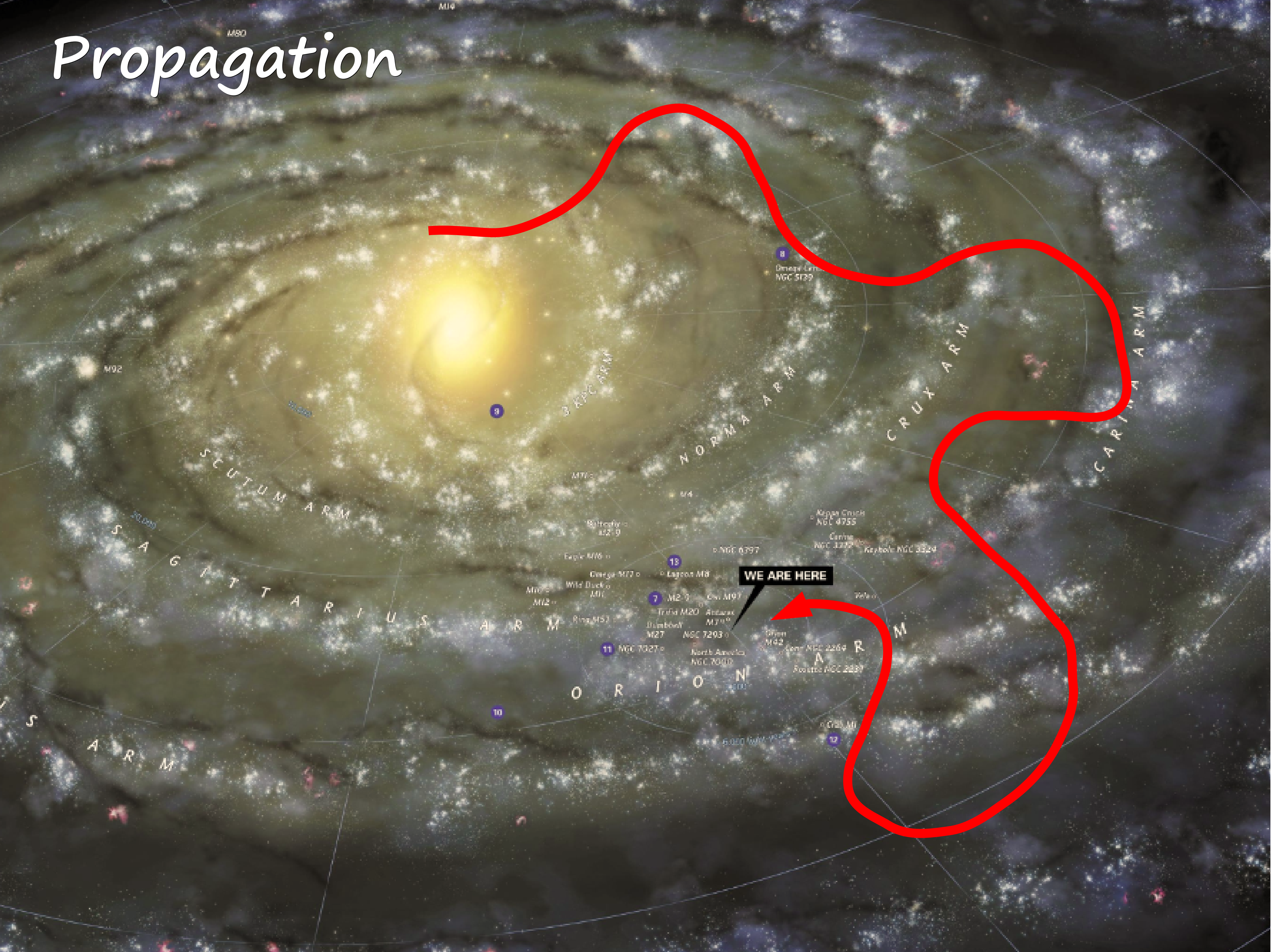


$$Q(E,\vec{r}) = \frac{\rho(\vec{r})}{m_{\mathrm{DM}}}\frac{1}{\tau_{\mathrm{DM}}}\frac{dN}{dE}$$

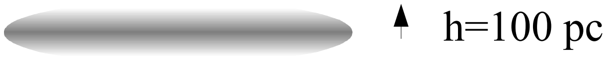
Propagation



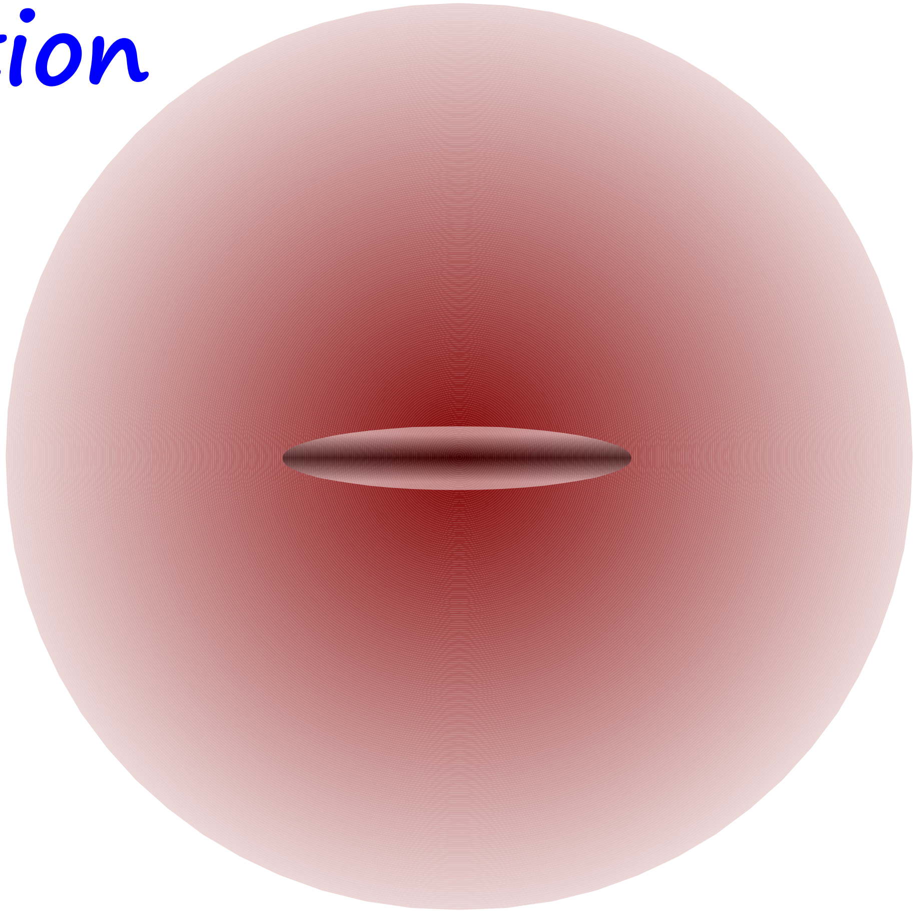
Propagation



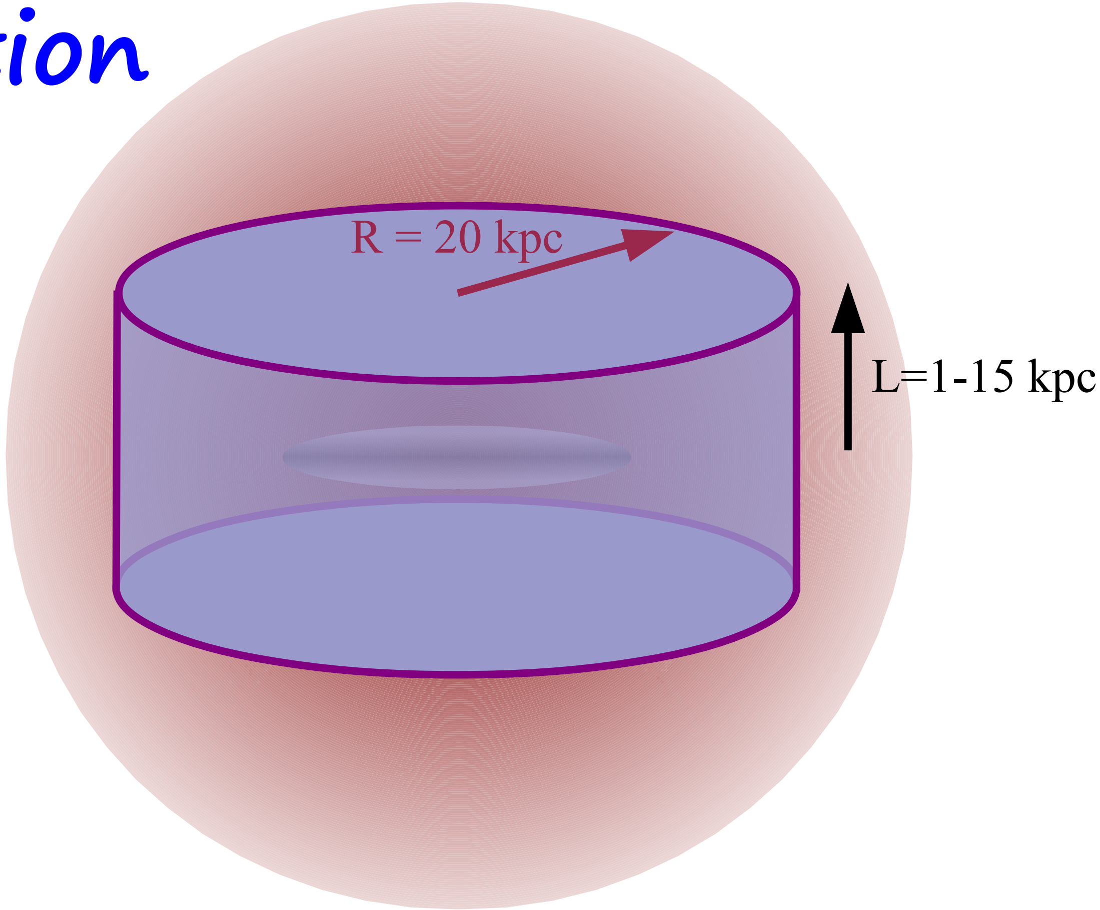
Propagation



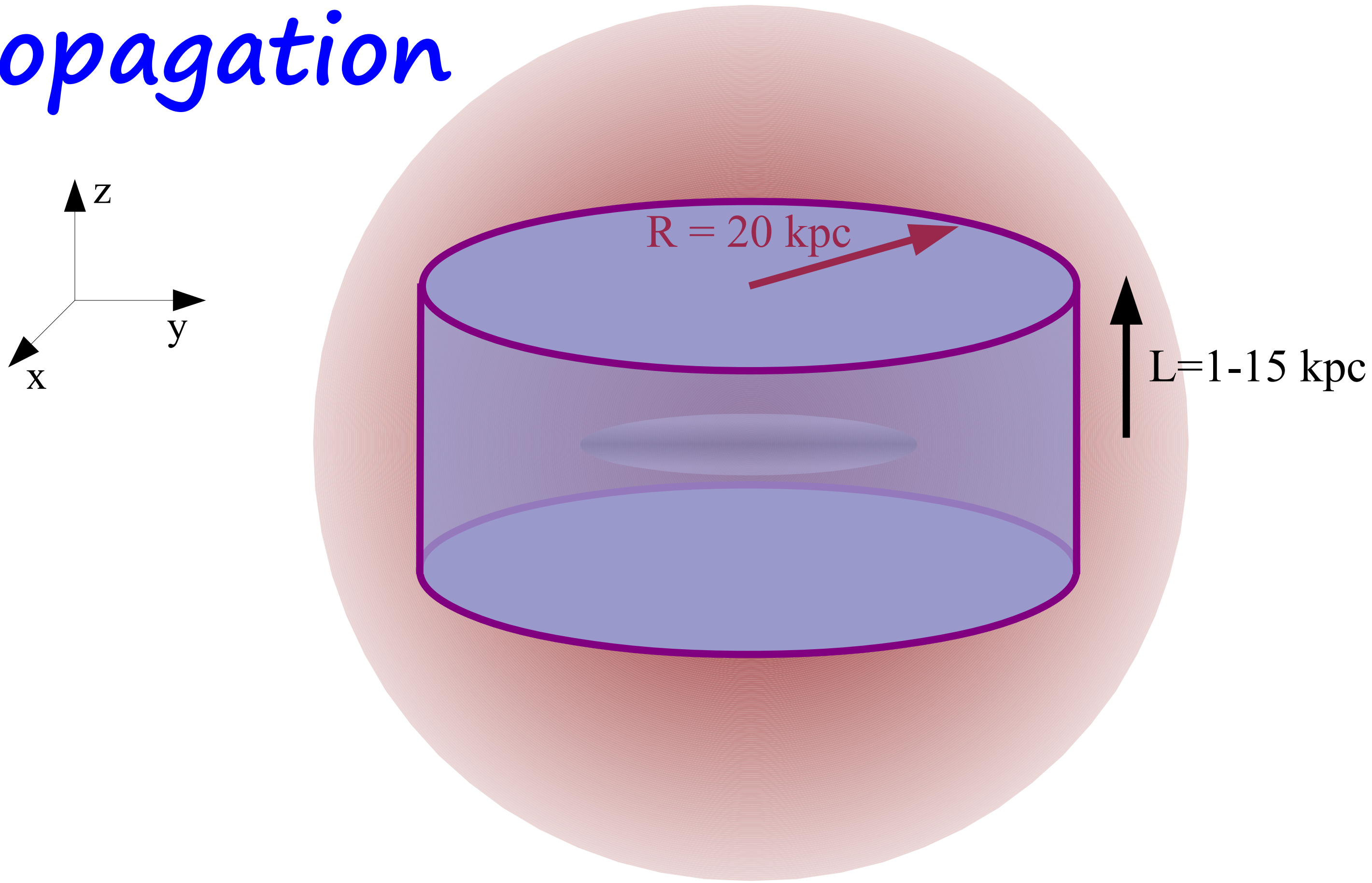
Propagation



Propagation



Propagation



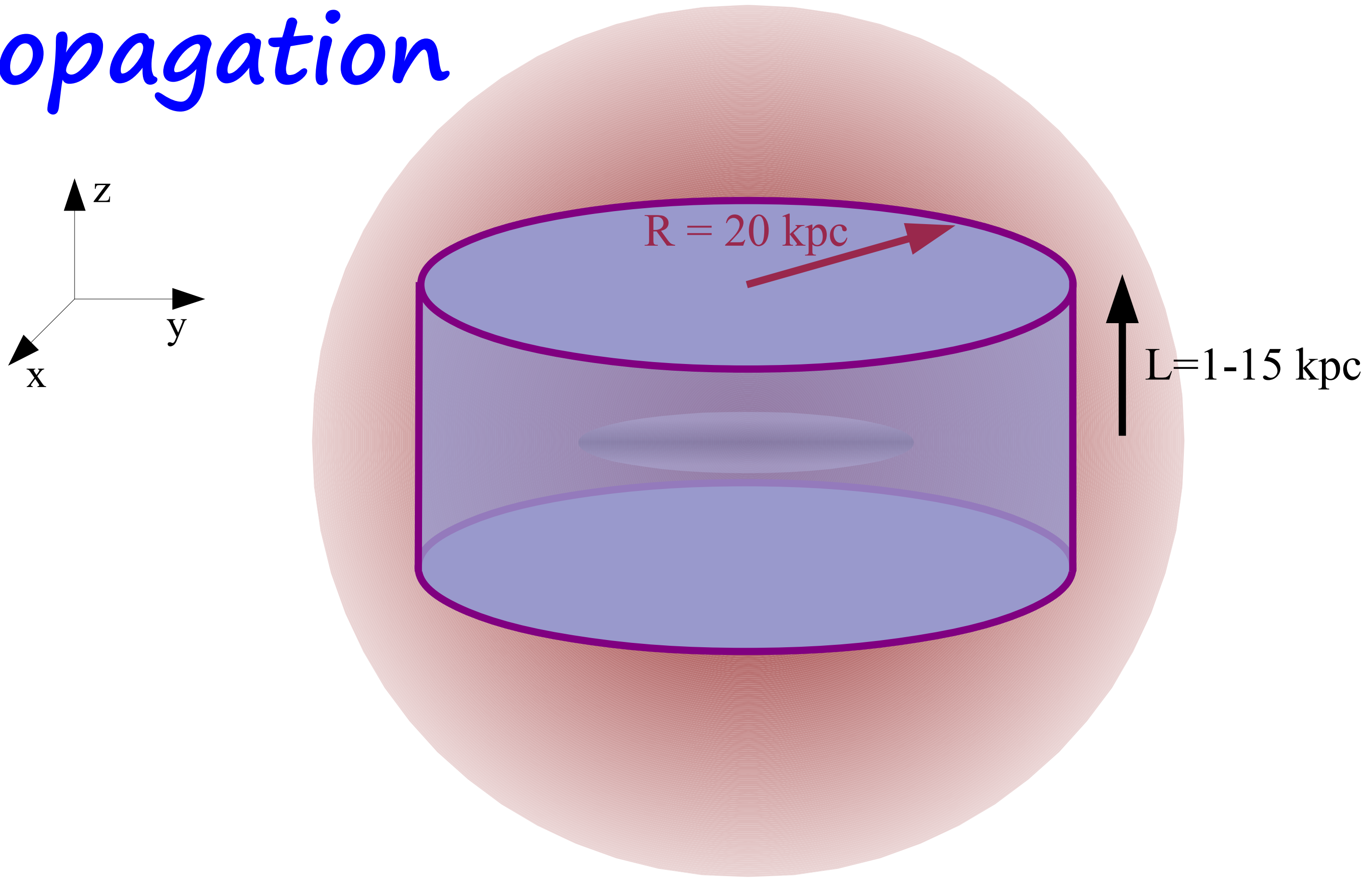
$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r}) f] - \nabla \cdot [\vec{V}_c(\vec{r}) f] - 2h\delta(z)\Gamma_{\mathrm{ann}} f + Q(T,\vec{r}) \ .$$

f: number density of antiparticles per unit kinetic energy

interstellar antimatter flux:

$$\Phi^{\mathrm{IS}}(T) = \frac{dN}{dt\, dS\, dT\, d\Omega} = \frac{v}{4\pi} f(T)$$

Propagation



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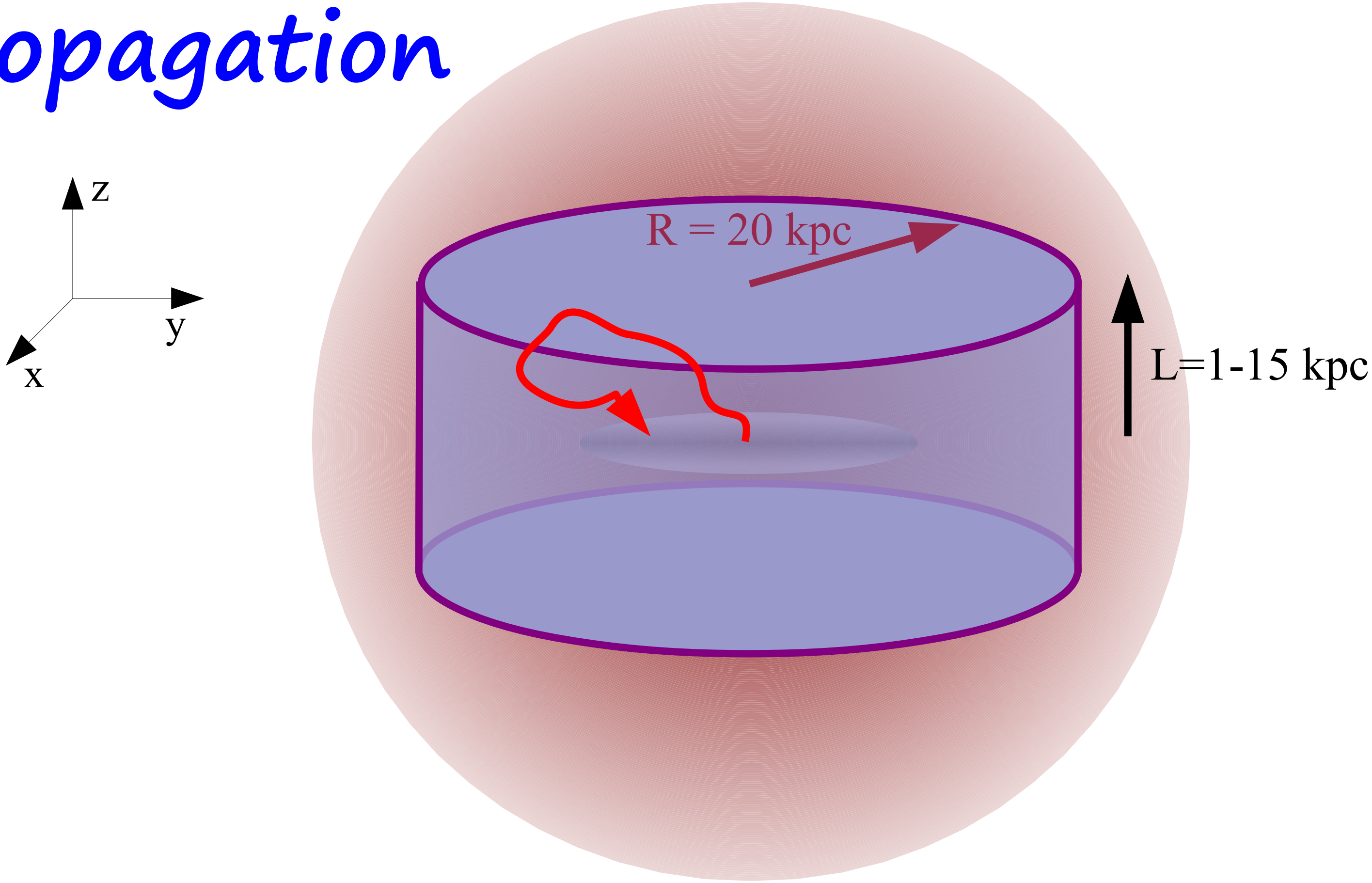
Source term

$$Q(T,\vec{r})=\begin{cases}\dfrac{1}{2}\dfrac{\rho^2(\vec{r})}{m_{\rm DM}^2}\langle\sigma v\rangle\dfrac{dN}{dT} & \text{dark matter annihilation}\\[2ex] \dfrac{\rho(\vec{r})}{m_{\rm DM}}\dfrac{1}{\tau_{\rm DM}}\dfrac{dN}{dE} & \text{dark matter decay}\end{cases}$$

Propagation



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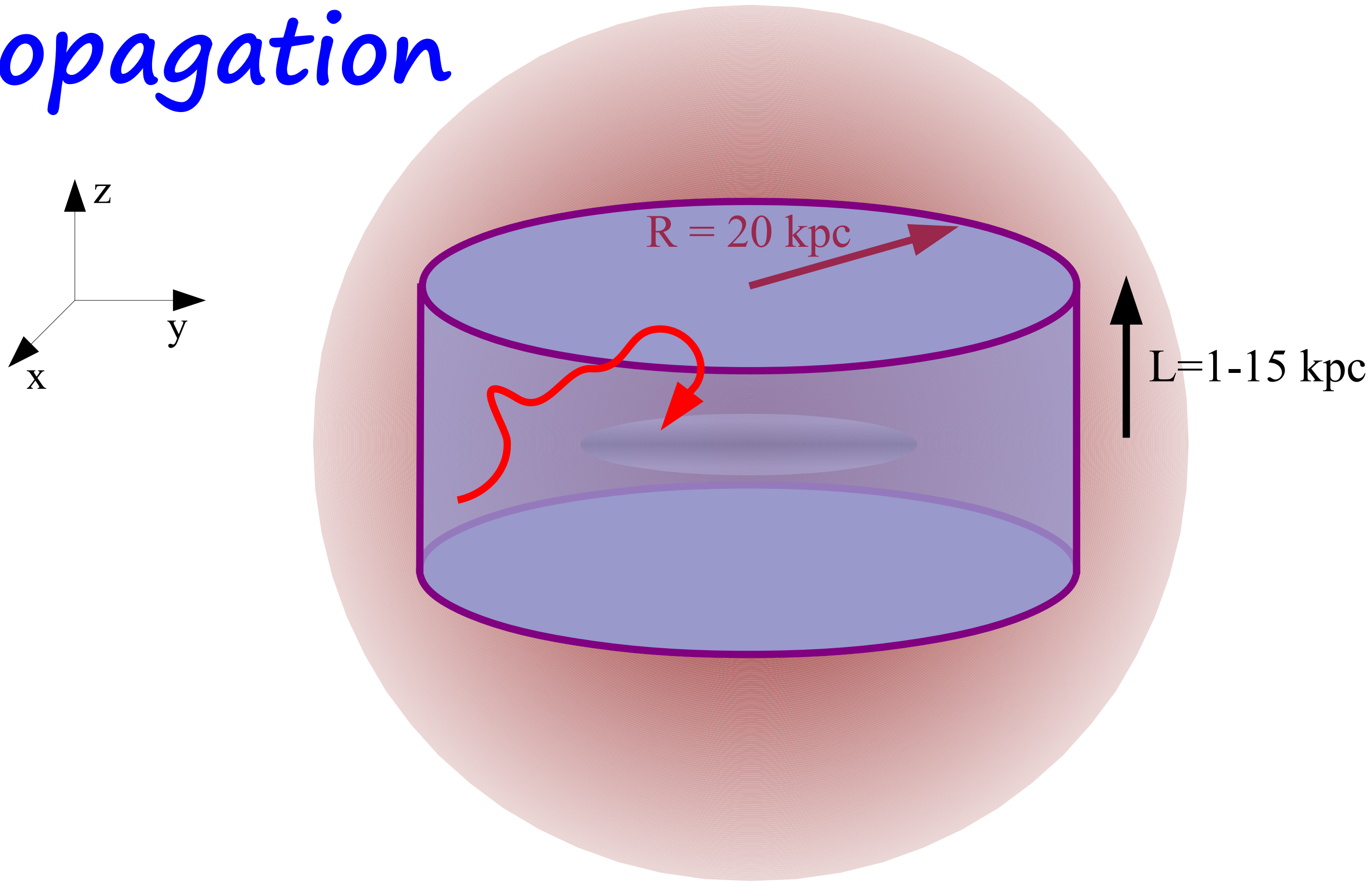
Propagation



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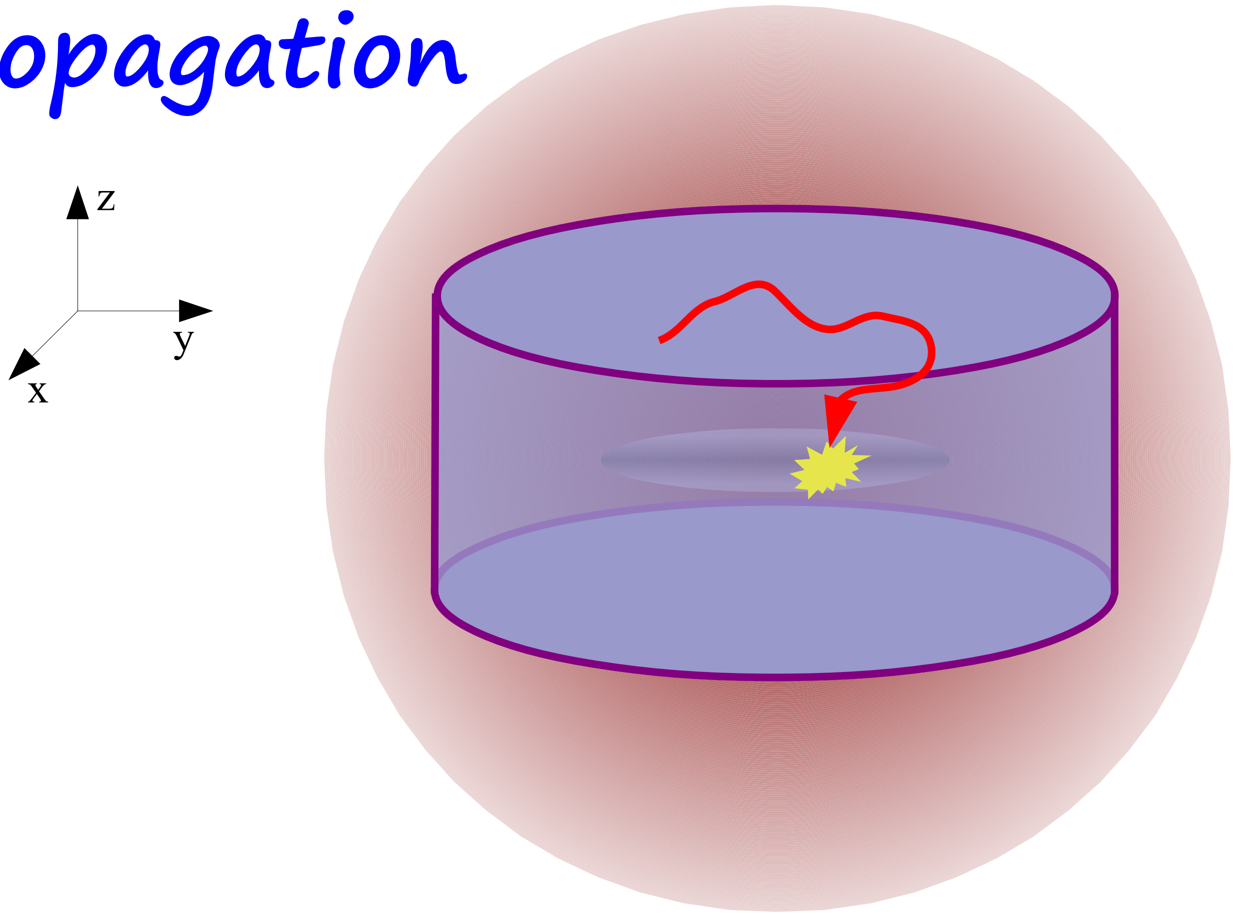
Propagation



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Annihilation term

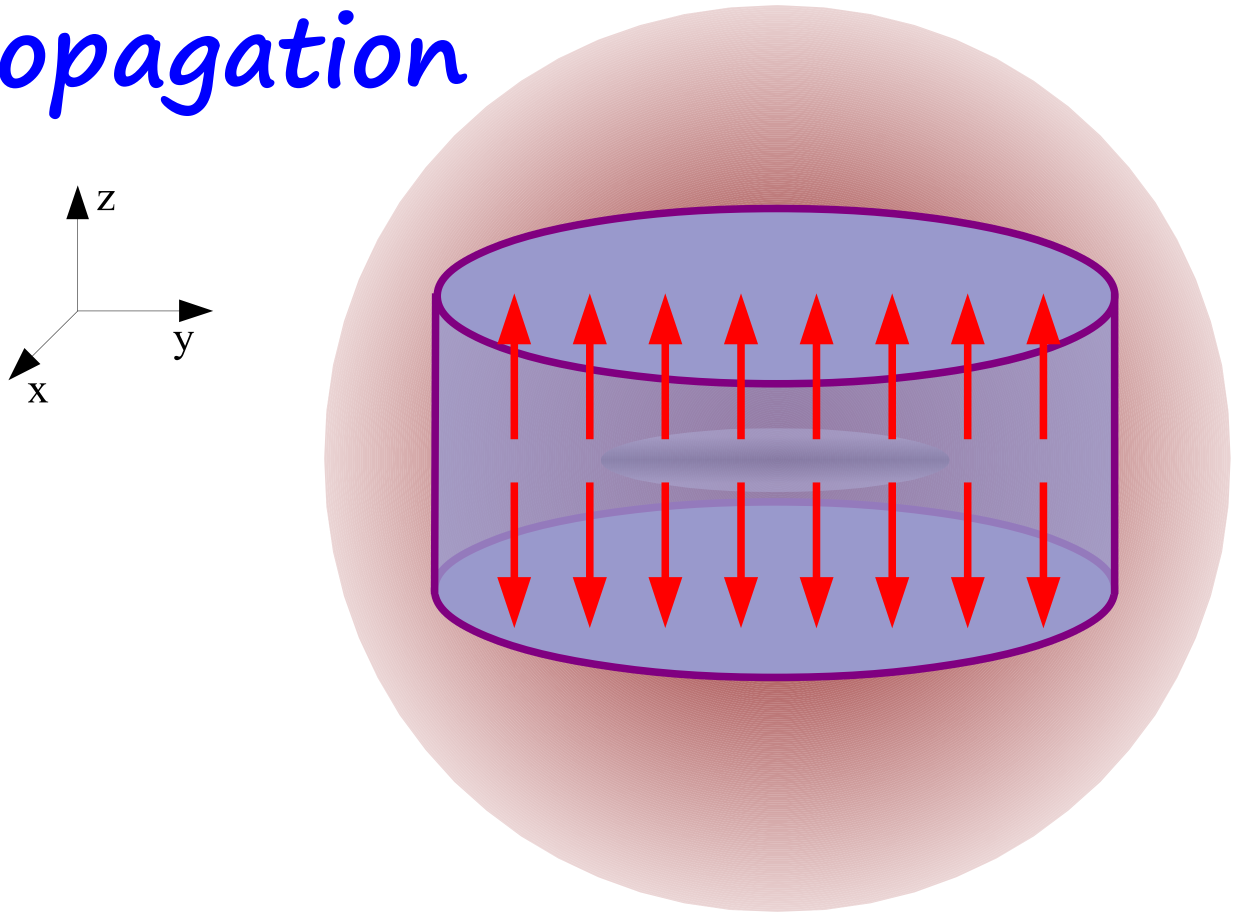
Negligible for positrons.
For antiprotons,

$$\Gamma_{\rm ann} = (n_{\rm H} + 4^{2/3} n_{\rm He})\sigma^{\rm ann}_{\bar{p}p} v_{\bar{p}} \ .$$

$$\sigma^{\rm ann}_{\bar{p}p}(T) = \begin{cases} 661\ (1 + 0.0115\ T^{-0.774} - 0.948\ T^{0.0151})\ \text{mbarn}\ , & T < 15.5\ \text{GeV}\ , \\ 36\ T^{-0.5}\ \text{mbarn}\ , & T \geq 15.5\ \text{GeV}\ , \end{cases}$$

Tan, Ng

Propagation



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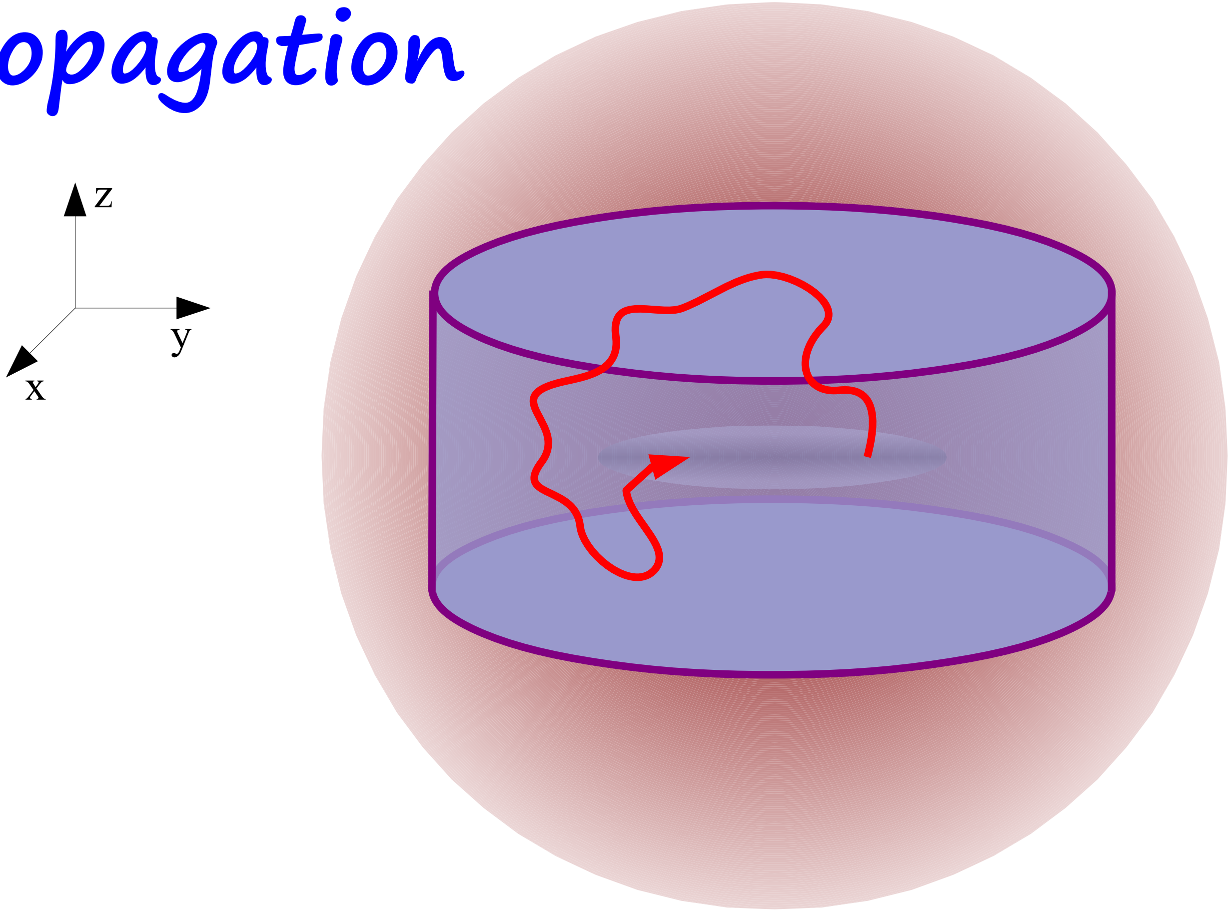
Convection term

- Due to the Milky Way galactic wind.
- It drifts particles away from the Galactic disk.
- Difficult to model. Assume:

$$\vec{V}_c(\vec{r}) = V_c \ \mathrm{sign}(z) \ \vec{k}$$

Propagation



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Energy loss term

- Due to inverse Compton scattering on the interstellar radiation field (starlight, thermal radiation of dust, CMB) and synchrotron radiation.
- Negligible for antiprotons and antideuterons
- Can be modelled

● Energy loss due to Inverse Compton scattering: $e^+\gamma \to e^+\gamma$

$$b_{\rm ICS}(E_e,\vec{r}) = \int_0^\infty d\epsilon \int_\epsilon^{E_\gamma^{\rm max}} dE_\gamma (E_\gamma - \epsilon)\frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma} f_{\rm ISRF}(\epsilon,\vec{r})$$

Number density
of photons in ISRF

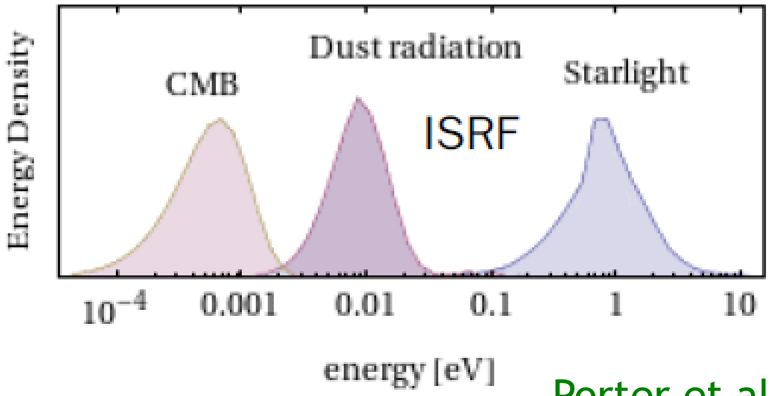
$$\frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma} = \frac{3}{4}\frac{\sigma_{\rm T}}{\gamma_e^2\,\epsilon} \times \left[2q\ln q + 1 + q - 2q^2 + \frac{1}{2}\frac{(q\Gamma)^2}{1+q\Gamma}(1-q)\right]$$

$\gamma_e = E_e/m_e$ ⟶ Lorentz factor.

$\Gamma_e = 4\,\gamma_e\,\varepsilon/m_e$

$q = E_\gamma/\Gamma(E_e - E_\gamma)$

$\sigma_T = 0.67$ barn ⟶ Compton scattering cross section in the Thomson limit.



Porter et al.

● Energy loss due to synchrotron radiation:

$$b_{\rm sync}(E_e,\vec{r}) = \frac{4}{3}\sigma_T\gamma_e^2\frac{B^2}{2}$$

$$B = 6\mu G \exp(-|z|/5{\rm kpc} - r/20{\rm kpc})$$

Approximately $b(E) = \dfrac{E^2}{E_0\tau_E}$, with $E_0 = 1$ GeV and $\tau_E = 10^{16}$s

- Energy loss due to Inverse Compton scattering: $e^+\gamma \rightarrow e^+\gamma$

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Not very well known, though...

$\gamma_e = E_e/m_e$ ⟶ Lorent

$\Gamma_e = 4\,\gamma_e\,\varepsilon/m_e$

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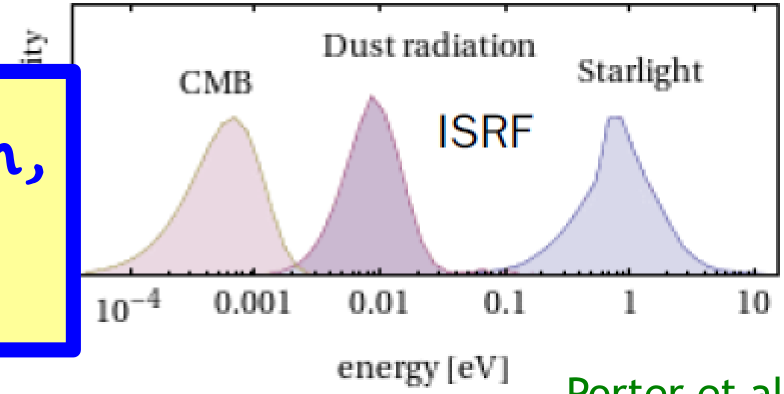

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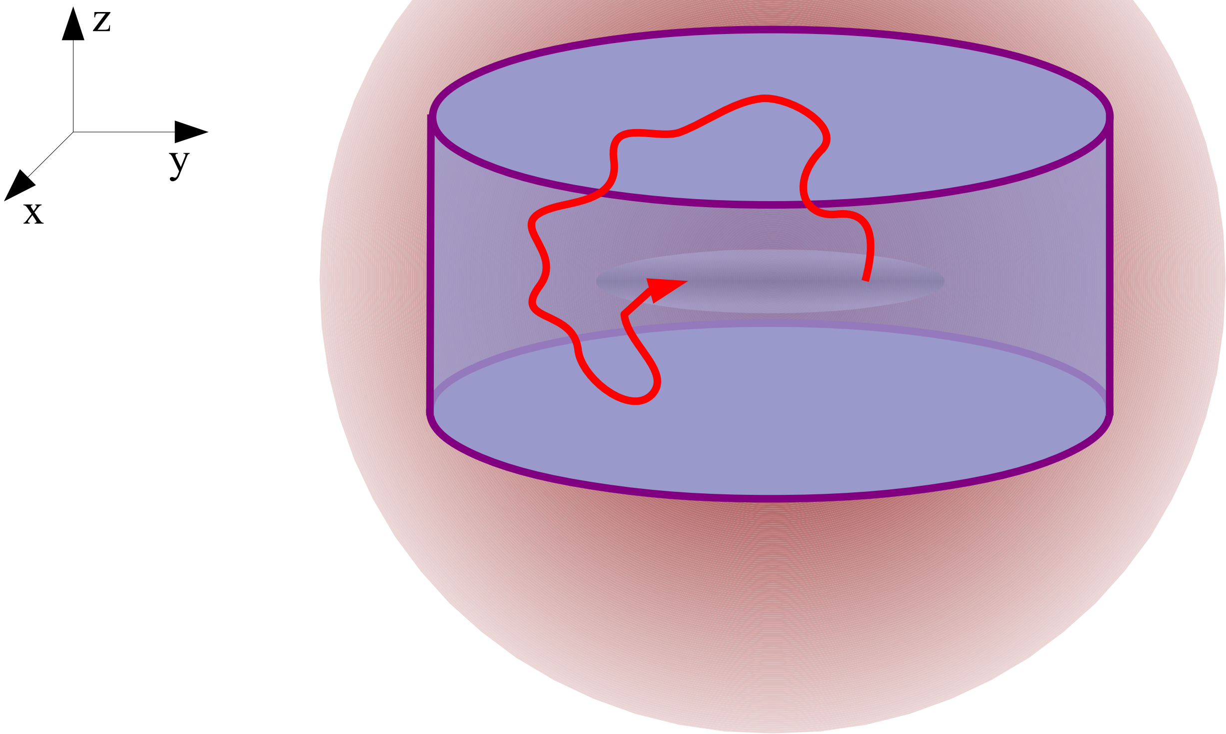

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Diffusion term

- Due to the tangled magnetic field of the Galaxy.
- Difficult to model. Assume

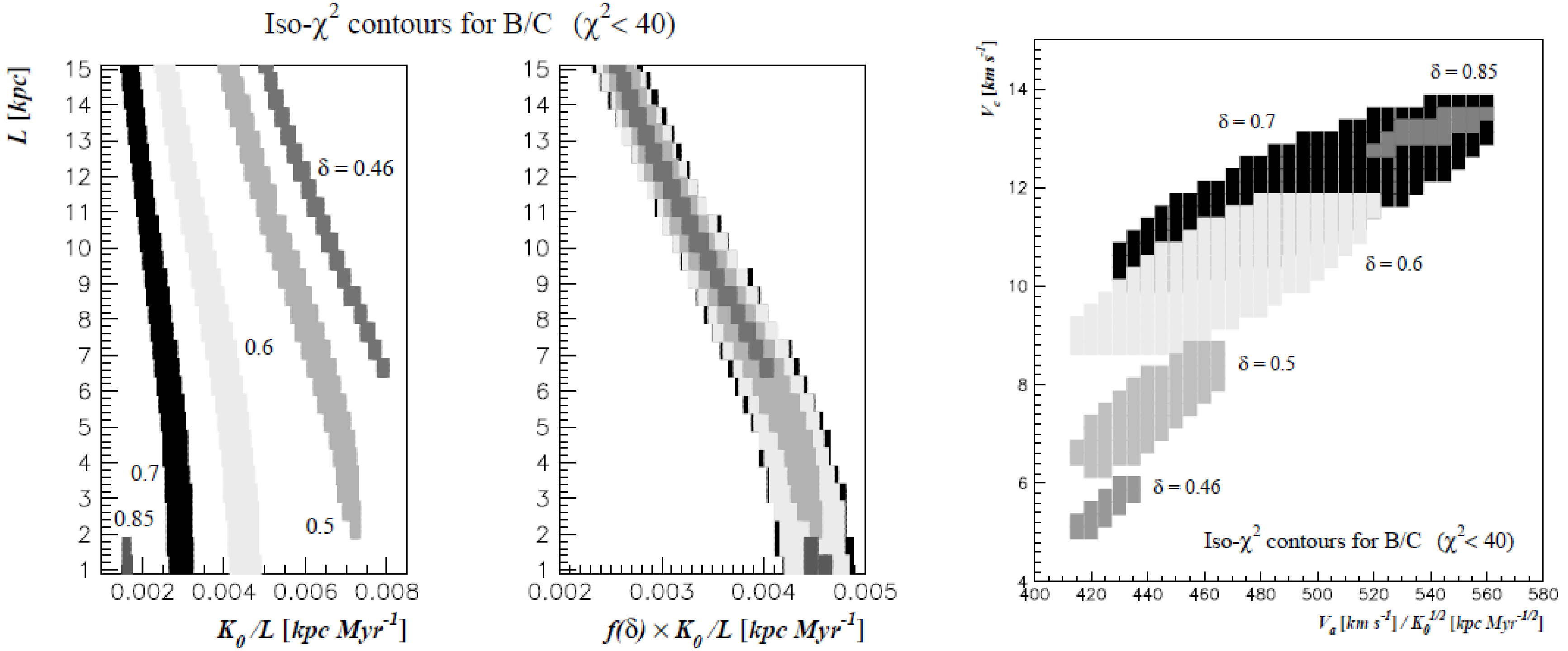
$$K(T) = K_0\, \beta\, \mathcal{R}^{\delta}$$

β = velocity
$\mathcal{R}$ = rigidity

$$0=\frac{\partial f}{\partial t}=\boxed{\nabla\cdot[K(T,\vec{r})\nabla f]}-\frac{\partial}{\partial T}[b(T,\vec{r})f]\boxed{-\nabla\cdot[\vec{V}_c(\vec{r})f]}-2h\delta(z)\Gamma_{\rm ann}f+Q(T,\vec{r})\ .$$

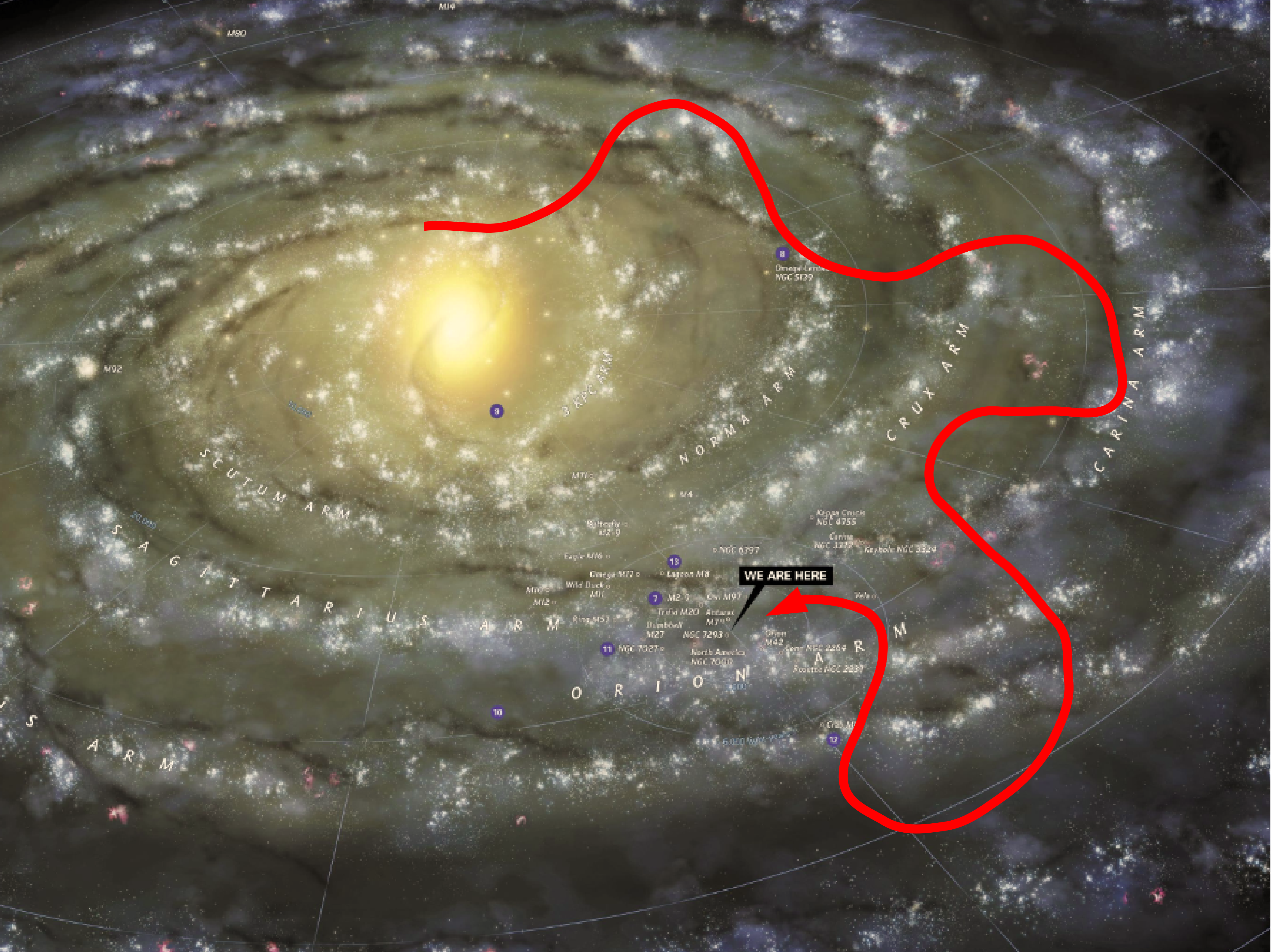
$$K(T)=K_0\ \beta\ \mathcal{R}^{\delta} \qquad\qquad \vec{V}_c(\vec{r})\ =\ V_c\ \mathrm{sign}(z)\ \vec{k}$$

K_0, δ, V_c (as well as L) must be determined with measurements of other cosmic ray species (mainly B/C ratio).

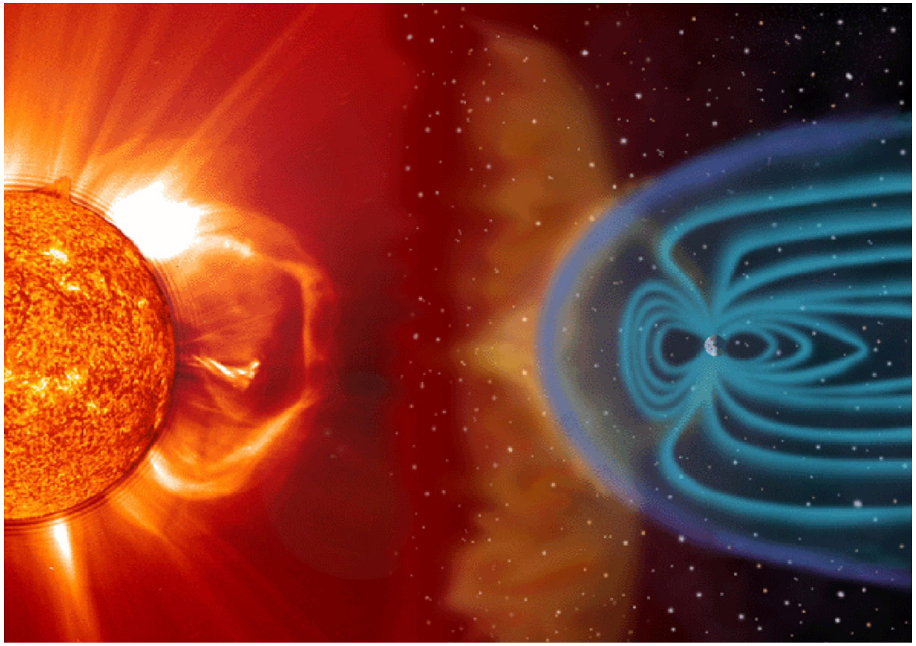


Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

Maurin, Donato, Taillet, Salati '01


M14
M80
M92
9
3 KPC ARM
NORMA ARM
CRUX ARM
CARINA ARM
8
Omega Centauri
NGC 5139
SCUTUM ARM
SAGITTARIUS ARM
M19
M4
Butterfly M6
Kappa Crucis NGC 4755
Carina NGC 3372
Keyhole NGC 3324
NGC 6397
Eagle M16
13
Omega M17
Lagoon M8
WE ARE HERE
M10
Wild Duck M11
M12
7
M22
Owl M97
Vela
Trifid M20
Antares M7
Ring M57
Dumbbell M27
NGC 7293
Orion M42
11
NGC 7027
Cone NGC 2264
North America NGC 7000
Rosette NGC 2237
ORION ARM
10
Crab M1
12
6,000 light-years
S ARM

Propagation inside the Solar System



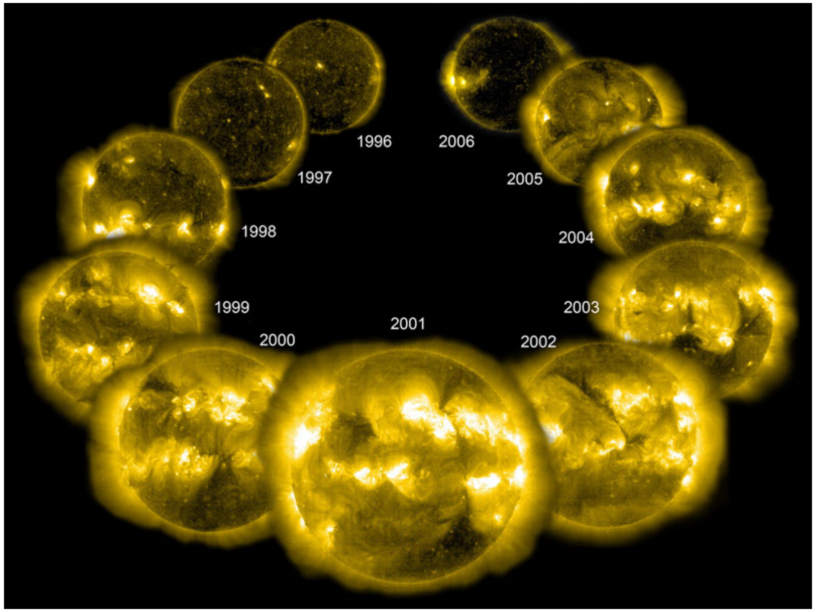
In the “force field approximation”,the flux at the top of the atmosphere (TOA) is related to the interstellar flux (IS) by

$$\Phi_{e^\pm}^{\mathrm{TOA}}(E_{\mathrm{TOA}}) = \frac{E_{\mathrm{TOA}}^2}{E_{\mathrm{IS}}^2}\,\Phi_{e^\pm}^{\mathrm{IS}}(E_{\mathrm{IS}})$$

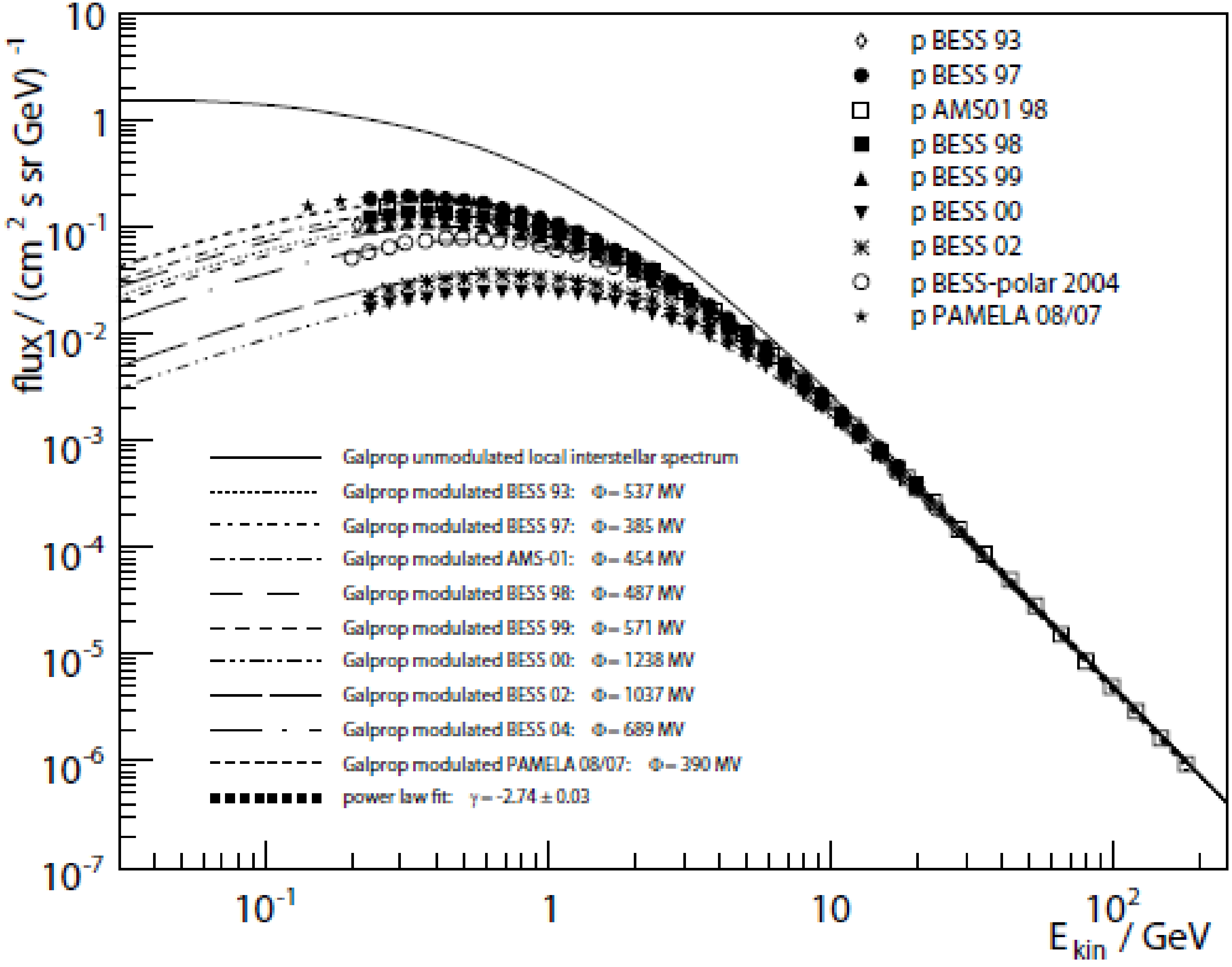
$$E_{\mathrm{IS}} = E_{\mathrm{TOA}} + \phi_F$$

solar modulation parameter

ϕ_F=500 MV – 1.3 GV



Cosmic ray proton spectrum as measured by BESS, AMS-01 and PAMELA



Gast, Schael '09