Dark Matter

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Summer School
on Particle Physics
ICTP, Trieste
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Outline

Lecture 1: Evidence for dark matter.

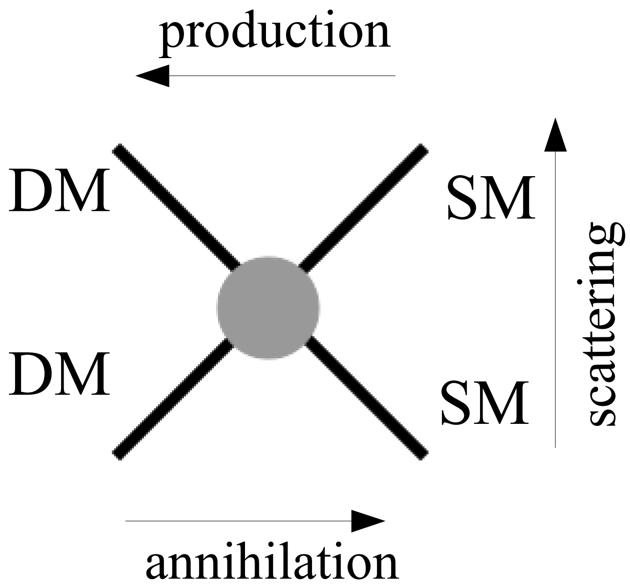
Lecture 2: Dark matter production.

Lecture 3: Indirect dark matter detection.

Lecture 4: Direct dark matter detection. Collider searches.

Main results from the previous lecture

WIMP dark matter



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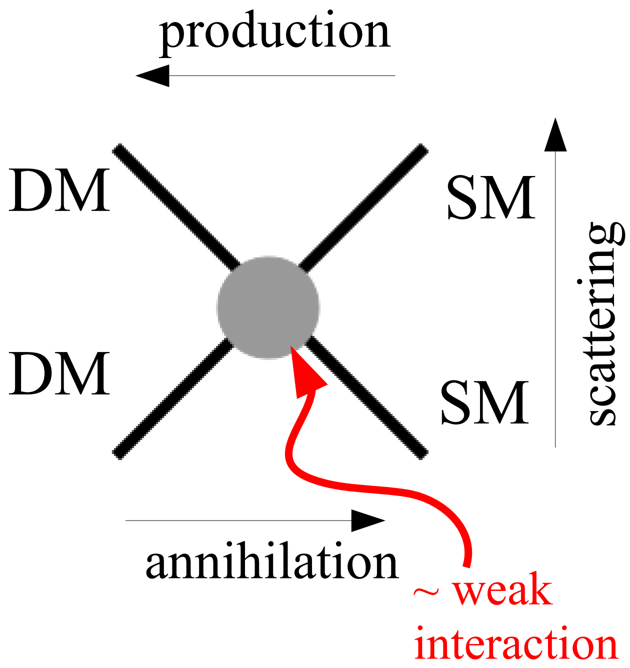

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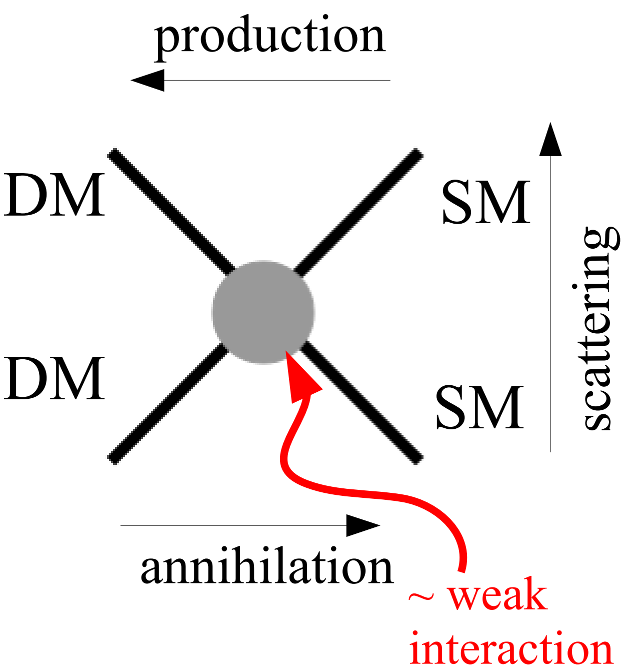

Relic abundance of DM particles

$$\Omega h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

Correct relic density if

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1} = 1\,\mathrm{pb} \cdot c$$

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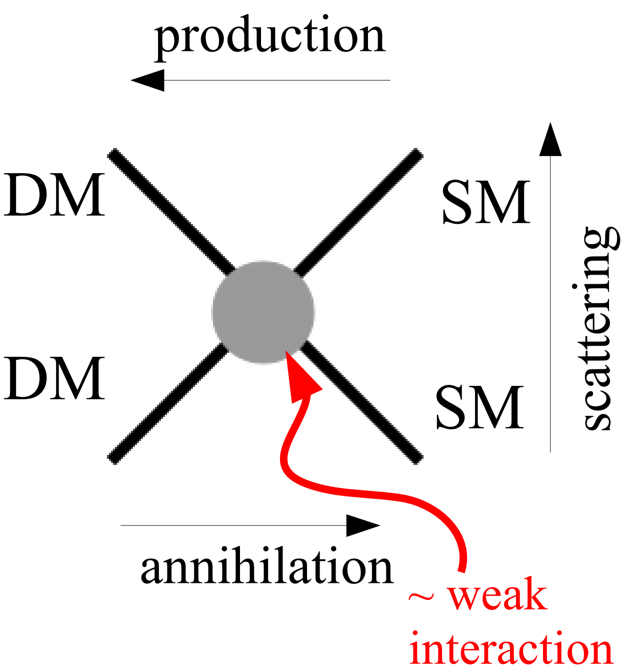

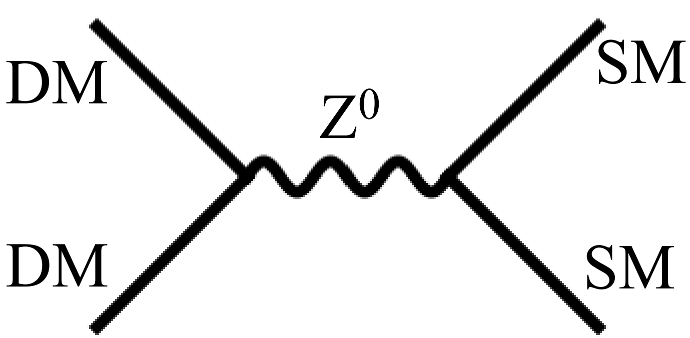

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$$\sigma \sim \frac{g^4}{m_{\mathrm{DM}}^2} = 1\,\mathrm{pb}$$

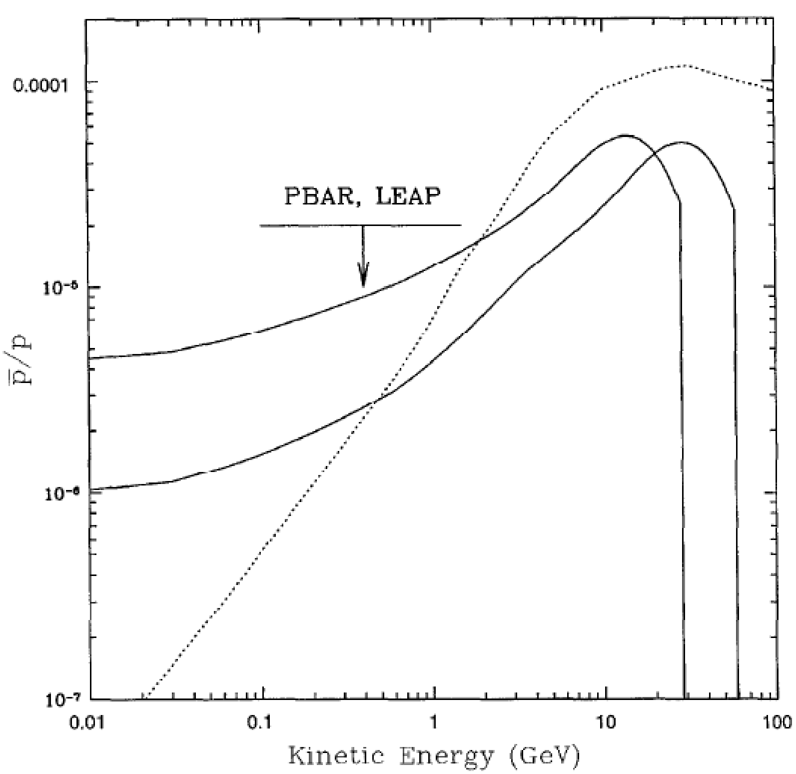
$$m_{\mathrm{DM}} \sim 100\,\mathrm{GeV} - 1\,\mathrm{TeV}$$

(provided $g \sim g_{\mathrm{weak}} \sim 0.1$)

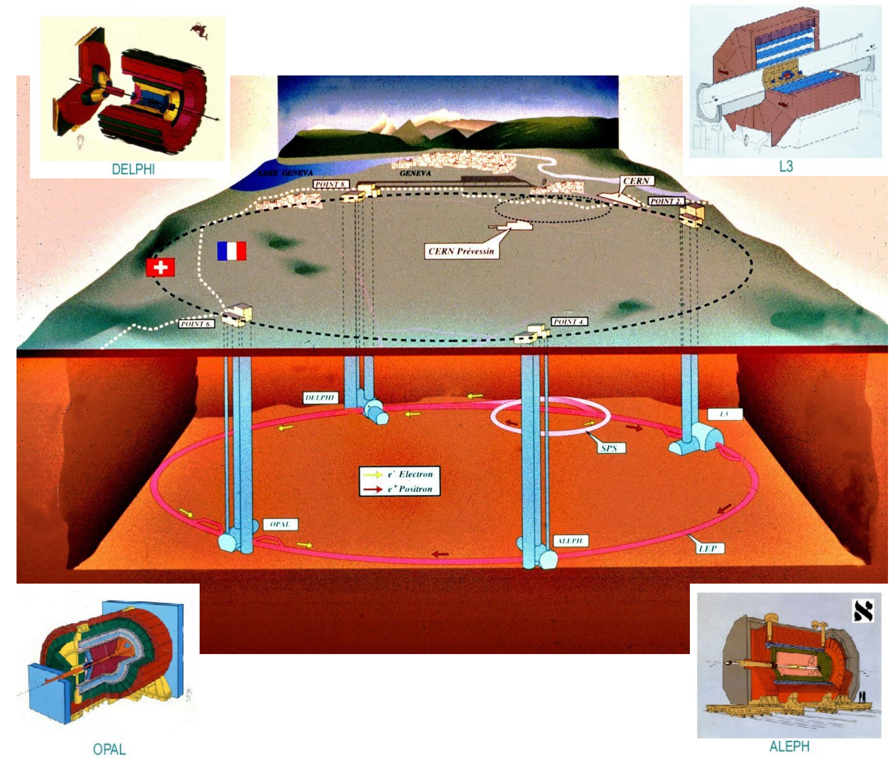
Fifteen years ago...

Cosmic antiprotons

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



Collider experiments

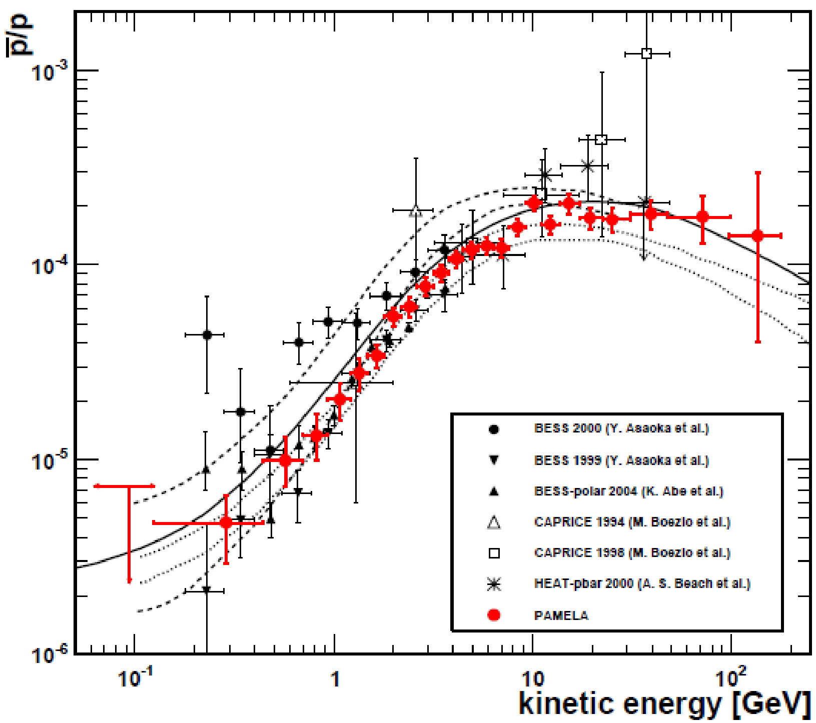


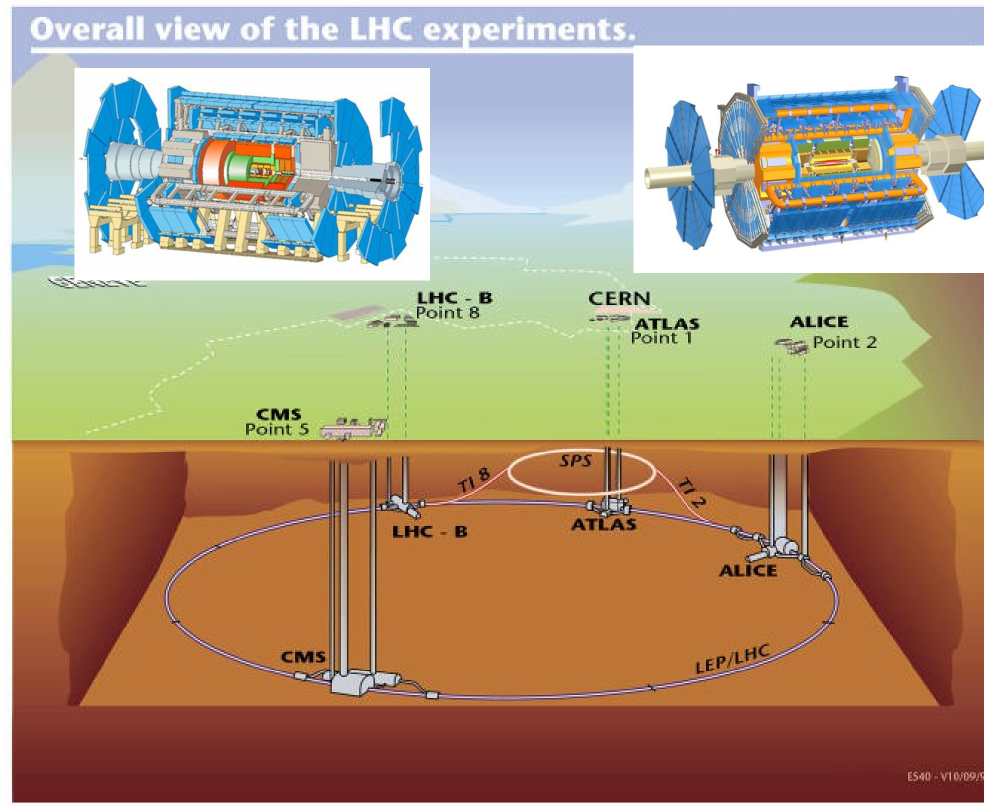
Year	Beam energy [GeV]	Maximum ξ_y	Total luminosity [pb^{-1}]	Average luminosity rate [pb^{-1}/day]
1994	45.6	0.045	64	0.31
1995	45.6 – 70.0	0.050	47	0.23
1996	80.5 – 86.0	0.040	25	0.17
1997	91.0 – 92.0	0.055	75	0.66
1998	94.5	0.075	200	1.16
1999	96.0 – 101.0	0.083	254	1.35
2000*	100.0 – 104.3	0.055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

Today

Cosmic antiprotons

Collider experiments



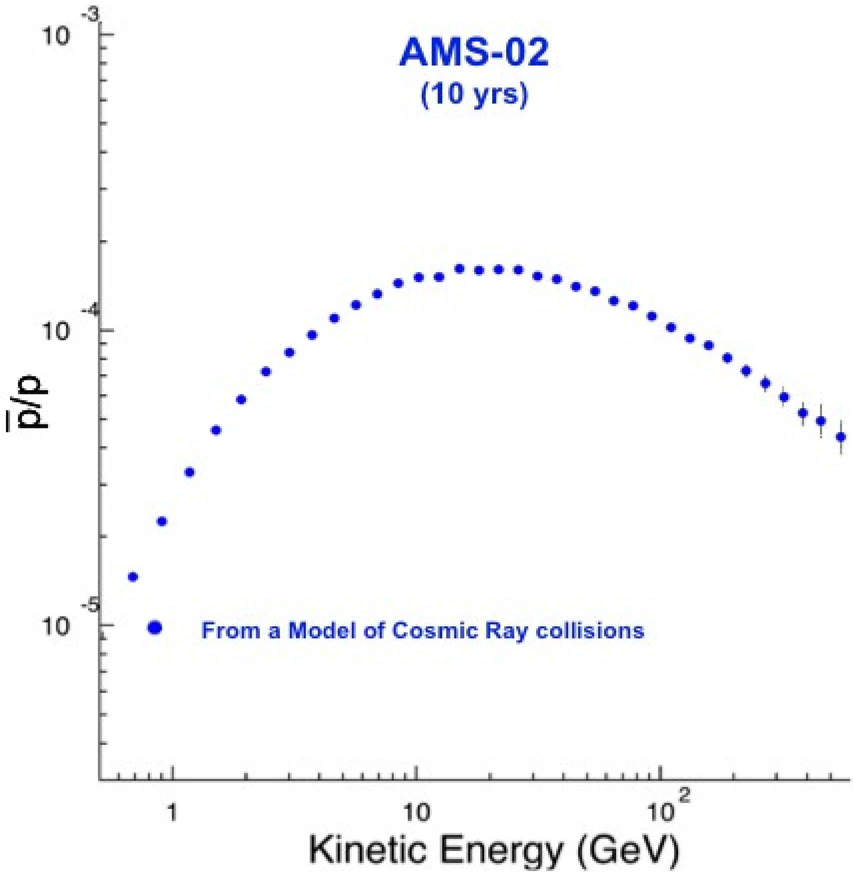


Beam energy: 4000 GeV

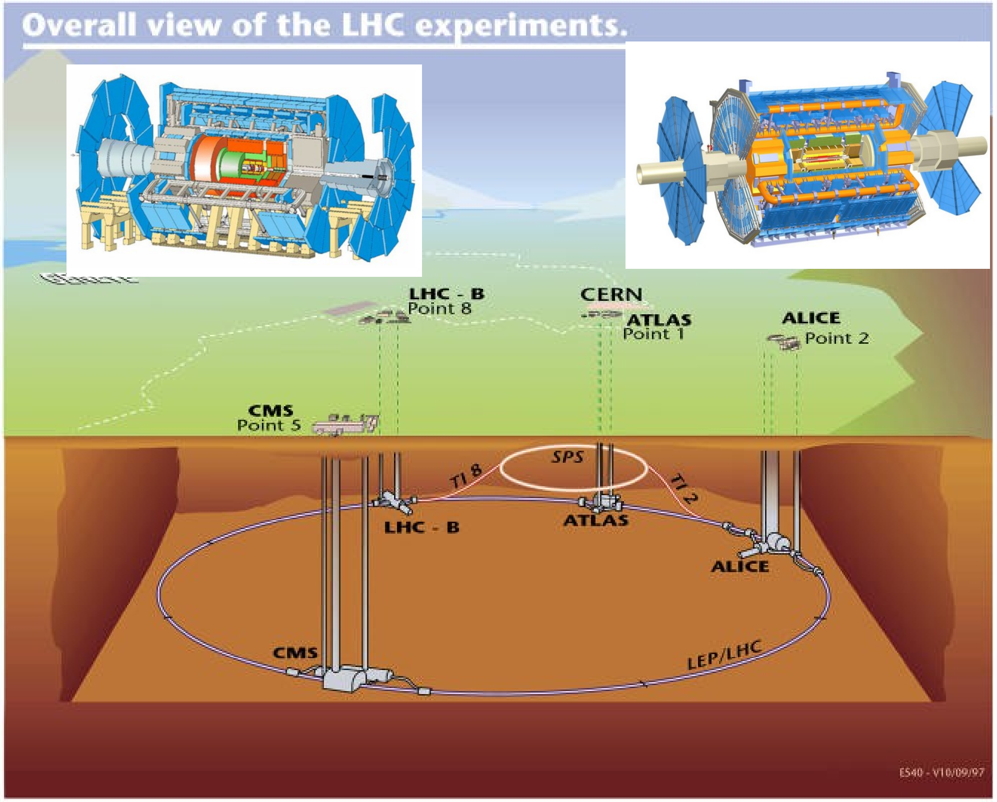
Integrated luminosity: 23.26 fb^{-1}

End of this decade

Cosmic antiprotons



Collider experiments

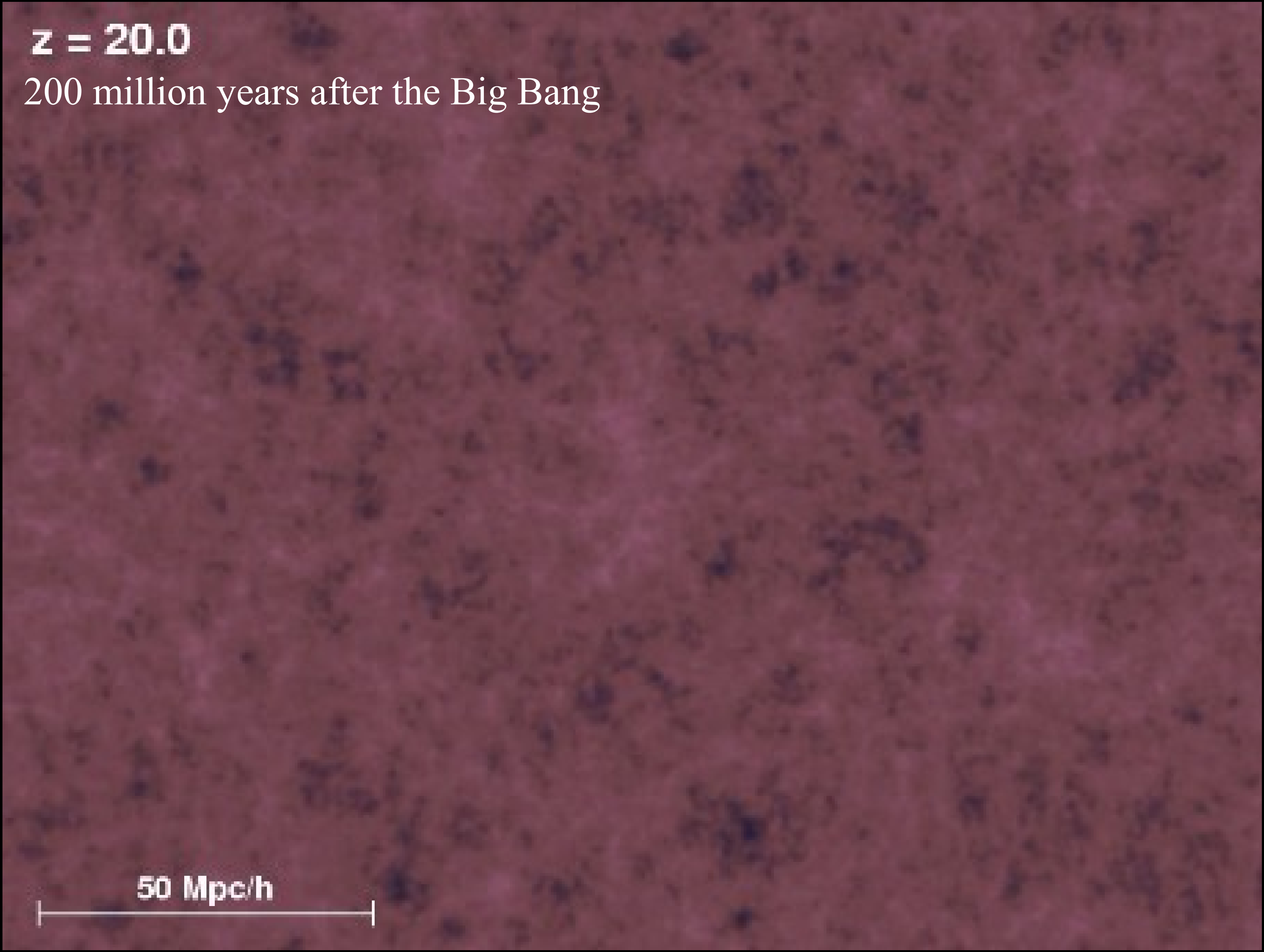


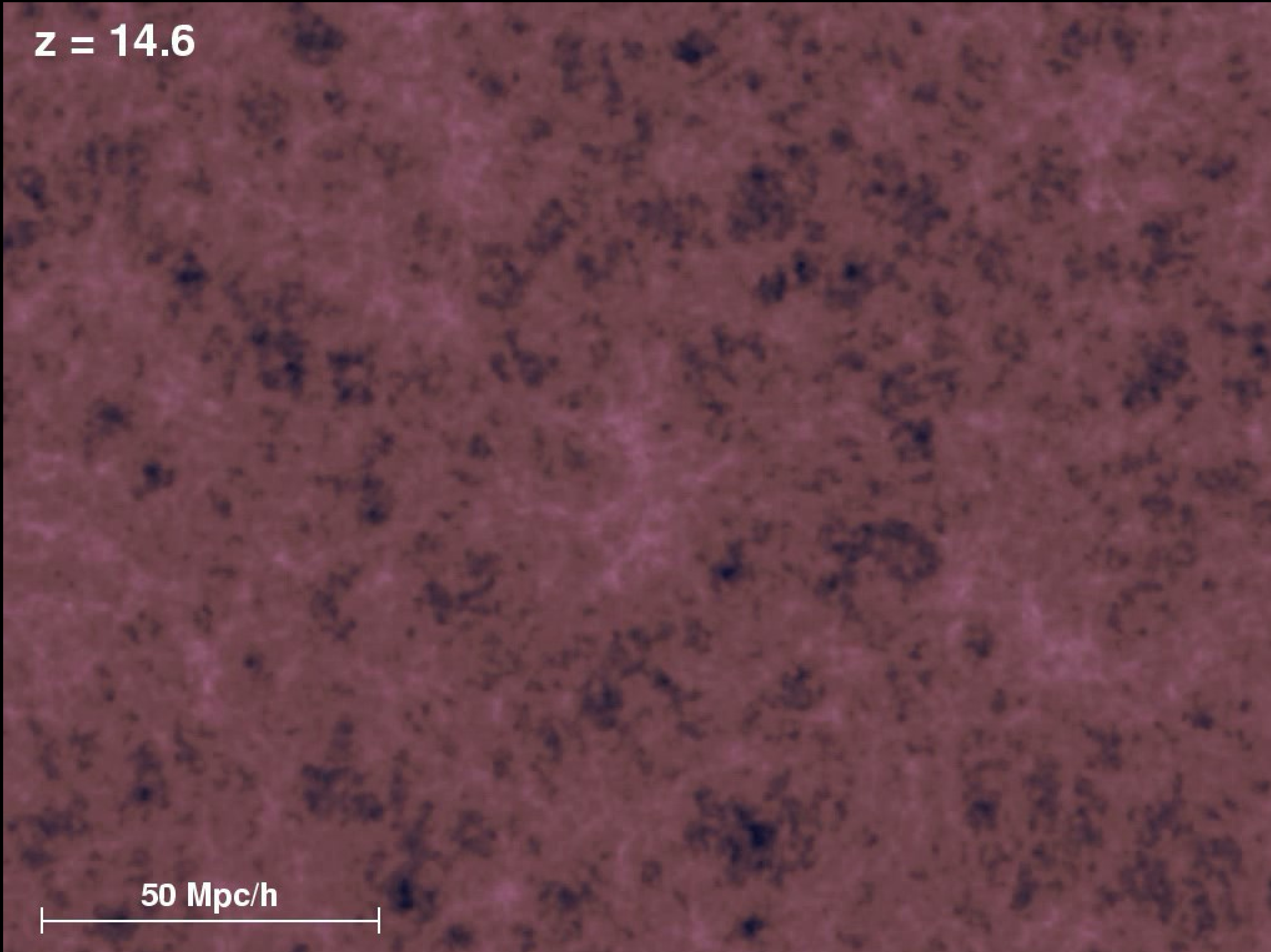
Beam energy: 6500 GeV

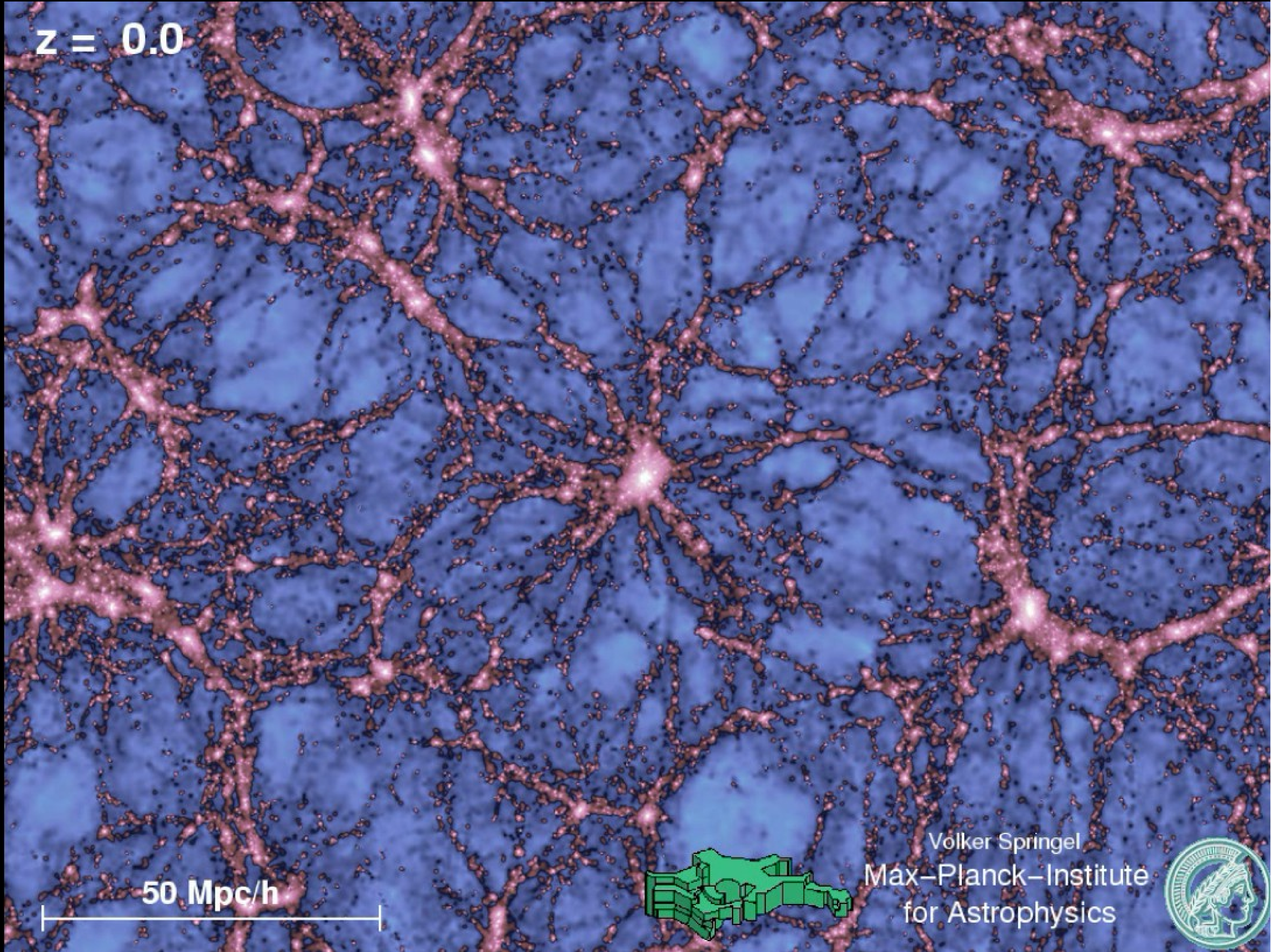
Integrated luminosity: 500 fb^{-1}

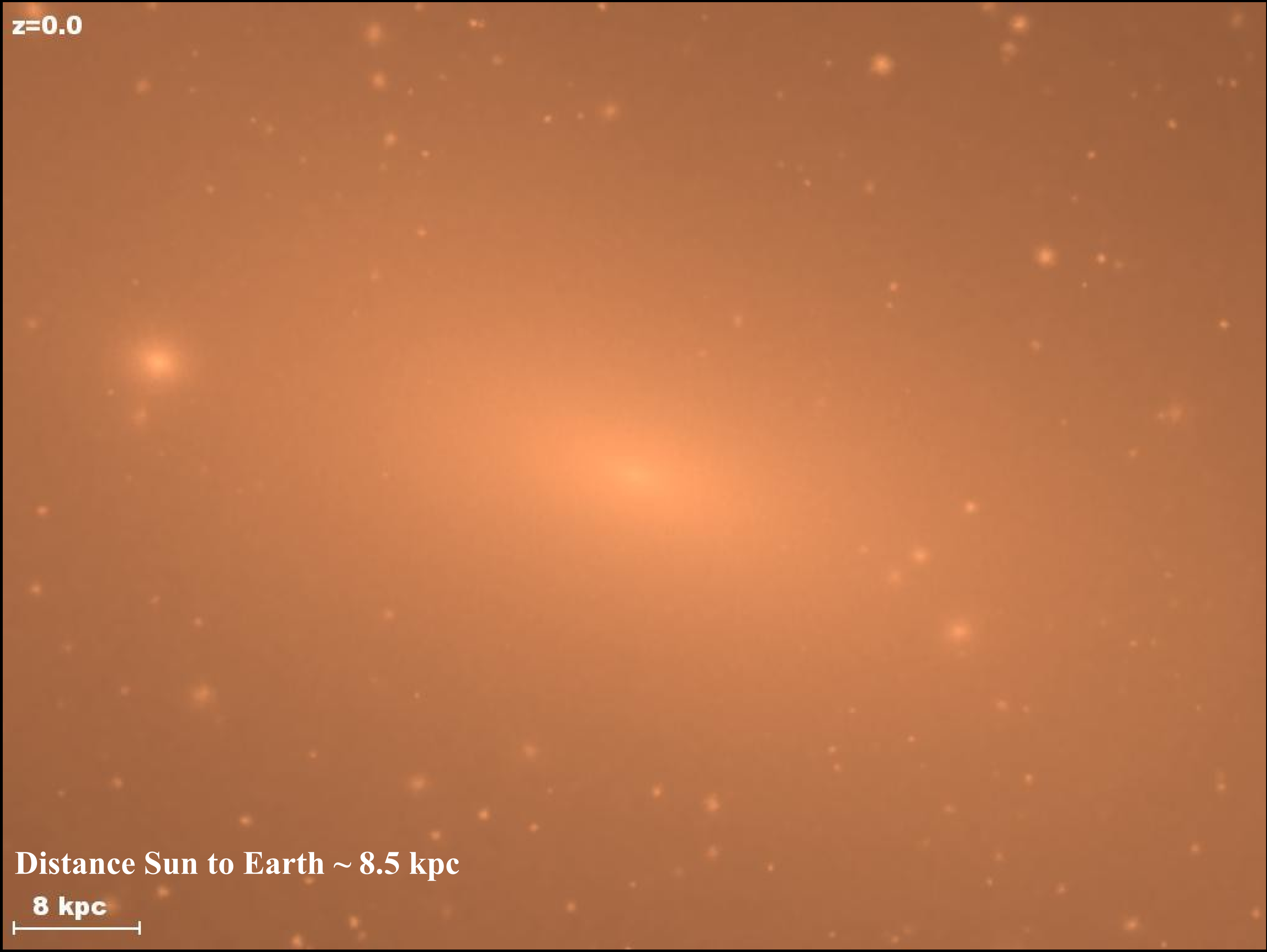
Dark matter distribution

The universe at T~1 GeV


z = 20.0
200 million years after the Big Bang
50 Mpc/h

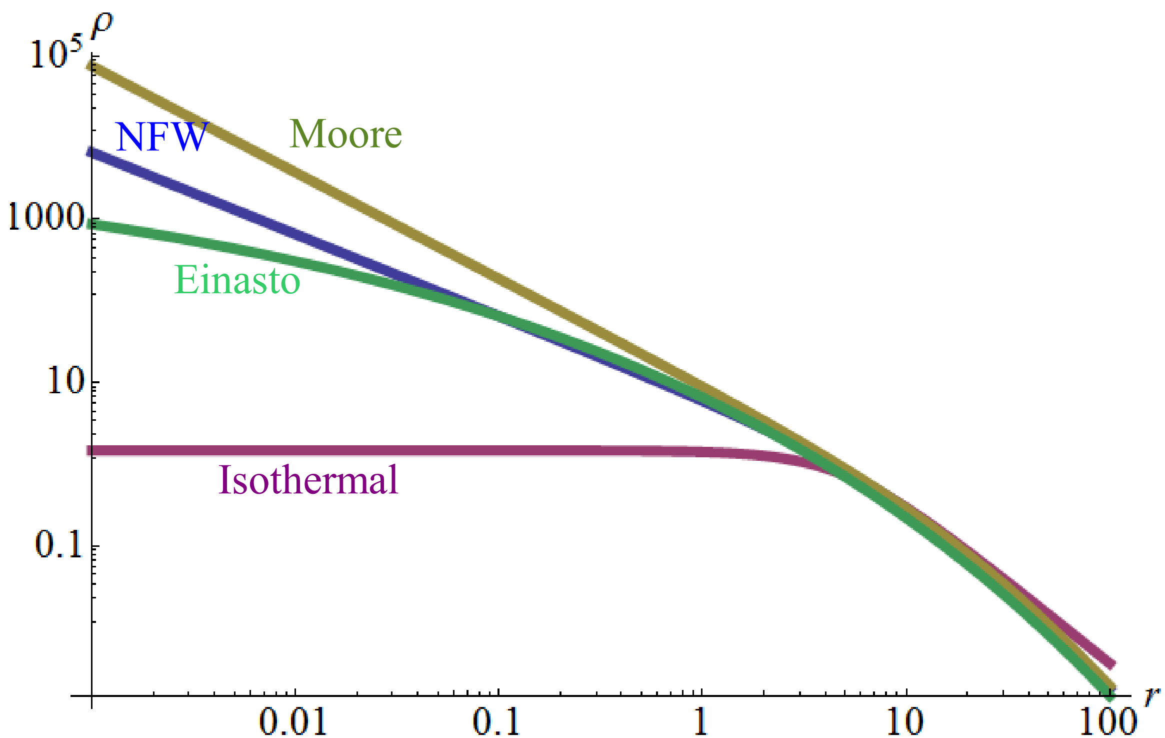

z = 14.6
50 Mpc/h


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


z=0.0
Distance Sun to Earth ~ 8.5 kpc
8 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

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

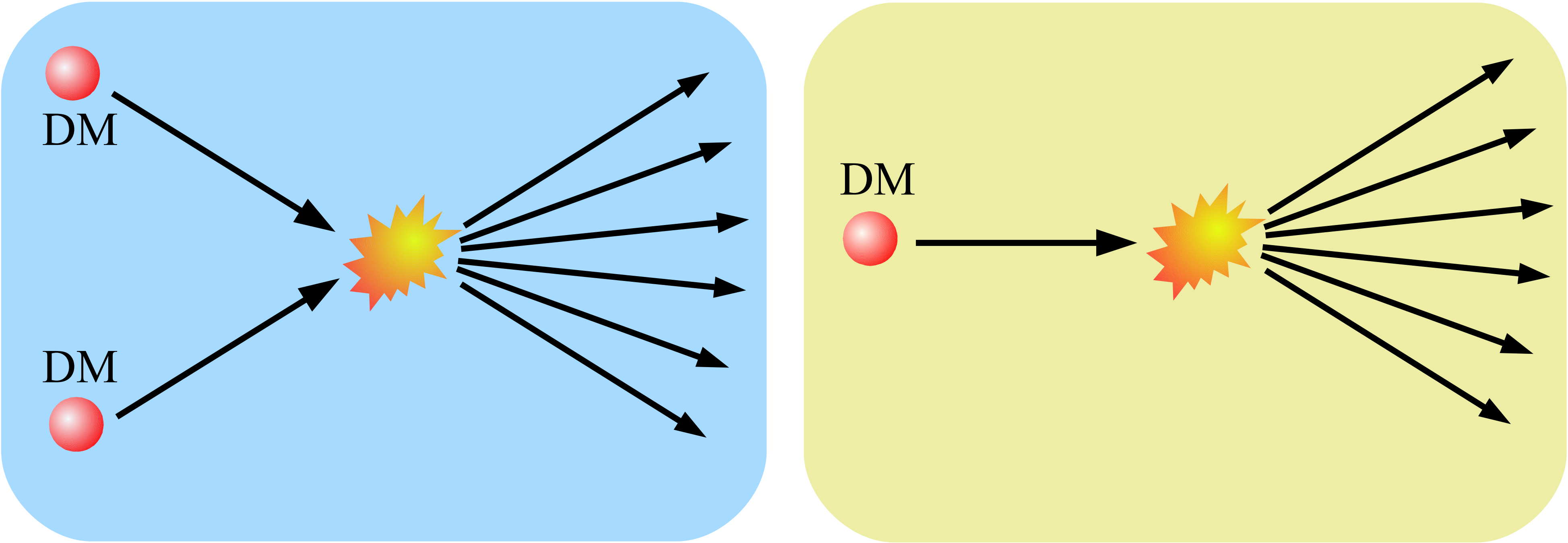
$\alpha = 0.17, \ r_s = 20$ kpc

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

Indirect dark matter searches

General idea:

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



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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 of 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.

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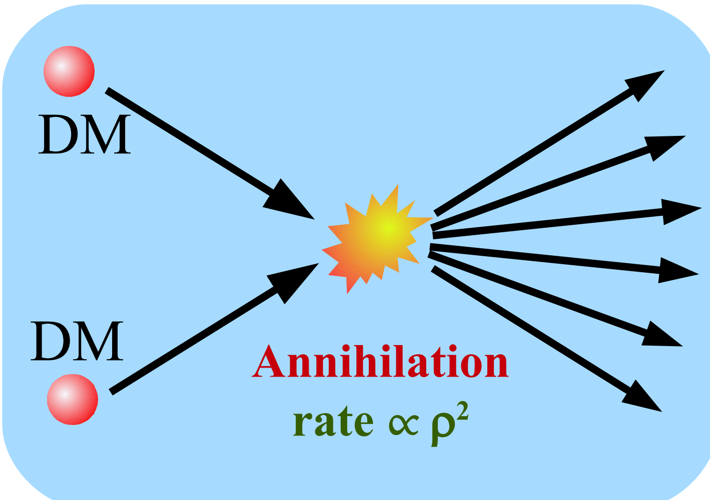
Indirect dark matter searches

Production			Antimatter
Propagation	}	of	{ Gamma-rays
Detection			Neutrinos

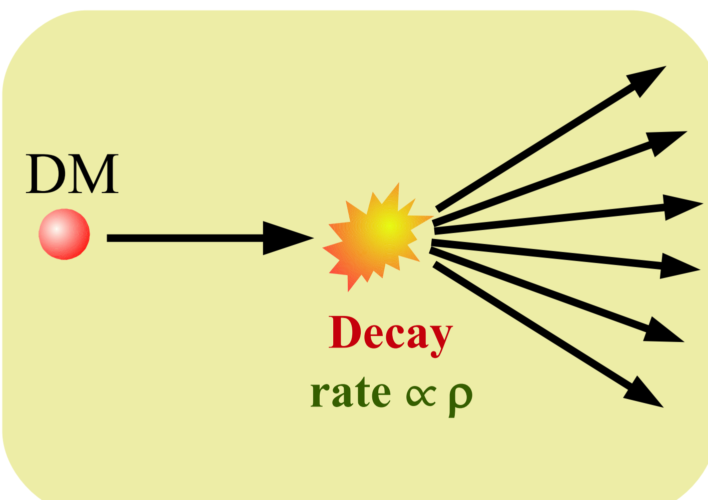
Antimatter

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.

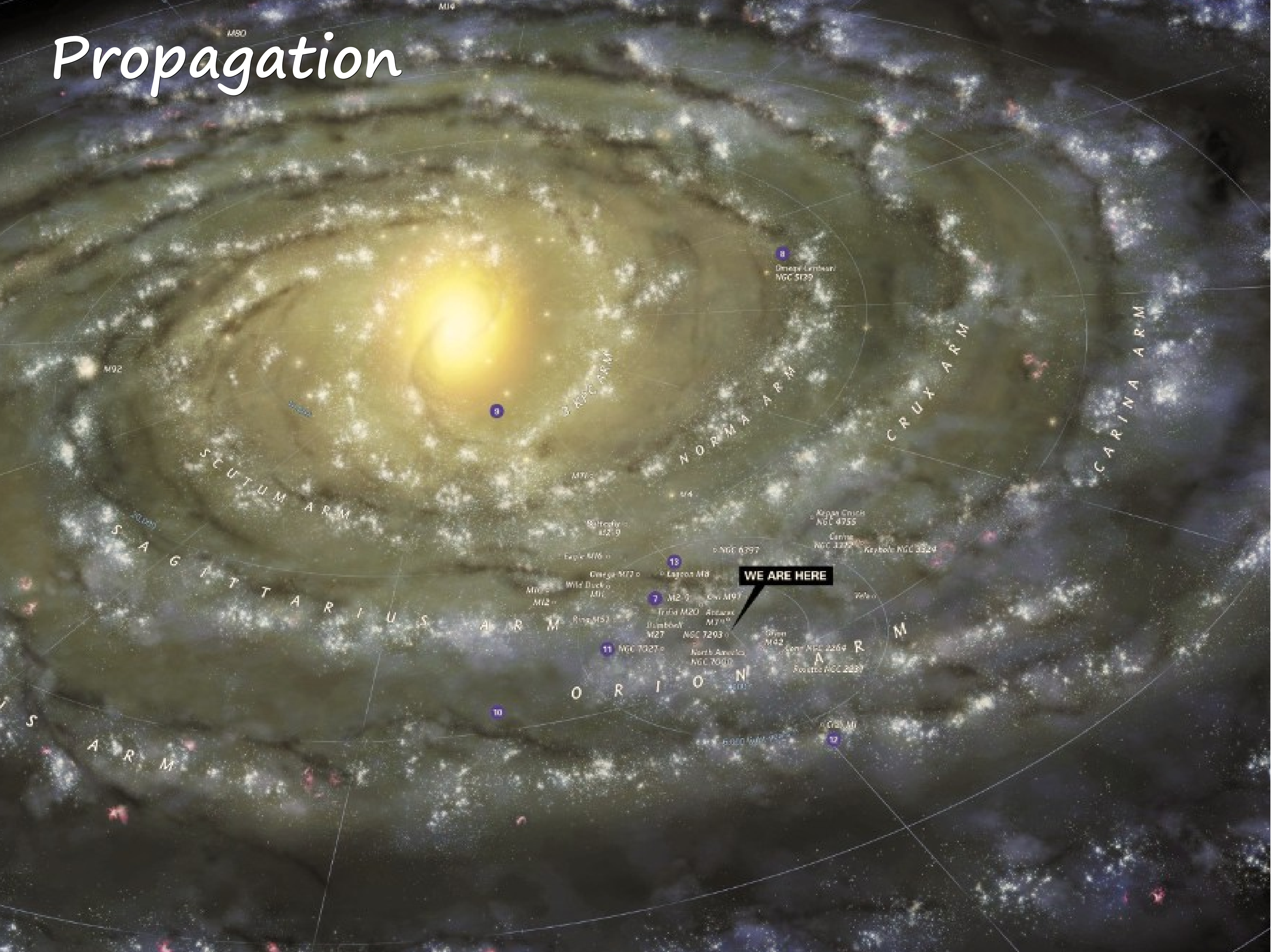


$$Q(E, \vec{r}) = \frac{1}{2} \frac{\rho^2(\vec{r})}{m_{\rm DM}^2} \langle \sigma v \rangle \frac{dN}{dE}$$



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

Propagation



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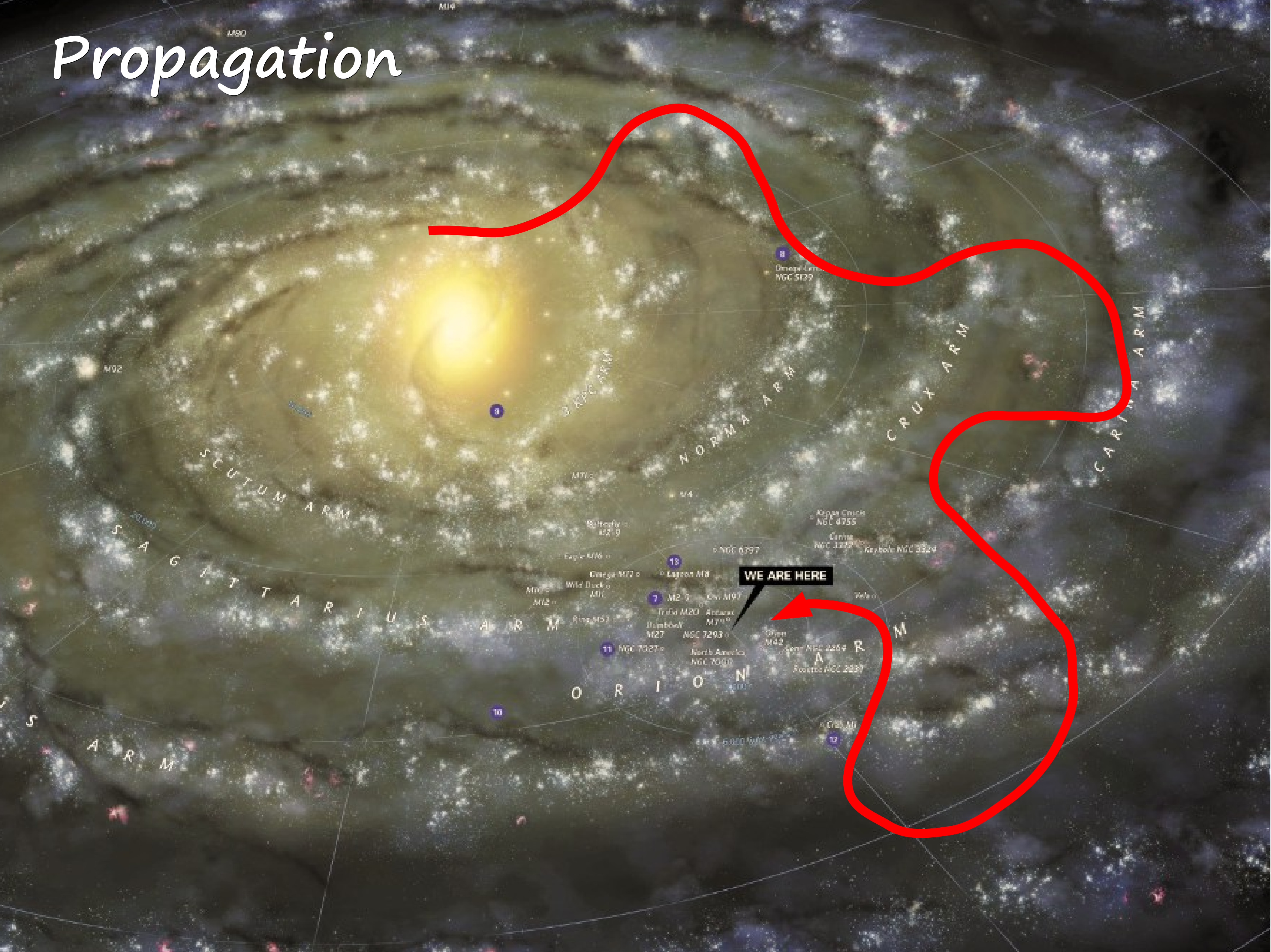

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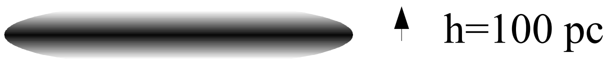

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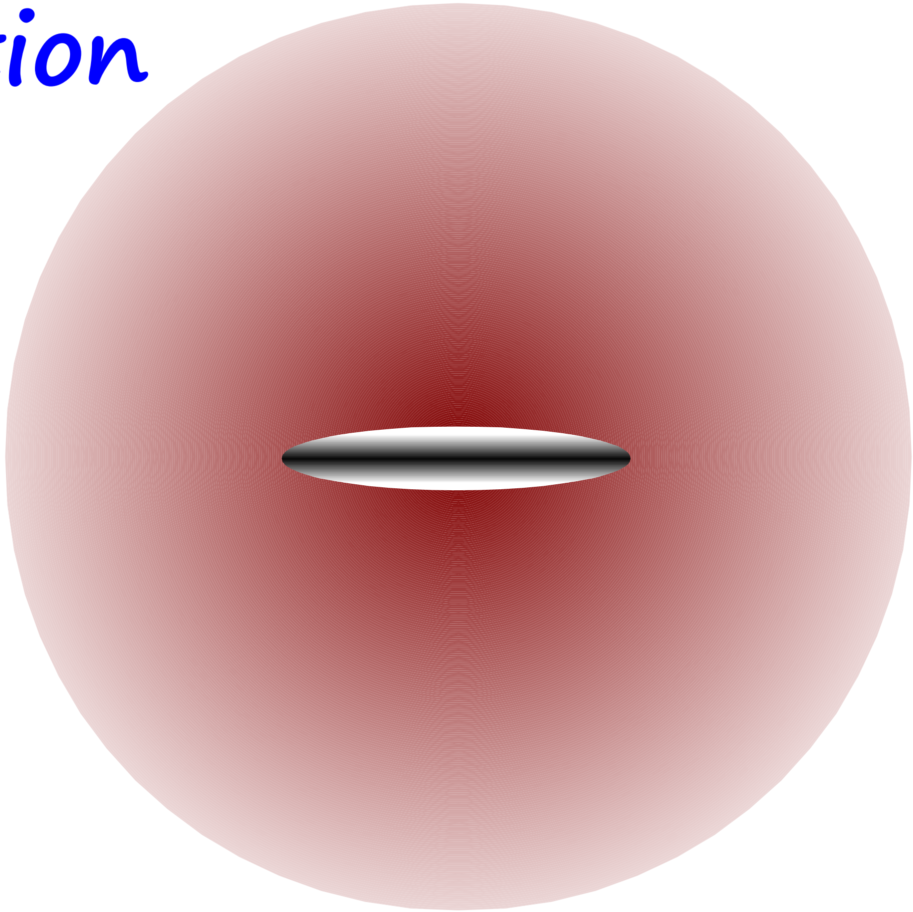

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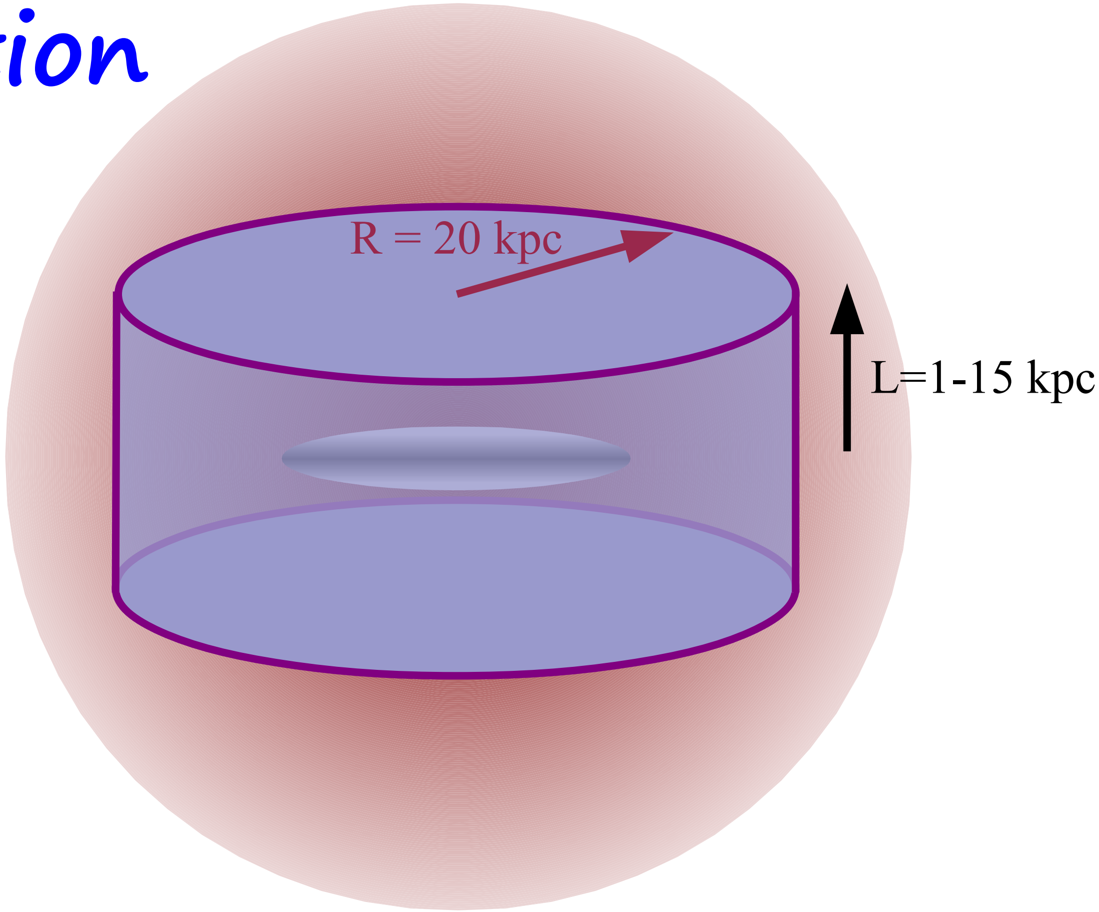

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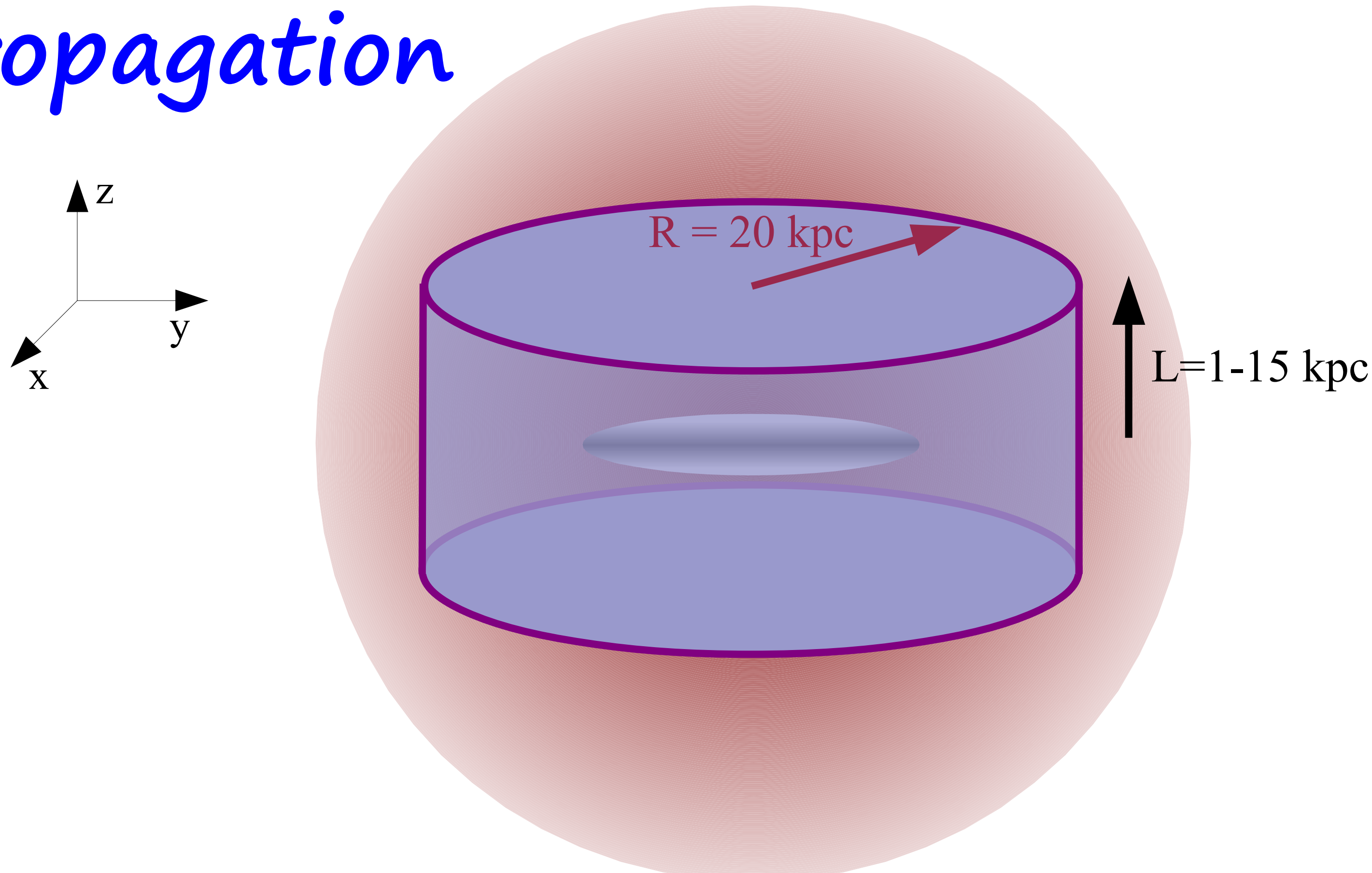


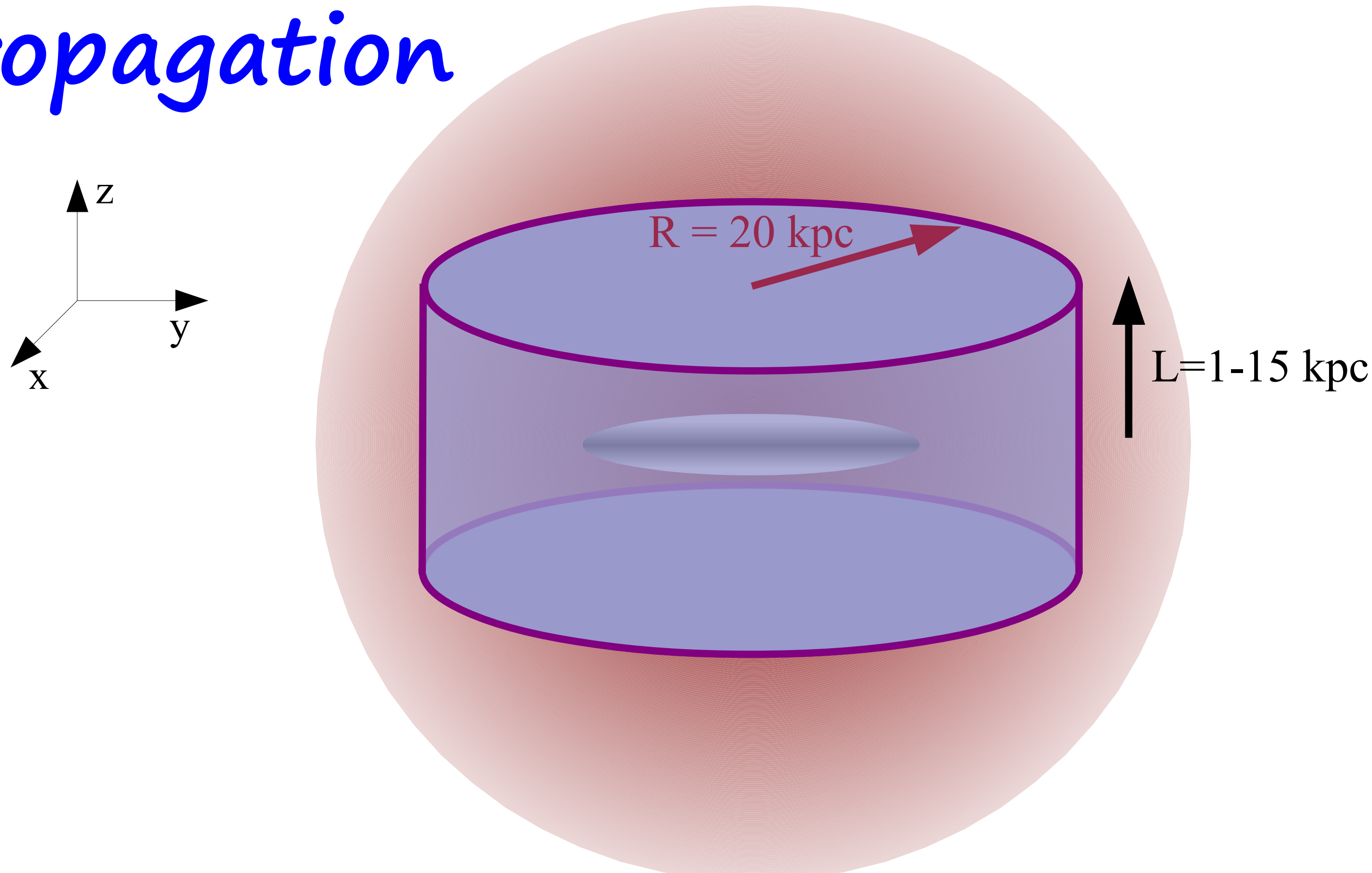
$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\rm ann} f + Q(T,\vec{r})\ .$$

f : number density of antiparticles per unit kinetic energy

interstellar antimatter flux:

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

Propagation



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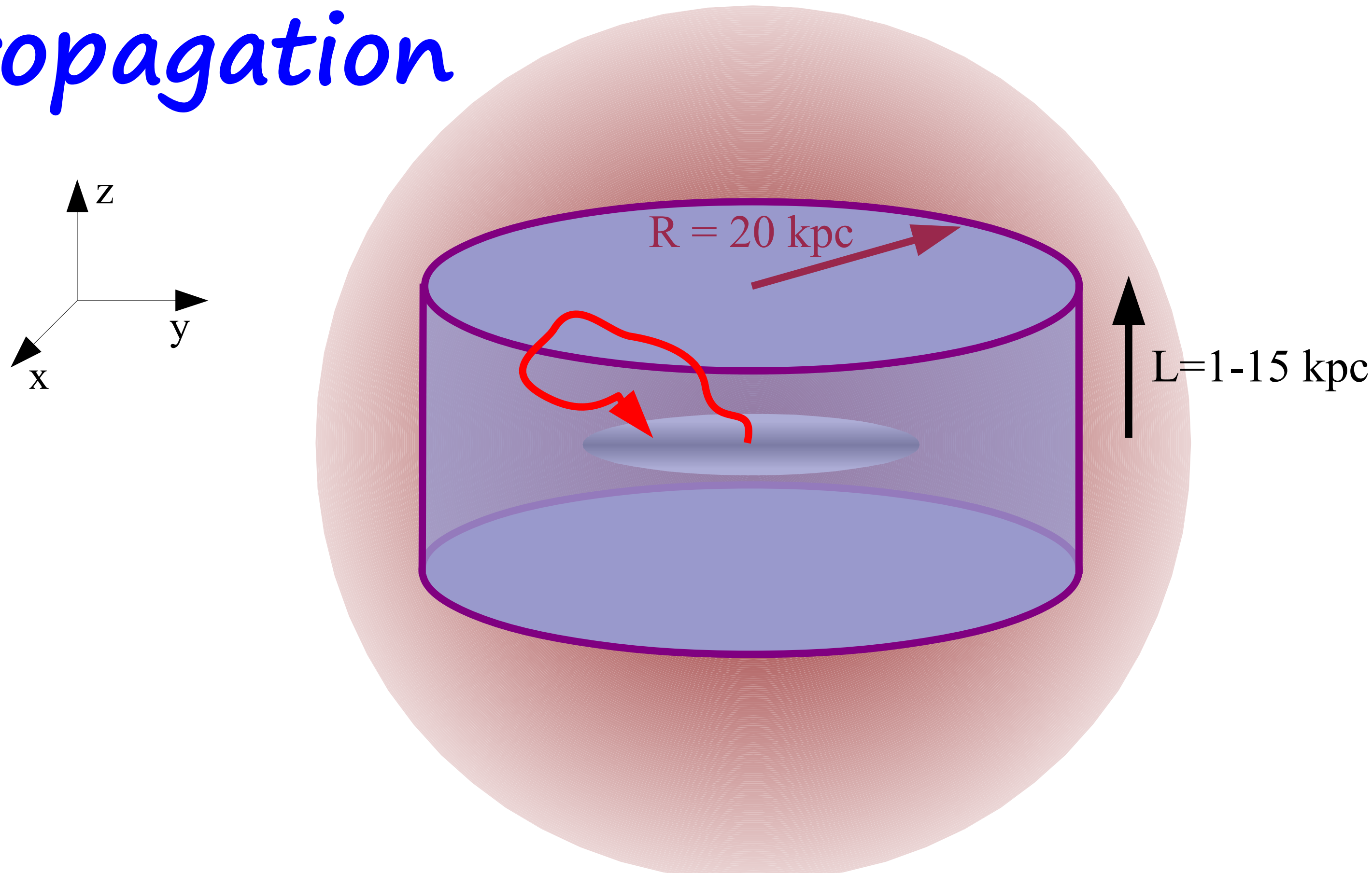
Source term

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

Propagation



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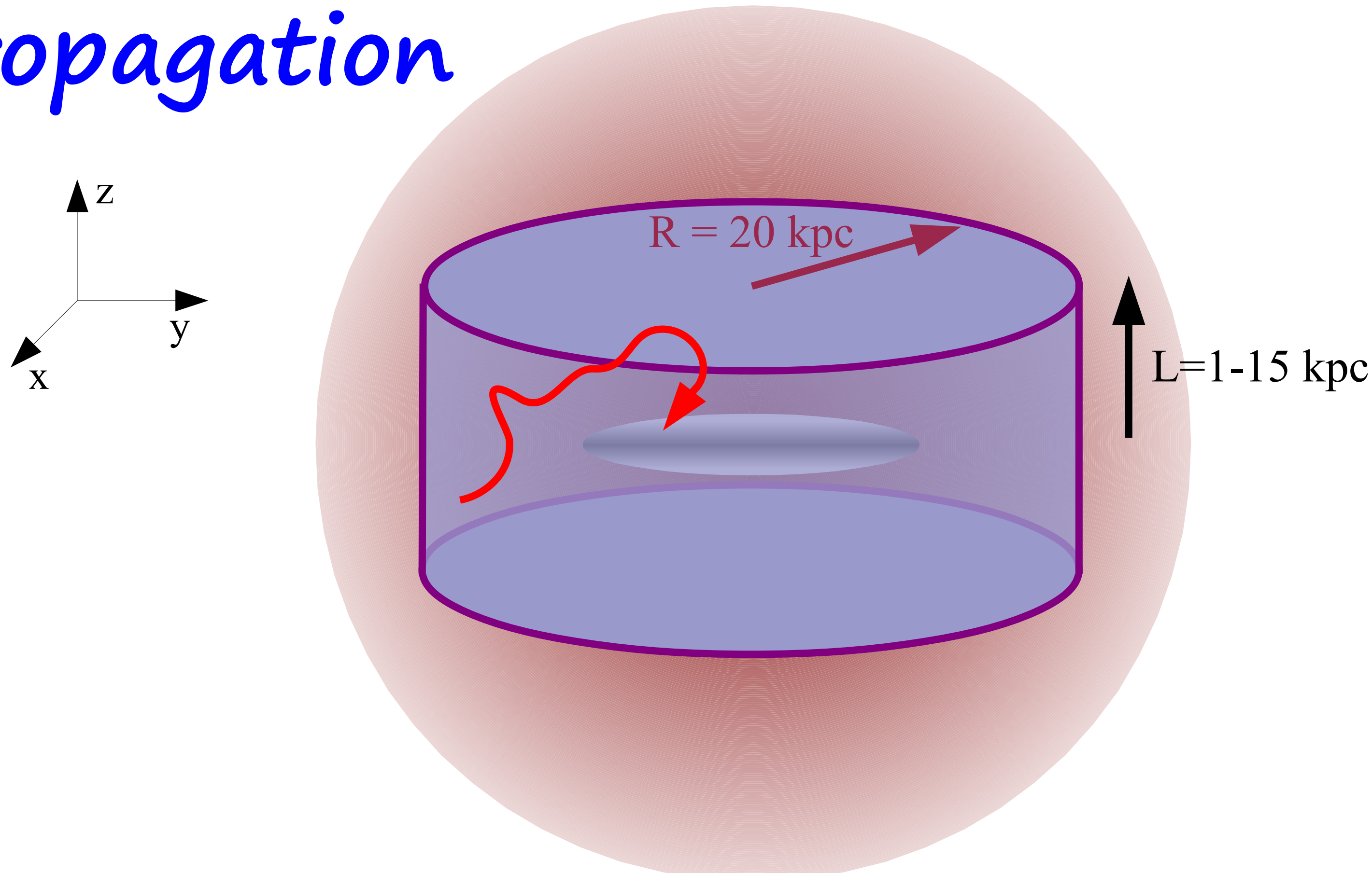

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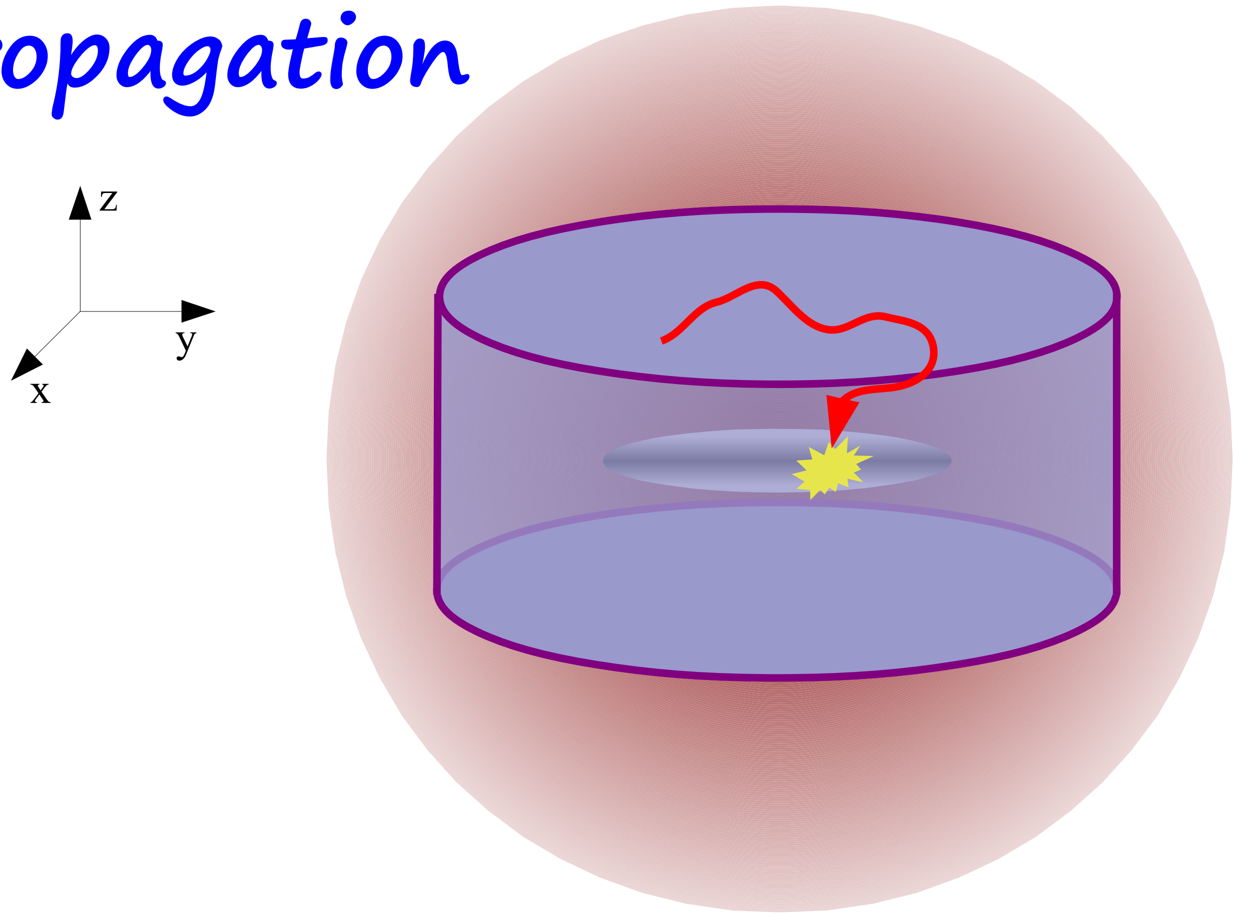
Propagation



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Annihilation term

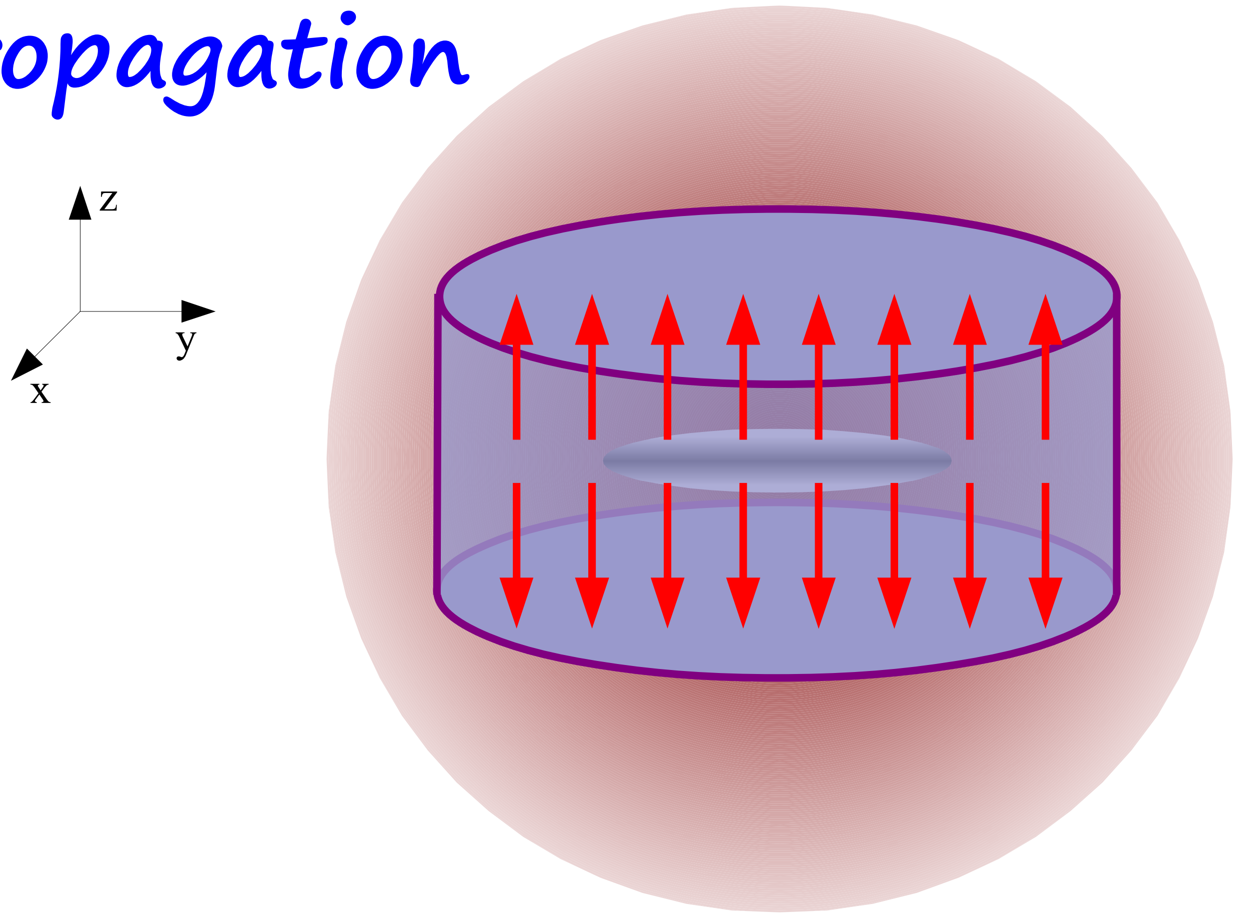
Negligible for positrons.
For antiprotons,

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

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

Tan, Ng

Propagation



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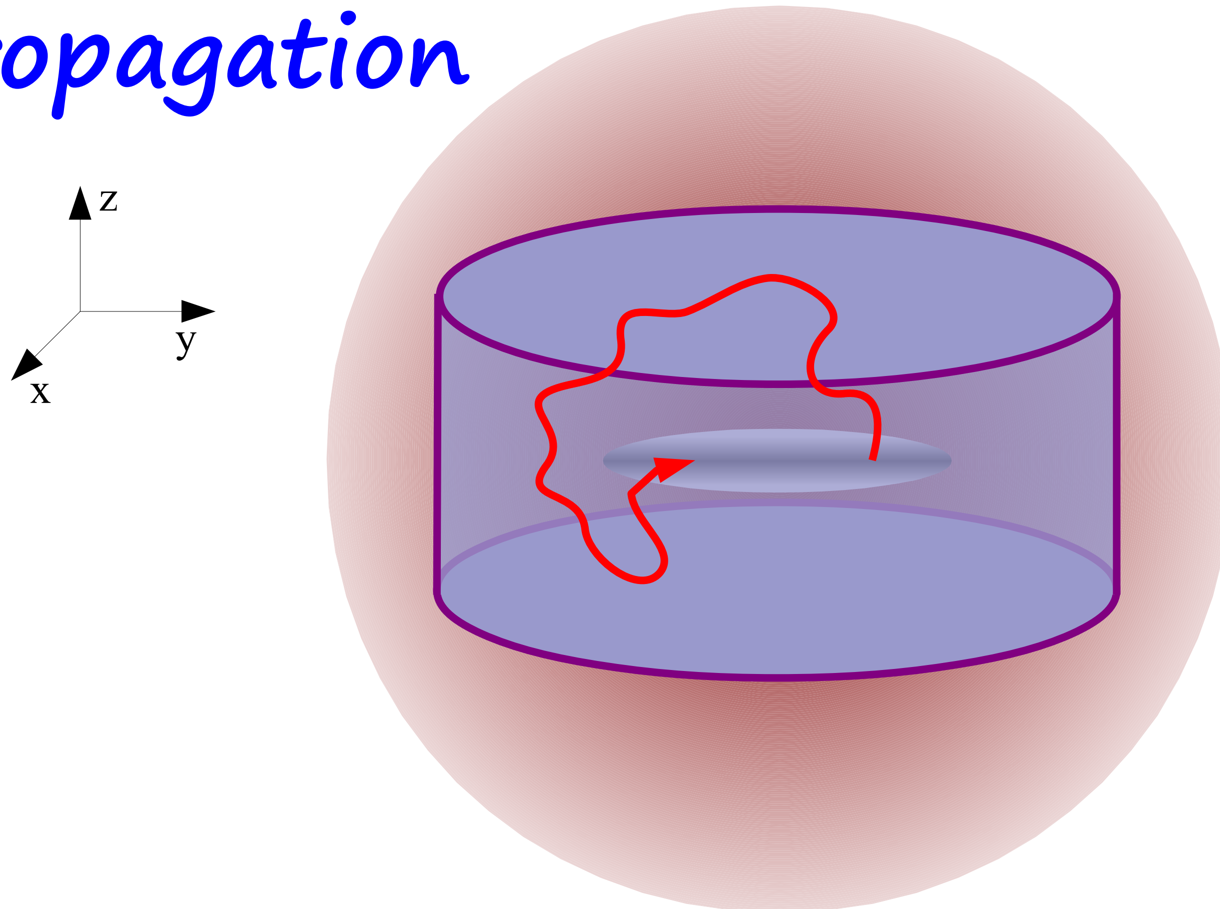
Convection term

- 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: $e^+\gamma \rightarrow e^+\gamma$

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

Number density of photons in ISRF

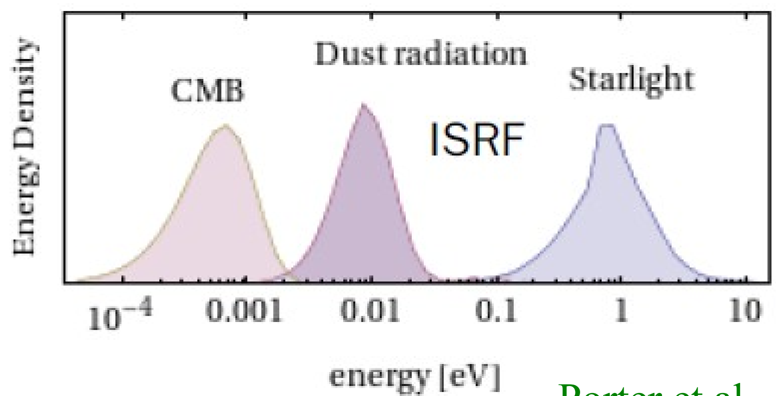
$$\frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma} = \frac{3}{4}\frac{\sigma_{\rm T}}{\gamma_e^2\,\epsilon} \times \left[2q\ln q + 1 + q - 2q^2 + \frac{1}{2}\frac{(q\Gamma)^2}{1+q\Gamma}(1-q)\right]$$

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

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

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

$\sigma_T = 0.67$ barn $\longrightarrow$ 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 $E_0 = 1\,{\rm GeV}$ and $\tau_E = 10^{16}{\rm s}$

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

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Not very well known, though...

$\gamma_e = E_e/m_e \longrightarrow$ Lorentz factor

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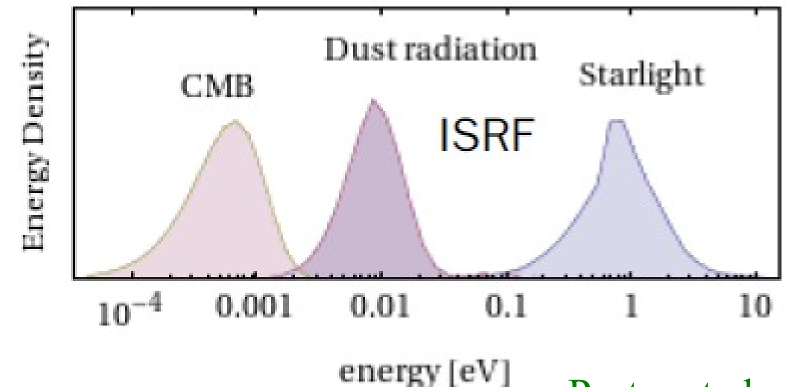

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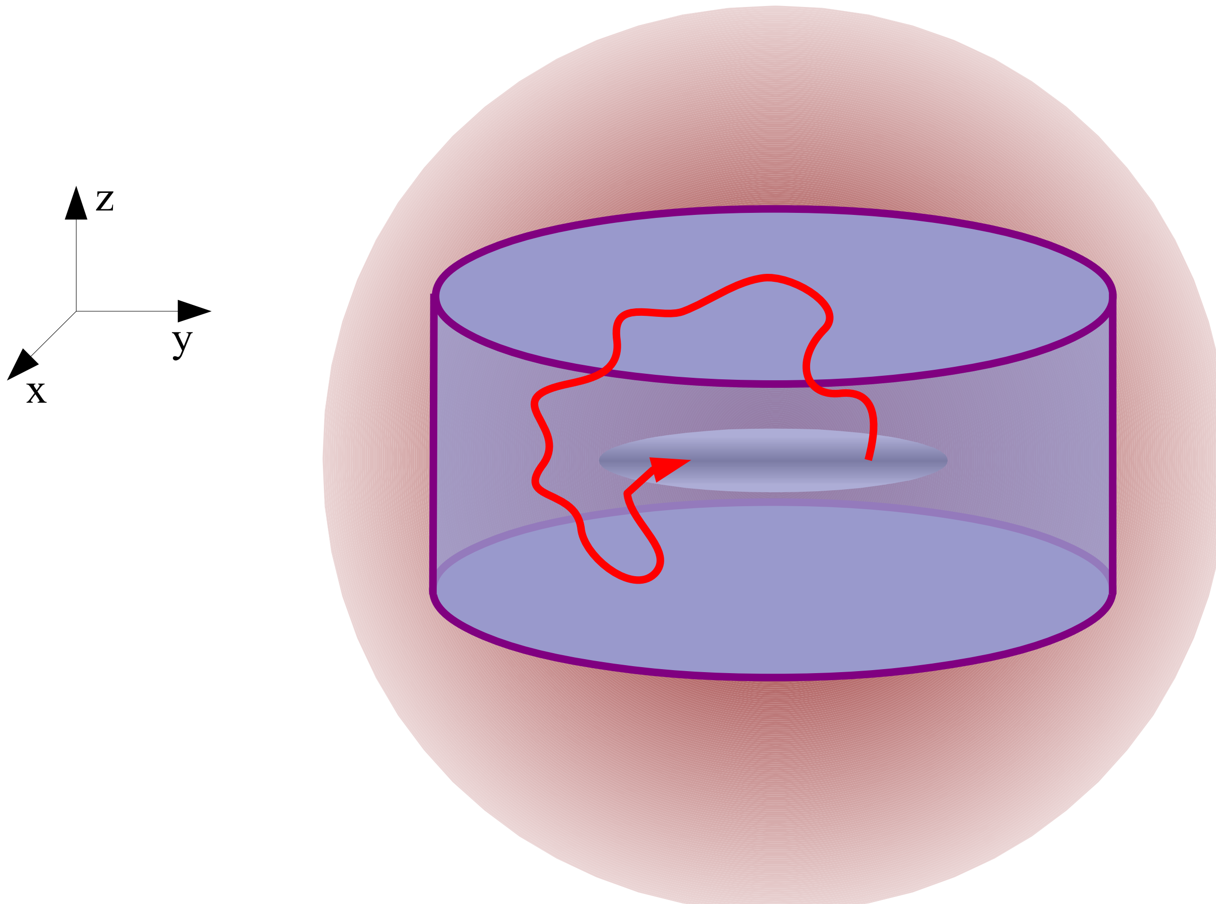

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Diffusion term

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

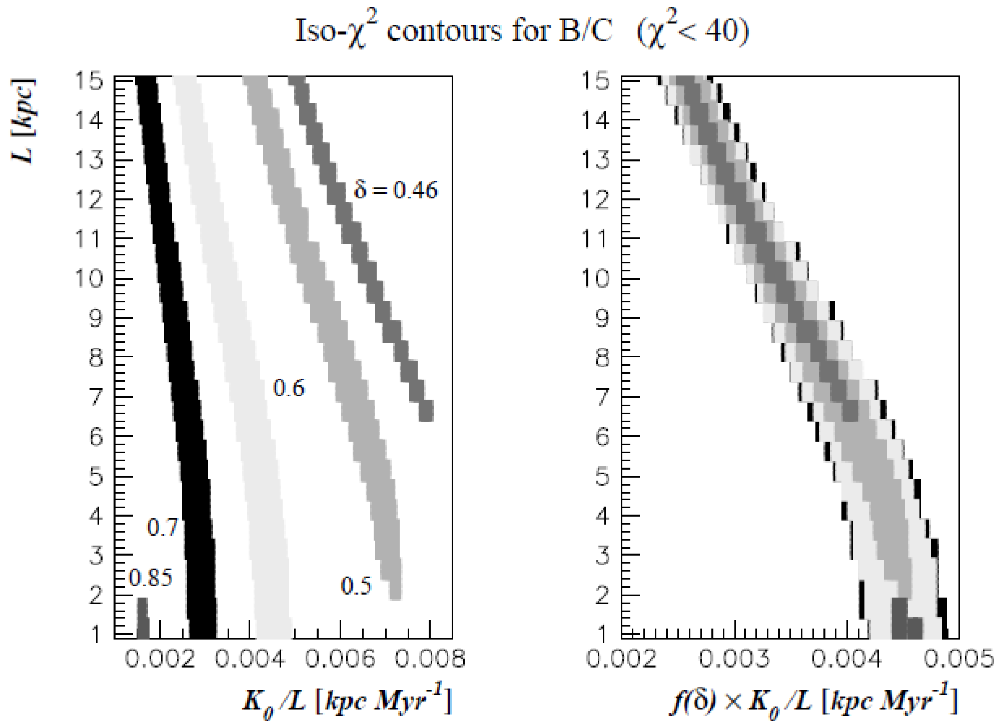
$$K(T) = K_0\, \beta\, \mathcal{R}^\delta$$

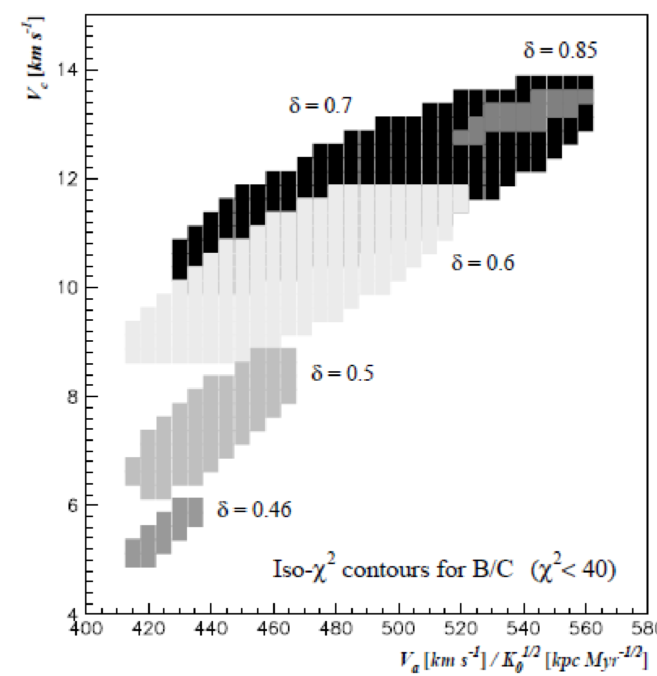
β = velocity
$\mathcal{R}$ = rigidity

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

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

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



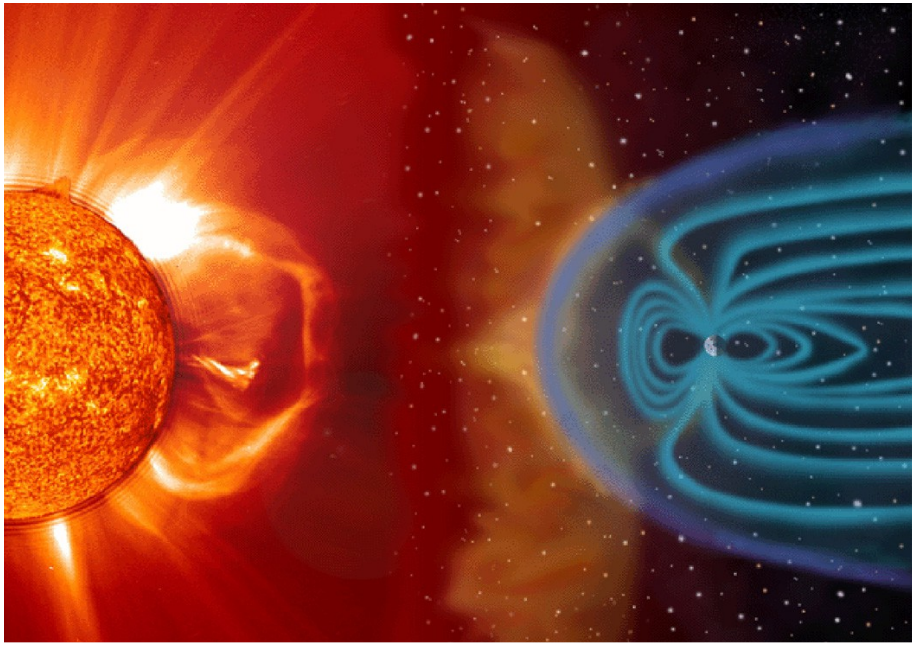


Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

Maurin, Donato, Taillet, Salati '01

WE ARE HERE
SCUTUM ARM
SAGITTARIUS ARM
NORMA ARM
CRUX ARM
CARINA ARM
ORION ARM
3 KPC ARM
Omega Centauri
NGC 5139
M92
M80
M4
Butterfly
M2 9
NGC 6397
Eagle M16
Lagoon M8
Omega M17
Wild Duck
M11
Trifid M20
Antares
Ring M57
Dumbbell
M27
NGC 7293
NGC 7027
North America
NGC 7000
Orion
M42
Cone NGC 2264
Rosette NGC 2237
Kappa Crucis
NGC 4755
Keyhole NGC 3324
Vela

Propagation inside the Solar System



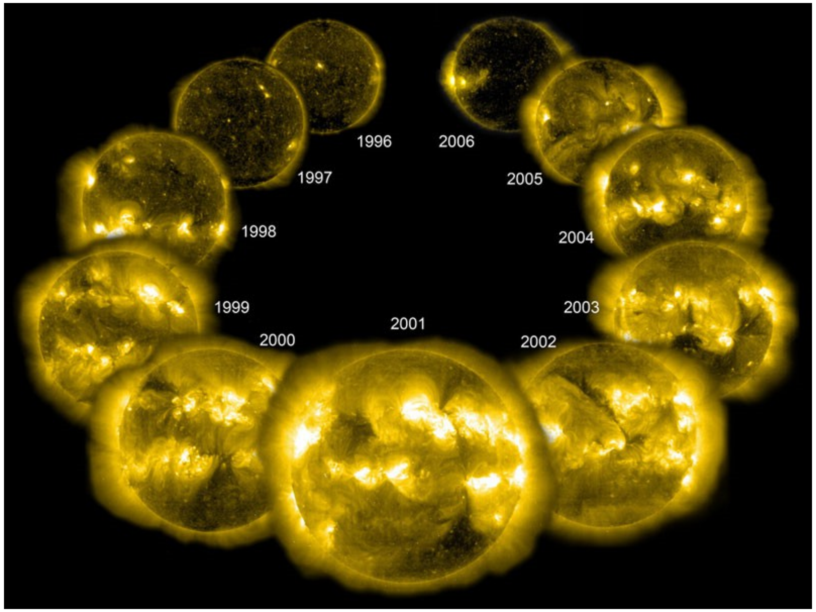
In the "force field approximation",the flux at the top of the atmosphere (TOA) is related to the interstellar flux (IS) by

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

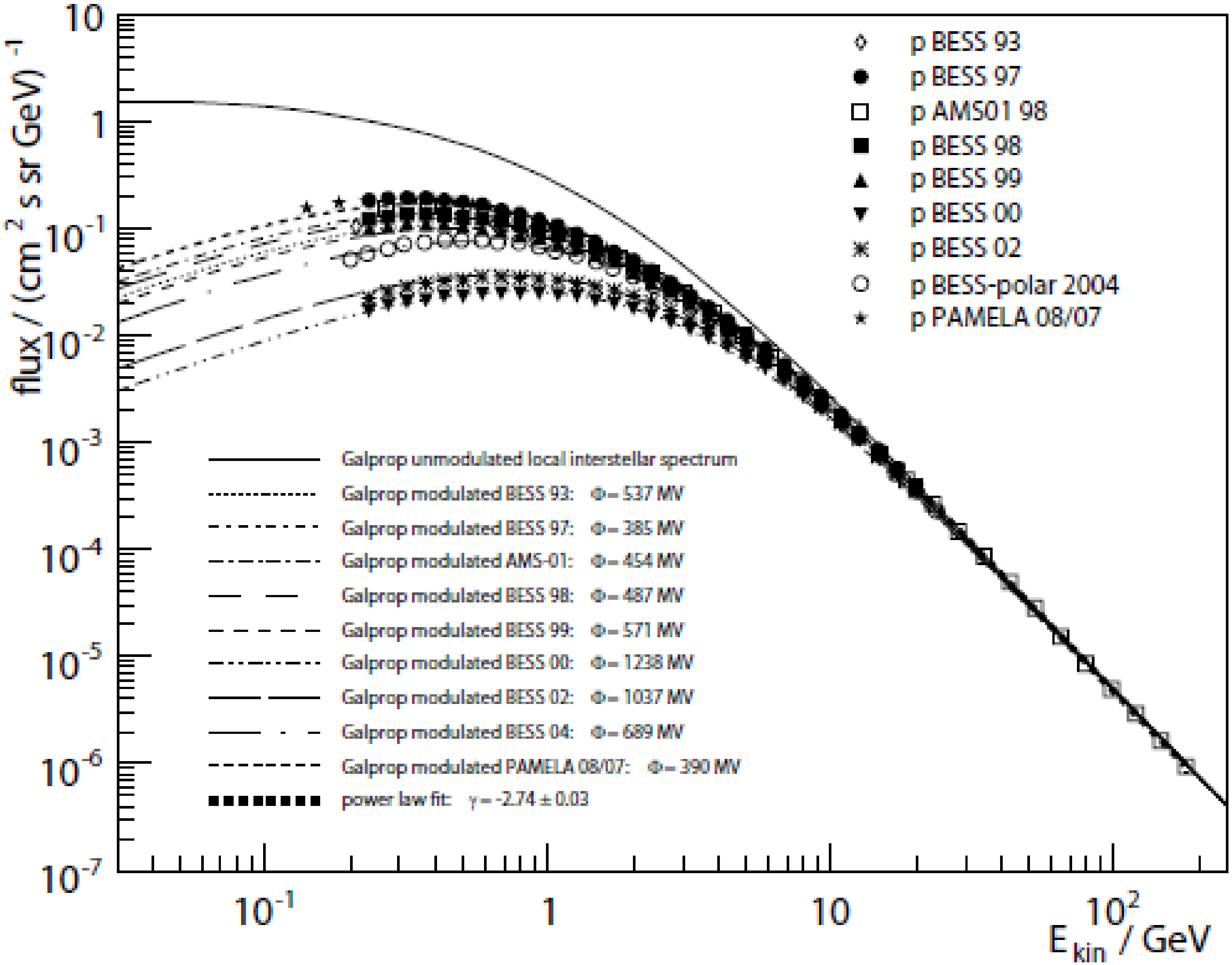
$$E_{\rm IS} = E_{\rm TOA} + \phi_F$$

solar modulation parameter

ϕ_F=500 MV – 1.3 GV

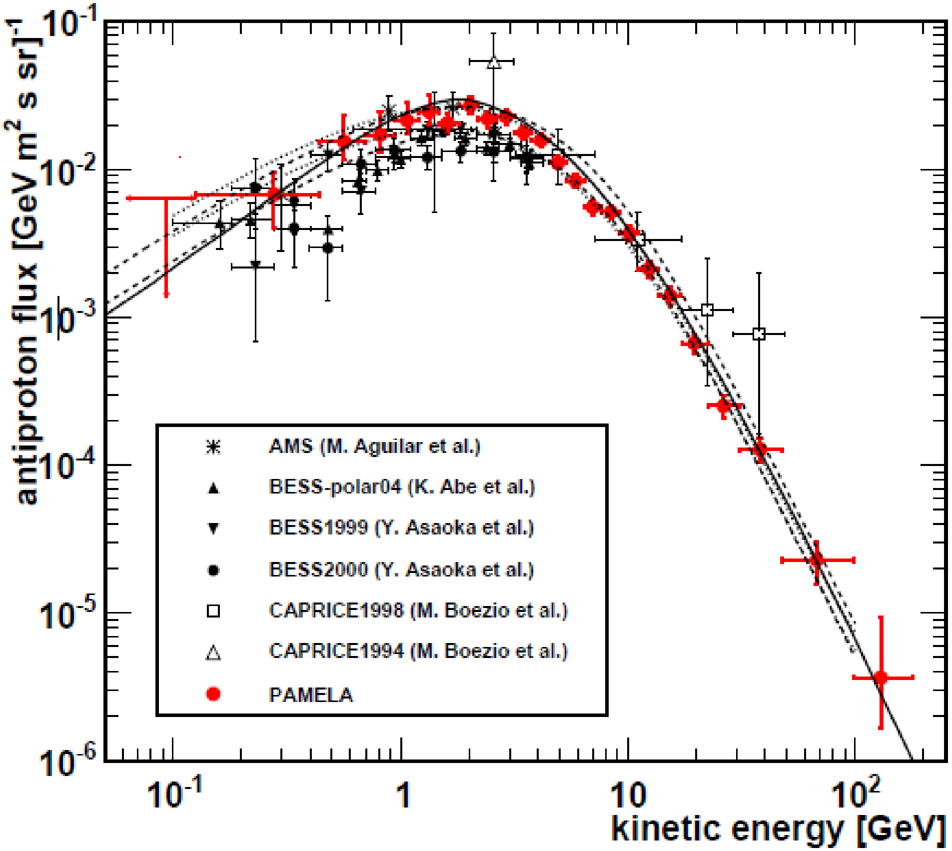


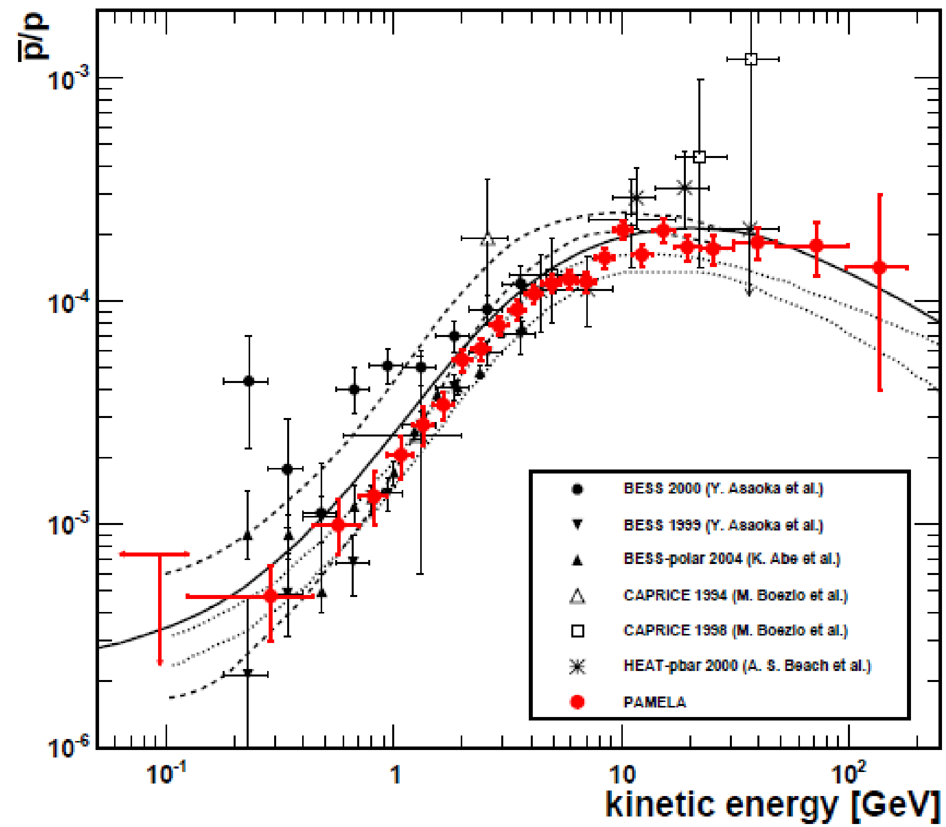
Cosmic ray proton spectrum as measured by BESS, AMS-01 and PAMELA



Gast, Schael '09

Experimental results: antiprotons





PAMELA collaboration
arXiv:1007.0821

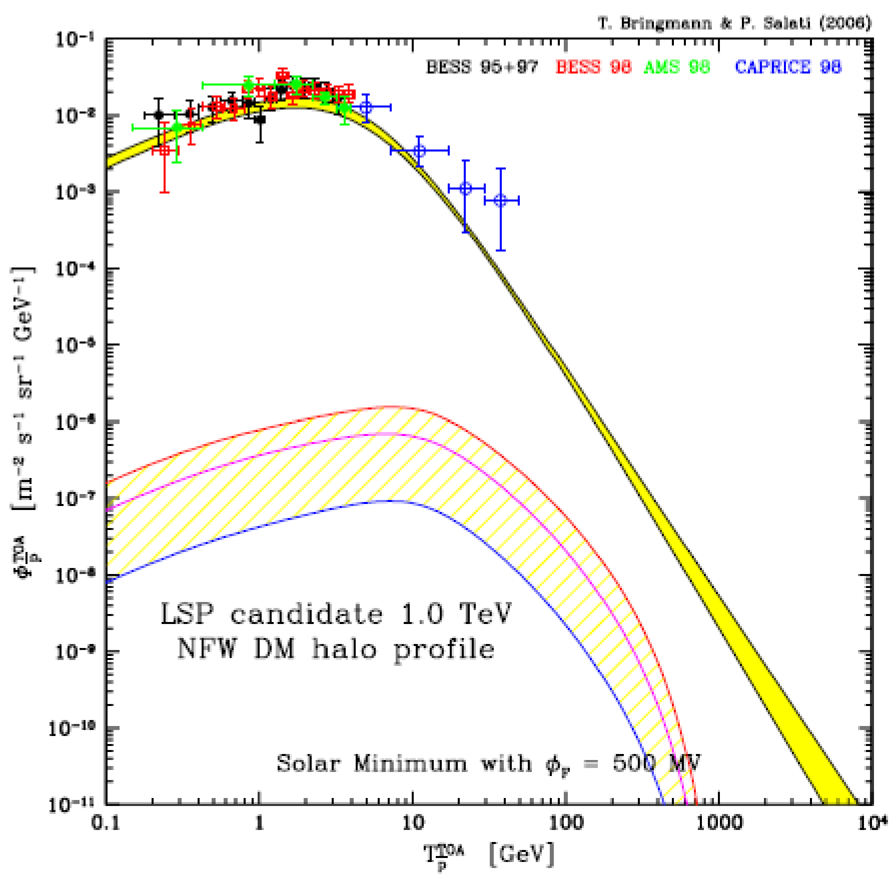
Fairly good agreement between the measurements and the theoretical predictions from collisions of cosmic rays on the interstellar medium $p\,p \rightarrow \bar{p}\,X$

Expectations from theory

A concrete example in the minimal supersymmetric standard model.

TeV $\times 10^{-26}$ cm^{3}s^{-1}

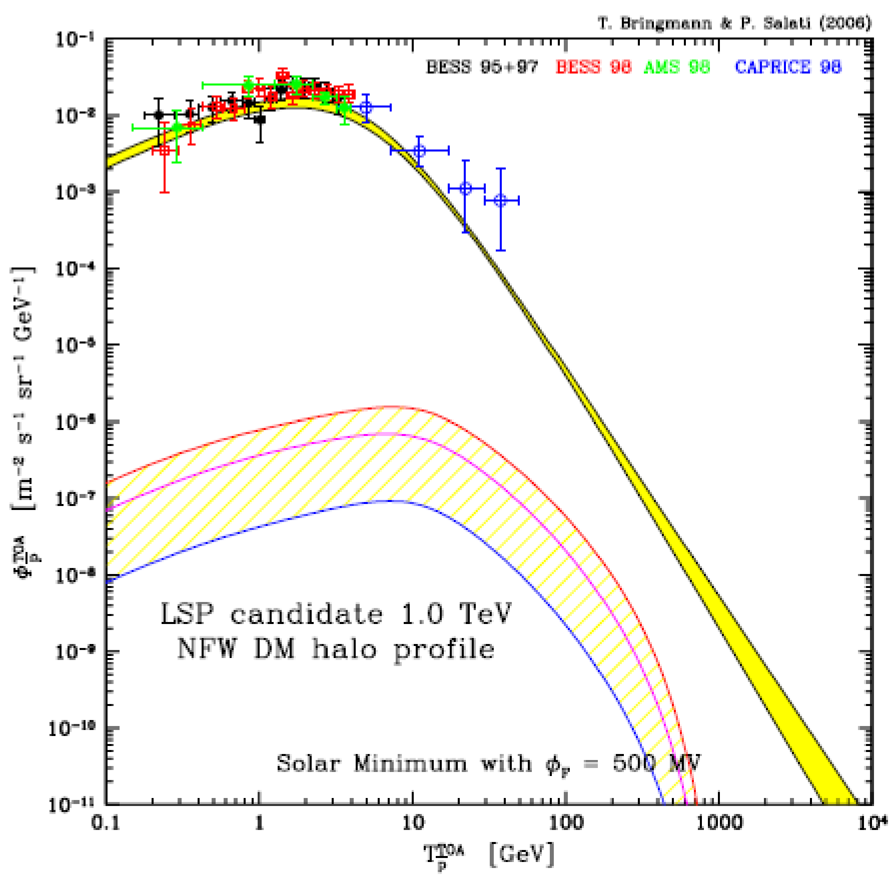
DM model	m	$\langle\sigma_{\rm ann}v\rangle$	$t\bar{t}$	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	ZZ	W^+W^-	HH	gg
LSP1.0	1.0	0.46	-	-	-	-	-	-	-	100	-	-

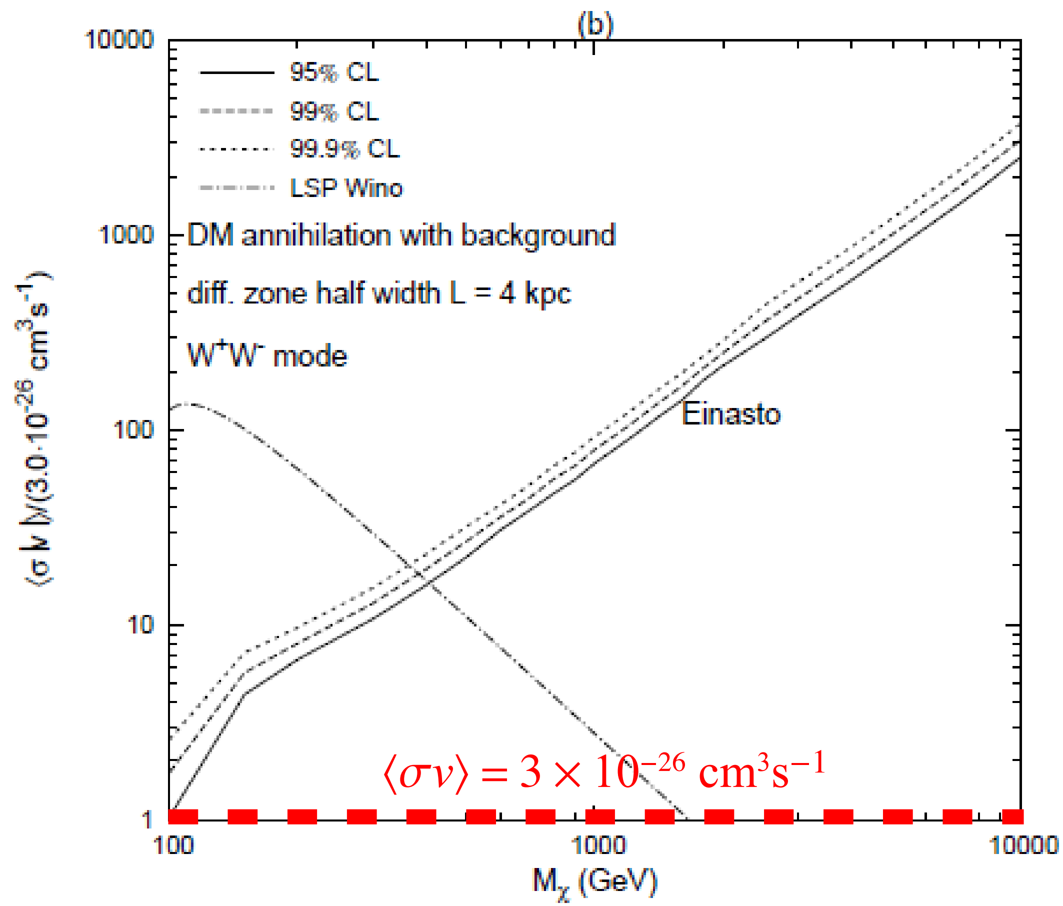


Expectations from theory

A concrete example in the minimal supersymmetric standard model.

DM model	m (TeV)	$\langle \sigma_{\rm ann} v \rangle$ ($\times 10^{-26}$ cm^{3}s^{-1})	$t\bar{t}$	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	ZZ	W^+W^-	HH	gg
LSP1.0	1.0	0.46	-	-	-	-	-	-	-	100	-	-





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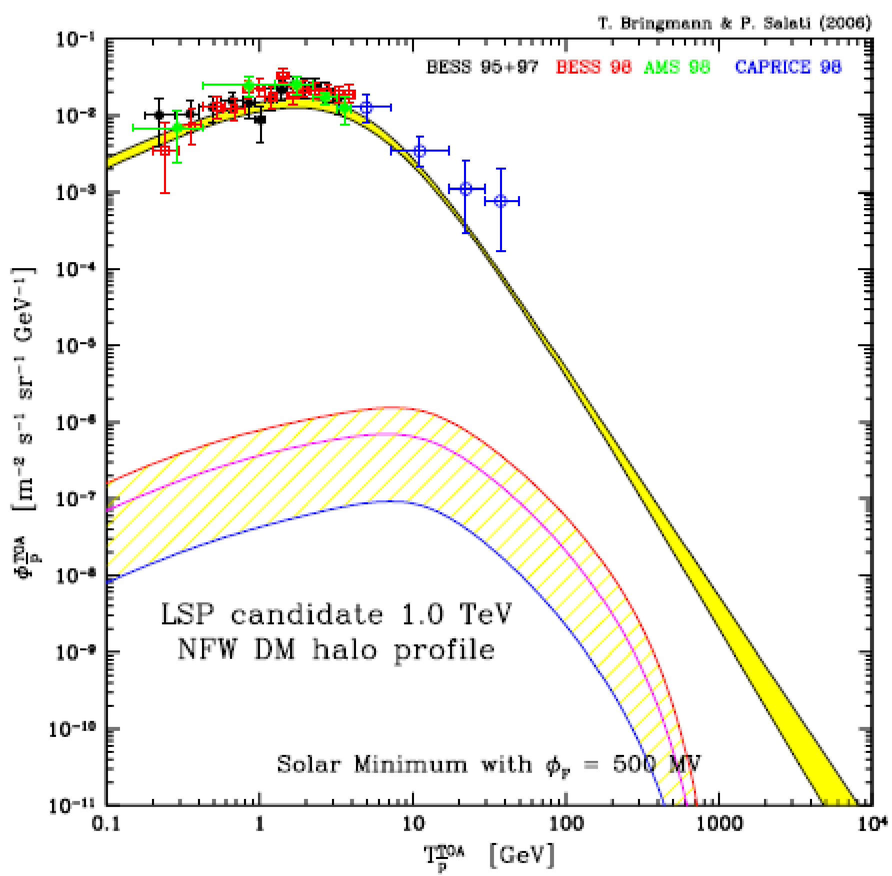
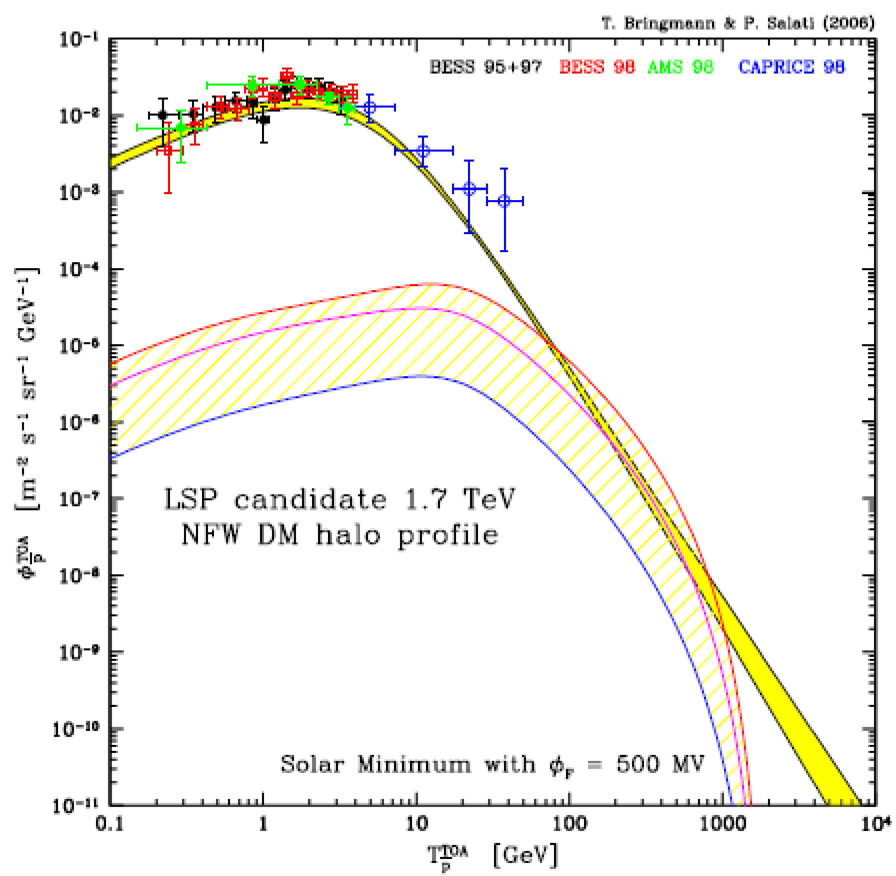
LSP1.0	1.0	0.46	-	-	-	-	-	-	-	100	-	-
LSP1.7	1.7	102	-	-	-	-	-	-	20.1	79.9	-	-





Expectations from theory

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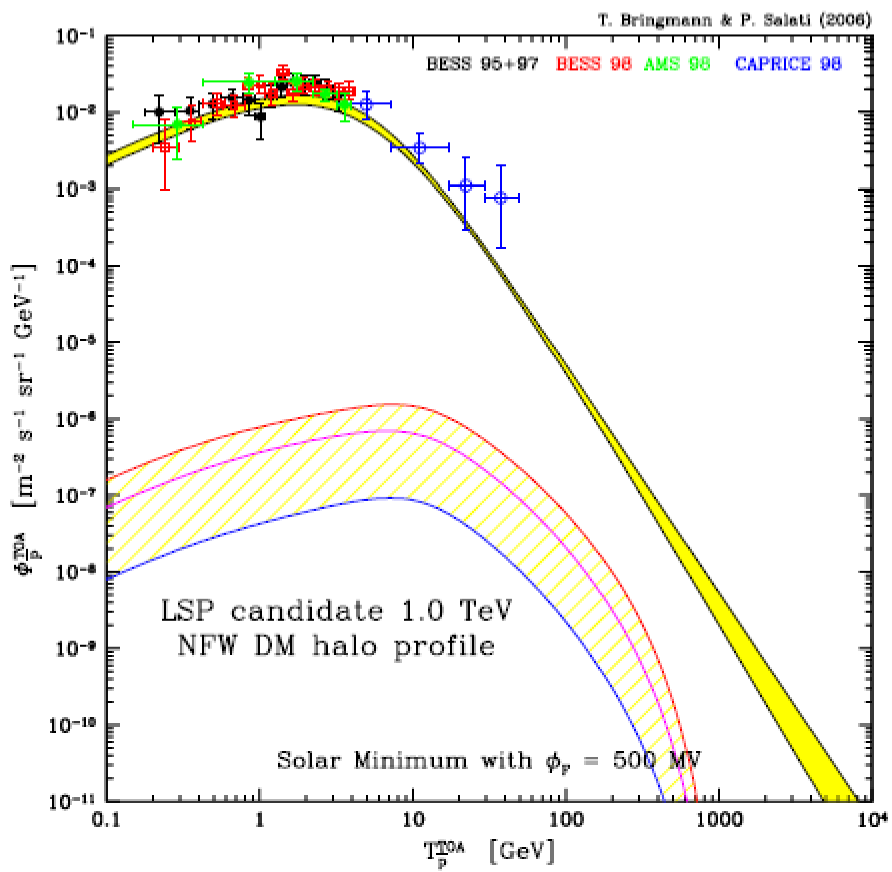
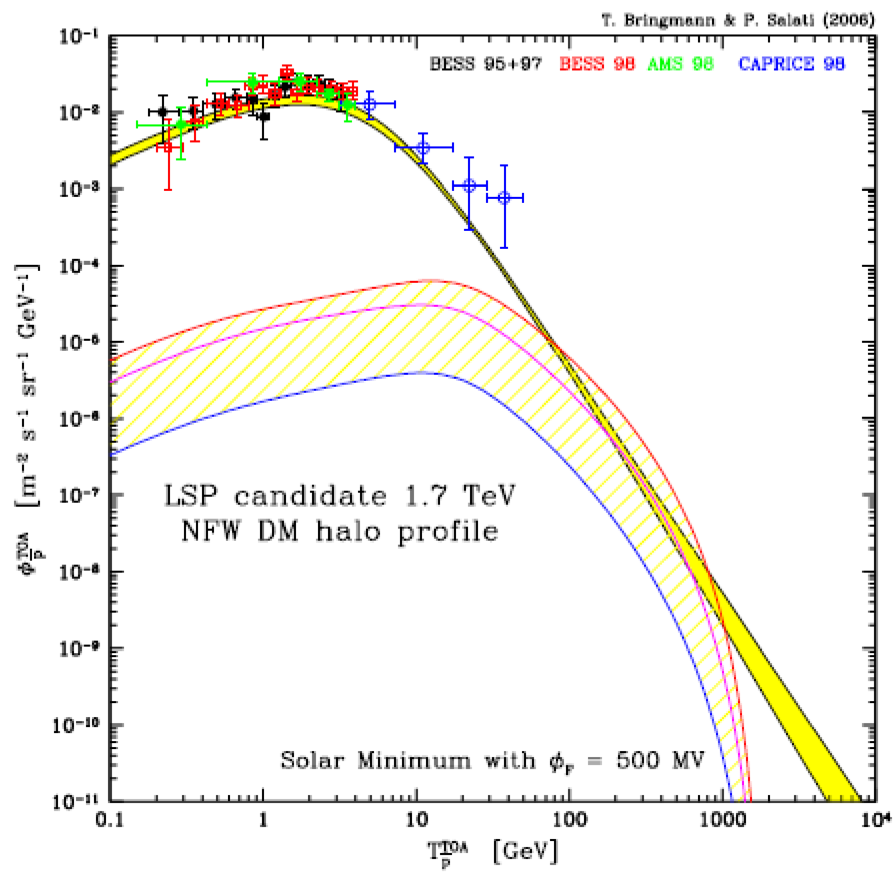
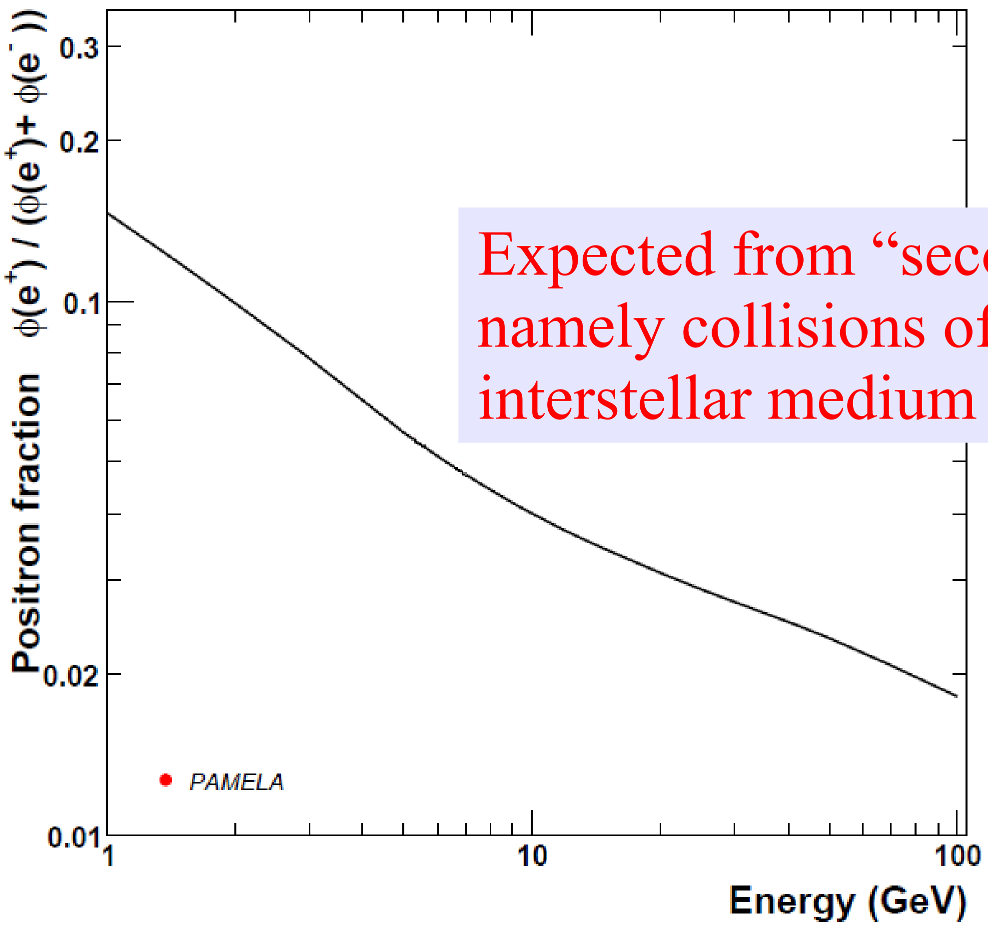
LSP1.0	1.0	0.46	-	-	-	-	-	-	-	100	-	-
LSP1.7	1.7	102	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-

Annihilation rate "boosted"!



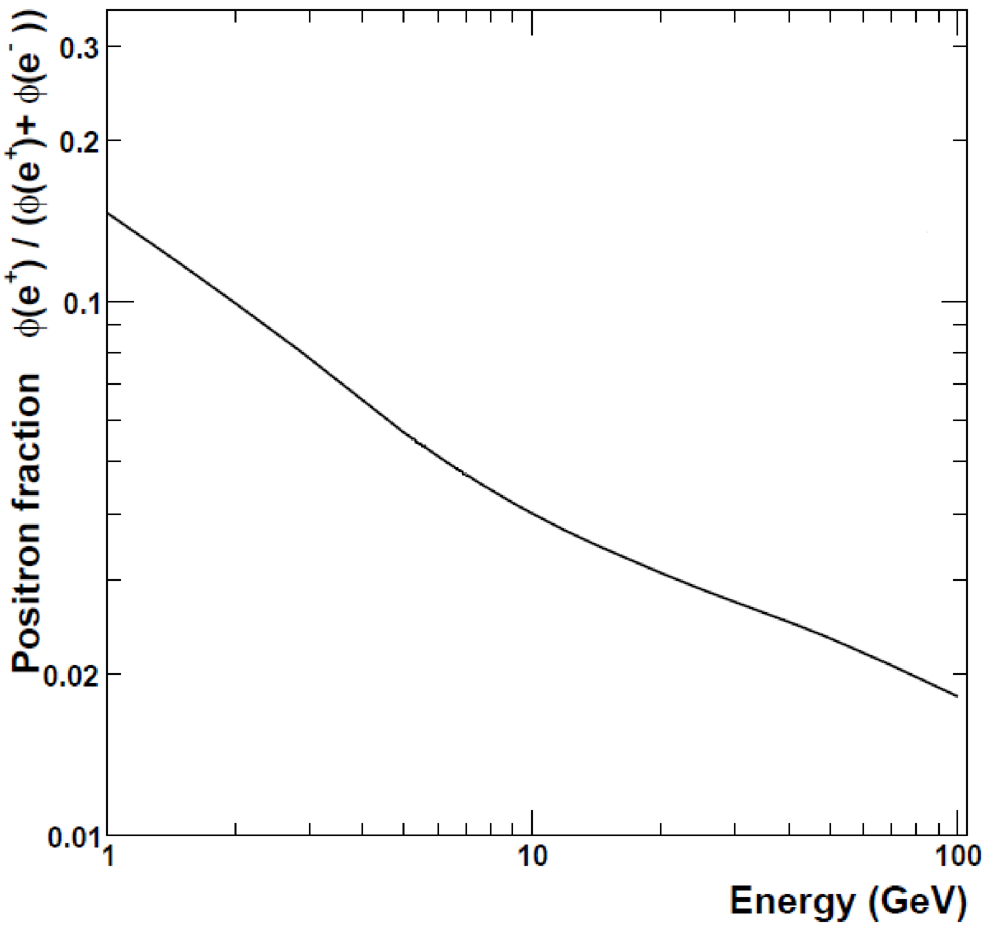


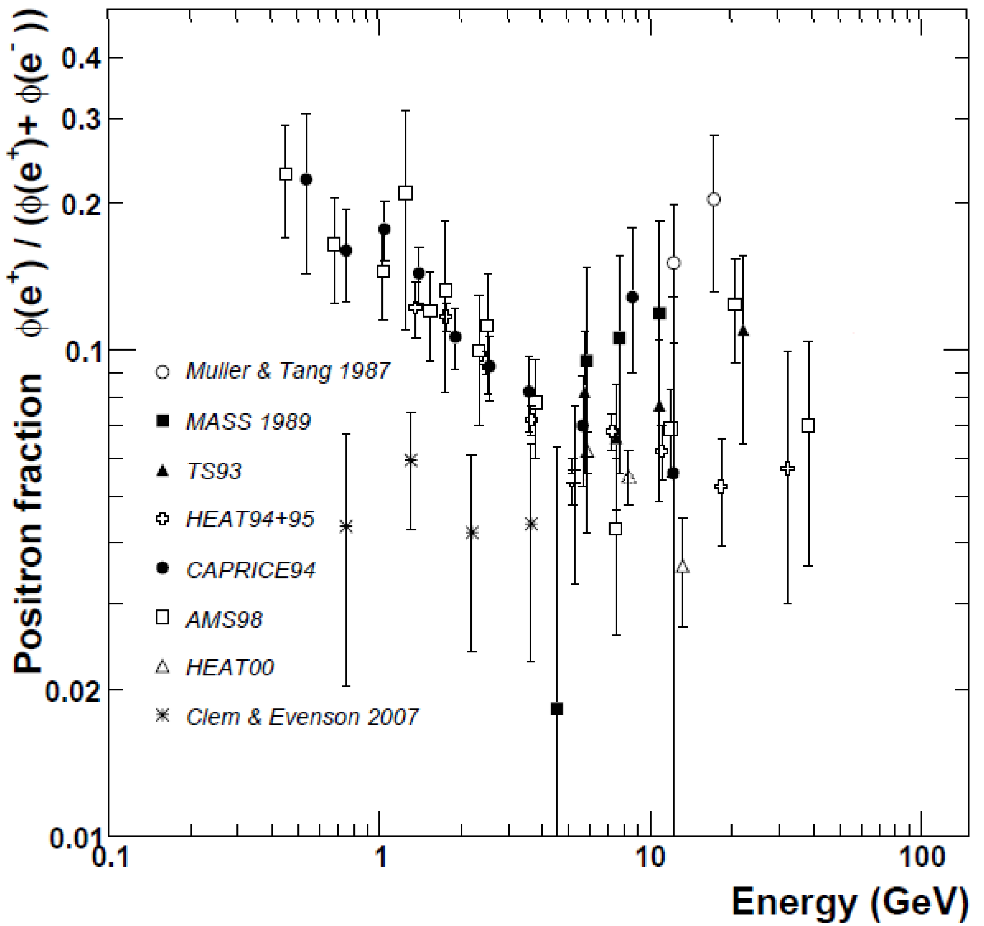
Experimental results: positrons



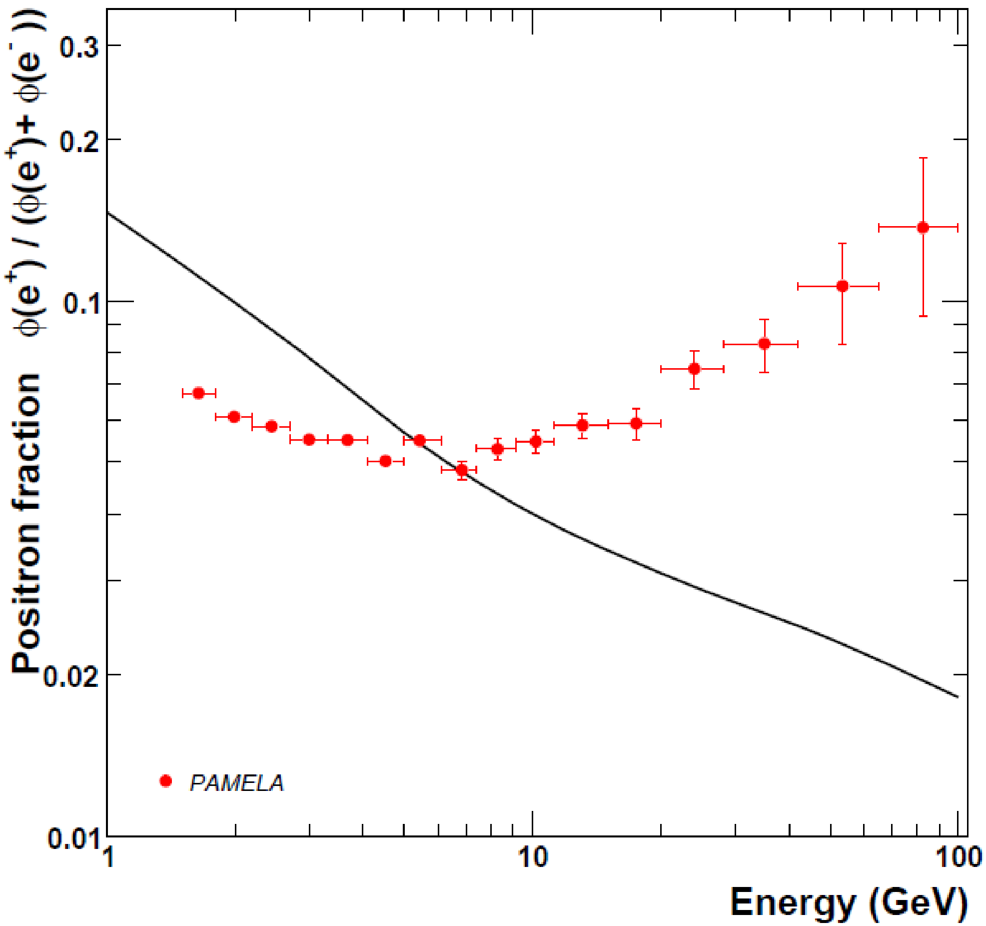
Expected from "secondary production", namely collisions of cosmic rays on the interstellar medium ($p\,p \to e^+ X$).

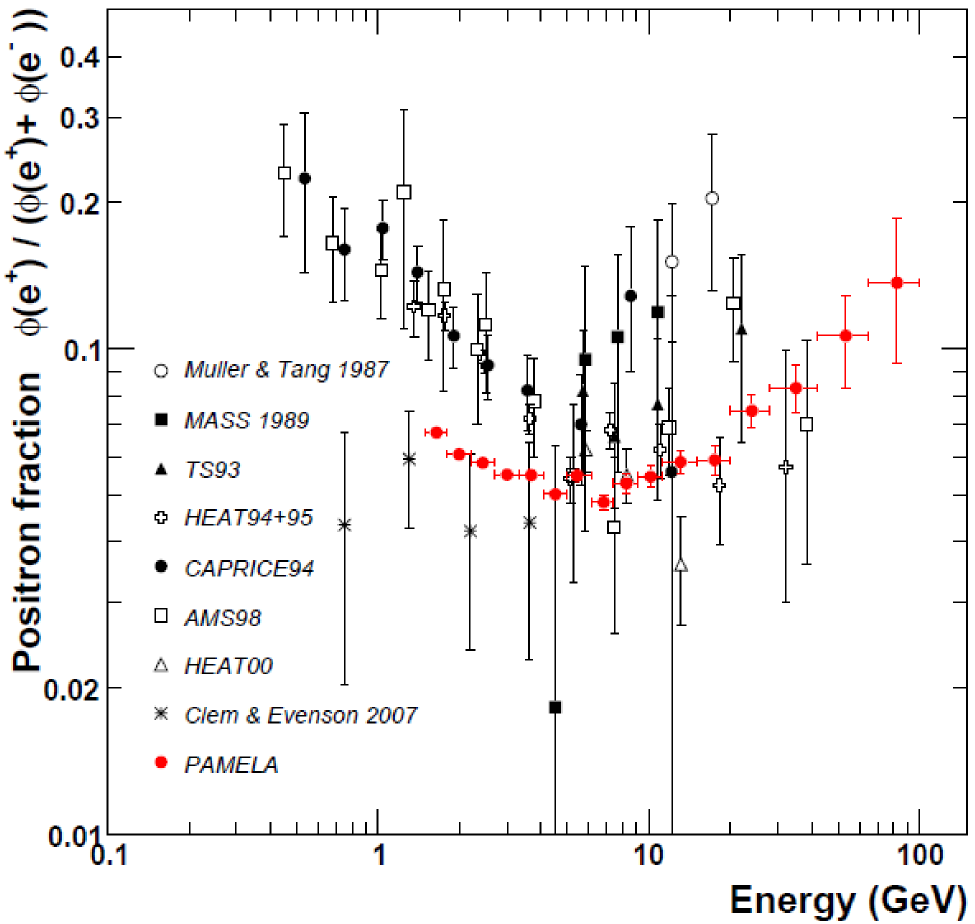
Experimental results: positrons





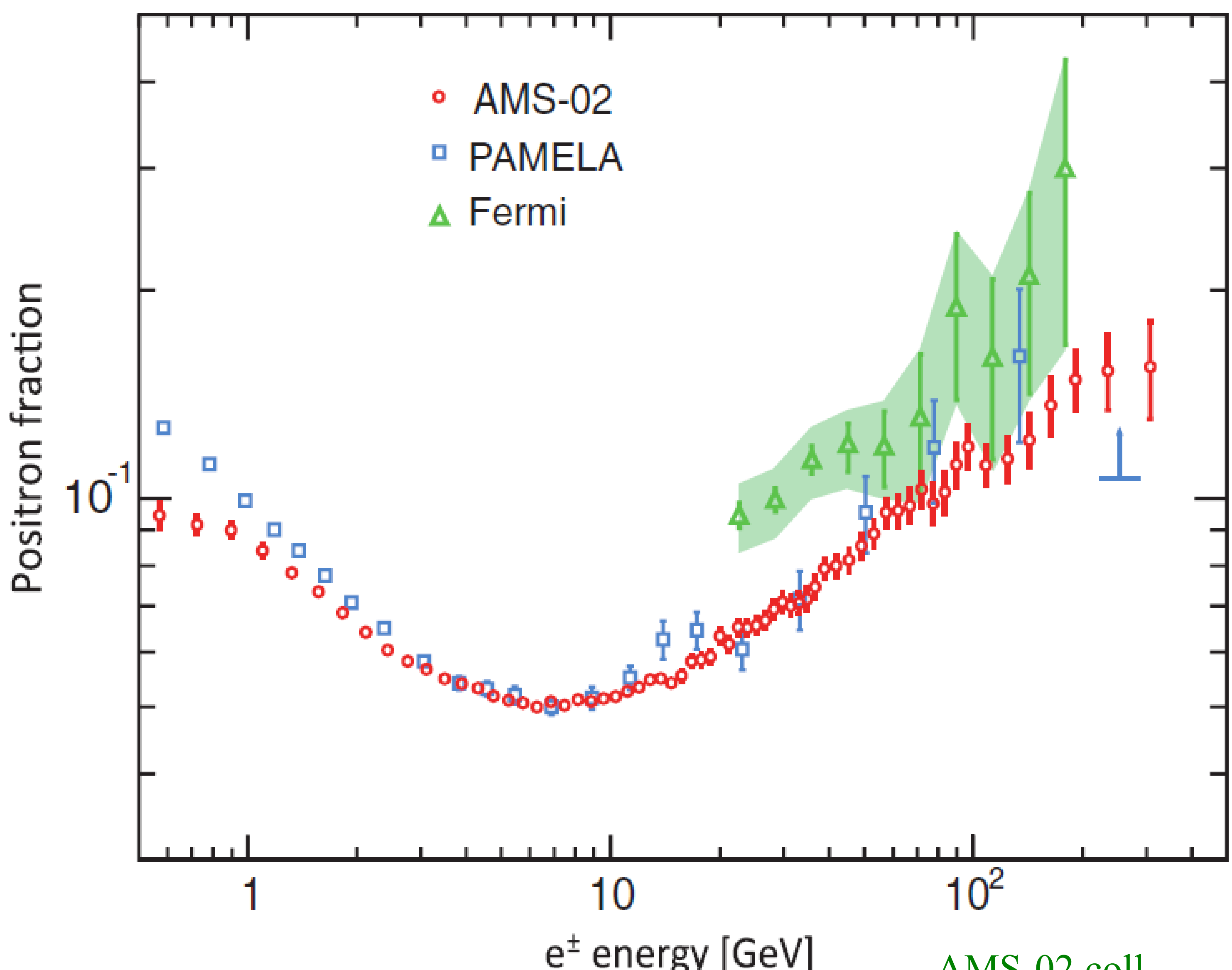
Experimental results: positrons





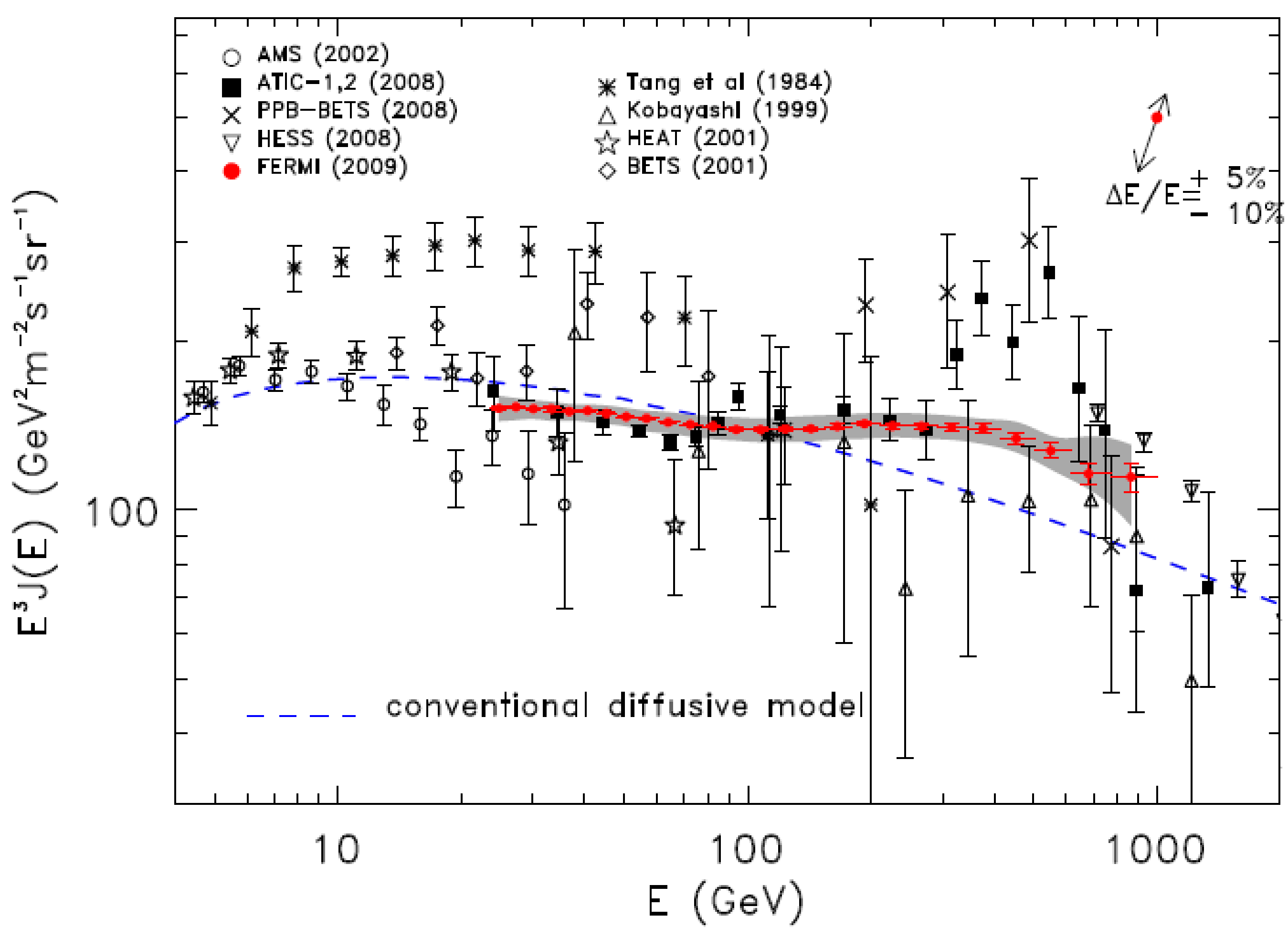
PAMELA coll.
arXiv:0810.4995

Experimental results: positrons



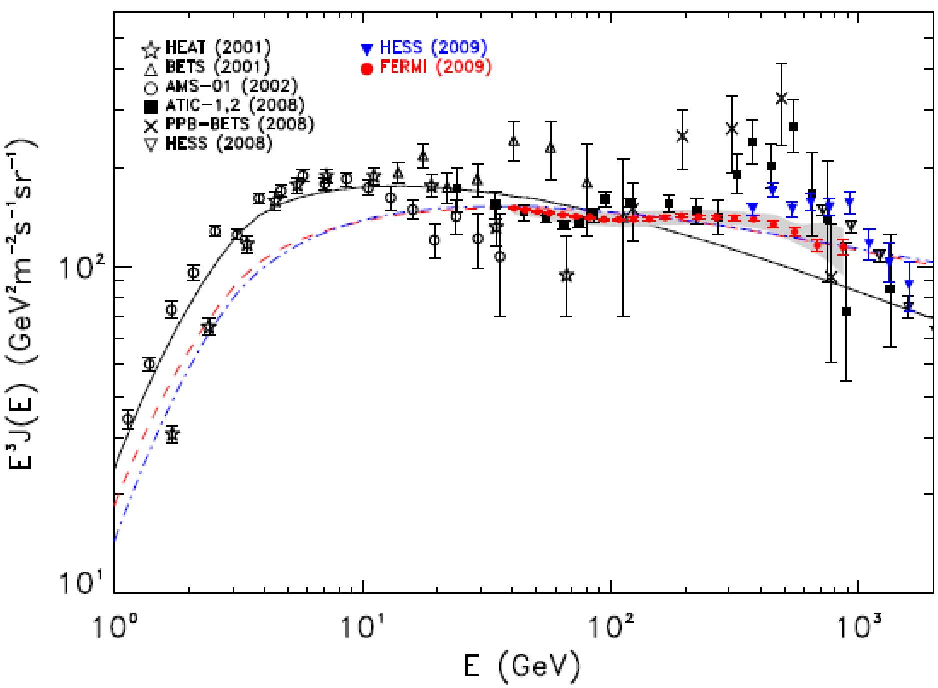
AMS-02 coll.
Phys.Rev.Lett. 110 (2013) 14, 141102

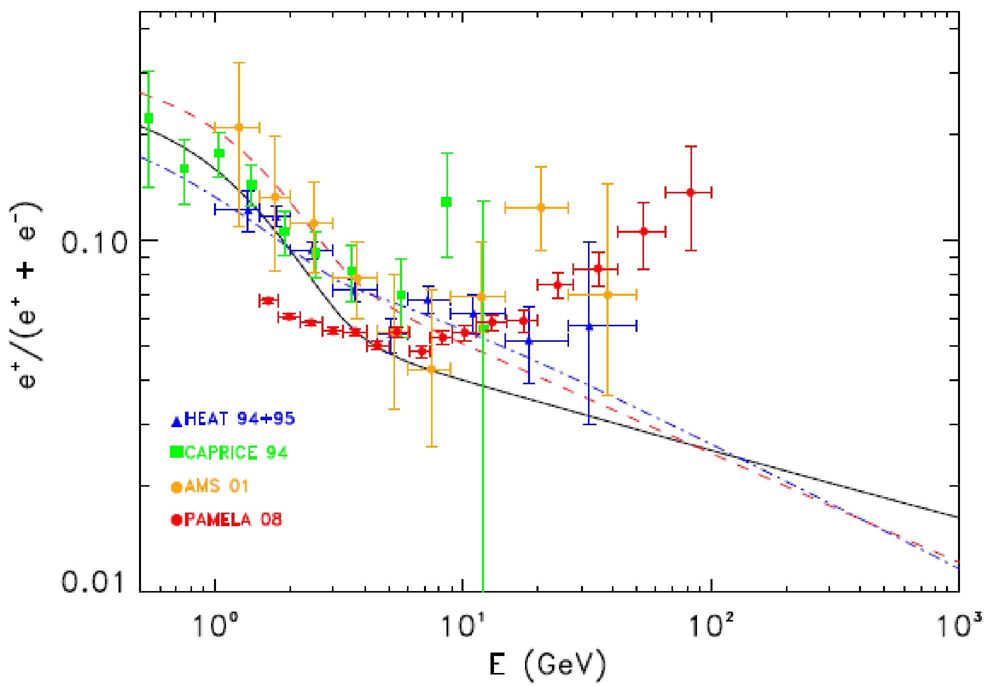
More puzzles: the electron+positron flux



Abdo et al.
ArXiv:0905.0025

Present situation:





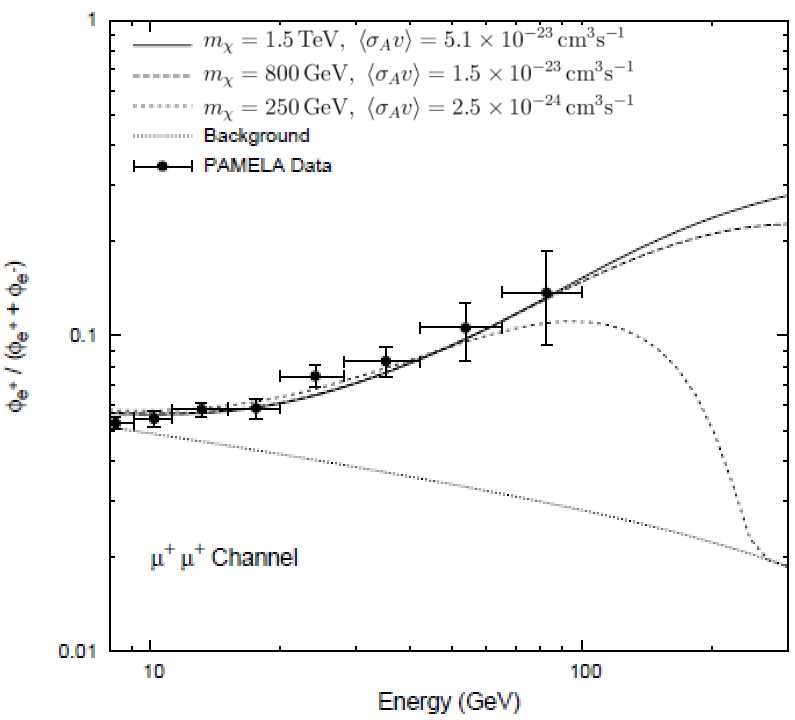
Evidence for a primary component of positrons

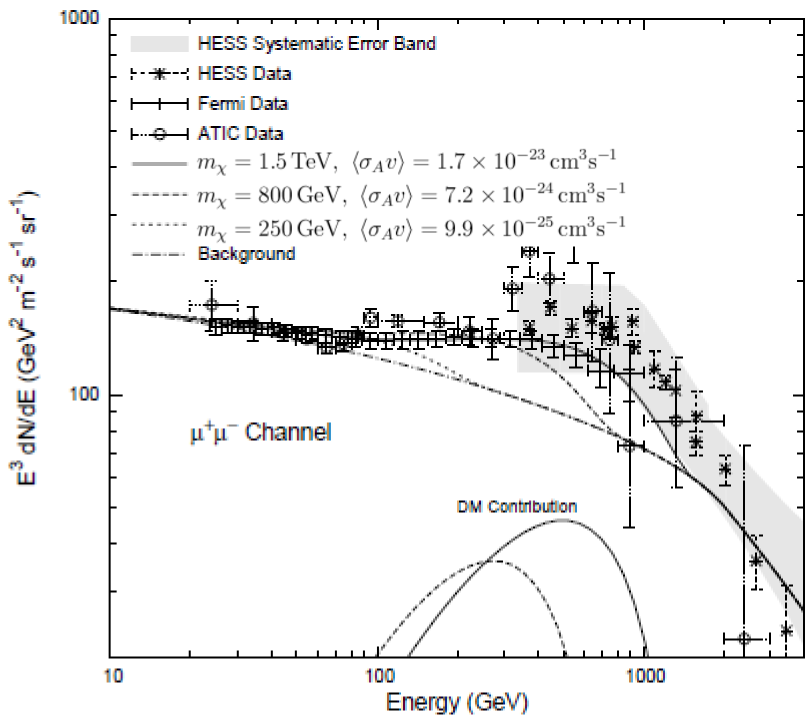
(possibly accompanied by electrons)

Dark matter interpretation

An electron/positron excess could arise from dark matter annihilations ...

$$\chi\chi \rightarrow \mu^+\mu^-$$

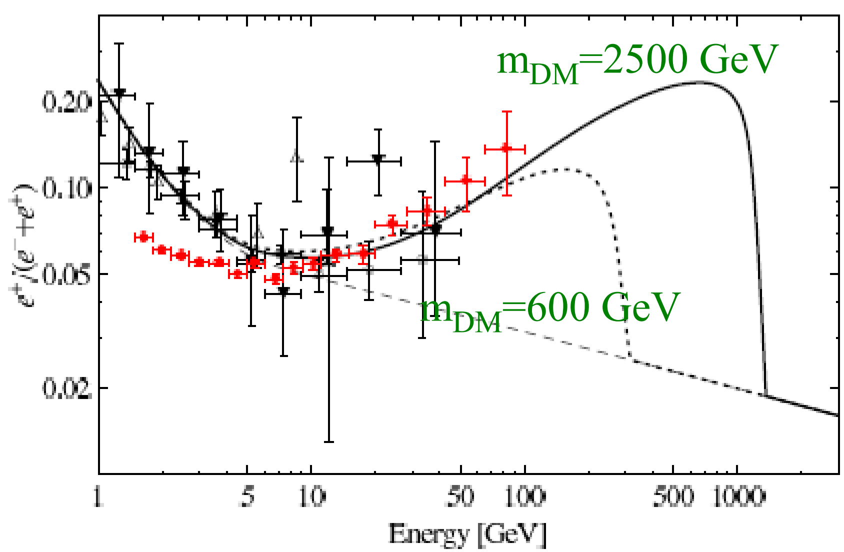


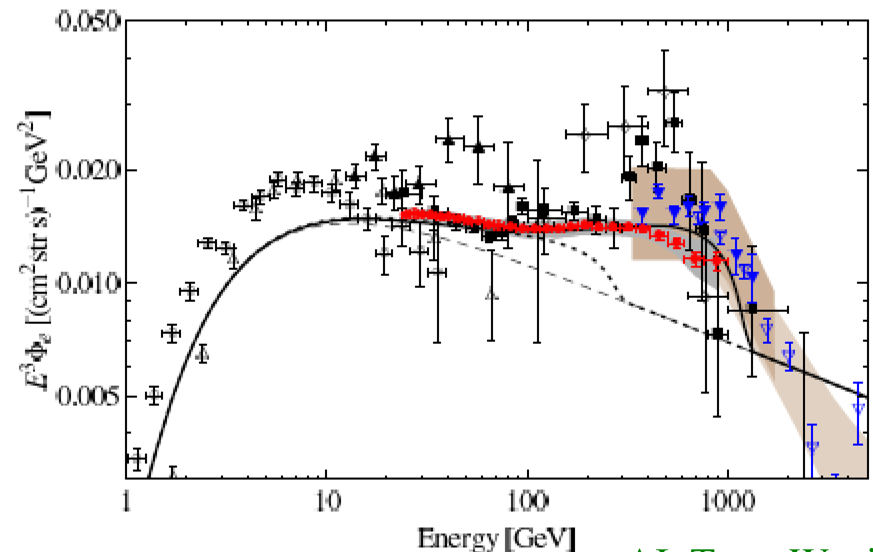


Cholis et al.
arXiv:0811.3641

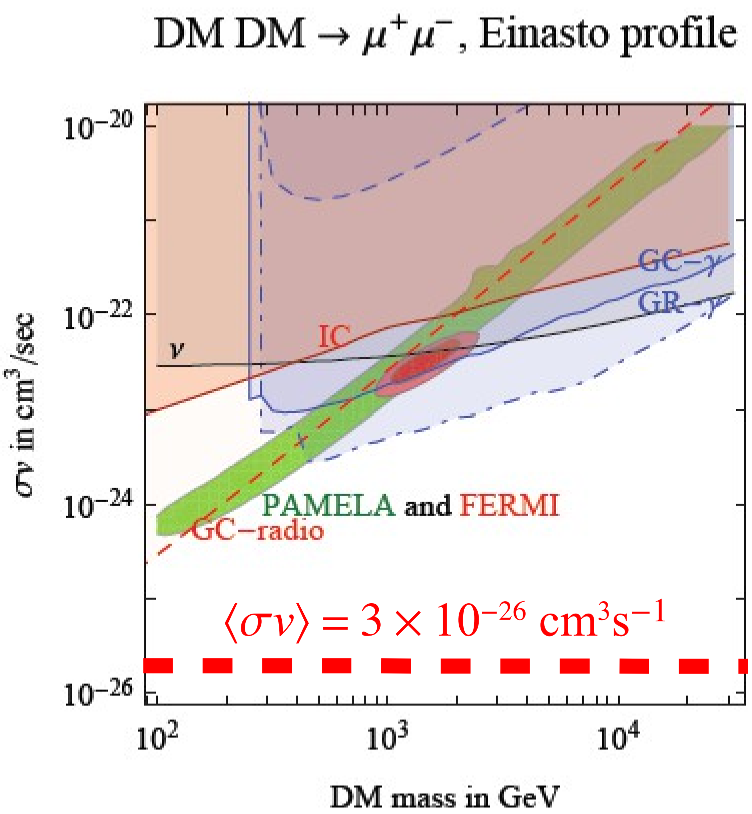
… or dark matter decays

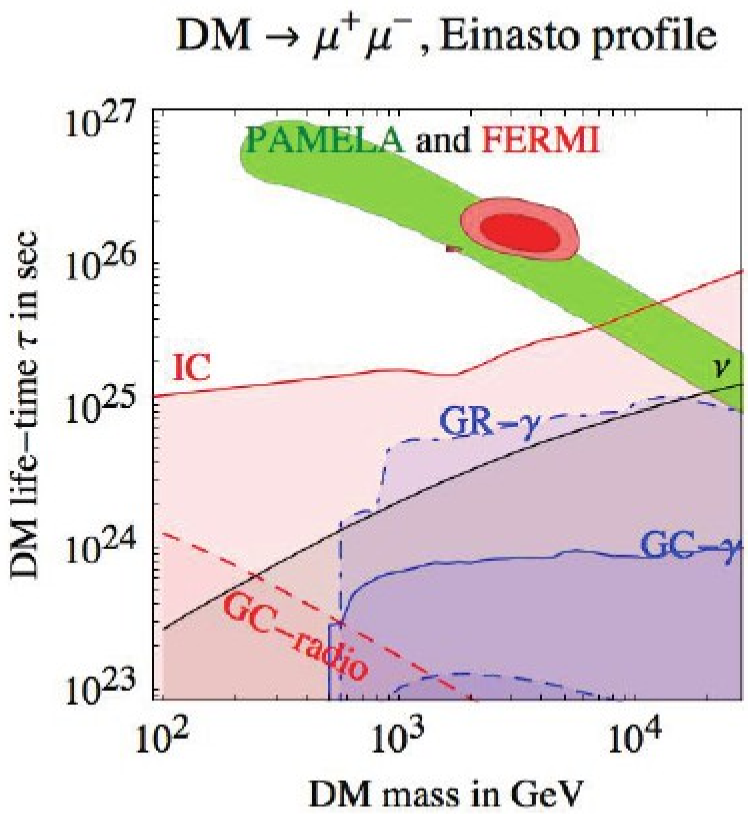
"Democratic" decay $\psi \to \ell^+ \ell^- \nu$





AI, Tran, Weniger
arXiv:0906.1571





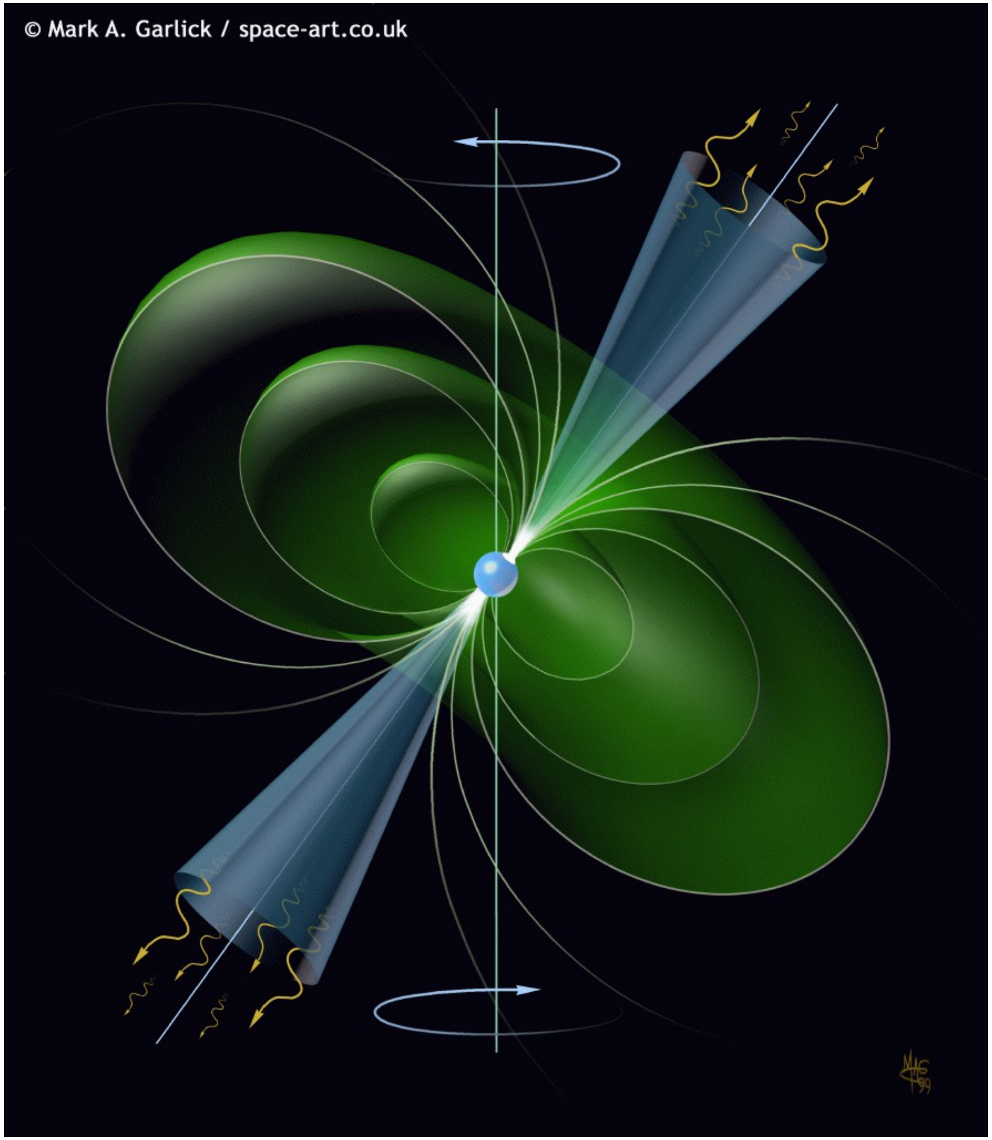
Is this the first non-gravitational evidence of dark matter?

"Extraordinary claims require extraordinary evidence"
Carl Sagan

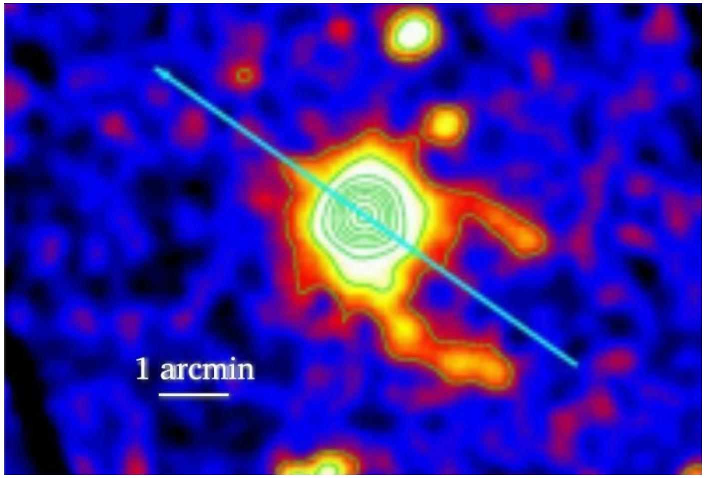
Beware of backgrounds!

Pulsars <u>are</u> sources of high energy electrons & positrons

Atoyan, Aharonian, Völk;
Chi, Cheng, Young;
Grimani

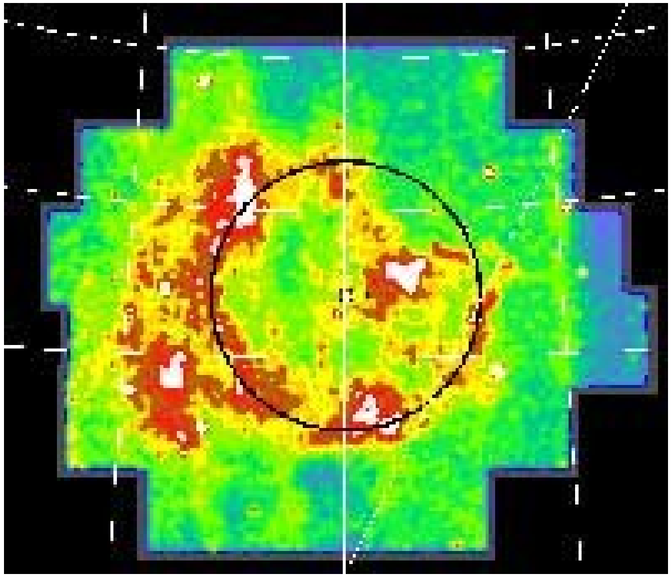


Pulsar explanation I: Geminga + Monogem



Geminga

T=370 000 years
D=157 pc

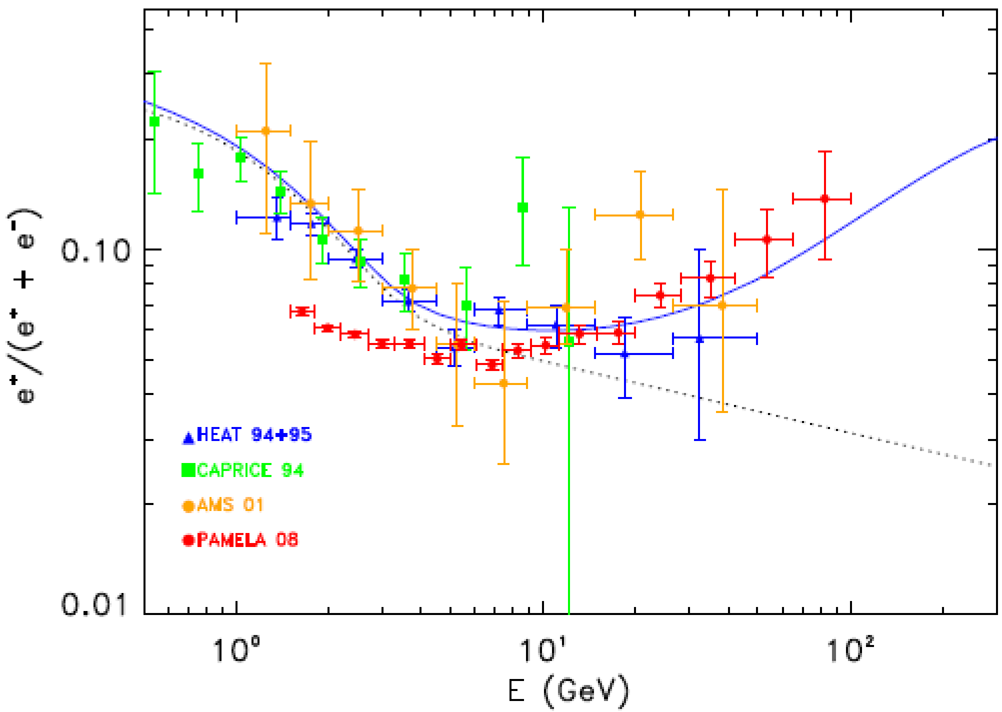


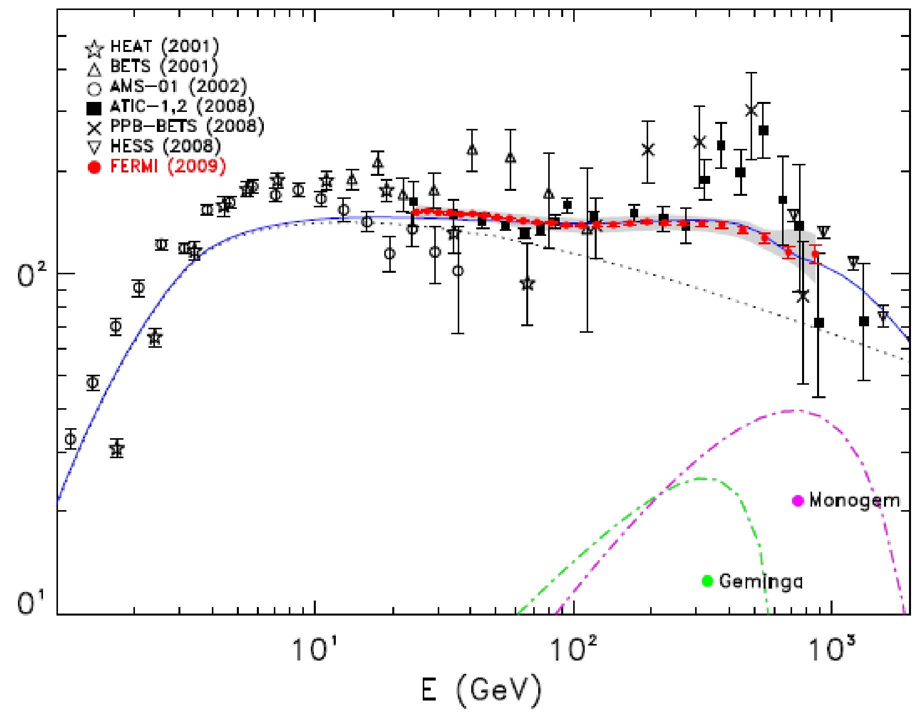
Monogem (B0656+14)

T=110 000 years
D=290 pc

Pulsar explanation I: Geminga + Monogem

Grasso et al.



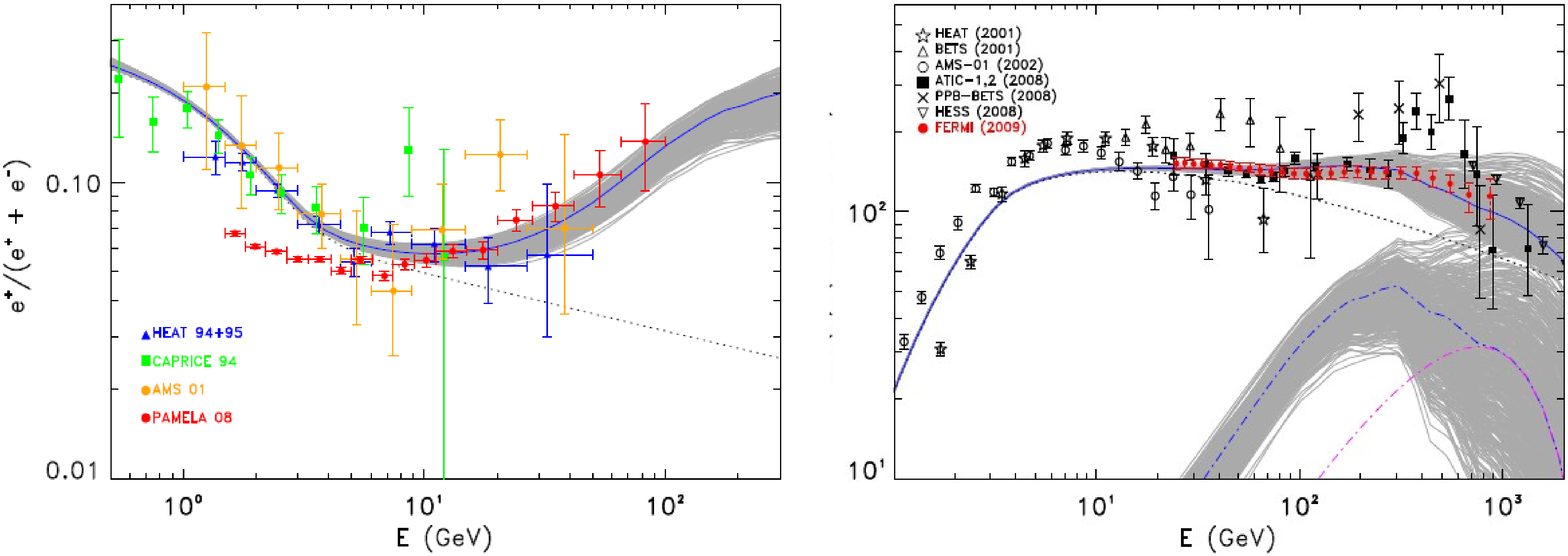


Nice agreement. However, it is <u>not</u> a prediction!

- $dN_e/dE_e \propto E_e^{-1.7} \exp(-E_e/1100\ \mathrm{GeV})$
- Energy output in e+e- pairs: 40% of the spin-down rate

Pulsar explanation II: Multiple pulsars

Grasso et al.



- $dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/E_0)$, $1.5 < \alpha < 1.9$, 800 GeV $< E_0 <$ 1400 GeV
- Energy output in e+e- pairs: between 10–30% of the spin-down rate

The origin of the positron excess is still unclear:

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- Dark matter? Probably not.

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- Pulsars? Perhaps yes.

The origin of the positron excess is still unclear:

- Dark matter? Probably not.
- Pulsars? Perhaps yes.
- Something else? Perhaps yes.