Indirect Dark Matter Detection

Alejandro Ibarra
Technische Universität München

Zakopane
May 2012

Dark matter
has been
indirectly detected

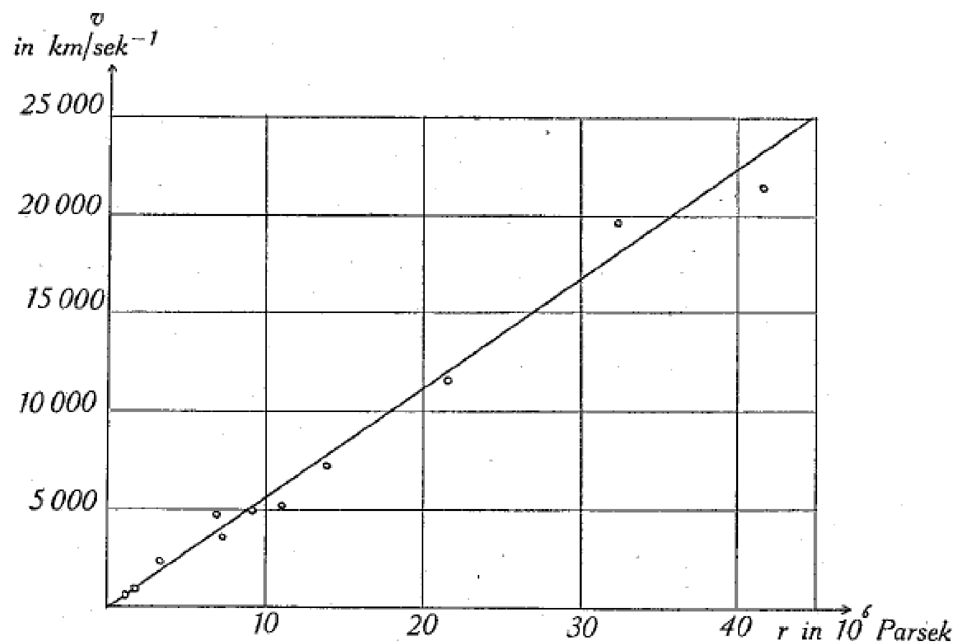
v
in km/sek⁻¹
25 000
20 000
15 000
10 000
5 000
10
20
30
40
r in 10⁶ Parsek

Fig. 2.

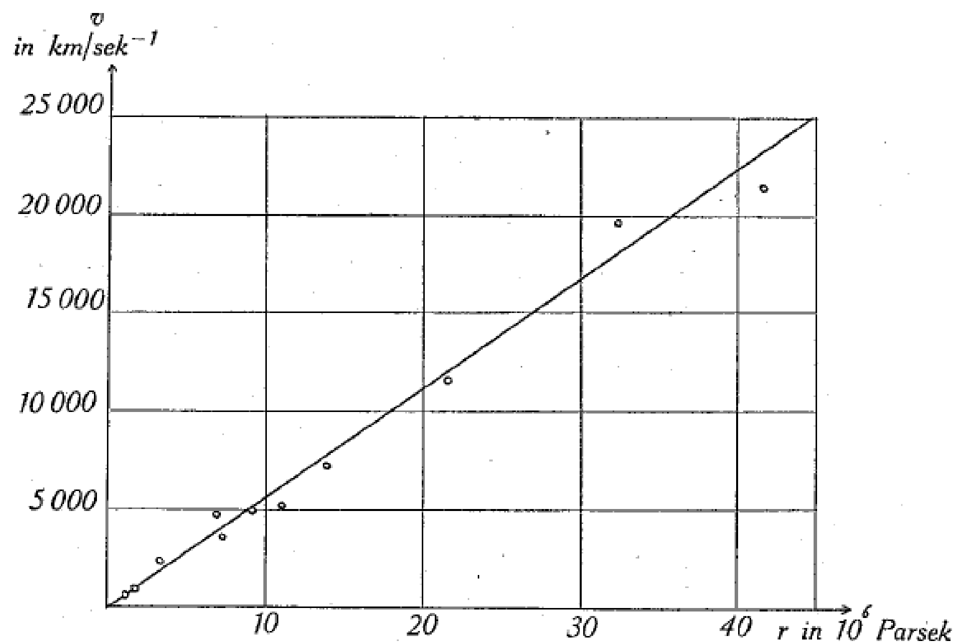

Fig. 2.

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung vøn Wichtigkeit zu werden verspricht.

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

1- Apply the virial theorem to determine the total mass of the Coma Cluster

For an isolated self-gravitating system,

$$2K + U = 0$$

$$K = \frac{1}{2}M\langle v^2\rangle \qquad U = -\frac{\alpha G M^2}{\mathcal{R}}$$

$$M = \frac{\langle v^2\rangle \mathcal{R}}{\alpha G}$$

$$\mathscr{M} > 9 \times 10^{46}\text{gr}$$

2- Count the number of galaxies (~1000) and calculate the average mass

$$\overline{M} > 9 \times 10^{43}\ \text{gr} = 4.5 \times 10^{10}\ M_{\odot}$$

1- Apply the virial theorem to determine the total mass of the Coma Cluster

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2- Count the number of galaxies (~1000) and calculate the average mass

$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_\odot$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500 , \tag{37}$$

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21

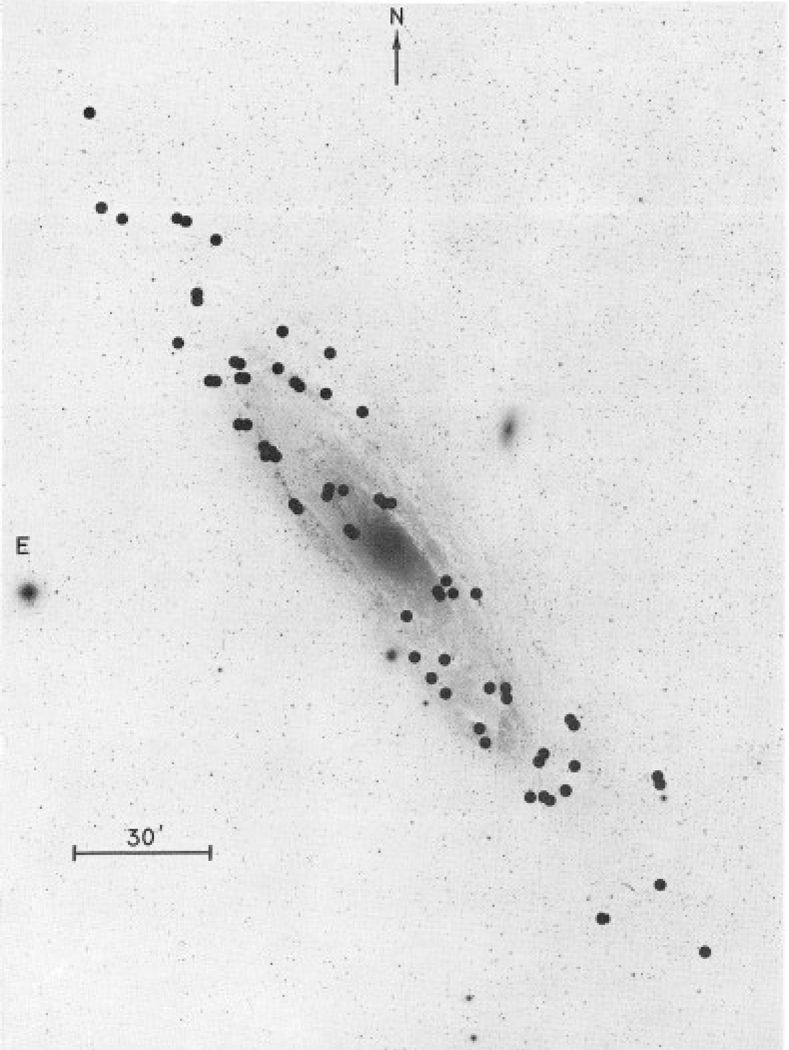
ABSTRACT

Spectra of sixty-seven H II regions from 3 to 24 kpc from the nucleus of M31 have been obtained with the DTM image-tube spectrograph at a dispersion of 135 Å mm^{-1}. Radial velocities, principally from Hα, have been determined with an accuracy of ± 10 km sec^{-1} for most regions. Rotational velocities have been calculated under the assumption of circular motions only.

For the region interior to 3 kpc where no emission regions have been identified, a narrow [N II] λ6583 emission line is observed. Velocities from this line indicate a rapid rotation in the nucleus, rising to a maximum circular velocity of $V = 225$ km sec^{-1} at $R = 400$ pc, and falling to a deep minimum near $R = 2$ kpc.

From the rotation curve for $R \leq 24$ kpc, the following disk model of M31 results. There is a dense, rapidly rotating nucleus of mass $M = (6 \pm 1) \times 10^9 M_\odot$. Near $R = 2$ kpc, the density is very low and the rotational motions are very small. In the region from 500 to 1.4 kpc (most notably on the southeast minor axis), gas is observed leaving the nucleus. Beyond $R = 4$ kpc the total mass of the galaxy increases approximately linearly to $R = 14$ kpc, and more slowly thereafter. The total mass to $R = 24$ kpc is $M = (1.85 \pm 0.1) \times 10^{11} M_\odot$; one-half of it is located in the disk interior to $R = 9$ kpc. In many respects this model resembles the model of the disk of our Galaxy. Outside the nuclear region, there is no evidence for noncircular motions.

The optical velocities, $R > 3$ kpc, agree with the 21-cm observations, although the maximum rotational velocity, $V = 270 \pm 10$ km sec^{-1}, is slightly higher than that obtained from 21-cm observations.



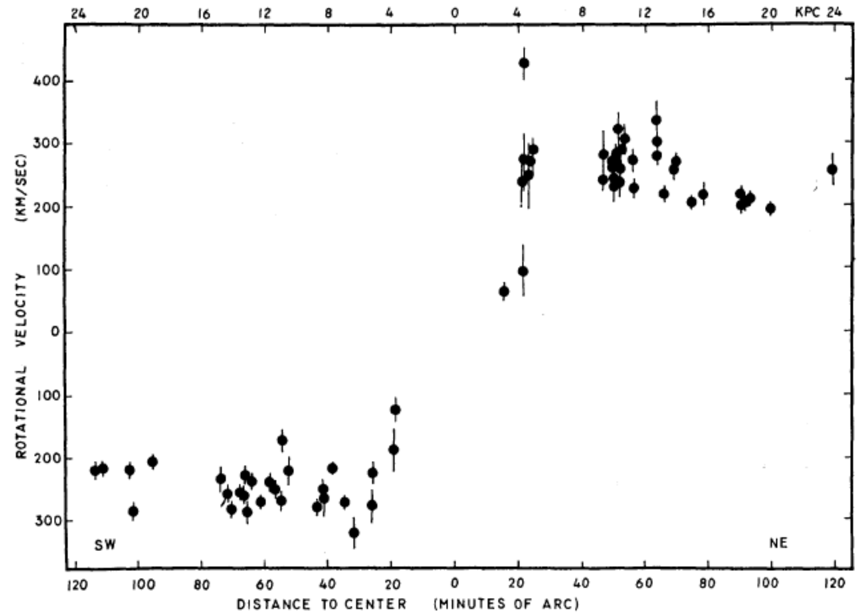


FIG. 3.—Rotational velocities for sixty-seven emission regions in M31, as a function of distance from the center. Error bars indicate average error of rotational velocities.

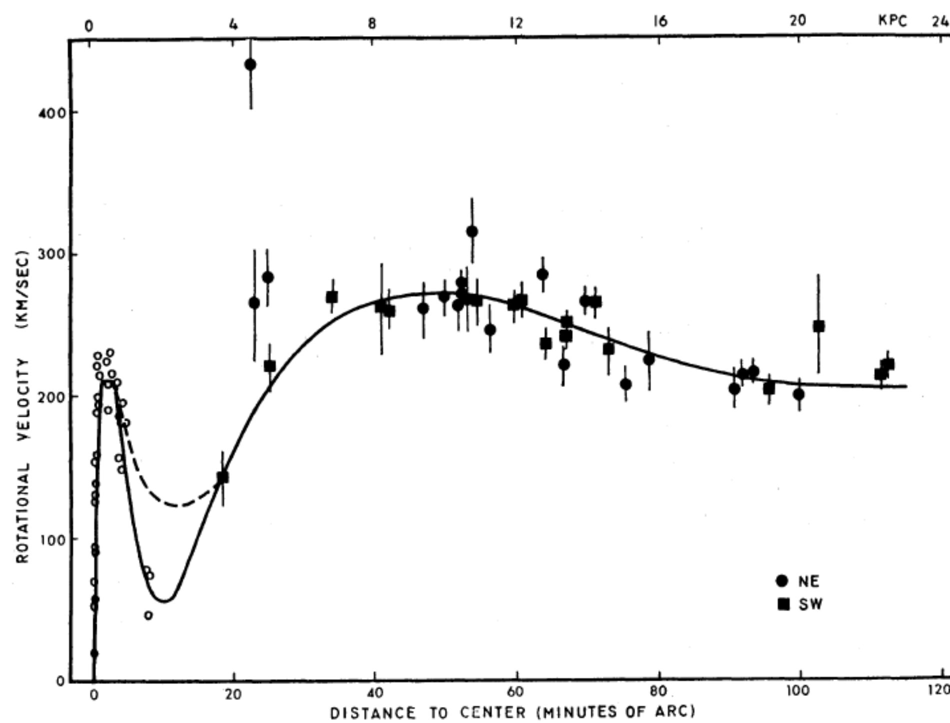


FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately flat near $R = 120'$. Dashed curve near $R = 10'$ is a second rotation curve with higher inner minimum.

THE ASTROPHYSICAL JOURNAL, **238**:471–487, 1980 June 1

ROTATIONAL PROPERTIES OF 21 Sc GALAXIES WITH A LARGE RANGE OF LUMINOSITIES AND RADII, FROM NGC 4605 ($R = 4$ kpc) TO UGC 2885 ($R = 122$ kpc)

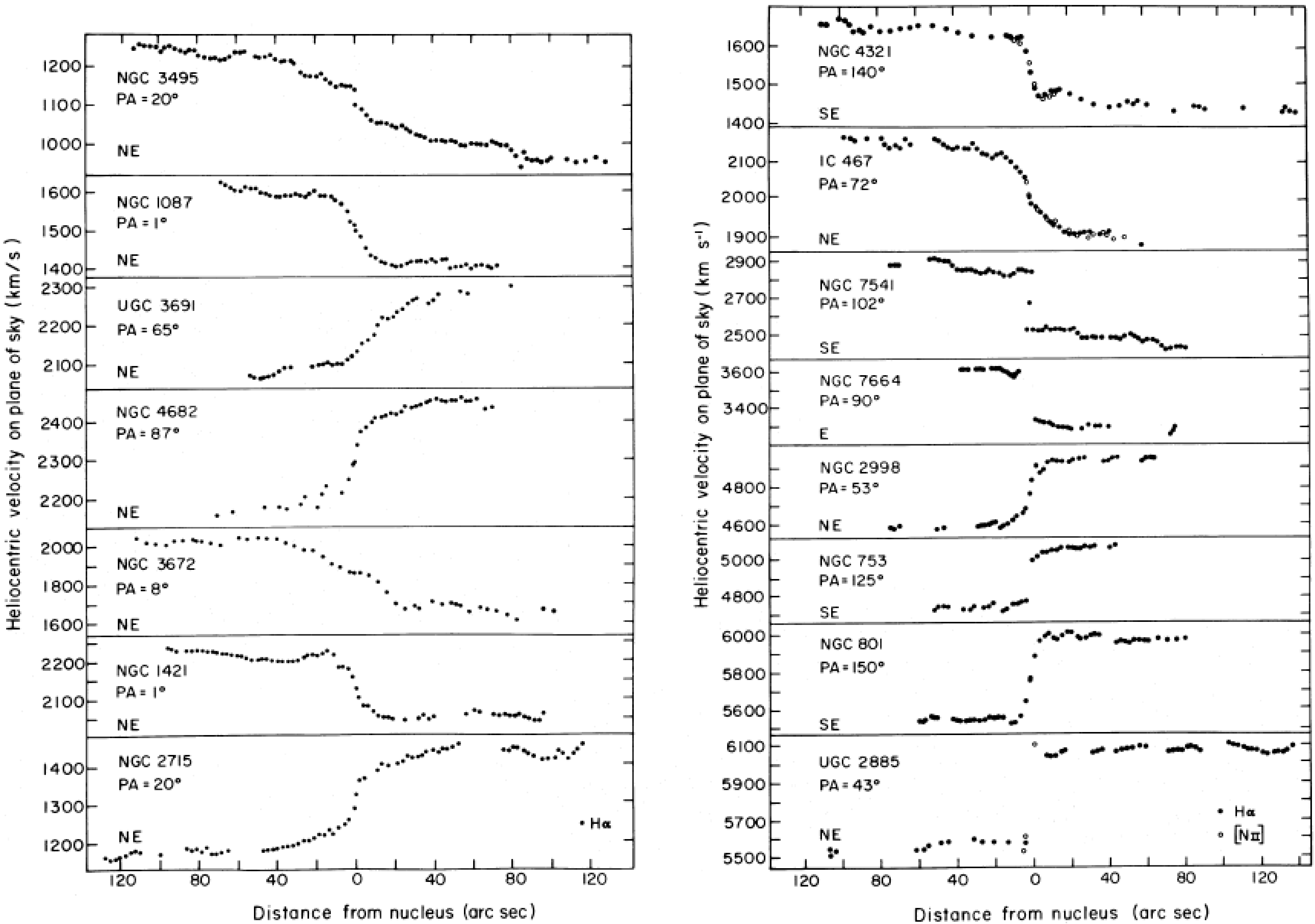
VERA C. RUBIN,[1,2] W. KENT FORD, JR.,[1] AND NORBERT THONNARD
Department of Terrestrial Magnetism, Carnegie Institution of Washington
Received 1979 October 11; accepted 1979 November 29

ABSTRACT

For 21 Sc galaxies whose properties encompass a wide range of radii, masses, and luminosities, we have obtained major axis spectra extending to the faint outer regions, and have deduced rotation curves. The galaxies are of high inclination, so uncertainties in the angle of inclination to the line of sight and in the position angle of the major axis are minimized. Their radii range from 4 to 122 kpc ($H = 50$ km s^{-1} Mpc^{-1}); in general, the rotation curves extend to 83% of $R_{25}{}^{i,b}$. When plotted on a linear scale with no scaling, the rotation curves for the smallest galaxies fall upon the initial parts of the rotation curves for the larger galaxies. All curves show a fairly rapid velocity rise to $V \sim 125$ km s^{-1} at $R \sim 5$ kpc, and a slower rise thereafter. Most rotation curves are rising slowly even at the farthest measured point. Neither high nor low luminosity Sc galaxies have falling rotation curves. Sc galaxies of all luminosities must have significant mass located beyond the optical image. A linear relation between log V_{max} and log R follows from the shape of the common rotation curve for all Sc's, and the tendency of smaller galaxies, at any R, to have lower velocities than the large galaxies at that R. The significantly shallower slope discovered for this relation by Tully and Fisher is attributed to their use of galaxies of various Hubble types and the known correlation of V_{max} with Hubble type.

The galaxies with very large central velocity gradients tend to be large, of high luminosity, with massive, dense nuclei. Often their nuclear spectra show a strong stellar continuum in the red, with emission lines of [N II] stronger than Hα. These galaxies also tend to be 13 cm radio continuum sources.

Because of the form of the rotation curves, small galaxies undergo many short-period, very differential, rotations. Large galaxies undergo (in their outer parts) few, only slightly differential, rotations. This suggests a relation between morphology, rotational properties, and the van den Bergh luminosity classification, which is discussed. UGC 2885, the largest Sc in the sample, has undergone fewer than 10 rotations in its outer parts since the origin of the universe but has a regular two-armed spiral pattern and no significant velocity asymmetries. This observation puts constraints on models of galaxy formation and evolution.


NGC 3495
PA = 20°
NE
NGC 1087
PA = 1°
NE
UGC 3691
PA = 65°
NE
NGC 4682
PA = 87°
NE
NGC 3672
PA = 8°
NE
NGC 1421
PA = 1°
NE
NGC 2715
PA = 20°
NE
• Hα
Heliocentric velocity on plane of sky (km/s)
Distance from nucleus (arc sec)
NGC 4321
PA = 140°
SE
IC 467
PA = 72°
NE
NGC 7541
PA = 102°
SE
NGC 7664
PA = 90°
E
NGC 2998
PA = 53°
NE
NGC 753
PA = 125°
SE
NGC 801
PA = 150°
SE
UGC 2885
PA = 43°
NE
• Hα
∘ [N II]
Heliocentric velocity on plane of sky (km s⁻¹)
Distance from nucleus (arc sec)

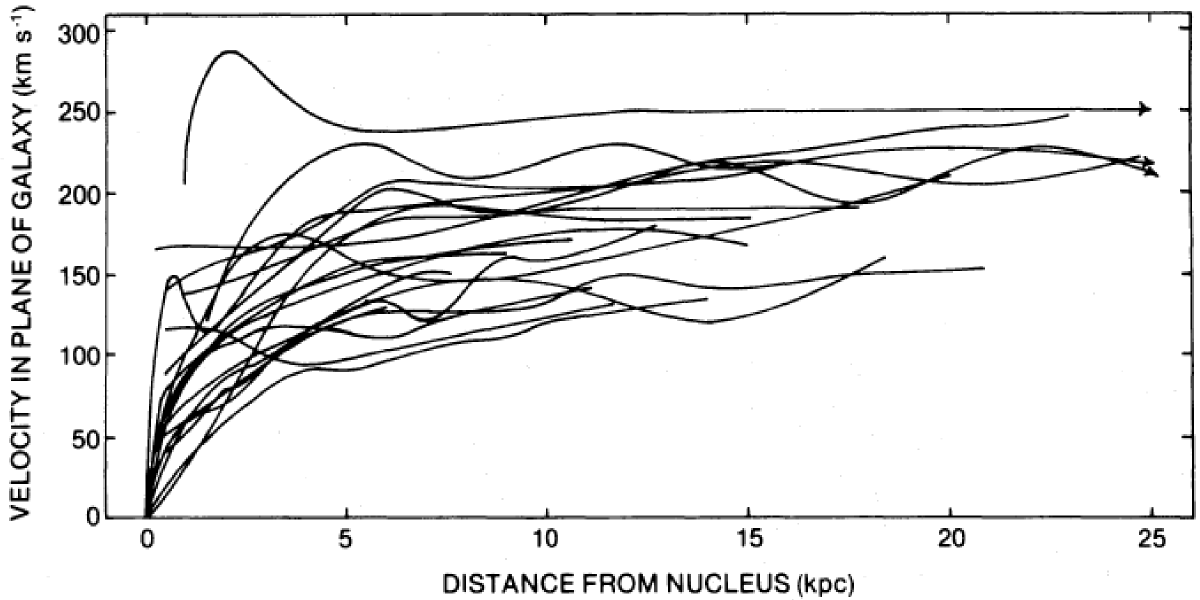


FIG. 6.—Superposition of all 21 Sc rotation curves. General form of rotation curves for small galaxies is similar to initial part of rotation curve for large galaxies, except that small galaxies often have shallower nuclear velocity gradient and tend to cover the low velocity range within the scatter at any R.

VIII. DISCUSSION AND CONCLUSIONS

We have obtained spectra and determined rotation curves to the faint outer limits of 21 Sc galaxies of high inclination. The galaxies span a range in luminosity from 3×10^9 to 2×10^{11} $L_\odot$, a range in mass from 10^{10} to 2×10^{12} $M_\odot$, and a range in radius from 4 to 122 kpc. In general, velocities are obtained over 83% of the optical image (defined by 25 mag arcsec^{-2}), a greater distance than previously observed. The major conclusions are intended to apply only to Sc galaxies.

1. Most galaxies exhibit rising rotational velocities at the last measured velocity; only for the very largest galaxies are the rotation curves flat. Thus the smallest Sc's (i.e., lowest luminosity) exhibit the same lack of a Keplerian velocity decrease at large R as do the high-luminosity spirals. This form for the rotation curves implies that the mass is not centrally condensed, but that significant mass is located at large R. The integral mass is increasing at least as fast as R. The mass is not converging to a limiting mass at the edge of the optical image. The conclusion is inescapable that non-luminous matter exists beyond the optical galaxy.

Inescapable?

THE ASTROPHYSICAL JOURNAL, **270**:365–370, 1983 July 15

A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

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The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I consider the possibility that there is not, in fact, much hidden mass in galaxies and galaxy systems. If a certain modified version of the Newtonian dynamics is used to describe the motion of bodies in a gravitational field (of a galaxy, say), the observational results are reproduced with no need to assume hidden mass in appreciable quantities. Various characteristics of galaxies result with no further assumptions.

In the basis of the modification is the assumption that in the limit of small acceleration $a \ll a_0$, the acceleration of a particle at distance r from a mass M satisfies approximately $a^2/a_0 \approx MGr^{-2}$, where a_0 is a constant of the dimensions of an acceleration.

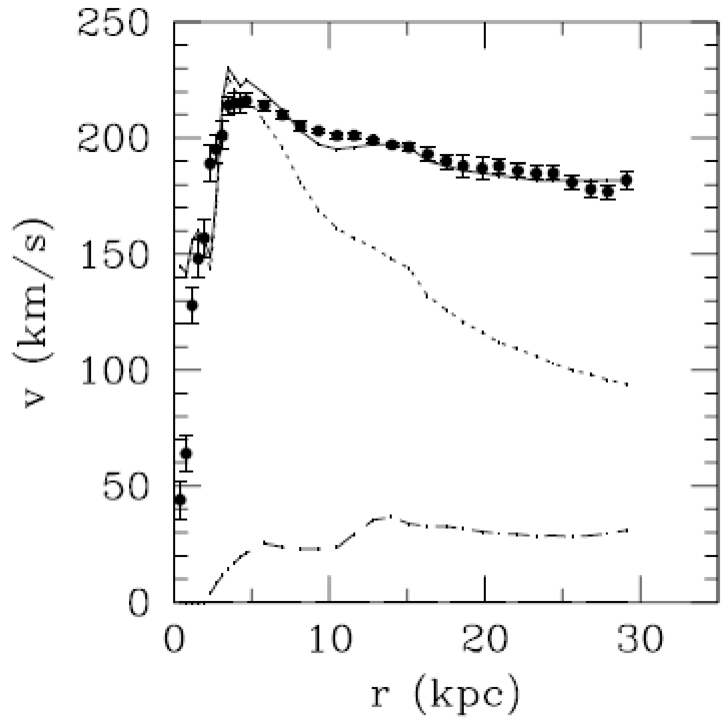
I have considered the possibility that Newton's second law does not describe the motion of objects under the conditions which prevail in galaxies and systems of galaxies. In particular I allowed for the inertia term not to be proportional to the acceleration of the object but rather be a more general function of it. With some simplifying assumptions I was led to the form

$$m_g \mu(a/a_0)\boldsymbol{a} = \boldsymbol{F}, \qquad (1)$$

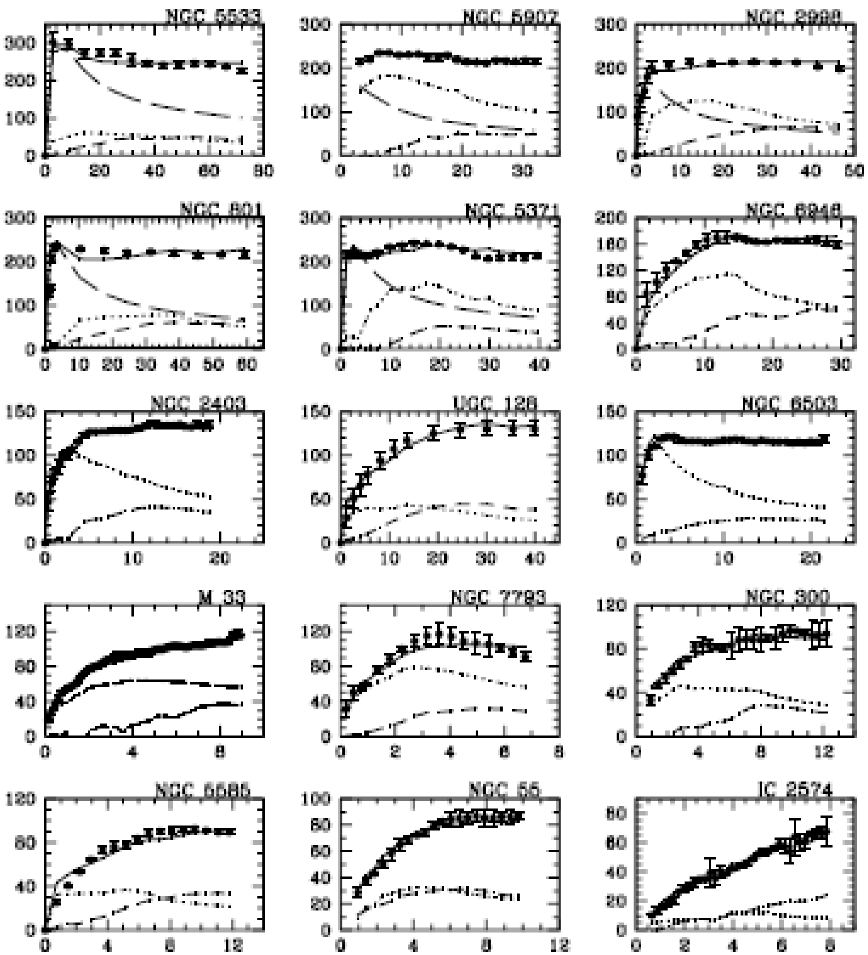
$$\mu(x \gg 1) \approx 1, \qquad \mu(x \ll 1) \approx x,$$

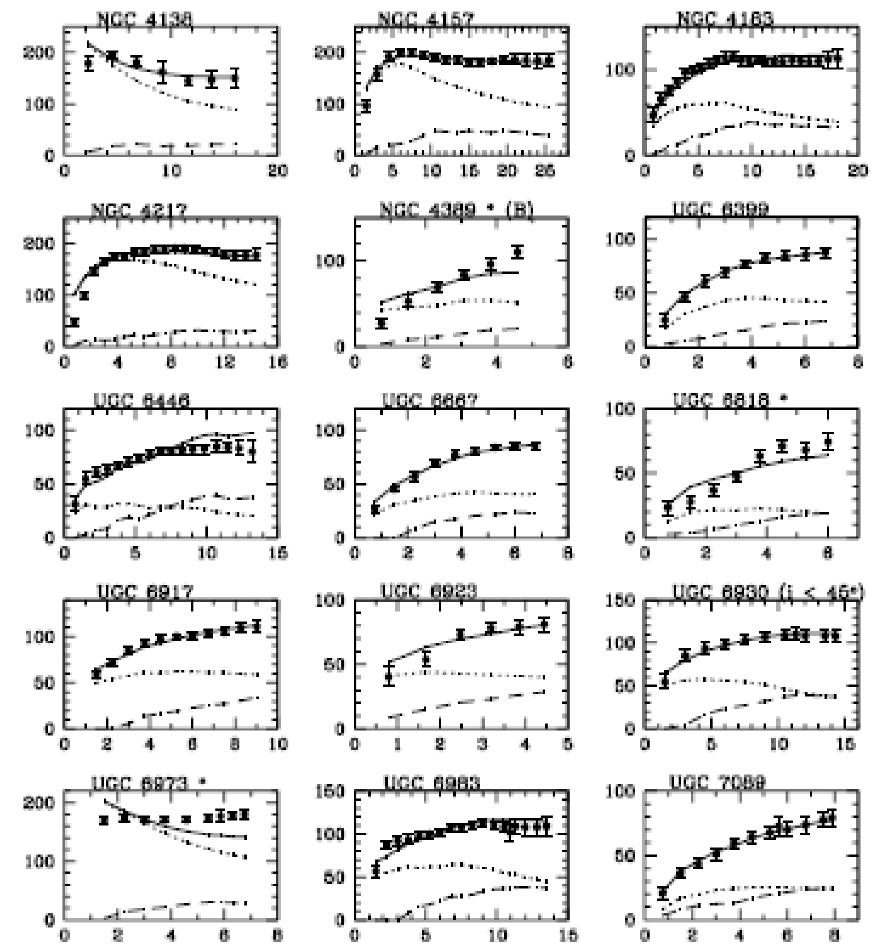
replacing $m_g \boldsymbol{a} = \boldsymbol{F}$.

$$a_0 \simeq 10^{-8}\,\mathrm{cm\,s^{-2}}$$

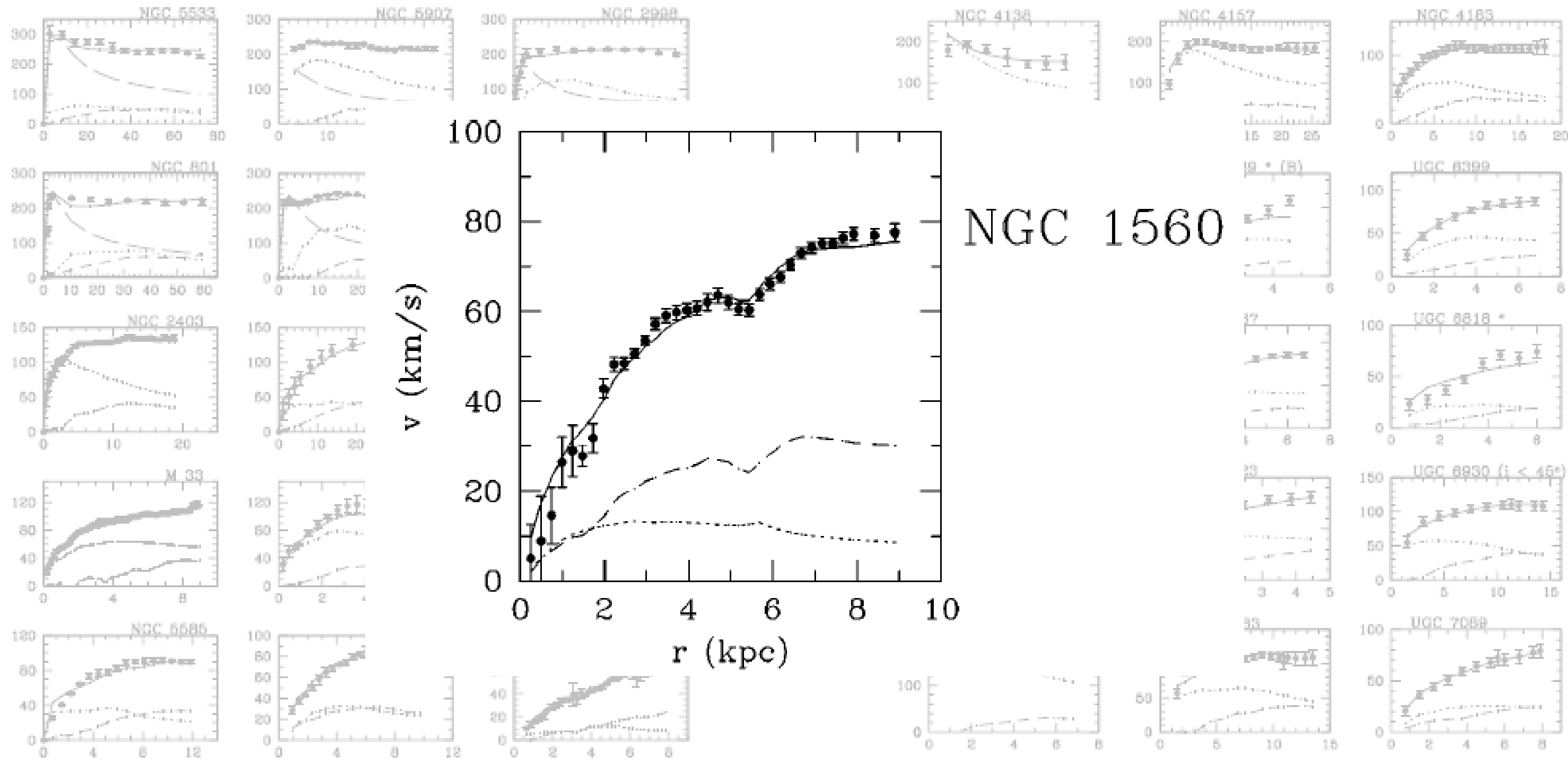


NGC 2903



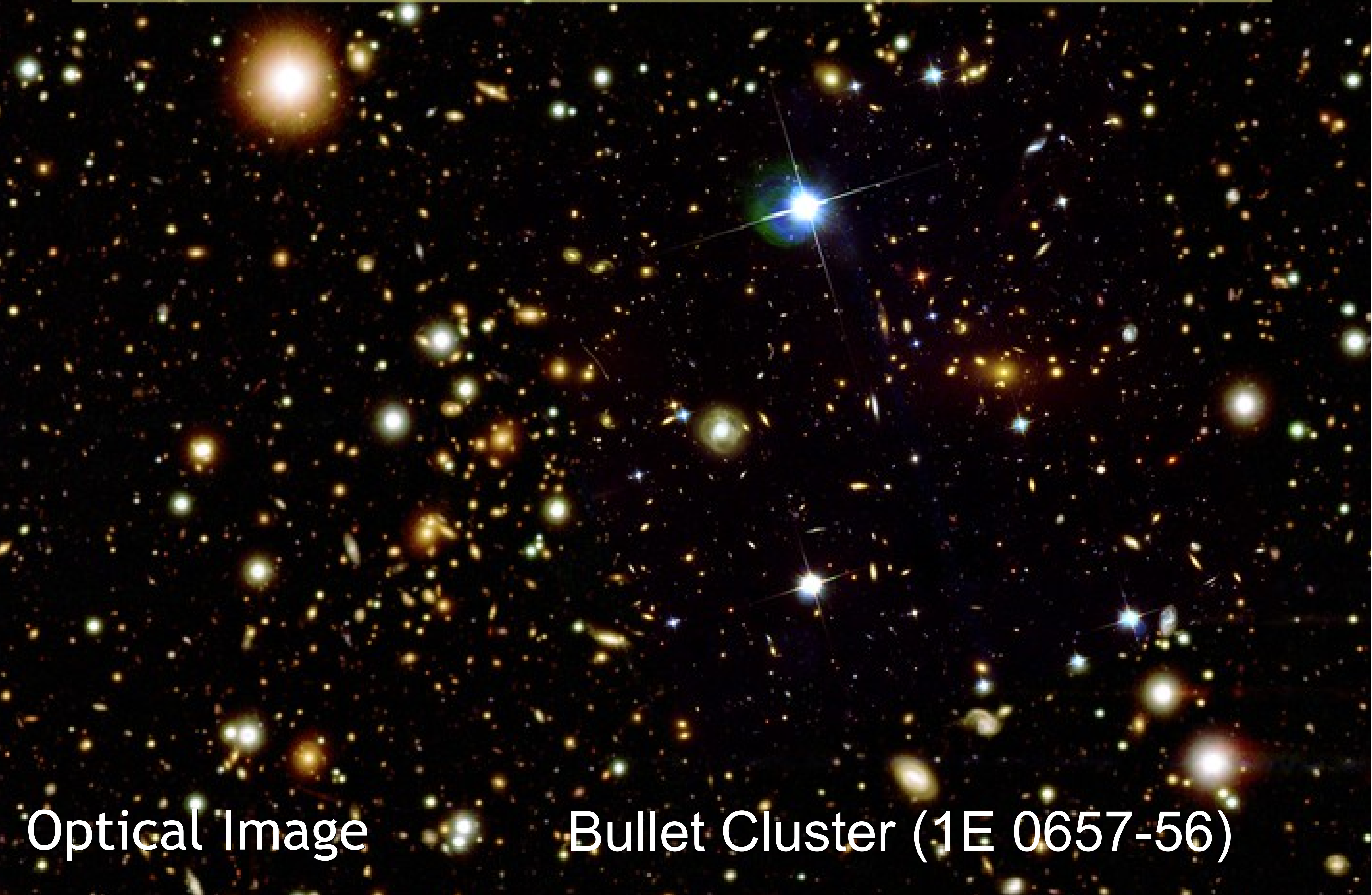


Sanders, McGaugh



Sanders, McGaugh

"A direct empirical proof of the existence of dark matter"
Clowe, *et al.*, Astrophys.J.648:L109-L113,2006.

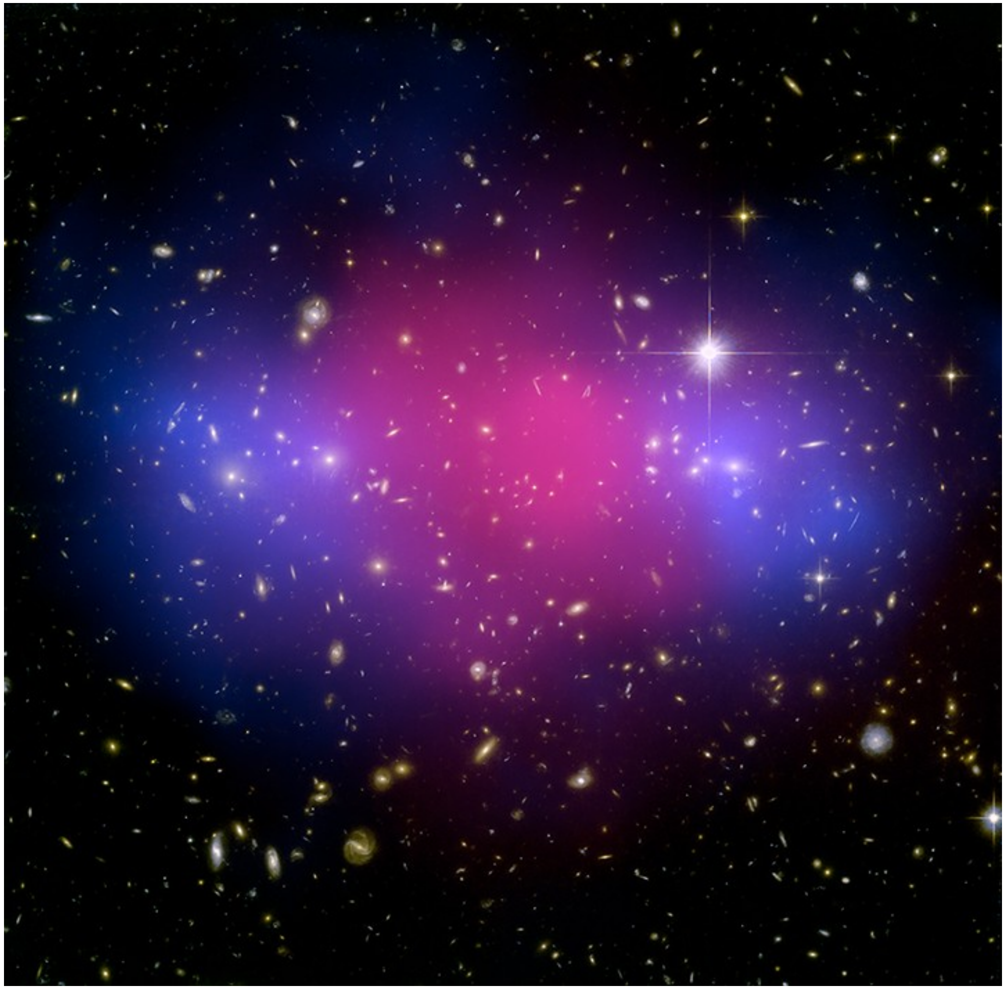


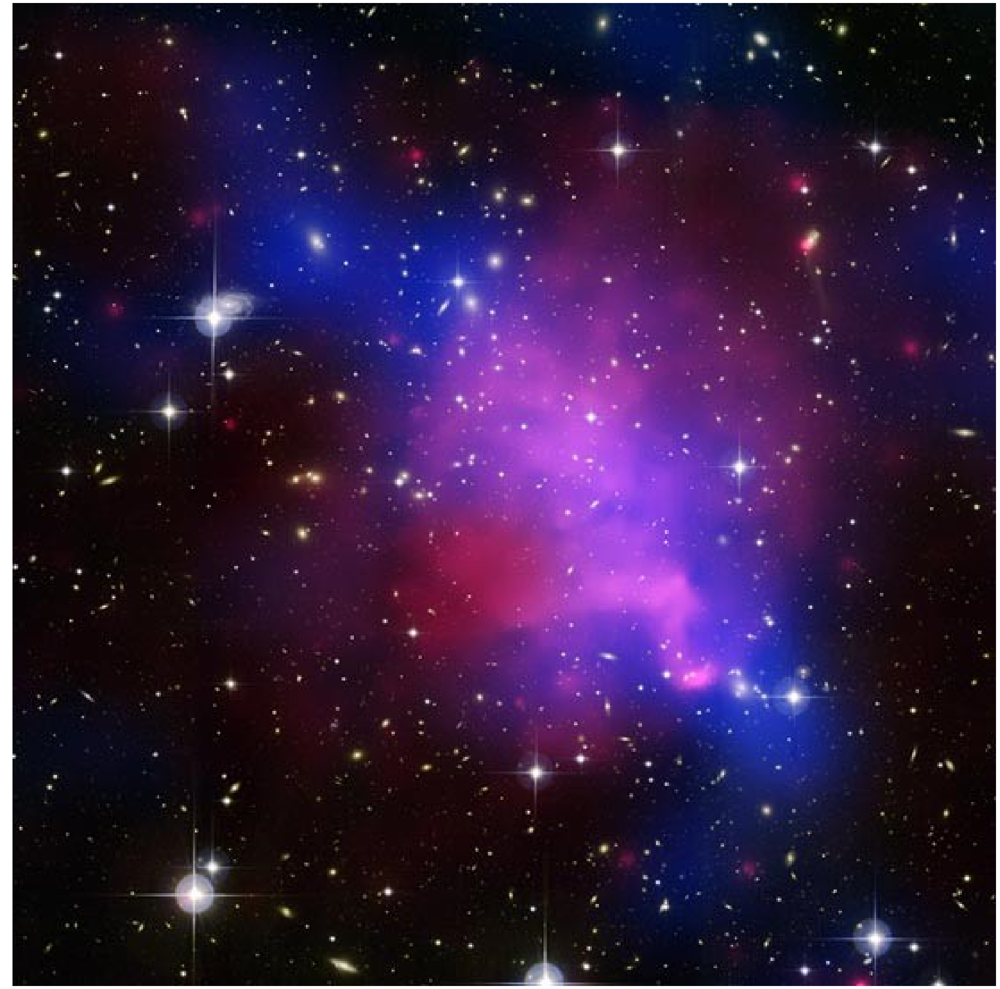
Optical Image Bullet Cluster (1E 0657-56)


X-ray Image


Weak lensing Image


Composite Image



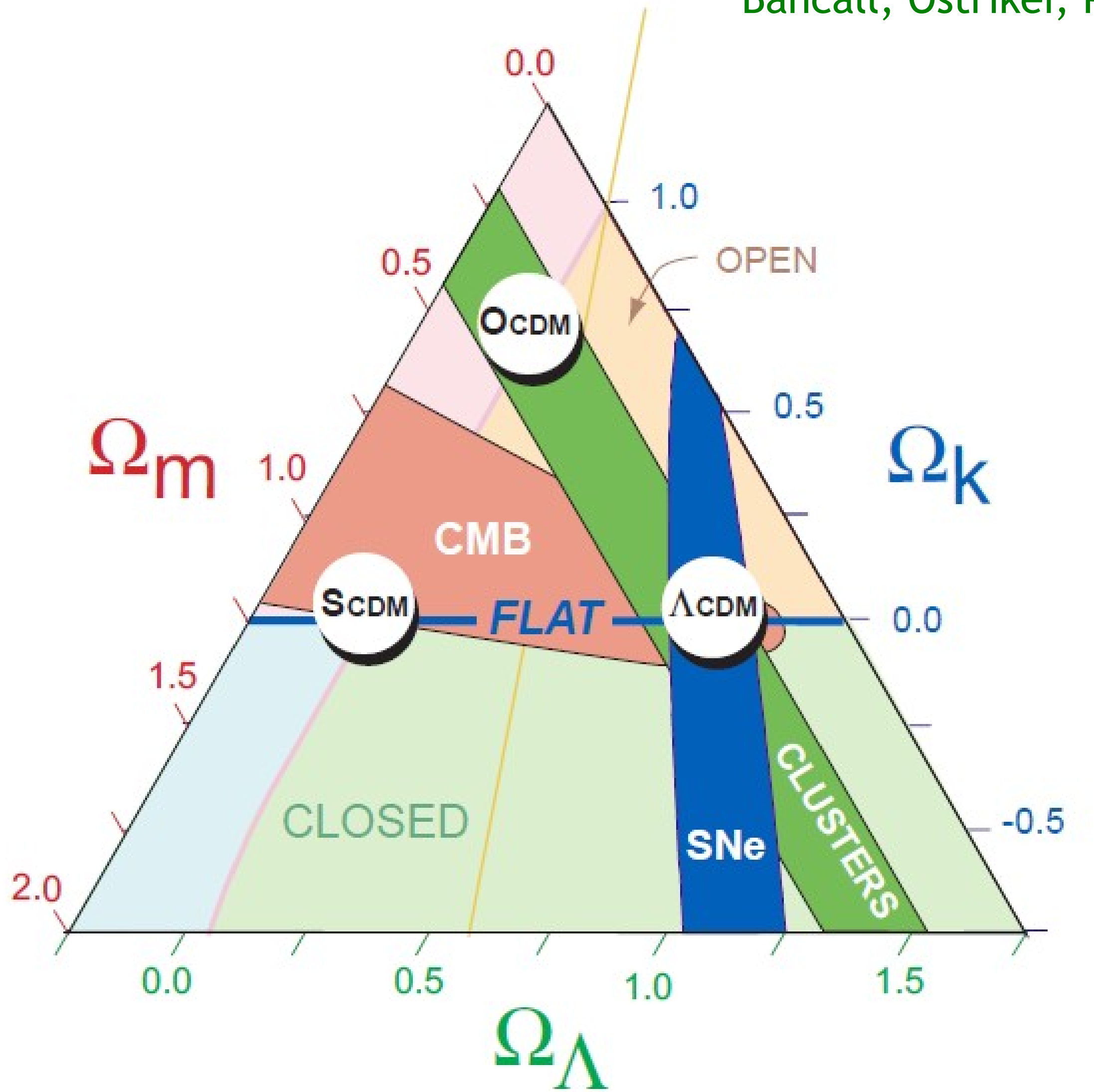


MACS J0025.4-1222:

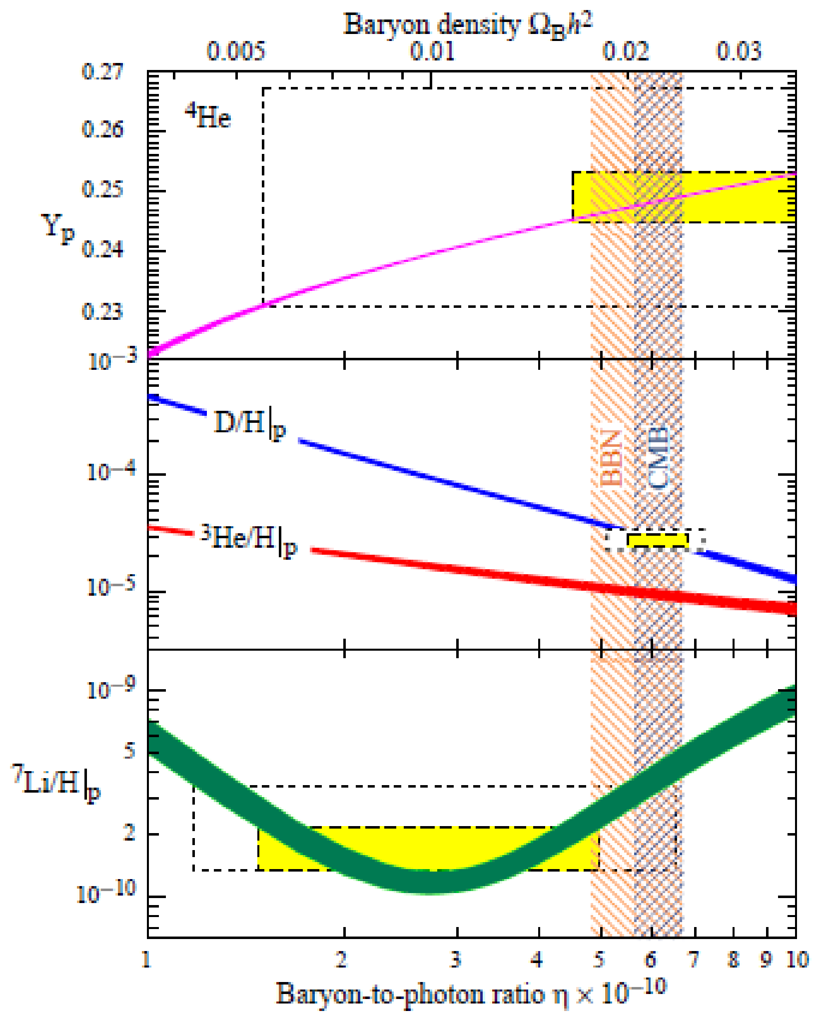
Abell 520

The cosmic triangle

Bahcall, Ostriker, Perlmutter, Steinhardt

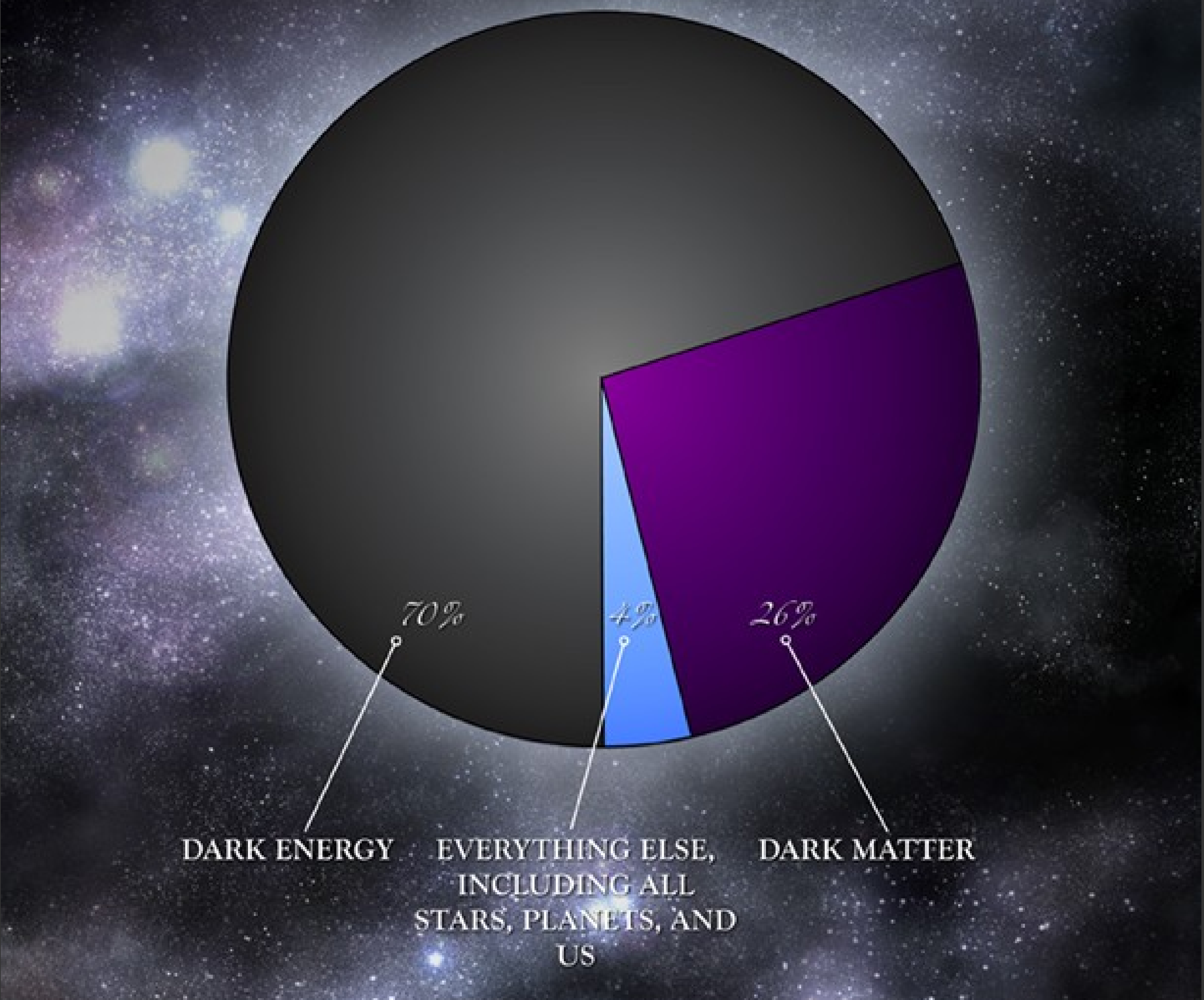


Compare to the density of baryonic matte, inferred from primordial nucleosynthesis

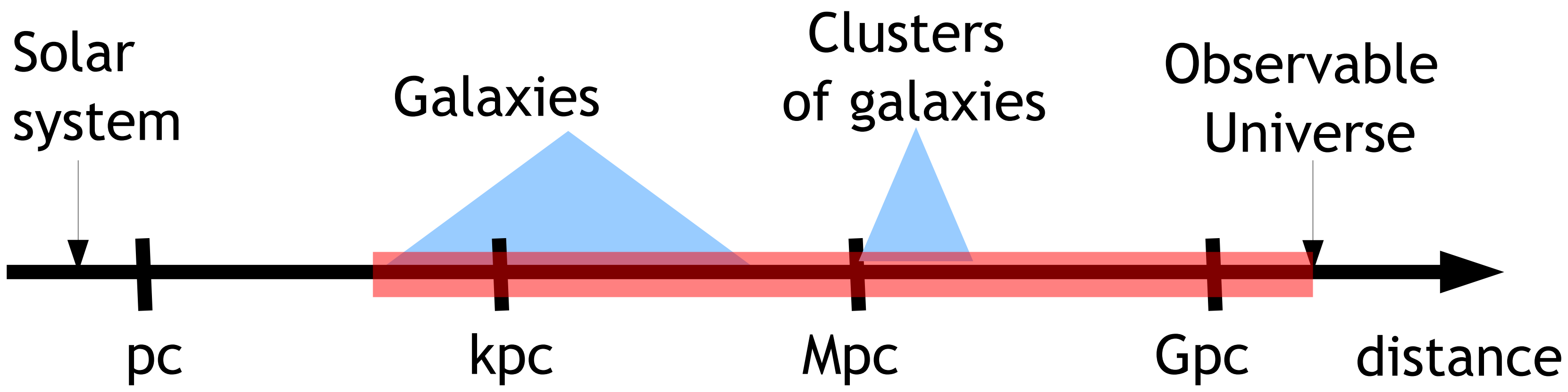


Fields, Sarkar

The cosmic pie



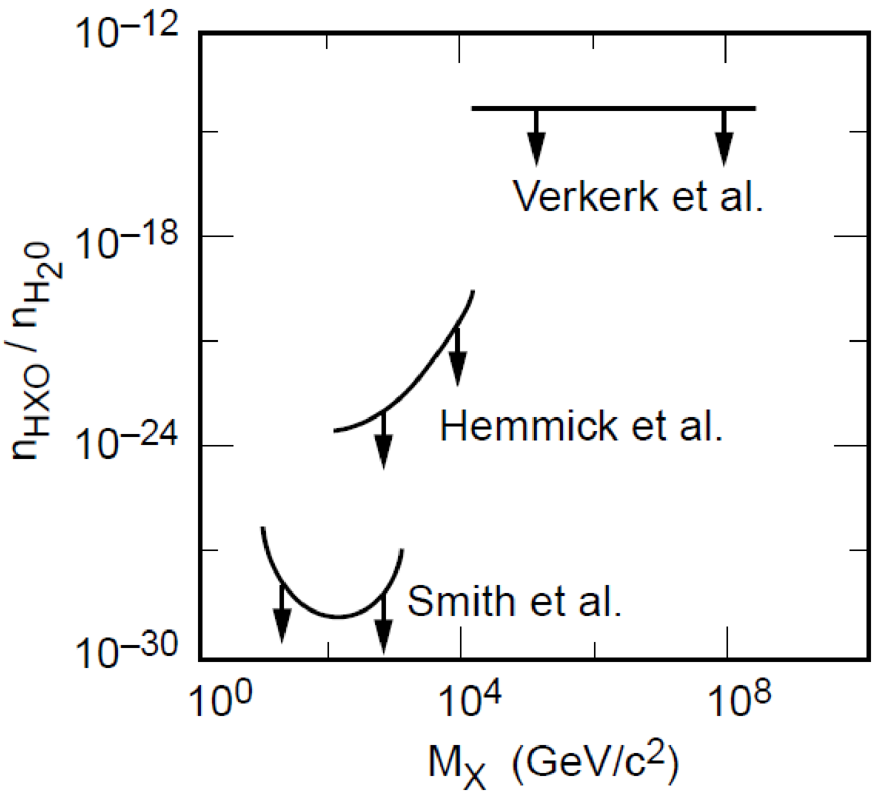
There is evidence for dark matter in a wide range of distance scales

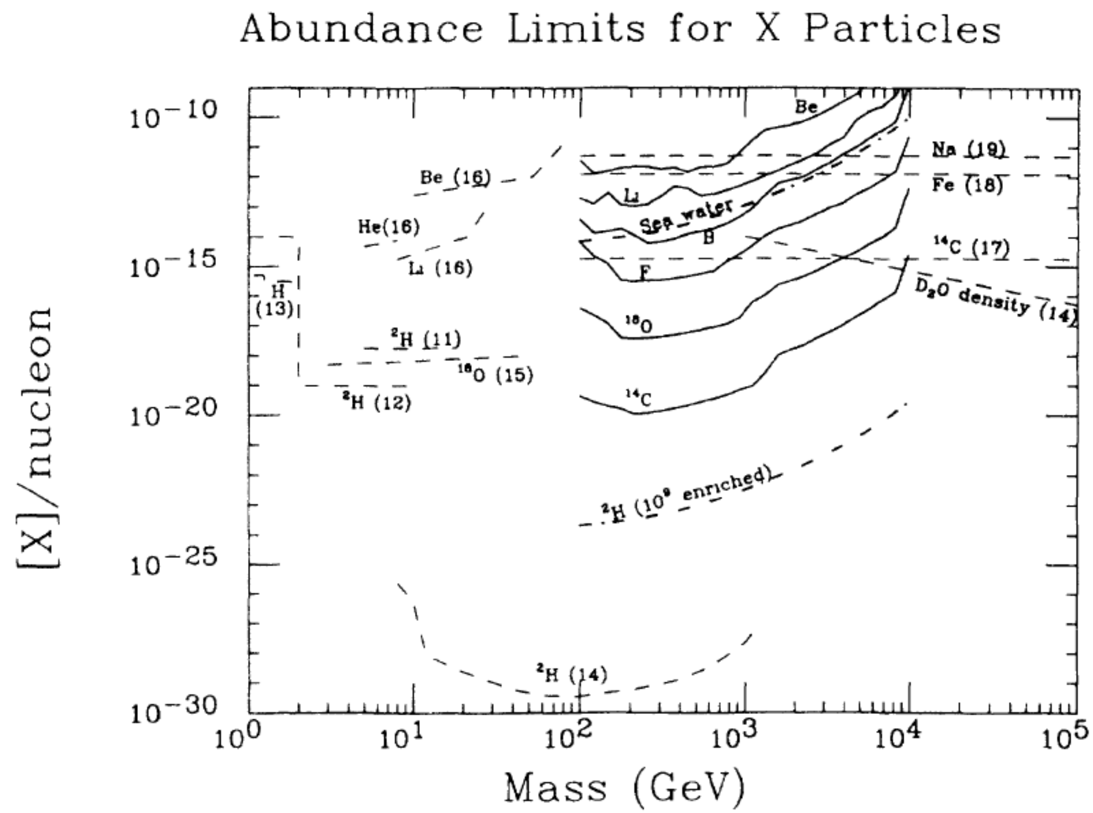


What do we know about dark matter?

1) It is dark. No electric charge.

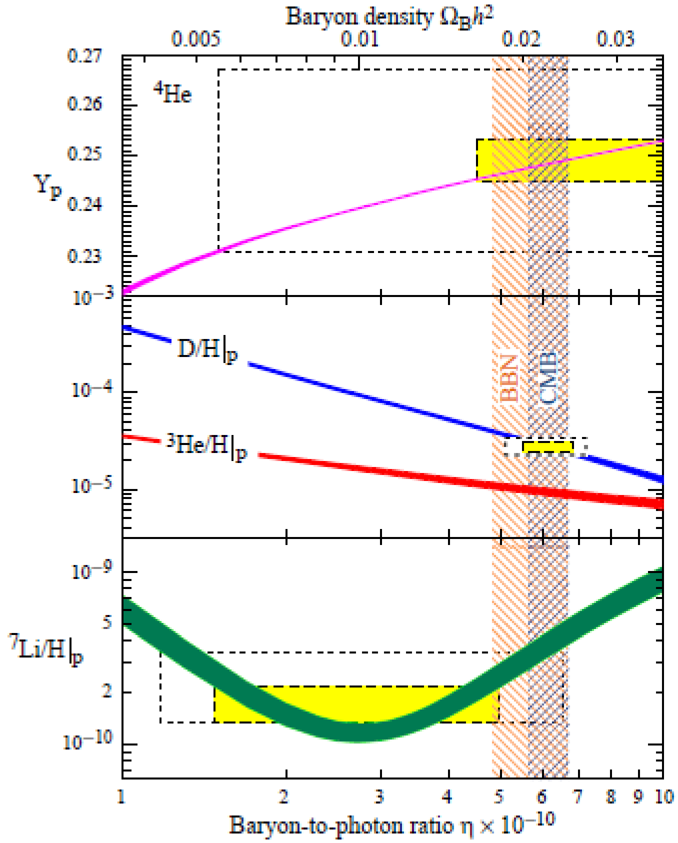
- If it has positive charge, it can form a bound state X^+e^-, an "anomalously heavy hydrogen atom".
- If it has negative charge, it can bind to nuclei, forming "anomalously heavy isotopes".



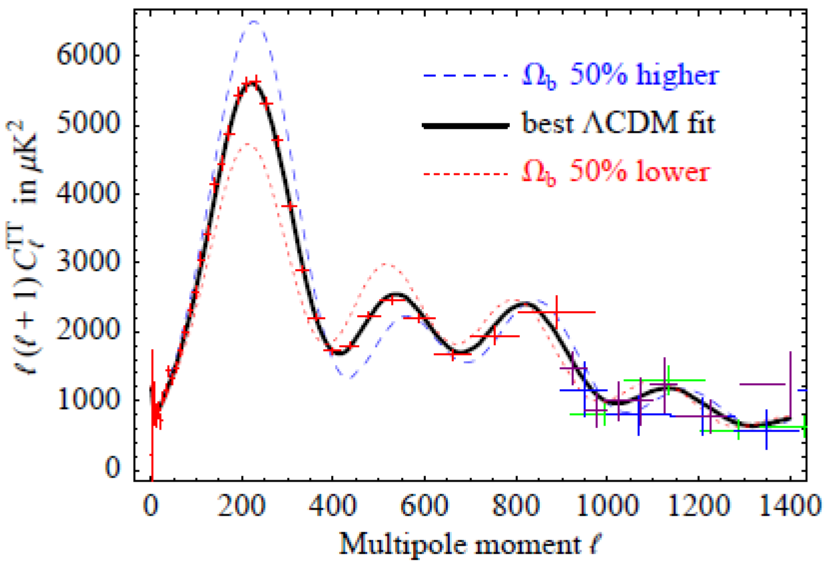


2) It is not made of baryons.

Primordial nucleosynthesis

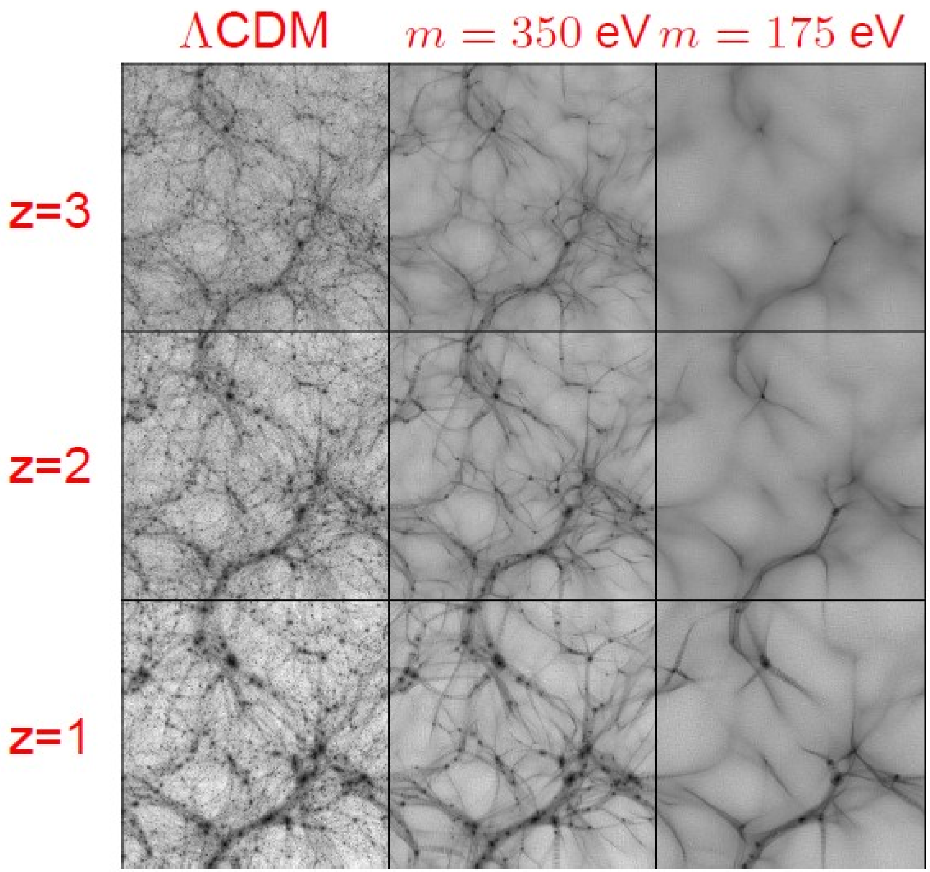


Cosmic Microwave Background radiation



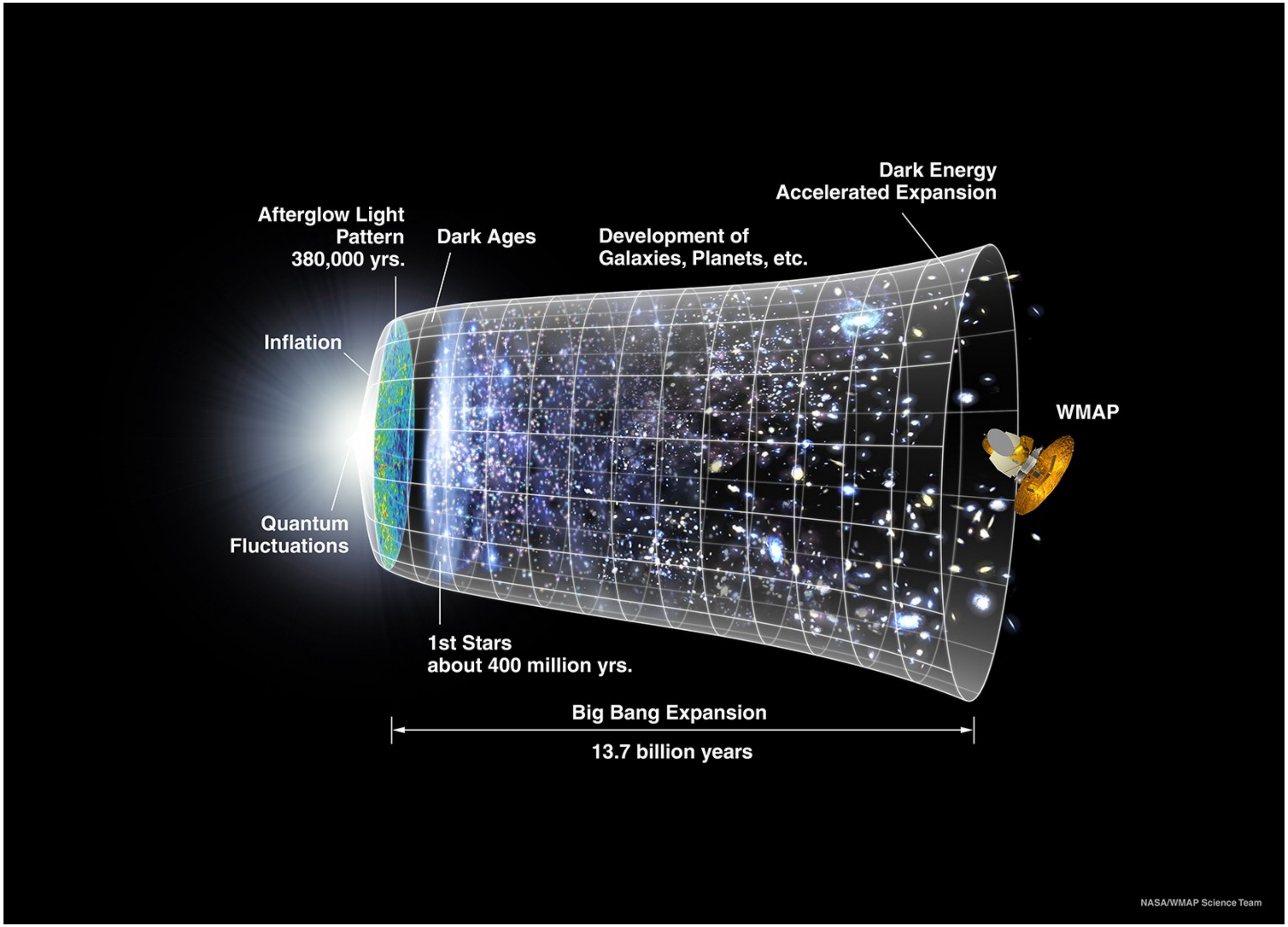
MACHOs (planets, brown dwarfs, etc) are excluded as the dominant component of dark matter.

3) It was "slow" at the time of the formation of the first structures.



Bode, Ostriker, Turok

4) It exists today.



To summarize, observations indicate that the dark matter is constituted by particles which have:

- No electric charge, no color.
- No baryon number.
- Low velocity at the time of structure formation.
- Lifetime longer than the age of the Universe.

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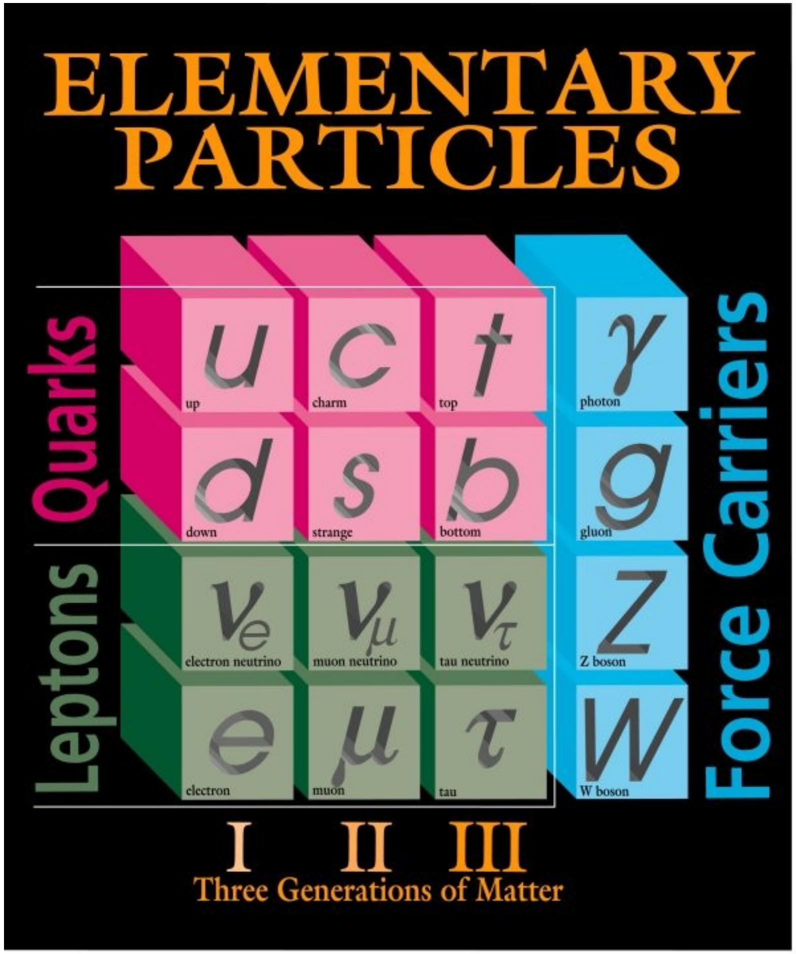

Fermilab 95-759

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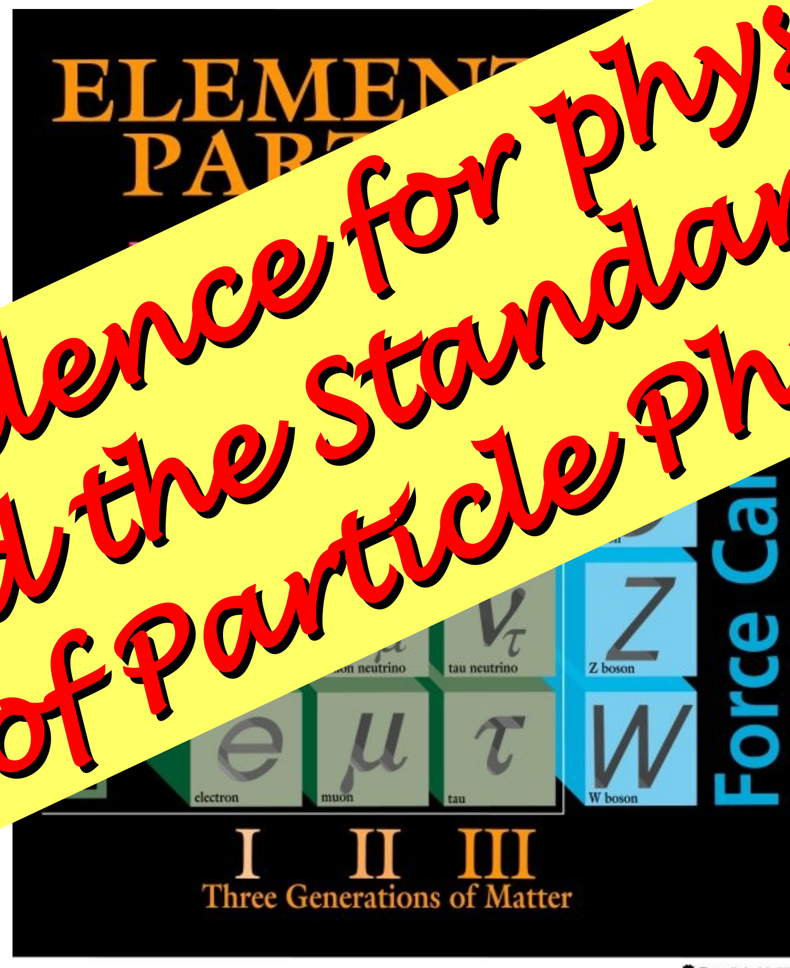


Evidence for physics beyond the Standard Model of Particle Physics

What do we know about dark matter, from the particle physics point of view??

(without prejudice)

Citation: K. Nakamura et al. (Particle Data Group), JPG 37, 075021 (2010) (URL: http://pdg.lbl.gov)

LIGHT UNFLAVORED MESONS $(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%	70

DARK MATTER

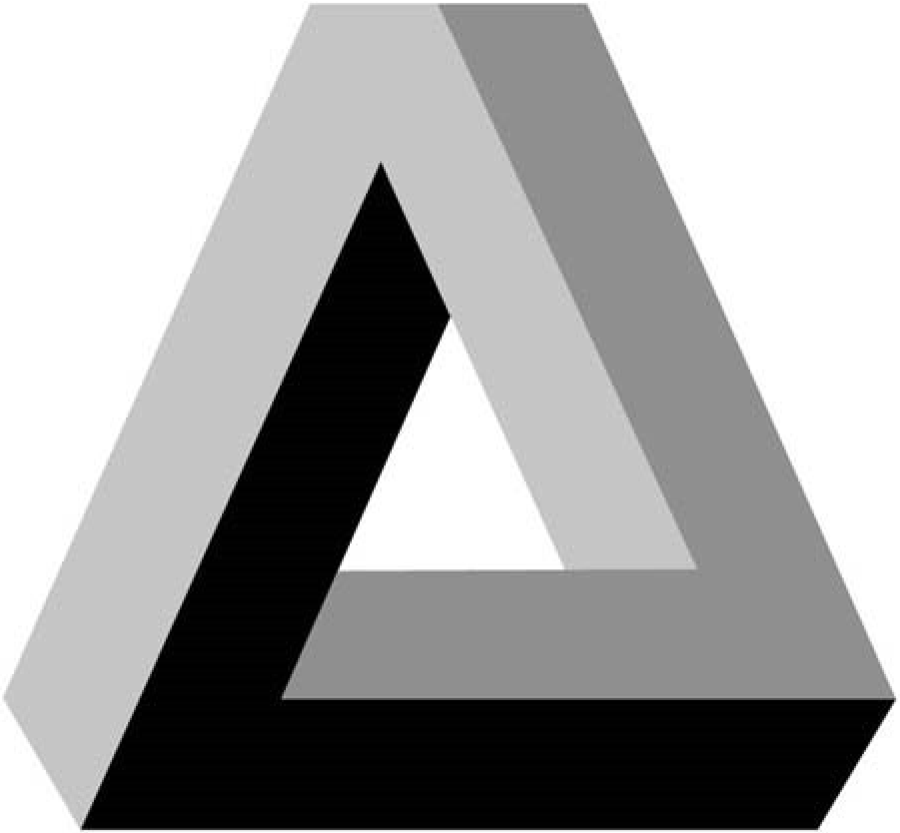
$J =$?

Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

Direct detection

DM nucleus $\rightarrow$ DM nucleus



Indirect detection

DM DM $\rightarrow \gamma X, e^+e^- \ldots$ (annihilation)

DM $\rightarrow \gamma X, e^+X \ldots$ (decay)

Collider searches

pp $\rightarrow$ DM X

Direct detection

DM nucleus → DM nucleus

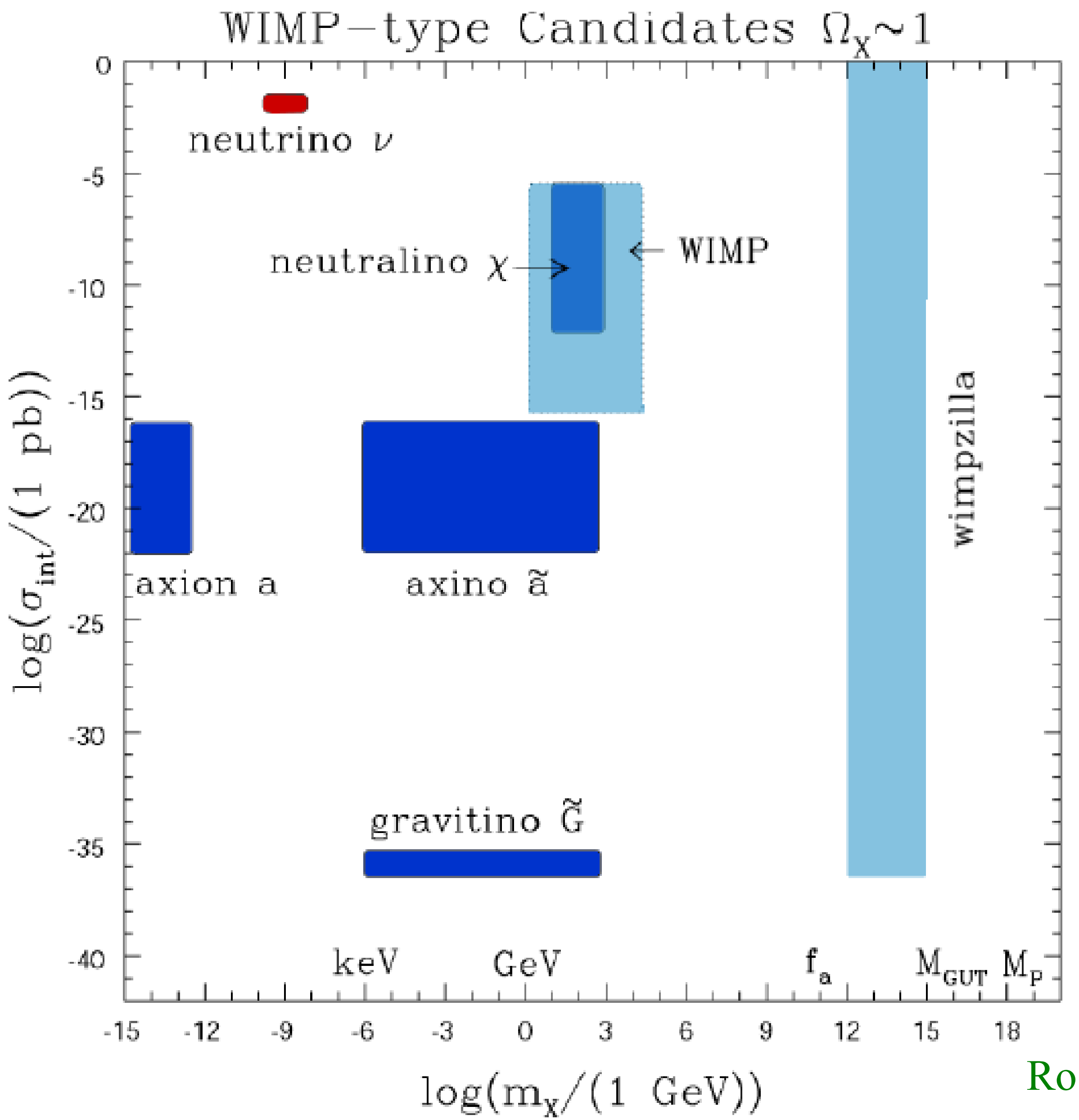
Indirect detection

DM DM → γ X, e⁺e⁻... (annihilation)

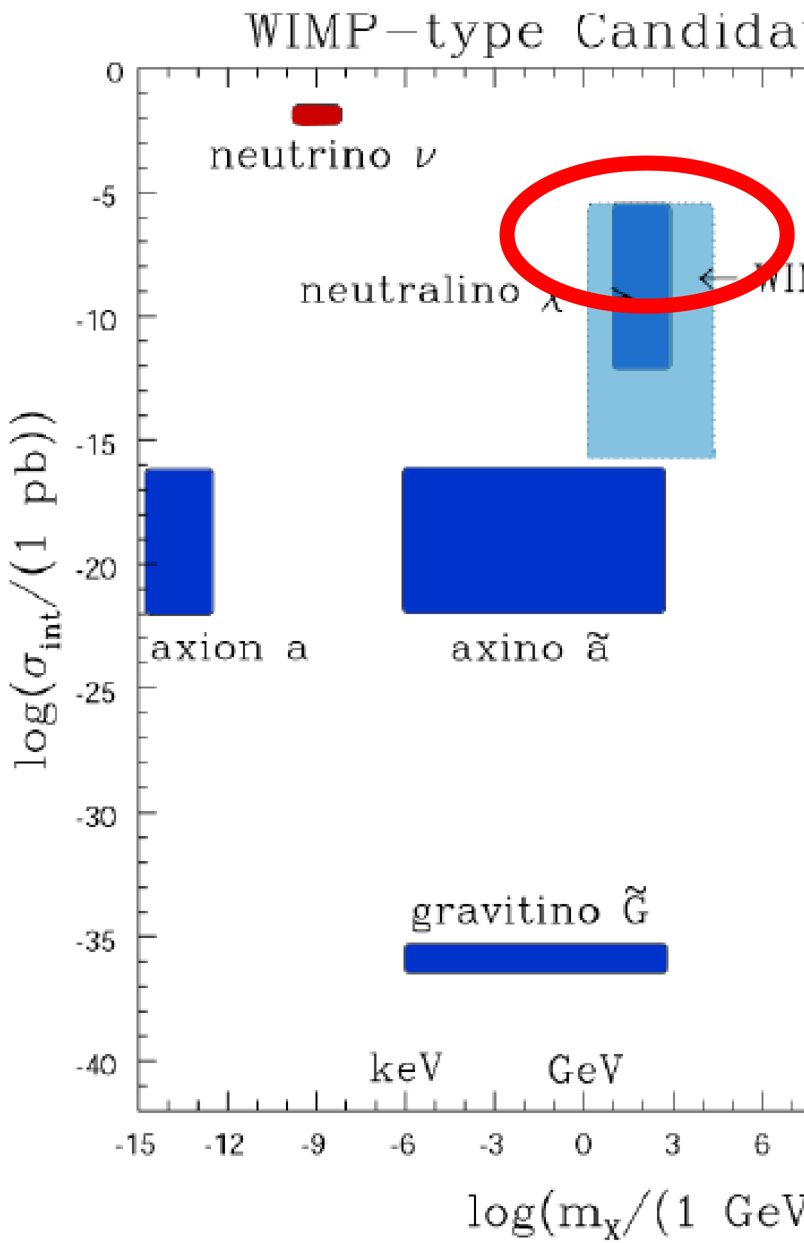
DM → γ X, e⁺X... (decay)

Collider searches

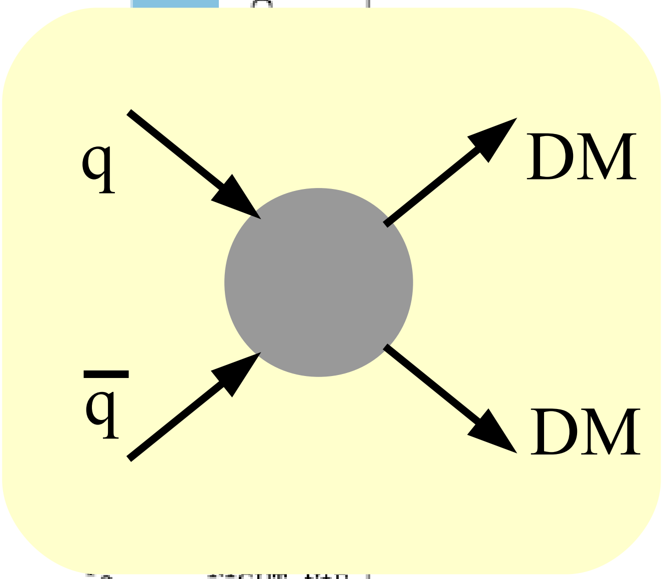
pp → DM X

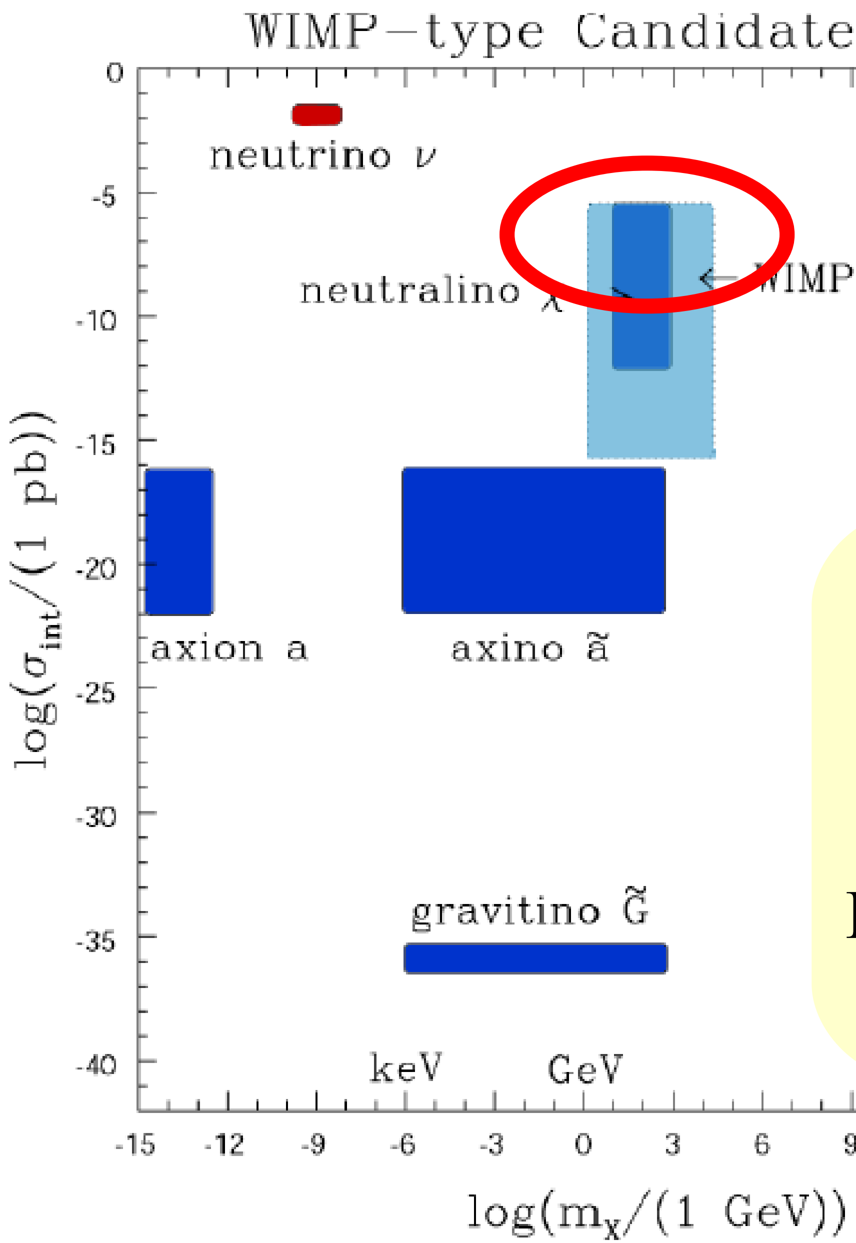

WIMP−type Candidates $\Omega_\chi \sim 1$
neutrino ν
neutralino χ
WIMP
wimpzilla
axion a
axino $\tilde{a}$
gravitino $\tilde{G}$
keV
GeV
f_a
M_{GUT}
M_P
$\log(\sigma_{int}/(1\ \mathrm{pb}))$
$\log(m_\chi/(1\ \mathrm{GeV}))$
0
-5
-10
-15
-20
-25
-30
-35
-40
-15
-12
-9
-6
-3
0
3
6
9
12
15
18

Roszkowski

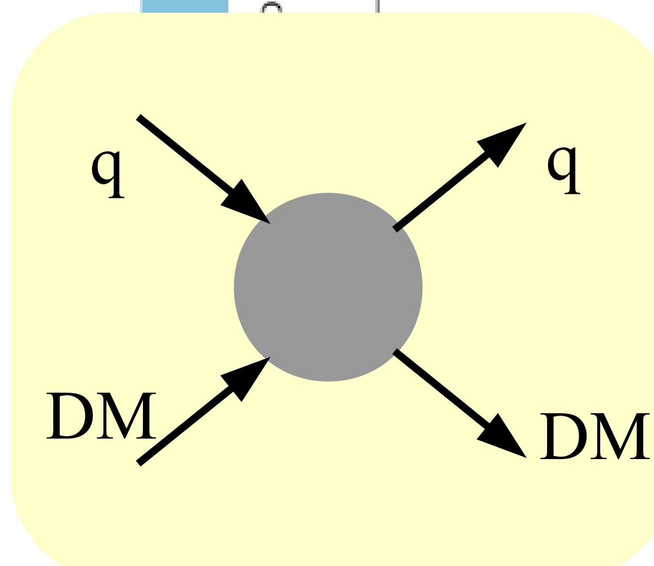


Direct DM searches
with prejudice:
focus on WIMPs
(possibility to
observe a signal)

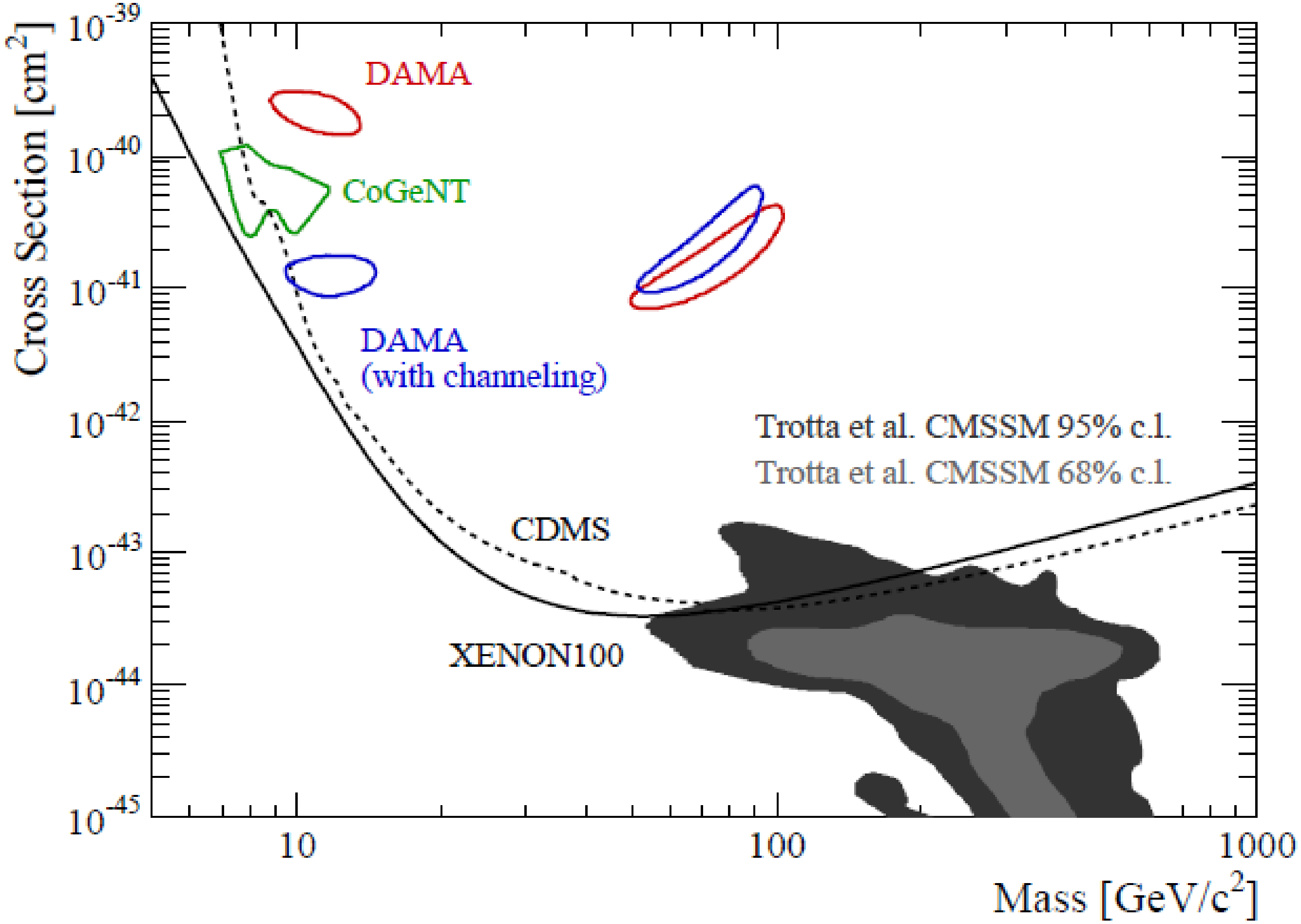


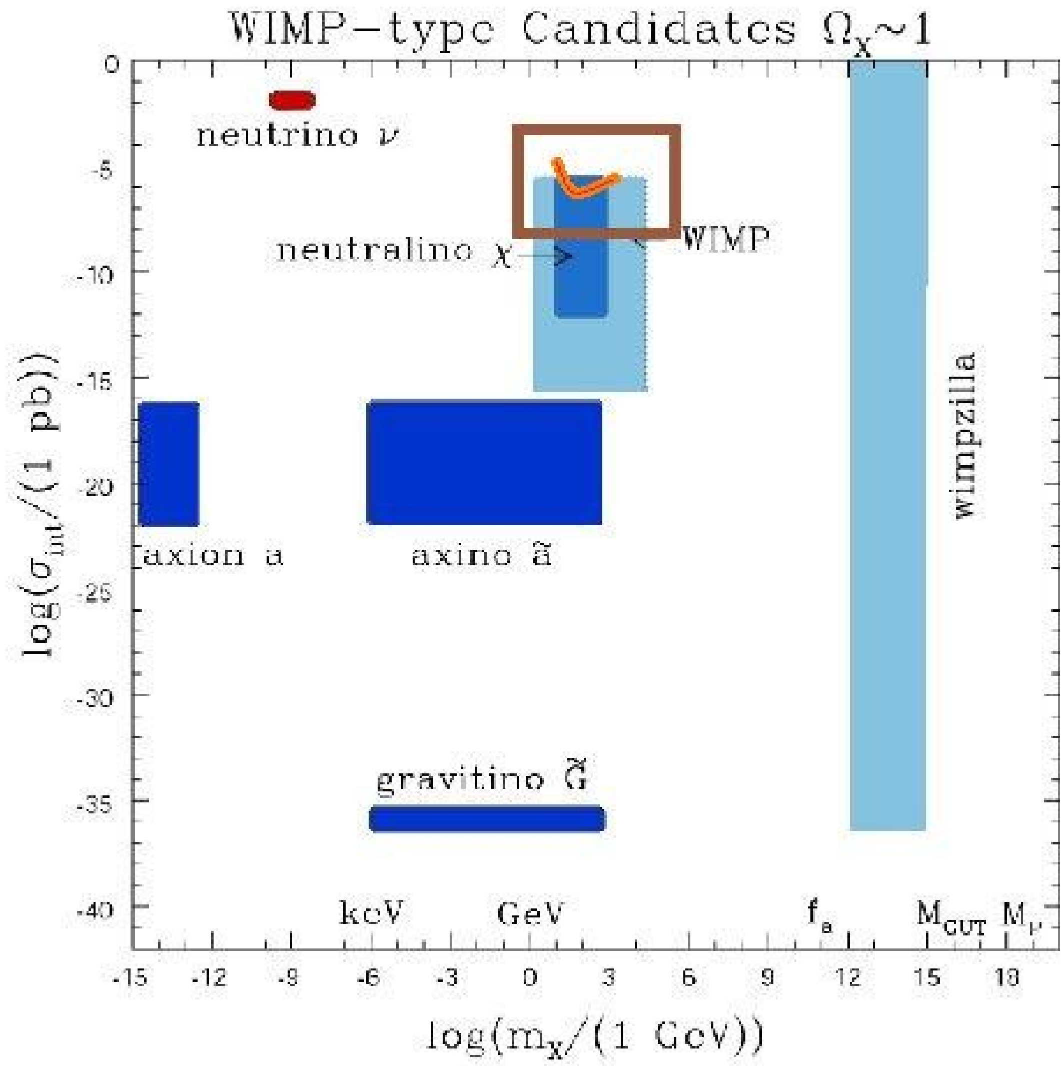


Direct DM searches
with prejudice:
focus on WIMPs
(possibility to
observe a signal)



Present status:




WIMP-type Candidates $\Omega_\chi \sim 1$
neutrino ν
neutralino χ
WIMP
wimpzilla
axion a
axino $\tilde{a}$
gravitino $\tilde{G}$
keV
GeV
f_a
M_{GUT}
M_P
$\log(\sigma_{int}/(1\ pb))$
$\log(m_\chi/(1\ GeV))$

Direct detection

DM nucleus $\rightarrow$ DM nucleus

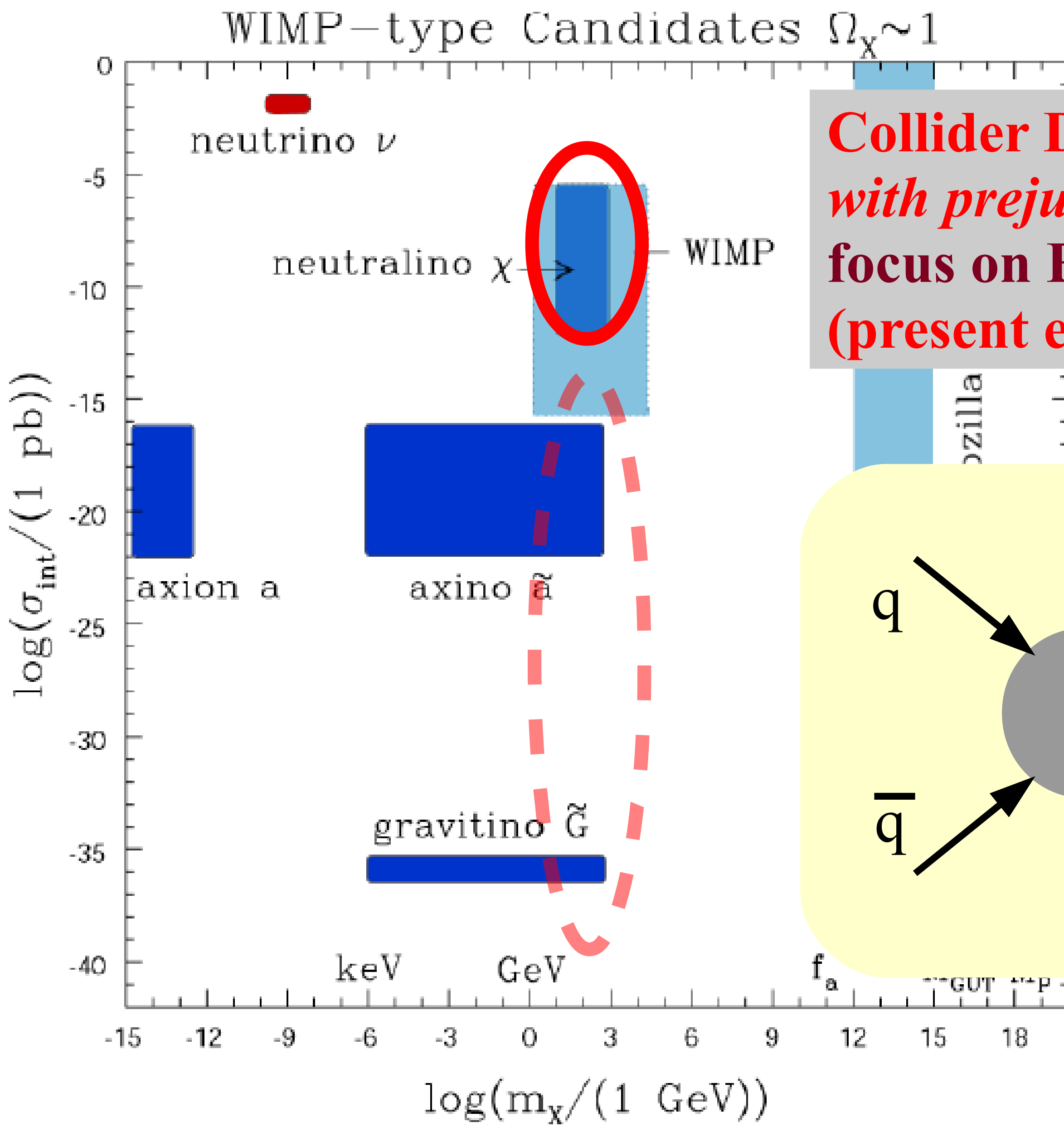
Indirect detection

DM DM $\rightarrow \gamma$ X, e^+e^-... (annihilation)

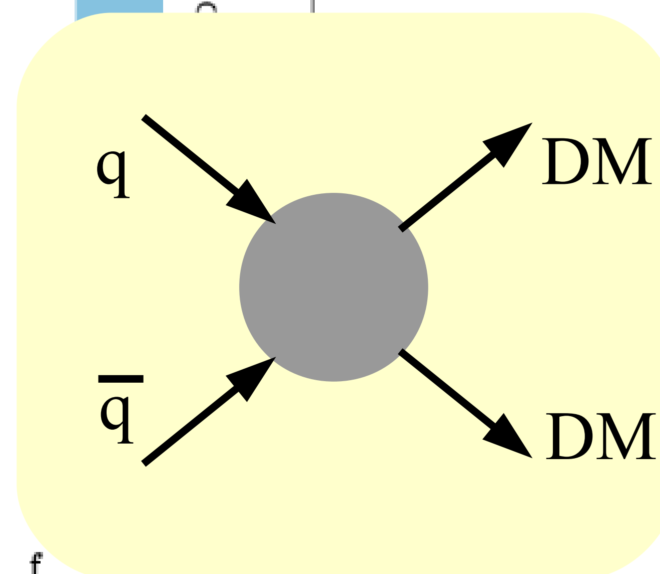
DM $\rightarrow \gamma$ X, e^+X... (decay)

Collider searches

pp $\rightarrow$ DM X



Collider DM searches
with prejudice:
focus on EW mass
(present energy frontier)



Direct detection

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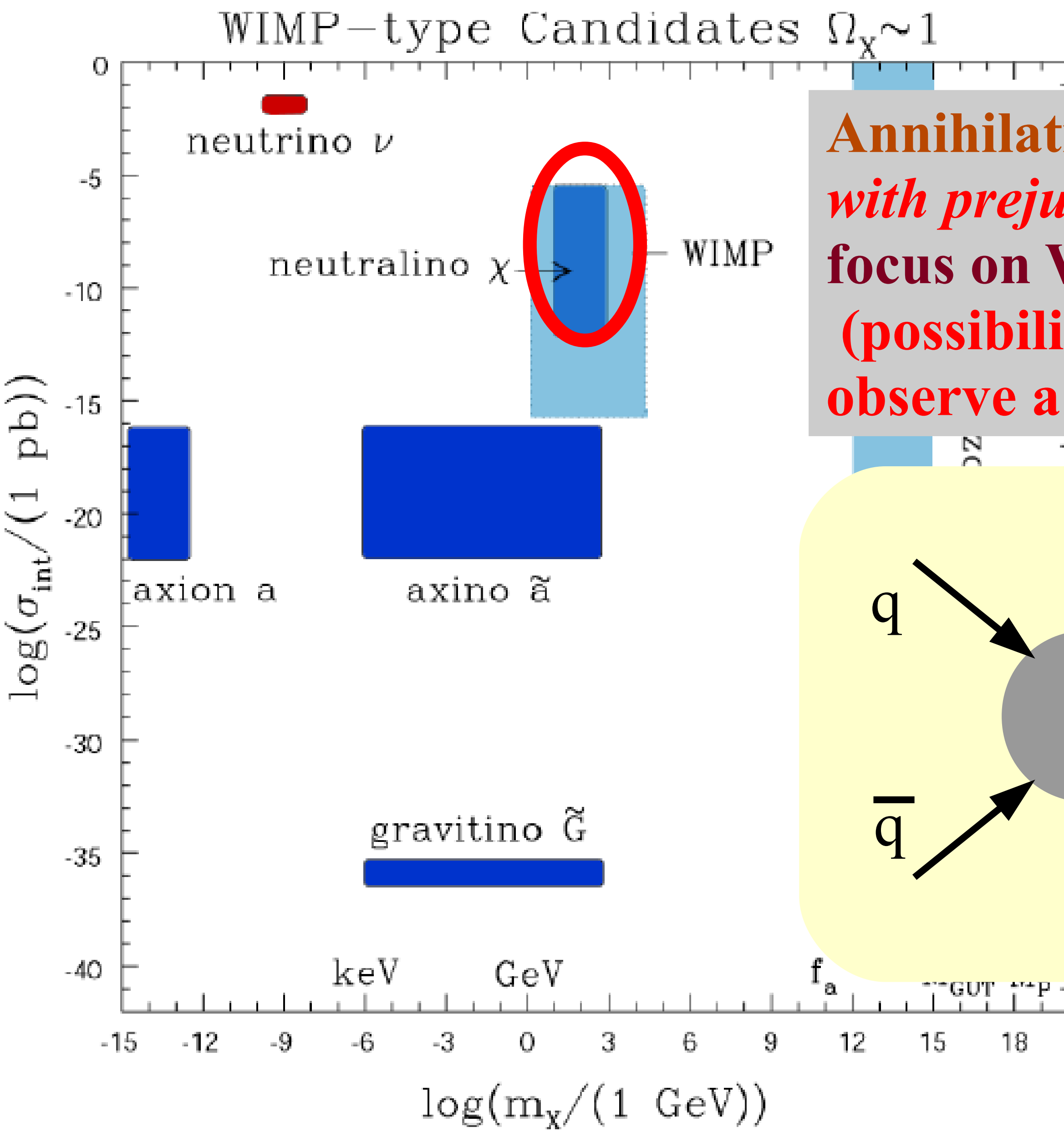
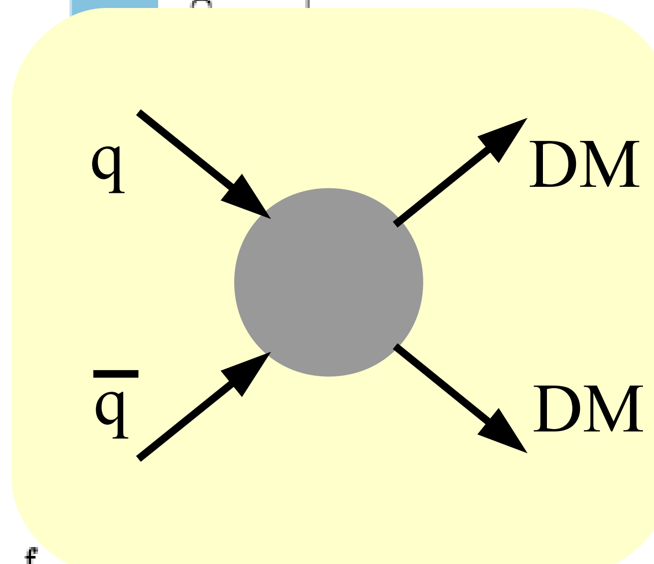
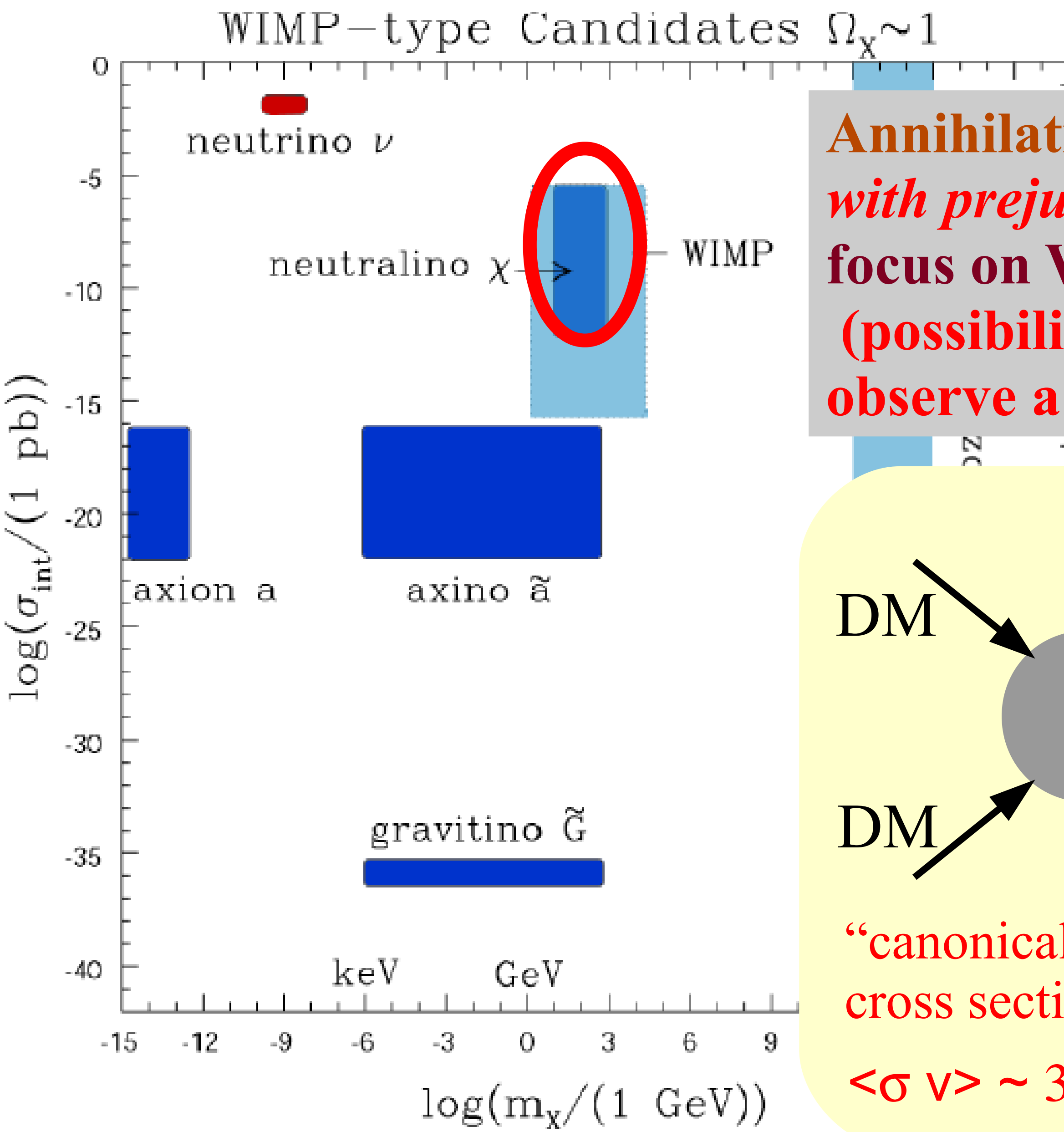
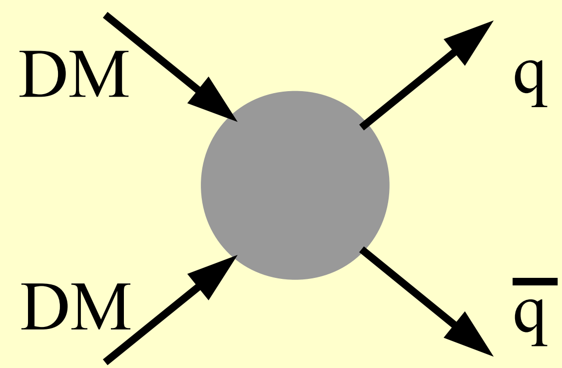


Annihilating DM searches
with prejudice:
focus on WIMPs
(possibility to
observe a signal)



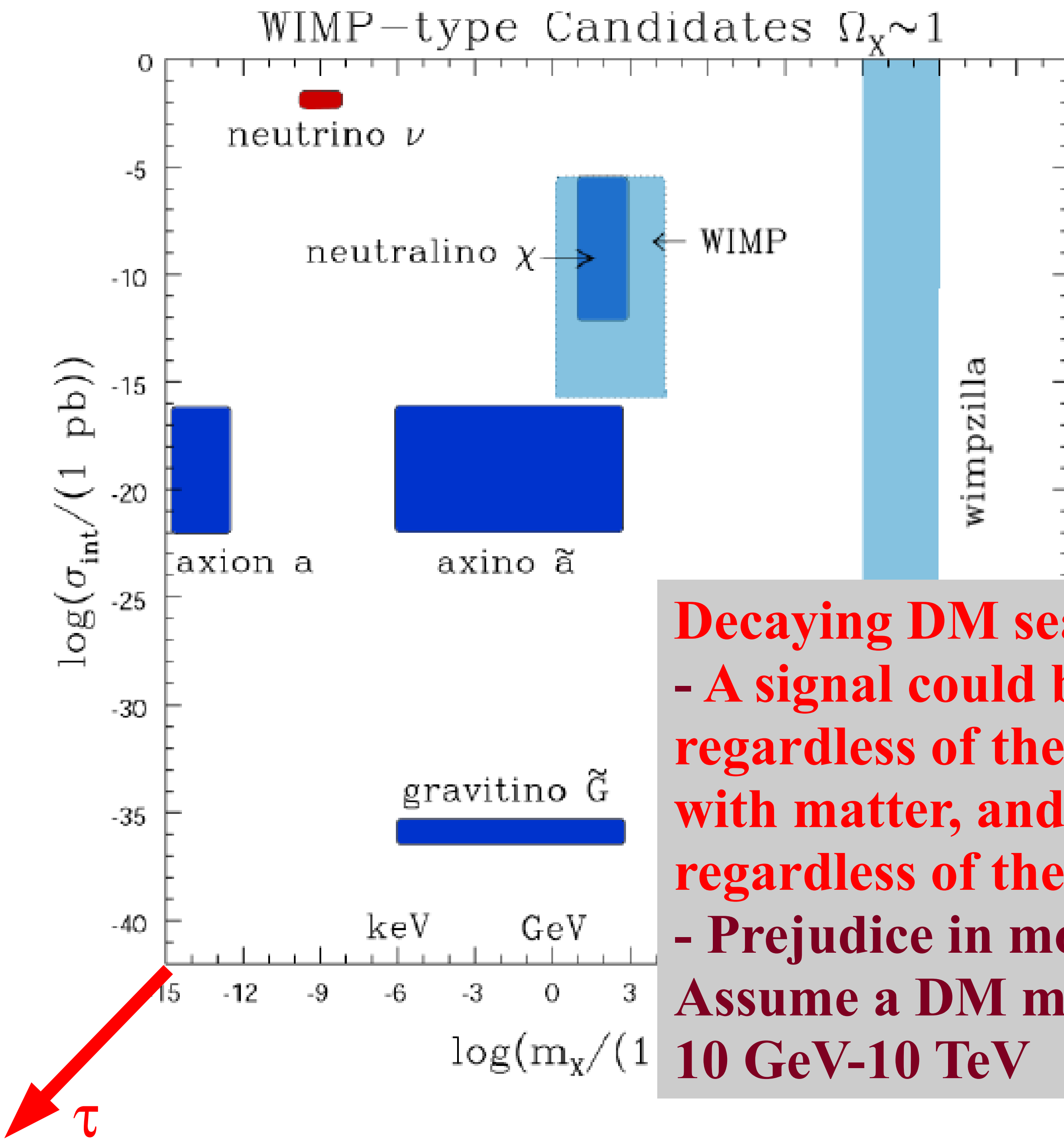


Annihilating DM searches ***with prejudice:*** **focus on WIMPs (possibility to observe a signal)**



"canonical" annihilation cross section

$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ cm^3/s$



Decaying DM searches:

- A signal could be observed regardless of the cross section with matter, and (almost) regardless of the mass.

- Prejudice in most of this talk: Assume a DM mass in the range 10 GeV-10 TeV

Decaying dark matter?

No matter particle is guaranteed to be stable

particle	Lifetime	Decay channel	Theoretical justification
proton	$\tau > 8.2\times10^{33}$ years	$p \to e^+ \pi^0$	Baryon number conservation
electron	$\tau > 4.6\times10^{26}$ years	$e \to \gamma \nu$	Electric charge conservation
neutrino	$\tau \gtrsim 10^{12}$ years	$\nu \to \gamma \gamma$	Lorentz symmetry conservation
neutron	$\tau = 885.7 \pm 0.8$ s	$n \to p \bar{\nu}_e e^-$	Isospin symmetry mildly broken.

} Accidental symmetry (proton)

} Local symmetry (electron, neutrino)

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neutron	τ=885.7±0.8 s	$n \to p\, \bar{\nu}_e\, e^-$	Isospin symmetry mildly broken.
dark matter	$\tau \gtrsim 10^9$ years	???	???

} Accidental symmetry (proton)

} Local symmetry (electron, neutrino)

It is conceivable that the dark matter particle is long lived due to an accidental symmetry of the renormalizable Lagrangian (as for the proton).

Higher dimensional operators may induce the dark matter decay (as for the proton). For a dimension six operator suppressed by a large scale M,

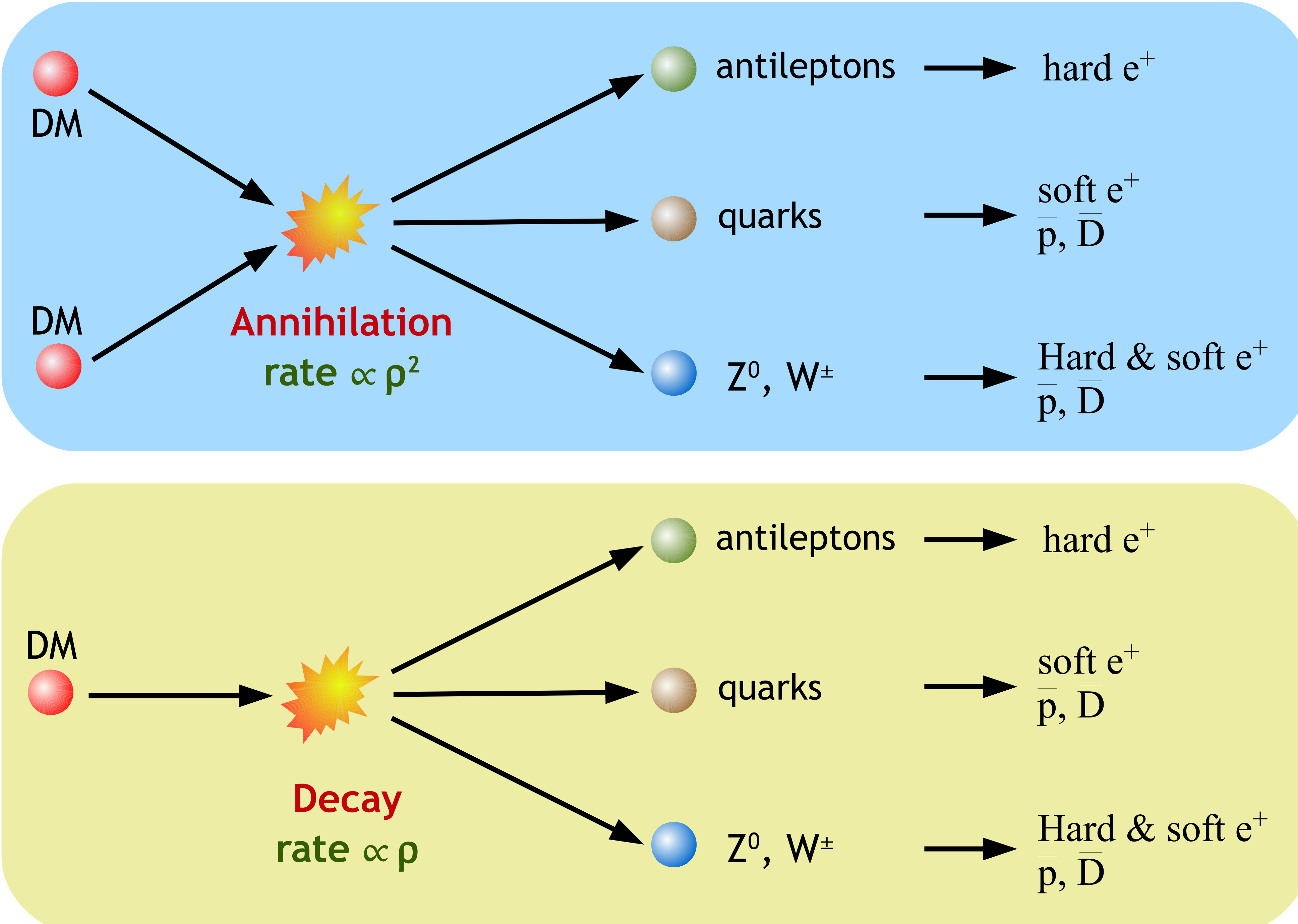
$$\tau_{\rm DM} \sim 10^{26}{\rm s} \left(\frac{\rm TeV}{m_{\rm DM}}\right)^5 \left(\frac{M}{10^{15}{\rm GeV}}\right)^4$$

Indirect dark matter searches

Production		Antimatter
Propagation	of	Gamma-rays
Detection		Neutrinos

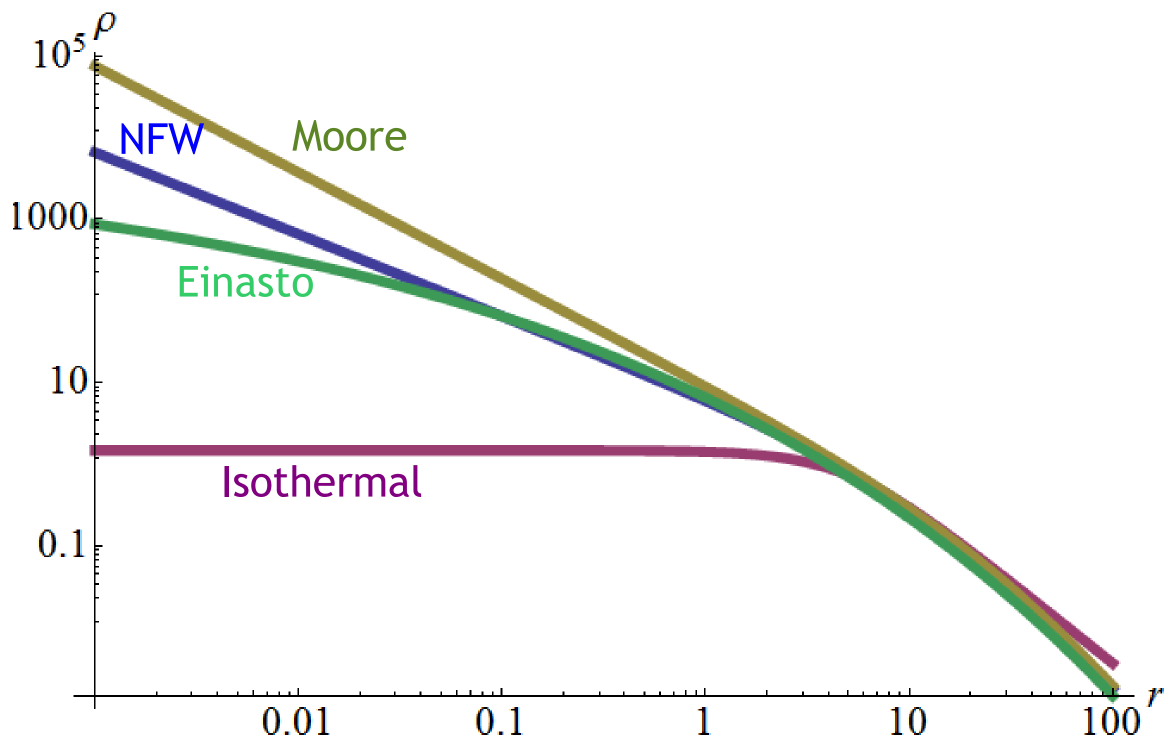
Antimatter

Production


DM
DM
Annihilation
rate ∝ ρ²
antileptons
hard e+
quarks
soft e+
p̄, D̄
Z0, W±
Hard & soft e+
p̄, D̄
DM
Decay
rate ∝ ρ
antileptons
hard e+
quarks
soft e+
p̄, D̄
Z0, W±
Hard & soft e+
p̄, D̄

Density distribution of dark matter particles. Unknown

- Assume spherical symmetry.
- 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

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

$$\alpha = 0.17, \; r_s = 20 \text{ kpc}$$

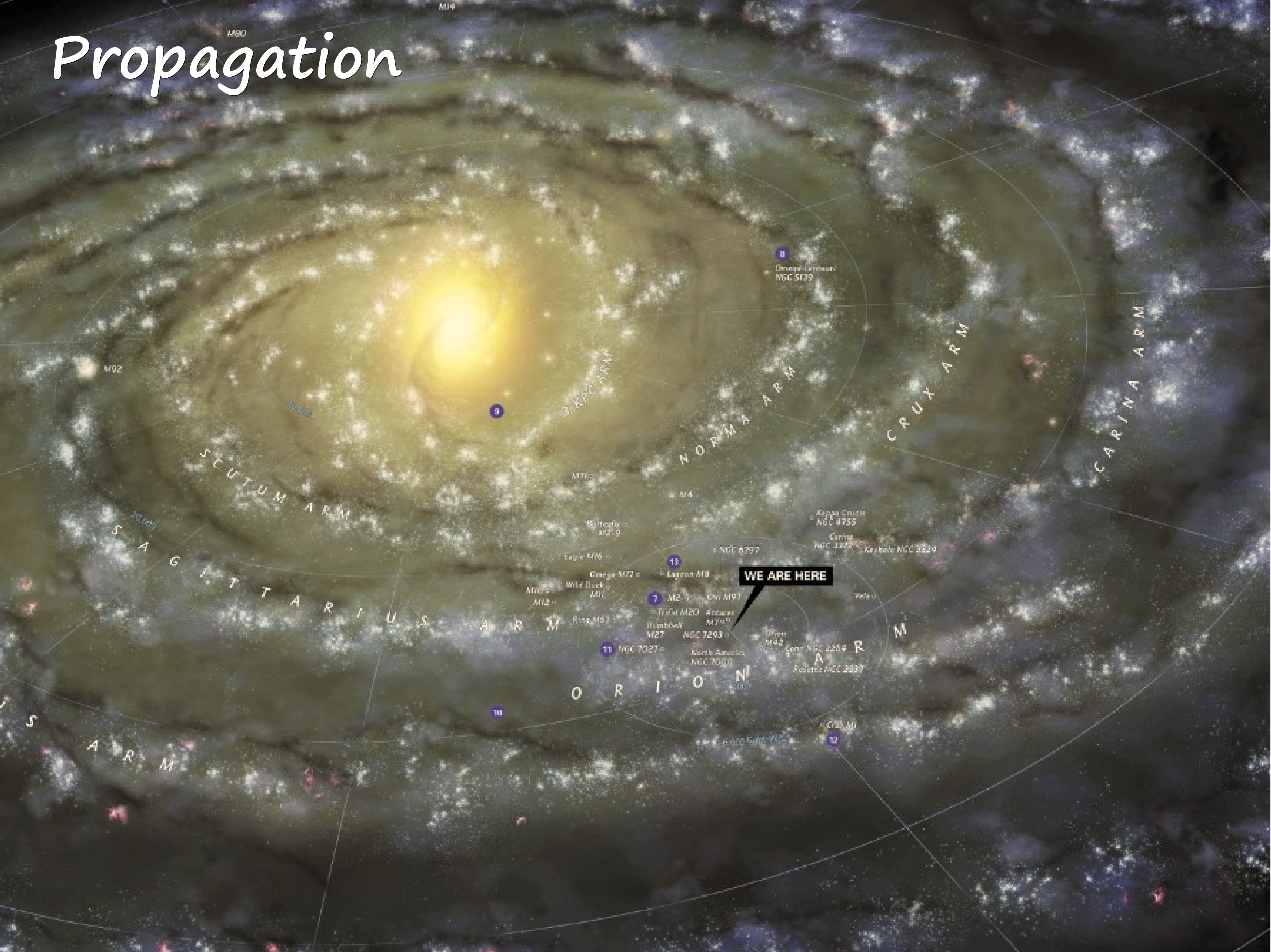
- Normalized such that the local DM density is

  $\rho(r=8.5 \text{ kpc}) = 0.38 \text{ GeV/cm}^3$

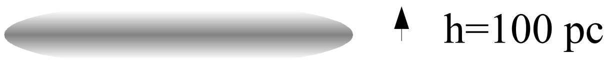
The production is described by the source function

$$Q(E,\vec{r}) = \begin{cases} \rho^2(\vec{r})\ \dfrac{\langle\sigma v\rangle_{\rm DM}}{2m_{\rm DM}^2}\sum_f \dfrac{dN^f}{dE}B_f & \text{annihilation} \\ \\ \rho(\vec{r})\ \dfrac{1}{m_{\rm DM}\tau_{\rm DM}}\sum_f \dfrac{dN^f}{dE}B_f & \text{decay} \end{cases}$$

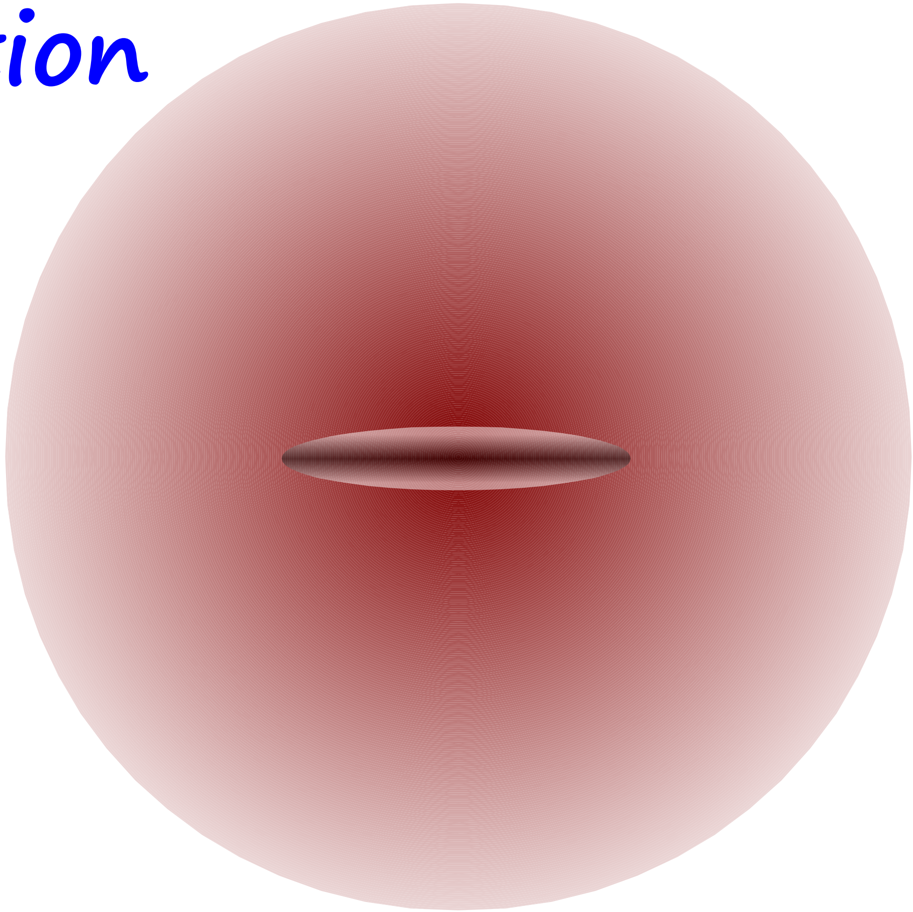
Propagation



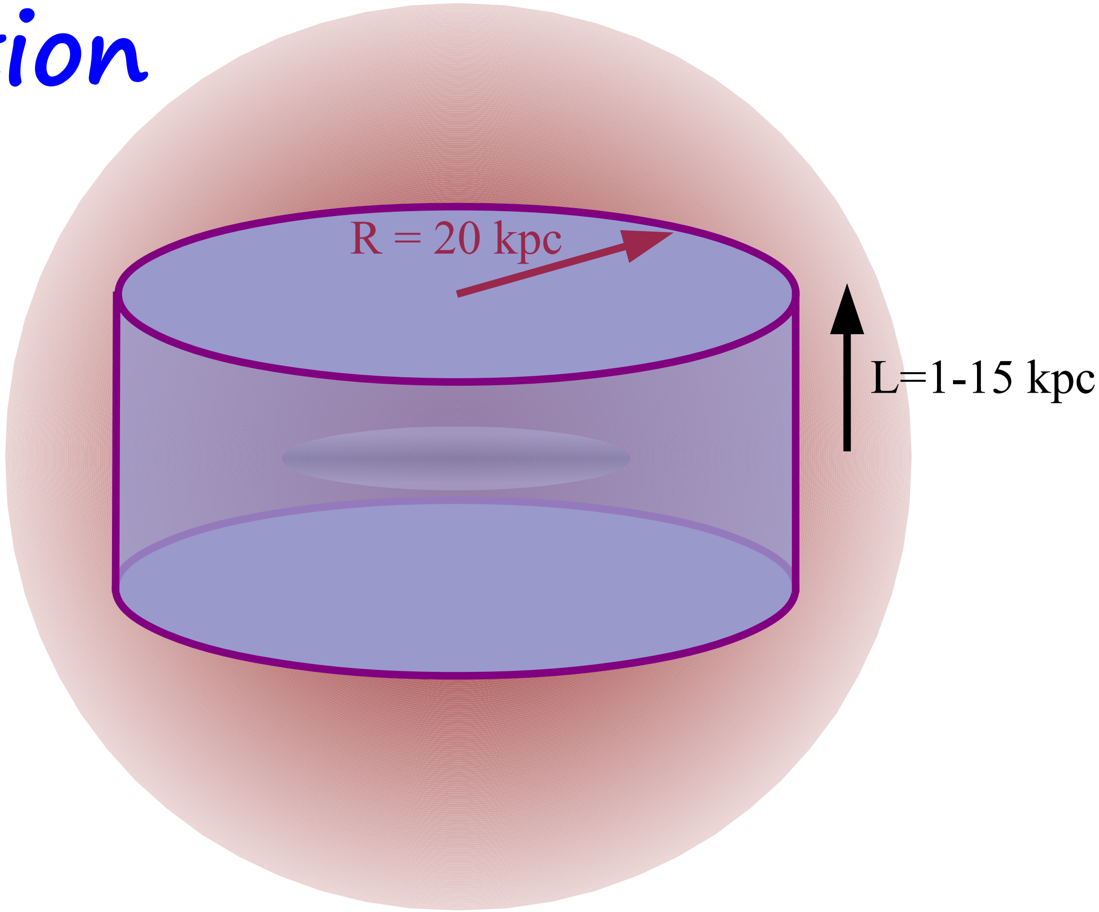
Propagation



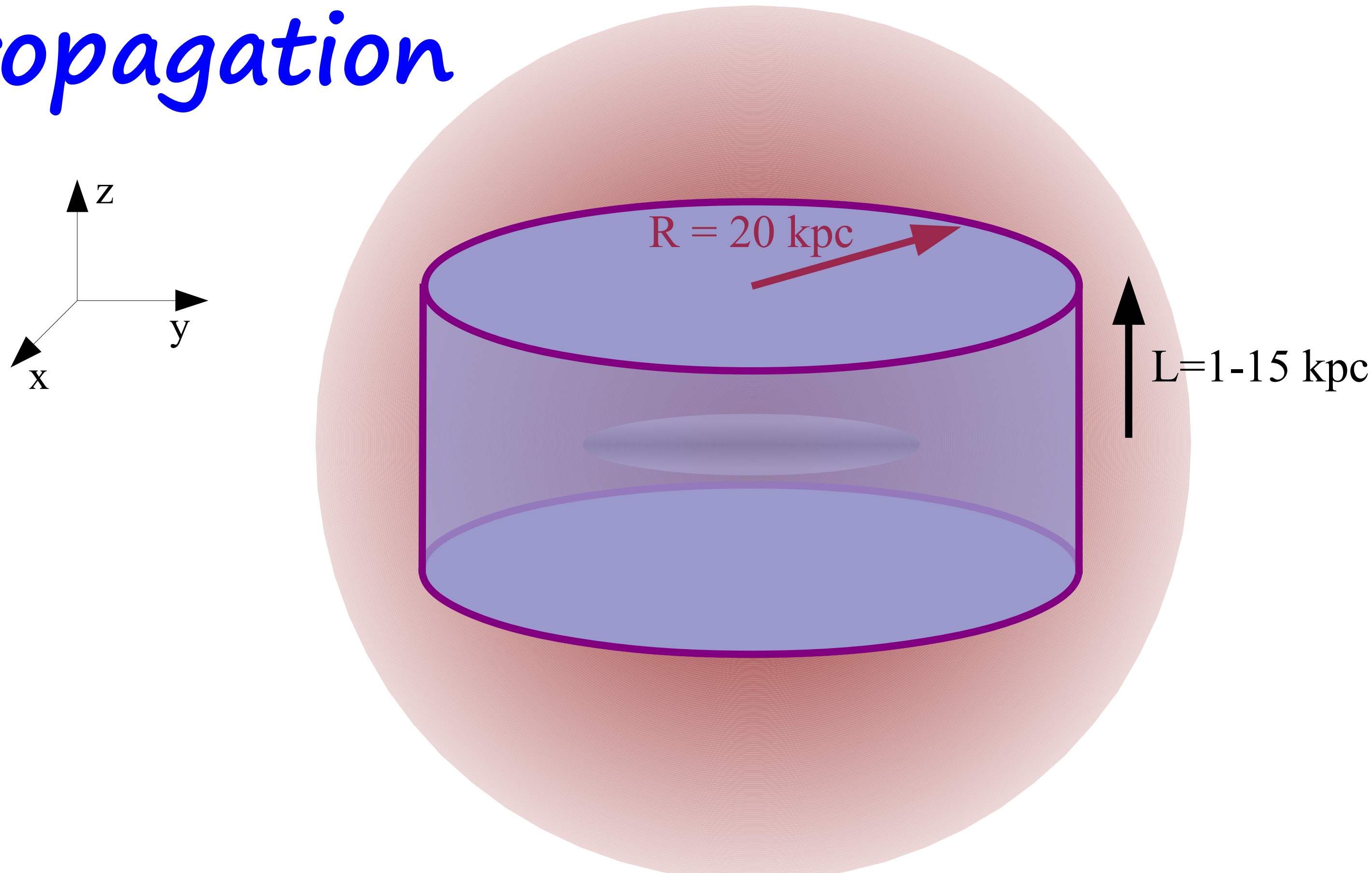
Propagation



Propagation



Propagation



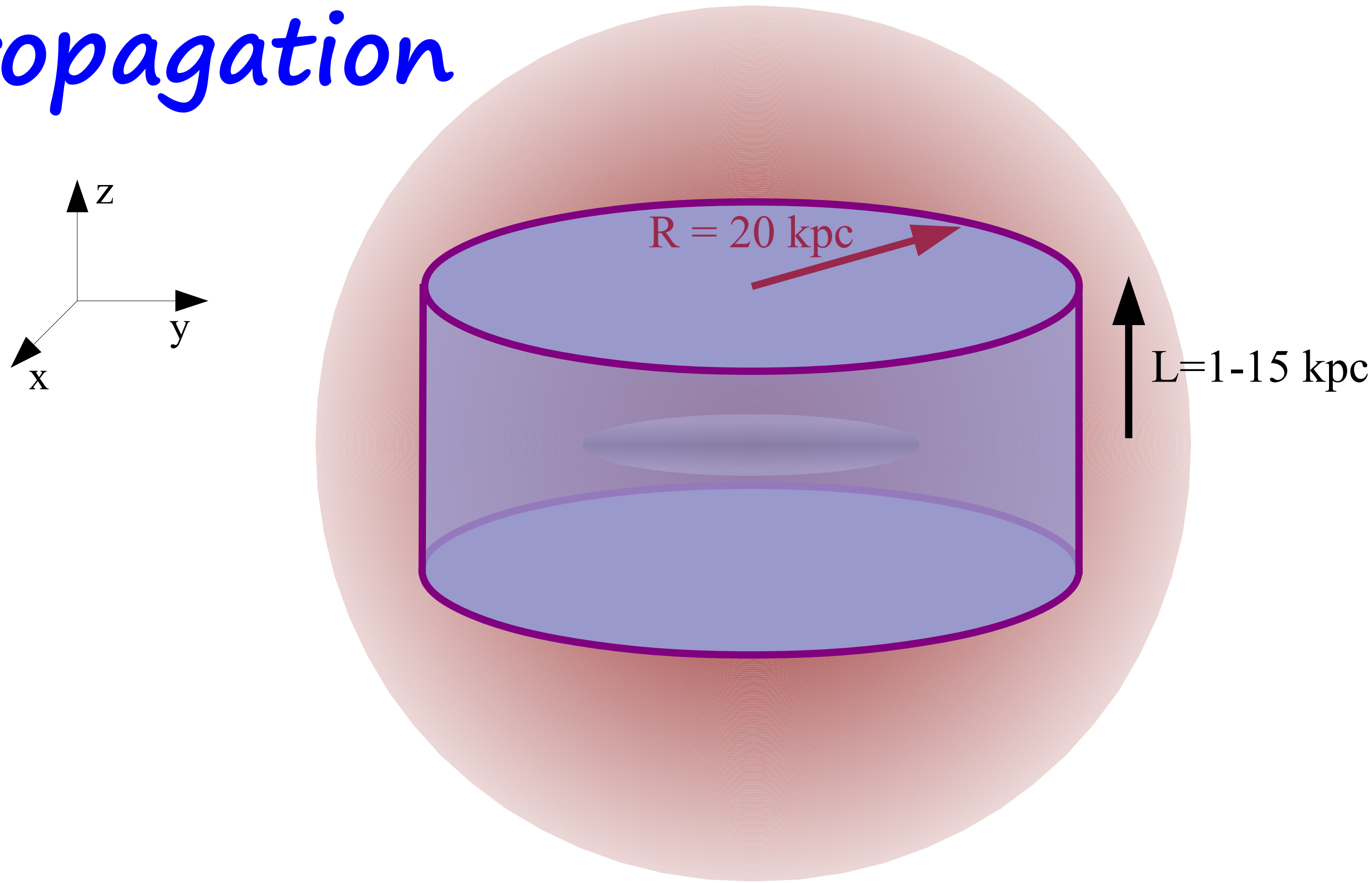
$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\rm ann} f + Q(T,\vec{r}) \ .$$

f: number density of antiparticles per unit kinetic energy

interstellar antimatter flux:

$$\Phi^{\rm IS}(T) = \frac{v}{4\pi} f(T)$$

Propagation



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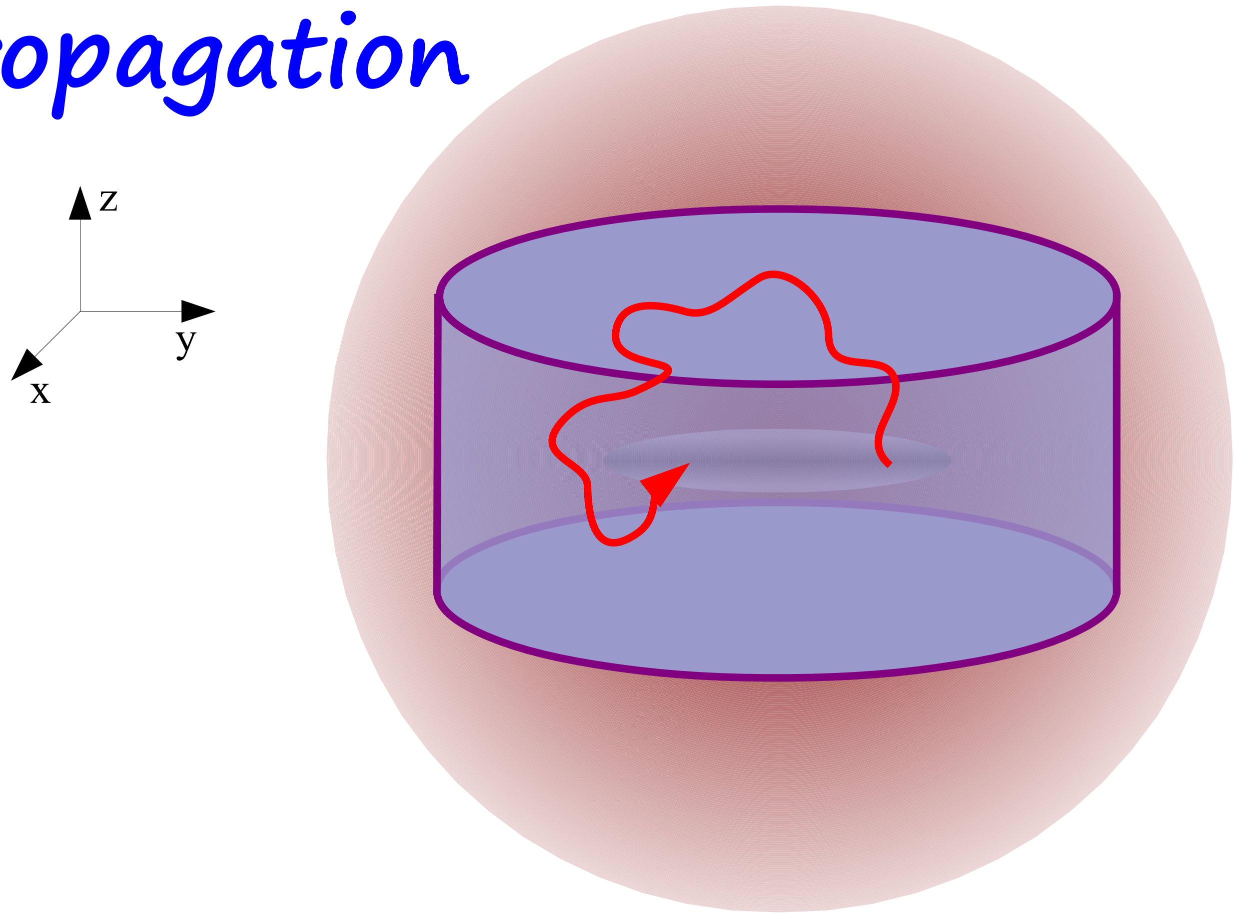
Source term

$$Q(T,\vec{r}) = \begin{cases} \int_0^\infty \frac{d\sigma_{pH\to X}}{dT_p} n_H(\vec{r}) v_P f_p(\vec{r},T_p)\, dT_p & \text{spallation} \\ \frac{\rho^2(\vec{r})\langle\sigma v\rangle_{\rm DM}}{2m_{\rm DM}^2}\frac{dN}{dT} & \text{dark matter annihilation} \\ \frac{\rho(\vec{r})}{m_{\rm DM}\tau_{\rm DM}}\frac{dN}{dT} & \text{dark matter decay} \end{cases}$$

Propagation



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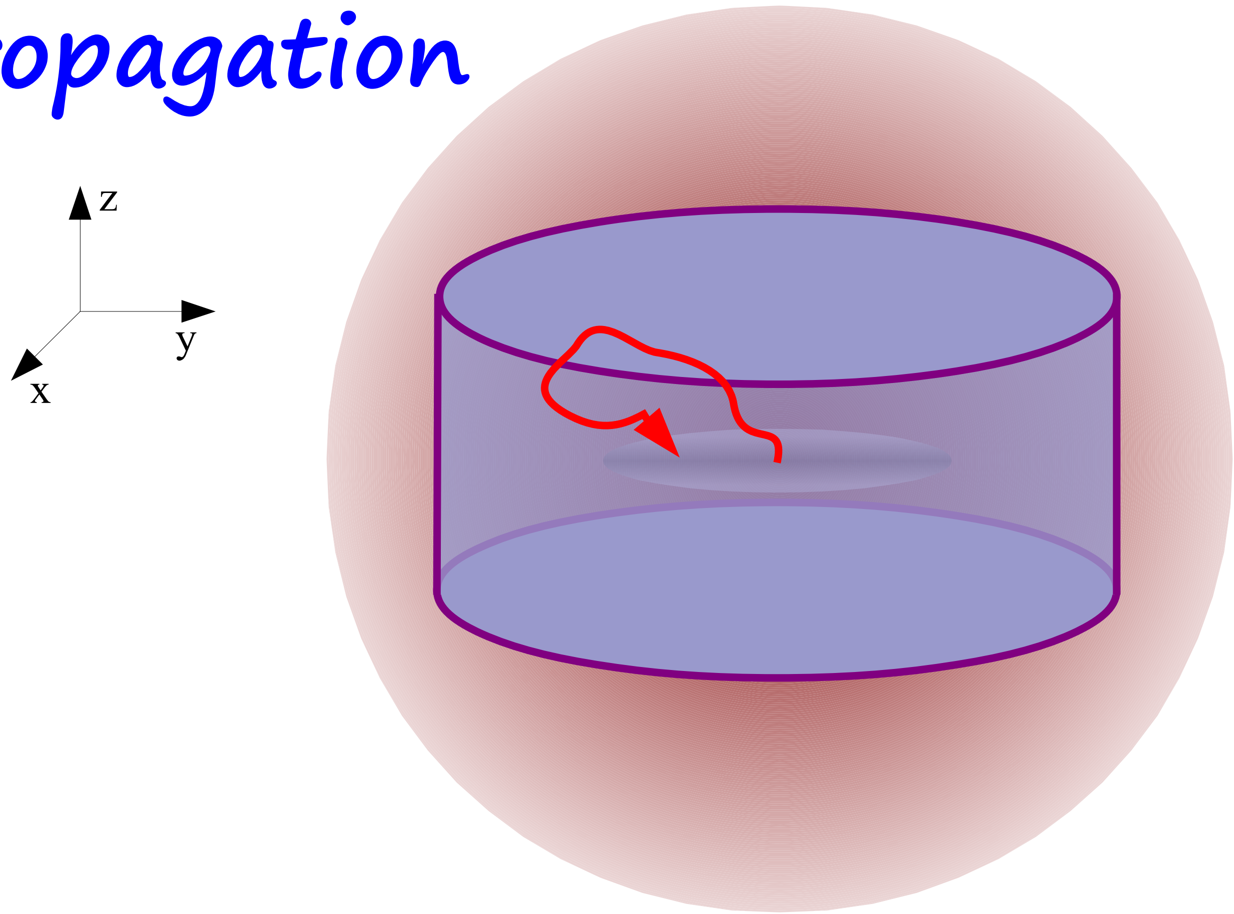

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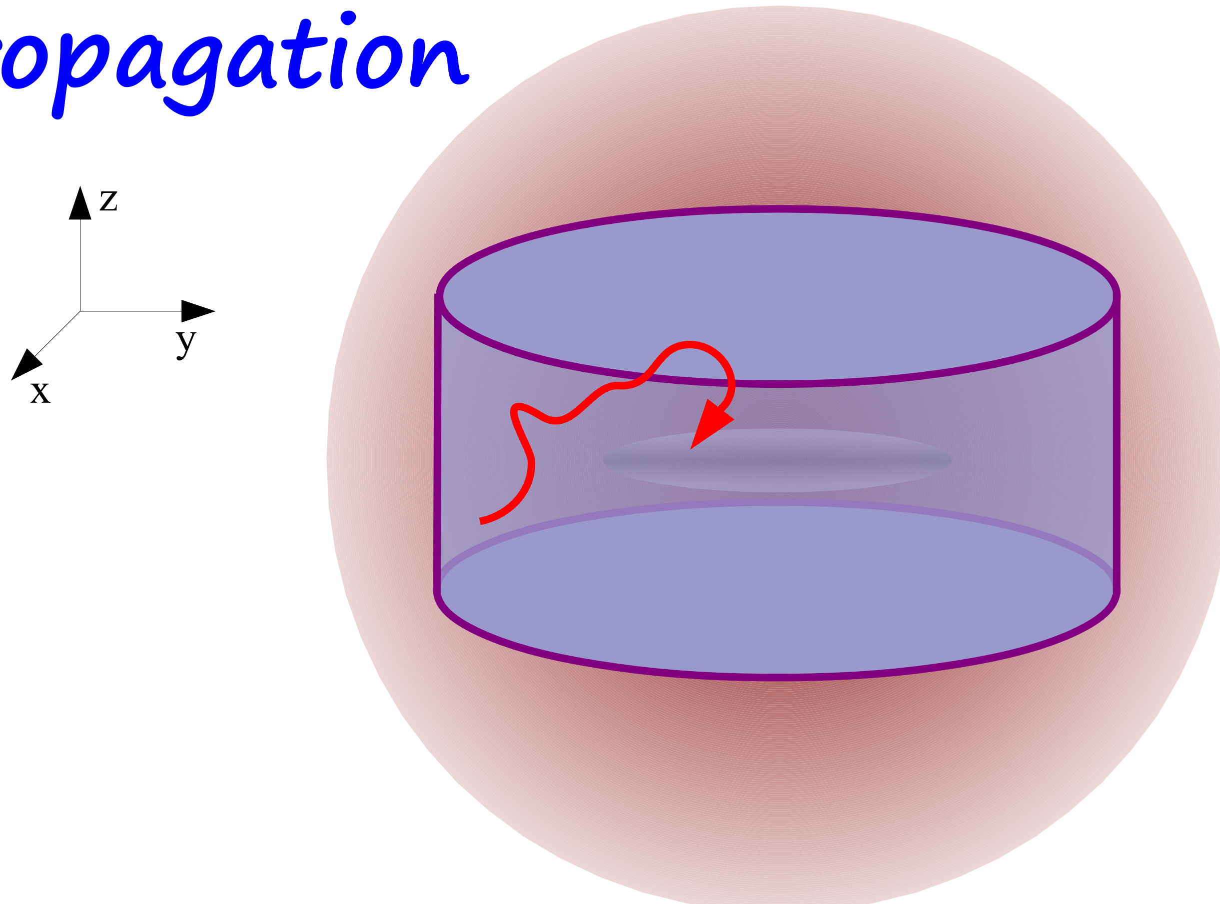

$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\mathrm{ann}} f + Q(T,\vec{r})\ .$$

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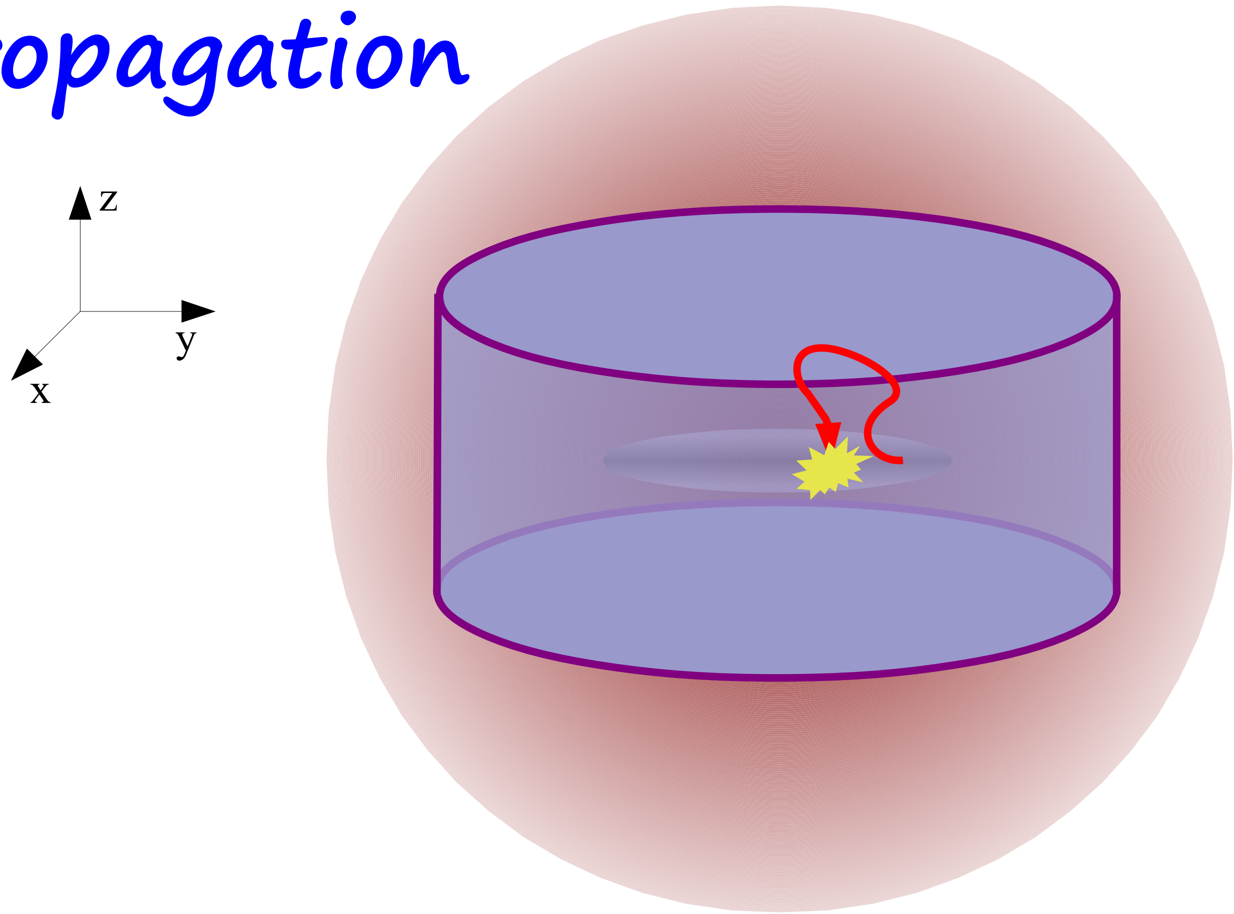
Propagation



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

Annihilation term

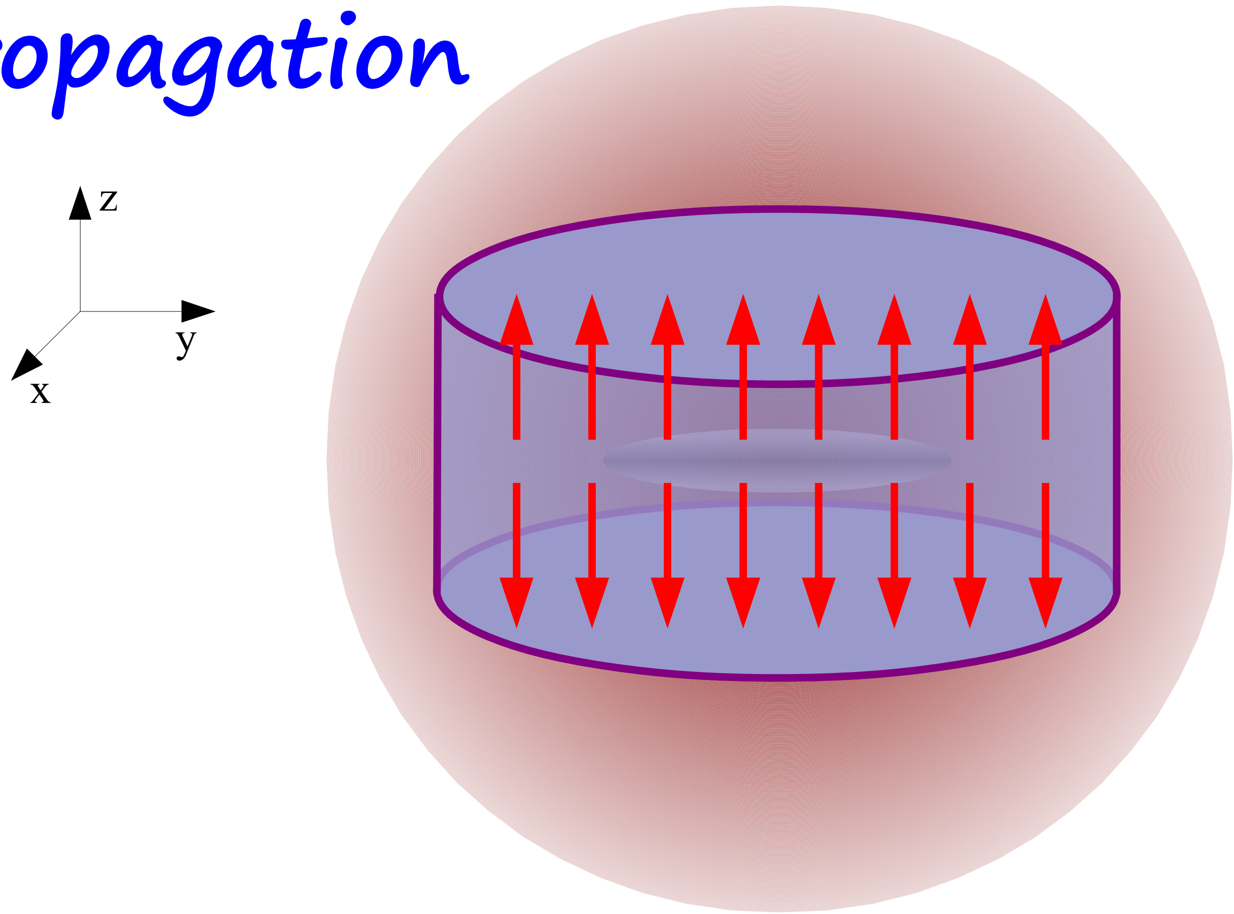
Negligible for positrons.
For antiprotons,

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

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

Tan, Ng

Propagation



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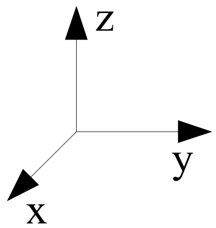
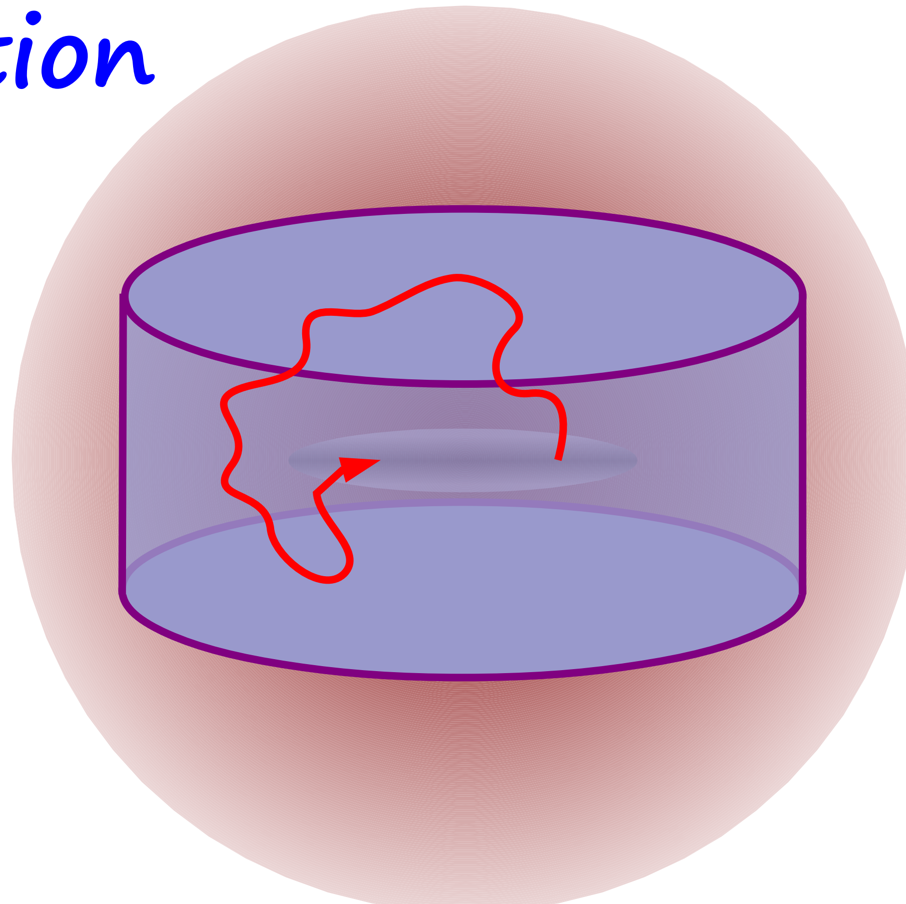
Convection term

- 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), synchrotron radiation and ionization.
- Negligible for antiprotons and antideuterons
- Can be modelled

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

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

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

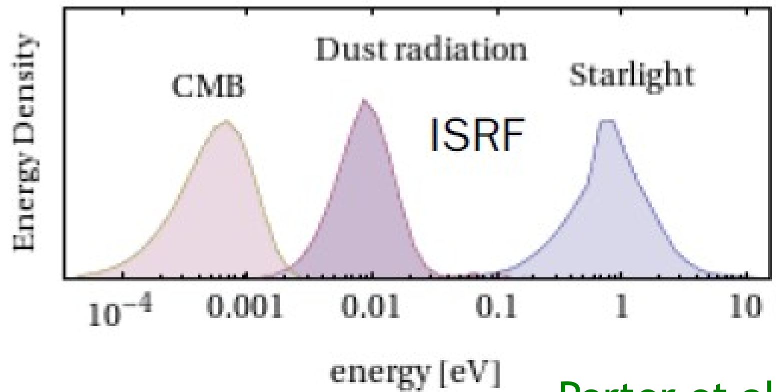
Number density of photons in ISRF

$\gamma_e = E_e/m_e \longrightarrow$ 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 $\tau_E = 10^{16}{\rm s}$

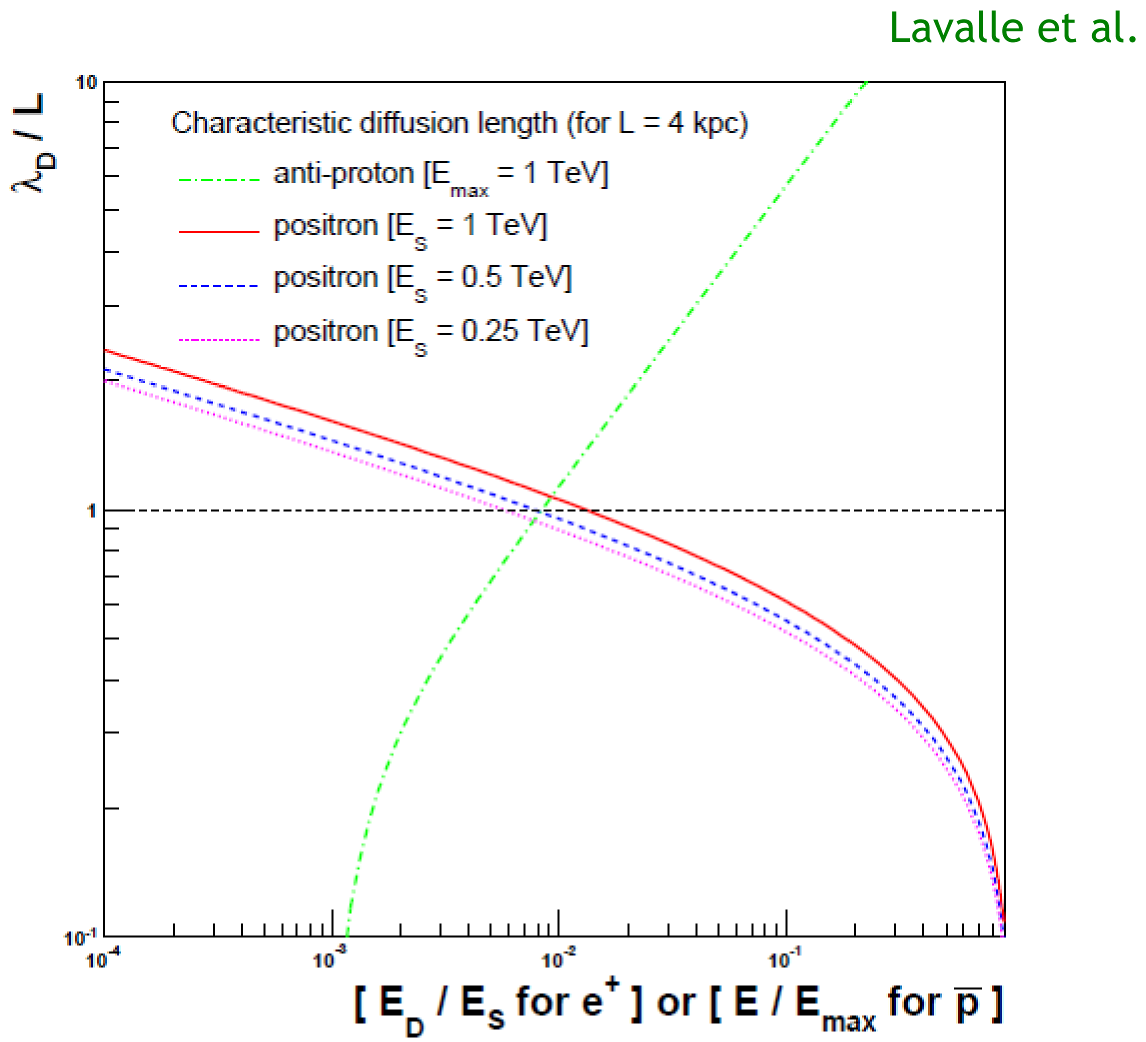
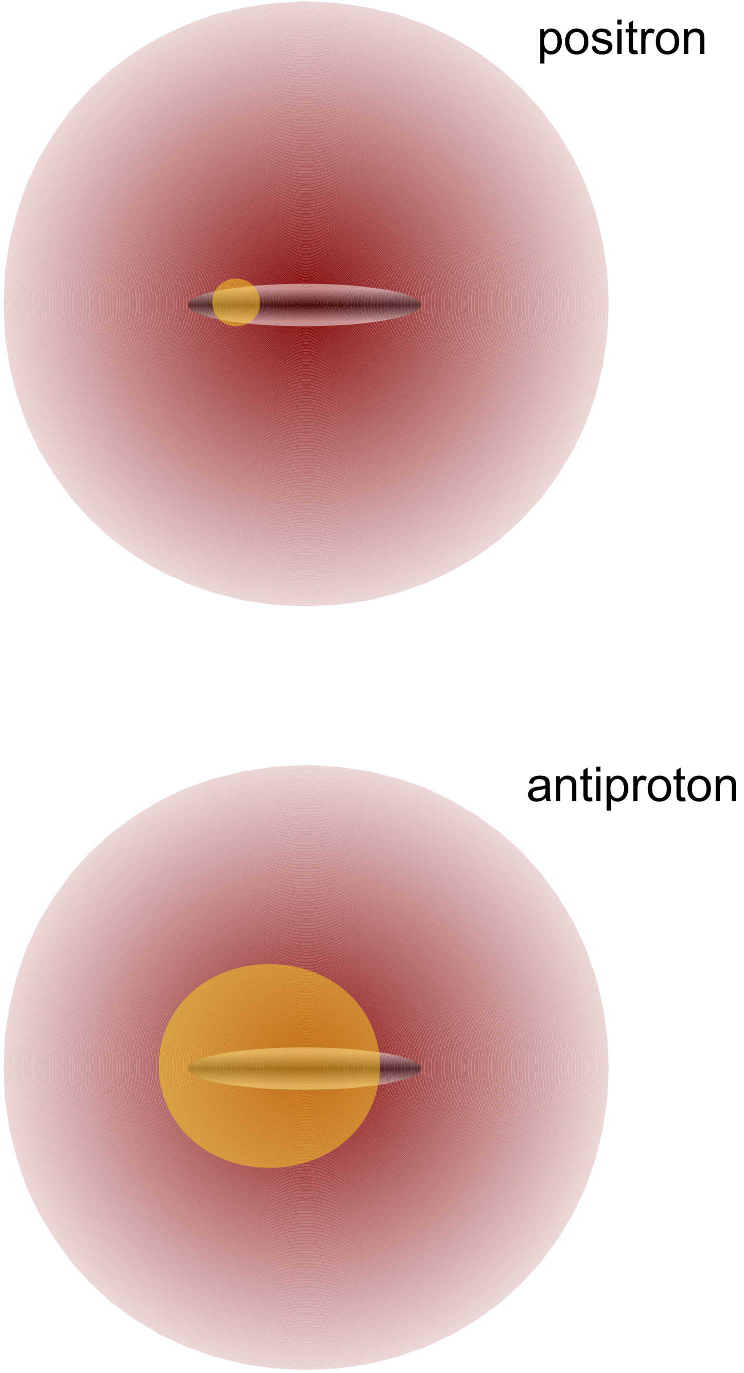
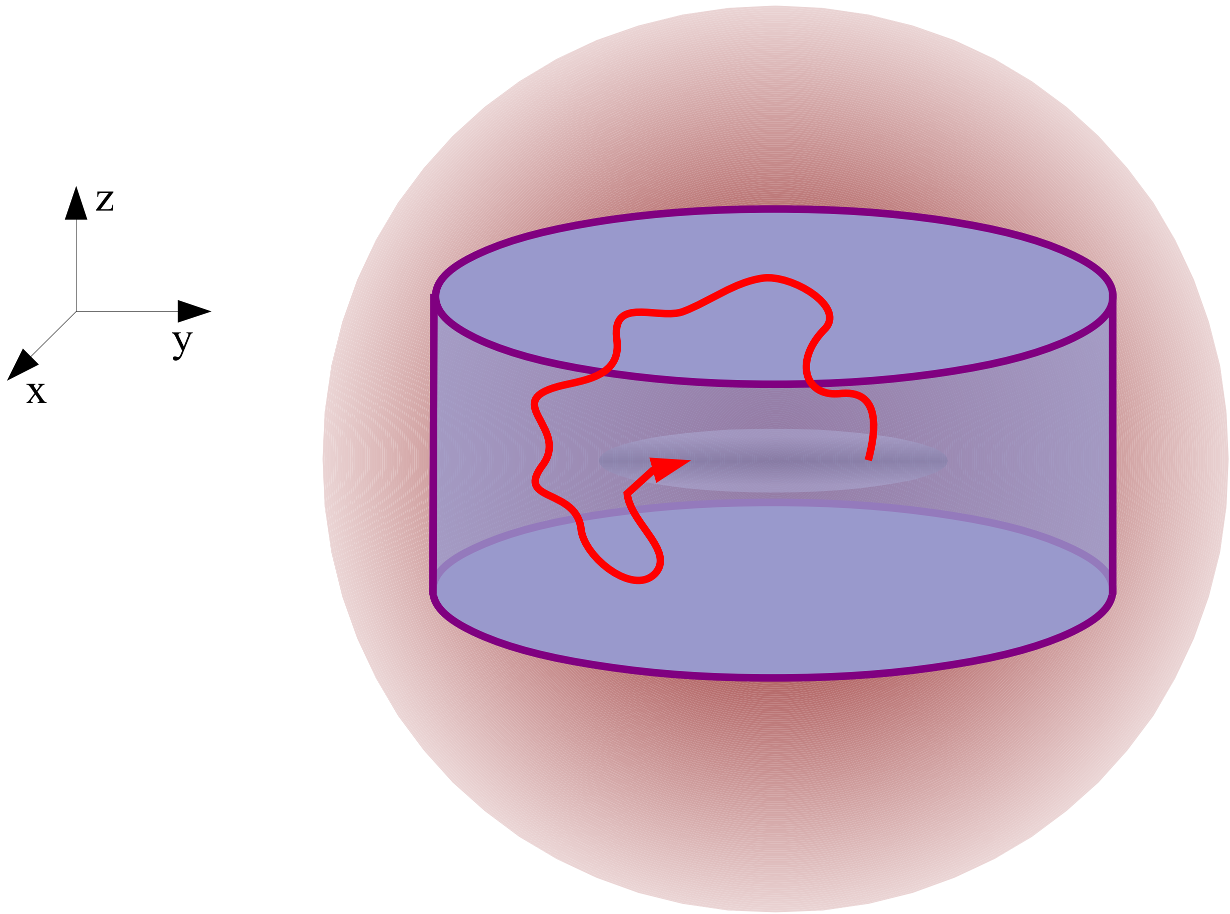


Figure 2: Propagation scales for positrons and antiprotons as functions of energy. For the former, the energy reported on the x axis is E_d/E_S, that is the detected energy divided by the injected energy (positrons loose energy), and for the latter, this is merely $E/E_{\max}$. Scales are normalized to $L = 4$ kpc, the vertical half-height of the diffusion zone.





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Diffusion term

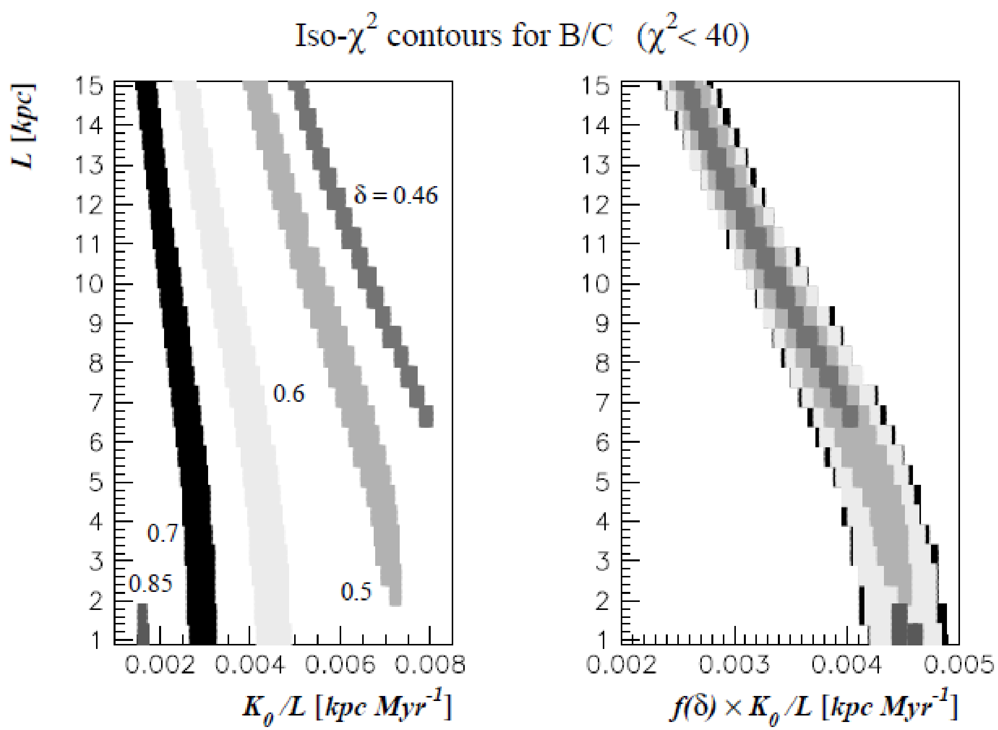
- Due to the tangled magnetic field of the Galaxy.
- Difficult to model. Assume

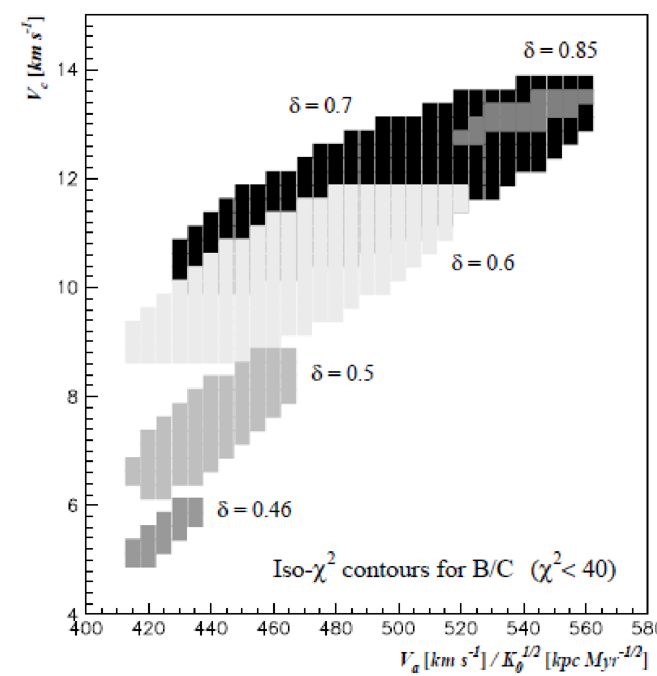
$$K(T) = K_0 \, \beta \, \mathcal{R}^\delta$$

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

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

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



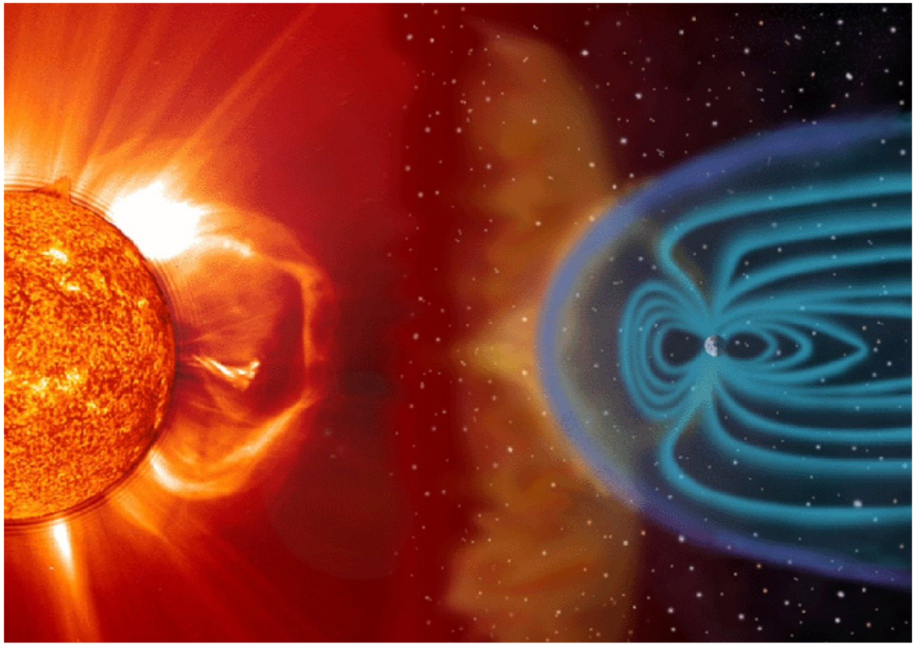


Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

Maurin, Donato, Taillet, Salati 2001

WE ARE HERE
3 KPC ARM
NORMA ARM
CRUX ARM
CARINA ARM
SCUTUM ARM
SAGITTARIUS ARM
ORION
M80
M92
NGC 6397
Lagoon M8
NGC 7293

Propagation inside the Solar System



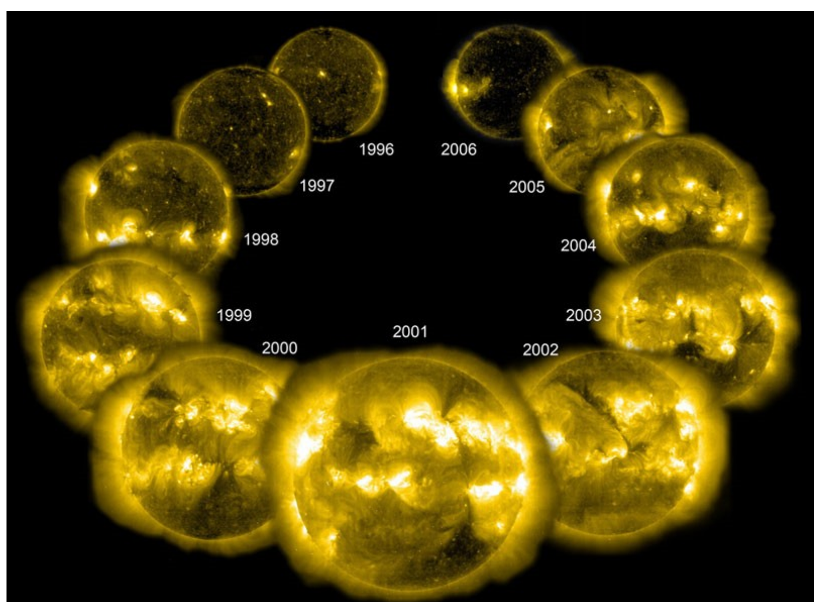
In the “force field approximation”,the flux at the top of the atmosphere (TOA) is related to the interstellar flux (IS) by

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

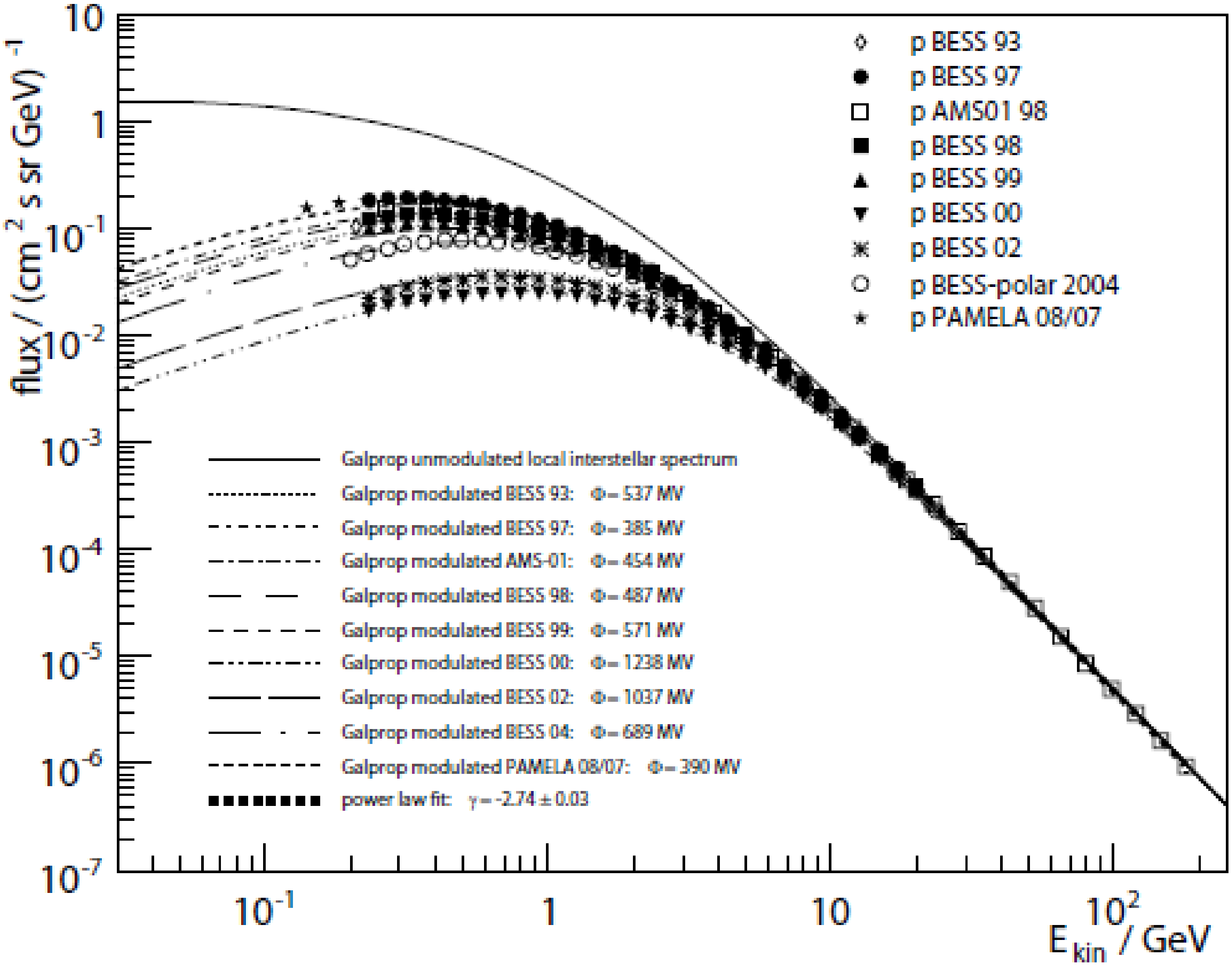
$$E_{\mathrm{IS}} = E_{\mathrm{TOA}} + \phi_F$$

solar modulation parameter

ϕ_F=500 MV – 1.3 GV

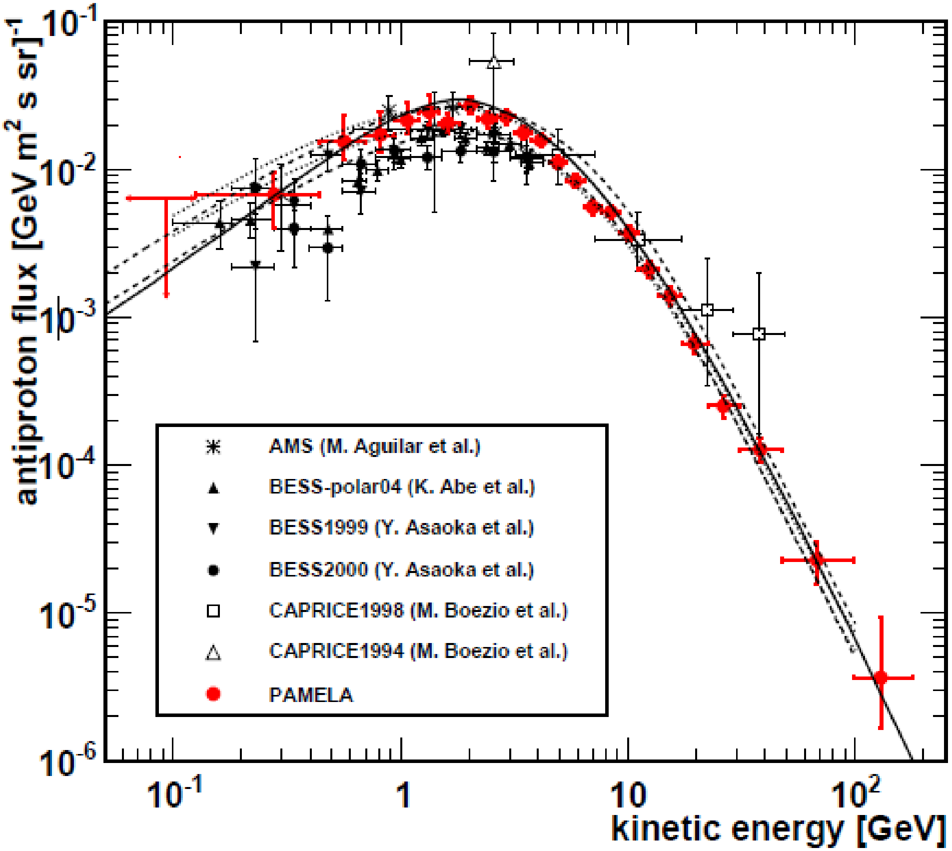


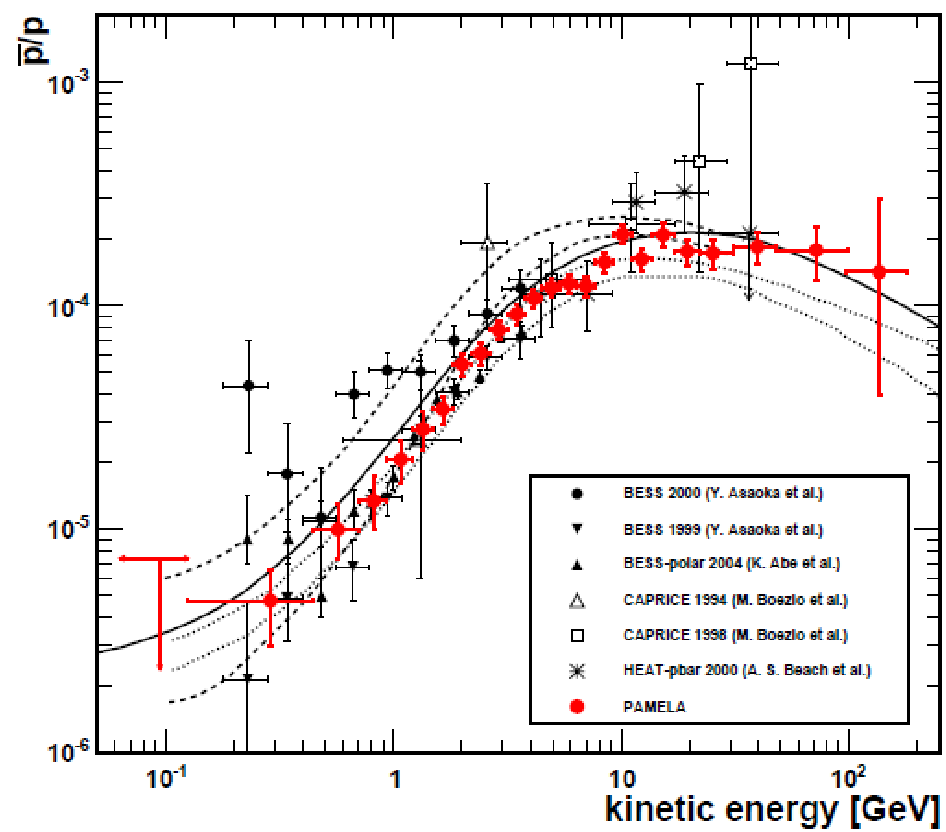
Cosmic ray proton spectrum as measured by BESS, AMS-01 and PAMELA



Gast, Schael '09

Experimental results: antiprotons





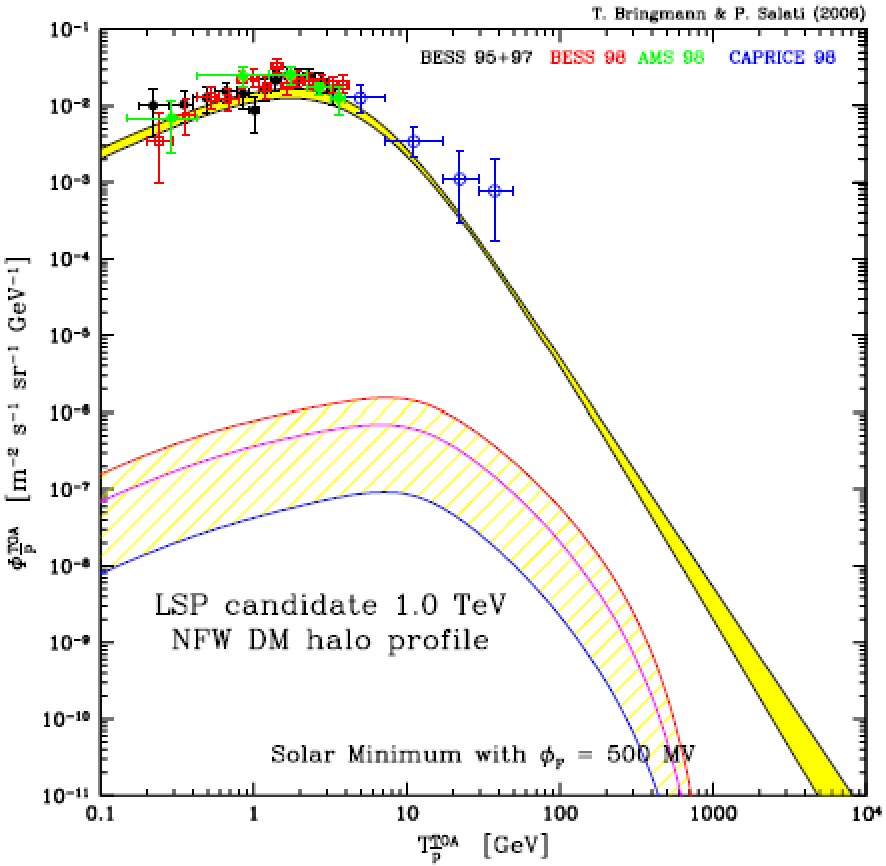
PAMELA collaboration
arXiv:1007.0821

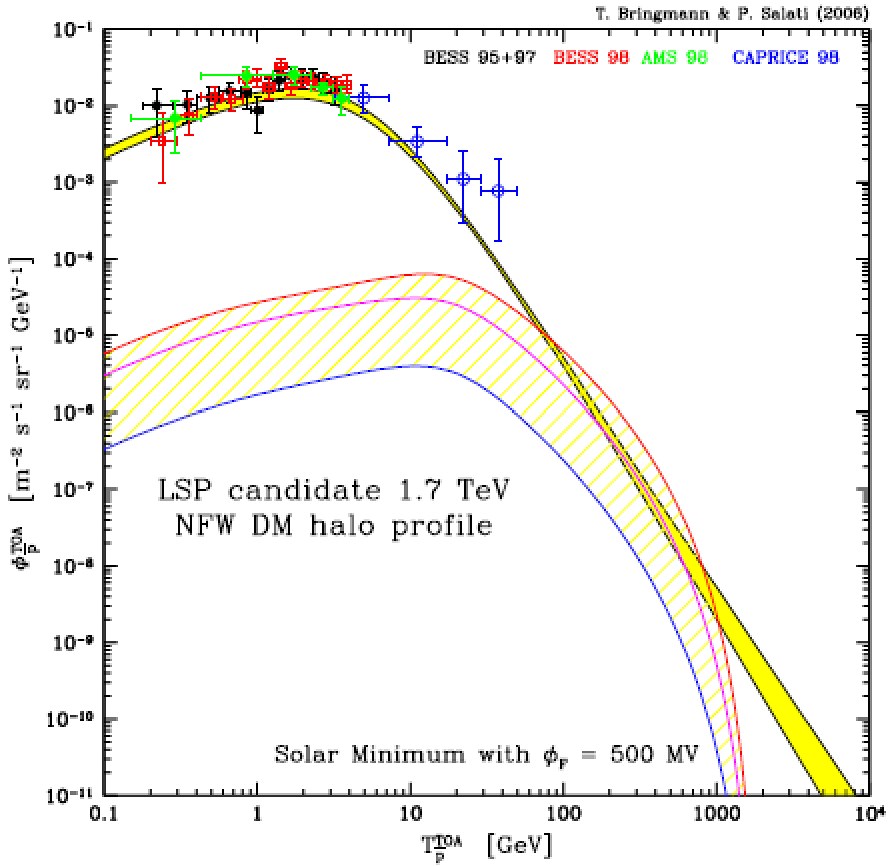
Fairly good agreement between the measurements and the theoretical predictions from spallation.

Annihilating dark matter: Lightest SUSY particle

$\times 10^{-26}$ 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	-	-
LSP1.7	1.7	102	-	-	-	-	-	-	20.1	79.9	-	-

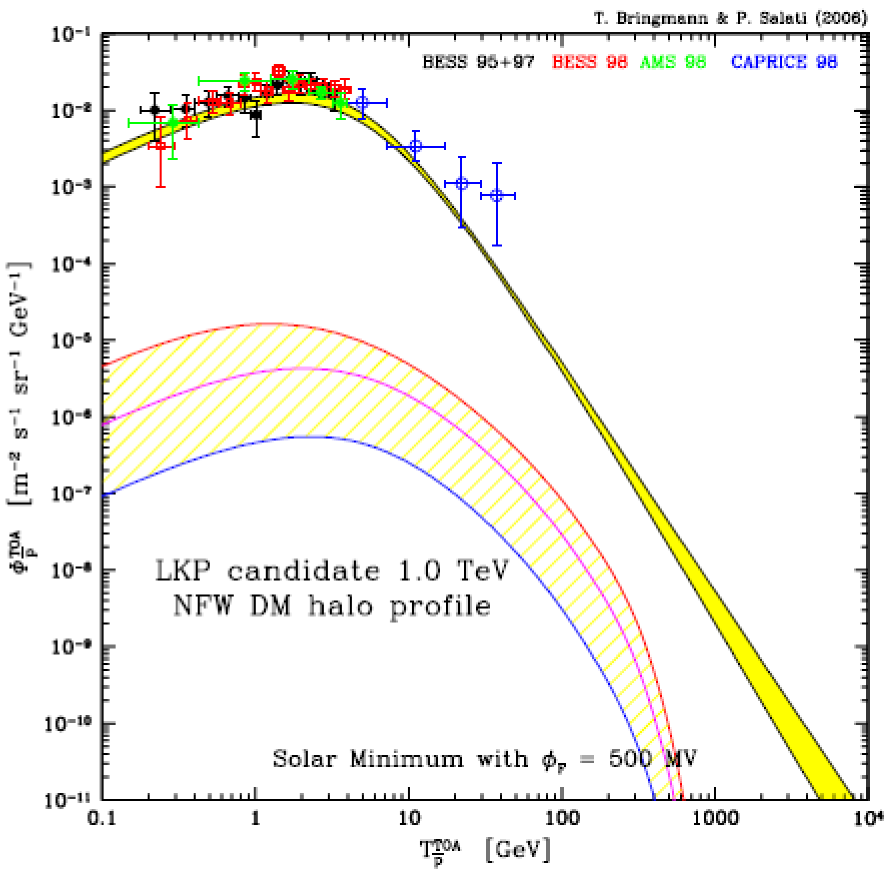


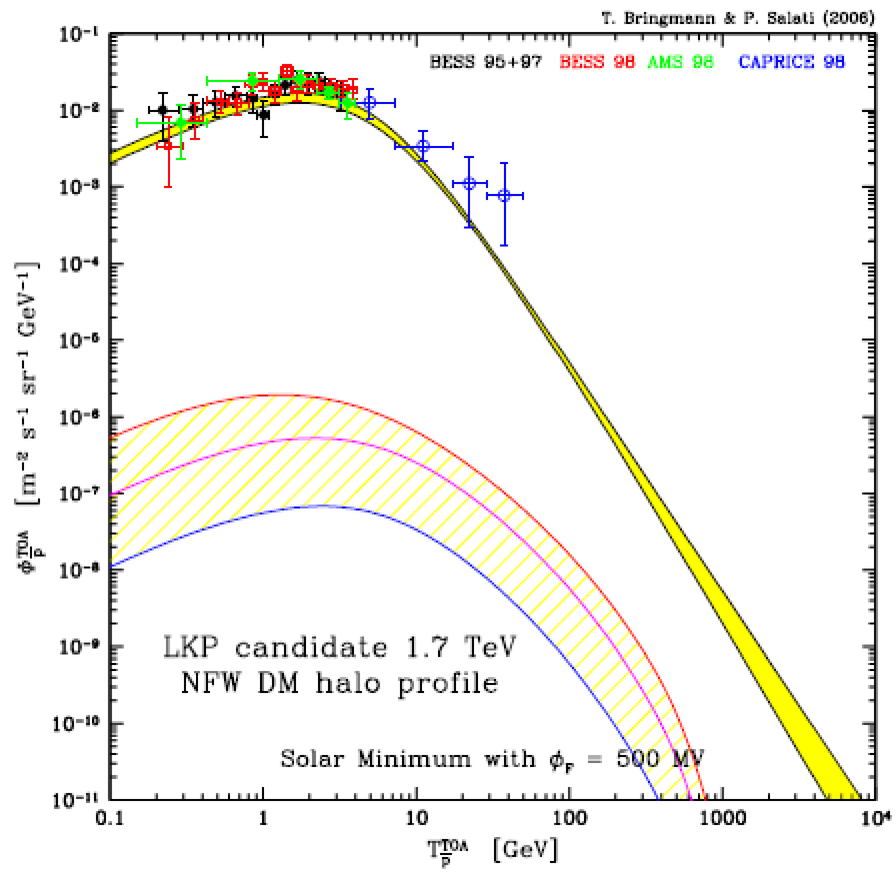


Annihilating dark matter: Lightest KK particle

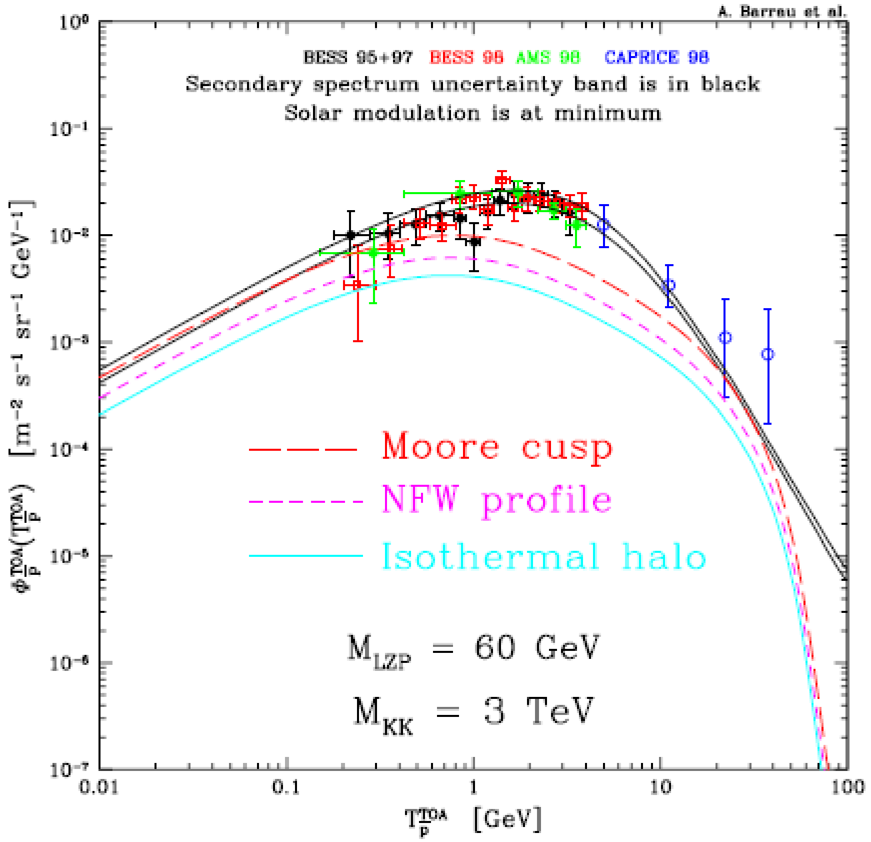
$\times 10^{-26}$ cm^{3}s^{-1}

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
LKP1.0	1.0	1.60	10.9	0.7	11.1	0.7	11.1	0.7	0.5	1.0	0.5	0.5
LKP1.7	1.7	0.55	11.0	0.7	11.1	0.7	11.1	0.7	0.5	0.9	0.5	0.5



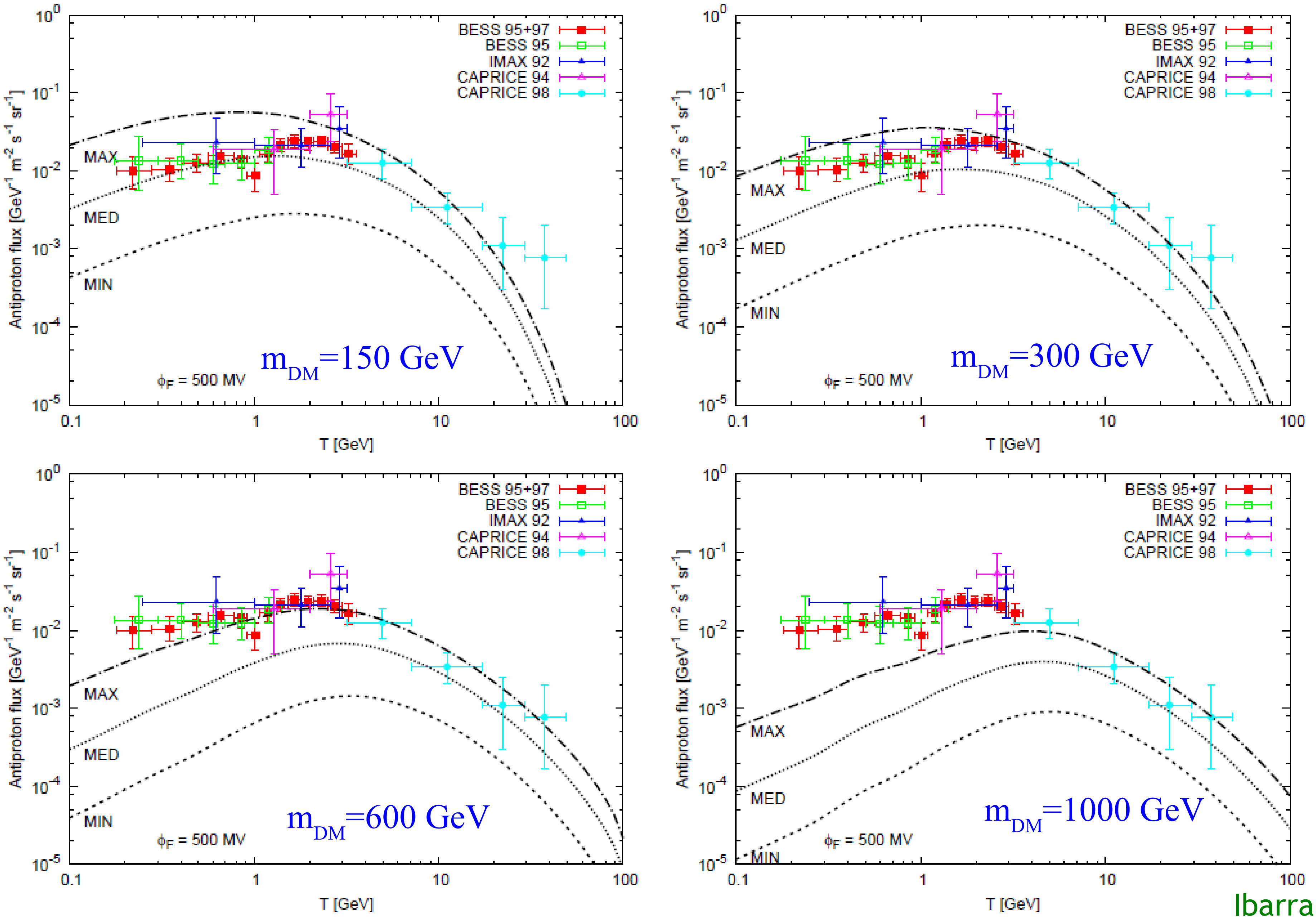


Annihilating dark matter: Sensitivity to the halo profile



Decaying dark matter: $\psi \to W\, e$

$\tau_{DM} = 10^{26}$ s



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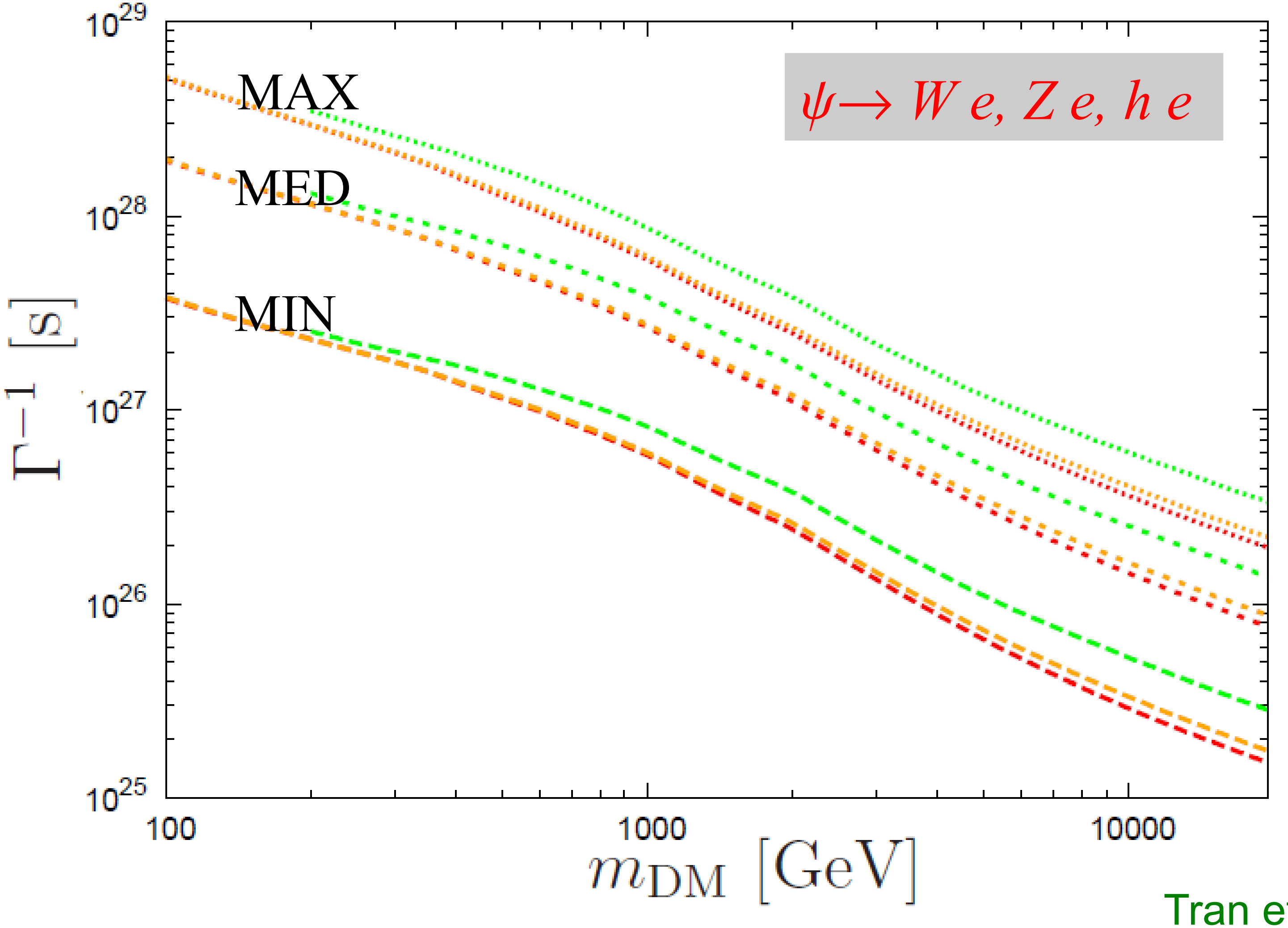
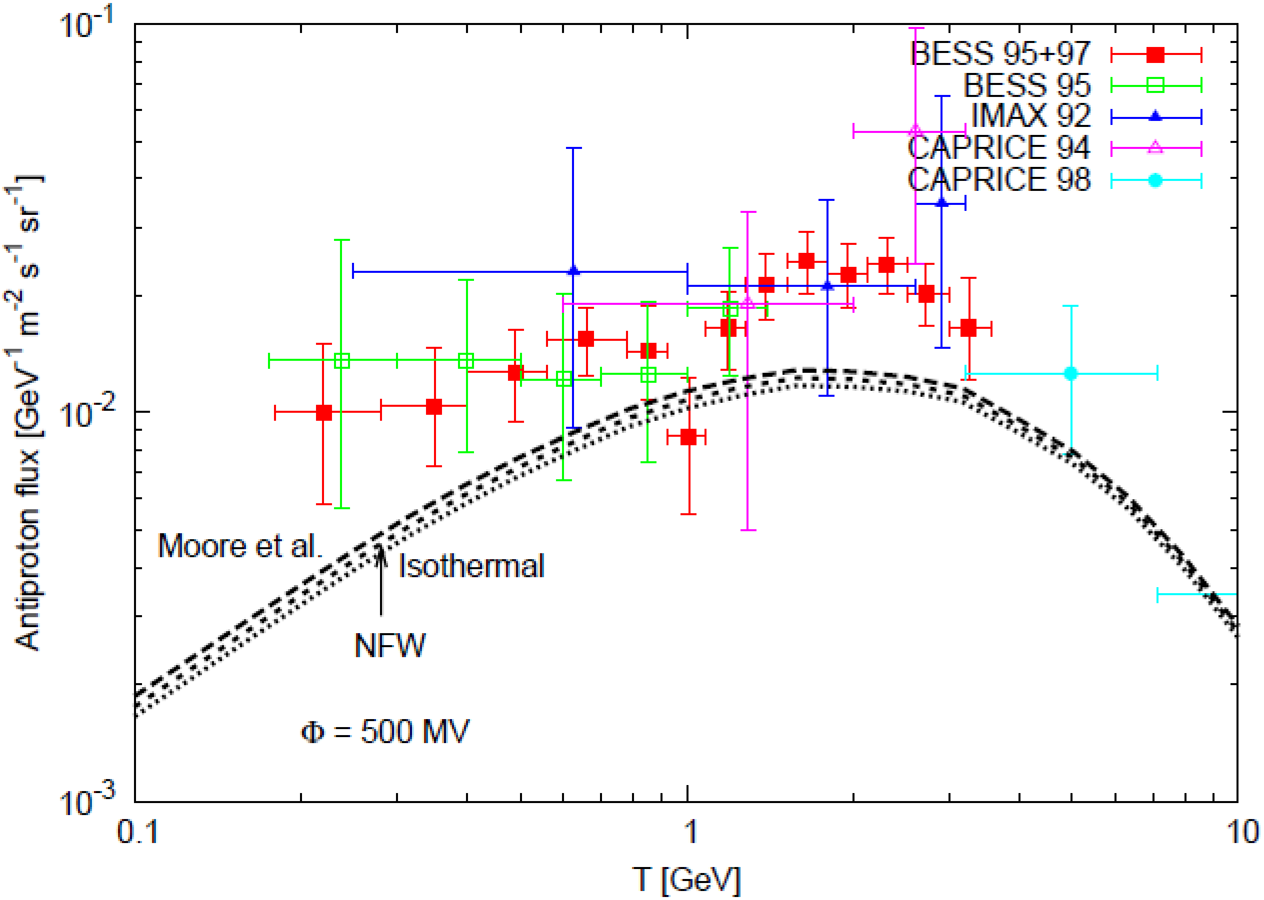


10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
Γ^{-1} [s]
MAX
MED
MIN
$\psi \rightarrow W\,e,\ Z\,e,\ h\,e$
100
1000
10000
$m_{\rm DM}$ [GeV]

Tran et al.

Decaying dark matter: Sensitivity to the halo profile



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