The quest for the dark matter particle

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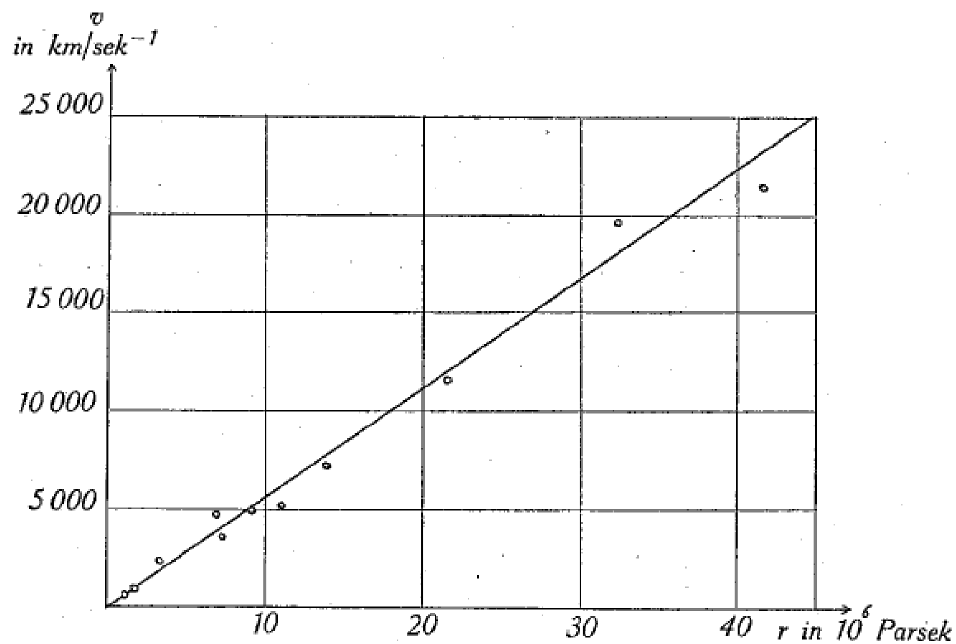
ICTP-SAIFR
October 23rd 2019

Dark matter is
a likely solution to
various long-standing
puzzles in astronomy



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.

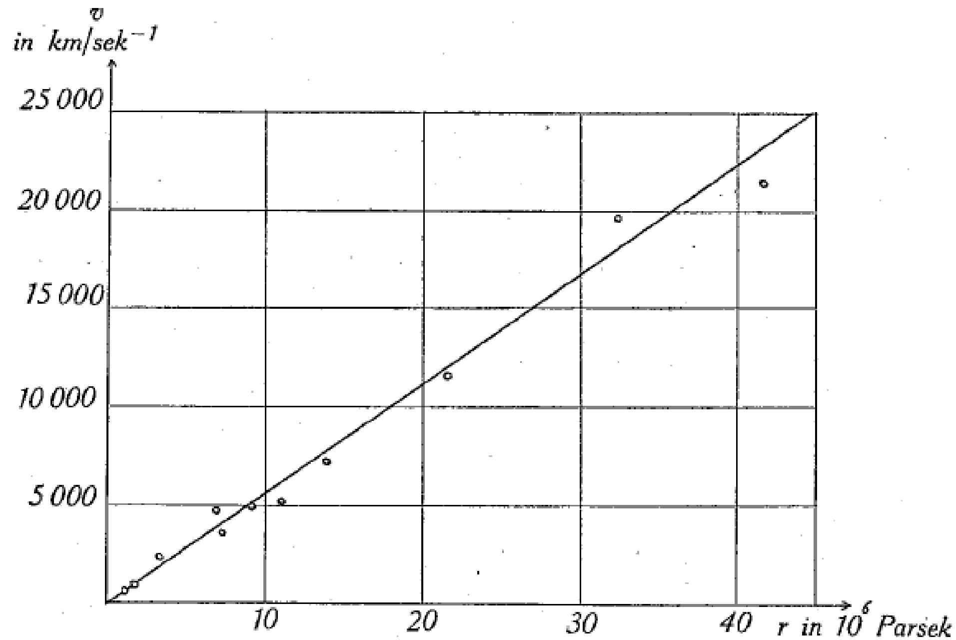


Fig. 2.

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

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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,

$$2K + U = 0$$

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

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

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

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

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

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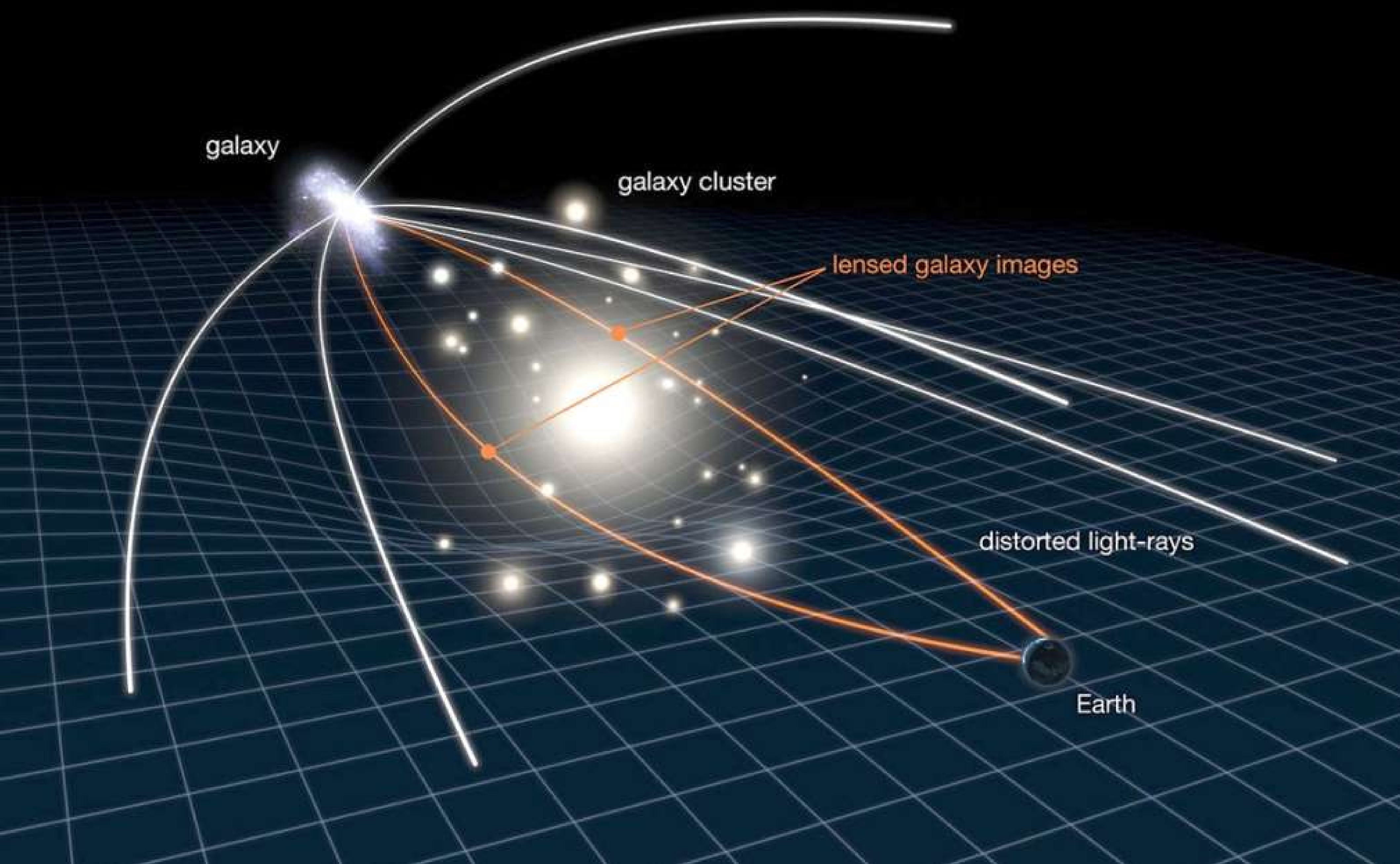
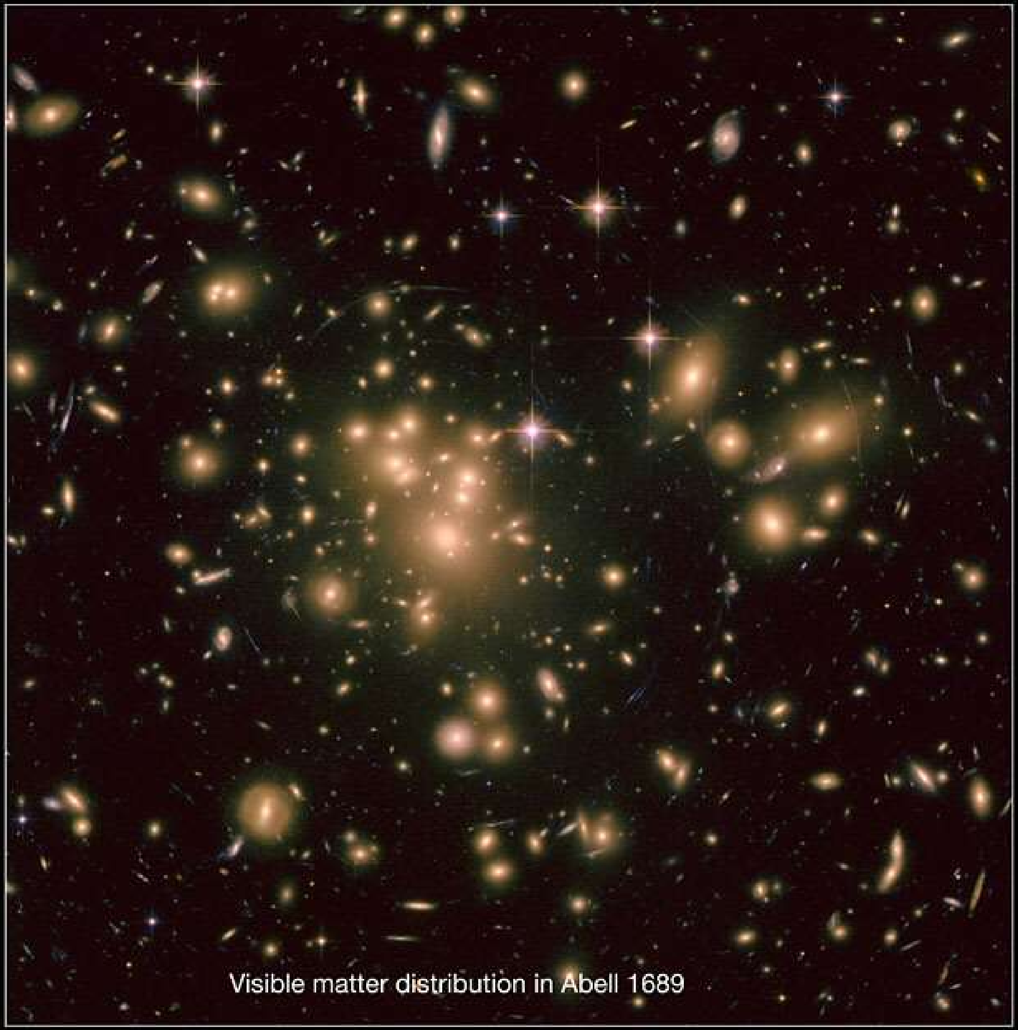
Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view 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

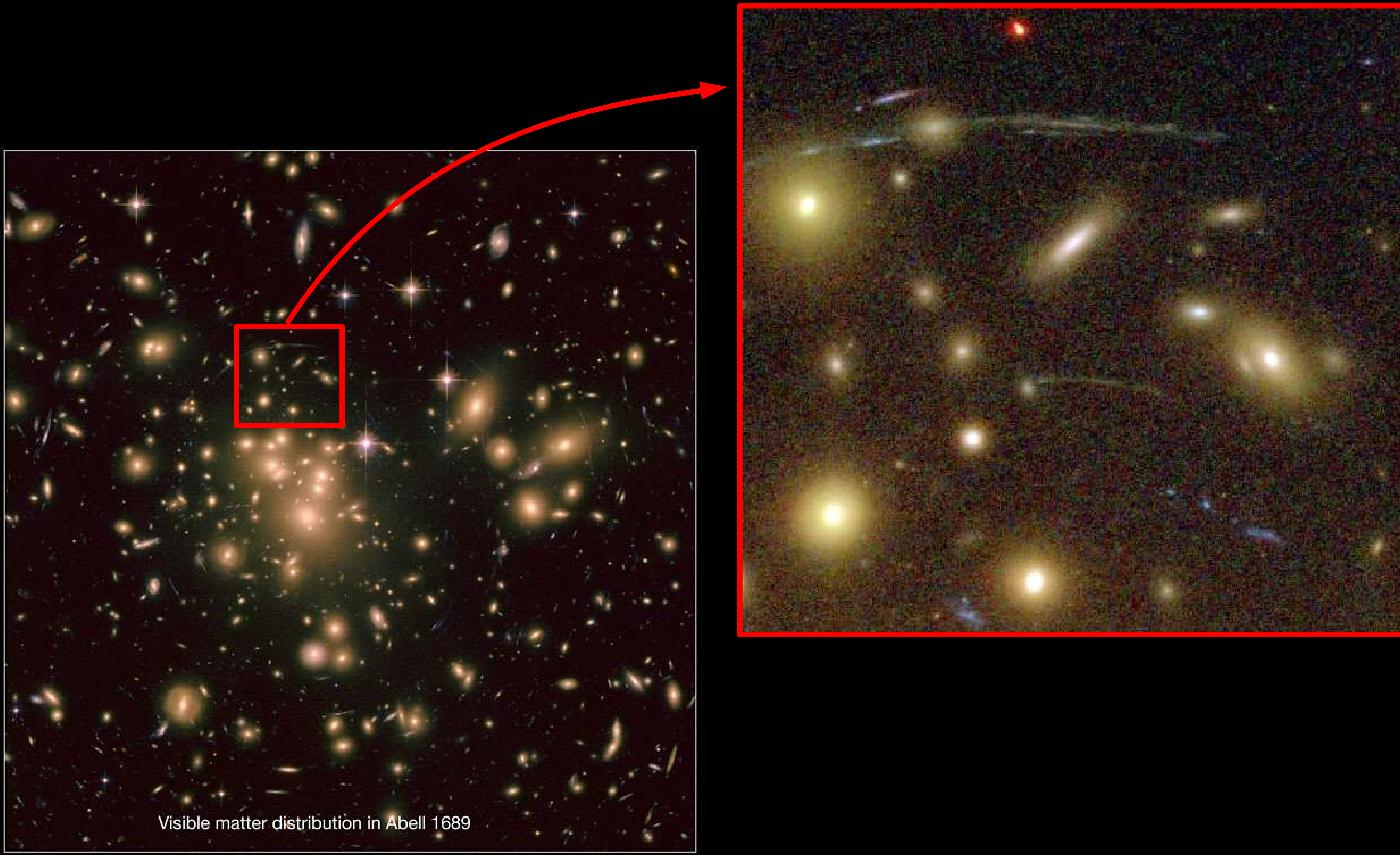
$$\gamma = 500 , \tag{37}$$

The modern technique: gravitational lensing

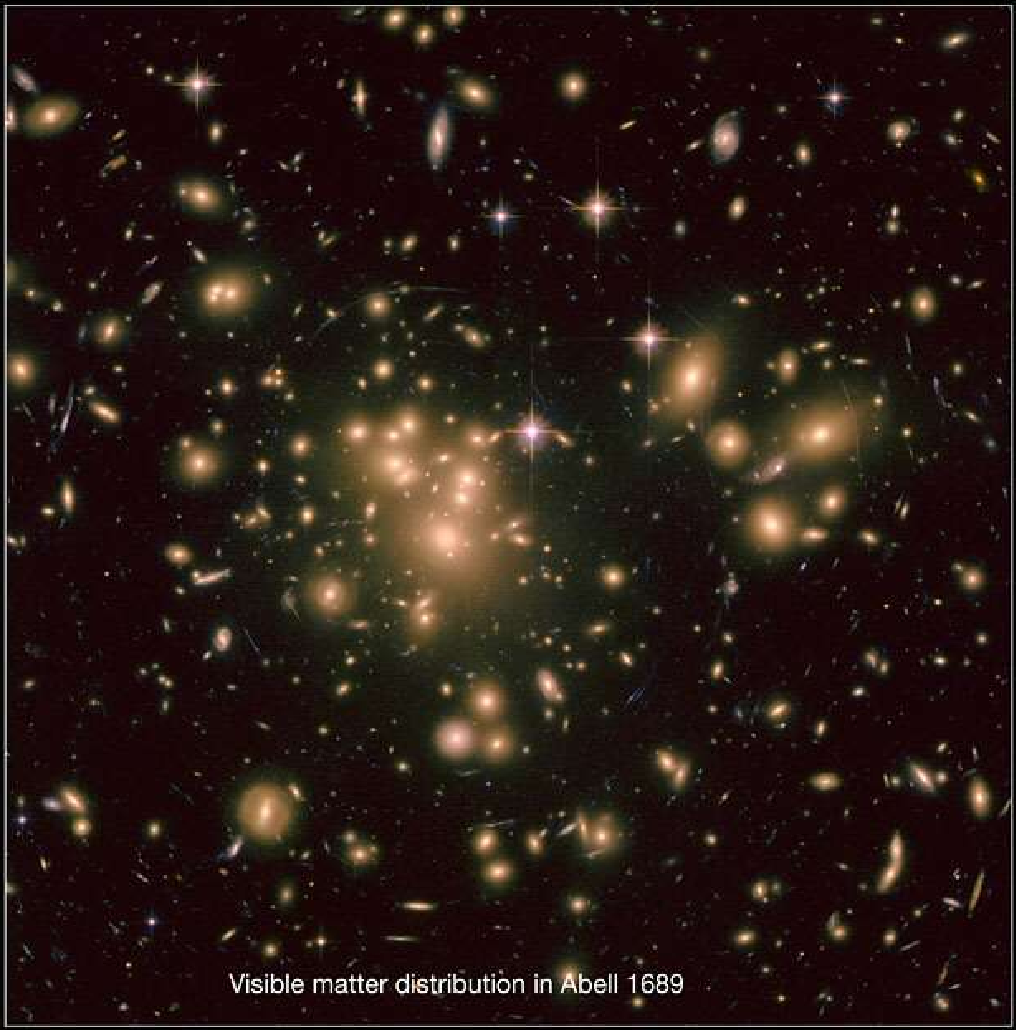


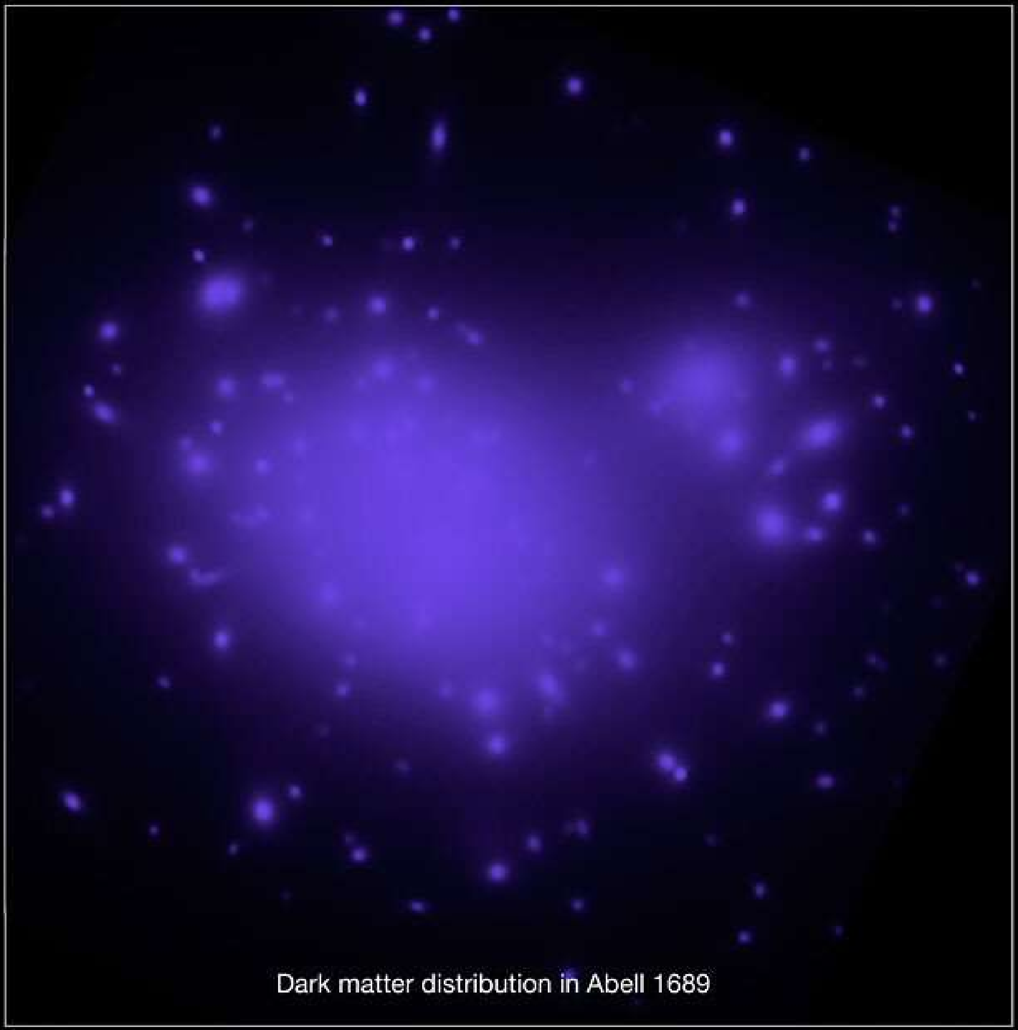


Abell 1689



Abell 1689


Visible matter distribution in Abell 1689


Dark matter distribution in Abell 1689

Abell 1689

Evidence from galaxies

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

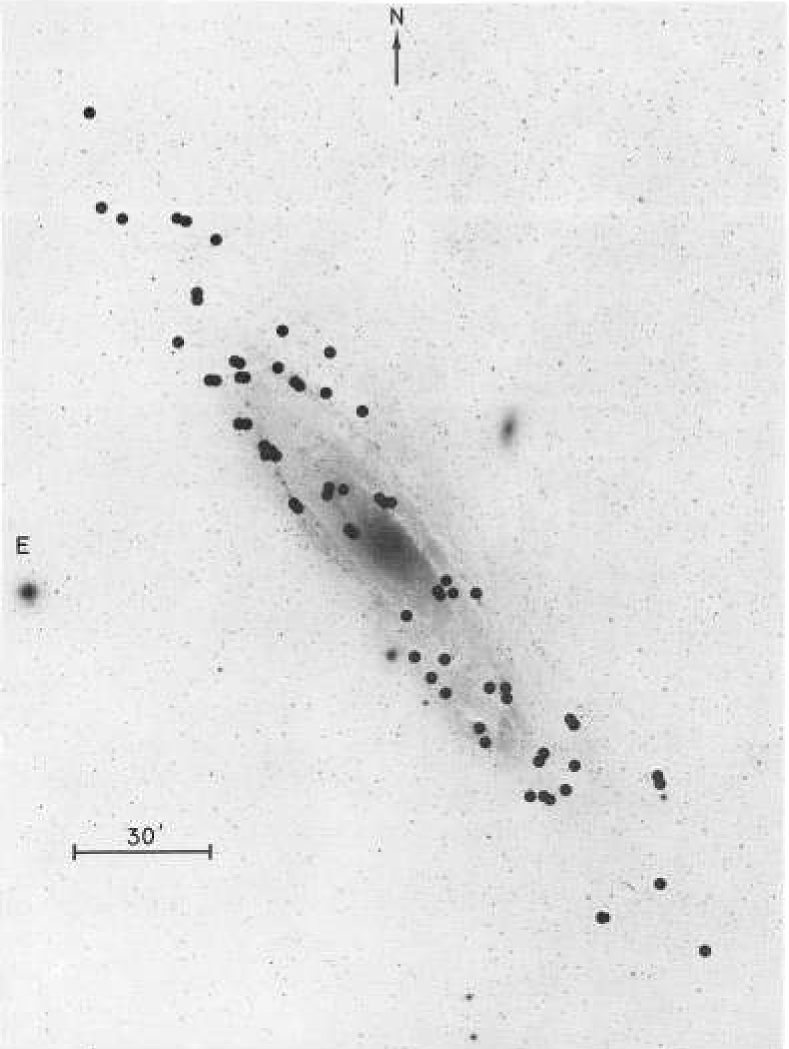
ABSTRACT

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] $\lambda 6583$ 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.



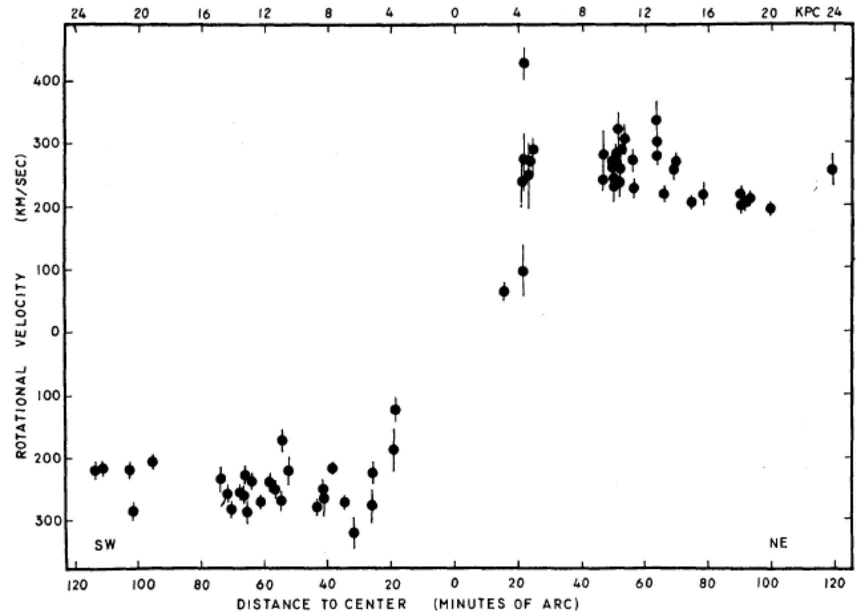


FIG. 3.—Rotational velocities for sixty-seven emission regions in M31, as a function of distance from the center. Error bars indicate average error of rotational velocities.

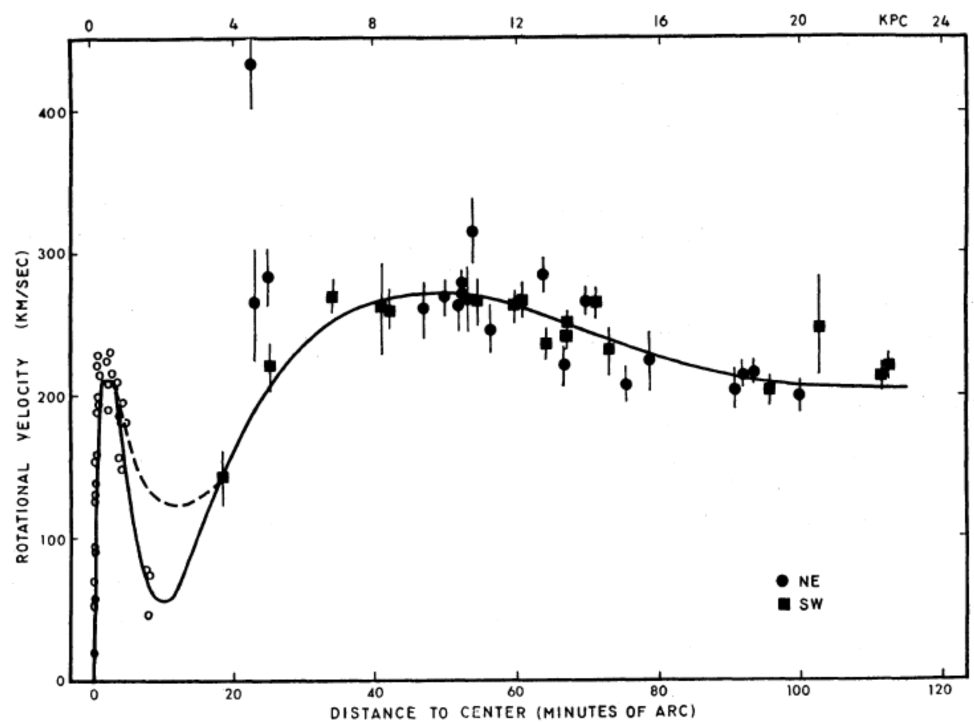
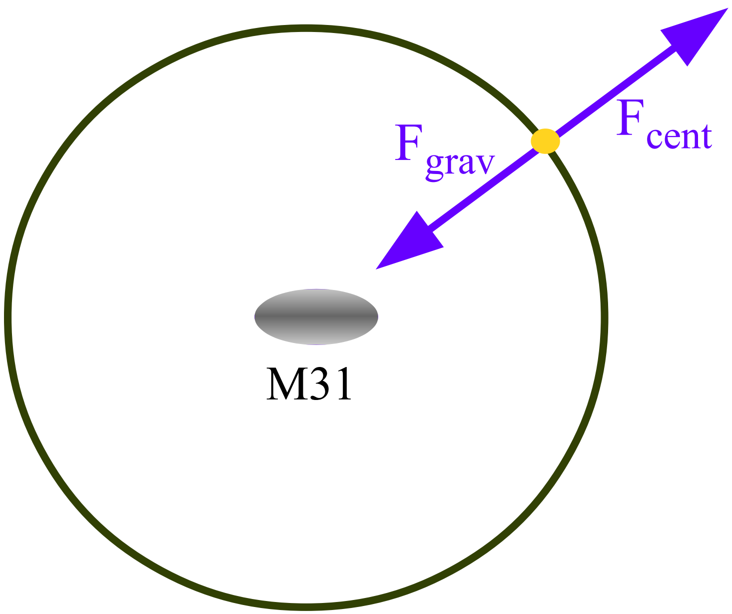


FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately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

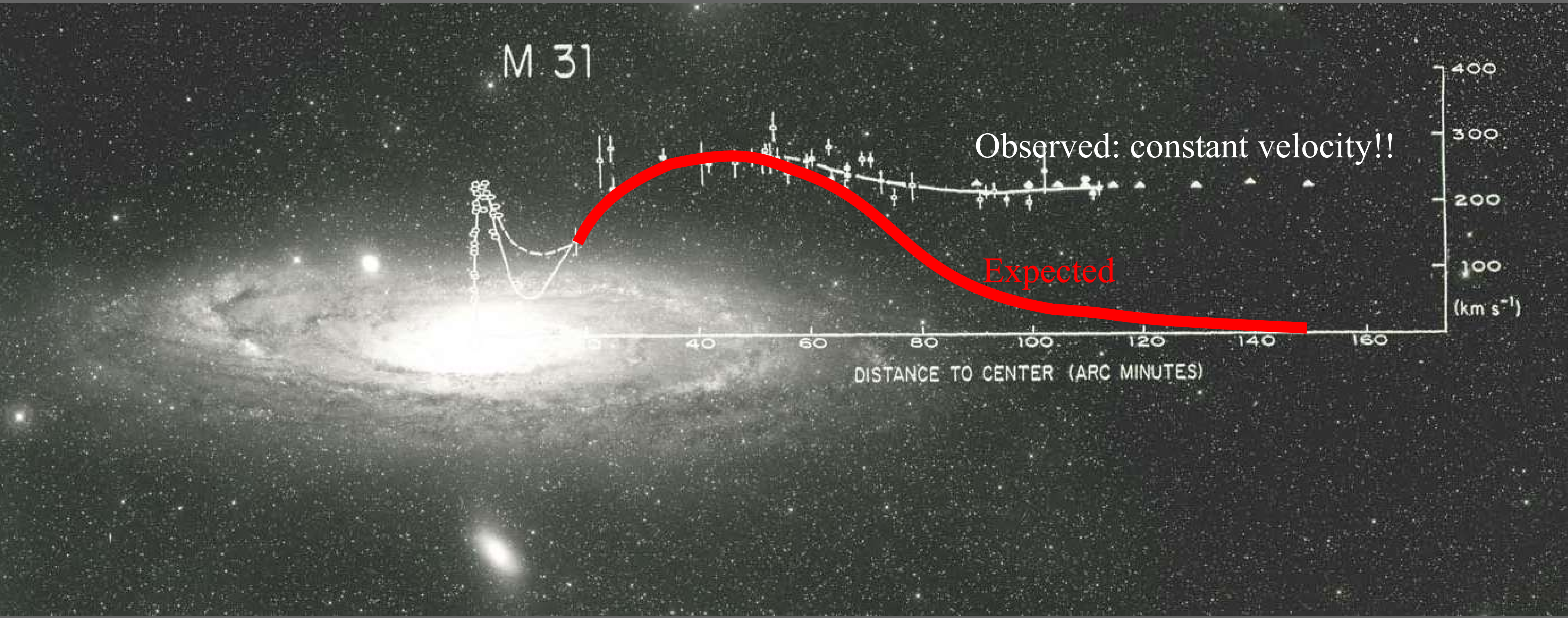
Expectations from Newtonian theory



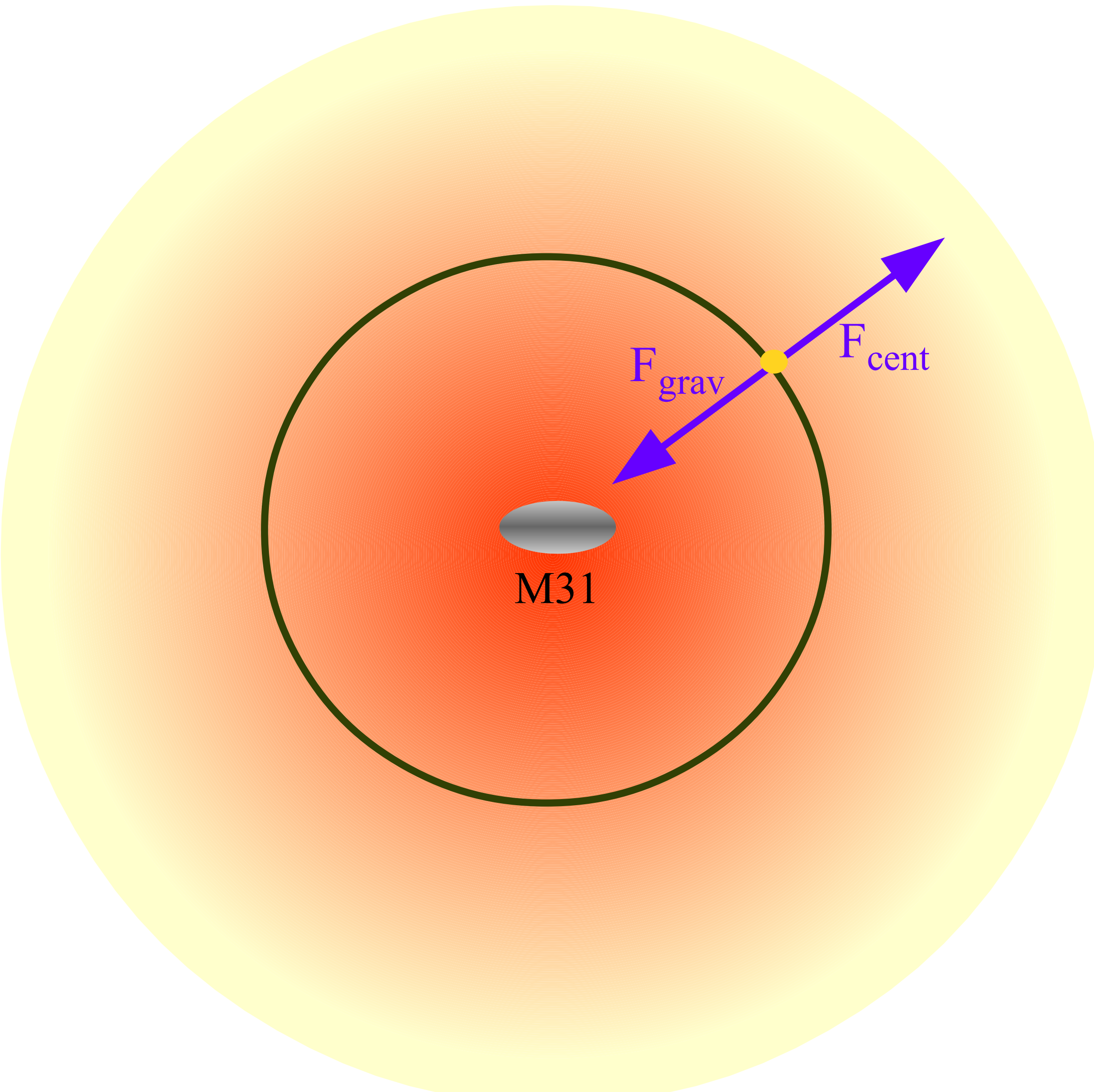
$$\vec{F}_{\text{cent}} = \vec{F}_{\text{grav}}$$

$$m\frac{v(r)^2}{r} = \frac{GMm}{r^2}$$

$$\boxed{v(r) = \sqrt{\frac{GM}{r}}}$$


M 31
Observed: constant velocity!!
Expected
400
300
200
100
(km s^{-1})
40
60
80
100
120
140
160
DISTANCE TO CENTER (ARC MINUTES)

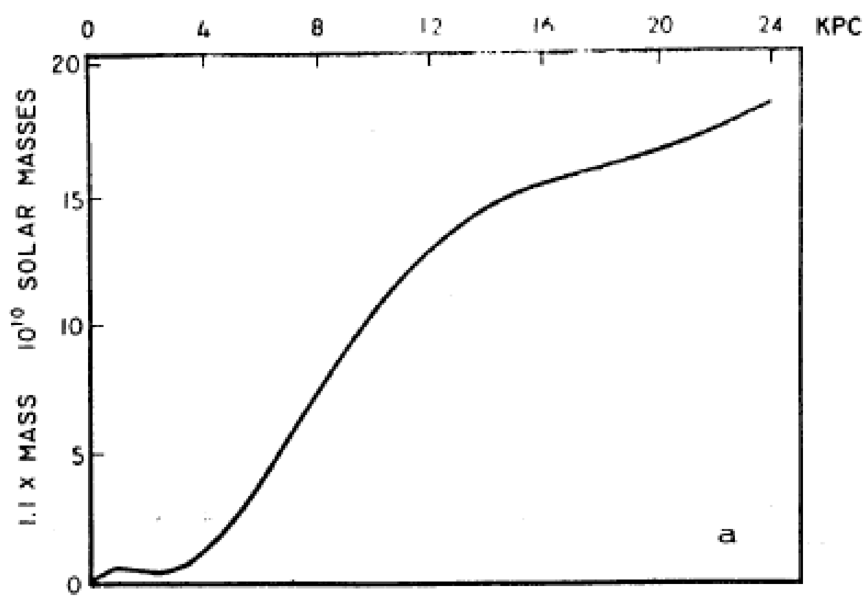
Something else around M31?



$$\vec{F}_{\text{cent}} = \vec{F}_{\text{grav}}$$

$$m\frac{v(r)^2}{r} = \frac{GM(r)m}{r^2}$$

$$\boxed{v(r) \sim \text{constant} \Rightarrow M(r) \sim r}$$



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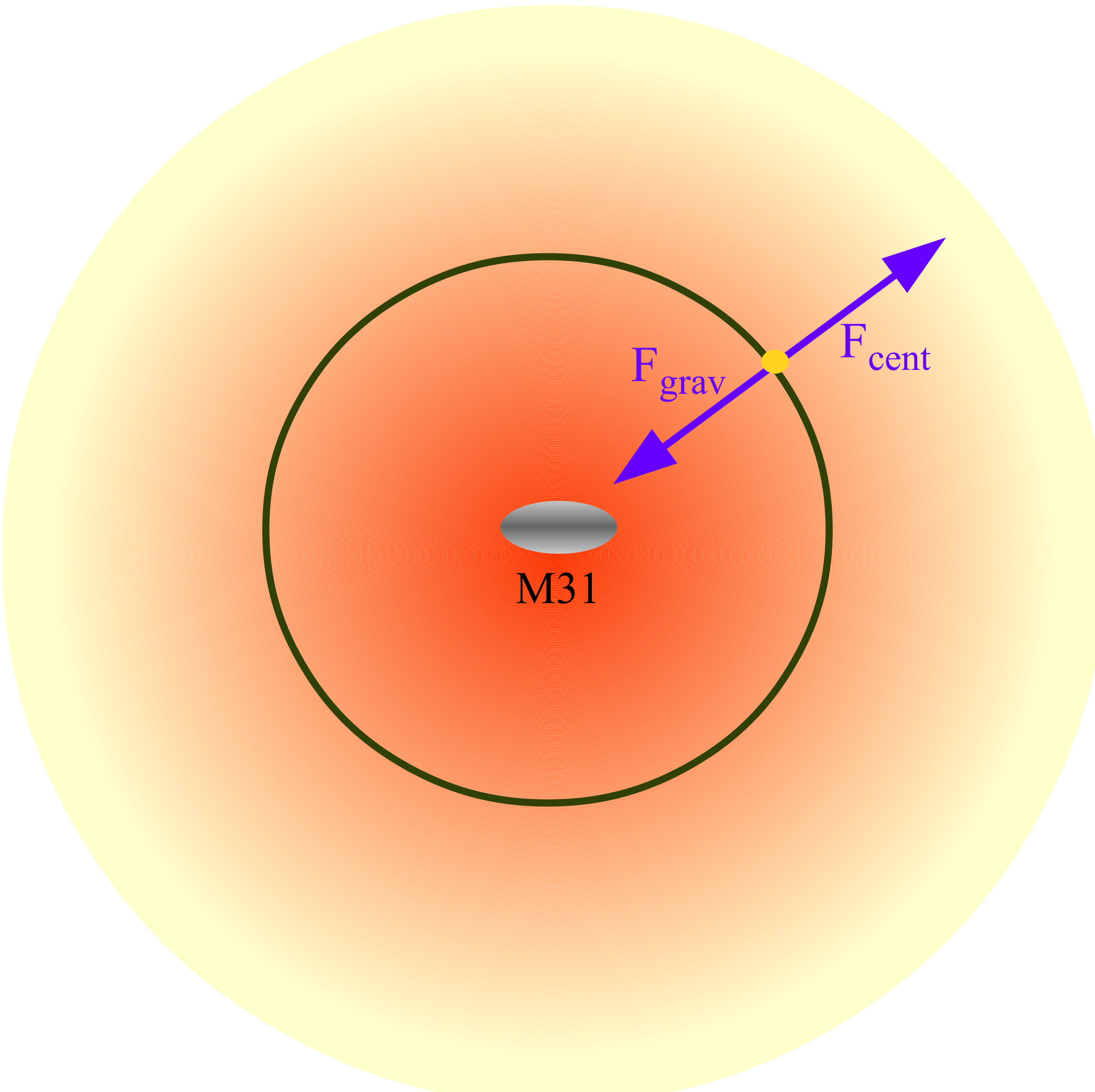


$$\vec{F}_{\text{cent}} = \vec{F}_{\text{grav}}$$

$$m\frac{v(r)^2}{r} = \frac{GM(r)m}{r^2}$$

$$\boxed{v(r) \sim \text{constant} \Rightarrow M(r) \sim r}$$

$$\begin{aligned} M(r) &= \int_V d^3r' \rho(r') \\ &= 4\pi \int_0^r dr' r'^2 \rho(r') \end{aligned}$$

$$\boxed{M(r) \sim r \Rightarrow \rho(r) \sim \frac{1}{r^2}}$$

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)

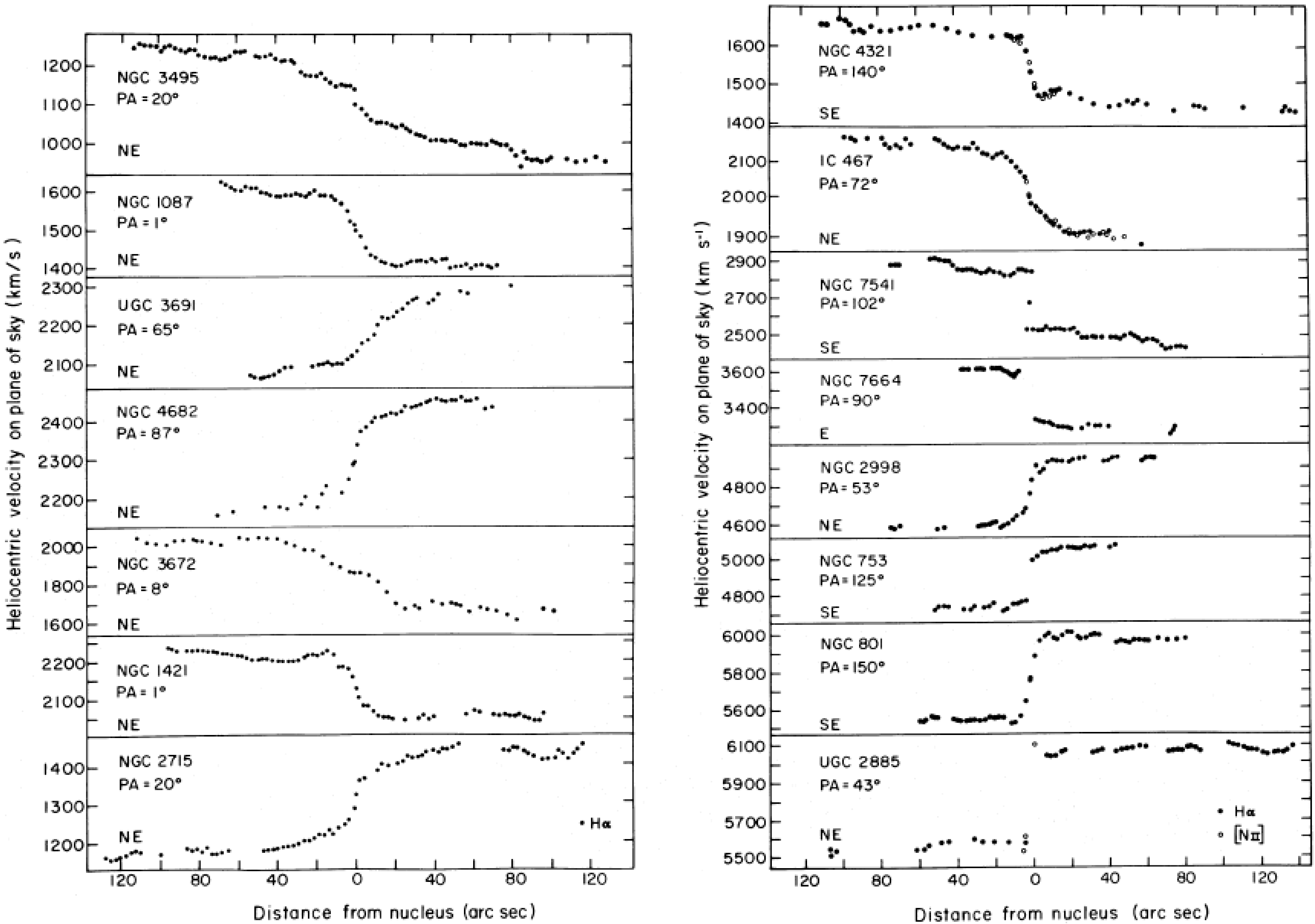
VERA C. RUBIN,[1,2] W. KENT FORD, JR.,[1] AND NORBERT THONNARD
Department of Terrestrial Magnetism, Carnegie Institution of Washington
Received 1979 October 11; accepted 1979 November 29

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
∘ [NII]
Heliocentric velocity on plane of sky (km s⁻¹)
Distance from nucleus (arc sec)

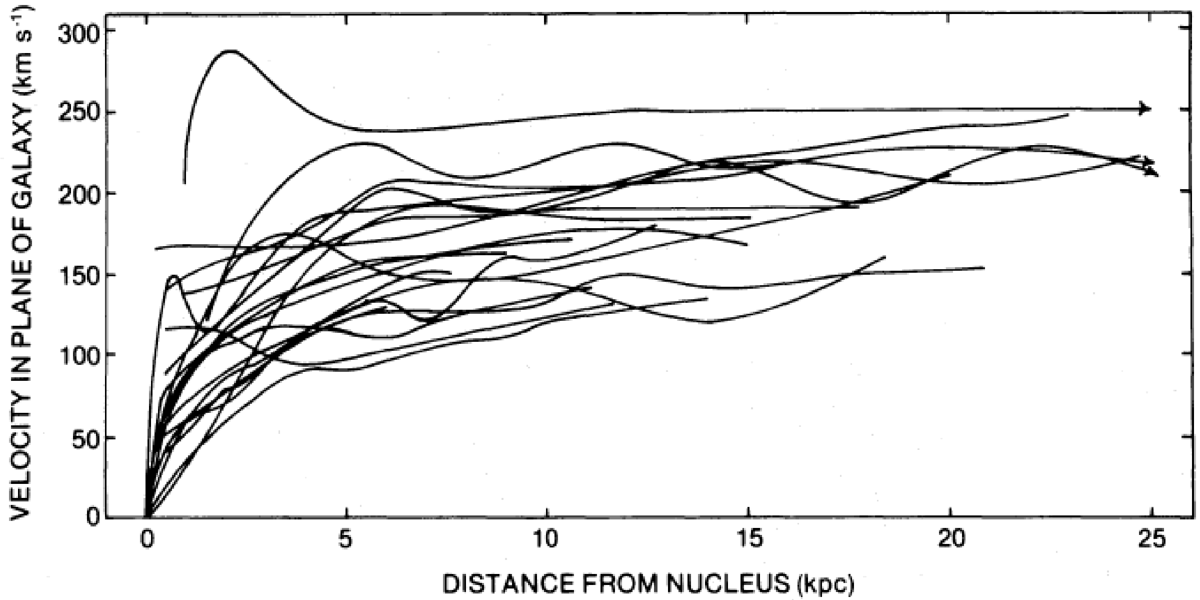


FIG. 6.—Superposition of all 21 Sc rotation curves. General form of rotation curves for small galaxies is similar to initial part of rotation curve for large galaxies, except that small galaxies often have shallower nuclear velocity gradient and tend to cover the low velocity range within the scatter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

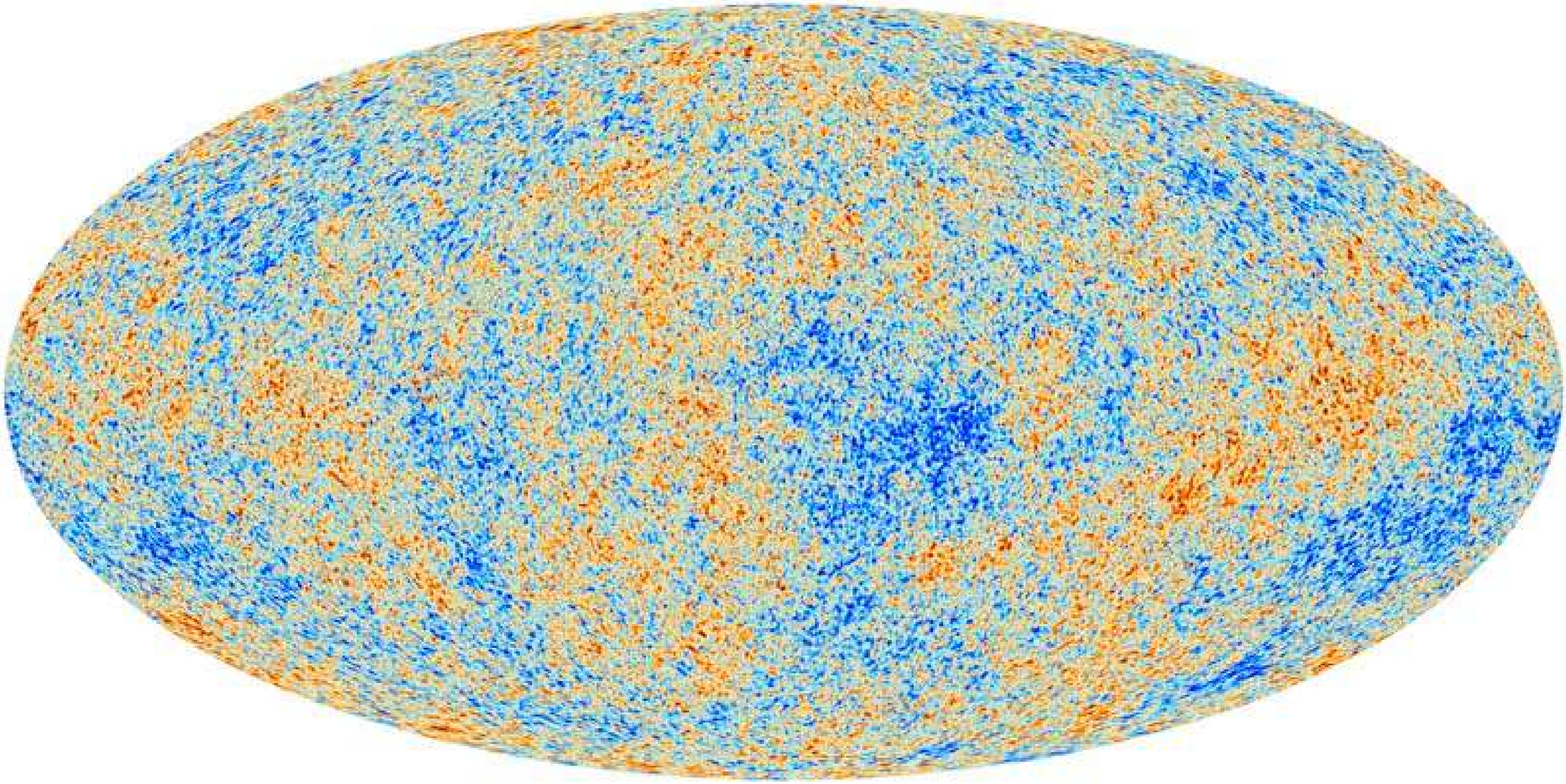
VIII. DISCUSSION AND CONCLUSIONS

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.

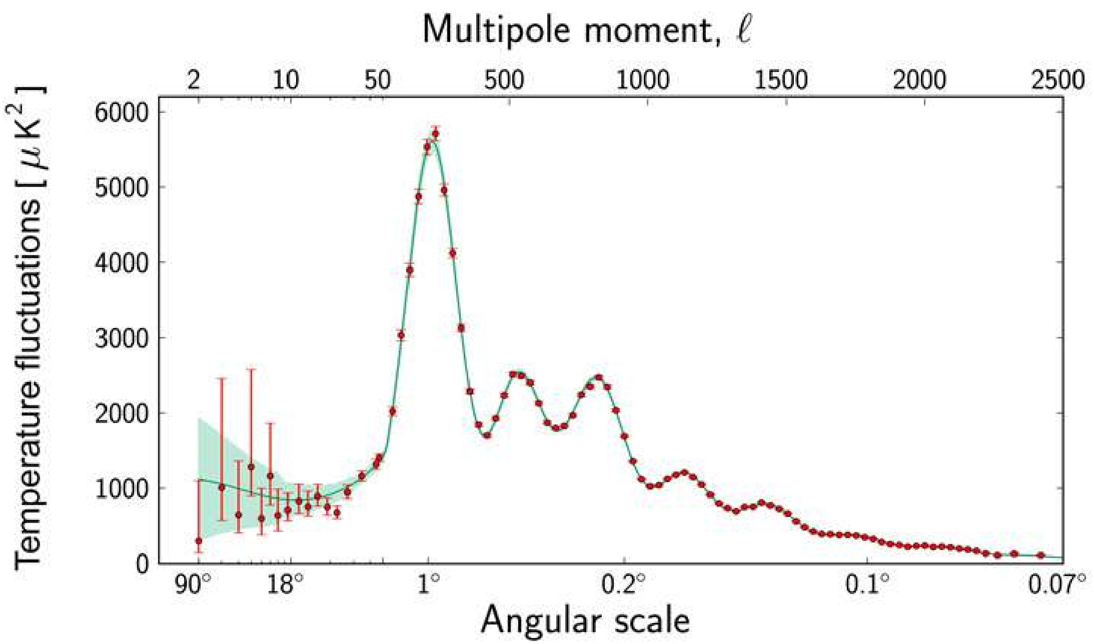
Evidence from the Universe at large scale

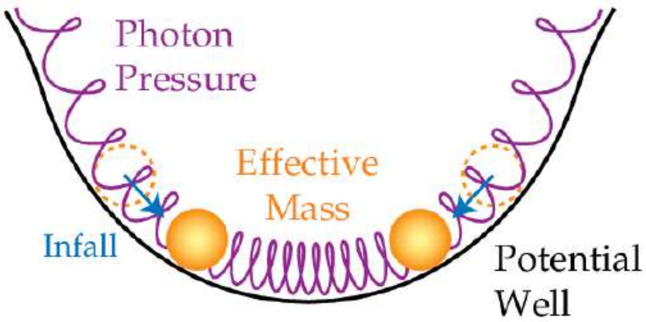
Cosmic microwave background temperature anisotropies

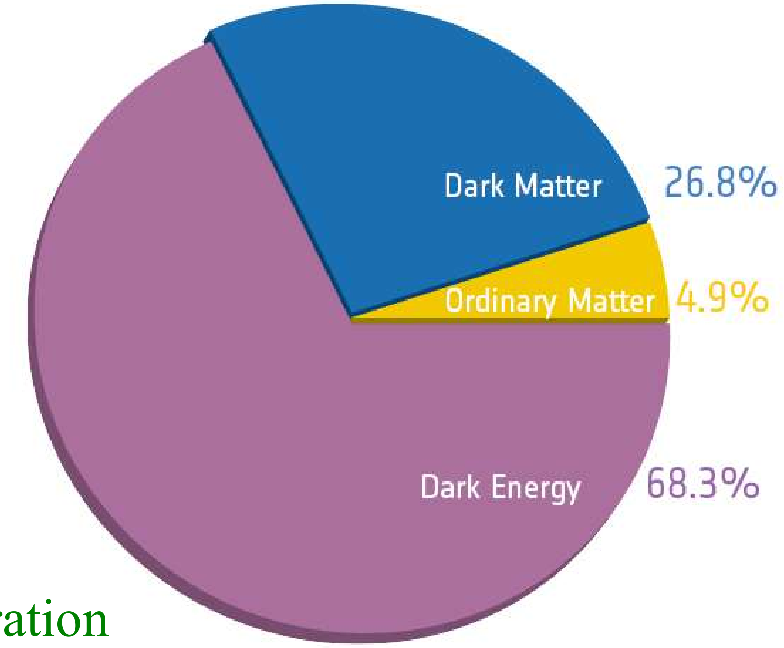


Planck Collaboration

CMB angular power spectrum

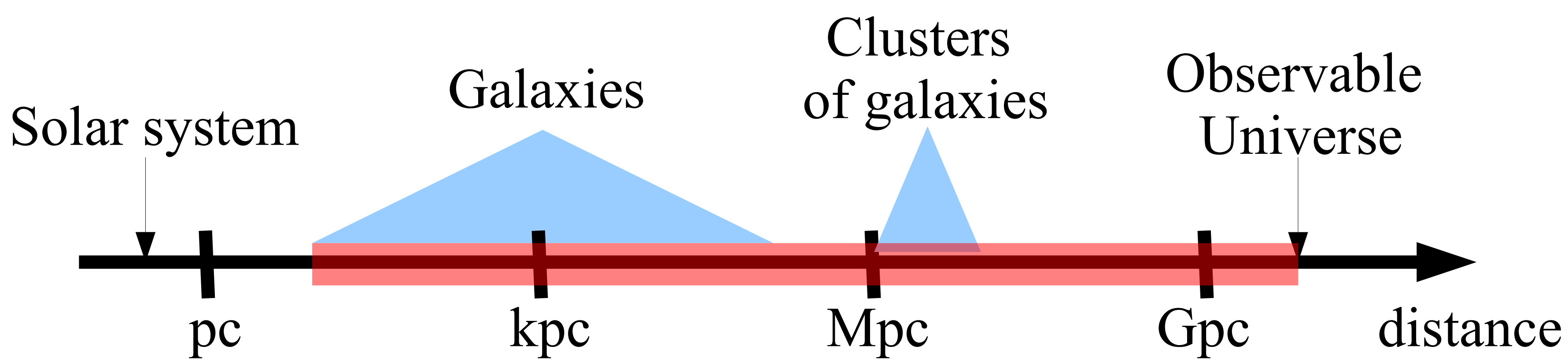






Planck Collaboration

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



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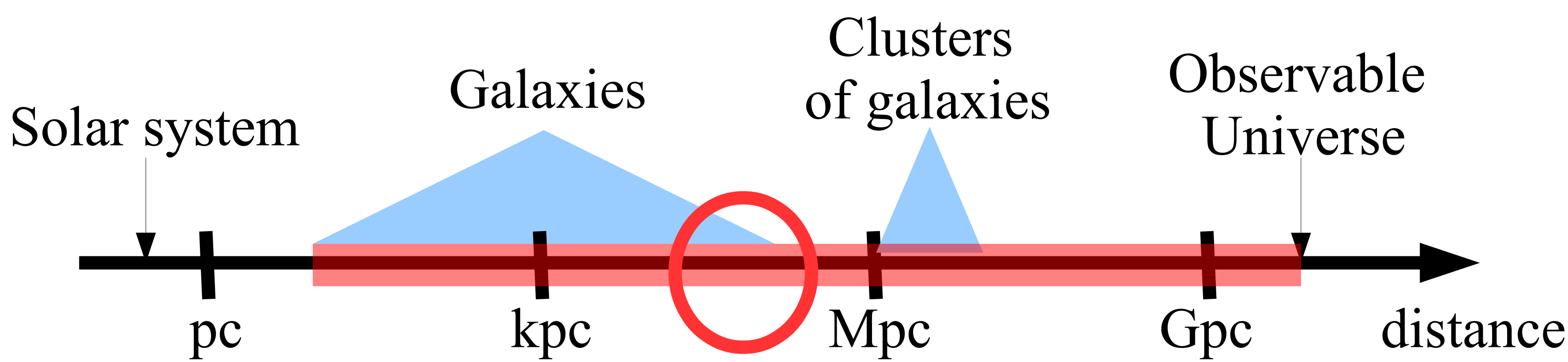
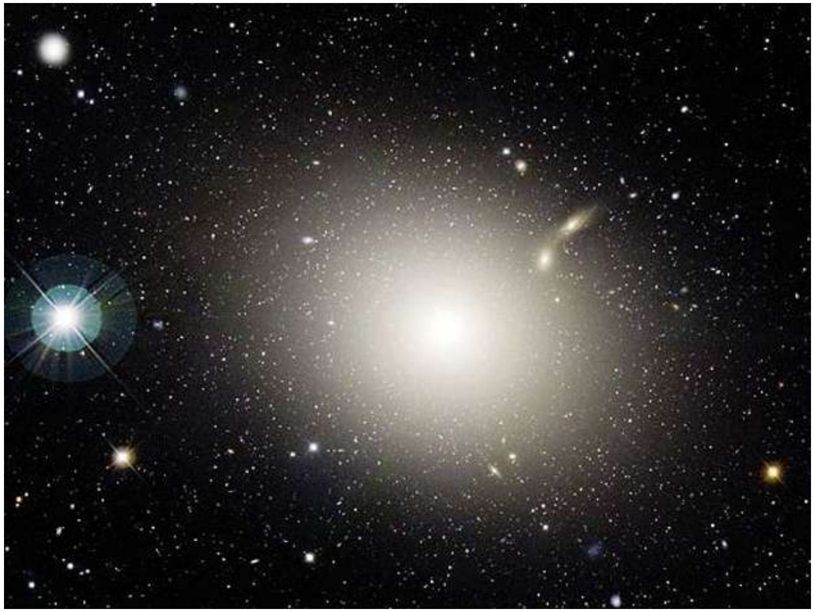


M87



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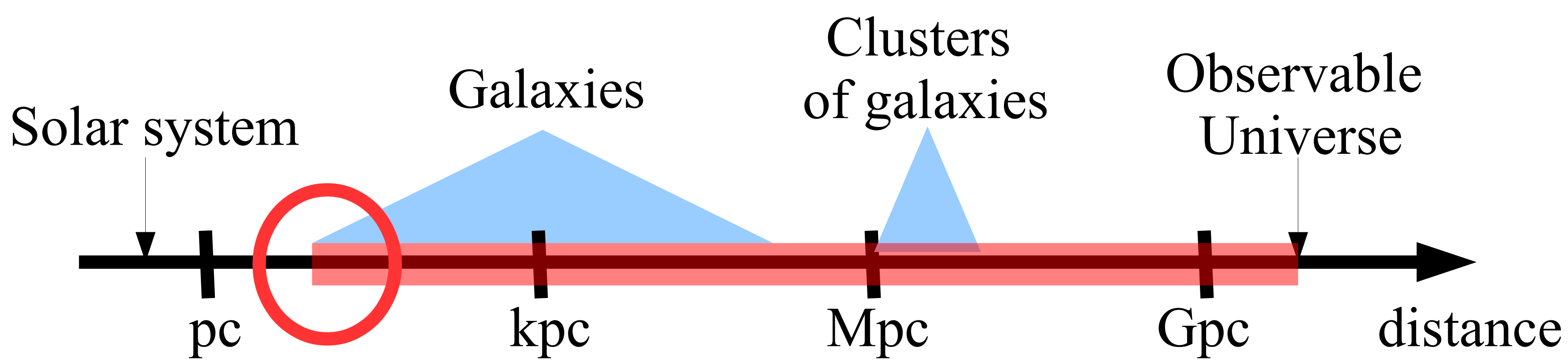
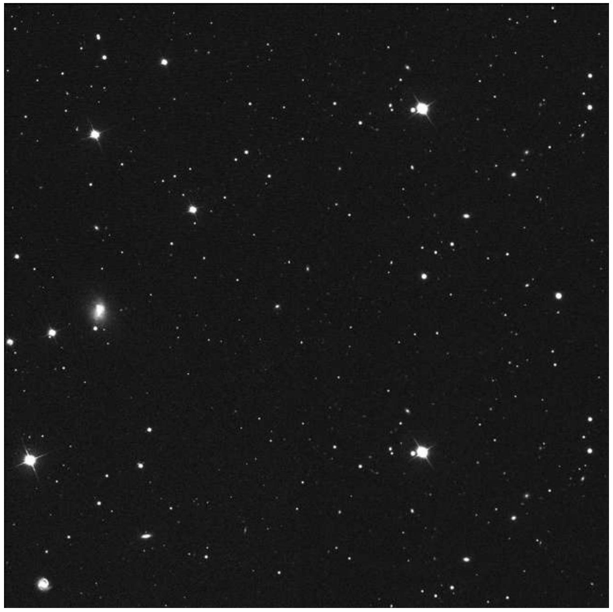
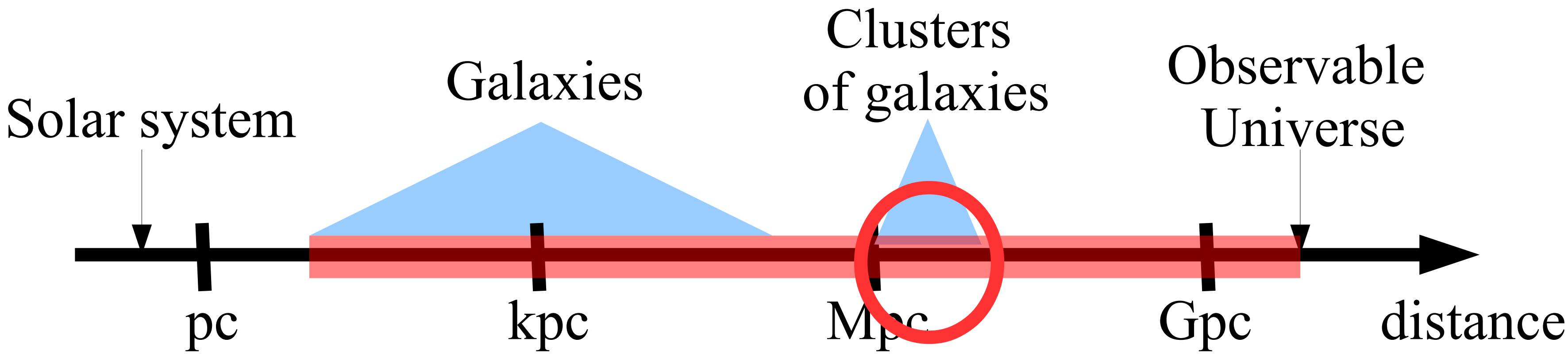
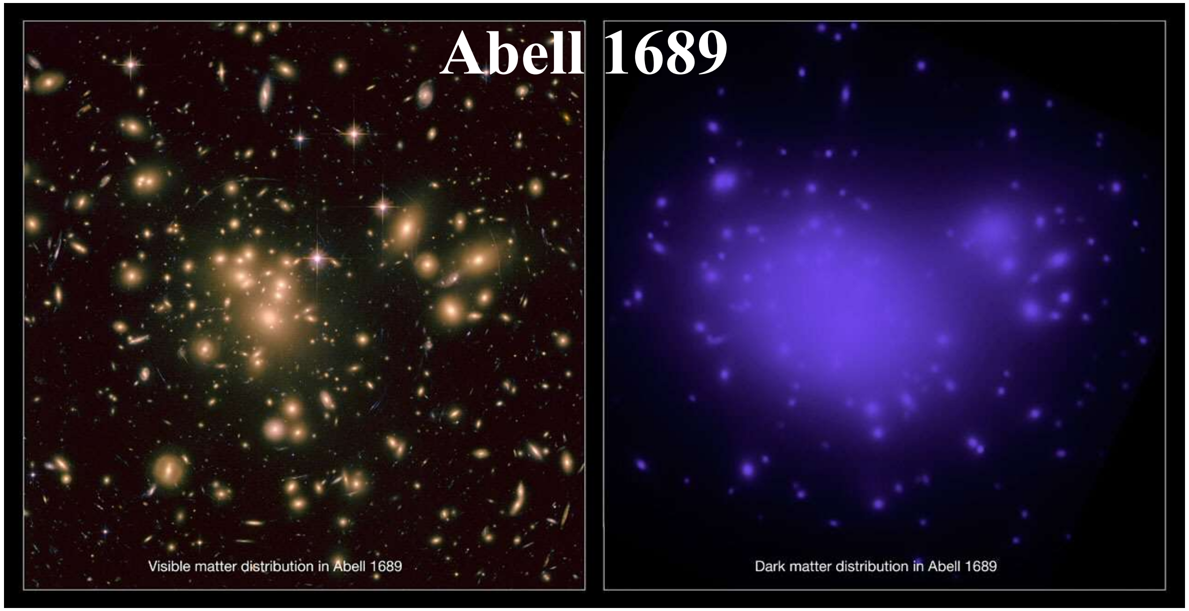




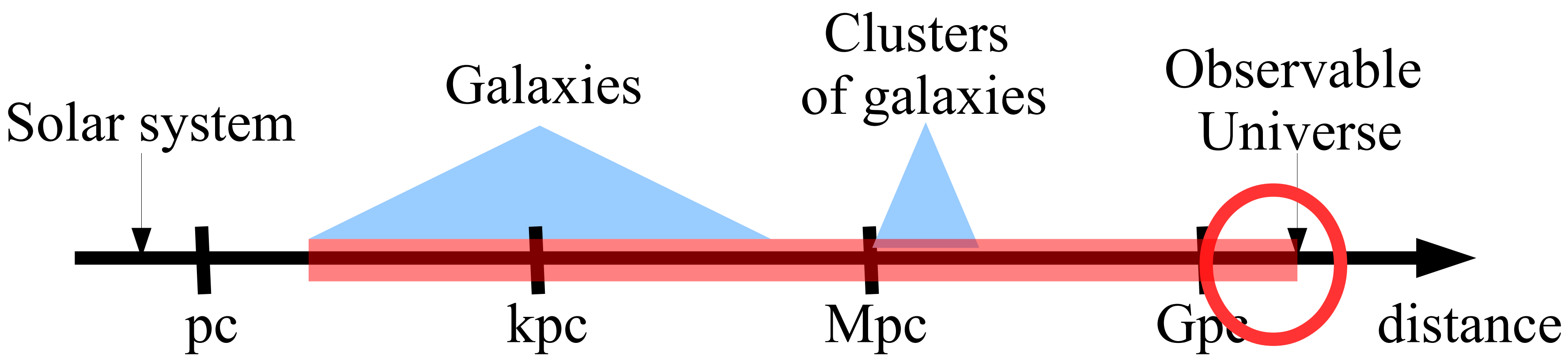
Segue 1

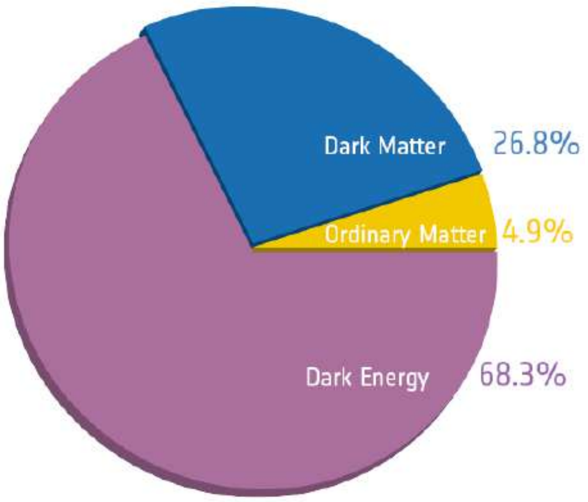
There is evidence for dark matter in a wide range of distance scales



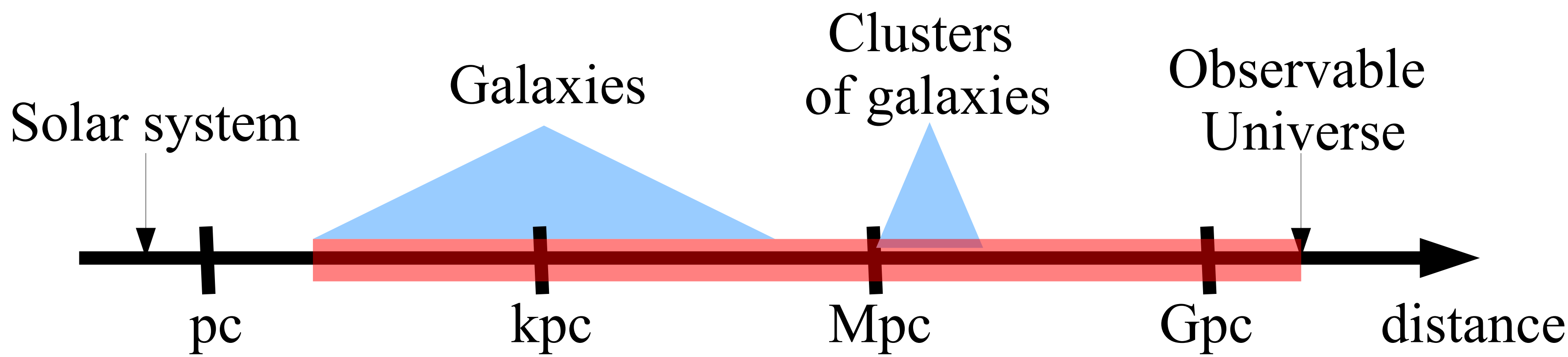


There is evidence for dark matter in a wide range of distance scales



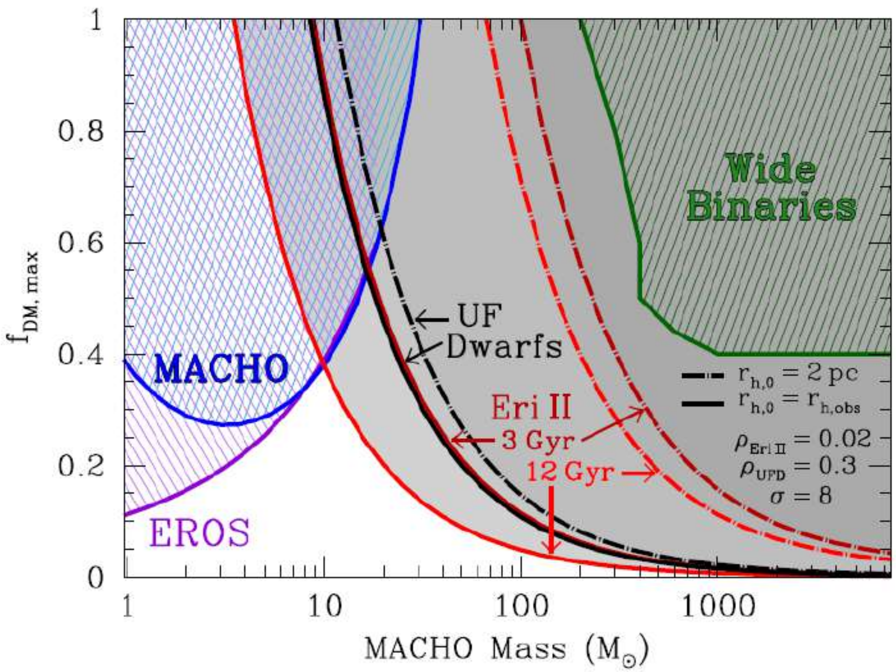


There is evidence for dark matter in a wide range of distance scales

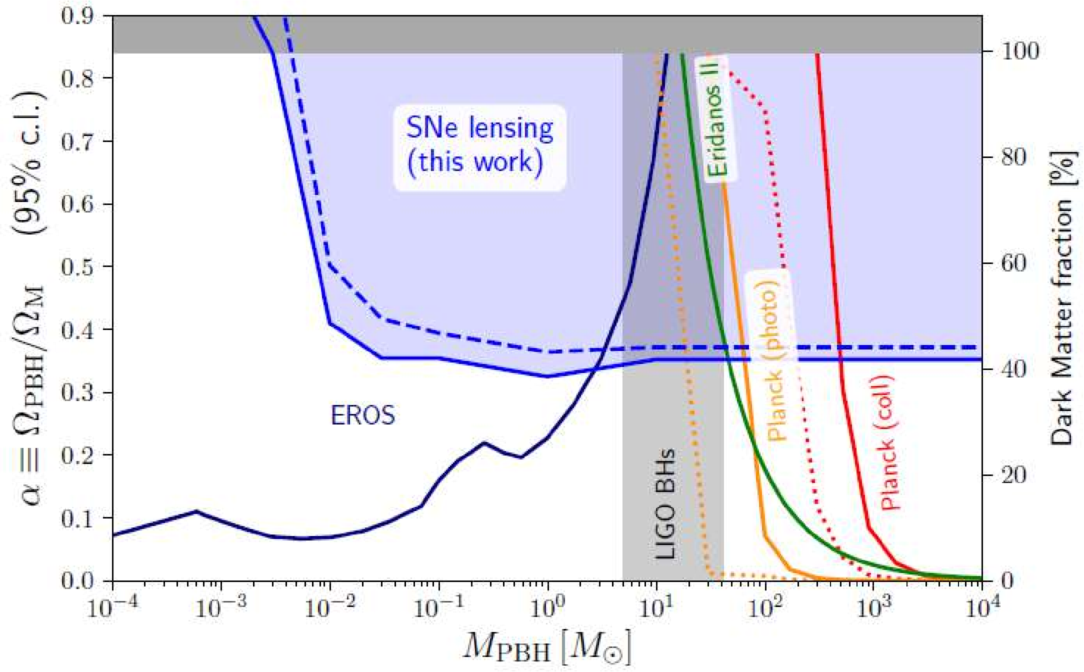


What do we know about the dark matter?

1) It is (maybe?) not made of compact objects



Brandt '16



Zumalacarregui, Seljak '17

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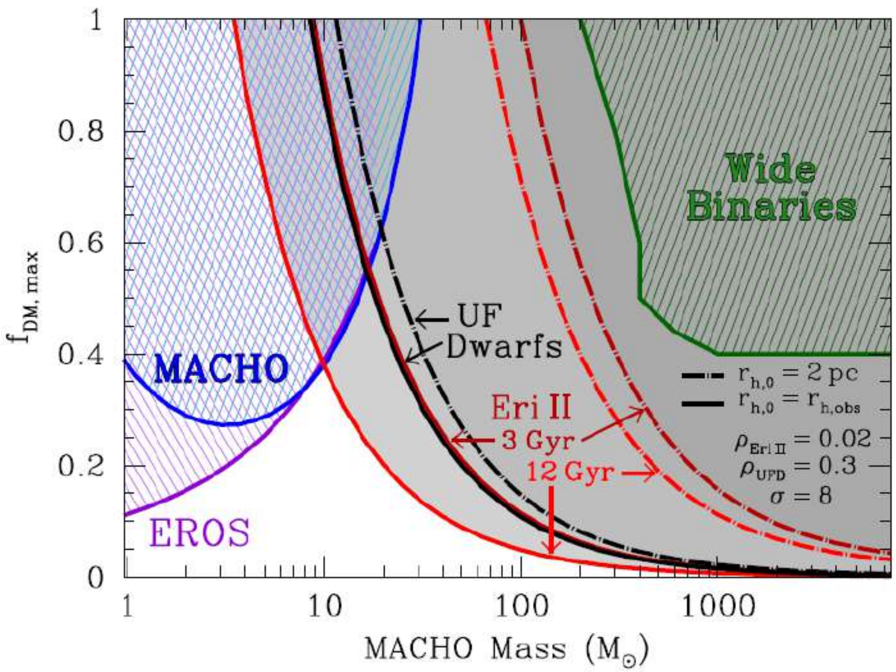
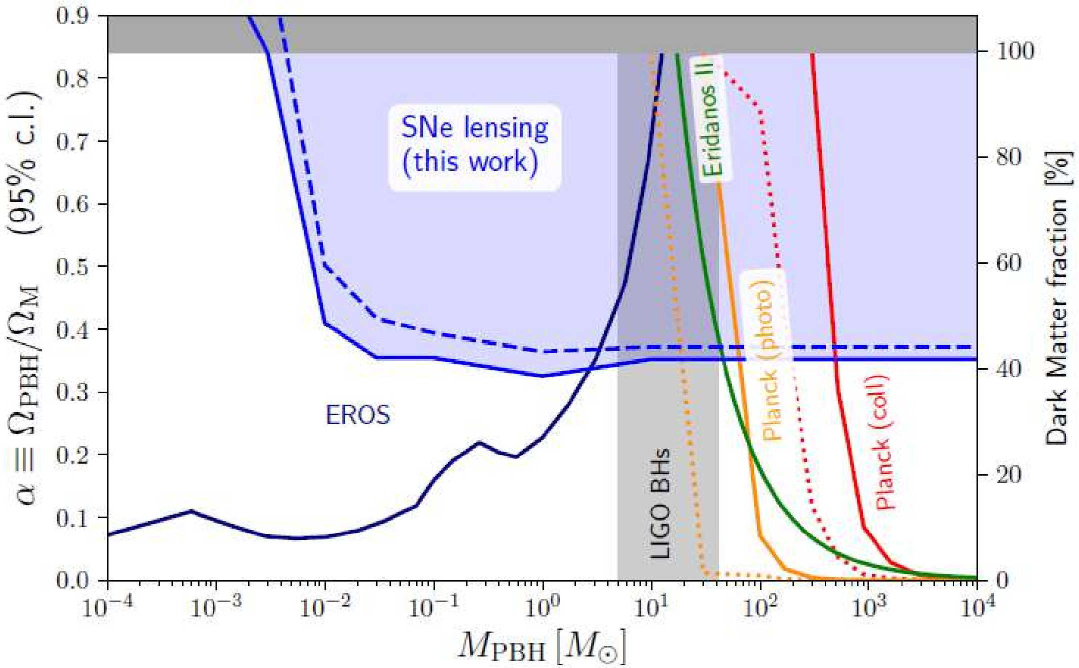


Brandt '16



Zumalacarregui, Seljak '17

Lots of discussions about the robustness and applicability of these limits...

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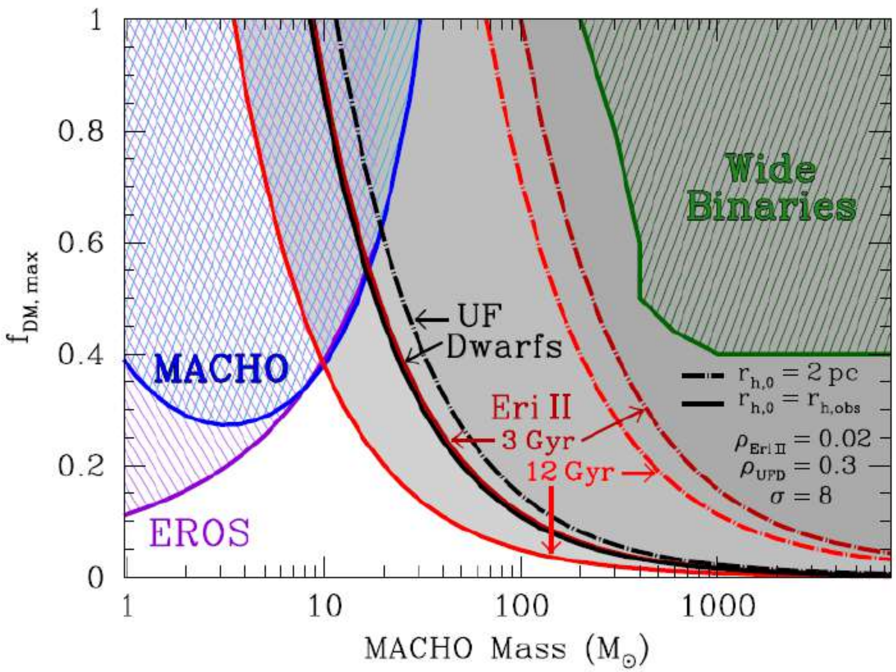
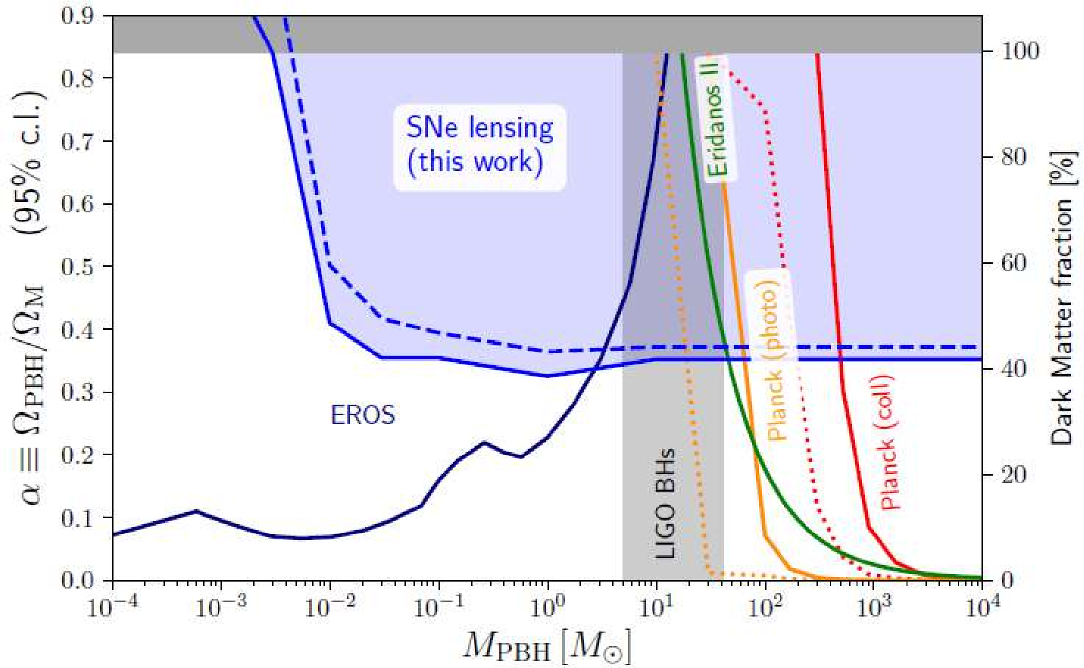


Brandt '16



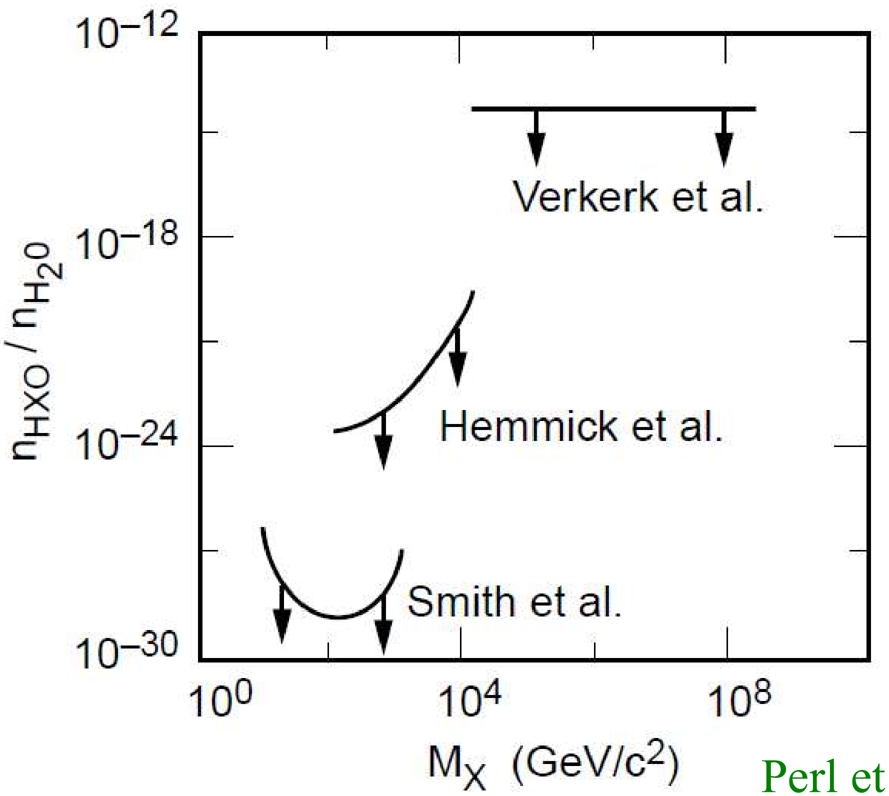
Zumalacarregui, Seljak '17

Lots of discussions about the robustness and applicability of these limits...

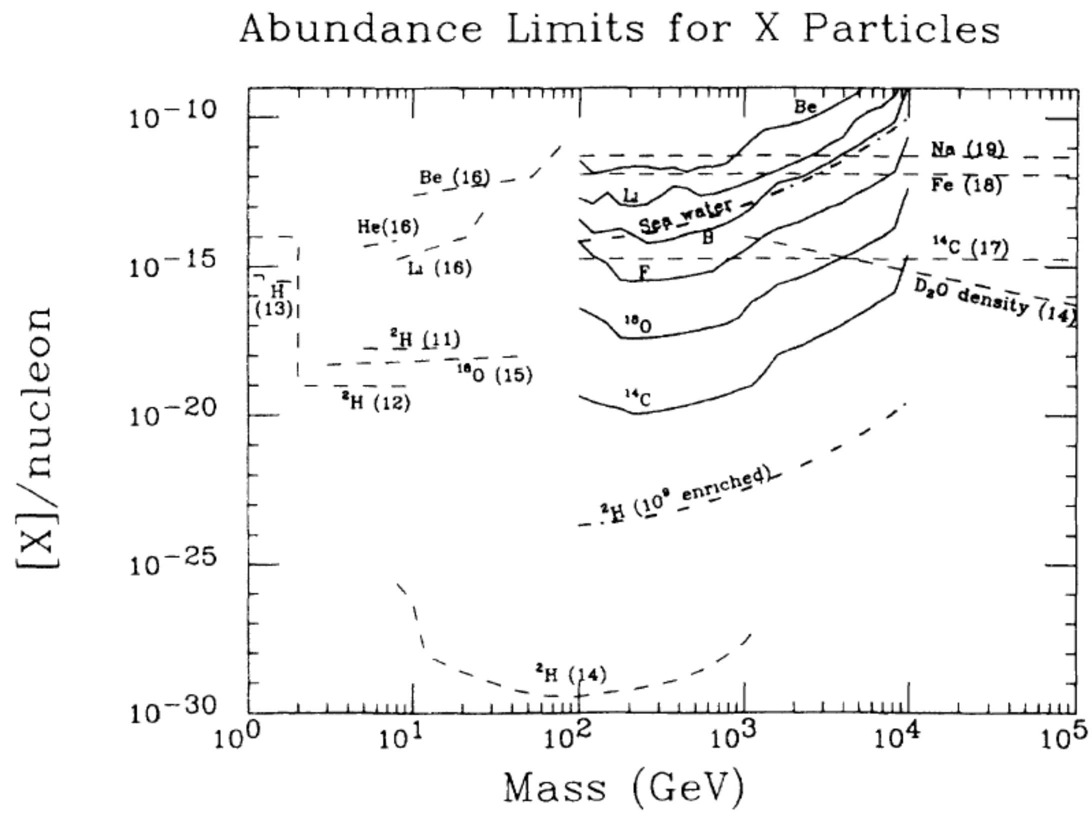
None of this limits apply if the dark matter distribution is smooth (rather than clumpy)

2) It is dark. It hardly interacts with visible matter.

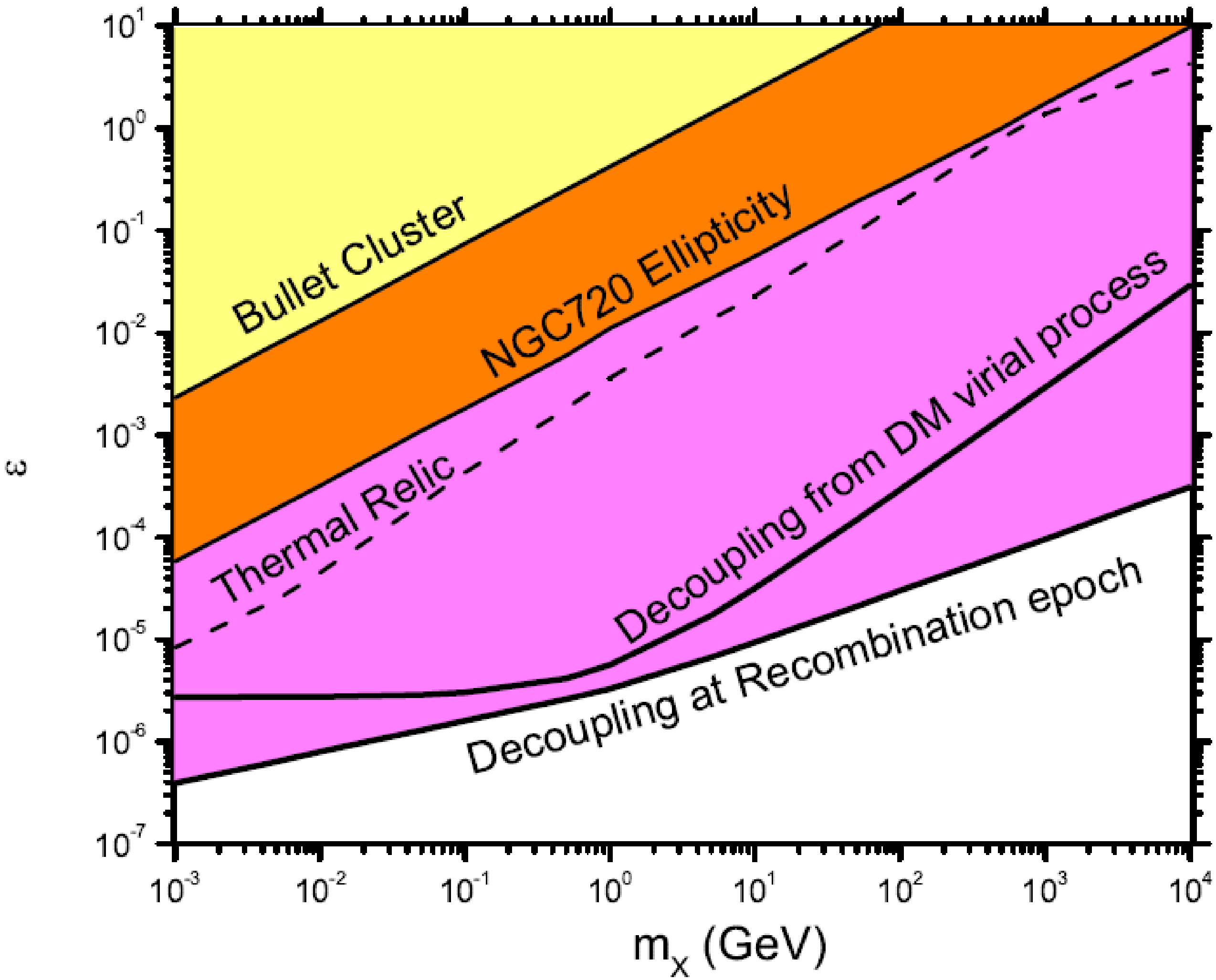
- If it has positive charge, it can form a bound state X^+e^-, an "anomalously heavy hydrogen atom".
- If it has negative charge, it can bind to nuclei, forming "anomalously heavy isotopes".



Perl et al.



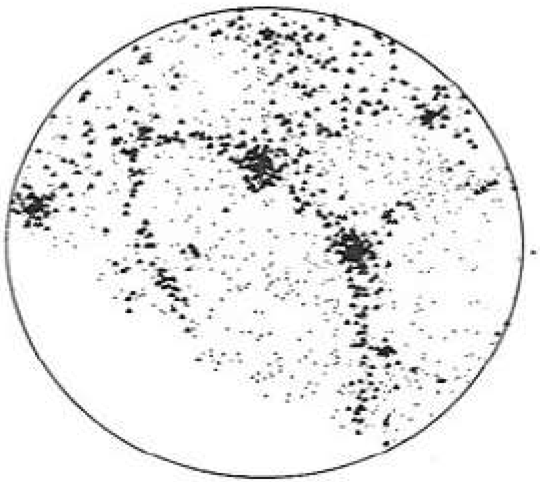
Millicharged dark matter?



McDermott et al'10

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

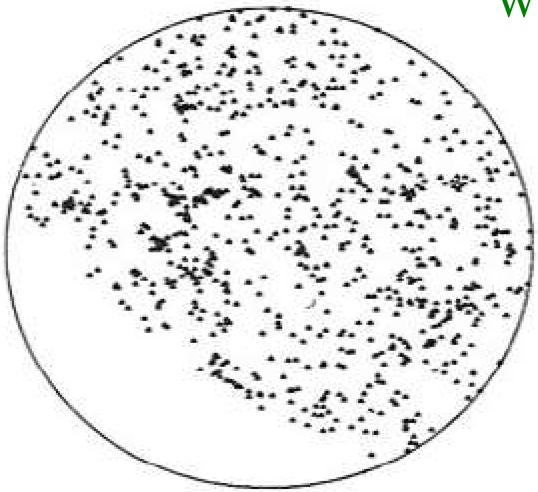
White'86



HDM

Hot Dark Matter

Relativistic



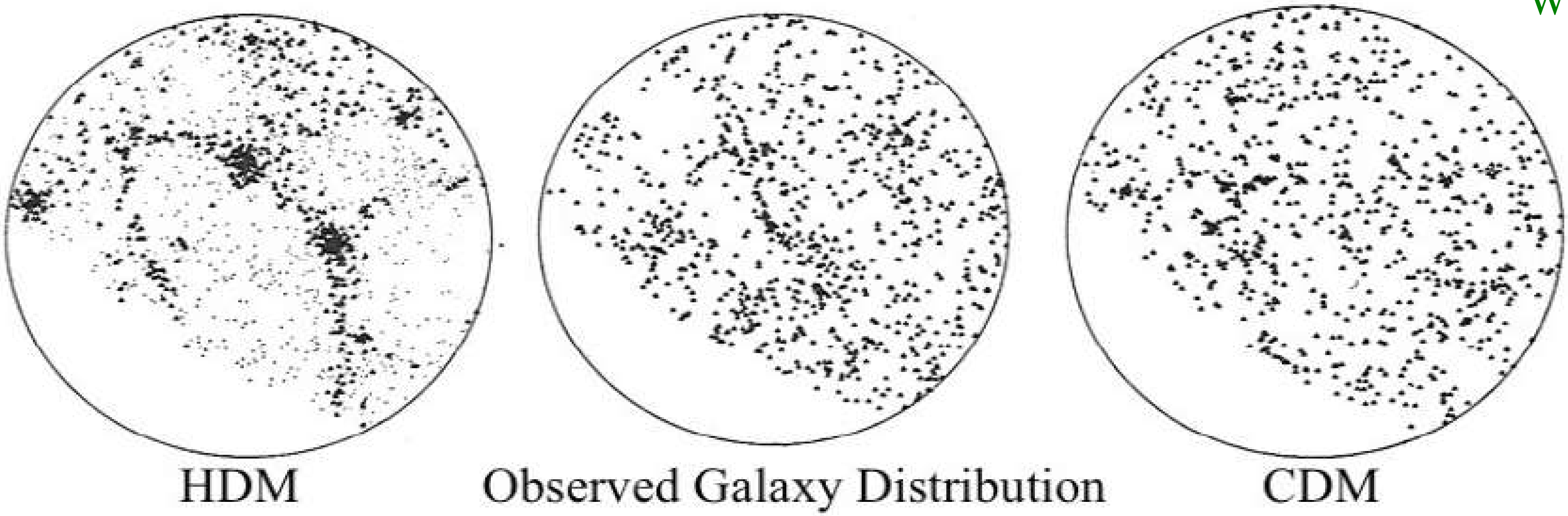
CDM

Cold Dark Matter

Non-relativistic

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

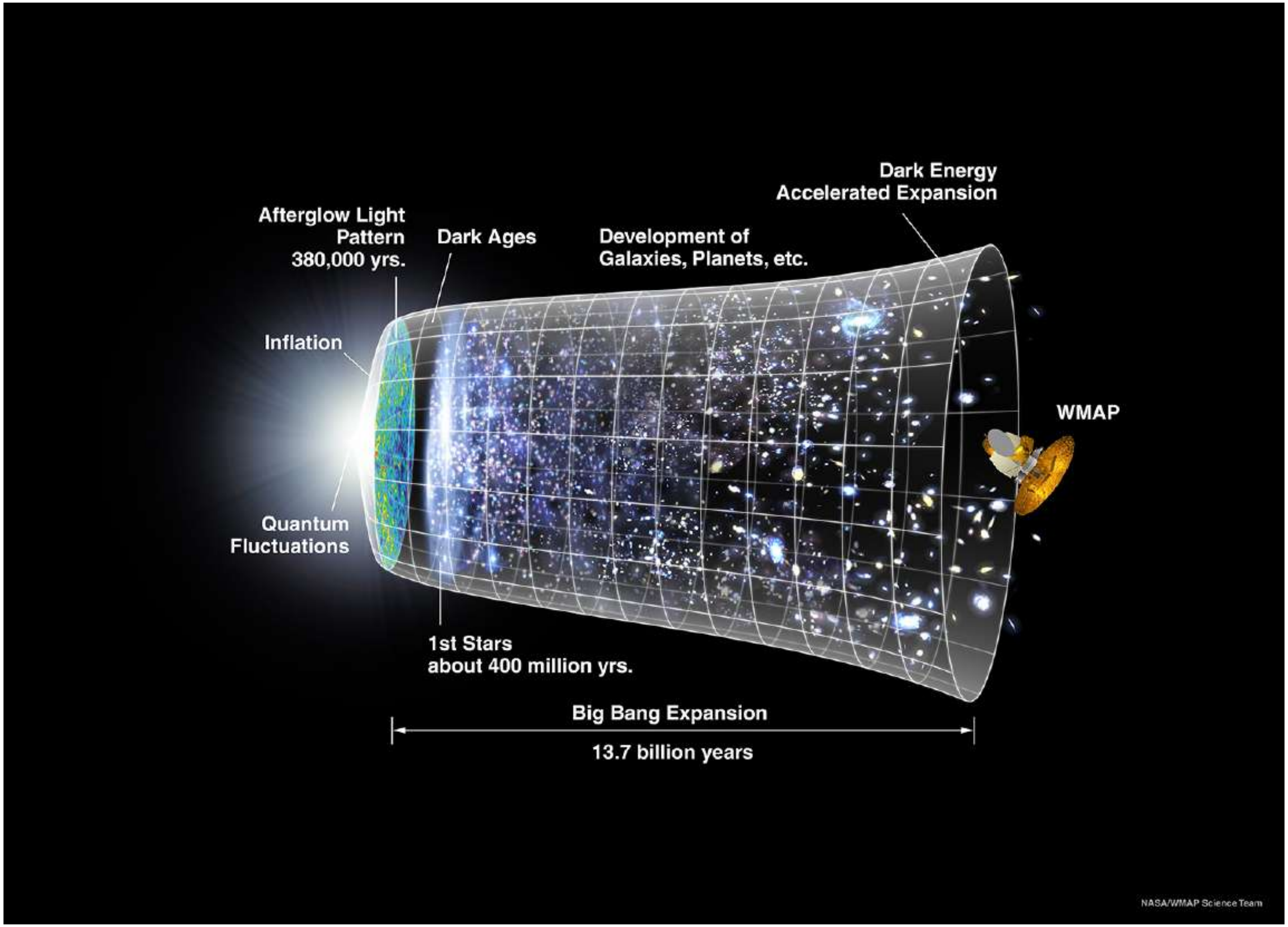
White'86



Hot Dark Matter
Relativistic

Cold Dark Matter
Non-relativistic

4) It exists today.



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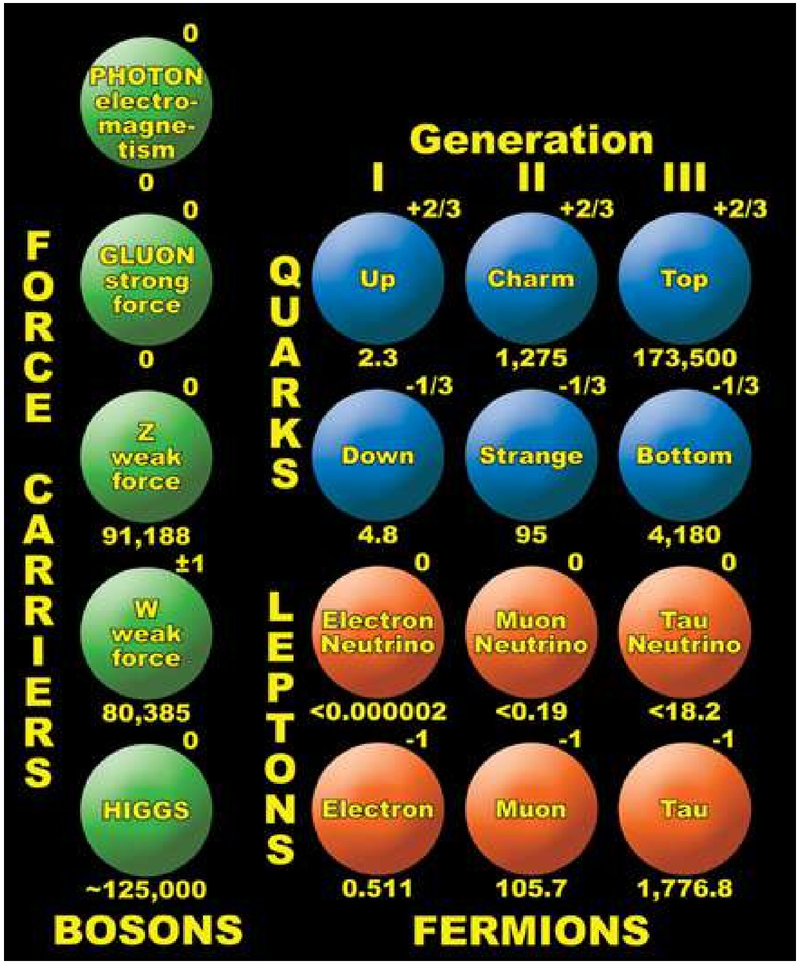

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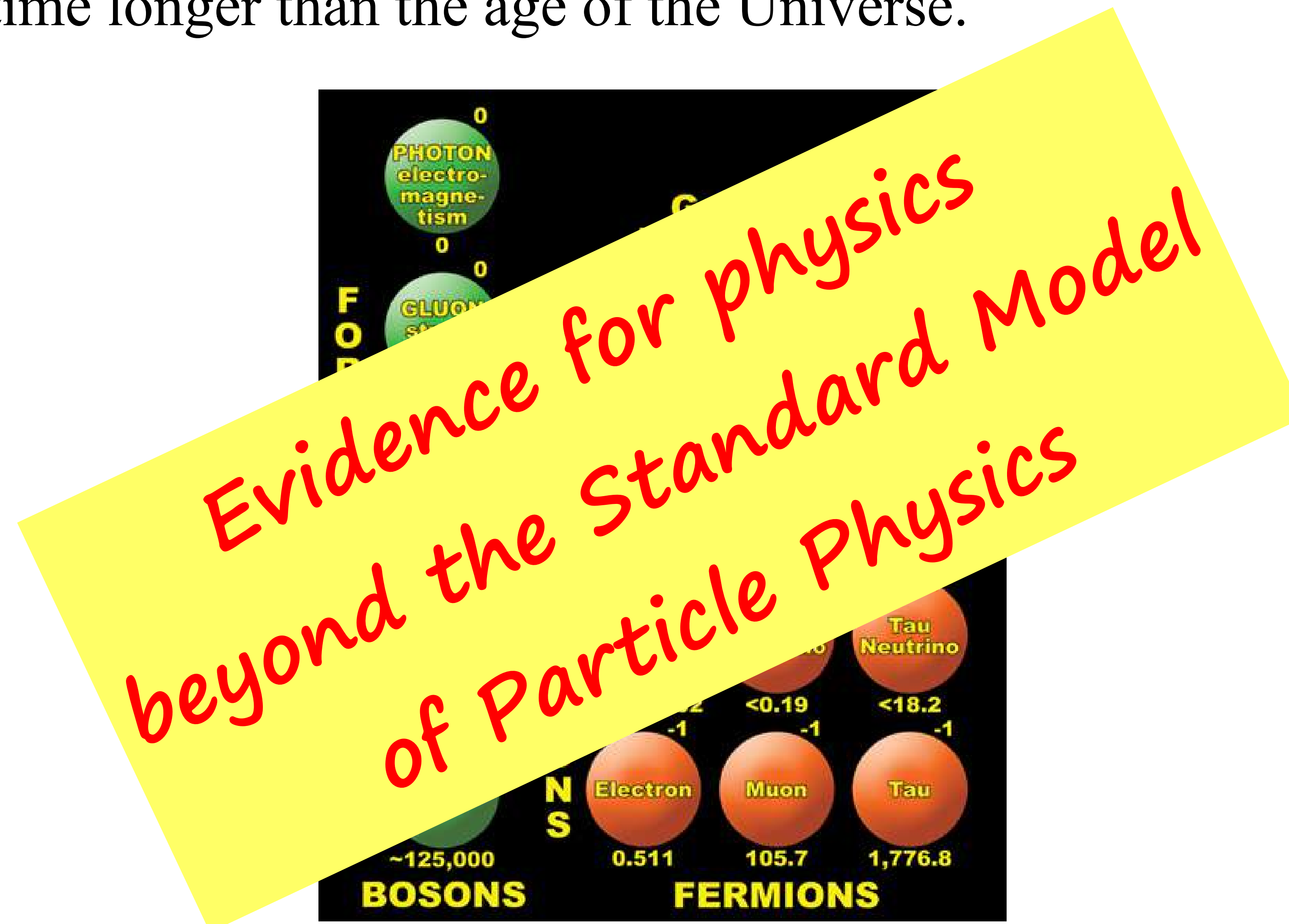

What do we know about dark matter, from the particle physics point of view?

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
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DARK MATTER

$J =$?

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

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

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

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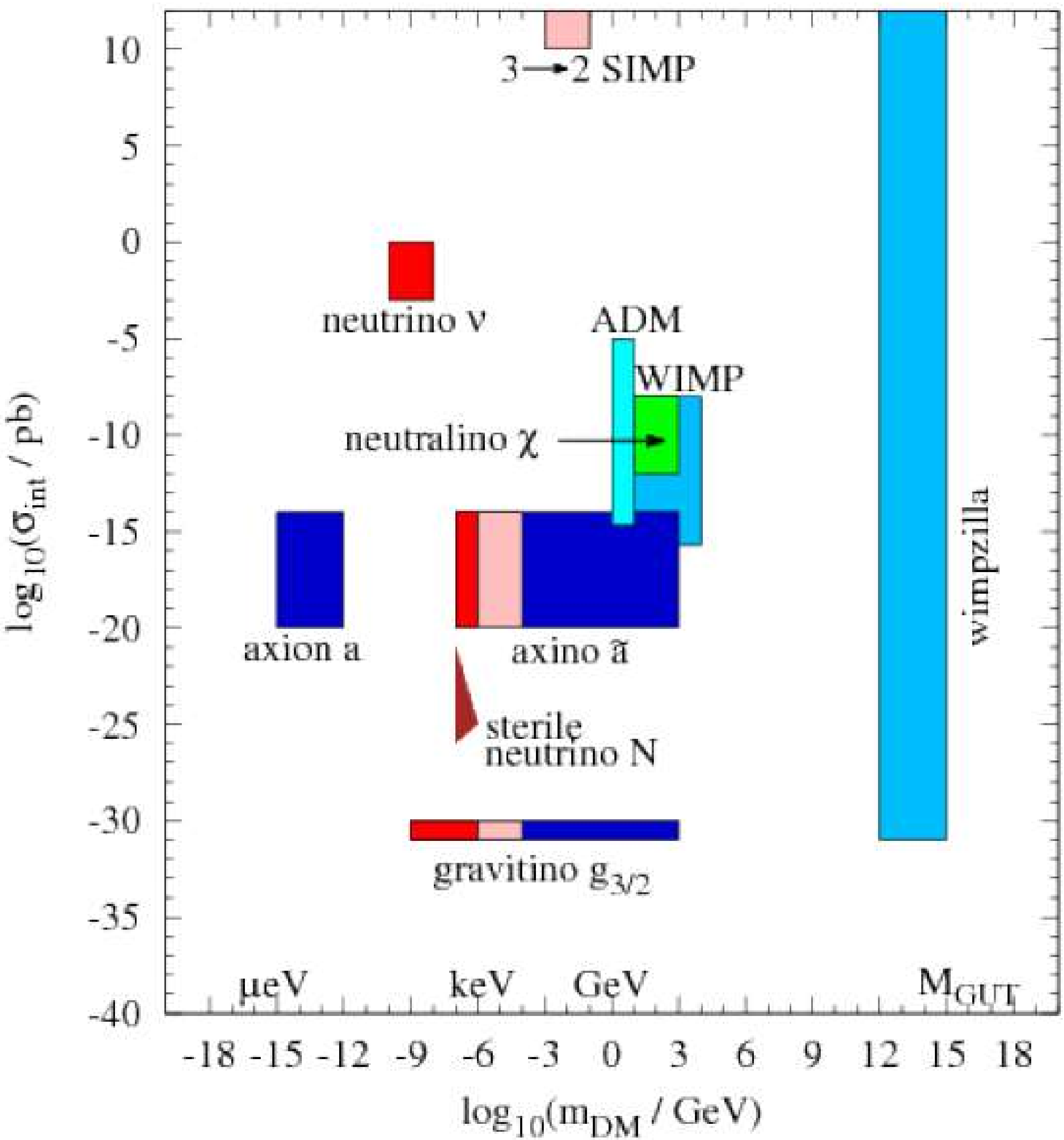
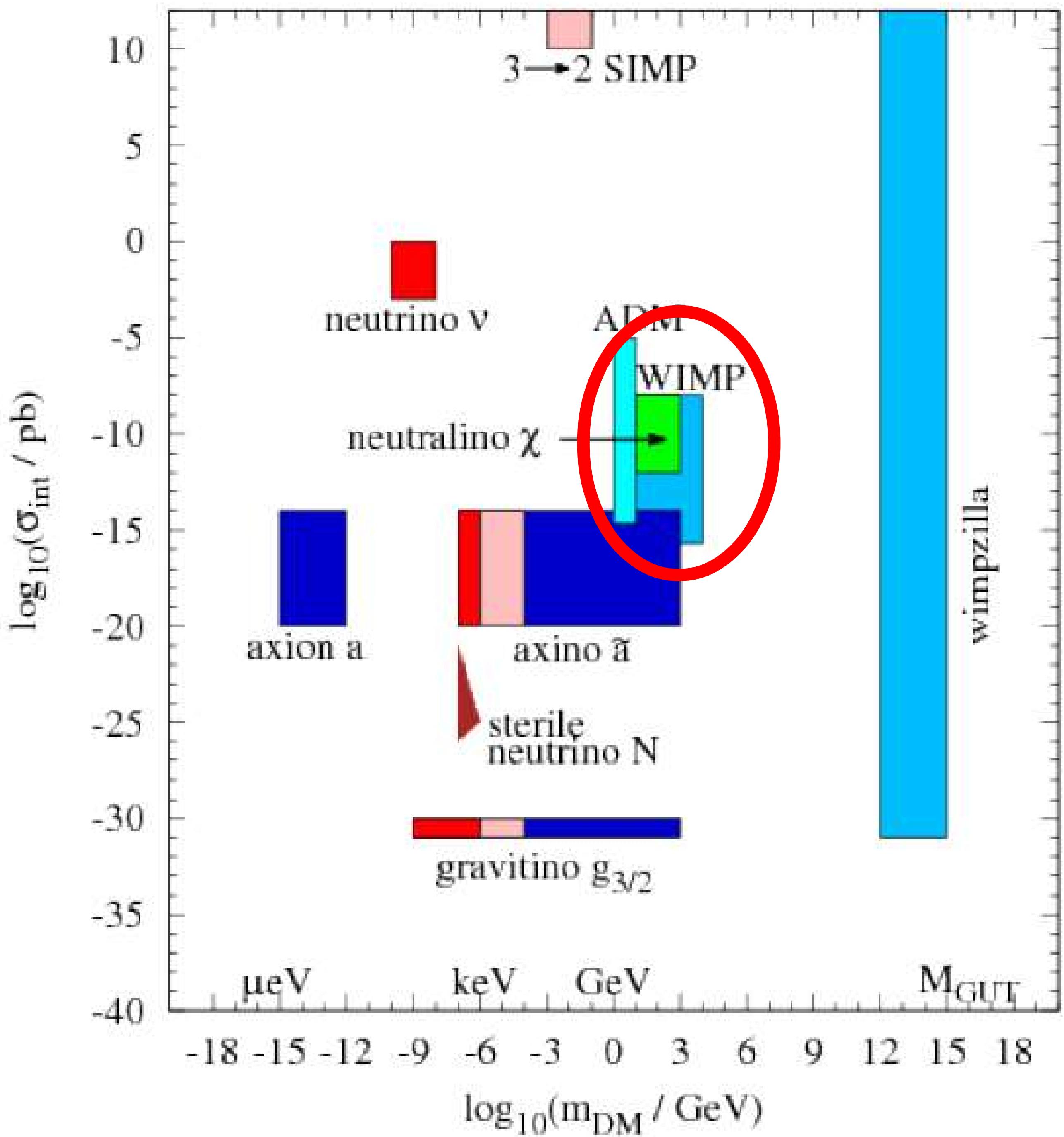
Goal for the 21st century:
identify the properties
of the dark matter particle


3→2 SIMP
neutrino ν
ADM
WIMP
neutralino χ
wimpzilla
axion a
axino ã
sterile neutrino N
gravitino $g_{3/2}$
μeV
keV
GeV
M_{GUT}
$\log_{10}(\sigma_{int}$ / pb)
$\log_{10}(m_{DM}$ / GeV)
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18



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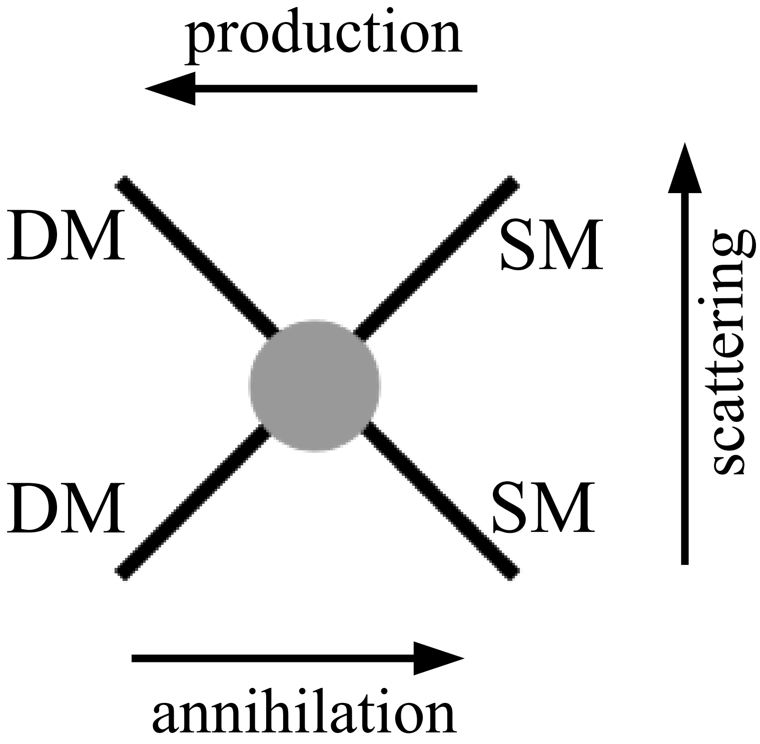
The freeze-out mechanism



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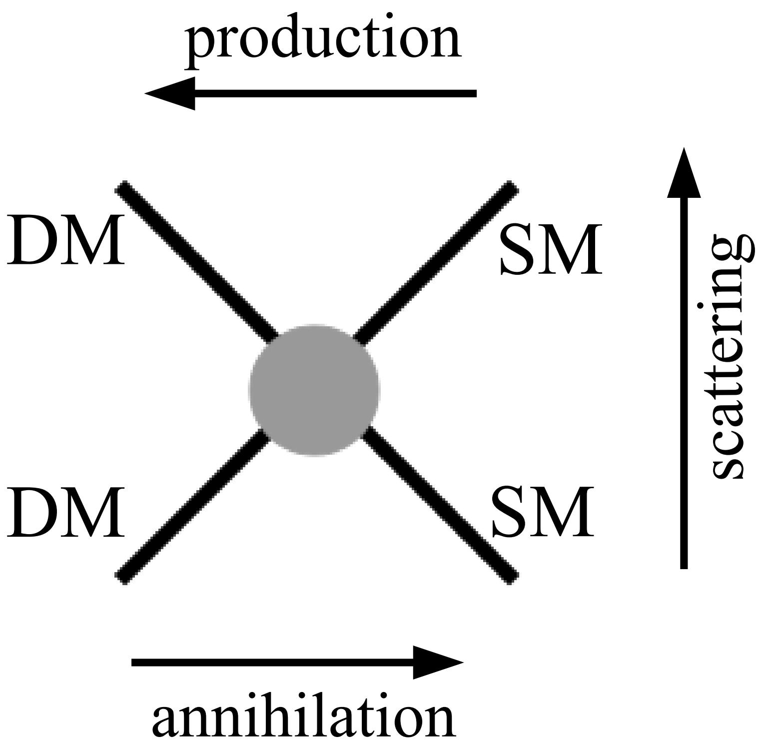
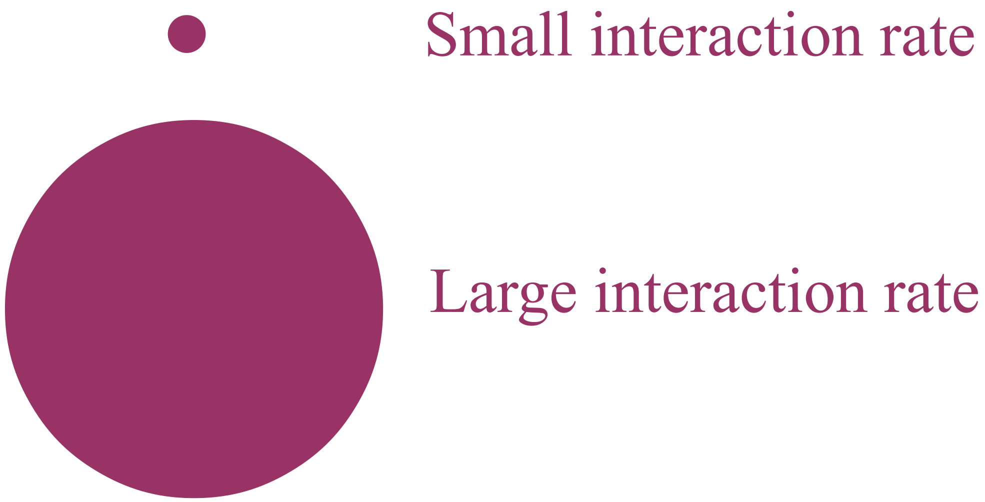


The probability of interaction controlled by the cross-section



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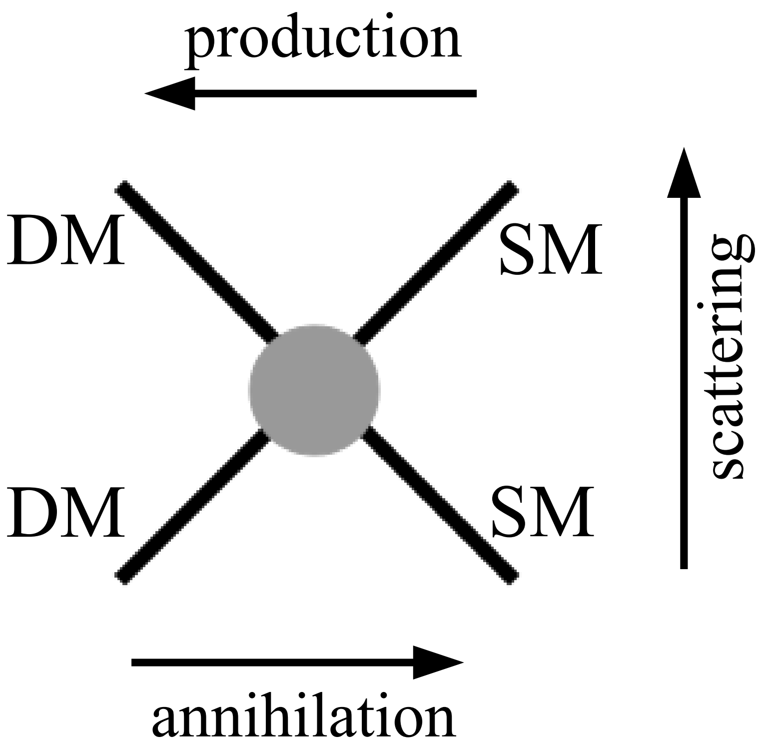
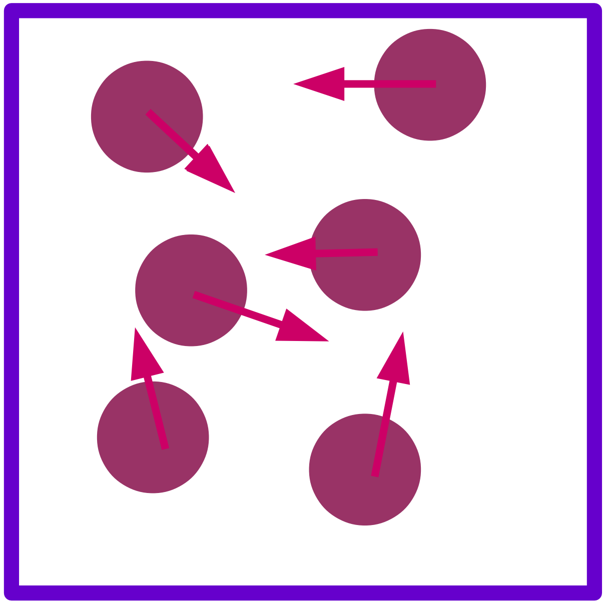


At very high temperatures,
dark matter particles are annihilated
and regenerated at the same rate.

However, at low temperatures,
the Standard Model particles do not
have enough kinetic energy to
regenerate DM particles, and DM
particles can only annihilate.

The subsequent evolution of the dark
matter number density depends
crucially on the fact that our Universe
is expanding.

Dark matter population in a static Universe



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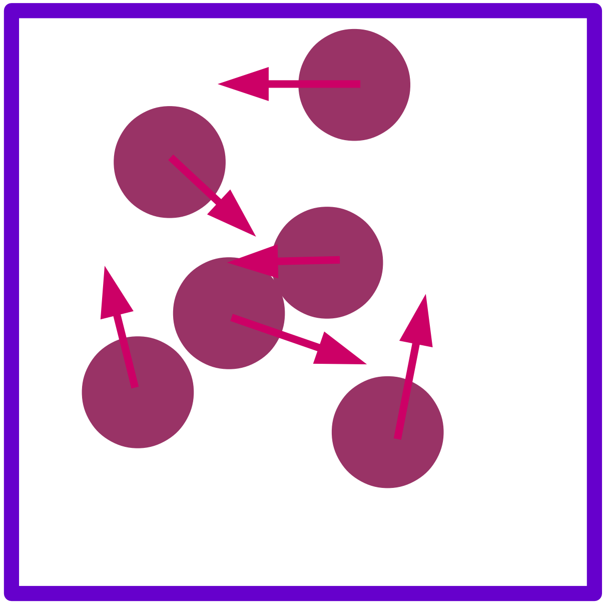

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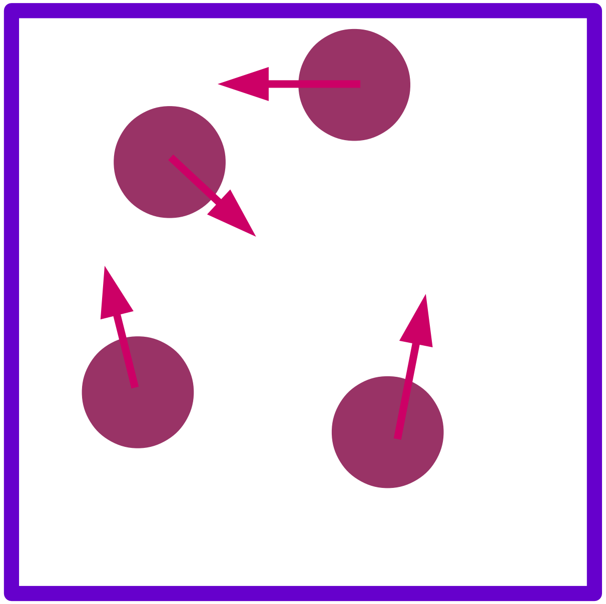

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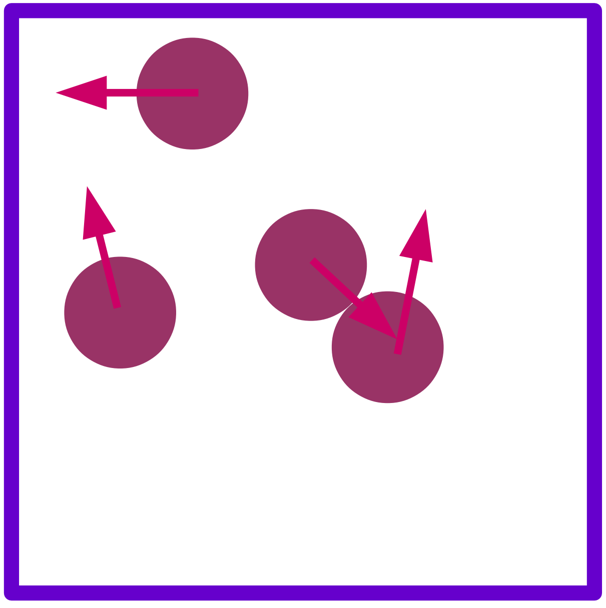

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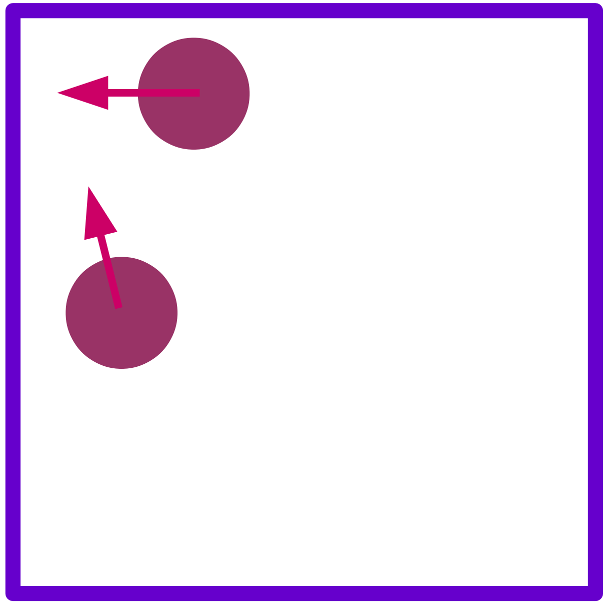

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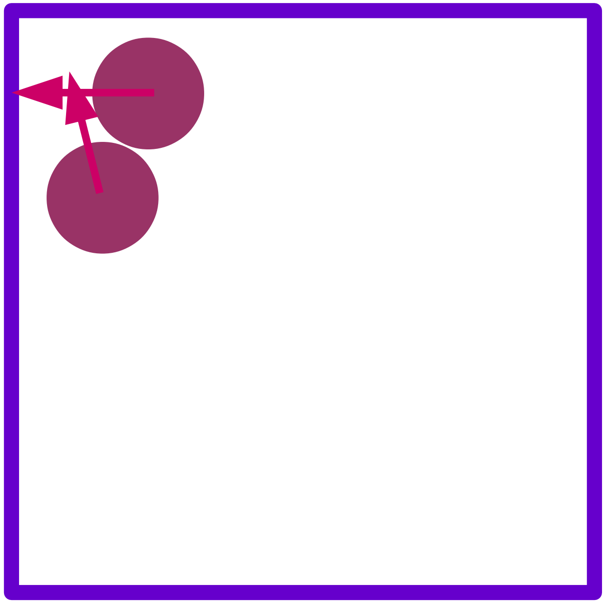

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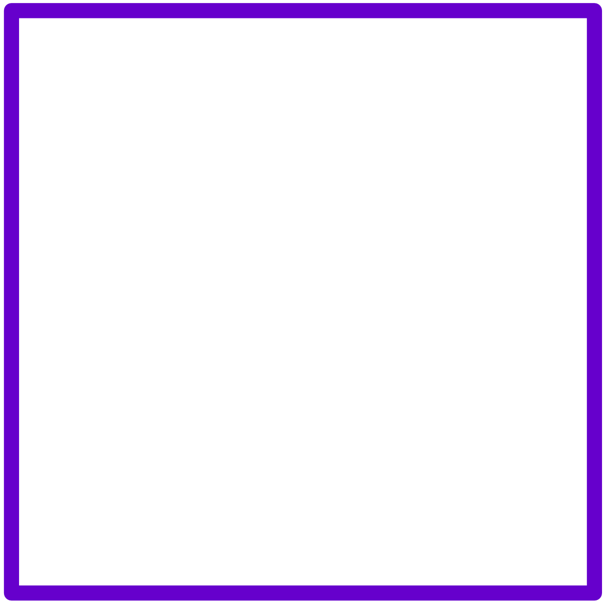
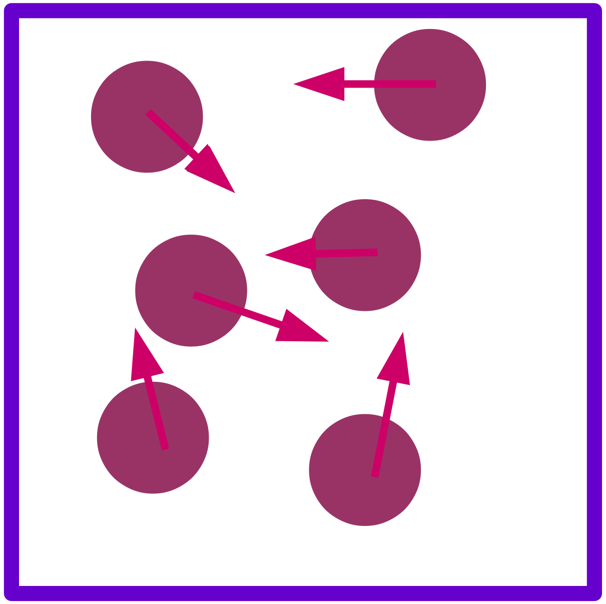
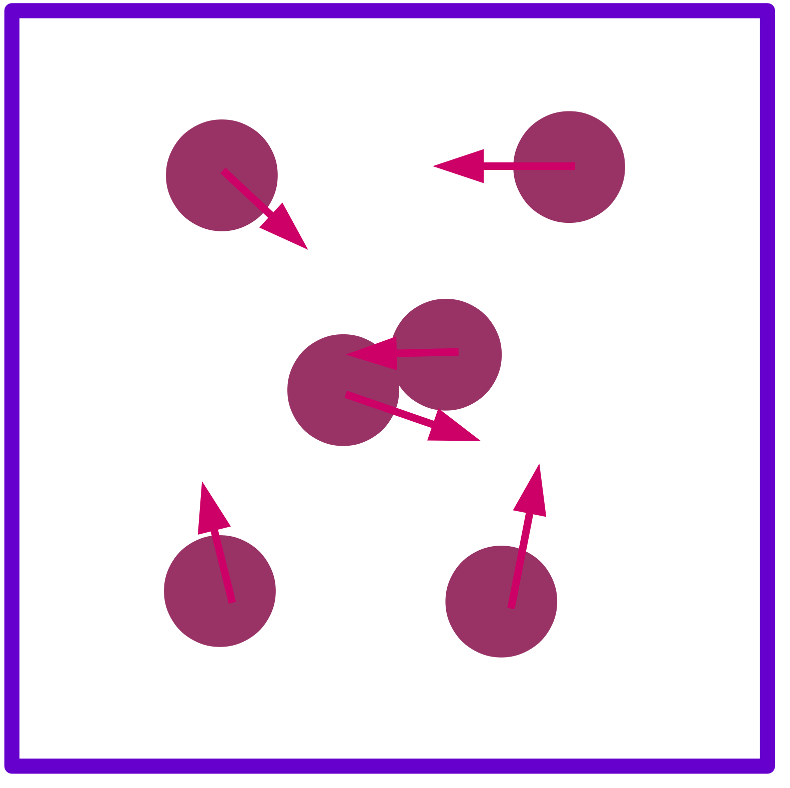
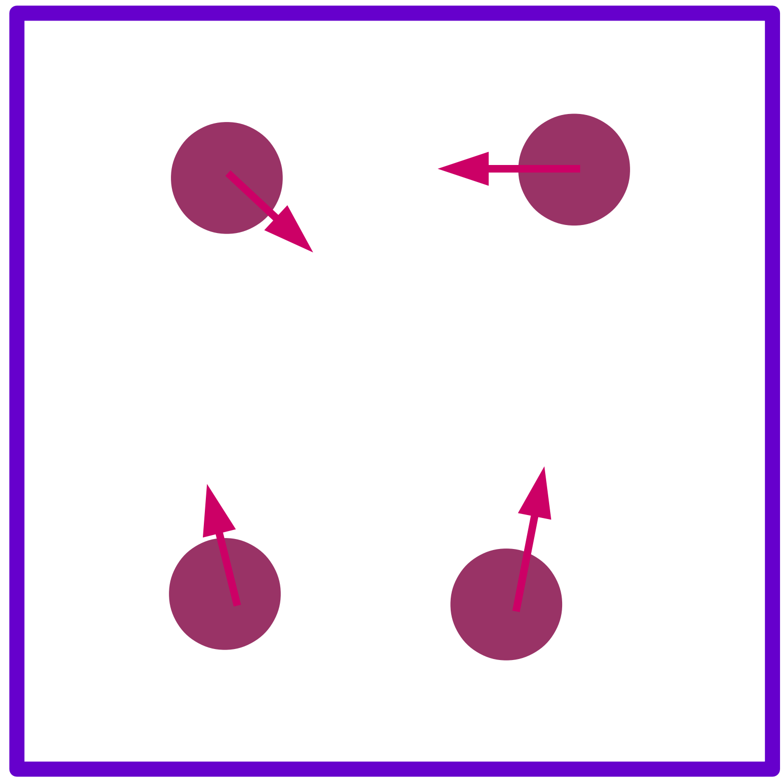


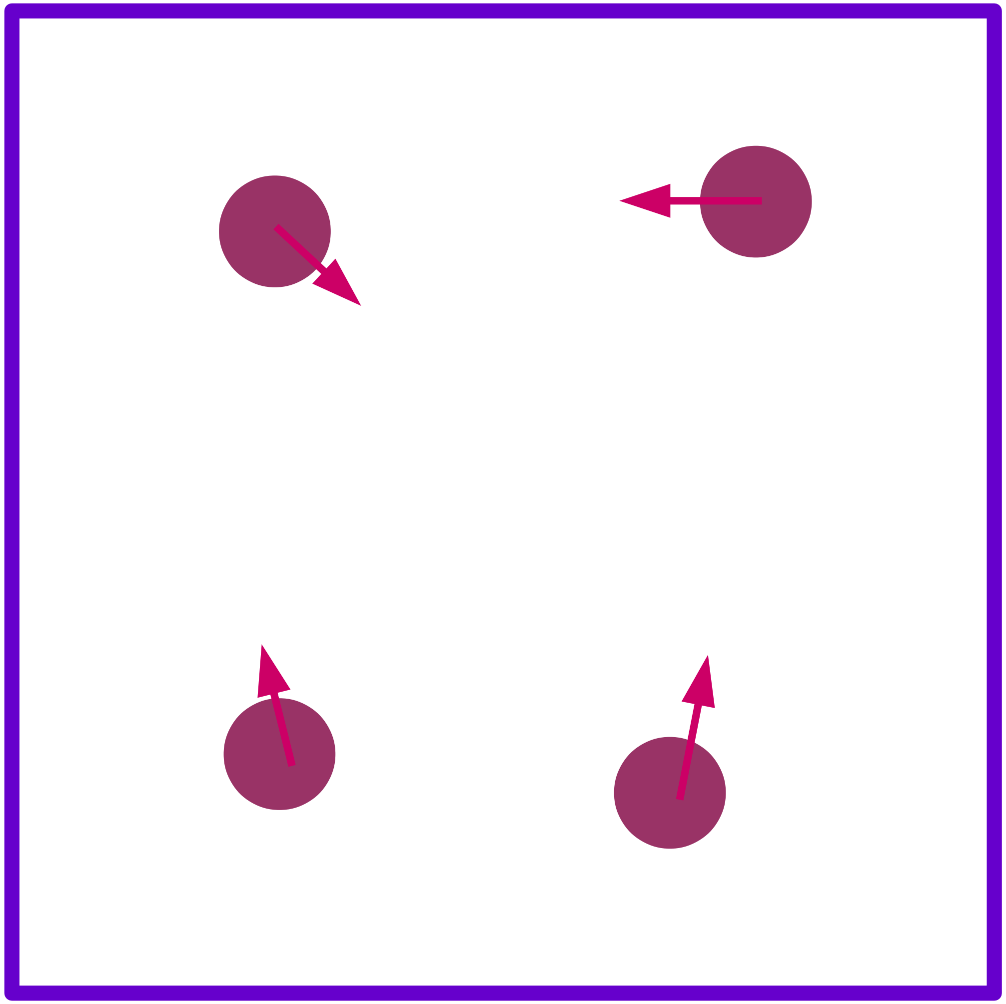
No DM particles at present times!

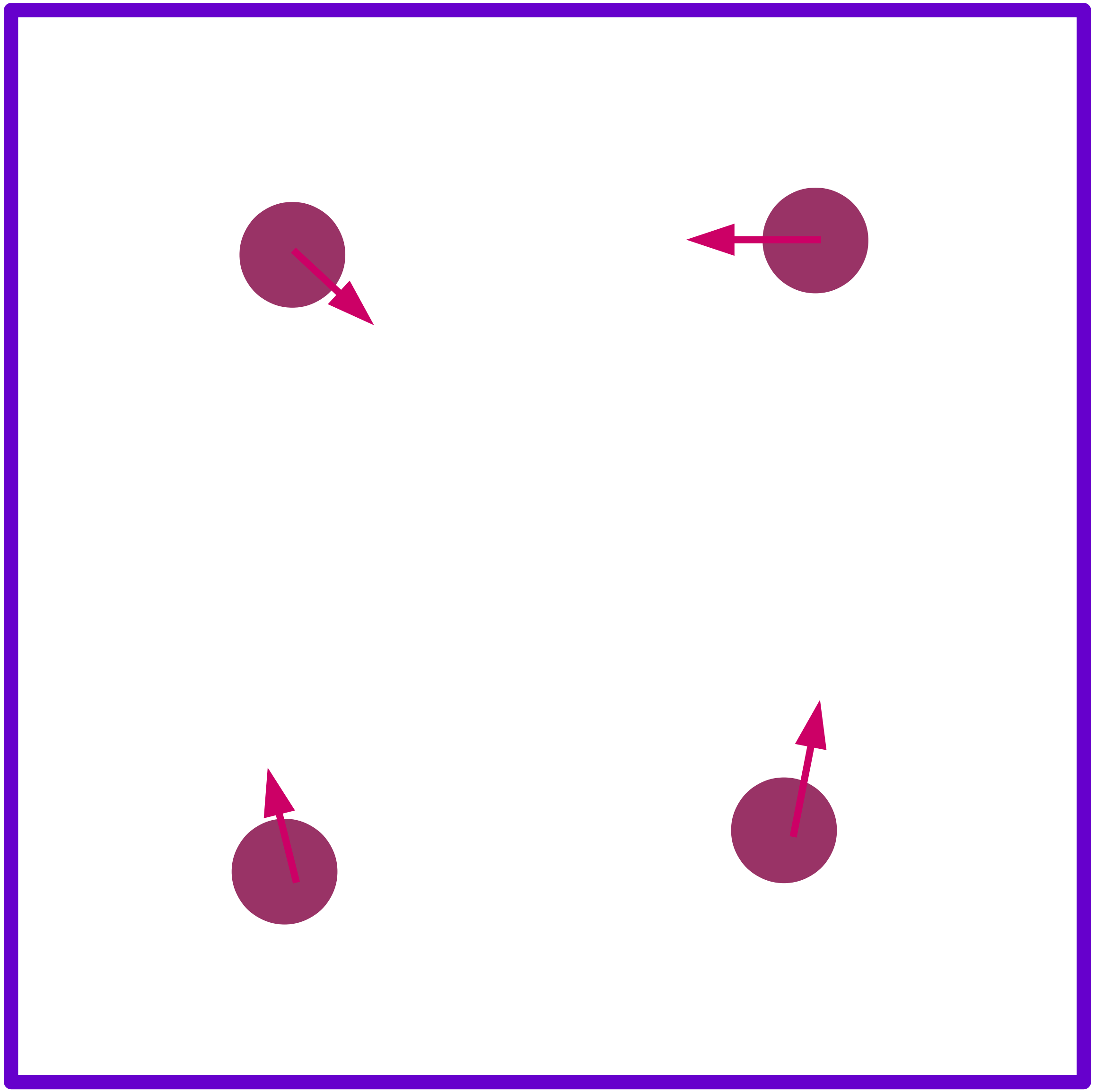
Dark matter population in an expanding Universe





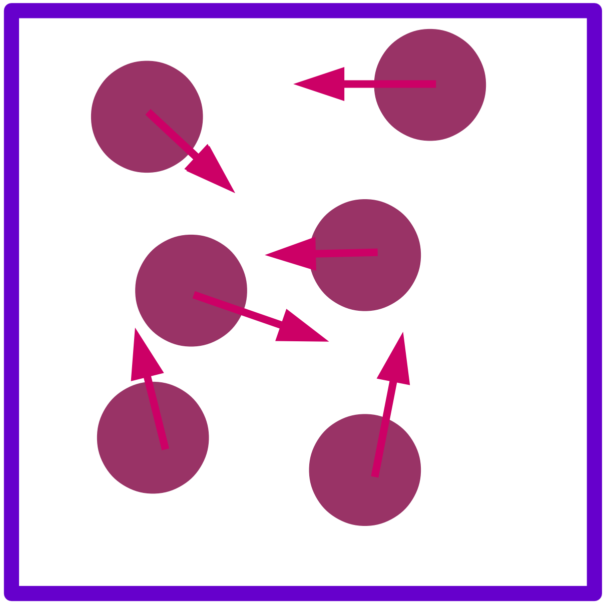






Dark matter particles can no longer annihilate.
The number of dark matter particles “freezes-out”

The “relic abundance” of dark matter particles depends on their annihilation cross section and on their relative velocity



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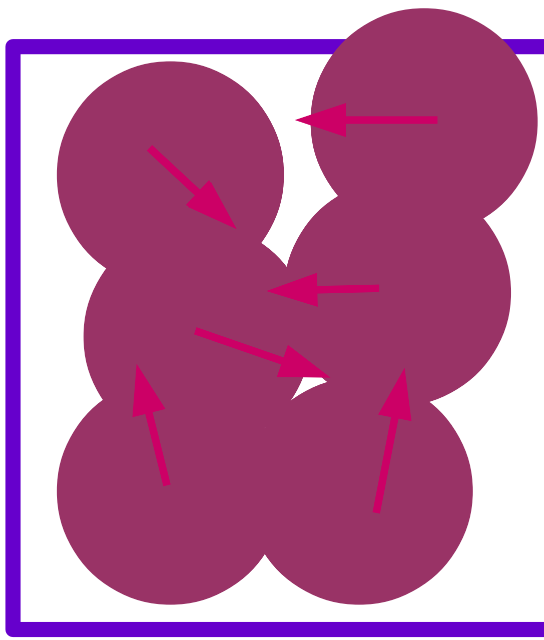

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Large annihilation cross section → Small relic abundance
Small annihilation cross section → Large relic abundance

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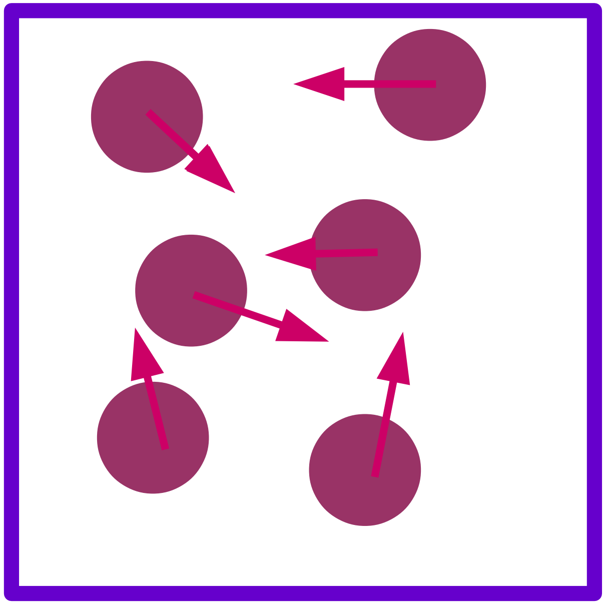

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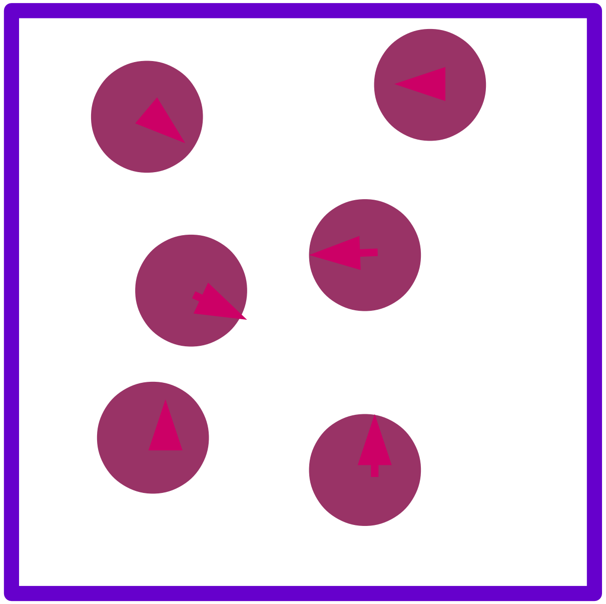

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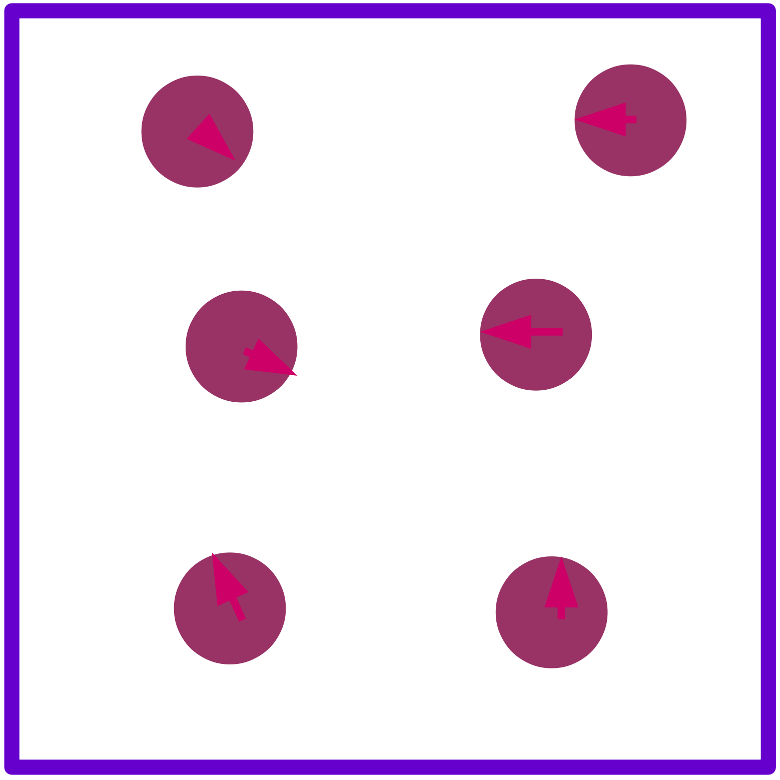

Small velocity → Large relic abundance
Large velocity → Small relic abundance

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Correct DM abundance (25% of the total energy of the Universe), if

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

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1 pb = 10^{-36} cm^2.
Typical strength of the weak interactions

Speed of light

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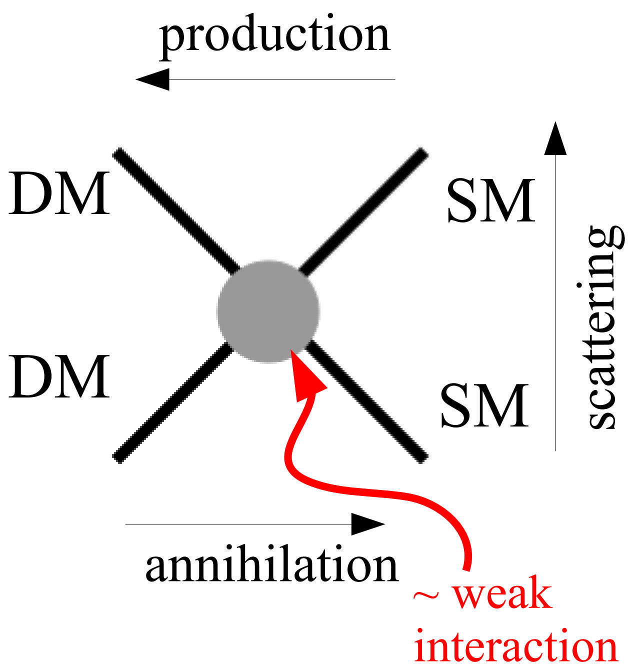

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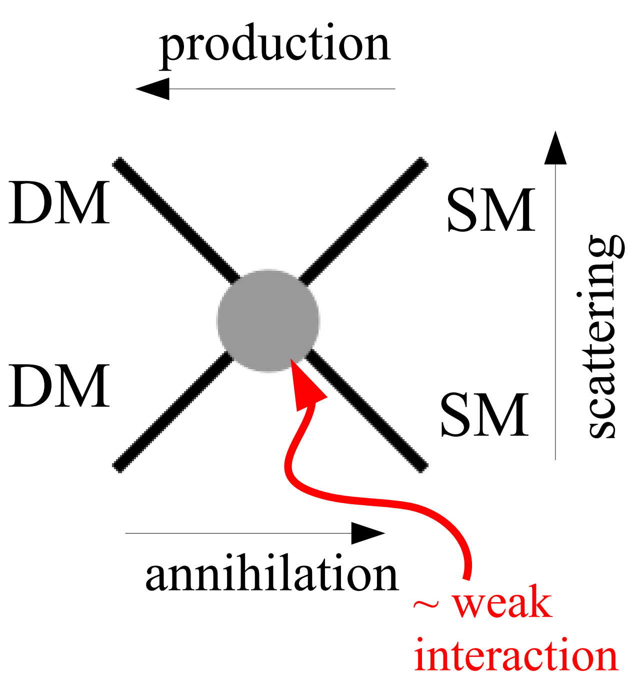

The dark matter is a Weakly Interacting Massive Particle (WIMP)

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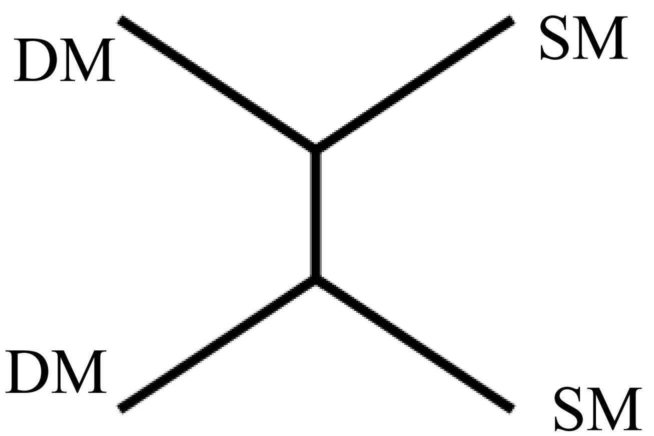

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More numerology:

$$1\,\mathrm{pb} \simeq \frac{(0.1)^4}{(100\,\mathrm{GeV})^2} = \frac{\mathrm{coupling}^4}{\mathrm{mass}^2}$$

The freeze-out mechanism suggests that the WIMP has mass ~ a few GeV – a few TeV and a coupling with ordinary matter ~ 0.1 – 0.01

LUX

CMS

ATLAS

MAGIC

Xe
XENON
Dark Matter Project

fermi
Gamma-ray
Space Telescope

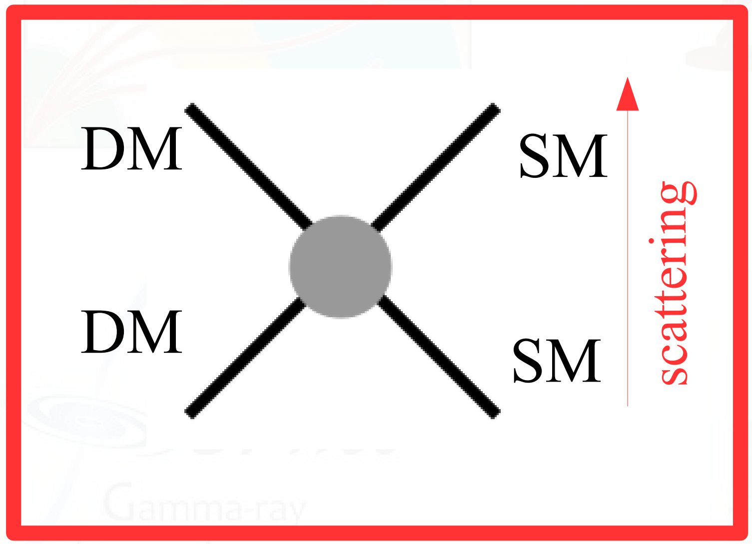
PaMeLa

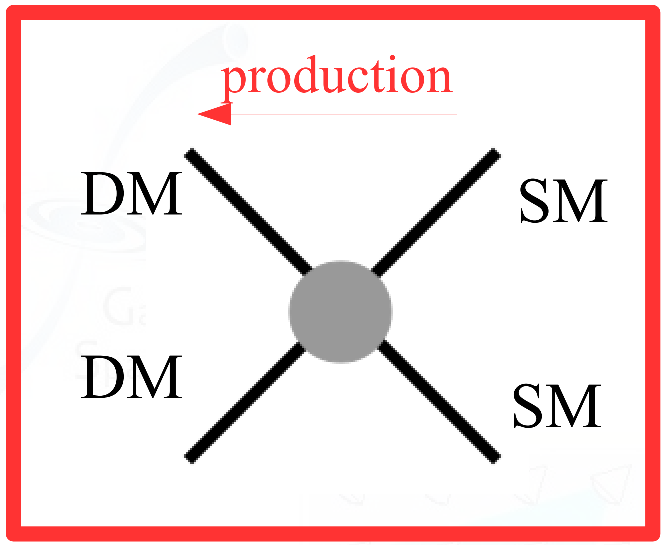
H E S S

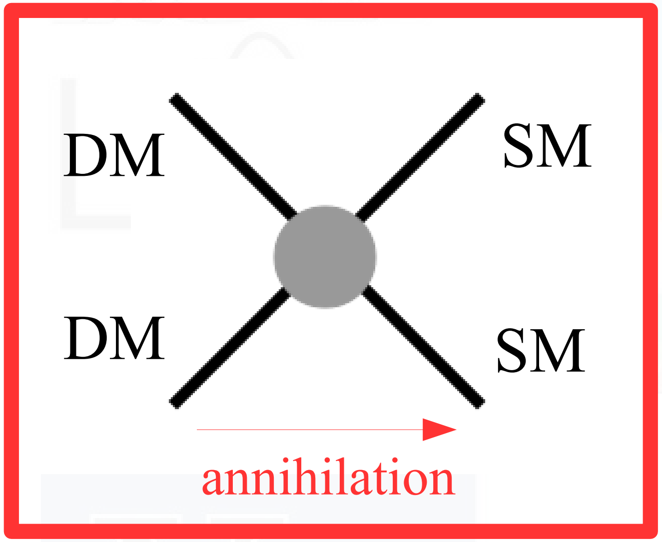
Alpha Magnetic Spectrometer
AMS-02
Europe • Asia
North America

VERITAS

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY


DM
DM
SM
SM
scattering


production
DM
SM
DM
SM



MAGIC

fermi
Gamma-ray Space Telescope

PaMeLa

H E S S

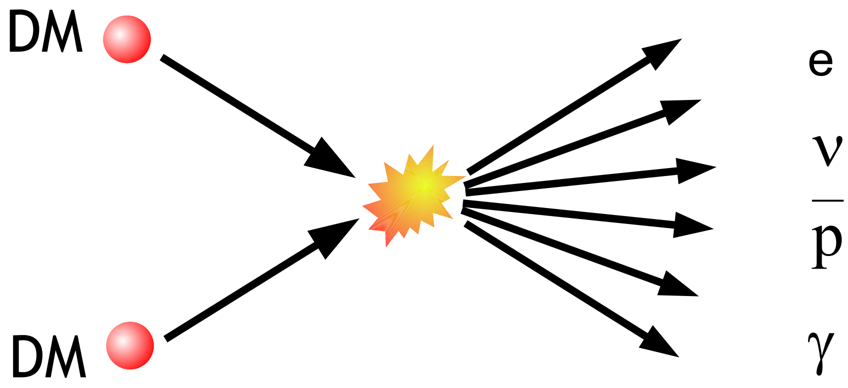
VERITAS

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Alpha Magnetic Spectrometer
AMS-02

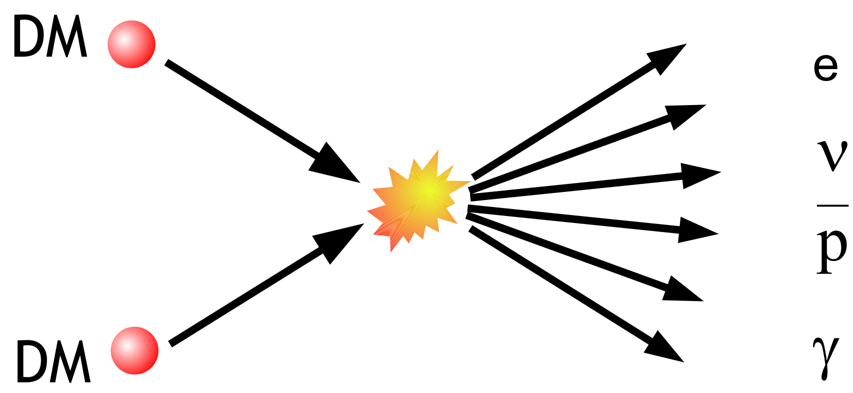
Indirect Dark Matter Searches

Indirect dark matter searches

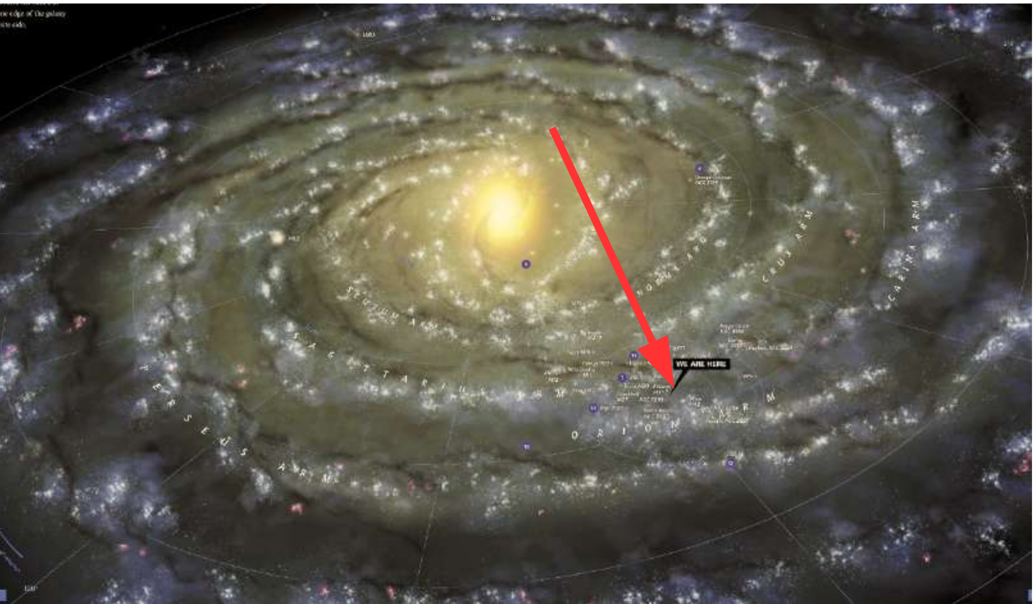


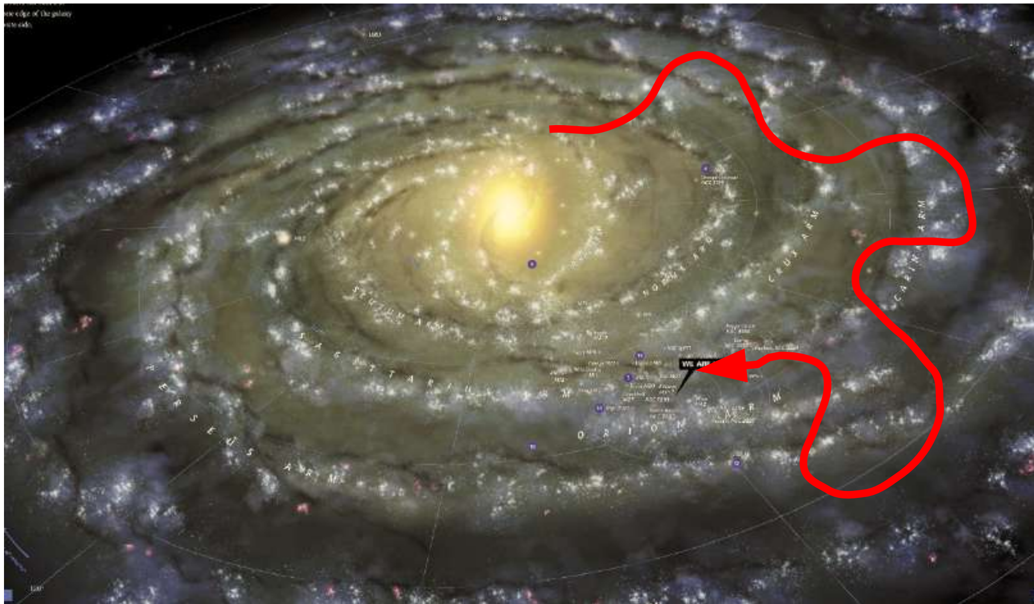
The dark matter annihilates into ordinary particles, such as electrons and positrons, antiprotons, neutrinos, photons...

Indirect dark matter searches

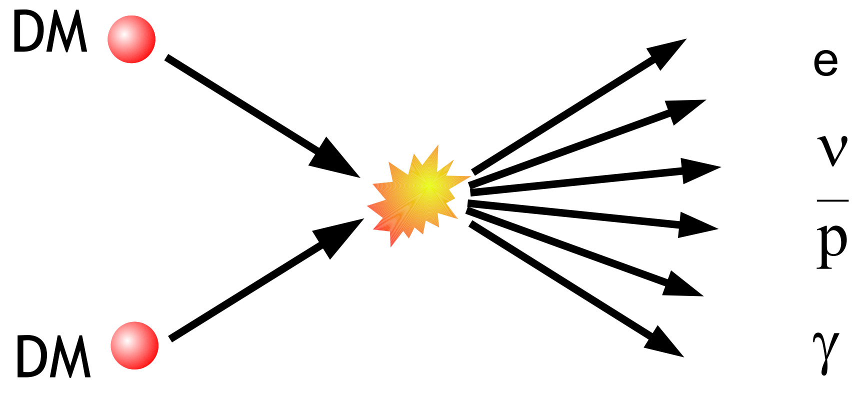


Neutral particles propagate in straight lines practically without losing energy. Charged particles, on the other hand, propagate in a complicated way through the tangled magnetic field of our Galaxy.





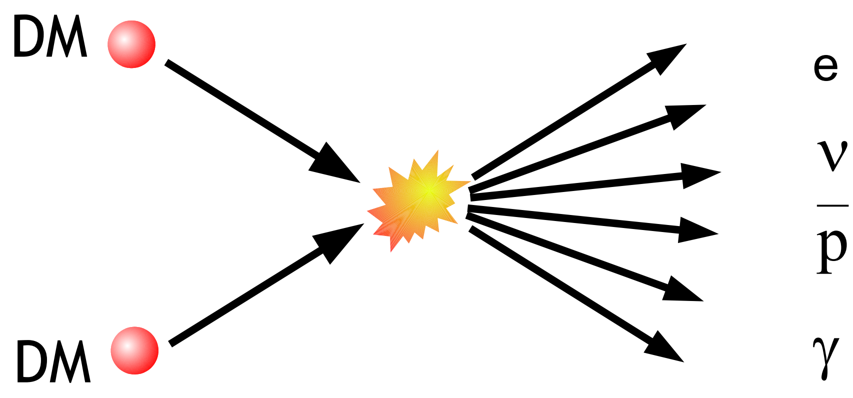
Indirect dark matter searches



The fluxes at Earth can be calculated and depend on:

- The dark matter mass (m_{DM})
- The annihilation cross section times the velocity (σv)

Indirect dark matter searches



The fluxes at Earth can be calculated and depend on:

- The dark matter mass (m_{DM})
- The annihilation cross section times the velocity (σv)

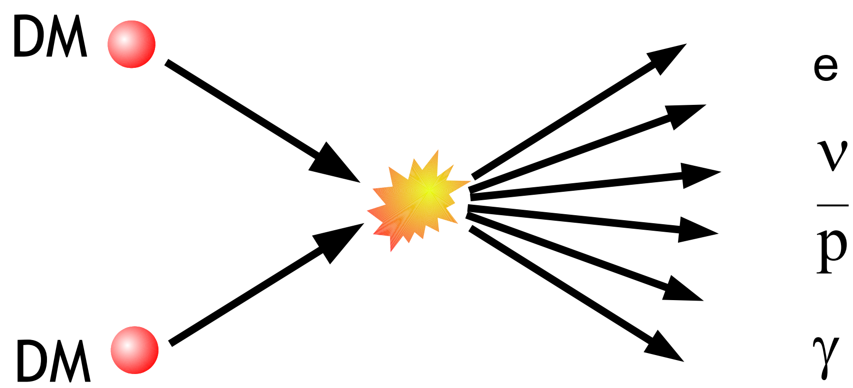
Which (σv)? A well motivated choice:

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

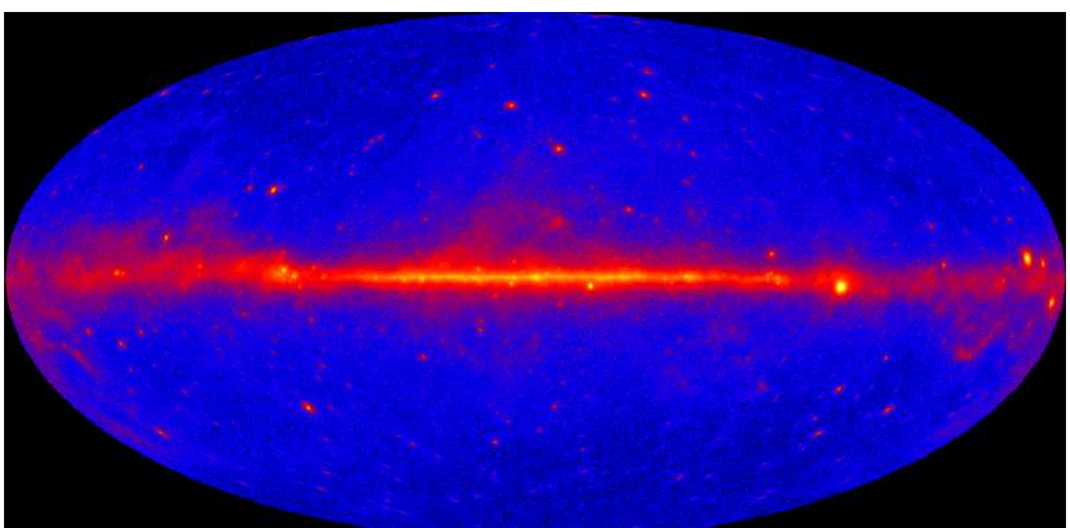
"Canonical" annihilation cross section for WIMP dark matter

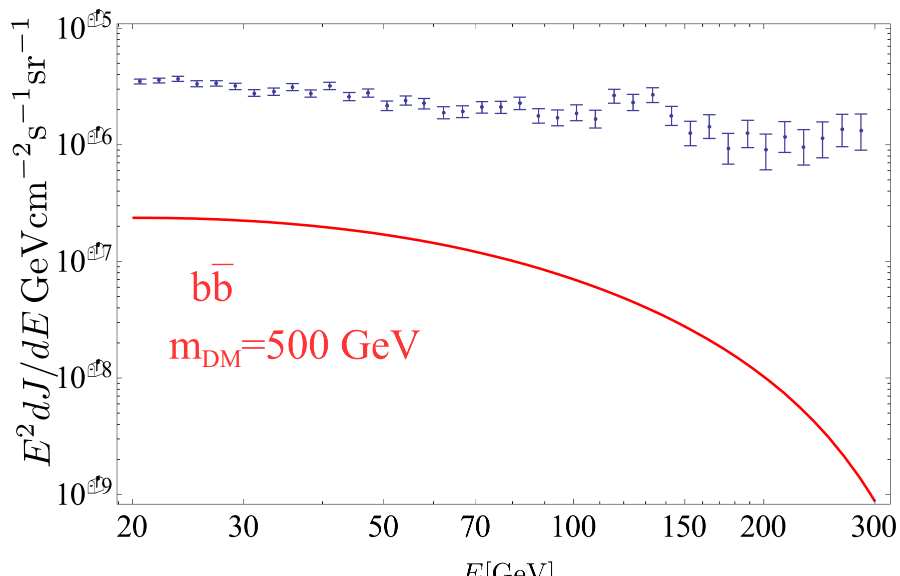
First milestone for experimental searches.

Indirect dark matter searches

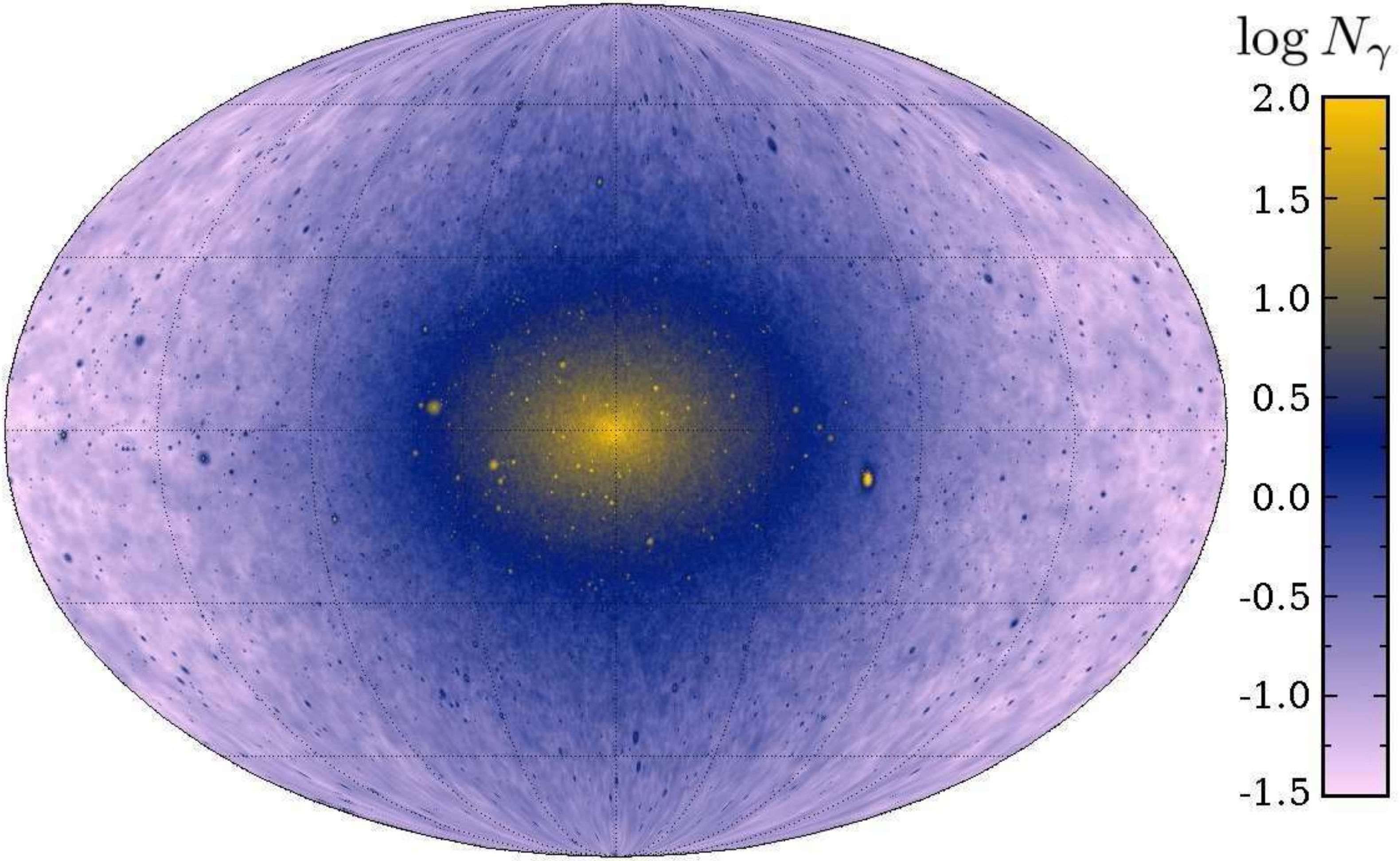


The annihilation products arrive to Earth, along with gamma-rays and cosmic rays produced in astrophysical processes.





Where to look for dark matter annihilations



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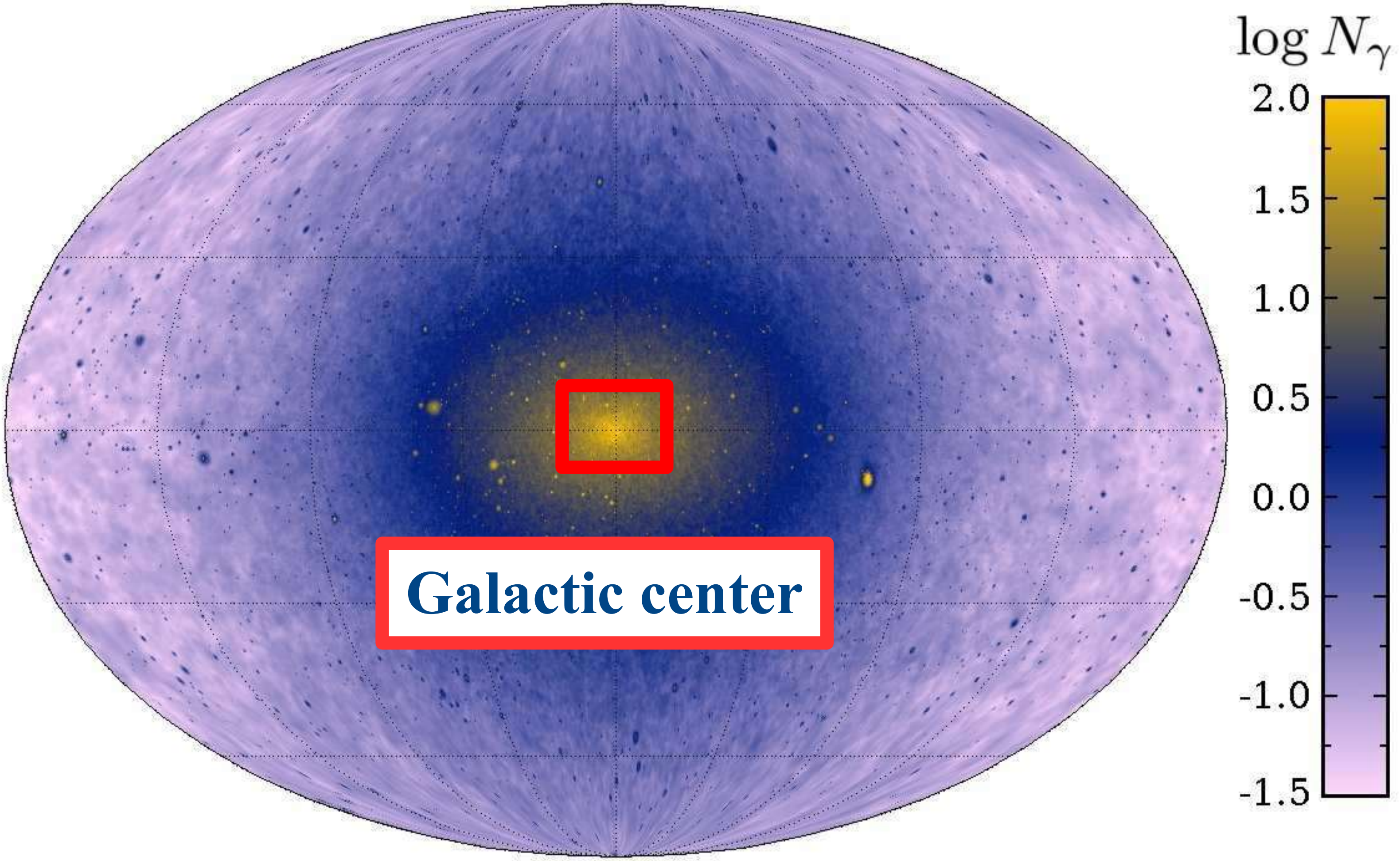
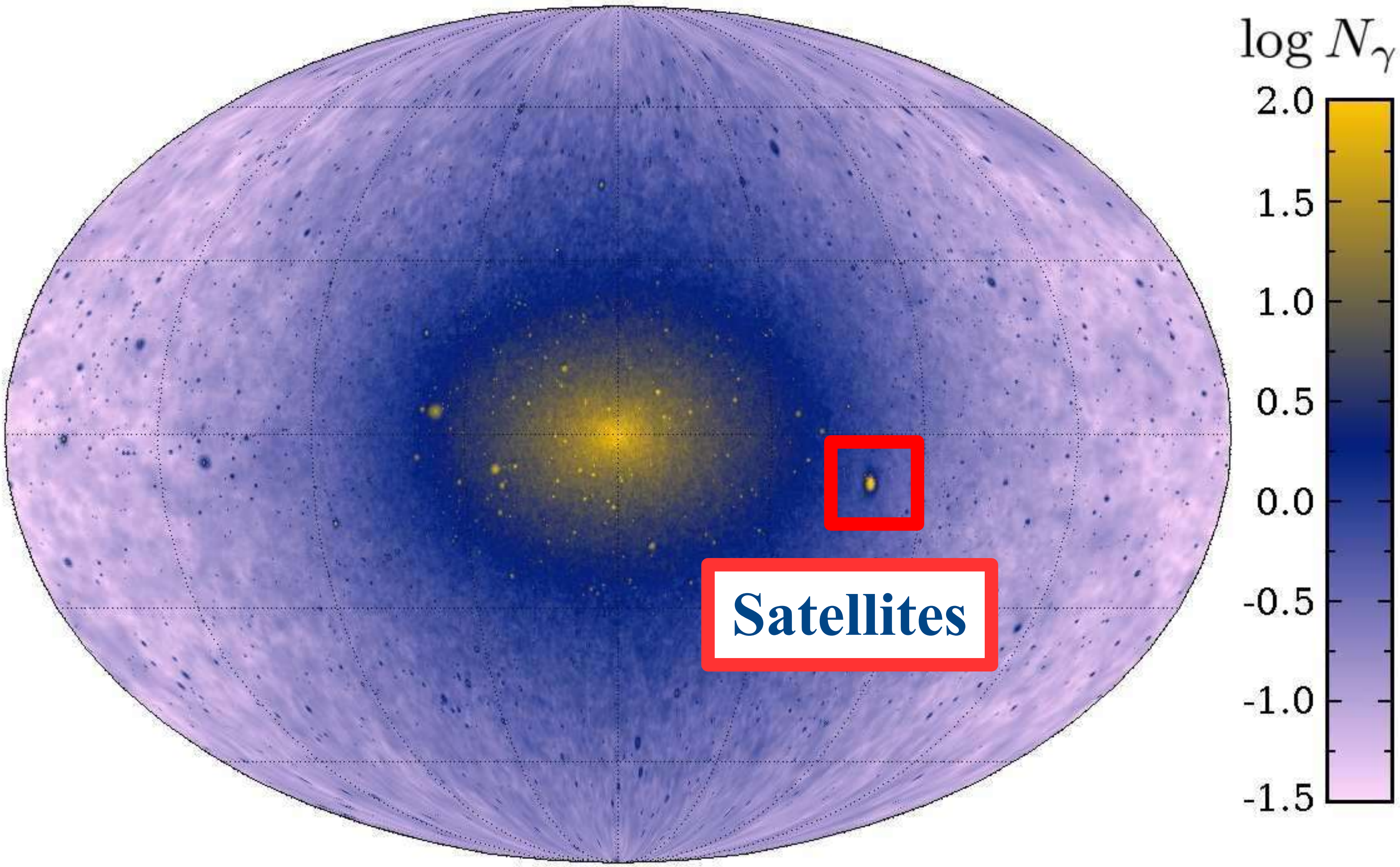


Where to look for dark matter annihilations



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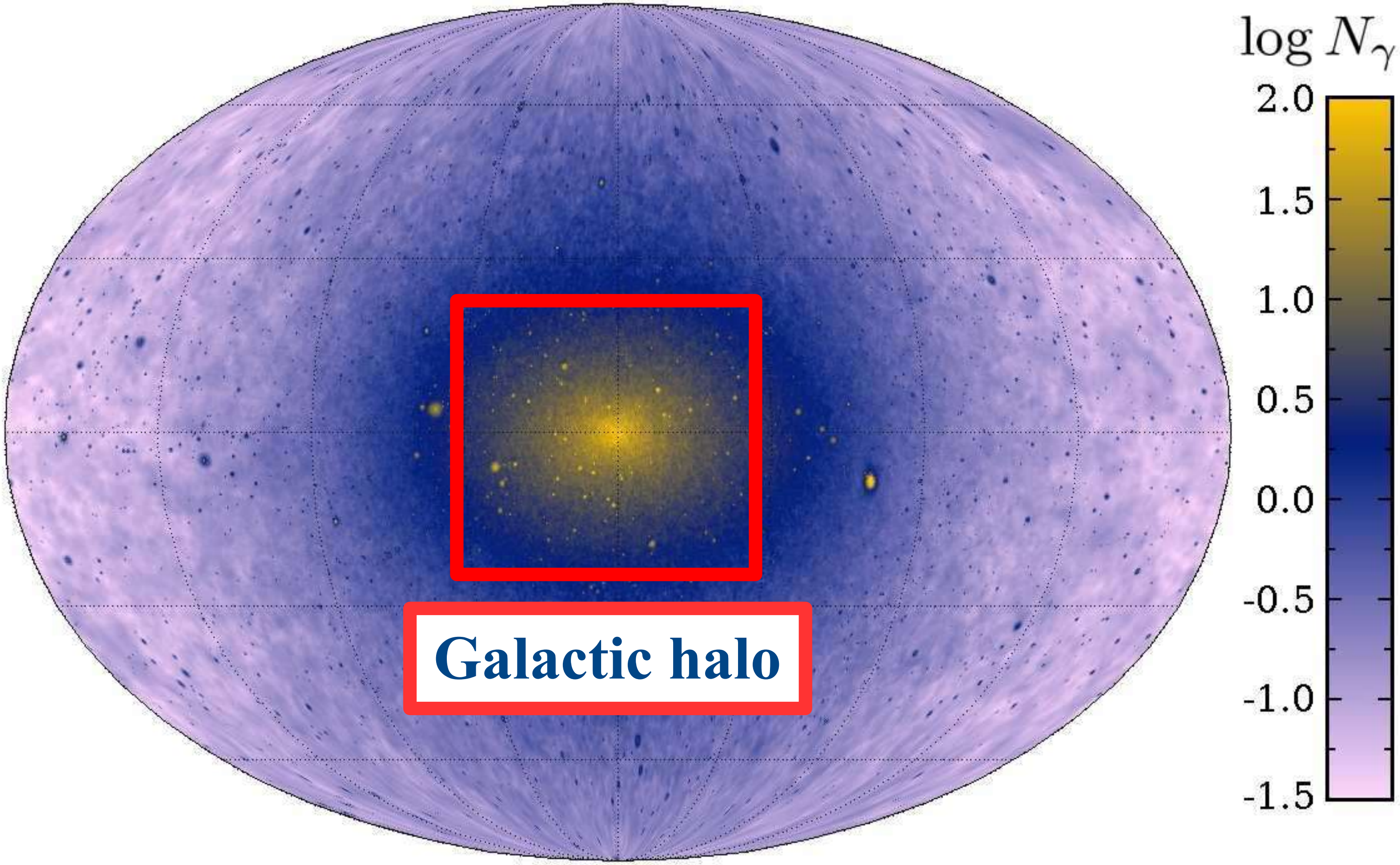

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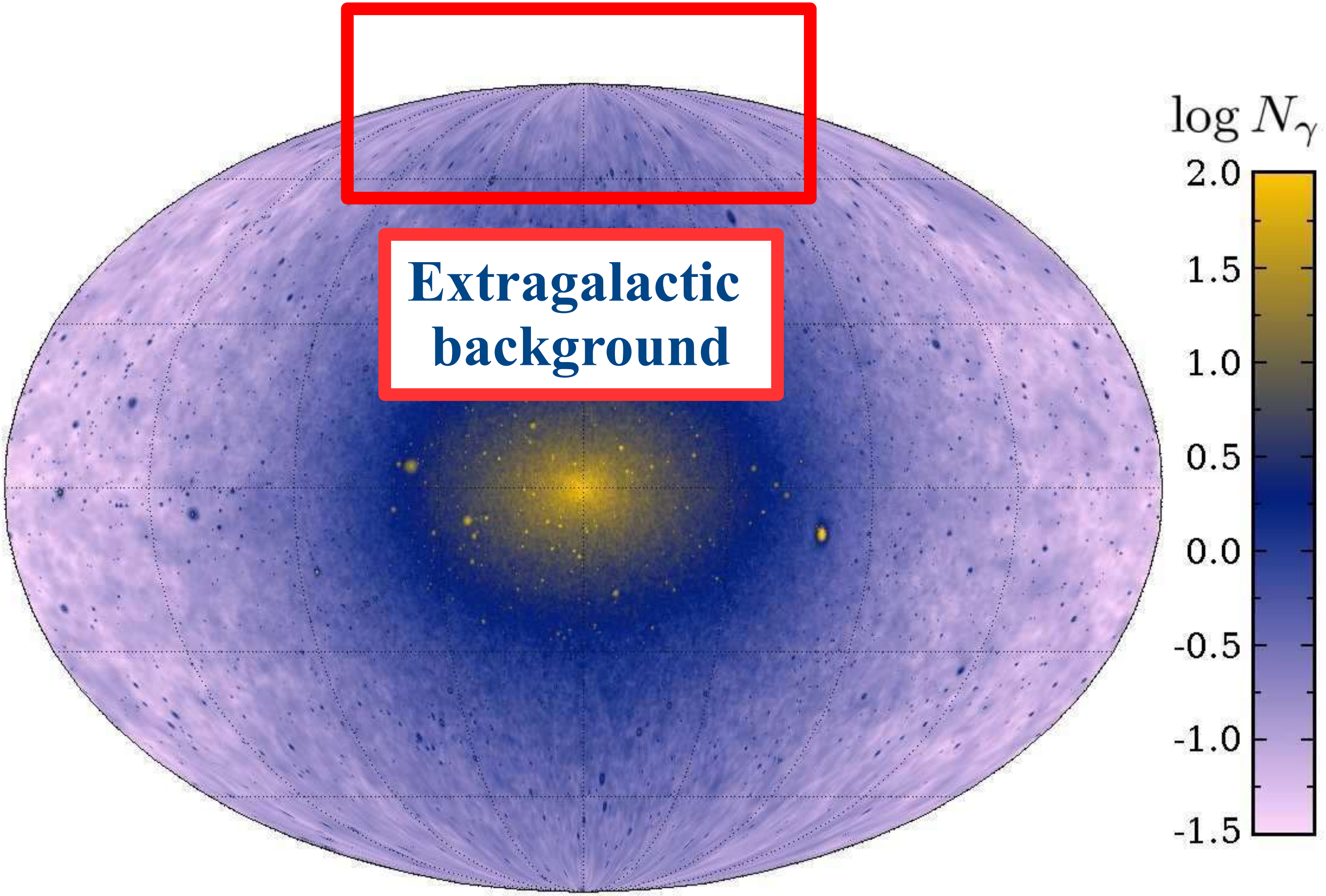

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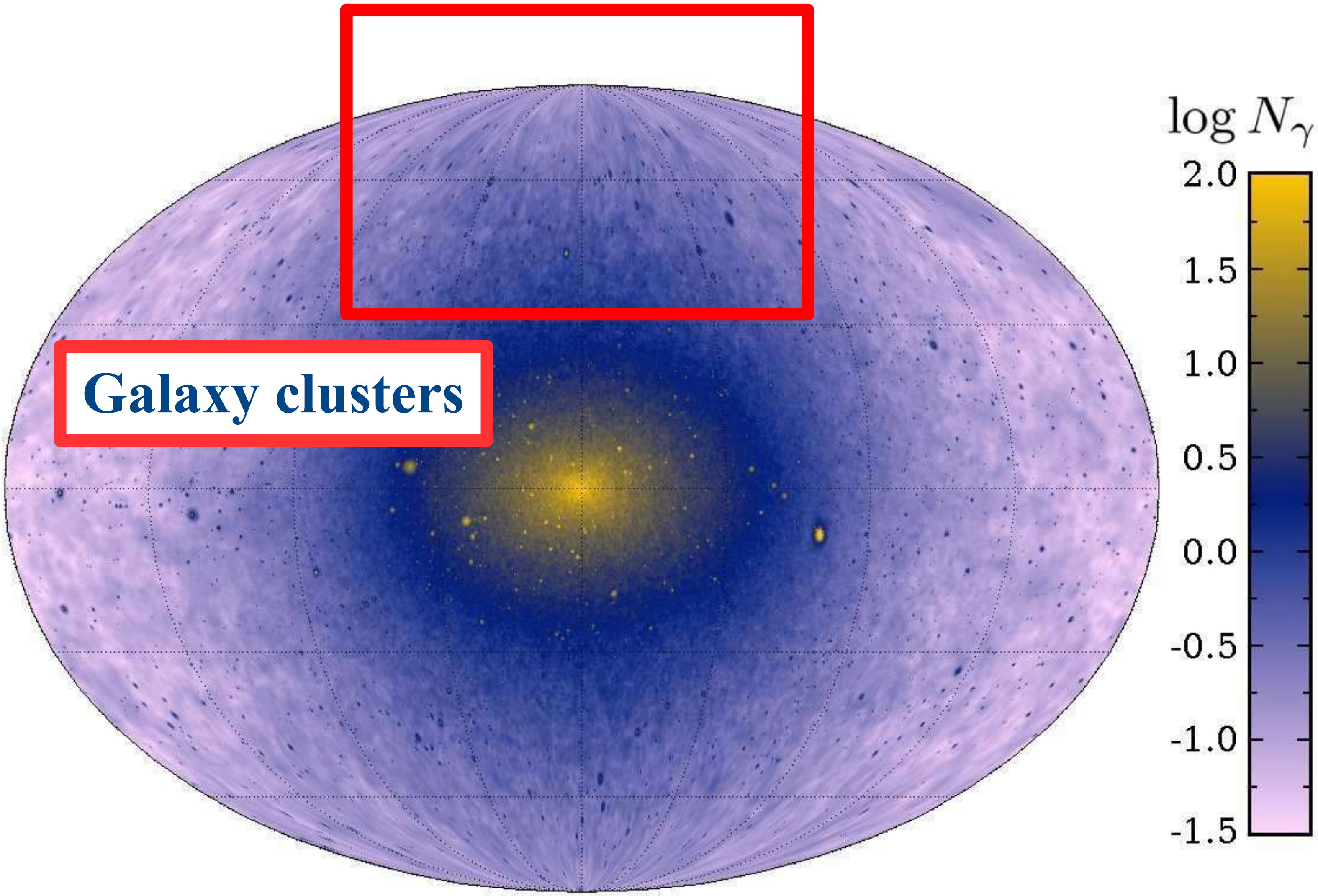

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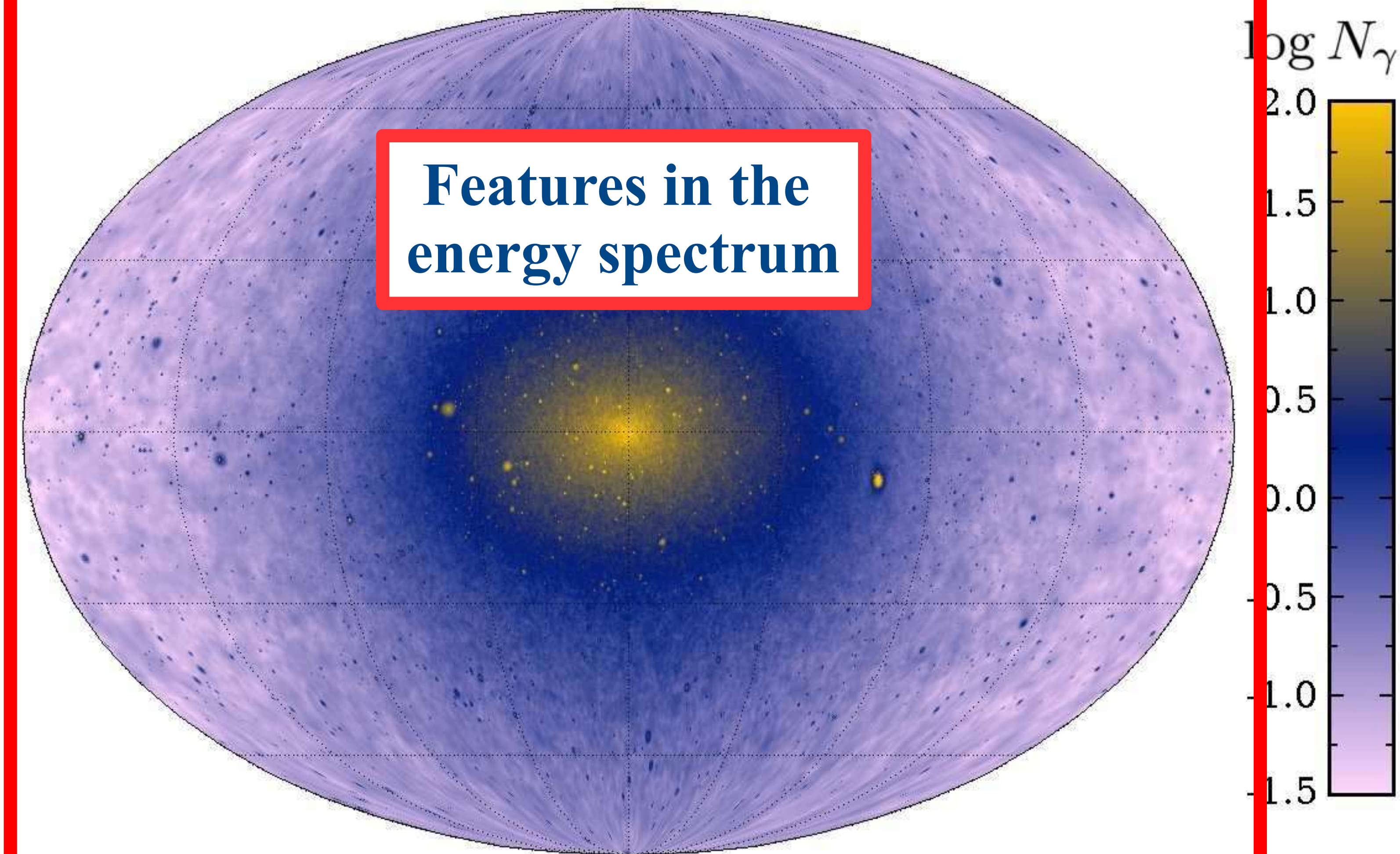
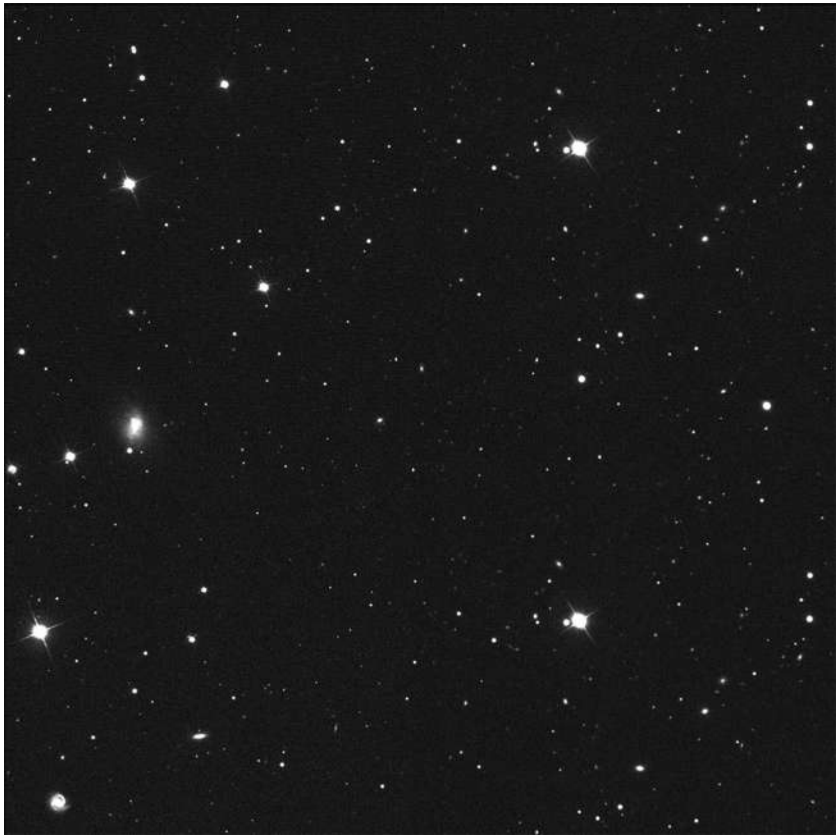


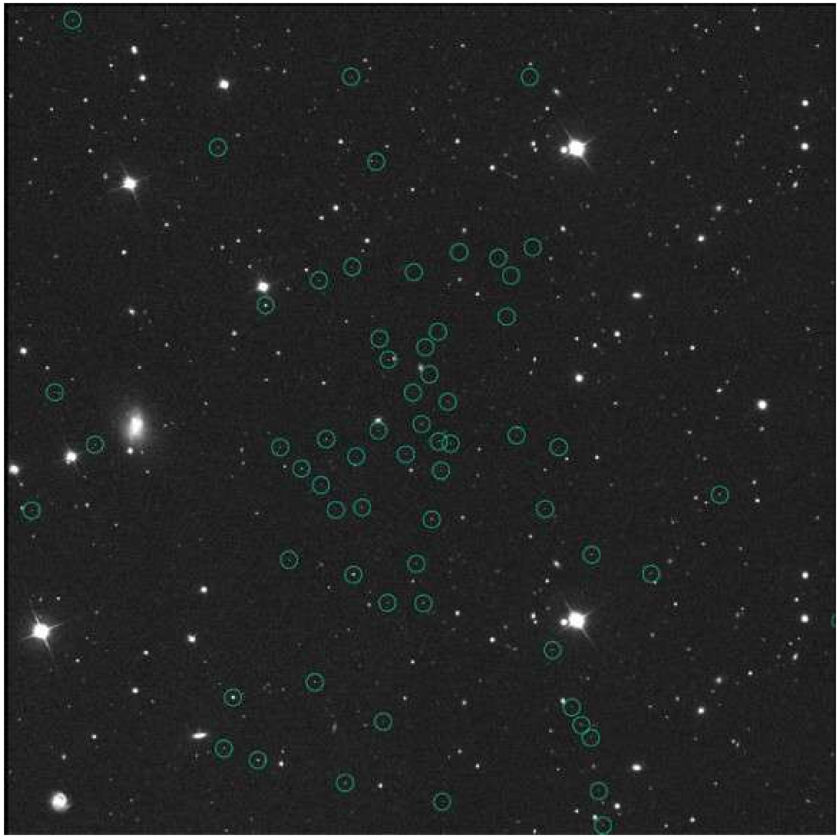
Features in the energy spectrum

A promising target for detection: dwarf galaxies



Segue 1: Optical image

A promising target for detection: dwarf galaxies



Segue 1: Optical image

A promising target for detection: dwarf galaxies

Segue 1: Optical image

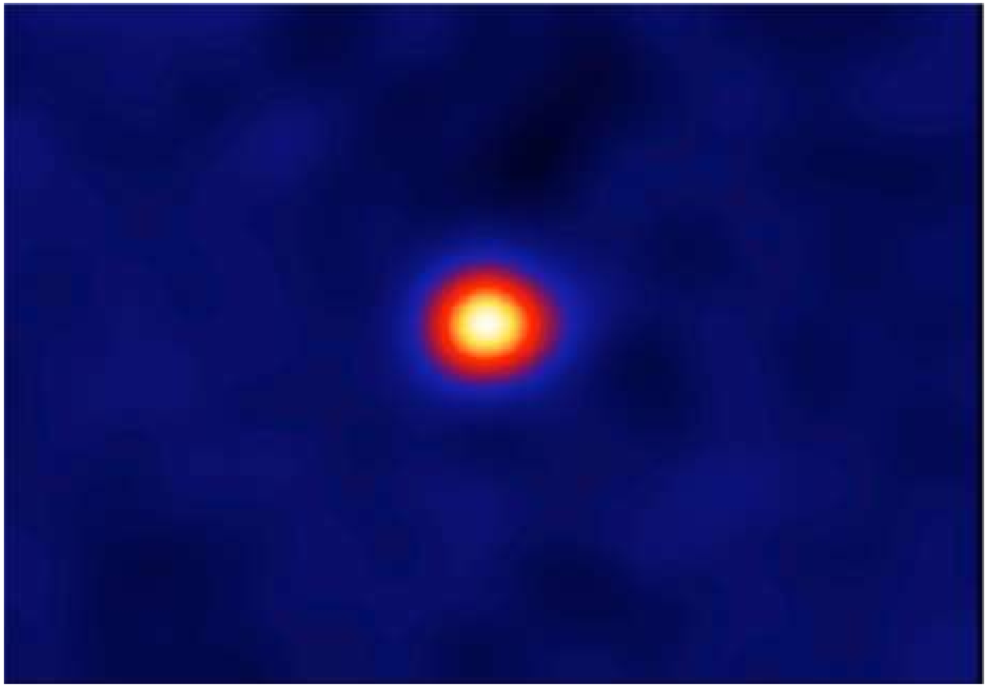
A promising target for detection: dwarf galaxies

Segue 1: Optical image

Mass-to-light ratio
$\sim 3400\ M_{sun}/L_{sun}$

Most DM-dominated object known so far!

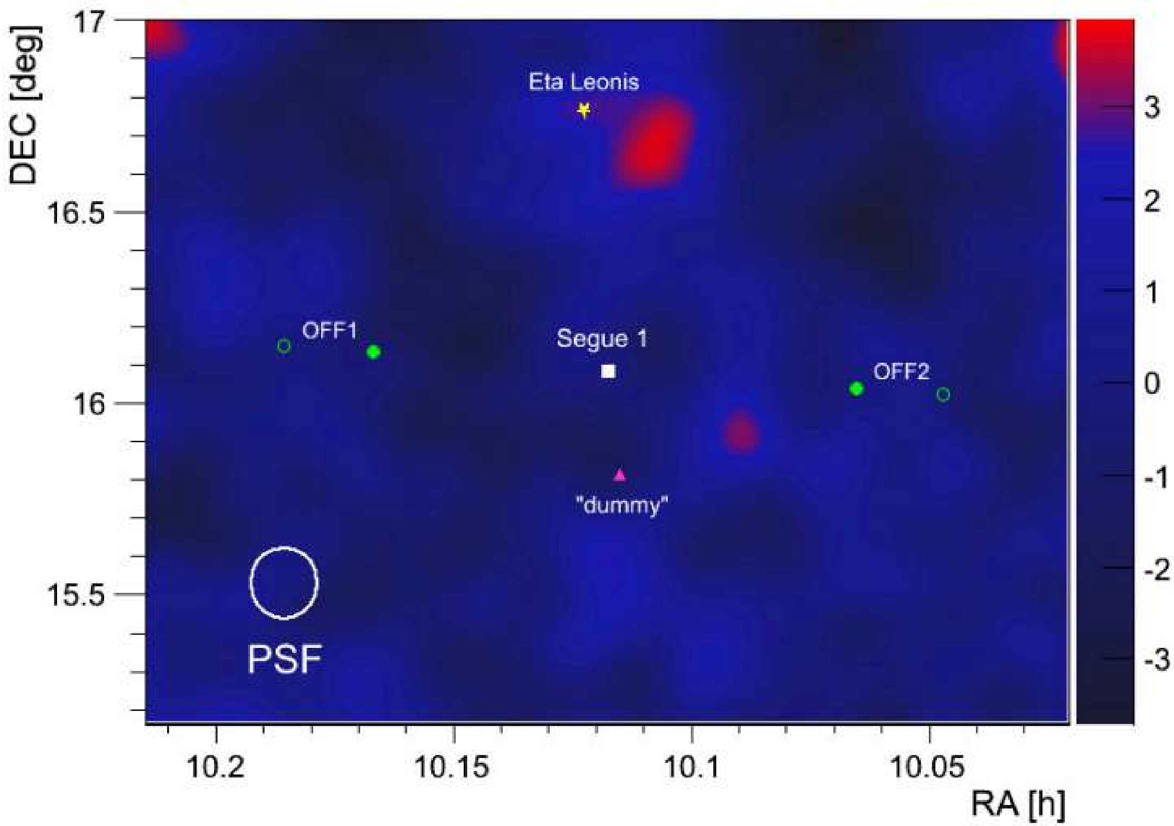
A promising target for detection: dwarf galaxies



Segue 1: Gamma-ray image

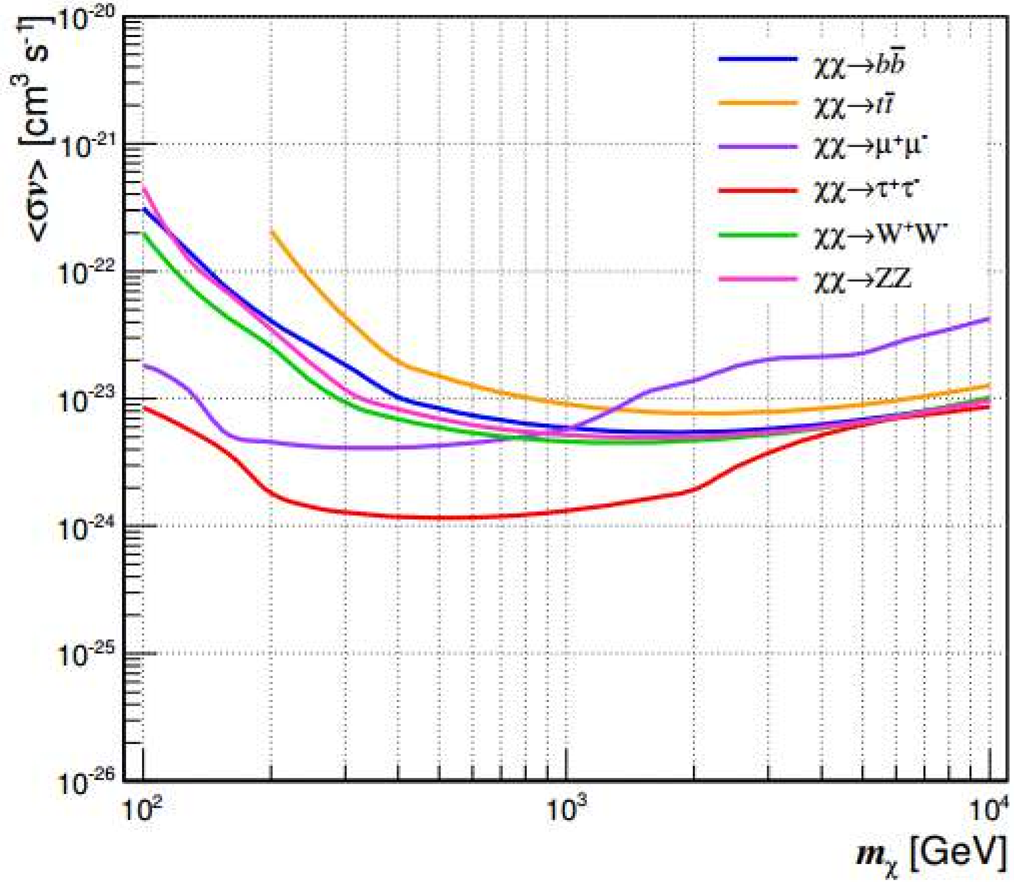
(simulated!)

A promising target for detection: dwarf galaxies



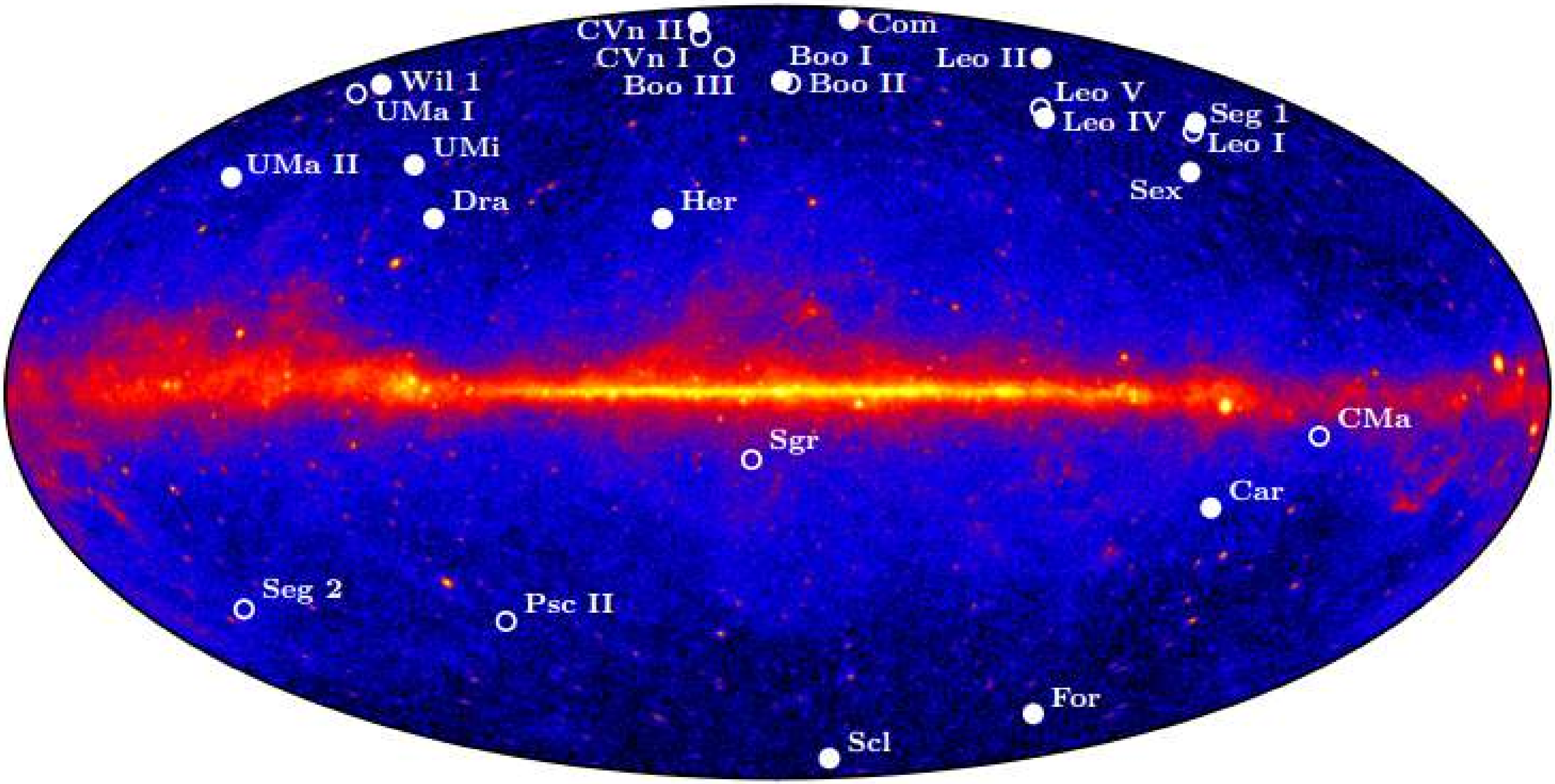
Gamma-ray image taken with the MAGIC telescopes

A promising target for detection: dwarf galaxies

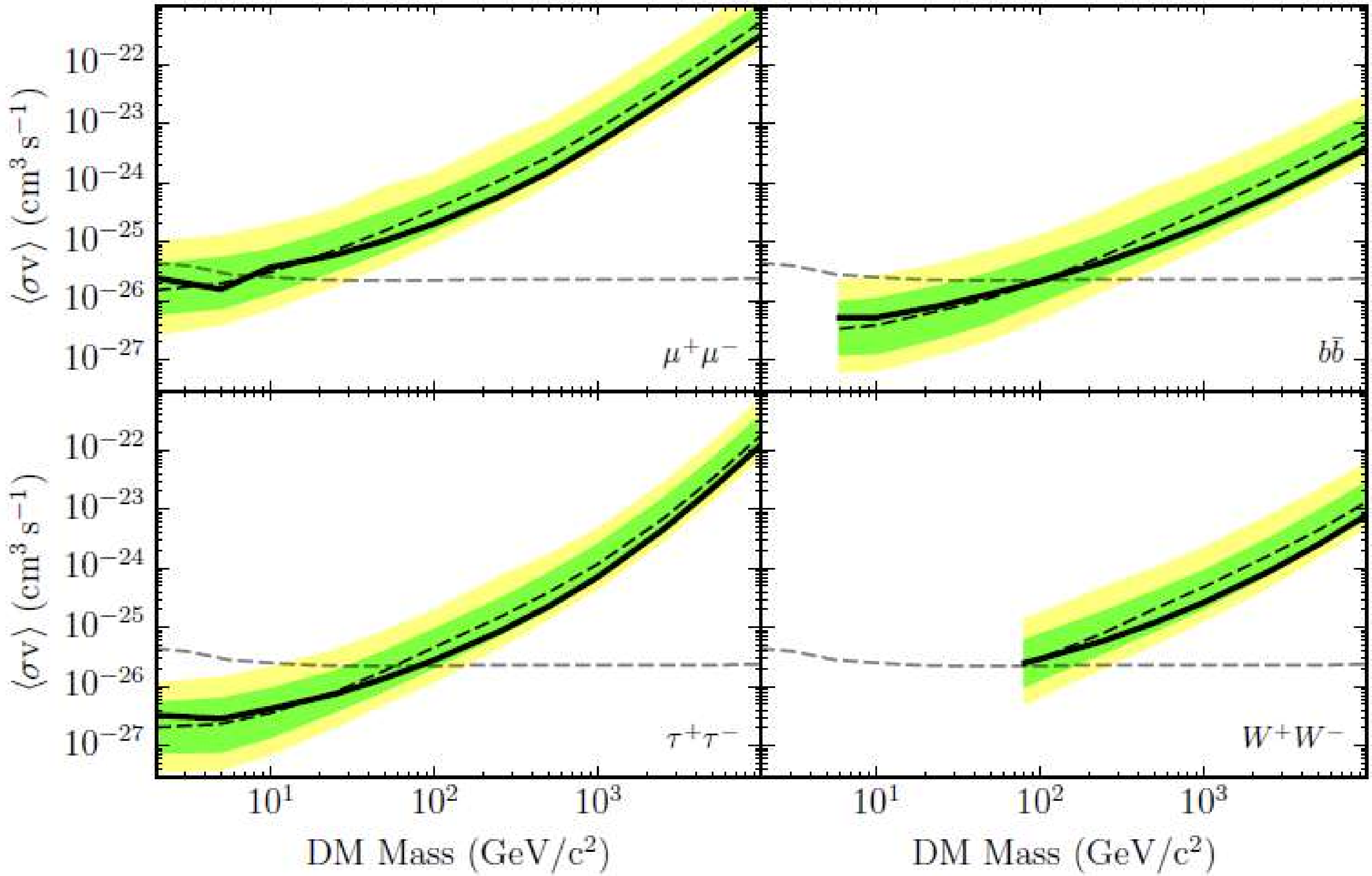


MAGIC coll.
arXiv:1312.1535

A promising target for detection: dwarf galaxies

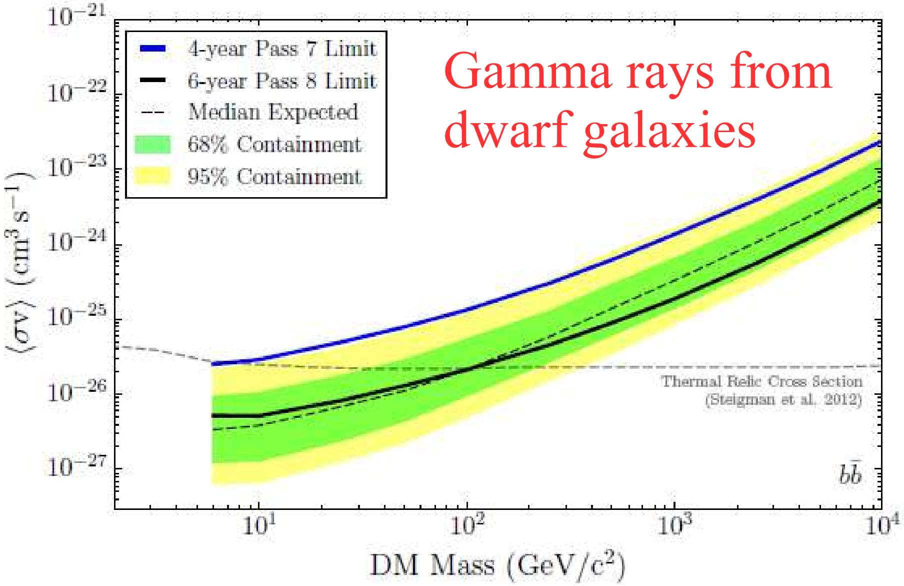


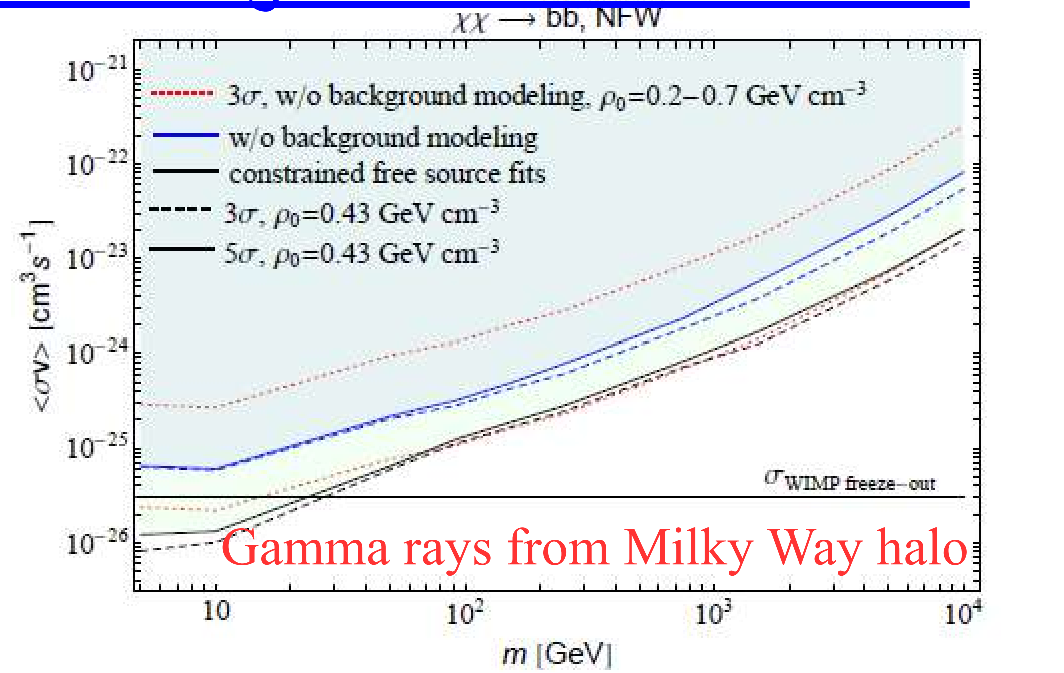
A promising target for detection: dwarf galaxies

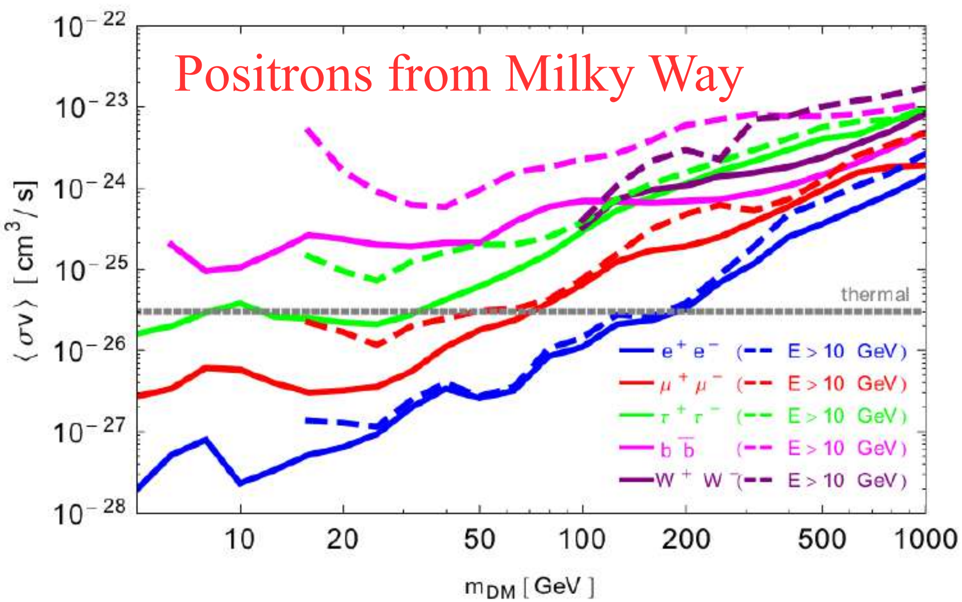


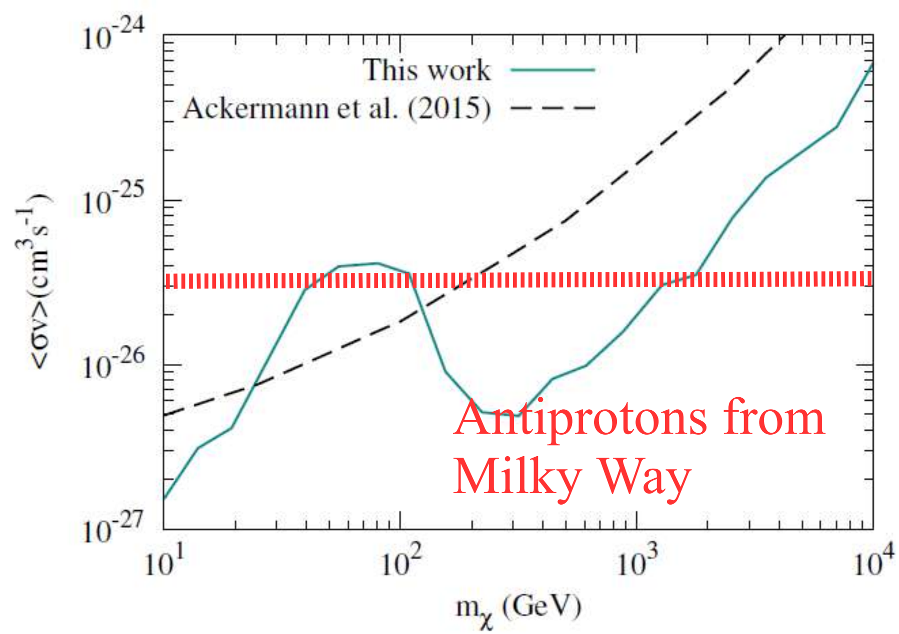
Fermi coll.
arXiv:1503.02641

Various experiments are currently sensitive to WIMPs





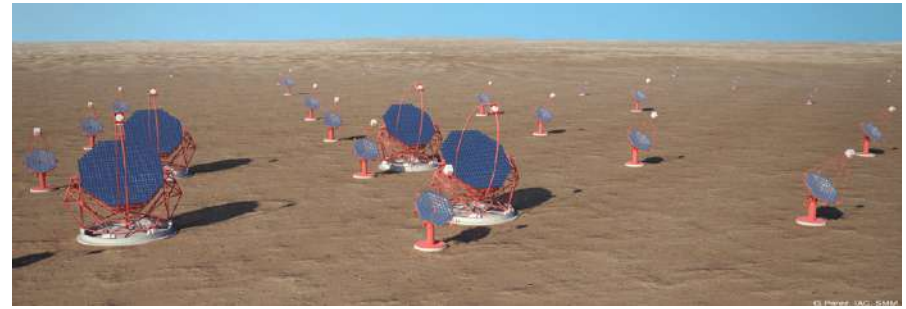




Bright future for dark matter searches using gamma-rays!

H.E.S.S. II – in operation

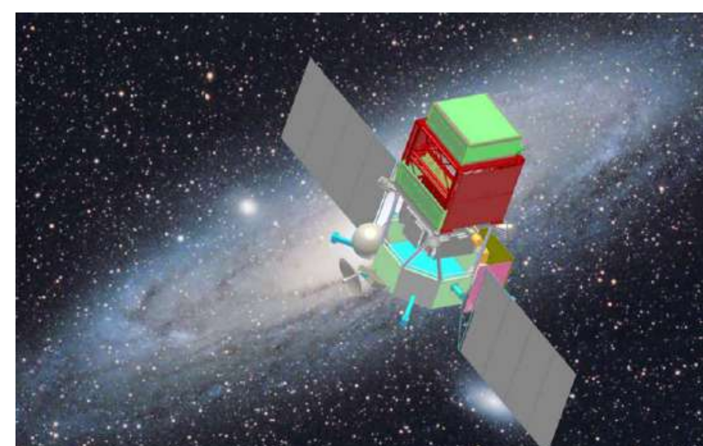
CTA – Construction starting in 2020



HAWC
in operation

DAMPE – Launched in 2015

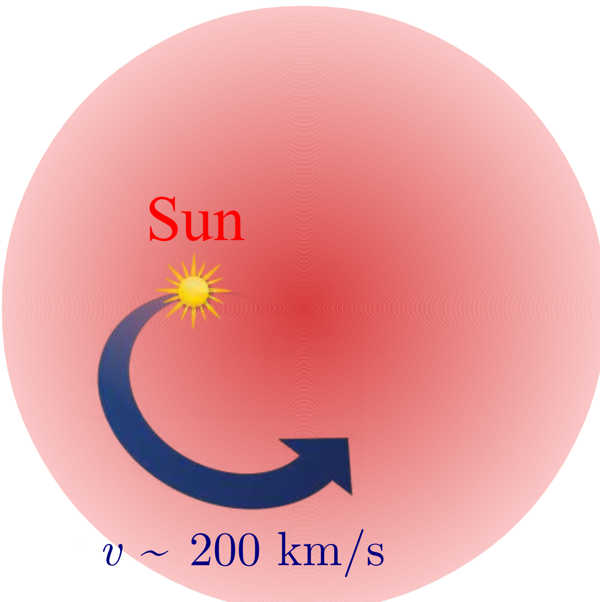
GAMMA 400
Launch in 2021

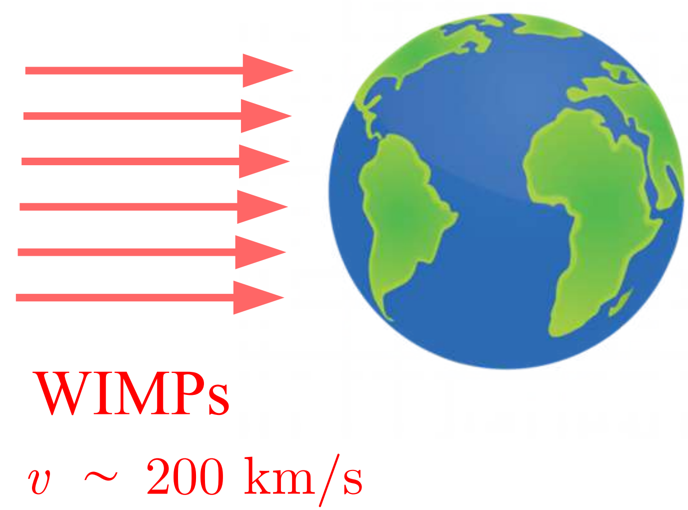


Direct Dark Matter Searches

Direct dark matter searches

The Sun (and the Earth) is moving through a "gas" of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.





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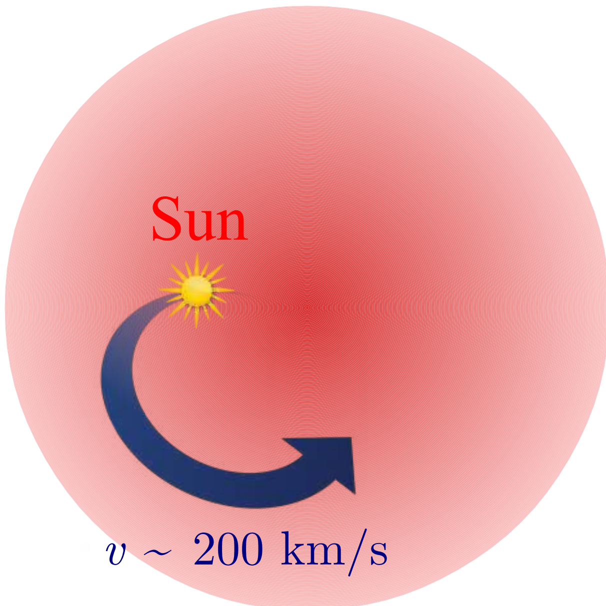
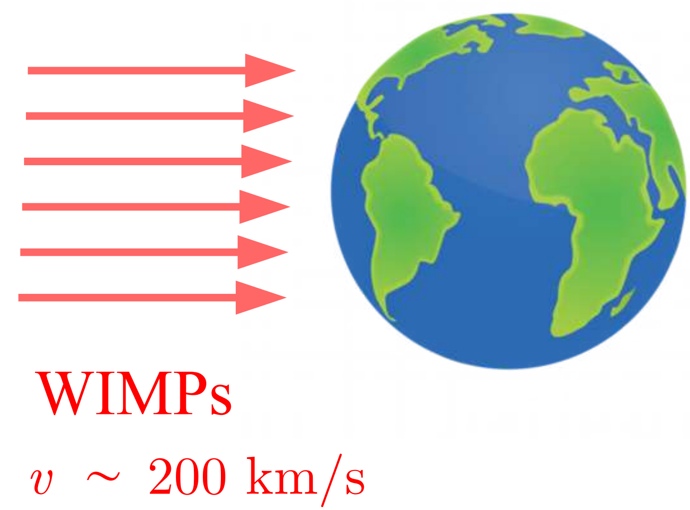
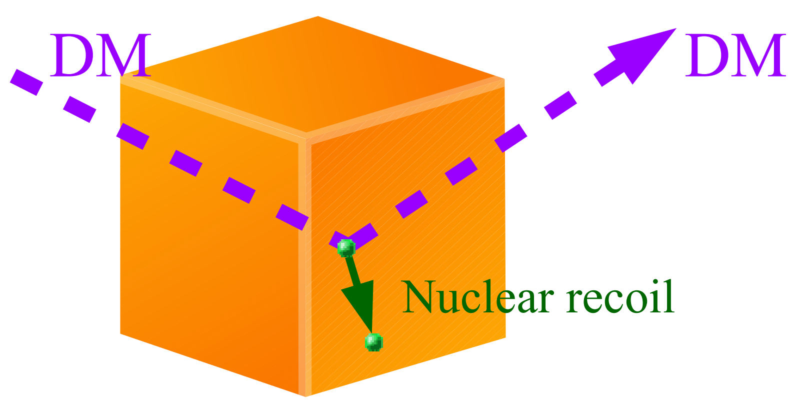
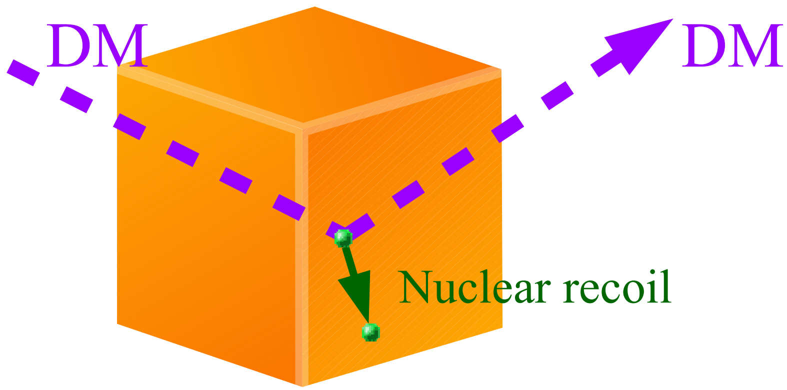




Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.



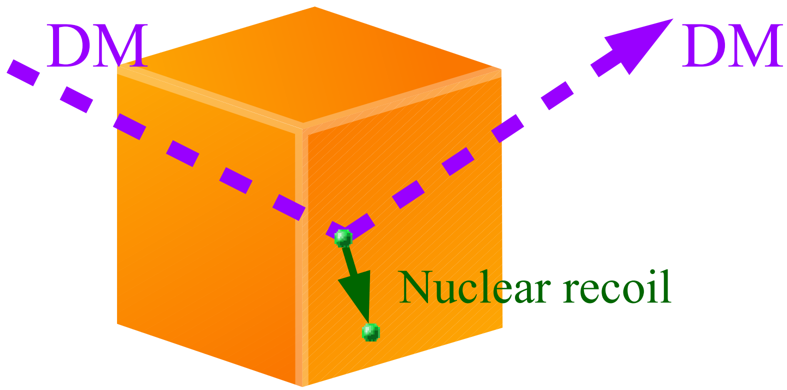
Direct dark matter searches



The rate of scatterings can be calculated and depend on:

- The dark matter mass (m_{DM})
- The interaction cross section with protons/neutrons (σ)

Direct dark matter searches



The rate of scatterings can be calculated and depend on:

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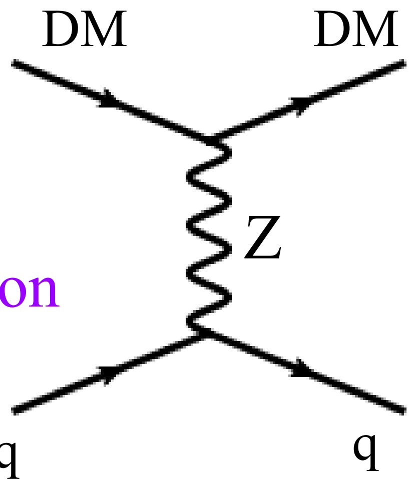
- The interaction cross section with protons/neutrons (σ)

Which interaction cross section?

Simplest WIMP framework: the dark matter interacts with the quarks via a (tree-level) Z-boson interaction



$$\sigma \sim 10^{-40}\,\mathrm{cm}^2$$

Fifteen orders of magnitude smaller than for the proton-proton interaction, and ten orders of magnitude smaller than for the electron-proton interaction .

Direct dark matter searches

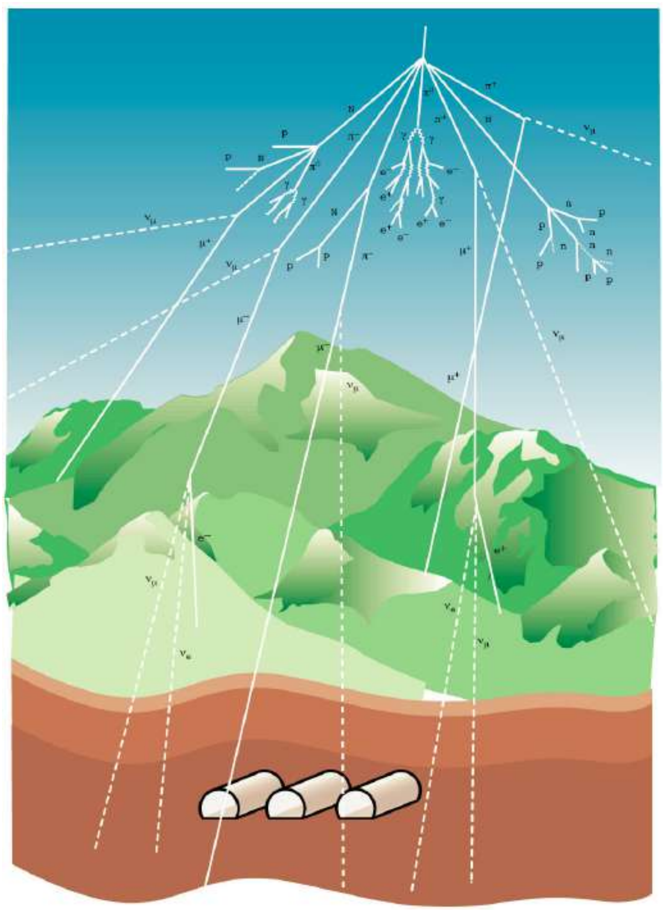
Backgrounds are very large: similar experimental signals can be induced by interactions of electrons, photons, neutrons...

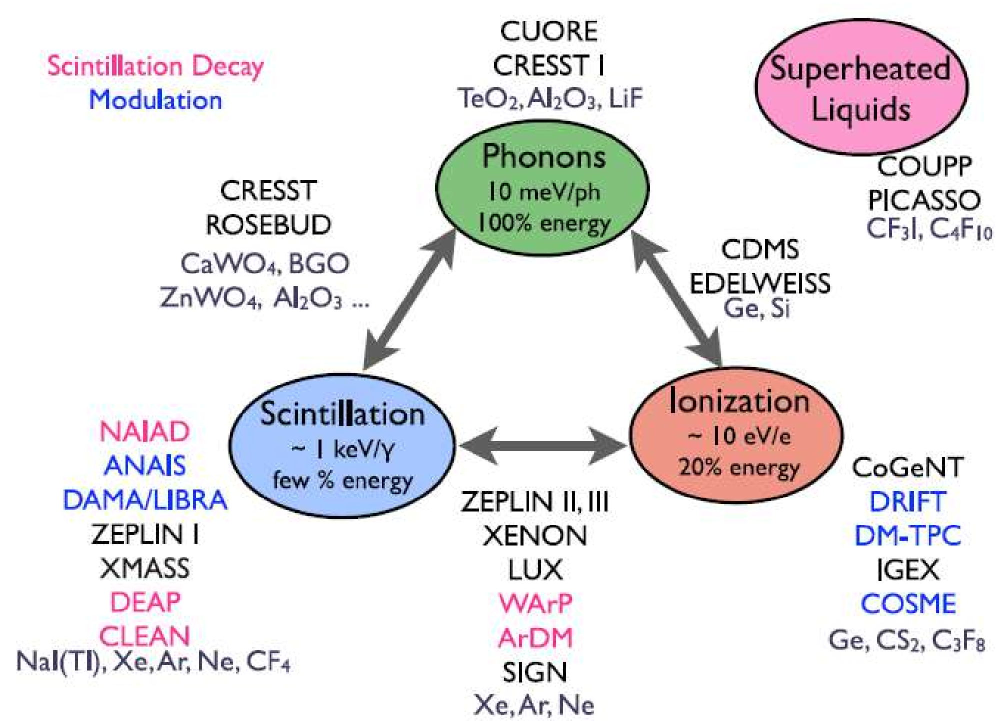
Current strategy:

1) Take experiments deep underground

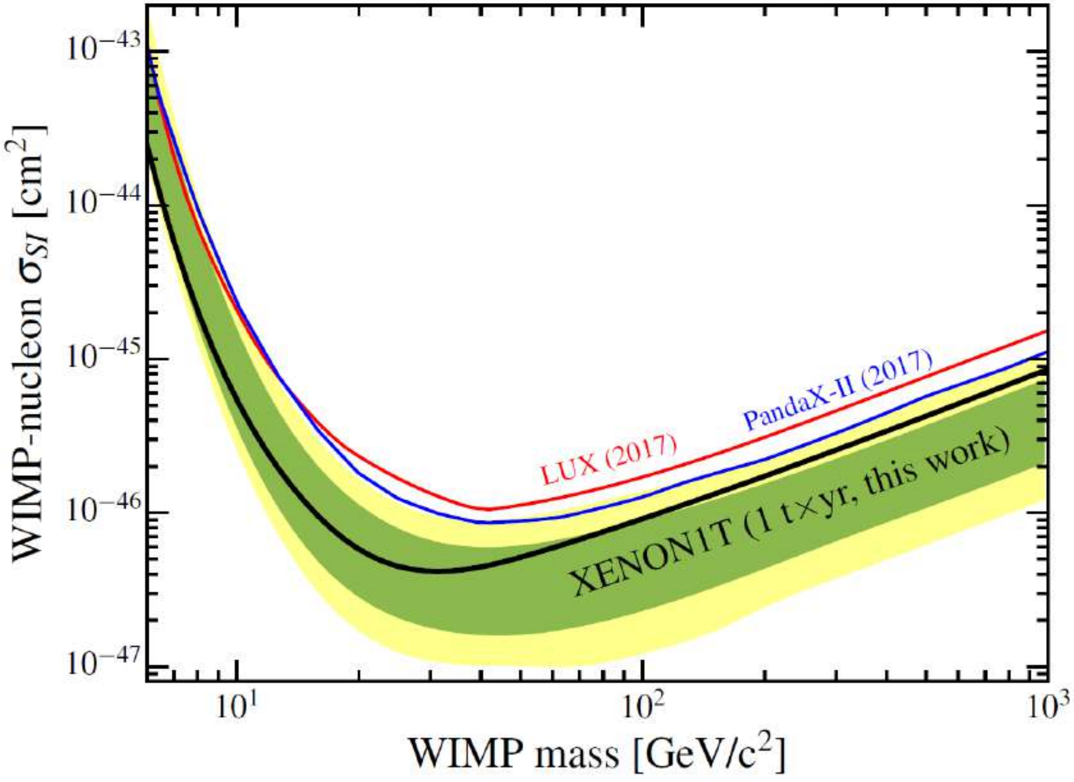
2) Shield the detector against natural radioactivity in the laboratory.

3) Devise techniques to further reduce residual backgrounds



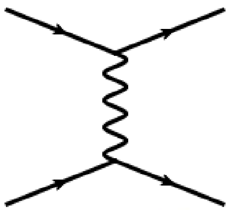


Direct dark matter searches

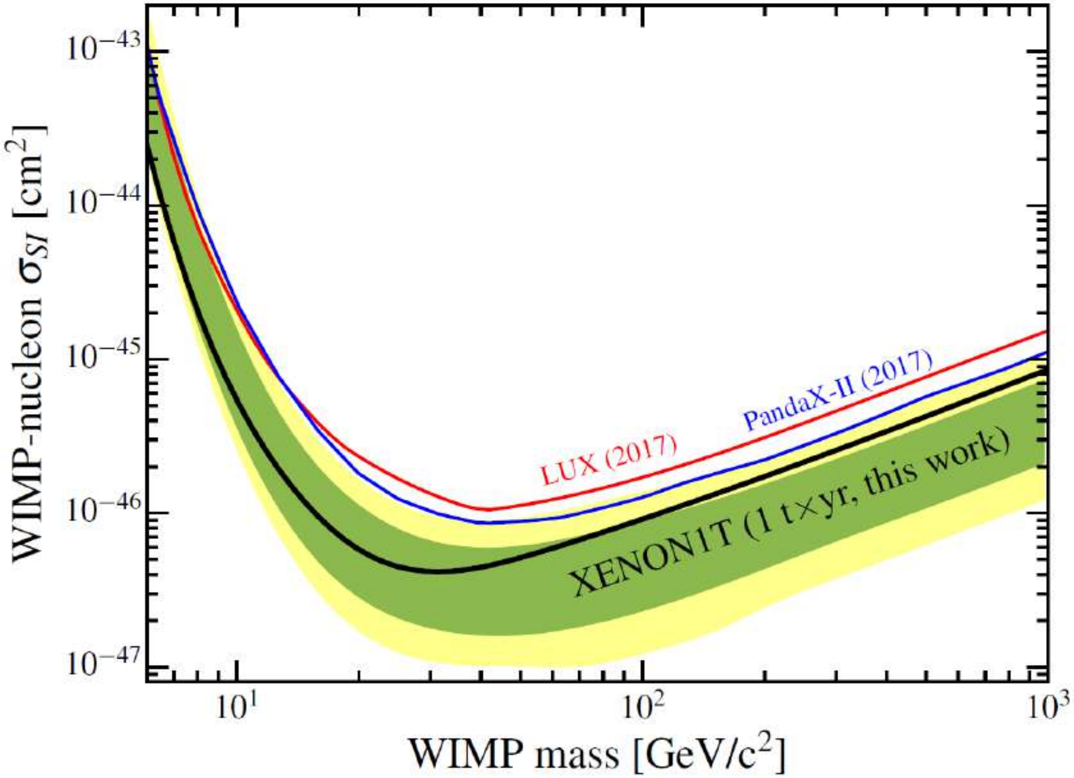


Direct dark matter searches

Tree-level Z-exchange



$\sigma \sim 10^{-40}\,\mathrm{cm}^2$



Direct dark matter searches

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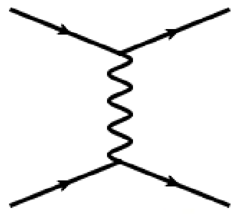

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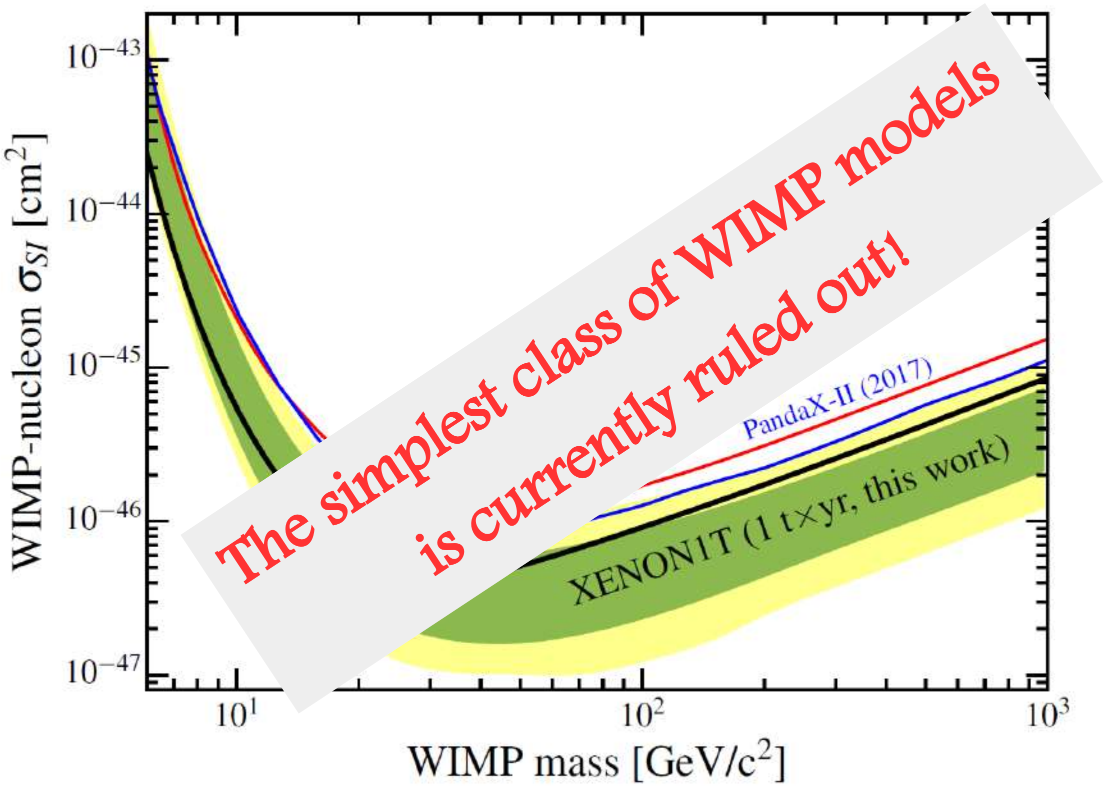
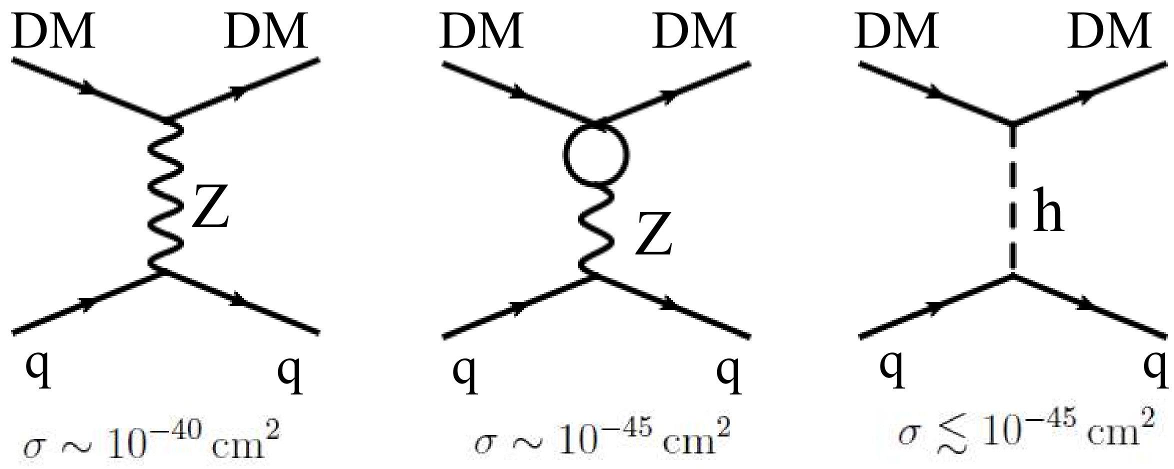
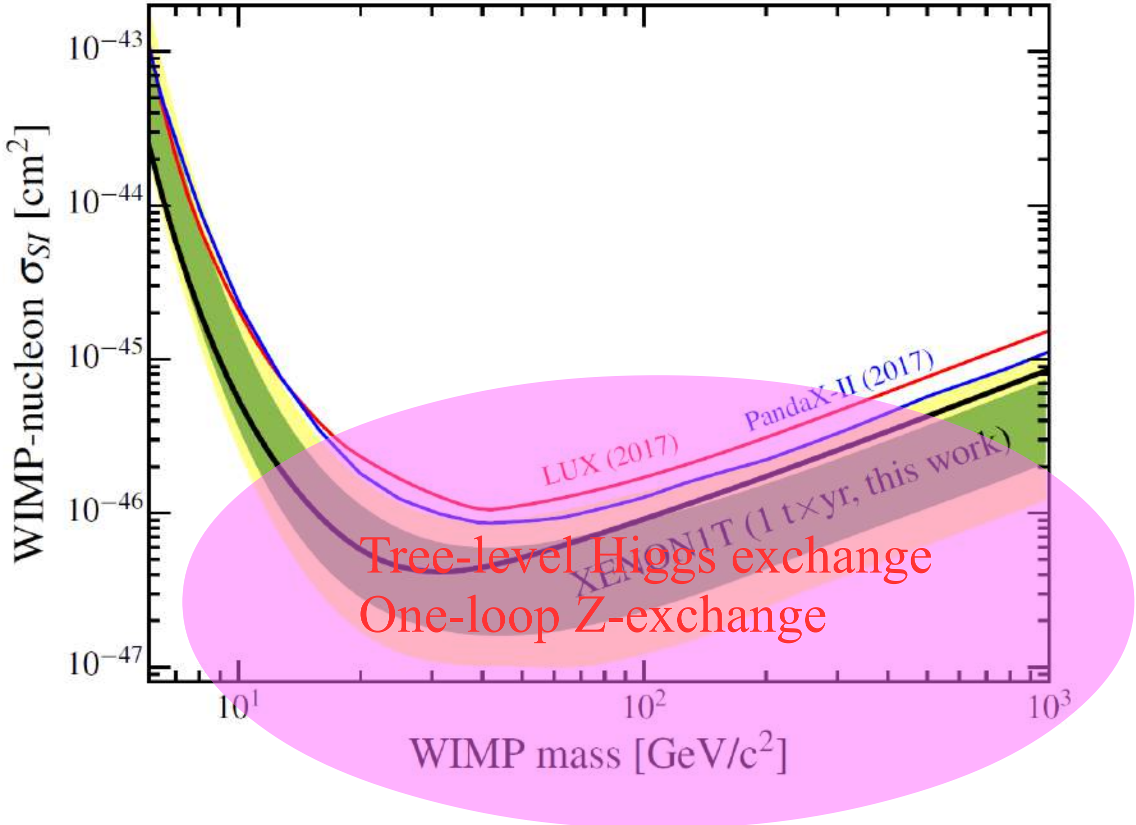
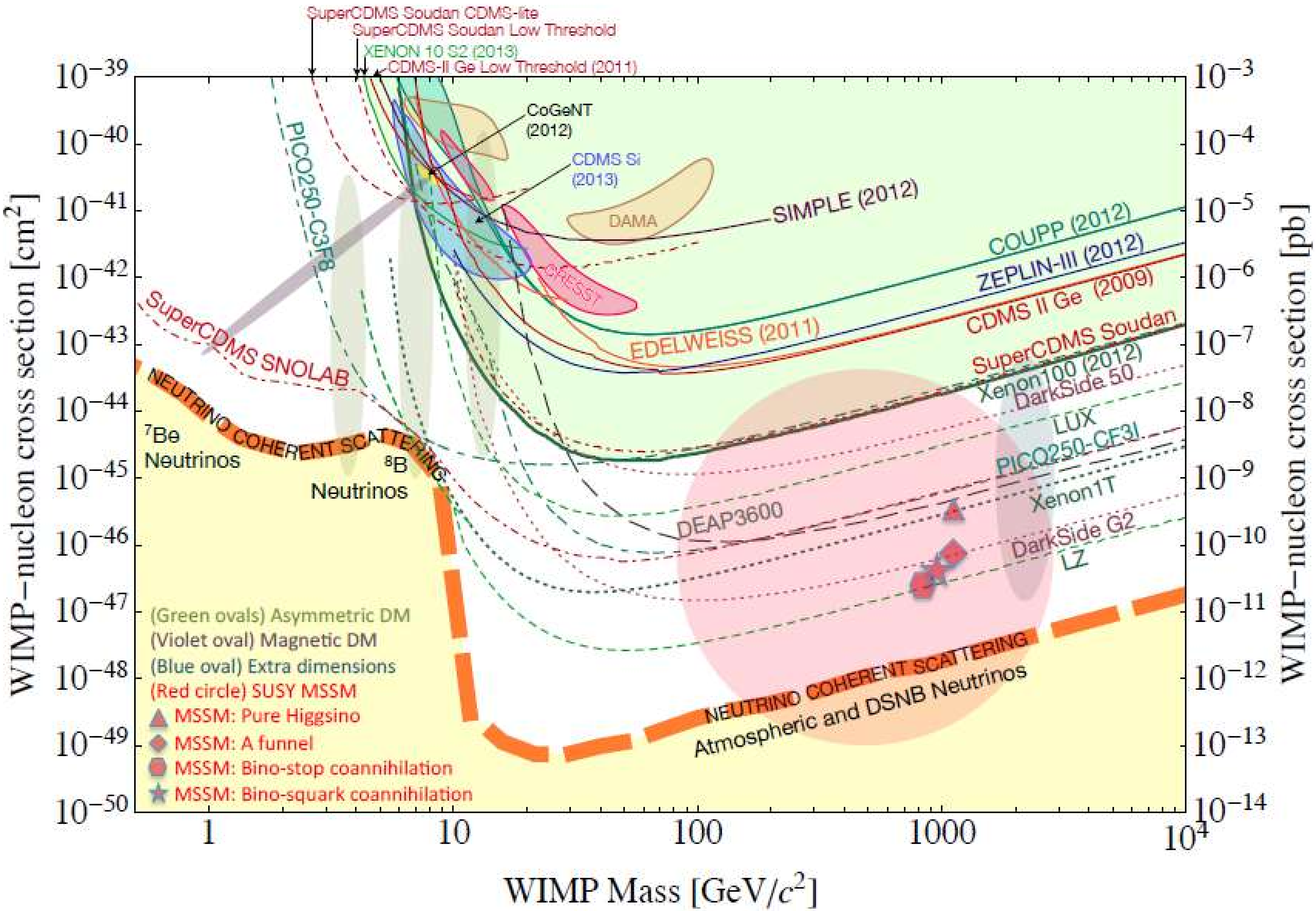


Direct dark matter searches



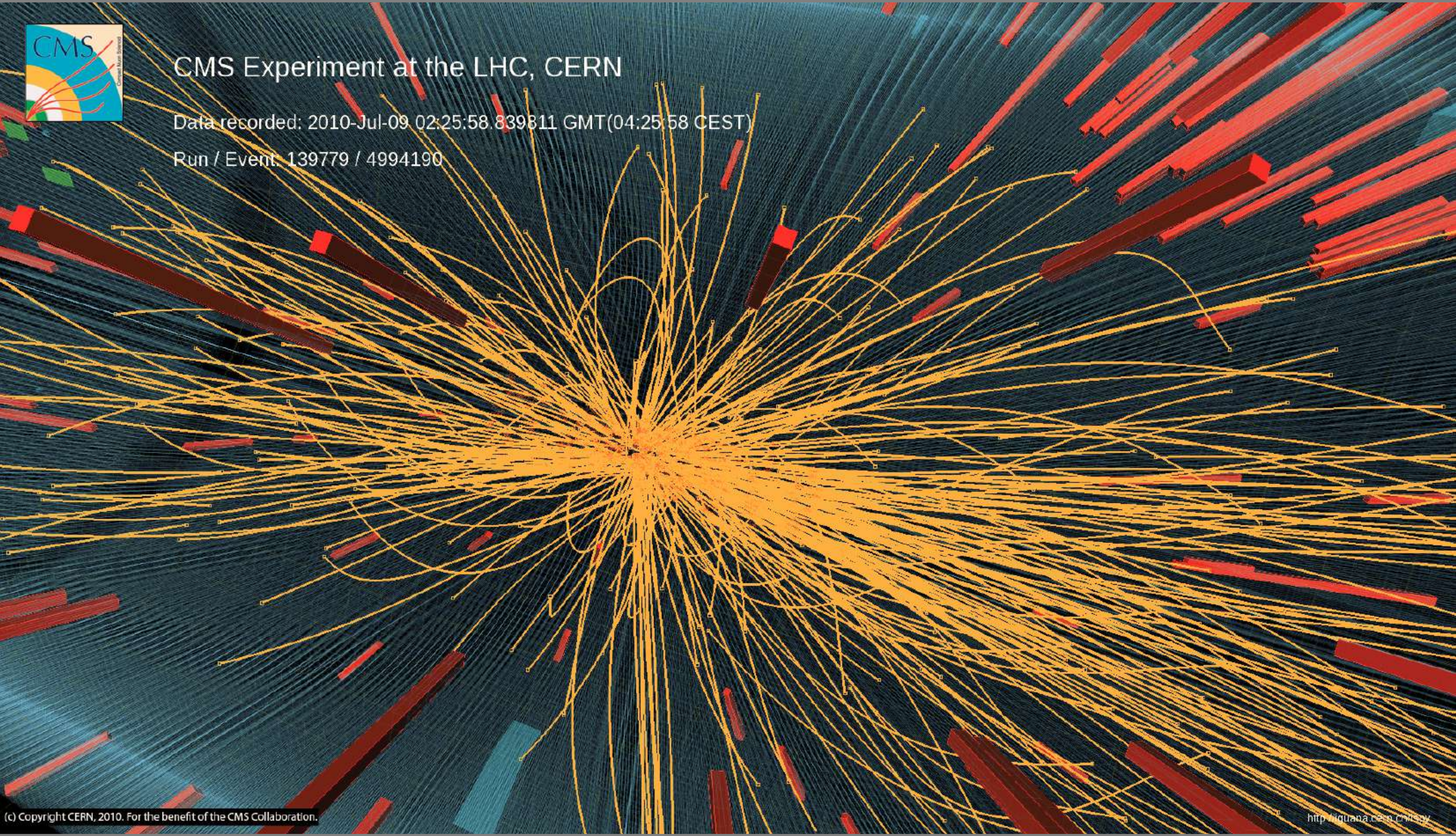




SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]

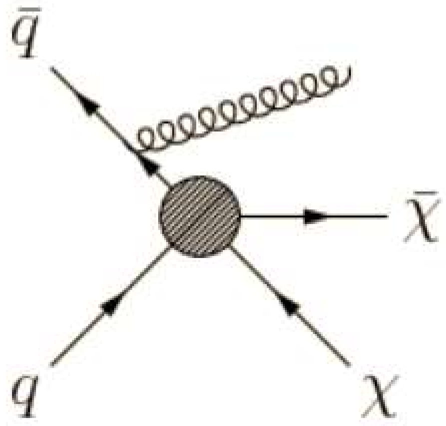
Collider Searches

The Large Hadron Collider


CMS Experiment at the LHC, CERN
Data recorded: 2010-Jul-09 02:25:58.839811 GMT(04:25:58 CEST)
Run / Event: 139779 / 4994190
(c) Copyright CERN, 2010. For the benefit of the CMS Collaboration.

Collider searches

Monojet + missing E_T



Collider searches

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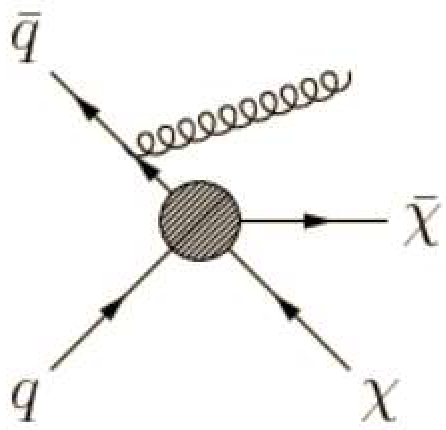

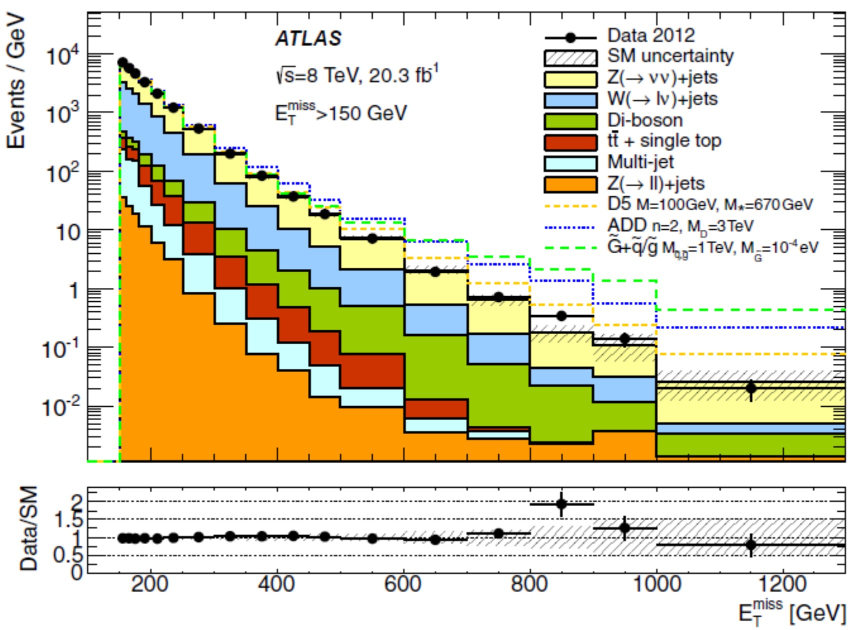

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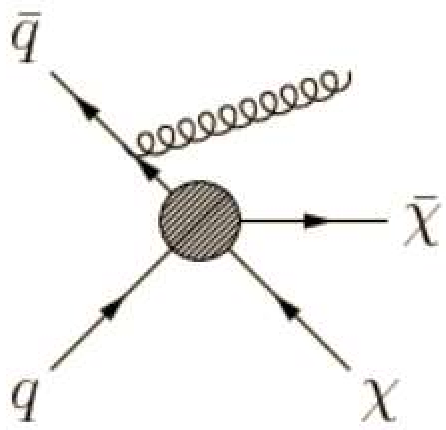

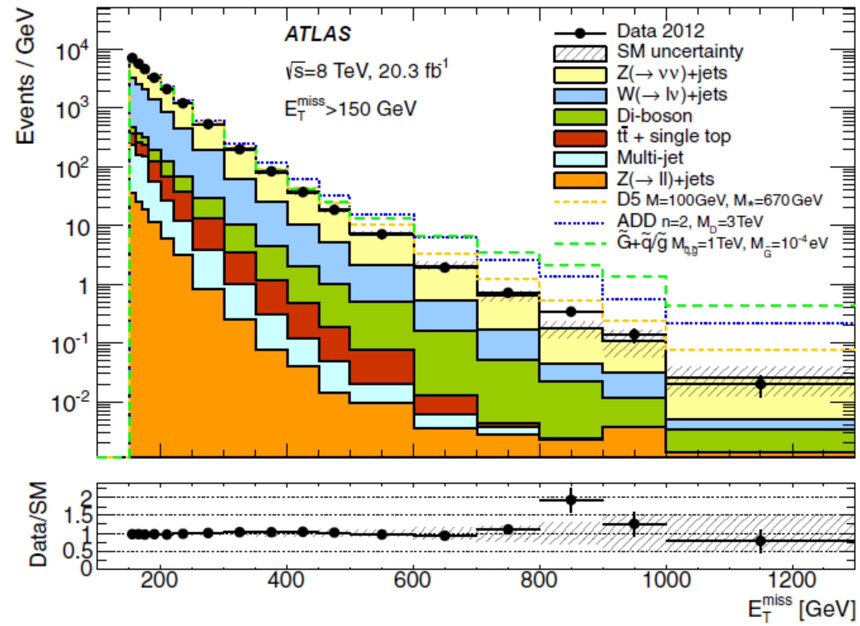

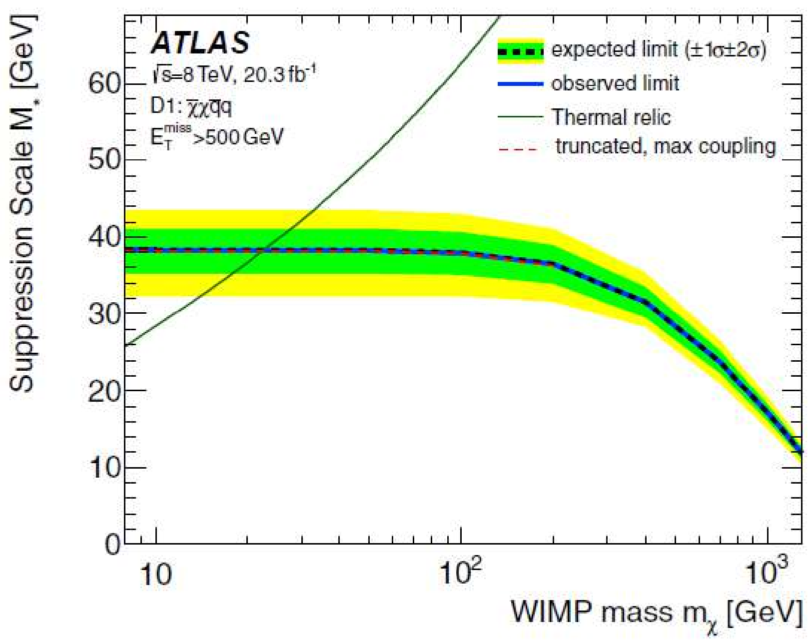

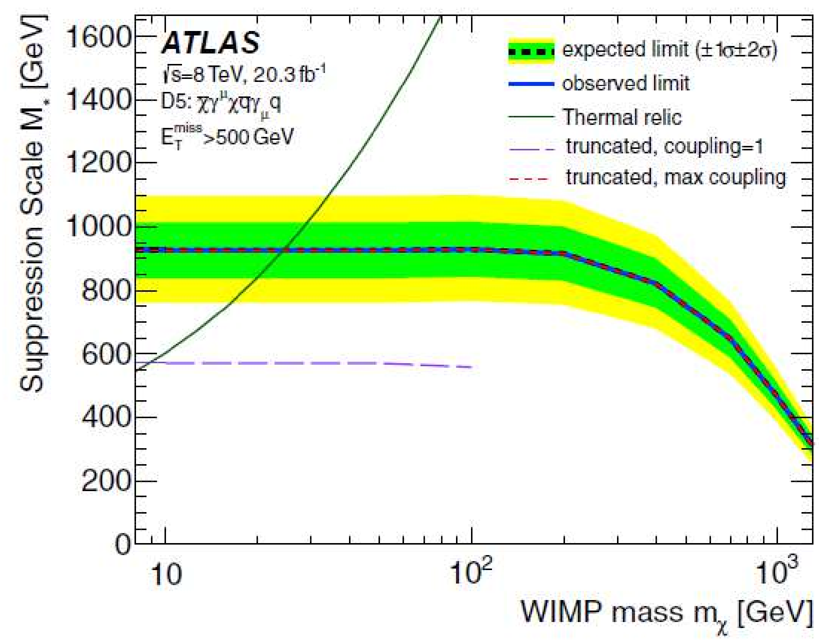

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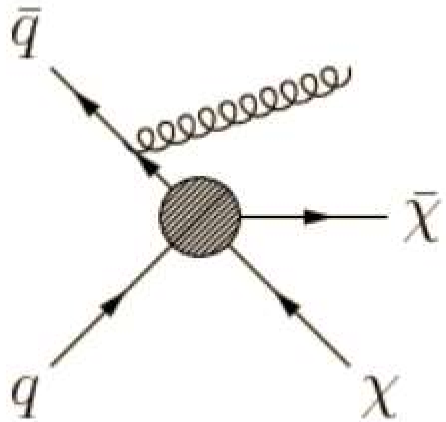
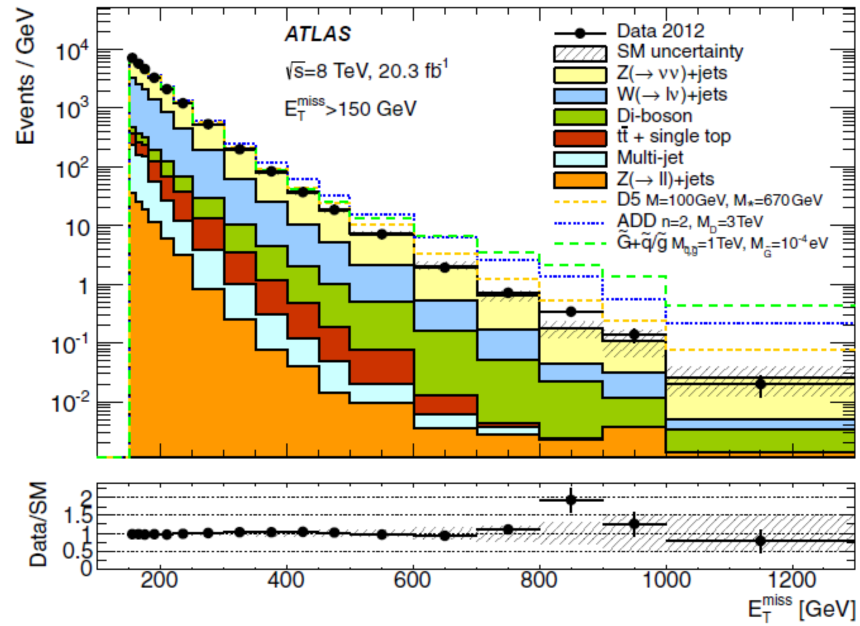
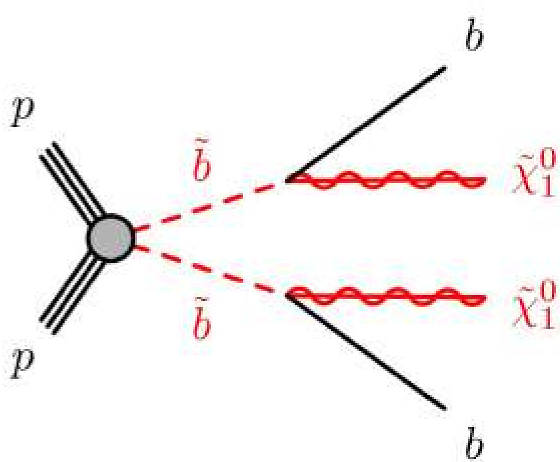
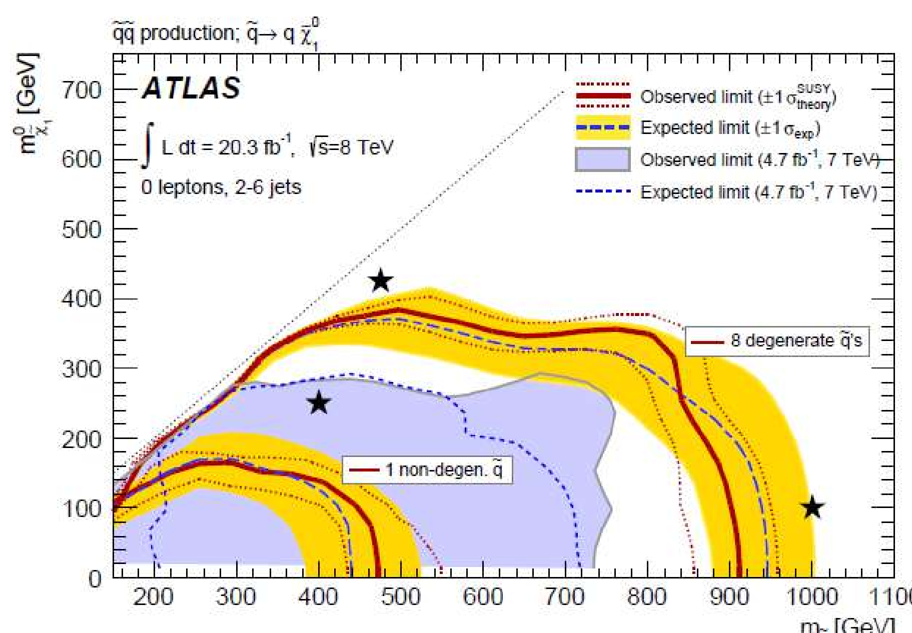




Mediator production





Concluding remarks

Zwicky's observations of 1933

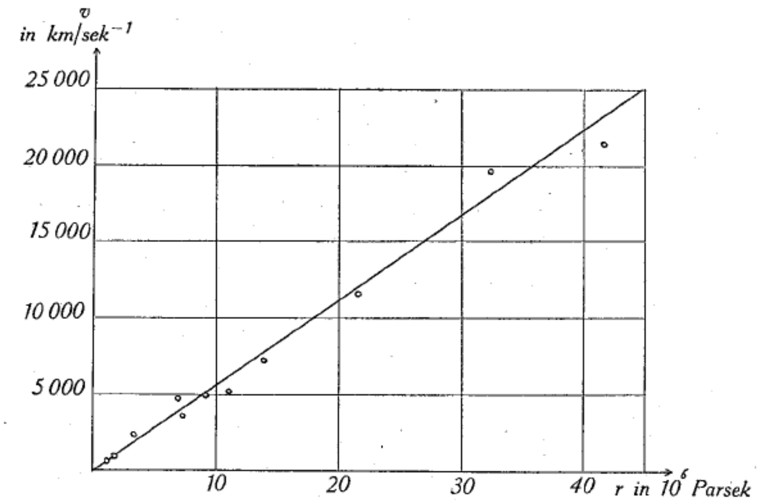


Fig. 2.

Concluding remarks

Zwicky's observations of 1933

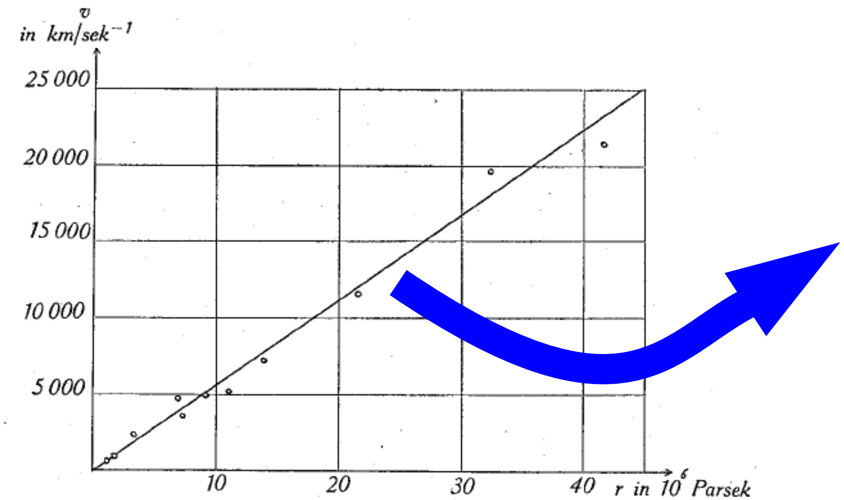


Fig. 2.

86 years later, we still don't know what is producing this.

If it is a Weakly Interacting Massive Particle, we might see signals in experiments in the next few years.

Concluding remarks

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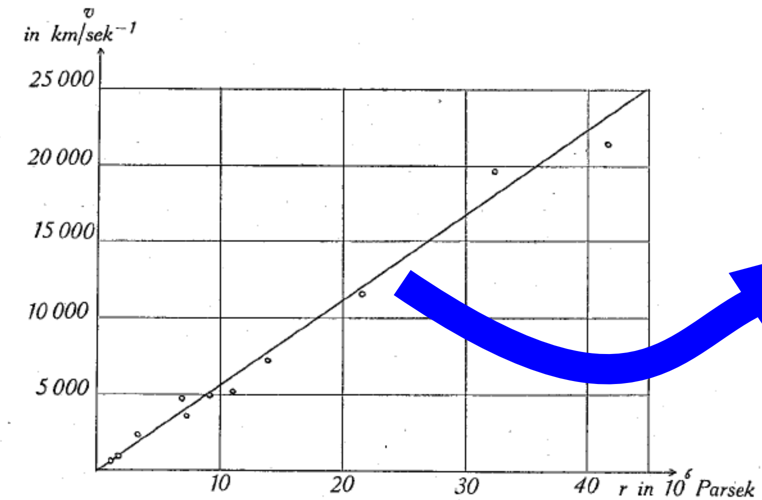

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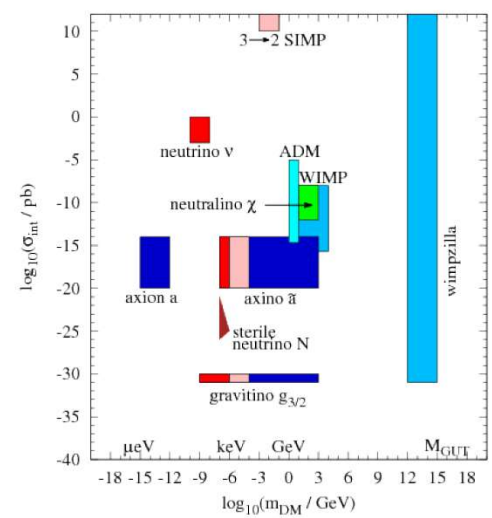

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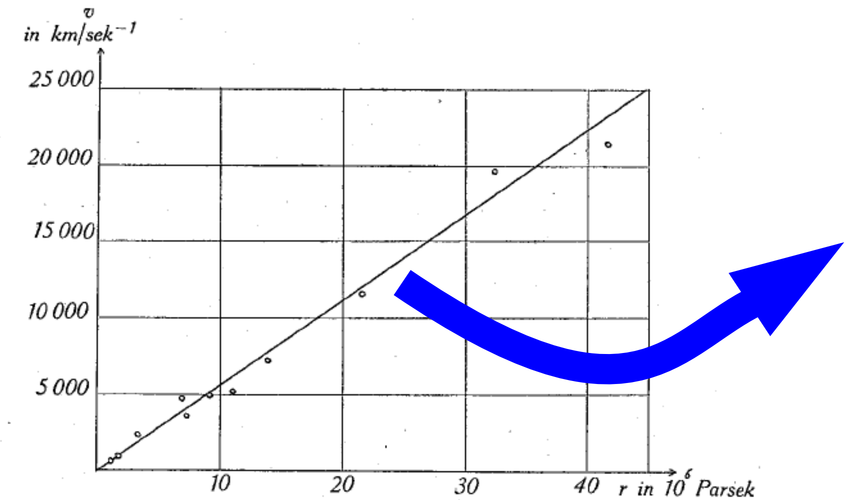

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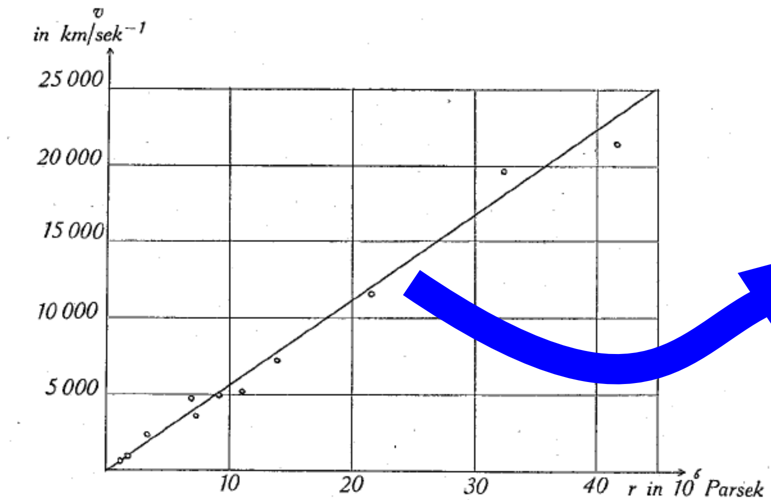

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The quest for the dark matter particle continues