DARK MATTER JUBILEE

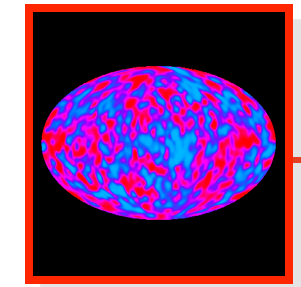
Rocky Kolb University of Chicago June 2012

Keynote Address

A keynote in literature, music or public speaking is the principal underlying theme.

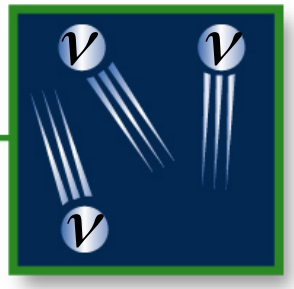
At academic conferences, the keynote address is delivered to set the underlying tone and summarize the core message or most important revelation of the event.

In politics, a keynote address is meant to “fire up” the base.

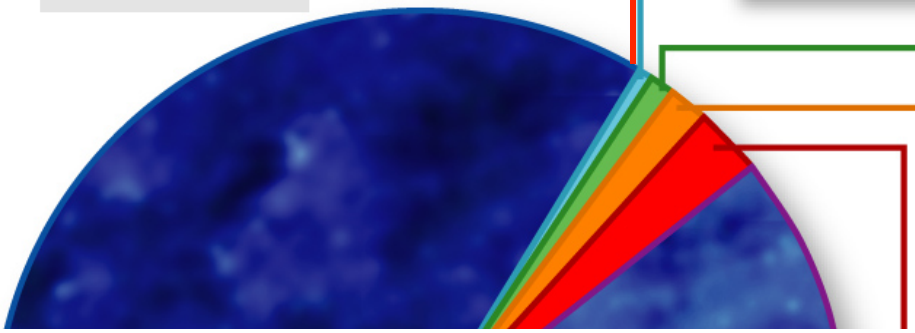


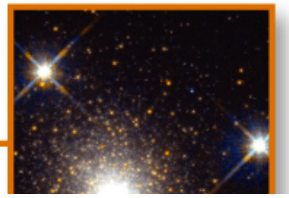
Radiation: 0.005%

Chemical Elements: (other than H & He) 0.025%



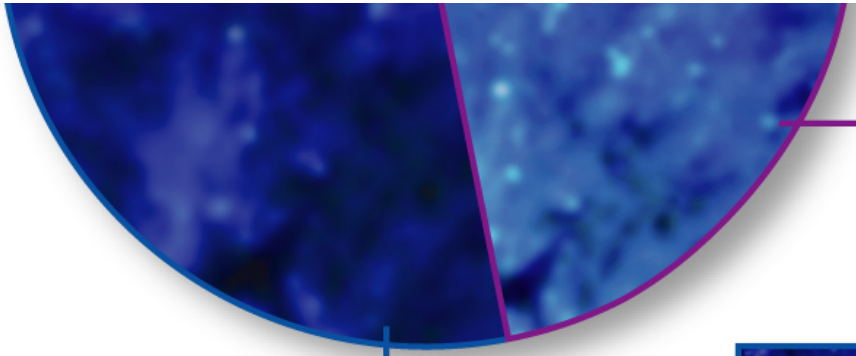
Neutrinos: 0.17%



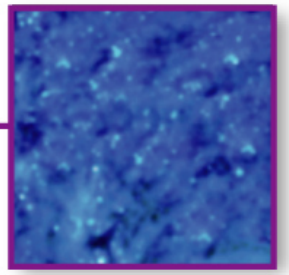


Stars: 0.8%

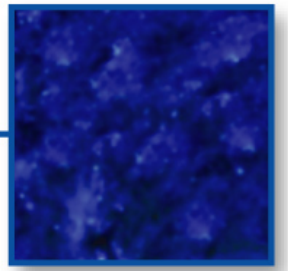
If I had been present at creation, I would have suggested a simpler scheme.
- Alfonse the Wise



H & He gas: 4%



Cold Dark Matter: (CDM) 25%



Dark Energy : (Λ) 70%

+ inflationary perturbations
+ baryo/lepto genesis

Oort 1932

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 Volume VI. No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort*.

Notations.

z distance from the galactic plane,

Z velocity component perpendicular to the

$z = 0$,

sian component of the

rmula (5), p. 253),

he direction of z,

ar from the sun,

ber cubic parsec between

er square degree between

4. From VAN RHIJN's tables in *Groningen Publication* No. 38 the density distribution $\Delta(z)$ has been computed for four intervals of visual absolute magnitude (Table 13 and Figu

log $\Delta(z)$ for A stars and

LINDBLAD and PETERSSO

5. With the aid of th

preceding sections I have

$K(z)$ between $z = 0$ and

were made by successive

were eliminated first. Th

Figure 4, $K'(z)$ giving th

good agreement between

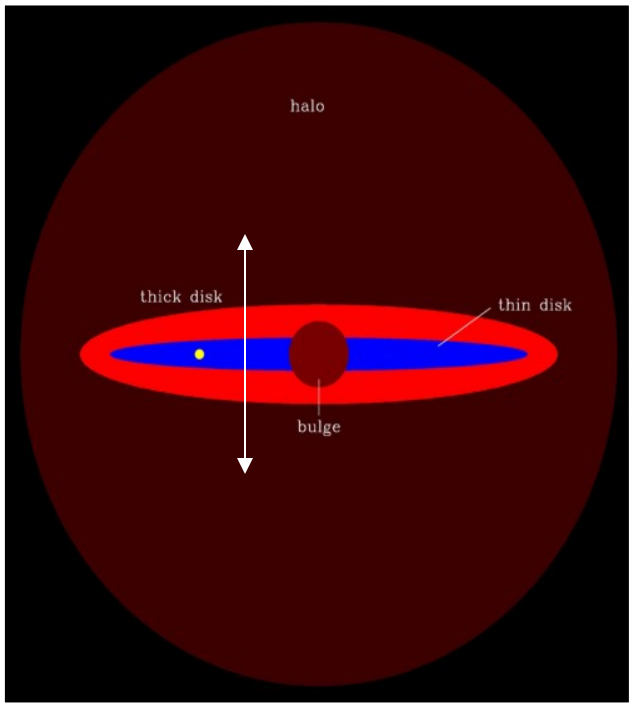
values of $K(z)$ derived

section the formulae are

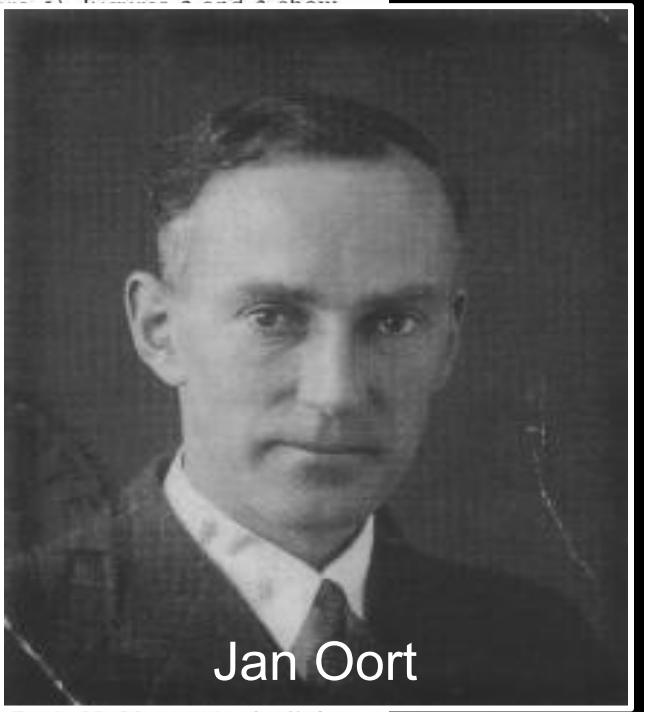
tion between $K(z)$, $\Delta(z)$

in high galactic latitude

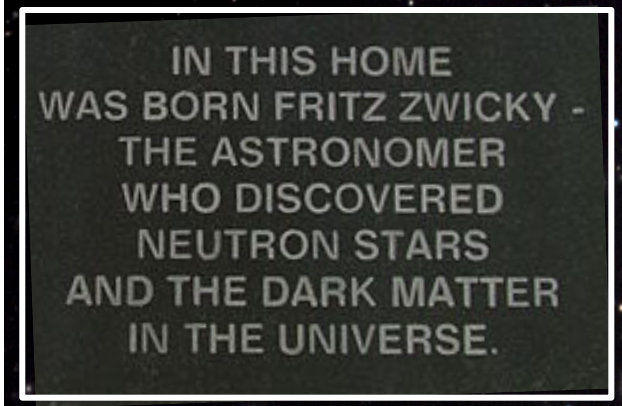
for the K stars, probably



Infer surface mass density from dynamics of stellar motions.



Dark Matter



Varna, Bulgaria

Fritz Zwicky 1930s

Galaxy Clusters (e.g., Coma)

Helvetica Physica Acta 6, 110 (1933)

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 von Wichtigkeit zu werden verspricht.

§ 1. Einleitung.

Es ist schon seit langer Zeit bekannt, dass es im Weltraum gewisse Objekte gibt, welche, wenn mit kleinen Teleskopen beobachtet, als stark verschwommene, selbstleuchtende Flecke erscheinen. Diese Objekte besitzen verschiedenartige Strukturen. Oft sind sie kugelförmig, oft elliptisch, und viele unter ihnen haben ein spiralartiges Aussehen, weshalb man sie gelegentlich als Spiralnebel bezeichnet. Dank des enormen Auflösungsvermögens der modernen Riesenteleskope gelang es, festzustellen, dass diese Nebel ausserhalb der Grenzen unseres eigenen Milchstrassensystems liegen. Aufnahmen, die mit dem Hundert-Zoll-Teleskop auf dem Mt. Wilson gemacht worden sind, offenbaren, dass diese Nebel Sternsysteme sind, ähnlich unserem eigenen Milchstrassensystem. Die extragalaktischen Nebel sind im grossen und ganzen gleichförmig über den Himmel und, wie gezeigt werden konnte, auch gleichförmig über den Weltraum verteilt. Sie treten als einzelne Individuen auf oder gruppieren sich zu Haufen. Die folgenden Zeilen beabsichtigen einen kurzen Abriss der wichtigeren Merkmale und eine Beschreibung der Methoden, welche es möglich gemacht haben, diese Merkmale zu fixieren.

§ 2. Entfernungen und allgemeine Merkmale extragalaktischer Nebel.

Wie schon erwähnt, gelingt es, mit Hilfe der modernen Teleskope eine ganze Anzahl von Nebeln ganz oder teilweise in einzelne Sterne aufzulösen. Im grossen Nebel in Andromeda z. B. sind eine grosse Zahl von individuellen Sternen beobachtet worden.

Kürzlich sind in diesem Nebel auch kugelförmige Sternhaufen entdeckt worden, ähnlich denjenigen, die im Bereiche unseres eigenen Milchstrassensystems liegen. Der glückliche Umstand der Beobachtbarkeit einzelner Sterne in Nebeln eröffnet zwei Wege zur Bestimmung von deren Entfernungen.

A) *Bestimmung der Entfernung mit Hilfe der Perioden-Helligkeitsbeziehung für Cepheiden.*

Cepheiden sind Sterne, deren Helligkeit periodisch mit der Zeit variiert. Die Perioden liegen gewöhnlich im Bereich von einem bis zu sechzig Tagen. Die absolute Helligkeit ist eine eindeutige Funktion der Periode, welche Funktion für Sterne unseres eigenen Systems bestimmt worden ist. Bei bekannter Periode ist es deshalb möglich, aus dieser Beziehung die absolute Helligkeit der Cepheiden abzuleiten. Bestimmt man dazu noch die scheinbare Helligkeit und vergleicht man diese mit der berechneten absoluten Helligkeit, so erhält man unmittelbar die Entfernung der Sterne. Eine ganze Reihe von Cepheiden sind im Andromedanebel beobachtet worden. Dessen Distanz und Durchmesser sind mit ihrer Hilfe auf ungefähr 900,000 resp. 42,000 Lichtjahre festgesetzt worden. Zum Vergleich sei daran erinnert, dass unser eigenes System einen Durchmesser besitzt, dessen obere Grenze auf ca. 100,000 Lichtjahre geschätzt wird. Auf gleiche Weise sind die Entfernungen von acht andern Nebeln gefunden worden. In Nebeln, deren Entfernung grösser ist als einige Millionen Lichtjahre, können keine individuellen Cepheiden mehr aufgelöst werden. Zur Bestimmung ihrer Entfernung müssen daher andere Methoden ersonnen werden.

B) *Statistik der Sterne grösster Helligkeit eines Nebels.*

Diese Methode stützt sich auf die Annahme, dass in den extragalaktischen Sternsystemen die relative Häufigkeit der absoluten Helligkeiten der Sterne dieselbe ist wie in unserem eigenen System. Die Erfahrungen mit den bisher untersuchten Nachbarsystemen sind in der Tat in Übereinstimmung mit dieser Annahme. Die absolute Helligkeit der hellsten Sterne in unserem eigenen und den ihm benachbarten Systemen ergibt sich im Mittel als $-6{,}1$ mit einer Streuung von weniger als einer halben Grössenklasse. Auf ähnliche Bestimmungen der Entfernungen mit Hilfe von Novas sei hier nur hingewiesen.

Ap. J. 86, 217 (1937)

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

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

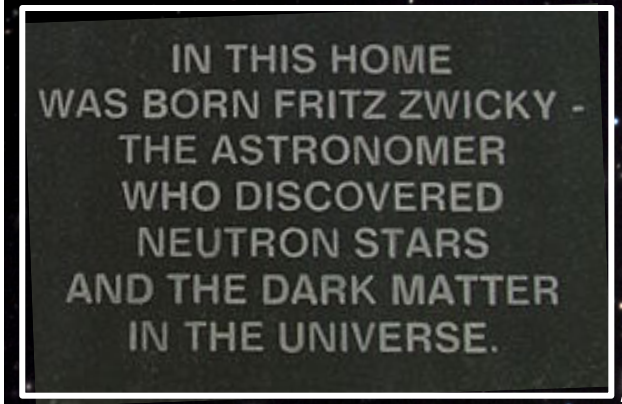
Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M}=4.5\times10^{10}M_{\odot}$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar. Counts of nebulae brighter than about $m=16.7$ given in section vi lead to the gratifying result that the distribution of nebulae in the Coma cluster is very similar to the distribution of luminosity in globular nebulae, which, according to Hubble's investigations, coincides closely with the theoretically determined distribution of matter in isothermal gravitational gas spheres. The high central condensation of the Coma cluster, the very gradual decrease of the number of nebulae per unit volume at great distances from its center, and the hitherto unexpected enormous extension of this cluster become here apparent for the first time. These results also suggest that the current classification of nebulae into relatively few *cluster nebulae* and a majority of

Dark Matter



Varna, Bulgaria

Fritz Zwicky 1930s

1. Phrase "Dark Matter"
2. Virial mass of Coma
3. M/L in Coma is 500 compared to 3 locally
4. Gravitational lensing could be used with larger telescopes

Zurich, Switzerland

Vladimir Lenin 1916

Galaxy Clusters (e.g., Coma)

THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970
© 1970. The University of Chicago. All rights reserved. Printed in U.S.A.

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

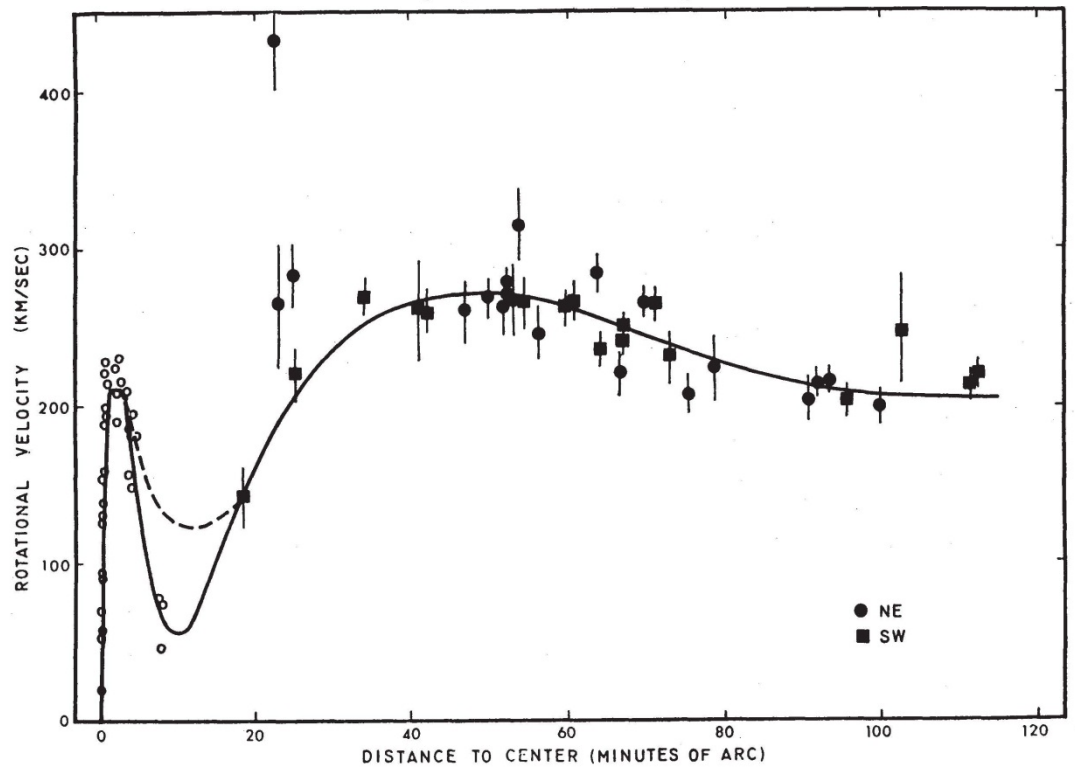
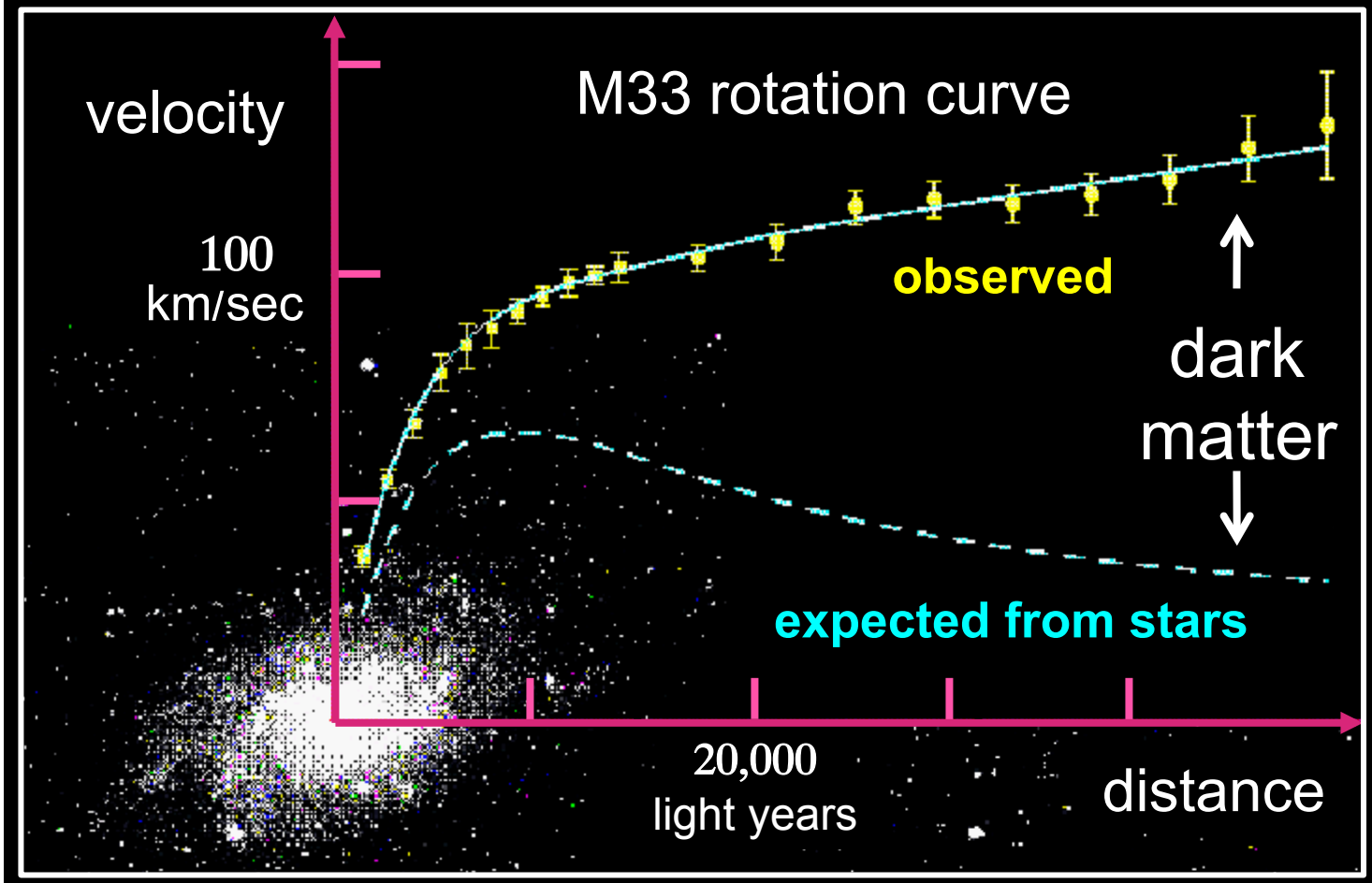


FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately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

Dark Matter



Vera Rubin 1970s

Individual Galaxies (e.g., M33)

The First WIMP Candidate

VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland
Department of Physics, University of California, Berkeley, California 94720
(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

Recently there has been a resurgence of interest in the possibility that neutrinos may have a finite rest mass. These discussions have been in the context of weak-interaction theories,[1] possible decay of solar neutrinos,[2] and enumerating the possible decay modes of the K_L^0 meson.[3] Elsewhere, we have pointed out that the gravitational interactions of neutrinos of finite rest mass may become very important in the discussion of the dynamics of clusters of galaxies and of the universe.[4] Considerations involving massive neutrinos are not new[5,6]; an excellent review of the early developments in the field is given by Kuchowicz.[7] Here we wish to point out that the recent measurement[8] of the deceleration parameter, q_0, implies an upper limit of a few tens of

and

$$n_{Bi} = \frac{2s_i+1}{2\pi^2\hbar^3}\int_0^\infty \frac{p^2dp}{\exp[E/kT(z_{eq})]-1}. \tag{1b}$$

Here n_{Fi} is the number density of fermions of the ith kind, n_{Bi} is the number density of bosons of the ith kind, s_i is the spin of the particle (notice that in writing the multiplicity of states of the particles we have not discriminated against the neutrinos; since we are discussing neutrinos of nonzero rest mass, we have assumed that both the helicity states are allowed), $E = c(p^2+m^2c^2)^{1/2}$, k is Boltzmann's constant, and $T(z_{eq}) = T_r(z_{eq}) = T_F(z_{eq}) = T_B(z_{eq}) = T_m(z_{eq}) = \cdots$ is the common temperature of radiation, fermions, bosons,

Fermi National Accelerator Laboratory

FERMILAB-Pub-77/41-THY
May 1977

Cosmological Lower Bound on Heavy Neutrino Masses

BENJAMIN W. LEE*
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

AND

STEVEN WEINBERG**
Stanford University, Physics Department, Stanford, California 94305

ABSTRACT

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be greater than a lower bound of the order of 2 GeV.

**On leave 1976-7 from Harvard University.

*Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

Ben Lee (1935 — June 1977)

Steve Weinberg

Physical Review Letters – 25 July 1977
Volume 39, Issue 4

- LETTERS
  - Elementary Particles and Fields
  - Nuclei
  - Atoms and Molecules
  - Classical Phenomenology and Applications
  - Fluids, Plasmas, and Electric Discharges
  - Condensed Matter: Structure, Etc.
  - Condensed Matter: Electronic Properties, Etc.

LETTERS

Elementary Particles and Fields

- **Cosmological Lower Bound on Heavy-Neutrino Masses**
  Benjamin W. Lee and Steven Weinberg
  pp. 165-168 [**View** Page Images or PDF (569 kB)]

- **Cosmological Upper Bound on Heavy-Neutrino Lifetimes**
  Duane A. Dicus, Edward W. Kolb, and Vigdor L. Teplitz
  pp. 168-171 [**View** Page Images or PDF (642 kB)]

$$\frac{dn}{dt} = -\frac{3\dot{R}}{R}n - \langle\sigma v\rangle n^2 + \langle\sigma v\rangle n_0^{\,2} \quad . \tag{2}$$

Here n is the actual number density of heavy neutrinos at time t; R is the cosmic scale factor; $\langle\sigma v\rangle$ is the average value of the $L^0\bar{L}^0$ annihilation cross-section times the relative velocity and n_0 is the number density of heavy neutrinos in thermal (and chemical) equilibrium[6]:

$$n_0(T) = \frac{2}{(2\pi)^3}\int_0^\infty 4\pi p^2 dp\left[\exp\left((m_L^{\,2}+p^2)^{\frac{1}{2}}/kT\right)+1\right]^{-1} \quad . \tag{3}$$

(We use units with $\hbar=c=1$ throughout.)

At the temperatures we are considering here, the energy

$$\frac{dn}{dt} = -\frac{3\dot{R}}{R}n - \langle\sigma v\rangle n^2 + \langle\sigma v\rangle n_0^{\,2}$$

where ρ is the energy density

$$\rho = N_F a T^4 = N_F \pi^2 (kT)^4/15 \tag{5}$$

with N_F an effective number of degrees of freedom, counting $\frac{1}{2}$ and 7/16 respectively for each boson or fermion species and spin state. For temperatures in the range of 10-100 MeV (which most concern us here) we must include just $\gamma, \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, e^-$, and e^+, so $N_F = 4.5$, a value we will adopt for most purposes. However, if current ideas about the strong interactions are correct, then N_F rises steeply at a temperature of order 500 MeV to a value[7] $N_F \approx 30$.

To estimate $\langle\sigma v\rangle$, we note that the heavy neutrinos must be quite non-relativistic at the temperature T_f where they freeze

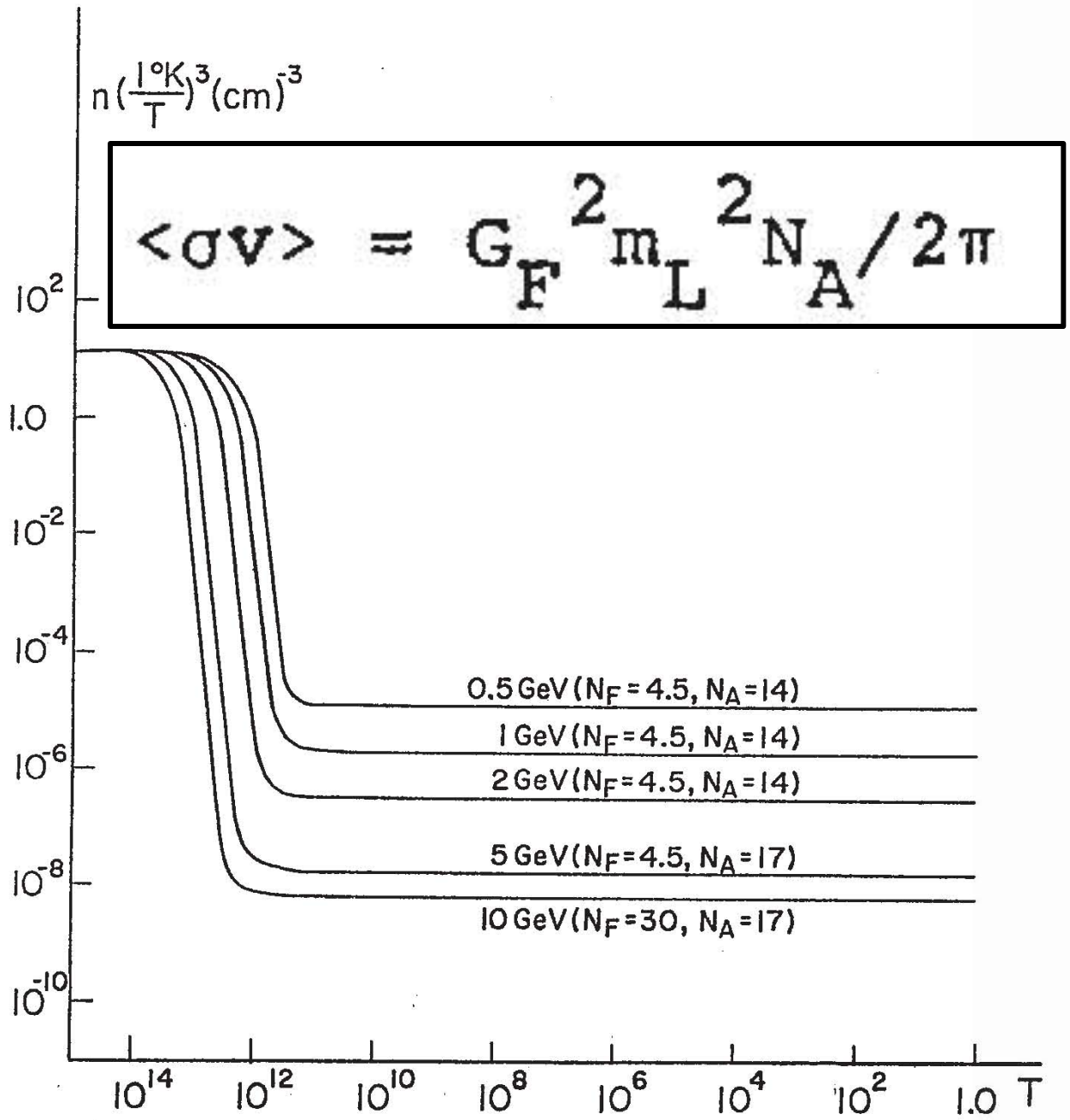
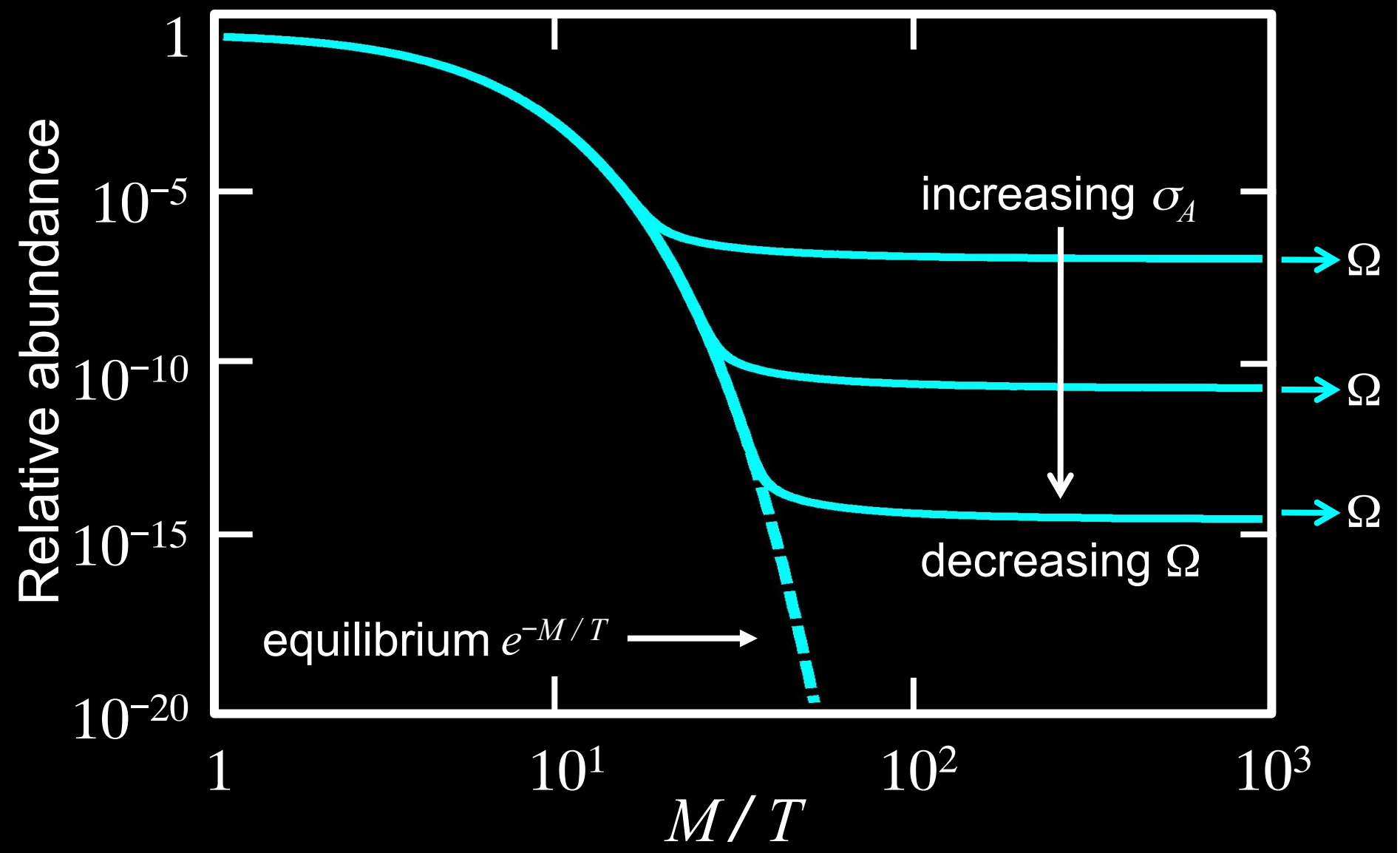

$n\left(\frac{1°K}{T}\right)^3 (cm)^{-3}$
$\langle\sigma v\rangle = G_F^2 m_L^2 N_A / 2\pi$
10^2
1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0.5 GeV (N_F = 4.5, N_A = 14)
1 GeV (N_F = 4.5, N_A = 14)
2 GeV (N_F = 4.5, N_A = 14)
5 GeV (N_F = 4.5, N_A = 17)
10 GeV (N_F = 30, N_A = 17)
10^{14}
10^{12}
10^{10}
10^8
10^6
10^4
10^2
1.0
T

FIG. 1

Cold Thermal Relics*



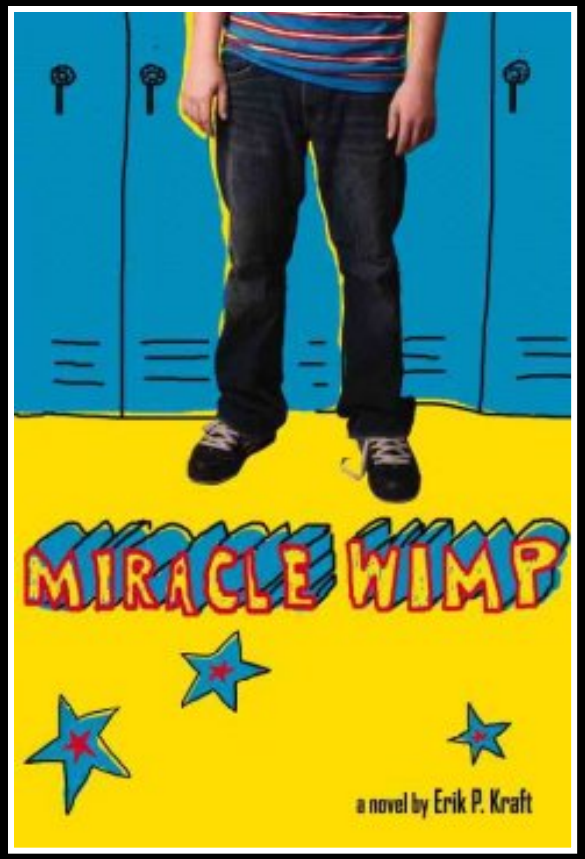
* An object of particular veneration.

Cold Thermal Relics Are WIMPs

$\Omega \Rightarrow$ Cross section (& mass ?) of order weak scale

WIMP (Weakly Interacting Massive Particle)

The WIMP Miracle



Merriam-Webster
Merriam-Webster OnLine

mir·a·cle
\ˈmir-i-kəl \
noun

1 : an extraordinary event manifesting divine intervention in human affairs

Coincidence or Causation?

THE ASTROPHYSICAL JOURNAL, 223:1032–1036, 1978 August 1
© 1978. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE COSMIC γ-RAY BACKGROUND FROM THE ANNIHILATION OF PRIMORDIAL STABLE NEUTRAL HEAVY LEPTONS

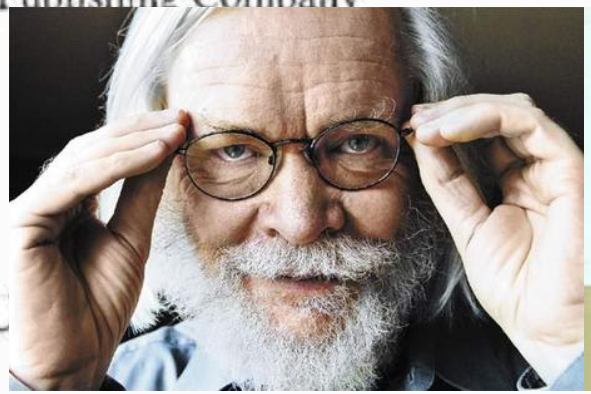
F. W. STECKER
Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center
Received 1977 December 12; accepted 1978 February 14

ABSTRACT

In light of the recent work on the astrophysical implications of the possible existence of stable neutral heavy leptons and the suggestion that continuing annihilation of heavy leptons produced in the big bang might produce a substantial cosmic γ-ray background radiation, we examine in detail the spectra and intensities of such radiation from (1) a homogeneous cosmic lepton background, (2) a possible lepton halo around the Galaxy, and (3) integrated background radiation from possible lepton halos around other galaxies and from rich galaxy clusters. In the case of our own galactic halo, γ-radiation from heavy-lepton annihilation appears to be able to account for the intensity of the observed background only if there are ~ 100 γ-rays produced per annihilation. However, in that case both the energy spectrum and isotropy would be inconsistent with the observations. More likely lepton annihilation fluxes from a galactic halo would be confused with cosmic-ray–produced radiation and therefore would be difficult to observe. Heavy-lepton annihilation radiation from the halos of other galaxies accounts for at most 5×10^{-3} of the background intensity, and those from rich clusters account for at most 5×10^{-5} of the background intensity. Those from a homogeneous cosmological lepton background appear to be able to account for $\lesssim 10^{-4}$ of the observed cosmic γ-ray background, although the spectrum and isotropy in this case would be consistent with the data.

Subject headings: cosmic rays: general — cosmology — elementary particles — gamma rays: general

Nuclear Physics B238 (1984) 453–476
© North-Holland Publishing Company



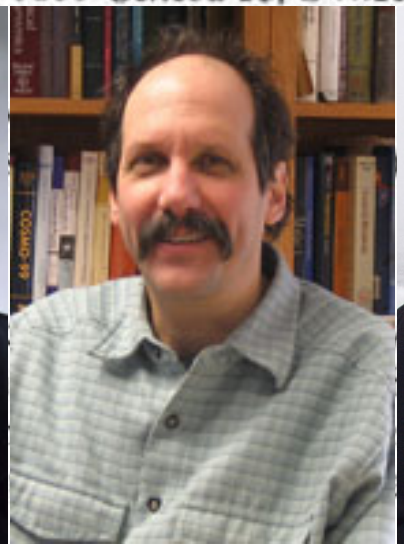
SU G*

John ELLIS and J. S. HAGELIN

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

D. V. NANOPOULOS, K. OLIVE†, and M. SREDNICKI‡

CERN, CH-1211 Geneva 23, Switzerland



We consid th a new, stable particle. Circun est candidate for this particle, an vern its mass and couplings. One ticle is predomi-

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Dark galactic halos[1] may be clouds of elementary particles so weakly interacting or so few and massive that they are not conspicuous. Many dark-matter candidates have been proposed. Magnetic monopoles are one dark-matter candidate accessible to experimental search,[2] and the same seems to be true for axions.[3] On the other hand, massive neutrinos are a popular dark-matter candidate which seems very difficult to detect except under very favorable conditions.[4] For many other dark-matter candidates considered in the literature, no practical experiments have been proposed.

Recently, Drukier and Stodolsky proposed[5] a new way of detecting solar and reactor neutrinos. The idea is to ex-

made in Ref. 5.

Let us first discuss the lower limit on detectable masses. If a halo particle of mass m and velocity v scatters from a target nucleus of mass M, the recoil momentum is at most $2mv$ and the recoil kinetic energy is at most $\epsilon=(2mv)^2/2M$. A reasonable value of v is $v=200$ km/sec. The lightest nucleus considered in Ref. 5 is aluminum, with $A=27$ and $M\simeq 27$ GeV. There seems to be a reasonable chance of building a detector sensitive to $\epsilon\sim 50-100$ eV (considerably more optimistic possibilities are discussed in Ref. 5). For $\epsilon \gtrsim 50-100$ eV, we need $m \gtrsim 1-2$ GeV, and this is the lower limit on the mass of detectable halo particles. It is important to note, though,

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

[a] *Department of Physics, Boston University, Boston, MA 02215, USA*
[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
[c] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[e] *Applied Research Corp., 8201 Corporate Dr, Landover MD 20785, USA*
[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[g] *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[h] *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z^0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is <0.4 GeV/cm^3 for masses between 17.5 GeV and 2 5 TeV, at the 68% confidence level.

Eighty Years of Dark Matter

Oort	1932	80 Years Ago	Dark Matter Exists
Zwicky	1933	79 Years Ago	Dark Matter Exists
	1937	75 Years Ago	Dark Matter Exists
Rubin & Ford	1969	43 Years Ago	Dark Matter Exists
Cowsik & McClelland	1972	40 Years Ago	WIMP Candidate
Lee & Weinberg	05/77	35 Years Ago	WIMP Candidate
Stecker	12/77	35 Years Ago	Indirect Detection
Ellis, Hagelin, *et al.*	09/83	28 Years Ago	WIMP Candidate
Goodman & Witten	01/85	27 Years Ago	Direct Detection
Ahlen *et al.*	05/87	25 Years Ago	

We Swim in a Sea of WIMPs

- A mysterious, invisible particle species is around us
- There are 10^7 in this room
- Zipping around at $500{,}000$ miles per hour
- About 10^{12} will pass through you during this talk
- You don't sense them since interactions are so weak

A Fantastical Story!

simulation

SECOND EDITION 1989

sim-sim
simson
simul
simulacral, *a.*
simulacre
simulacrum
simulance
simuland
simulant, *a.* and *n.*
simular, *n.* and *a.*
simulate, *ppl. a.*
simulate, *v.*
simulated, *ppl. a.*
simulately, *adv.*
simulation
simulative, *a.*
simulator
simulatory, *a.*
simulcast, *v.*
simule, *v.*
simuler
simulfix
simuliid, *n.* and *a.*
simulium
simultal, *a.*
simultanagnosia
simultane, *v.*
Simultaneism
simultaneity
simultaneous, *a.*
simultaneously, *adv.*
simultaneousness
simultation
simulty[1]

Pronunciation | Spellings | Etymology | Quotations | Date chart

1. a. The action or practice of simulating, with intent to deceive; false pretence, deceitful profession.

1340 *Ayenb.* 23 And þerof wexeþ uele zennes, ase ariȝthalf; þet is to wytene: lozengerie, simulacion. **c1400** *Rom. Rose* 7230 He nys no full good championn That dredith such similacioun. **1412-20** Lydg. *Chron. Troy* iv. 4504 Amonge hem silfe to bringe in tresoun, Feyned trouþe and symulacioun. **1542** Udall *Erasm. Apoph.* 170 He..did with mutual simulacion on his partie cover & kepe secrete the colorable dooyng of the saied feloe. **1577** tr. *Bullinger's Decades* (1592) 319 This precept doth commaunde vs..that..wee doe our neighbor harme..neither by simulation nor dissimulation. **1611** Speed *Hist. Gt. Brit.* vi. (1632) 114 His nature relishing too much of the Punick craft and simulation. **1692** South *Serm.* (1697) I. 525 A Deceiving by Actions, Gestures, or Behaviour, is called Simulation, or Hypocrisie. **1711** Steele *Tatler* No. 213 ¶1 Simulation is a Pretence of what is not, and Dissimulation a Concealment of what is. **1788** Wesley *Wks.* (1872) VII. 43 Simulation is the seeming to be what we are not; dissimulation, the seeming not to be what we are. **1836** Landor *Pericles & Aspasia* Wks. 1846 II. 379, I wish he were as pious as you are: occasionally he appears so. I attacked him on his simulation. **1872** Shipley *Gloss. Eccl. Terms* 71 Fraud.., whether it consists in simulation or dissimulation.

b. Tendency to assume a form resembling that of something else; unconscious imitation.

1870 March *Anglo-Saxon Gram.* 28 *Simulation.* The feigning a connection with words of similar sound is an important fact in English and other modern languages: asparagus > sparrow-grass.

2. A false assumption or display, a surface resemblance or imitation, *of* something.

WIMPs

Dark matter is a complex physical phenomenon.

WIMPs are a simple, elegant, compelling explanation for a complex physical phenomenon.

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

— *Tommy Gold*

WIMPs: Cold Thermal Relics

- neutrinos (hot)
- sterile neutrinos, gravitinos (warm)
- Lightest supersymmetric particle (cold)
- Lightest Kaluza-Klein particle (cold)

} thermal relics

- B.E.C.s, axions, axion clusters
- solitons (Q-balls, B-balls, odd-balls, …)
- supermassive wimpzillas

} nonthermal relics

Mass range	
$10^{-22}\,\mathrm{eV}$	$(10^{-56}\,\mathrm{g})$ B.E.C.s
$10^{-8}\,M_{\odot}$	$(10^{+25}\,\mathrm{g})$ axion clusters

Interaction strength range
Only gravitational: wimpzillas
Strongly interacting: B balls

WIMPs

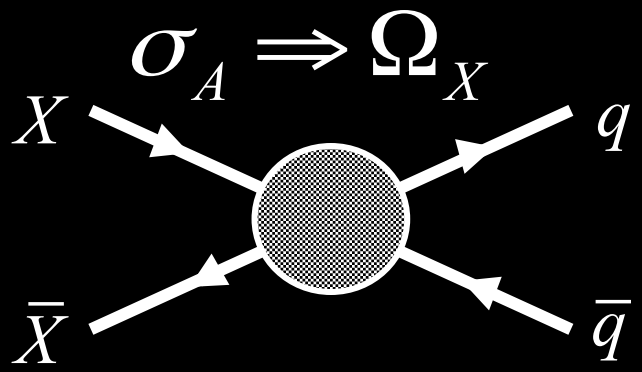
Goal: Discover dark matter and its role in shaping the universe

<u>Particle Physics:</u>
Discover dark matter and learn how it is …
… grounded in physical law
… embedded in an overarching physics model/theory

<u>Astro Physics:</u>
Understand the role of dark matter in …
… formation of structure
… evolution of structure

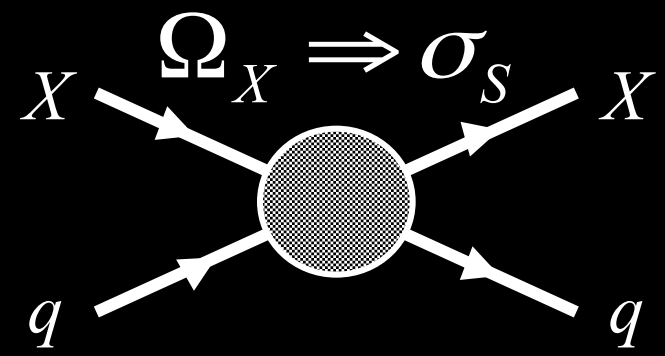
<u>WIMPs</u>:
massive, stable, "weakly" interacting, $\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{U}(1)_{\mathrm{EM}}$ singlet
WIMP must be a *BSM* (but perhaps not far BSM) particle.

WIMP Crossings



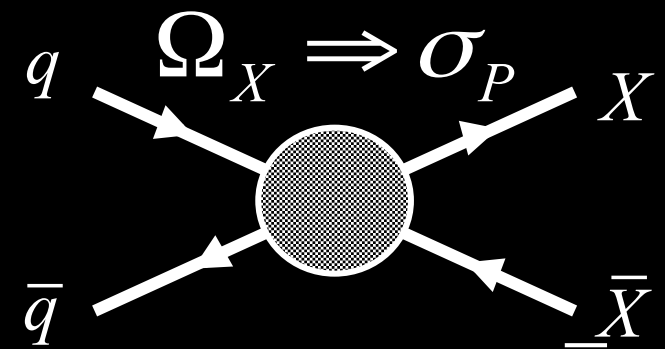
$$X + \bar{X} \rightarrow q + \bar{q}$$

Primordial Production
Indirect Detection



$$X + q \rightarrow X + q$$

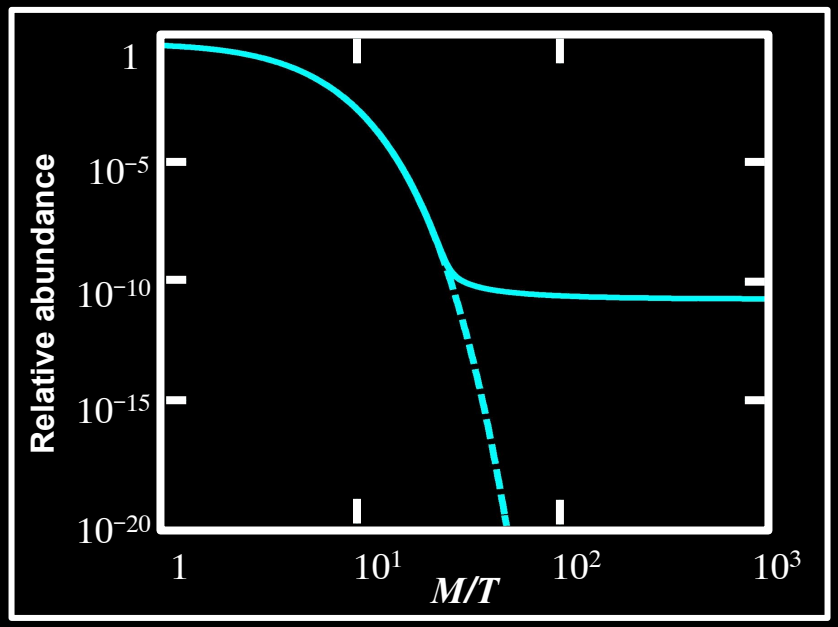
Direct Detection

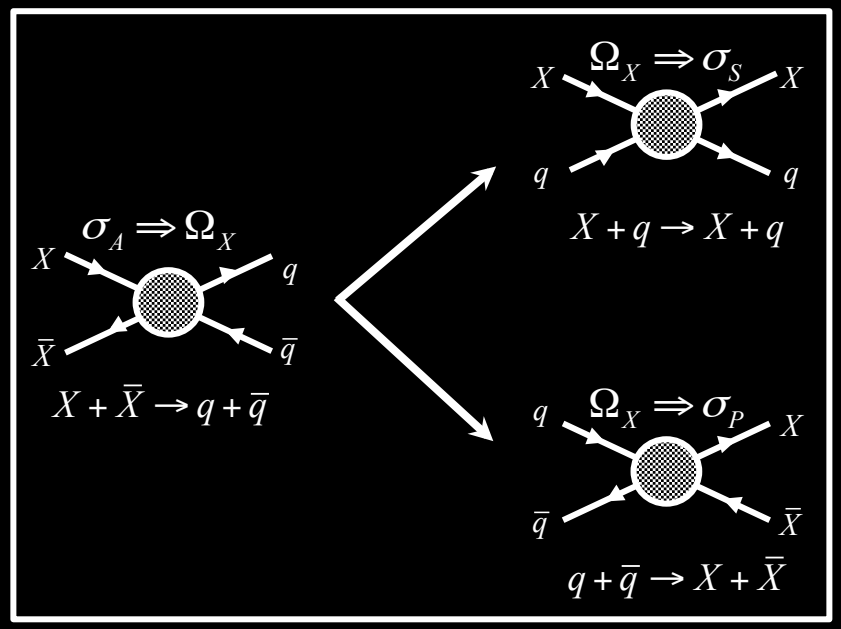


$$q + \bar{q} \rightarrow X + \bar{X}$$

Accelerator Production

WIMPs





Not quite so simple:

- velocity dependence
- co-annihilation
- resonances
- superwimps
- dependence on M, g_*,
- ...

Not quite so simple:

- velocity dependence
- local phase-space density
- flavor dependence
- co-production
- Sommerfield enhancement
- …

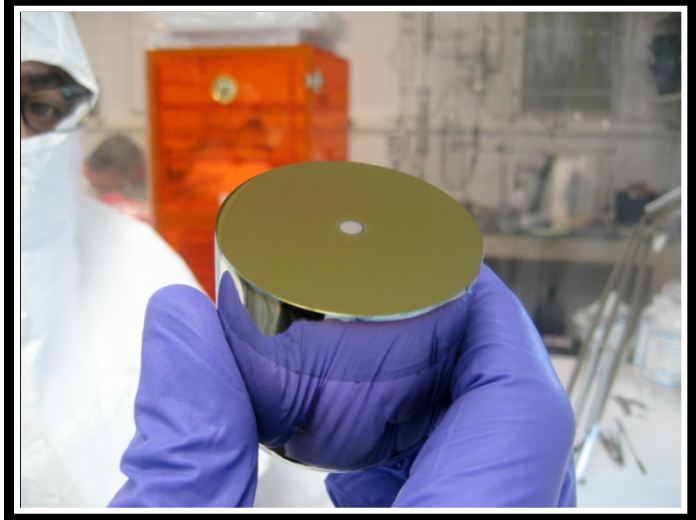
WIMPs

- WIMPs: causation or coincidence?
- Situation now is muddled
  - direct hints: DAMA/LIBRA, CoGeNT, CRESST II, …
  - indirect hints: PAMELA, ATIC, Fermi/GLAST, …
  - LHC beginning to weigh in: …

WIMPs

Dan Hooper: What would it take for you to "believe" in a 7 GeV WIMP seen in CoGeNT, DAMA/LIBRA, CRESST-II, Fermi/GLAST?

CoGeNT



Model Dependent

LHC

nonrelativistic

$\chi + N \rightarrow \chi + N$

relativistic

$q + \bar{q} \rightarrow \chi + \chi$

My Answer: Produce and detect it at the LHC!

WIMPs: Socialists or Mavericks

WIMPs: Socialists or Mavericks

Social WIMP	Maverick WIMP*
• WIMP part of a social network.	• WIMP is a loner.
• Motivated model framework, *e.g.,* low-energy SUSY.	• Use effective field theory, *e.g.*: 4-Fermi interaction.
• Many new particles/parameters.	• WIMP only new species.
• Muddy relationships between annihilation-scattering-production cross sections.	• Clearer relationships between annihilation-scattering-production cross sections.

* Beltran, Hooper, Kolb, Krusberg, Tait 1002.5137
Rajaraman, Shepherd, Tait, Wijangco 1108.1196
Fox, Harnik, Kopp, Tsai 1109.4398

SUSY WIMPs

Favorite cold thermal relic: the neutralino

Neutralino:

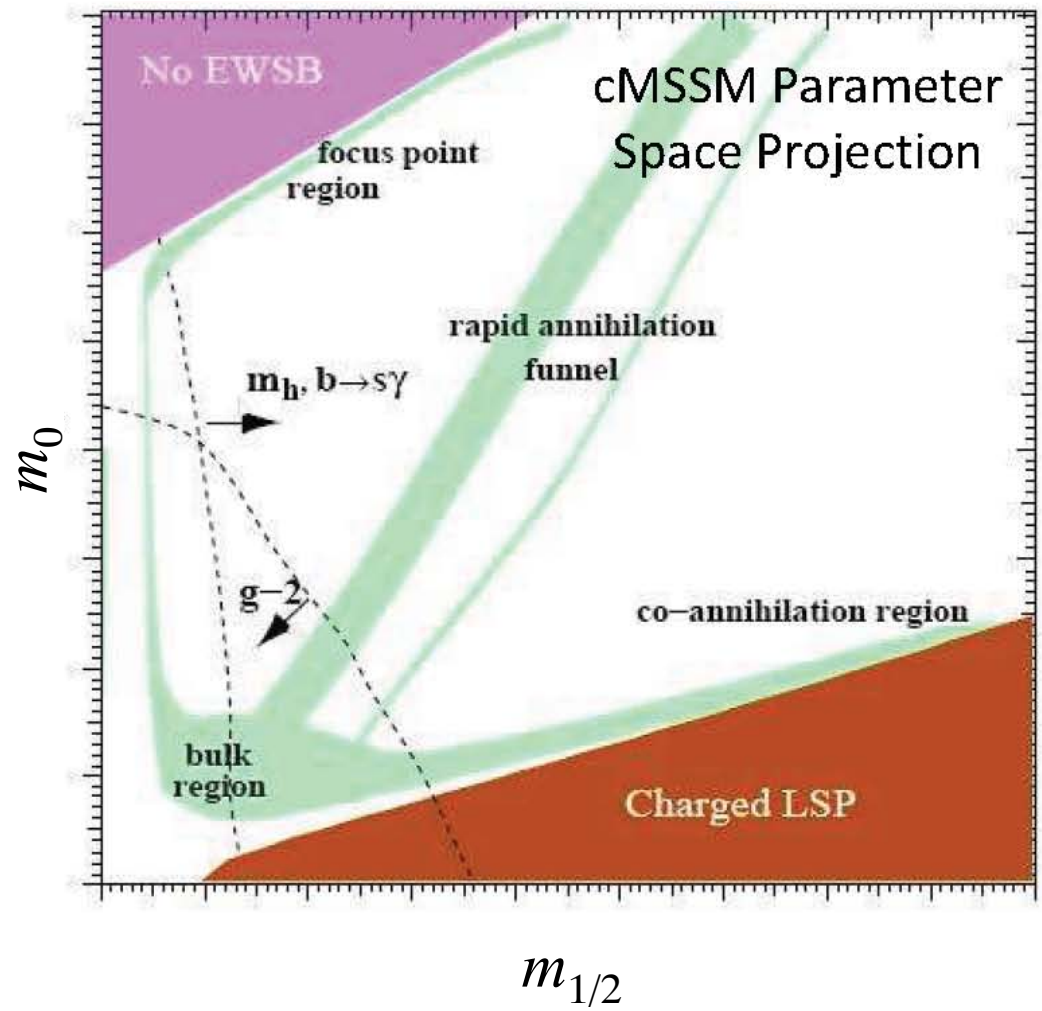
$$\tilde{\chi}^0 = \alpha \tilde{B}^0 + \beta \tilde{W}^0 + \gamma \tilde{H}_1^0 + \delta \tilde{H}_2^0$$

$m_{\tilde{\chi}^0}$ and interactions:

100+ parameters of SUSY

cMSSM

m_0 , $m_{1/2}$, $\tan\beta$, A_0 , sign μ



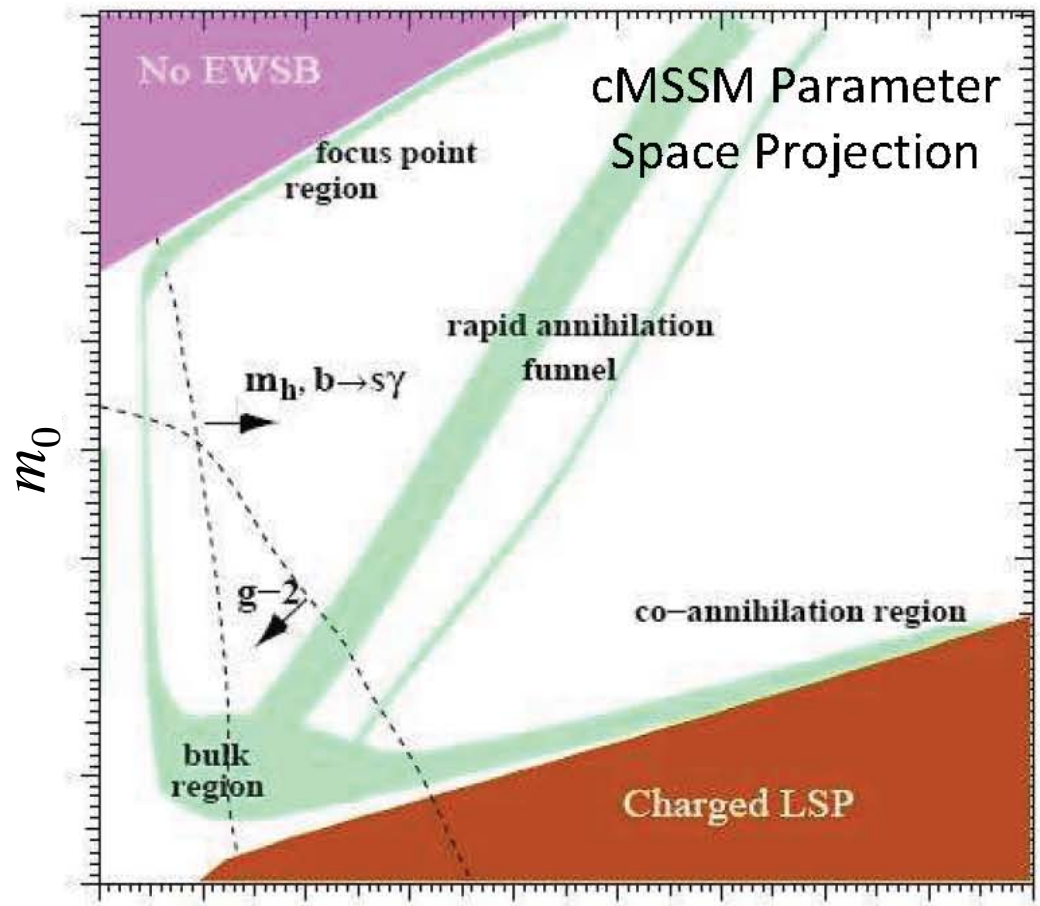
Ellis, Olive, Santoso, Spanos 2003

SUSY WIMPs

- Typical SUSY models consistent w/ collider and other HEP data have too small annihilation cross section → too large Ω

- Need chicanery to increase annihilation cross section
  - s-channel resonance through light H and Z poles
  - co-annihilation with $\tilde{\tau}$ or $\tilde{\ell}$
  - large tanβ (s-channel annihilation via broad A resonance)
  - high values of m_0: Higgsino-like neutralino annihilates into W & Z pairs (focus point)
  - …

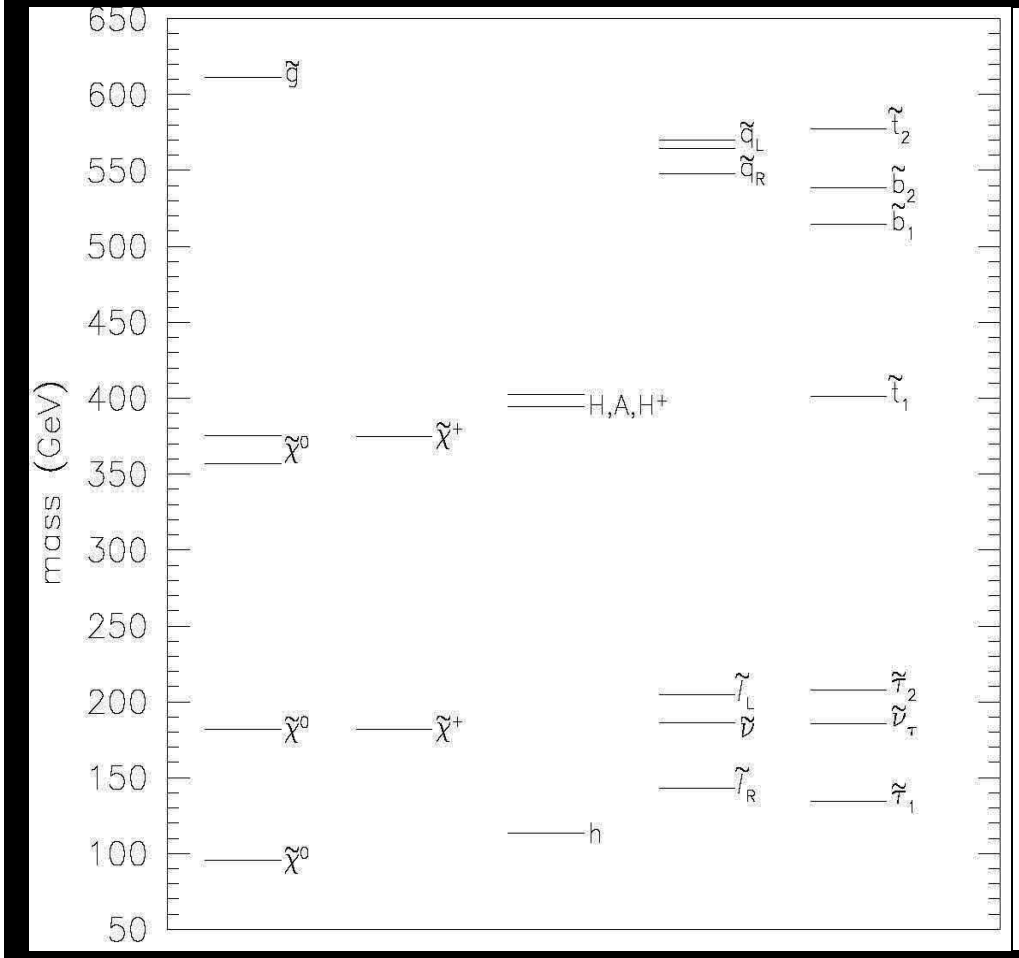
- Or, unconstrained

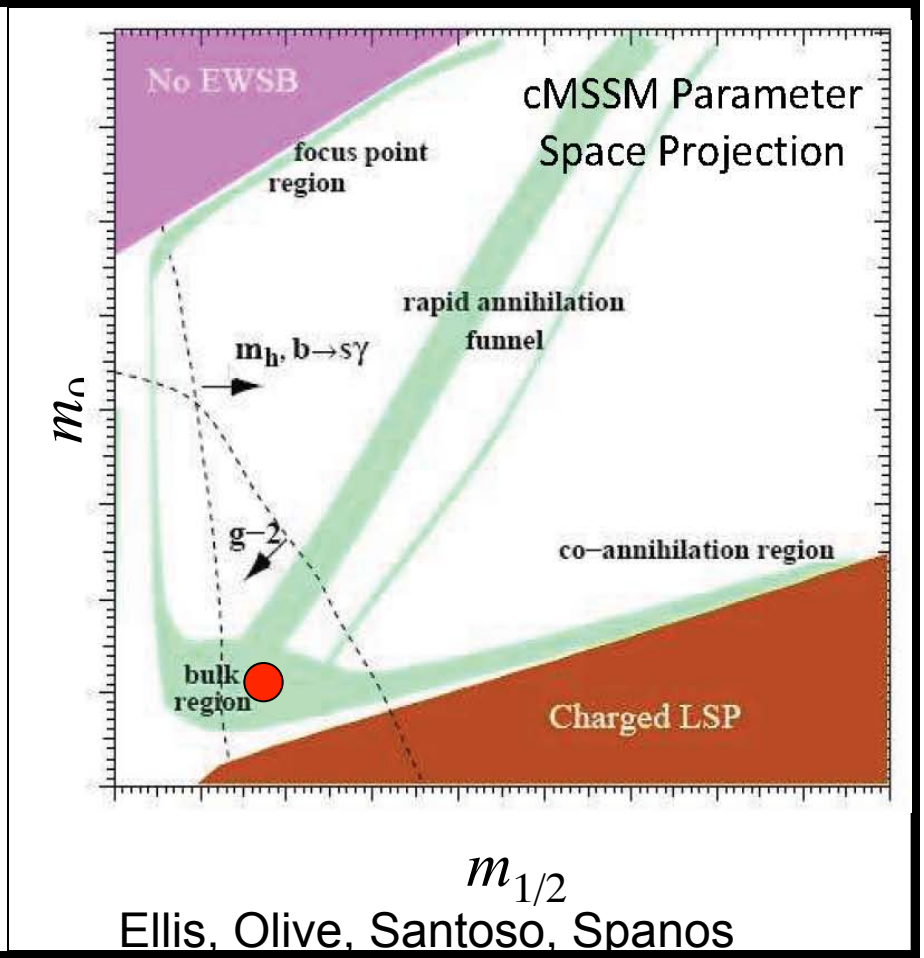


Ellis, Olive, Santoso, Spanos

SUSY WIMPs

Bulk Region: light superpartners





Ellis, Olive, Santoso, Spanos

LHC chewing away at allowed region

Recent SUSY Statements

- It's not yet time to throw in the Towelino.
- No one took the MSSM seriously anyway.
- The evidence for SUSY* has never been stronger.
- By the end of 2012 we will have proof of low-energy SUSY, String Theory, and a $130\ \mathrm{GeV}$ WIMP.

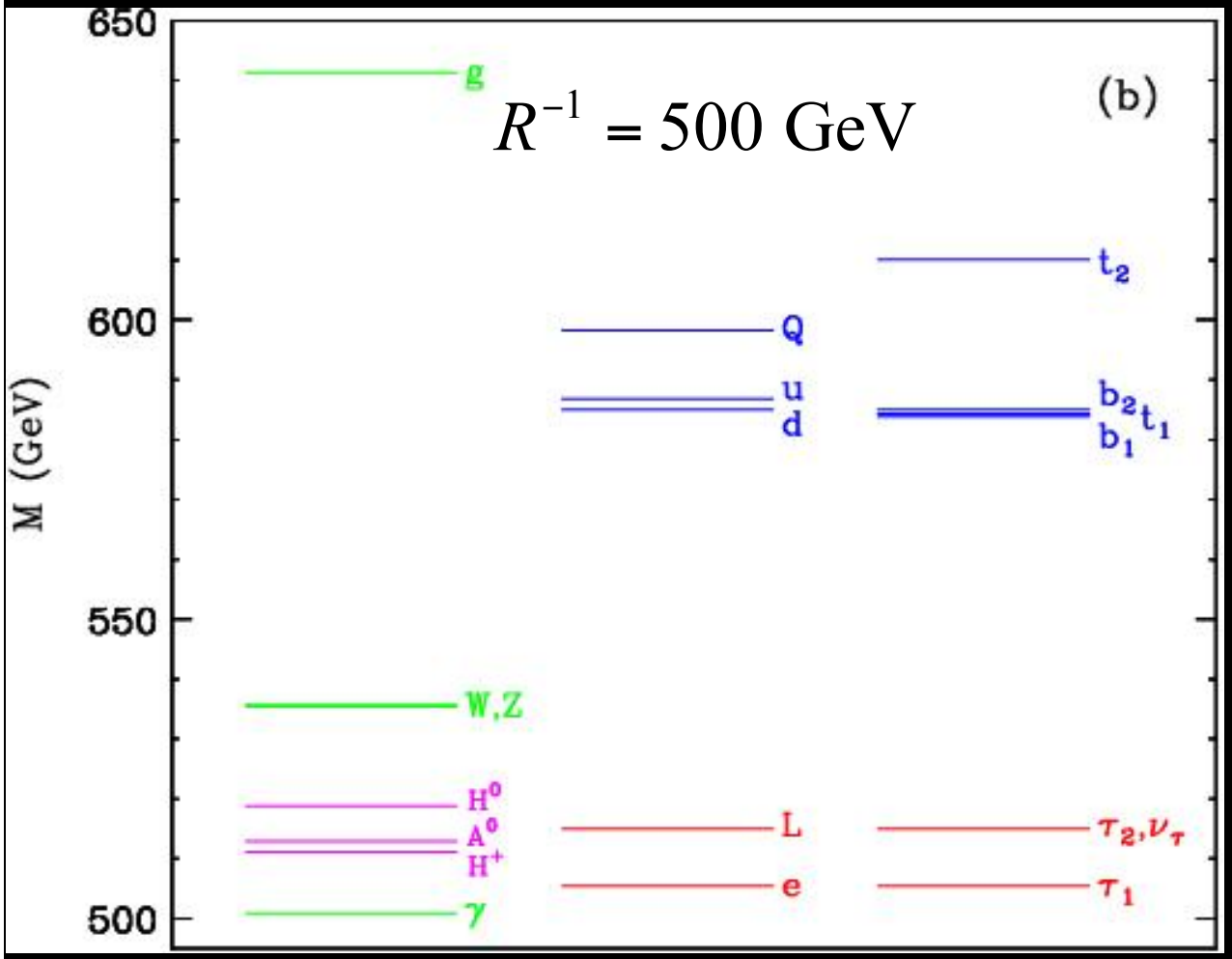
Really?

---

* … and Bigfoot, and Loch Ness Monster, Elvis, Aliens, …

Kaluza-Klein WIMPs

Kolb & Slansky (84); Servant & Tait (02); Cheng, Feng & Matchev (02)



- LKP = KK photon
  Cheng, Matchev & Schmaltz
- Looks like SUSY
  Cheng, Matchev & Schmaltz
- Beware KK graviton
  Kolb, Servant & Tait
- Direct detection
  Servant & Tait
  Cheng, Feng & Matchev
- Indirect detection
  Bertrone, Servant, Sigl

LHC chewing away at allowed region

Maverick WIMPs

Dirac fermion Maverick WIMP, χ

$$\mathcal{L} = \sum_q \frac{G_{i,2}}{\sqrt{2}} \left[\bar{c}\, \Gamma_i\, c\right] \left[\bar{q}\, \Gamma_j\, q\right]$$

$$\Gamma_{i,j} = \left\{ 1, \gamma^5, \gamma^\mu, \gamma^\mu \gamma^5, \sigma^{\mu\nu} \right\}$$

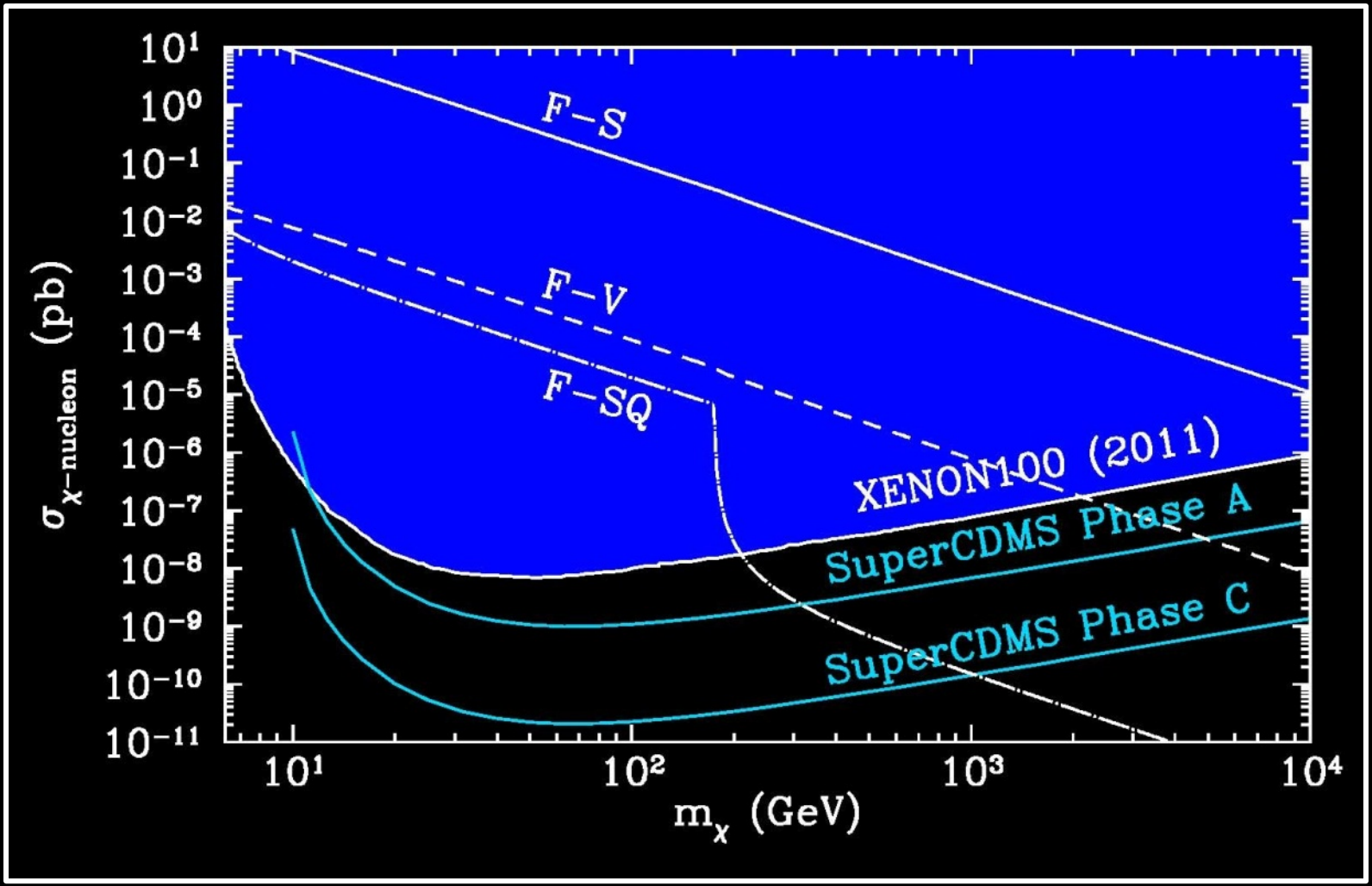
Complex scalar Maverick WIMP, ϕ

$$\mathcal{L} = \sum_q \frac{F_{i,2}}{\sqrt{2}} \left[\phi^\dagger \Gamma_i \phi\right] \left[\bar{q}\, \Gamma_j\, q\right]$$

$$\Gamma_i = \left\{ 1, \partial^\mu \right\}$$

Maverick WIMPs

spin-independent

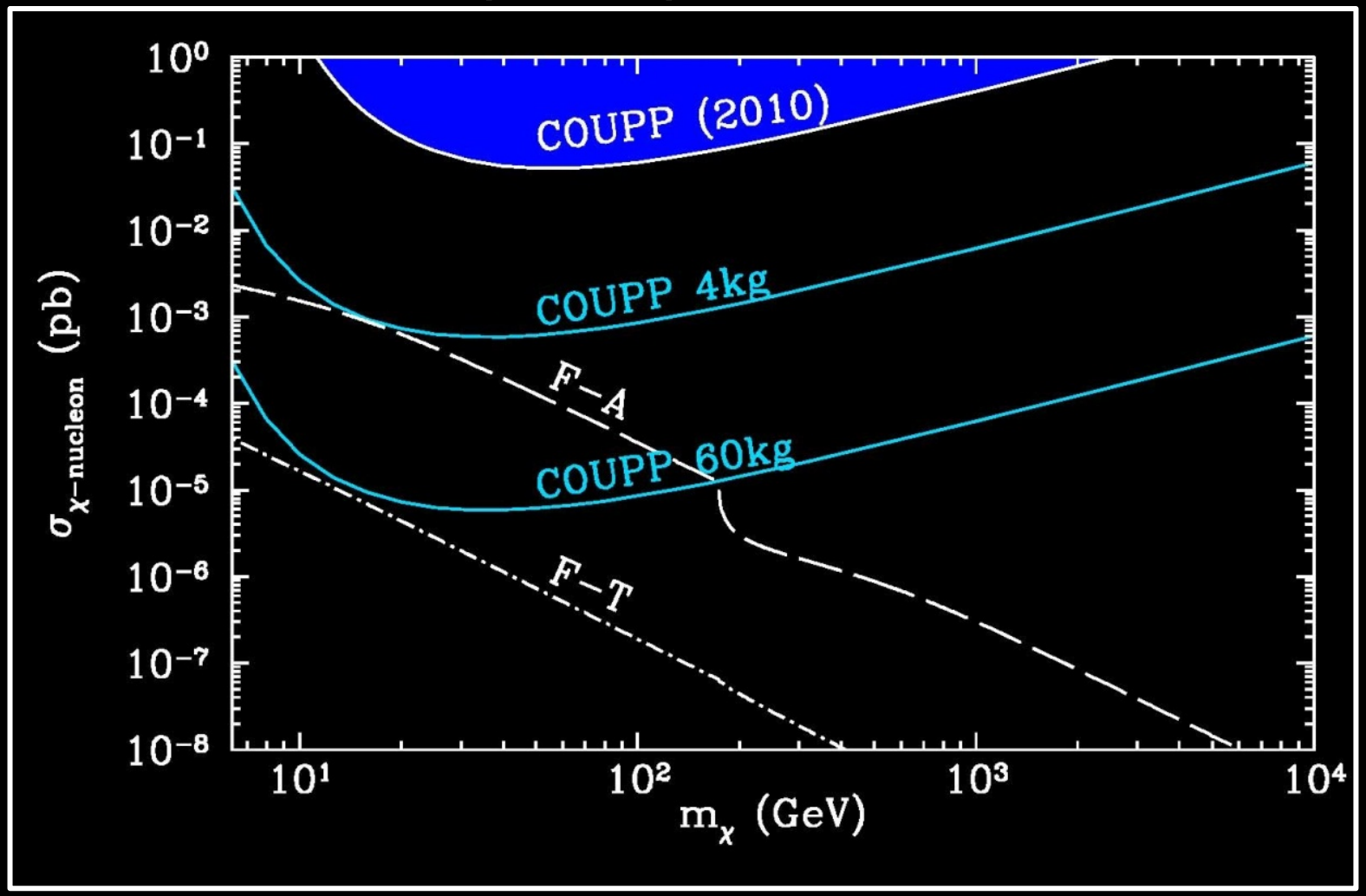


For $m \geq 10$ GeV or so $\sigma \leq 10^{-6}$ pb

Around a few GeV $\sigma \sim 10^{-6}$ pb

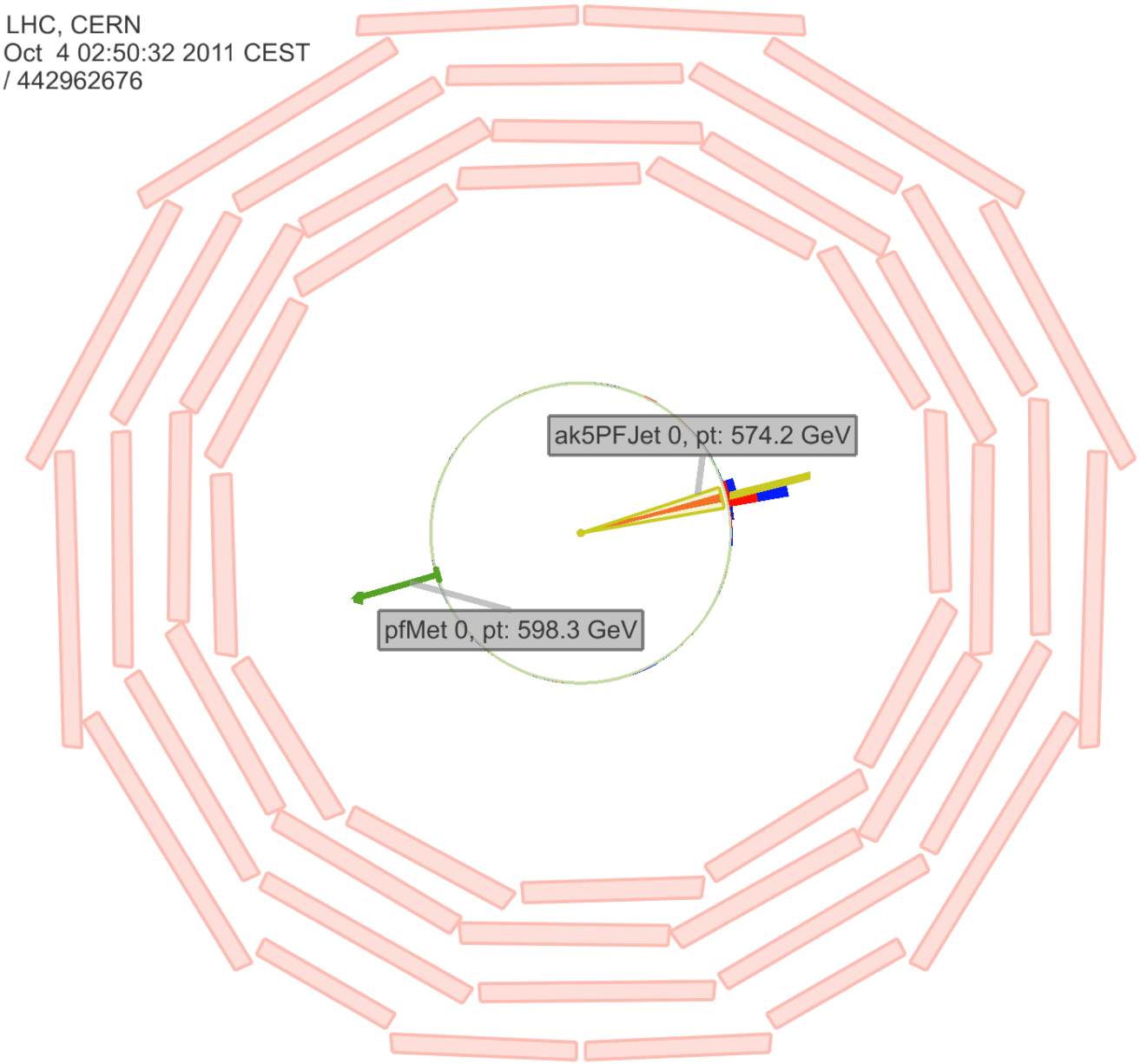
Maverick WIMPs

spin-dependent



σ can be as large as 10^{-3} pb to 10^{-6} pb

Missing Momentum = Missing Mass?

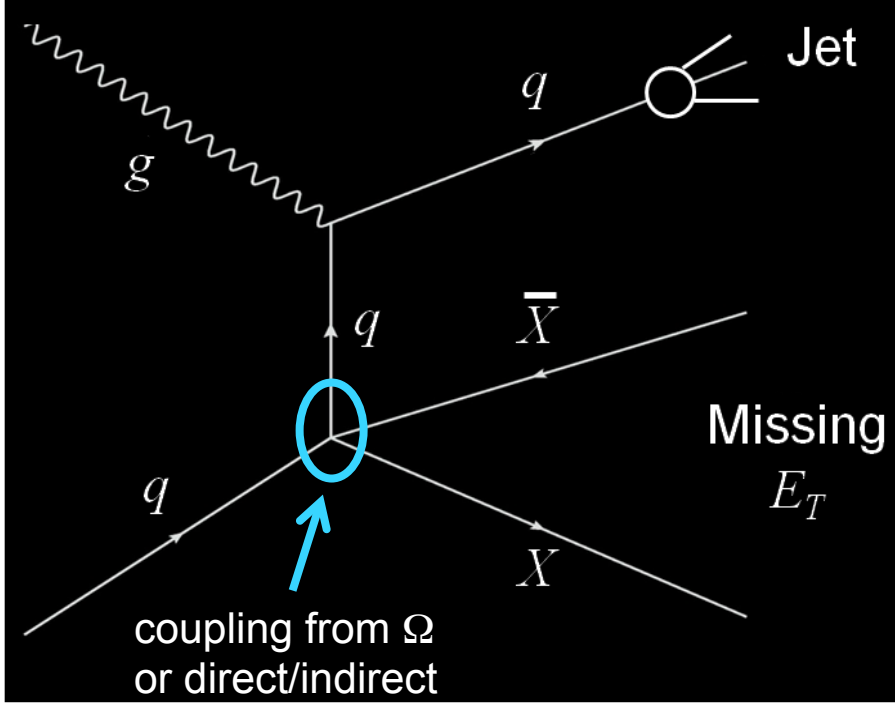


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012

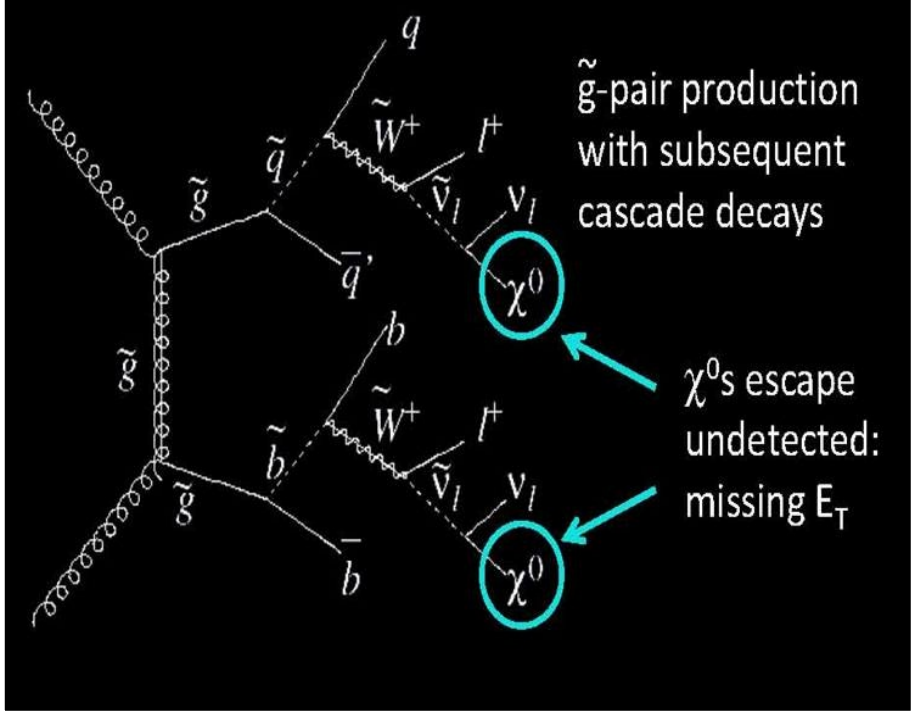
WIMPs

Collider Searches

Maverick WIMPs



Social WIMPs



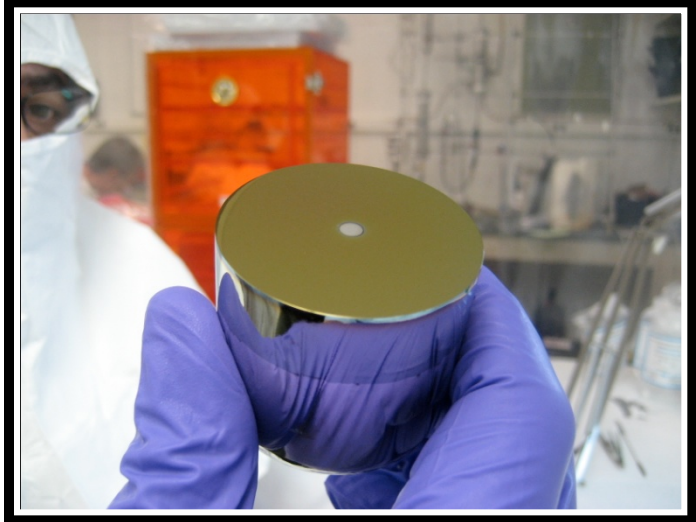
Backgrounds (neutrino, QCD, …)

Complicated decay chain

Beltran, Hooper, Kolb, Krusberg, Tait 1002.5137
Rajaraman, Shepherd, Tait, Wijangco 1108.1196
Fox, Harnik, Kopp, Tsai 1109.4398

WIMPs

CoGeNT



LHC

Model Dependent

nonrelativistic

$\chi + N \rightarrow \chi + N$

10^{-4} **pb** – 10^{-6} **pb**

Described by
Effective field theory

relativistic

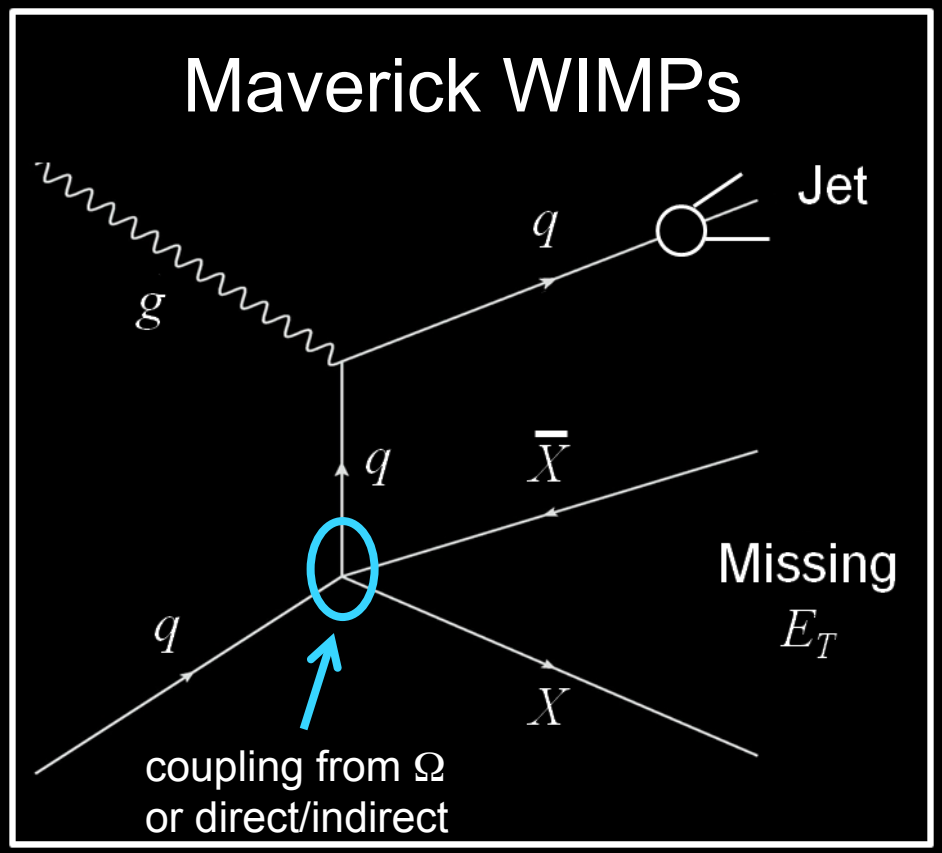
$q + \bar{q} \rightarrow \chi + \chi$

???

Assume described by
effective field theory

Maverick WIMPs

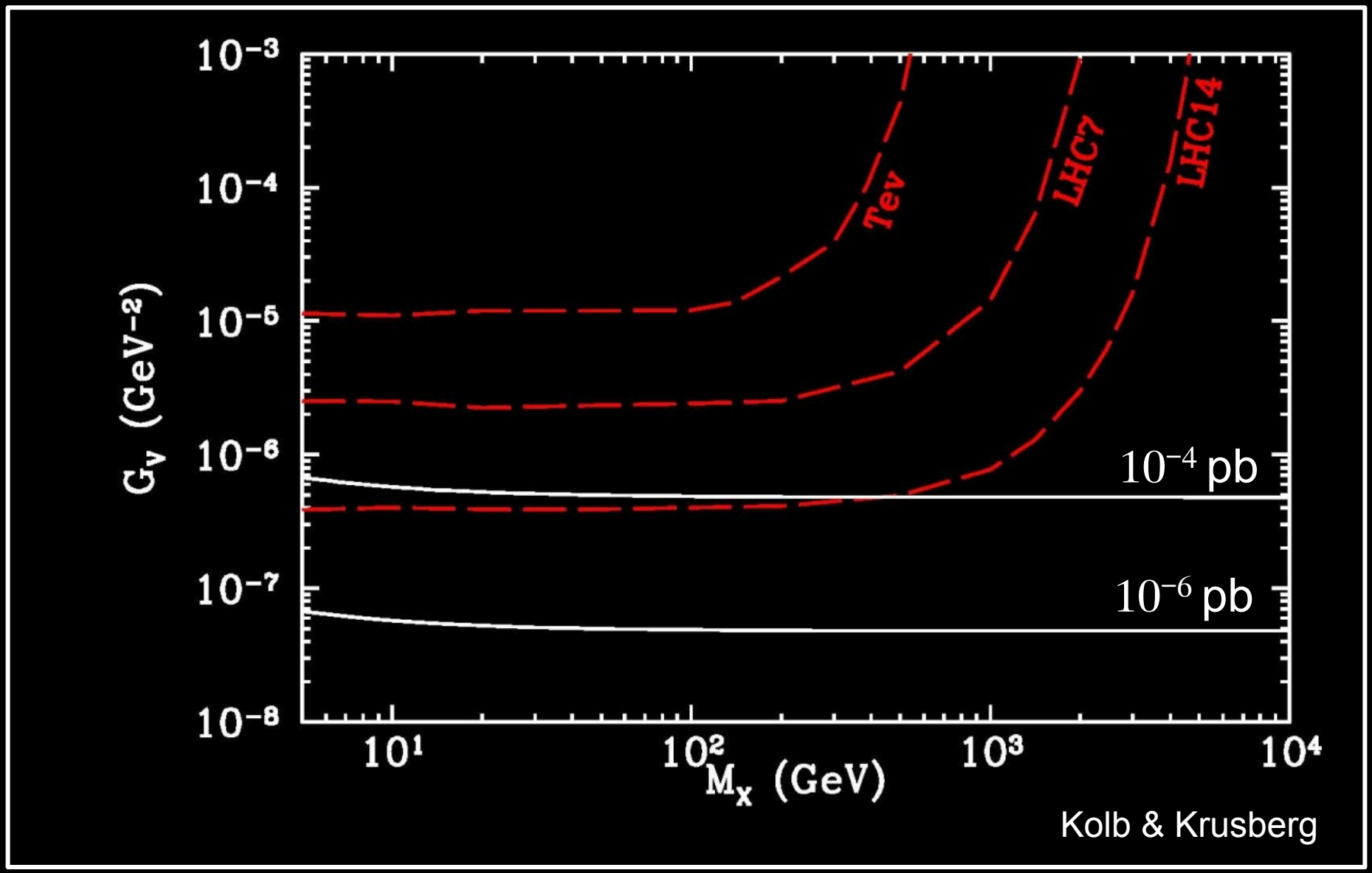
Collider Searches

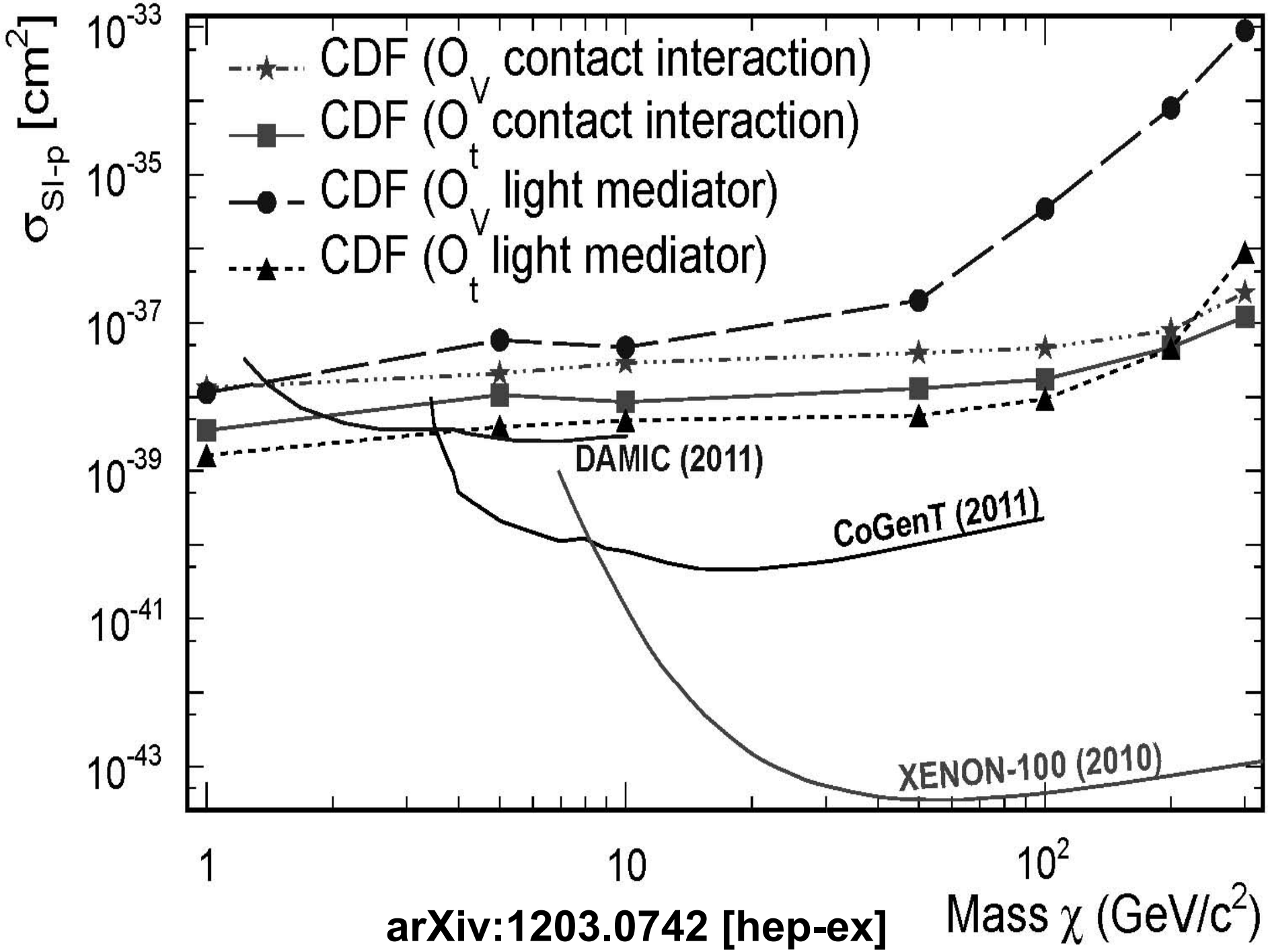


Backgrounds (neutrino, QCD, …)

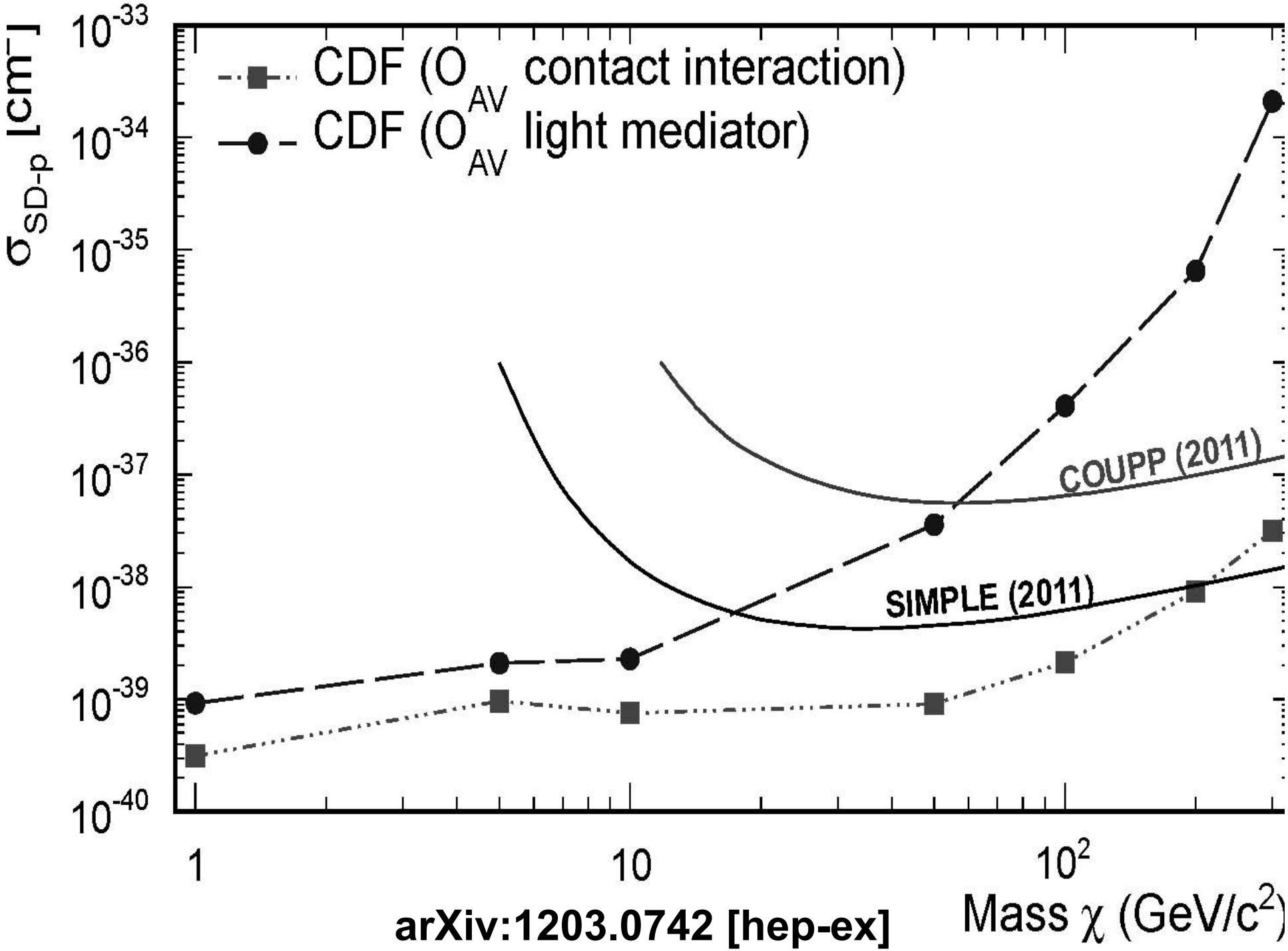
- MadGraph/MadEvent:
  Feynman diagrams,
  cross sections,
  parton-level events
- Pythia:
  Hadron-level events
  via Monte Carlo showering
- PGS:
  Reconstructed events
  at collider

Maverick WIMPs



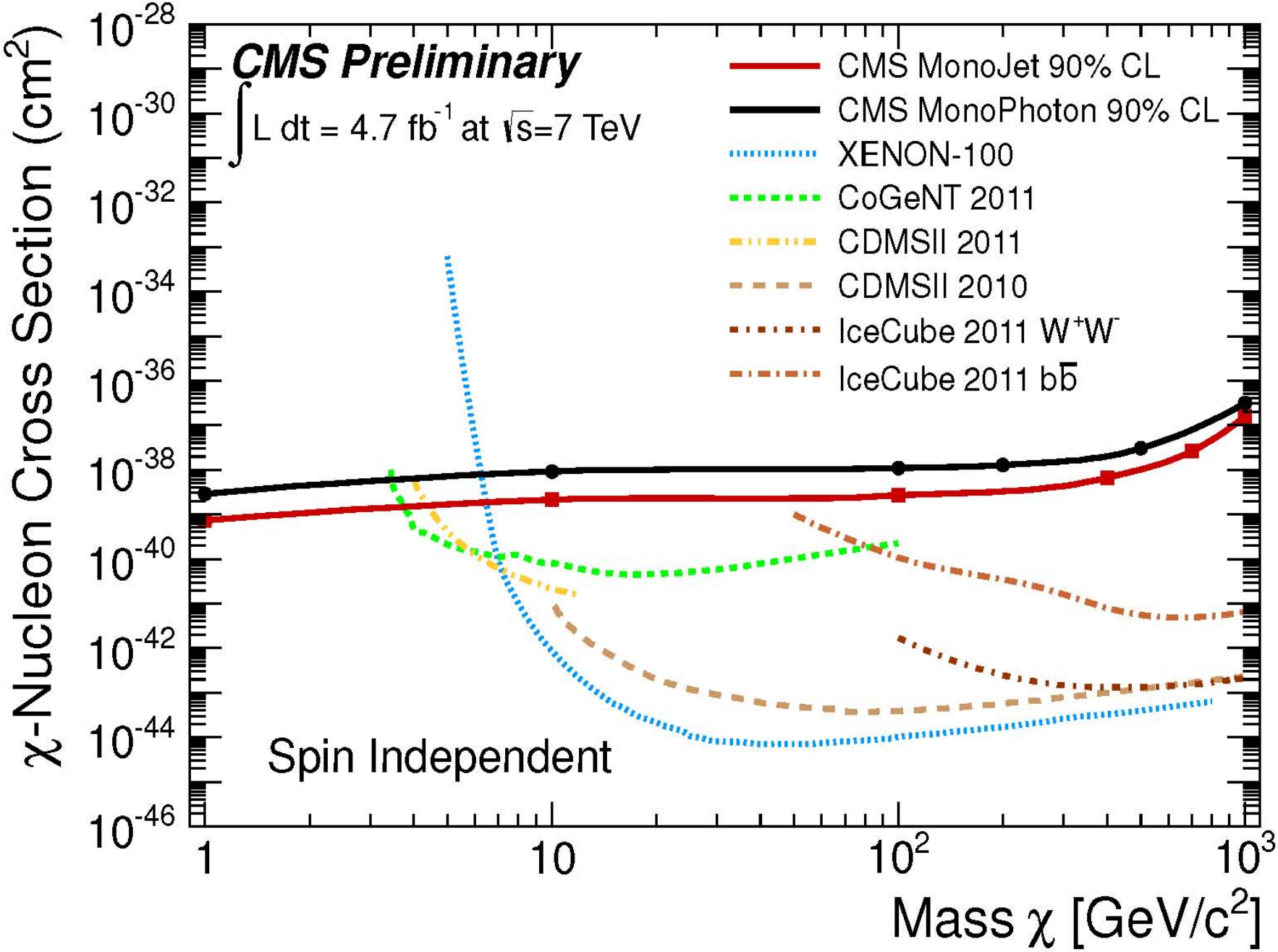


arXiv:1203.0742 [hep-ex]

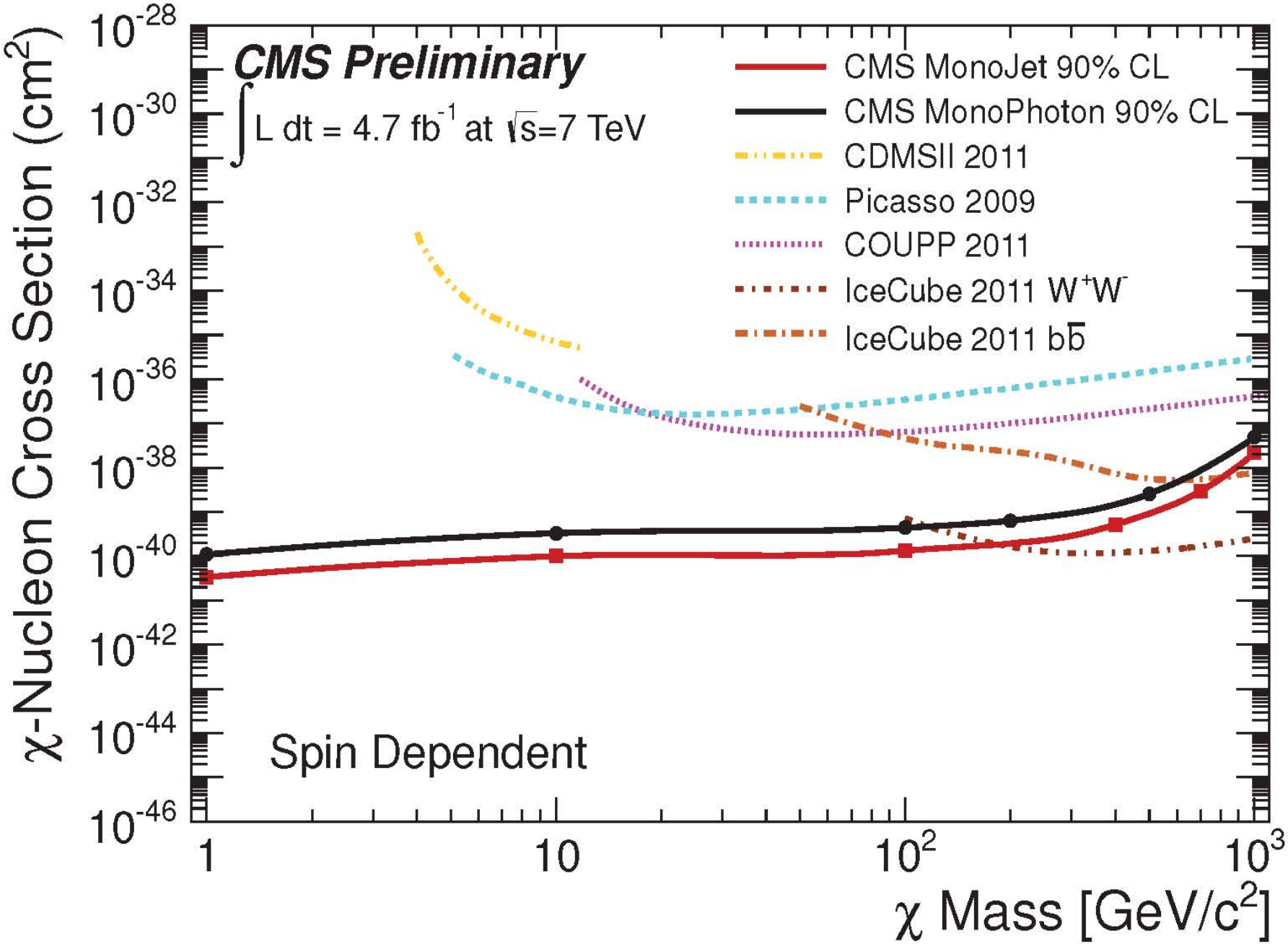


arXiv:1203.0742 [hep-ex]

twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012



twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012



WIMP Questions

- Only <u>one</u> WIMP?

  The 4% of matter we see is pretty complex and varied.

  If social network of several WIMPs, stronger interacting ones:
  - Easier to detect
  - Smaller Ω
- Thermal Production of WIMPS?
  - Super-WIMPs
  - Asymmetric Freeze out
- Maverick WIMPs?
  - Suppose LHC only sees SM Higgs?
  - Wither SNOOZY?
- Leptophilic, Leptophobic, Flavorful, Self-Interacting WIMPs?
- Annual modulation: do we really understand DM phase space?
- Indirect detection gives indirect information

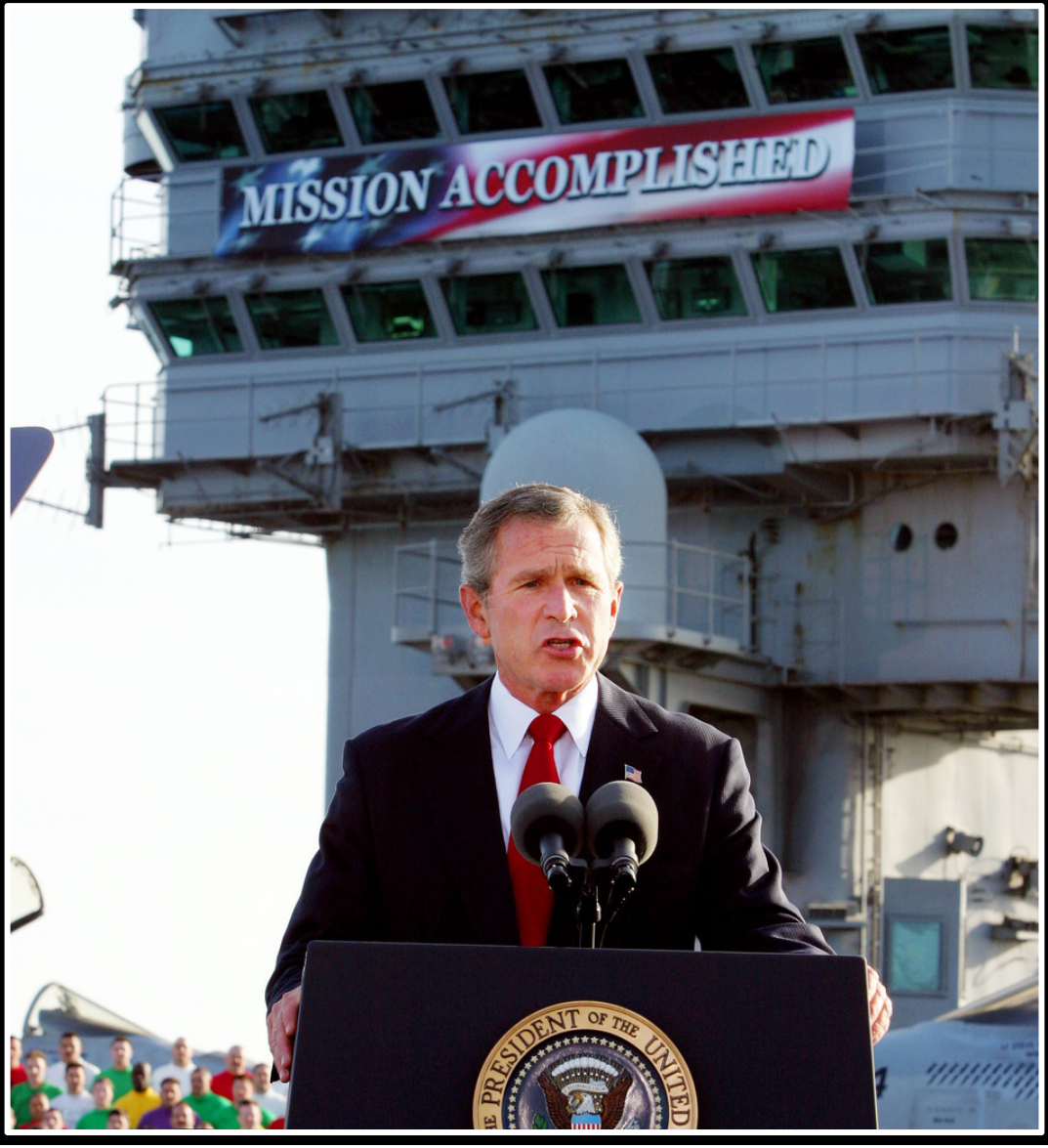
The Decade of the WIMP

- WIMP causation or coincidence (miracle)?
- Situation now is muddled
- Ten years from now the WIMP hypothesis will have either:
  Convincing evidence, or Near-death experience
- Direct detectors, indirect detectors, & colliders race for discovery
- Suppose by 2020 have credible signals from all three???
- Do we need three miracles for WIMP sainthood?

How will we know they are all seeing the same phenomenon?

- When do we stop?

“Mission Accomplished”
What Would It Take?



IT TAKES THE VILLAGE PEOPLE

Big Chief Spokesperson

Cowboy Cosmologist

Hardhat Experimentalist

Swiss-Army at CERN

Beyond SM Guy

SUSY Cop

DARK MATTER JUBILEE

Rocky Kolb University of Chicago June 2012