ISAPP International School on AstroParticle Physics

2 - 13 July 2012
Paris (France)

European Doctorate School

International School of AstroParticle Physics
Multi-Messenger Approach in High Energy Astrophysics

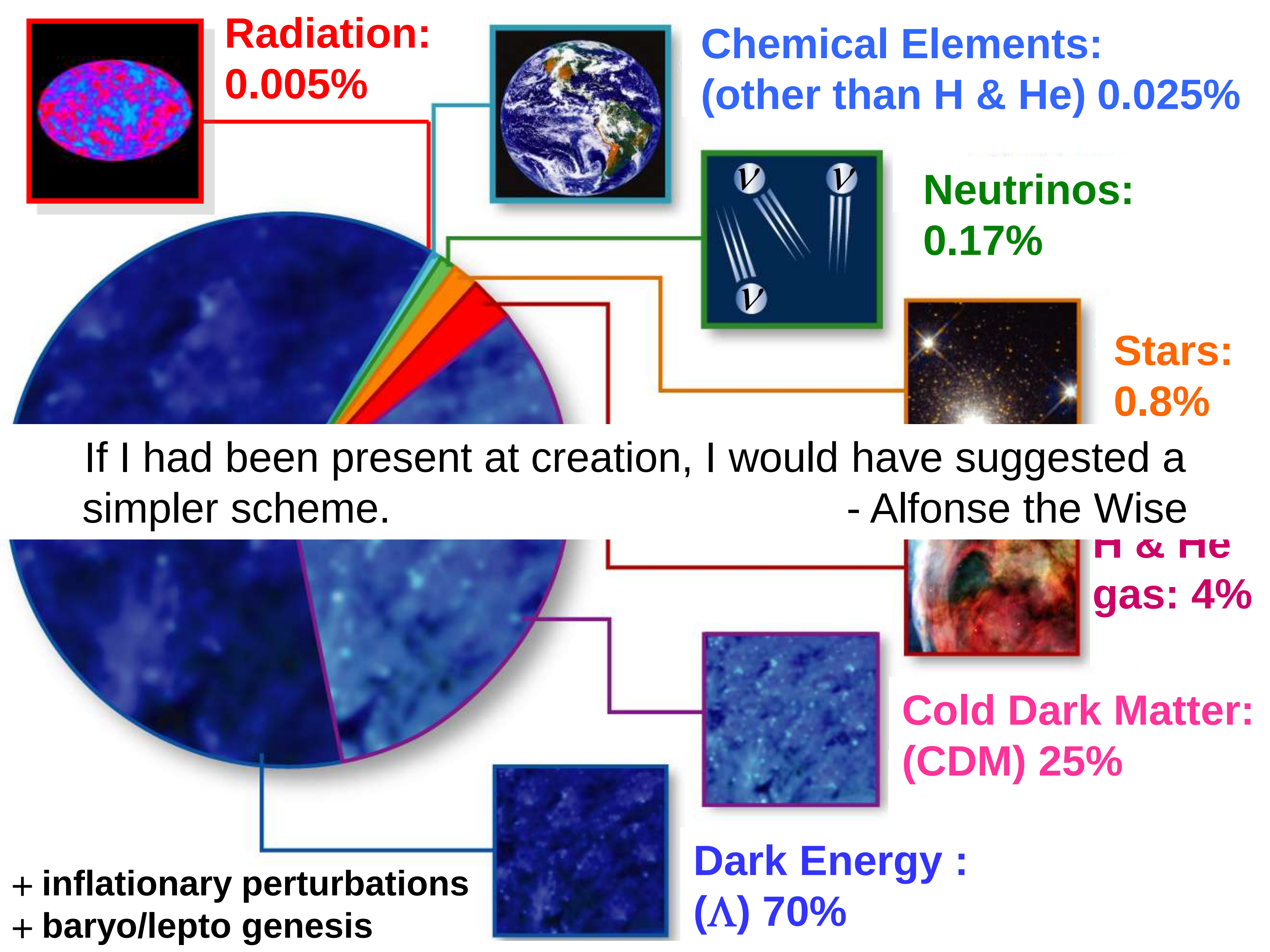
Exotic Physics: Dark Matter and Dark Energy

Rocky I: (Wednesday) Dark Matter
Rocky II: (Thursday) Dark Energy

Rocky Kolb **University of Chicago**


PROUDLY SERVING
DARK MATTER
COFFEE


REGULAR GRIND
CDM
Café du Monde
coffee & chicory
FULL STRENGTH
NET WT. 13 OZS. (369g)



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.

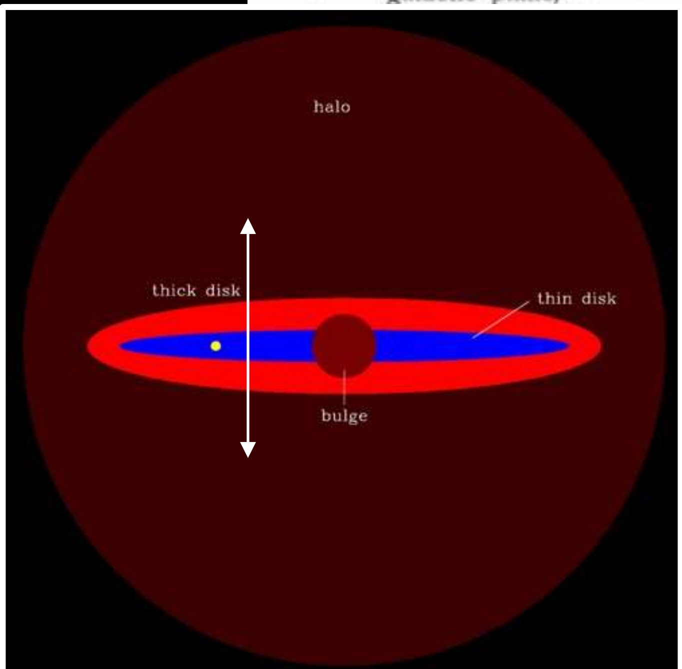
1932 August 17 Volume VI. No. 238.

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.*

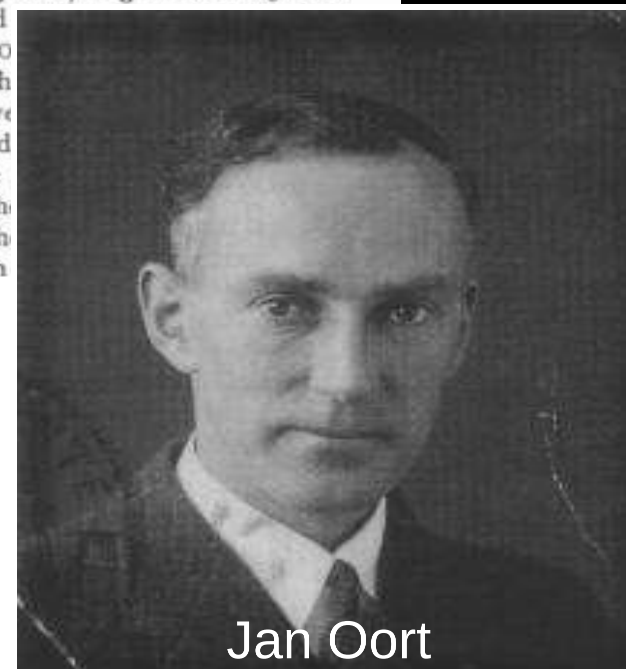
Notations.
z distance from the galactic plane,
Z velocity component perpendicular to the galactic plane,
o,
component of the
la (5), p. 253),
direction of z,
rom the sun,
cubic parsec between

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 Figure 1). Figures 2 and 3 show 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

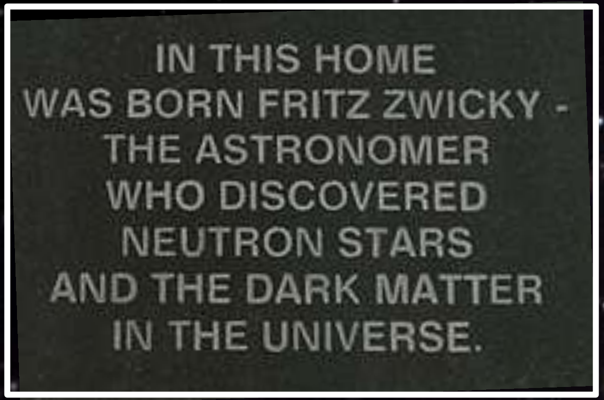


Infer surface mass density from dynamics of stellar motions.

Spoke of "Dark Matter" and "Invisible Matter"



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.

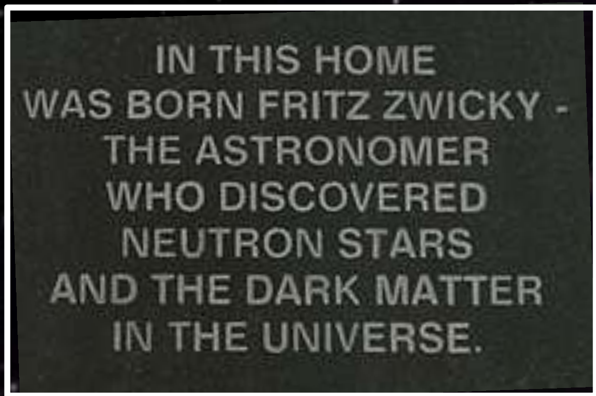
Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_{\odot}$ for the average mass of its member nebulae.

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

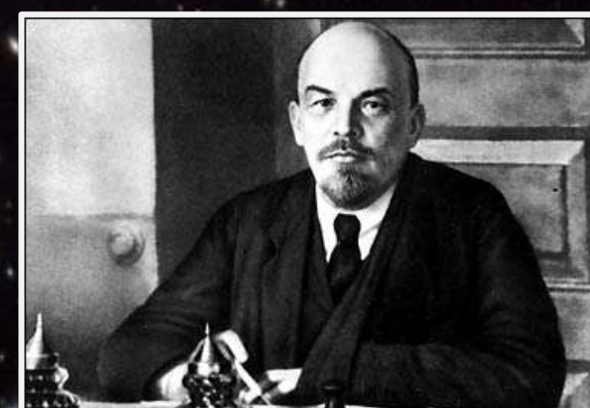


Varna, Bulgaria

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

Fritz Zwicky 1930s

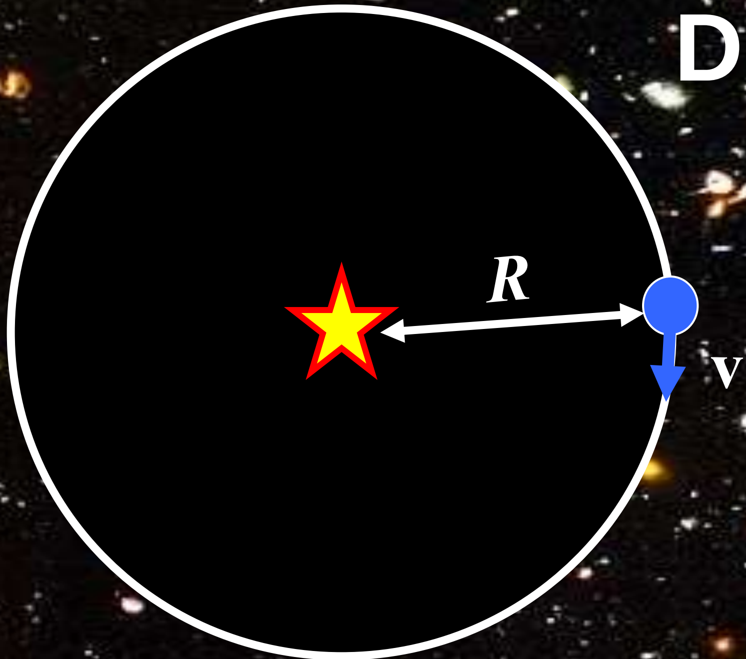
Zurich, Switzerland
(Spiegelgasse 17)



Vladimir Lenin 1916

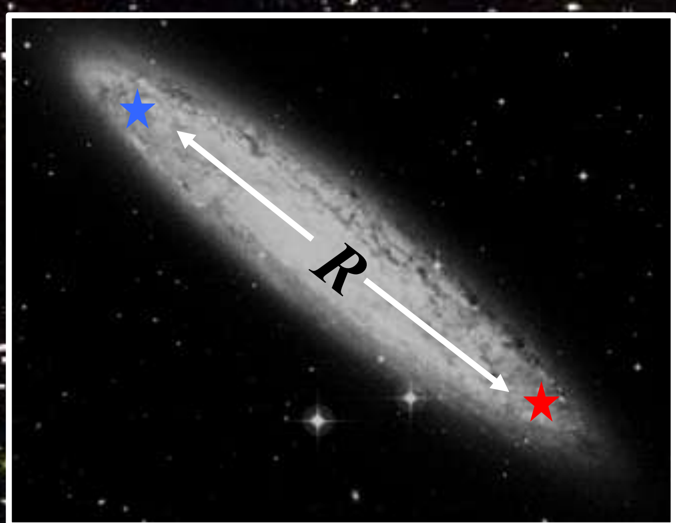
Galaxy Clusters (e.g., Coma)

Dark Matter



$$v^2 = \frac{G_N M_{\odot}}{R}$$

measure v **&** $R \Rightarrow M_{\odot}$



$$v^2 = \frac{G_N M_{<R}}{R}$$

measure v **&** $R \Rightarrow M_{<R}$

"outside" of galaxy, measure v **&** $R \Rightarrow M_{\mathrm{GALAXY}}$

THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970

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

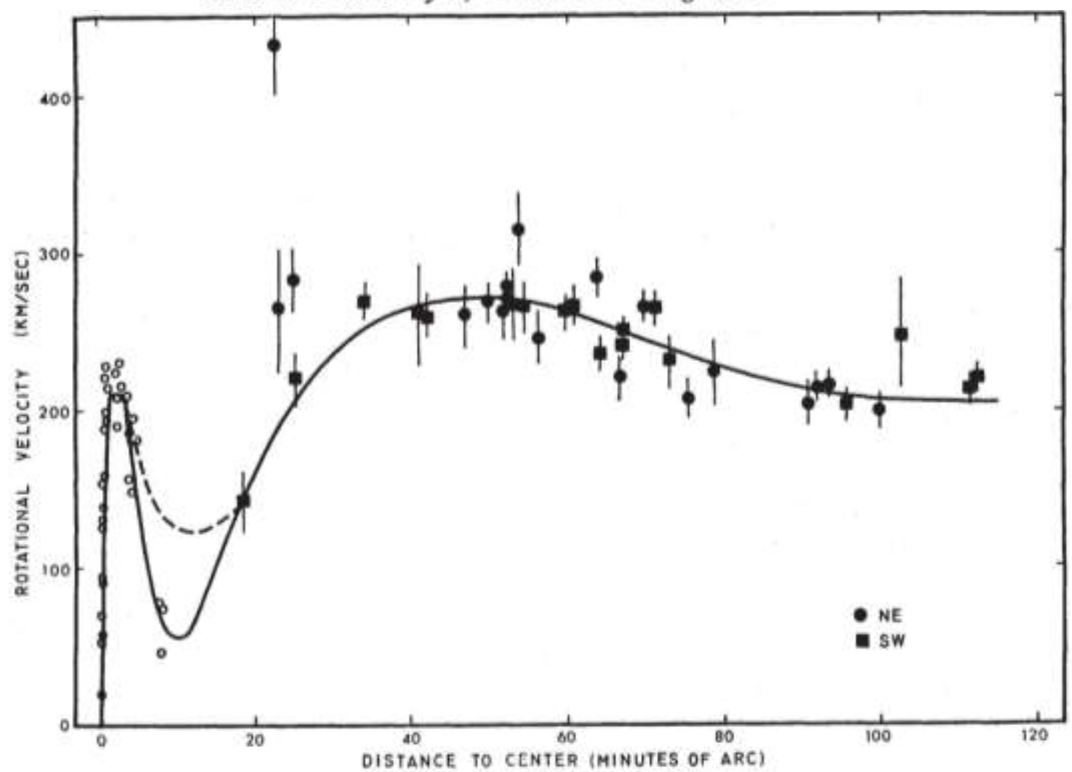
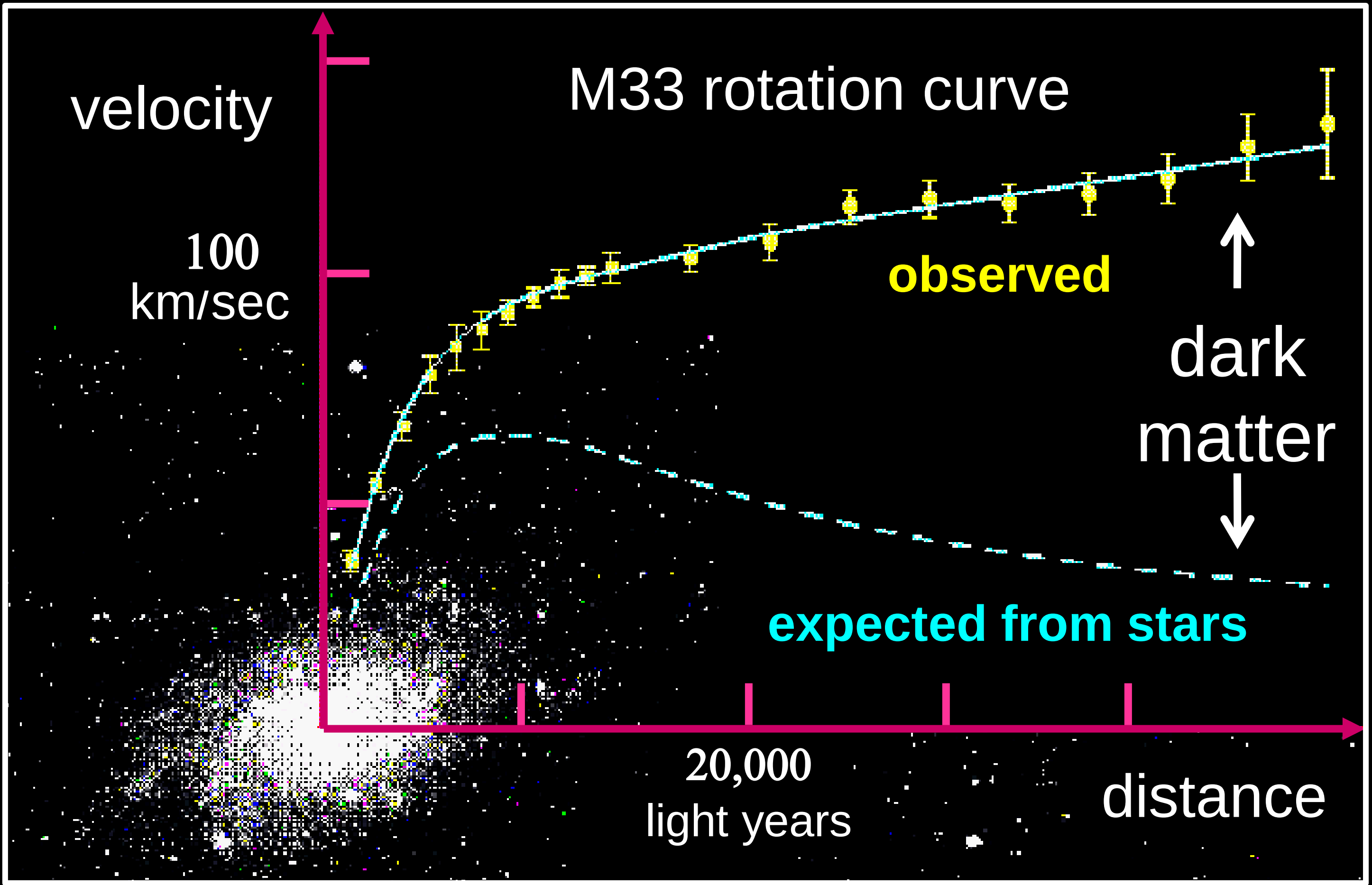


FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately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

Dark Matter

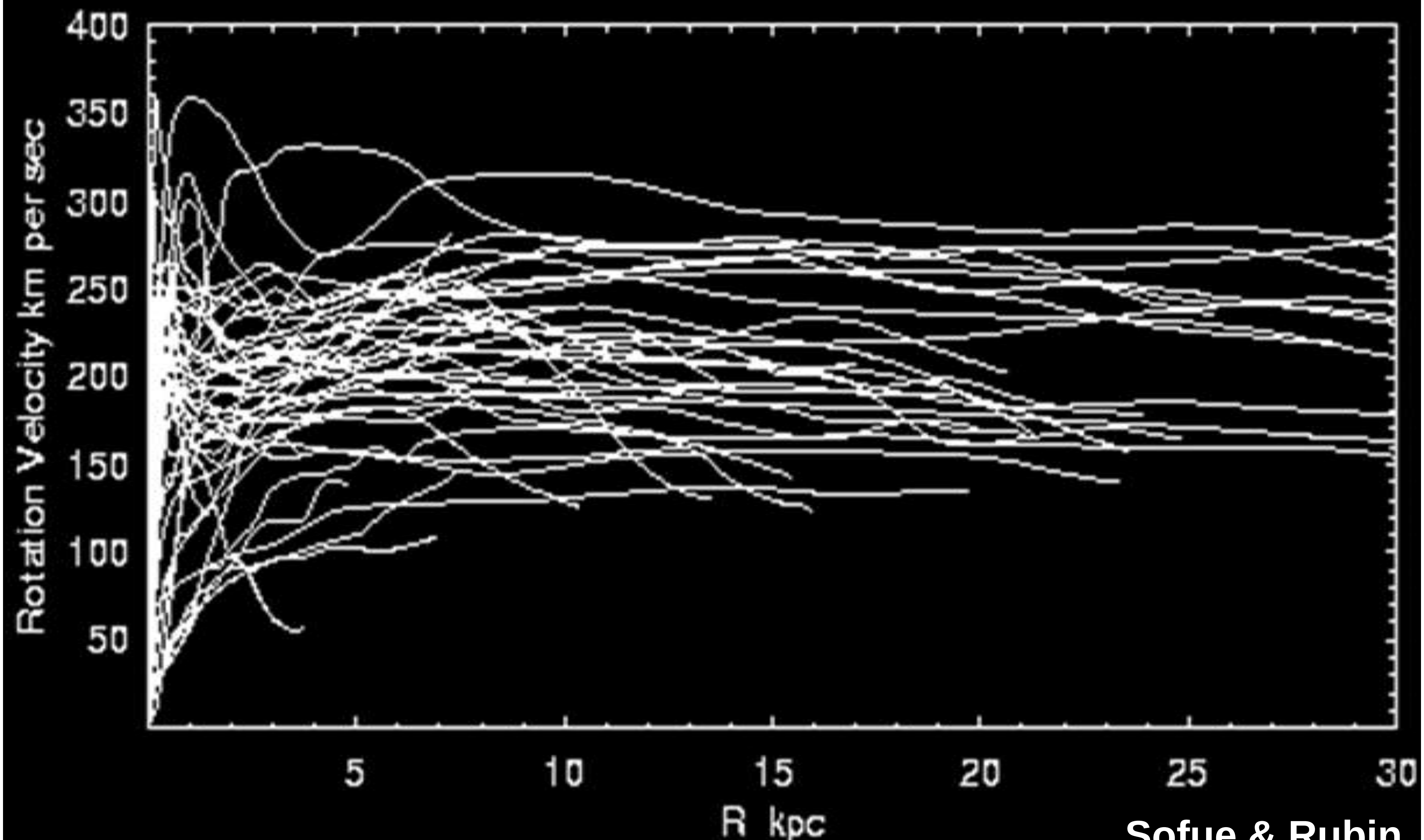


Vera Rubin 1970s

Individual Galaxies (e.g., M33)

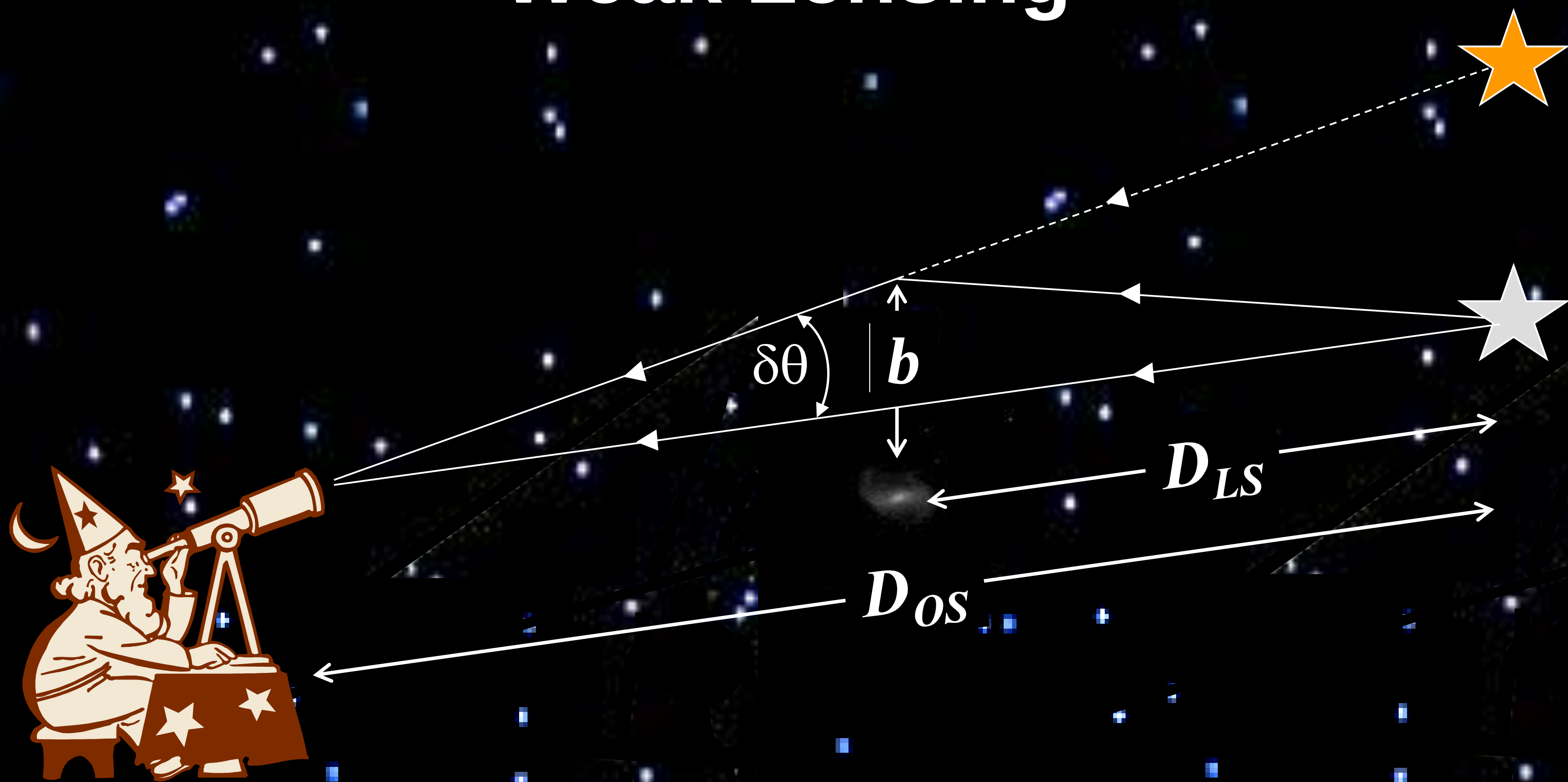
Dark Matter

CO – central regions Optical – disks HI – outer disk & halo



Sofue & Rubin

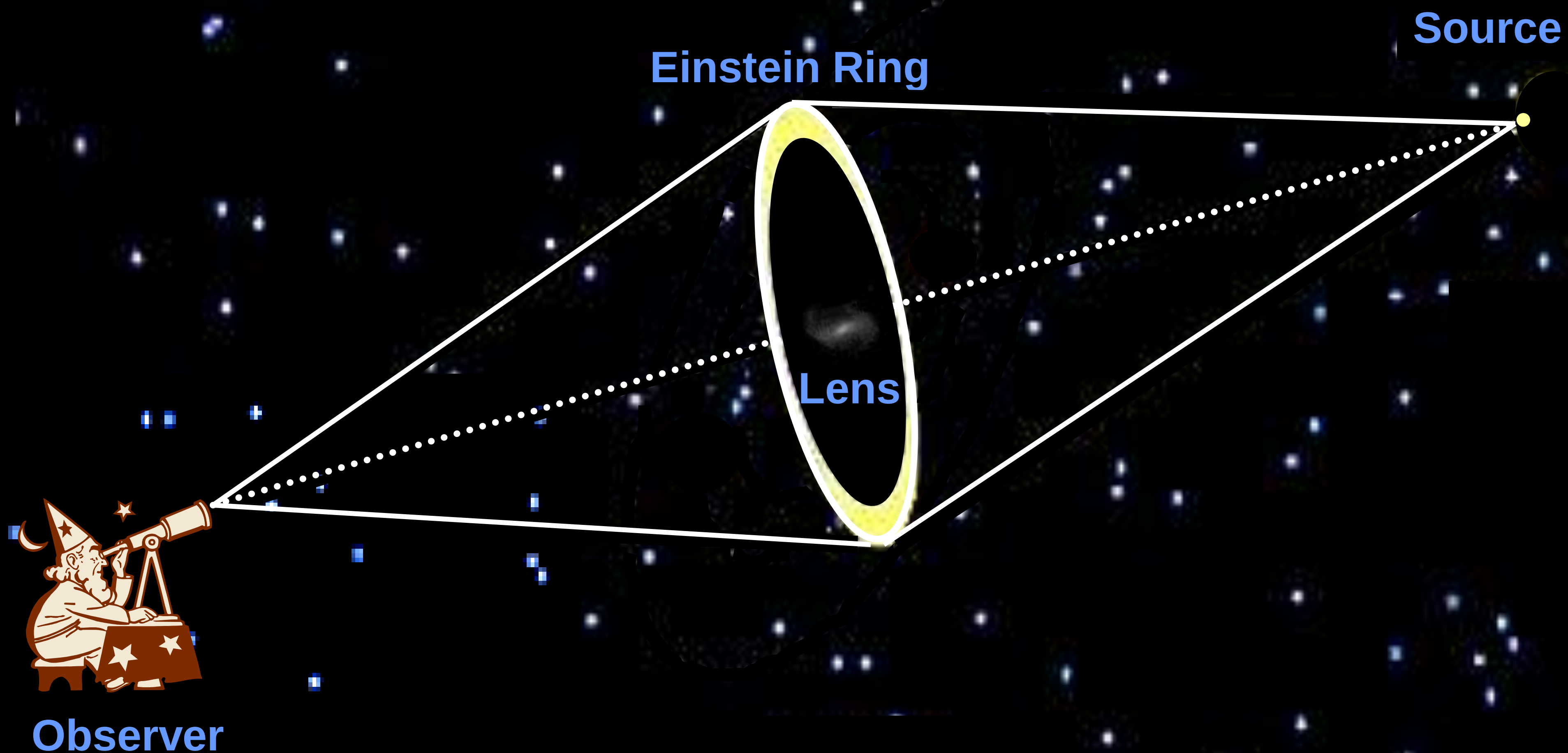
Weak Lensing



observe
deflection
angle

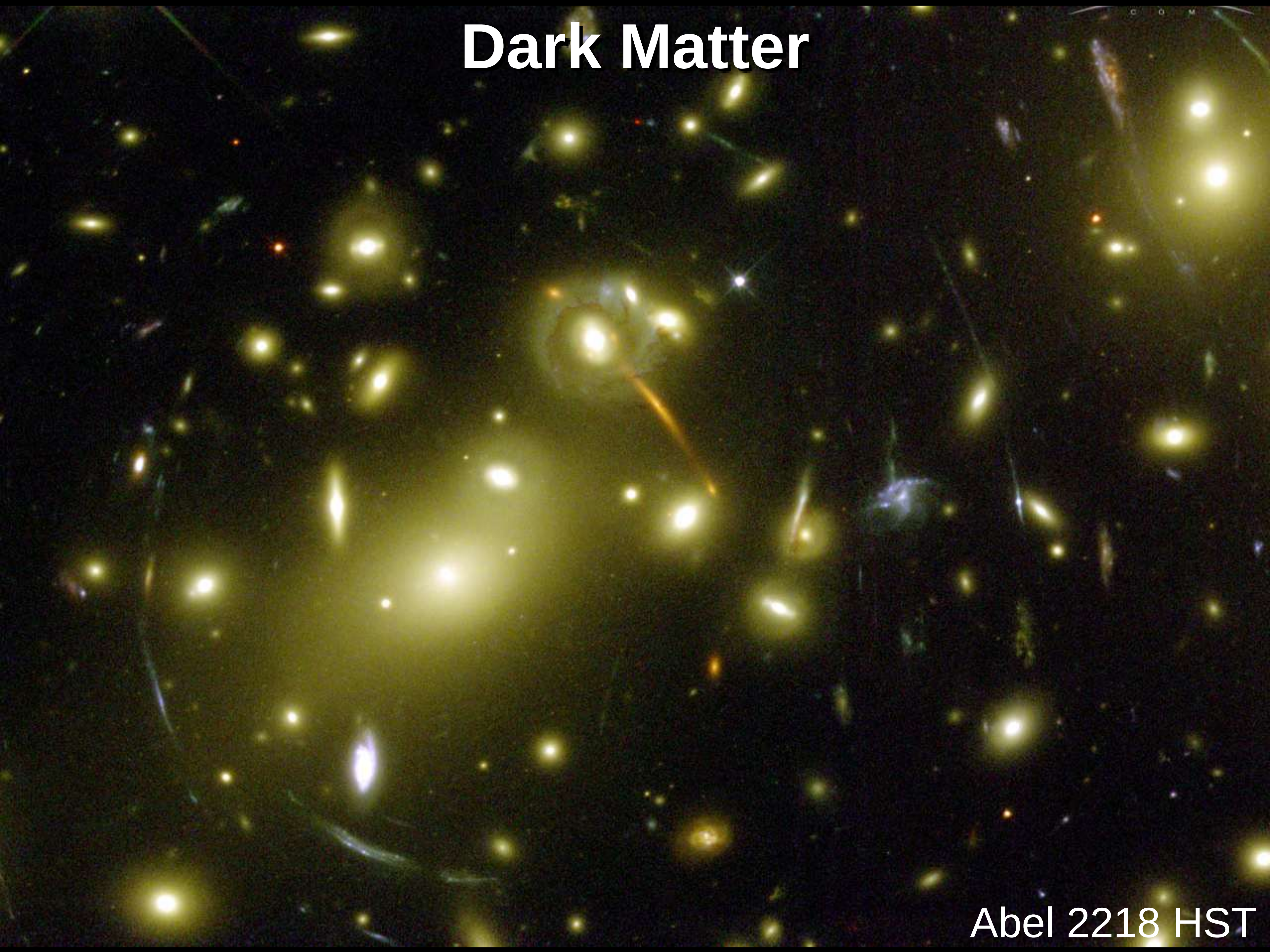
$$\delta\theta = \frac{4GM}{b}\frac{D_{LS}}{D_{OS}}$$

Einstein Ring



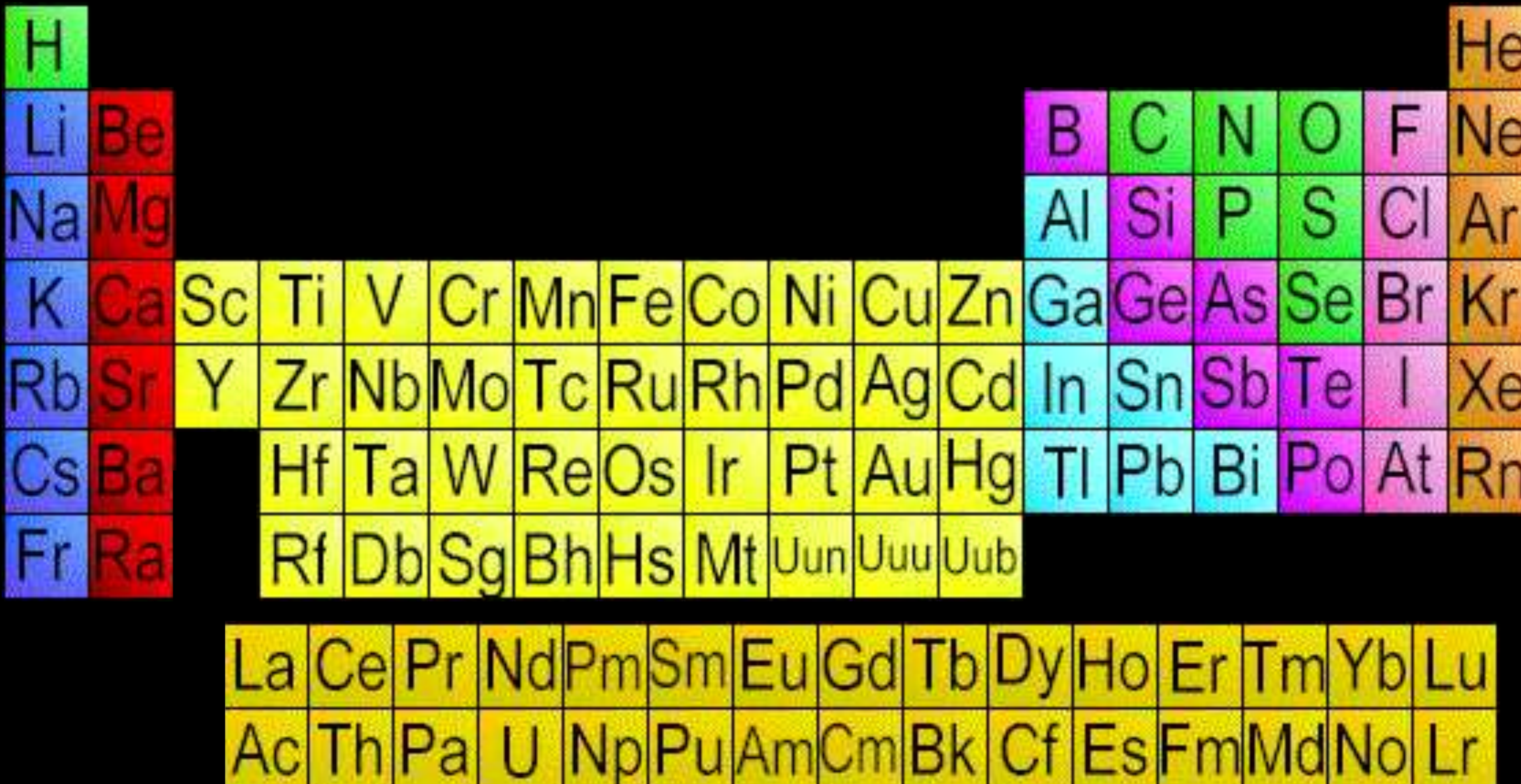
Mass of lens determines angular size of ring

Dark Matter

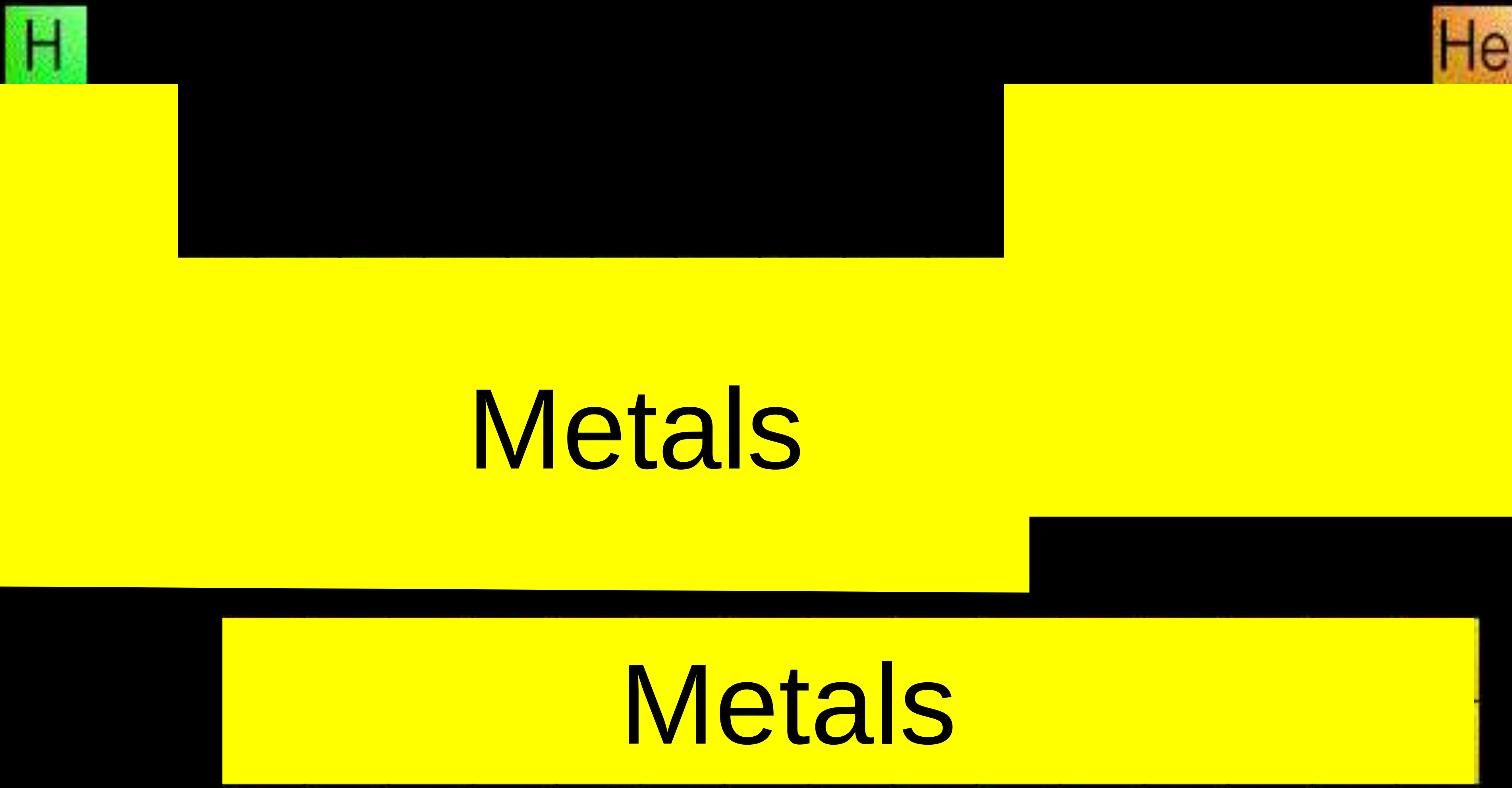


Abel 2218 HST

Periodic Table – Chemist



Periodic Table – Cosmologist



The Universe Today

73%	Hydrogen	(10^{-5} ^{2}H-deuterium)
26%	Helium	(10^{-5} ^{3}He)
1%	Metals	

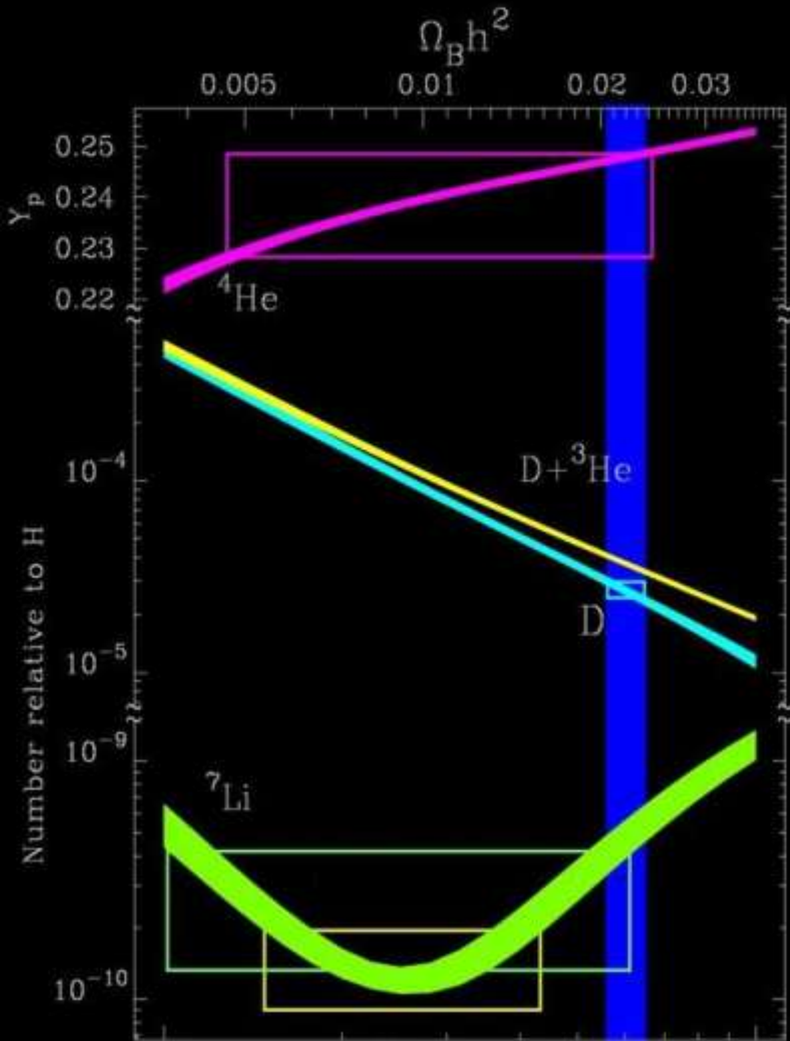
The Universe 3 minutes AB

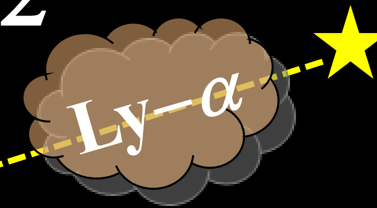
76%	Hydrogen	(10^{-5} ^{2}H- deuterium)
24%	Helium	(10^{-5} ^{3}He)
10^{-8}%	Lithium	

Dark Matter $\Omega_B h^2 \sim 0.02$

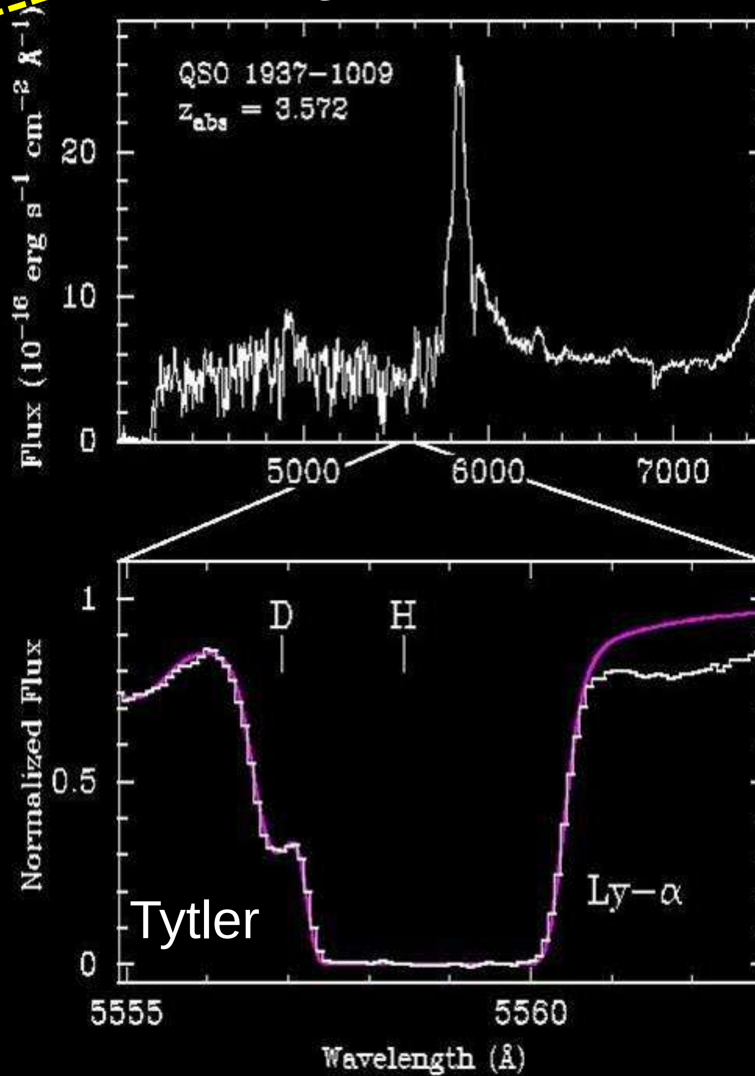
$H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$

$$\Omega_i = \frac{\rho_i}{3H_0^2/8\pi G}$$



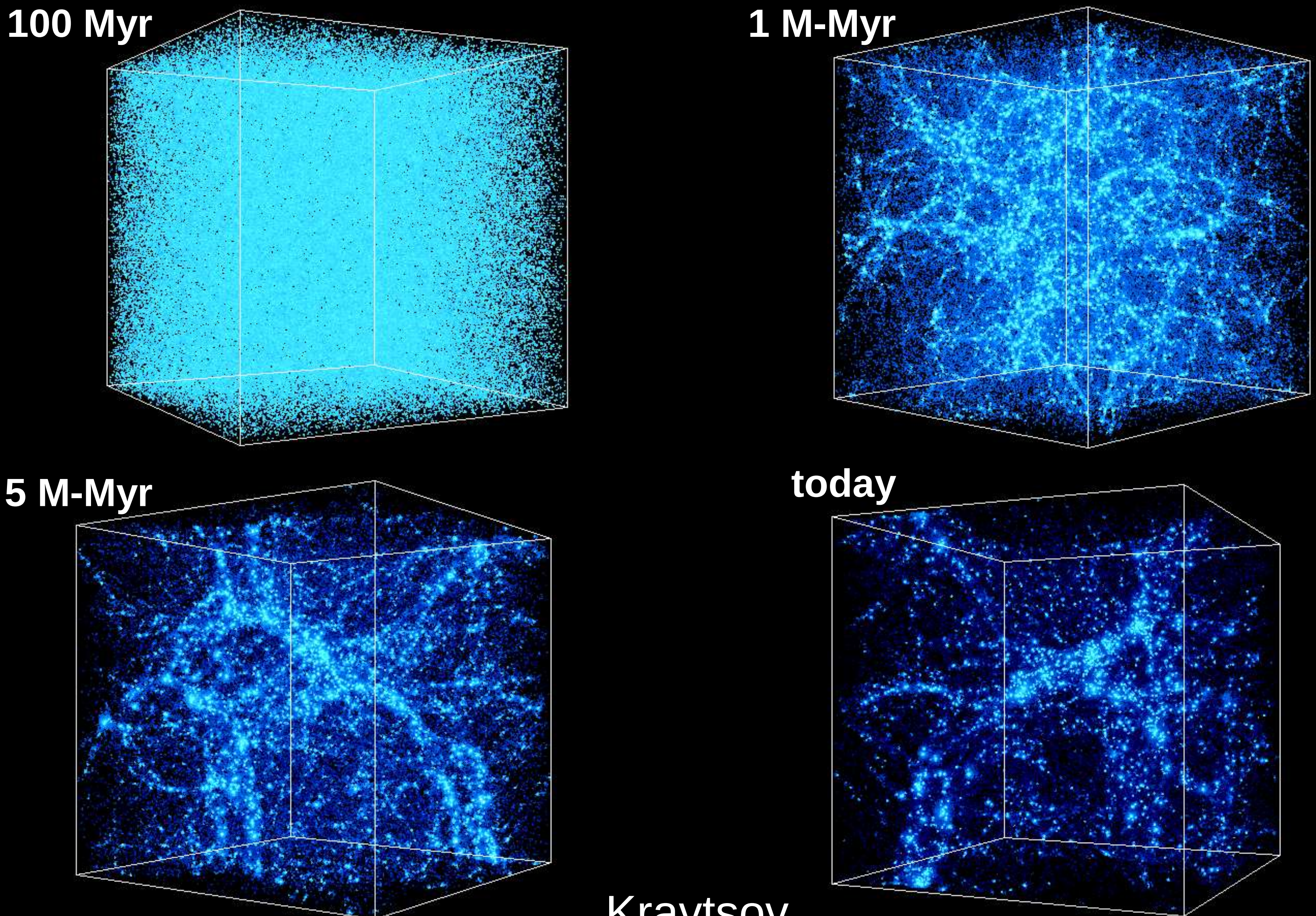


QSO 1937-1009



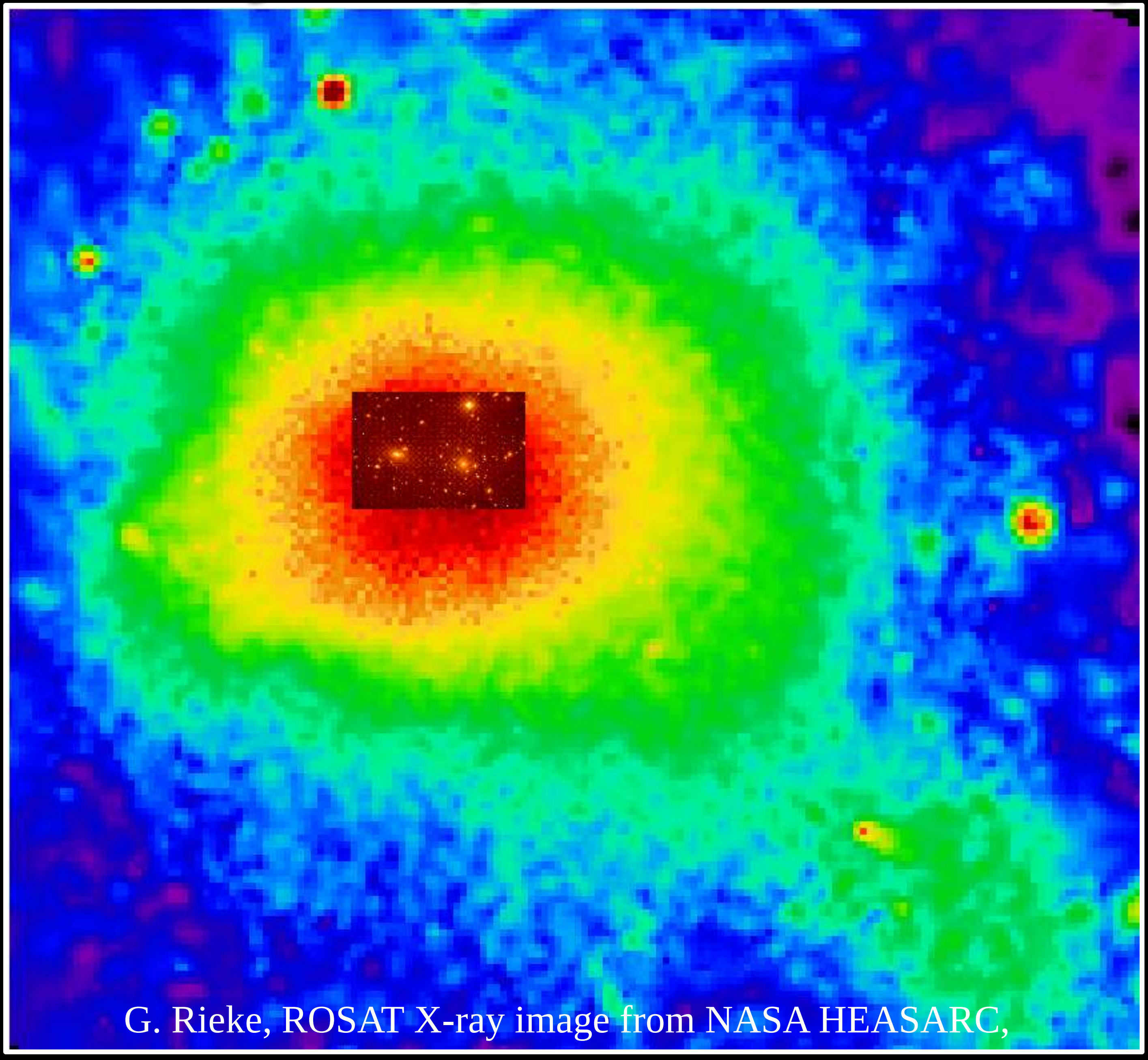
WMAP: $\Omega_B h^2 = 0.0229 \pm 0.00073$

Structure Formation



Kravtsov

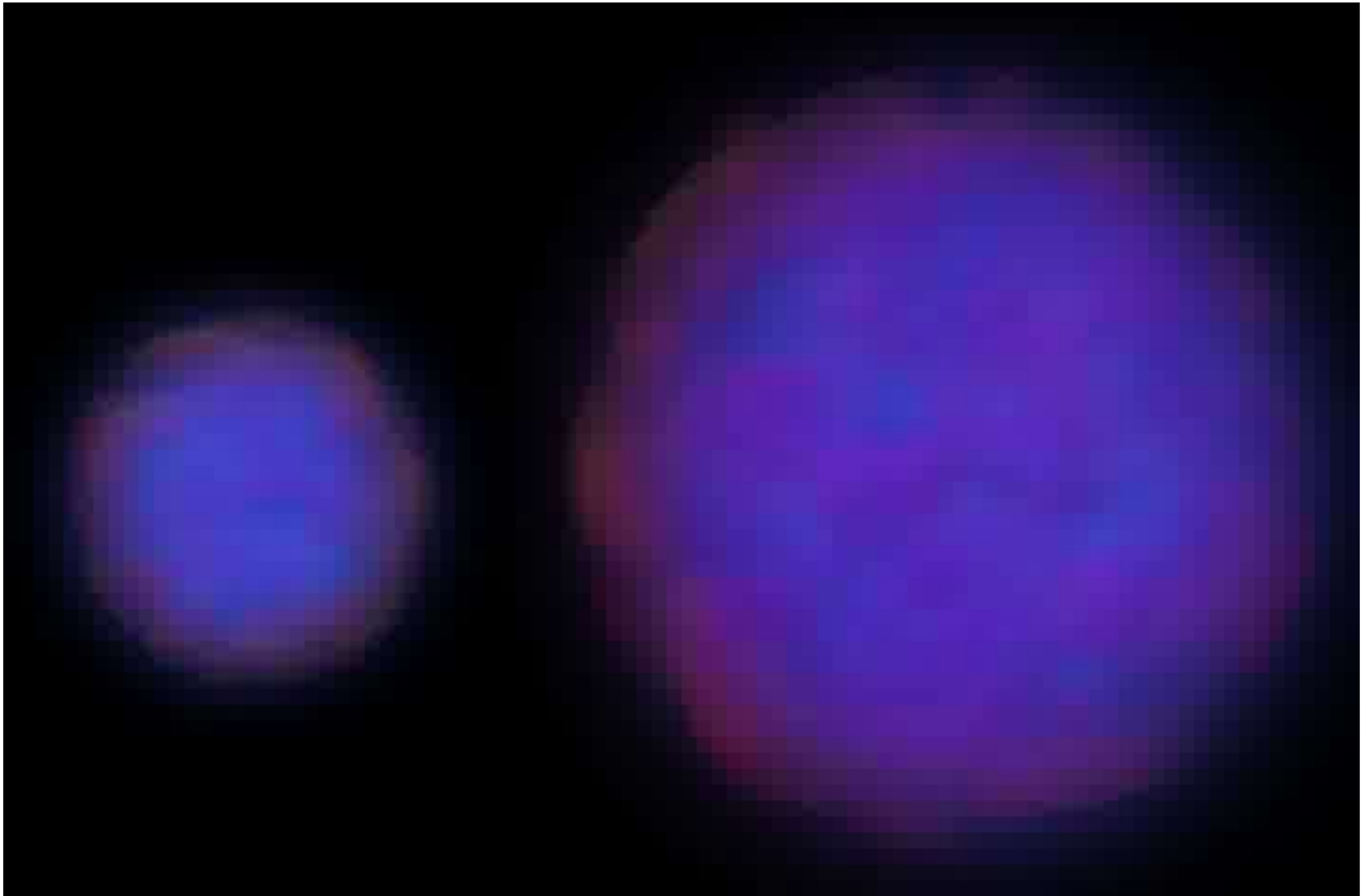
X-Ray Temperature of Galaxy Clusters



Coma cluster in X rays with visual image superimposed

X-Ray temperature measures depth of gravitational potential

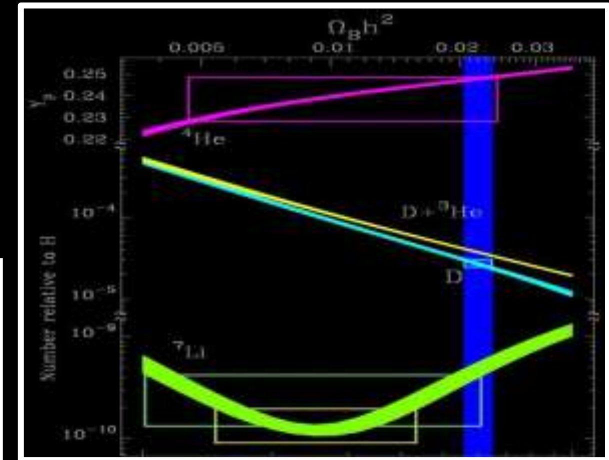
Dark Matter

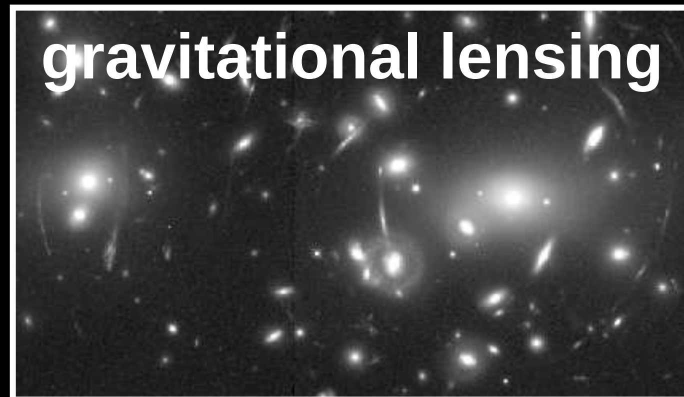


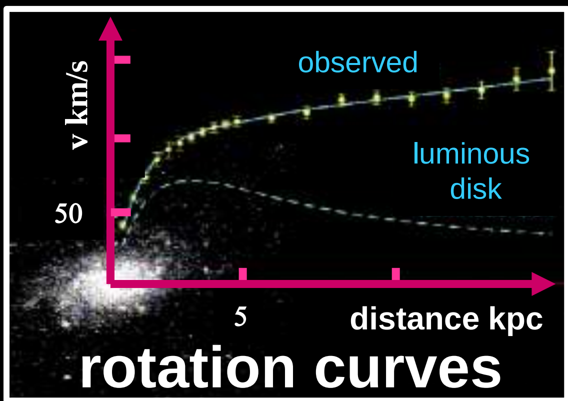
Chandra Science Center

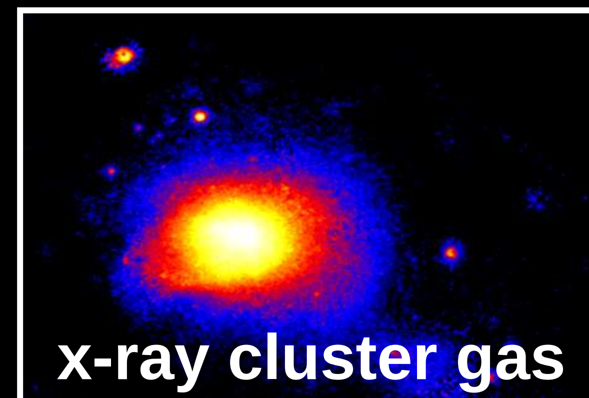
Dark Matter

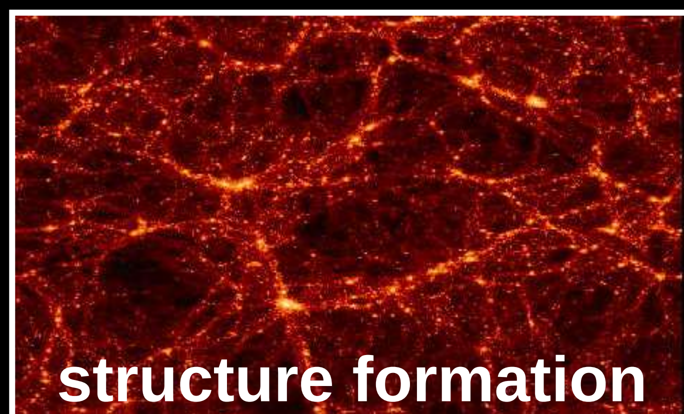

cluster dynamics

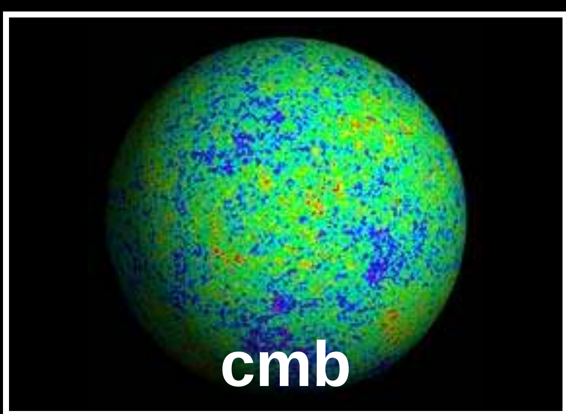

Ω_B h²
0.005
0.01
0.02
0.03
0.25
0.24
0.23
0.22
⁴He
D + ³He
D
⁷Li
Number relative to H


gravitational lensing


v km/s
observed
luminous
disk
50
5
distance kpc
rotation curves

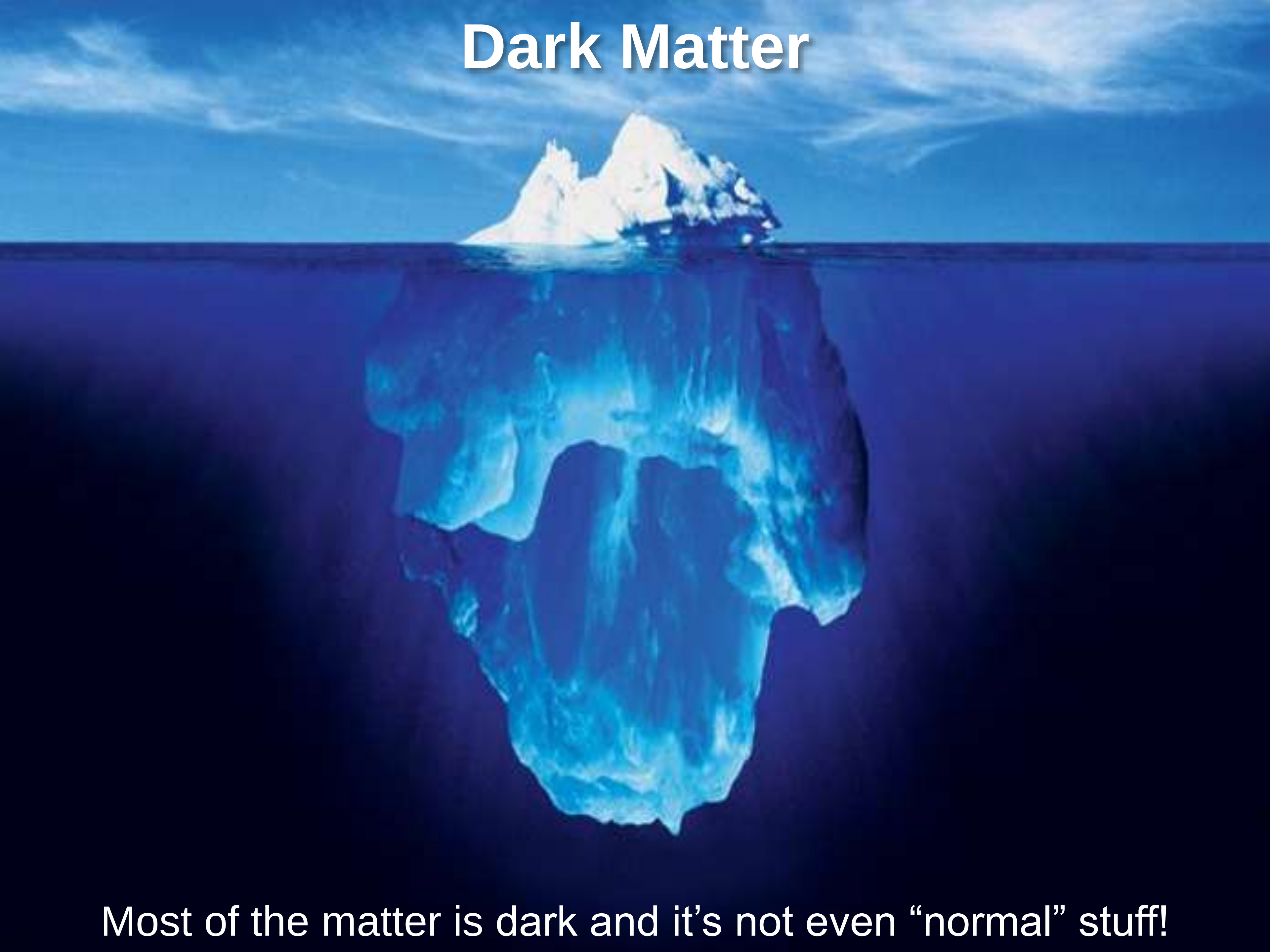

x-ray cluster gas


structure formation


cmb

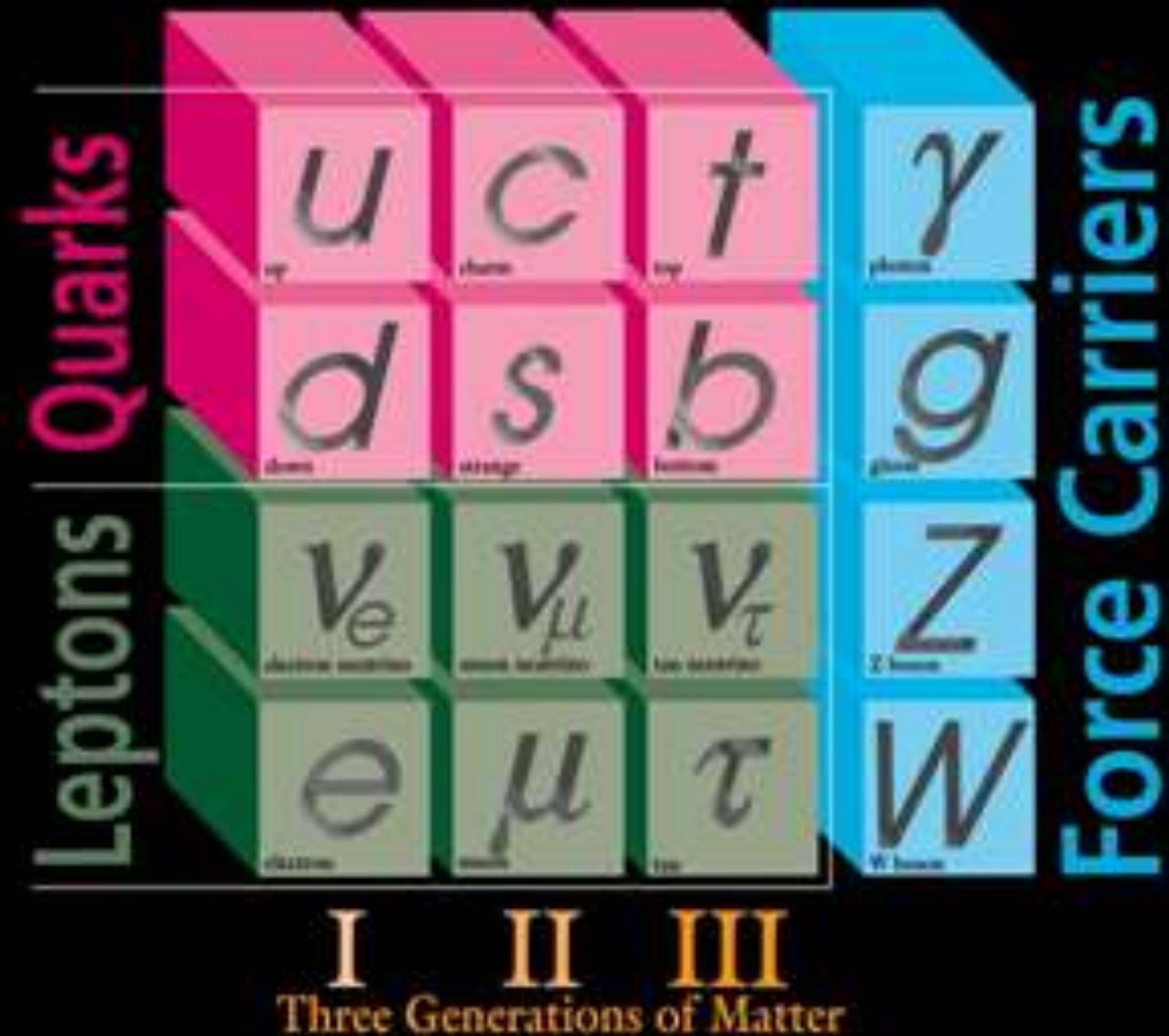

Optical
Dark Matter
X-ray Gas
cluster collisions

Dark Matter



Most of the matter is dark and it’s not even “normal” stuff!

Particles of the Standard Model



ΛCDM: The Standard Model

"How helpful is astronomy's pedantic accuracy, which I used to secretly ridicule!"

Einstein's to Arnold Sommerfeld on December 9, 1915 (measurements of the perihelion advance of Mercury)

Beyond Standard Model Physics

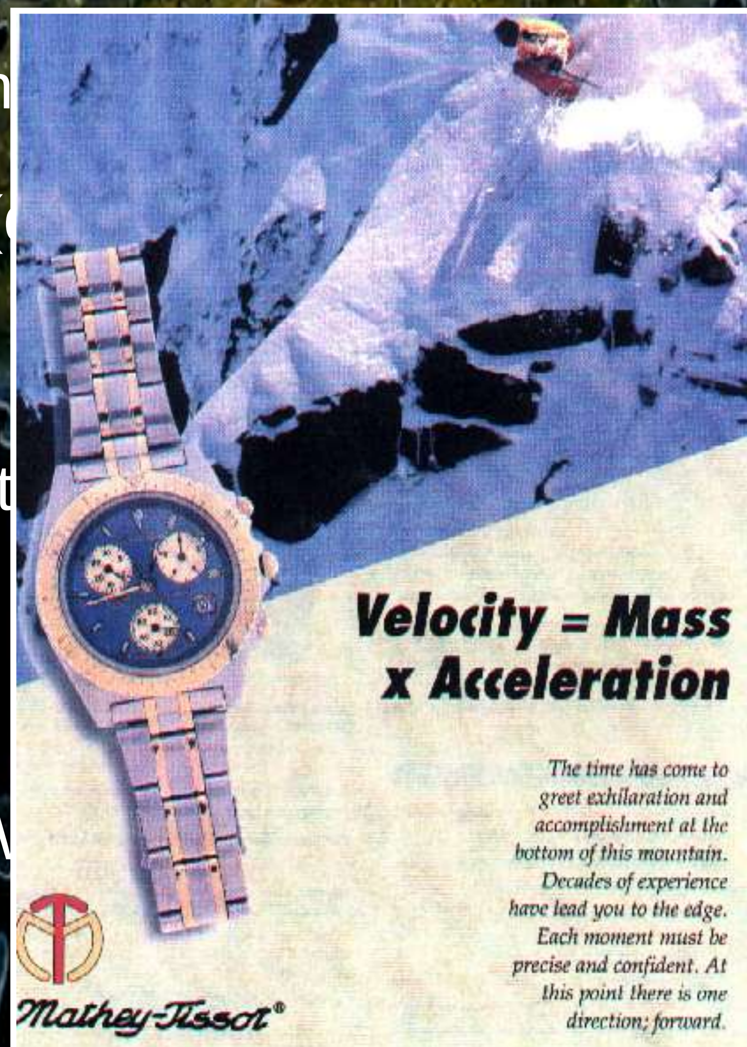
Inner Space / Outer Space

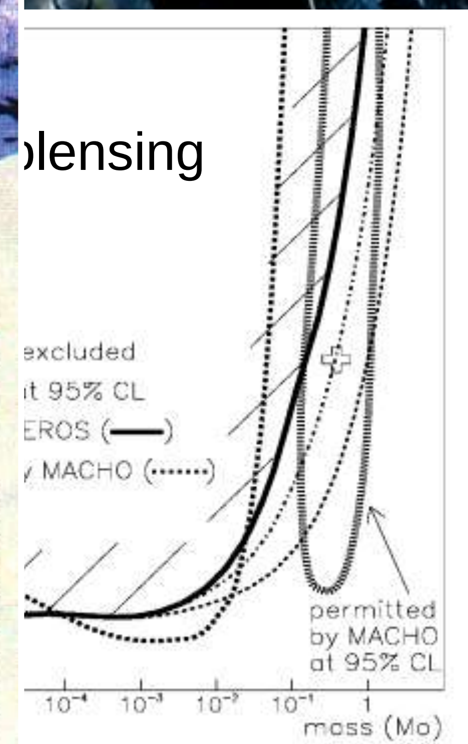
Dark Matter

- Modified Newtonian Dynamics
- Rogue Rocky Plan
- Mass challenged (
- Black holes
- Particle relic from t

plensing

The V





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

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

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

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,

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200$ eV/c^2 for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6$ eV/c^2 for the muonic neutrino.

Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than 5×10^9 years, and Hubble's constant H is not smaller than 75 km/sec-Mparsec $= (13 \times 10^9 \text{ years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1)]

$$\rho < 2 \times 10^{-28} \text{ g/cm}^3.$$

The space surrounding us is filled presently with equilibrium radiation of temperature 3°K [4]. It is proposed that this is "relict" radiation and is proof of the high temperature possessed by the plasma during the pre-stellar high-density period.

At a temperature of the order of 3 MeV for ν_e and of the order of 15 MeV for ν_μ, complete thermodynamic equilibrium existed between ν, γ, e^+, and e^-. The number of other particles in this equilibrium is small, except perhaps gravitons, which, however, have no effect on the arguments that follow. In thermodynamic equilibrium, the ratio of the number of fermions and antifermions with spin 1/2 to the number of quanta is

$$[\nu_e] + [\bar{\nu}_e] = [\nu_\mu] + [\bar{\nu}_\mu] = [e^+] + [e^-] = 2\frac{\int(e^x + 1)^{-1}x^2dx}{\int(e^x - 1)^{-1}x^2dx}[\gamma] = 1.5[\gamma].$$

However, during the course of the cooling from $T > m_ec^2$ (for which these relations are written) to the present time, when $T \ll m_ec^2$, these relations change, since the annihilation

NEUTRINO MASS AND MIXING IMPLIED BY UNDERGROUND DEFICIT OF LOW ENERGY MUON-NEUTRINO EVENTS

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Received 14 March 1988

Recent observations of a deficit of cosmic ray muon-neutrino interactions in underground detectors suggest that the muon neutrinos may have oscillated to another state. We examine possible neutrino mass and mixing patterns, and their implications for vacuum and matter effects on solar neutrinos, on neutrinos passing through the earth, and on terrastrial neutrino beams. By invoking the see-saw mechanism of neutrino mass generation, we draw inferences on closure of the universe with neutrino masses, on the number of generations, on t-quark and fourth generation masses, and on the Peccei–Quinn symmetry breaking scale. Testable predictions are suggested.

The Kamiokande Collaboration has recently re-

(d) Relic tau neutrinos have sufficient energy density to close the university [11] (thus favoring hot

nos, to electron single-prong events, presumably dominantly due to electron-neutrinos is 59% with a 7% statistical error, of the expected ratio found by Monte Carlo calculation. Input to the Monte Carlo are the atmospheric neutrino fluxes calculated for the Kamioka site [2], which include the effects of the earth's magnetic field and mean solar activity, and measured low energy neutrino cross sections, including π–^{16}O nuclear effects. Although there are 20% uncertainties in the calculated flux normalizations, and 10% imprecision in the low energy neutrino cross sections, the reported uncertainty in the ν_e/ν flux ratio is less than 5% Similarly a small ambiguity is ob-

gamma rays or neutrons. No systematic effect has

other similar underground experiments [3], although those results are not statistically compelling in themselves. Barring some undetected systematic effect, it appears that neutrino oscillations offer the simplest explanation of the data.

In this letter we analyze the data in terms of the neutrino oscillation hypothesis. Combining the oscillation parameters thus determined with the see-saw model for neutrino masses, we make further predictions and propose future experimental tests.

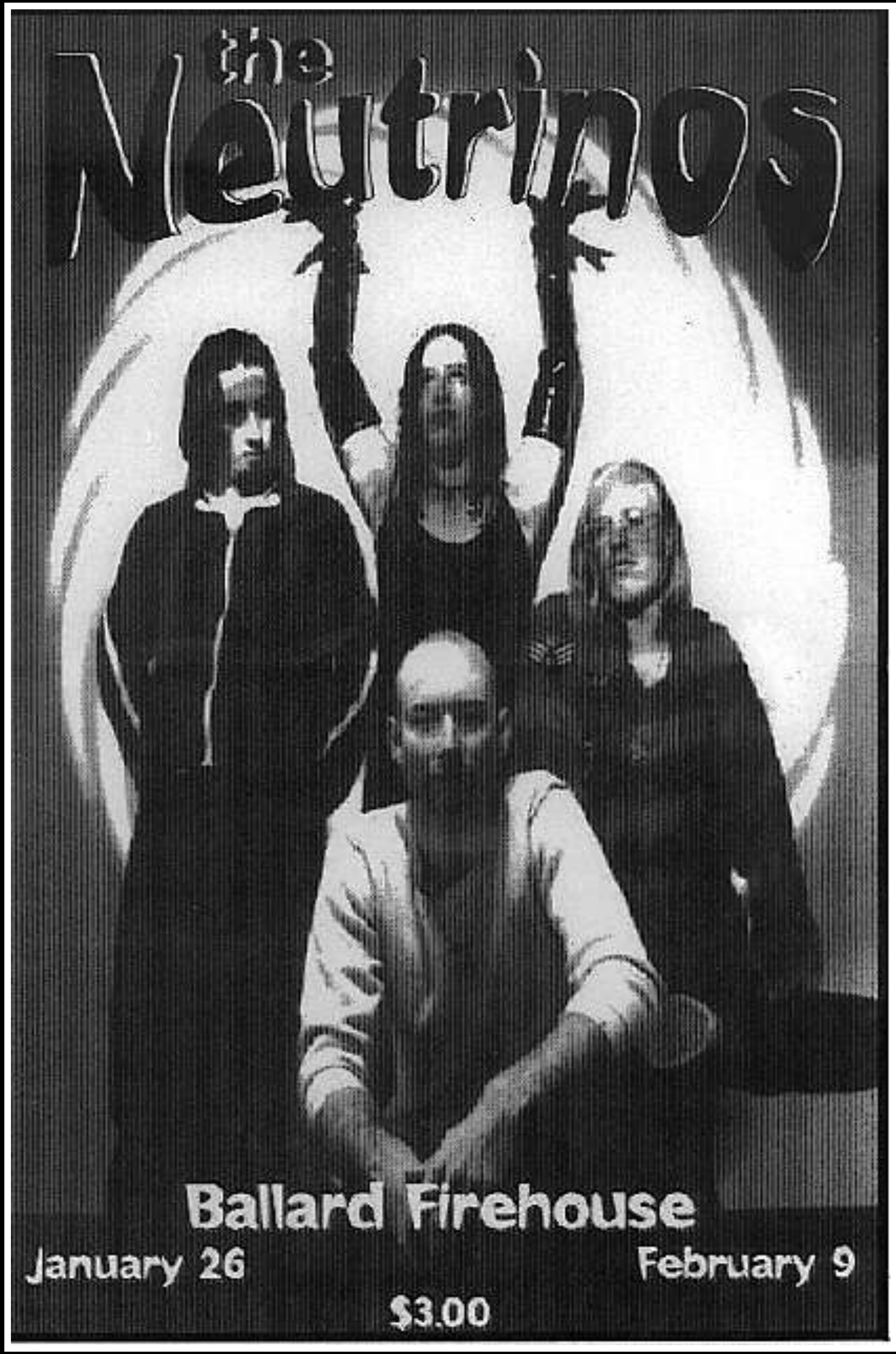
We begin by listing the experimental facts that are relevant in the determination of the oscillation parameters. They are:

WIMPy Neutrinos

- Neutrinos exist:
  three active + sterile?
- Neutrinos have mass:
  Atmospheric (10^{-2} eV)
  Solar (10^{-3} eV)
- Contribute to Ω
  hot thermal relic:

$$\Omega_{\nu\nu} \approx \frac{m_\nu}{47\ \mathrm{eV}}$$

- Not most of dark matter
  too light! too hot!



WIMPy Sterile Neutrinos (or Gravitinos)

- weaker interactions
- decouple earlier
- diluted more
- can have larger mass
- smaller velocity than neutrinos: “warm”

Particle models with sterile neutrinos (or gravitinos) in desired mass range are “unfashionable” (IMO).

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

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)]

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

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

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]:

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

(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 ½ 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

$$\langle \sigma v \rangle \simeq G_F^{\,2} m_L^{\,2} N_A / 2\pi$$

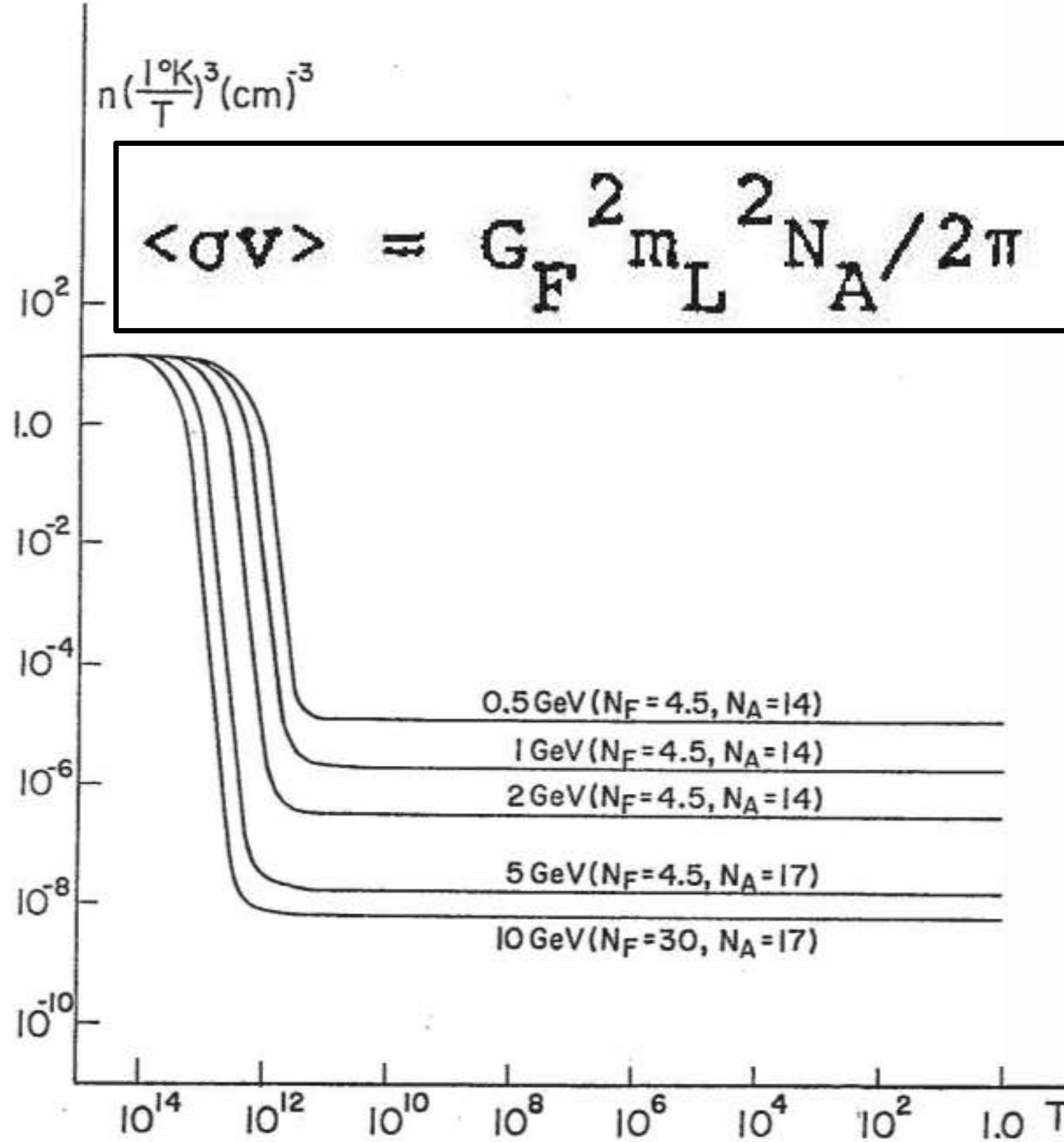
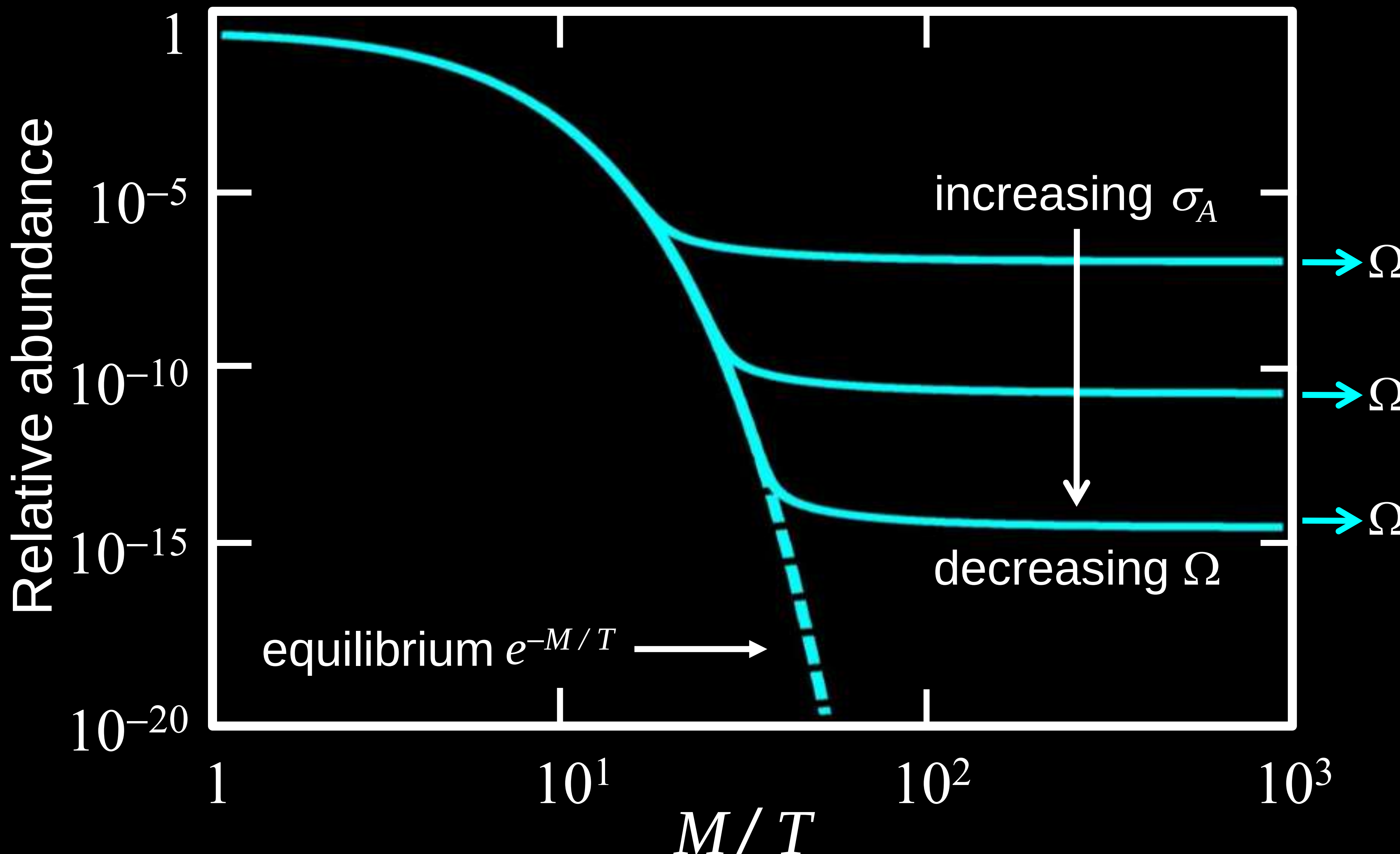


FIG. 1

Cold Thermal Relics*



* An object of particular veneration.

Cold Thermal Relics Are WIMPs

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

WIMP (<u>W</u>eakly <u>I</u>nteracting <u>M</u>assive <u>P</u>article)

The WIMP Miracle

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

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

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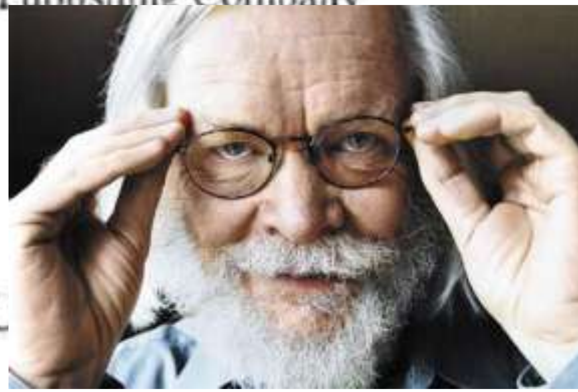
Received 1977 December 12; accepted 1978 February 14

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



SU … G*

John ELLIS and J. S. HAGELIN

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

CERN, CH-1211 Geneva 23, Switzerland

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

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
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(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 $M\simeq27$ GeV. There seems to be a reasonable chance of building a detector sensitive to $\epsilon\sim50-100$ eV (considerably more optimistic possibilities are discussed in Ref. 5). For $\epsilon\gtrsim50-100$ eV, we need $m\gtrsim1-2$ 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

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[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
[c] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
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[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
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[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	1st WIMP Candidate
Lee & Weinberg	05/77	35 Years Ago	Prototype WIMP
Stecker	12/77	35 Years Ago	Indirect Detection
Ellis, Hagelin, *et al.*	09/83	28 Years Ago	SUSY WIMPs
Goodman & Witten	01/85	27 Years Ago	Direct Detection
Ahlen *et al.*	05/87	25 Years Ago	First Limits

We Swim in a Sea of WIMPs

- A mysterious, invisible particle species is around us
- There are 10^7 in this room
- With a mass $30–100$ times the mass of a proton
- 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

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 champioun 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

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

Particle Physics:

Discover dark matter and learn how it is …

… grounded in physical law

… embedded in an overarching physics model/theory

Astro Physics:

Understand the role of dark matter in …

… formation of structure

… evolution of structure

WIMPs:

massive, stable, “weakly” interacting, $SU(3)_C \times U(1)_{EM}$ singlet

WIMP must be a *BSM* (but perhaps not far BSM) particle.

WIMPs

(Dark is the New Black)

Dark matter is a complex physical phenomenon.

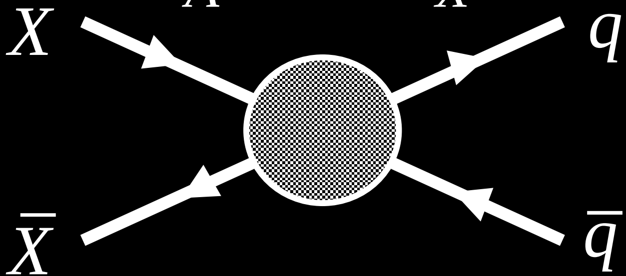
WIMPs are a simple, elegant, compelling explanation for a complex physical phenomenon.

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

— *Tommy Gold*

WIMP Crossings

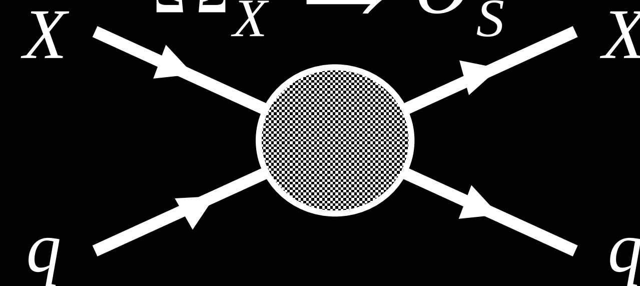
$$\sigma_A \Rightarrow \Omega_X$$



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

Primordial Production
Indirect Detection

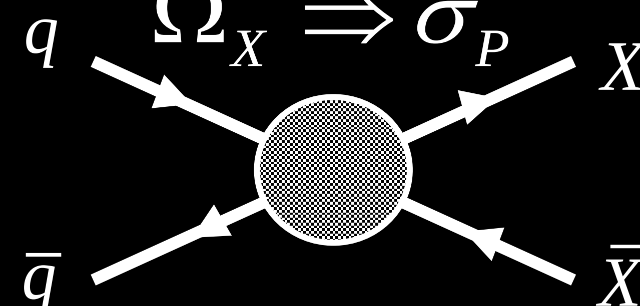
$$\Omega_X \Rightarrow \sigma_S$$



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

Direct Detection

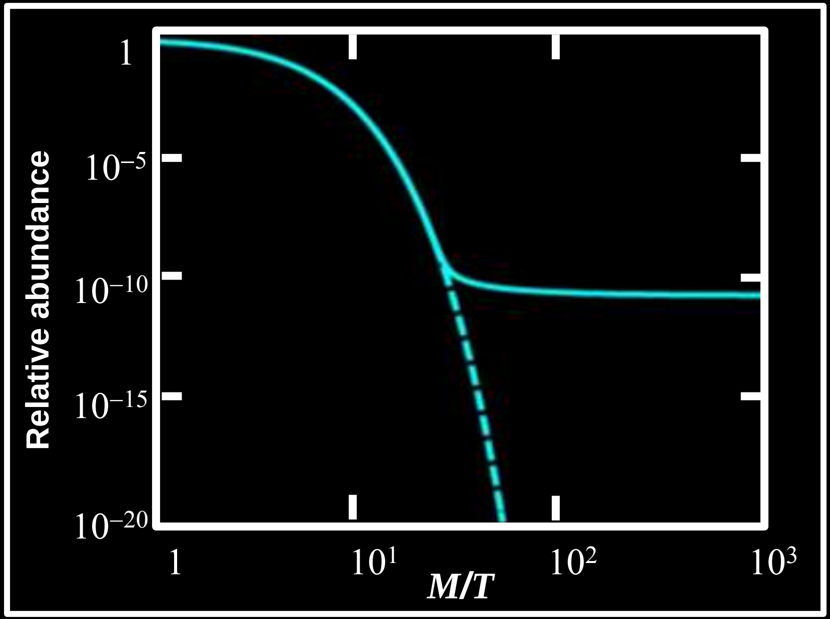
$$\Omega_X \Rightarrow \sigma_P$$

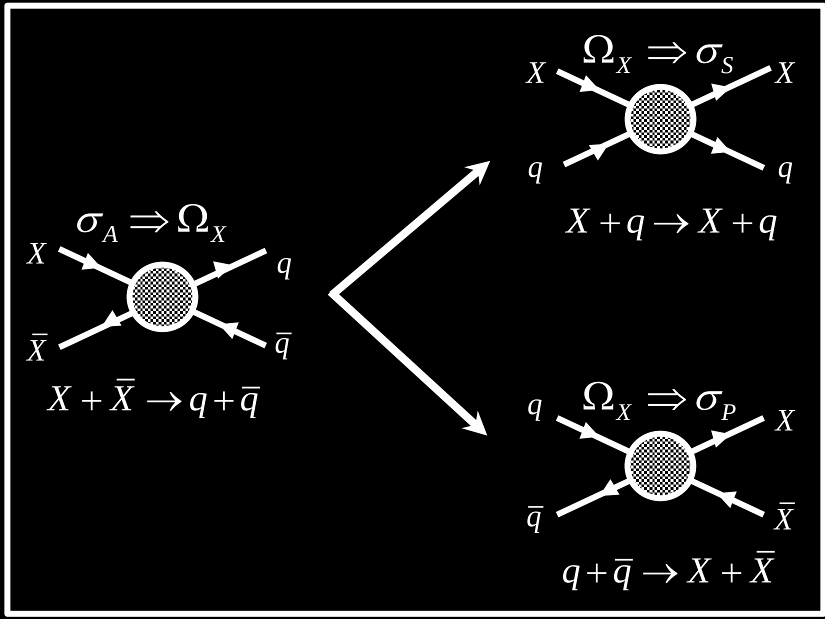


$$q + \bar{q} \rightarrow X + \bar{X}$$

Accelerator Production

WIMP Crossings





Not quite so simple:

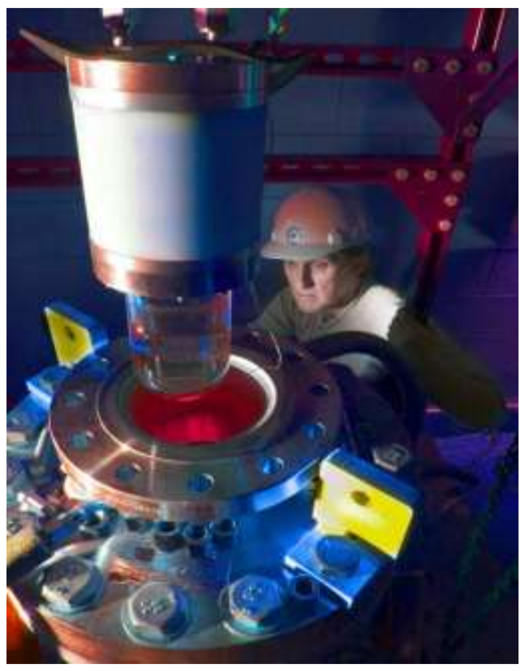
- velocity dependence
- co-annihilation
- resonances
- superwimps
- dependence on M, g_*,
- ...

Not quite so simple:

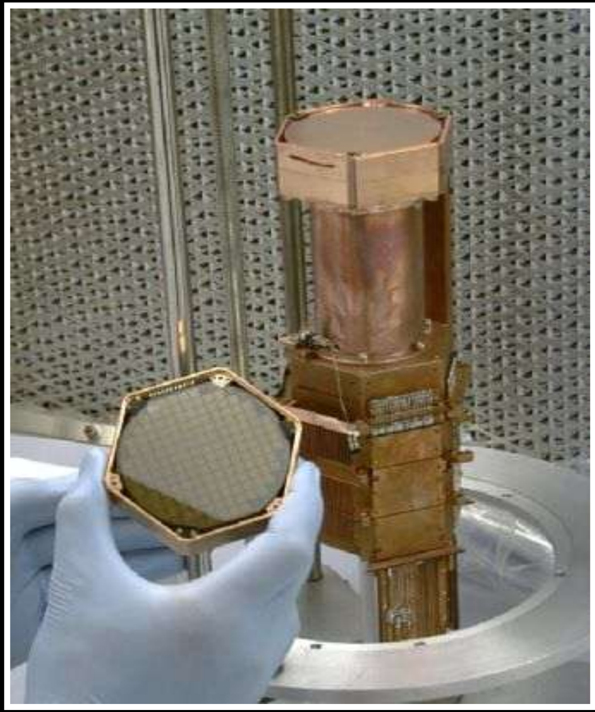
- velocity dependence
- local phase-space density
- flavor dependence
- co-production
- Sommerfield enhancement
- …

Direct Detection

COUPP



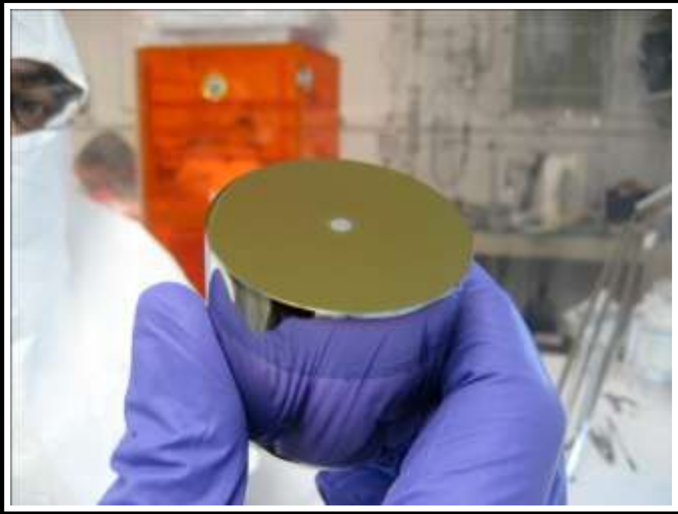
CDMS



CRESST

DAMA

CoGeNT



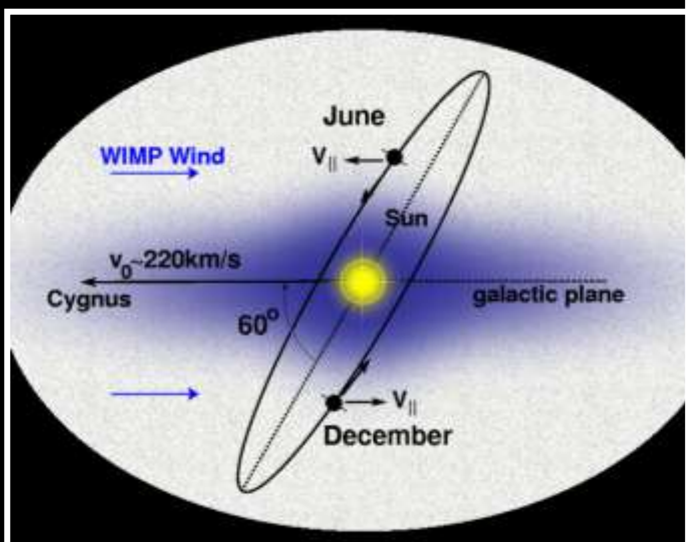
(+ EDELWEISS, XENON, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, …)

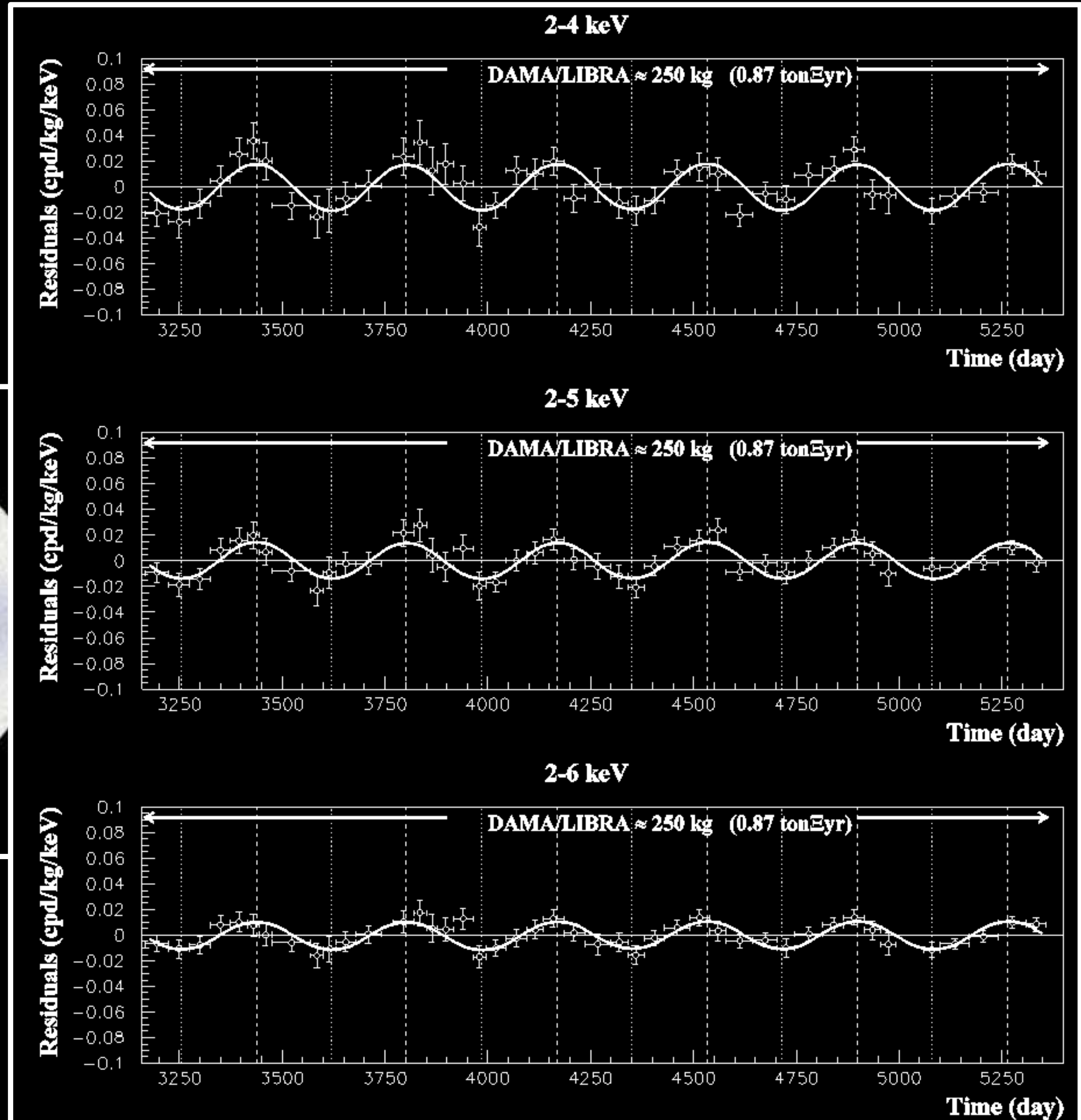
Direct Detection

- Depends on local WIMP phase-space density
- Usual assumption: $\rho_{DM} = 0.3\ \mathrm{GeV\ cm^{-3}}$
- Usual assumption: Maxwellian velocity distribution in galactic rest frame

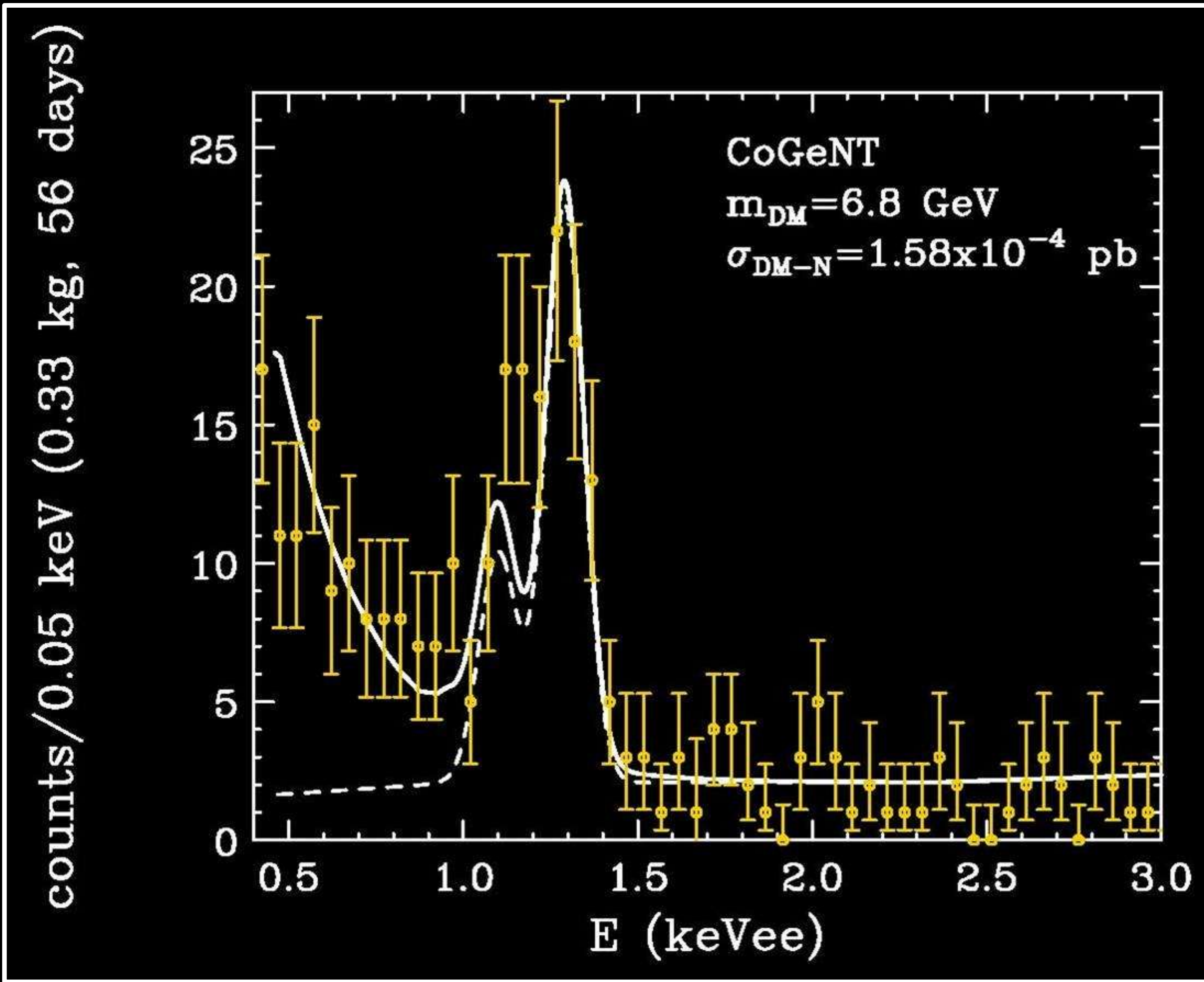
DAMA/LIBRA

$$\cos\,\omega\,(t-t_0)$$
$$T = 2\pi/\omega = 1 \text{ year}$$
$$t_0 = 152.5^d \text{ (2 June)}$$



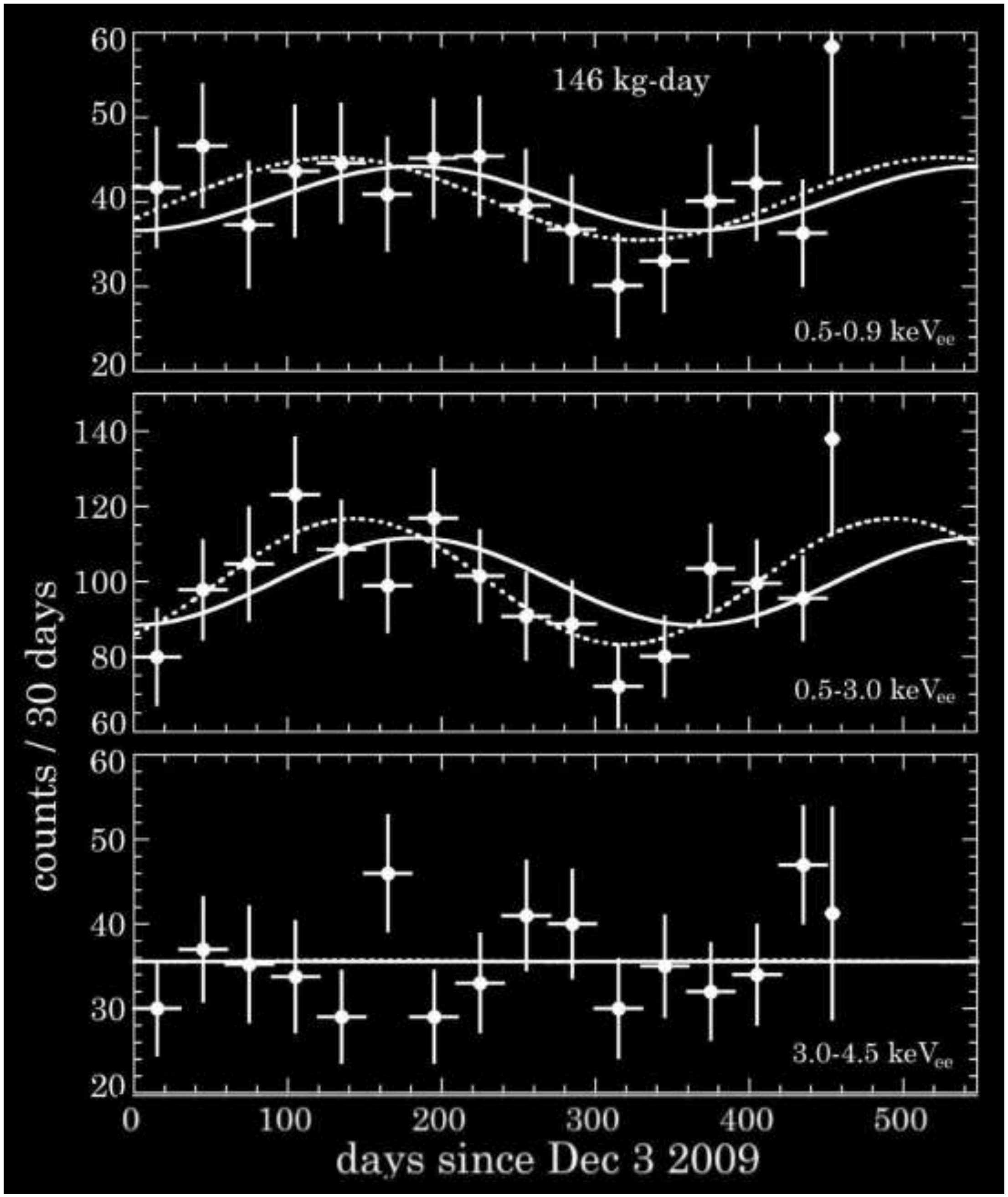


CoGeNT



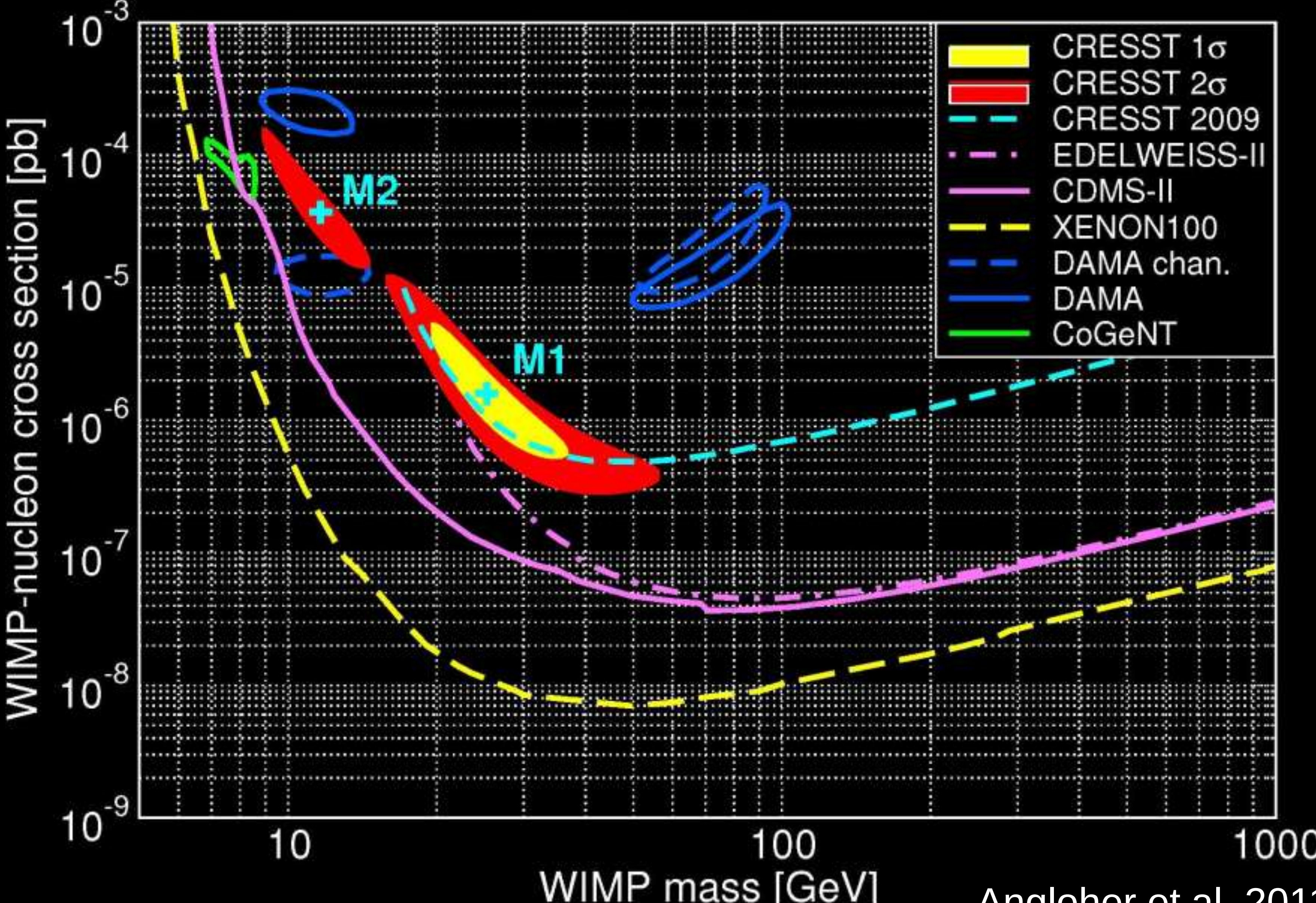
CoGeNT
m_{DM}=6.8 GeV
σ_{DM-N}=1.58x10^{-4} pb
counts/0.05 keV (0.33 kg, 56 days)
E (keVee)
0
5
10
15
20
25
0.5
1.0
1.5
2.0
2.5
3.0

CoGeNT



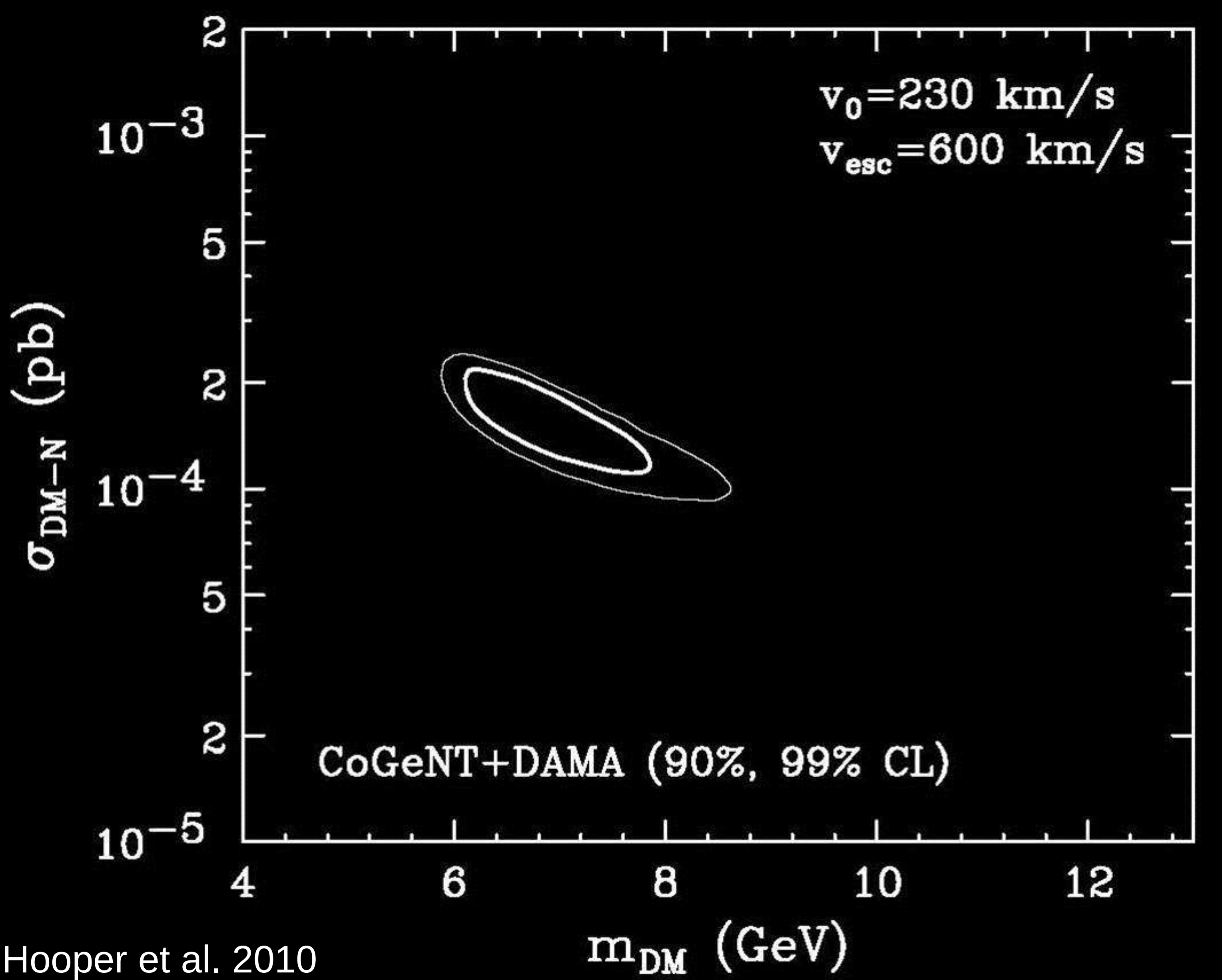
annual modulation
at 2.8σ
Aalseth et al. 2011

CRESST



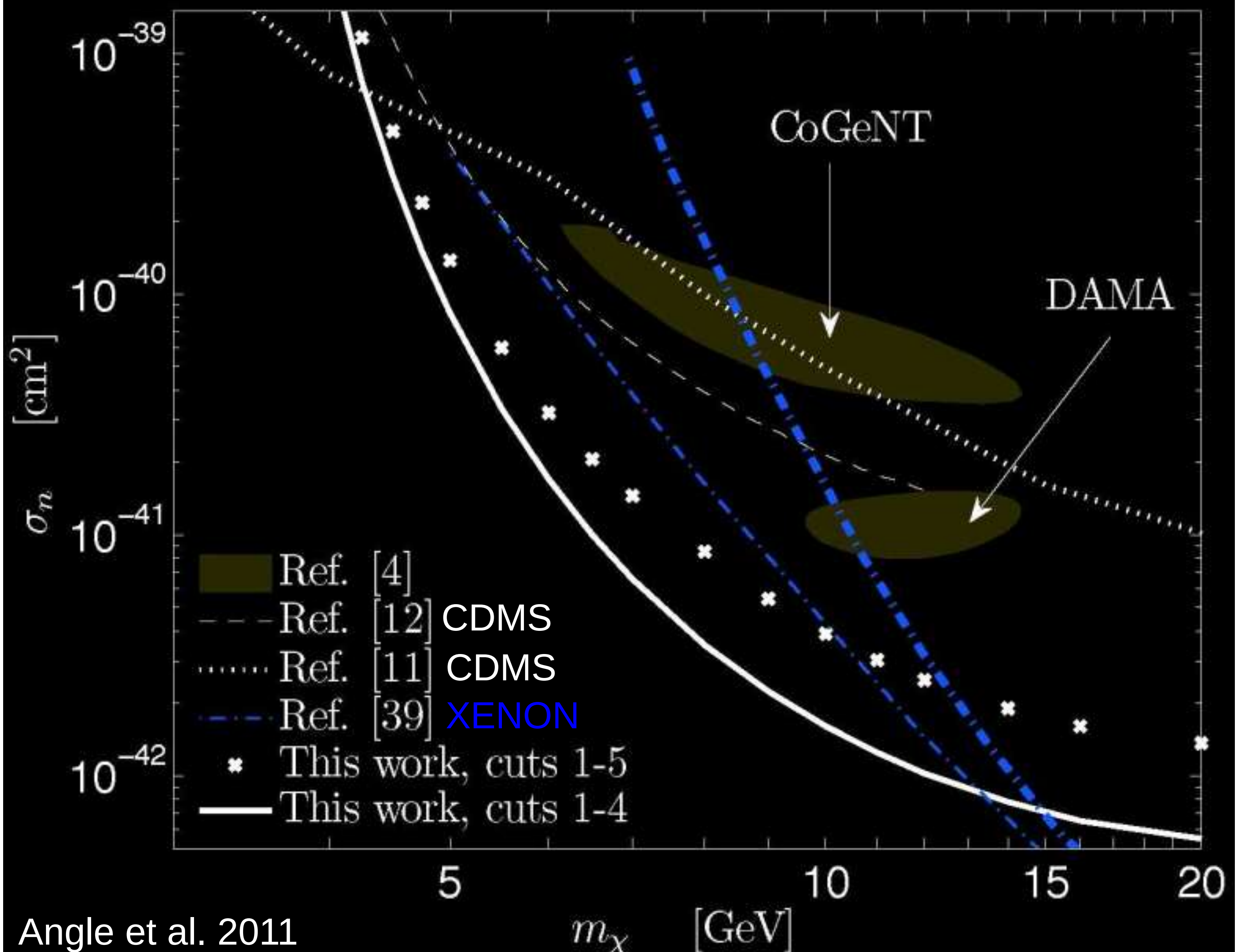
Angloher et al. 2011

CoGeNT + DAMA



Hooper et al. 2010

XENON/CDMS



Angle et al. 2011

A Maximum Likelihood Analysis of Low-Energy CDMS Data

J.I. Collar and N.E. Fields[1]

[1]*Enrico Fermi Institute, Kavli Institute for Cosmological Physics and Department of Physics, University of Chicago, Chicago, IL 60637*

An unbinned maximum likelihood analysis of CDMS low-energy data reveals a strong preference (5.7σ C.L.) for a model containing an exponential excess of events in the nuclear recoil band, when compared to the null hypothesis. We comment on the possible origin of such an excess, establishing a comparison with anomalies in other dark matter experiments. A recent annual modulation search in CDMS data is shown to be insufficiently sensitive to test a dark matter origin for this excess.

PACS numbers: 95.35.+d, 85.30.-z

The CDMS collaboration has recently made public a negative search for an annual modulation in low-energy signals from their cryogenic germanium detectors [1]. This effect is expected from Weakly Interacting Massive Particle (WIMP) interactions with dark matter detector targets [2]. Observation of this WIMP signature has been claimed by the DAMA collaboration with high statistical significance [3], using low-background NaI(Tl) scintillators. The CoGeNT collaboration recently released fifteen months of data from underground germanium detector operation [4]. These display a compatible modulation [4–6], albeit with the smaller statistical significance that would be expected from a short exposure.

Fig. 6 in [1] shows, for the first time, detailed information from all eight CDMS germanium detectors employed in the modulation search and a previous low-energy analysis [7]. Specifically, it contains the distribution of single-interaction events in the ionization energy (E_i) vs. recoil energy (E_r) plane that can be used to identify their origin in nuclear recoils (NR) like those expected from WIMP and neutron interactions, or electron recoils (ER) like those induced by gamma backgrounds.

A formal assessment of the possibility that a significant

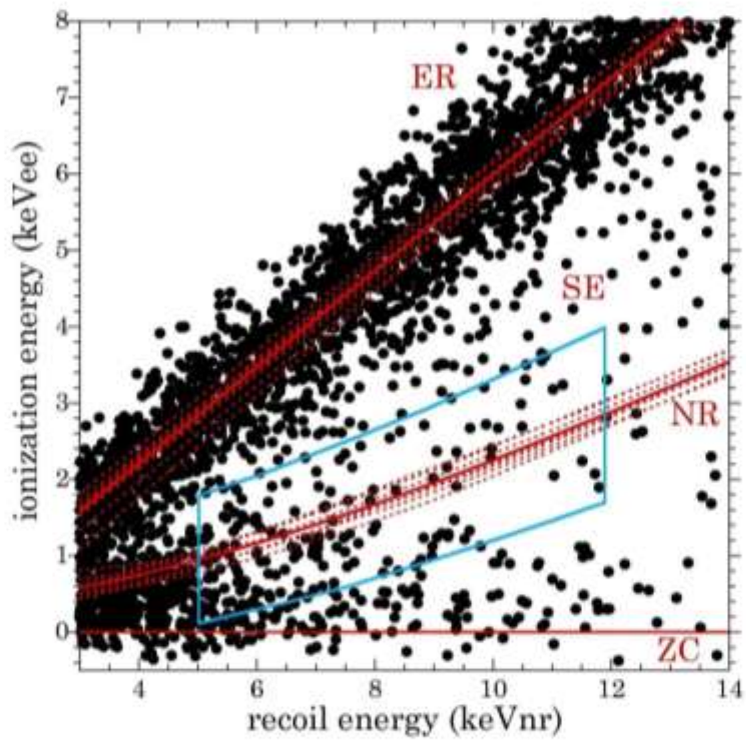
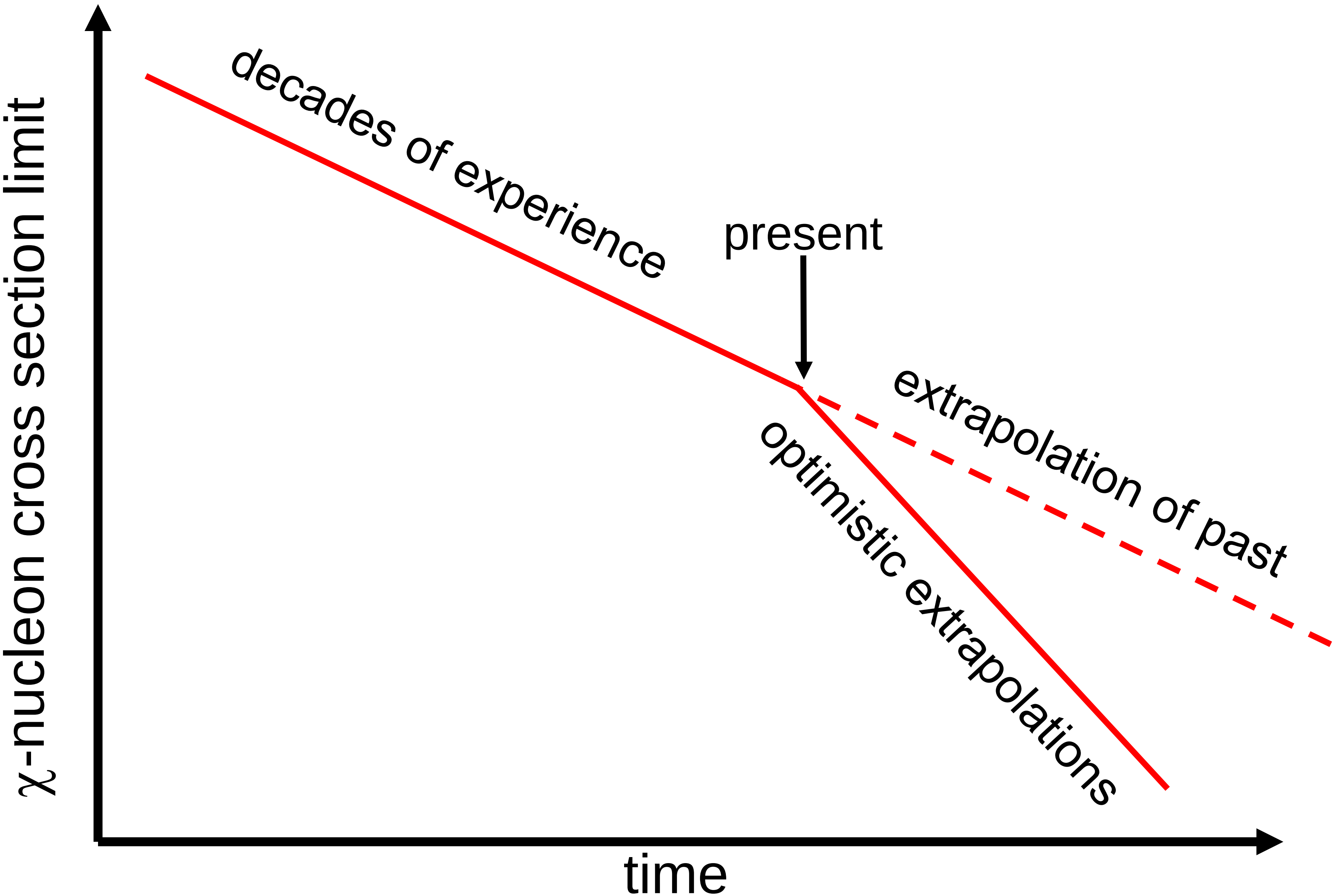
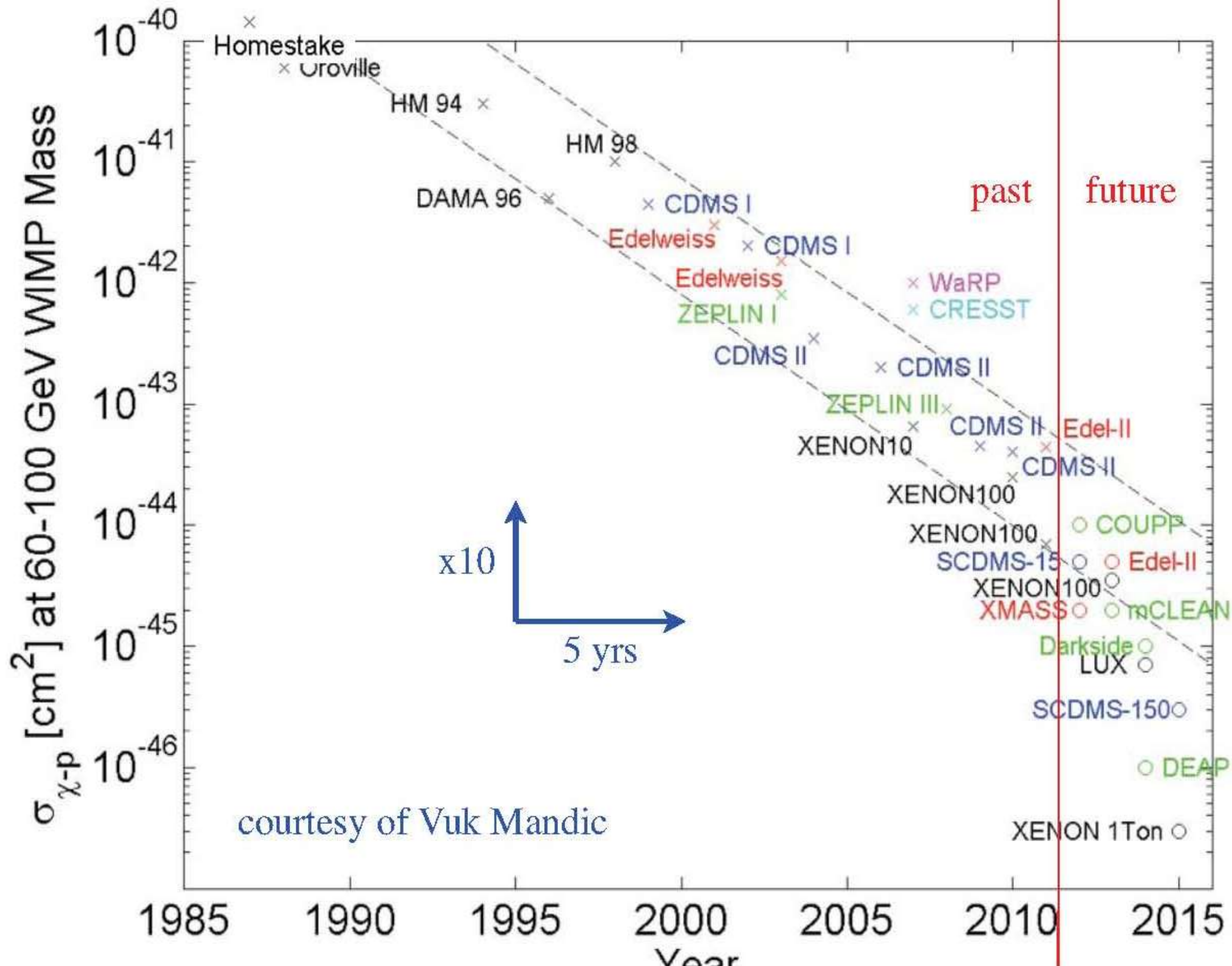


FIG. 1: Scatter plot of single-interaction events in all eight CDMS detectors, digitized from individual plots in [1], using

Predictions of WIMP Search Sensitivity

"Things take longer than they do."



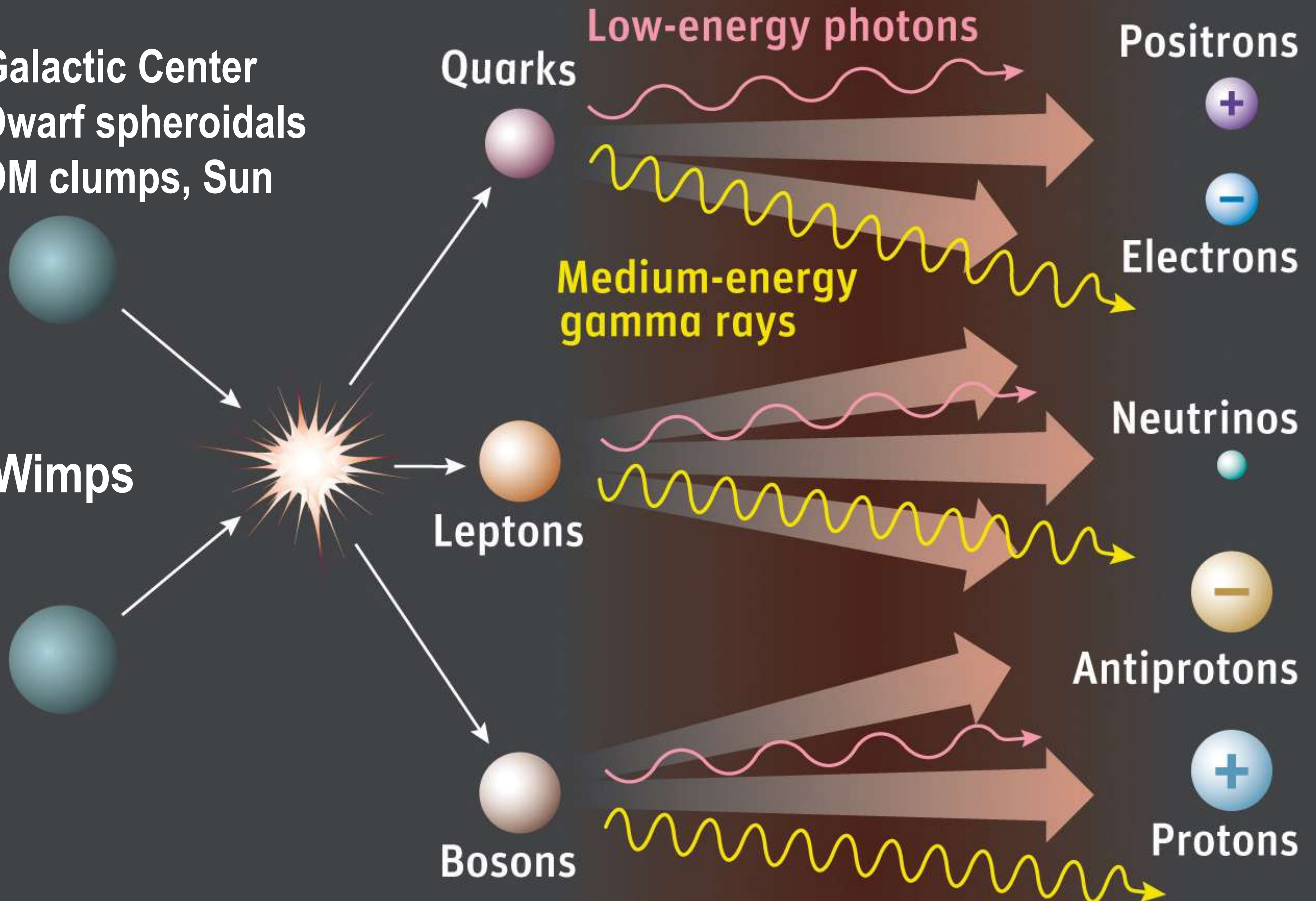


$\sigma_{\chi\text{-}p}$ [cm^2] at 60-100 GeV WIMP Mass
Year
past
future
x10
5 yrs
courtesy of Vuk Mandic
Homestake
Oroville
HM 94
HM 98
DAMA 96
CDMS I
Edelweiss
CDMS I
Edelweiss
WaRP
CRESST
ZEPLIN I
CDMS II
CDMS II
ZEPLIN III
CDMS II
Edel-II
XENON10
CDMS-II
XENON100
XENON100
COUPP
SCDMS-15
Edel-II
XENON100
XMASS
mCLEAN
Darkside
LUX
SCDMS-150
DEAP
XENON 1Ton

Indirect Detection

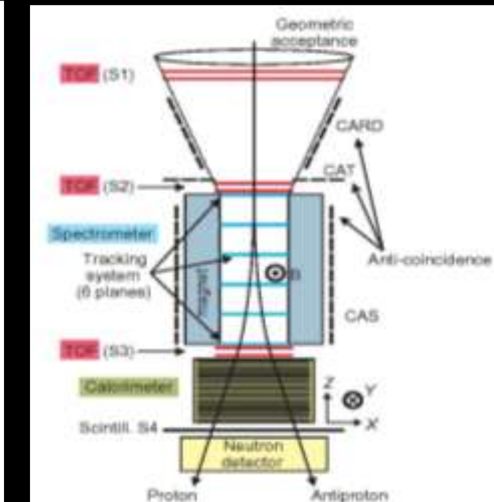
Galactic Center
Dwarf spheroidals
DM clumps, Sun

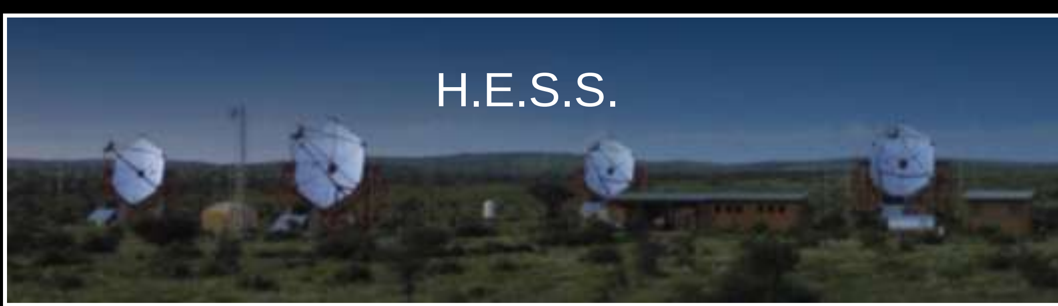
Wimps



Indirect Detection

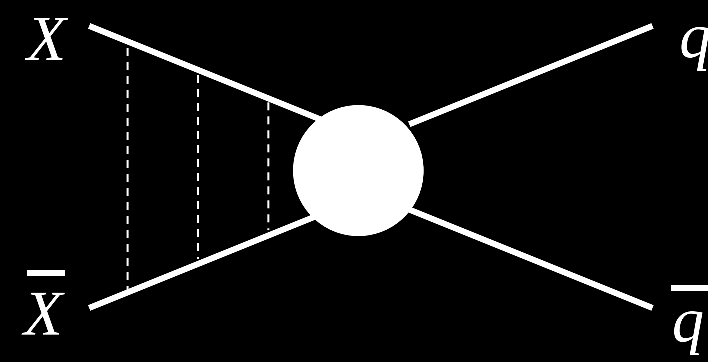
PAMELA





Indirect Detection

- Depends on WIMP density in galactic center or other structures—simulations unable to completely resolve



- Sommerfeld enhancement

$$\pi \alpha / v \qquad (\alpha / v \gg 1)$$

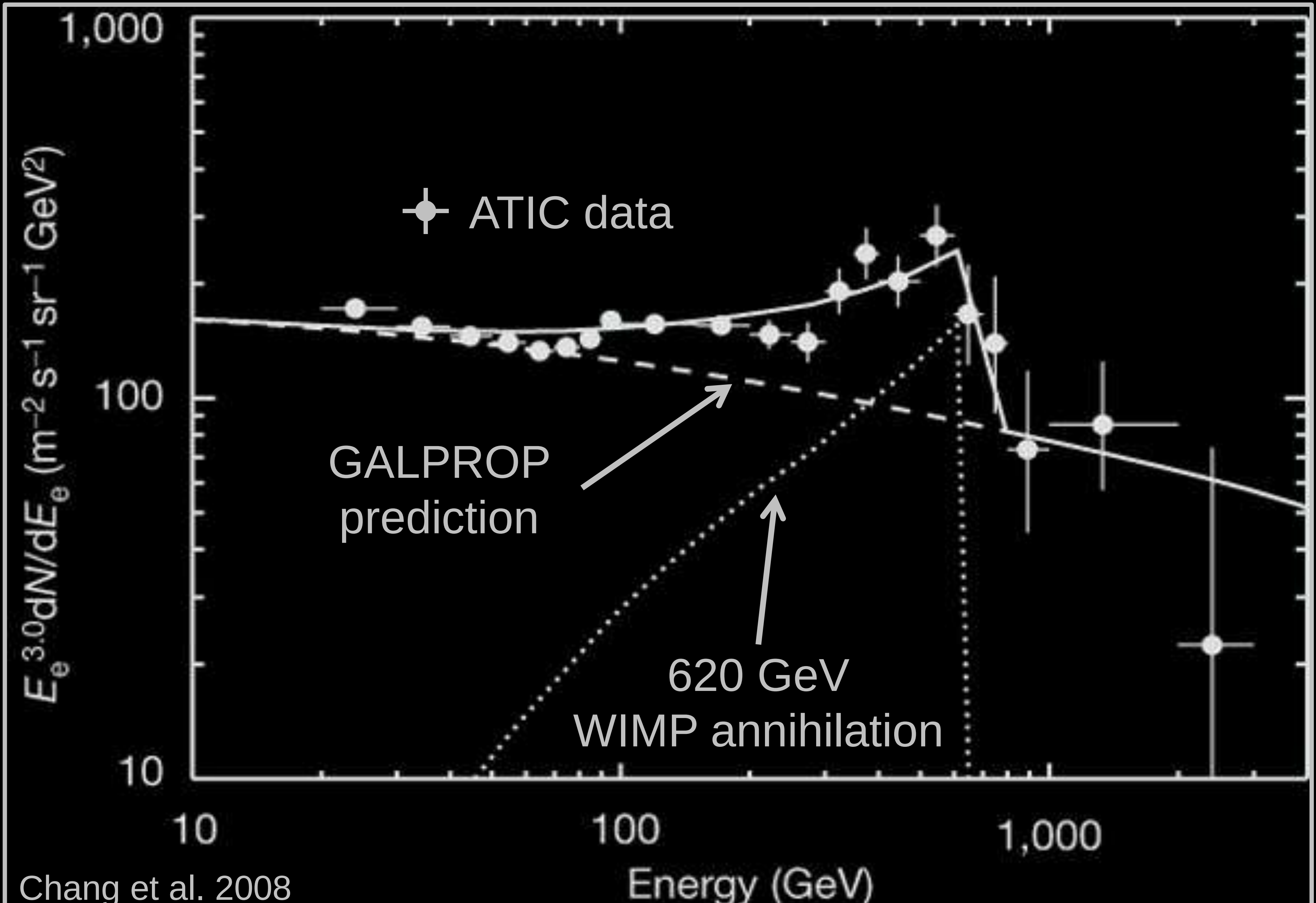
- Boost Factor

- γ-ray lines; internal bremss.; final-state radiation

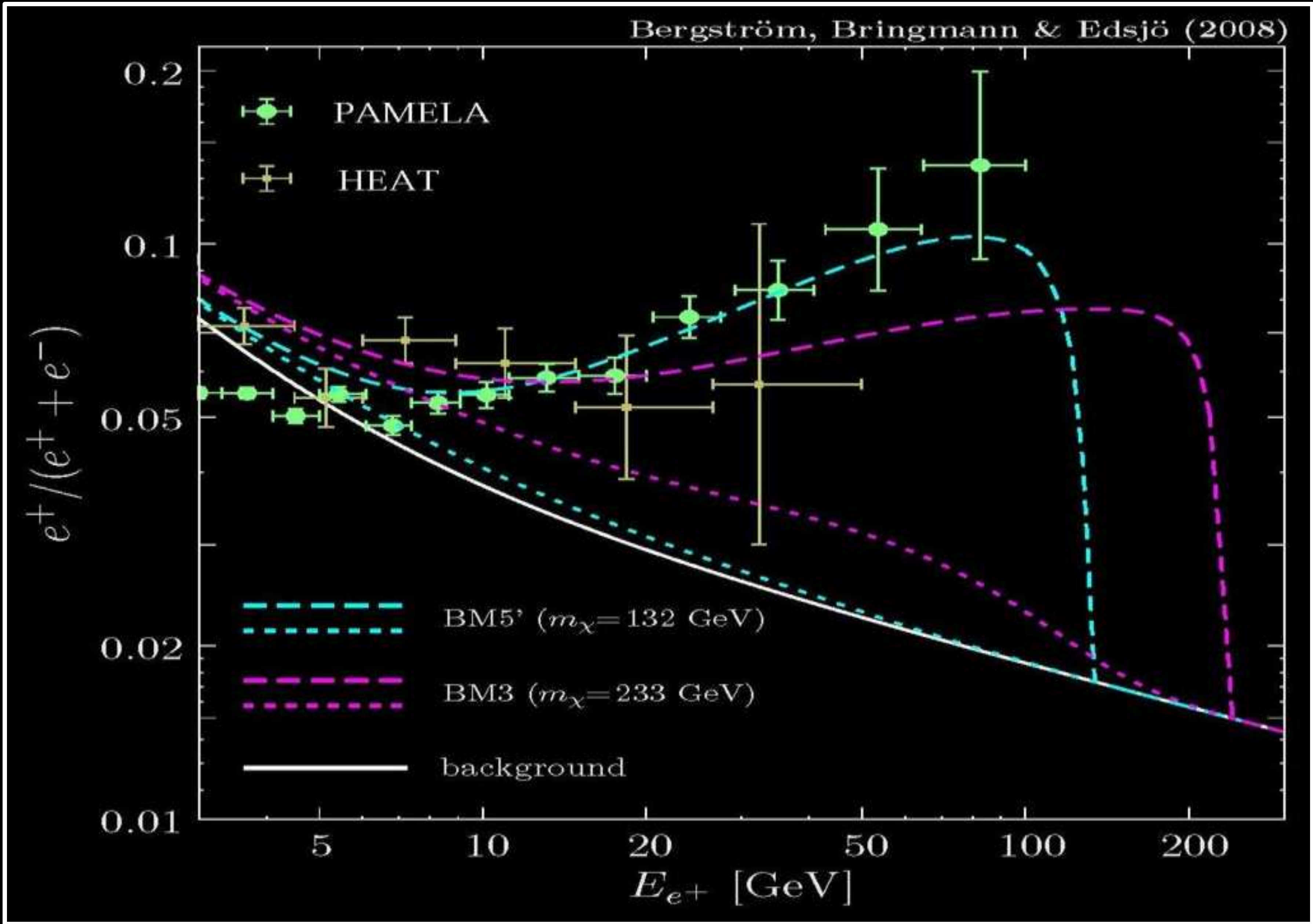
- If charged products, propagation in magnetic fields

- Astrophysical backgrounds, hazes, fogs, …

ATIC

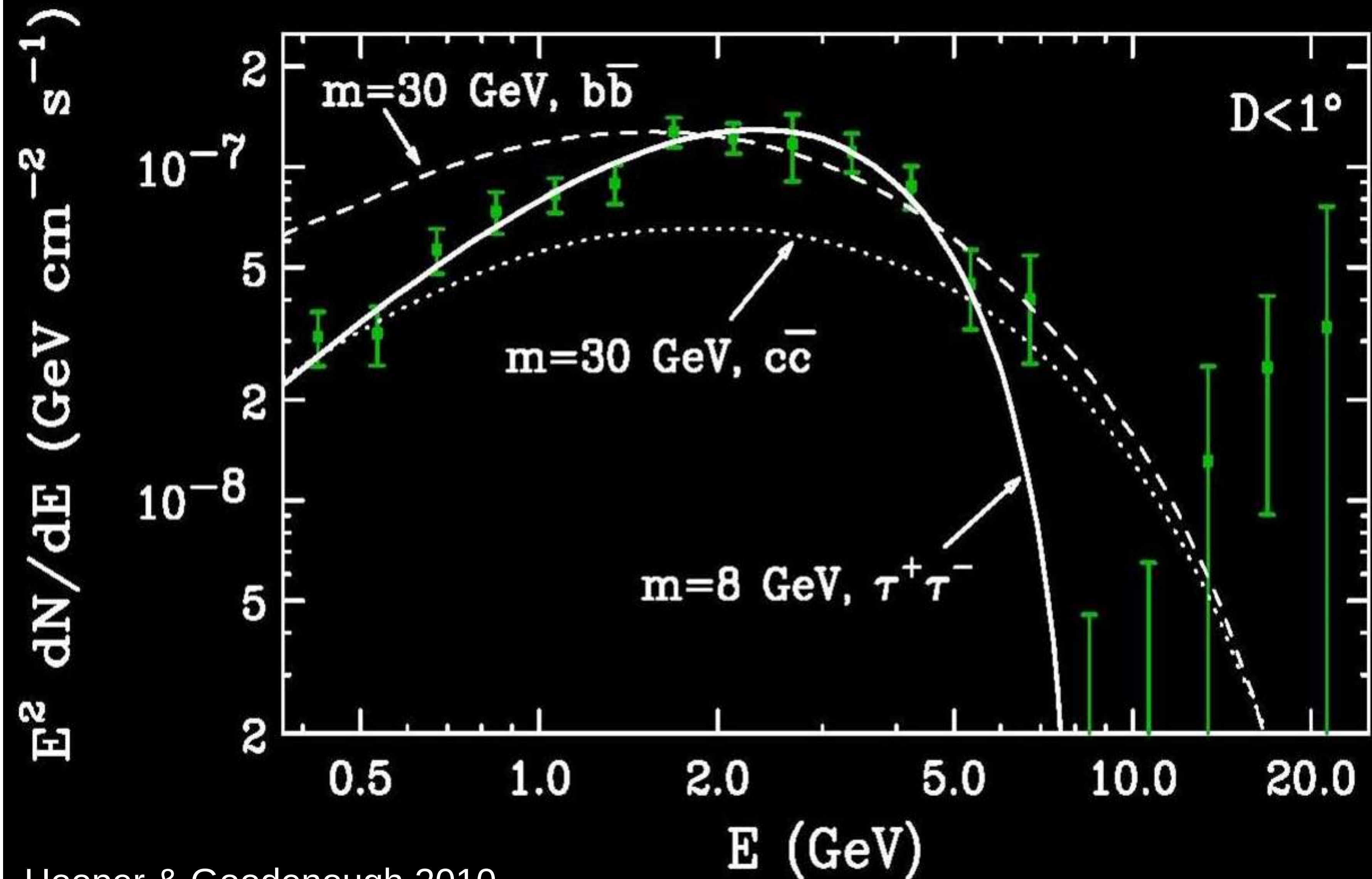

ATIC data
GALPROP
prediction
620 GeV
WIMP annihilation
1,000
100
10
10
100
1,000
Energy (GeV)
$E_e^{3.0}dN/dE_e$ (m^{-2} s^{-1} sr^{-1} GeV^2)
Chang et al. 2008

PAMELA



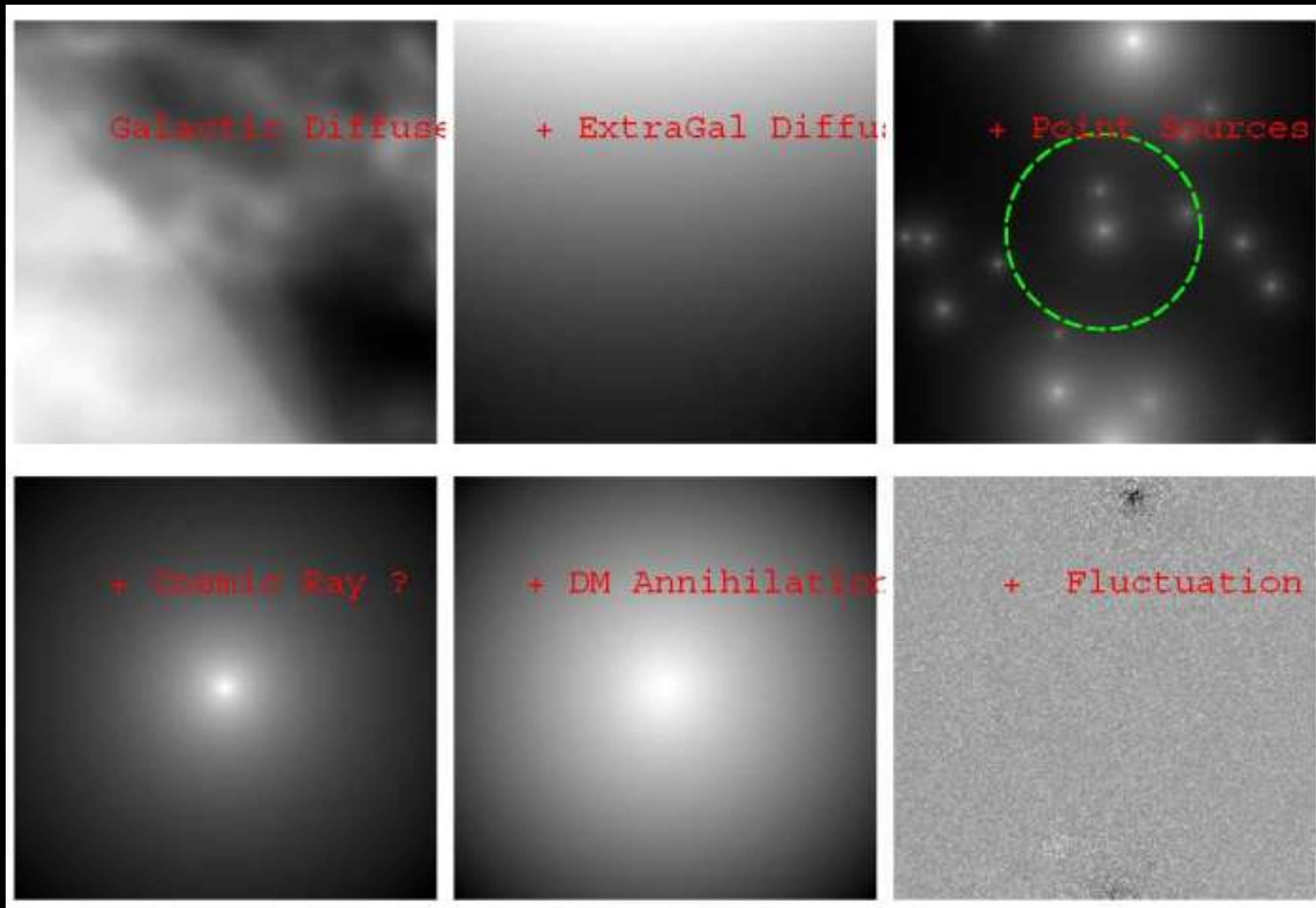
Bergström, Bringmann & Edsjö (2008)
PAMELA
HEAT
BM5' (m_χ= 132 GeV)
BM3 (m_χ= 233 GeV)
background
$e^+/(e^+ + e^-)$
0.2
0.1
0.05
0.02
0.01
5
10
20
50
100
200
E_{e^+} [GeV]

Fermi/GLAST Feature



Hooper & Goodenough 2010

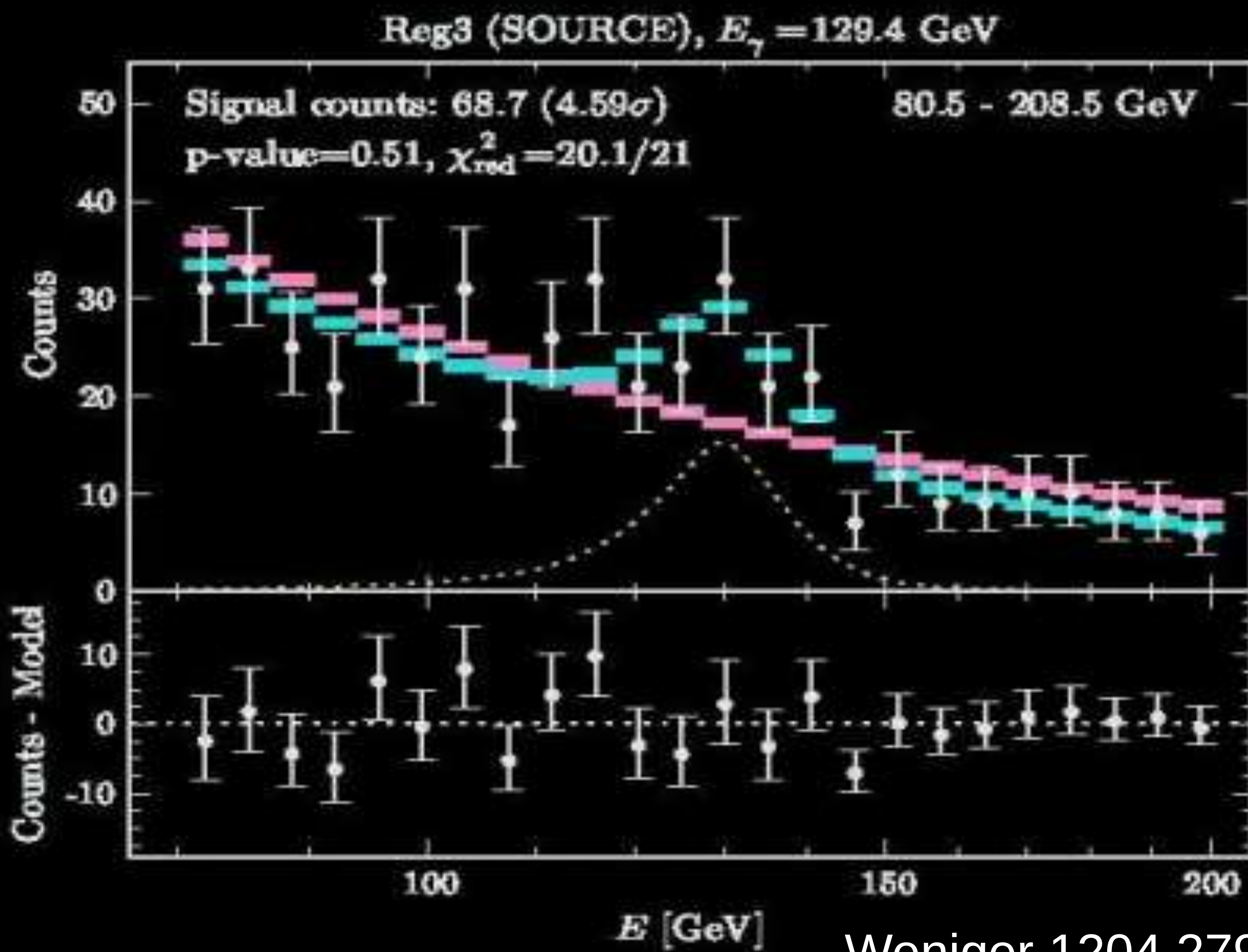
Fermi/GLAST Haze



1. 20 - 60 GeV in $\bar{b}\,b$ channel
2. 2 - 10 GeV in $\mu^+\mu^-$ channel
3. □ 1 TeV in $\mu^+\mu^-$ channel

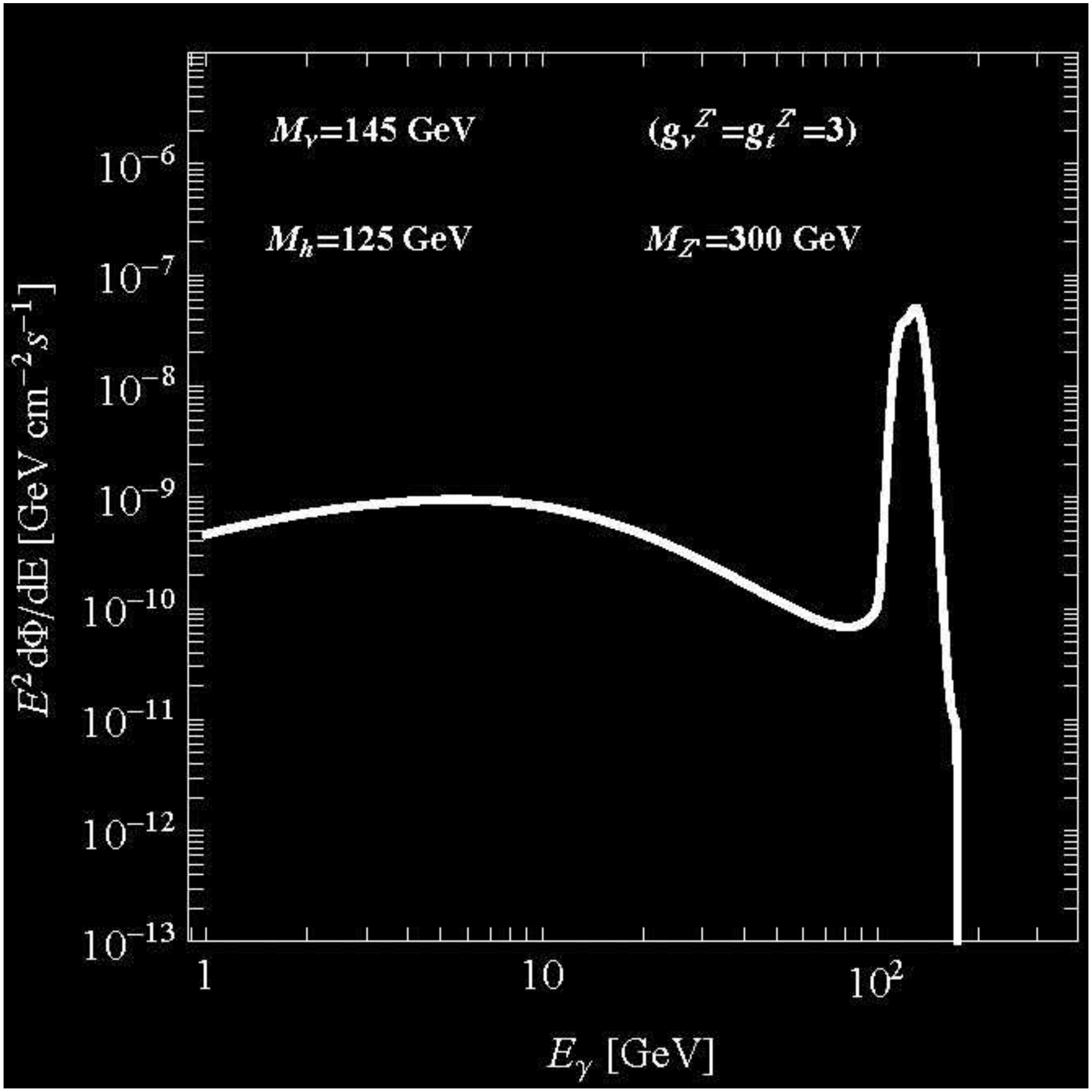
Han, Frenk, Eke, Gao, White (2011)

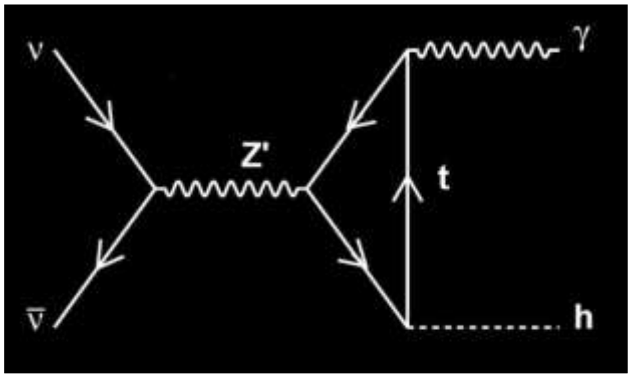
Fermi/GLAST Line



Weniger 1204.2797

Fermi/GLAST Line





Jackson, Servant, Shaughnessy, Tait, Taoso
0912.0004

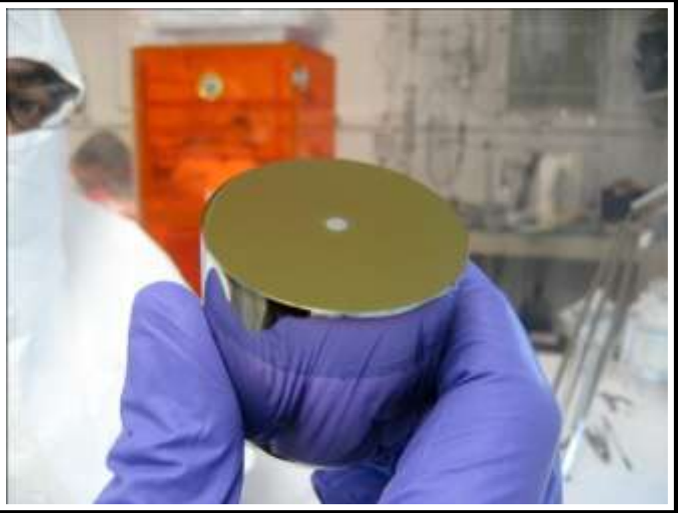
WIMPs

- 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 $7\ \mathrm{GeV}$ 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

Socialist WIMPs	Maverick WIMPs*
• 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:

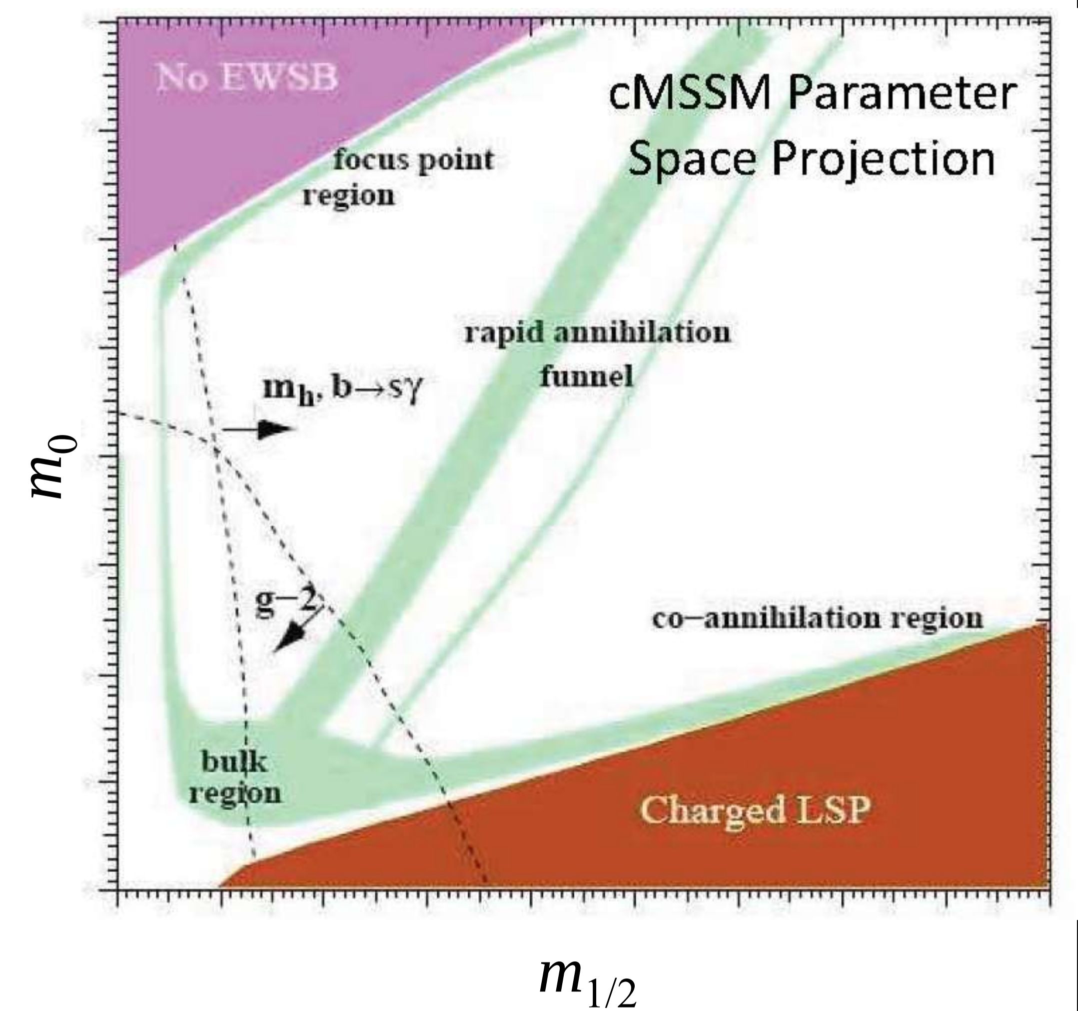
$$\tilde{\chi}^0 = \alpha \tilde{B} + \beta \tilde{W}^3 + \gamma \tilde{H}_1^0 + \delta \tilde{H}_2^0$$

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

100+ parameters of SUSY

cMSSM

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



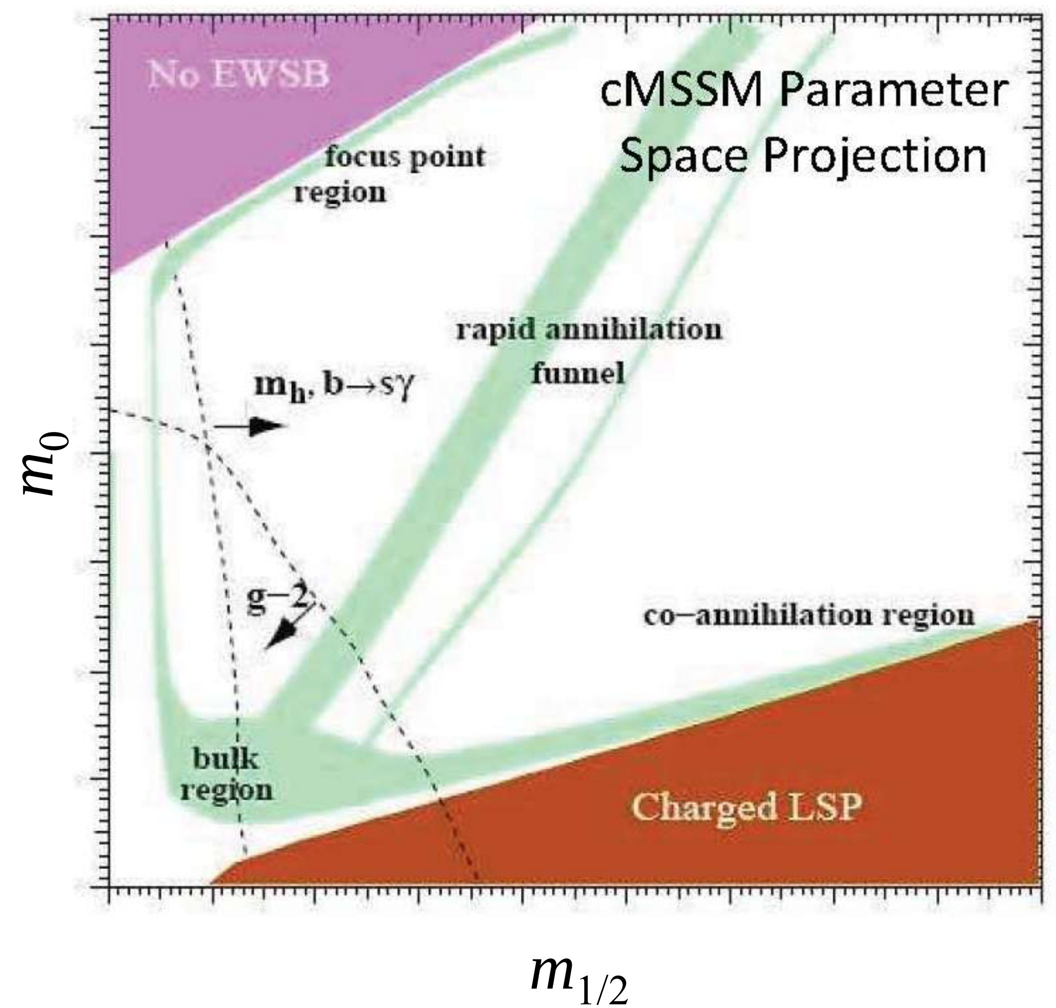
Ellis, Olive, Santoso, Spanos 2003

SUSY WIMPs

- Typical SUSY models consistent w/ collider and other HEP data have too small annihilation cross section $\rightarrow$ 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 $\tilde{t}$
  - large tanβ (s-channel annihilation via broad A resonance)
  - high values of m_0: Higgsino-like neutralino annihilates into W & Z pairs (focus point)
  - …

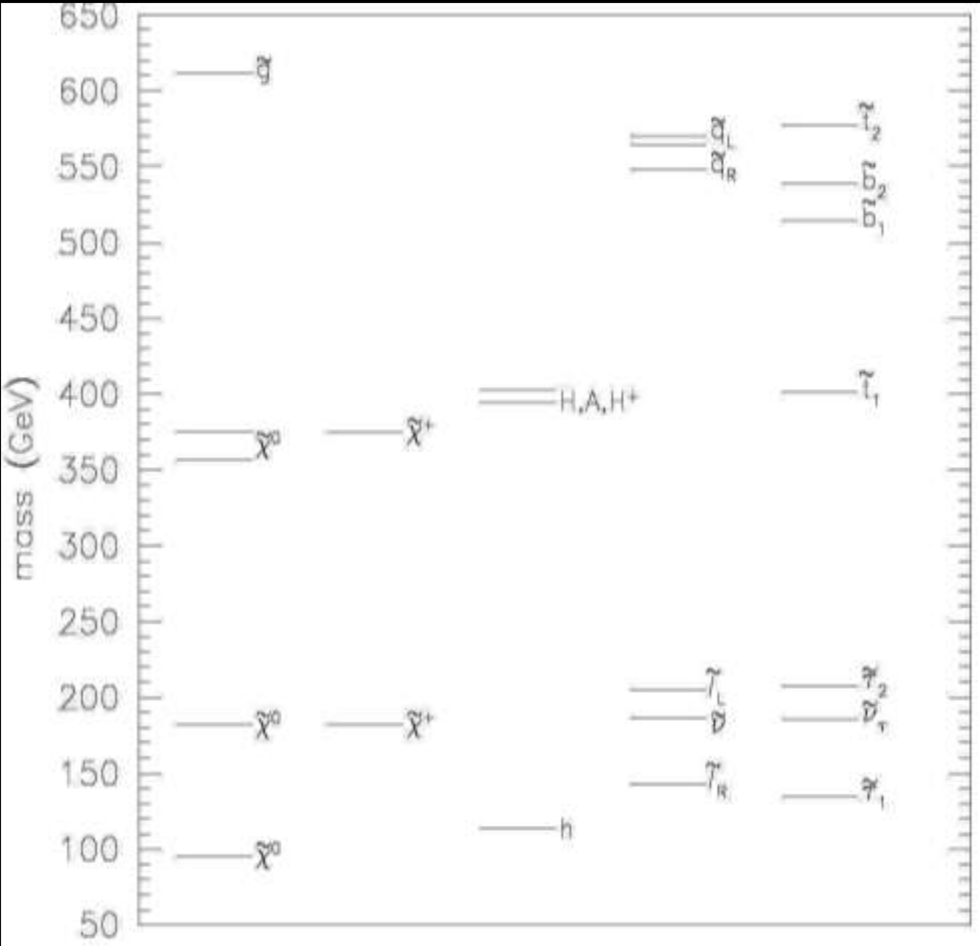
- Or, unconstrained

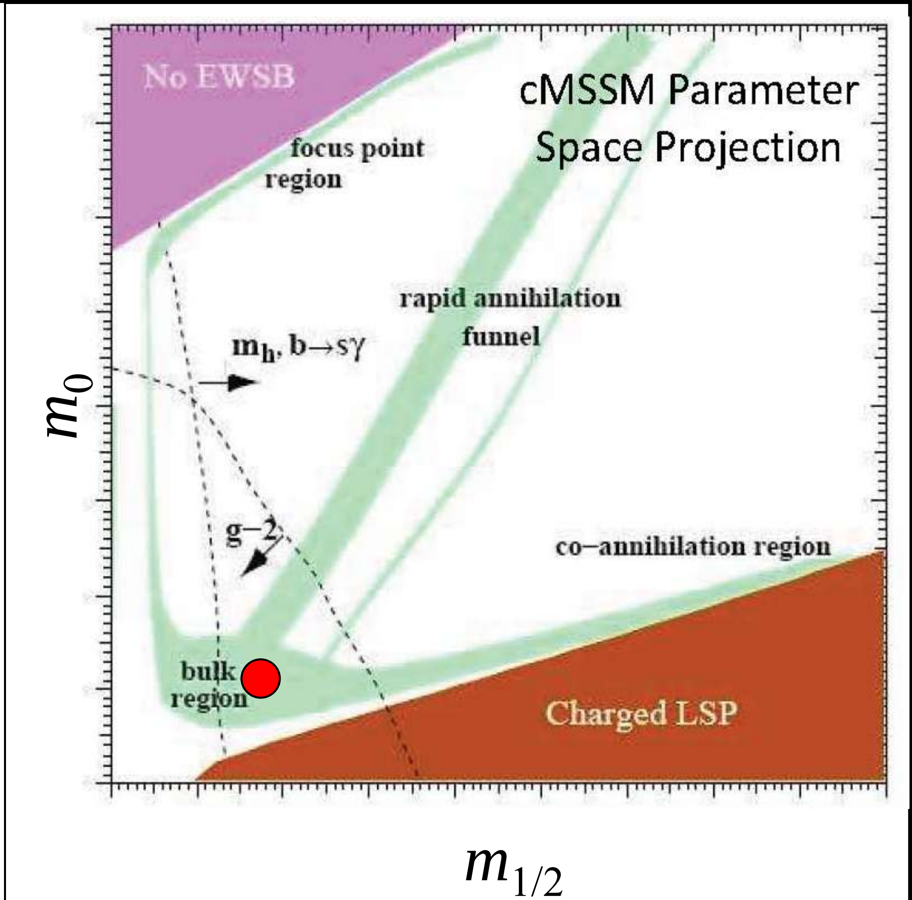


Ellis, Olive, Santoso, Spanos

SUSY WIMPs

Bulk Region: light superpartners





Ellis, Olive, Santoso, Spanos

LHC chewing away at allowed region

Recent SUSY Statements

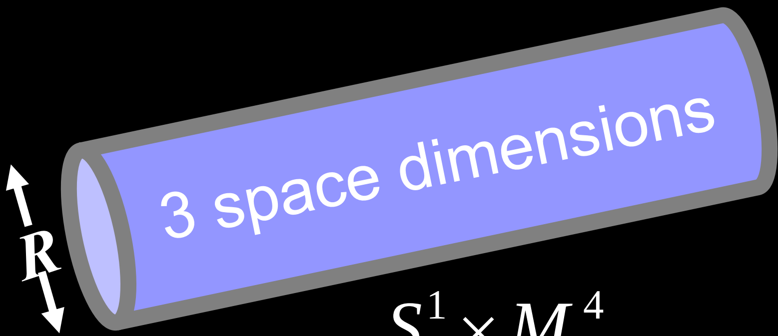
• It’s not yet time to throw in the Towelino.	**Agree!**
• No one took the MSSM seriously anyway.	**Really?**
• The evidence for SUSY has never been stronger.	**Really?**
• By the end of 2012 we will have proof of low-energy SUSY, String Theory, and a $130\ \mathrm{GeV}$ WIMP.	**Really?**

---

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

Kaluza-Klein WIMPs

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



$S^1 \times M^4$

Quantized Kaluza-Klein excitations

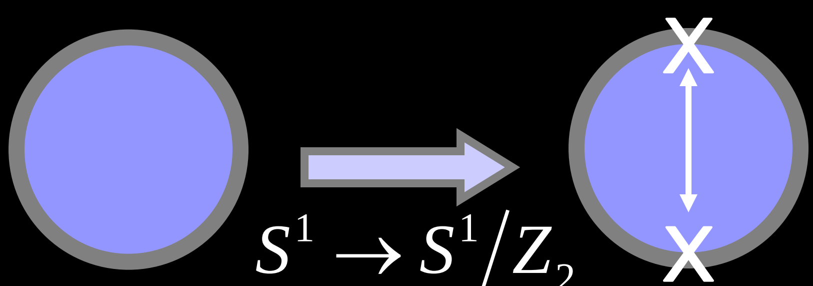
$$E^2 = \vec{p}^{\,2} + p_5^2 \qquad p_5^2 = n^2/R^2$$

$$= \vec{p}^{\,2} + M_n^2 \qquad M_n^2 = n^2/R^2$$

Conservation of momentum ⟶ conservation of KK mode number

First excited mode (n = 1) stable, mass R^{-1}

need chiral fermions



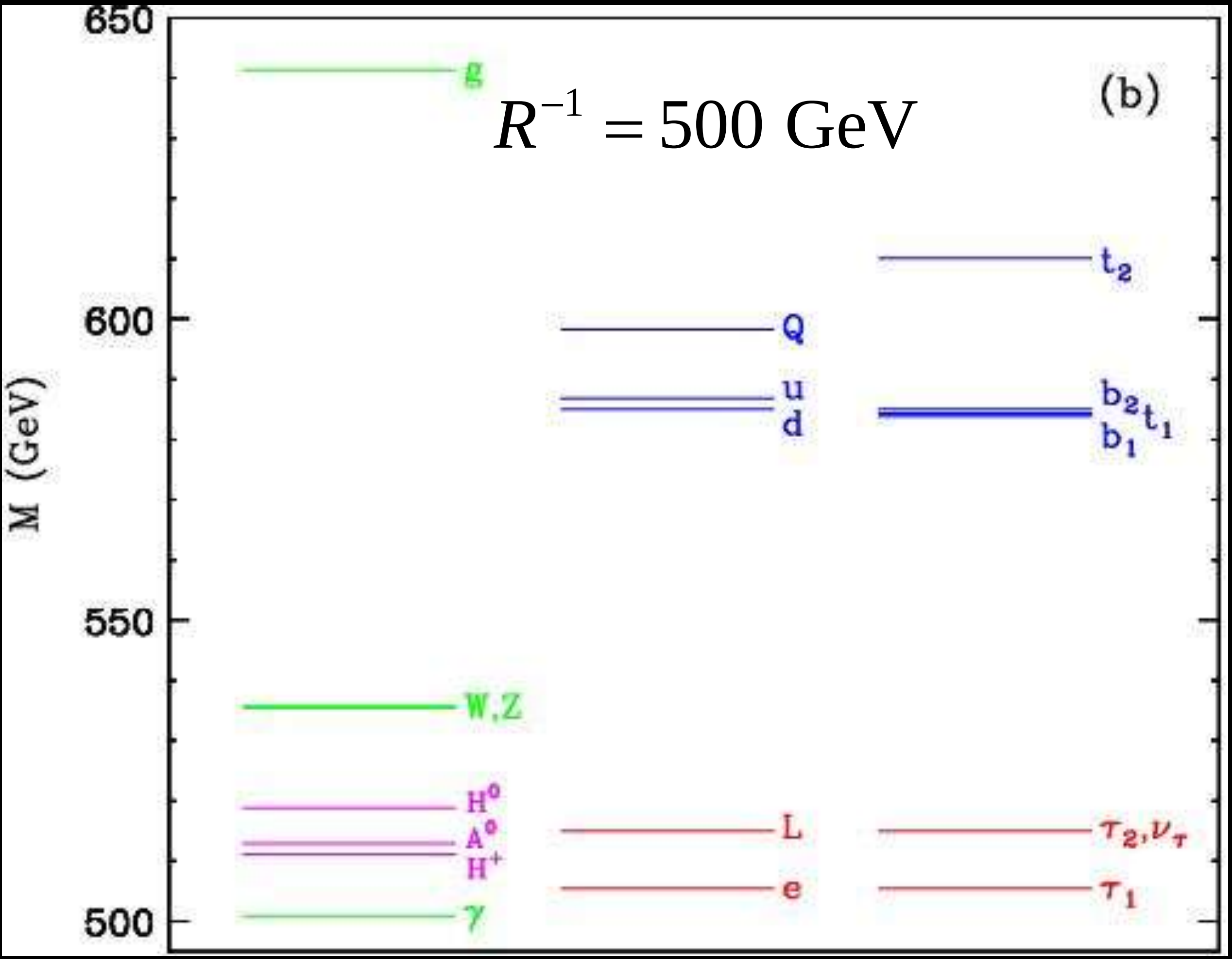
$S^1 \rightarrow S^1/Z_2$

KK quantum number ⟶ KK parity

First excited mode (n = 1) stable, mass R^{-1}

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

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

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

Complex scalar Maverick WIMP, ϕ

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

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

Expect terms that break $\mathrm{SU(2)_L}$ must do so through SM Yukawa couplings, so operators that flip quark chirality should be $\propto m_q$.

Some terms vanish for Majorana χ.

Can write G as M_*^{-2}
F as M_*^{-1}

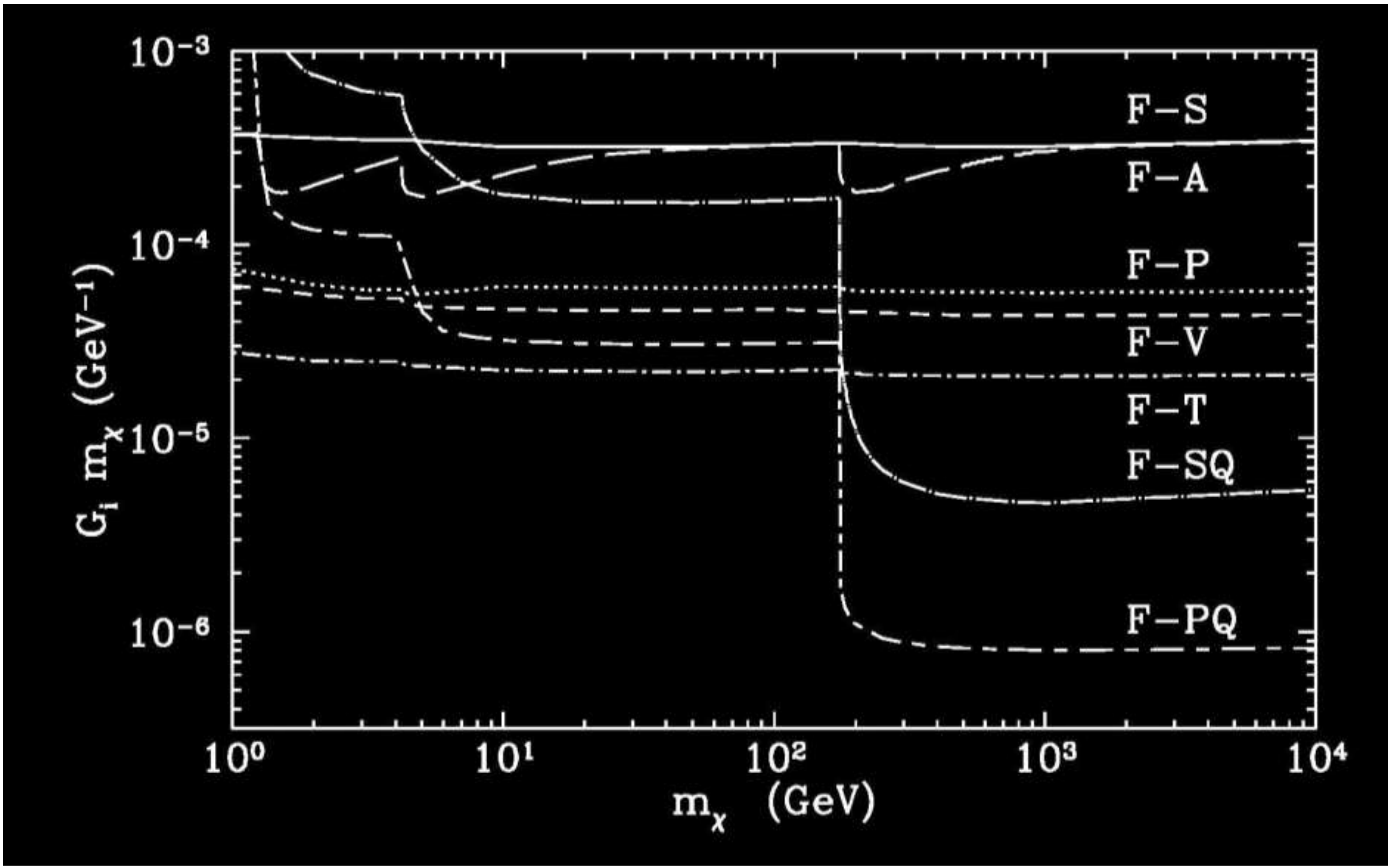
Fierz identities relate various combinations

Maverick WIMPs

Spin	Operator	Coupling	Label
0	$\phi^\dagger\phi\bar{q}q$	$F_{S,q} = F_S$	S-S
	$\phi^\dagger\phi\bar{q}q$	$F_{S,q} \sim m_q$	S-SQ
	$\phi^\dagger\phi\bar{q}\gamma^5 q$	$F_{SP,q} = F_{SP}$	S-SP
	$\phi^\dagger\phi\bar{q}\gamma^5 q$	$F_{SP,q} \sim m_q$	S-SPQ
	$\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu q$	$F_{V,q} = F_V$	S-V
	$\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	$F_{VA,q} = F_{VA}$	S-VA
1/2	$\bar{\chi}\chi\bar{q}q$	$G_{S,q} = G_S$	F-S
	$\bar{\chi}\chi\bar{q}q$	$G_{S,q} \sim m_q$	F-SQ
	$\bar{\chi}\chi\bar{q}\gamma^5 q$	$G_{SP,q} = G_{SP}$	F-SP
	$\bar{\chi}\chi\bar{q}\gamma^5 q$	$G_{SP,q} \sim m_q$	F-SPQ
	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$G_{P,q} = G_P$	F-P
	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$G_{P,q} \sim m_q$	F-PQ
	$\bar{\chi}\gamma^5\chi\bar{q}q$	$G_{PS,q} = G_{PS}$	F-PS
	$\bar{\chi}\gamma^5\chi\bar{q}q$	$G_{PS,q} \sim m_q$	F-PSQ
	$\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$	$G_{V,q} = G_V$	F-V
	$\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$G_{VA,q} = G_{VA}$	F-VA
	$\bar{\chi}\gamma_\mu\gamma^5\chi\bar{q}\gamma^\mu\gamma^5 q$	$G_{A,q} = G_A$	F-A
	$\bar{\chi}\gamma_\mu\gamma^5\chi\bar{q}\gamma^\mu q$	$G_{AV,q} = G_{AV}$	F-AV
	$\bar{\chi}\sigma_{\mu\nu}\chi\bar{q}\sigma^{\mu\nu} q$	$G_{T,q} = G_T$	F-T

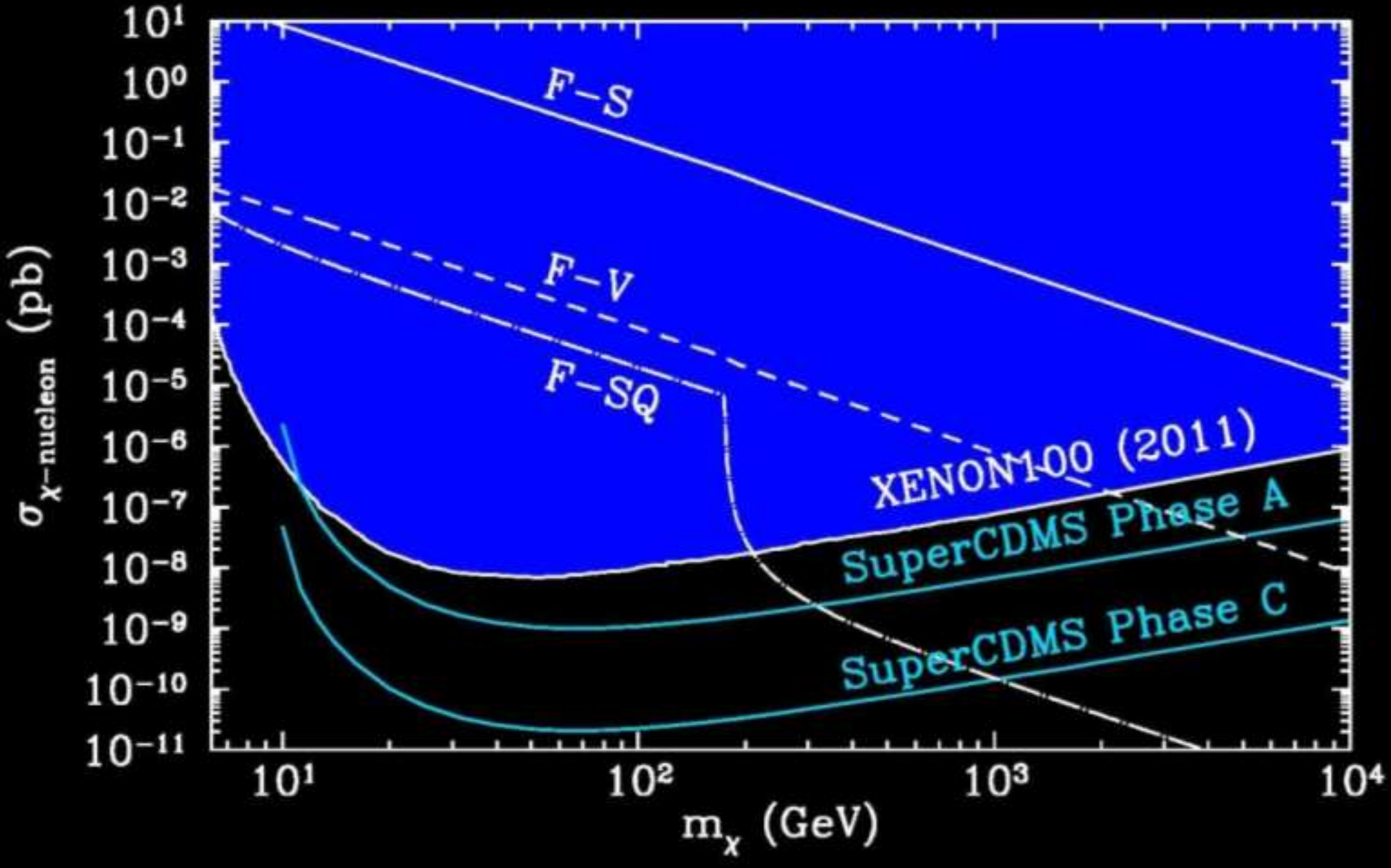
Maverick WIMPs

Values of G to give correct dark matter density



Maverick WIMPs

spin-independent

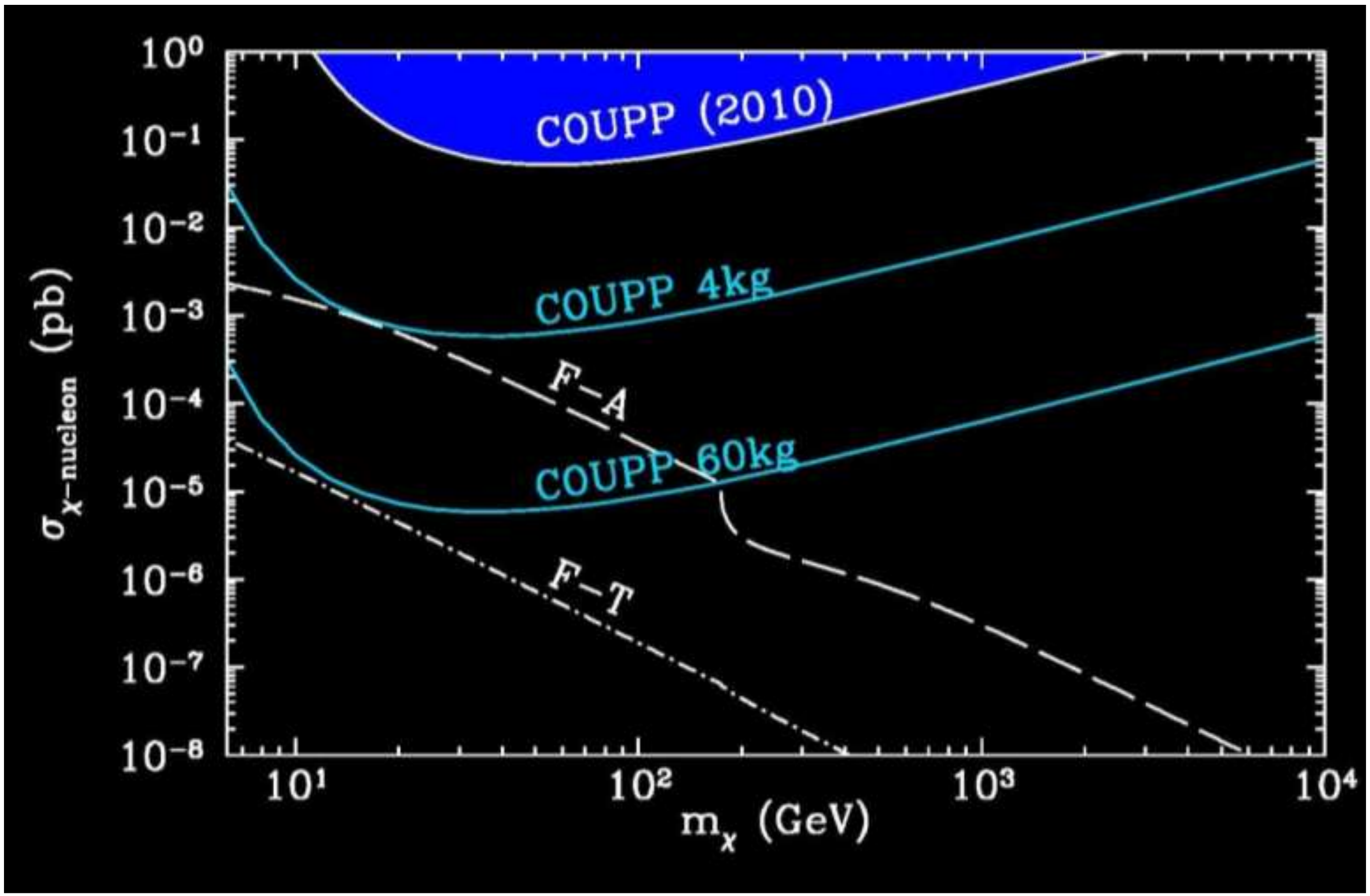


For $m \geq 10$ GeV or so $\sigma \leq 10^{-7}$ pb

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

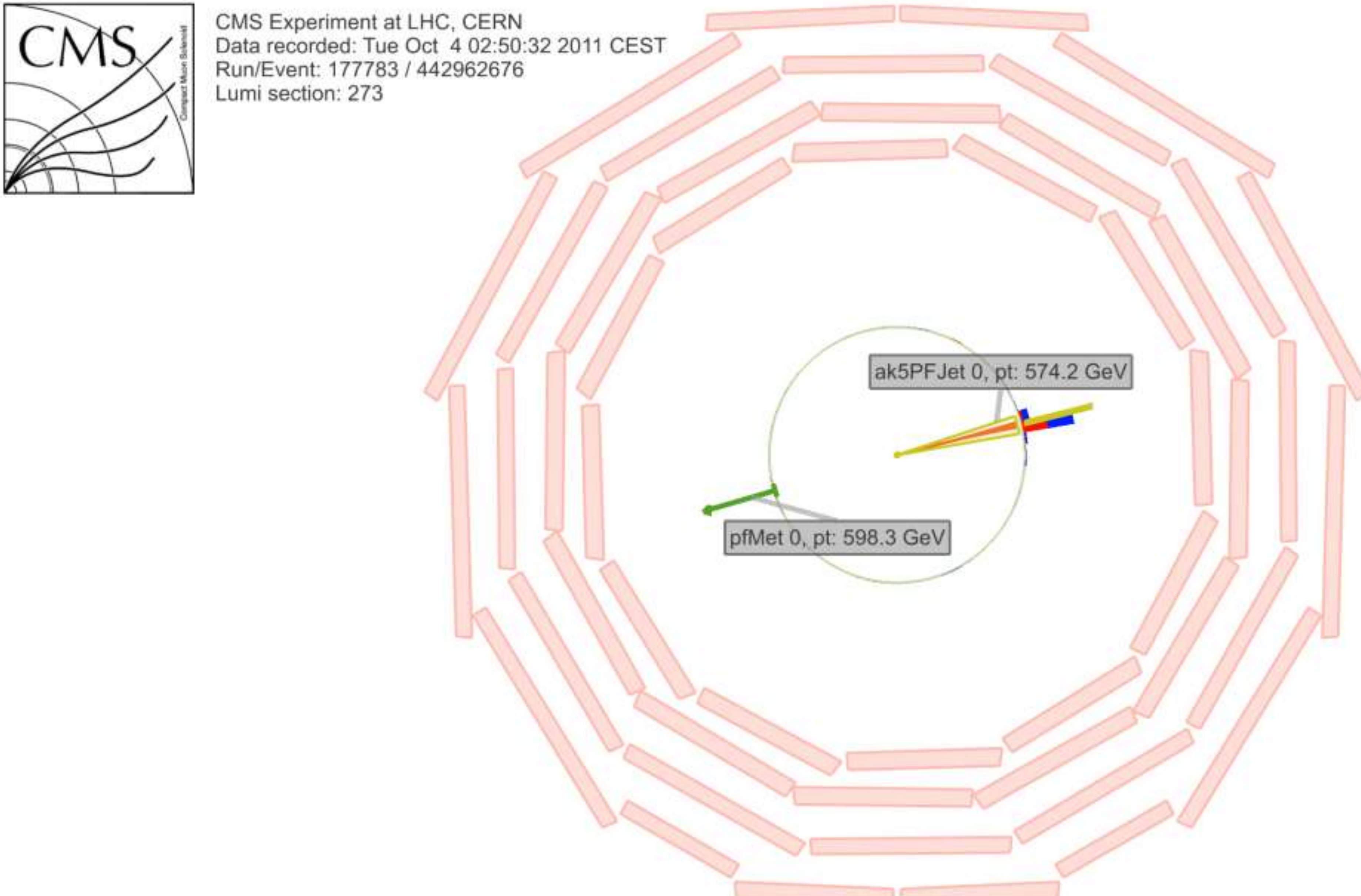
Maverick WIMPs

spin-dependent



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

Missing Momentum = Missing Mass?

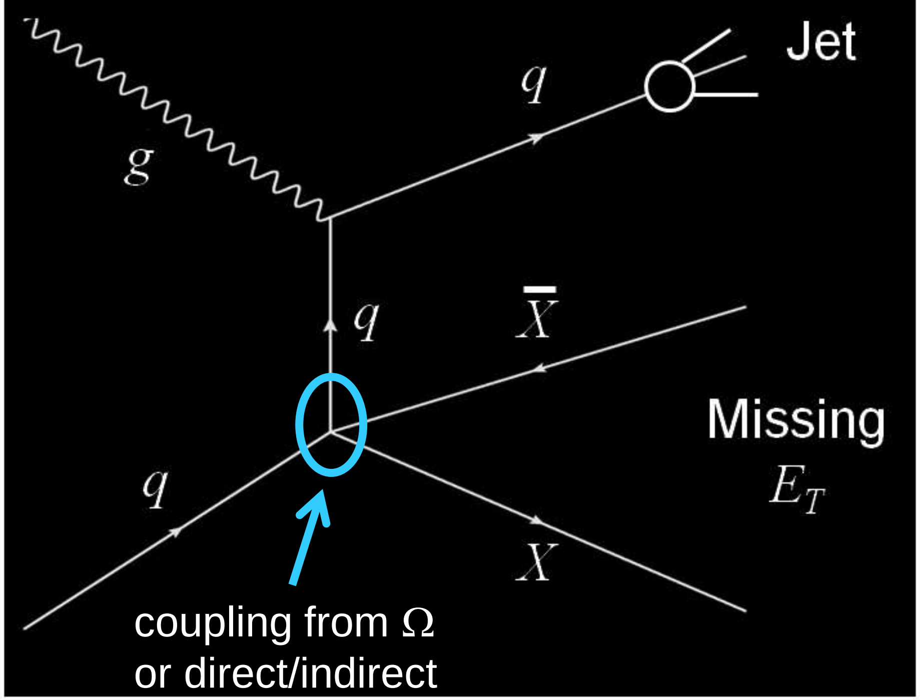


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012

WIMPs

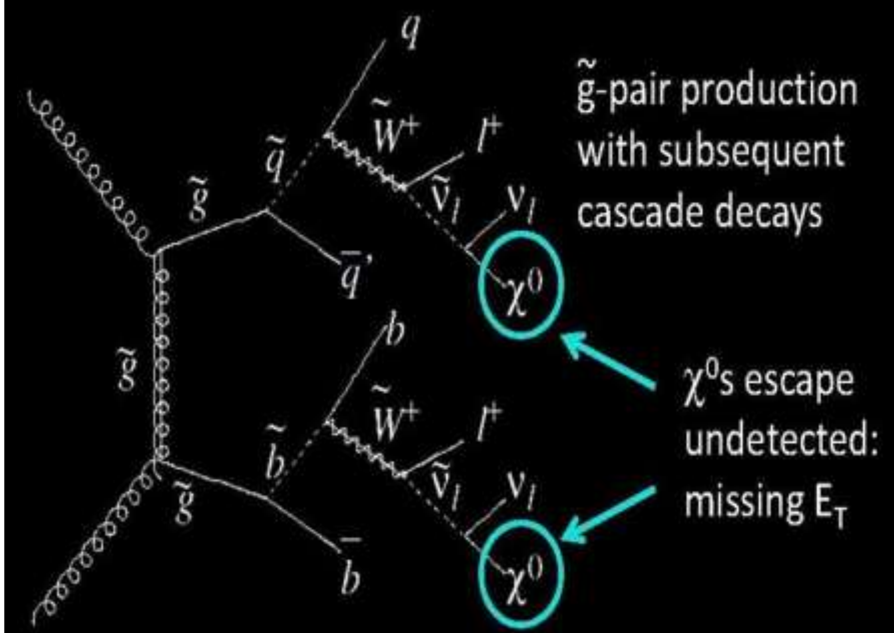
Collider Searches

Maverick WIMPs



Backgrounds (neutrino, QCD, …)

Social WIMPs

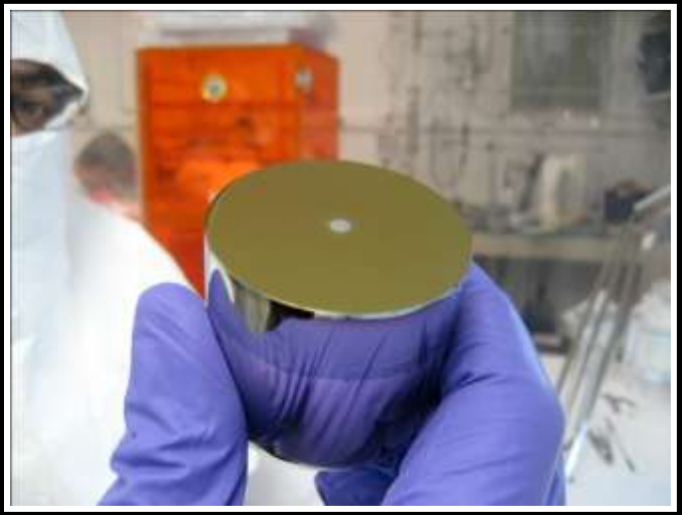


Complicated decay chain

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

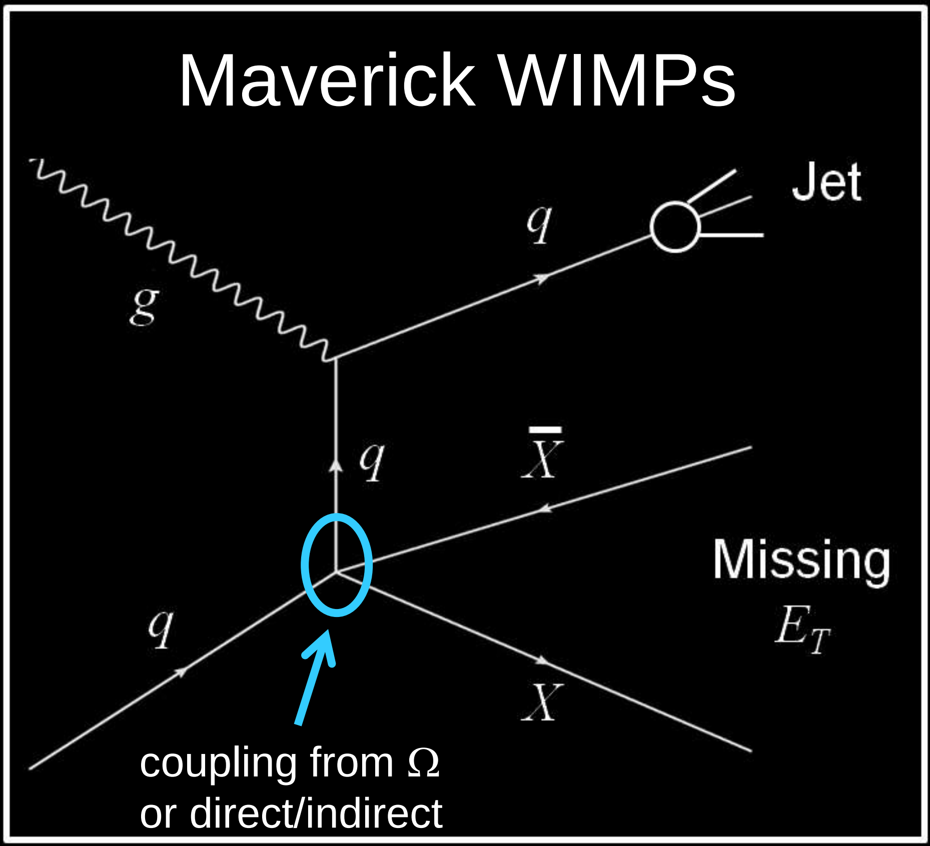
$q + \overline{q} \rightarrow \chi + \chi$

???

Assume described by effective field theory

Maverick WIMPs

Collider Searches

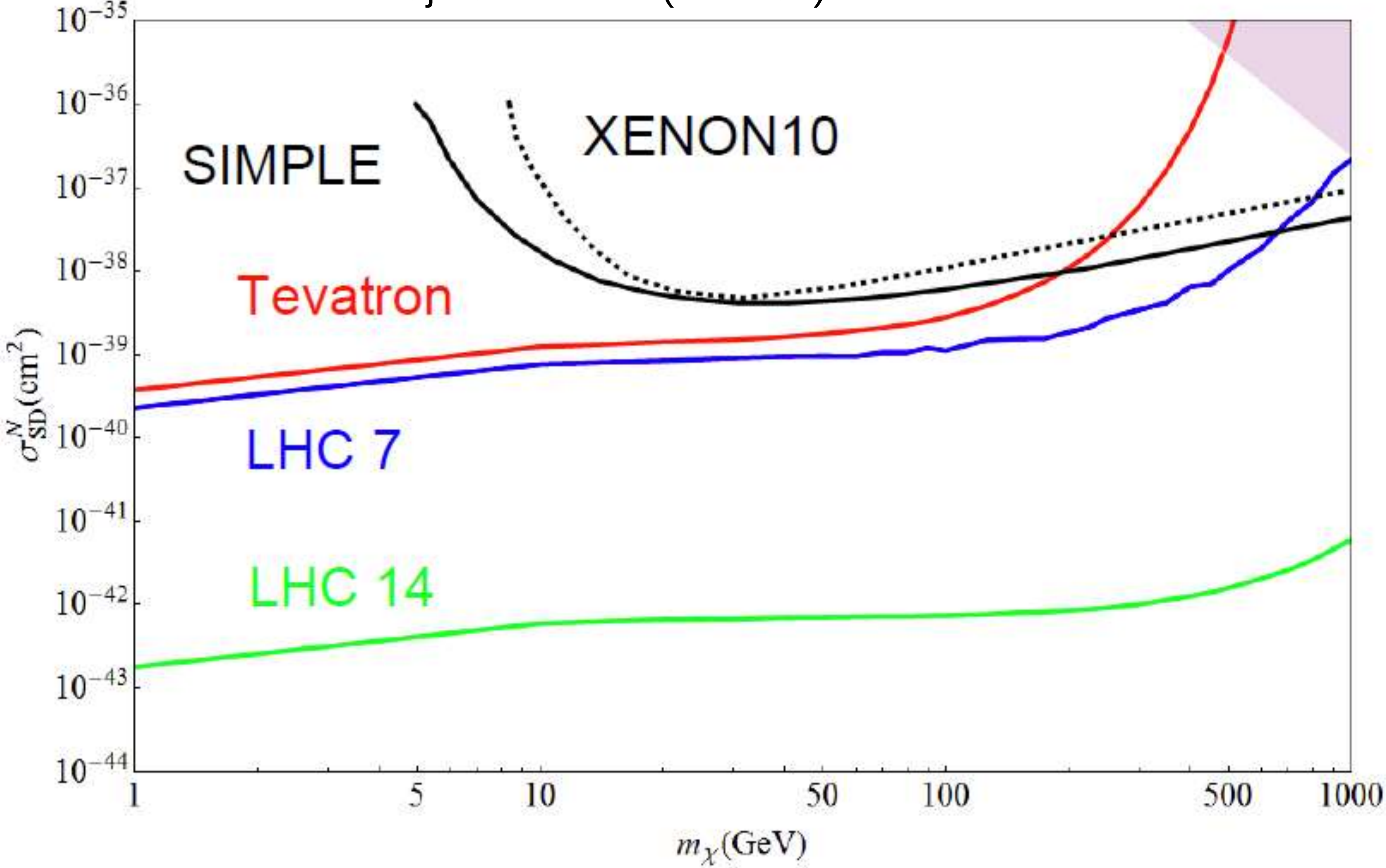


Backgrounds (neutrino, QCD, …)

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

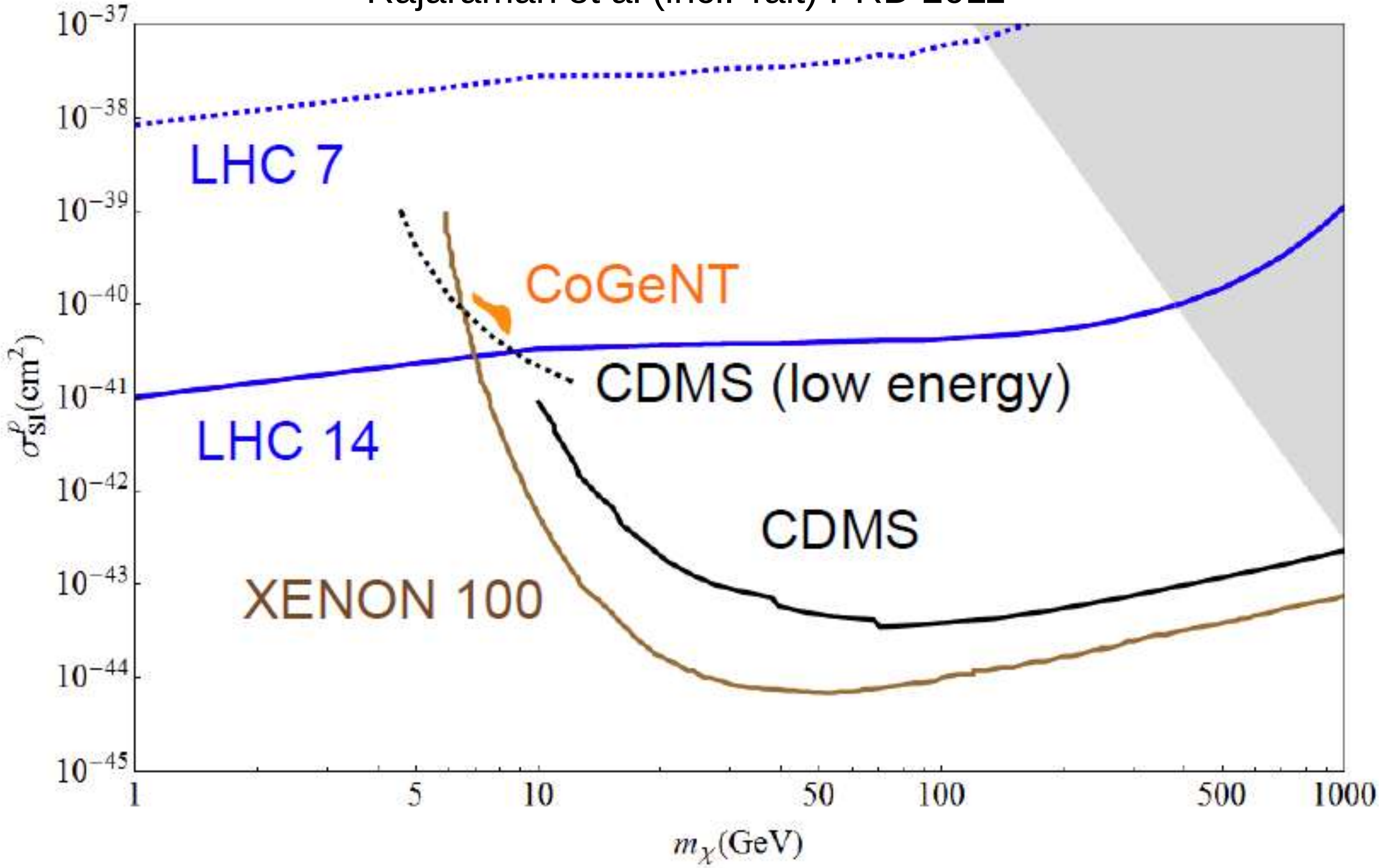
Predicted LHC Sensitivity

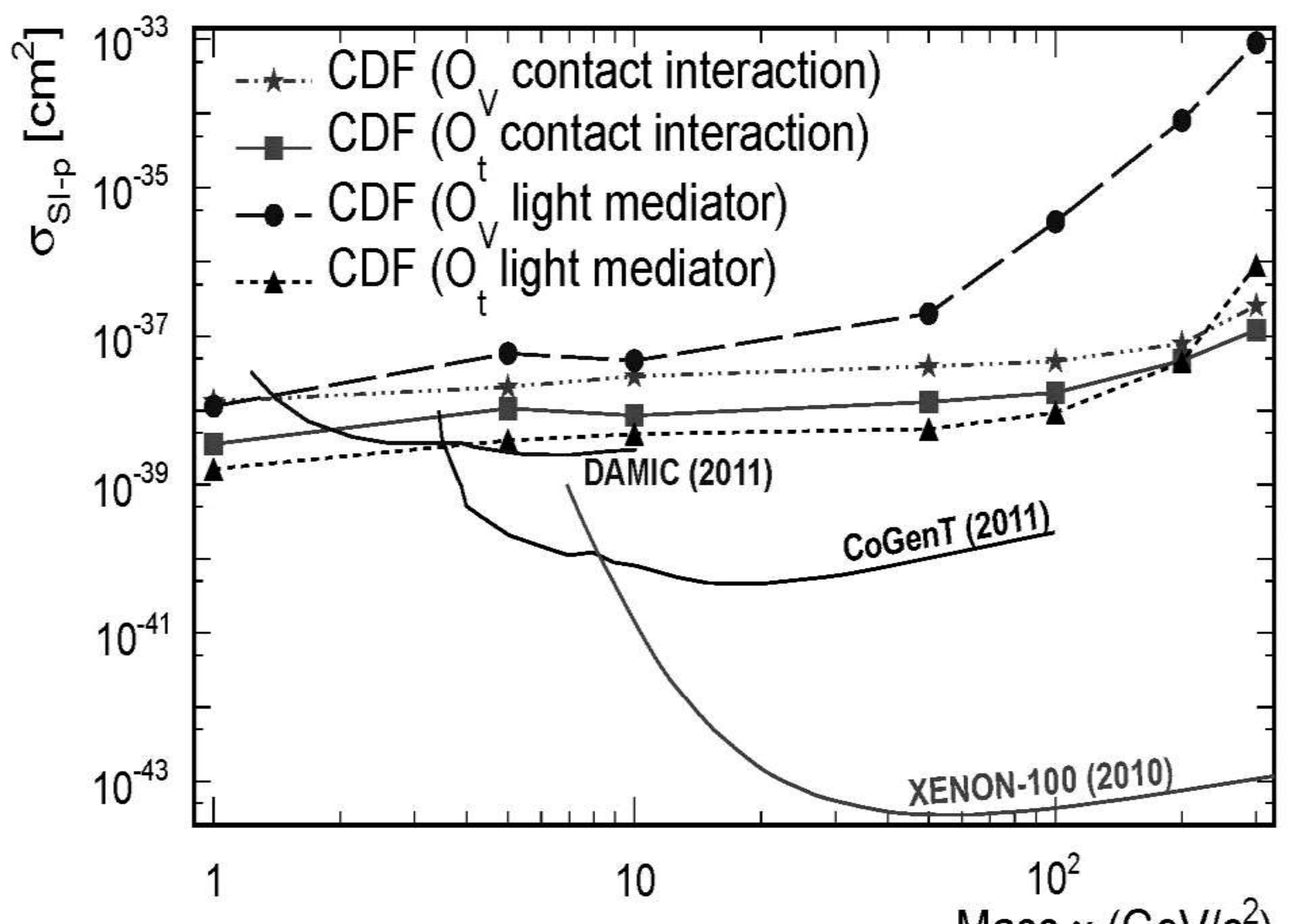
Rajaraman et al (incl. Tait) PRD 2011



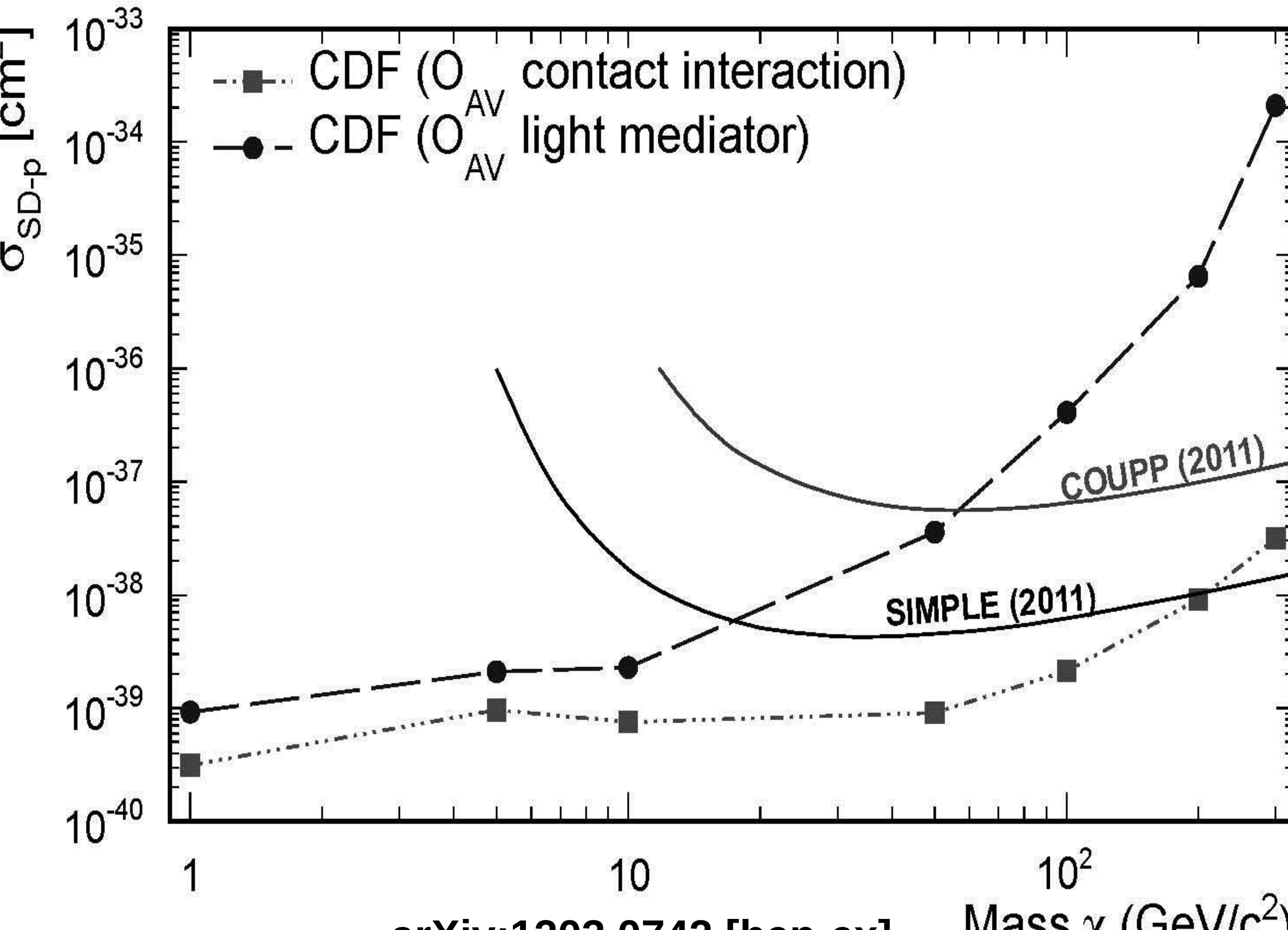
Predicted LHC Sensitivity

Rajaraman et al (incl. Tait) PRD 2011



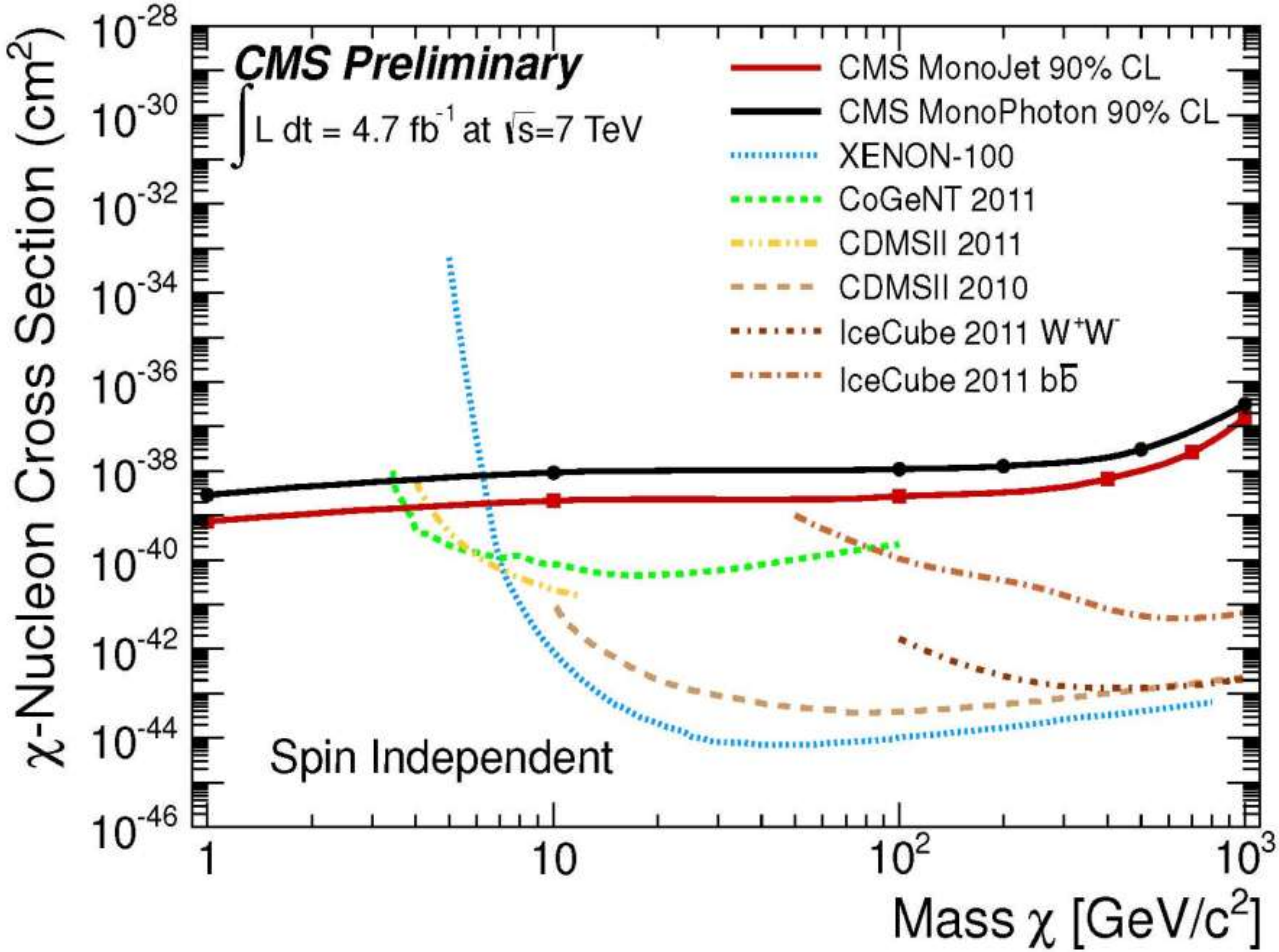


arXiv:1203.0742 [hep-ex]

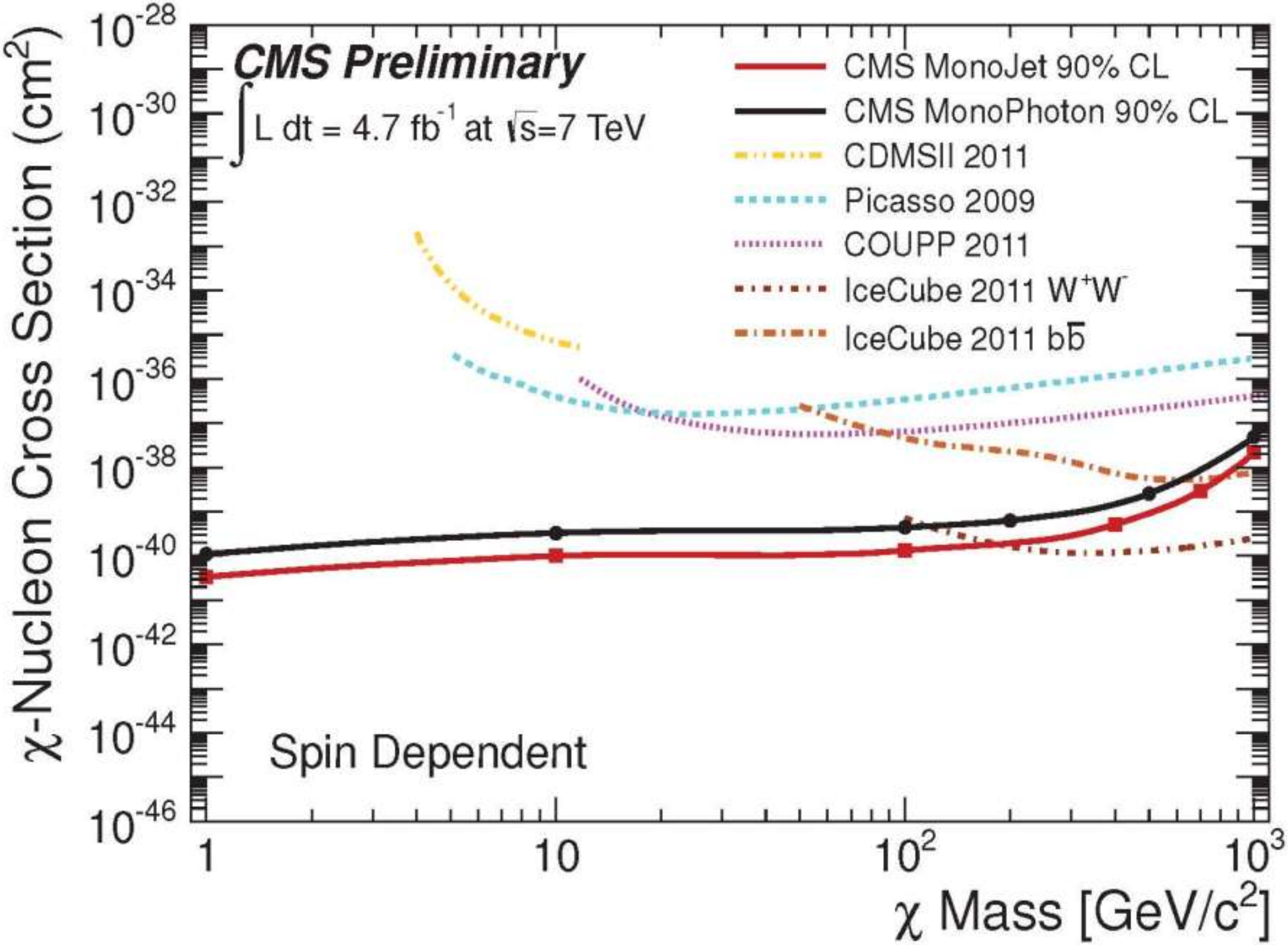


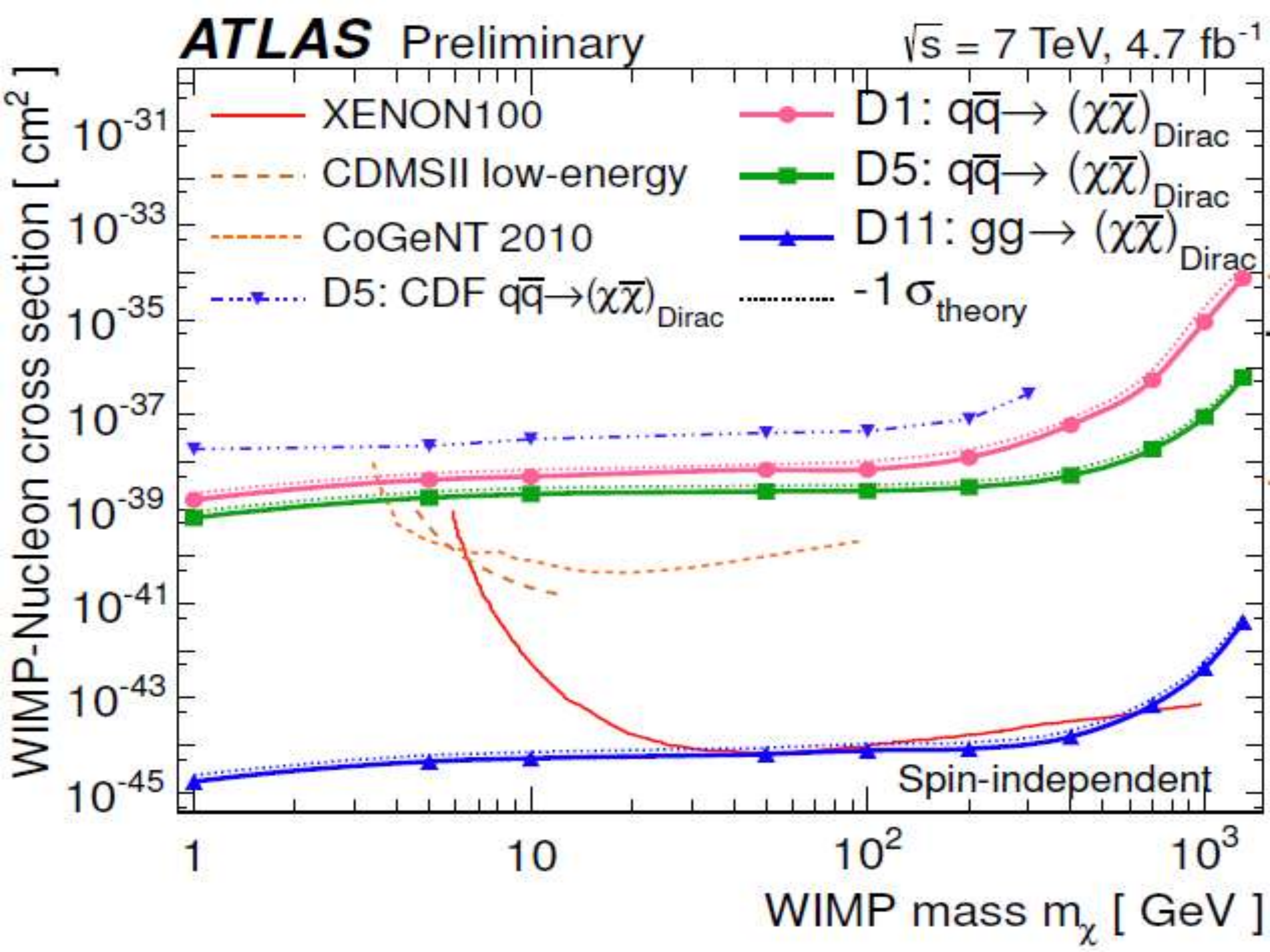
arXiv:1203.0742 [hep-ex]

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

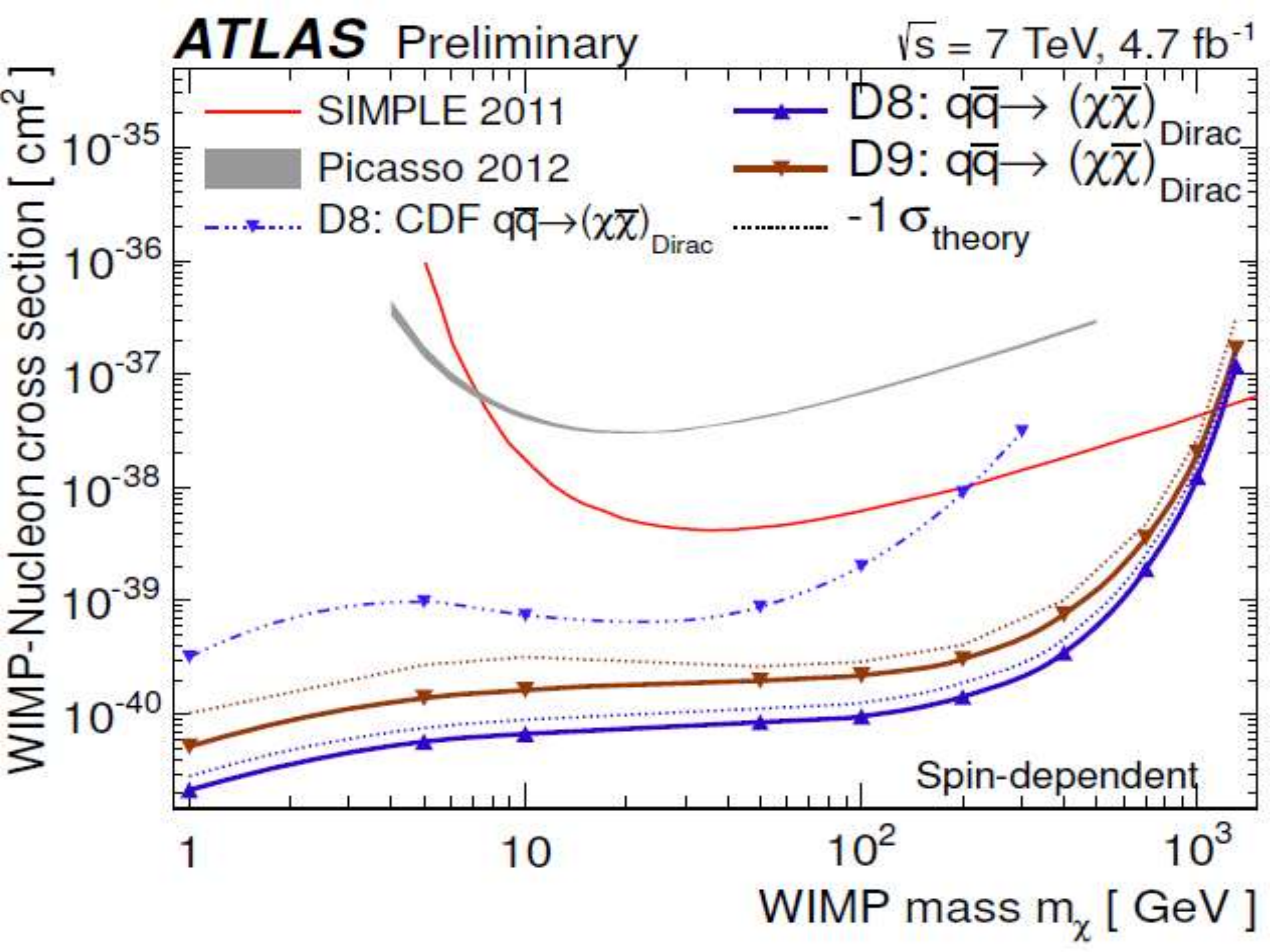


twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012





ATLAS Preliminary
$\sqrt{s}$ = 7 TeV, 4.7 fb^{-1}
XENON100
CDMSII low-energy
CoGeNT 2010
D5: CDF $q\bar{q}\rightarrow(\chi\bar{\chi})_{Dirac}$
D1: $q\bar{q}\rightarrow(\chi\bar{\chi})_{Dirac}$
D5: $q\bar{q}\rightarrow(\chi\bar{\chi})_{Dirac}$
D11: $gg\rightarrow(\chi\bar{\chi})_{Dirac}$
-1 σ_{theory}
Spin-independent
WIMP-Nucleon cross section [cm^2]
WIMP mass m_χ [GeV]
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
1
10
10^2
10^3



ATLAS Preliminary
$\sqrt{s}$ = 7 TeV, 4.7 fb^{-1}
SIMPLE 2011
Picasso 2012
D8: CDF $q\bar{q}\rightarrow(\chi\bar{\chi})_{Dirac}$
D8: $q\bar{q}\rightarrow(\chi\bar{\chi})_{Dirac}$
D9: $q\bar{q}\rightarrow(\chi\bar{\chi})_{Dirac}$
$-1\sigma_{theory}$
Spin-dependent
WIMP-Nucleon cross section [cm^2]
WIMP mass m_χ [GeV]
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
1
10
10^2
10^3

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

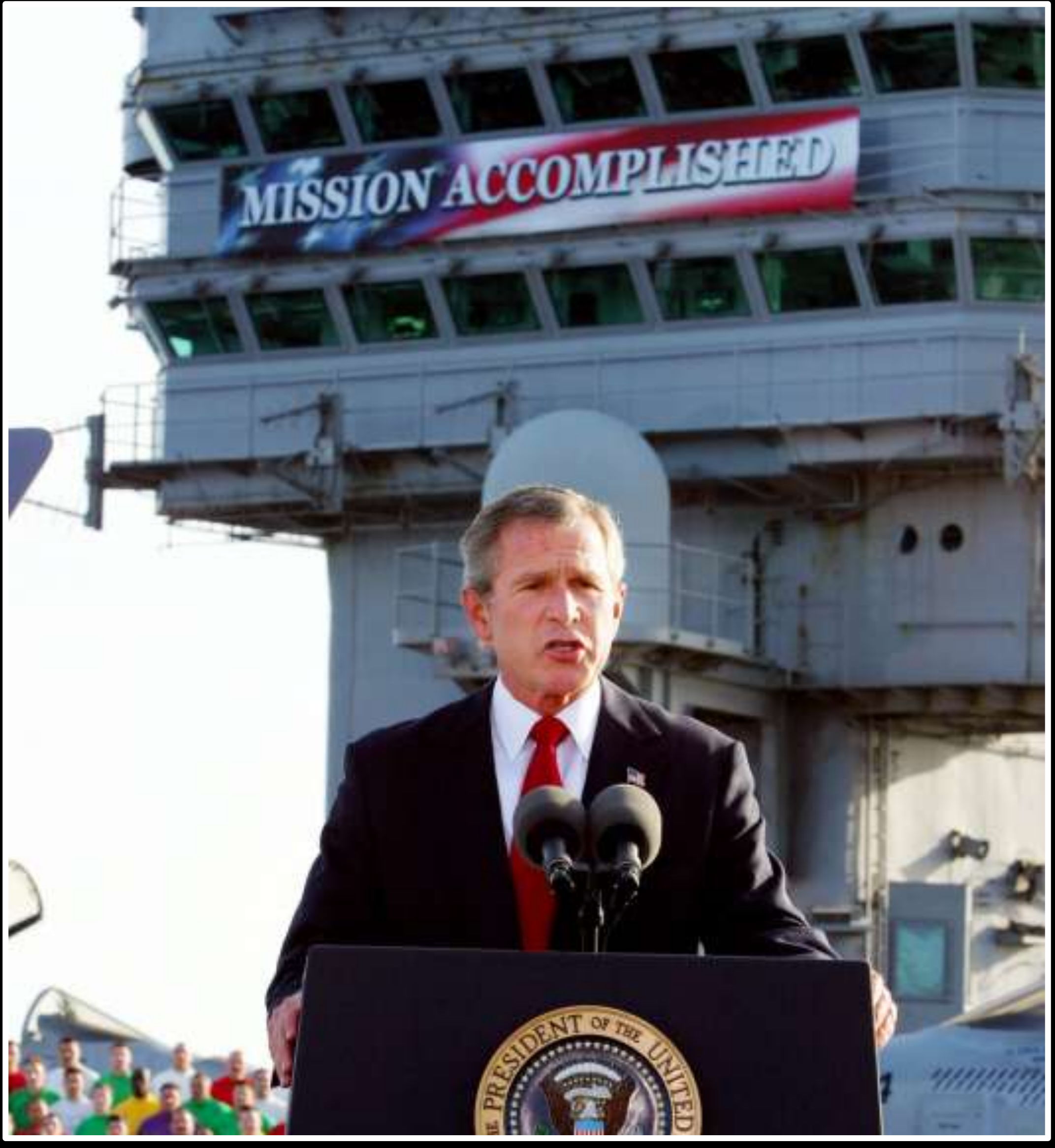
The Decade of the WIMP

- WIMP coincidence or causation (it ain’t a 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 (direct + indirect + accelerator) “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

Exotic Physics: Dark Matter and Dark Energy

Rocky I: (Wednesday) Dark Matter
Rocky II: (Thursday) Dark Energy

Rocky Kolb **University of Chicago**