Particle Physics Foundations of Dark Matter, Dark Energy, and Inflation

ROCKY I: DARK MATTER (WEDNESDAY, 11:00)
ROCKY 1.5 DARK MATTER II (THURSDAY, 11:00)
ROCKY II: DARK ENERGY (THURSDAY, 11:00)

ROCKY III: INFLATION (FRIDAY, 11:00)

Rocky Kolb
University of Chicago

Particle Dark Matter

- 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} eV (10^{-56} g) B.E.C.s

$10^{-8}\,M_{\odot}$ (10^{+25} g) axion clusters

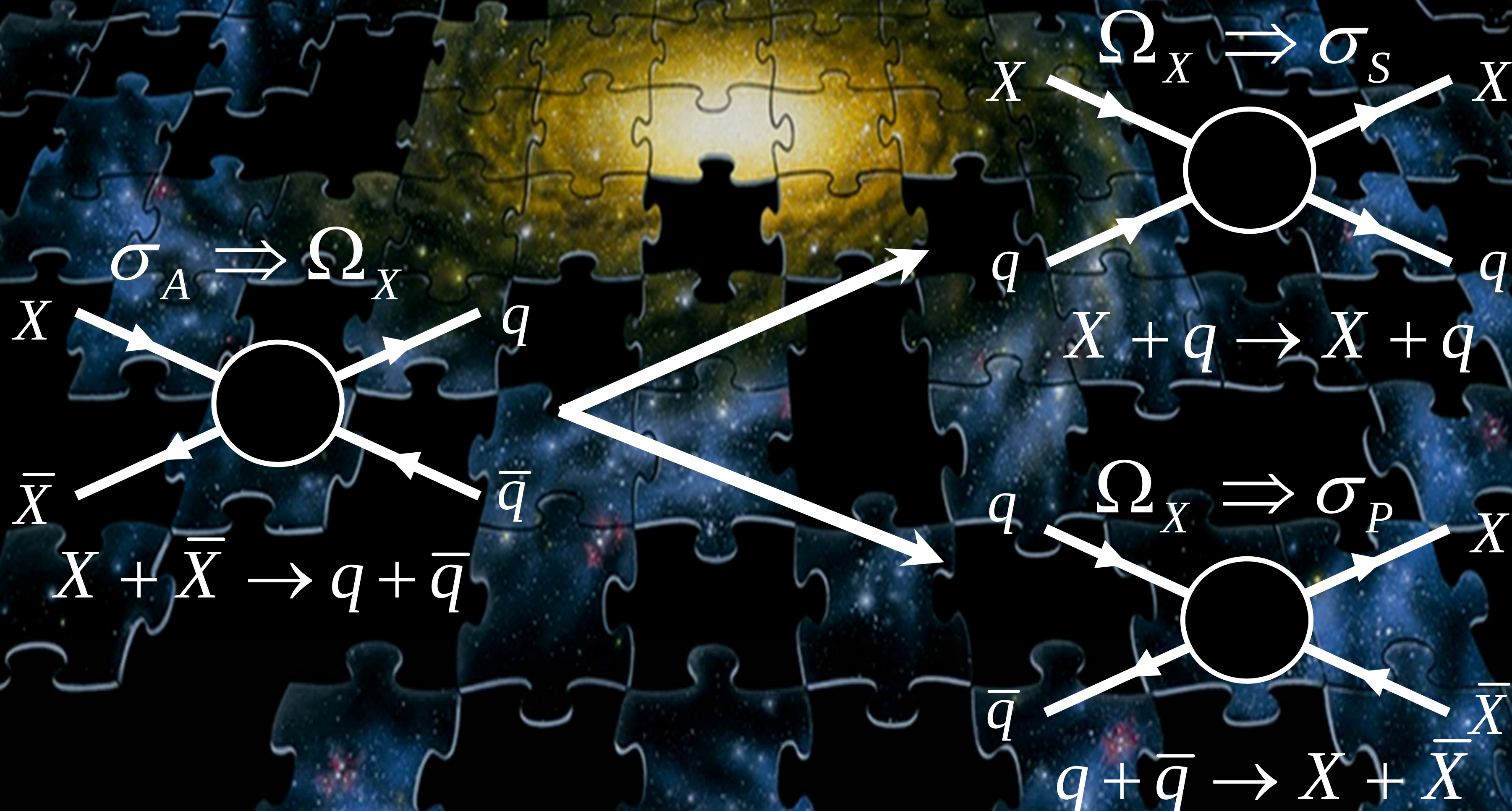
Interaction strength range

Only gravitational: wimpzillas

Strongly interacting: B balls

WIMPs

Too good to be true?



PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

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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 $M\simeq 27$ 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]

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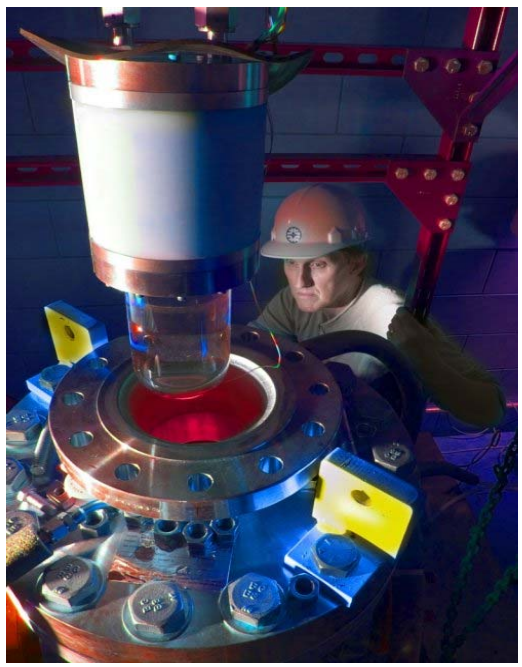
Received 5 May 1987

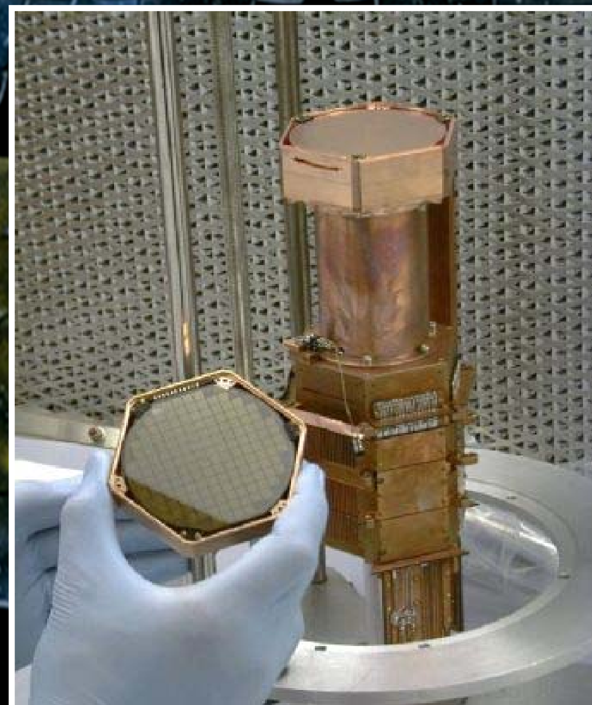
An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy. Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy 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.

Direct Detection

COUPP



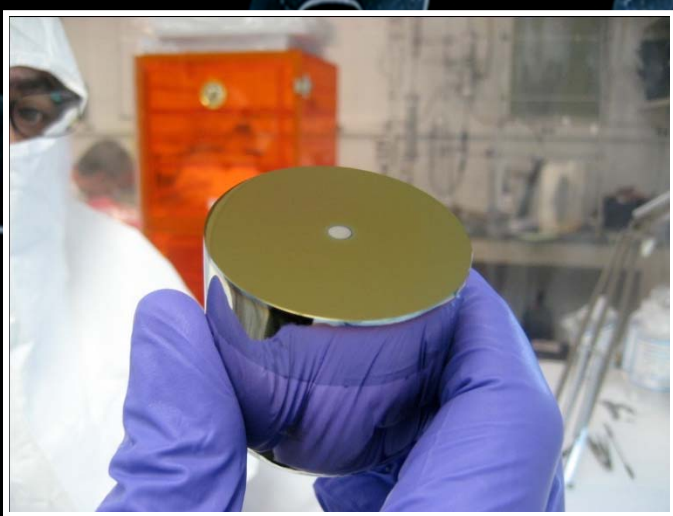
CDMS



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: $\rho_{DM} = 0.3 \text{ GeV cm}^{-3}$
- Usual assumption: Maxwellian velocity distribution in galactic rest frame

Kinematical and chemical vertical structure of the Galactic thick disk[1,2]
II. A lack of dark matter in the solar neighborhood

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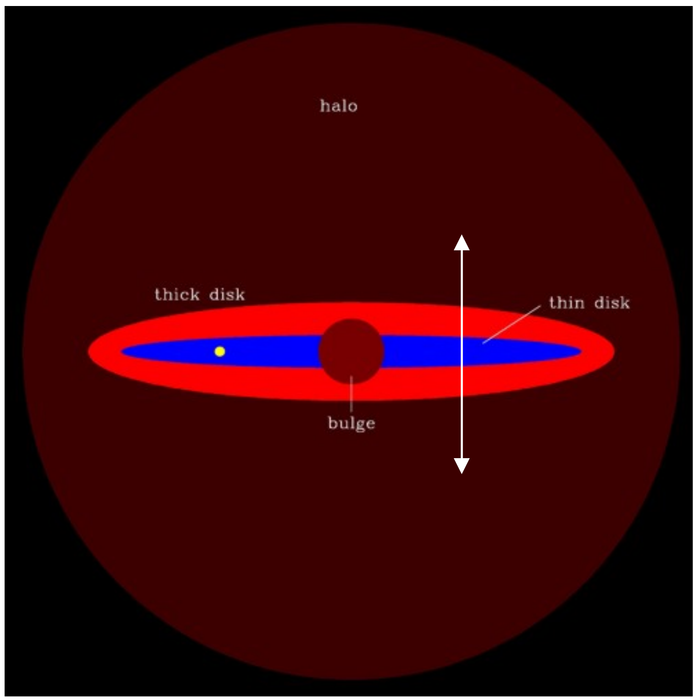
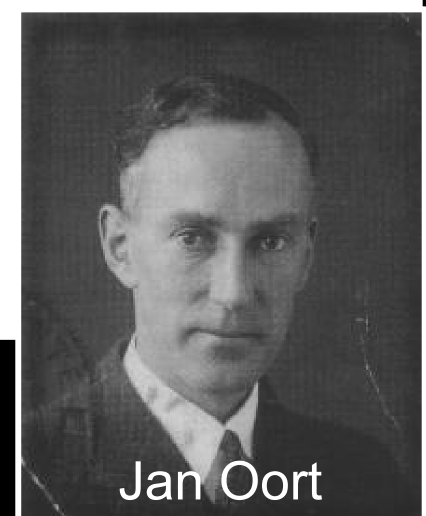


Infer surface mass density from dynamics of stellar motions.

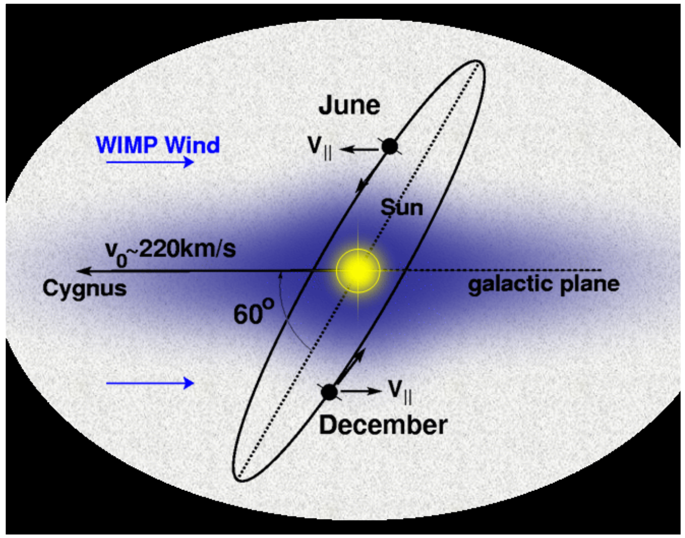


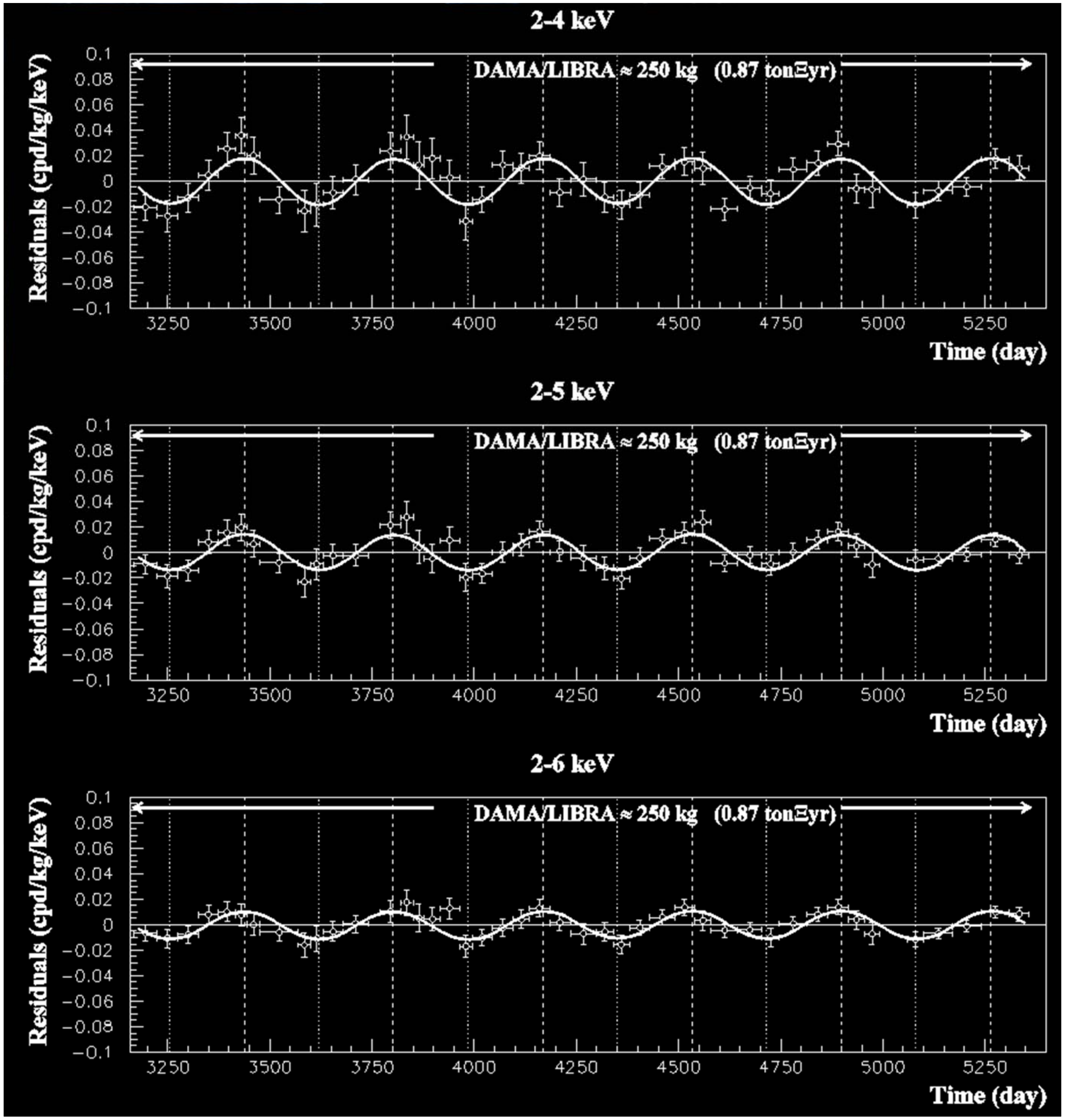
DAMA/LIBRA

$\cos\,\omega\,(t - t_0)$

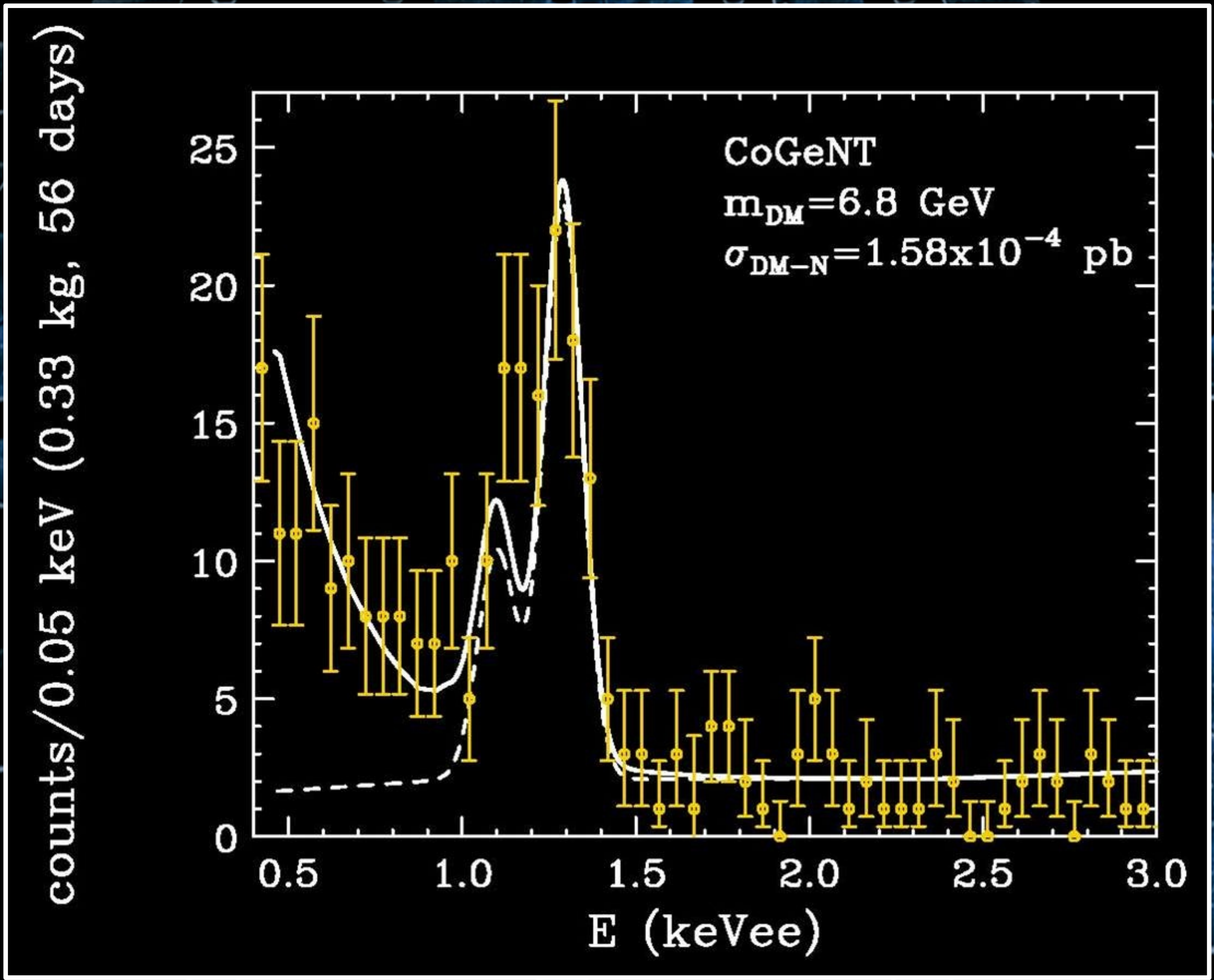
$T = 2\pi/\omega = 1$ year

$t_0 = 152.5^d$ (2 June)



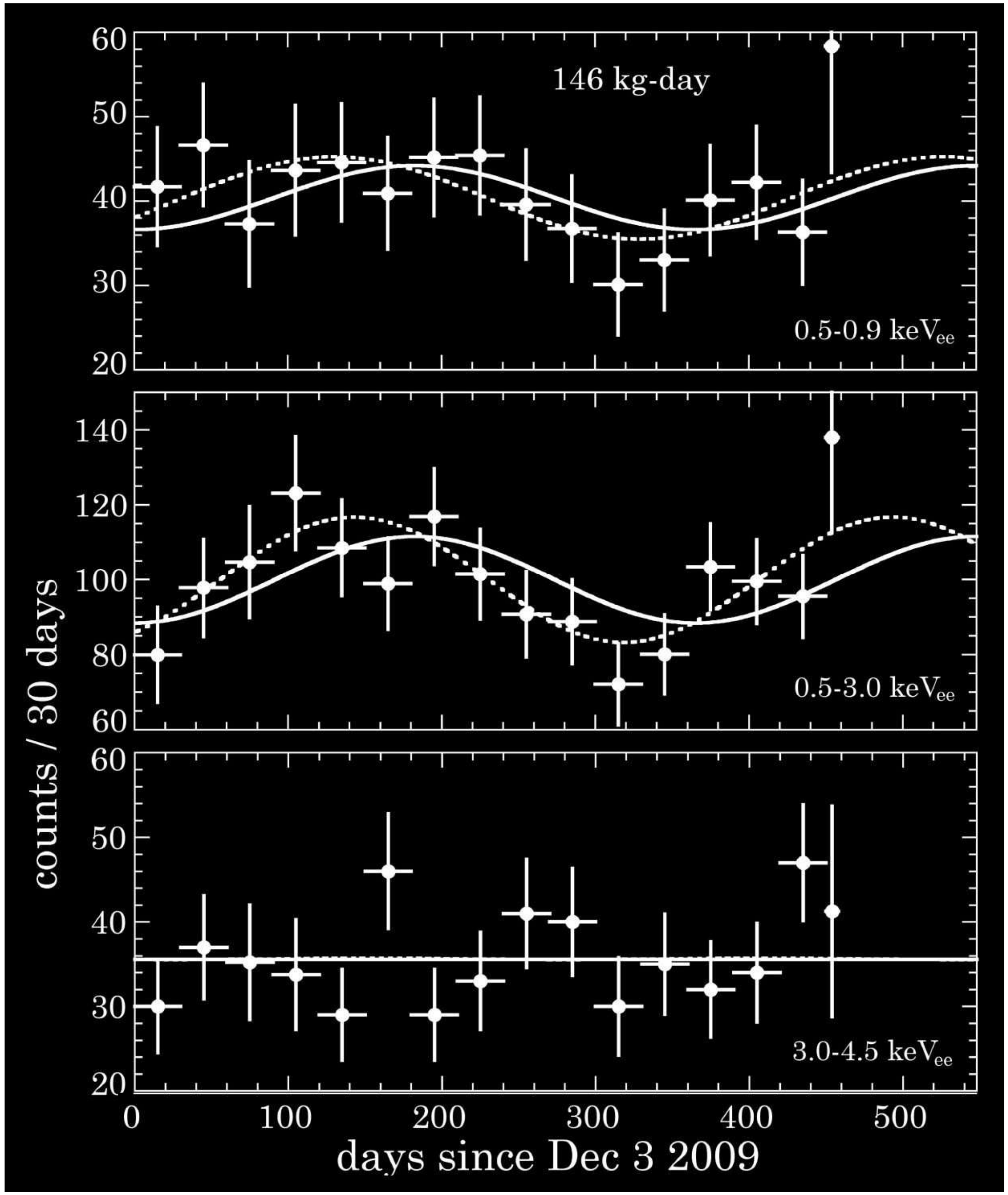


CoGeNT



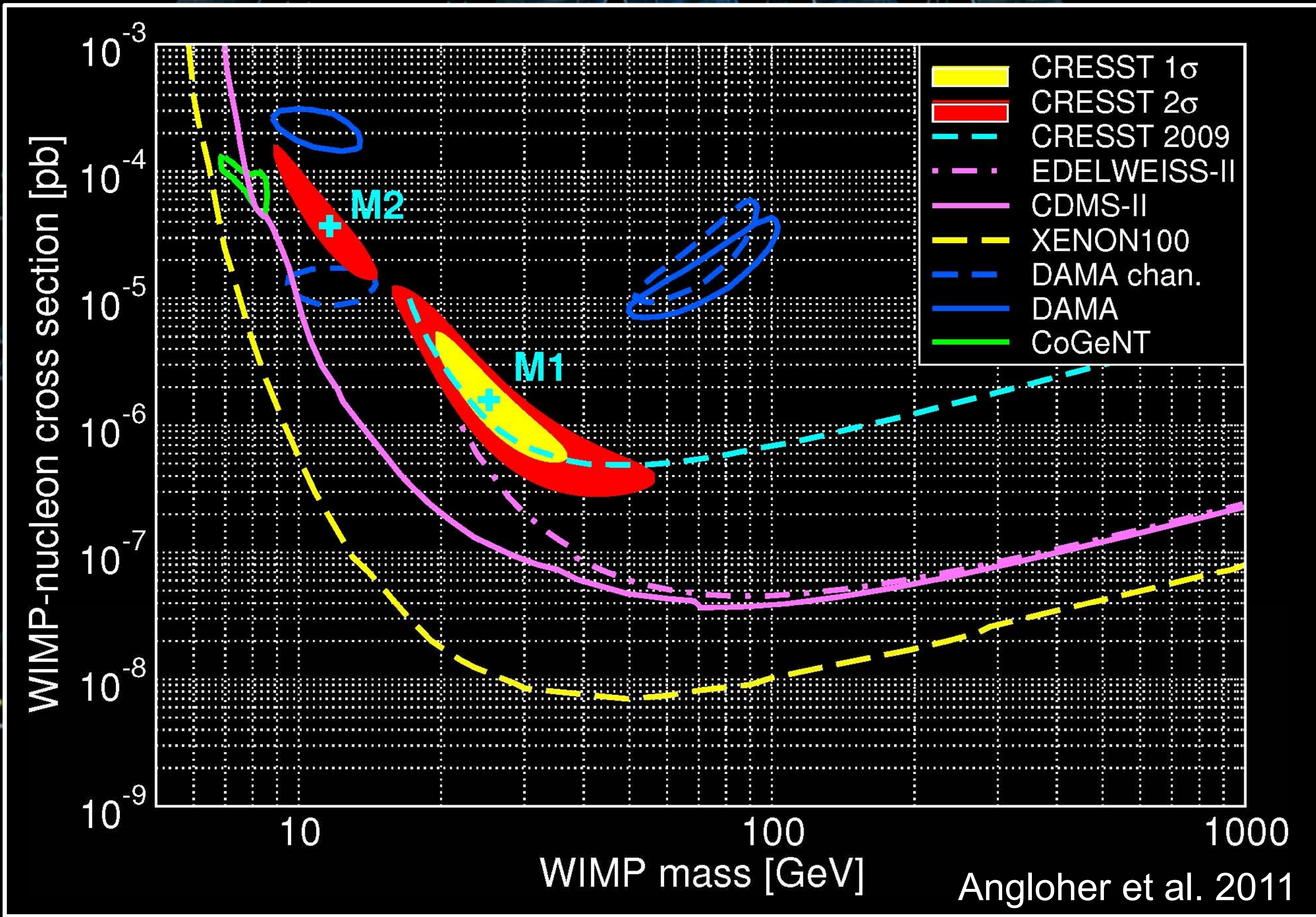
CoGeNT
m_{DM}=6.8 GeV
σ_{DM-N}=1.58x10^{-4} pb
counts/0.05 keV (0.33 kg, 56 days)
E (keVee)
0 5 10 15 20 25
0.5 1.0 1.5 2.0 2.5 3.0

CoGeNT



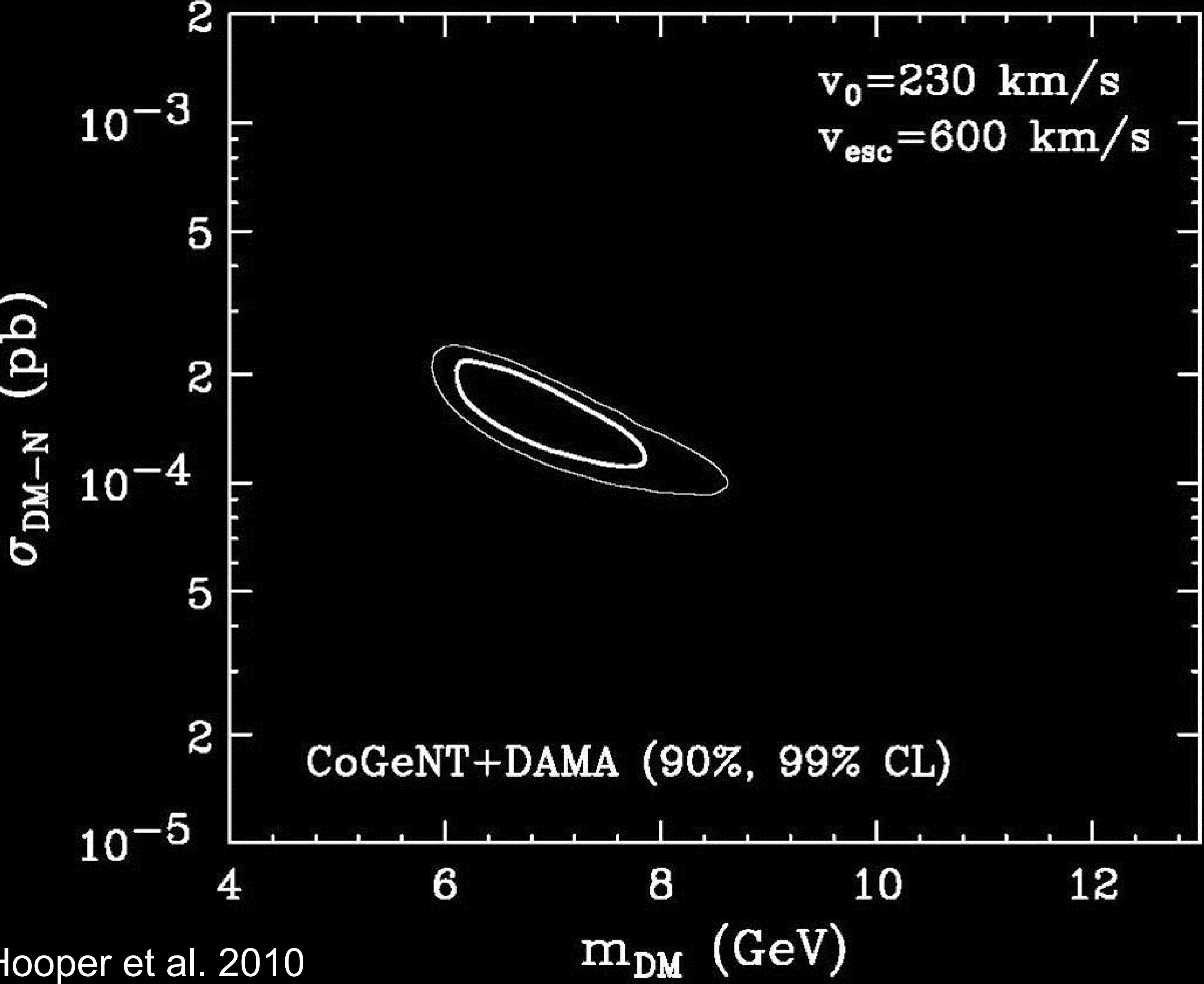
annual modulation
at 2.8σ
Aalseth et al. 2011

CRESST



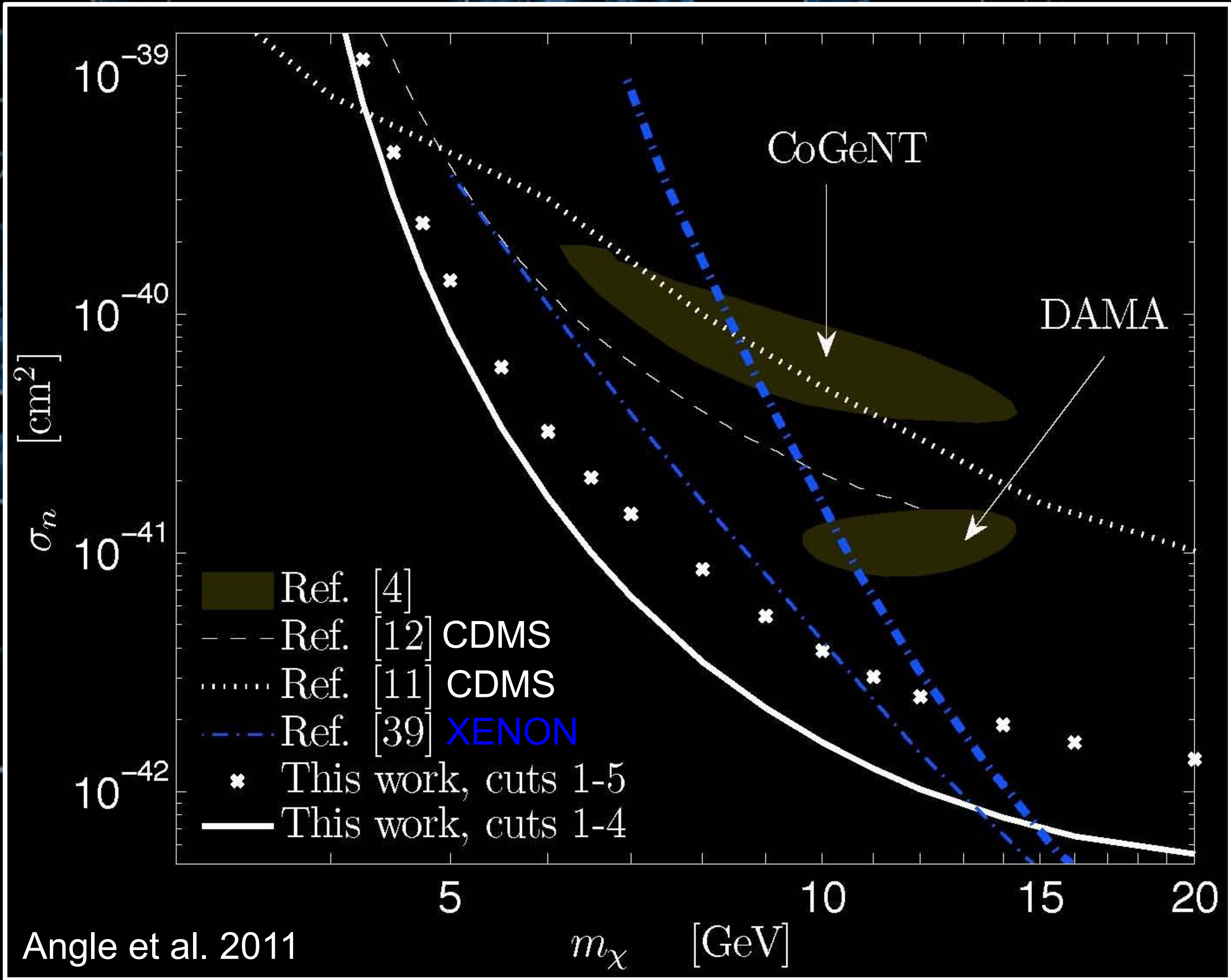
CRESST 1σ
CRESST 2σ
CRESST 2009
EDELWEISS-II
CDMS-II
XENON100
DAMA chan.
DAMA
CoGeNT
M2
M1
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
WIMP-nucleon cross section [pb]
10
100
1000
WIMP mass [GeV]
Angloher et al. 2011

CoGeNT + DAMA



Hooper et al. 2010

XENON/CDMS



CoGeNT
DAMA
Ref. [4]
Ref. [12] CDMS
Ref. [11] CDMS
Ref. [39] XENON
This work, cuts 1-5
This work, cuts 1-4
σ_n [cm^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
5
10
15
20
m_χ [GeV]
Angle et al. 2011

A Maximum Likelihood Analysis of Low-Energy CDMS Data

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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

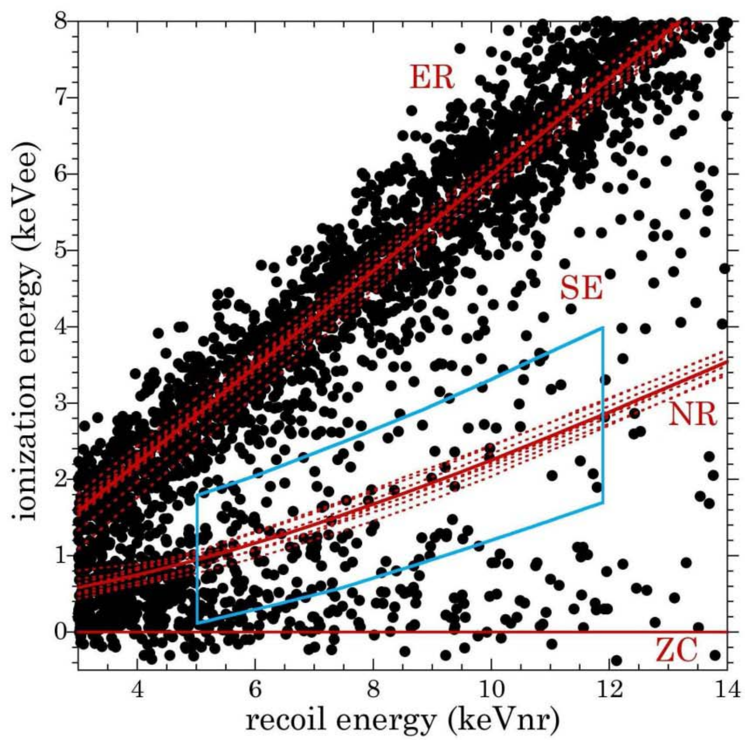

FIG. 1: Scatter plot of single-interaction events in all eight CDMS detectors, digitized from individual plots in [1], using g3DATA software [9]. Thick solid lines represent the approx-

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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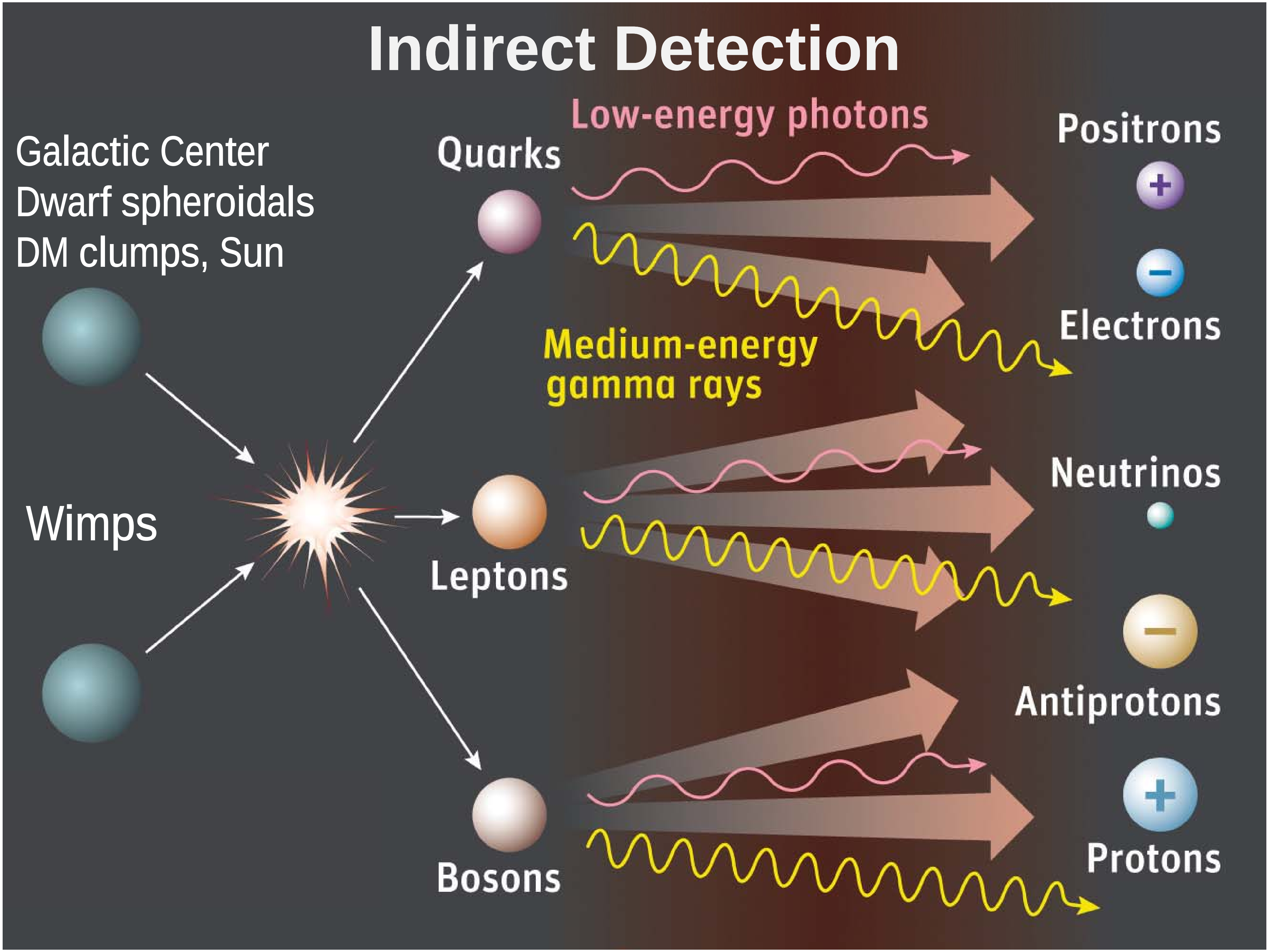
Received 1977 December 12; accepted 1978 February 14

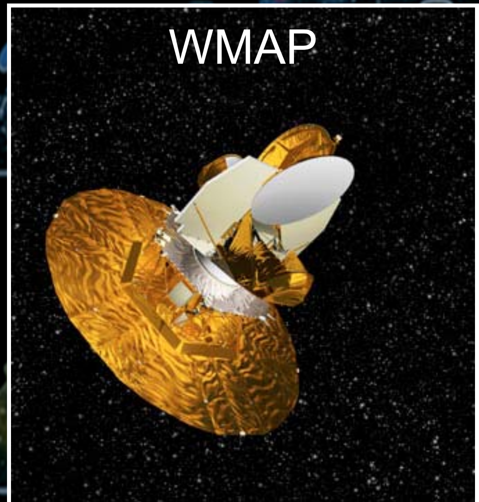
ABSTRACT

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.

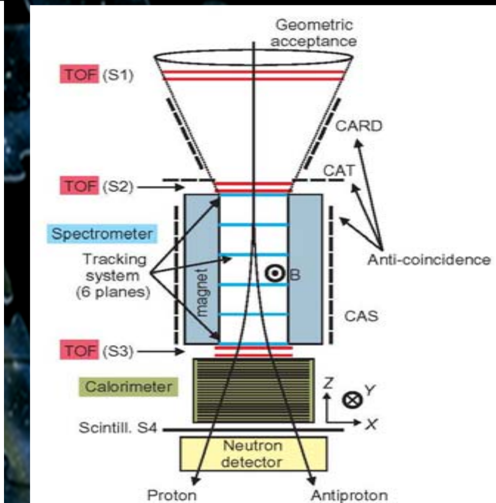
Subject headings: cosmic rays: general — cosmology — elementary particles — gamma rays: general

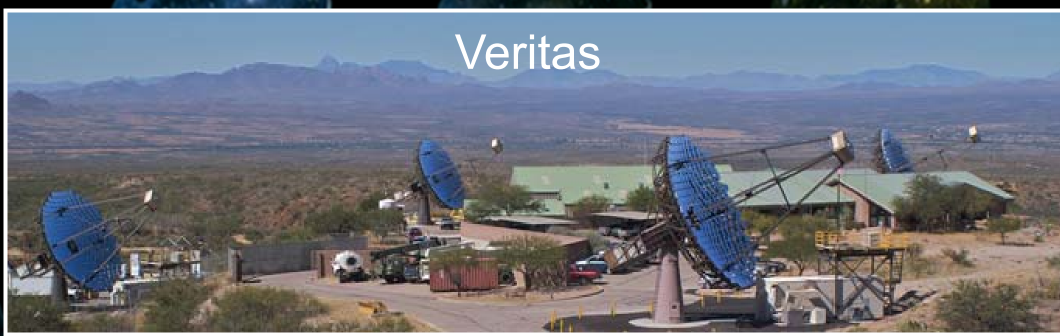

Indirect Detection
Galactic Center
Dwarf spheroidals
DM clumps, Sun
Wimps
Quarks
Leptons
Bosons
Low-energy photons
Medium-energy gamma rays
Positrons
Electrons
Neutrinos
Antiprotons
Protons

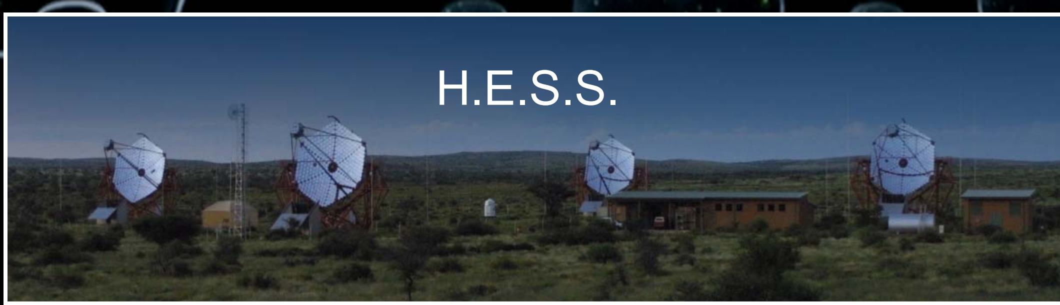
Indirect Detection



PAMELA



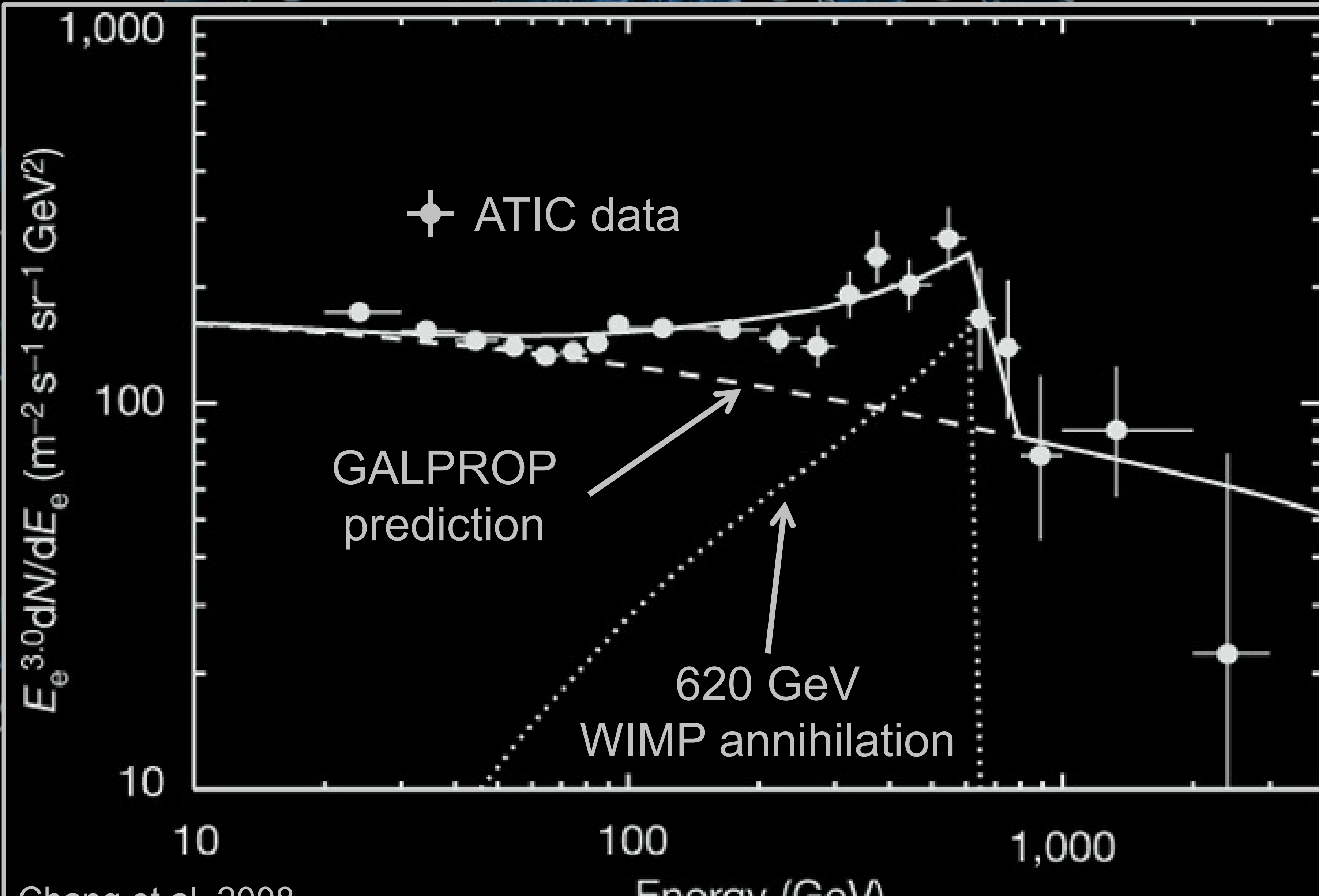




Inirect Detection

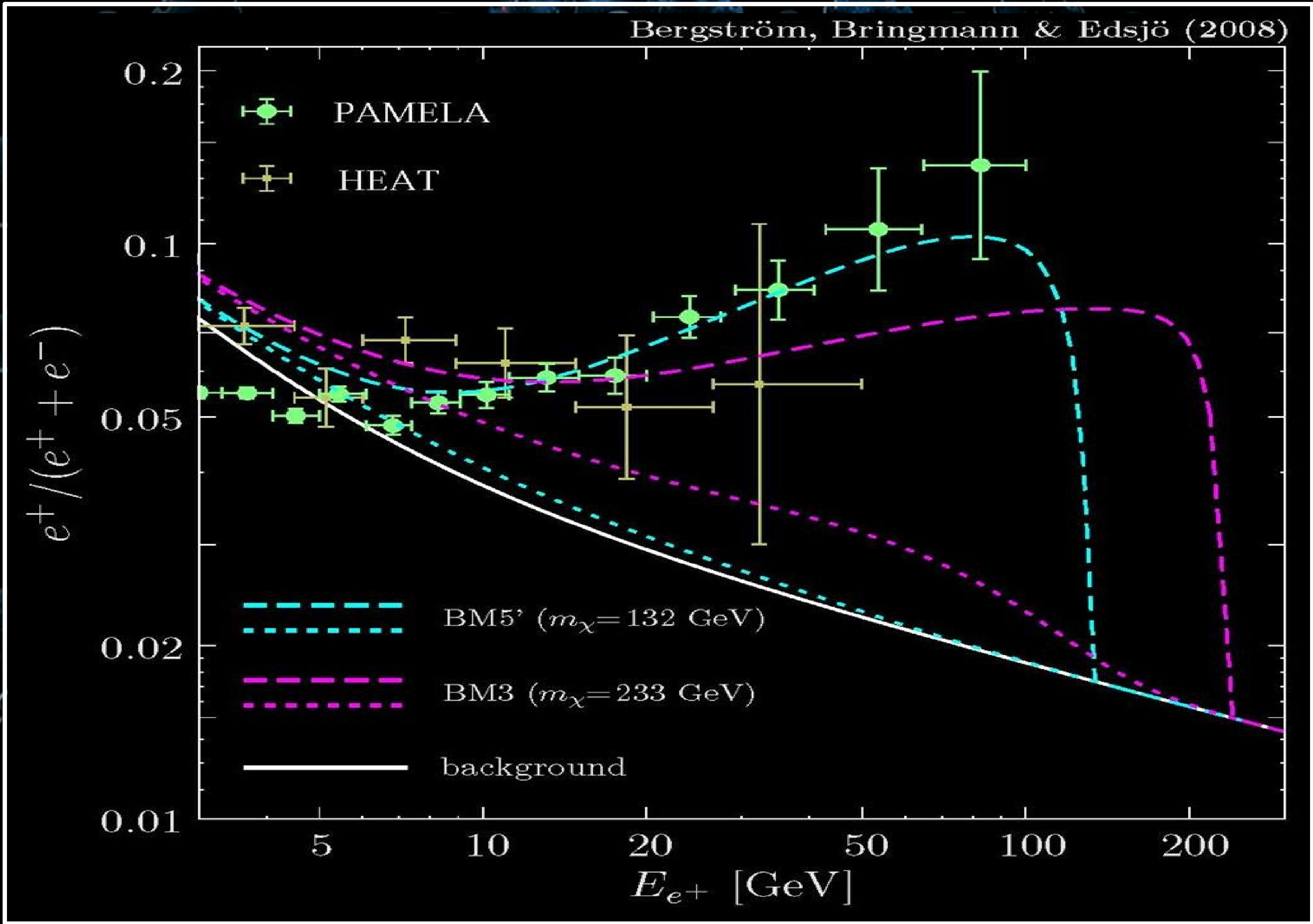
- Depends on WIMP density in galactic center or other structures.
- Simulations unable to resolve issue completely.
- Boost factor.
- If charged particles, propagation in magnetic fields.
- Astrophysical backgrounds.

ATIC



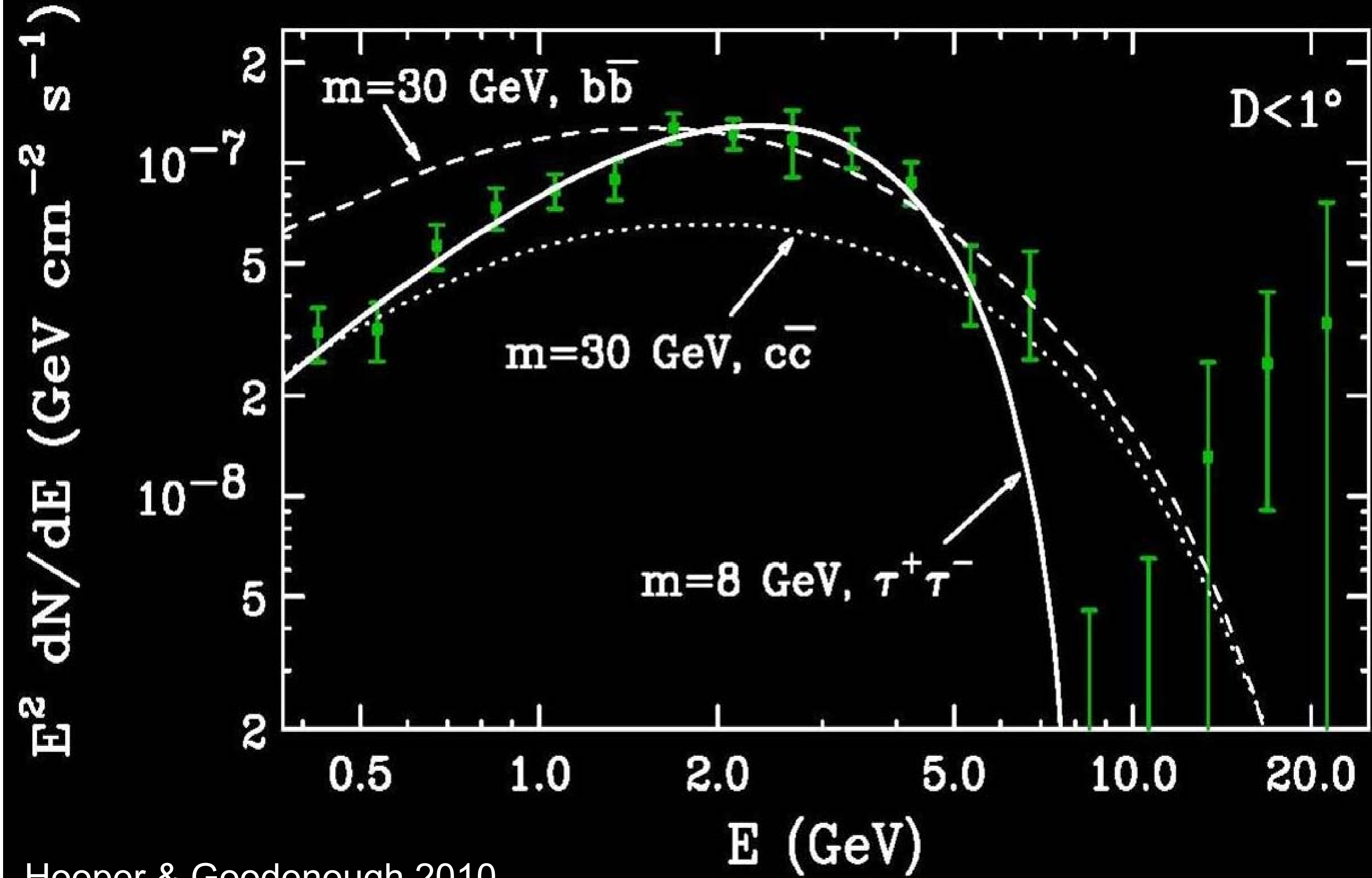
Chang et al. 2008

PAMELA



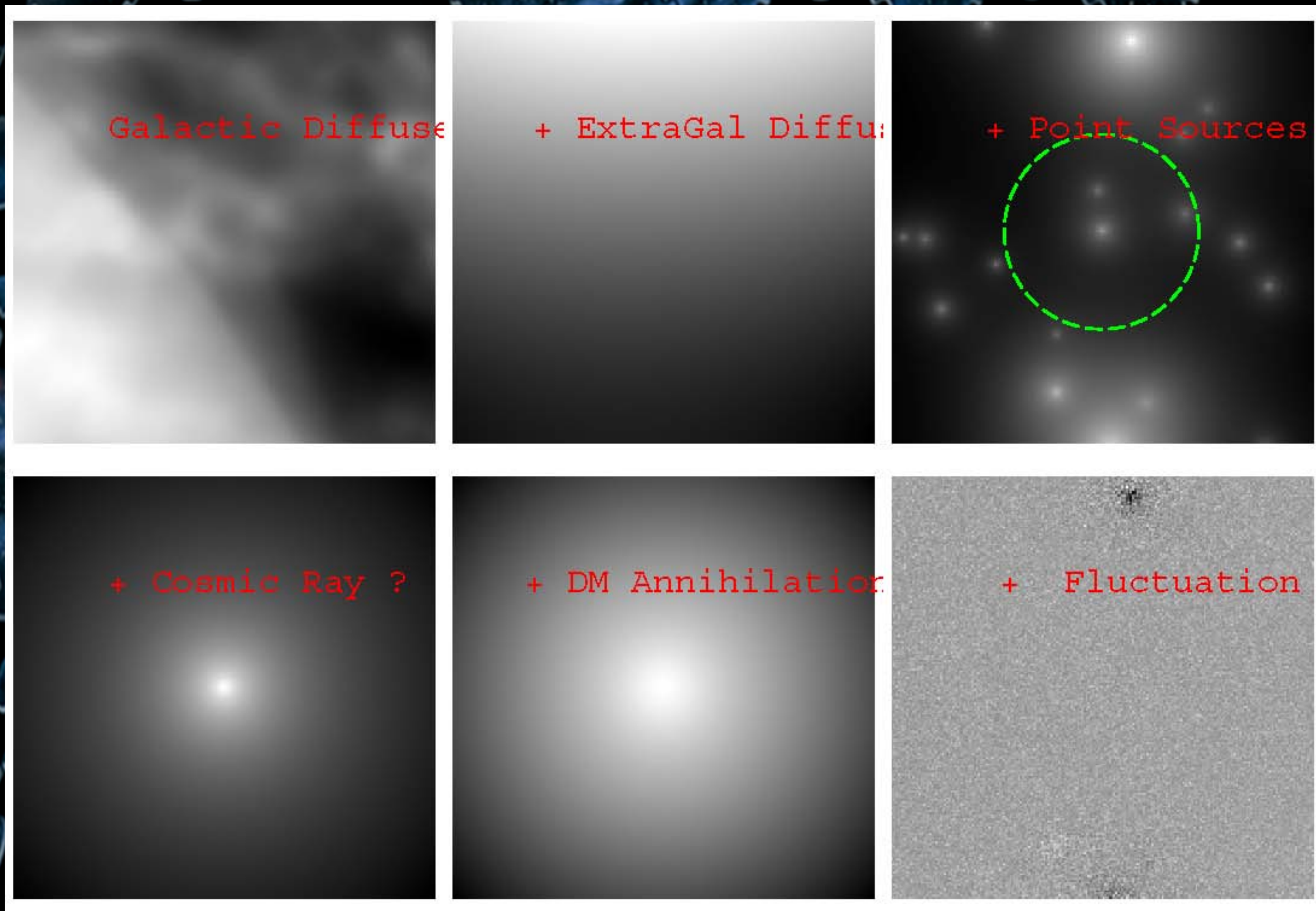
Bergström, Bringmann & Edsjö (2008)
PAMELA
HEAT
BM5' (m_χ=132 GeV)
BM3 (m_χ=233 GeV)
background
0.2
0.1
0.05
0.02
0.01
5
10
20
50
100
200
$e^+/(e^+ + e^-)$
E_{e^+} [GeV]

Fermi/GLAST Feature



Hooper & Goodenough 2010

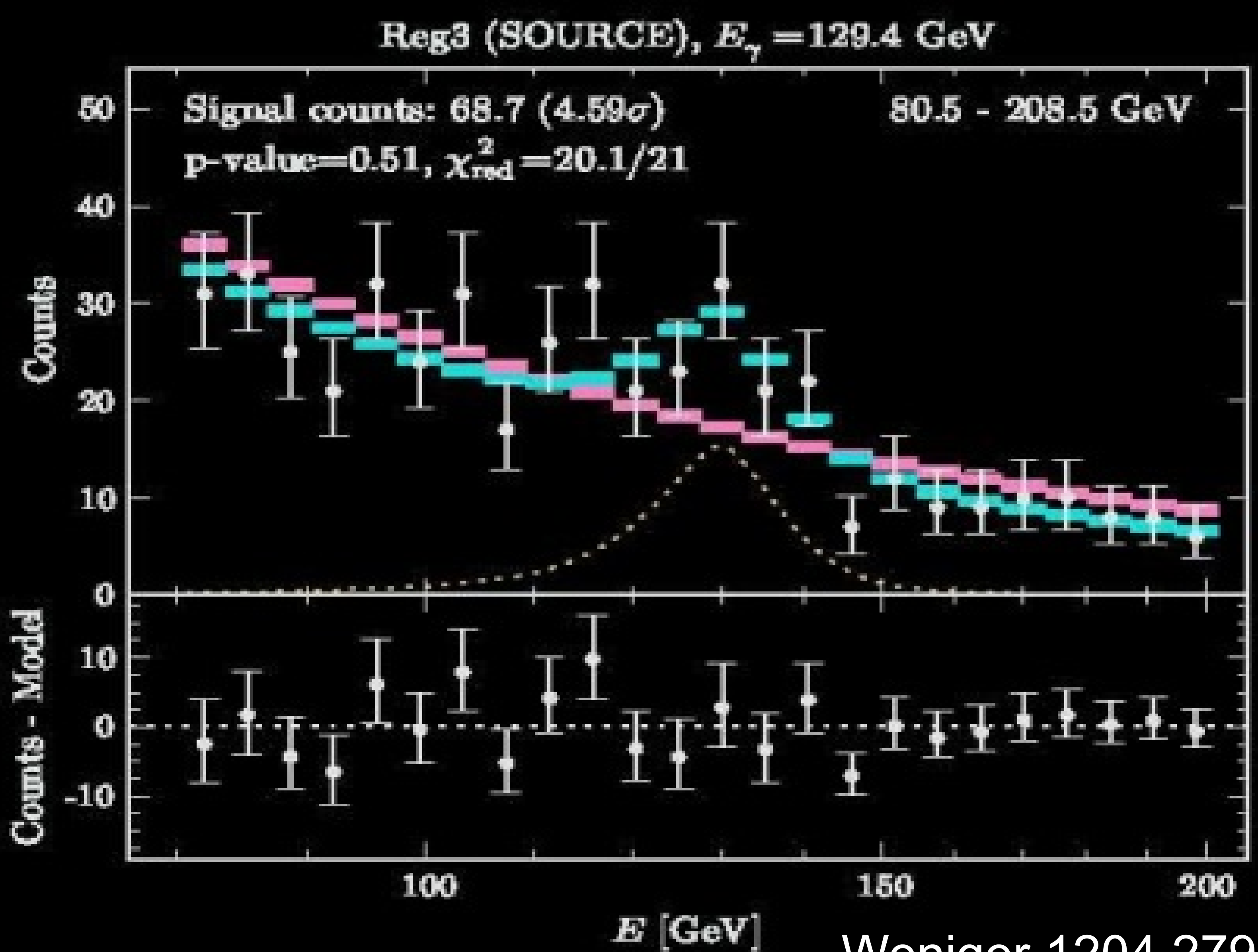
Fermi/GLAST Haze



1. 20 - 60 GeV in $b\,b$ channel
2. 2 - 10 GeV in $\mu^+\mu^-$ channel
3. ≥ 1 TeV in $\mu^+\mu^-$ channel

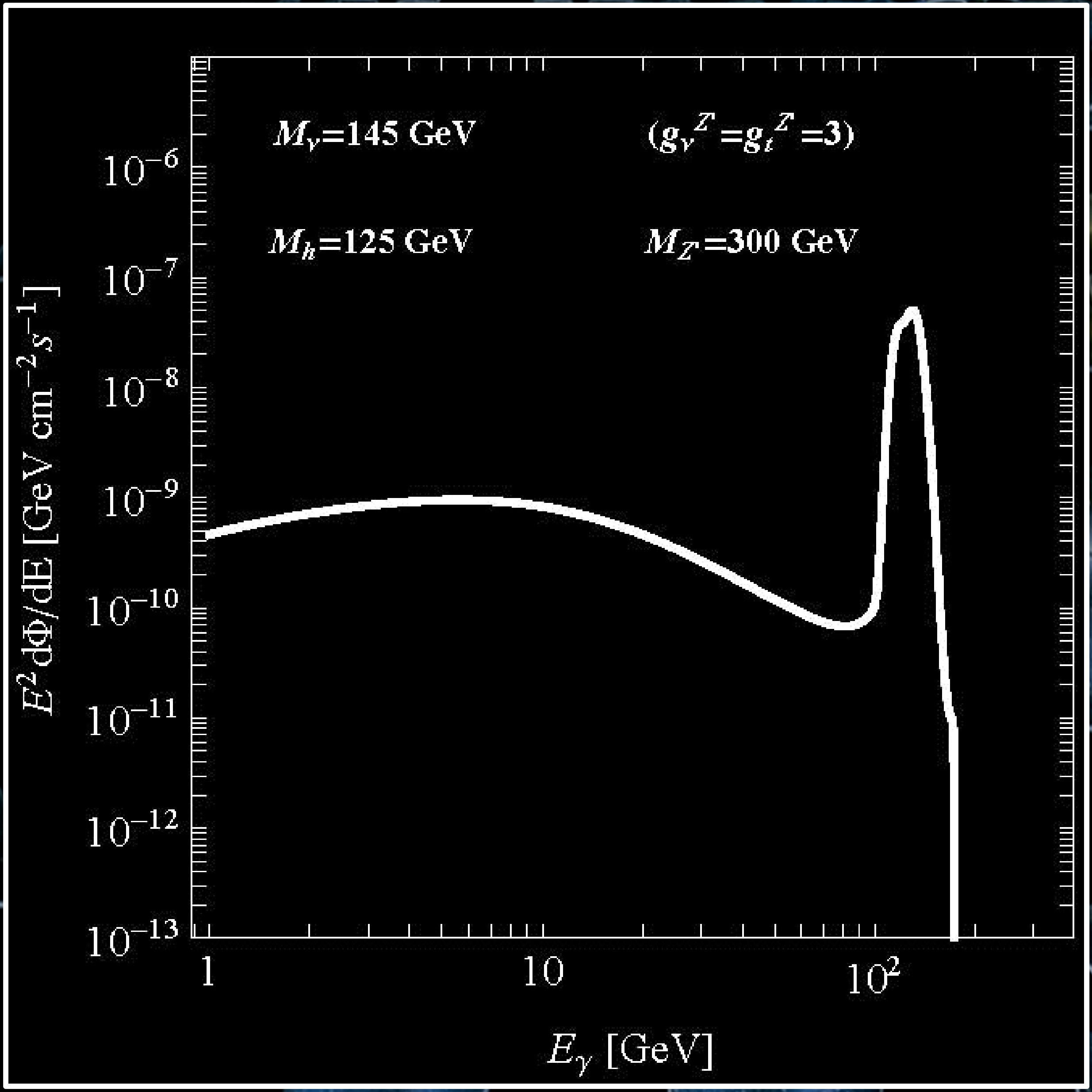
Han, Frenk, Eke, Gao, White (2011)

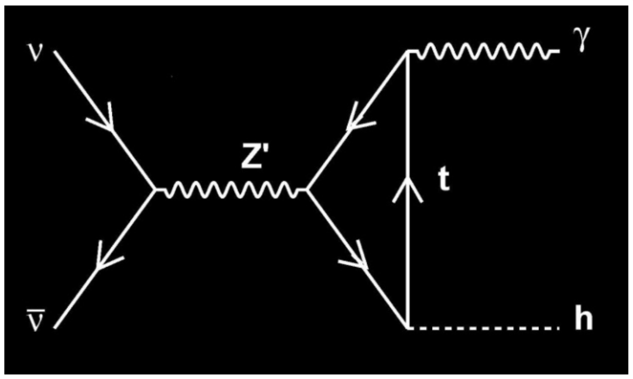
Fermi/GLAST Line



Weniger 1204.2797

Fermi/GLAST Line

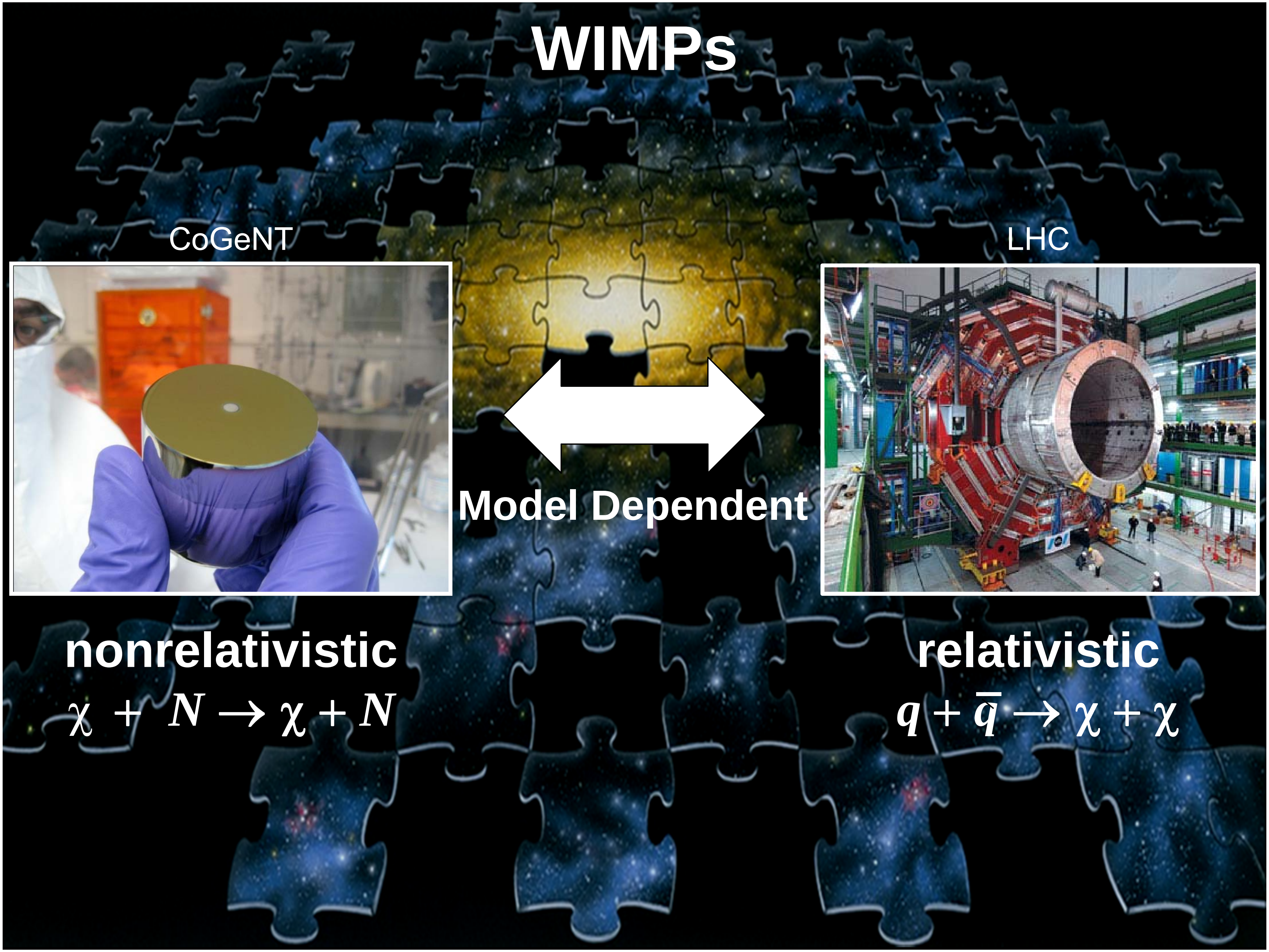




Jackson, Servant, Shaughnessy, Tait, Taoso 0912.0004

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
CoGeNT
LHC
Model Dependent
nonrelativistic
χ + N → χ + N
relativistic
q + q̄ → χ + χ

WIMPs

Maverick WIMP*

- WIMP is a loner.
- Use effective field theory,
  e.g.: 4-Fermi interaction.
- WIMP only new species.
- Clear relationships between
  annihilation-scattering-production cross sections.

Social WIMP

- WIMP part of a social network.
- Motivated model framework,
  e.g., low-energy SUSY.
- Many new particles/parameters.
- Muddy relationships between
  annihilation-scattering-production cross sections.

*Beltran, Hooper, Kolb, Krusberg, Tait

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

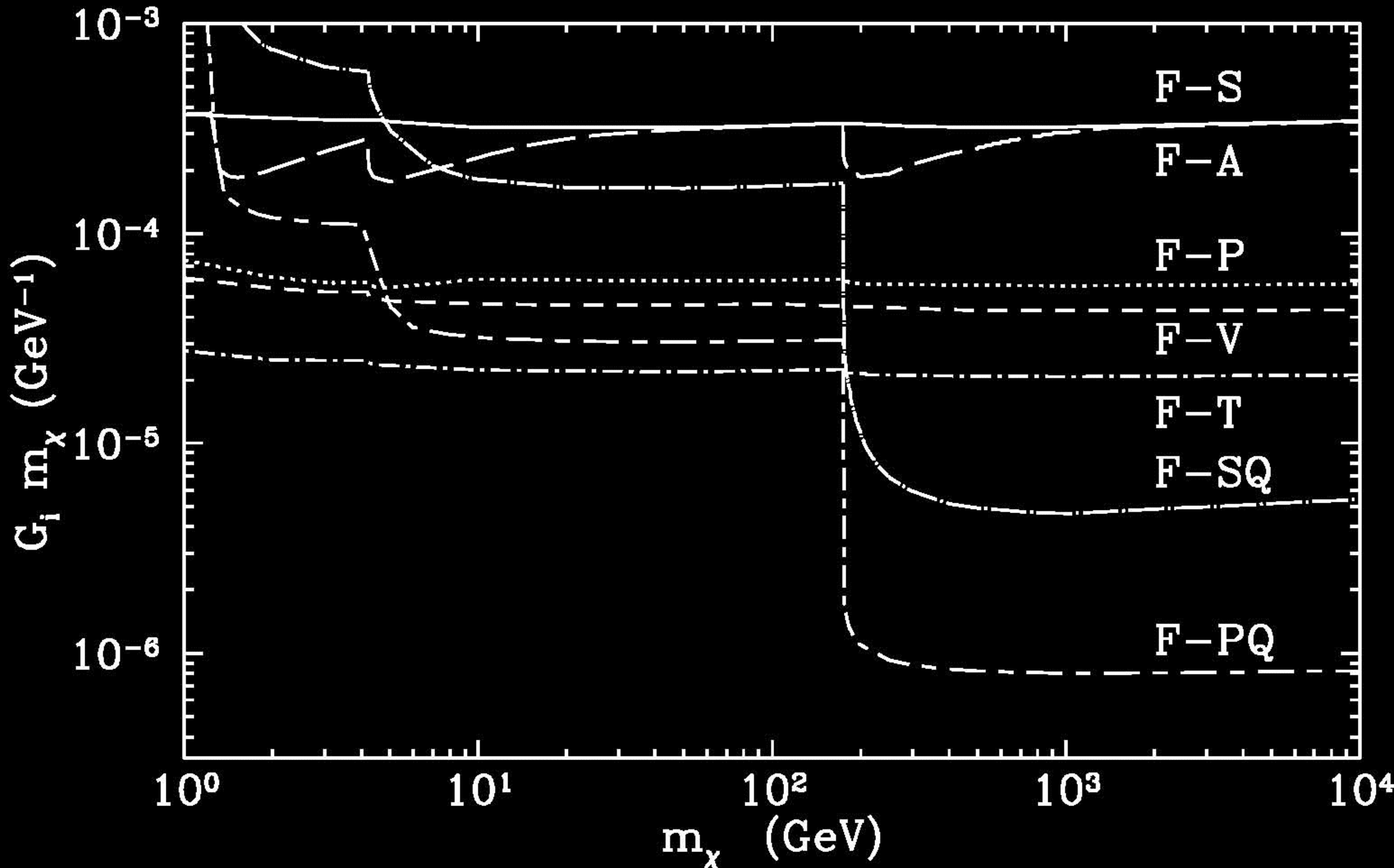
$$\mathcal{L} = \sum_q \frac{F_{i,2}}{\sqrt{2}} \left[\phi^\dagger \Gamma_i\,\phi\right]\left[\bar{q}\,\Gamma_j\,q\right]$$

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

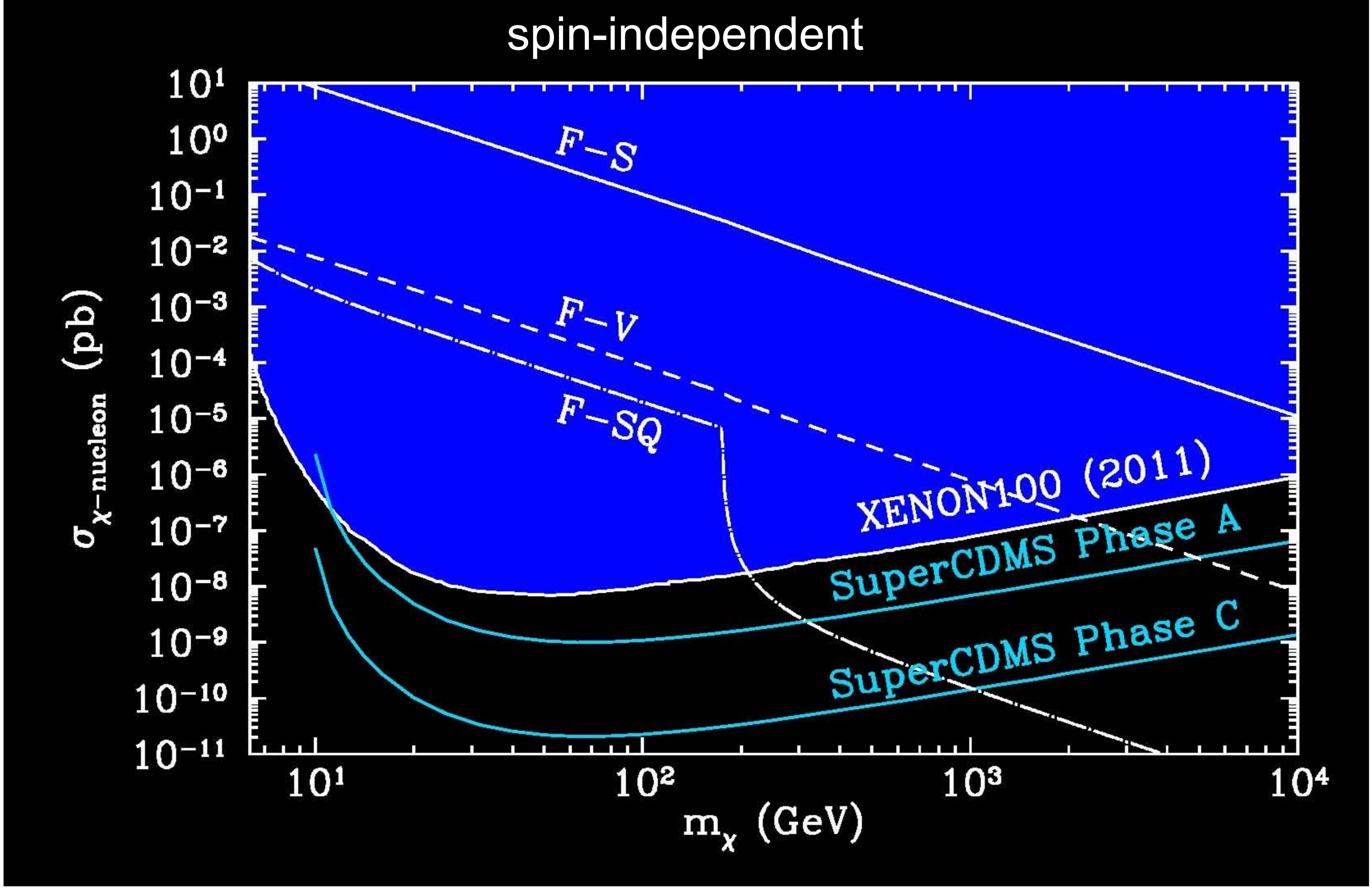
Maverick WIMPs

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

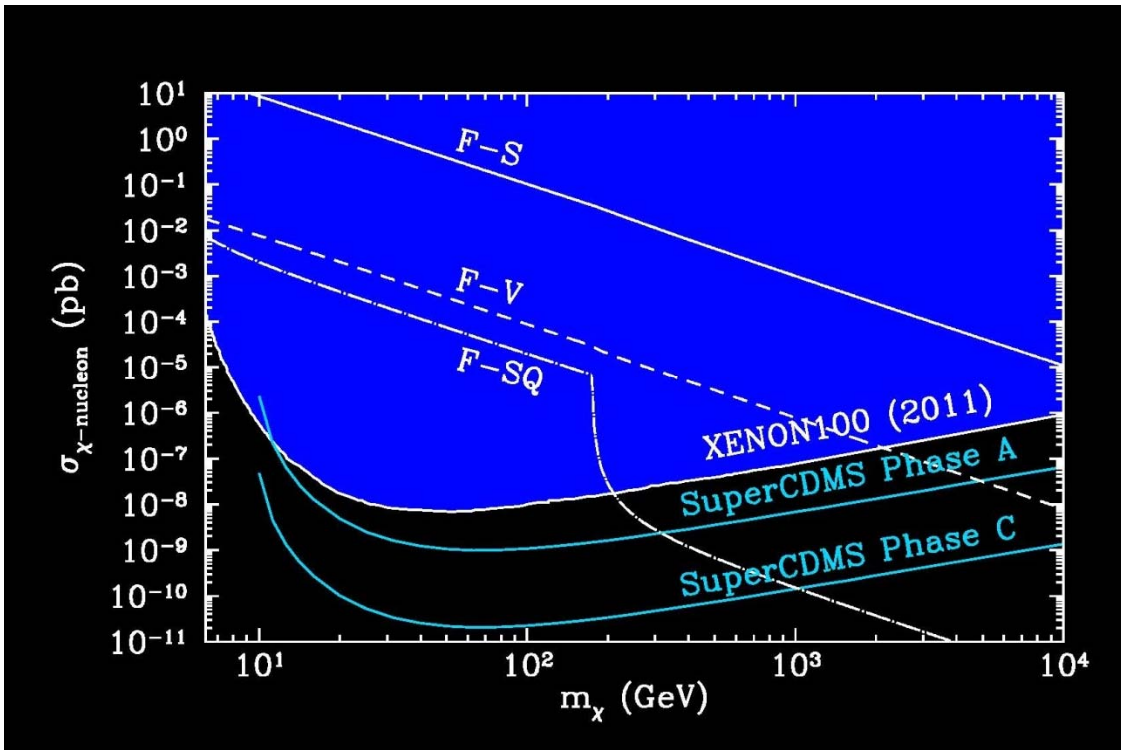
Maverick WIMPs



Maverick WIMPs



Maverick WIMPs



spin-independent

For $m \geq 10$ GeV or so

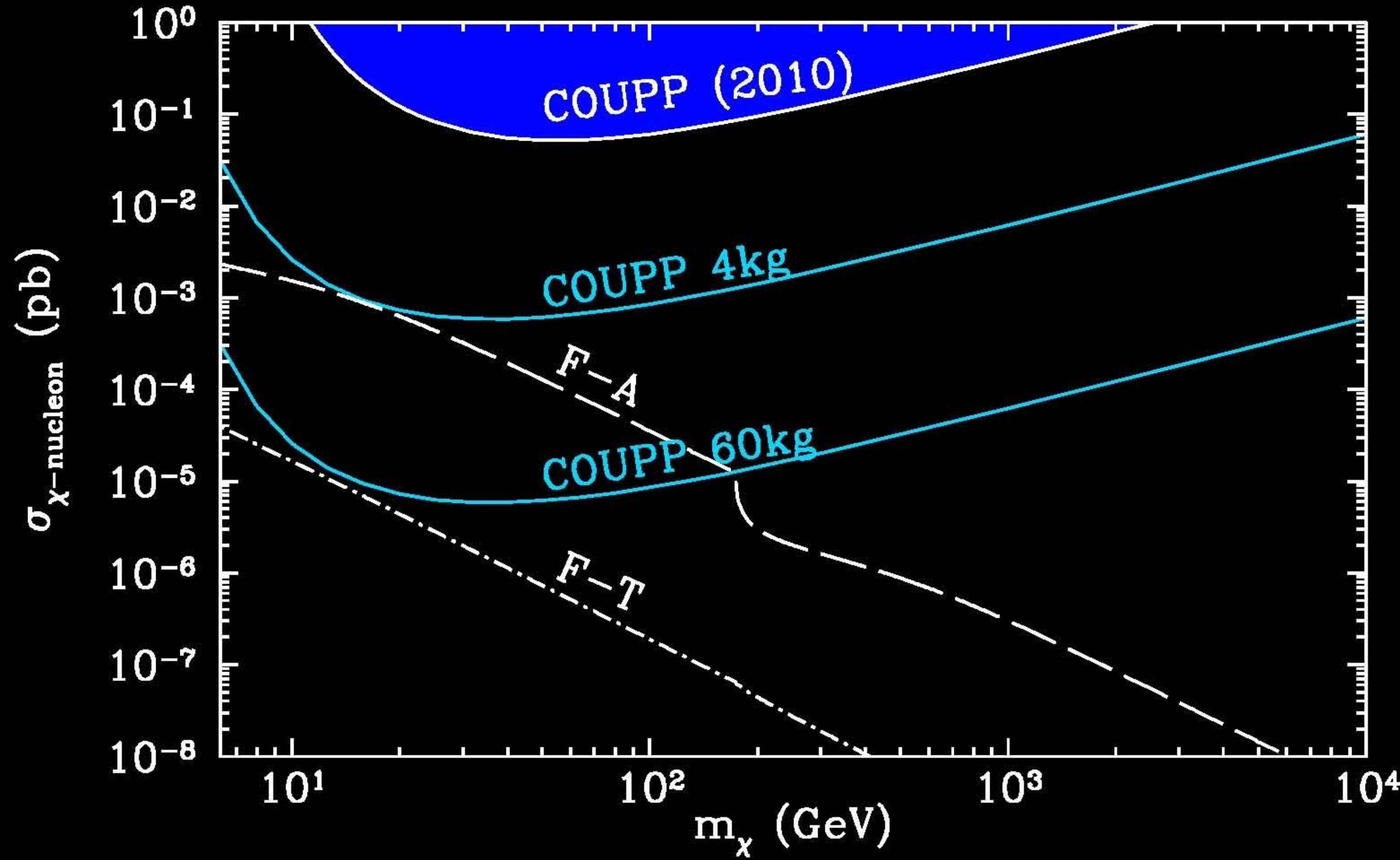
$\sigma \leq 10^{-6}$ pb

Around a few GeV

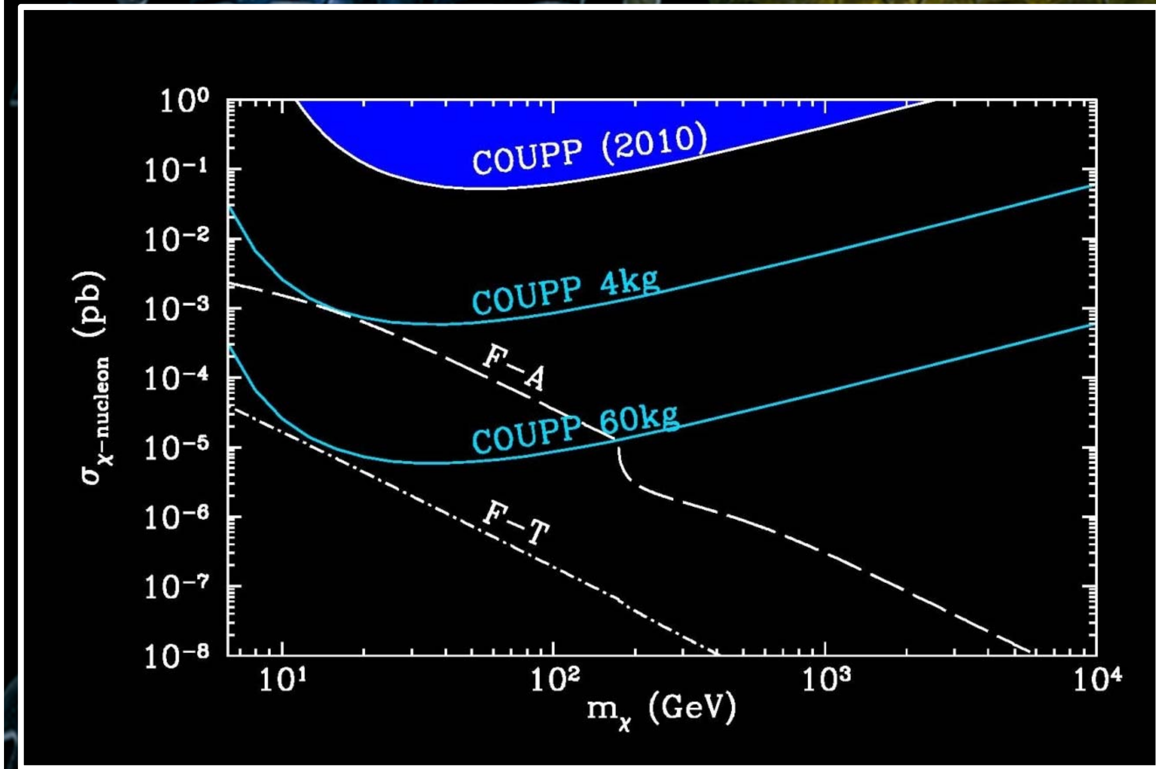
$\sigma \sim 10^{-6}$ pb

Maverick WIMPs

spin-dependent



WIMPs



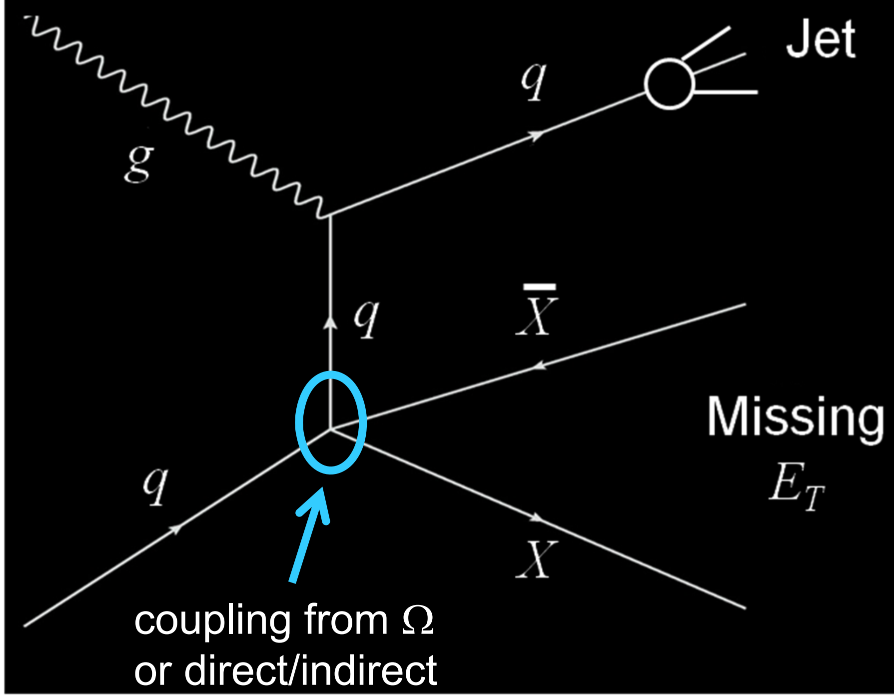
spin-dependent

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

WIMPs

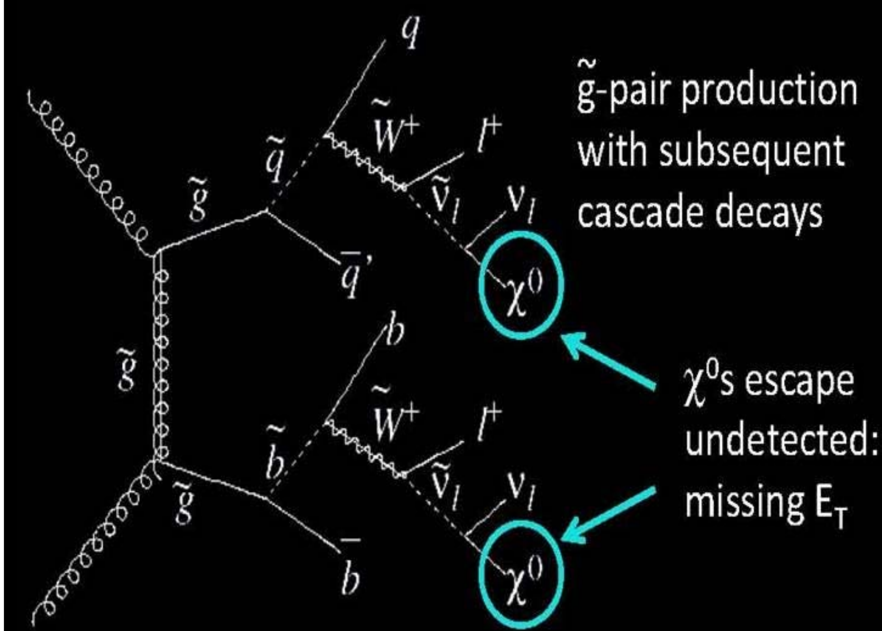
Collider Searches

Maverick WIMPs



Backgrounds (neutrino, QCD, …)

Social WIMPs

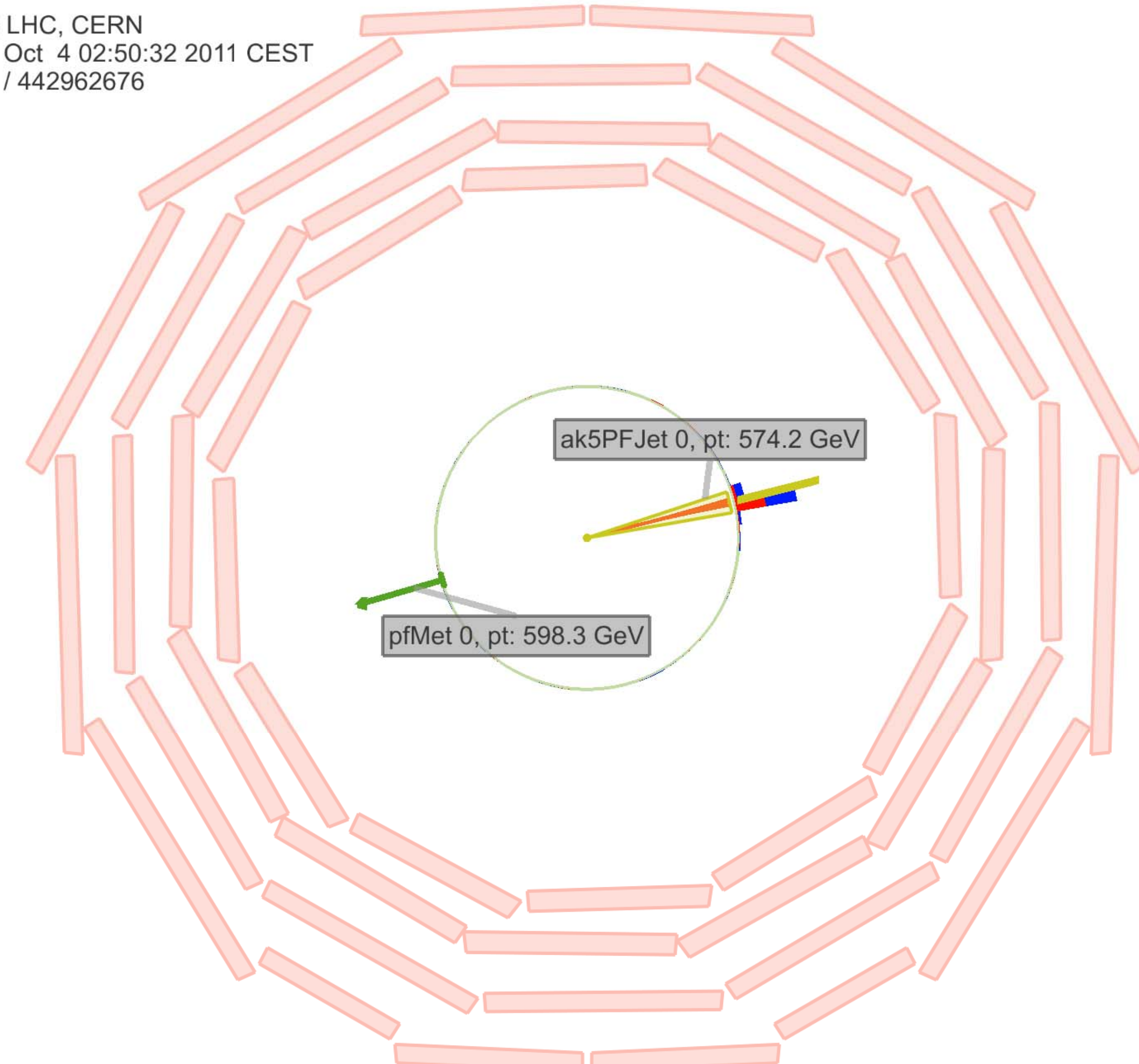


Complicated decay chain

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

Missing Momentum = Missing Mass?

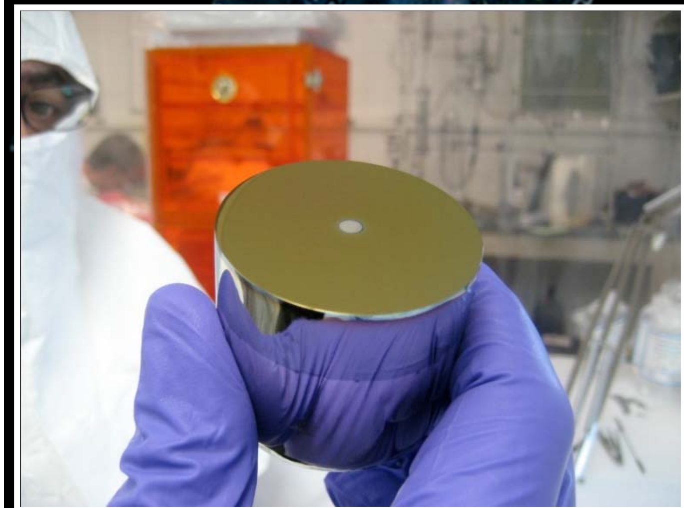
CMS Experiment at LHC, CERN
Data recorded: Tue Oct 4 02:50:32 2011 CEST
Run/Event: 177783 / 442962676
Lumi section: 273



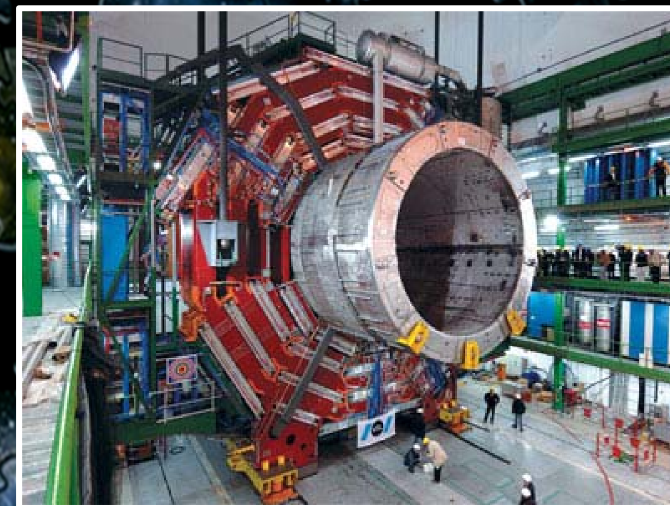
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012

WIMPs

CoGeNT



LHC



Model Dependent

nonrelativistic

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

10^{-4} **pb** – 10^{-6} **pb**

Described by
Effective field theory

relativistic

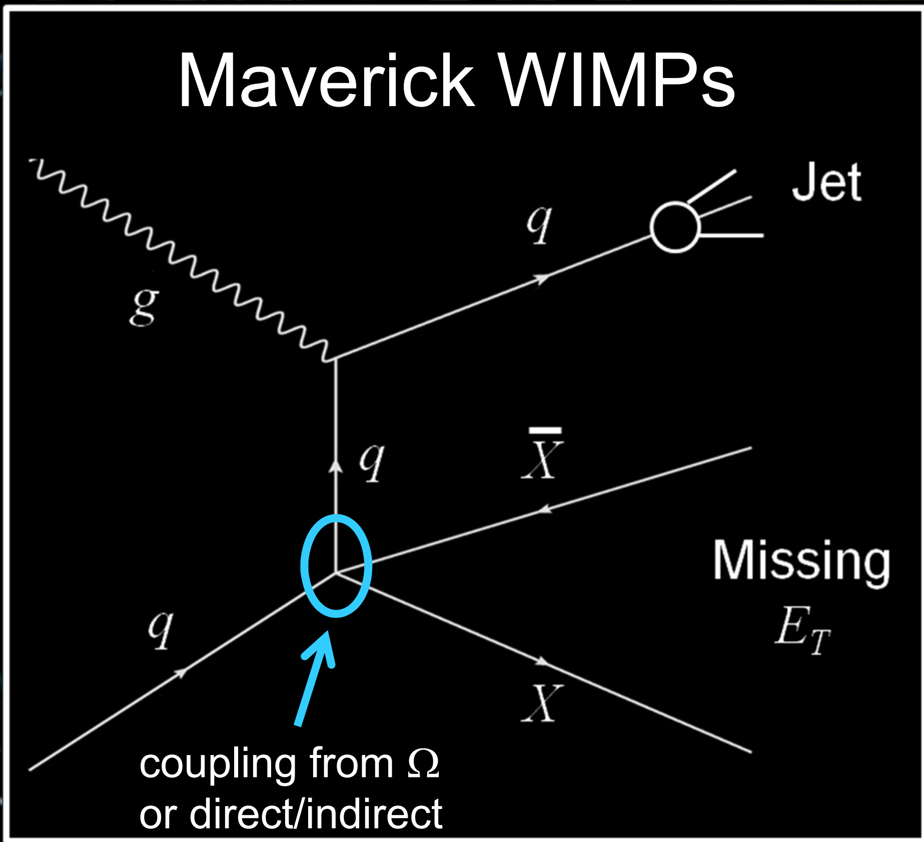
$q + \bar{q} \rightarrow \chi + \chi$

???

Assume described by
effective field theory

Maverick WIMPs

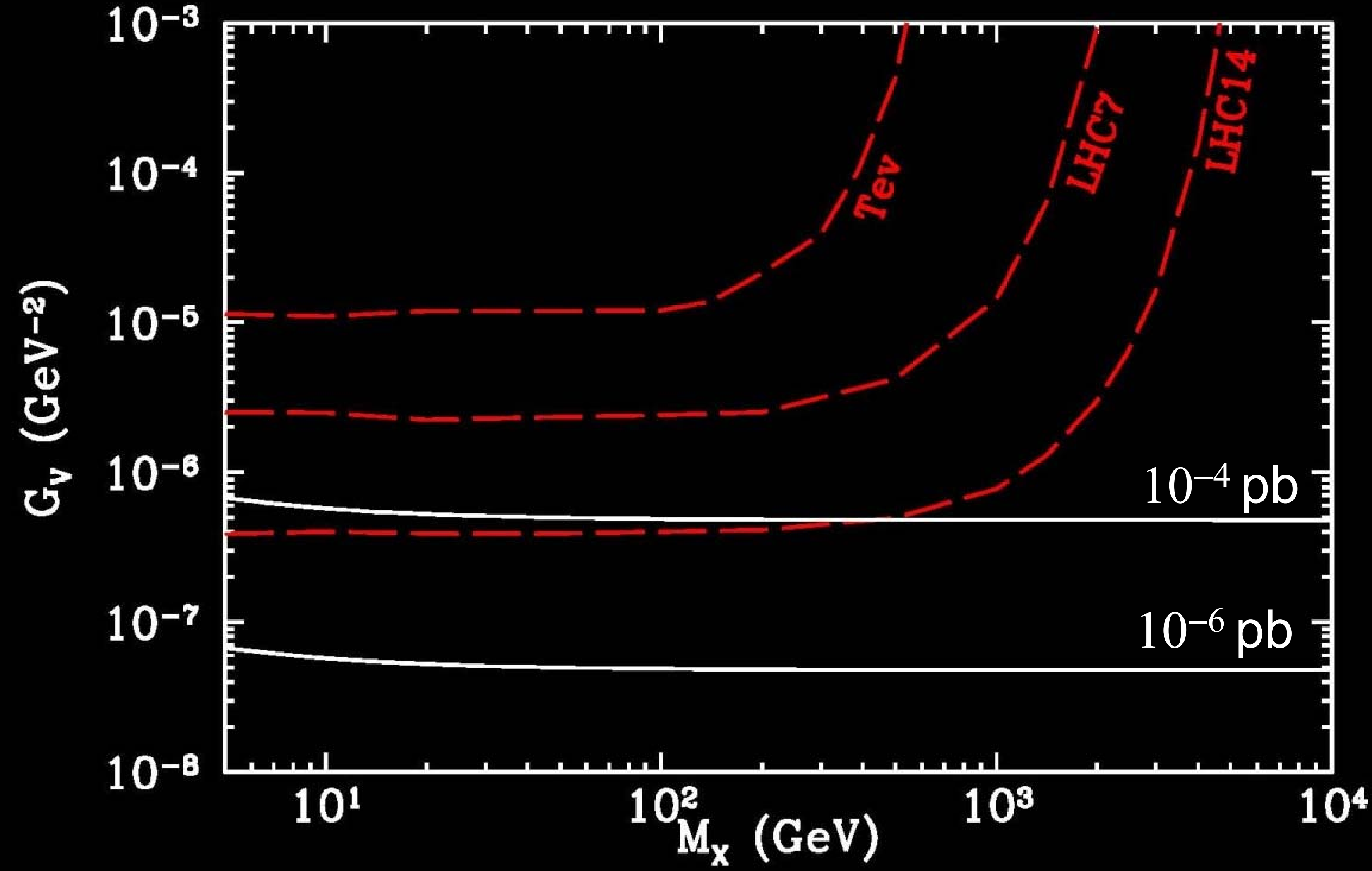
Collider Searches



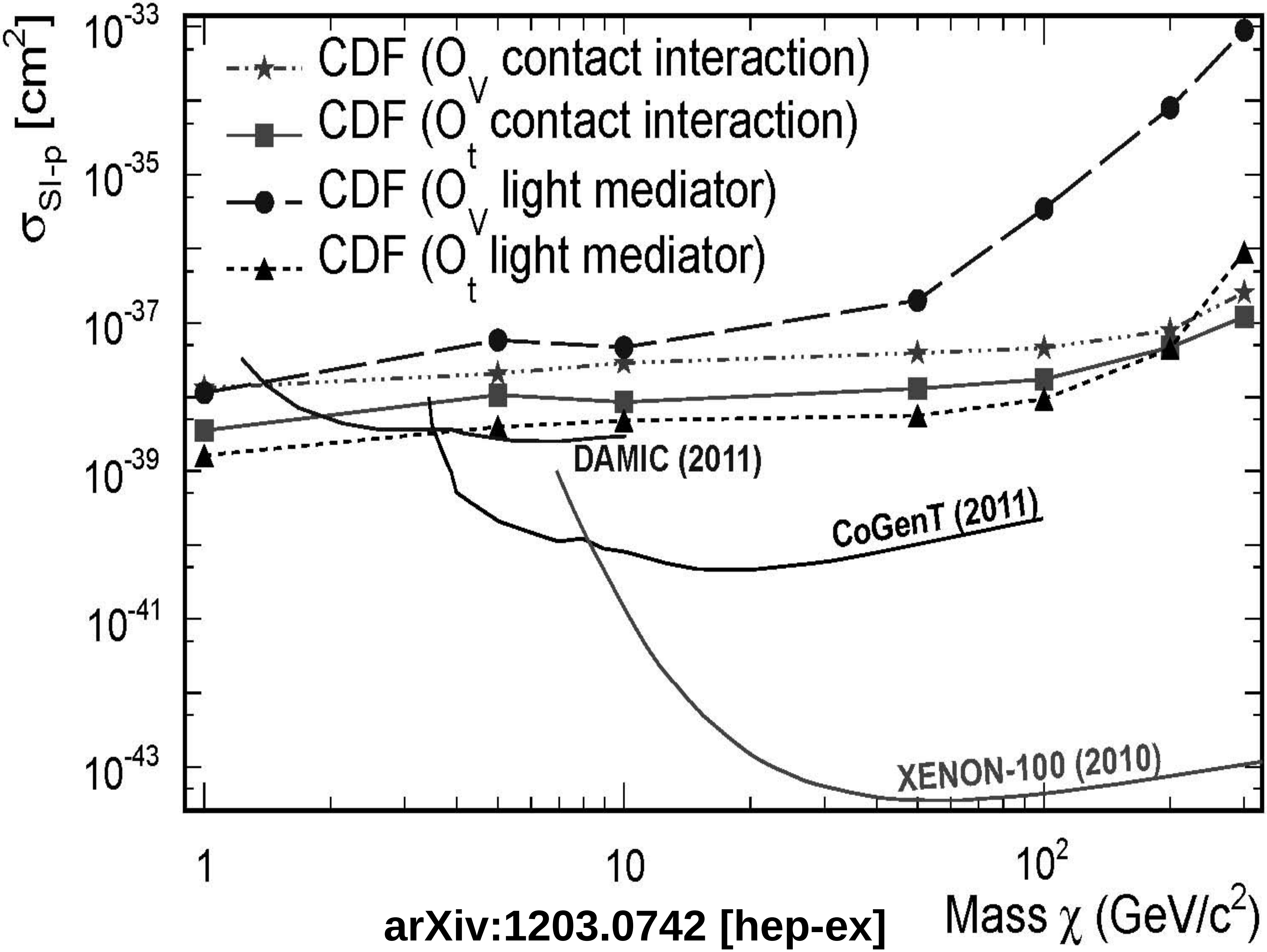
Backgrounds (neutrino, QCD, …)

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

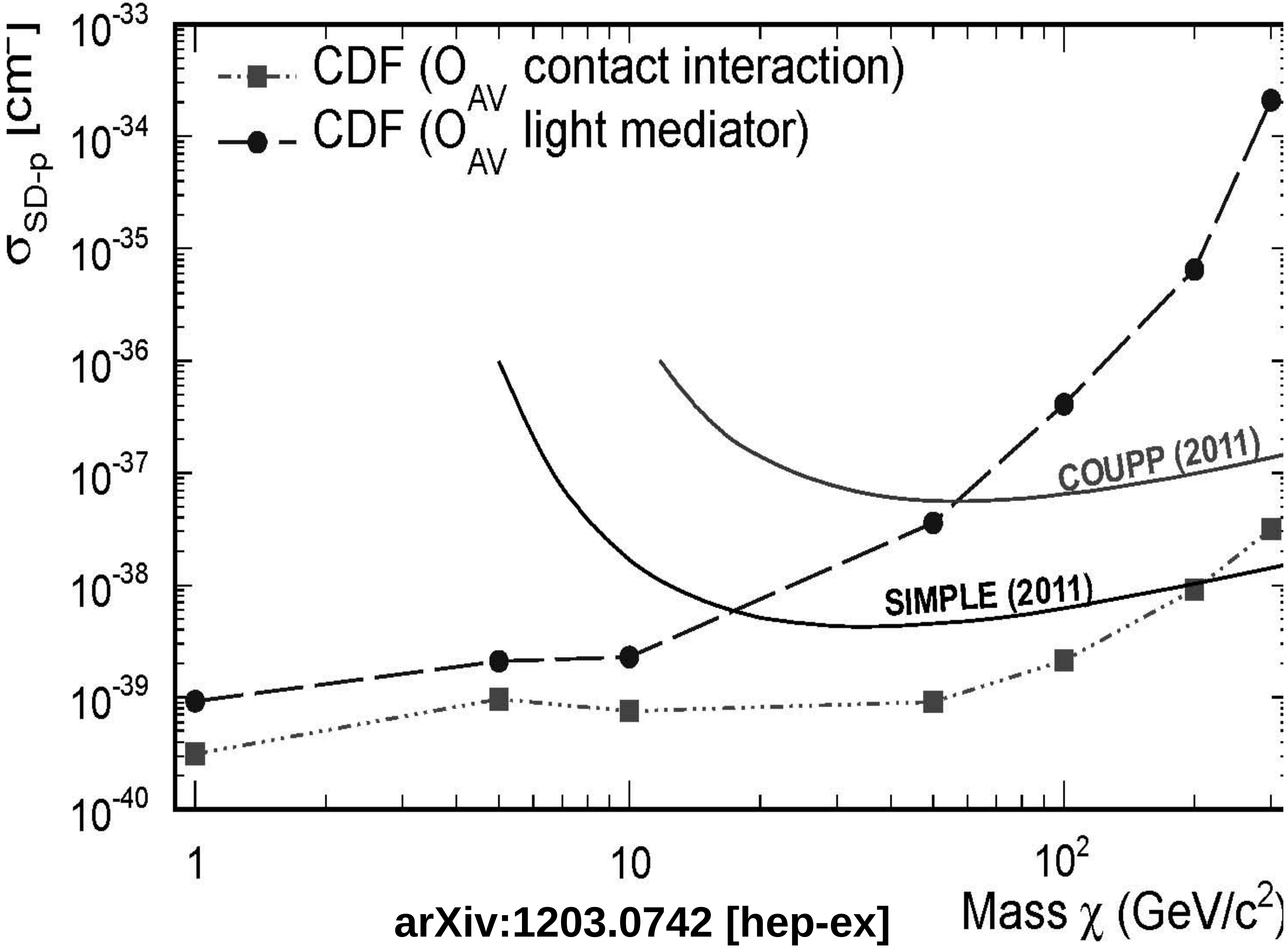
Maverick WIMPs



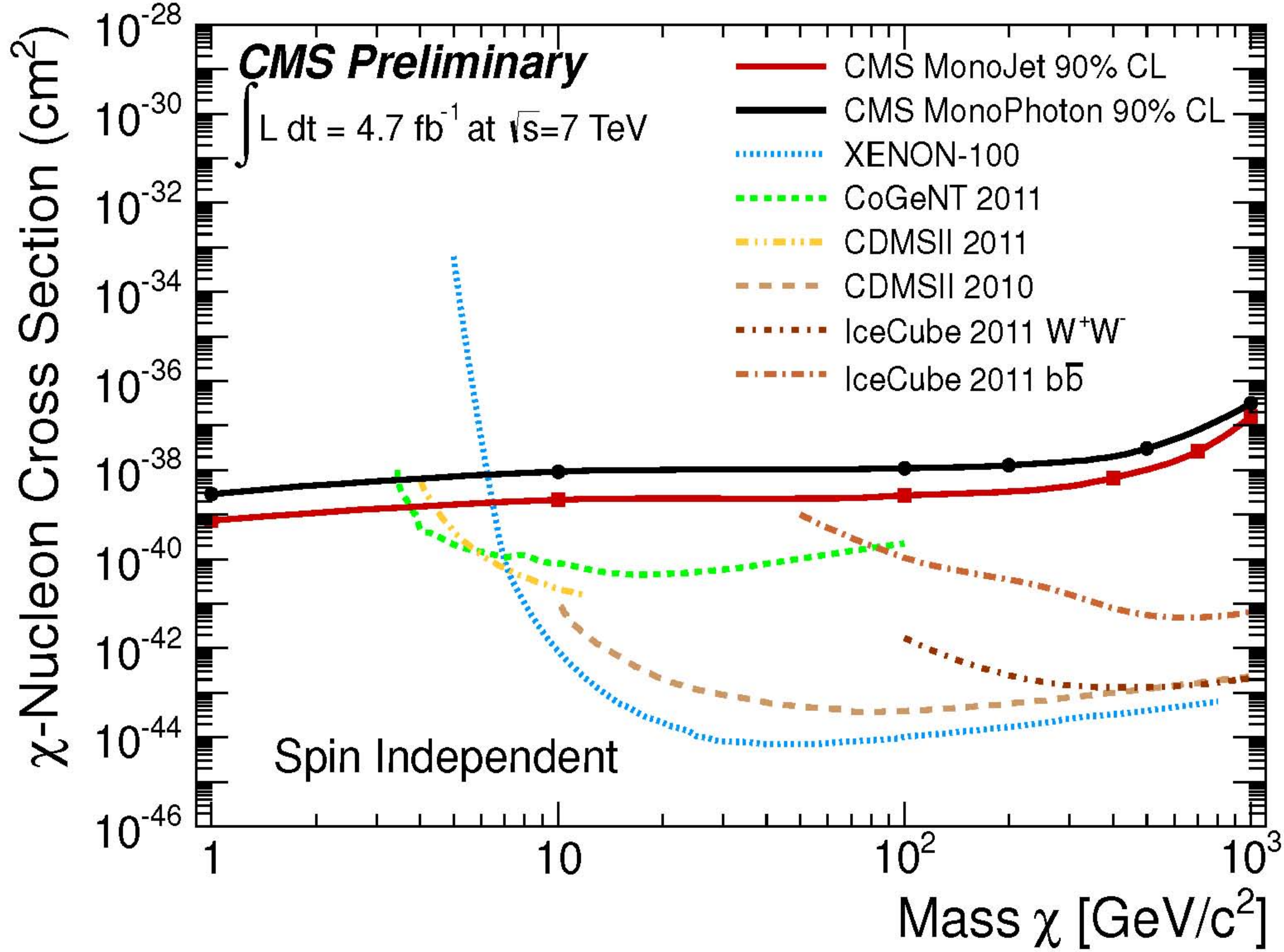
Kolb & Krusberg



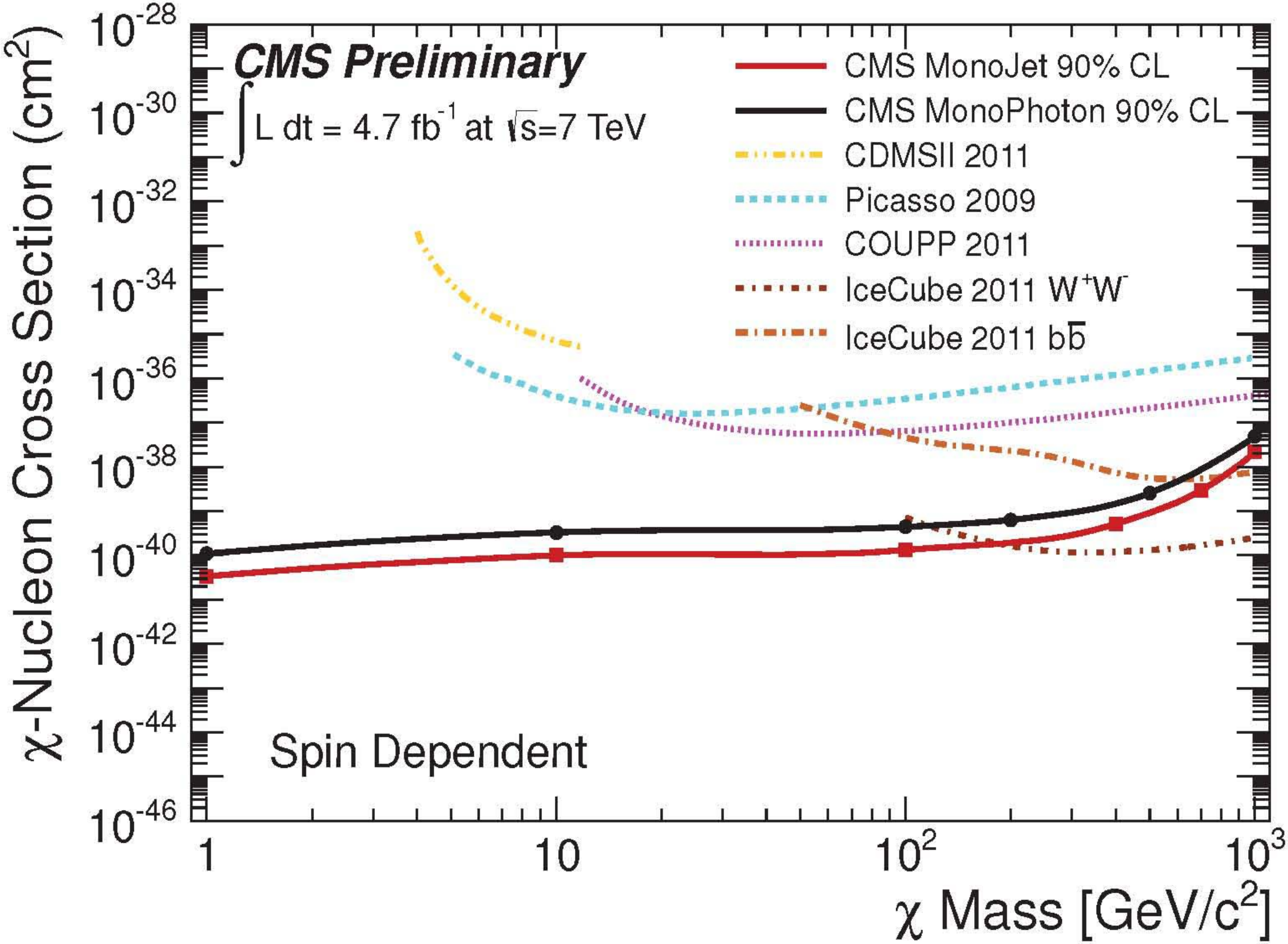
arXiv:1203.0742 [hep-ex]



arXiv:1203.0742 [hep-ex]



CMS Preliminary
∫L dt = 4.7 fb-1 at √s=7 TeV
CMS MonoJet 90% CL
CMS MonoPhoton 90% CL
XENON-100
CoGeNT 2011
CDMSII 2011
CDMSII 2010
IceCube 2011 W+W-
IceCube 2011 bb̄
Spin Independent
χ-Nucleon Cross Section (cm2)
Mass χ [GeV/c2]
10-28
10-30
10-32
10-34
10-36
10-38
10-40
10-42
10-44
10-46
1
10
102
103


CMS Preliminary
∫L dt = 4.7 fb⁻¹ at √s=7 TeV
CMS MonoJet 90% CL
CMS MonoPhoton 90% CL
CDMSII 2011
Picasso 2009
COUPP 2011
IceCube 2011 W+W-
IceCube 2011 bb̄
Spin Dependent
χ-Nucleon Cross Section (cm²)
χ Mass [GeV/c²]
10^-28
10^-30
10^-32
10^-34
10^-36
10^-38
10^-40
10^-42
10^-44
10^-46
1
10
10^2
10^3

WIMP Questions

- Why only one WIMP?
- If social network of several WIMPs, stronger interacting ones:
  - — Easier to detect
  - — Smaller Ω
- Super-WIMPs
- Self-interacting WIMPs
- Inelastic WIMPs
- Leptophilic/Leptophobic WIMPs
- Flavor-dependent WIMP couplings
- Haze, fog, mist

And this is just for WIMPs!

The Decade of the WIMP

- Is there a WIMP 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 2015 have credible signals from all three???

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

- Lots of opinions (papers)

- ***Let’s hope for this problem!!!!***

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*

IT TAKES THE VILLAGE PEOPLE

Big Chief CERN Director

Cowboy Cosmologist

Hardhat Experimentalist

Swiss Army Member

Beyond SM Guy

SUSY Cop

Particle Physics Foundations of Dark Matter, Dark Energy, and Inflation

Rocky I:	Dark Matter	(Wednesday, 11:00)
Rocky 1.5	Dark Matter II	(Thursday, 11:00)
Rocky II:	Dark Energy	(Thursday, 11:00)
Rocky III:	Inflation	(Friday, 11:00)

Rocky Kolb
University of Chicago