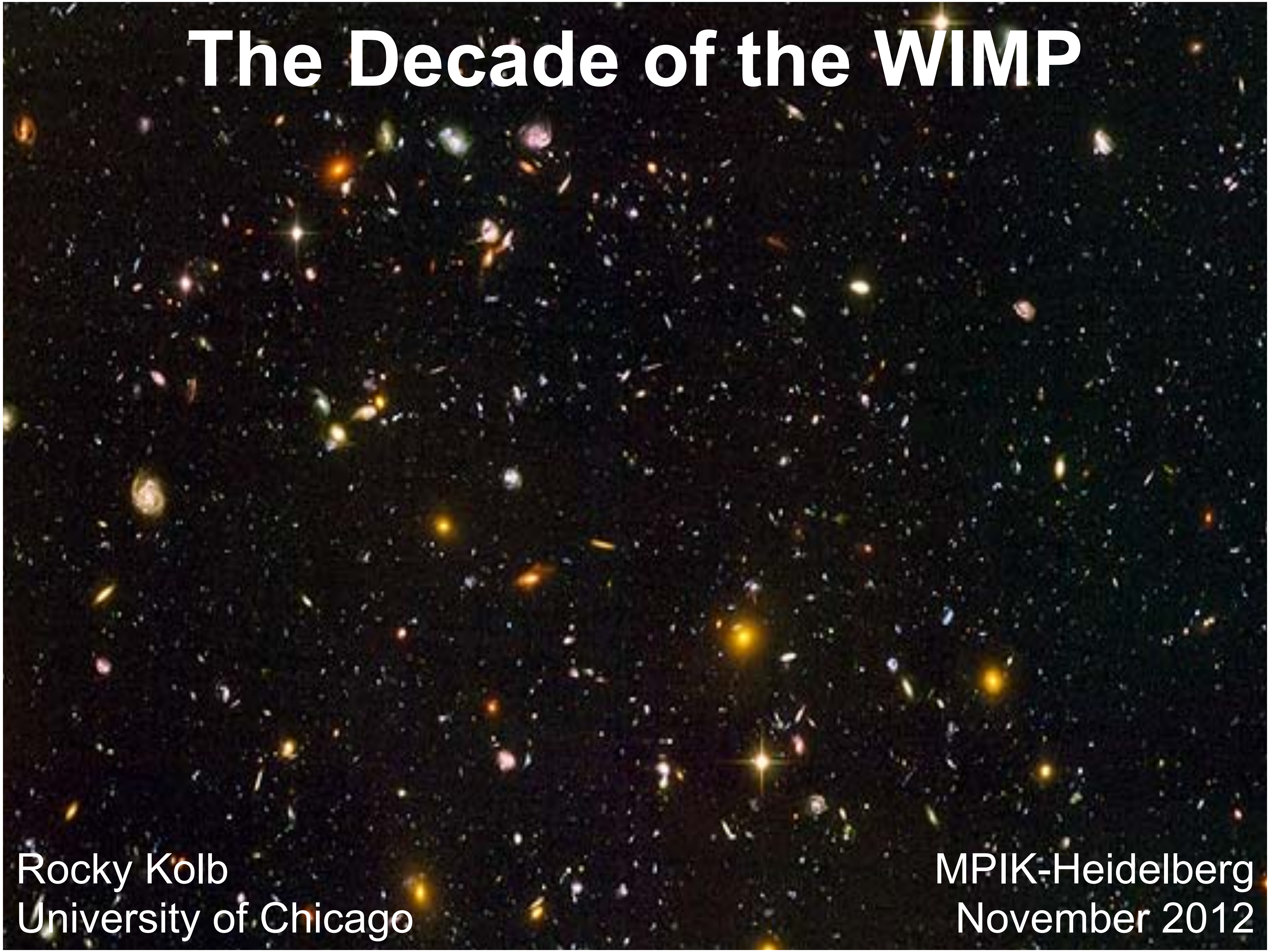
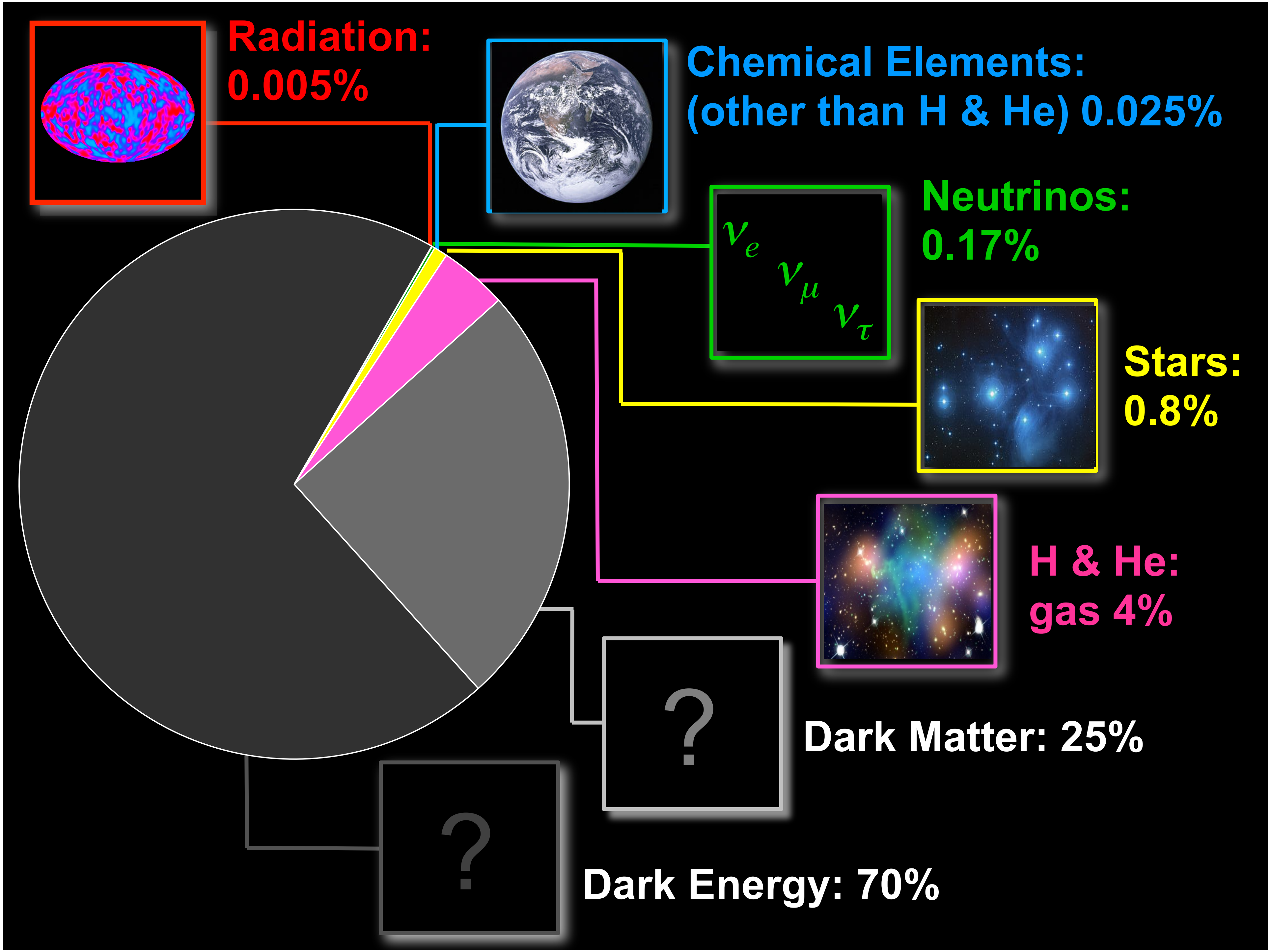
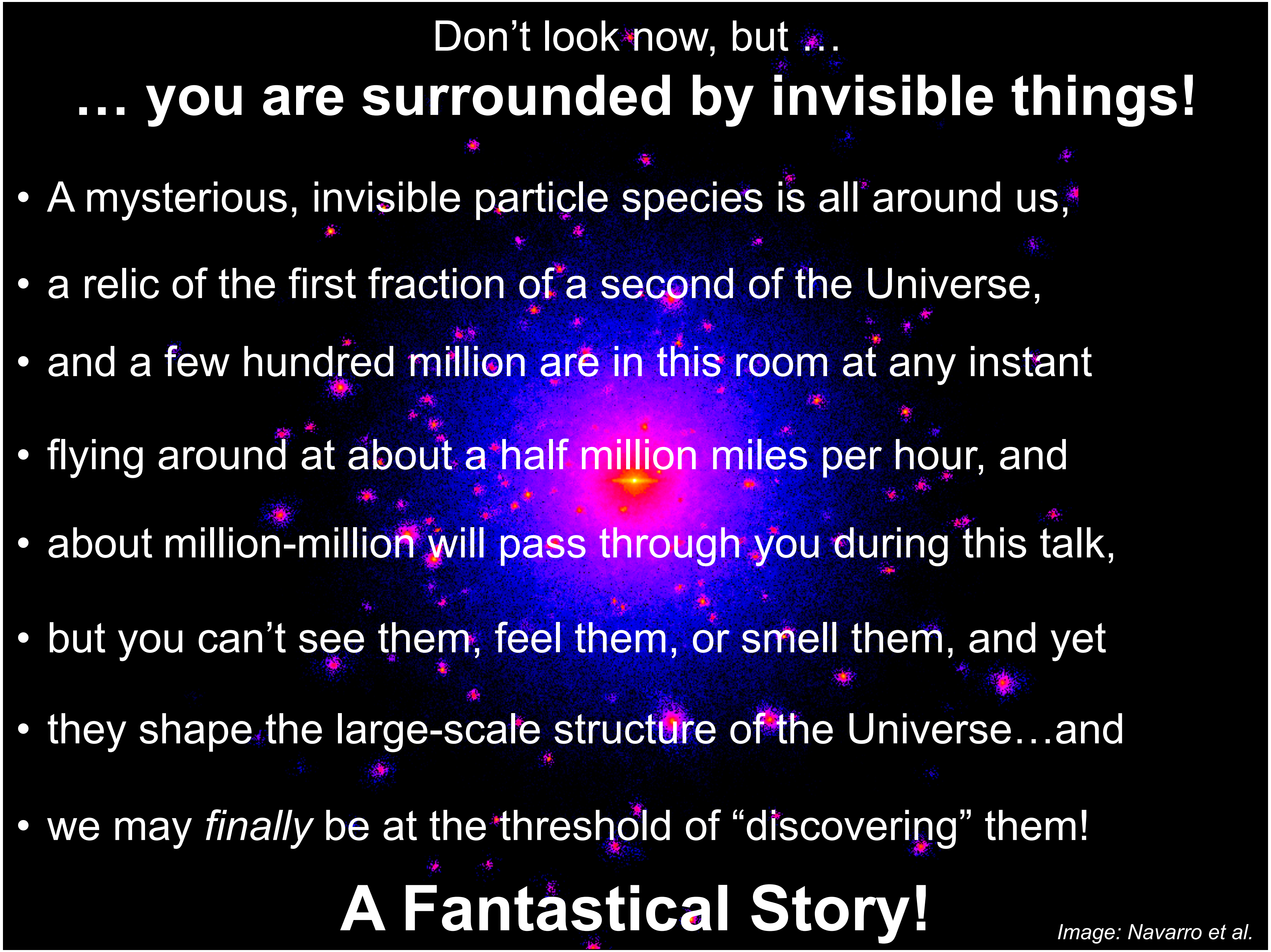

The Decade of the WIMP
Rocky Kolb
University of Chicago
MPIK-Heidelberg
November 2012


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
ν_e ν_μ ν_τ
Stars:
0.8%
H & He:
gas 4%
?
Dark Matter: 25%
?
Dark Energy: 70%



Don’t look now, but …

… you are surrounded by invisible things!

- A mysterious, invisible particle species is all around us,
- a relic of the first fraction of a second of the Universe,
- and a few hundred million are in this room at any instant
- flying around at about a half million miles per hour, and
- about million-million will pass through you during this talk,
- but you can’t see them, feel them, or smell them, and yet
- they shape the large-scale structure of the Universe…and
- we may *finally* be at the threshold of “discovering” them!

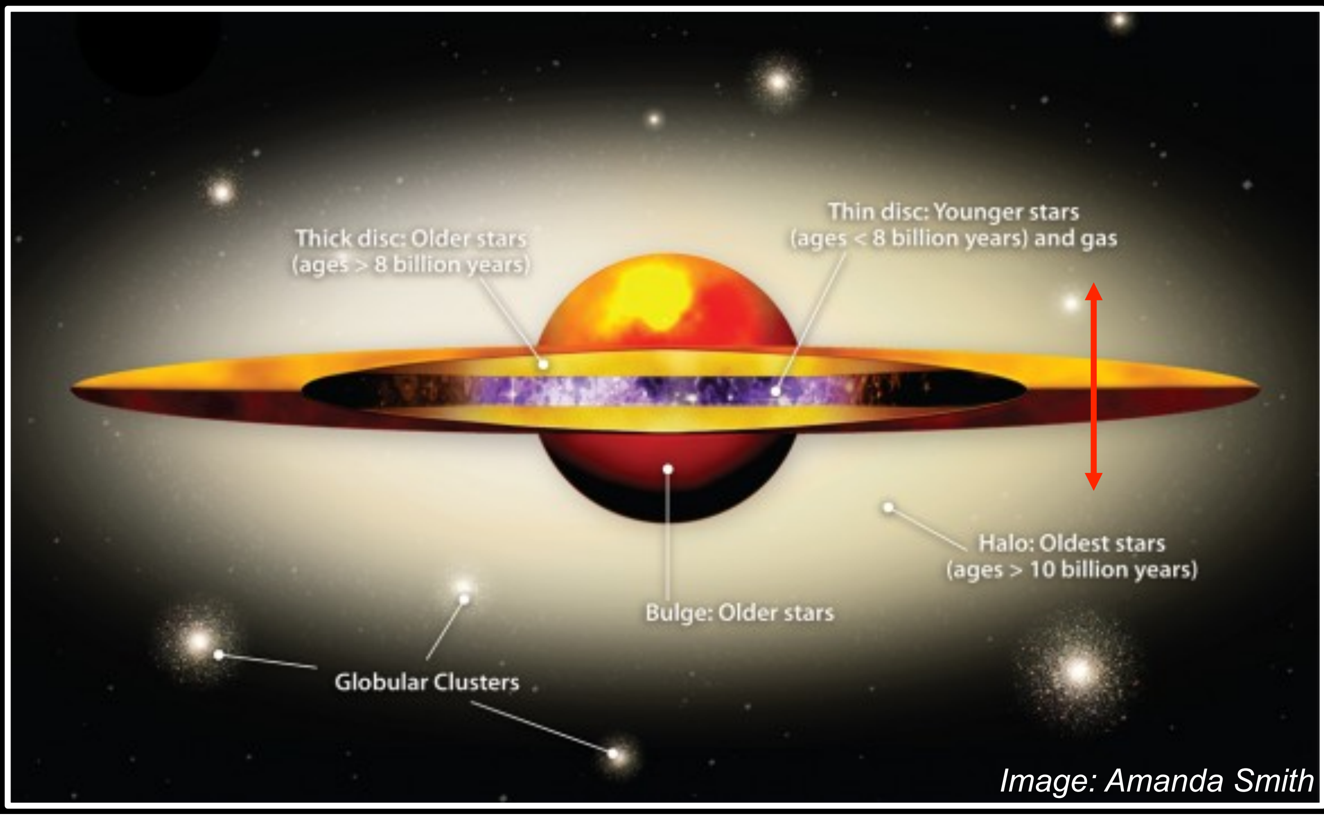
A Fantastical Story!

Image: Navarro et al.

Eighty Years of Dark Matter

Astronomers Discover Dark Matter

Oort 1932 Local Neighborhood a Little Dim $(M/L)_{\odot} \sim 2-3$

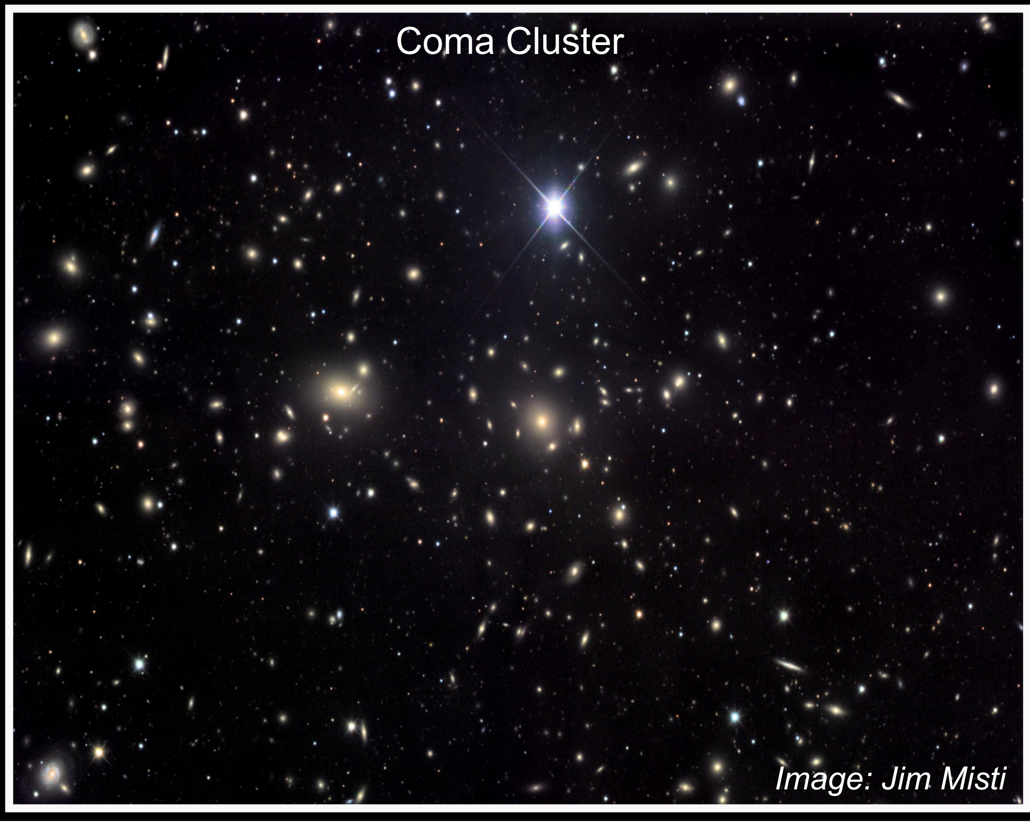


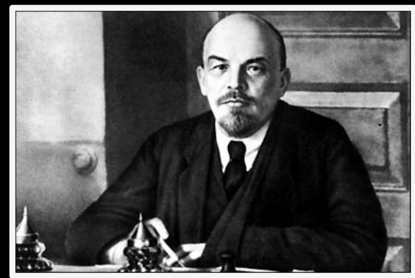
Eighty Years of Dark Matter

Astronomers Discover Dark Matter

Oort	1932	Local Neighborhood a Little Dim	$(M/L)_{\odot} \sim 2-3$
Zwicky	1937	Galaxy Clusters Really Dark	$(M/L)_{\odot} \sim 500$

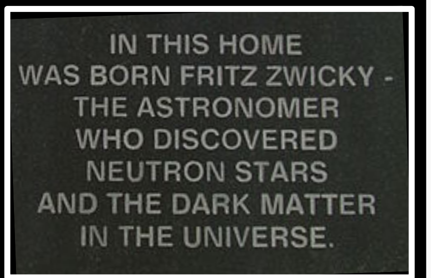
Fritz Zwicky





Vladimir Lenin 1916

Varna, Bulgaria



Zurich, Switzerland
(Spiegelgasse 17)

Eighty Years of Dark Matter

Astronomers Discover Dark Matter

Oort	1932	Local Neighborhood a Little Dim	$(M/L)_{\odot} \sim 2{-}3$
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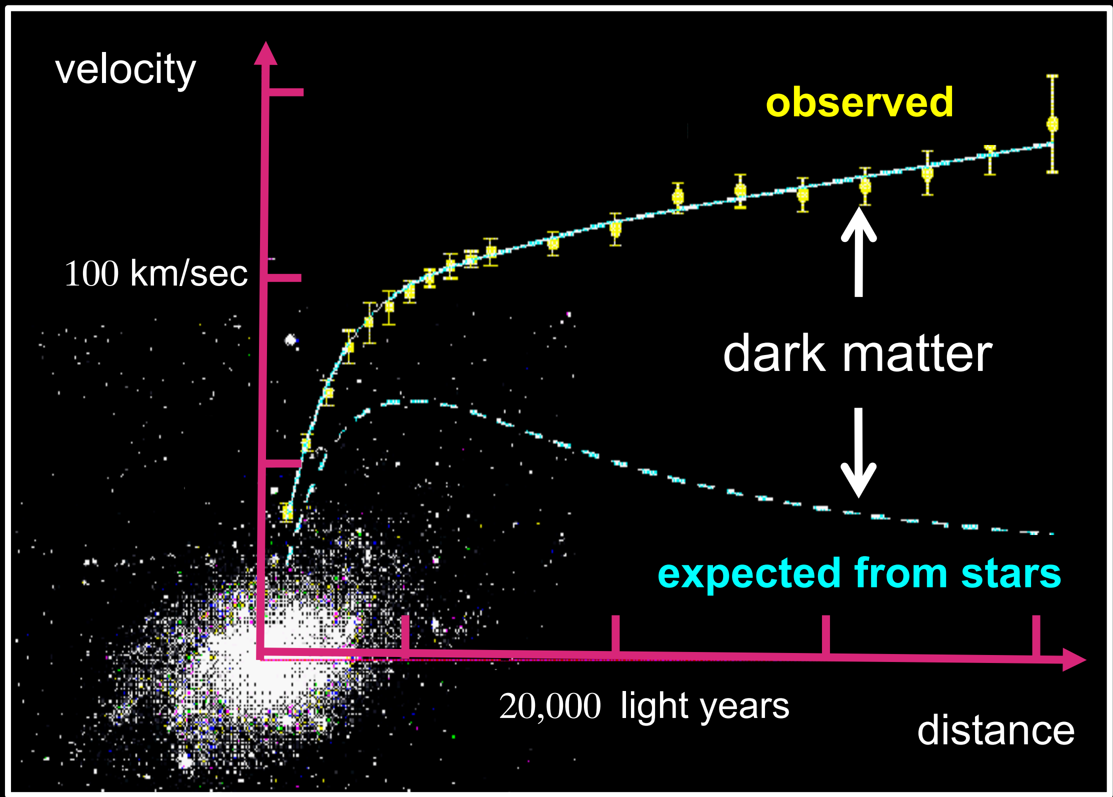
Rubin & Ford	1970s	Individual Galaxy Halos Also Dark	$(M/L)_{\odot} \sim 60$

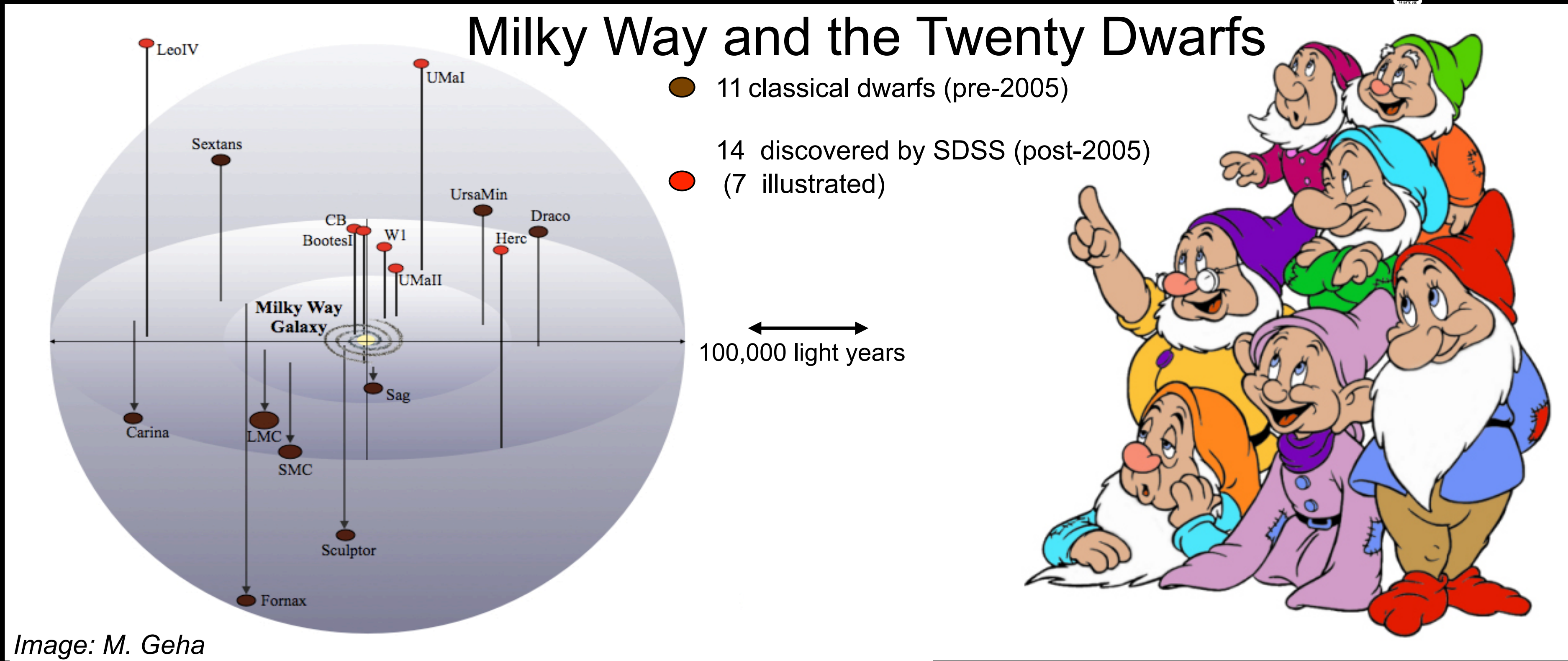


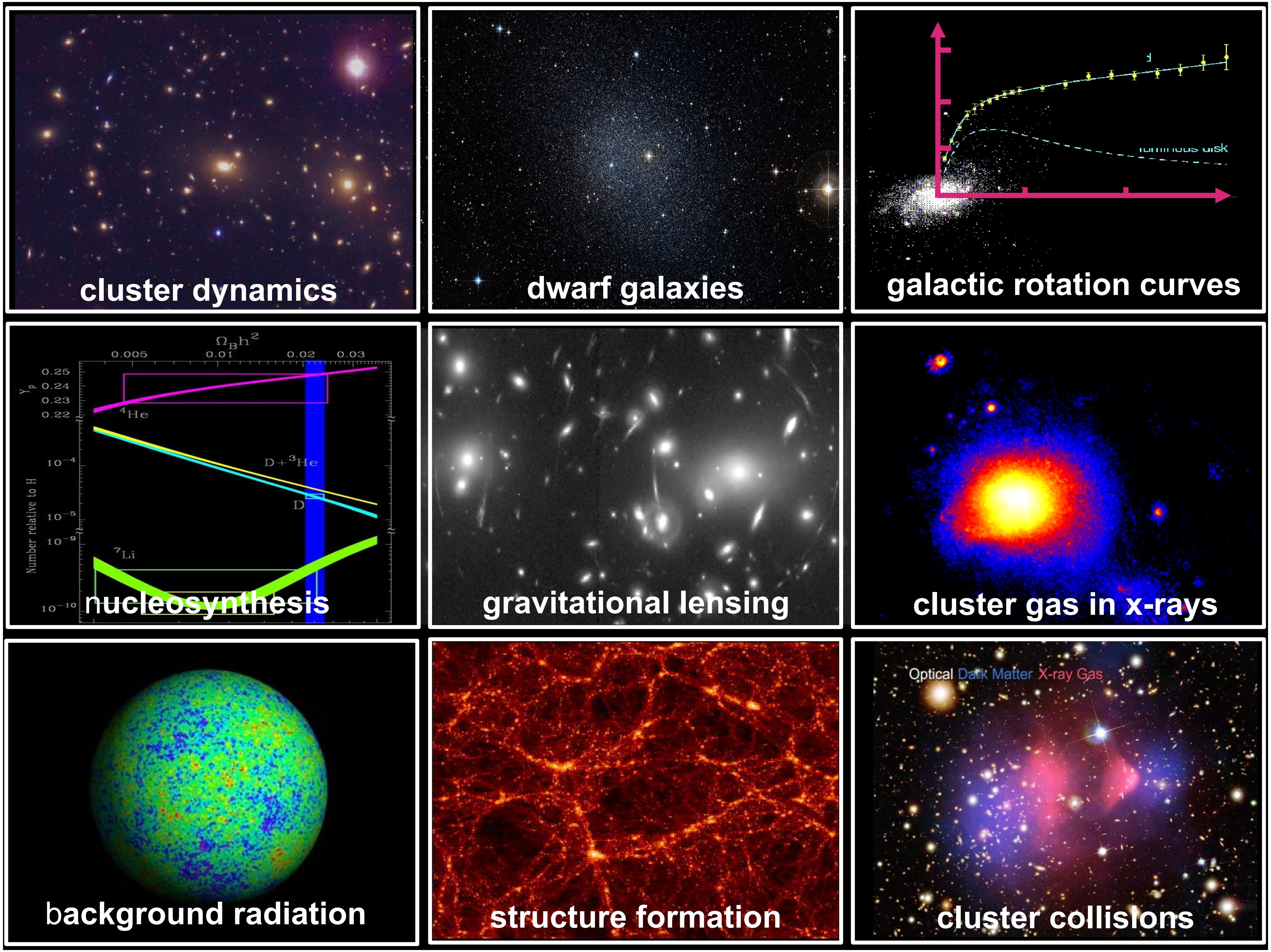
Vera Rubin 1970s

Eighty Years of Dark Matter

Astronomers Discover Dark Matter

Oort	1932	Local Neighborhood a Little Dim	$(M/L)_{\odot} \sim 2-3$
Zwicky	1937	Galaxy Clusters Really Dark	$(M/L)_{\odot} \sim 500$
Rubin & Ford	1970s	Individual Galaxy Halos Also Dark	$(M/L)_{\odot} \sim 60$
Dwarf Observers	1990s	Dwarf Galaxies Really, Really Dark	$(M/L)_{\odot} \sim 3000$




cluster dynamics
dwarf galaxies
galactic rotation curves
$\Omega_B h^2$
0.005
0.01
0.02
0.03
Y_p
0.25
0.24
0.23
0.22
^4He
10^{-4}
$D+^3He$
D
10^{-5}
10^{-9}
^7Li
10^{-10}
Number relative to H
nucleosynthesis
gravitational lensing
cluster gas in x-rays
background radiation
structure formation
Optical Dark Matter X-ray Gas
cluster collisions

Particle Dark Matter Taxonomy

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

} thermal relics or decay of or oscillation from thermal relics

- Bose-Einstein condensates
- axions, axion clusters
- solitons (Q-balls, B-balls, …)

} coherent state of a scalar field

- supermassive wimpzillas from inflation

} nonthermal relics

Mass
$10^{-22}\,\mathrm{eV}$ $(10^{-56}\,\mathrm{g})$ Bose-Einstein
$10^{-8}\,M_{\odot}$ $(10^{+25}\,\mathrm{g})$ axion clusters

Interaction Strength
only gravitational: wimpzillas
strongly interacting: B balls

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

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

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]:

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

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

At the temperatures we are considering here, the expansion

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

where ρ is the energy density

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

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

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

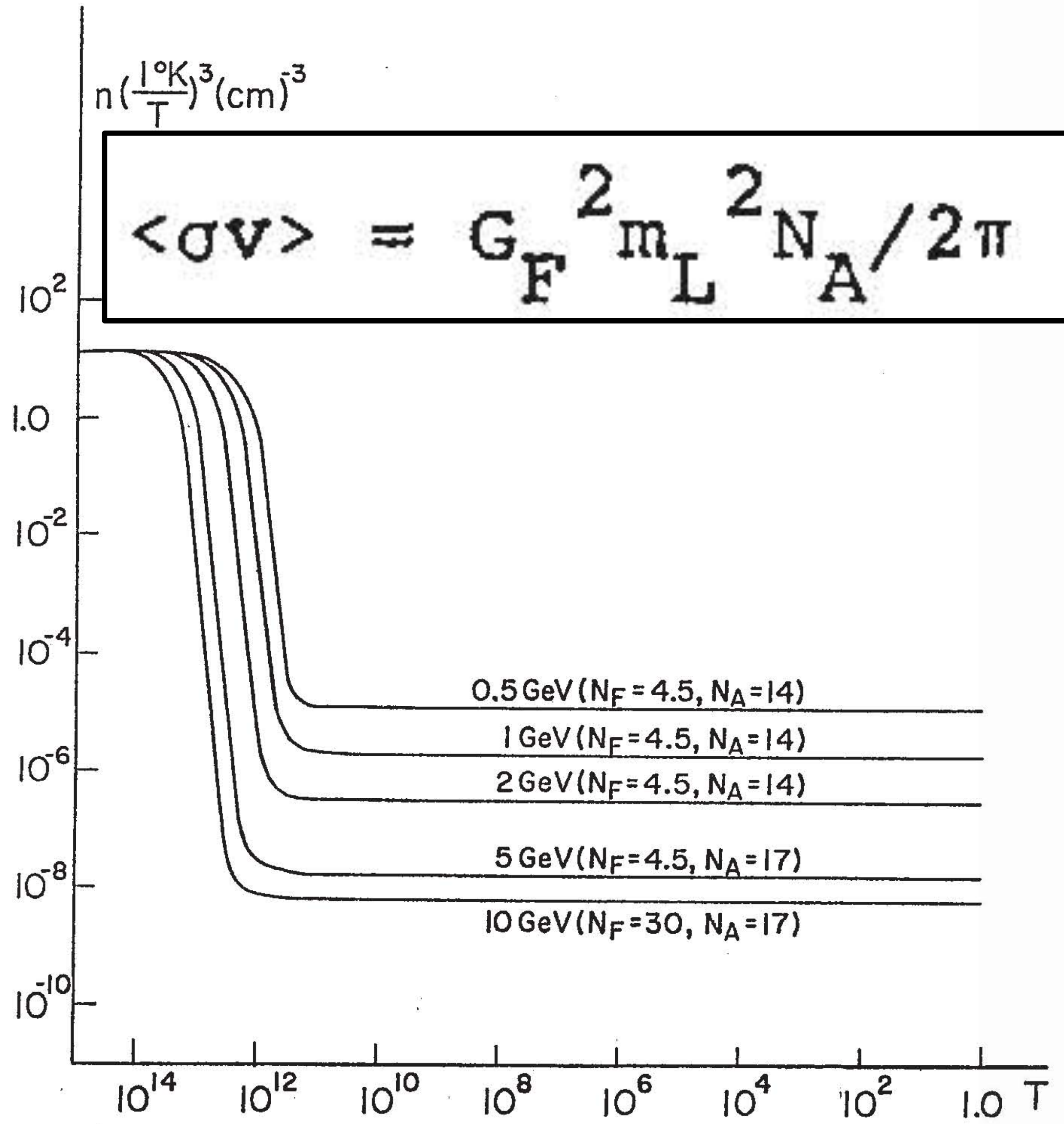
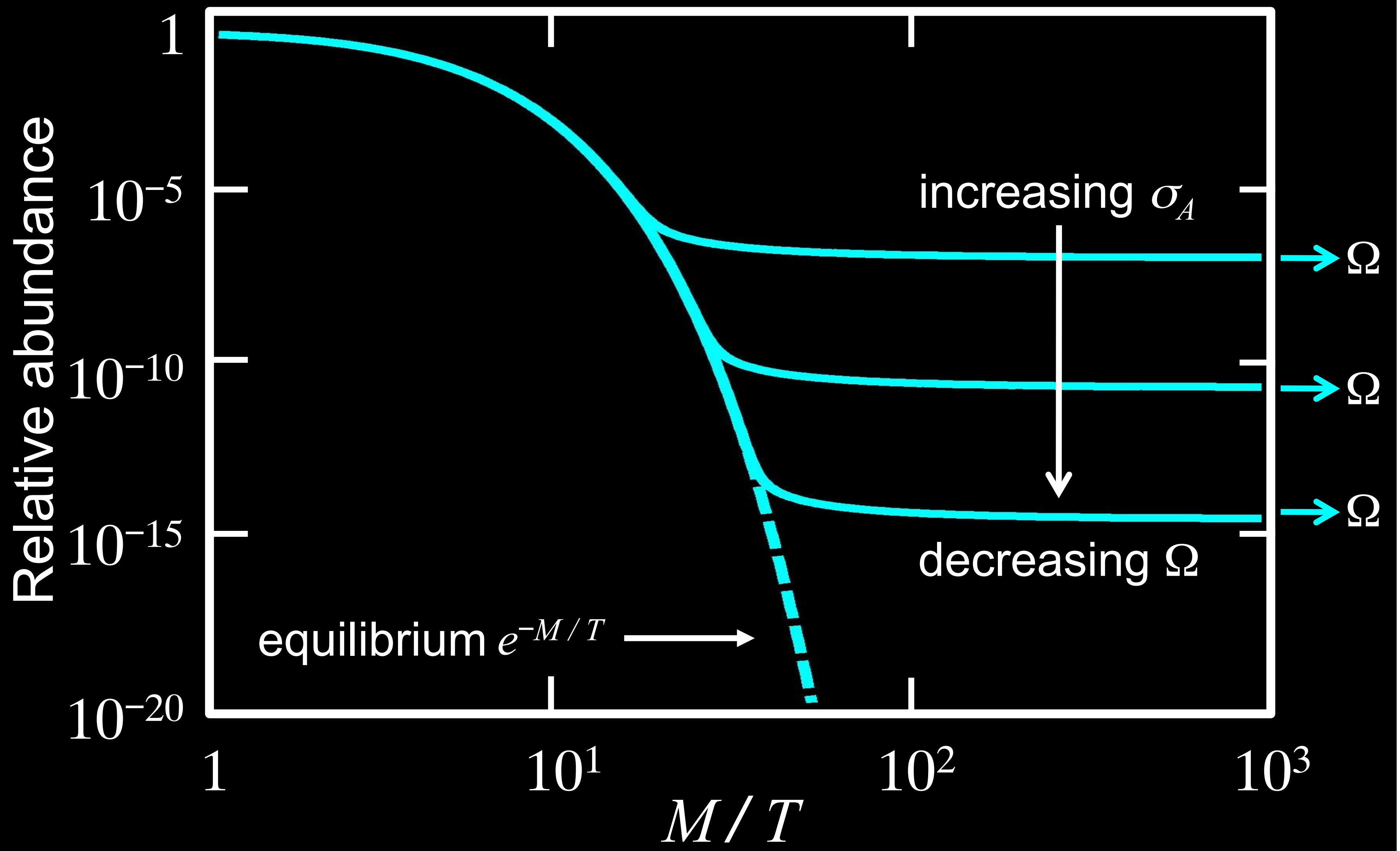


FIG. 1

Cold Thermal Relics*



* An object of particular veneration.

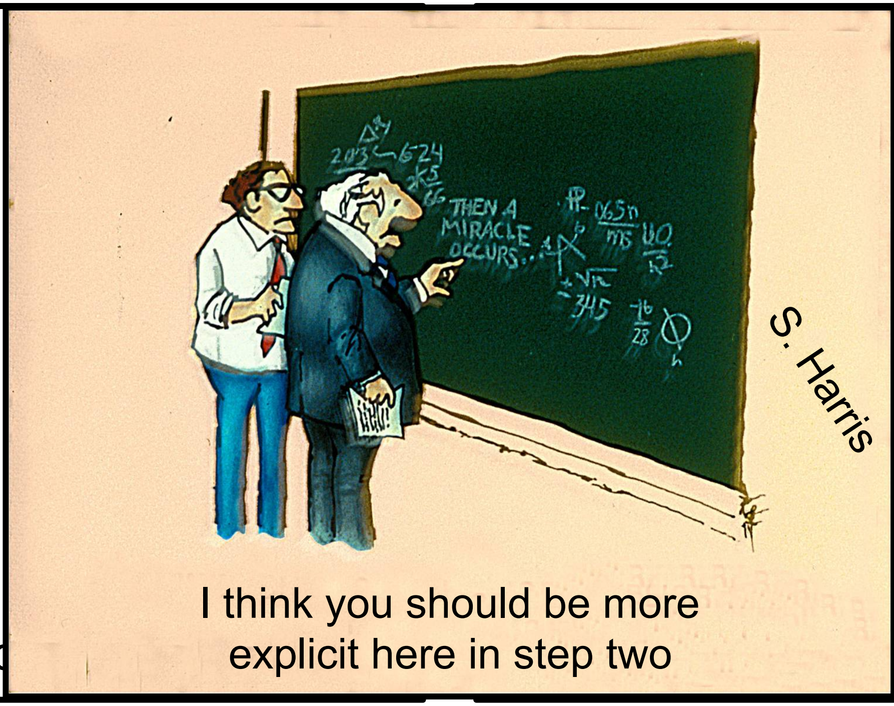
The WIMP "Miracle"

Cold thermal relic: weak scale cross section (and mass?)
(1 GeV − 1000 GeV)   WIMP (<u>W</u>eakly <u>I</u>nteracting <u>M</u>assive <u>P</u>article)

WIMPs are BSM, but not far BSM

Merriam-Webster
Merriam-Webster OnLine

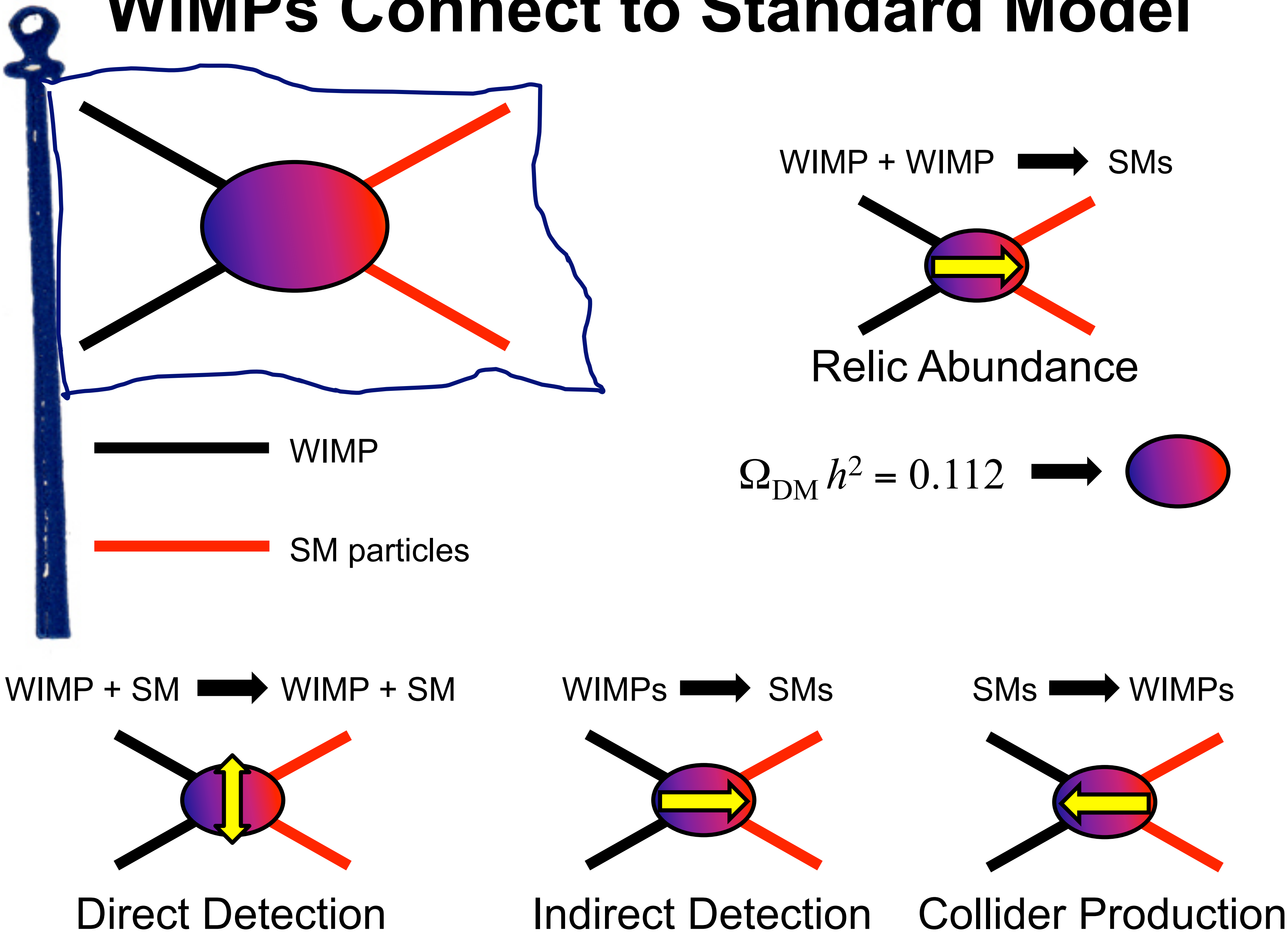
1 : an extraordinary
divine interventi



encyclopedia

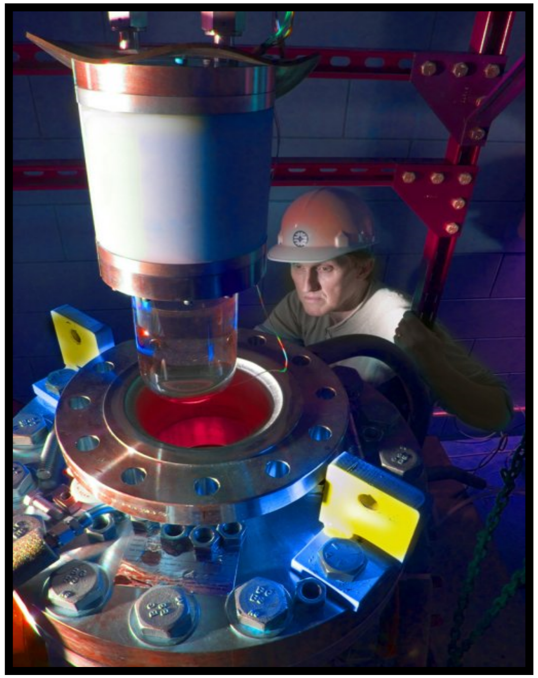
. often used to give an
npression of great and
nusual value in a trivial
ontext …

WIMPs Connect to Standard Model

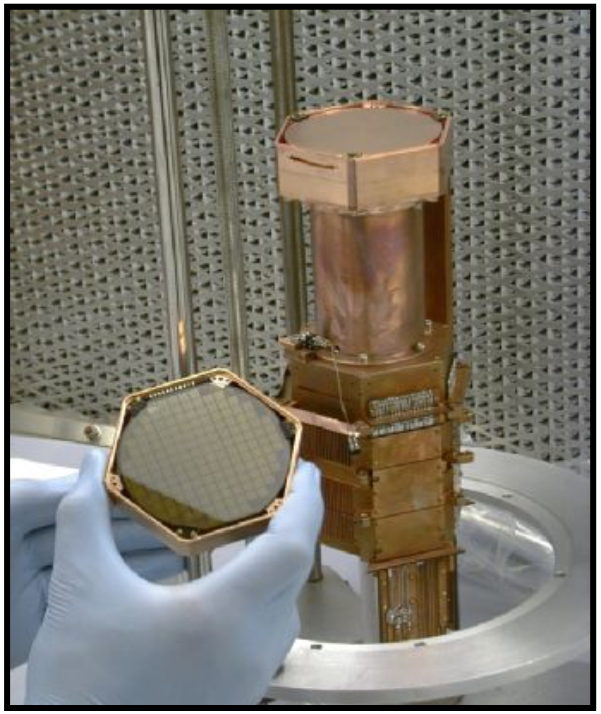


Direct Detection

COUPP



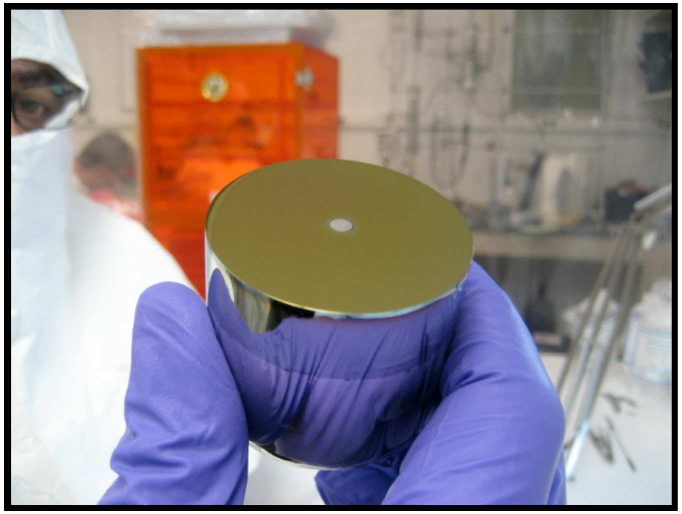
CDMS



CRESST

Xenon

CoGeNT



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

Direct Detection

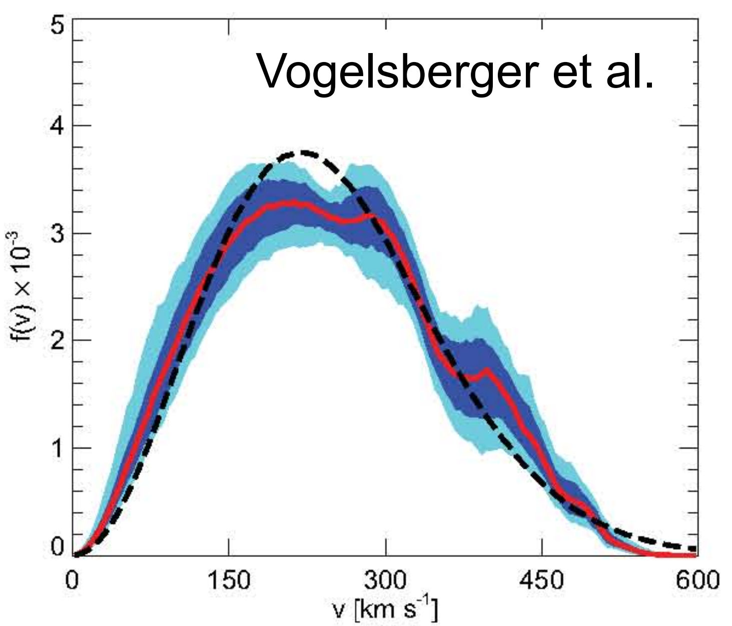
- Local WIMP phase-space density
  - Assume: $\rho_{DM} = 0.3\ \text{GeV cm}^{-3}$ (subclumps, streams, cusps,…?)
  - Assume: Maxwellian velocity distribution $\langle v^2 \rangle^{1/2} = 220\ \text{km s}^{-1}$
- Spin dependence (A, T)?

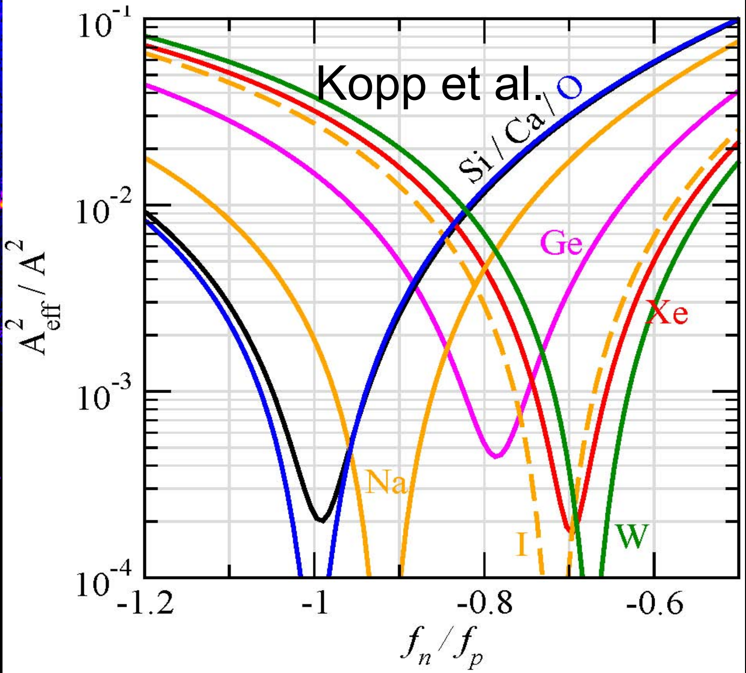
$$\sigma_{\chi N}(\text{axial}) = \frac{8}{\pi} \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \Lambda^2 J(J+1)$$

- Same coupling to p and n (scalar)?

$$\sigma_{\chi N} = \frac{1}{\pi} \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \left[Z f_p + (A - Z) f_n \right]^2$$

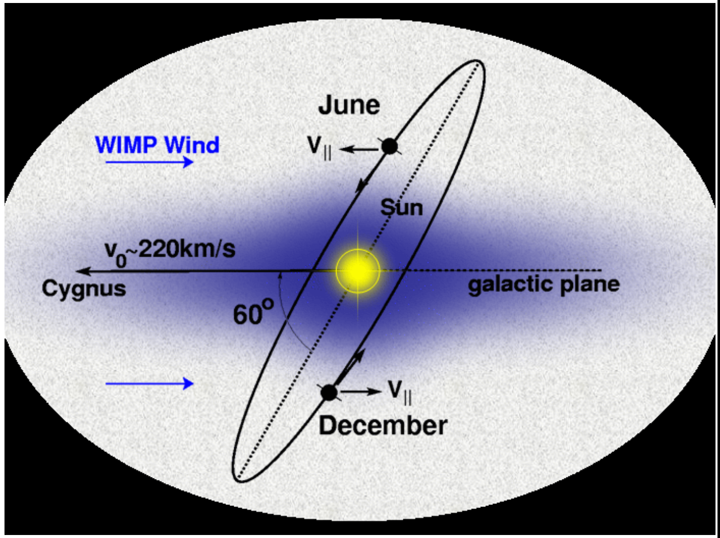
- Compare different expts. w/ care





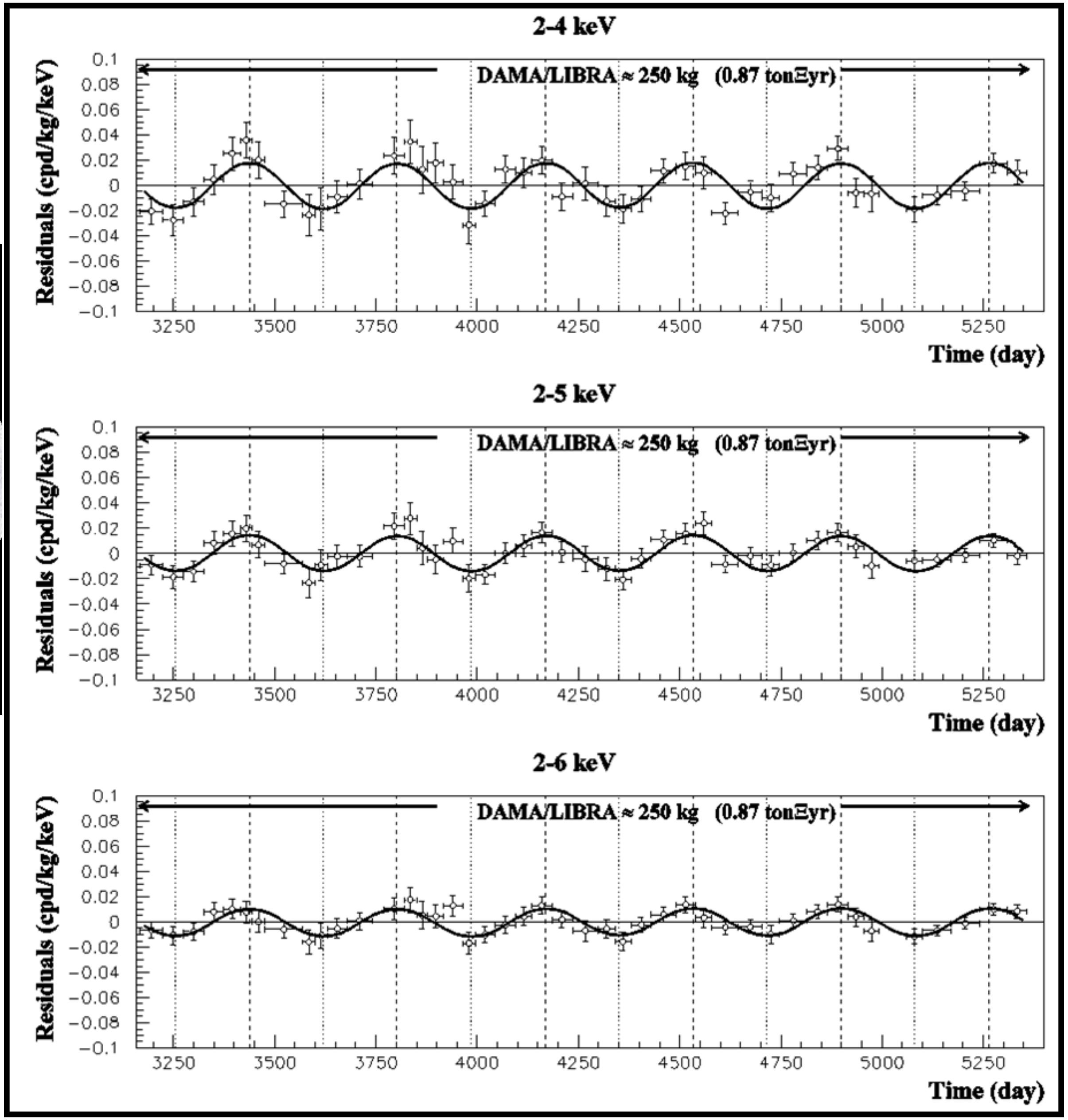
DAMA/LIBRA (NaI)

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



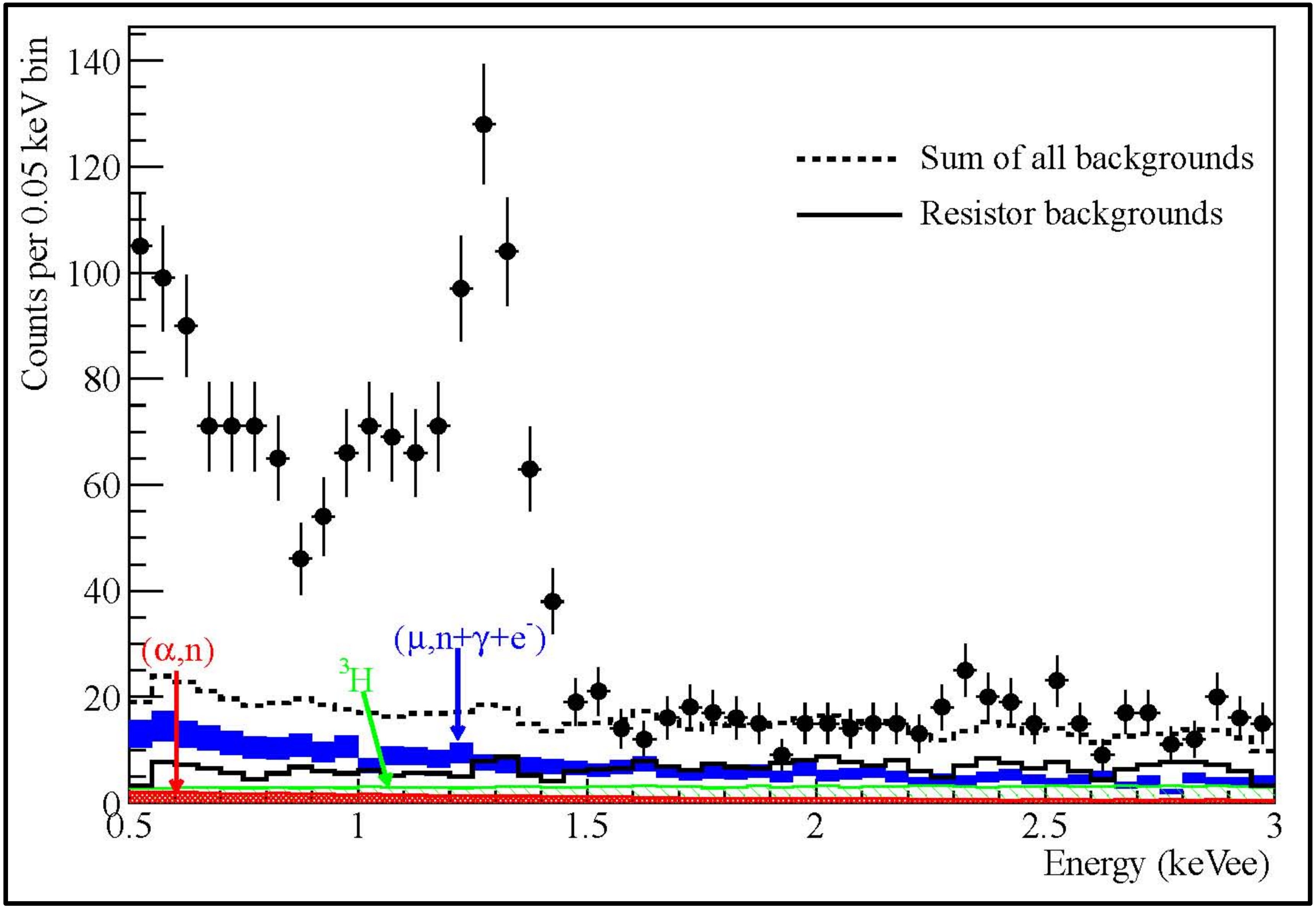
Amplitude of modulation surprisingly high

KIMS (CsI) → modulation not due to WIMP scattering on Iodine



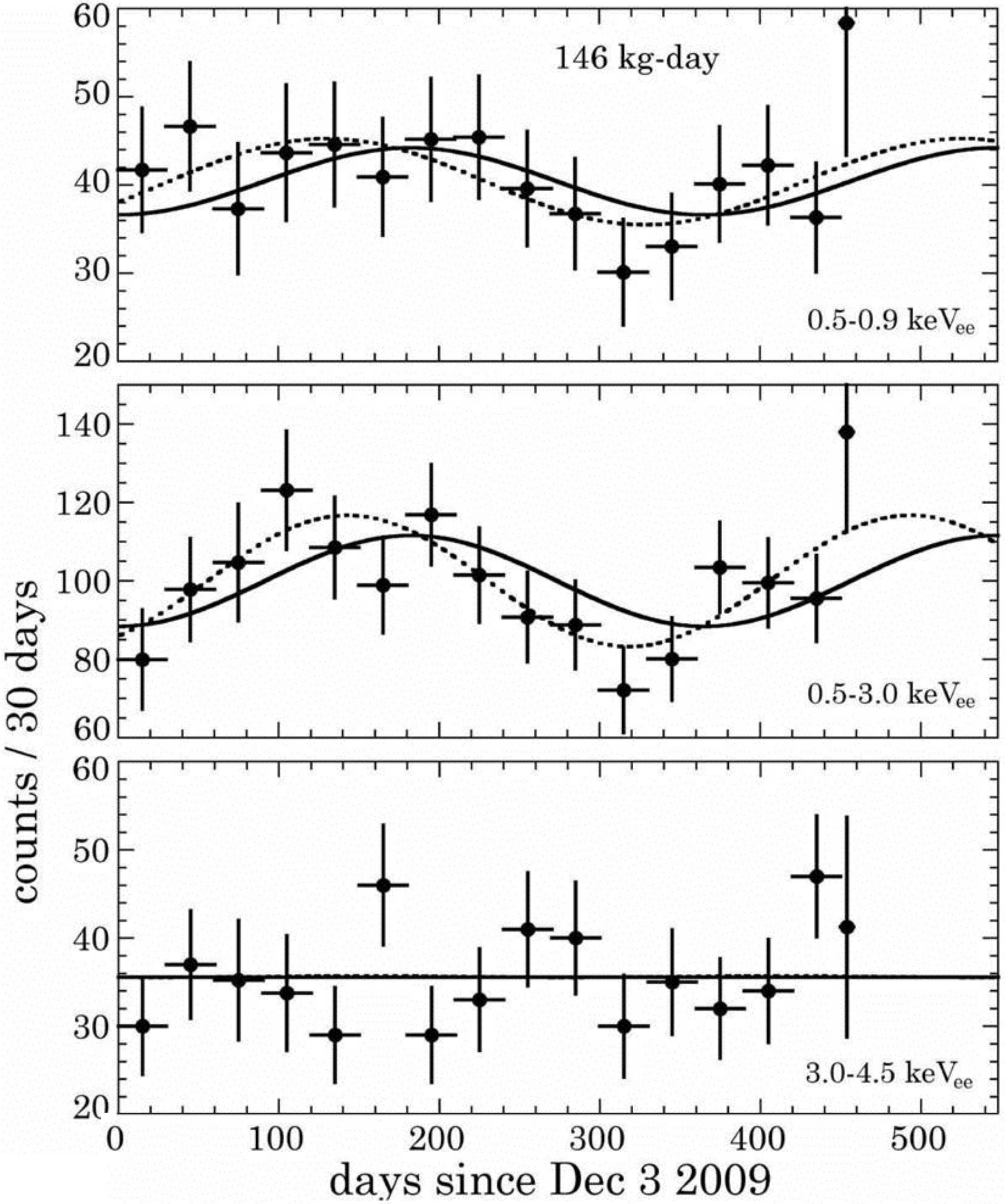
CoGeNT (Ge)

1208.5737



30% surface events, low-mass (10 GeV) WIMP with large cross section (10^{-4} pb)

CoGeNT (Ge)



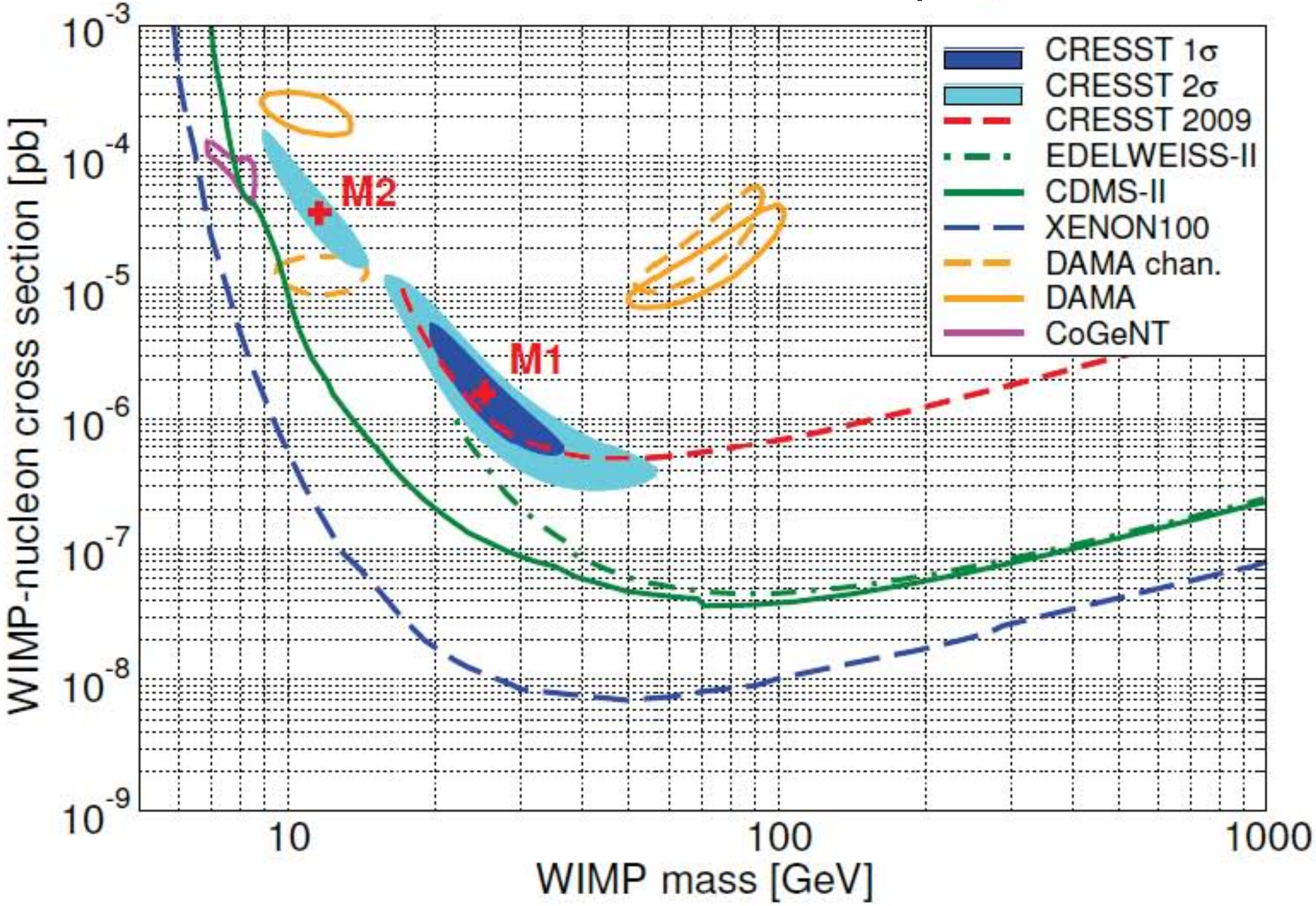
In 2011 data: 2.8σ annual modulation signal Aalseth et al.

Including 2012 data results in smaller significance

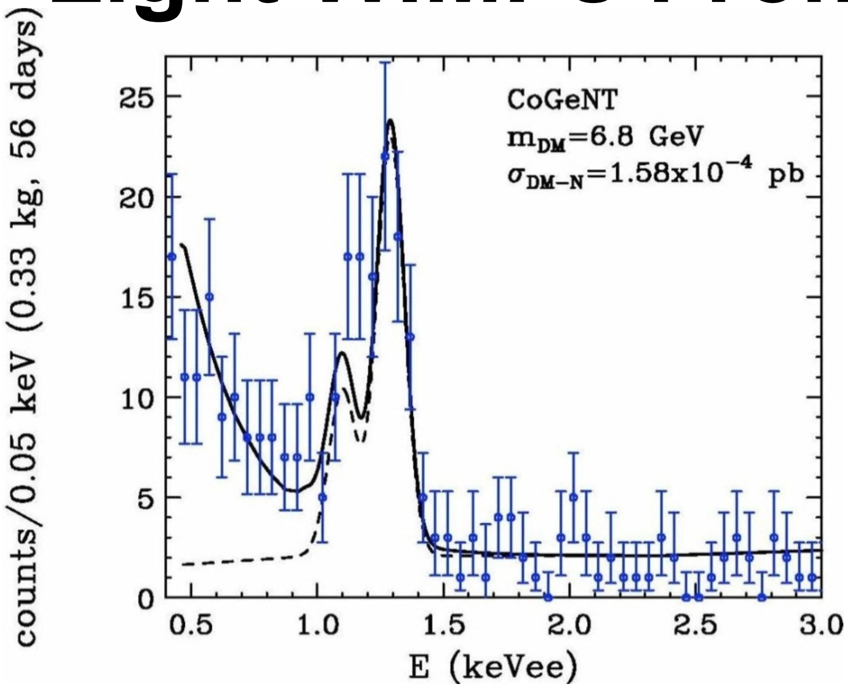
Skeptic:
Signal was never there in the first place (it was a fluctuation). Evidence for light WIMP weaker.

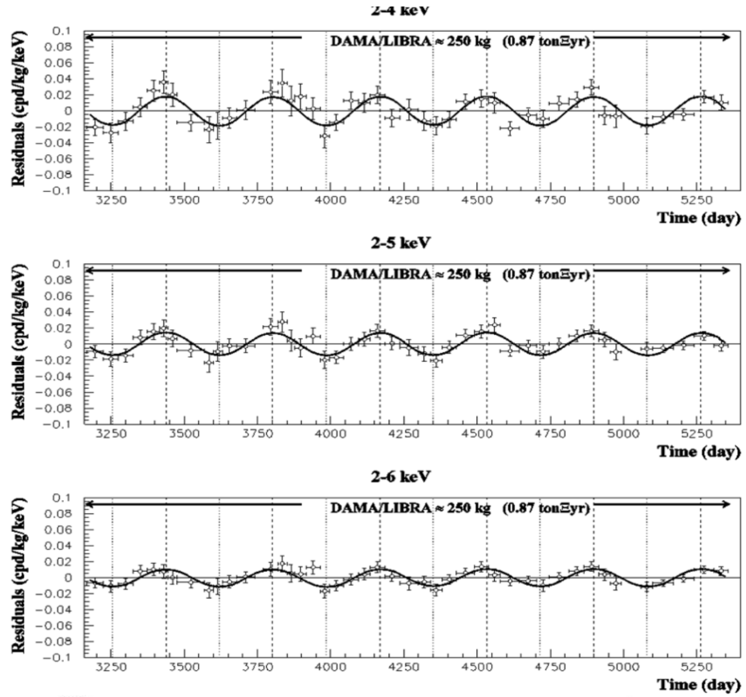
True Believer:
Amplitude of modulation was too high anyway. Evidence for light WIMP even stronger!

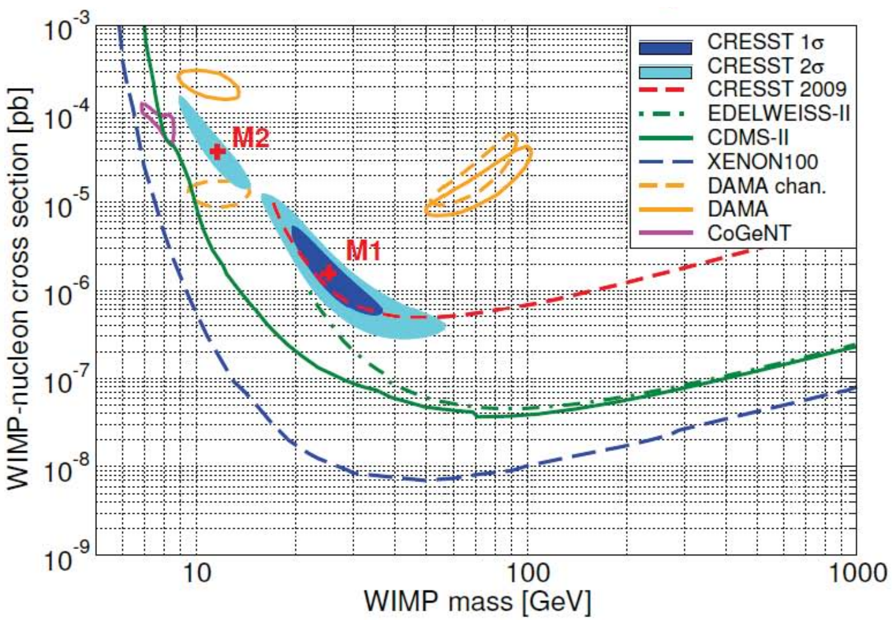
CRESST ($CaWO_4$)

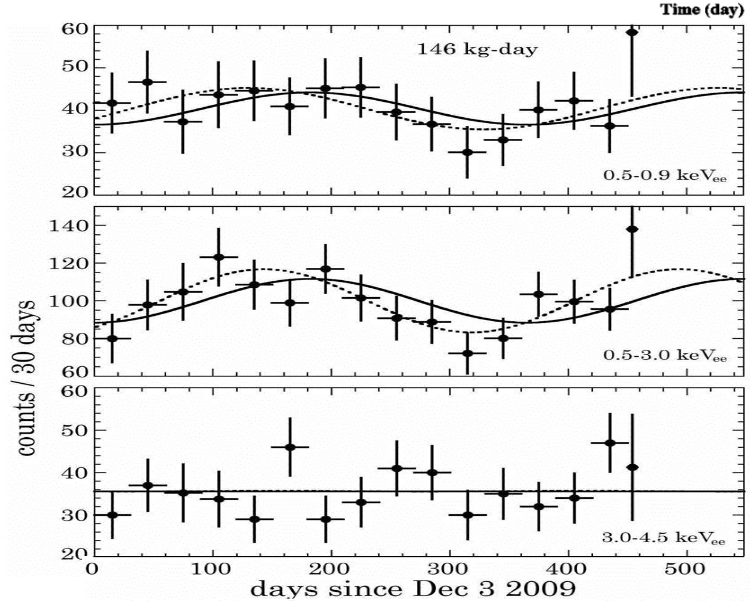


Light WIMPs From Direct Detection?

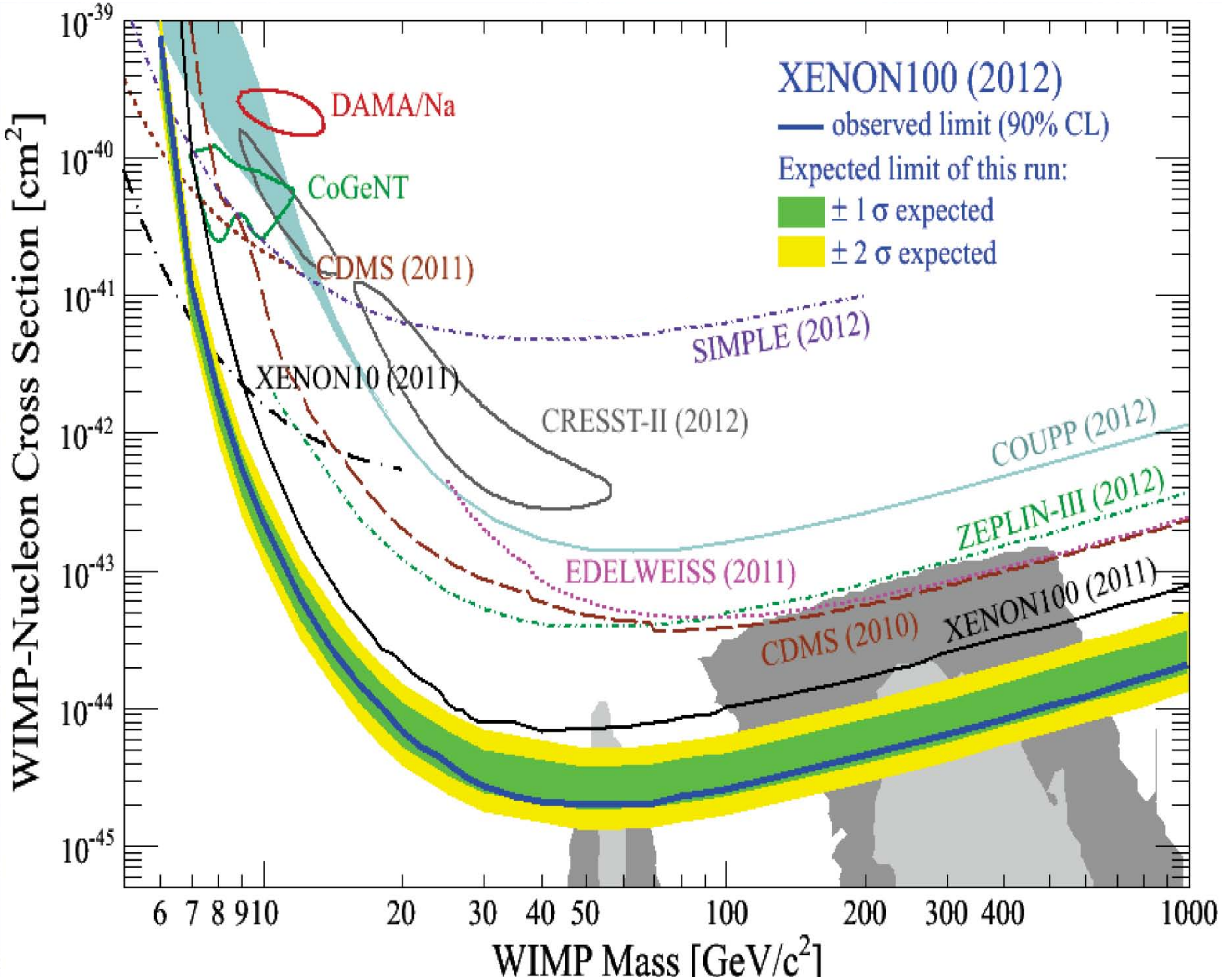








Direct Detection



Low-mass region:

either unexplained backgrounds in DAMA, CoGeNT, and CRESST-II, …

or

… other experiments do not understand low recoil energy calibration, …

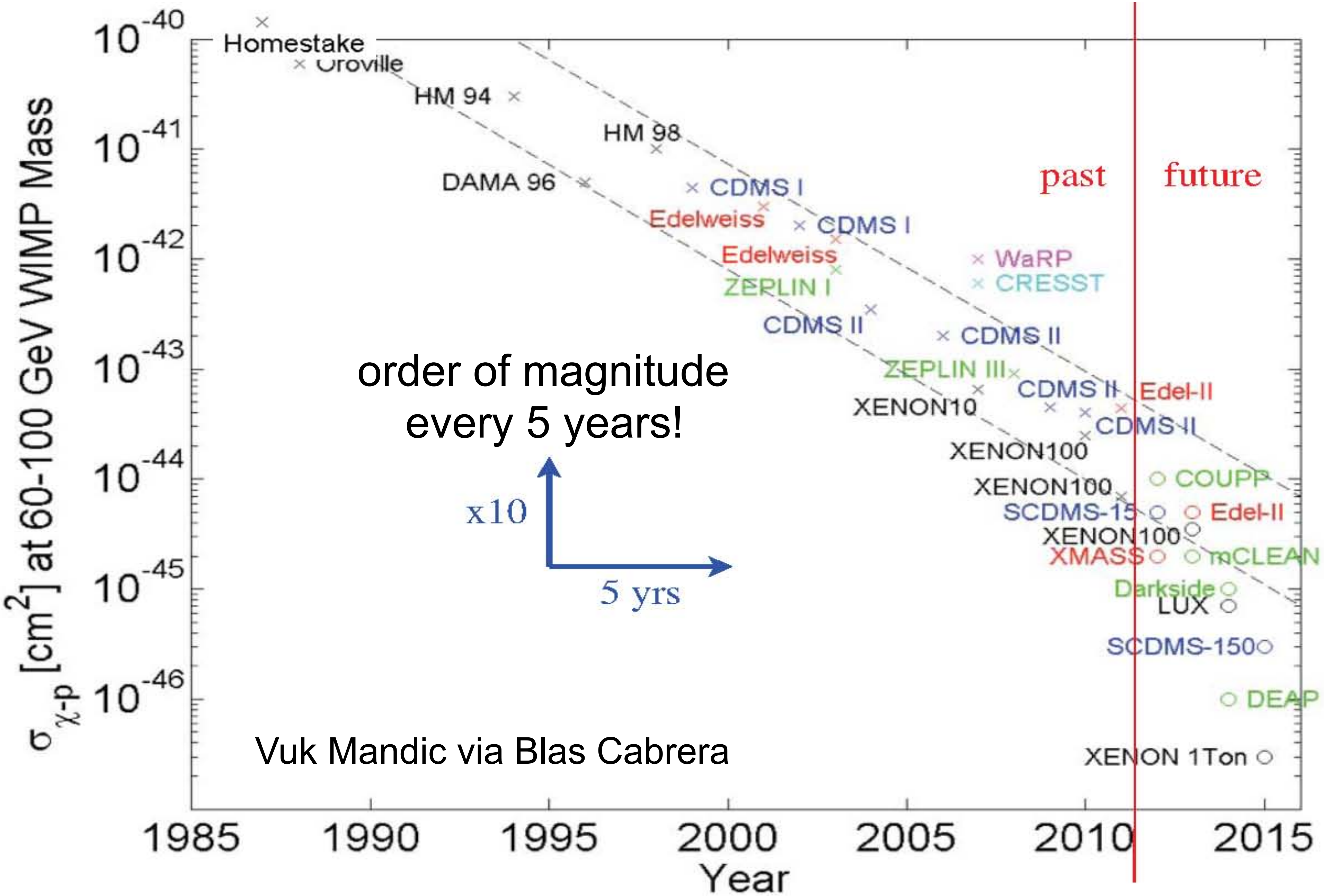
or

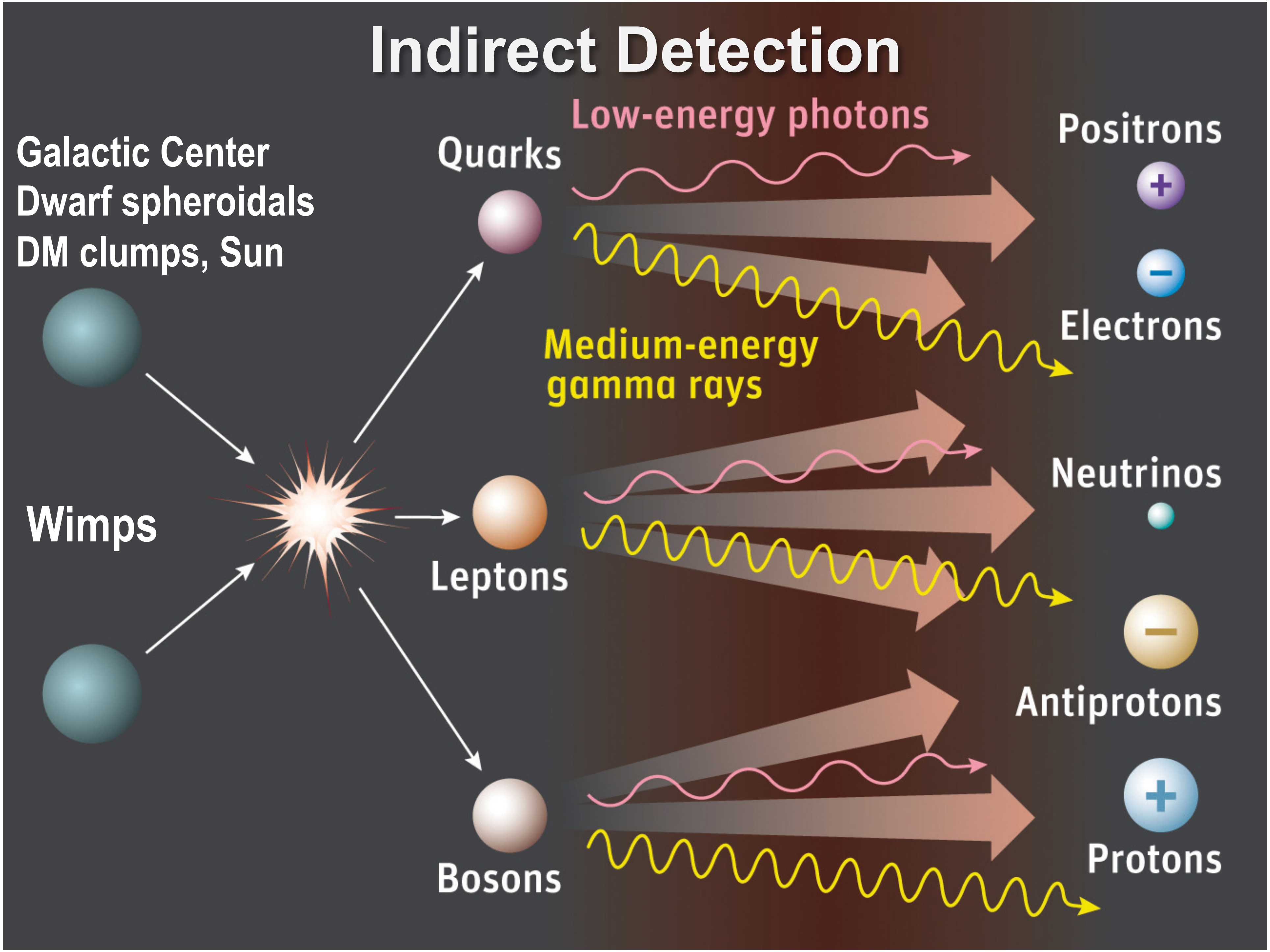
… can't compare different experiments

High-mass region:

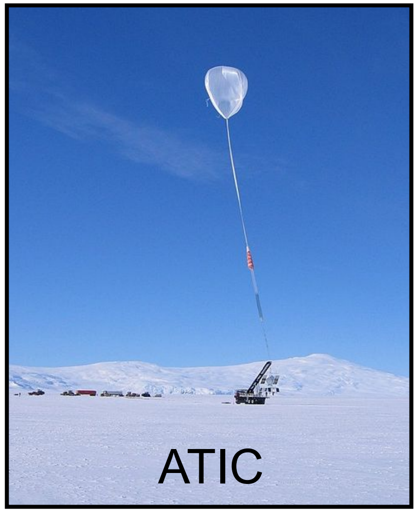
Reaching shades of grey of the CMSSM iceberg, just as heat from LHC melts it!

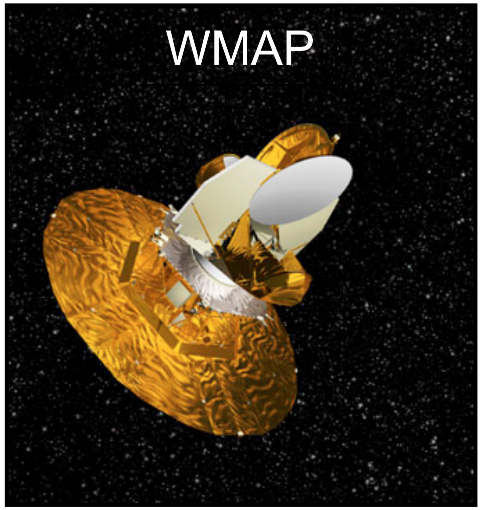
The Past Is Prelude to the Future



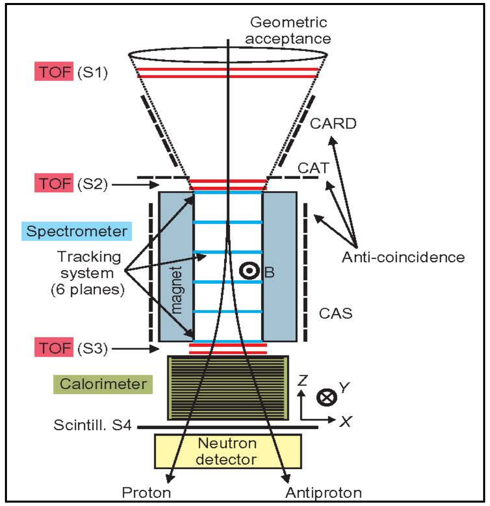

Indirect Detection
Galactic Center
Dwarf spheroidals
DM clumps, Sun
Wimps
Quarks
Leptons
Bosons
Low-energy photons
Medium-energy gamma rays
Positrons
Electrons
Neutrinos
Antiprotons
Protons

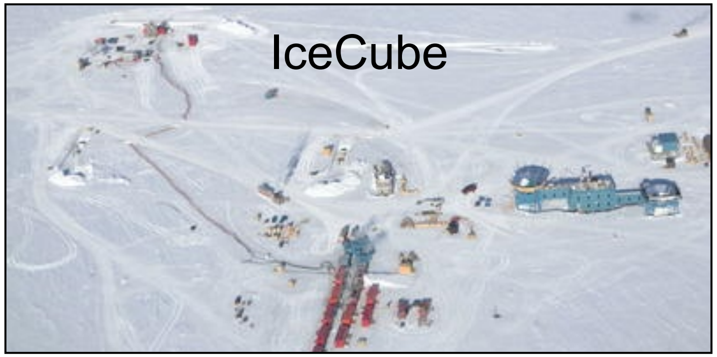
Indirect Detection





PAMELA





Indirect Detection

$$I_{g,n}(y) = \frac{N_{g,n}\langle s\,\mathrm{v}\rangle}{4p}\ \acute{U}_{\text{line of sight}}\ ds\ \frac{r^2(s,y)}{2m^2_{\mathrm{WIMP}}}$$

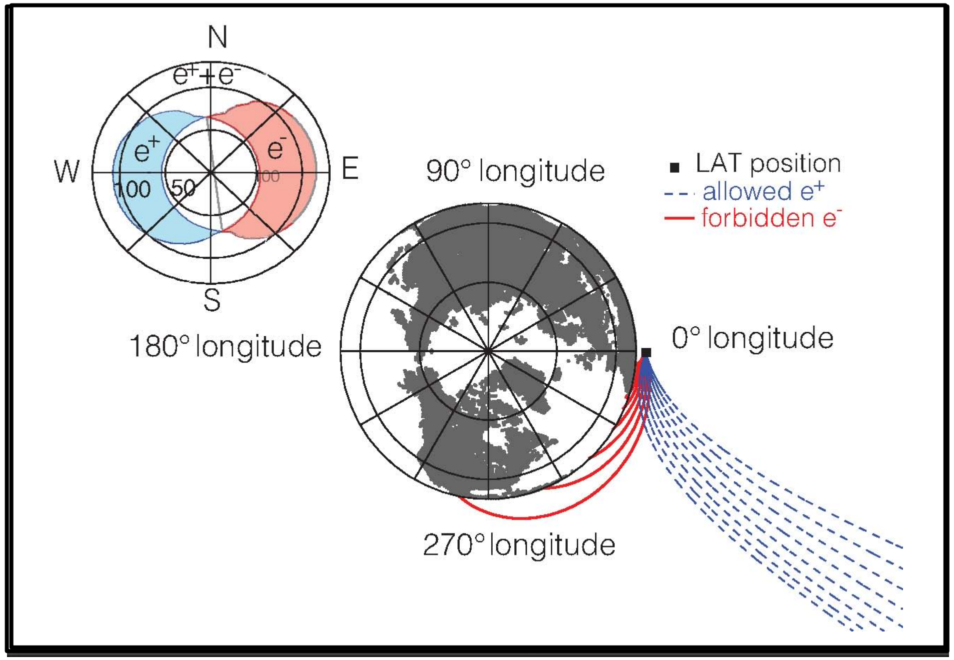
What to look for

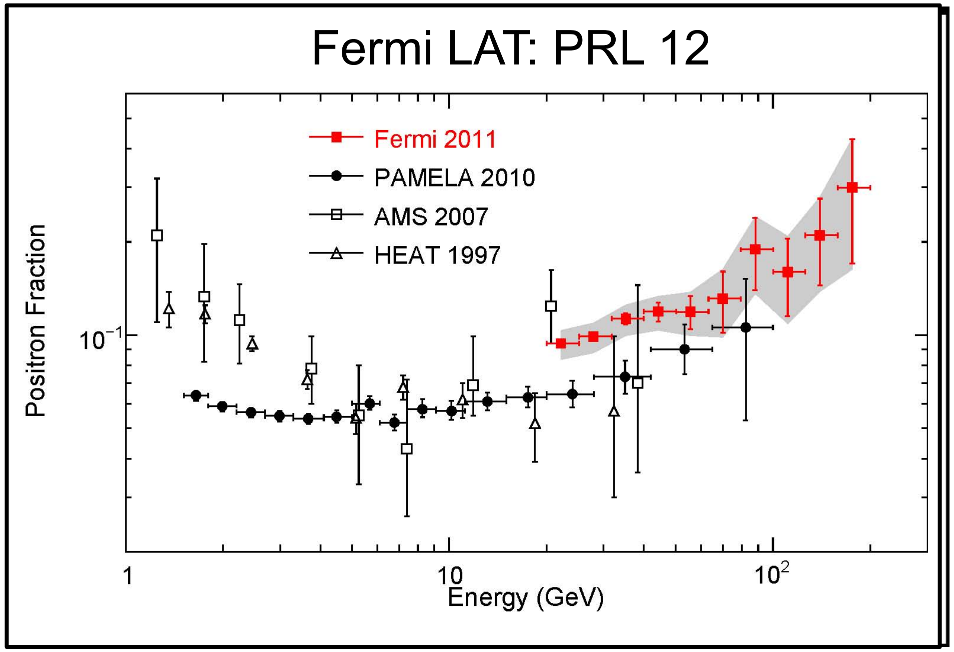
- Charged particles easier to see
  $\bar{p}$, high-energy e^+e^-
  bent by magnetic field
  astronomical backgrounds
- Continuum photons, neutrinos
  usually not dominant channel
  background from astro. sources
  neutrinos hard to see
- Photon line
  low background
  (probably) low signal
  “golden” detection channel

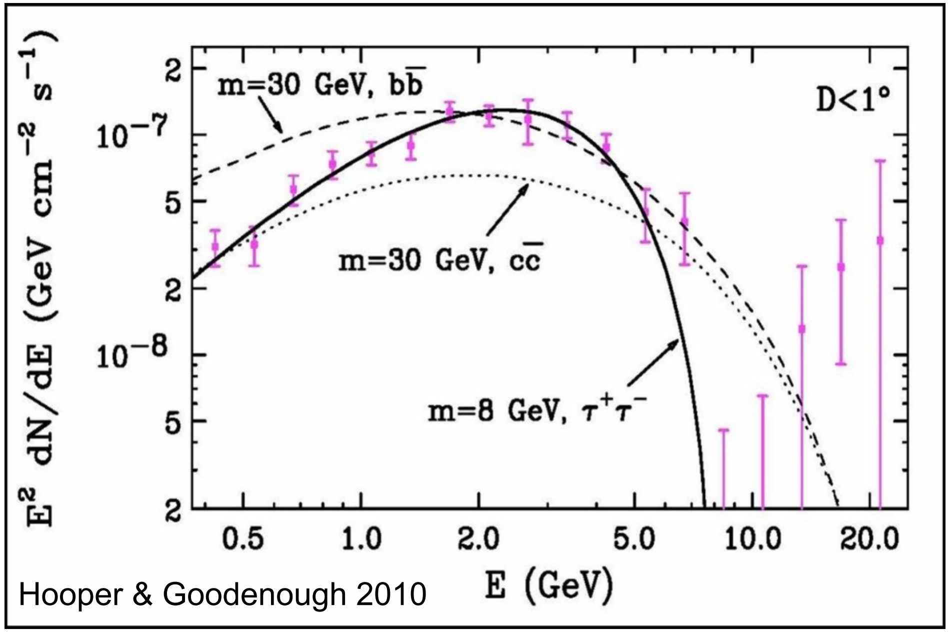
Where to look for it

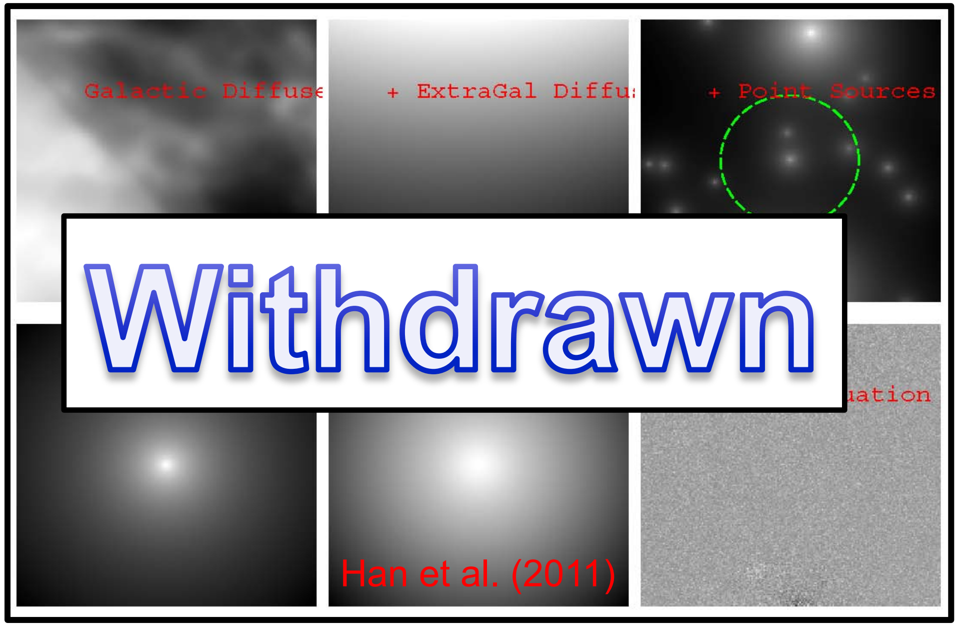
- Galactic Center
  largest signal
  largest backgrounds
  know where to look
- Nearby subclump
  signal down 10^{-3}
  clean: no baryons
  don’t know where it is
- Dwarf spheroidals $(M/L)_{\odot} > 3000$
  signal down another 10^{-3}
  clean: few baryons
  know where to look (about 20)

Indirect Signals Have Come (and Gone?)

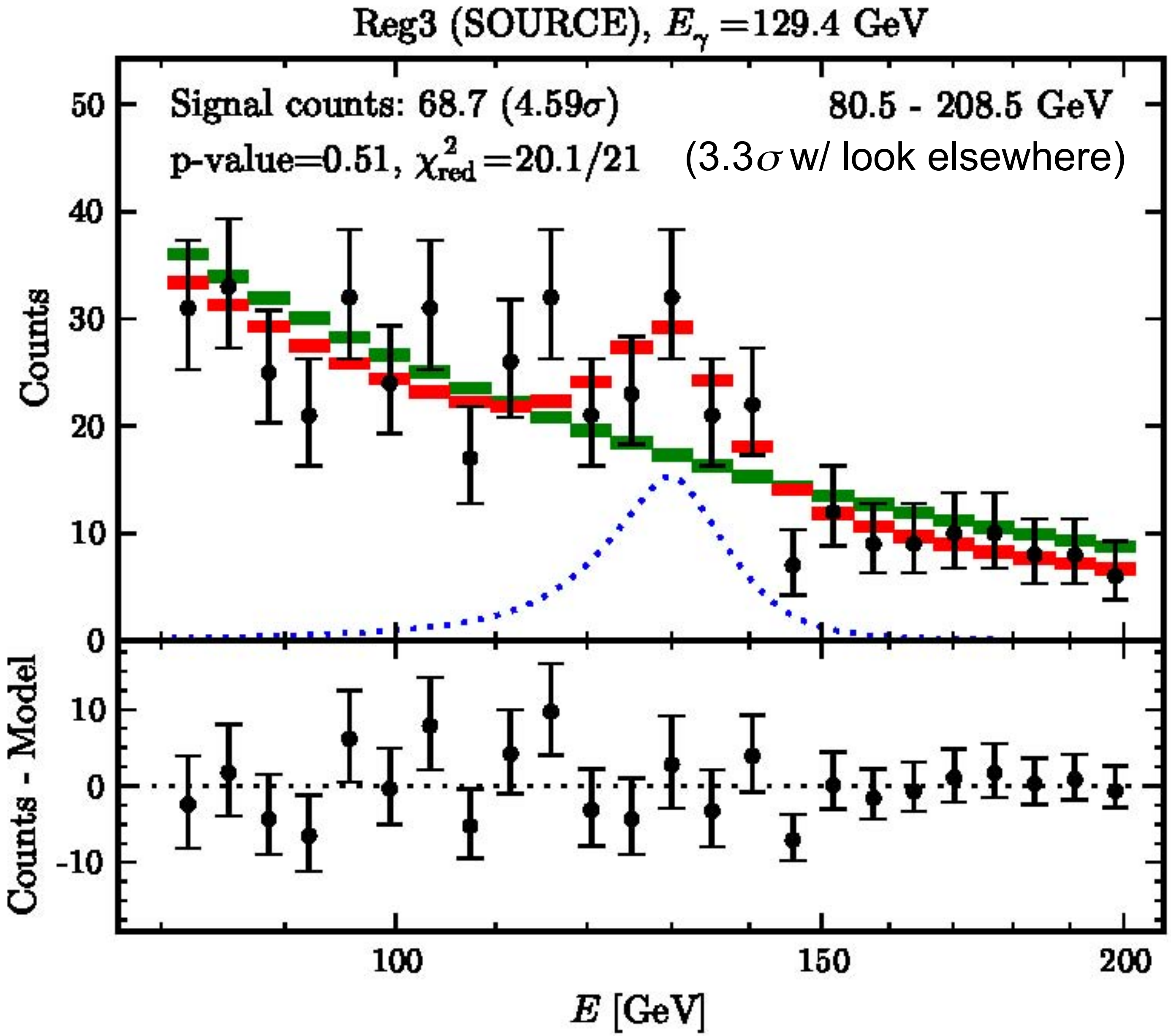








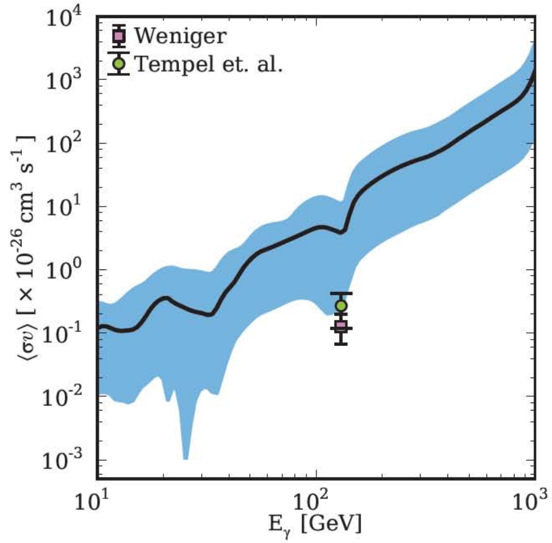
Fermi/GLAST Line

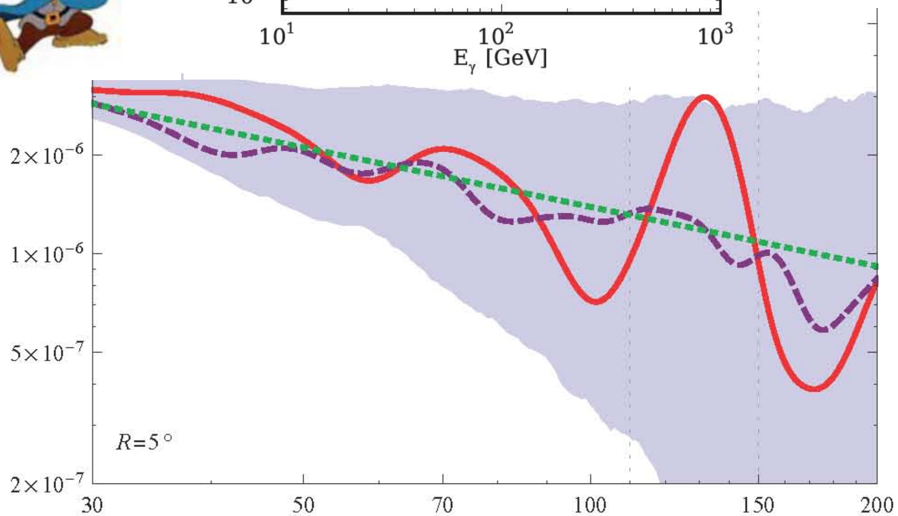


Weniger 1204.2797

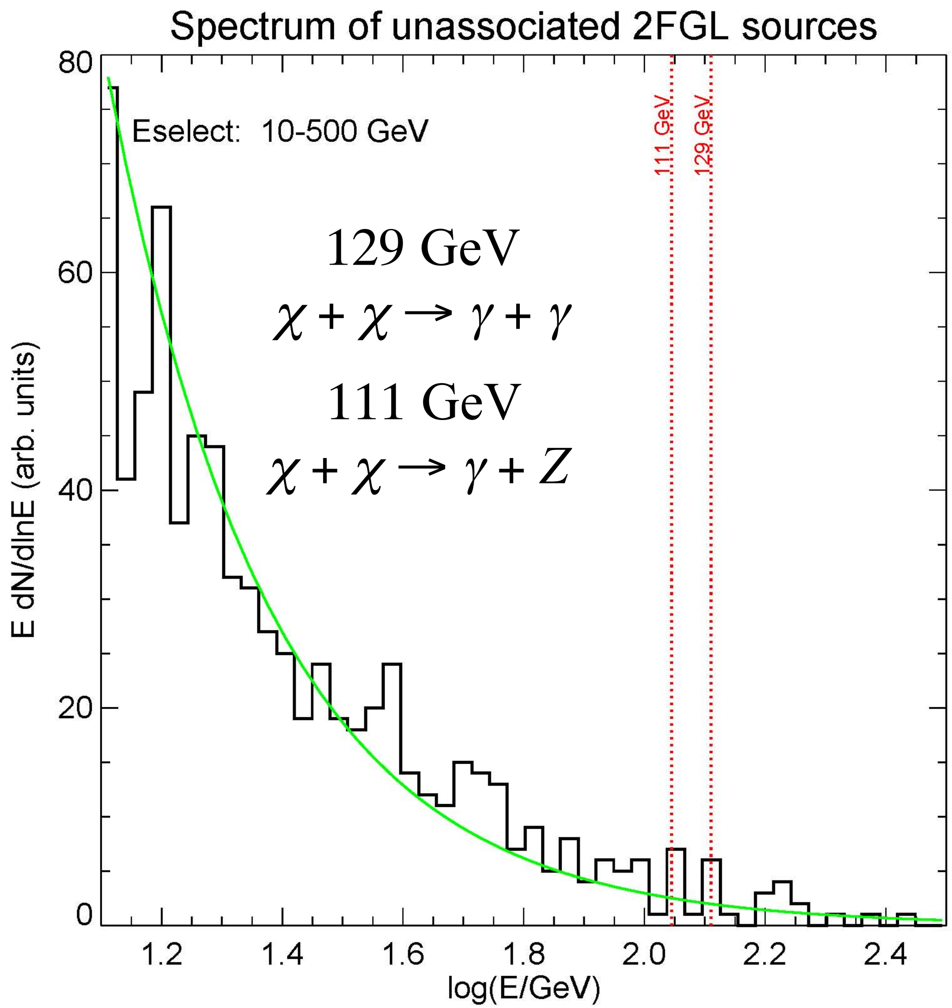
Fermi/GLAST Line(s)

No results yet from dwarf stacking Geringger-Saneth, & Koushiappas 1206.0796





Six stacked galaxy clusters: 3.2σ signal
Hektor, Raidal, Tempel 1207.4466

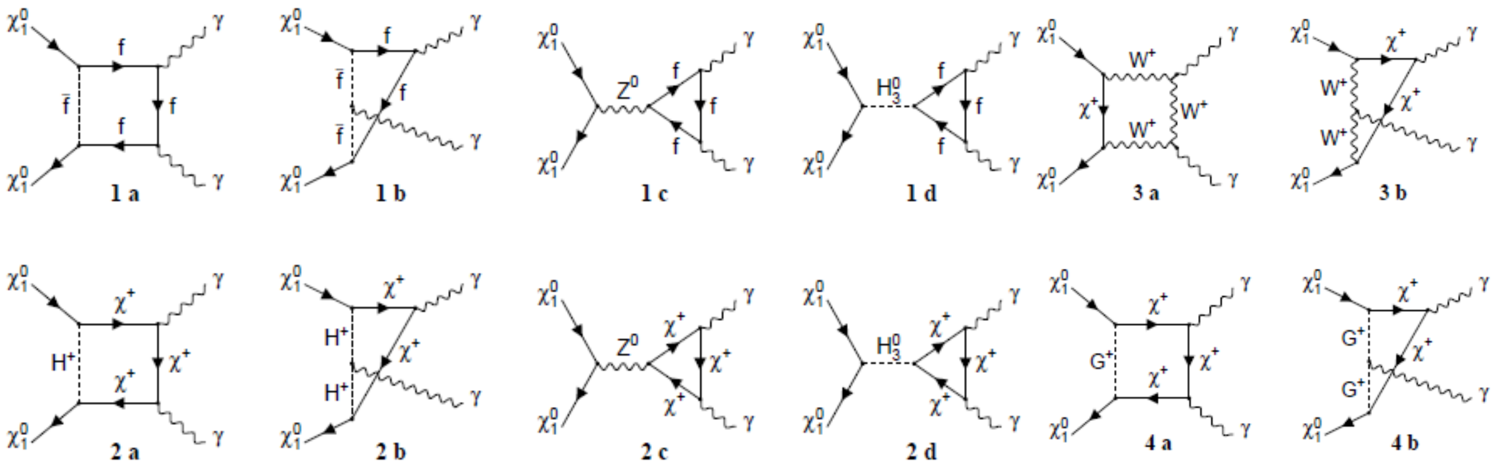


$E_1 = m_c \qquad E_2 = m_c\left(1 - m_c^2/4m_z^2\right)$

About 3σ: Finkbeiner & Su 1207.7060

Fermi/GLAST Line(s)

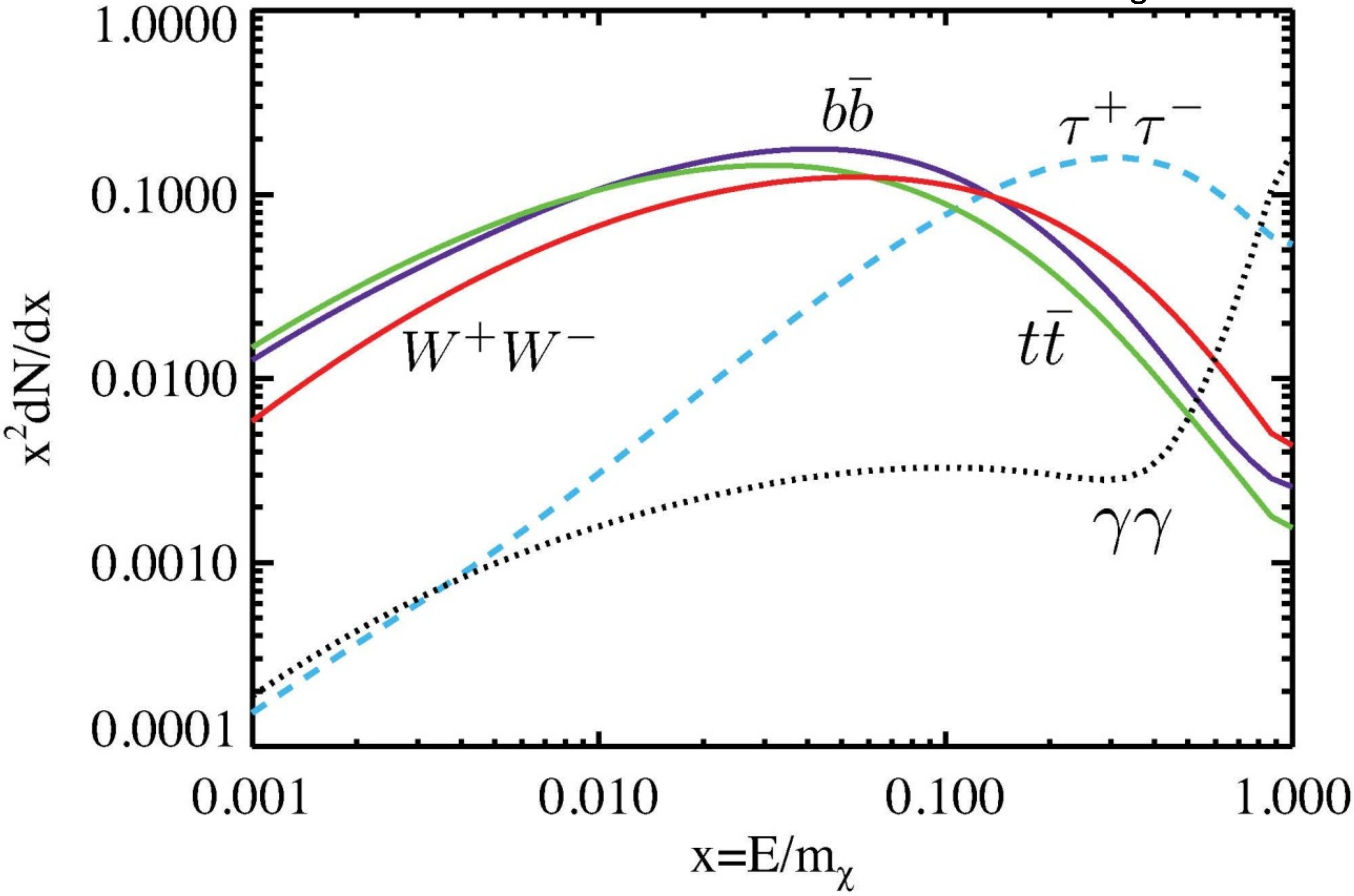
- Wimp−charged particle coupling → decays to $\gamma\gamma + \gamma Z + ZZ + \ldots$).



Bergstrom & Ullio 97

- But also decays at tree-level to e^+e^-, quarks, …, producing “continuum” γ-ray background. Tree larger than loop by $\mathcal{O}(\alpha^2/4\pi)$.

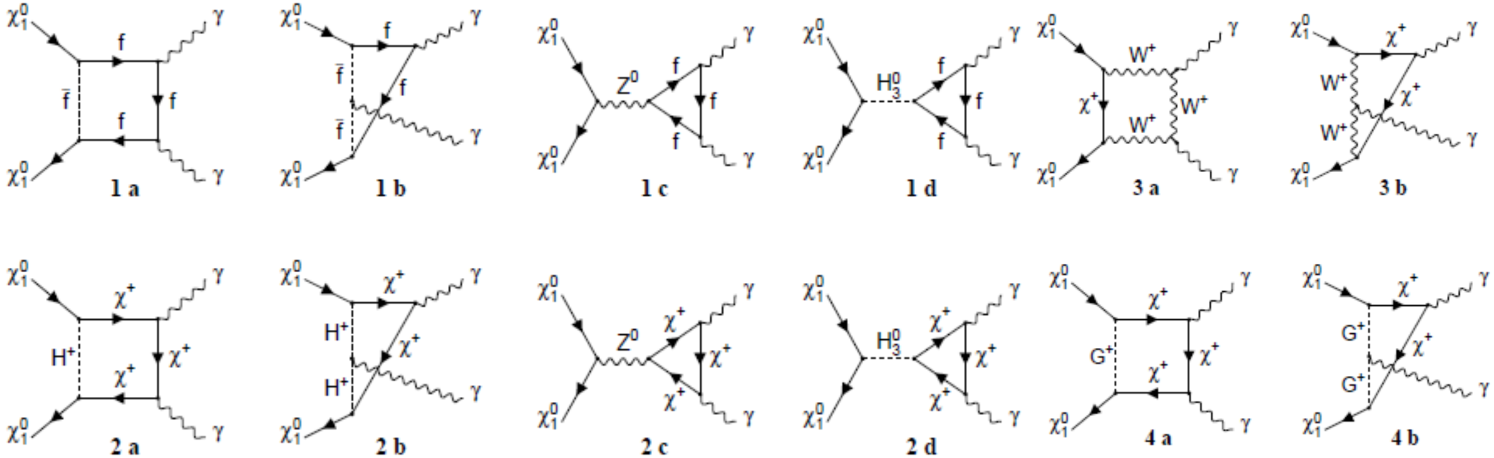
from Seigel-Gaskins



Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

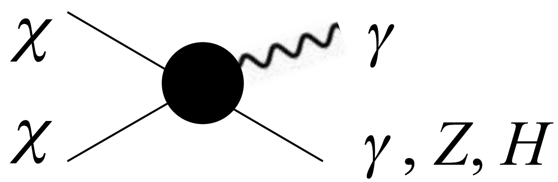
Fermi/GLAST Line(s)

- Wimp−charged particle coupling → decays to $\gamma\gamma + \gamma Z + ZZ + \ldots$).



Bergstrom & Ullio 97

- But also decays at tree-level to e^+e^-, quarks, …, producing “continuum” γ-ray background. Tree larger than loop by $\mathcal{O}(\alpha^2/4\pi)$.
- Continuum constrained by observations, BR($\gamma\gamma$) must be $\mathcal{O}(1)$.
- Inner bremsstrahlung also produces γ’s, only suppressed $\mathcal{O}(\alpha)$.
- Models with no tree-level annihilation: *e.g.,* Jackson *et al*. 0912.0004
- Could take effective field theory approach (in progress w/ Liantao Wang and Jingyuan Chen; also Tait *et al*.), e.g., $\Lambda^{-4}\chi\gamma_\mu\gamma^5\chi\ B^{\mu\alpha}\ \Phi^\dagger D_\alpha\Phi$

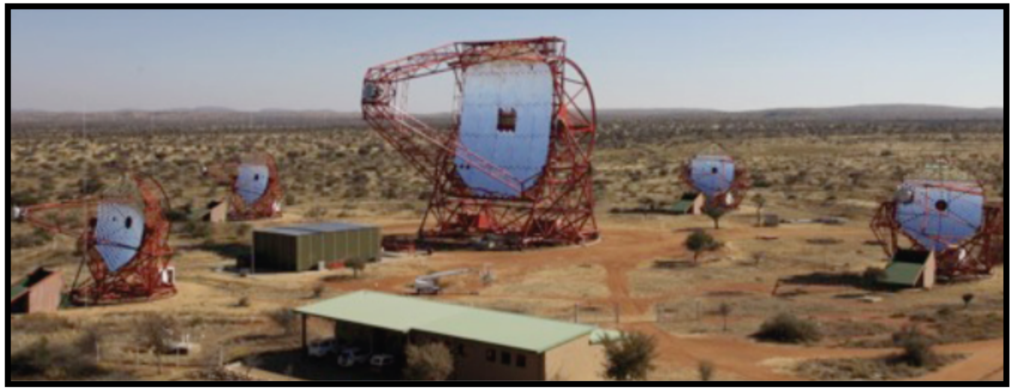


Fermi/GLAST Line(s)

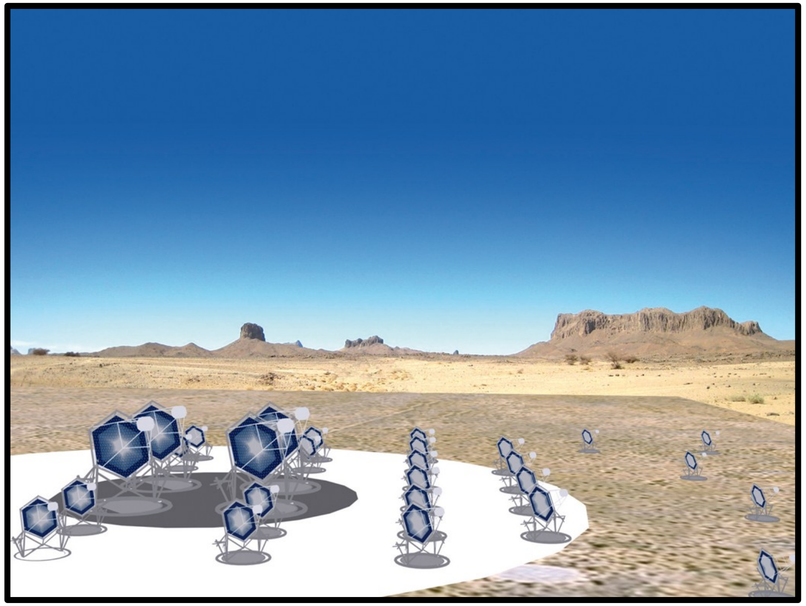
Fermi/GLAST

LOFTY AMBITIONS

Mission	Chief scientist	Goals	Estimated launch
HXMT	Li Tipei, CAS Institute of High Energy Physics and Tsinghua University	Survey of x-ray sources; detailed observations of known objects	2014
Shijian-10	Hu Wenrui, CAS Institute of Mechanics	Study physical and biological systems in microgravity and strong radiation environment	Early 2015
KuaFu Project	William Liu, Canadian Space Agency and CAS Center for Space Science and Applied Research	Study solar influence on space weather	Mid-2015
Dark Matter Satellite	Chang Jin, CAS Purple Mountain Observatory	Search for dark matter; study cosmic ray acceleration	Late 2015
Quantum Science Satellite	Pan Jianwei, University of Science and Technology of China	Quantum key distribution for secure communication; long-distance quantum entanglement	2016



HESS-II 600 m^2



Cherenkov Telescope Array


WIMP Production at the LHC

WIMPs: Socialists or Mavericks

Socialist WIMPs:

Socialist WIMPs are part of a social network.
Pal around with new un-WIMPy particles.
Part of a larger framework.
Find the WIMP through its friends.
Example: SUSY

Maverick WIMPs:

Maverick WIMPs don't relate to others.
Not friended by any new particles.
Have no discernible core positions.
Find the WIMP through what is not seen.
Example: Neutrinos before late 1960s.

WIMP: Social or Maverick Species

Social WIMP

- WIMP part of a social network
- Motivated model framework, *e.g.,* low-energy SUSY, UED, ...
- Many new particles/parameters
- Unclear relationships between σ_A , σ_S , and σ_P

Maverick* WIMP

- WIMP is a loner
- Use effective field theory, *e.g.*: 4-Fermi interaction
- WIMP only new species
- Clearer relationship between σ_A , σ_S , and σ_P

---

* Beltran, Hooper, Kolb, Krusberg PRD 2009
  Beltran, Hooper, Kolb, Krusberg, Tait JHEP 2010

SUSY WIMPs at the LHC

Favorite cold thermal relic: the neutralino

Neutralino:

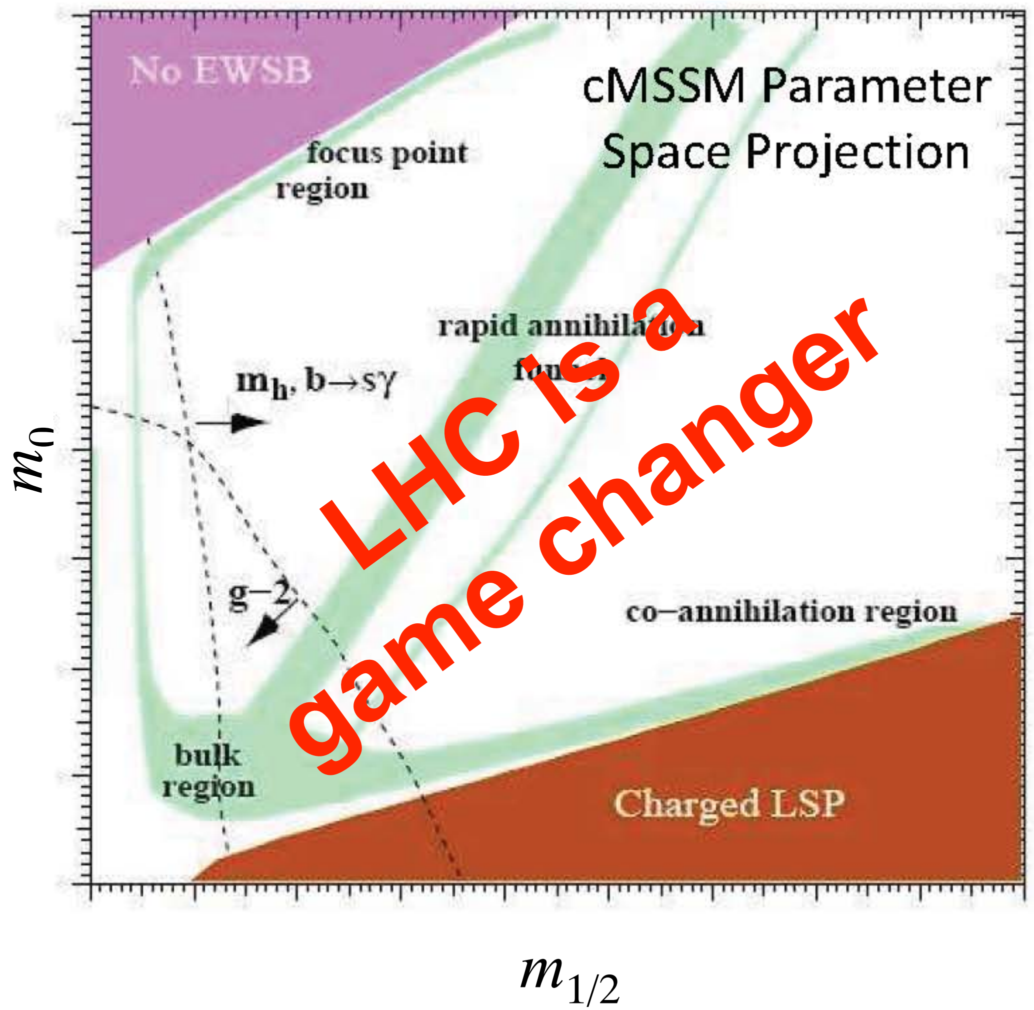
$$\tilde{\chi}^0 = \alpha \tilde{B}^0 + \beta \tilde{W}^0 + \gamma \tilde{H}_1^0 + \delta \tilde{H}_2^0$$

$m_{\tilde{\chi}^0}$ 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 at the LHC

- 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 $\tilde{t}$
  - large tanβ (*s*-channel annihilation via broad *A* resonance)
  - high values of m_0: Higgsino- like neutralino annihilates into *W* & *Z* pairs (focus point region)
  - …

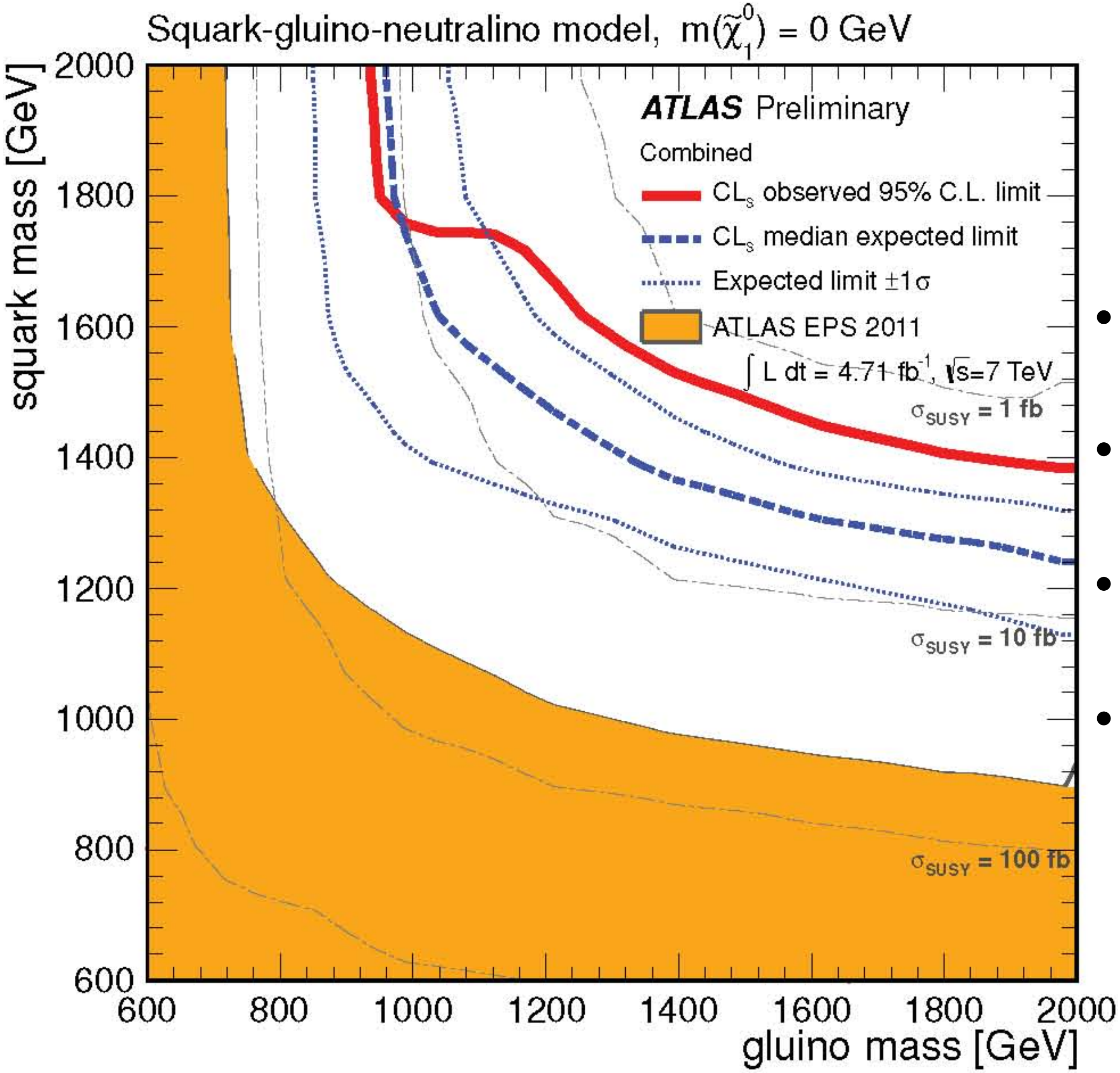
- Higgs mass limit constrains SUSY models

- Squark/gluino ssearchs constrain SUSY models

- Or, unconstrained, nonminimal

SUSY WIMPs at the LHC

gluinos, squarks, charginos will be discovered before neutralinos

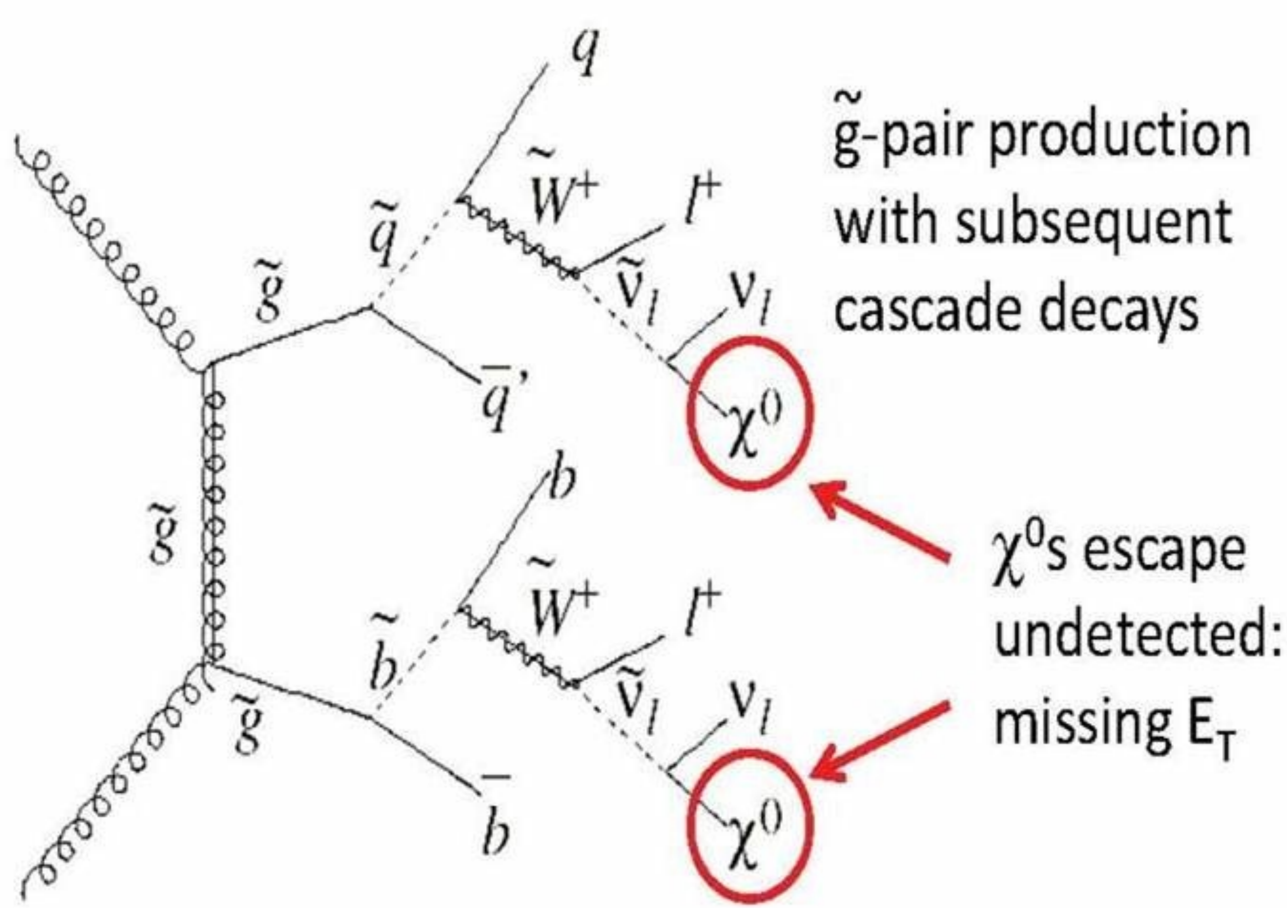


- Analysis model dependent
- Can swiggle out
- But it is getting harder
- Don’t throw in towelino

LHC chewing away at allowed region

Collider Searches for WIMPs

SUSY Trickle Down



Complicated decay chain
First see squarks, gluinos, *etc.*
Very model dependent

Maybe, just maybe, SUSY won't be seen at the LHC, and dark matter is not a neutralino (or sneutrino, or gravitino, or any ino).

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 $\mathrm{SU(2)_L}$ via SM Yukawa couplings → operators that flip quark chirality should be $\propto m_q$ (S,P)

Some terms vanish for Majorana χ

Can write $G \sim M_*^{-2}$

(S,P) $G \sim m_q M_*^{-3}$

$F \sim M_*^{-1}$

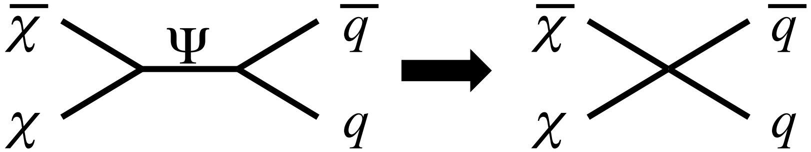
(S,P) $F \sim m_q M_*^{-2}$

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~~

- Dirac fermions
- Could also couple WIMP to gluons
- Could imagine "light" mediators (not a true Maverick)
- Range where effective field theory valid

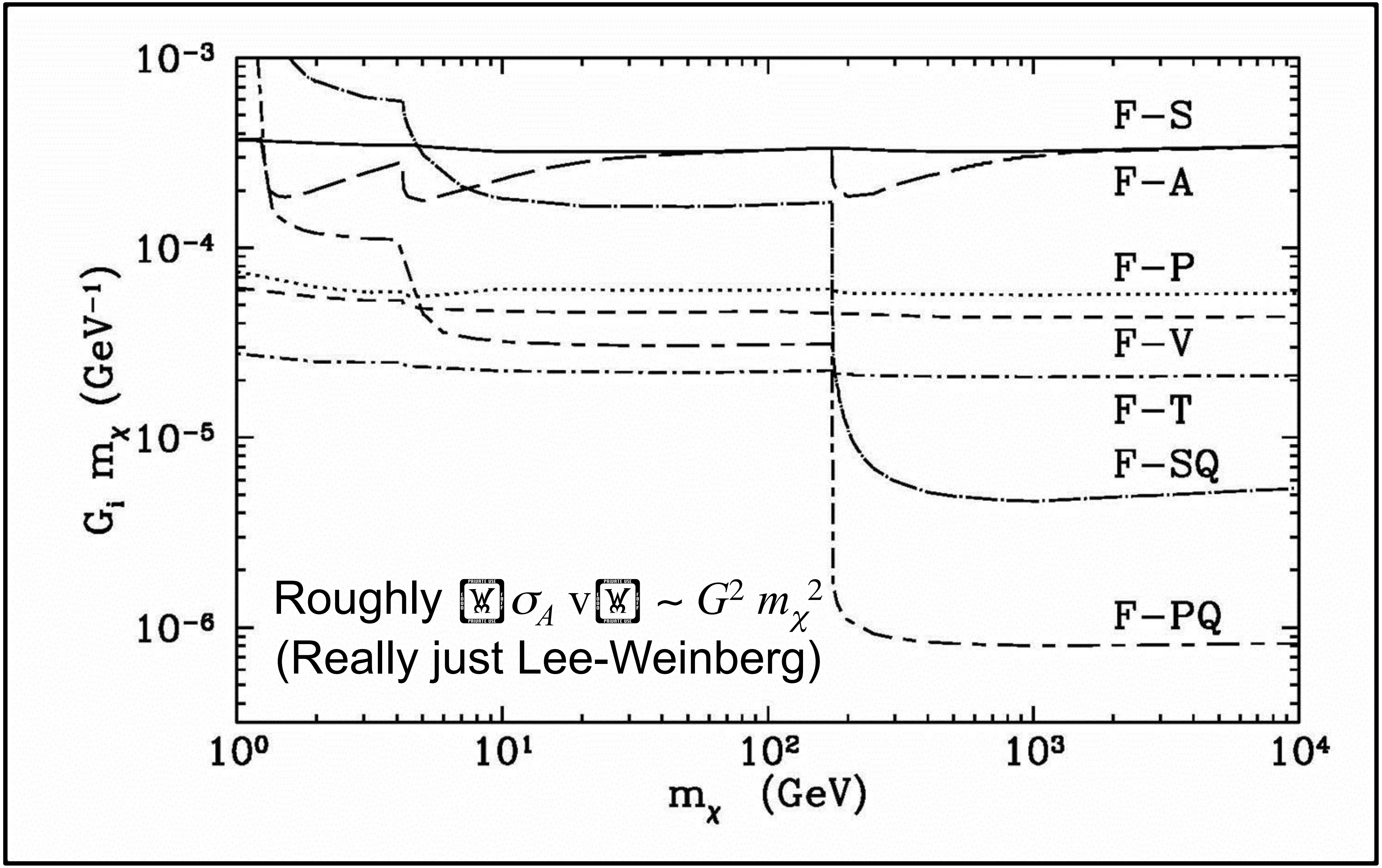


$$\frac{g_\chi g_q}{p^2 - M_\Psi^2} \rightarrow \frac{G}{\sqrt{2}}$$

- Could also include couplings to leptons

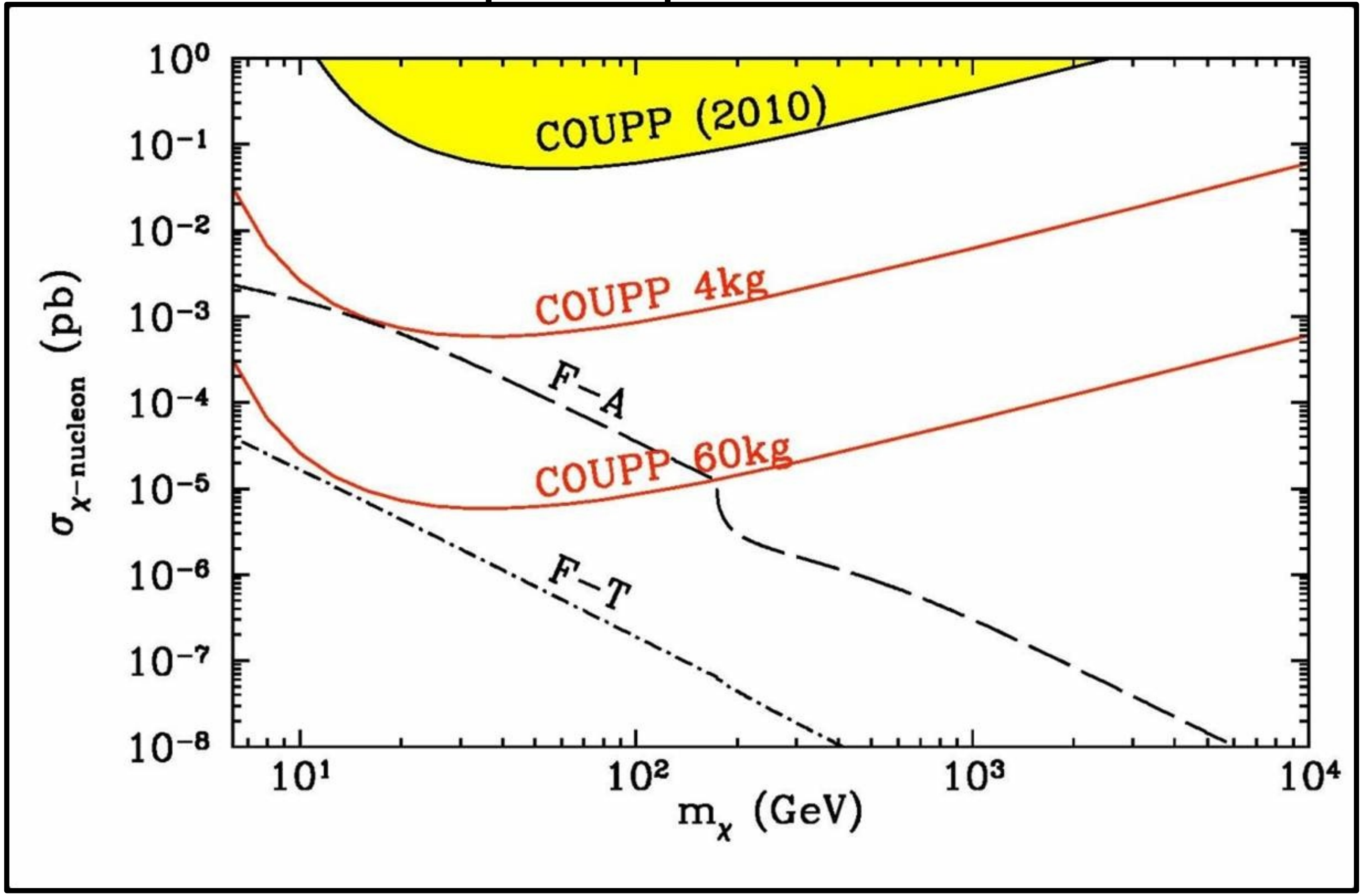
Maverick WIMPs

Values of G to give correct dark matter density



Maverick WIMPs

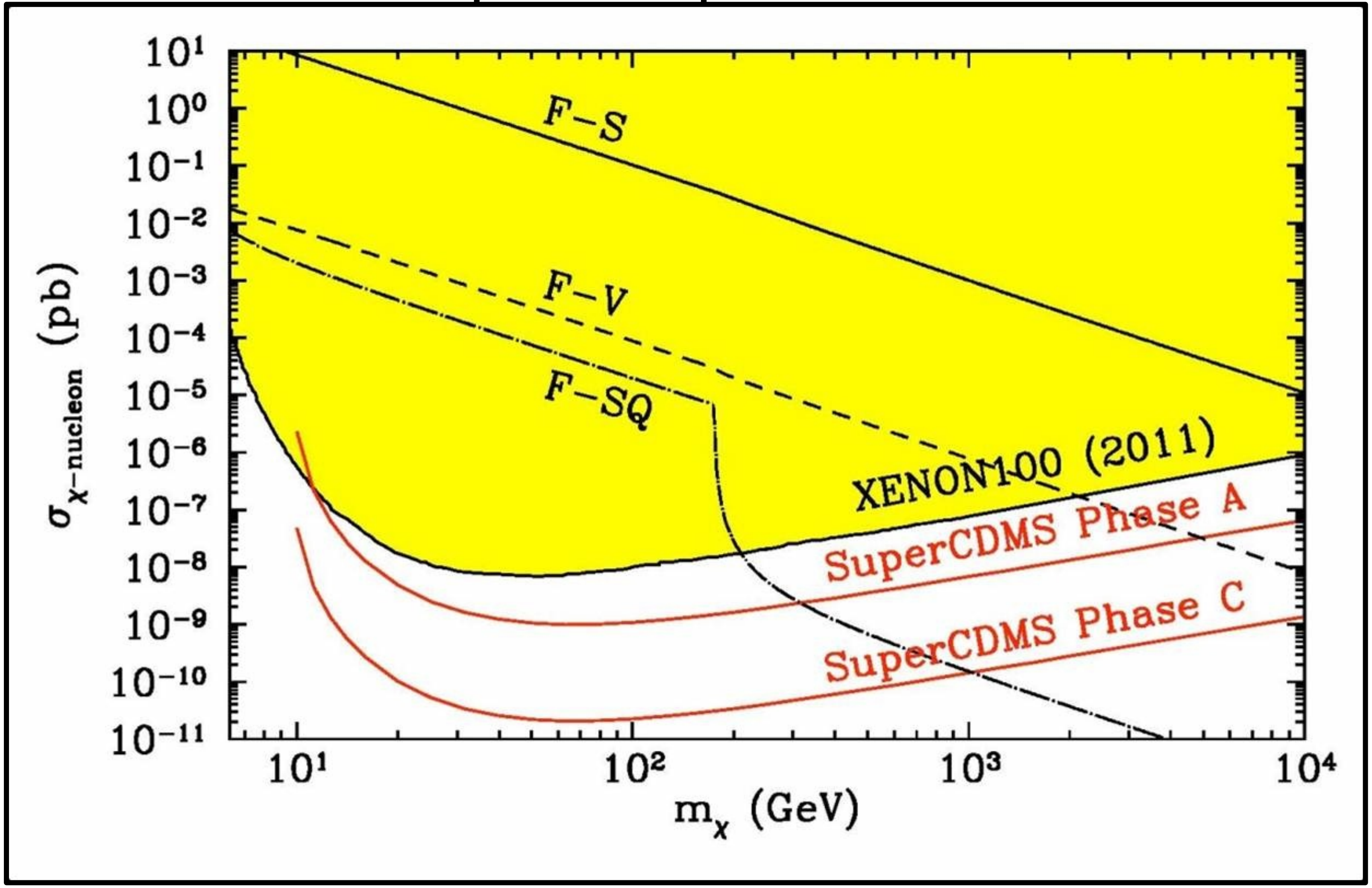
spin-dependent



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

Maverick WIMPs

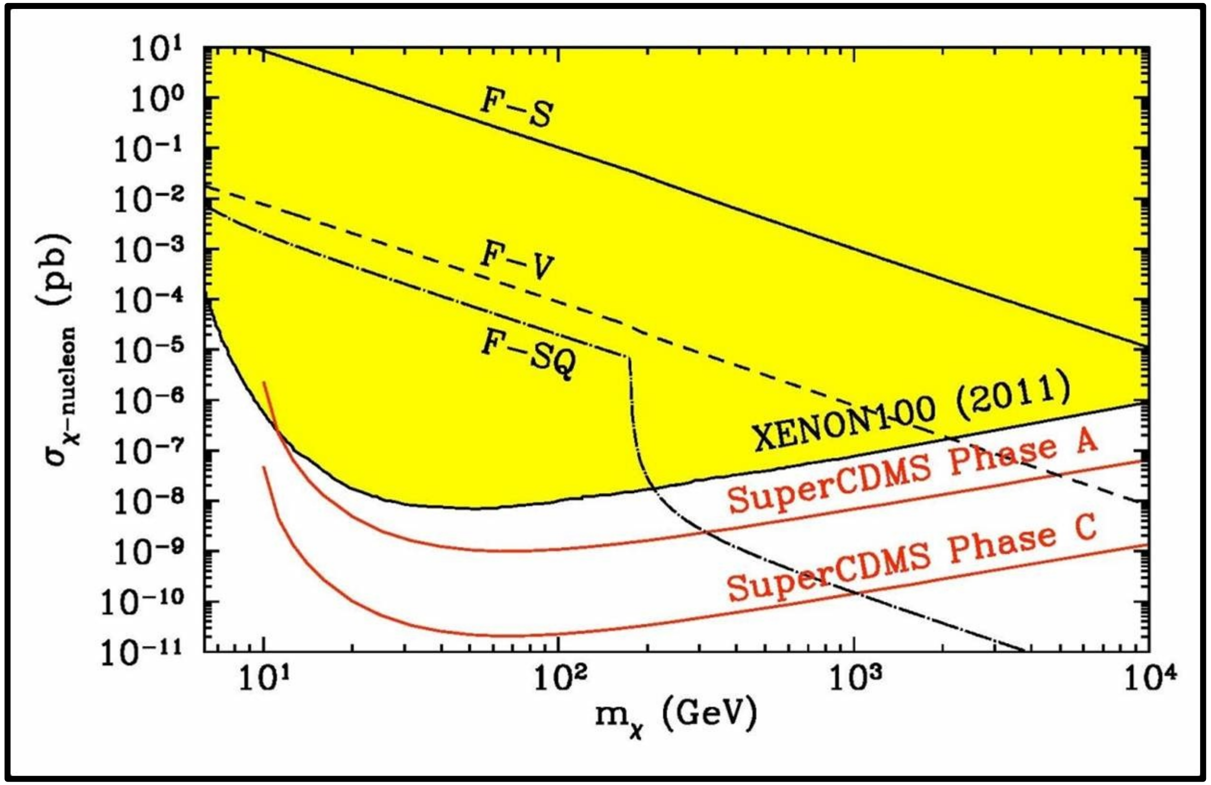
spin-independent



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

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

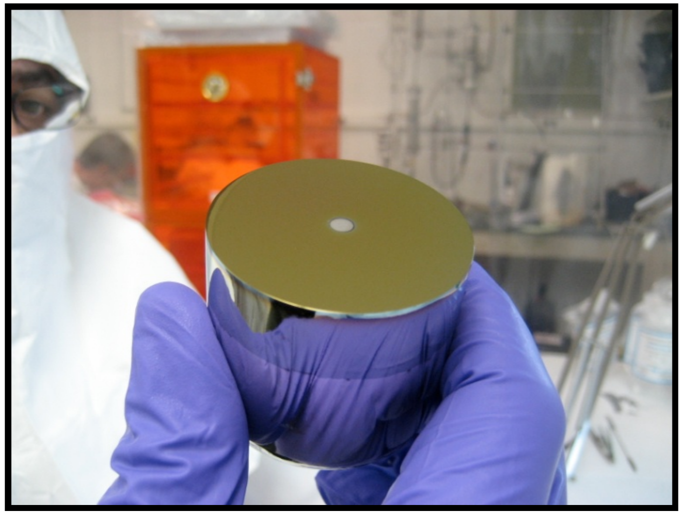
Maverick WIMPs



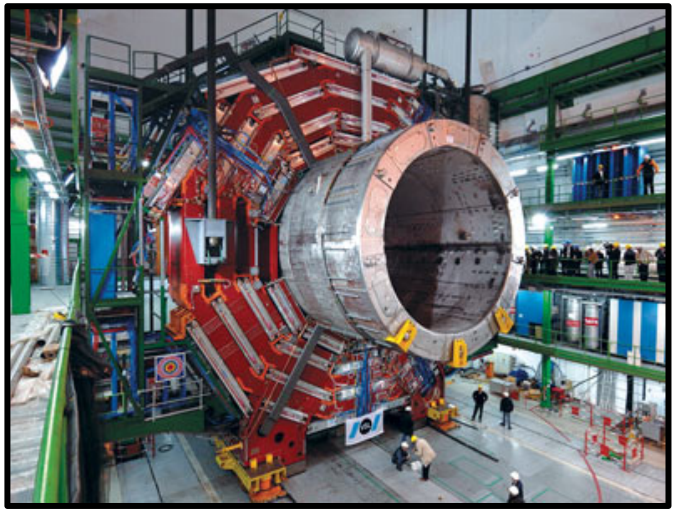
- Coupling $\propto m_q$ is very important effect
- Could have smaller coupling producing larger abundance & subsequent entropy dilutes WIMPs
- Perhaps WIMPs not thermal relics, but asymmetric relics
- Usual Super-WIMP trick not in Maverick spirit

Direct Detection & Collider Production

CoGeNT



LHC



Model Dependent

nonrelativistic

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

10^{-4} pb – 10^{-6} pb

Probably described by effective field theory (several operators?)

relativistic

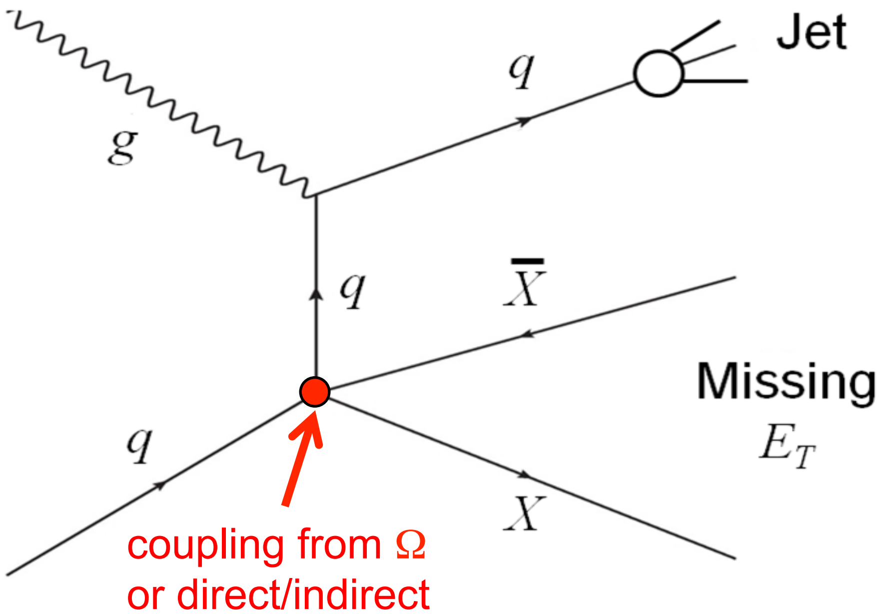
$$q + \bar{q} \rightarrow \chi + \chi$$

???

Assume described by effective field theory "Maverick" WIMPs

Collider Searches for WIMPs

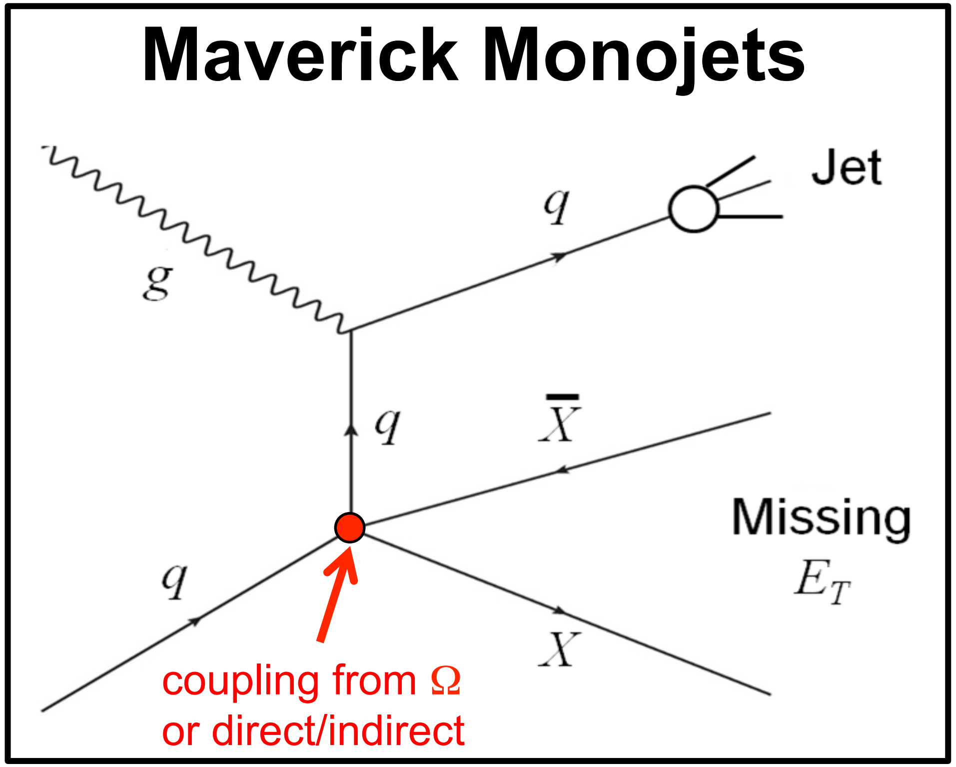
Maverick Monojets



Beltran, Hooper, Kolb, Krusberg, Tait 2009
Goodman, Ibe, Rajaraman, Shepard, Tait, Yu 2010
Rajaraman, Shepherd, Tait, Wijangco
Bai, Fox, Harnik; Fox, Harnik, Kopp, Tsai
CDF, CMS, Atlas

Backgrounds (neutrinos, QCD, …)
Only signal (other than mono-γ)
Largely model independent

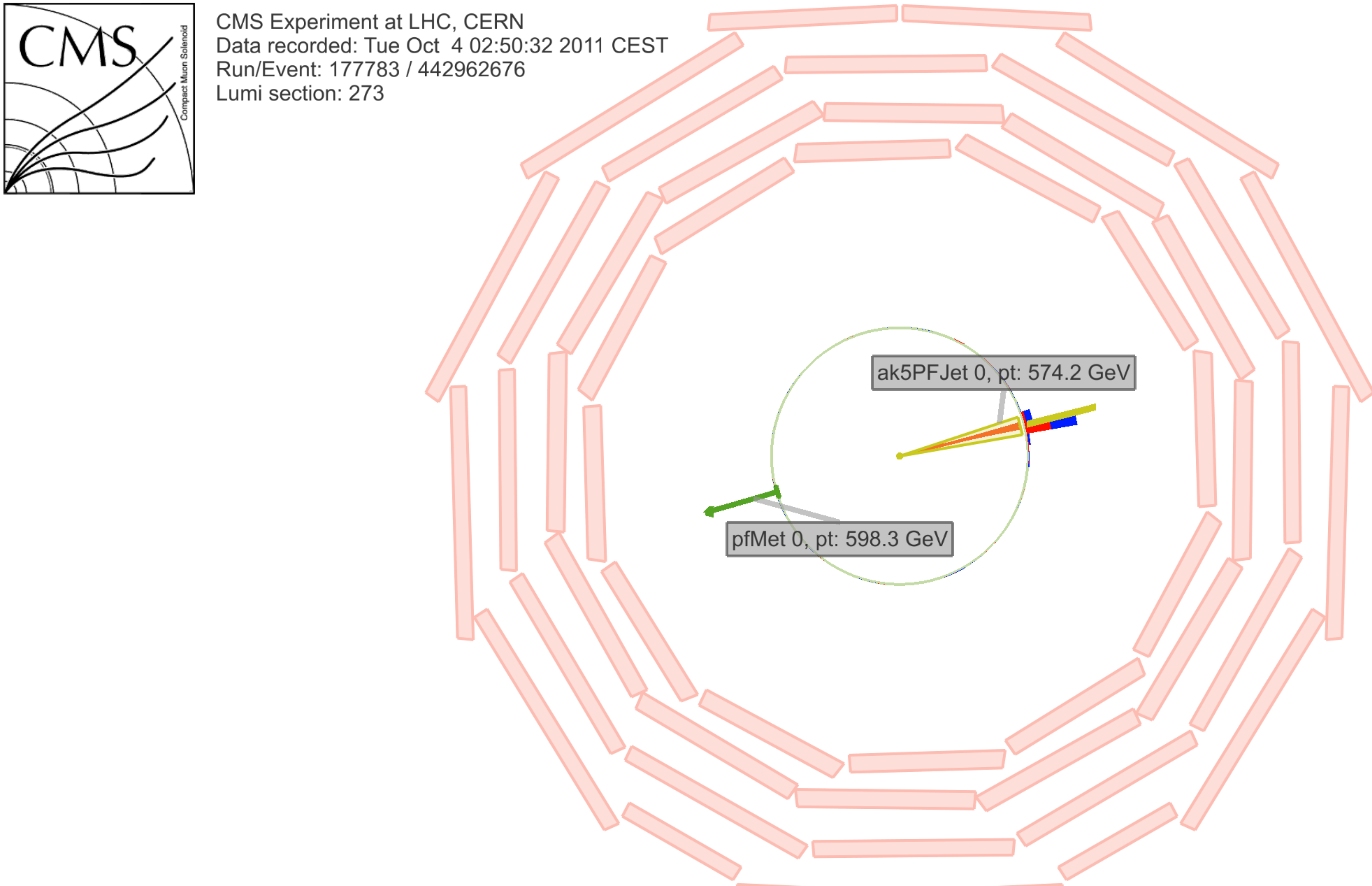
Collider Searches for WIMPs



Backgrounds (neutrinos, QCD, …)
Only signal (other than mono-γ)
Largely model independent

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

Missing Momentum = Missing Mass?

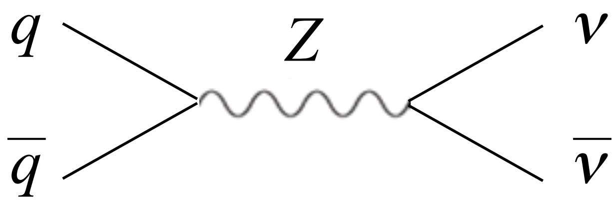


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012

Neutrino Background for Mavericks

Once thought that $\nu \bar{\nu}$ background

$$q + \bar{q} \rightarrow Z \rightarrow \nu + \bar{\nu}$$

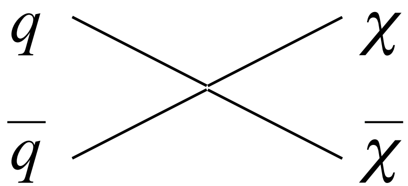


Renormalizible

$\sigma \propto s^{-1}$ (parton level)

Swamps WIMP signal

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



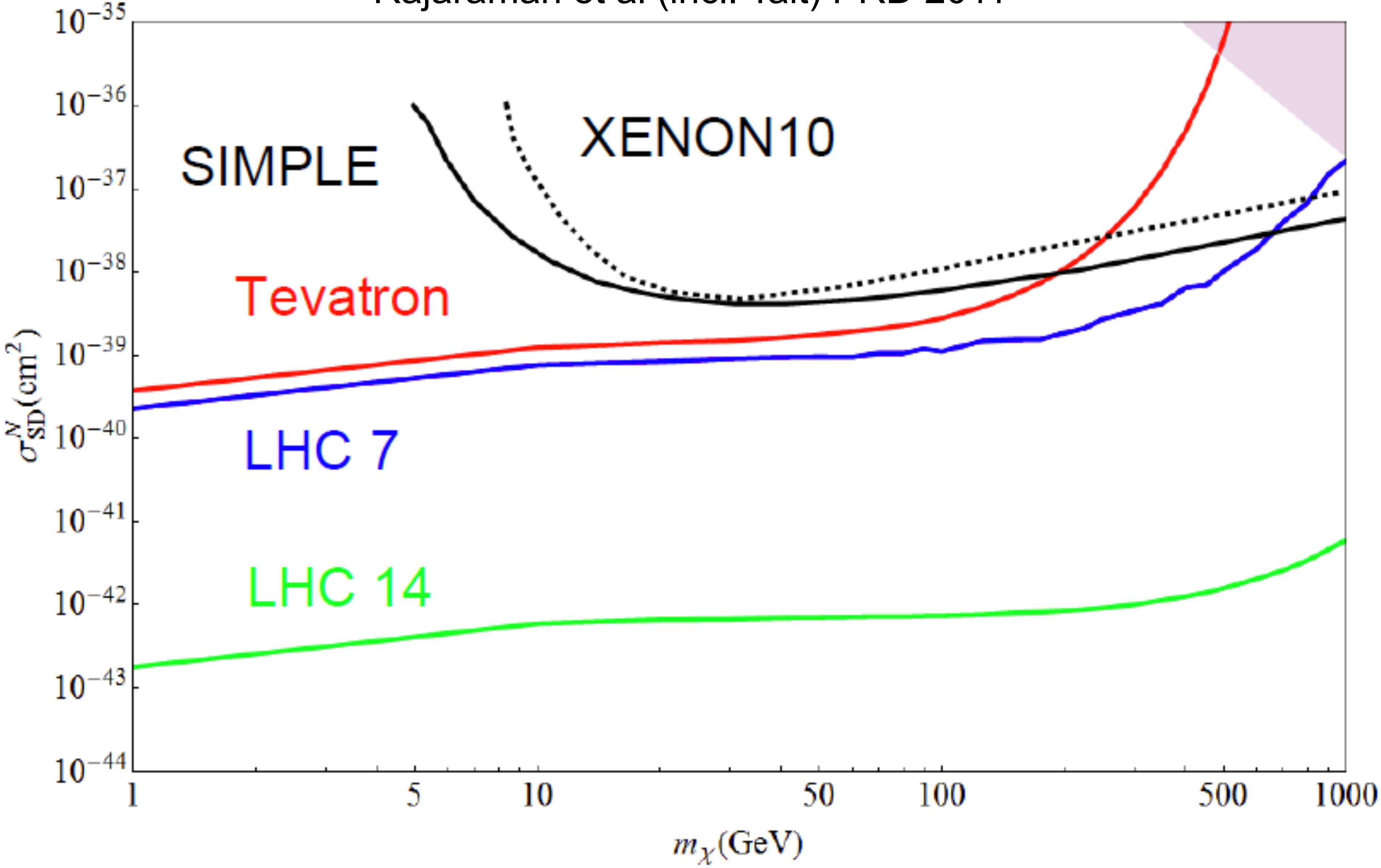
Nonrenormalizible

$\sigma \propto s$ (parton level)

Judicious cuts on MET can pull out signal

Predicted LHC Sensitivity

Rajaraman et al (incl. Tait) PRD 2011



Predicted LHC Sensitivity

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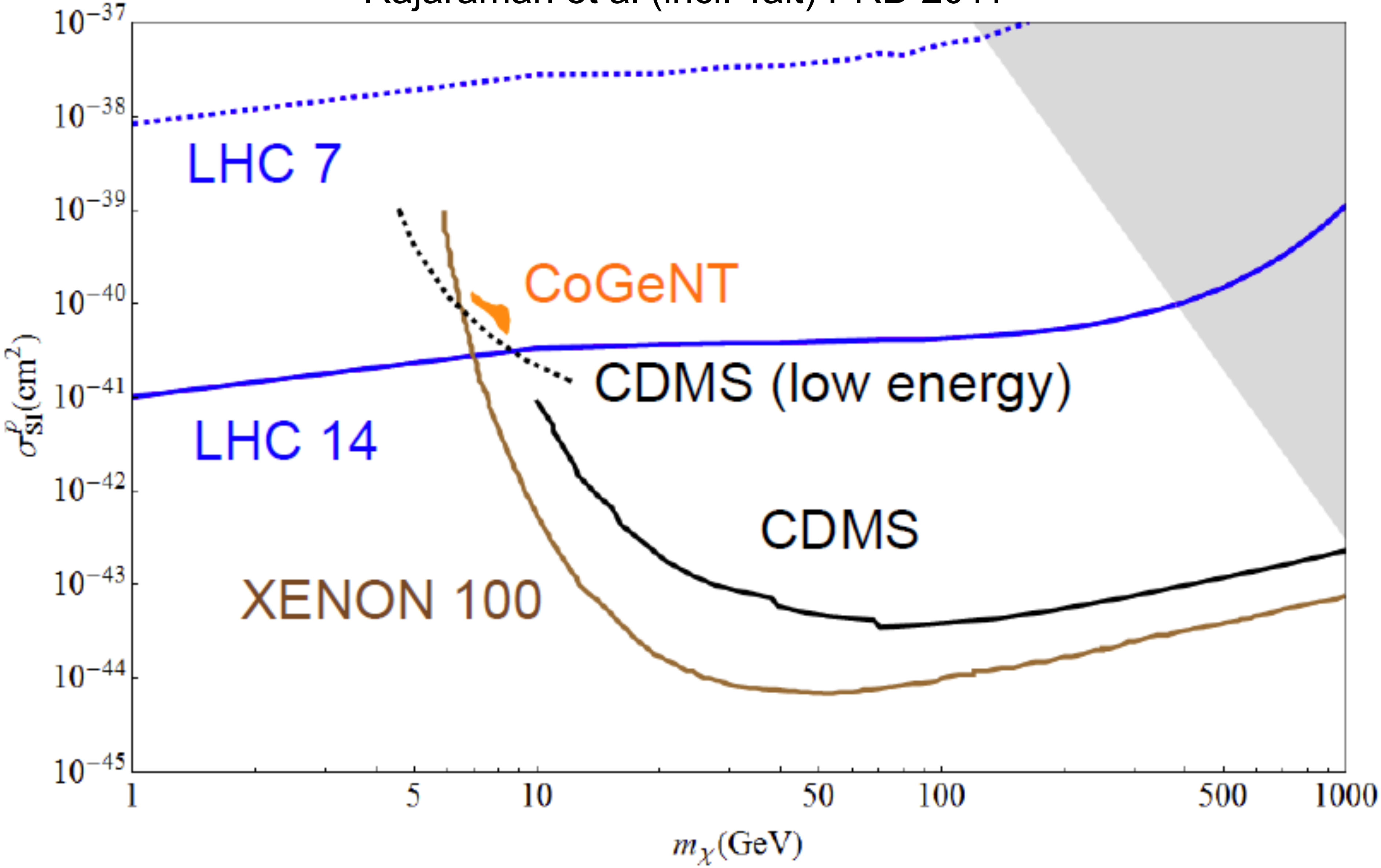
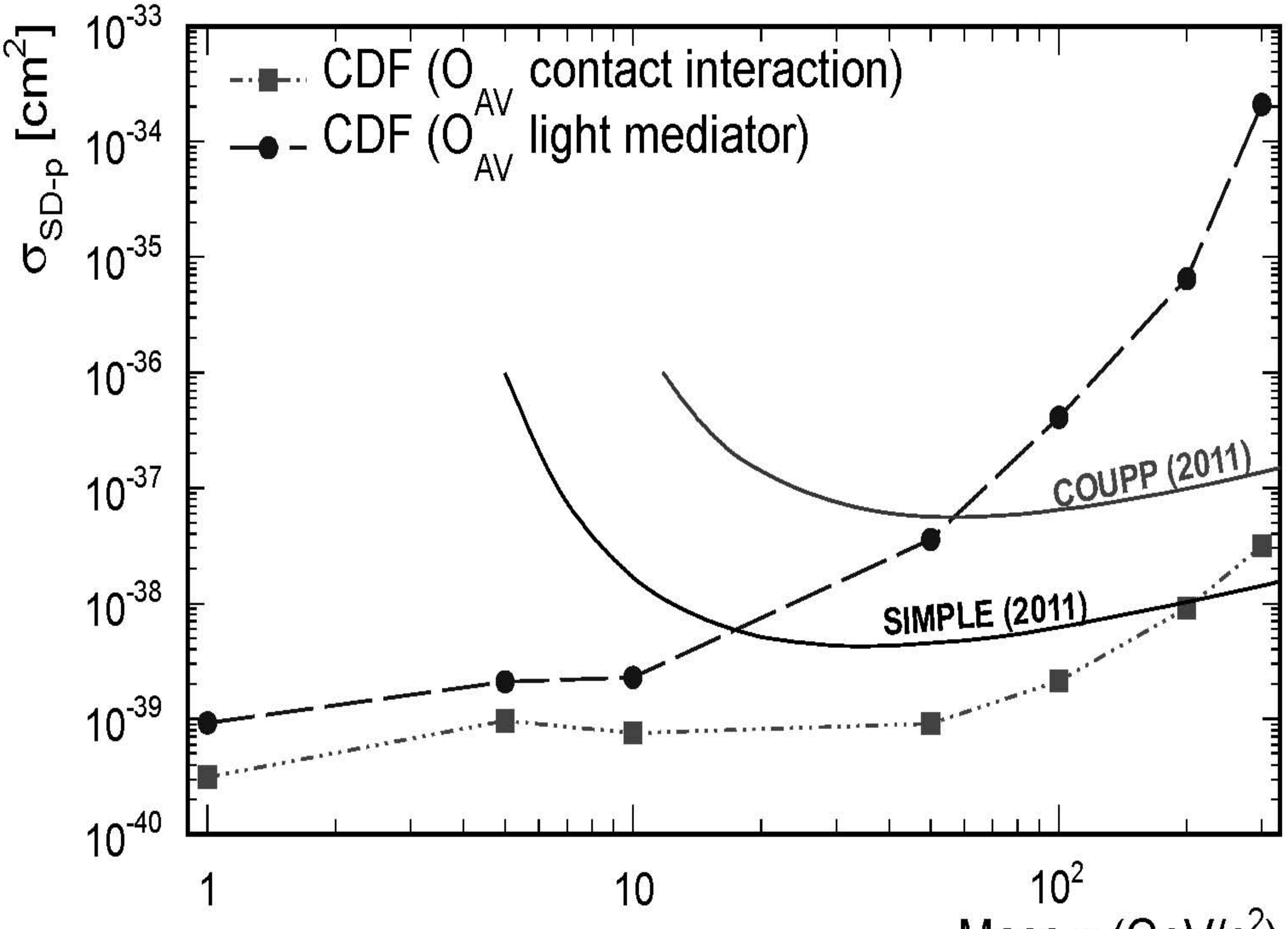
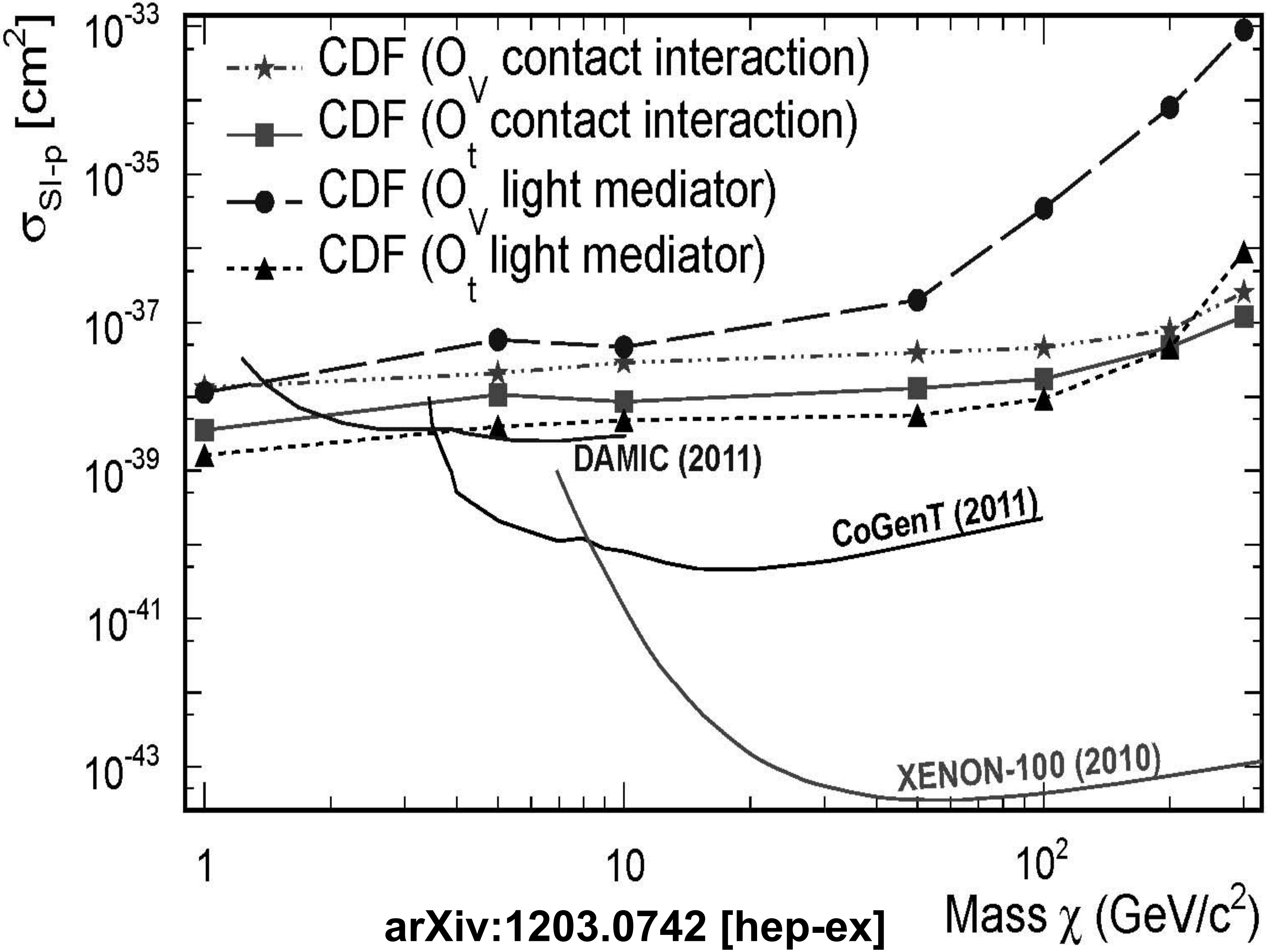


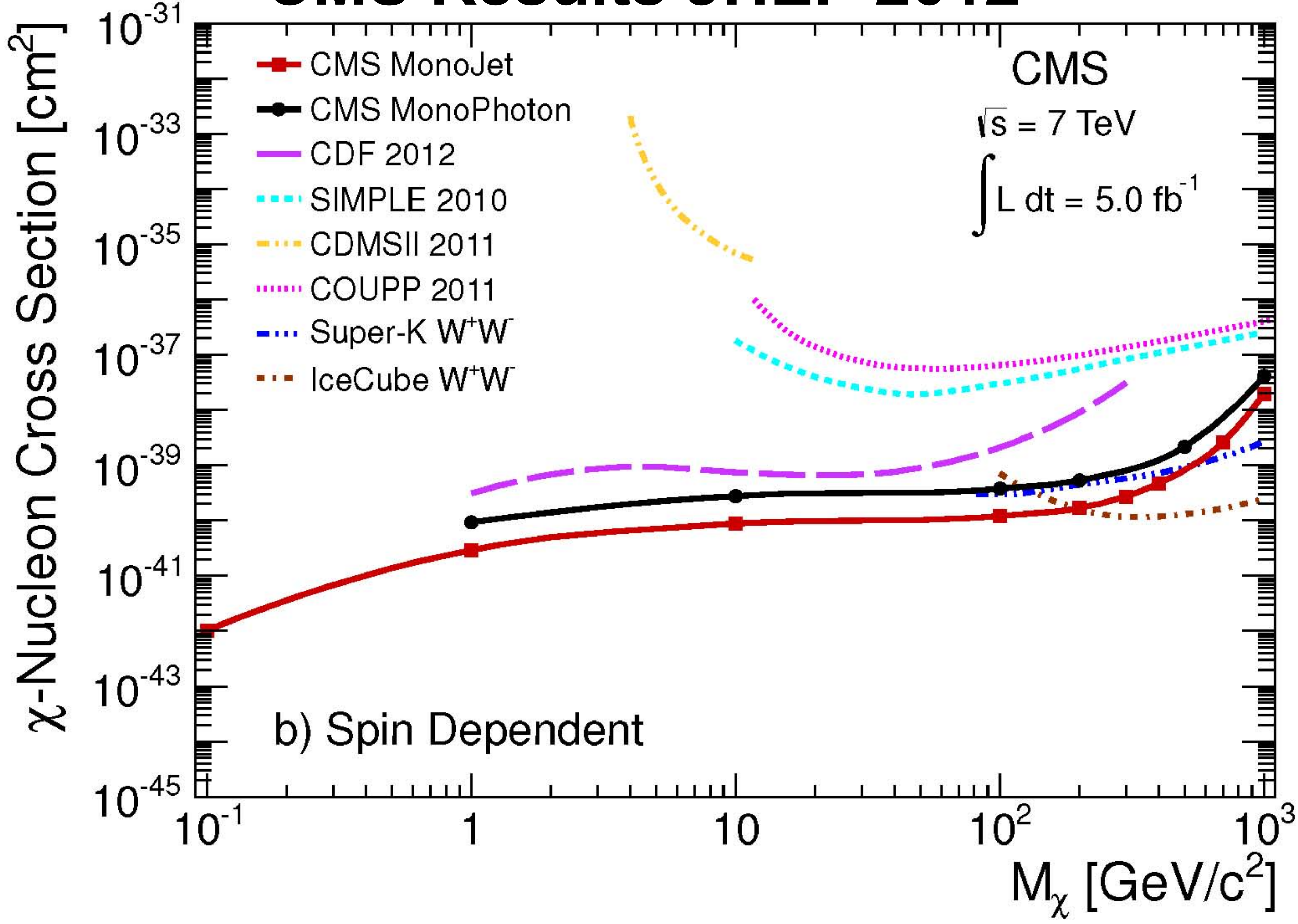


arXiv:1203.0742 [hep-ex]

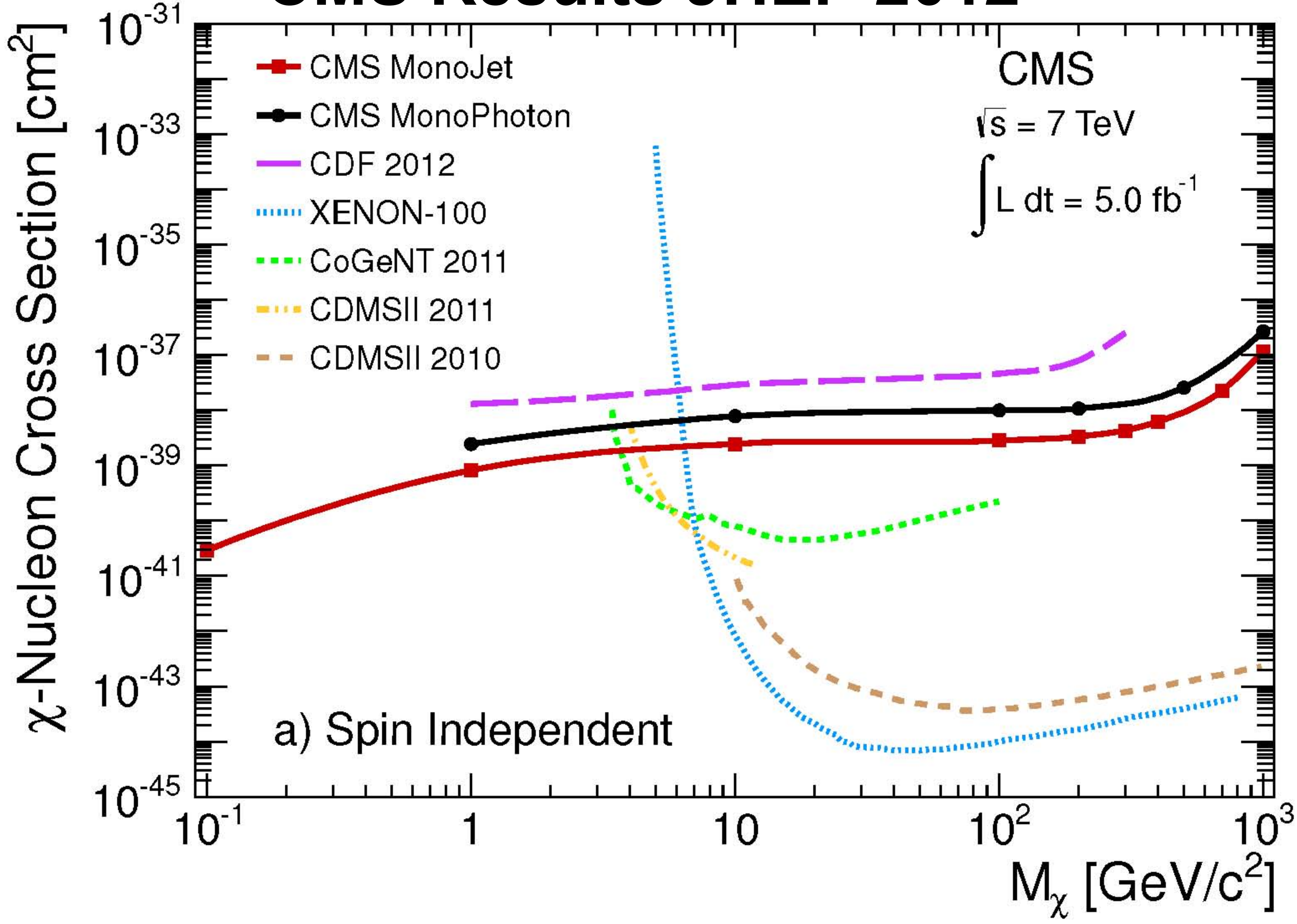


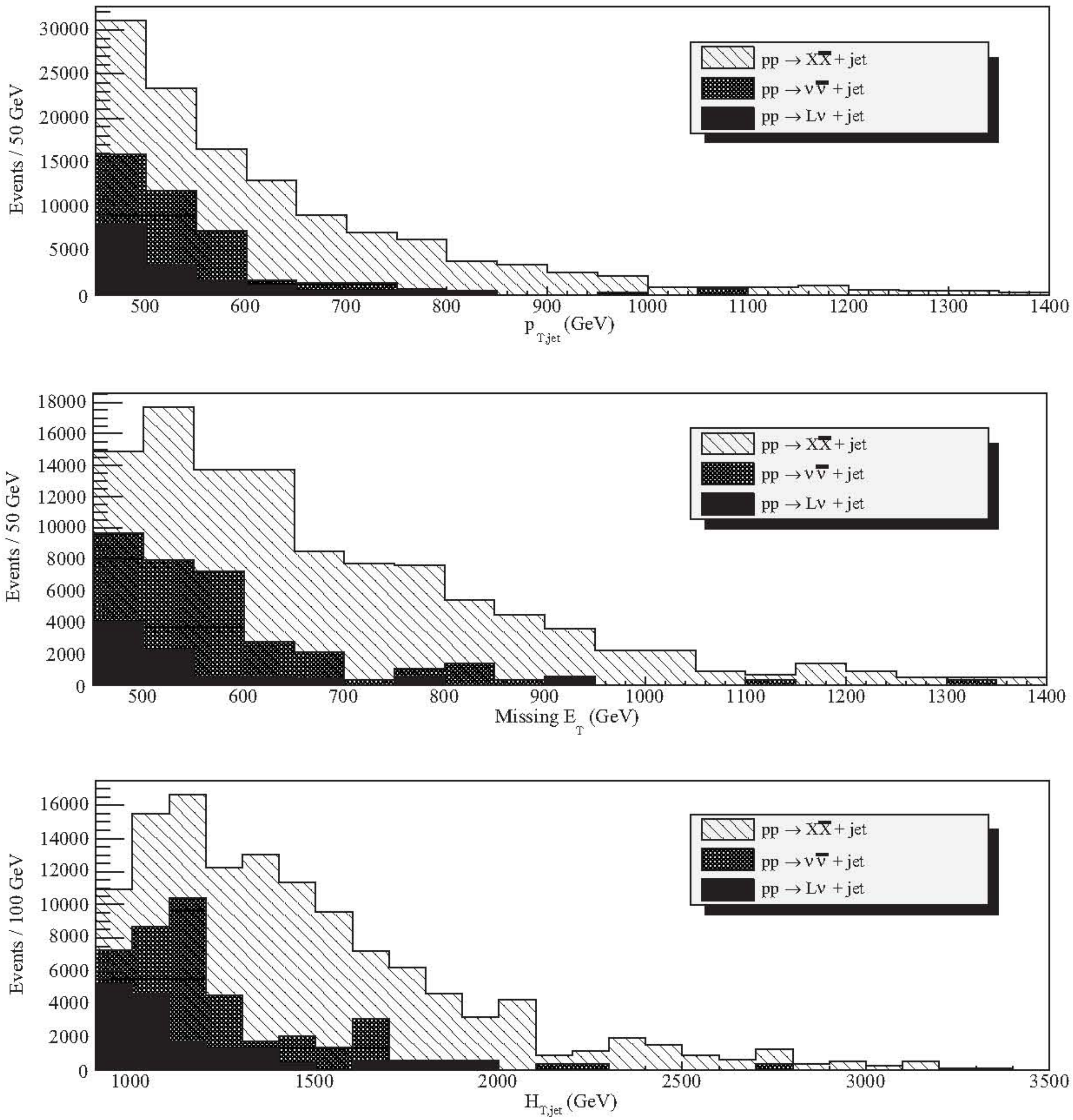
arXiv:1203.0742 [hep-ex]

CMS Results JHEP 2012



CMS Results JHEP 2012





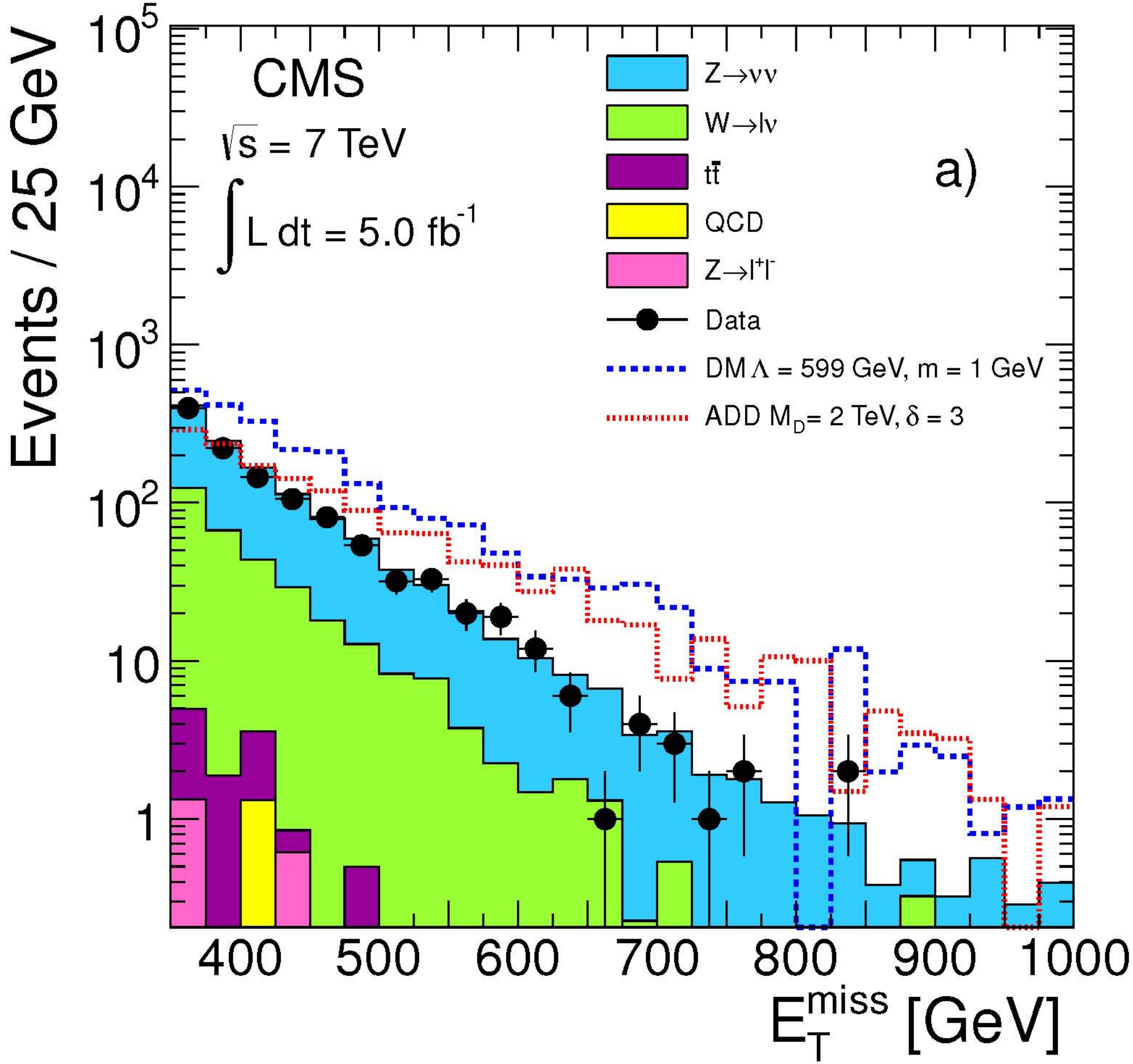
BHKKT

$M_\chi = 50$ GeV

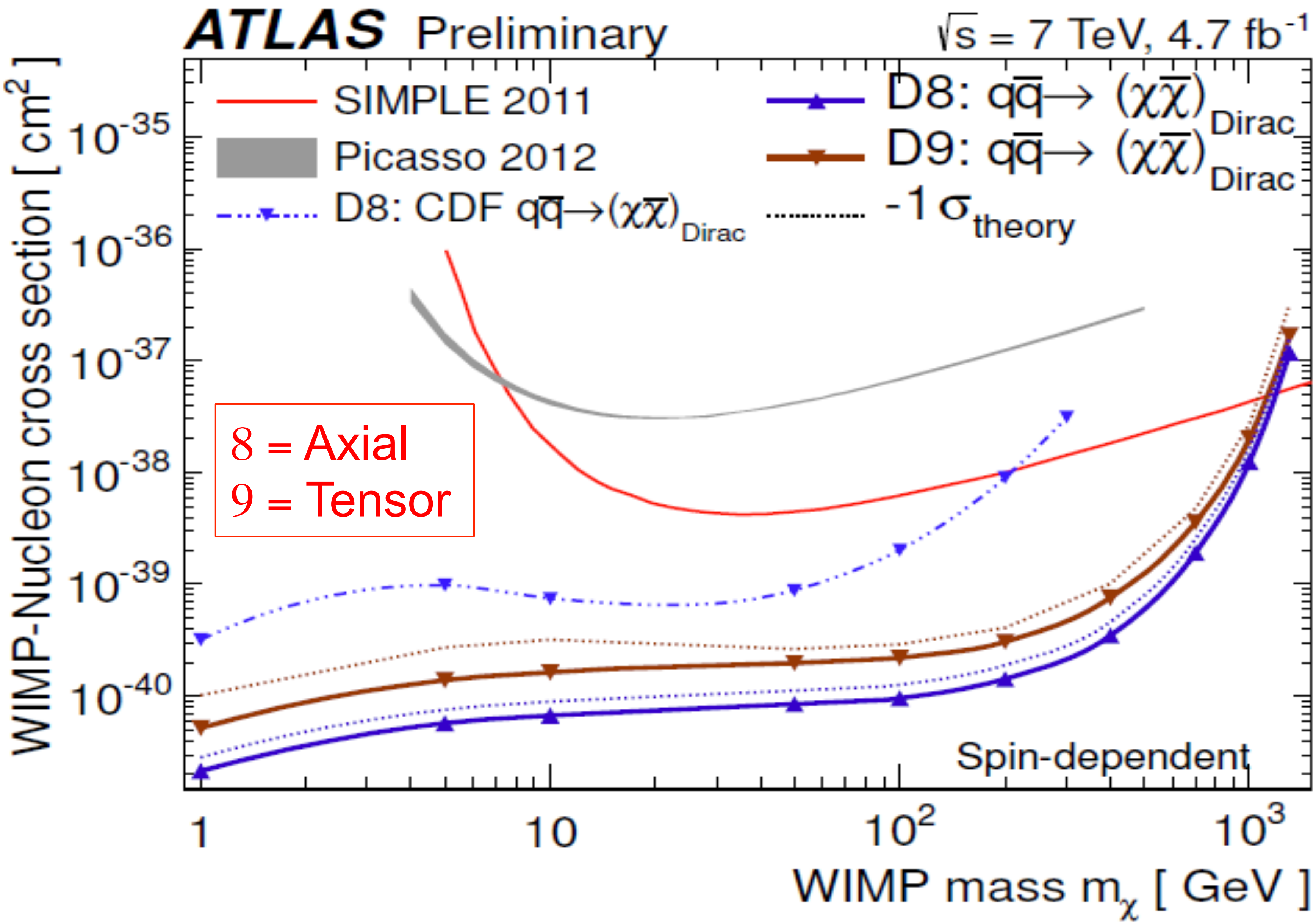
LHC 14 TeV

100 fb^{-1}

CMS Results JHEP 2012

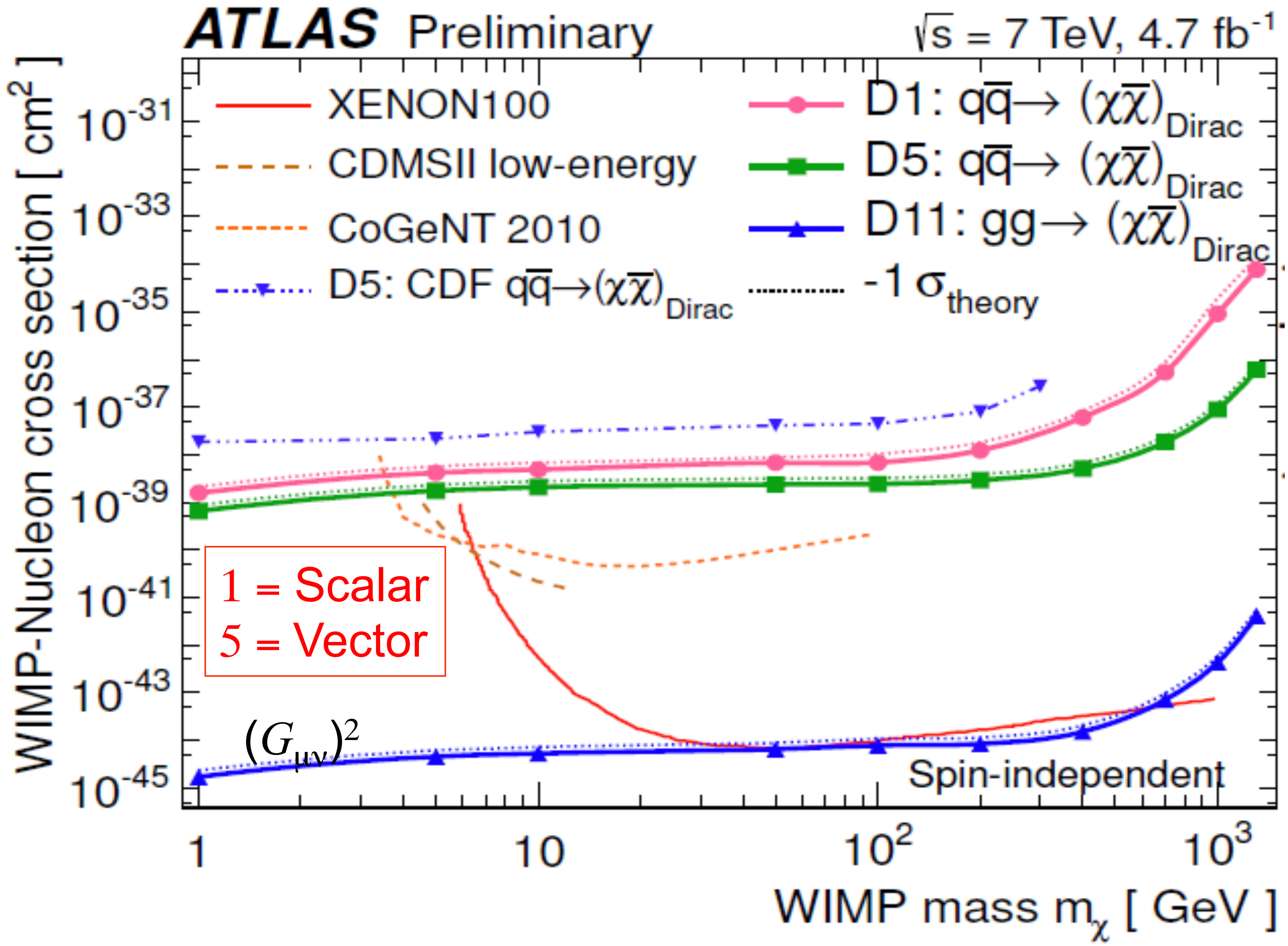


Atlas Results



http://indico.cern.ch/getFile.py/access?contribId=24&sessionId=10&resId=0&materialId=slides&confId=173388

Atlas Results



http://indico.cern.ch/getFile.py/access?contribId=24&sessionId=10&resId=0&materialId=slides&confId=173388

WIMP Questions

- Why 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
    - Dilution after freeze out via entropy production

- Maverick WIMPs?
    - Suppose LHC only sees SM Higgs?
    - Wither SNOOZY?

- Leptophilic, Leptophobic, Flavorful, Self-Interacting, Dynamical, Inelastic, …

- 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 WIMP *miracles* for WIMP sainthood ?
- **How will we know they are all seeing the same phenomenon?**
- When can we say we have made darkness visible?

Will Darkness Be Visible

Paradise Lost John Milton (1667)

No light, but rather darkness visible
Served only to discover sights of woe...

John Baptist de Medina (1688)

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

(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*

The Decade of the WIMP

- WIMP coincidence or causation (it ain't a miracle)?
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  convincing evidence or near-death experience

Direct detectors, indirect detectors, & colliders race for discovery

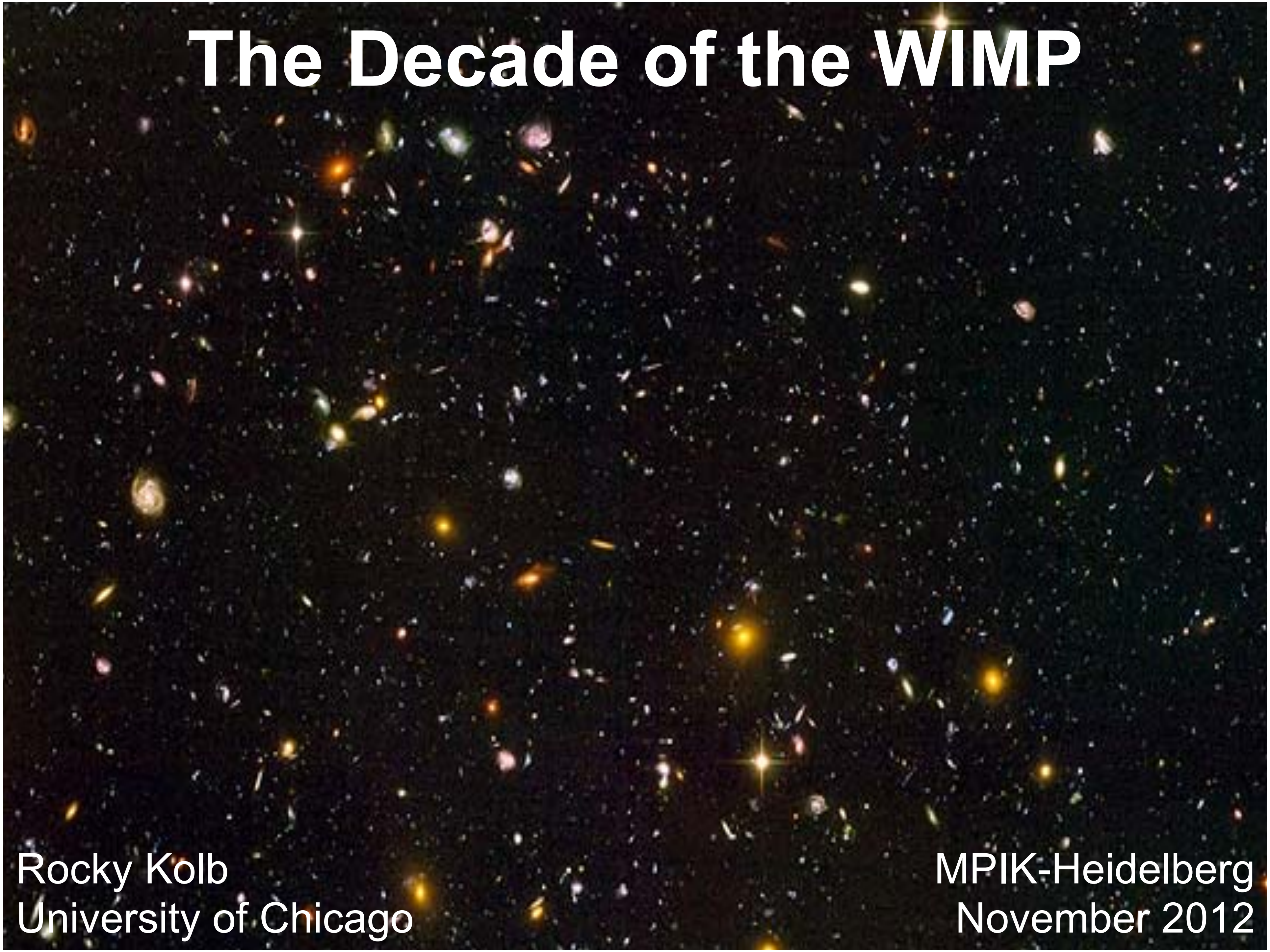
Suppose by 2020 have credible signals from all three ???

Do we need three WIMP *miracles* for WIMP sainthood ?

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

- When do we stop?

The Decade of the WIMP



Rocky Kolb
University of Chicago

MPIK-Heidelberg
November 2012