Challenges and uncertainties in dark matter theory

Paolo Gondolo
University of Utah

Challenges

(1) Prepare this talk.

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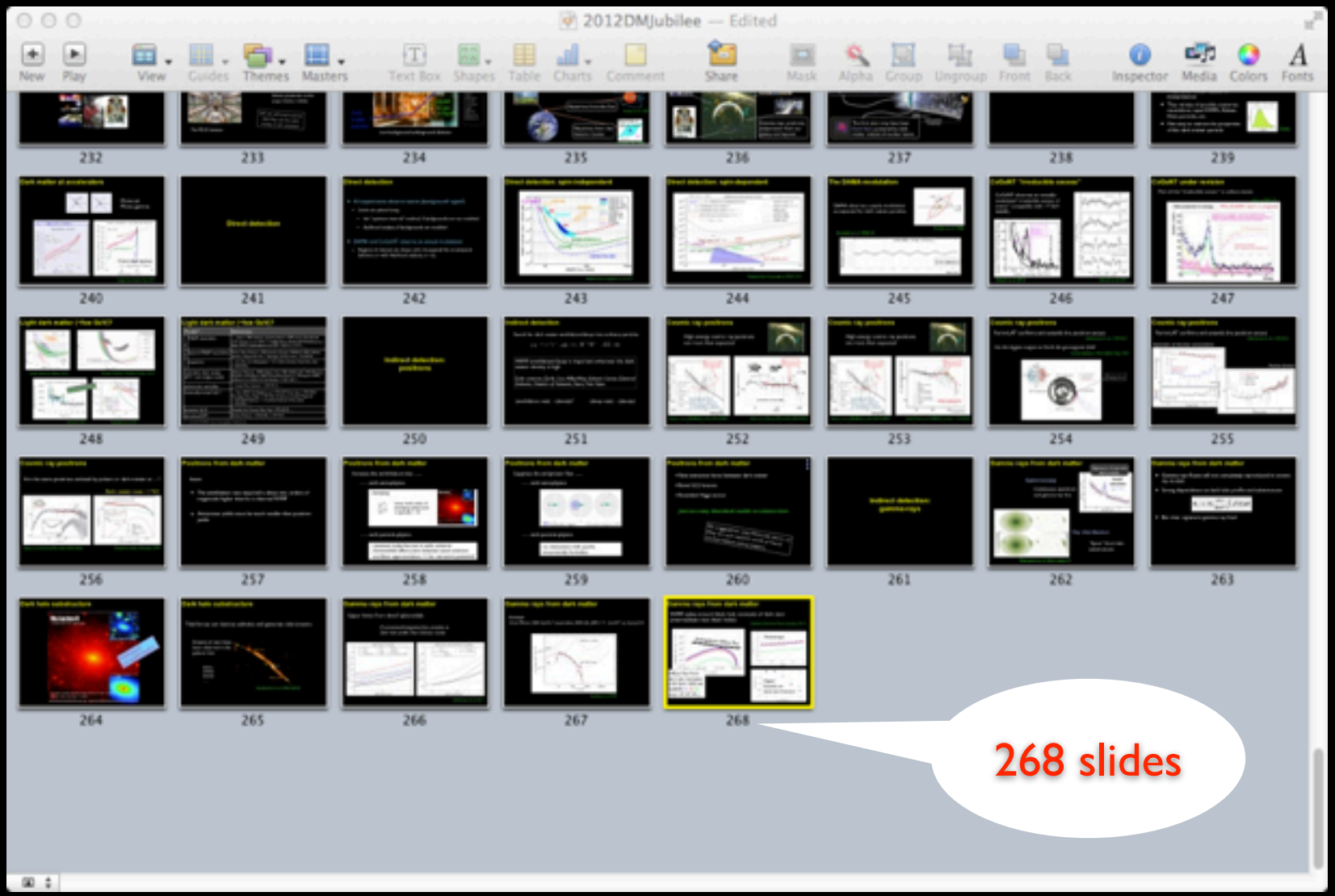


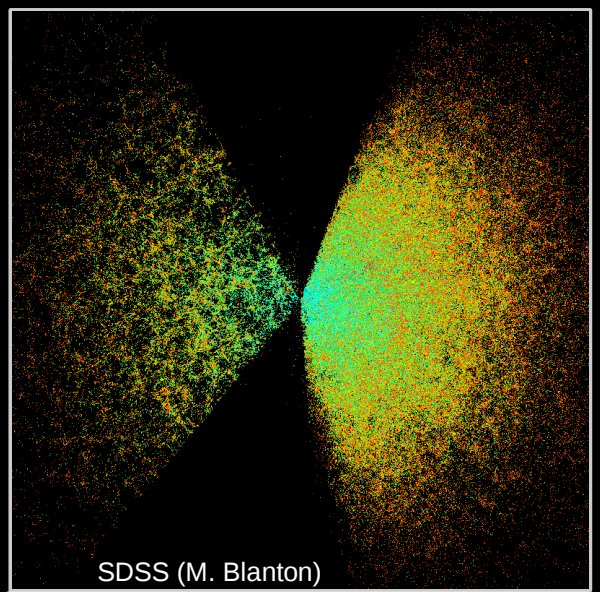
Challenges

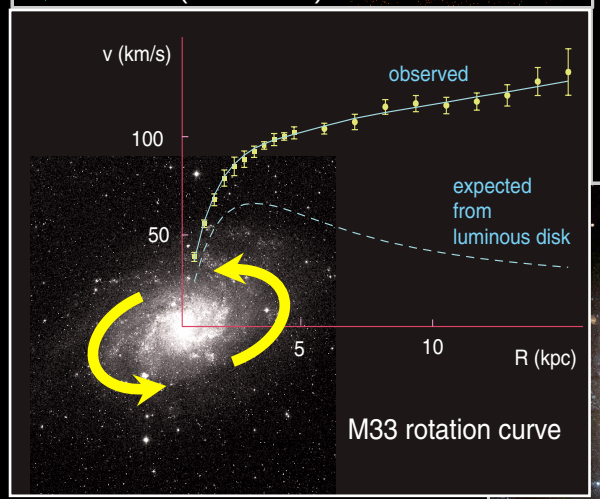
(1) Prepare this talk.

(2) Does cold dark matter exist?

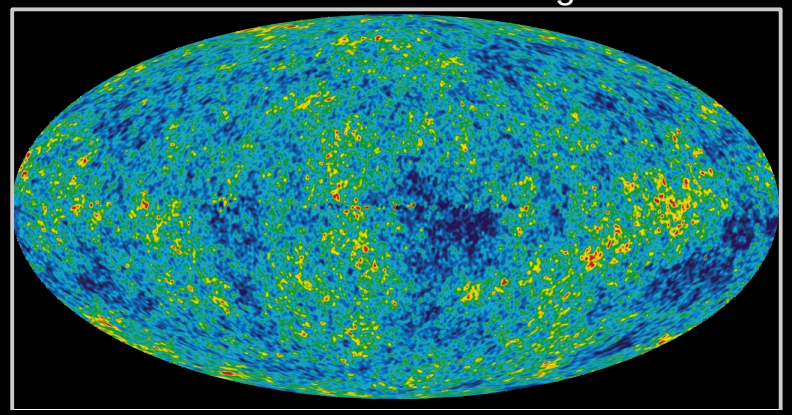
Evidence for cold dark matter

Large Scale Structure



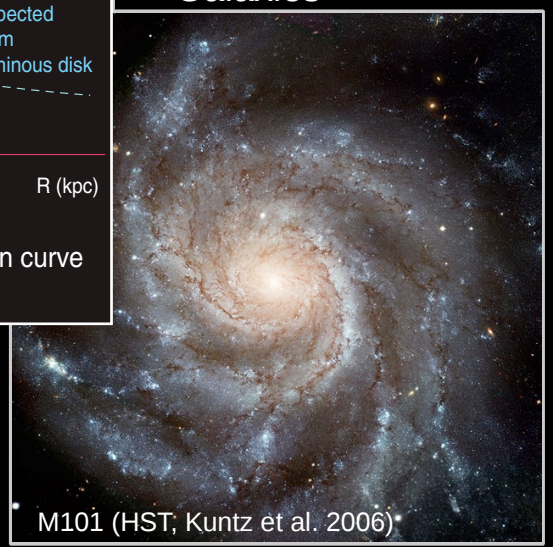


Cosmic Microwave Background

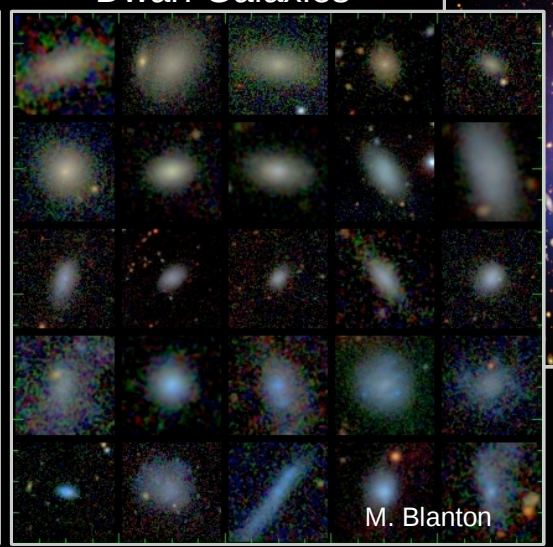


Supernovae

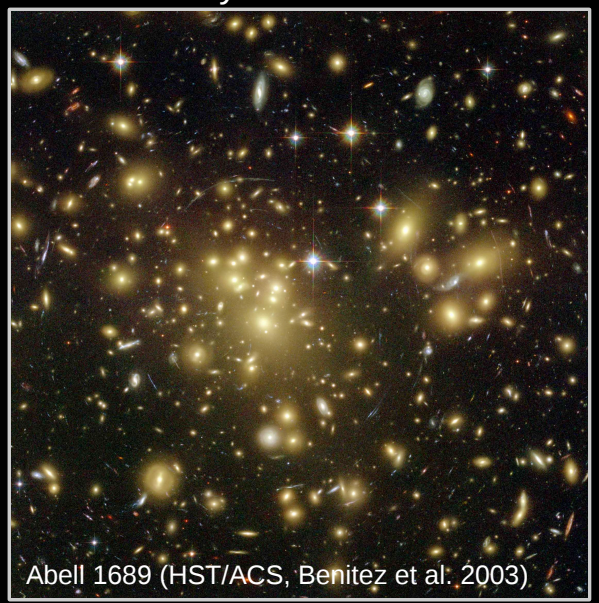
Galaxies

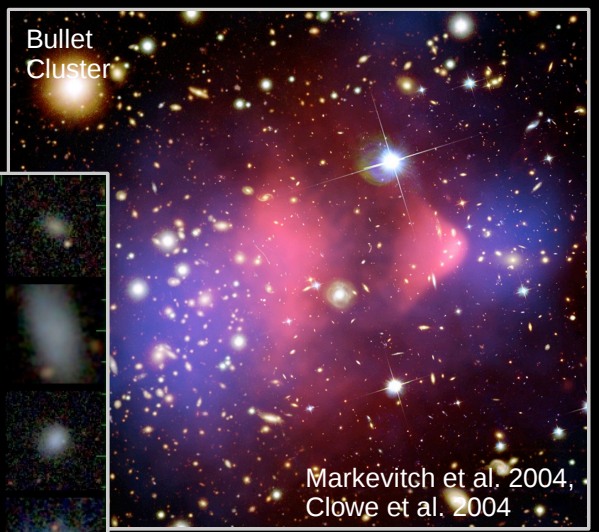


Dwarf Galaxies



Galaxy Clusters





The warning

"For any complex physical phenomenon there is a simple, elegant, compelling, wrong explanation."

Thomas Gold, 1920-2004, Austrian-born astronomer at Cambridge University and Cornell University

Modified gravity

Is it excluded?

- MOND ($F=ma^2/a_0$ for $a<$universal a_0) is only non-relativistic and so cannot be tested on cosmological scales
- TeVeS, MOND's generalization, contains new fields that could be interpreted as cold dark matter interacting only gravitationally. It does not reproduce the pattern of CMB peaks.
- There are other ideas, like conformal gravity, but are less studied

Cold dark matter, not modified gravity

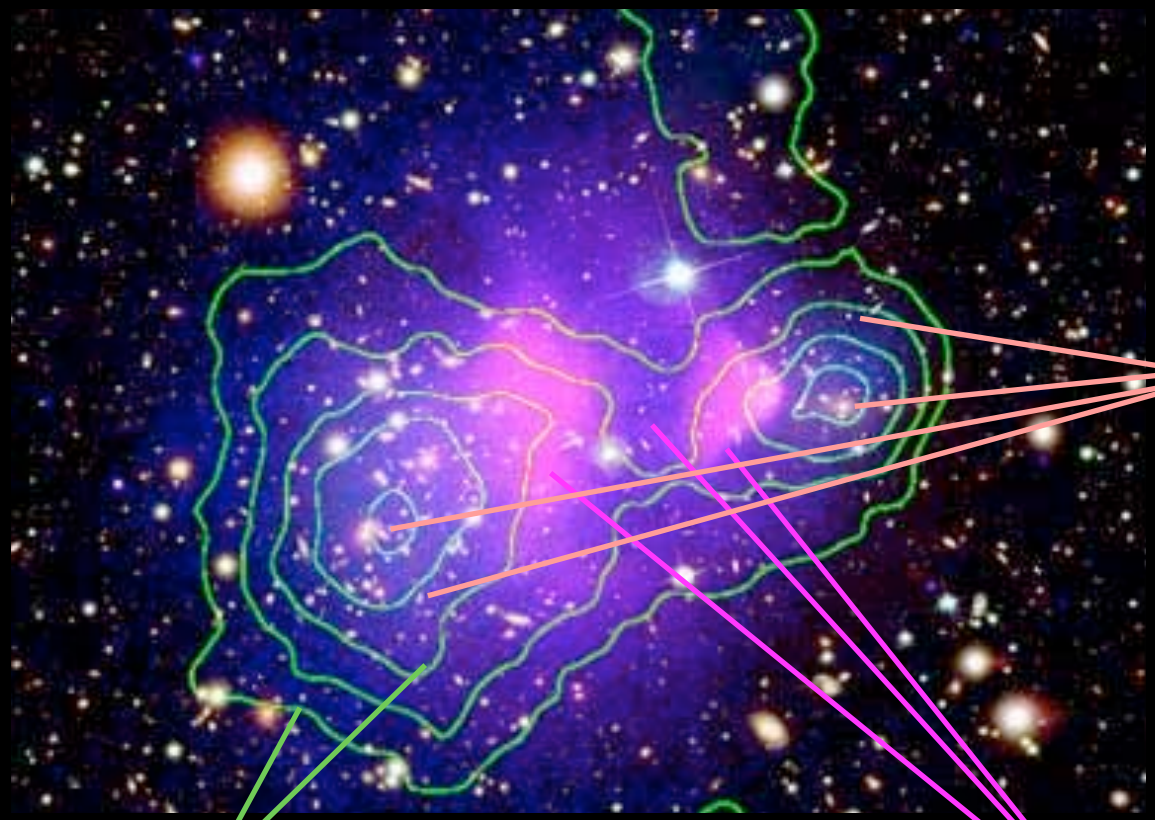
The Bullet Cluster

Symmetry argument: baryons are at center, but potential has two wells.

Cold dark matter, not modified gravity

The Bullet Cluster

Symmetry argument: baryons are at center, but potential has two wells.



Galaxies in optical (Hubble Space Telescope)

X-ray emitting hot gas (Chandra)

Gravitational potential from weak lensing

Cold dark matter, not modified gravity

The Bullet Cluster

Symmetry argument: baryons are at center, but potential has two wells.

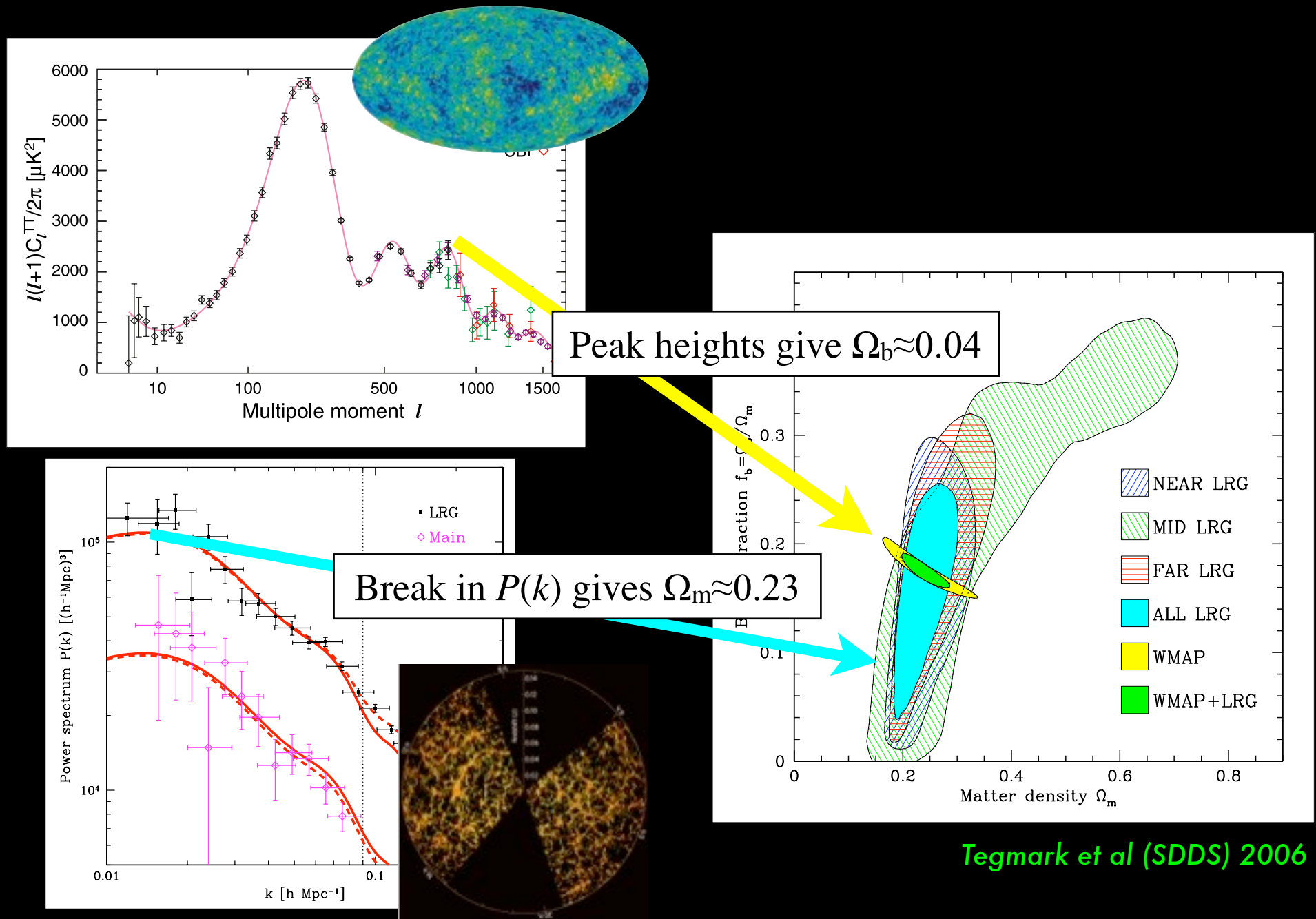
Challenges

(1) Prepare this talk.

(2) Does cold dark matter exist?

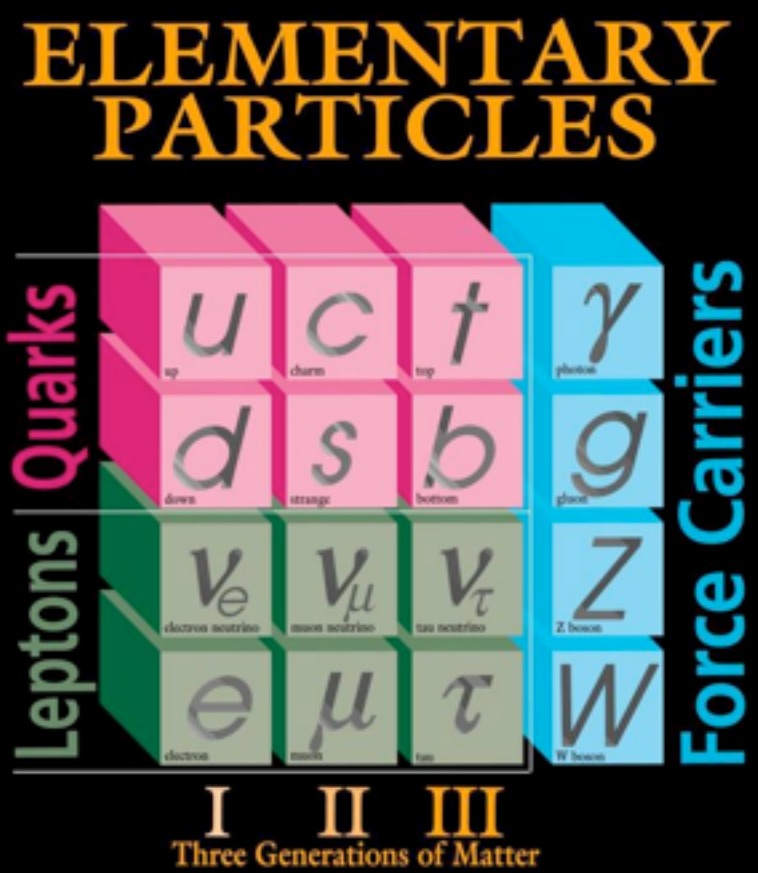
(3) What is the nature of cold dark matter?

Evidence for *non-baryonic* dark matter



Tegmark et al (SDDS) 2006

No known particle can be cold dark matter



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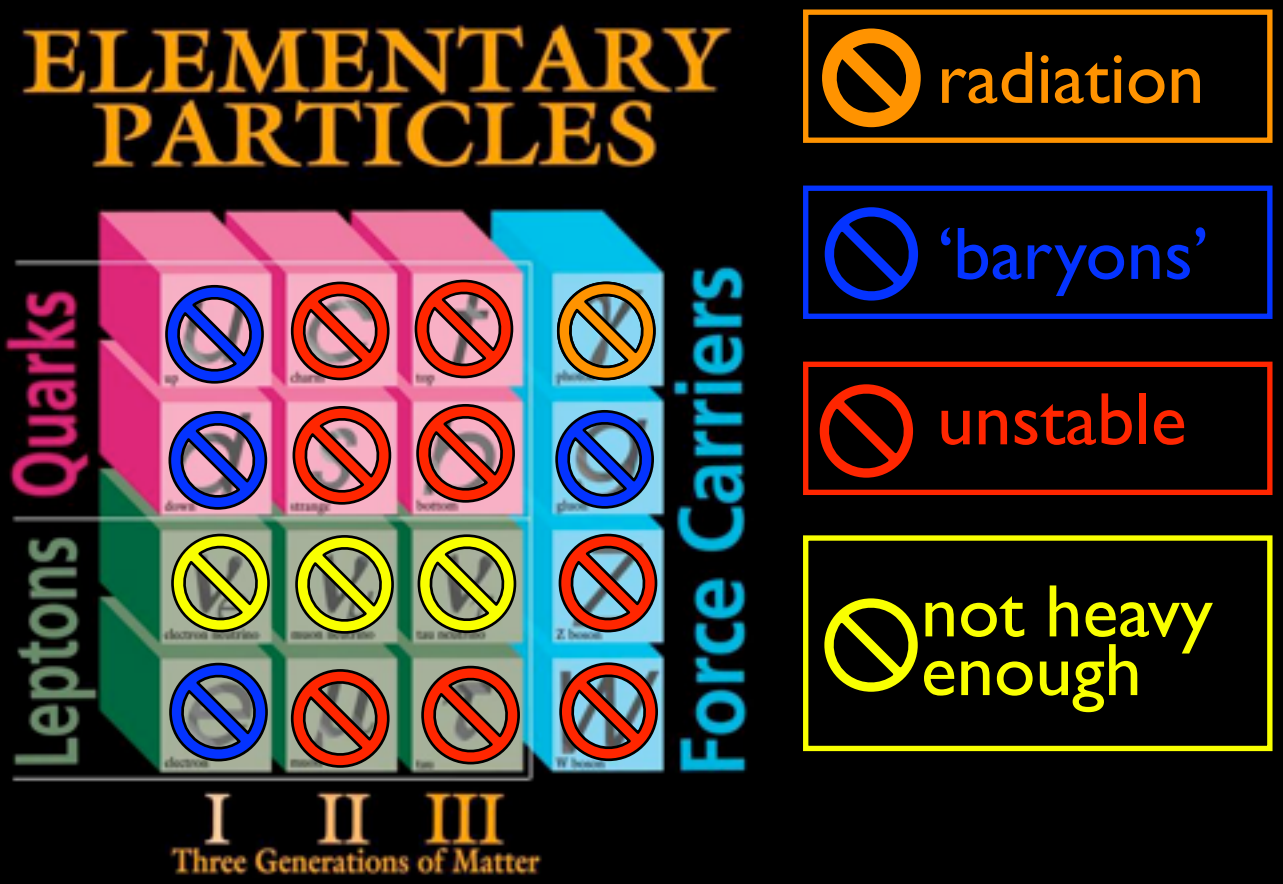


Is cold dark matter a new elementary particle?

Is cold dark matter a new elementary particle?

IS HINCHLIFFE'S RULE TRUE? *

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

Is cold dark matter a new elementary particle?

The simplest and most elegant idea

The Magnificent WIMP
(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs
- One can experimentally test the WIMP hypothesis

  The same physical processes that produce the right density of WIMPs make their detection possible

The original WIMP

PHYSICAL REVIEW LETTERS

VOLUME 39 | 25 JULY 1977 | NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] *Batavia, Illinois 60510*

and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

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.

2 GeV/c^2 for Ω_c=1

Now 4 GeV/c^2 for Ω_c=0.25

The original WIMP

- Lee and Weinberg's heavy neutrinos were Dirac neutrinos

$$\mathrm{WIMP} \neq \mathrm{antiWIMP}$$

In this case, an asymmetry is possible in their density

$$n_{\mathrm{WIMP}} \neq n_{\mathrm{antiWIMP}}$$ (asymmetric dark matter)

Lee and Weinberg set it to zero

- Many other dark matter candidates (Majorana neutrinos, neutralinos, gauge singlet scalars) are self-conjugate

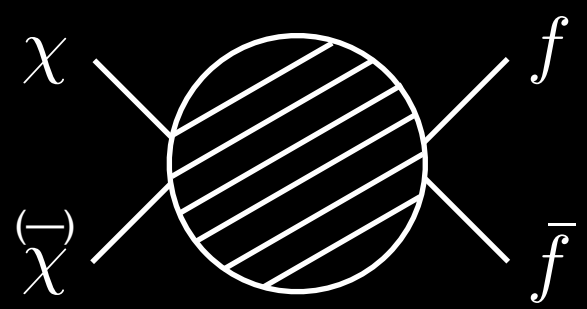
$$\mathrm{WIMP} = \mathrm{antiWIMP}$$

In this case, no asymmetry is possible

Cosmic density of thermal WIMPs

- At early times, WIMPs are produced in e^+e^-, $\mu^+\mu^-$, etc collisions in the hot primordial soup [*thermal production*].

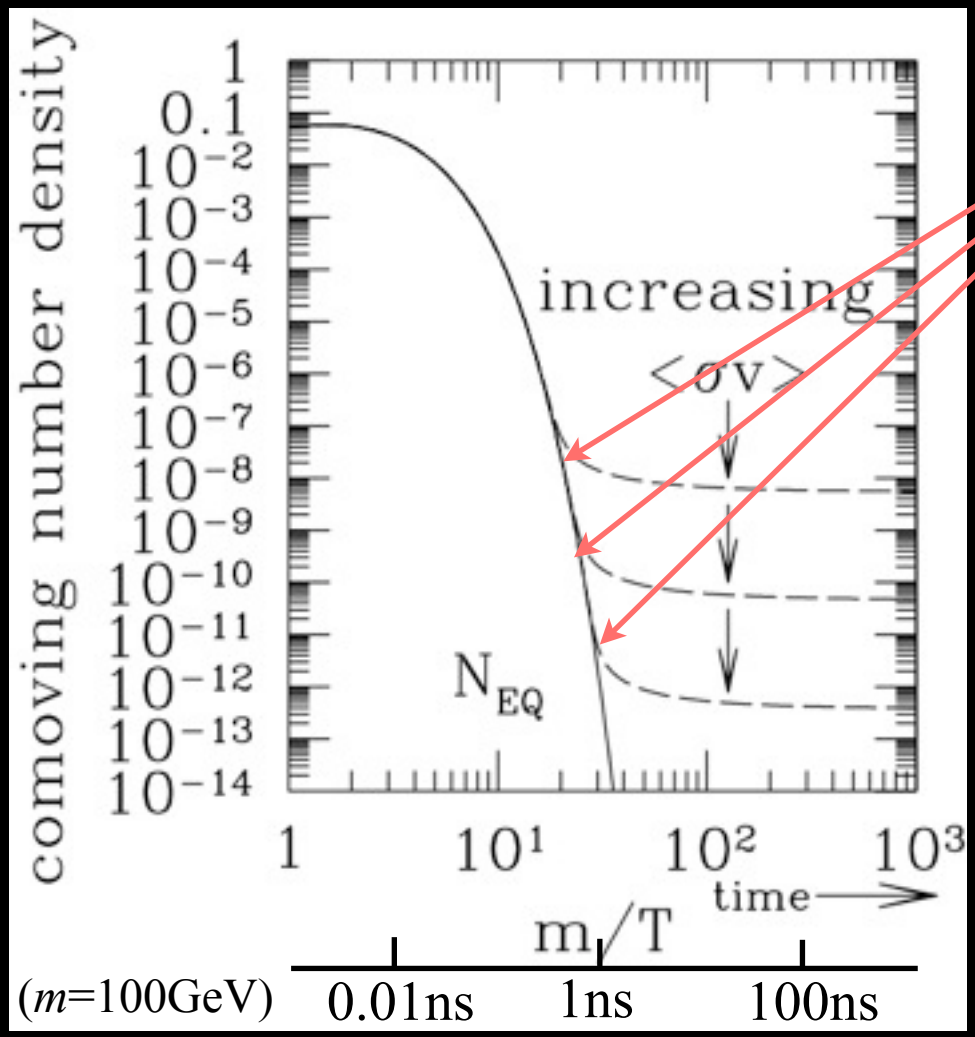
$$e^+ + e^-, \mu^+ + \mu^-, \text{etc.} \leftrightarrow \chi + \overset{(-)}{\chi}$$



- WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate [*freeze-out*].

- After freeze-out, the number of WIMPs per photon is constant.

Cosmic density of thermal WIMPs



freeze-out

$$\Gamma_{\rm ann} \equiv n\langle\sigma v\rangle \sim H$$

annihilation rate *expansion rate*

$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}{\rm cm}^3/{\rm s}}{\langle\sigma v\rangle_{\rm ann}}$$

$$\Omega_\chi h^2 = \Omega_{\rm cdm} h^2 \simeq 0.1143$$

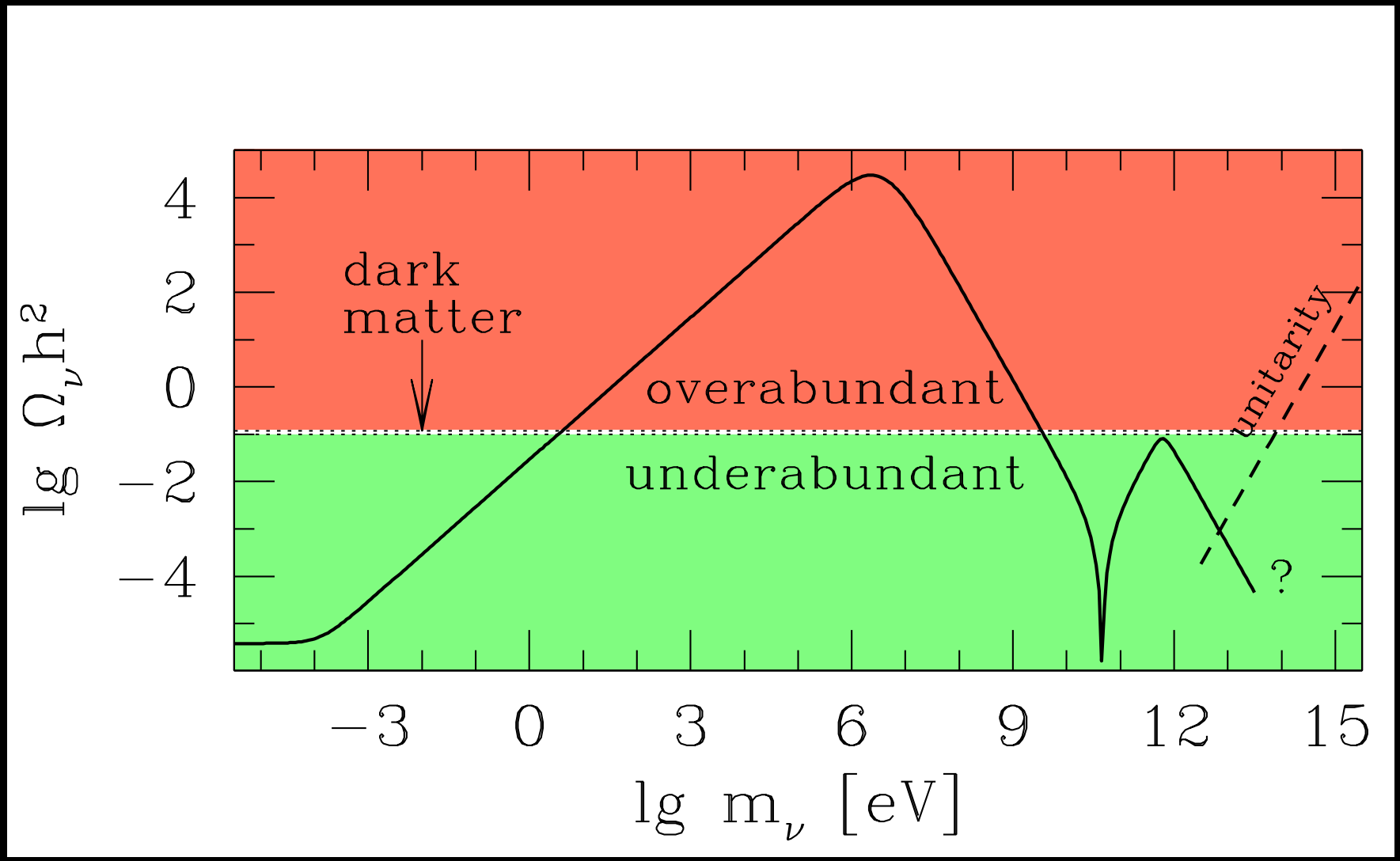
for $\langle\sigma v\rangle_{\rm ann} \simeq 3\times 10^{-26}{\rm cm}^3/{\rm s}$

This is why they are called Weakly Interacting Massive Particles

(WIMPless candidates are WIMPs!)

Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrino



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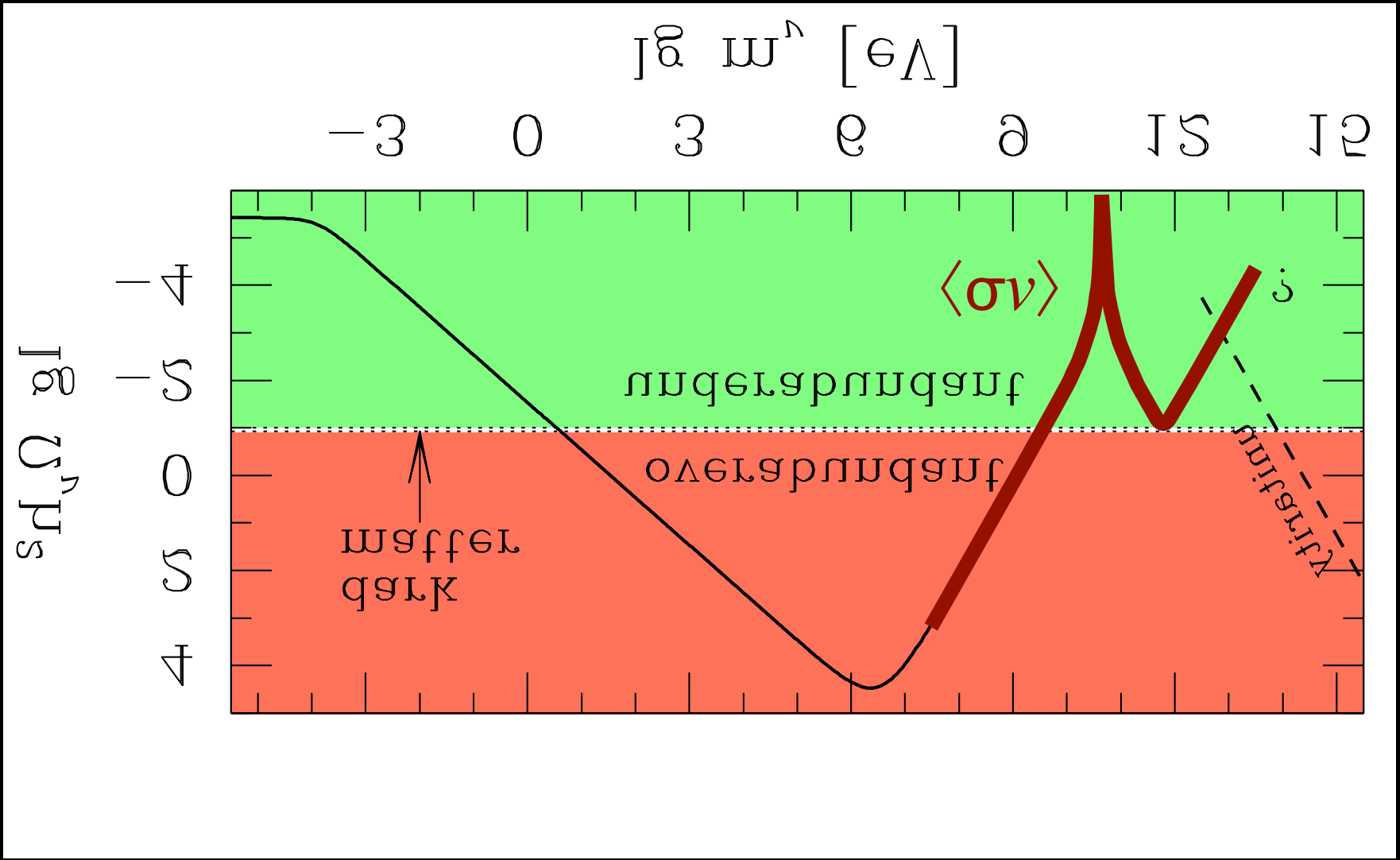

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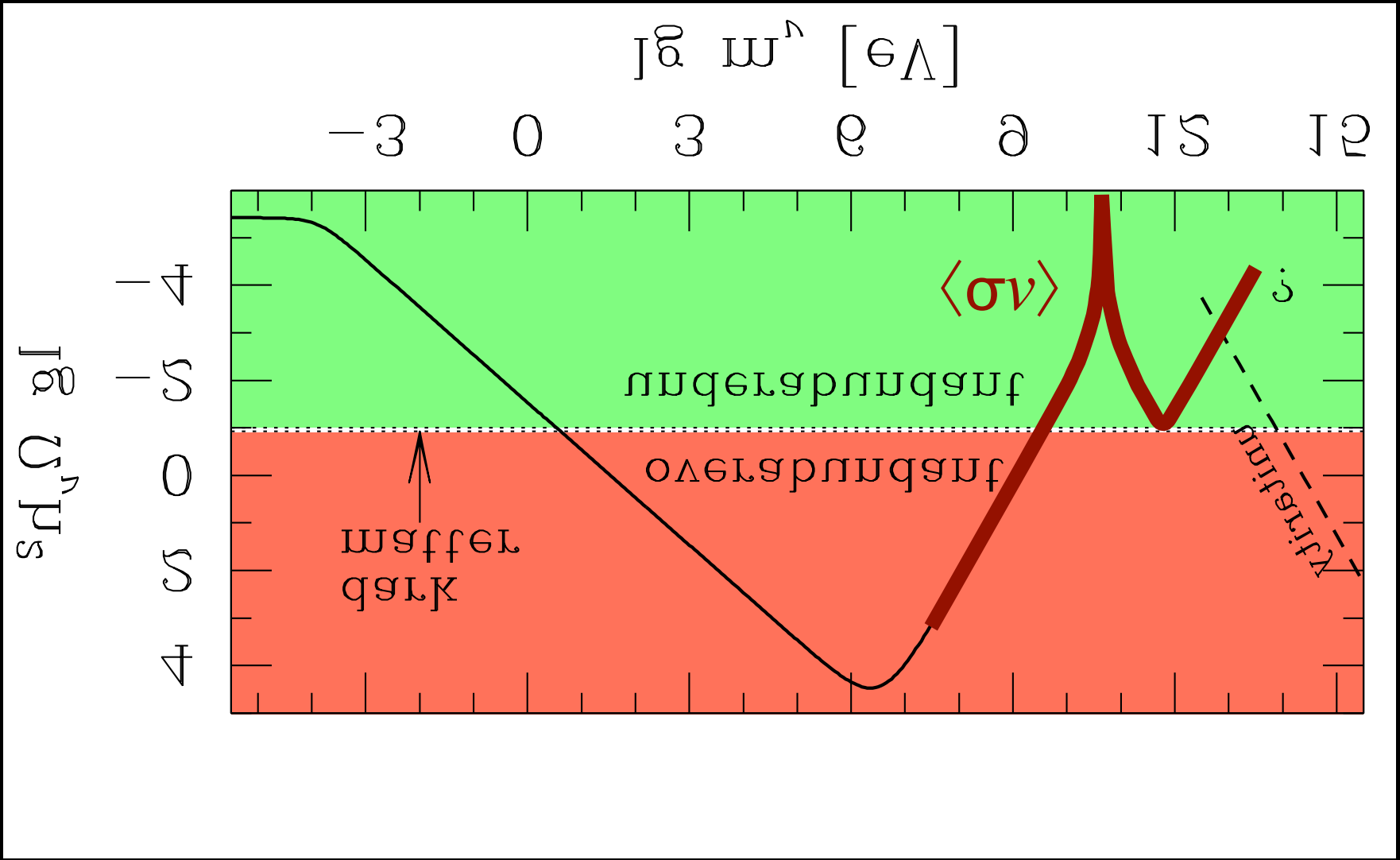

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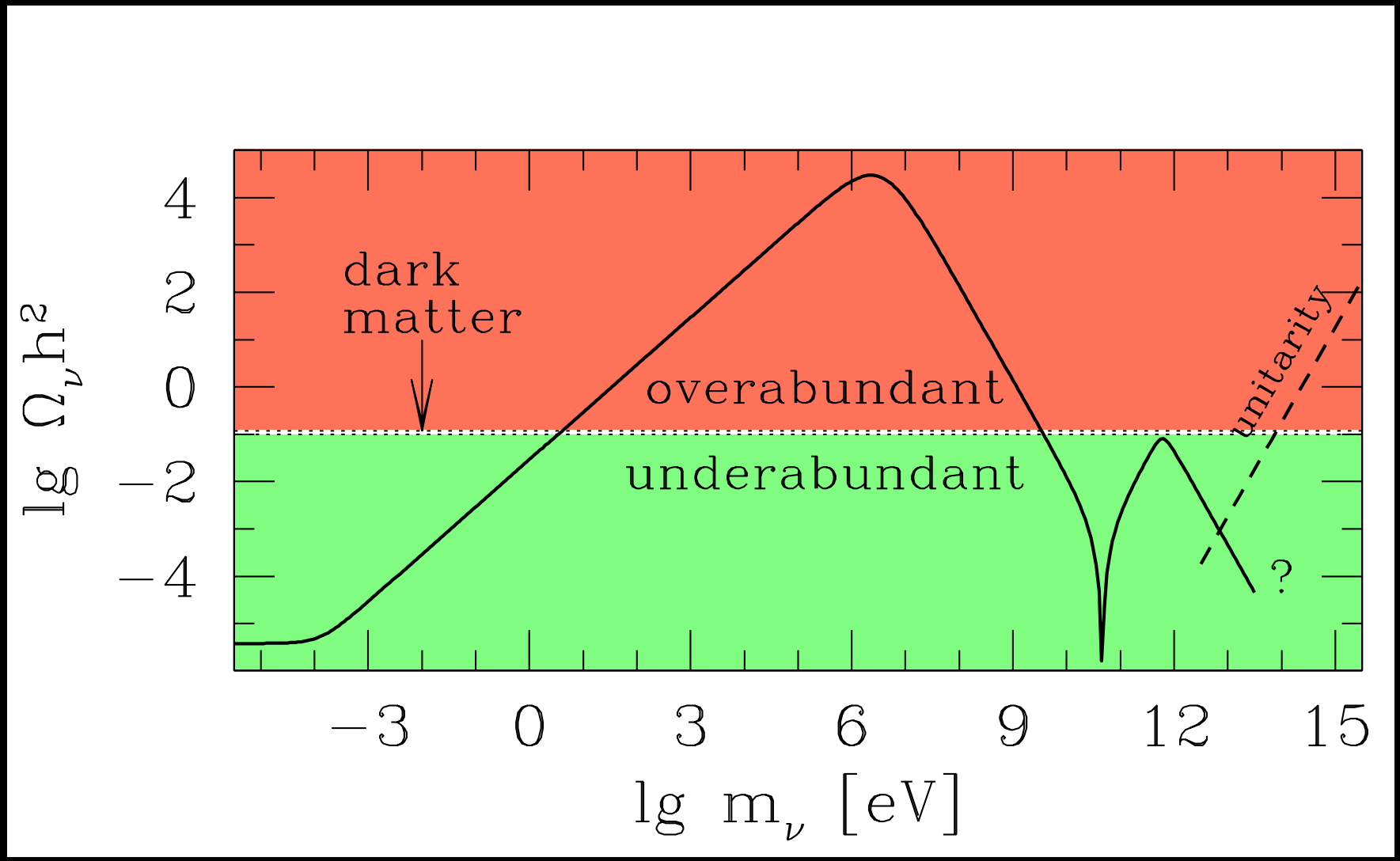

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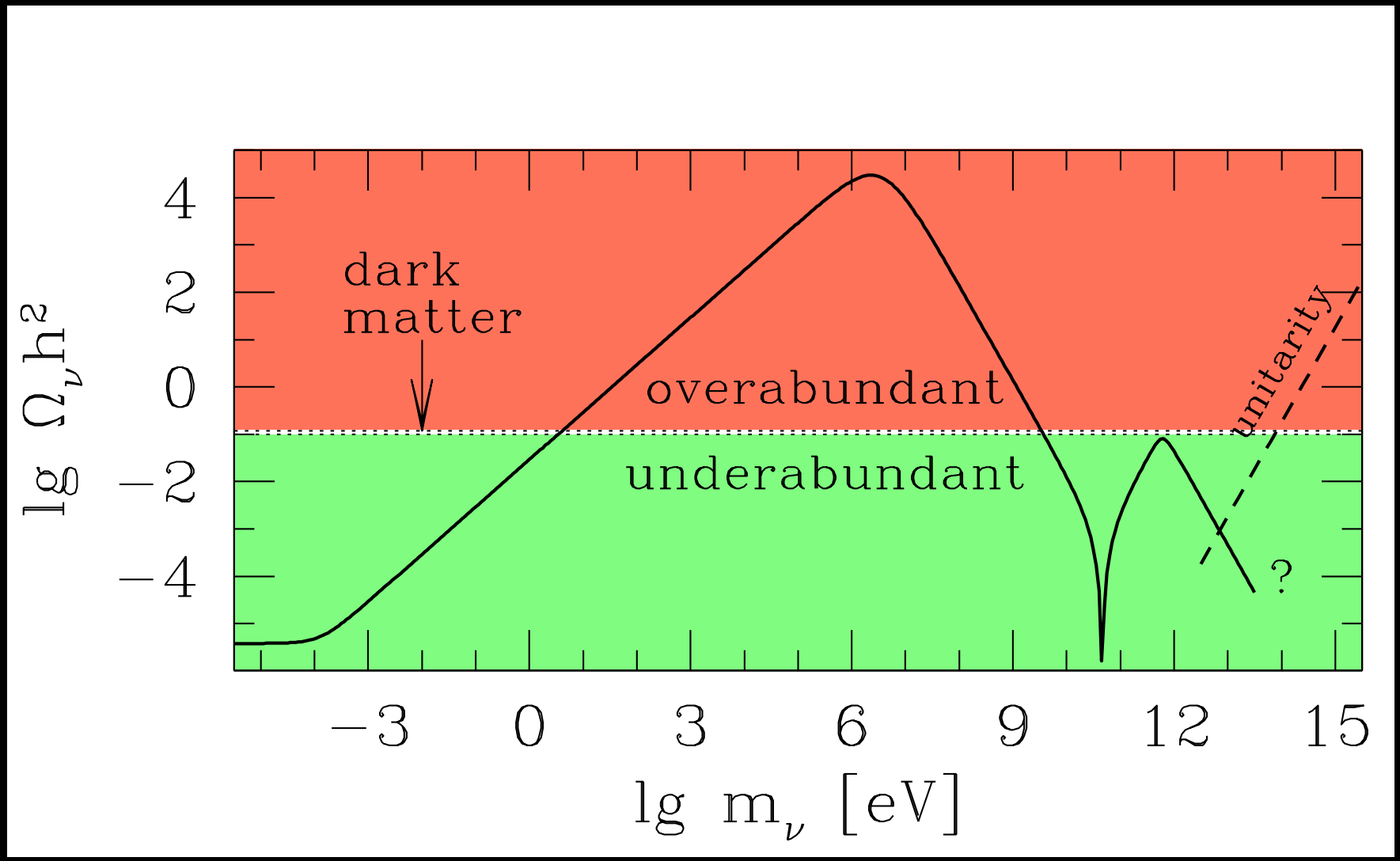
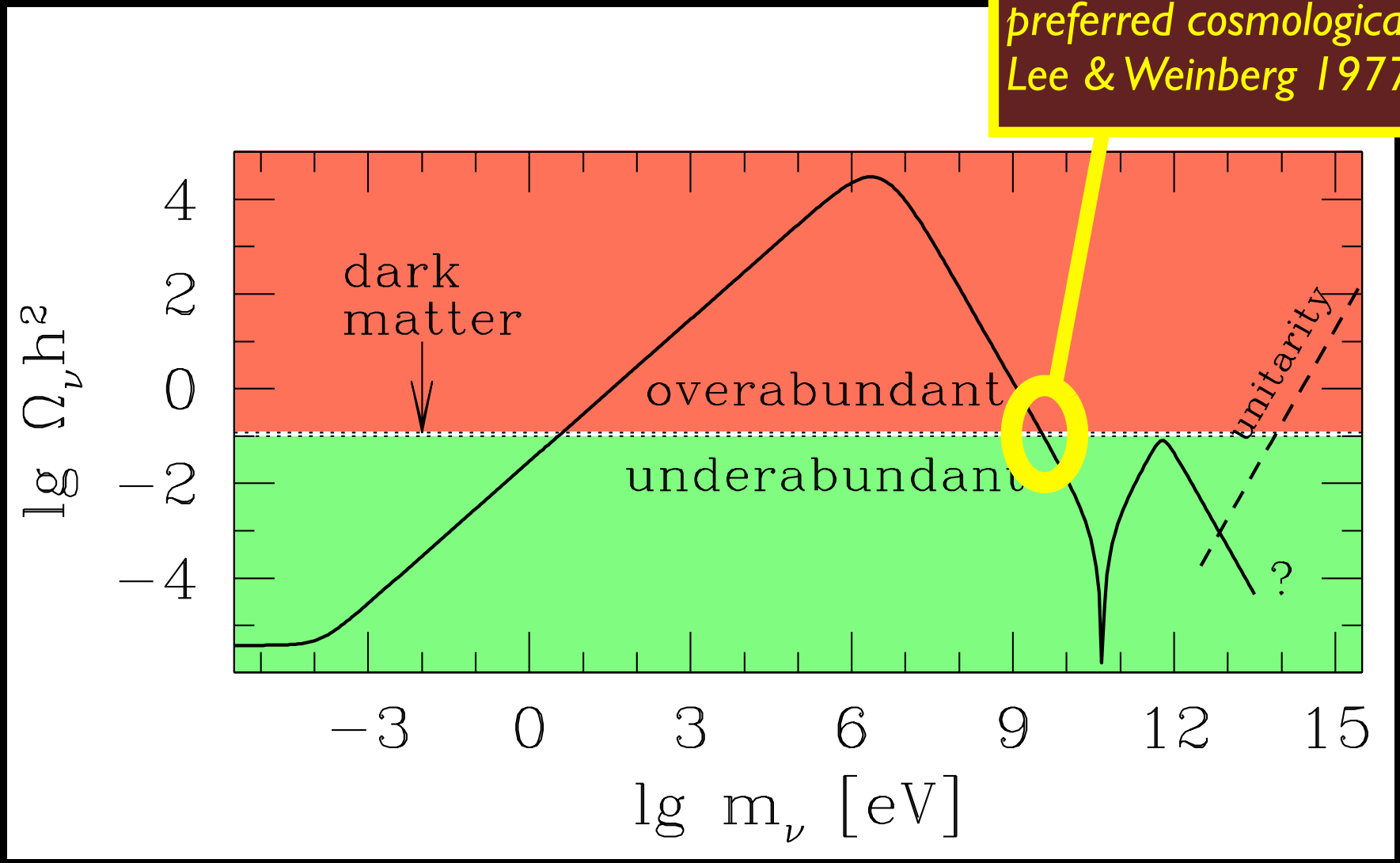


Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrin

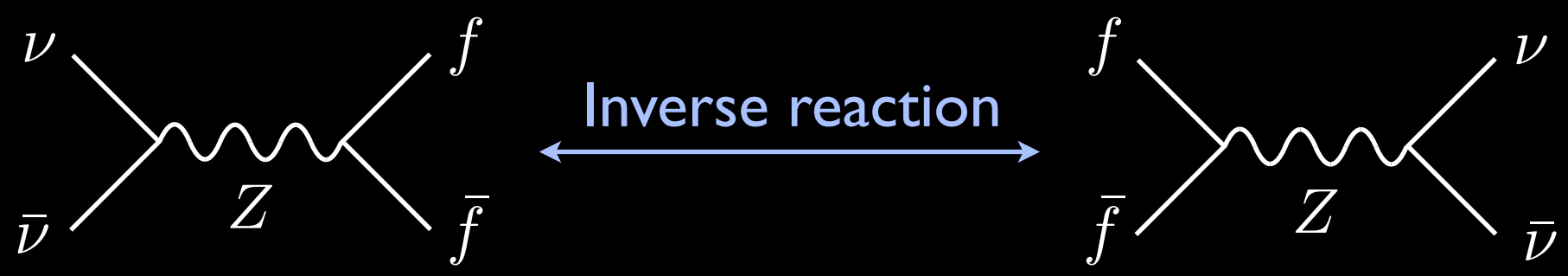
~ few GeV
preferred cosmological mass
Lee & Weinberg 1977



Connection to colliders

Annihilation $\nu\bar{\nu} \rightarrow f\bar{f}$

Production $f\bar{f} \rightarrow \nu\bar{\nu}$

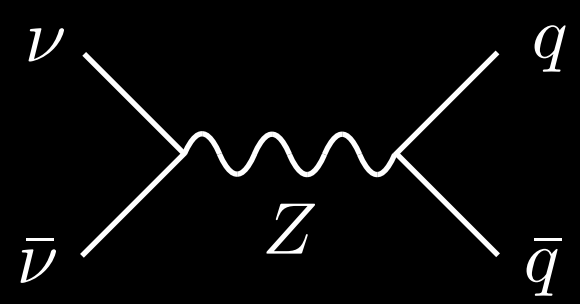


For example, a ~4 GeV/c^2 dark matter neutrino would be copiously produced in resonant Z boson decays

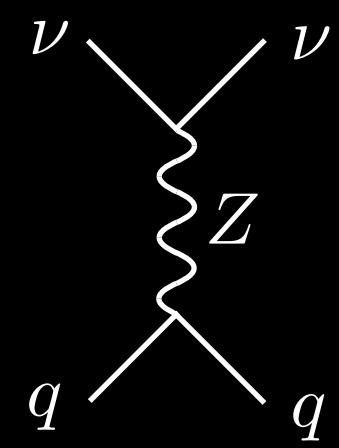
Connection to direct detection

Annihilation $\nu\bar{\nu} \longrightarrow q\bar{q}$

Scattering $\nu q \longrightarrow \nu q$



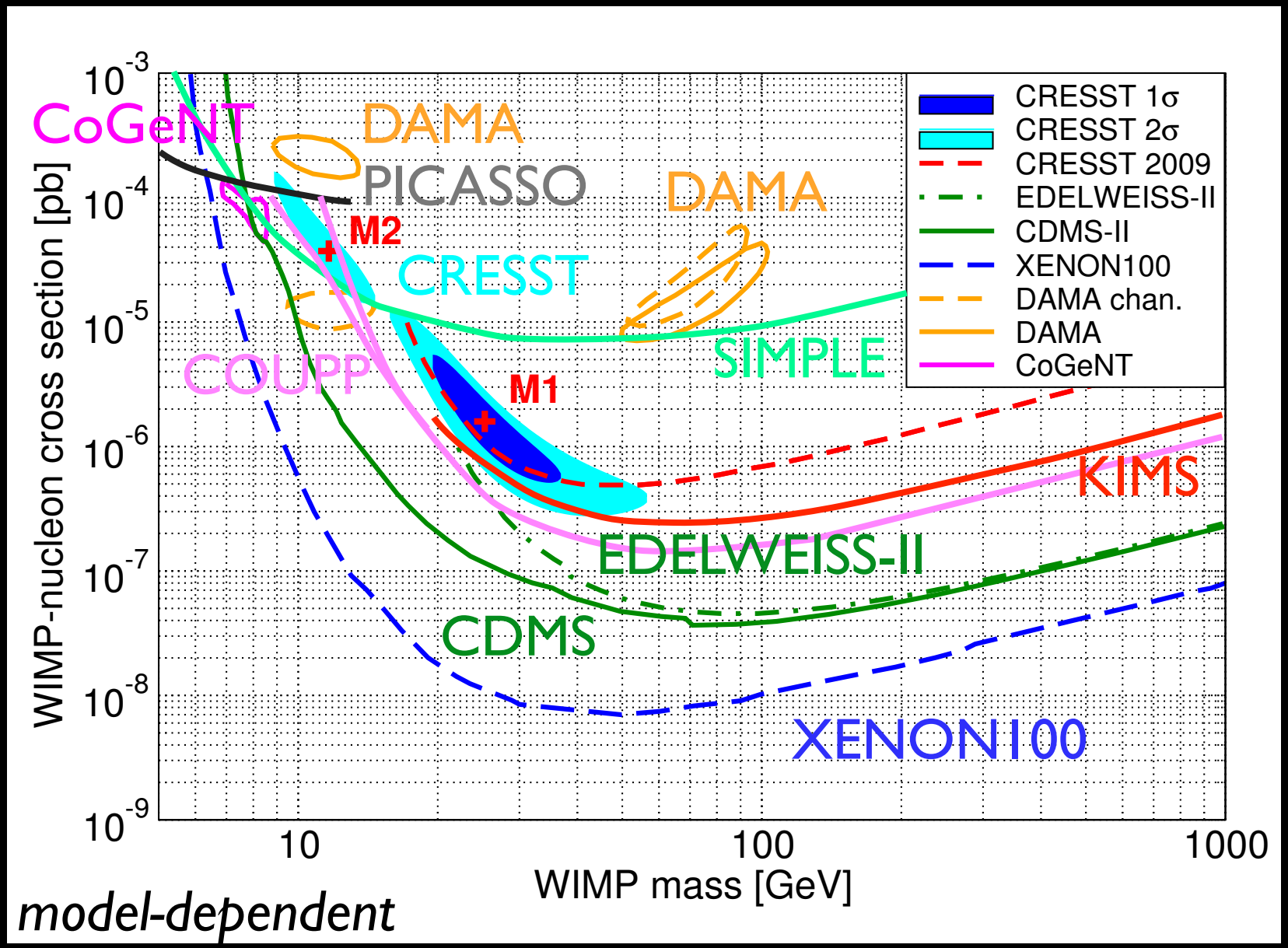
Crossing



For example, for a ~4 GeV/c² dark matter neutrino, the scattering cross section is

$$\sigma_{\nu n} \simeq 0.01 \frac{\langle \sigma v \rangle}{c} \simeq 10^{-38}\,\mathrm{cm}^2$$

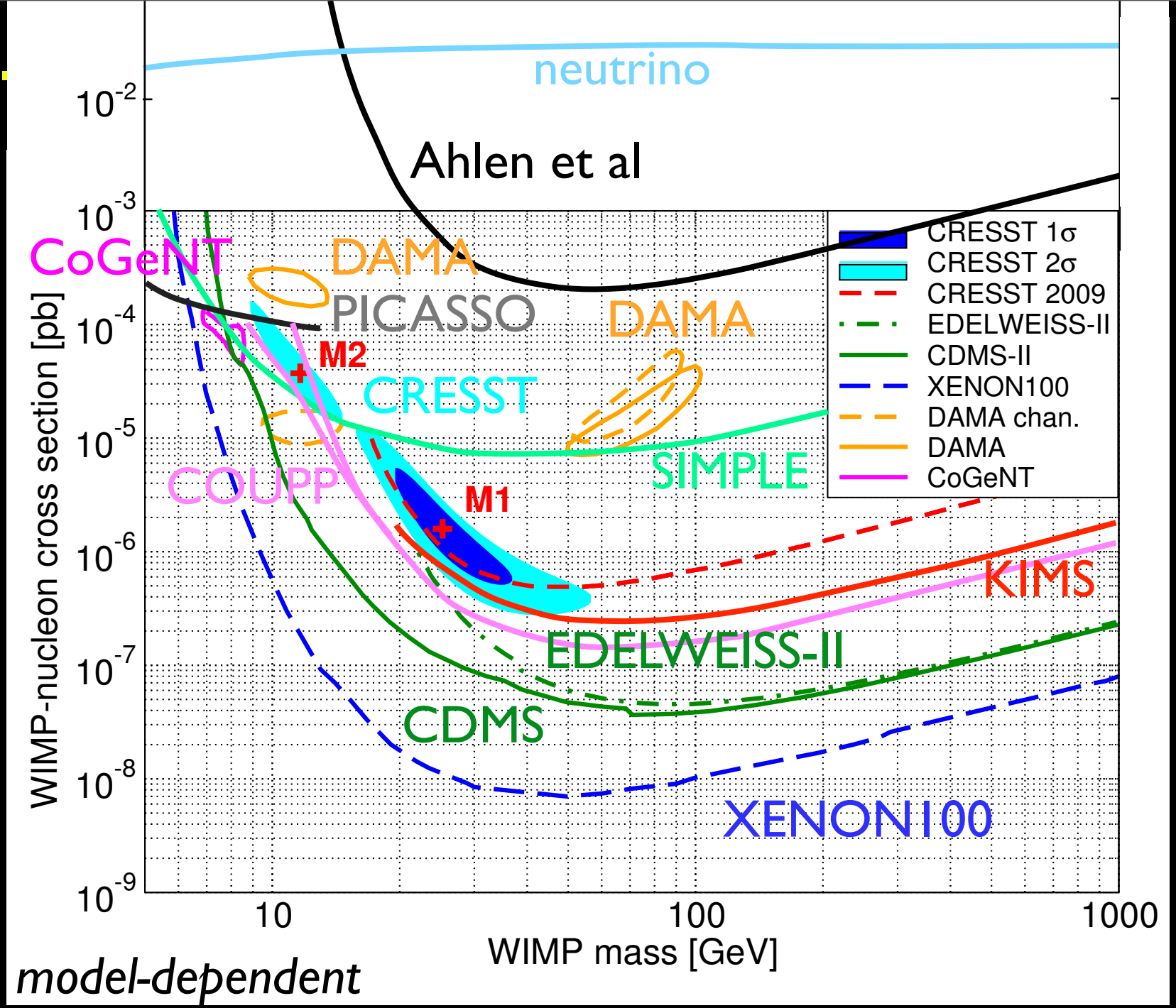
Spin-independent (June 2012)



1pb = 10^{-36} cm^2

Updated from Anglehor et al 2011

Spin-



model-dependent

1pb = 10^{-36} cm^2

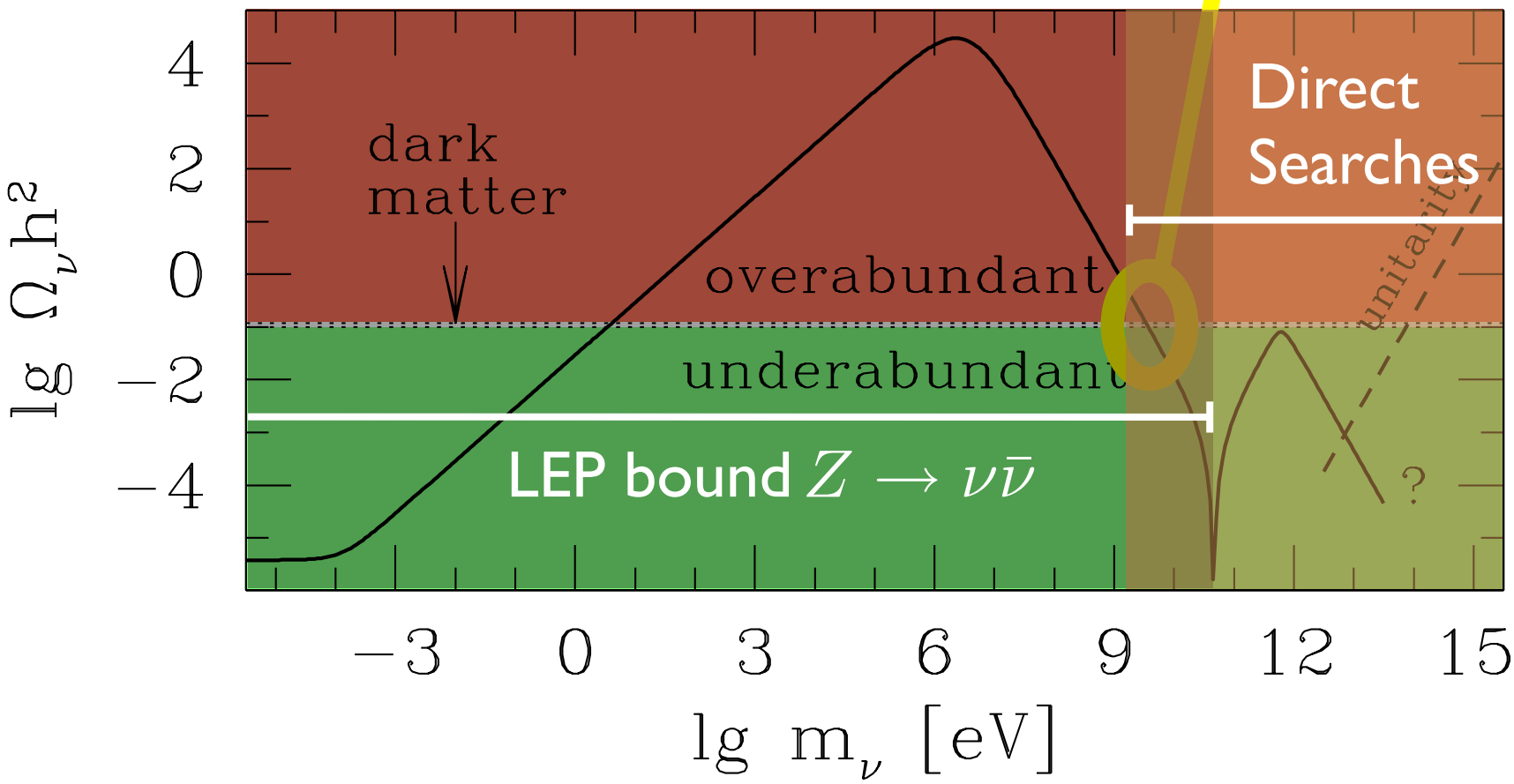
Updated from Anglehor et al 2011

Cosmic density of massive neutrinos

Fourth-generation Standard Model neutrin

~ few GeV
preferred cosmological mass
Lee & Weinberg 1977

Excluded as dark matter (1991)



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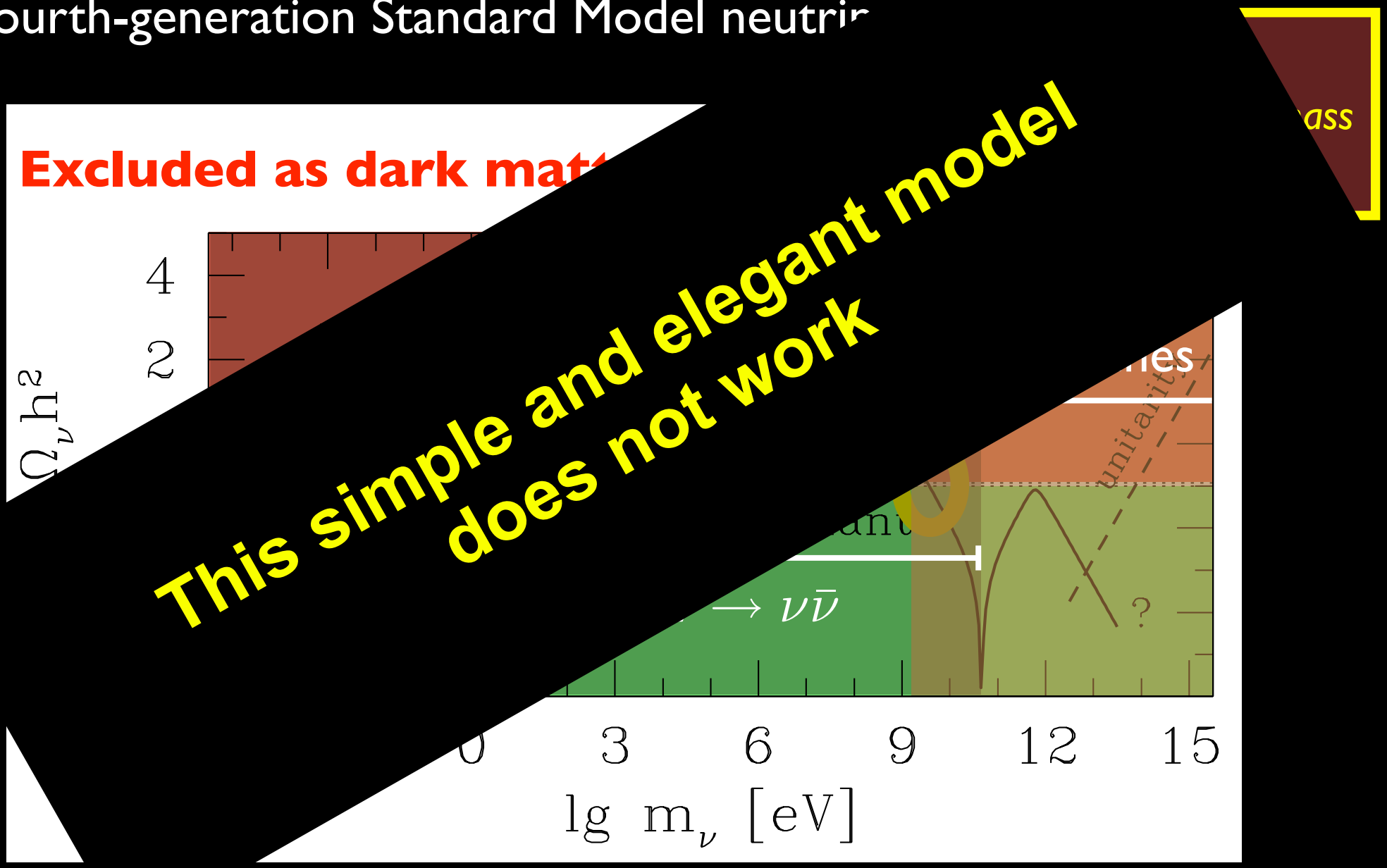


Challenges

(1) Prepare this talk.

(2) Does cold dark matter exist?

(3) What is the nature of cold dark matter?

(4) The failure of the simple and elegant WIMP neutrino.

Is cold dark matter a new elementary particle?

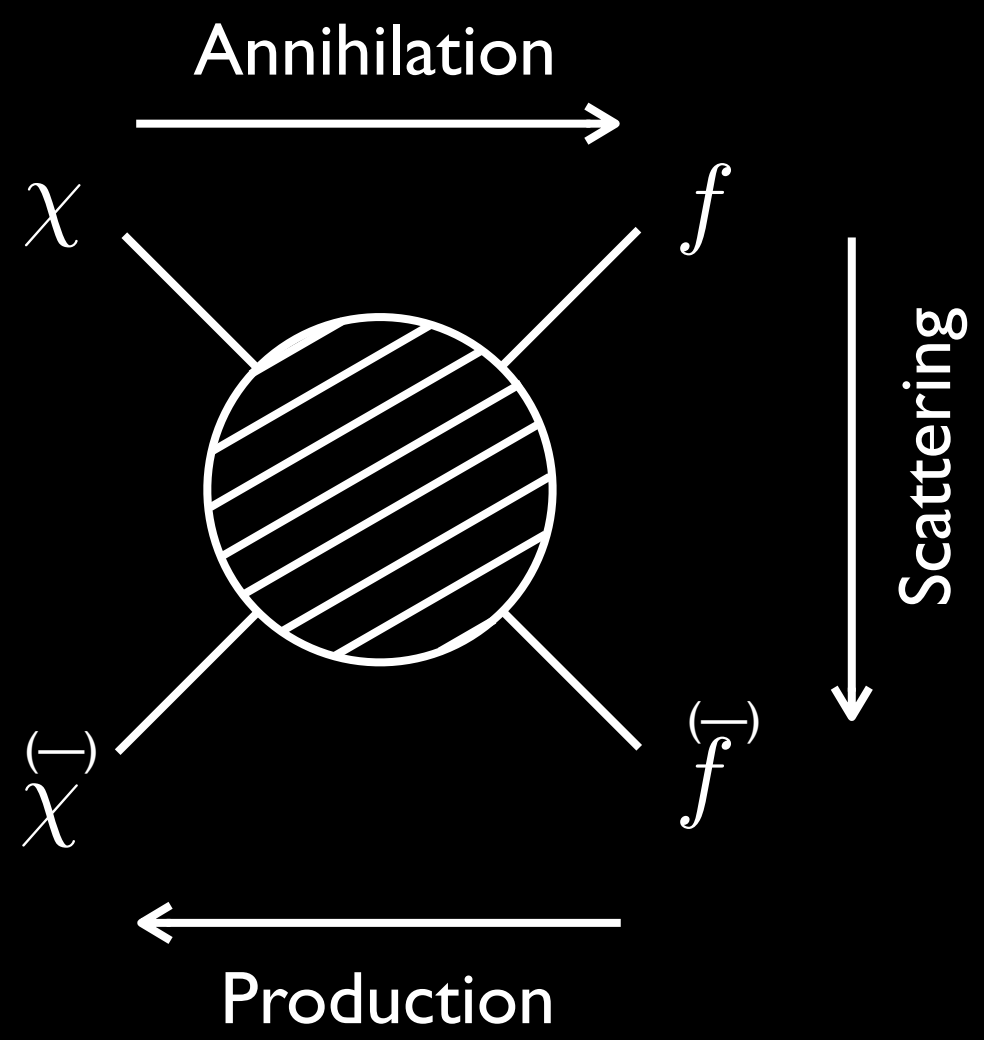
Ideas from theoretical particle physics:

- From Quantum Chromodynamics:
  - Axions
- From Grand Unified Theories & String Theories:
  - Lightest Supersymmetric Particle
- From String Theories & Extra-dimensions:
  - Kaluza-Klein Particle
- Etc., etc., etc.

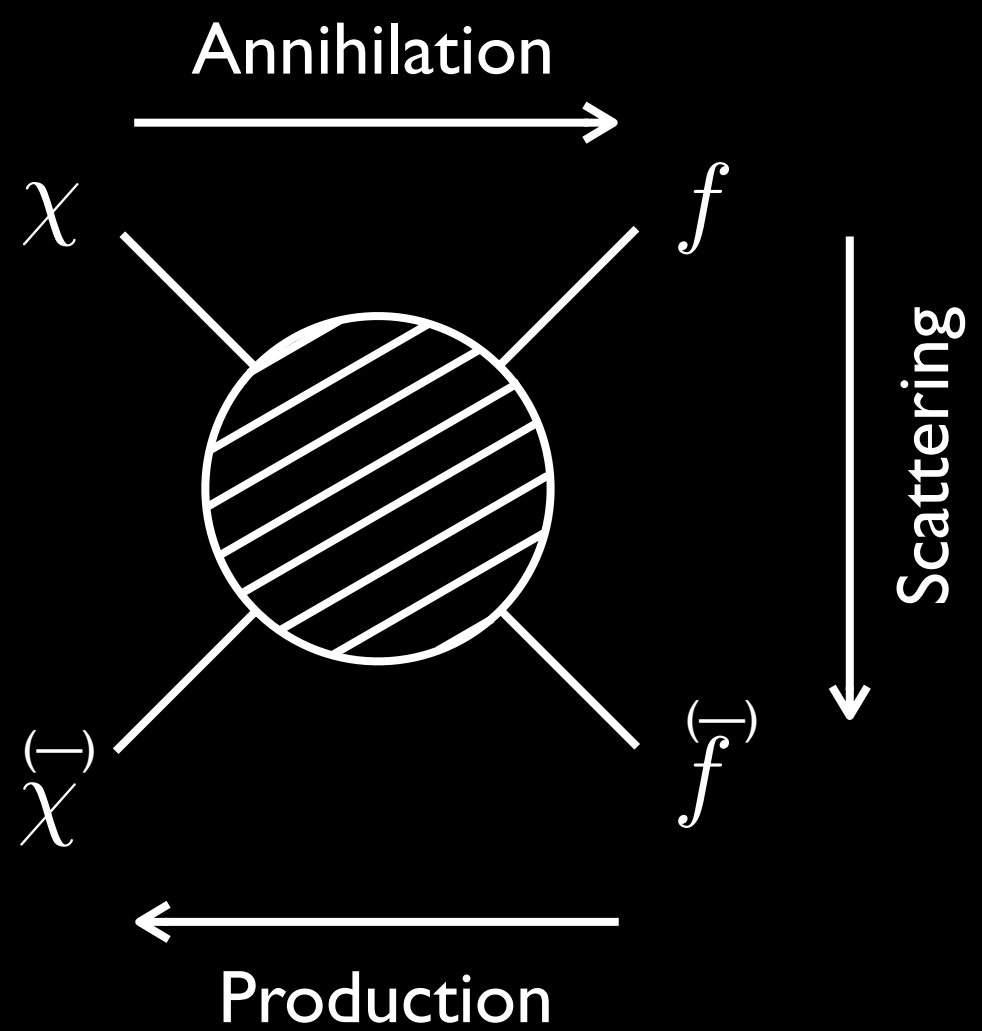
Supersymmetric dark matter

- Neutralinos
  the most fashionable/studied
- SuperWIMPs
  they solve the Lithium problem in primordial nucleosynthesis
- Sneutrinos
  they may account for the DAMA modulation
- Gravitinos
  they may solve the "satellite problem" but are undetectable
- Particles in the hidden sector
  they might have the right properties for Cold Dark Matter
- NMSSM (Next-to-Minimal Susy Standard Model)
  more parameters, more possibilities
- .....

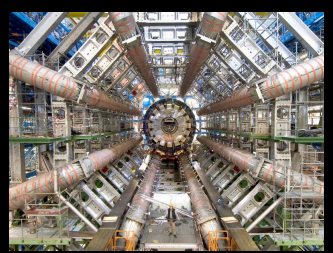
The power of the WIMP hypothesis

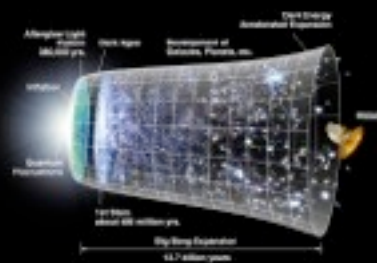


The power of the WIMP hypothesis



Colliders

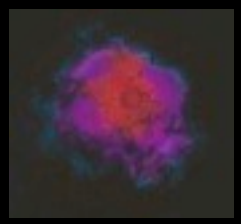


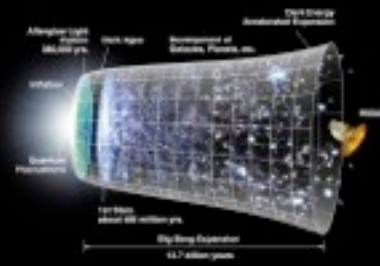


Cosmic density

The power of the WIMP hypothesis

Indirect detection





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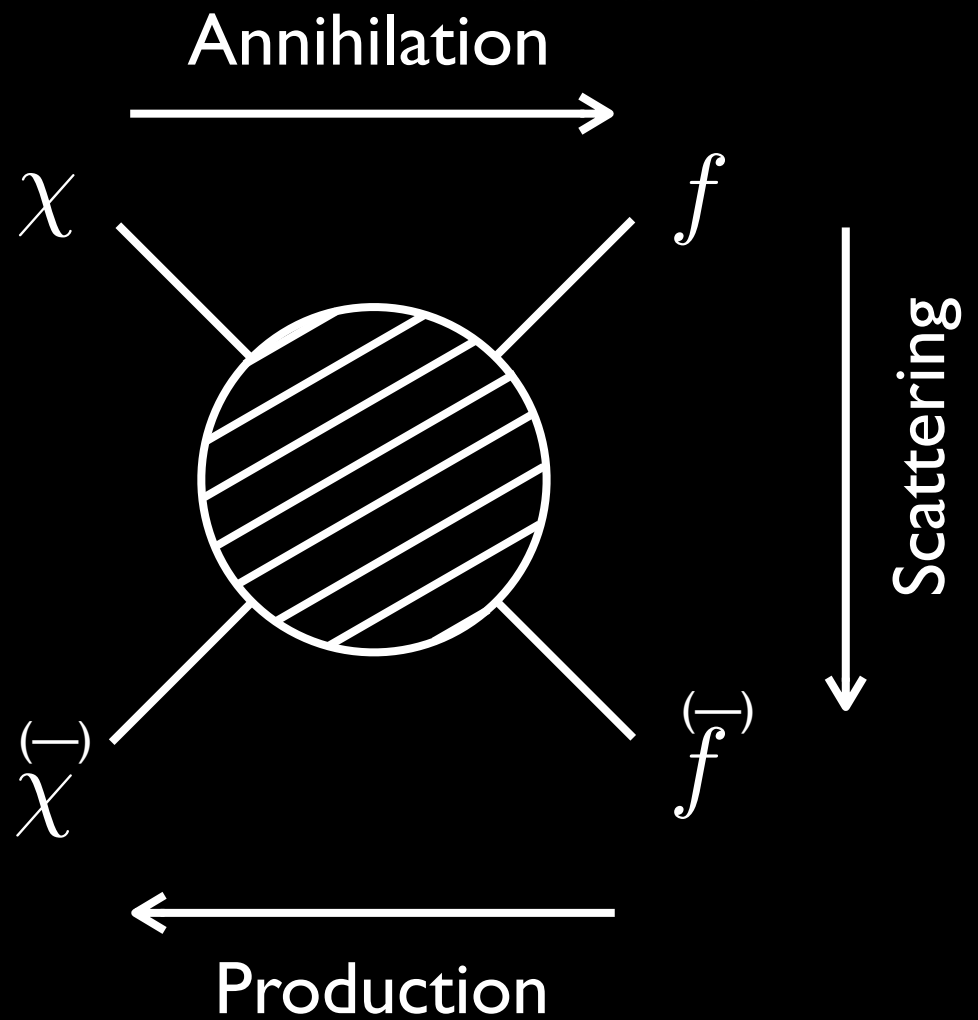

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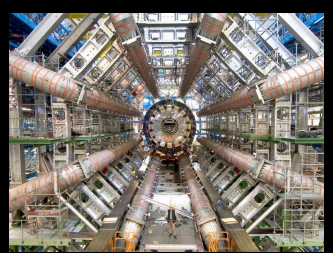

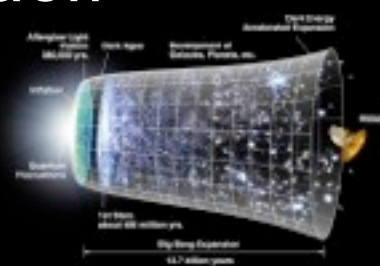

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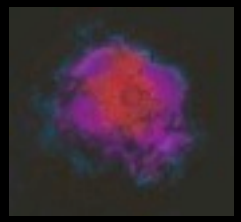
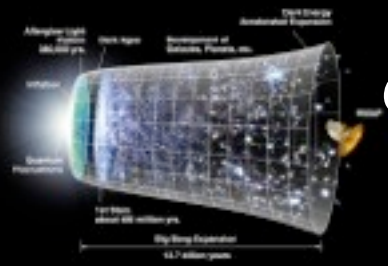
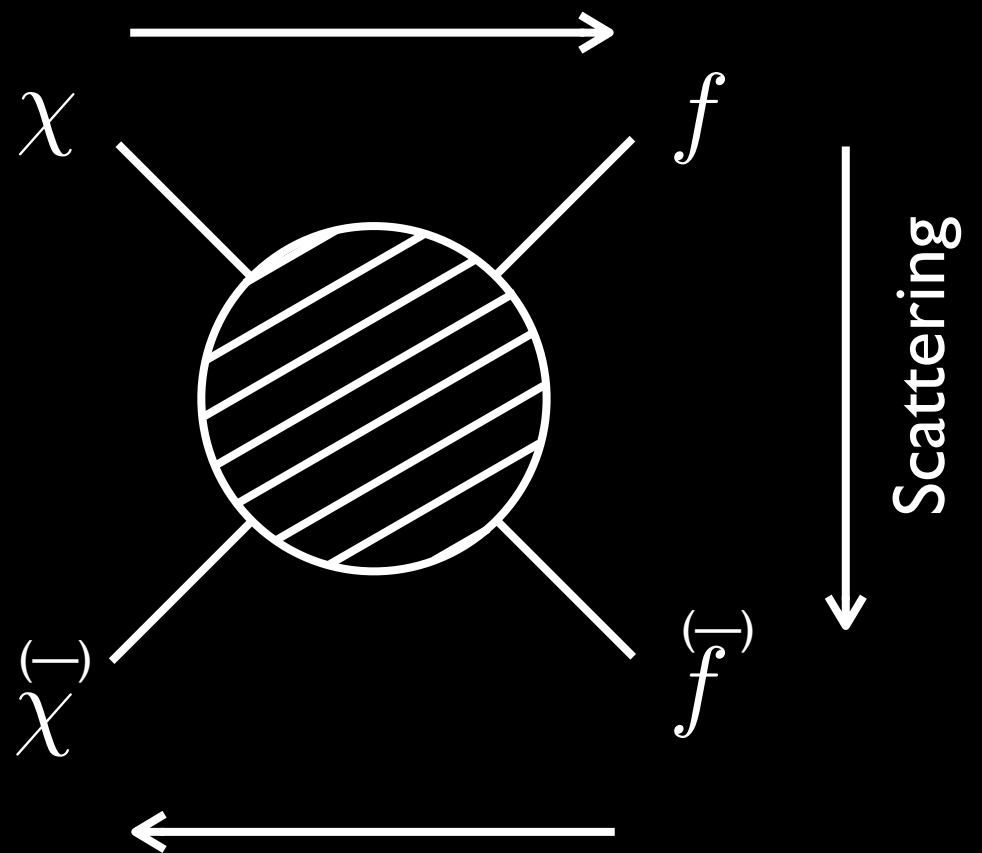




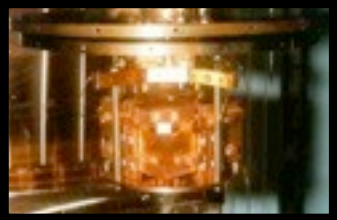
Cosmic density

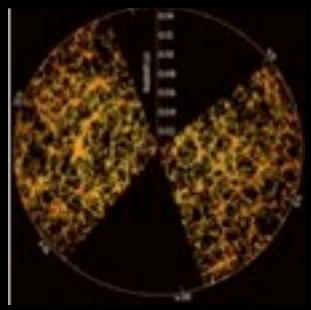
Annihilation



Scattering

Direct detection

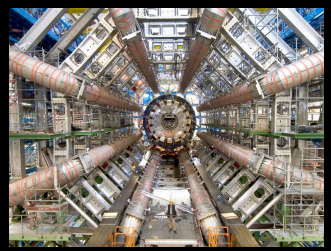


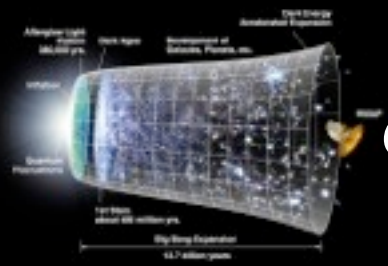


Large scale structure

Production

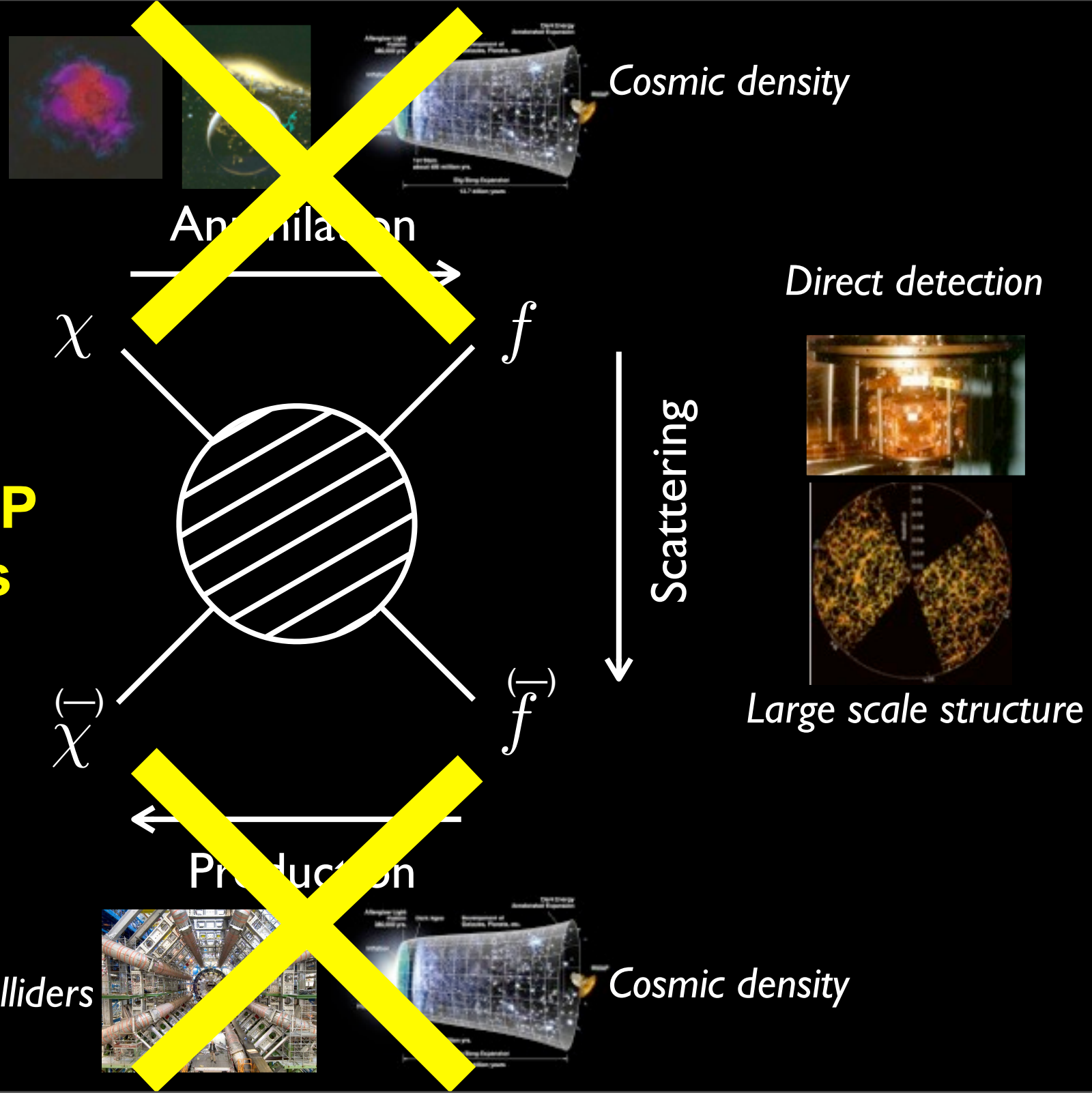
Colliders





Cosmic density

The power of the WIMP hypothesis

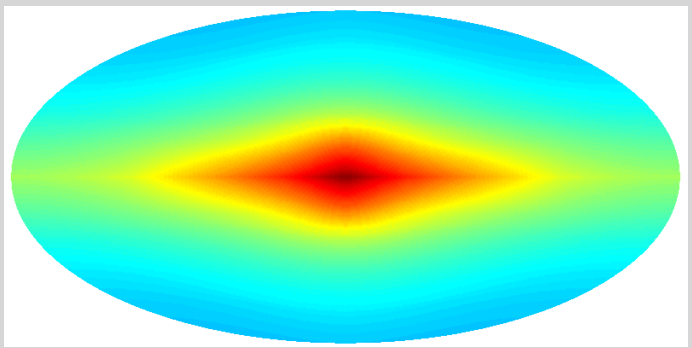


Indirect detection

Cosmic density

Decaying dark matter

- Acceptable explanation for positron excess
- Upper bounds on lifetime from neutrino and gamma-ray fluxes (diffuse and from clusters), from the CMB, Lyman-α, and large scale structure



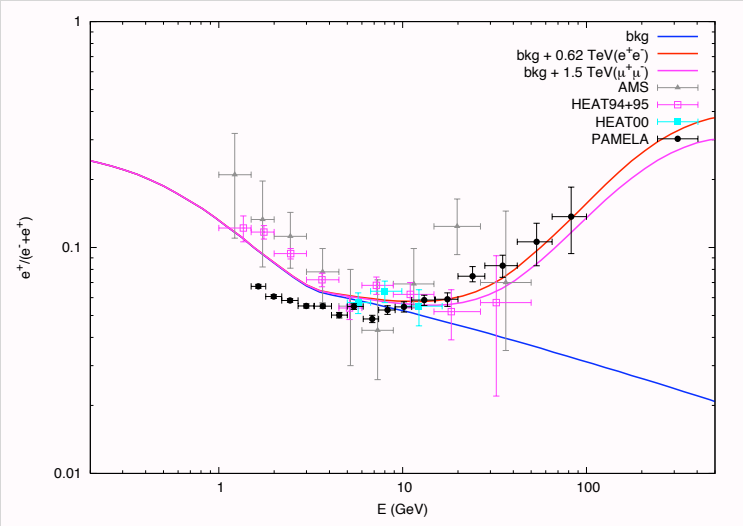
The WMAP/Planck haze?

Predicted 1.42 GHz microwave halo from decaying dark matter

Zhang, Redondo, Sigl 2009

Non-thermal dark matter

- Produced by the decay of heavier particles or topological defects or in other ways (see axions)
- Invoked e.g. for positron excess



Model connecting positron excess to neutrino masses, cosmic strings and leptogenesis.

Bi et al 2009

Axions

Axions as solution to the strong CP problem

The strong CP problem

In QCD, the *neutron electric dipole moment* d_n should be ~10^{-16} $e\mathrm{cm}$, but experimentally $d_n < 1.1 \times 10^{-26}\, e\mathrm{cm}$

The Peccei-Quinn solution

Introduce a new $U(1)_{PQ}$ symmetry and a new field to break it spontaneously. The remaining pseudoscalar Goldstone boson is the axion. It acquires mass through QCD instanton effects.

Axions as dark matter

Hot

Produced thermally in early universe

Important for $m_a > 0.1 eV$ ($f_a < 10^8$), mostly excluded by astrophysics

Cold

Produced by coherent field oscillations around mimimum of $V(\theta)$

(Vacuum realignment)

Produced by decay of topological defects

(Axionic string decays)

Still a very complicated and uncertain calculation!

e.g. Harimatsu et al 2012

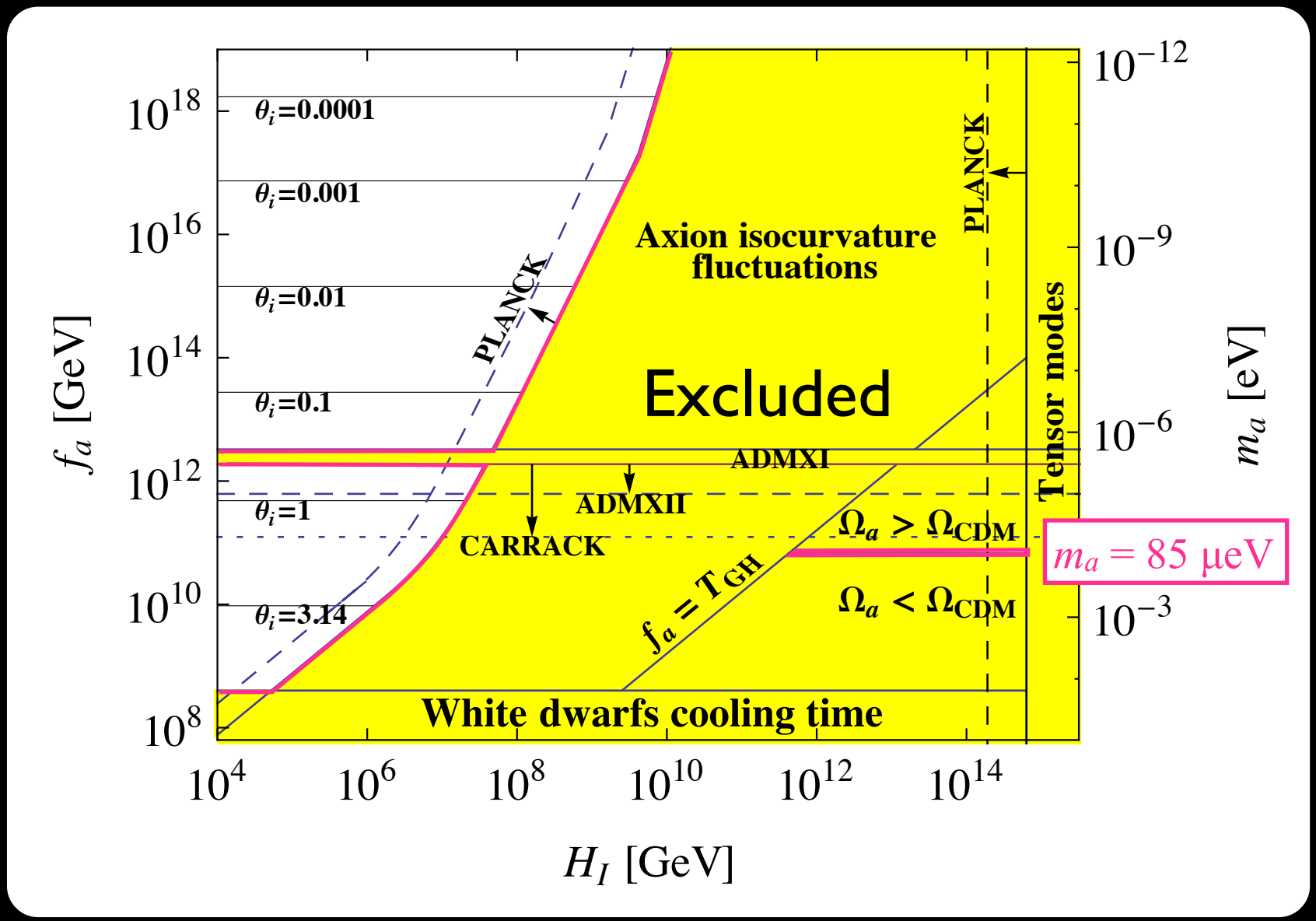
Axion cold dark matter parameter space

f_a	Peccei-Quinn symmetry breaking scale
N	Peccei-Quinn color anomaly
N_d	Number of degenerate QCD vacua
Kim-Shifman-Vainshtain-Zakharov Dine-Fischler-Srednicki-Zhitnistki	Couplings to quarks, leptons, and photons
$H_{\rm I}$	Expansion rate at end of inflation
θ_i	Initial misalignment angle
Harari-Sikivie-Hagmann-Chang Davis-Battye-Shellard	Axionic string parameters

Assume $N = N_d = 1$ *and show results for KSVZ and HSHC string network*

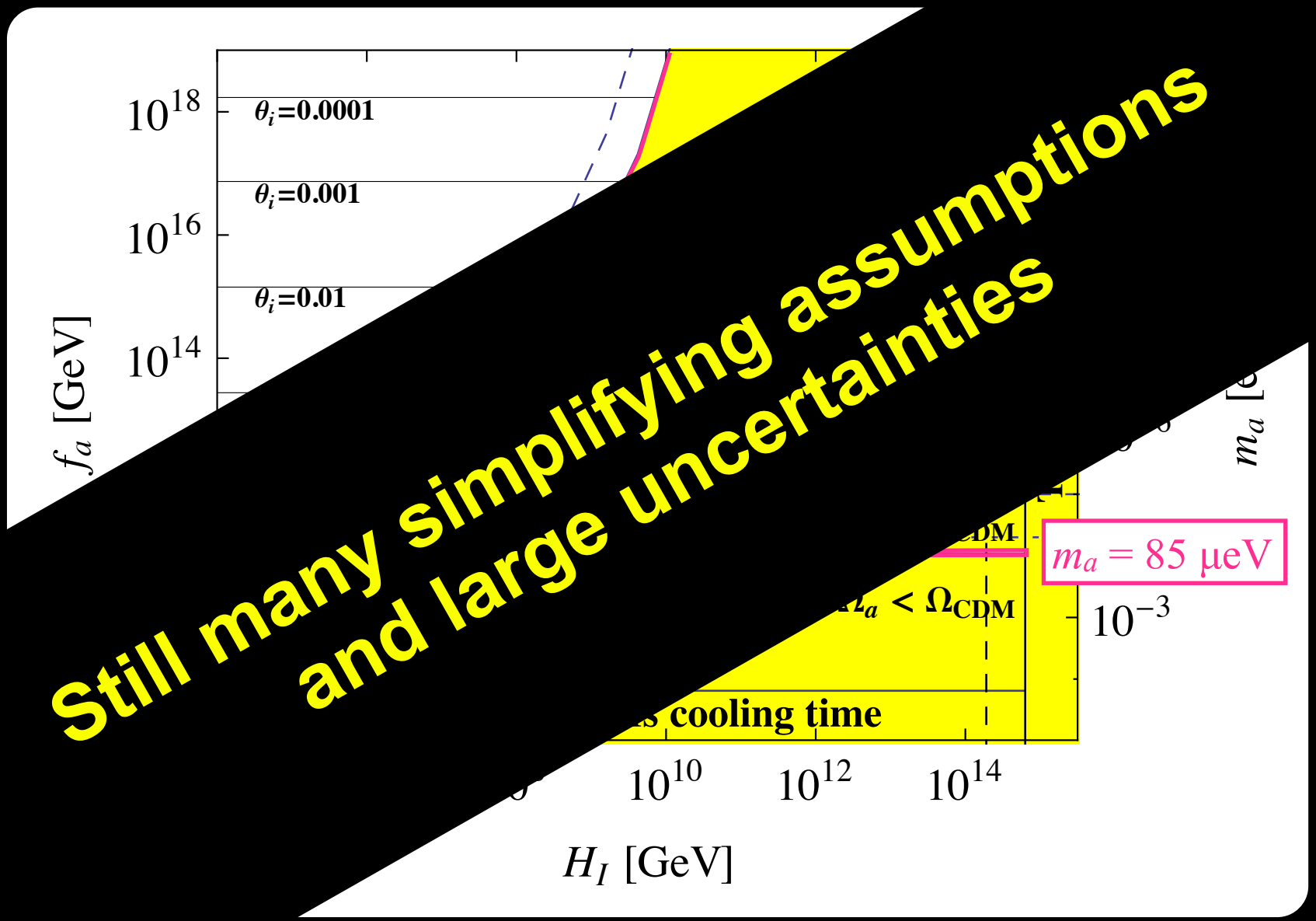
Thus 3 free parameters f_a, θ_i, $H_{\rm I}$ *and one constraint* $\Omega_a = \Omega_{\rm CDM}$

Axions as cold dark matter



Visinelli, Gondolo 2009

Axions as cold dark matter

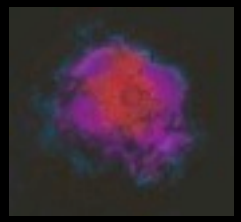


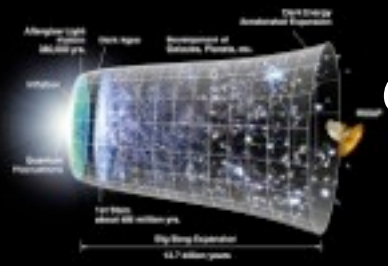
Still many simplifying assumptions and large uncertainties

Visinelli, Gondolo 2009

The power of the WIMP hypothesis

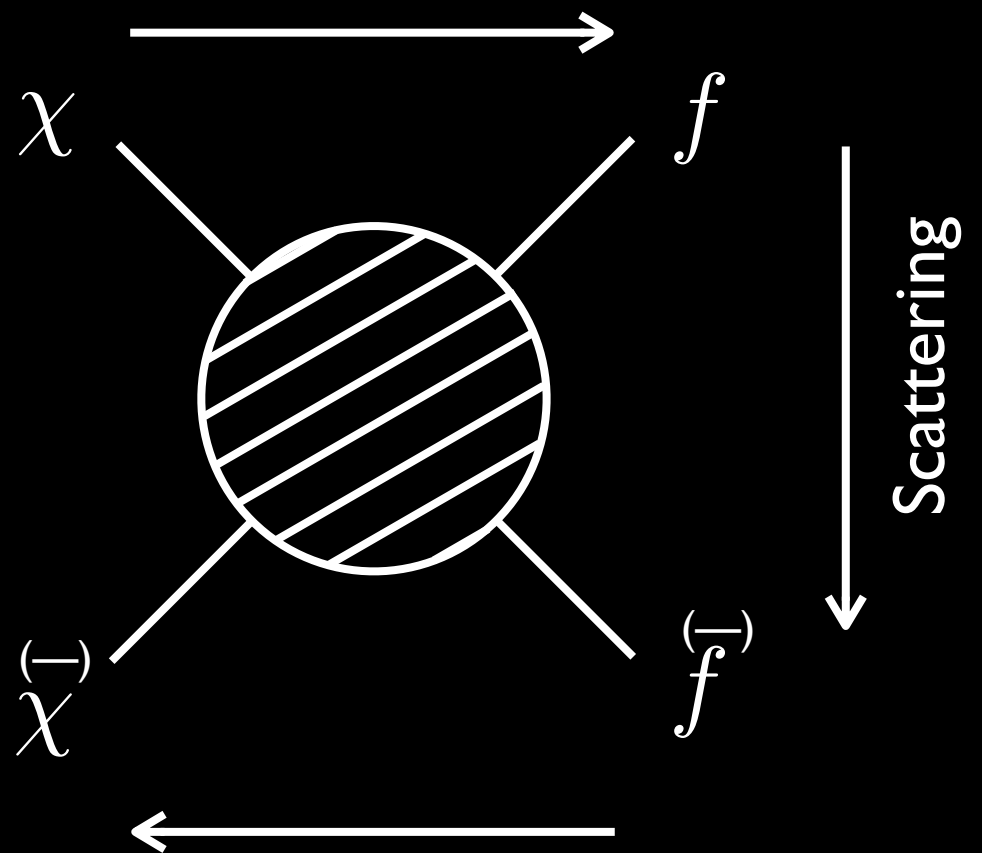
Indirect detection





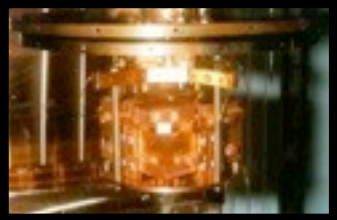
Cosmic density

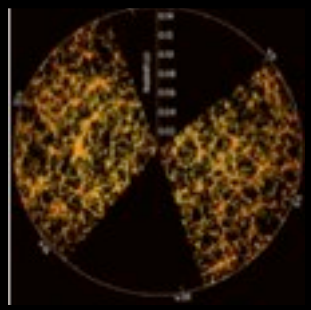
Annihilation



Scattering

Direct detection

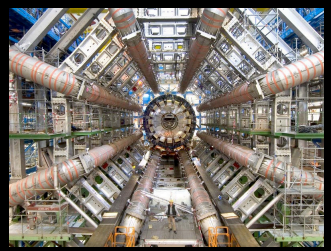


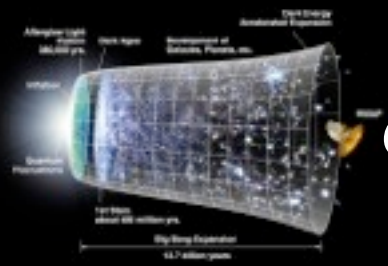


Large scale structure

Production

Colliders

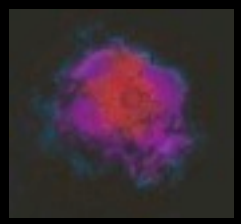


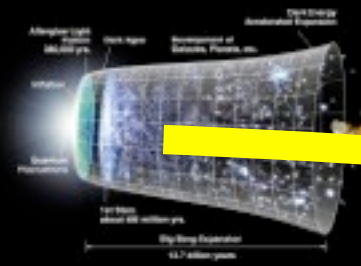


Cosmic density

The power of the WIMP hypothesis

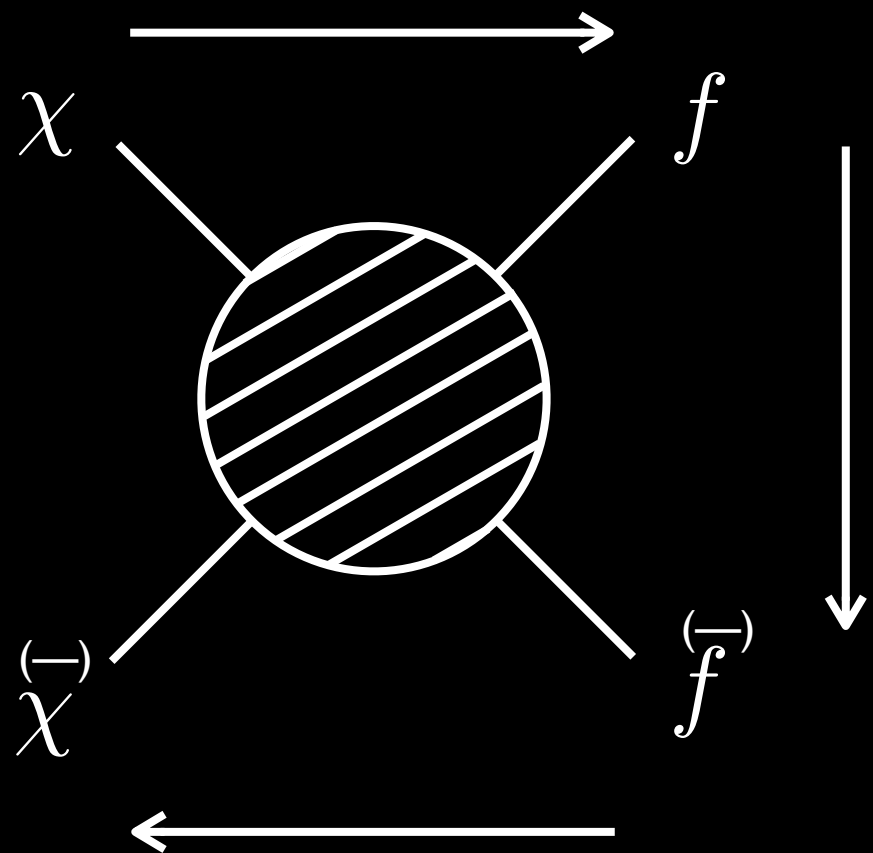
Indirect detection





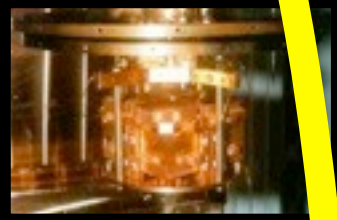
Cosmic density

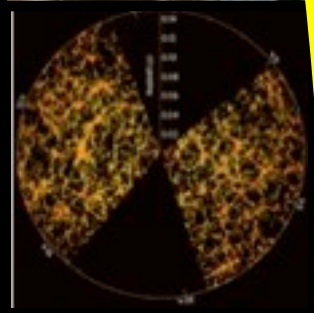
Annihilation



Scattering

Direct detection





Large scale structure

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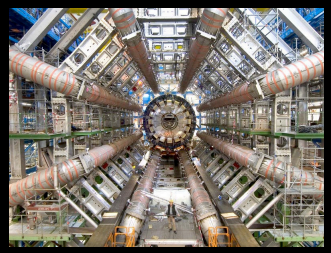
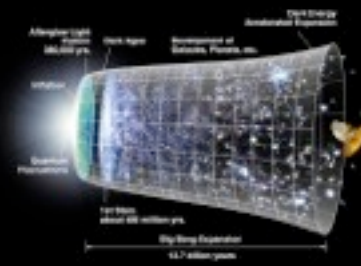
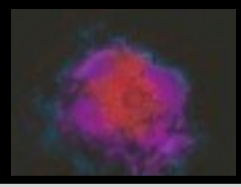
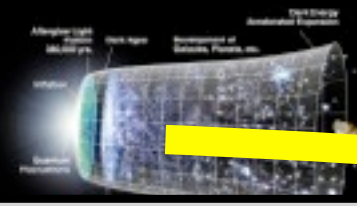




Cosmic density



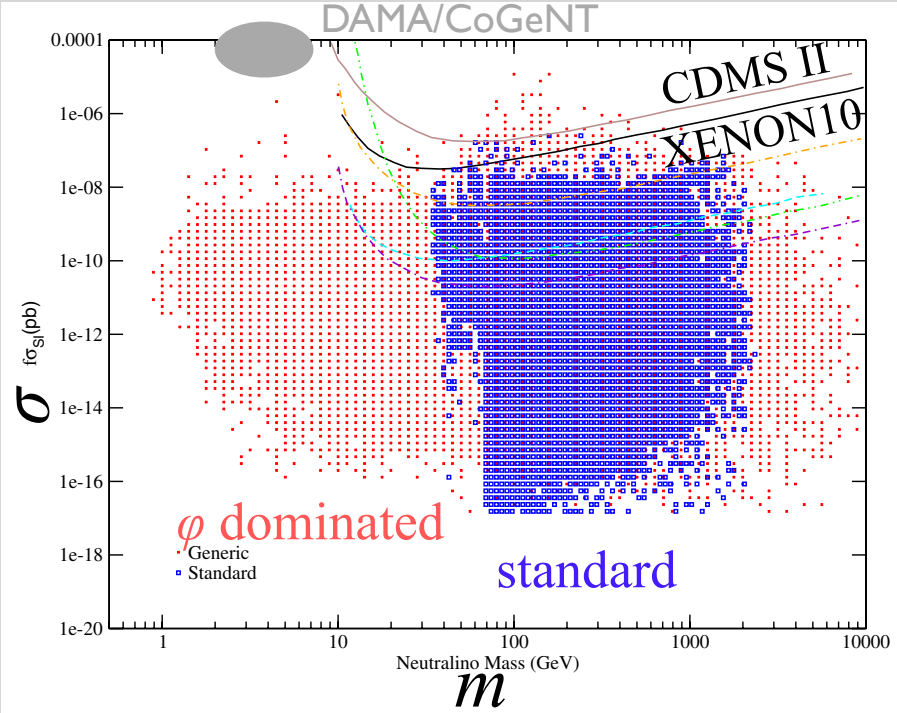


Indirect detection

Cosmic density

Modified cosmology

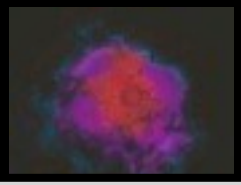
- The universe history before Big Bang Nucleosynthesis is unknown. A faster or slower expansion changes the relation between annihilation and scattering.

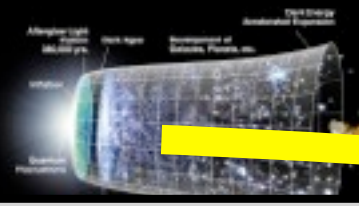


With epoch dominated by decaying scalar field, low mass WIMPs are possible (but not DAMA/CoGeNT).

Gelmini, Gondolo, Yaguna, Soldatenko 2007

Indirect detection





Cosmic density

Heavy WIMPs

- Annihilation into WW, ZZ, etc. unrelated to scattering off quarks and gluons

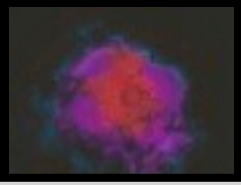
Coannihilations

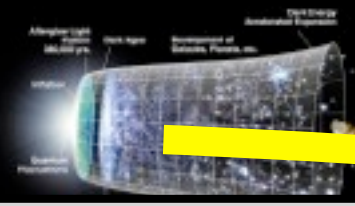
- Annihilation proceeds through intermediate production of fast-annihilating particles

Resonant annihilation

- Annihilation proceeds through resonances

Indirect detection





Cosmic density

Heavy WIMPs

- Annihilation into WW, ZZ
  scattering off quarks and

Coannihilations

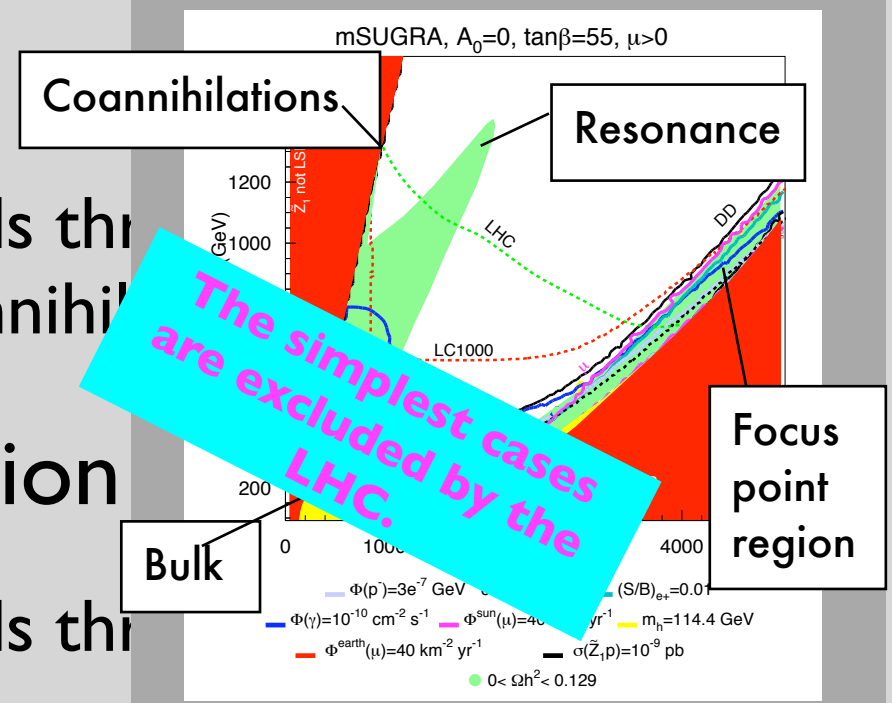
- Annihilation proceeds thr
  production of fast-annihil

Resonant annihilation

- Annihilation proceeds thr

This is the case of the neutralino after the LHC constraints.

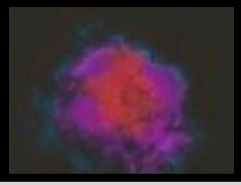
See Pearl Sandick's talk

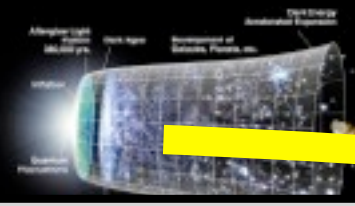


The simplest cases are excluded by the LHC.

Baer et al, 2004

Indirect detection





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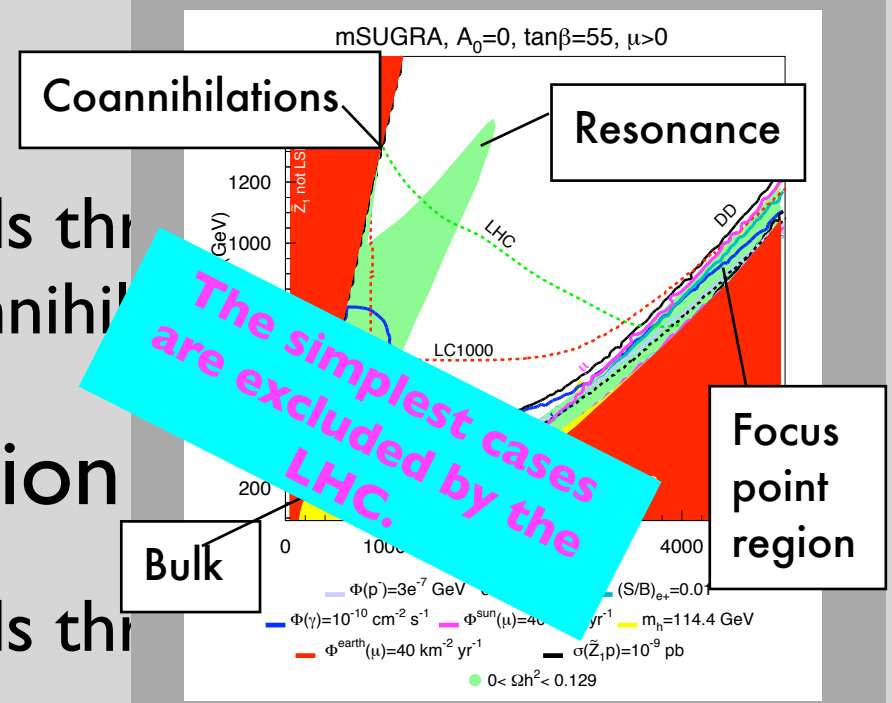

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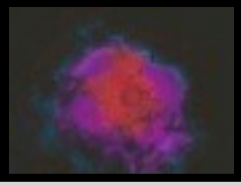

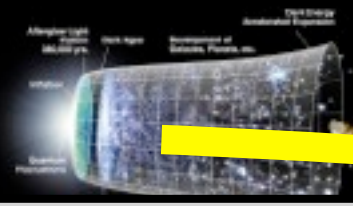

Cosmic

Heavy WIMPs

- Annihilation into W
  scattering off

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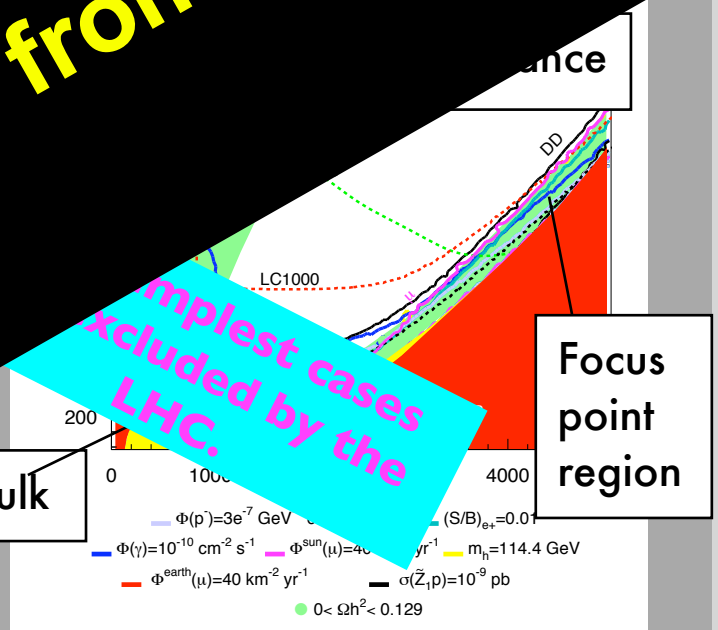
This is getting complex and confusing.
Is there any guidance from experiments?



Baer et al, 2004

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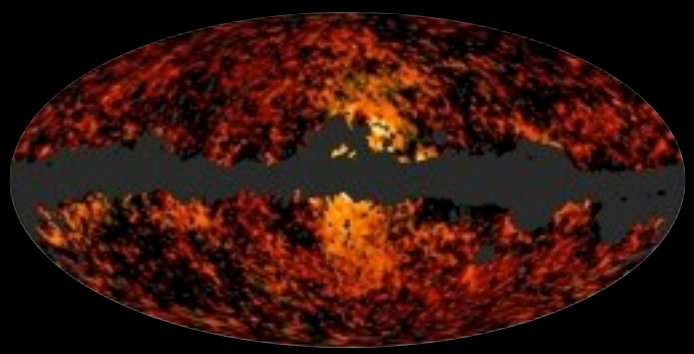
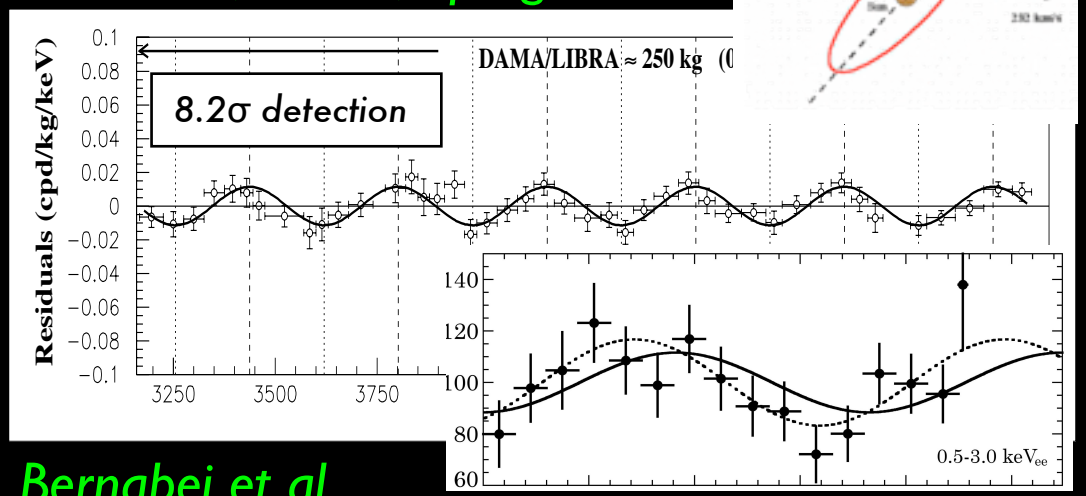
Evidence for cold dark matter particles?

WMAP/Planck haze



Annual modulation

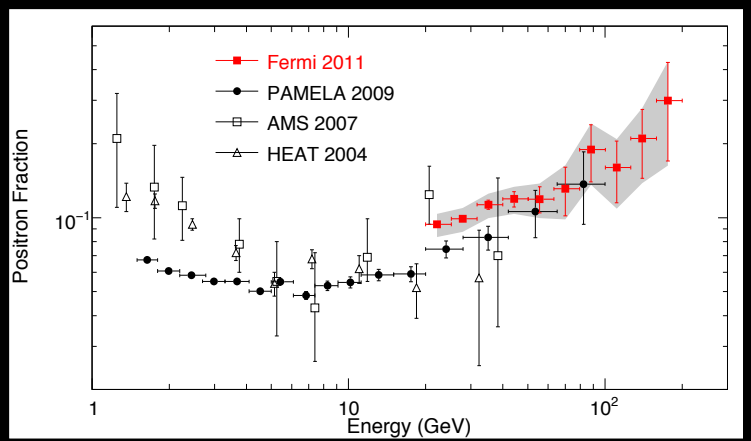
Drukier, Freese, Spergel 1986



Bernabei et al 1997-2012

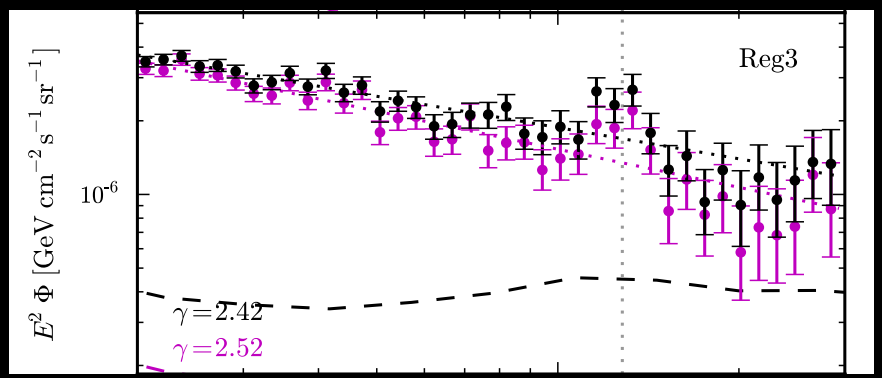
Aalseth et al 2011

Positron excess



Adriani et al 2009;Ackerman et al 2011

130 GeV γ-ray line



Weniger 2012

The situation

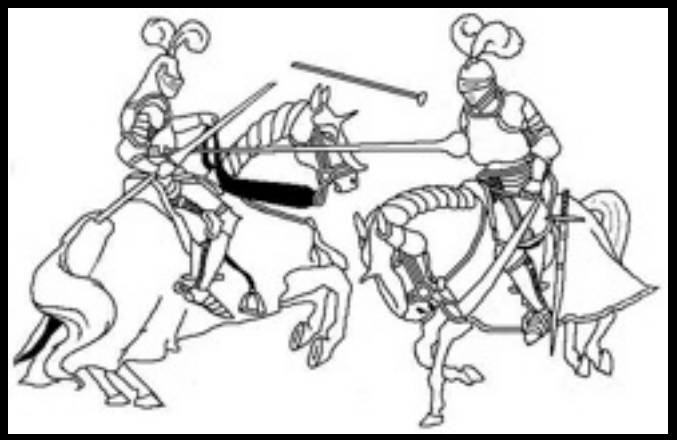
"There are known knowns. These are things we know that we know. There are known unknowns. That it to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know."

Donald H. Rumsfeld, b. 1932, American politician

The probability of the (un)known

Statistical and systematic errors

Frequentist?



Bayesian?

John Venn

Pierre Simon Laplace

"There are three kinds of lies: lies, damned lies, and statistics."

Attributed to Benjamin Disraeli (1804-1881), British Prime Minister

Challenges

(1) Prepare this talk.

(2) Does cold dark matter exist?

(3) What is the nature of cold dark matter?

(4) The failure of the simple and elegant WIMP neutrino.

(5) At how many sigmas are experimental results worth of a theoretician's time? *Mentally estimate the probability of winning a Nobel prize.*

The bane

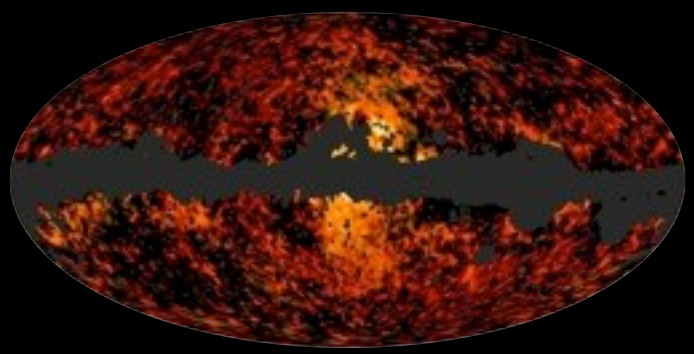
Roderick O. Redman, 1905-1975, Professor of Astronomy at Cambridge University

"Any competent theoretician can fit any theory to any given set of facts."

- Explaining direct and indirect claims of detection often requires complicated and contrived models.

Evidence for cold dark matter particles?

WMAP/Planck haze



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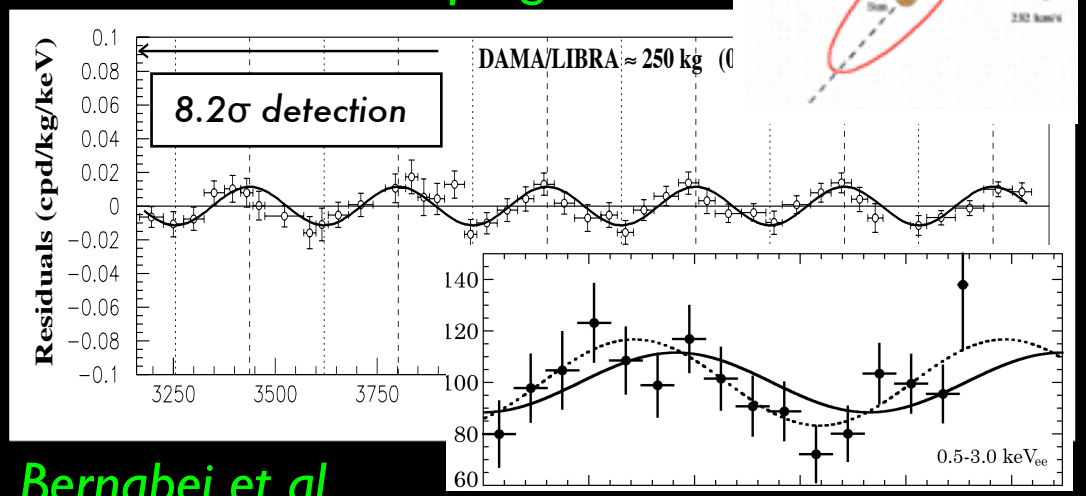
Drukier, Freese, Spergel 1986



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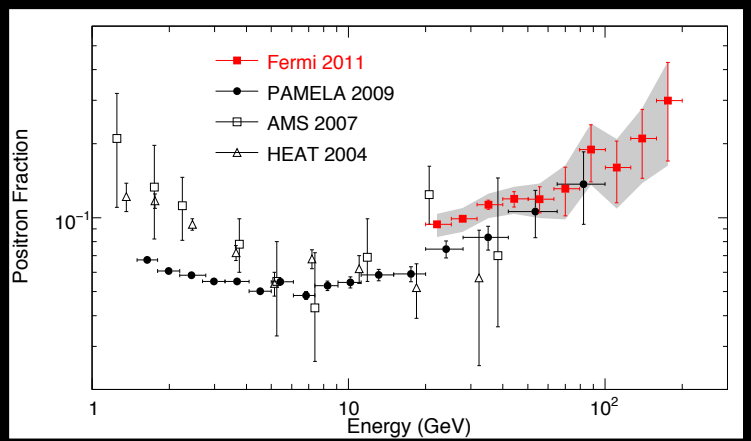

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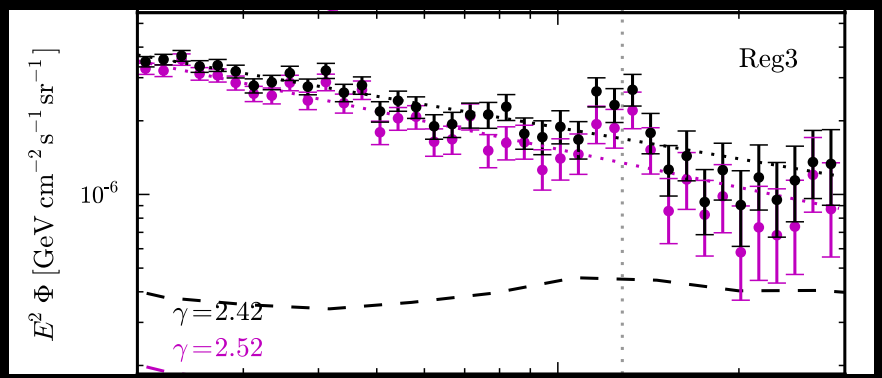

Weniger 2012

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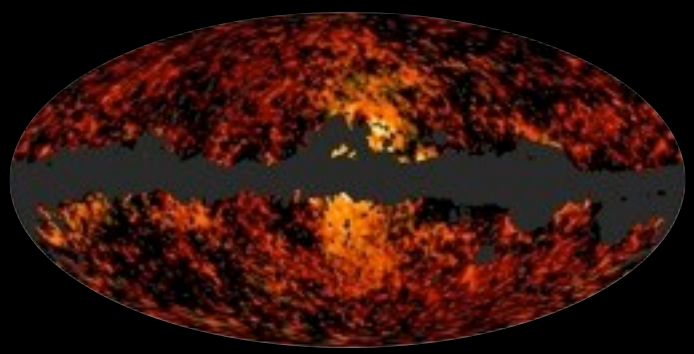

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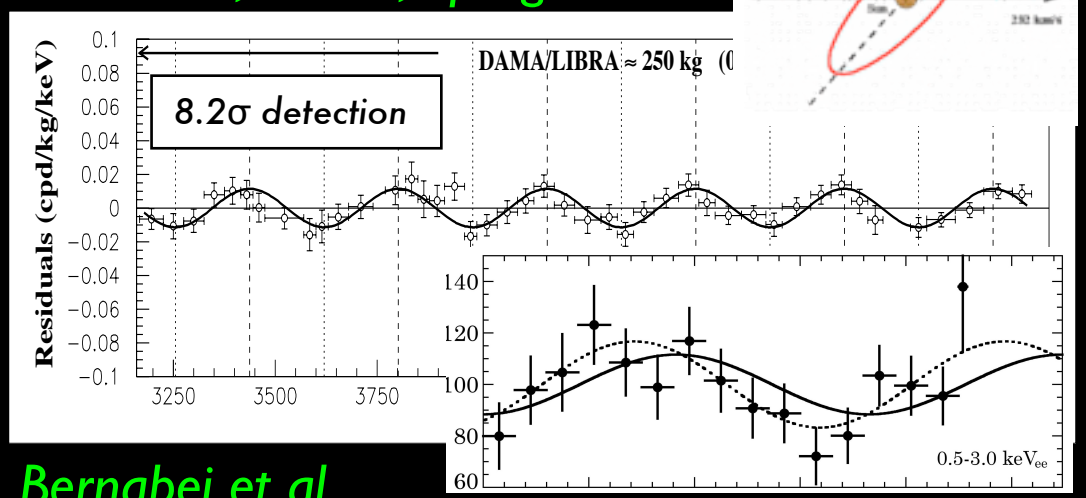

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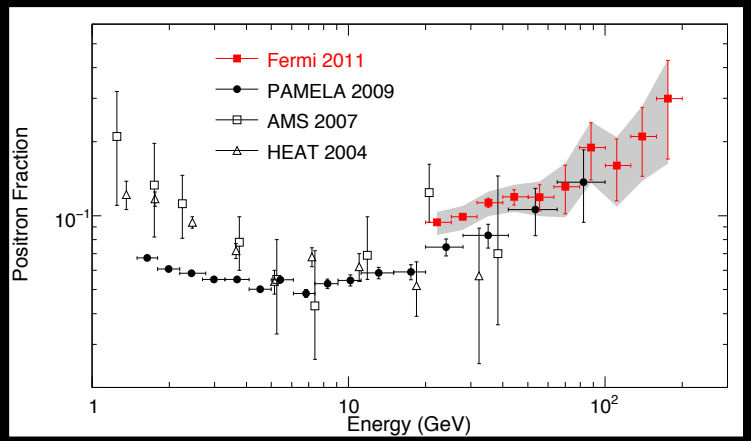

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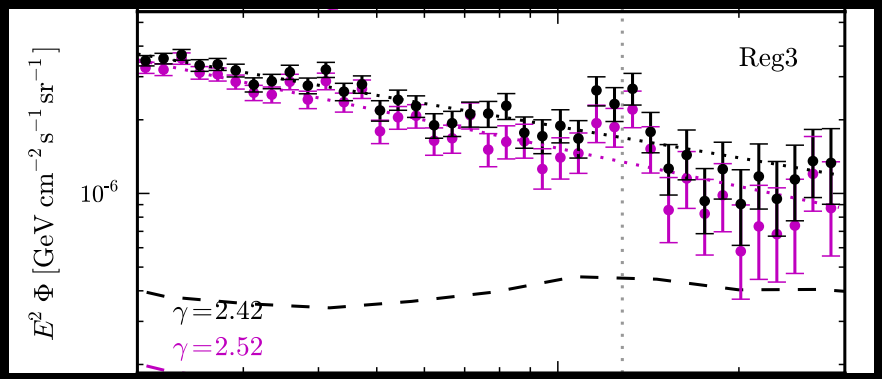
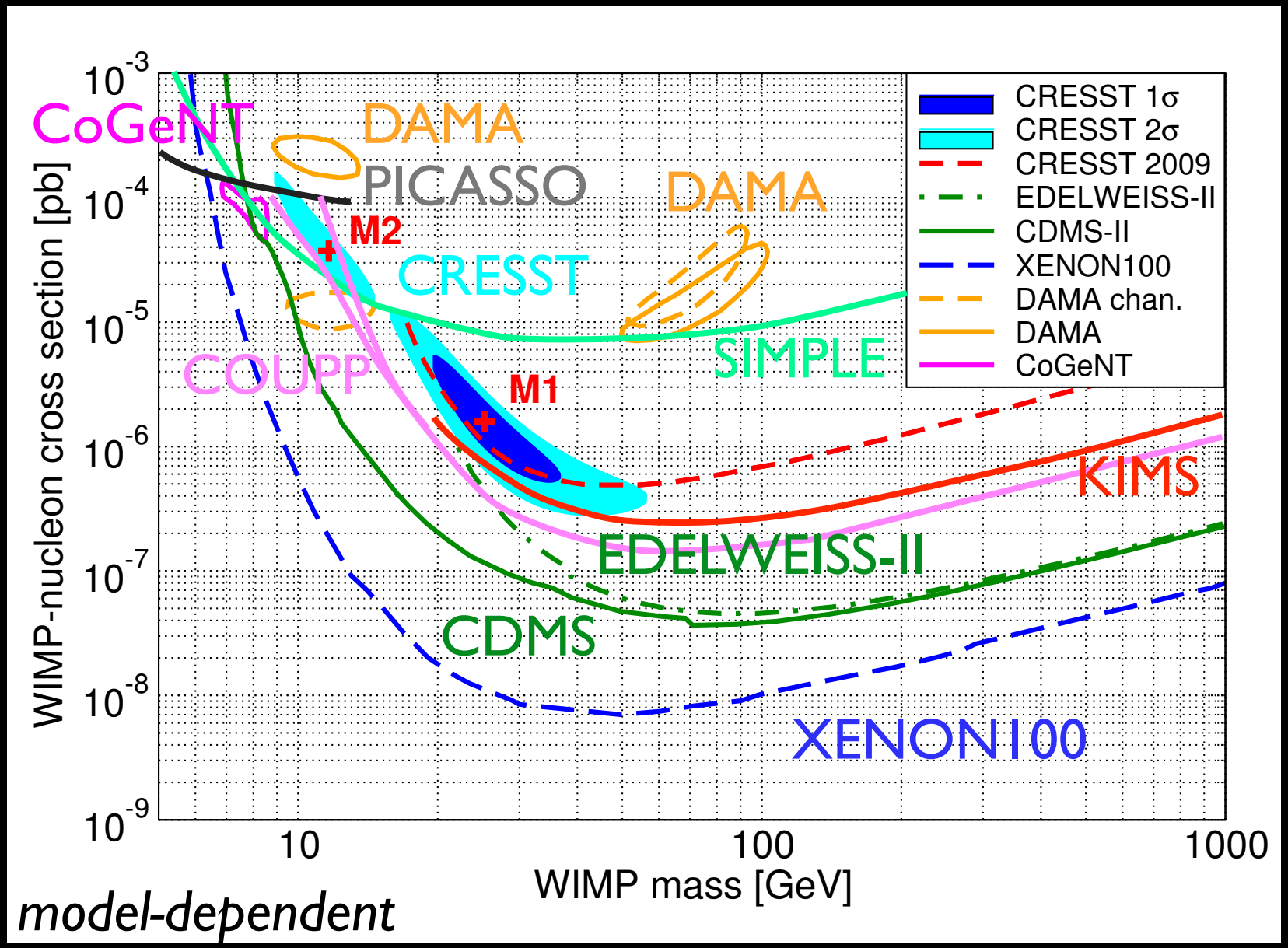


Weniger 2012

Light WIMPs

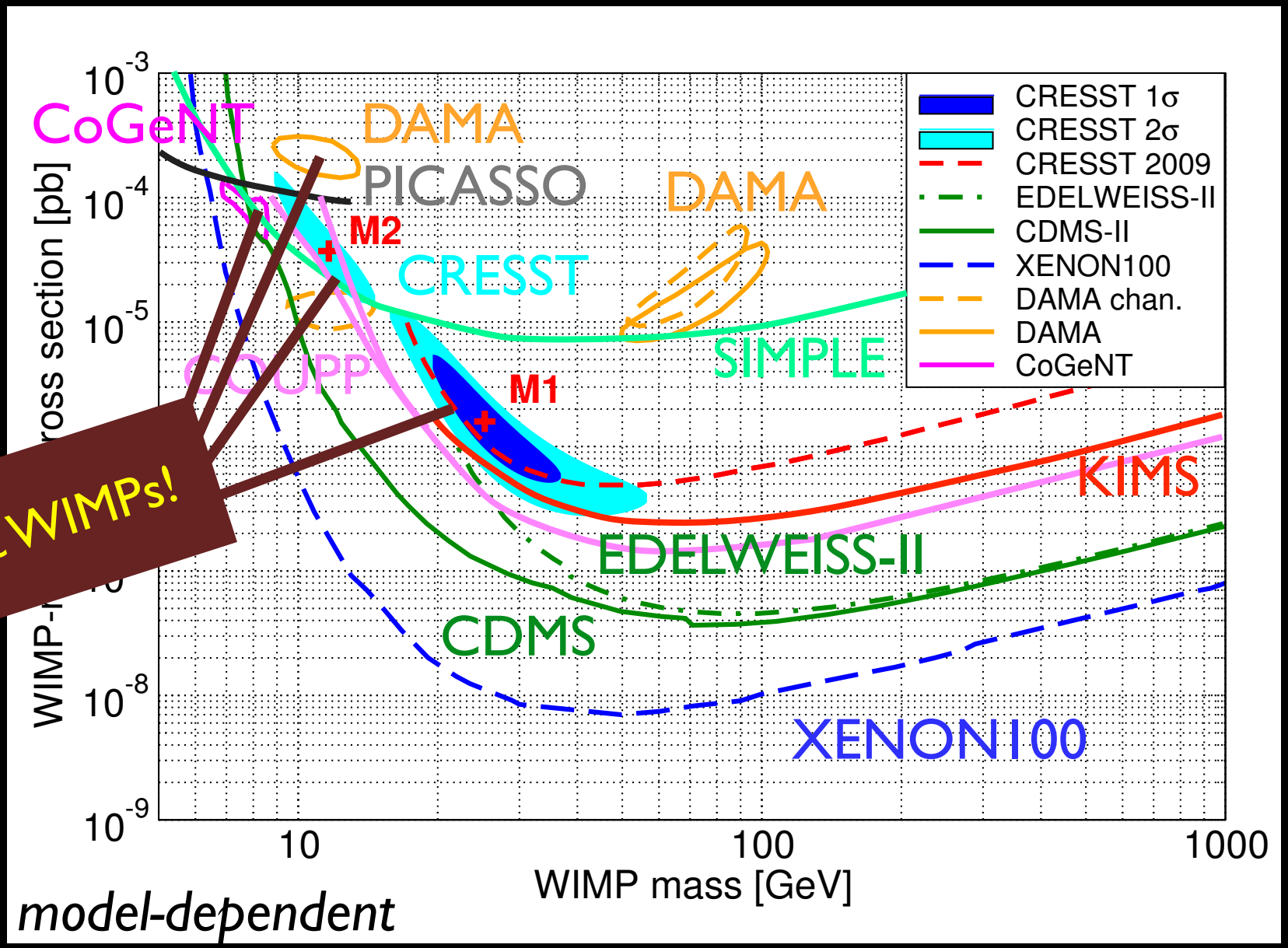
Spin-independent (June 2012)



1pb = 10^{-36} cm^2

Updated from Anglehor et al 2011

Spin-independent (June 2012)

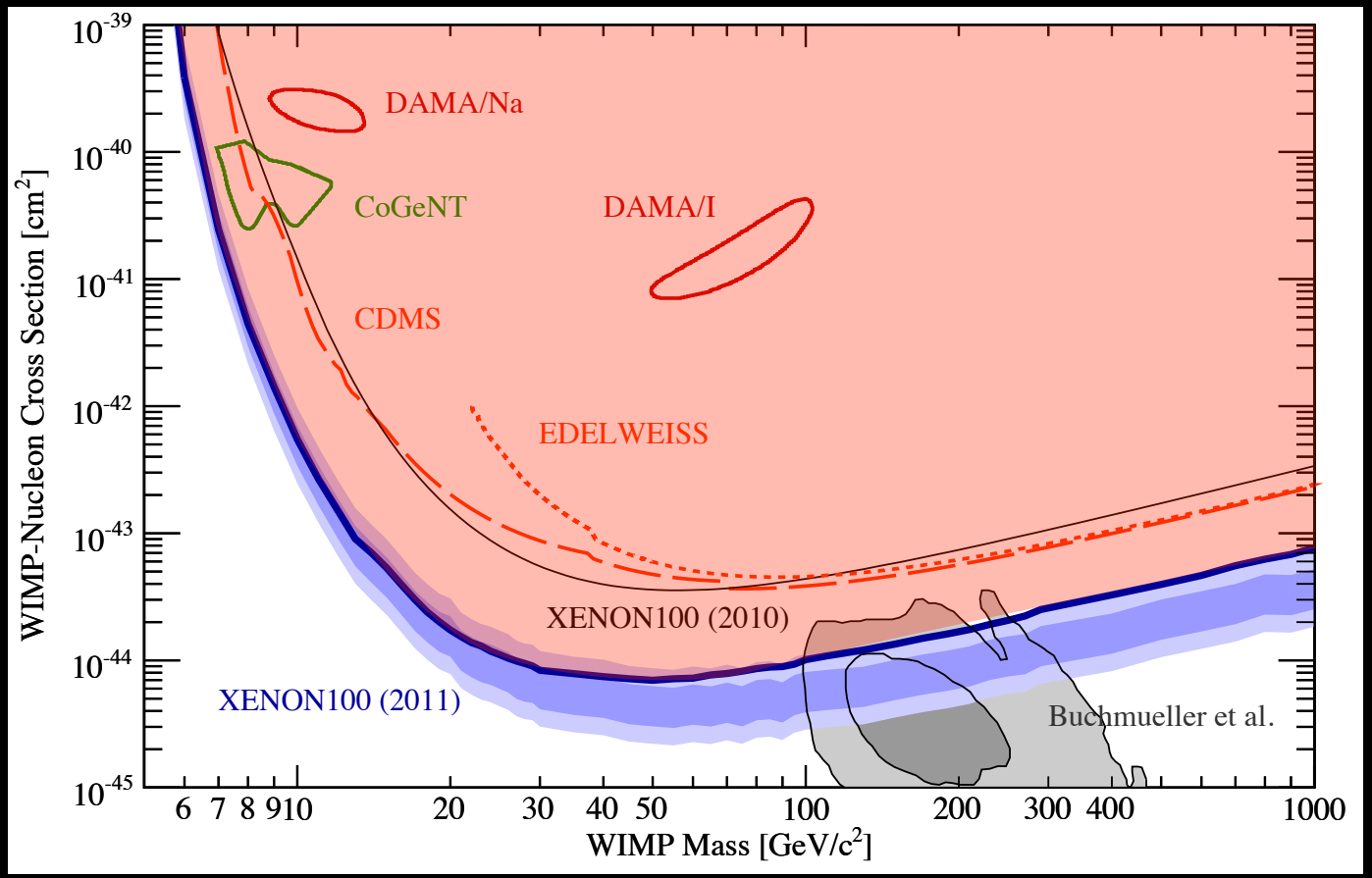


1pb = 10^{-36} cm^2

Updated from Anglehor et al 2011

Limits from XENON-100, KIMS, CDMS, ...

Upper limit on WIMP-nucleon cross section from XENON-100 (model dependent)



3 events observed

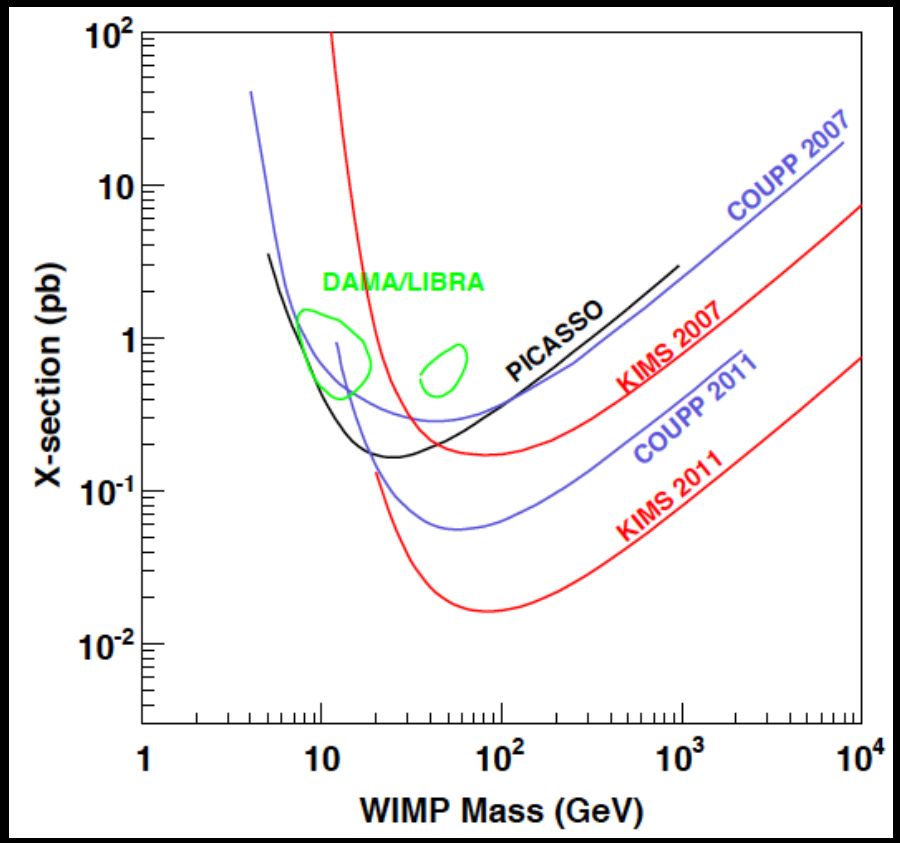
1.8±0.6 expected background

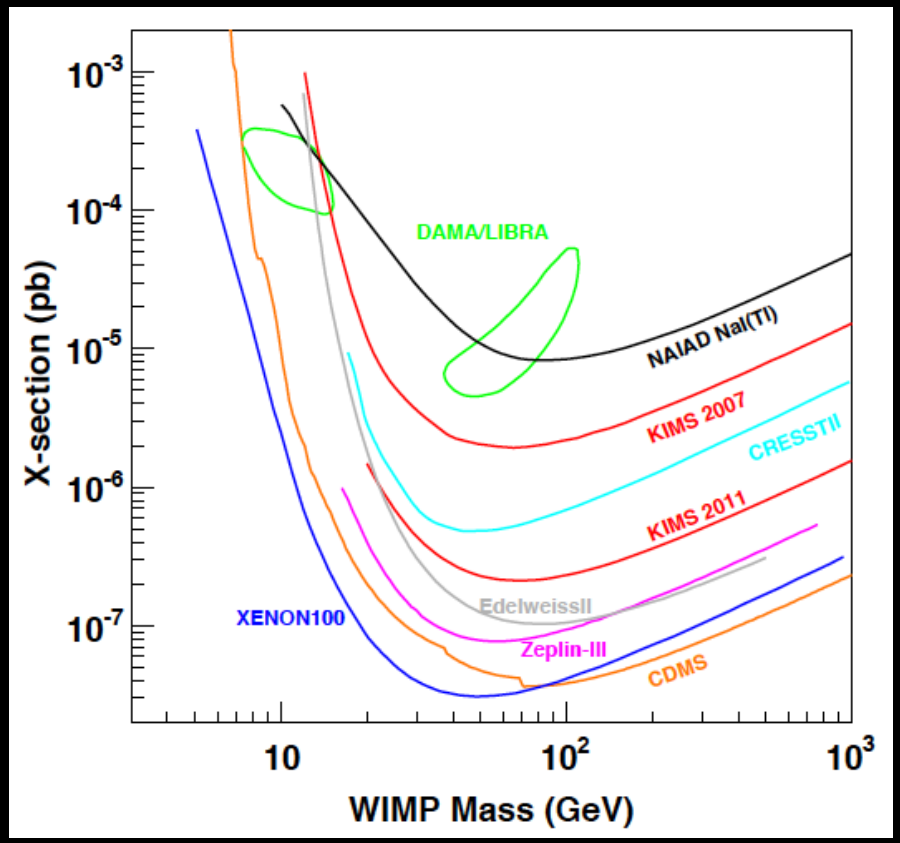
Aprile et al (XENON-100) 1104.2549

Limits from XENON-100, KIMS, CDMS, ...

KIMS: CsI scintillation detector
(similar to DAMA)

- *Excludes inelastic dark matter*
- *Excludes 60 GeV/c^2 DAMA region*

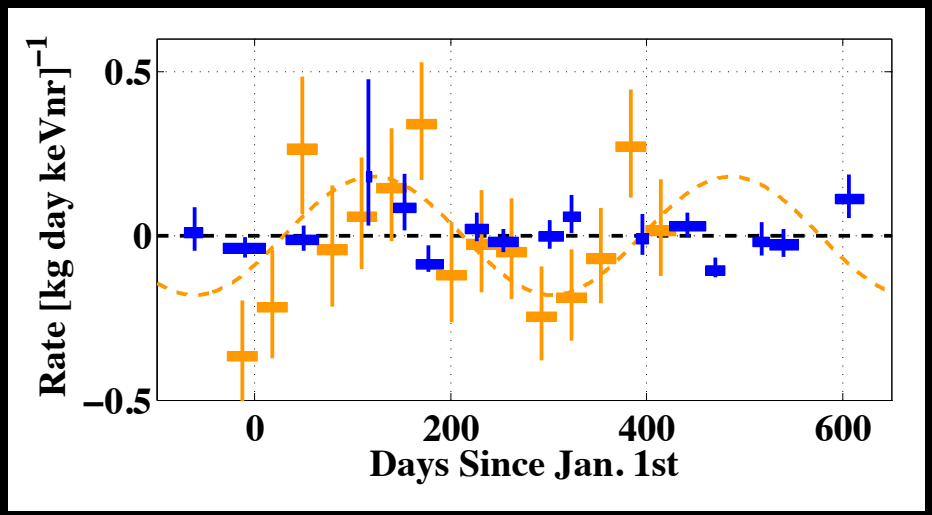




Without using detectors with large surface α background

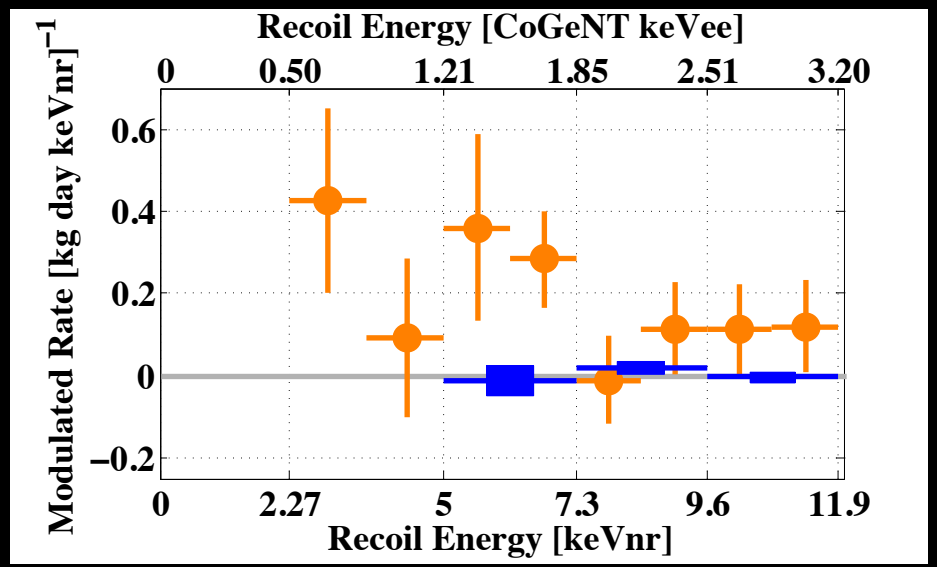
Kim at TAUP 2011

Limits from XENON-100, KIMS, CDMS, ...



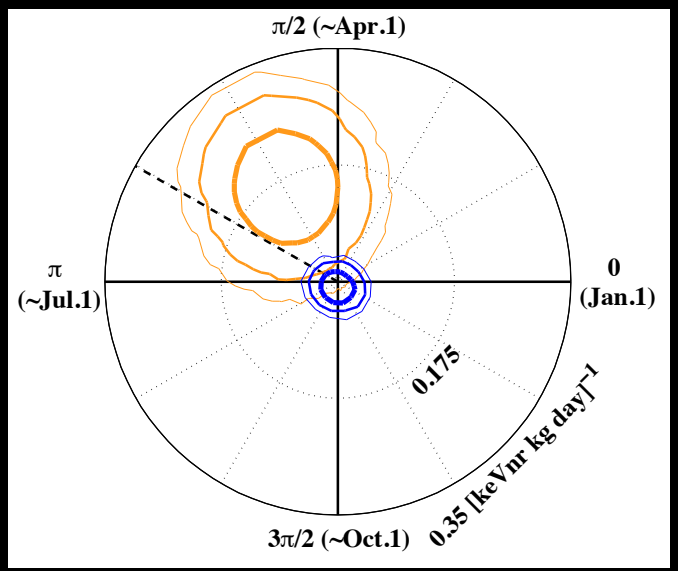
CDMS does not observe an annual modulation and constrains its amplitude

Ahmed et al 1203.1309

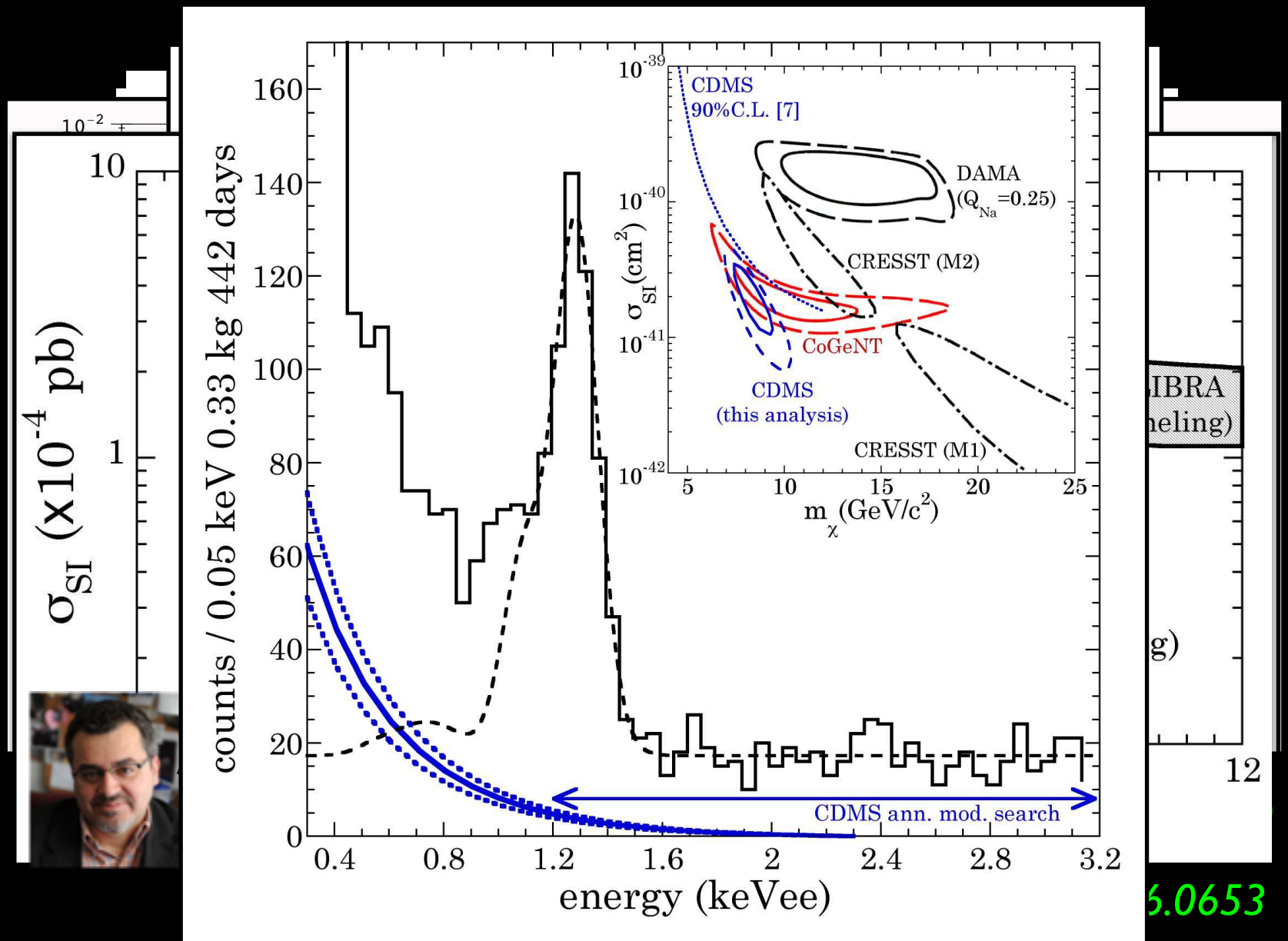


model-independent

CoGeNT CDMS



CoGeNT & DAMA vs. XENON, CDMS, et al



Collar Fields 1204.3559

The expected number of events

$$\begin{pmatrix}\text{number of}\\ \text{events}\end{pmatrix} = (\text{exposure}) \times \begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} \otimes \begin{pmatrix}\text{recoil}\\ \text{rate}\end{pmatrix}$$

$$\begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} = \begin{pmatrix}\text{energy}\\ \text{response function}\end{pmatrix} \times \begin{pmatrix}\text{counting}\\ \text{acceptance}\end{pmatrix}$$

$$\begin{pmatrix}\text{recoil}\\ \text{rate}\end{pmatrix} = \begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} \times (\text{astrophysics})$$

The expected number of events

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$$\begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} = \boxed{\begin{pmatrix}\text{energy}\\ \text{response function}\end{pmatrix}} \times \begin{pmatrix}\text{counting}\\ \text{acceptance}\end{pmatrix}$$

$$\begin{pmatrix}\text{recoil}\\ \text{rate}\end{pmatrix} = \begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} \times (\text{astrophysics})$$

Detector response model

From measured energy to recoil energy

$$\begin{pmatrix}\text{energy}\\ \text{response function}\end{pmatrix} = g(E_{\text{ee}}, E)$$

Recoil energy (keV)

Energy observed in detector, typically expressed in keV electron equivalent (keV_{ee})

Typically written as a single Gaussian with mean value

$$E_{\text{ee}} = \boxed{Q}\,E$$

Quenching factor

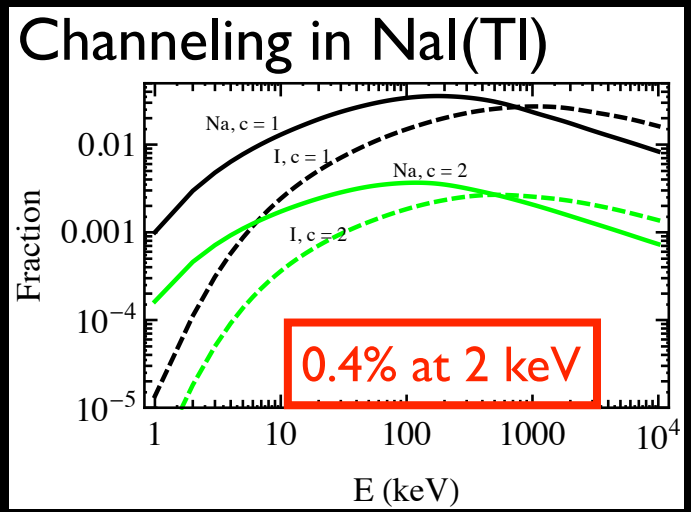
and standard deviation σ_E, but *may be different.*

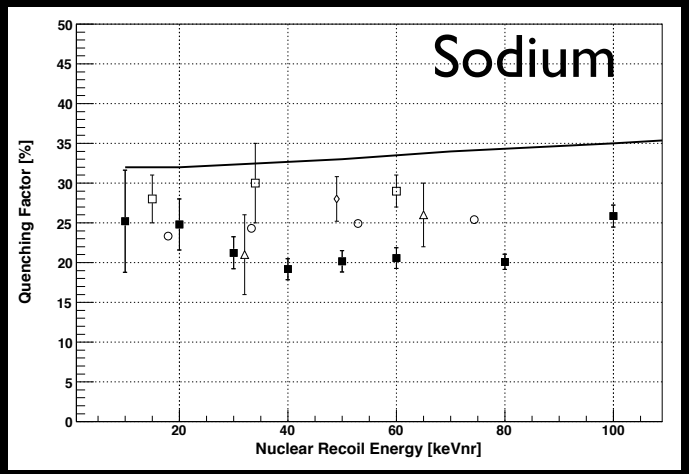
Detector response model

Bozorgnia et al 2010

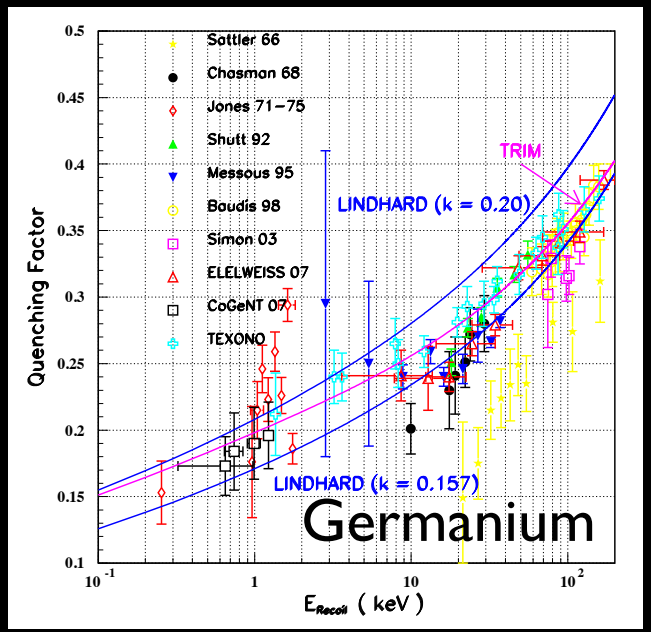
Quenching factor $E_{\rm ee} = \boxed{Q} E$

This is where one can tweak to make experiments compatible.

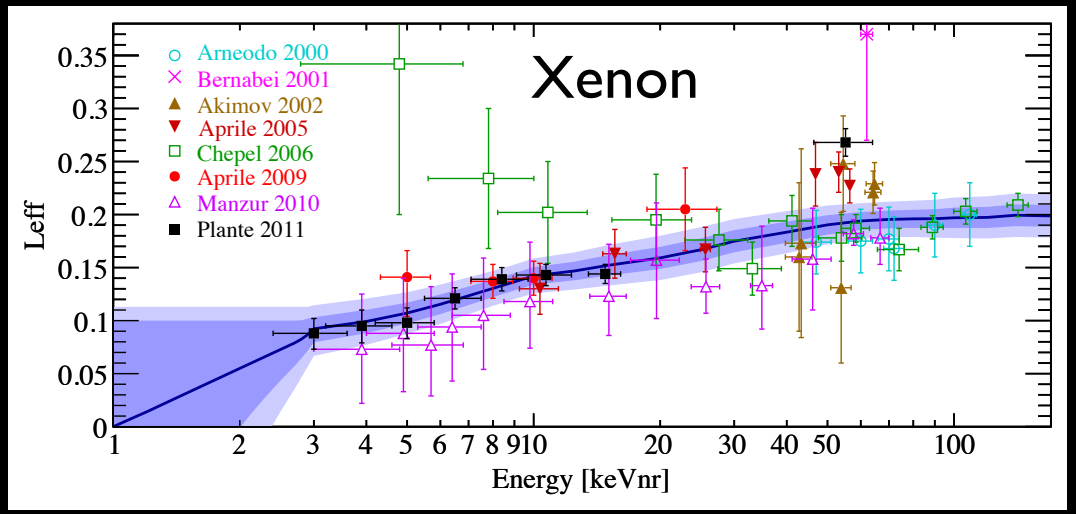




Chagani et al 0806.1916



Lin et al (TEXONO) 2007



Aprile et al (XENON100), 1104.2549

The expected number of events

$$\begin{pmatrix}\text{number of}\\ \text{events}\end{pmatrix} = (\text{exposure}) \times \begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} \otimes \begin{pmatrix}\text{recoil}\\ \text{rate}\end{pmatrix}$$

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$$\begin{pmatrix}\text{recoil}\\ \text{rate}\end{pmatrix} = \begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} \times \boxed{(\text{astrophysics})}$$

Astrophysics model

How much dark matter comes to Earth?

$$(\text{astrophysics}) = \rho \int_{v > v_{\min}(E)} \frac{f(\vec{v}, t)}{v} \, \mathrm{d}^3 v$$

Astrophysics model

How much dark matter comes to Earth?

Local halo density

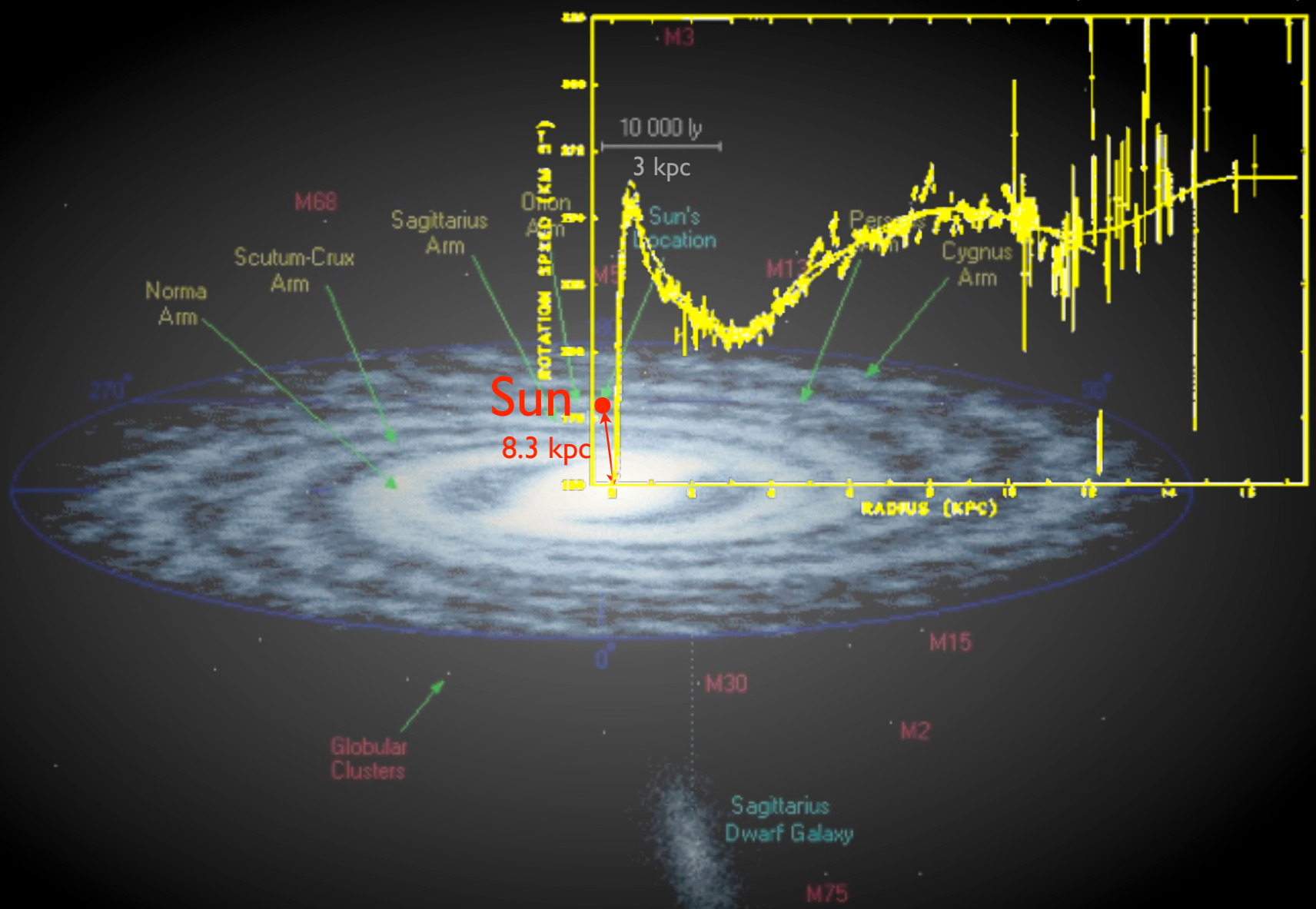
Velocity distribution

$$(\text{astrophysics}) = \rho \int_{v > v_{\min}(E)} \frac{f(\vec{v}, t)}{v} \, \mathrm{d}^3 v$$

Minimum speed to impart energy E, $v_{\min}(E) = (ME/\mu + \delta)/\sqrt{2ME}$

Astrophysics model

Rotation curve (Clemens 1985)



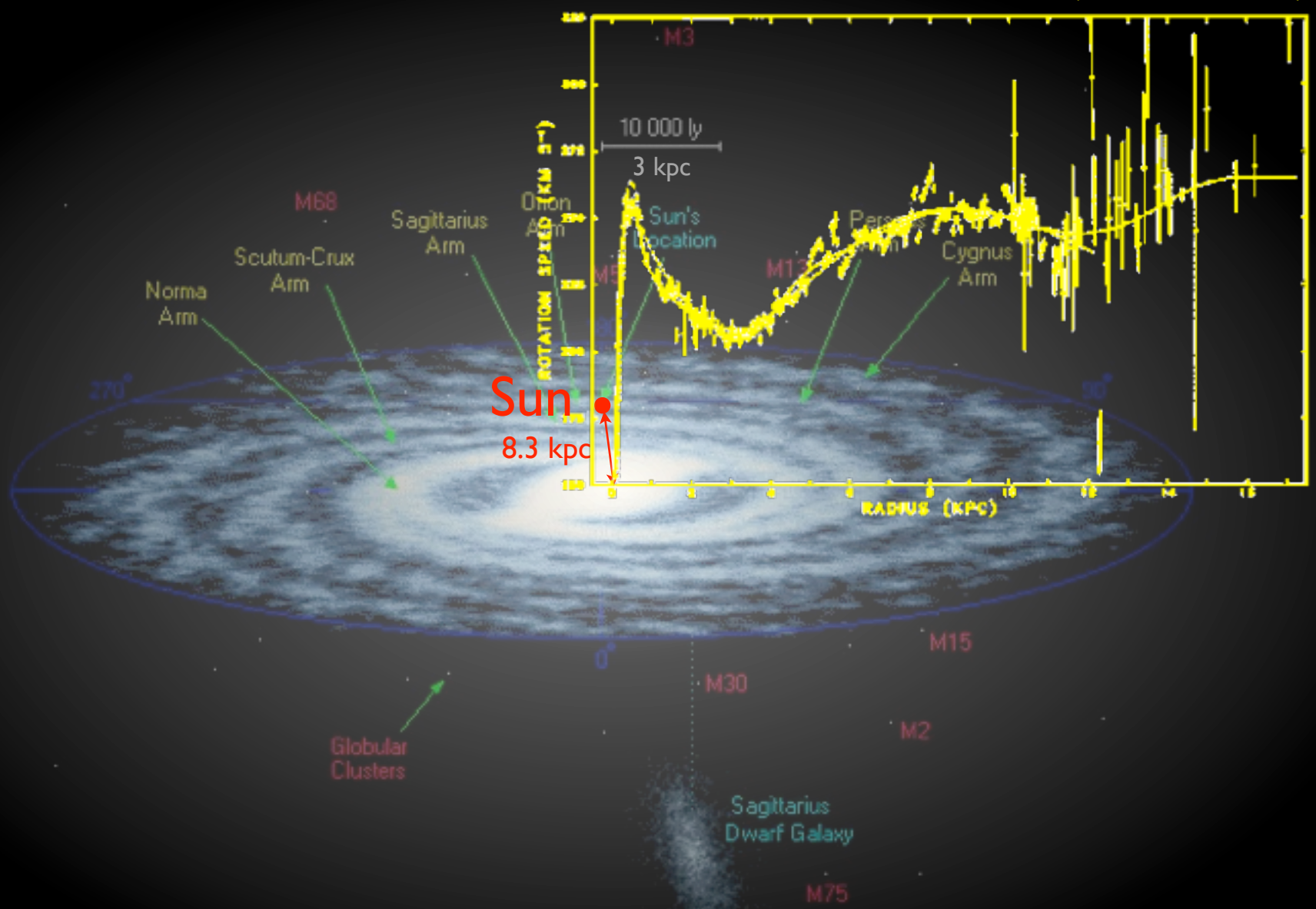
Our galaxy is inside a halo of dark matter particles

1 kpc = 2.06×10^{11} AU

Image by R. Powell using DSS data

Astrophysics model

Rotation curve (Clemens 1985)



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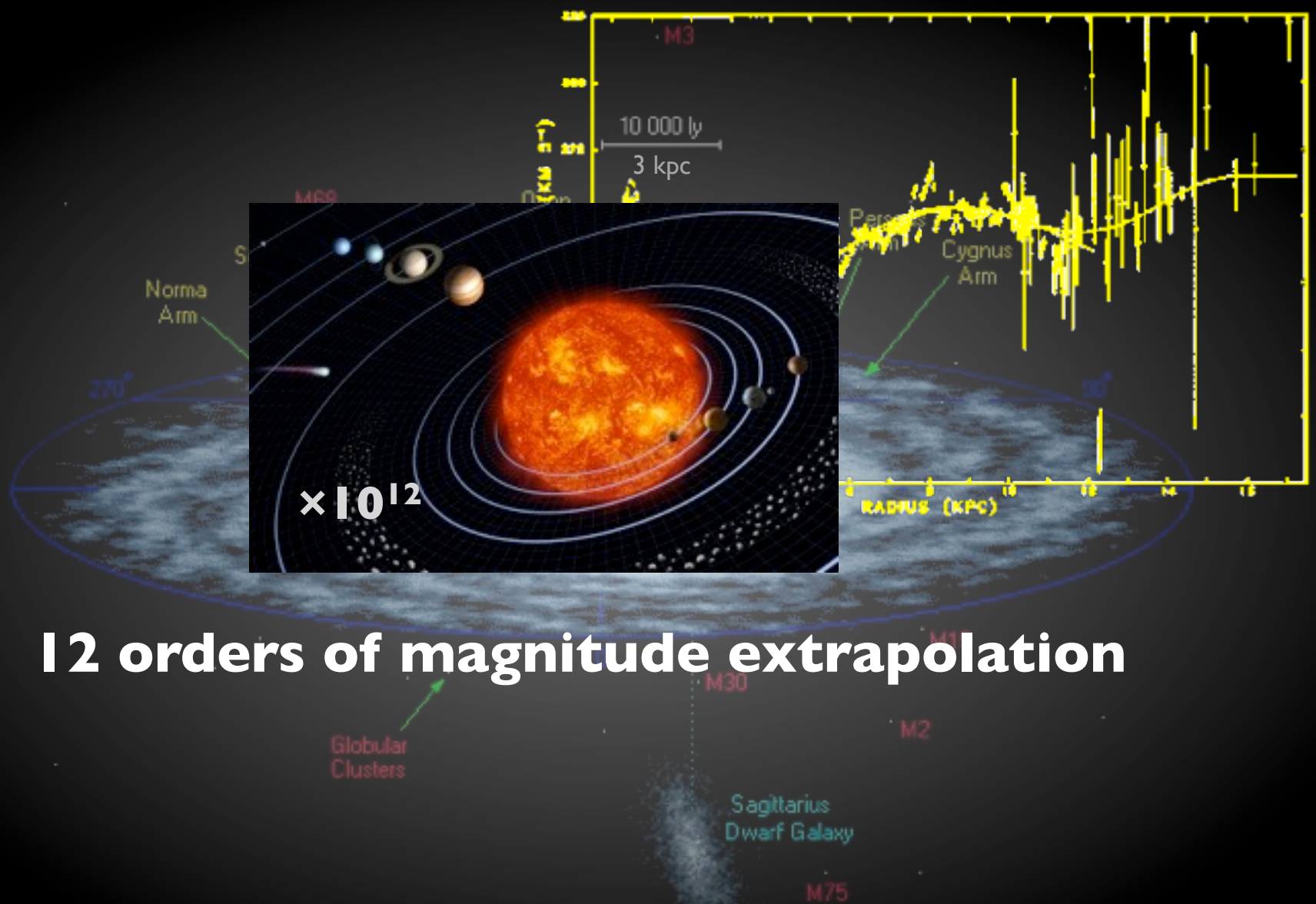


12 orders of magnitude extrapolation

Our galaxy is inside a halo of dark matter particles

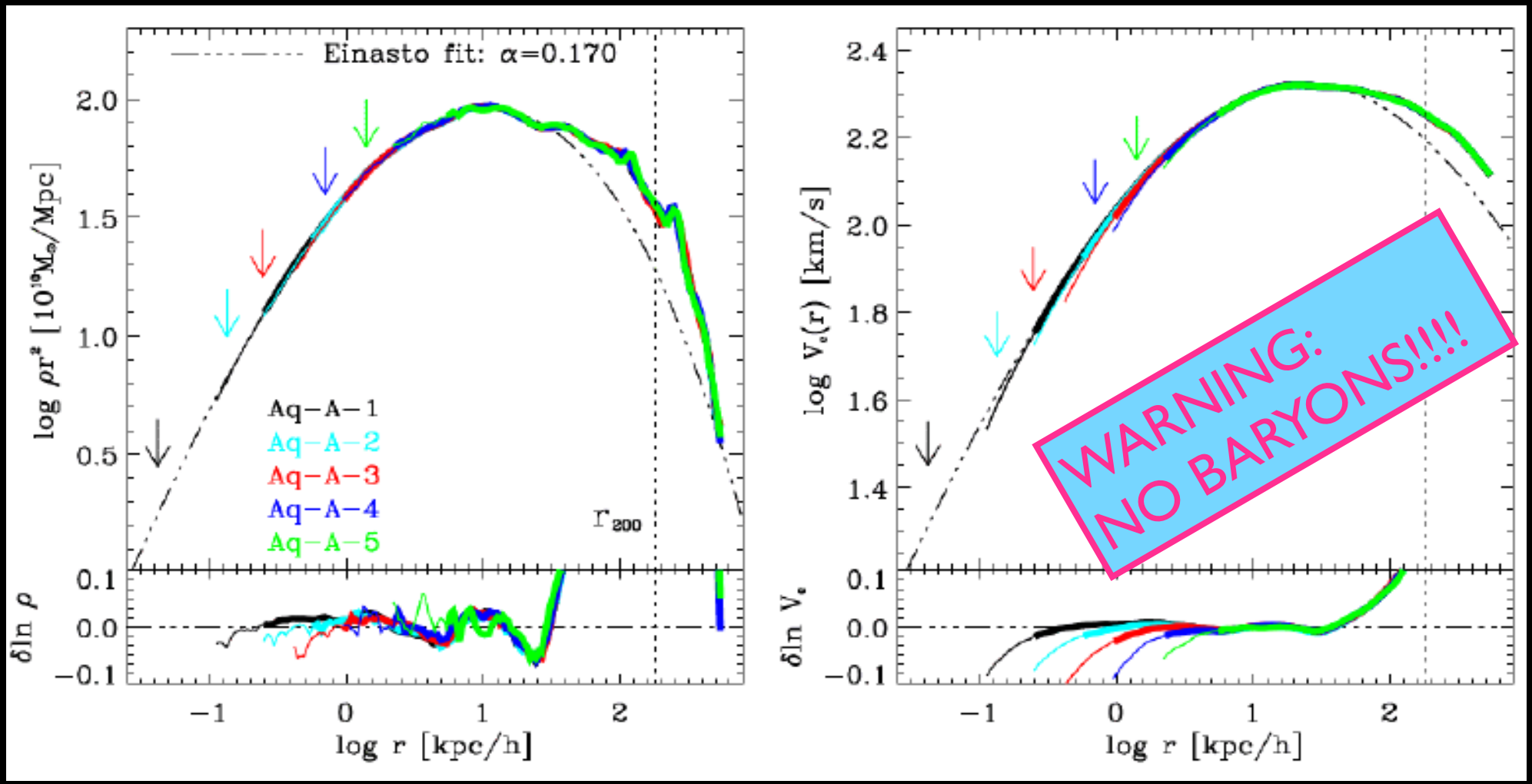
1 kpc = 2.06×10^{11} AU

Image by R. Powell using DSS data

Astrophysics model: local density

Galactic density profile from Aquarius simulations

$$\rho(r) \propto \exp\left(-Ar^{\alpha}\right).$$



Diemand's comments on "Via Lactea":

our approach:

collisionless (pure N-body, DM only) simulations

- treat all of Omega_m like dark matter
- bad approximation near and in large galaxies
  OK for dwarf galaxies and smaller scales
- simple physics: just gravity, good #CPU scaling → allows high resolution
- no free parameters (ICs known thanks to CMB + ...)

→ accurate solution of the idealized problem

complementary approach:

hydrodynamical simulations

- computationally expensive, resolution relatively low
- SPH and grid disagree even in simple tests, Agertz et al 2007
- processes far below the resolved scales (star formation, SN, ... ?)
  implemented through uncertain functions and free parameters

→ approximate solution of the more realistic problem

Courtesy J. Diemand

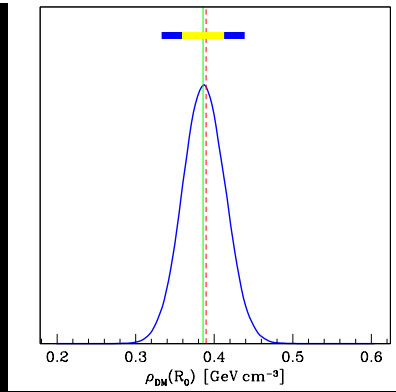
Astrophysics model: local density

$$\rho_\odot = \left(0.430 \pm 0.113_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right)\frac{\mathrm{GeV}}{\mathrm{cm}^3}\,.$$

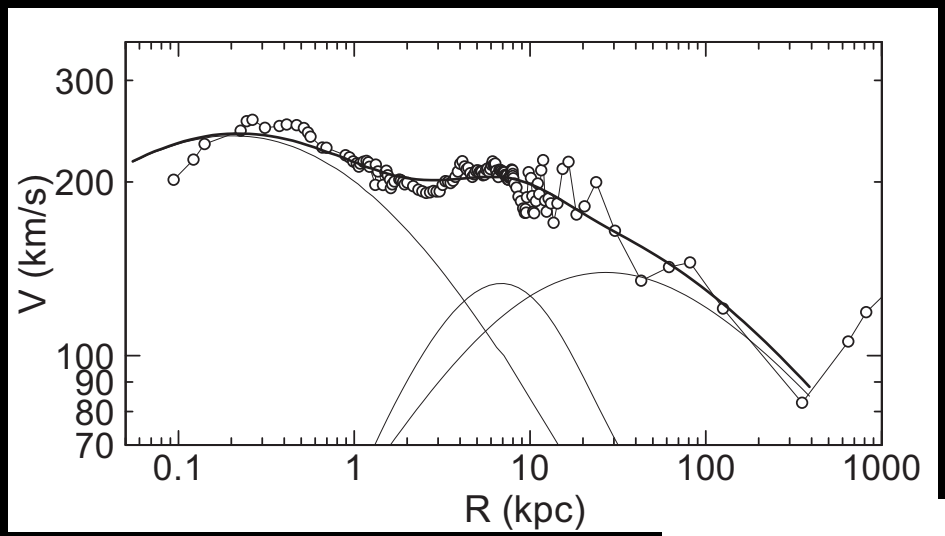
Salucci et al 2010

$$\rho_{DM}(R_0) = 0.385 \pm 0.027\,\mathrm{GeV\ cm^{-3}}$$

Ullio, Catena 2009

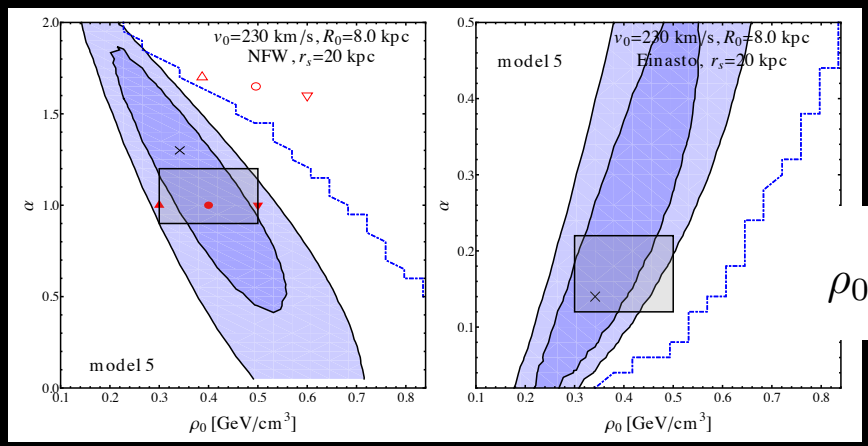


Local density from galactic modeling



Sofue 2011

$$\rho_0^\odot = 0.235 \pm 0.030\ \mathrm{GeV\ cm^{-3}}$$



$$\rho_0 = 0.20 - 0.55\ \mathrm{GeV/cm^3}$$

Iocco, Pato, Bertone, Jetzer 2010

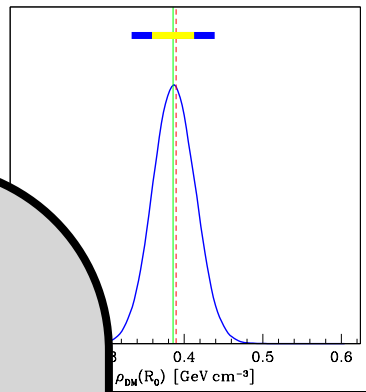
Astrophysics model: local density

$$\rho_\odot = \left(0.430 \pm 0.113_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right)\frac{\mathrm{GeV}}{\mathrm{cm}^3}\,.$$

Salucci et al 2010

$$\rho_{DM}(R_0) = 0.385 \pm 0.027\,\mathrm{GeV\ cm}^{-3}$$

Ullio, Catena 2009



Lo
gal

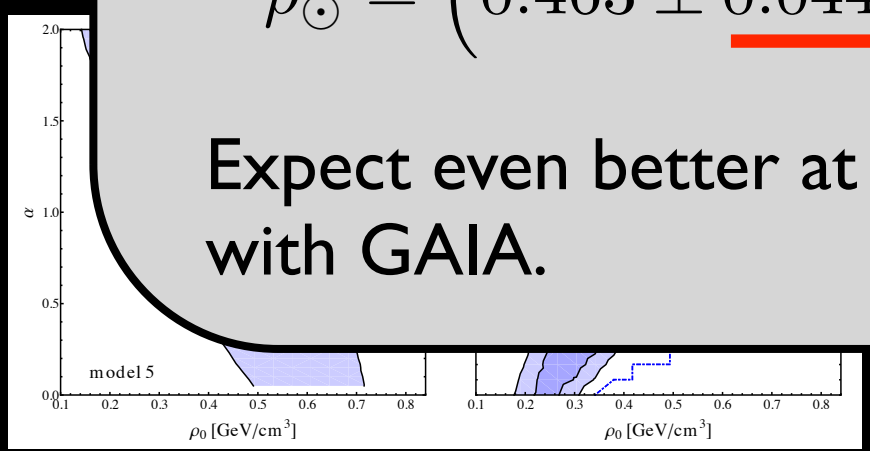
The most direct method, requiring only local measurements of the disk contribution and the slope of rotation curve at the Sun's distance.
Now even more precise with preliminary VERA:

Honma at NDM12

$$\rho_\odot = \left(0.463 \pm 0.044_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right)\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

cm^{-3}

Expect even better at VERA completion and with GAIA.

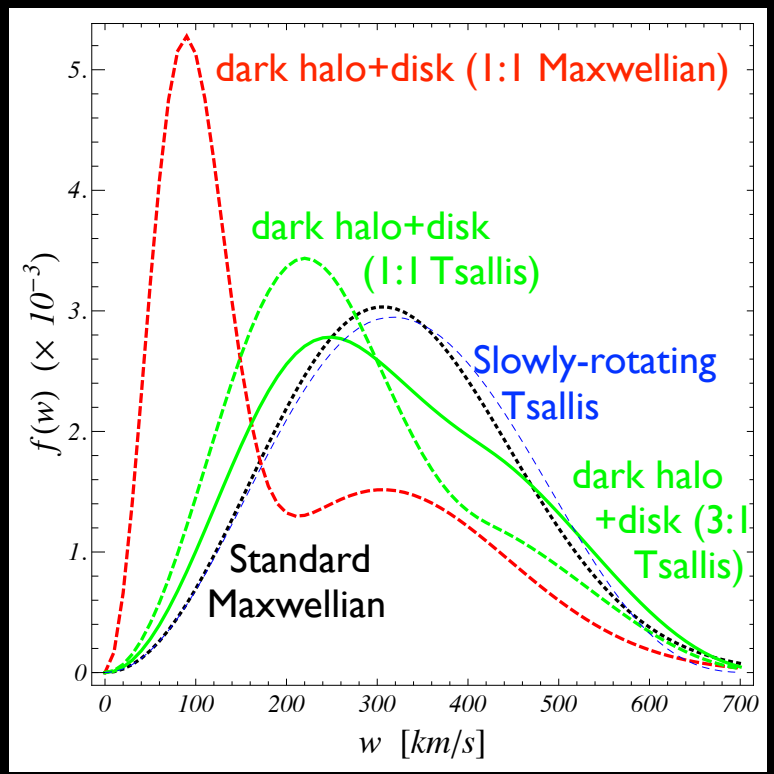


Iocco, Pato, Bertone, Jetzer 2010

Astrophysics model: velocity distribution

The local density may be "known" within a factor of 2, but the velocity distribution is still very very uncertain

Analytic models

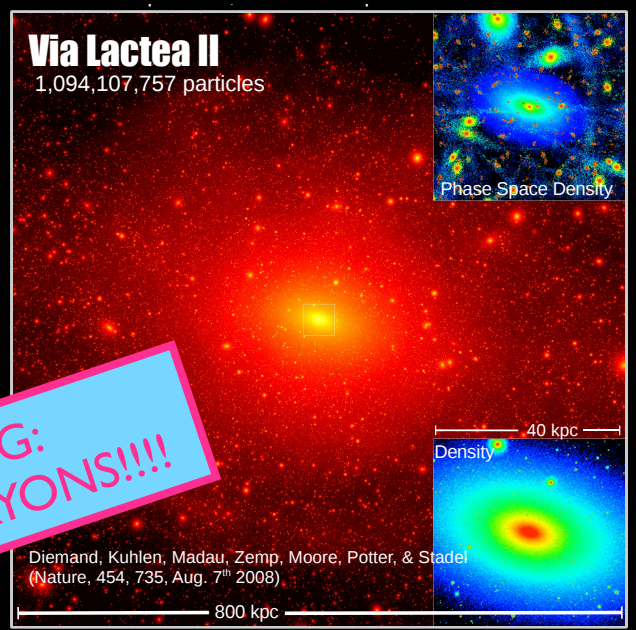


Ling 2009

N-body simulations

Read et al 2008

Kuhlen et al



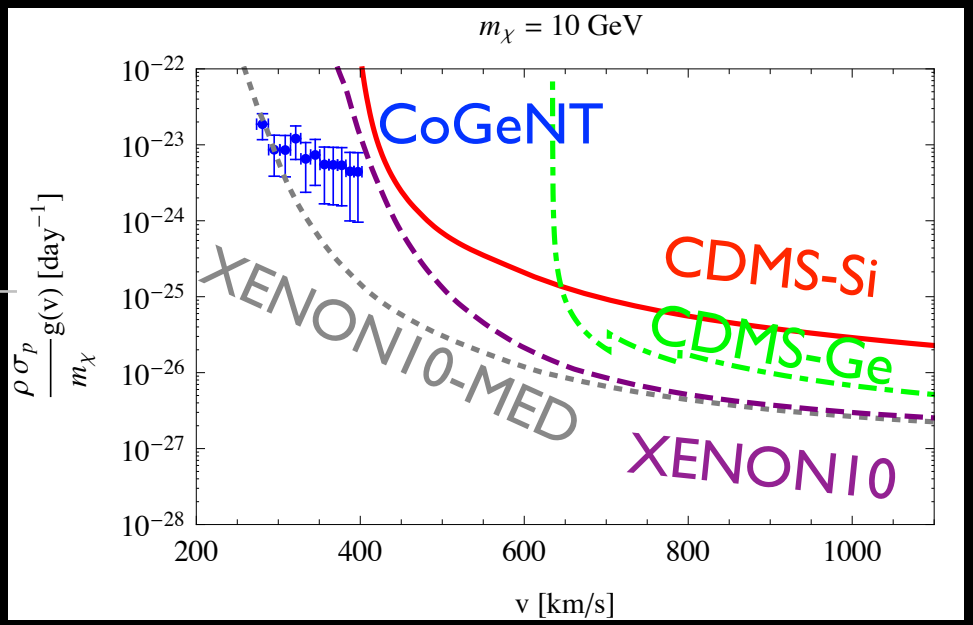
WARNING:
NO BARYONS!!!!

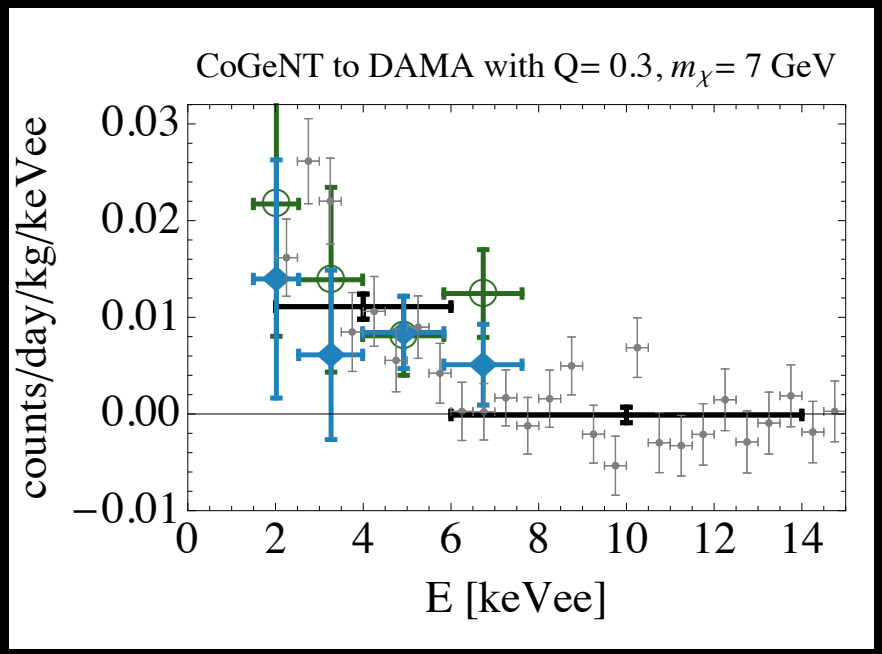
Astrophysics-independent approach

Fox, Liu, Weiner 2011

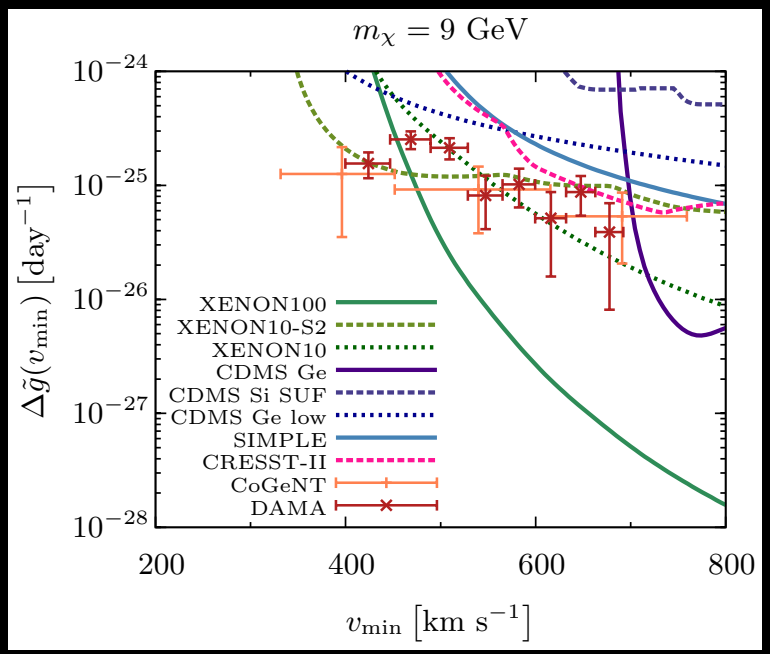
Astrophysics factor

$$\frac{\rho_\chi \sigma_{\chi p} c^2}{m_\chi} \int_v^\infty \frac{f(v')}{v'} dv'$$



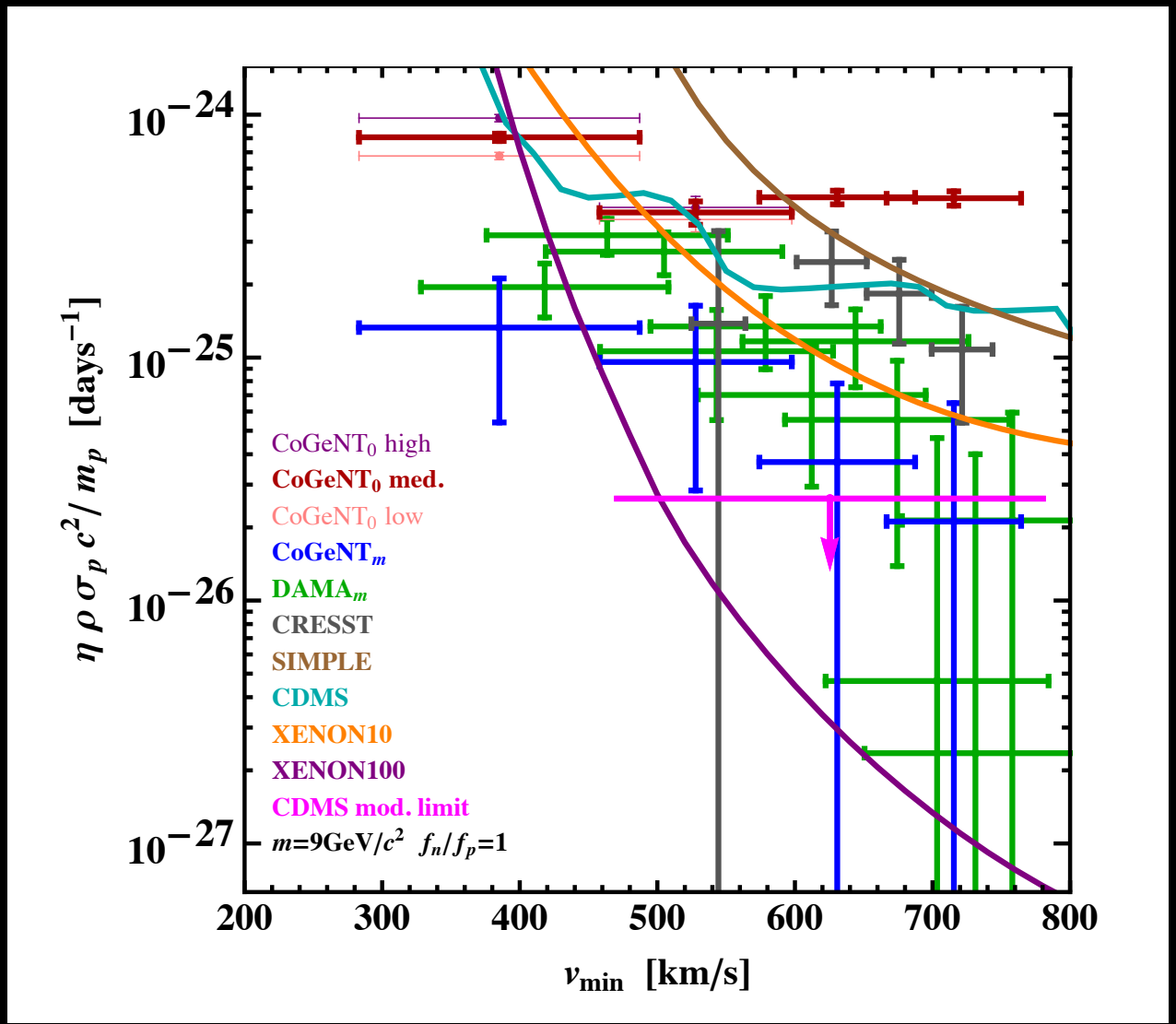


Fox, Kopp, Lisanti, Weiner 2011



Frandsen et al 2011

Astrophysics-independent approach



Still depends on particle model

Analysis extends Fox, Liu, Weiner method to include energy response function

Gondolo Gelmini 1202.6359

The expected number of events

$$\begin{pmatrix}\text{number of}\\ \text{events}\end{pmatrix} = (\text{exposure}) \times \begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} \otimes \begin{pmatrix}\text{recoil}\\ \text{rate}\end{pmatrix}$$

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$$\begin{pmatrix}\text{recoil}\\ \text{rate}\end{pmatrix} = \boxed{\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix}} \times (\text{astrophysics})$$

Particle physics model

What force couples dark matter to nuclei?

$$\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} = \frac{\sigma_{SI}(E) + \sigma_{SD}(E)}{2m\mu^2}$$

$$\sigma(E) = E_{\max}\frac{d\sigma}{dE} = \frac{2\mu^2 v^2}{m}\frac{d\sigma}{dE}$$

Particle physics model

What force couples dark matter to nuclei?

Spin-independent and spin-dependent cross sections

$$\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix} = \frac{\sigma_{SI}(E) + \sigma_{SD}(E)}{2m\mu^2}$$

Reduced mass $\mu = mM/(m+M)$

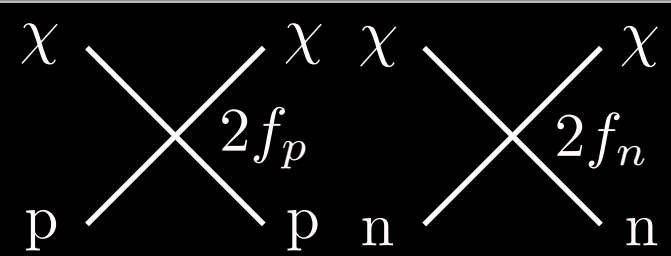
$$\sigma(E) = E_{\max}\frac{d\sigma}{dE} = \frac{2\mu^2 v^2}{m}\frac{d\sigma}{dE}$$

Particle physics model

Scalar and vector currents give spin-independent terms

$$\sigma_{SI}(E) = \frac{4\mu^2}{\pi}\left|Zf_p + (A-Z)f_n\right|^2 \left|F(E)\right|^2$$

Effective four-particle vertices



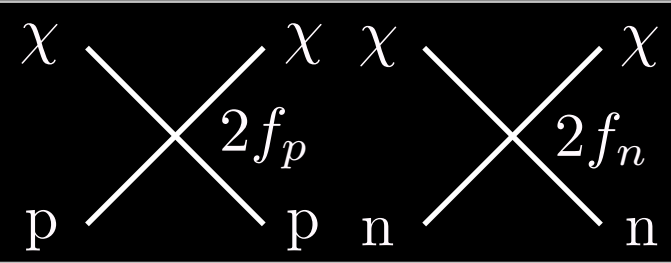
Nuclear density form factor

Particle physics model

Scalar and vector currents give spin-independent terms

$$\sigma_{SI}(E) = \frac{4\mu^2}{\pi}\left|Zf_p + (A-Z)f_n\right|^2 \left|F(E)\right|^2$$

Effective four-particle vertices



Nuclear density form factor

Example: neutralino

$$2f_p \simeq 2f_n \simeq \sum_q \langle \bar{q}q \rangle \left[-\sum_h \frac{g_{h\chi\chi} g_{hqq}}{m_h^2} + \sum_{\tilde{q}} \frac{g_{L\tilde{q}\chi q} g_{R\tilde{q}\chi q}}{m_{\tilde{q}}^2} \right]$$

Main uncertainty is $\langle m_s \bar{s} s \rangle$ (strange content of nucleon)

Particle physics model

Axi

σ

E
p

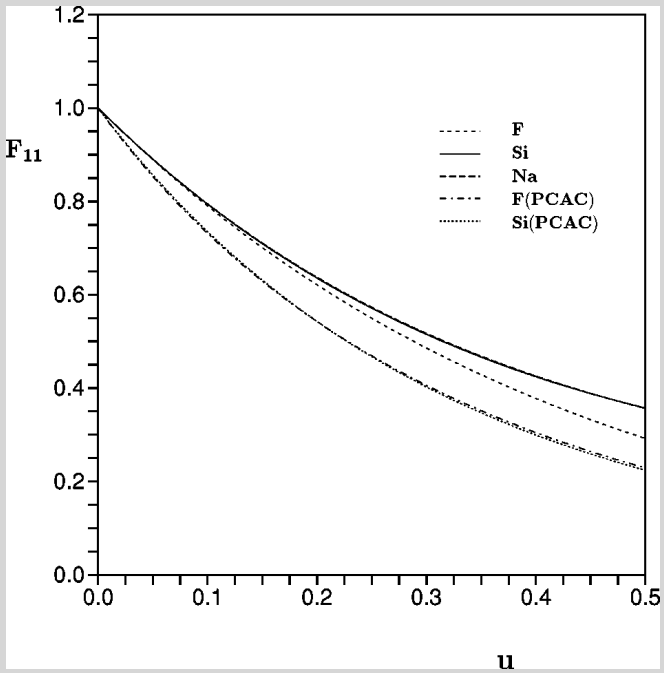
in
tions

Exa

Nuclear spin structure functions

$$H_{\rm SD}^{\rm nuc} = \hat{\mathbf{s}}_\chi(0) \cdot \int \hat{\mathbf{j}}_{\rm SD}(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}\, d\mathbf{r}$$

$$\hat{\mathbf{j}}_{\rm SD}(\mathbf{r}) = \sum_{i=1}^{A} \left[G_{\rm SD}^0 + G_{\rm SD}^1 \tau_3(i)\right]\, \boldsymbol{\sigma}(i)\, \delta(\mathbf{r} - \mathbf{r}_i)$$



Divari, Kosmas, Vergados, Skouras 2000

Main uncertainty is nuclear spin structure functions $S(q)$

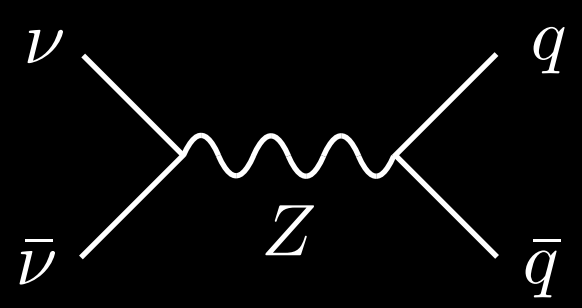
A few particle models for light WIMPs*

Models		References
SUSY	MSSM neutralino	*Goldberg 1983; Griest 1988; Gelmini, Gondolo, Roulet 1989; Griest, Roszkowski 1991; Bottino et al 2002-11; ~~Kuflik, Pierce, Zurek 2010~~; ~~Feldman et al 2010~~; ~~Cumberbatch et al 2011~~; Belli et al 2011; .....*
	beyond-MSSM neutralino	*Flores, Olive, Thomas 1990; Gunion, Hooper, McElrath 2005; Belikov, Gunion, Hooper, Tait 2011; Belanger, Kraml, Lessa 1105.4878; .....*
	sneutrino	*.....; An, Dev, Cai, Mohapatra 1110.1366; Cerdeno, Huh, Peiro, Seto 1108.0978; .....*
minimalist dark matter (real singlet scalar with Z_2)		*Silveira, Zee 1985; Veltman, Ydnurain 1989; McDonald 1994; Burgess, Pospelov, ter Veldhuis 2000; Davoudiasl, Kitano, Li, Murayama 2004; Andreas et al 2008-10; He, Tandean 1109.1267; .....*
technicolor and alike		*....; Lewis, Pica, Sannino 1109.3513; .....*
kinetically-mixed U(1)' (Higgs portal)		*.....; Foot 2003-10; Kaplan et al 1105.2073; An, Gao 1108.3943; Fornengo, Panci, Regis 1108.4661; Andreas, Goodsell, Ringwald 1109.2869; Andreas 1110.2636; Feldman, Perez, Nath 1109.2901; .....*
baryonic U(1)'		*Gondolo, Ko, Omura ; Cline, Frey 1109.4639; .....*
.....		.....

* 1-10 GeV WIMP; very incomplete references.

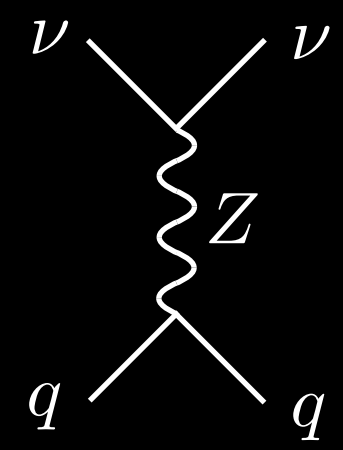
Break the annihilation/scattering relation

Annihilation $\nu\bar{\nu} \longrightarrow q\bar{q}$



Crossing

Scattering $\nu q \longrightarrow \nu q$

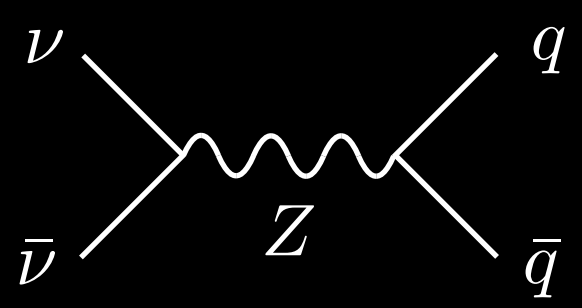


For example, for a ~4 GeV/c² dark matter neutrino, the scattering cross section is

$$\sigma_{\nu n} \simeq 0.01 \frac{\langle \sigma v \rangle}{c} \simeq 10^{-38}\,\mathrm{cm}^2$$

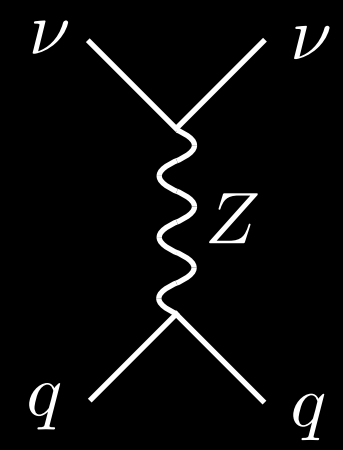
Break the annihilation/scattering relation

Annihilation $\nu\bar{\nu} \longrightarrow q\bar{q}$



Crossing

Scattering $\nu q \longrightarrow \nu q$



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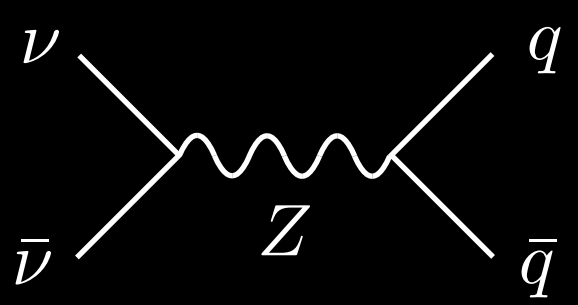
$$\sigma_{\nu n} \simeq 0.01 \frac{\langle \sigma v \rangle}{c} \simeq 10^{-38}\,\mathrm{cm}^2$$

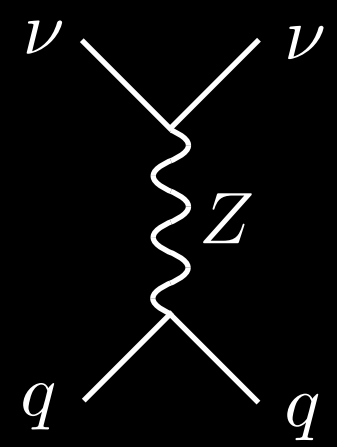
Break the annihilation/scattering relation

Annihilation $\nu\bar{\nu} \to q\bar{q}$

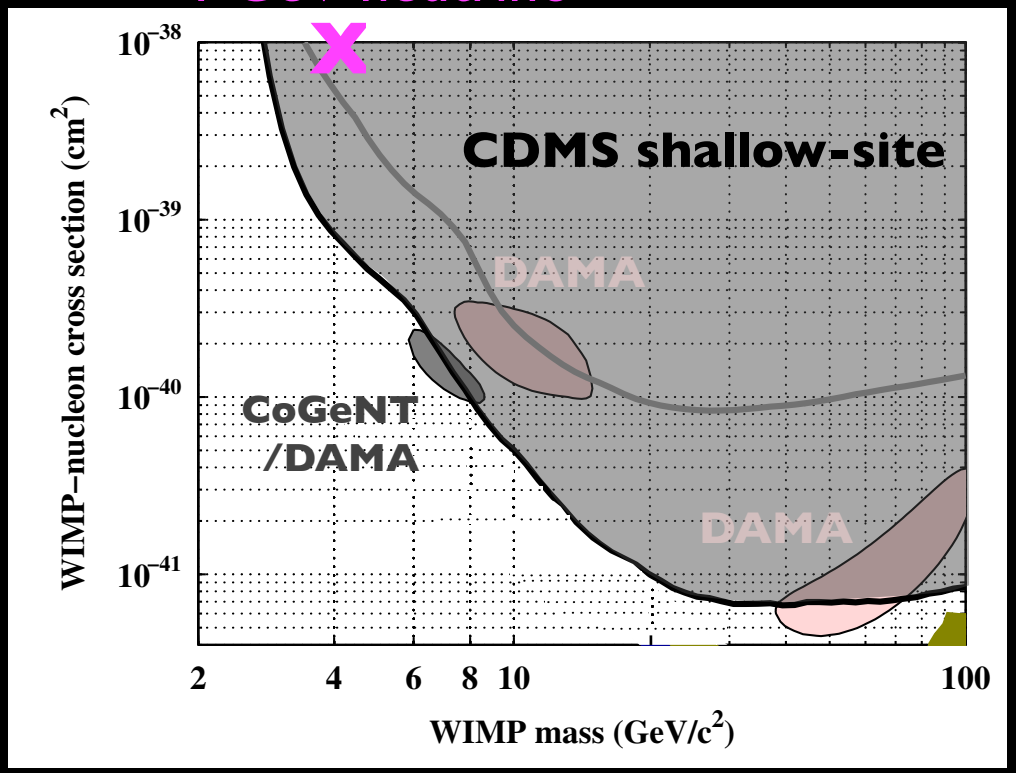


Crossing

Scattering $\nu q \to \nu q$



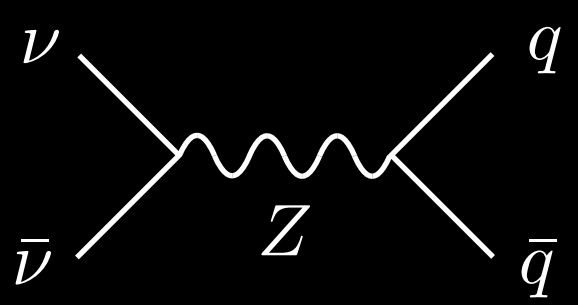
4-GeV neutrino



Akerib et al (CDMS) 2010

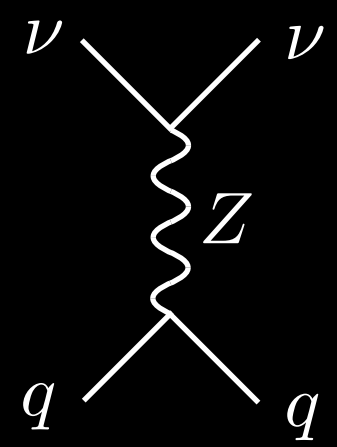
Break the annihilation/scattering relation

Annihilation $\nu\bar{\nu} \to q\bar{q}$

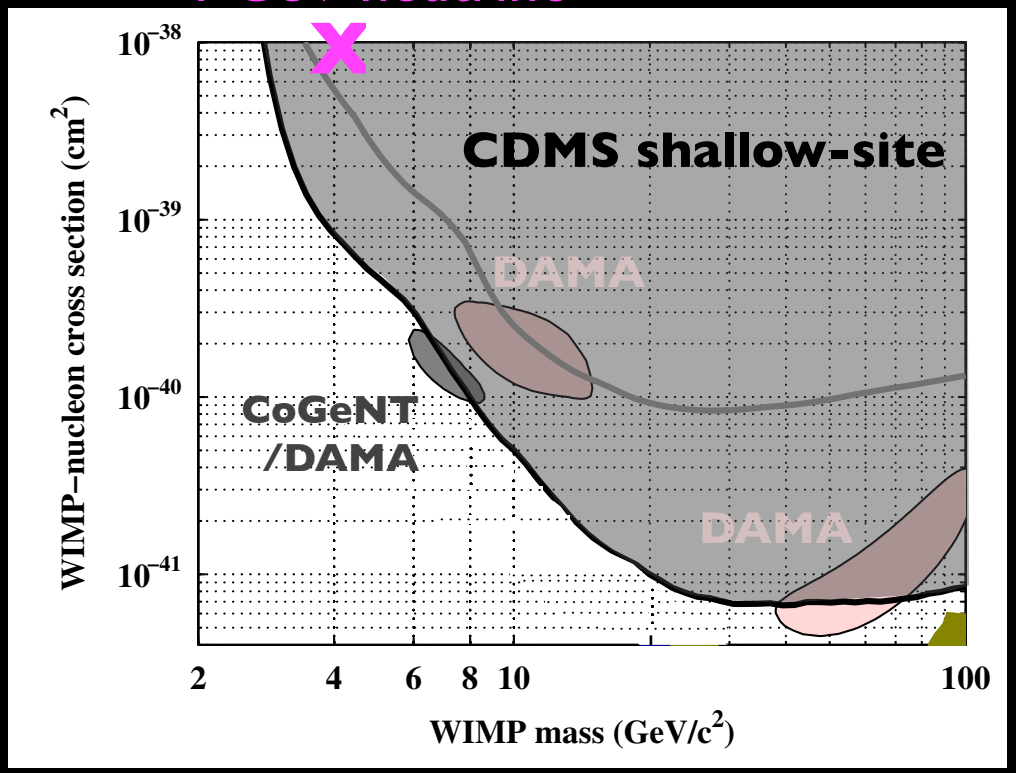


Crossing

Scattering $\nu q \to \nu q$



4-GeV neutrino



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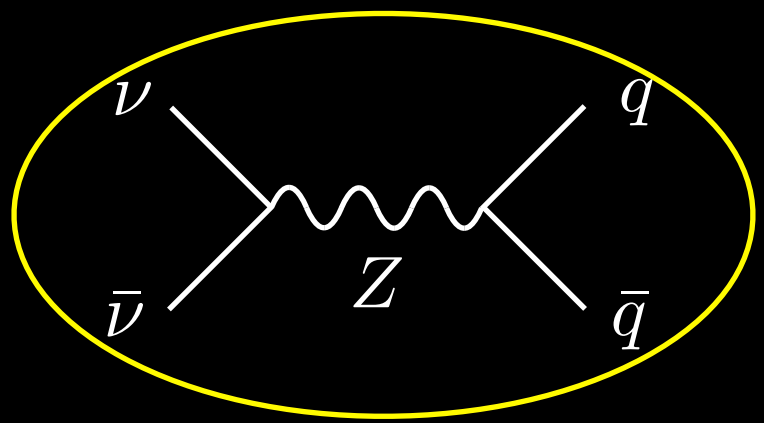
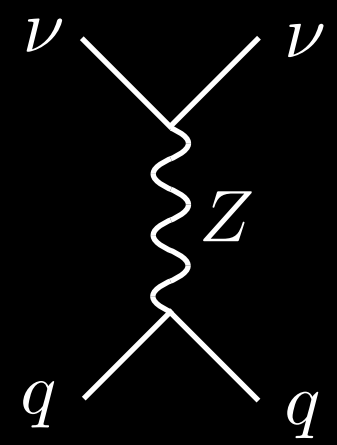


Resonant when $m_\nu \approx m_Z/2$

Crossing

Scattering $\nu q \to \nu q$

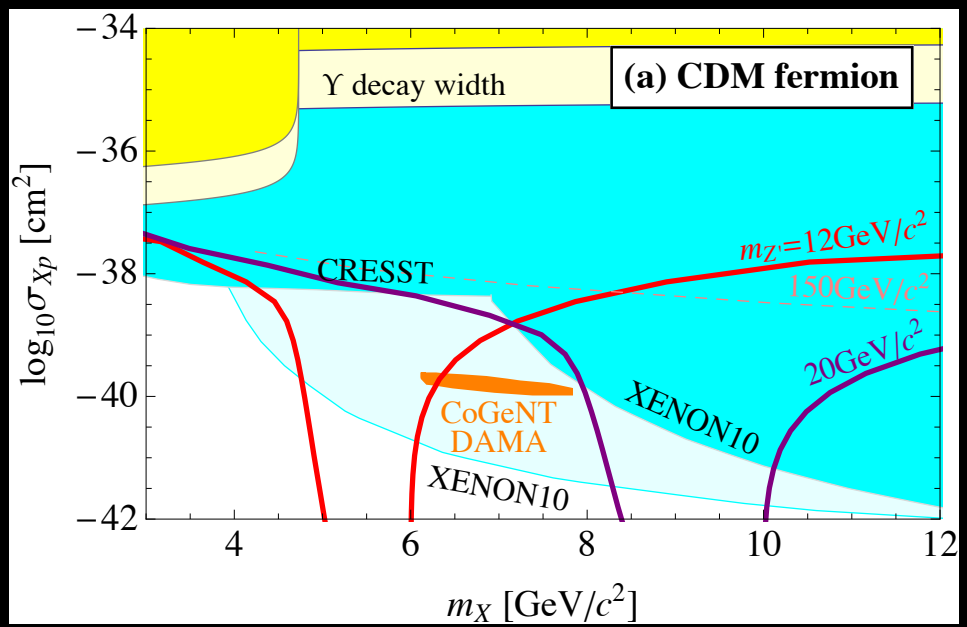


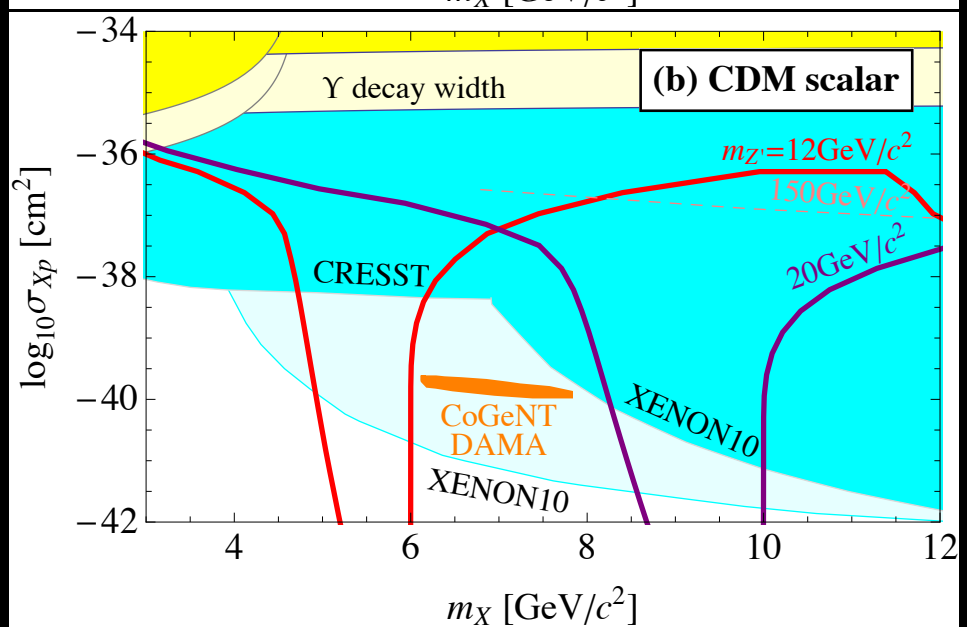
$$\sigma_{\nu n} \simeq \frac{0.02}{1 + m_n/m_\nu} \left(1 - \frac{4m_\nu^2}{m_Z^2}\right)^2 \frac{\langle \sigma v \rangle}{c}$$

$\sigma_{\nu n}$ would perhaps match DAMA/CoGeNT if m_Z were $\approx 2m_\nu$

Try a new particle χ and a new vector boson Z'

Break the annihilation/scattering relation

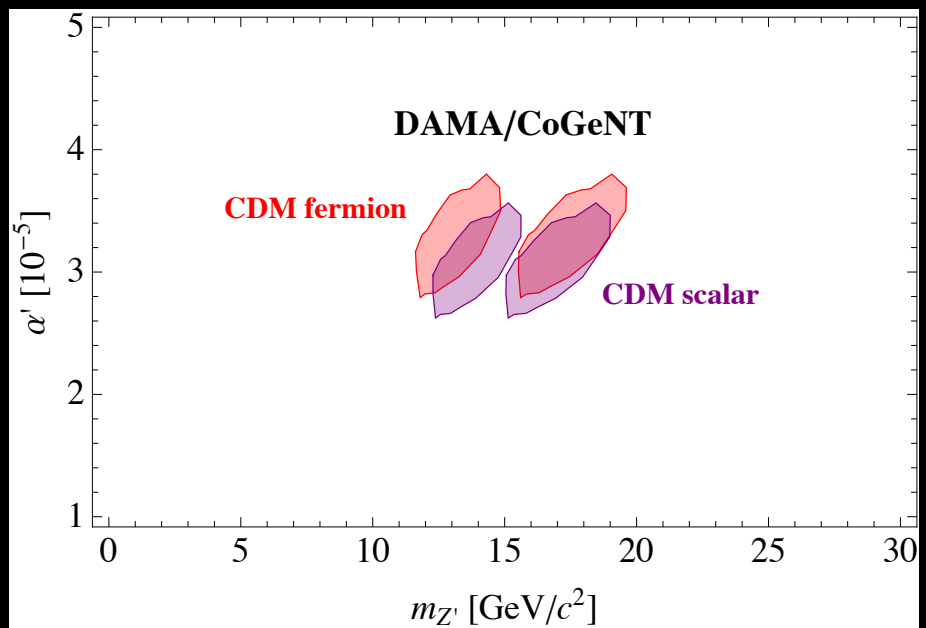




Example: Leptophobic Z'

- An extra U(1) gauge boson Z' coupled to quarks but no leptons, with no significant kinetic mixing
- Works for $m_{Z'}$~10-20 GeV and α'~10^{-5}

Gondolo, Ko, Omura 2011



Challenges and uncertainties

- Does cold dark matter exist?
- What is the nature of cold dark matter?
- The failure of the simple and elegant WIMP neutrino
- The numerous claims of detection in gamma-rays, cosmic-rays, microwaves, radio
- The universe before Big Bang nucleosynthesis
- The phase space density of dark matter near the Sun
- The apparently conflicting detections of light WIMPs

知不知，尚矣；不知知，病也。

道德经

It is a noble insight to realize that knowledge is ignorance,

It is mental sickness to regard ignorance as knowledge.

The Tao