Dark Matter

Evidence, Theory and Detection Prospects

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Current Issues in Cosmology, Astrophysics and High Energy Physics
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Outline

Large Scale Structure - Cosmology

- Cosmological Principle
  - Isotropy, Homogeniety
- Friedman-Lemaitre-Robertson-Walker (FLRW) metric
  - $ds^2 = dt^2 - a^2(t)\left(\frac{1}{1-kr^2}dr^2 + r^2 d\theta^2 + r^2 sin^2\theta d\phi^2\right)$
    - $k = 0$ flat; $k = -1$ open; $k = +1$ closed

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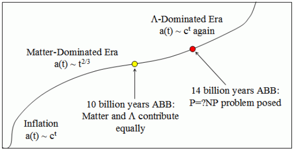
    - $k = 0$ flat; $k = -1$ open; $k = +1$ closed
- Einstein's Equation determines $a(t)$ given matter content
- Equation of State (EOS) : $p = w\rho$
  (p pressure; ρ Energy-density)
  - Radiation (Photons) : $w = 1/3$
  - Matter (Baryonic, Dark, ...) : $w = 0$
  - Cosmological Constant (Dark Energy) : $w = -1$



[Image: Scott Aaronson]

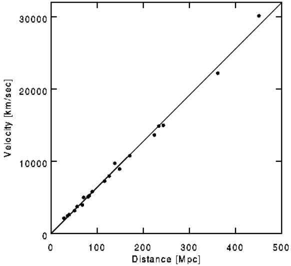
- Define $\Omega = \frac{\rho}{\rho_c}$ $\quad\rho_c \equiv 8.098 \times 10^{-11} h^2 eV^4$ critical energy-density

The expanding universe

- Vesto Slipher : measured Red-shift (Doppler shift) of galaxies (1917) $z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$
- Georges Lemaitre : Universe is expanding (1927)
- Edwin Hubble

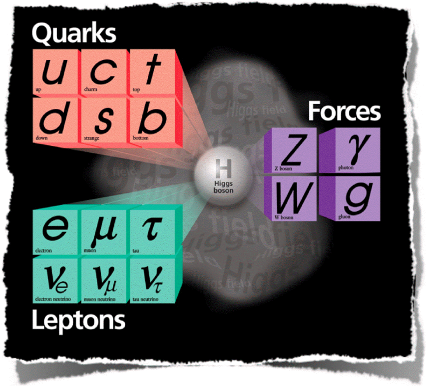
  $v = H_0\, d$ (H_0 : Hubble constant) (1929)

  $H_0 = 67.8 \pm 0.9\ km\, s^{-1}\ Mpc^{-1}$ [Planck 2015]
- $z = \frac{1-a}{a}$ in FLRW cosmology



[Riess, Press and Kirshner (1996)]

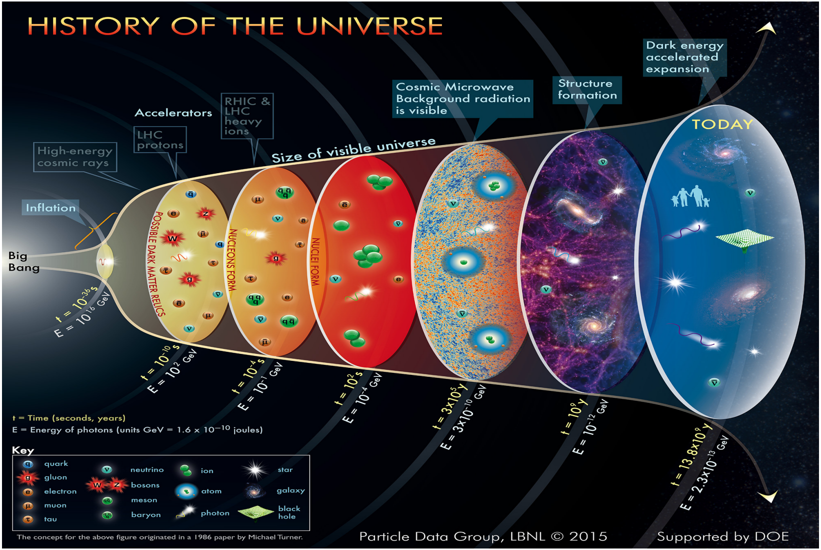
The Standard Model (SM) of Particle Physics



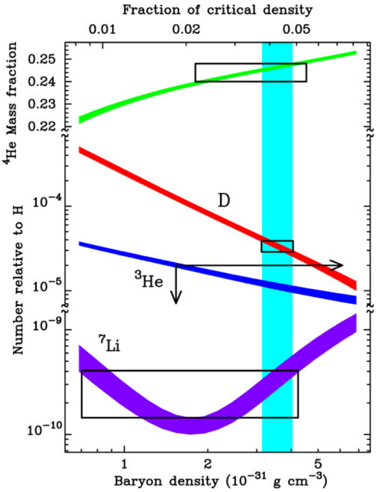
[Fermilab Visual Media]

Units: Mass & Energy in **GeV** $(E = m\,c^2,\ \text{set}\ c = 1)$ $(1\,GeV = 10^9\,eV)$

Cosmology $\Leftrightarrow$ (Particle) Physics



Big-Bang Neucleosynthesis (BBN)



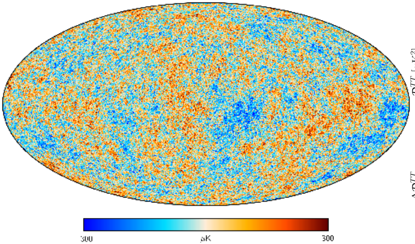
[Tytler et al., 2000]

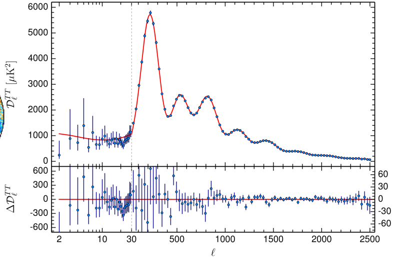
Note: Planck 2015

$\Omega_b h^2 = 0.02226 \pm 0.00023$

Cosmic Microwave Background (CMB)

- COBE, WMAP, Planck

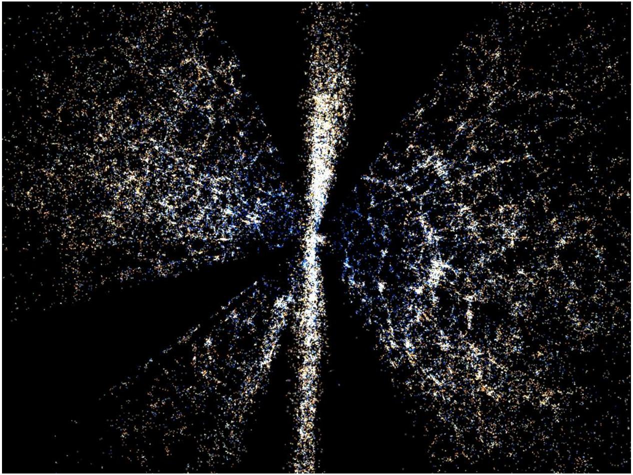




[Planck 2015]

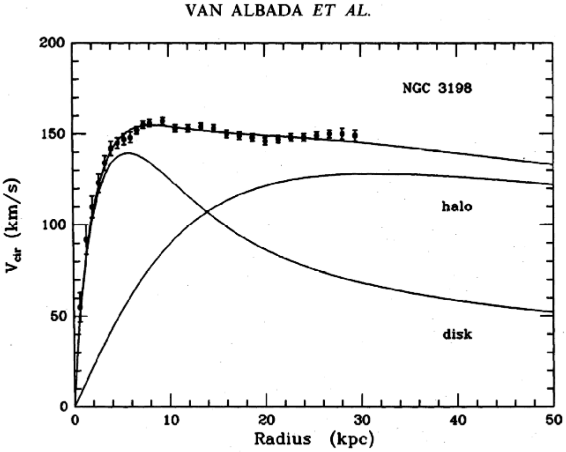
Structure formation

- 2dF, SDSS, BOSS

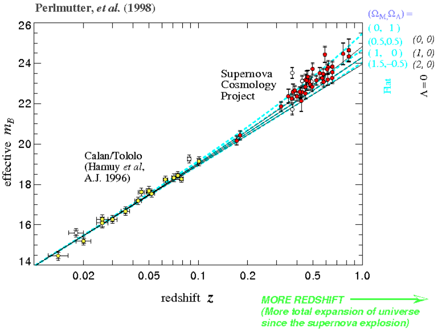


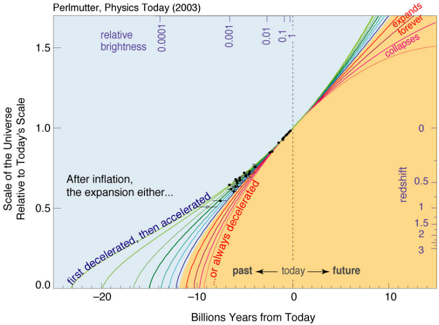
[SDSS]

Galaxy Rotation Curve

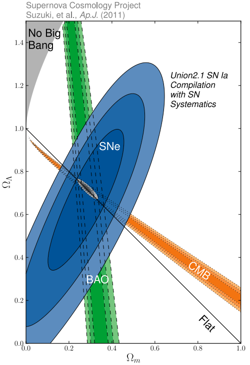


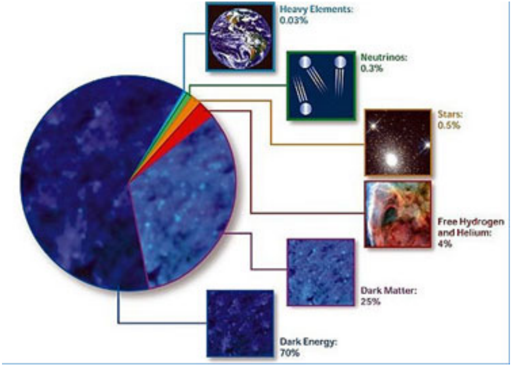
Supernova Cosmology Project



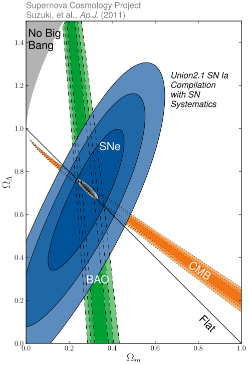


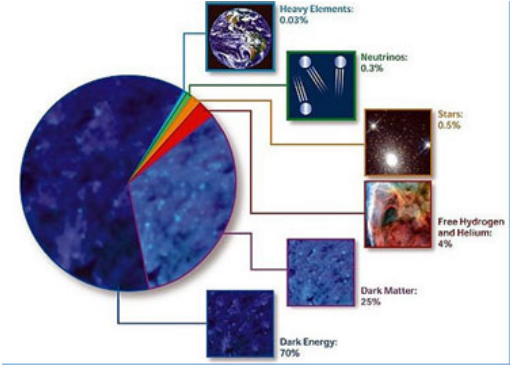
Inference


Supernova Cosmology Project
Suzuki, et al., Ap.J. (2011)
No Big Bang
Union2.1 SN Ia Compilation with SN Systematics
SNe
BAO
CMB
Flat
Ω_Λ
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4


Heavy Elements: 0.03%
Neutrinos: 0.3%
Stars: 0.5%
Free Hydrogen and Helium: 4%
Dark Matter: 25%
Dark Energy: 70%

Inference





- **Flat** on large scales
- Expansion is **Accelerating**
- **95%** is unknown **dark matter** + **dark energy**
    - **What is it**??

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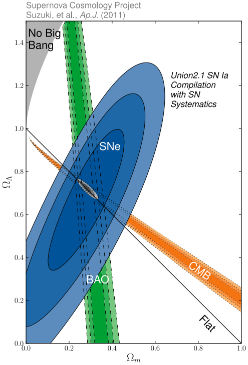

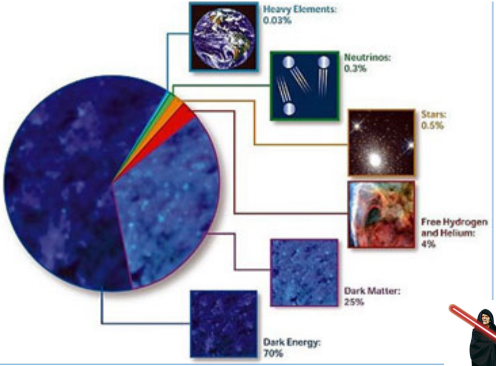

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The DARK SIDE rules!

What is the dark sector?

- Dark Matter
  - Astrophysical objects? (Disfavoured)
    - MAssive Compact Halo Objects (MACHO) or Black Holes or . . .
  - Particle dark matter? More on this...
    - Hot or Warm or Cold Dark Matter (CDM)

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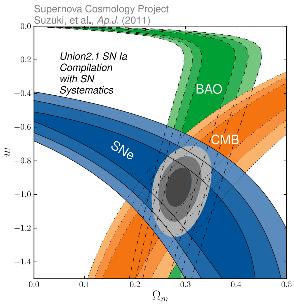
- Dark energy

Equation Of State $p = w\rho$

(p pressure; ρ energy-density)

$$\frac{1}{a}\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}(\rho + 3p)$$

Acceleration needs $w < -\frac{1}{3}$



- Favored : ΛCDM model

Theory for dark energy

- Experiment
  - $\Lambda \sim (10^{-3} eV)^4$

- Theory calculation
  - $\Lambda \sim (10^{11} eV)^4$

This is ABSURD!!!

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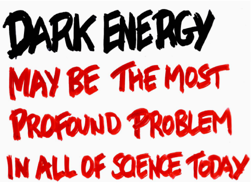


[Mike Turner, Neutrino 2006]

Particle DM Requirements

- Should be around for a long long long time ...
  - Absolutely stable : Conserved quantum number
    - p charged! So not possible
    - Active ν : disfavored
    - Beyond SM (BSM) particle with Z_2 symmetry
  - Decays, but with very very very long life-time
    - Very very very tiny coupling to other SM states

Particle Dark Matter

- Thermal Relic
  - In thermal equilibrium in early universe
  - Details of its origin do NOT matter
    - So most studied
- Nonthermal Relic
  - Never in thermal equilibrium
  - Details of its origin matter

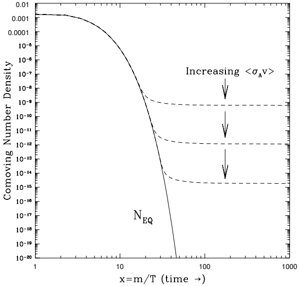
Computing Thermal DM Relic Density: Boltzmann Eqn

$$\frac{d}{dt}n = -3Hn - \langle\sigma v\rangle_{SI}\left(n^2 - n_{eq}^2\right) - \langle\sigma v\rangle_{CI}\left(nn_\phi - n_{eq}n_{\phi\,eq}\right) + C_\Gamma$$

Thermal equilibrium if : $\langle\sigma v\rangle_{SI}\, n_{\tilde{\nu}_0} > 3H$ OR $\langle\sigma v\rangle_{CI}\, n_\phi > 3H$

$$n_{eq} = \begin{cases} (\zeta(3)/\pi^2) g T^3 & T \gg M \\ g\left(\frac{MT}{2\pi}\right)^{3/2} e^{-(M-\mu)/T} & T \lesssim M \end{cases}$$

Freeze-out



[Kolb & Turner, Early Universe]

$$\Omega_0 h^2 \equiv \frac{n_0 M}{\rho_c} \approx 2\times 10^{-10}\left(\frac{\mathrm{GeV}^{-2}}{\langle\sigma v\rangle}\right)$$

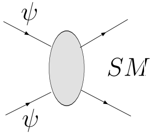
(h is H_0 in units of $100\, Km\, s^{-1} Mpc^{-1}$)

Planck 2015

$\Omega_0 = 0.308 \pm 0.012$

Computing $\langle \sigma v \rangle$

Self-annihilation



$$\sigma v_{rel} = a + b\ v_{rel}^2 + O(v_{rel}^4)$$

$$\langle \sigma v \rangle \approx a + (6b - 9a)/x_f \ ; \quad x_f \equiv M_\psi / T_f \approx 25$$

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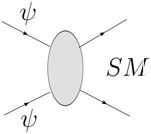

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Co-annihilation and/or decays into DM may also be important

Some Particle DM Candidates

- LSP - Lightest Supersymmetric Particle
  - $\tilde{\chi}_1^0$ Neutralino (SUSY partner of neutral gauge boson)
  - $\tilde{\nu}$ Sneutrino (SUSY partner of neutrino)
- Hidden sector DM
- LKP - Lightest Kaluza-Klein Particle - Extra space dimensions
- LTP - Lightest T-odd Particle - Little-higgs theory with Z_2
- SuperWIMP - Gravitino (SUSY partner of graviton)
- E-WIMP - Right-handed sneutrino (partner of neutrino)
- WIMPzilla - Extremely massive particle

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- Your candidate here

Weakly Interacting Massive Particle (WIMP)

WIMP Cold dark matter - New particle

- Mass: $M \sim 100\,\text{GeV}$
- Interaction strength: $g \sim g_{EW}$

"WIMP Miracle"

$$\Omega_0 \equiv \frac{n_0 M}{\rho_c} \approx 4 \times 10^{-10} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

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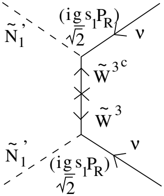
- Precisely the scale being explored at colliders!
  - DM at present colliders? (LHC connection)

Thermal (Mixed) $\tilde{\nu}_0$ DM



$$\Omega_0 h^2 = \frac{10^{-4}}{s_1^4}\left\{\left[g^2\left(\frac{100\ \mathrm{GeV}}{M_{\tilde{W}}}\right) + g'^2\left(\frac{100\ \mathrm{GeV}}{M_{\tilde{B}}}\right)\right]^2\right\}^{-1}$$

$\therefore s_1 \approx 0.2$ results in observed relic density

Nonthermal $\tilde{\nu}_0$ DM

[de Gouvea, SG, Porod 2006]

If thermalization conditions not met $\Rightarrow$ Nonthermal $\tilde{\nu}_0$

Happens when :

- $Y_N \lesssim 10^{-6}$ i.e., $\tilde{\nu}_0$ is almost pure right-handed
- Low Reheat temp $T_{RH} < 100$ GeV ; Reheat into $\tilde{\nu}_0$ + SM

  No Relic-from-decay of heavier SUSY particles
  No $\tilde{\nu}_0$ thermalization from co-interaction with SUSY or Top

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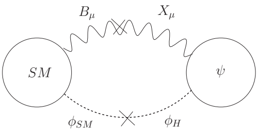
$\tilde{N}$ Relic density depends on Inflaton coupling to SM and $\tilde{N}$

Hidden sector DM ψ

[SG, Lee, Wells 2009]

SM $\times U(1)_X$: $U(1)_X$ sector: X_μ, Φ_H, ψ

$$\mathcal{L} \supset -\alpha \, |\Phi_{SM}|^2 |\Phi_H|^2 + \frac{\eta}{2} \, X_{\mu\nu} B^{\mu\nu} - \kappa \phi_H \bar{\psi} \psi$$



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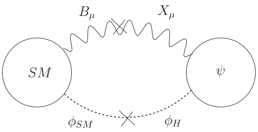

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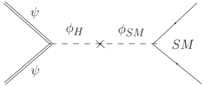
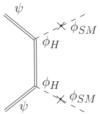
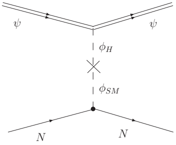
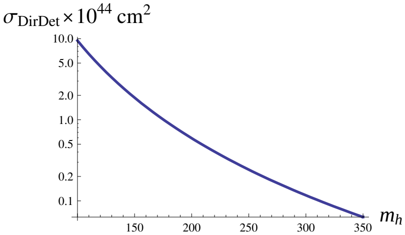




Channels $\psi\psi \to b\bar{b}, W^+W^-, ZZ, hh, t\bar{t}$

Direct Detection of Hidden sector





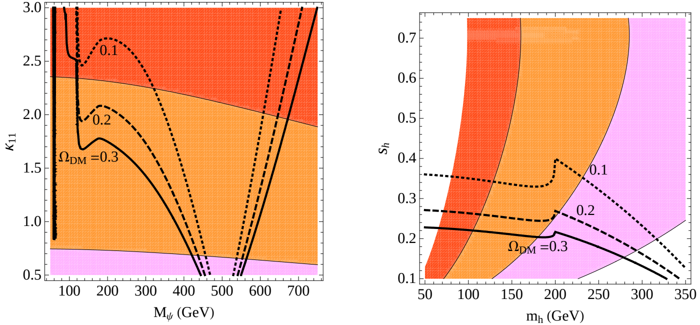
$M_\psi = 125\ GeV,\ \kappa_{11} = 1.5,\ s_h = 0.25$

Effective $h\bar{N}N$ coupling $\approx 2 \times 10^{-3}$ [Shifman, Vainshtein, Zakharov (1973)]

ψ- Nucleon c.s. :

$$\sigma\left(\psi N \to \psi N\right) \approx \frac{\kappa_{11}^2 s_h^2 c_h^2 \lambda_N^2}{8\pi v_{rel}} \frac{(|\mathbf{p}_\psi|^2 + m_N^2)}{(t - m_h^2)^2}$$

ψ Relic Density + Direct Detection



[SG, S.Lee, J.Wells 2009]

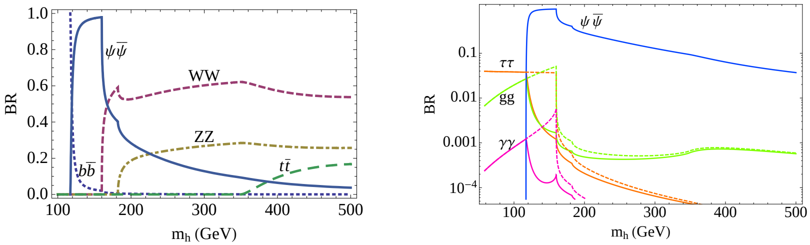
$M_\psi = 250 GeV$, $m_h = 120 GeV$, $\kappa_{11} = 2.0$, $s_h = 0.25$, $\kappa_{3\phi} = 1$, $m_H = 1 TeV$

Shaded:

$\sigma_{Dir} \gtrsim 10^{-43}\ \mathrm{cm}^2$ (dark); $\gtrsim 10^{-44}\ \mathrm{cm}^2$ (medium); $\gtrsim 10^{-45}\ \mathrm{cm}^2$ (light)

Higgs decay to DM

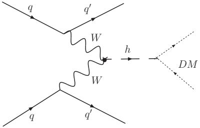
- Higgs decay and BR
  - If $m_h > 2M_\psi$: $h \to \psi\overline{\psi}$ Invisible Decay!
    - Decay channels: $h \to \psi\bar{\psi}$, $b\bar{b}$, WW , ZZ , $t\bar{t}$



$M_\psi \approx 59 GeV, s_h = 0.25, \kappa_{11} = 2.0, \kappa_{3\phi} = 1.0, m_H = 1 TeV$

NB: Relic density not enforced

Hidden sector DM @ 14 TeV LHC



[O. J. P. Eboli and D. Zeppenfeld, 2000]

$$p_T^j > 40\ ,\ |\eta_j| < 5.0\ ,\ |\eta_{j_1} - \eta_{j_2}| > 4.4\ ,\ \eta_{j_1} \cdot \eta_{j_2} < 0\ ,$$
$$\not{p}_T > 100\ \mathrm{GeV}\ ,\ M_{jj} > 1200\ \mathrm{GeV}\ ,\ \phi_{jj} < 1\ .$$

For $s_h = 0.25$, $BR_{INV} = 0.25$:

m_h (GeV)	$\sigma_S BR_{inv}(fb)$	$\sigma_B(fb)$	$\mathcal{L}_{5\sigma}$ (fb^{-1})
120	22.7	167	8
200	18	167	12.8
300	13.2	167	23.7

Axions

- Strong interactions - Quantum Chromo Dynamics (QCD)
  Charge-Parity (CP) symmetry conserved - Why???
- Axion [Peccei-Quinn] $\Omega_m = (\frac{10^{-5} eV}{m_a})^{7/6}$ $m_a = 6\ eV\ (\frac{10^6 GeV}{f_a})$

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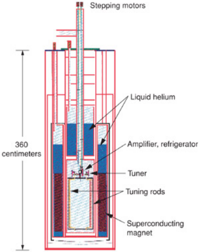
- CERN Axion Solar Telescope (CAST)

- Axion Dark Matter Expt. (ADMX)



Neutrinos

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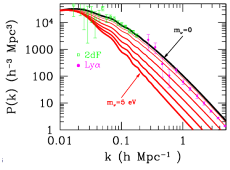
  Cannot be all of dark-matter $\Omega = 0.02 \frac{m_\nu}{1\, eV}$



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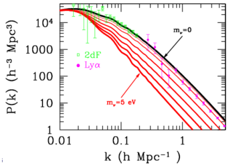


[Dodelson]

- Right-handed Neutrino (Sterile Neutrino) can be DM
  Warm Dark Matter
  Solves many puzzles : LSND, Small scale structure, etc.

Dark Matter Detection

- Direct Detection
  - DM directly intereacts with a detector
- Indirect Detection
  - Look for indirect emmissions from DM
- Collider Detection
  - DM escapes as missing momentum at colliders

DAMA

- DAMA, Gran Sasso, Italy. Detection claimed!!

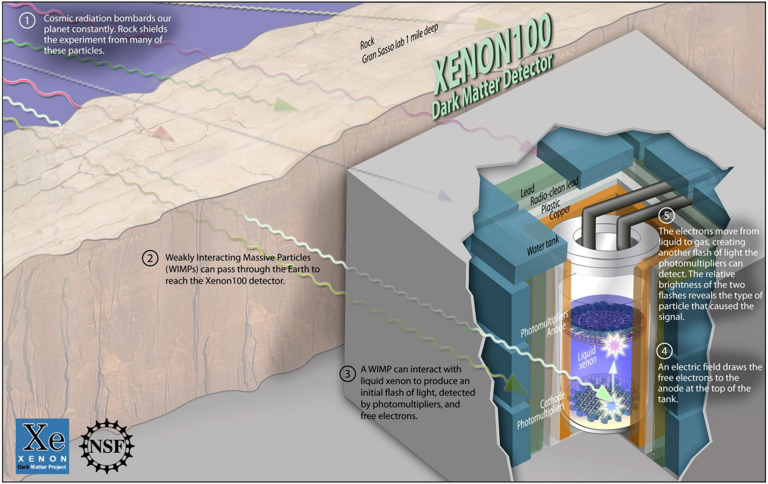

NaI scintillators

CDMS

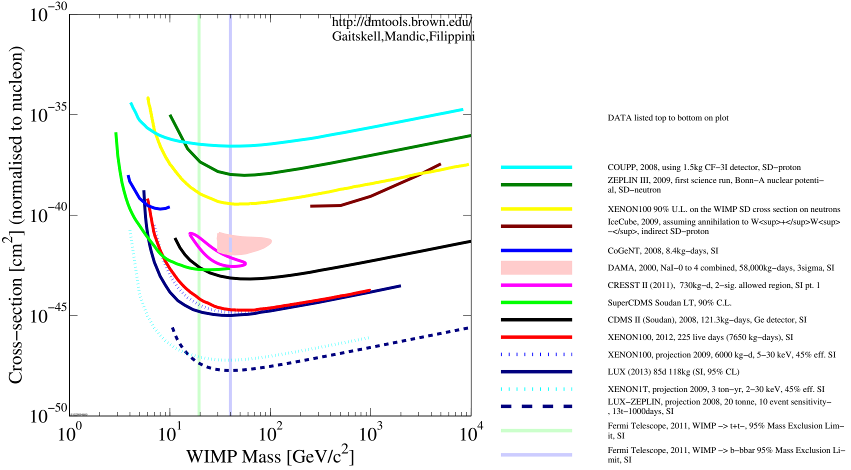
- Cryogenic Dark Matter Search (CDMS), Soudan Mine, USA

Ge detector

XENON 100 Detector

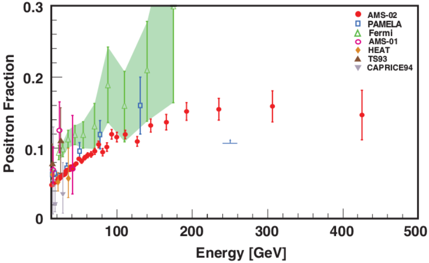


Direct Detection Experimental Limits

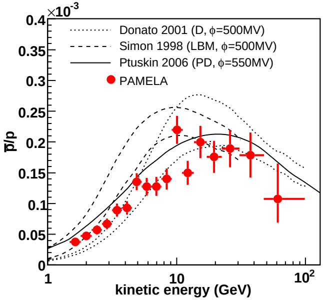


- DAMA vs. CDMS/XENON/LUX puzzle
  - Confusing situation!

e^+, $\bar{p}$ data



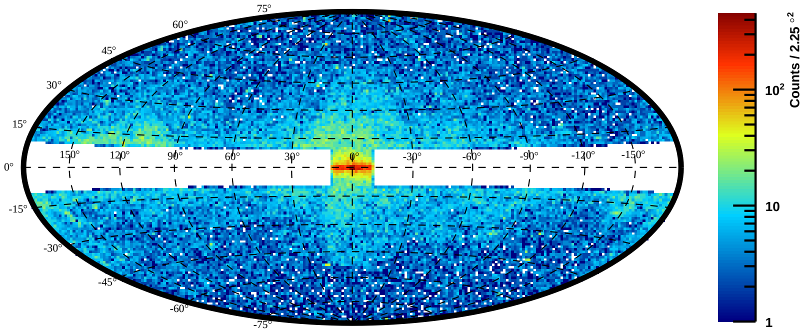
AMS02 e^+ [PRL113, 2014]



PAMELA $\bar{p}$ [Nature 09]

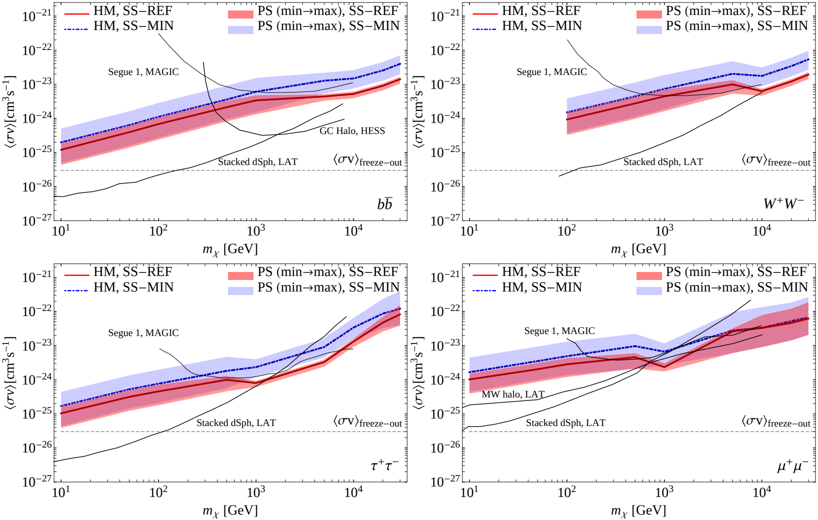
Dark matter annihilations? .... or astro sources (pulsars) ? ... or other bkgnd?

Fermi LAT γ



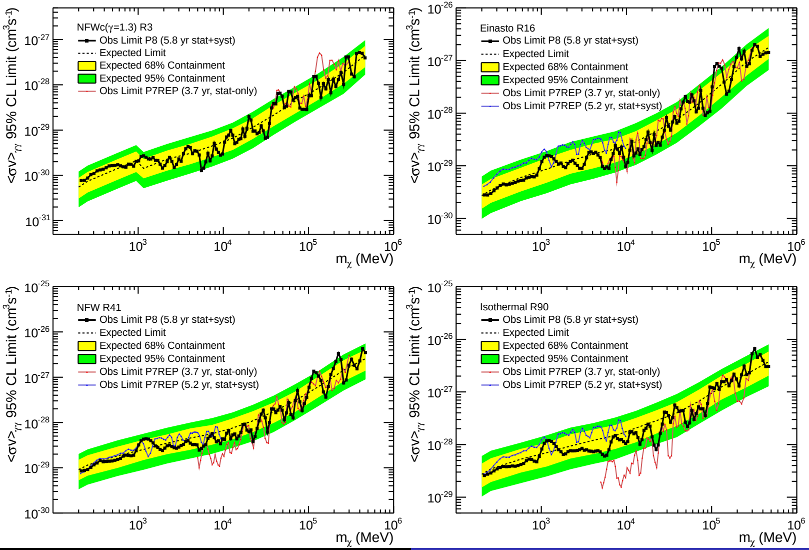
- Typical WIMP
  - $\langle \sigma v \rangle \sim 0.45\, pb \approx 1.4 \times 10^{-28} \frac{cm^3}{s}$
    - Getting close!

Fermi LAT diffuse γ search



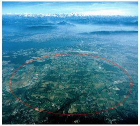
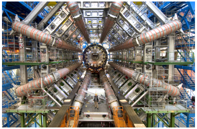
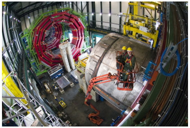
2015 limits: "Conservative procedure" (shaded) [1501.05464 [astro-ph]]; dwarf-spheroidal [1503.02641 [astro-ph]]

Fermi LAT γ spectral line search



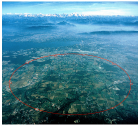
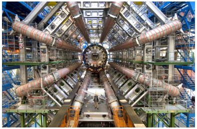
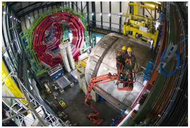
DM at Colliders I

- CERN Large Hadron Collider (LHC): ATLAS, CMS

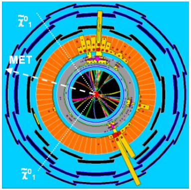
DM at Colliders I

- CERN Large Hadron Collider (LHC): ATLAS, CMS

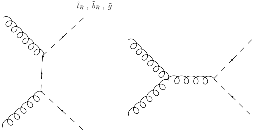




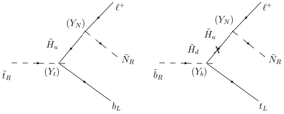
- The Future: Linear Collider:

DM at Colliders II



- Example: Supersymmetry





- LSP leads to "missing momentum"

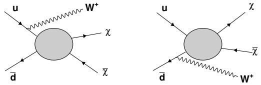
Effective Operators

[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 1008.1783]

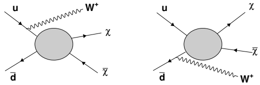
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

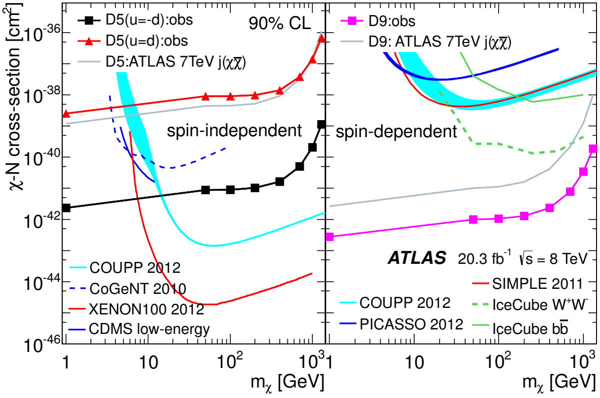
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

ATLAS : 8 TeV, 20.3 fb^{-1} : $(Z/W)_{hadr} + \not{E}_T$ [1309.4017]

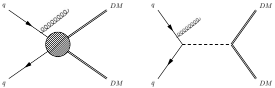


ATLAS : 8 TeV, 20.3 fb^{-1} : $(Z/W)_{hadr} + \not{E}_T$ [1309.4017]

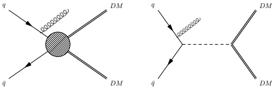


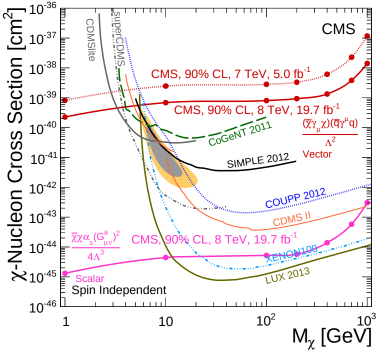


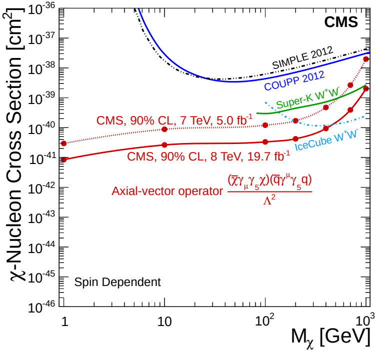
CMS : 8 TeV, 19.7 fb^{-1} : $jet + \not{E}_T$ [1408.3583]



CMS : 8 TeV, 19.7 fb^{-1} : $jet + \not{E}_T$ [1408.3583]







Final Thoughts

- Large scale structure of the Universe
  - FLRW works well
  - Particle physics interplay
  - Remarkable observations in past few decades. More underway ...
- Strong evidence for Dark Matter
  - But what is it?
    - Many Candidates, Mass range 10^{-5}eV - 10^{12}GeV
  - Vigorous search underway - Direct, Indirect, Collider
    - Exciting times! We might discover DM particle soon
    - Can we study DM at the LHC?
- Dark Energy - theoretical embarassment!

Backup Slides

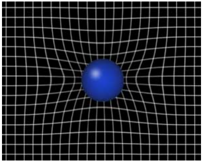
Backup Slides

Special Relativity

- Speed of light is the same in different inertial frames
  - $c = const$: Work in "Natural Units" $c = 1$
    - 4-dimensional coordinates $x^\mu \sim (t, \vec{x})$
- Invariance under Rotations + Boosts (Lorentz Invariance)
  - Transformation constant in space-time (Rigid)
- Invariant line element
  - $ds^2 = dt^2 - dx^2 = \eta_{\mu\nu} dx^\mu dx^\nu$
    - $\eta_{\mu\nu} = diag(1, -1, -1, -1)$
- Two neighboring points are
  - Light-like if $ds^2 = 0$
  - Time-like if $ds^2 > 0$
  - Space-like if $ds^2 < 0$ (space-like points are NOT in causal contact)

General Relativity (GR)

- General Coordinate (x^μ dependent) transformations
- Equivalence principle
  - Inertial mass = Gravitational mass
- Weak Gravity limit → Newtons (Keplers) laws
- Invariant line element
  - $ds^2 = g_{\mu\nu}(x)\ dx^\mu dx^\nu$
  - 4-dim space-time dynamical



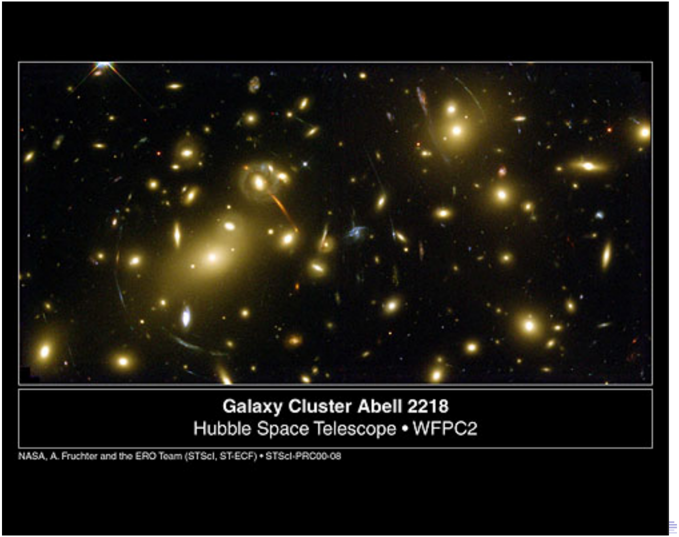
[Image: ThinkQuest]

- Einstein's equation
  - $G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R} = 8\pi G\ T_{\mu\nu}$
    - LHS:Geometry ↔ RHS:Matter

$T_{\mu\nu} = diag(\rho,\ -p,\ -p,\ -p)$

- All matter/energy in $T_{\mu\nu}$
  Particle Physics

Gravitational Lensing



The Standard Model (SM) of Particle Physics

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c²	Electric charge
H Higgs	126	0

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

[particleadventure.org]

Units: Mass & Energy in **GeV** $(E = m\,c^2$, set $c = 1)$ $(1GeV = 10^9\ eV)$

Composites

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ — Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Mesons $q\bar{q}$ — Mesons are bosonic hadrons. These are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.140	0
$\mathbf{K}^-$	kaon	$\mathbf{s}\bar{\mathbf{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.776	1
$\mathbf{B}^0$	B-zero	$\mathbf{d}\bar{\mathbf{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c}\bar{\mathbf{c}}$	0	2.980	0

[particleadventure.org]

Thermal history of the Universe

Big Bang $\rightarrow$ Inflation $\rightarrow$ DM freeze-out$\rightarrow$ BBN $\rightarrow \gamma$ decouples $\rightarrow$ Today

Hubble rate:

$$H \equiv \frac{\dot{a}}{a}\,; \quad H^2 = \frac{8\pi G}{3}\rho$$

$$H = 1.66\sqrt{g_*}\frac{T^2}{M_{Pl}} \quad \text{(Rad Dom)}$$

Ω_m

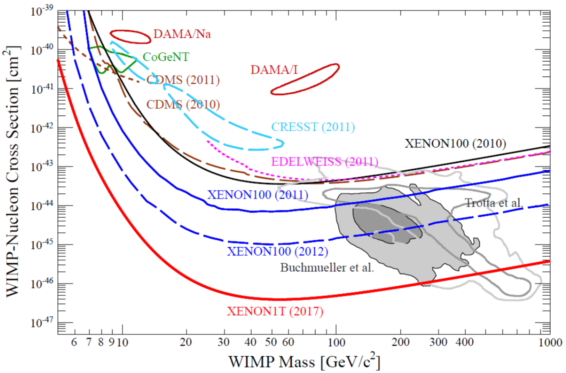
WMAP result (2003) $\Omega_m h^2 = 0.135\ ^{+0.008}_{-0.009}$; $h^2 \approx 0.5$

SUSY WIMP

Extend the Standard Model (SM) - **Supersymmetry (SUSY)**

- To stabilize the Higgs sector
    - SM Higgs has a quadratic divergence instability
- Extension of space-time symmetry to Superspace
    - Boson $\Longleftrightarrow$ Fermion symmetry.
        - Every known particle has a **Superpartner**
- If conserved R_p, Lightest Supersymmetric Particle (LSP) stable
    - LSP (Eg: Neutralino) can be WIMP DM

XENON 100 (2011) Limit (Old), Showing Theory Region



Relic from Decays

Contribution from $C_\Gamma \sim n_\chi \Gamma(\chi \to \tilde{\nu}_0 X)$

- $\tilde{H}_u \to \tilde{\nu}_0 L$

$$\Omega_{0\,(a_D)} h^2 \sim 10^{26} c_1^2 Y_N^2 \frac{M_{\rm LSP}}{M_{\tilde{H}}} f_{PS}^2$$

- $\tilde{\nu}_H \to \tilde{\nu}_0 \overline{\psi} \psi$ $\qquad h_u$ exchange

$$\Omega_{0\,(b_D)} h^2 = 10^{24} (c_1^2 - s_1^2)^2 Y_c^2 \frac{A_N^2 M_{\tilde{\nu}_H} M_{\rm LSP}}{M_{h_u}^4} f_{3PS}^2$$

Does not overclose if $Y_N \lesssim 10^{-13}$; $\quad A_N \lesssim 10$ eV ; $\quad s_1 \lesssim 10^{-12}$

(Decays just before BBN!)

Dirac case [Asaka et al. '05]

When is $\tilde{\nu}_0$ Thermal? $\langle \sigma v \rangle \, n > 3H$

Self-interaction processes

(a_s) $\tilde{\nu}_0 \tilde{\nu}_0 \to \nu_L \nu_L$ $\tilde{W}^3$; $\tilde{B}$ exchange

(d_s) $\tilde{\nu}_0 \tilde{\nu}_0 \to \nu_L \overline{\nu_L}$; $e_L \overline{e_L}$ $\tilde{H}_u^+$; $\tilde{H}_u^0$ exchange

When is $\tilde{\nu}_0$ Thermal? $\langle \sigma v \rangle n > 3H$

Self-interaction processes

(a_s) $\tilde{\nu}_0 \tilde{\nu}_0 \rightarrow \nu_L \nu_L$ $\tilde{W}^3$; $\tilde{B}$ exchange

(d_s) $\tilde{\nu}_0 \tilde{\nu}_0 \rightarrow \nu_L \overline{\nu_L}$; $e_L \overline{e_L}$ $\tilde{H}_u^+$; $\tilde{H}_u^0$ exchange

Process	Cross-section	Limit
(a_s)	$\frac{s_1^4}{16\pi} \left(\frac{g^2}{M_{\tilde{W}}} + \frac{g'^2}{M_{\tilde{B}}} \right)^2$	$\alpha_m Y_N > 10^{-3}$
(d_s)	$\frac{Y_N^4 c_1^4}{16\pi} \frac{1}{M_{\tilde{H}}^2} \left(\frac{m_e}{M_{\mathrm{LSP}}} \right)^2$	$Y_N > 10^{-3}$

When is $\tilde{\nu}_0$ Thermal?

Co-interaction processes with other SUSY particles
Boltzmann suppressed by

$$\beta_\phi \equiv e^{-(\Delta M_\phi / T)} \; ; \quad \Delta M_\phi \equiv (M_\phi - M_{\rm LSP})$$

Co-interaction with SUSY

(b_c) $\tilde{\nu}_0 \tilde{s} \to \tilde{e}_L \tilde{s}'$ $\quad W^\pm$ exchange

(e_c) $\tilde{\nu}_0 \tilde{\nu}_H \to c\bar{c}$; $t\bar{t}$ $\quad h_u$ exchange

Process	Cross-section	Limit
(b_c)	$\frac{g^4 s_1^2}{16\pi} \frac{M_{\rm LSP}^2}{M_Z^4} f_{PS}^2$	$\beta_{\tilde{s}} \alpha_m f_{PS} Y_N > 10^{-6.5}$
(e_c)	$\frac{(c_1^2 - s_1^2)^2 Y_u^2}{16\pi} \frac{1}{M_{h_u}^2} \left(\frac{A_N}{M_{h_u}}\right)^2 f_{PS}^2$	$Y_u \beta_{\tilde{\nu}_H} \alpha_m f_{PS} Y_N > 10^{-7}$

When is $\tilde{\nu}_0$ Thermal?

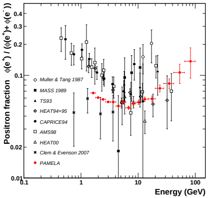
Co-interaction with SM

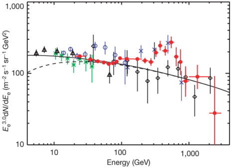
(a_M) $\tilde{\nu}_0 t_{R,L} \to \tilde{\nu}_L t_{L,R}$ h_u exchange

(b_M) $\tilde{\nu}_0 t_L \to \nu_L \tilde{t}_R$ $\tilde{H}_u$ exchange

Process	Cross-section	Limit
(a_M)	$\frac{A_N^2 Y_t^2}{16\pi} \frac{1}{M_{h_u}^4} f_{PS}^2$	$\beta_t \alpha_m f_{PS} Y_N > 10^{-7}$
(b_M)	$\frac{Y_N^2 Y_t^2}{16\pi} \frac{1}{M_{\tilde{H}}^2} f_{PS}^2$	$\beta_t f_{PS} Y_N > 10^{-7}$

PAMELA e^+

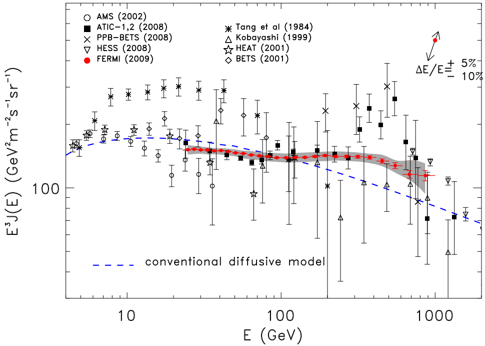

Positron fraction φ(e⁺) / (φ(e⁺)+ φ(e⁻))
Energy (GeV)
Muller & Tang 1987
MASS 1989
TS93
HEAT94+95
CAPRICE94
AMS98
HEAT00
Clem & Evenson 2007
PAMELA


Energy (GeV)

PAMELA e^+
[Nature 09]

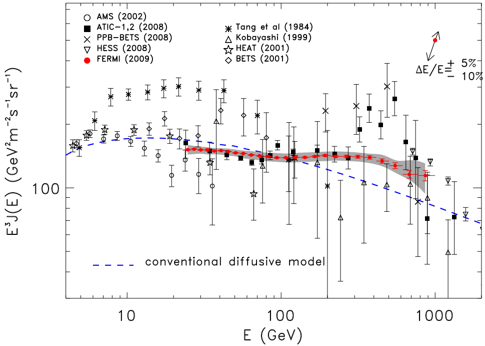
ATIC e
[PRL 08]

Fermi LAT γ from e



[PRL 09]

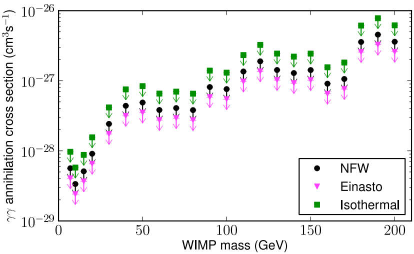
Fermi LAT γ from e



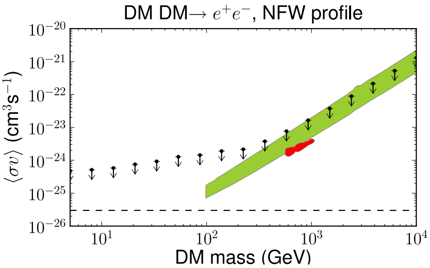
[PRL 09]

- Similarly we have γ from W, b, μ, τ, $\ldots$

Fermi LAT γ 2012



Spectral γ line



Diffuse γ

[May 2012 : 1205.2739v1 [astro-ph.HE]]