Dark Matter

Leszek Roszkowski

CERN, CH & Sheffield, UK

The Two Universes

The Two Universes

shining Universe

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shining Universe

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shining Universe

dark Universe

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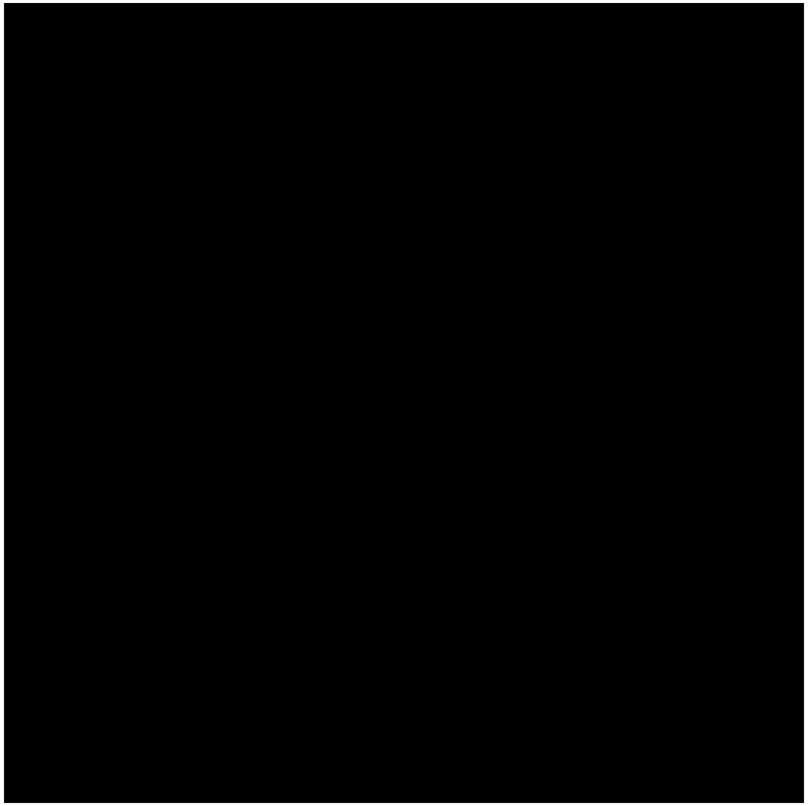
shining Universe

dark Universe



Outline

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- evidence for DM

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- properties of DM, WIMP

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- particle candidates for DM

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- summary

Dark Matter - Evidence

among the oldest puzzles in cosmology

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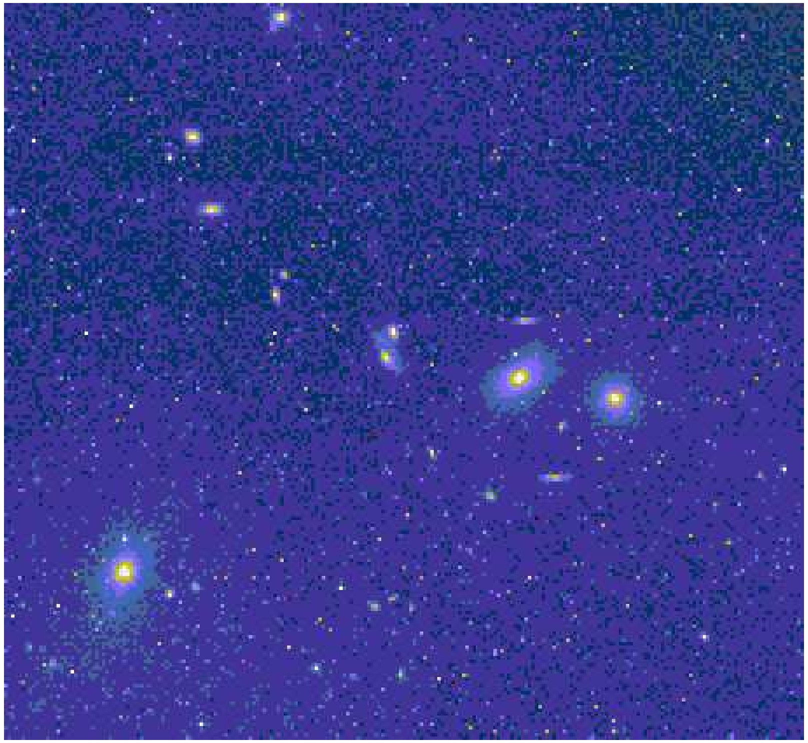
- Zwicky ('33): Coma cluster

visible mass not enough to bound it



Dark Matter - Evidence

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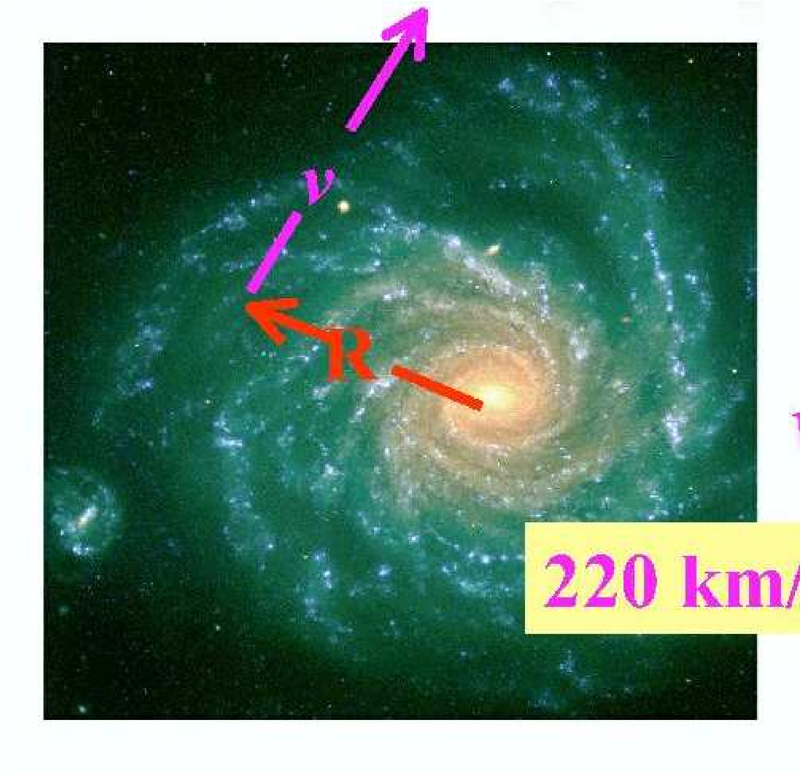
flat rotation curves



Dark Matter - Evidence

among the oldest puzzles in cosmology

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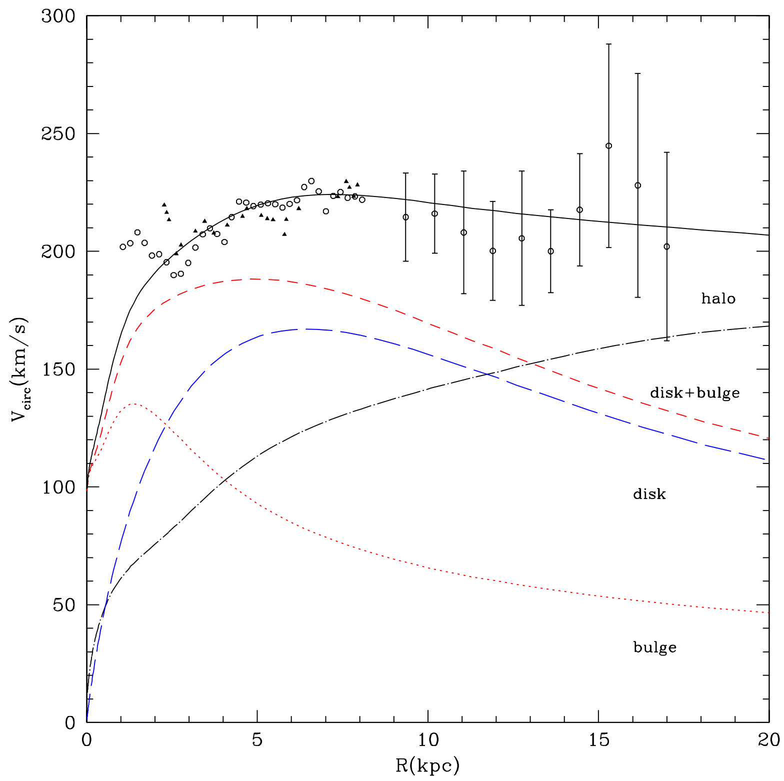
Milky Way (Klypin, et al.)



Dark Matter - Evidence

among the oldest puzzles in cosmology

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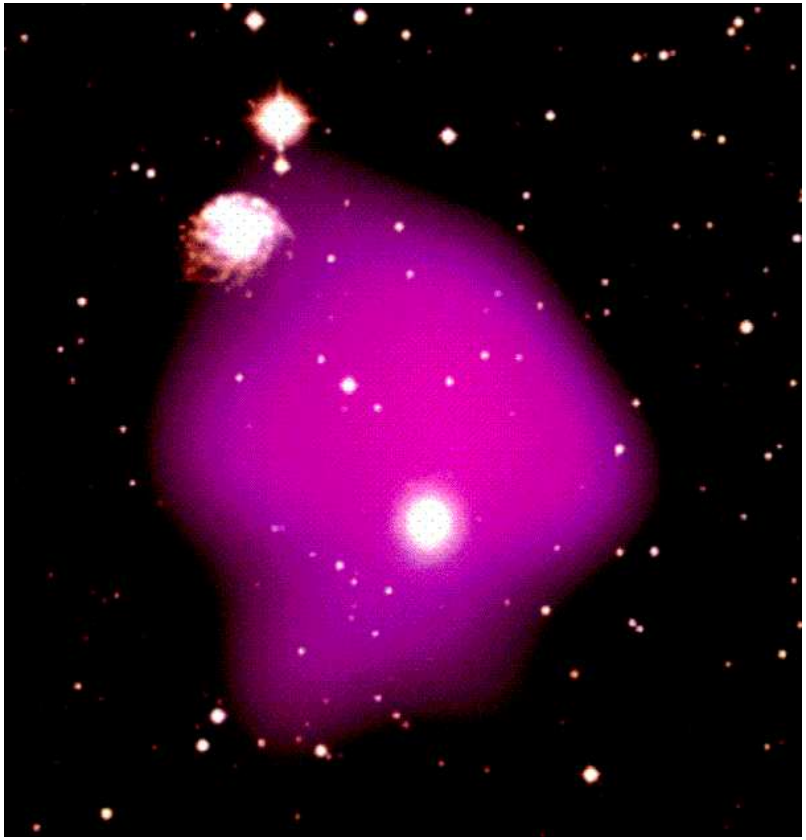
- clusters of galaxies

hot gas, $\sim 10^8$ K



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among the oldest puzzles in cosmology

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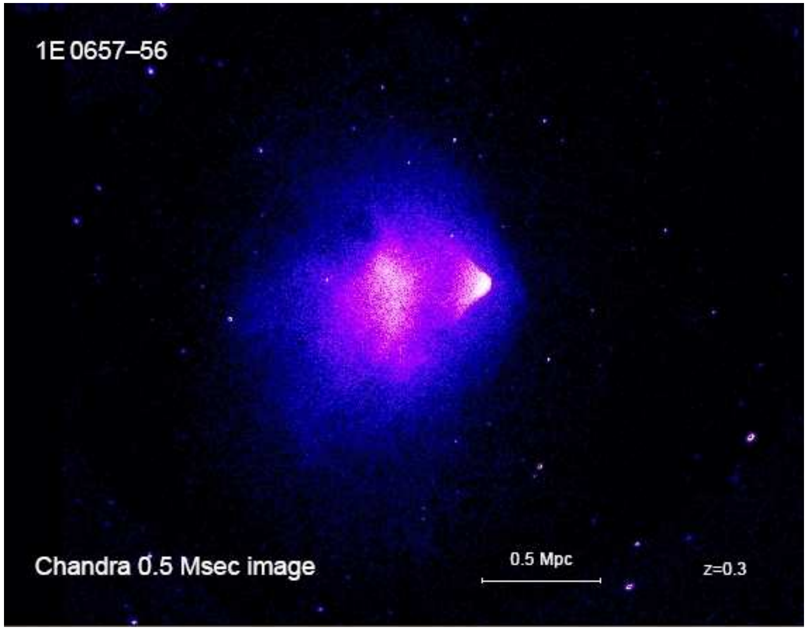
Bullet cluster, 2006



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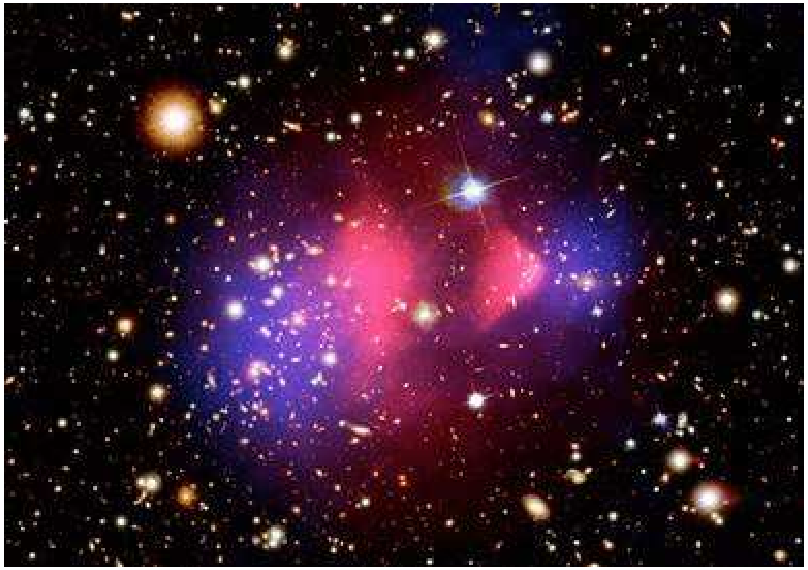
inferred DM distribution



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among the oldest puzzles in cosmology

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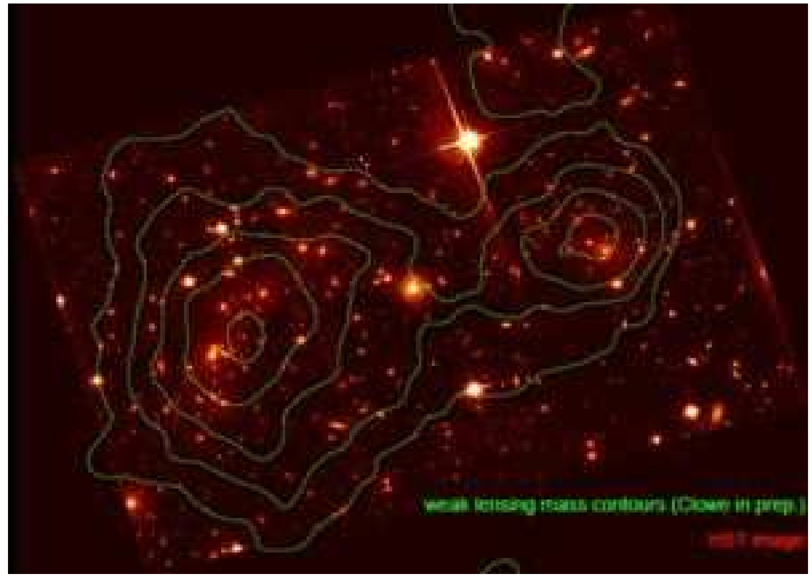
DM separated from baryons



Dark Matter - Evidence

among the oldest puzzles in cosmology

- Zwicky ('33): Coma cluster
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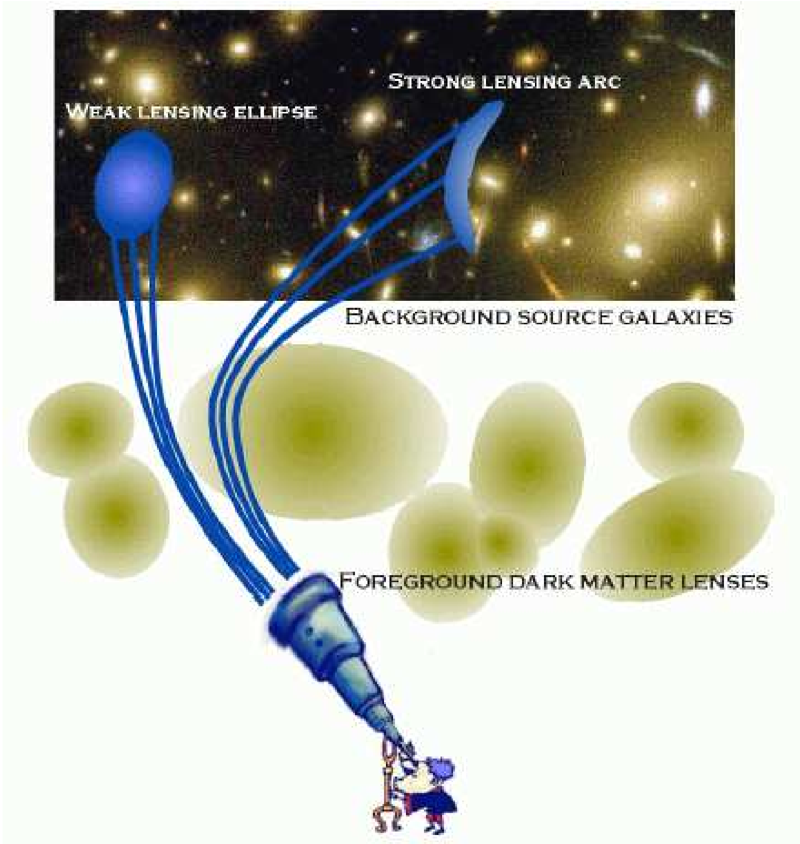
- gravitational lensing

images of distant objects



Dark Matter - Evidence

among the oldest puzzles in cosmology

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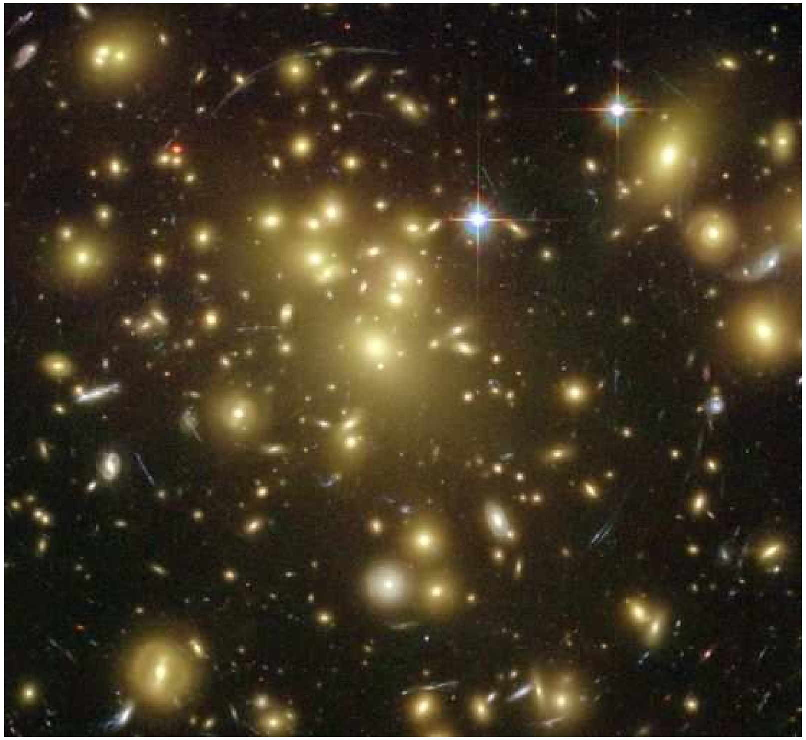
- gravitational lensing
- strong gravitational lensing: arcs

arc images of distant quasars



Dark Matter - Evidence

among the oldest puzzles in cosmology

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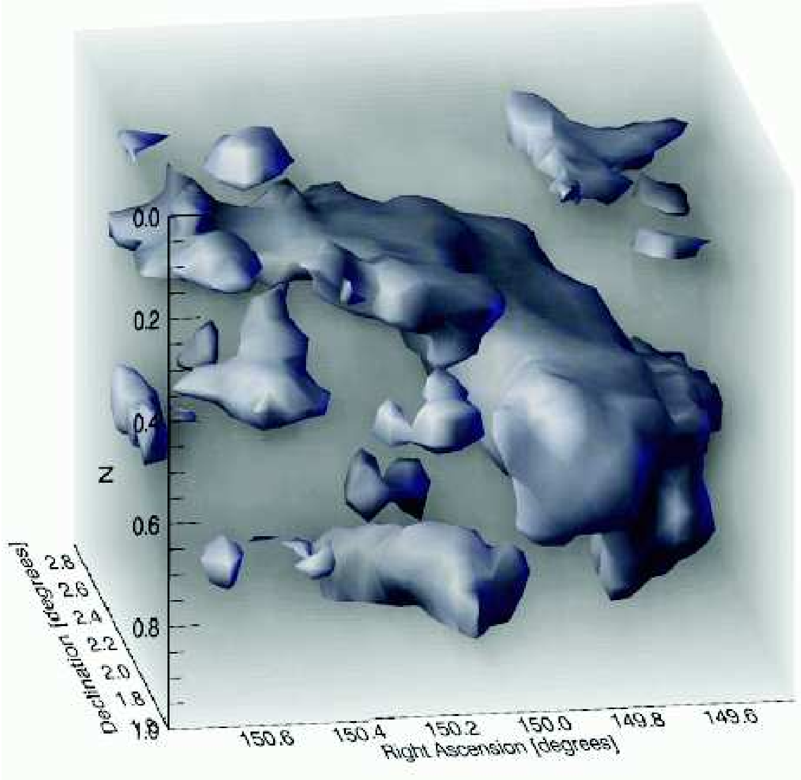
- gravitational lensing
- strong gravitational lensing: arcs
- weak lensing

3dim DM distribution, Massey, et al, 2007



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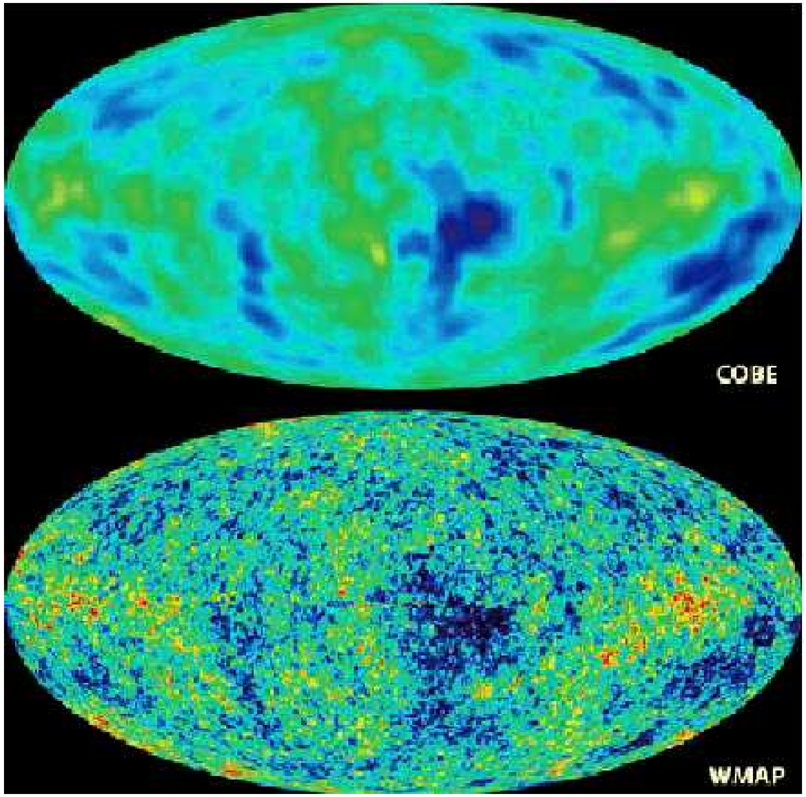
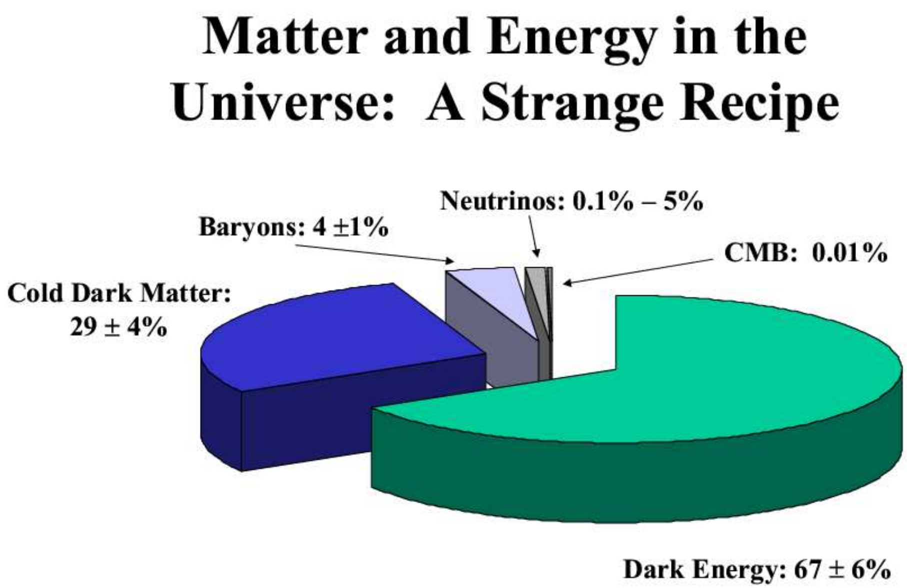
- CMB: precision measurements



Cosmic Pie



Freedman+Turner (0308)

What is the DM?

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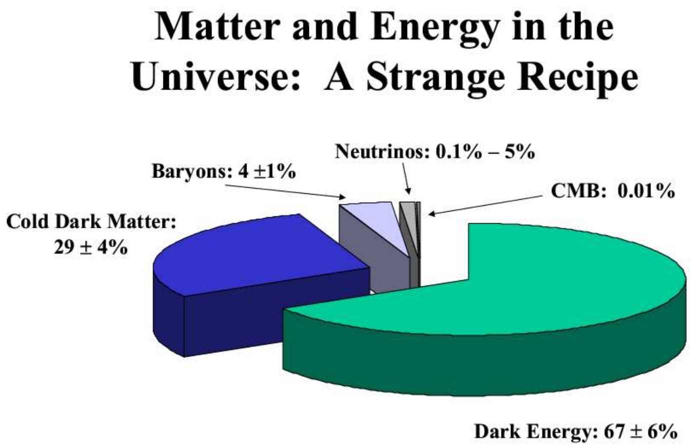
$\Rightarrow$ most matter non–baryonic
(DM problem)

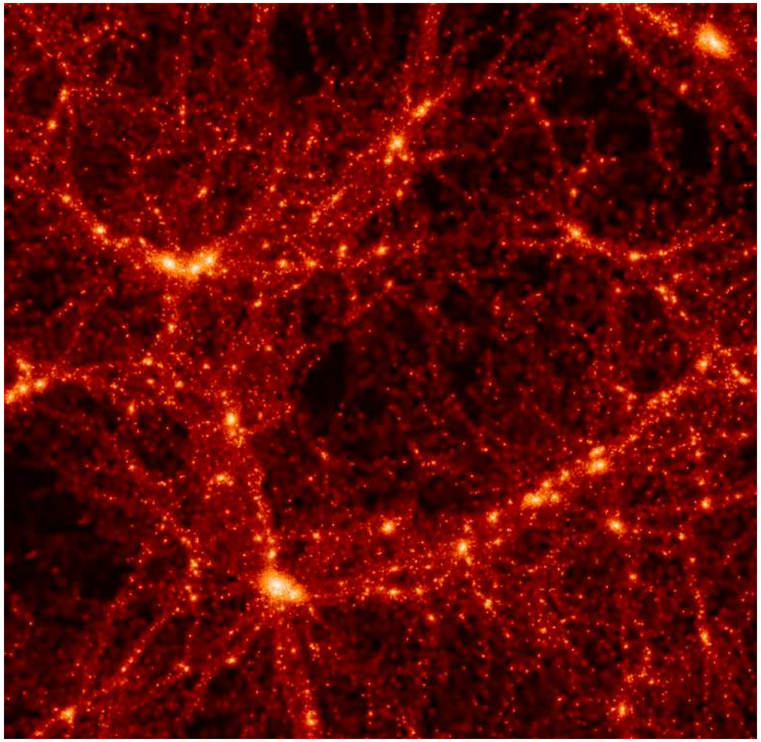


What is the DM?

⇒ most matter non–baryonic (DM problem)

⇒ DM is cold (CDM) or possibly (?) warm

numerical simulations of LSS



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⇒ most matter non–baryonic

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⇒ DM is cold (CDM)
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⇒ no electric nor (preferably)
color interactions

- limits on exotic elements
  (anomalous nuclei)
- DM is **DARK**

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plausible choice ⇒ WIMP

weakly interacting massive particle

A WIMPy Idea

favored scenario: DM is made up of:

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WIMP: some new, unknown particle

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WIMP: some new, unknown particle

...How weak can weak be?

A simple, persuasive argument:

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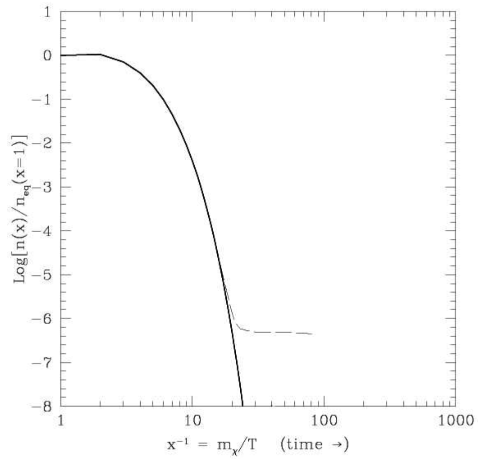
- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$



$$x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$$

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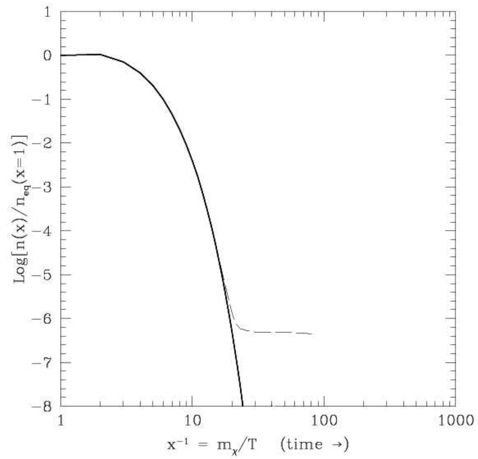


WIMP relic abundance

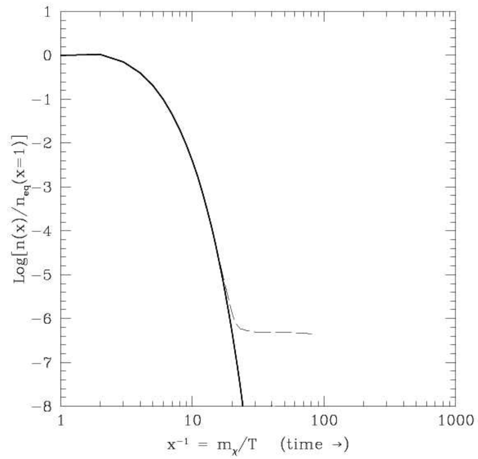
$$\Omega h^2 \simeq \frac{1}{\left\langle \left(\frac{\sigma_{\rm ann}}{10^{-38}\rm cm^2}\right) \left(\frac{v/c}{0.1}\right) \right\rangle}$$

$$x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$$

$\sigma_{\rm ann}$ – c.s. for WIMP pair–annihilation in the early Universe

v – their relative velocity, $\langle \ldots \rangle$– thermal average

A simple, persuasive argument:



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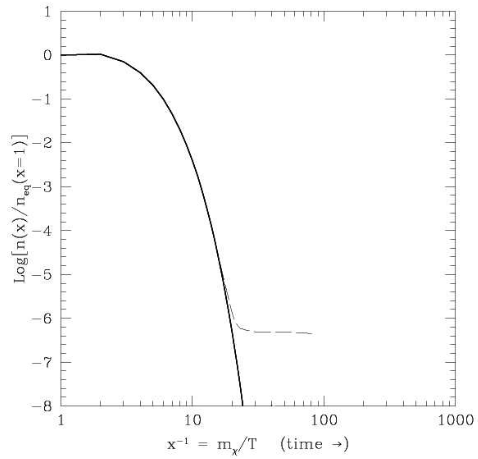

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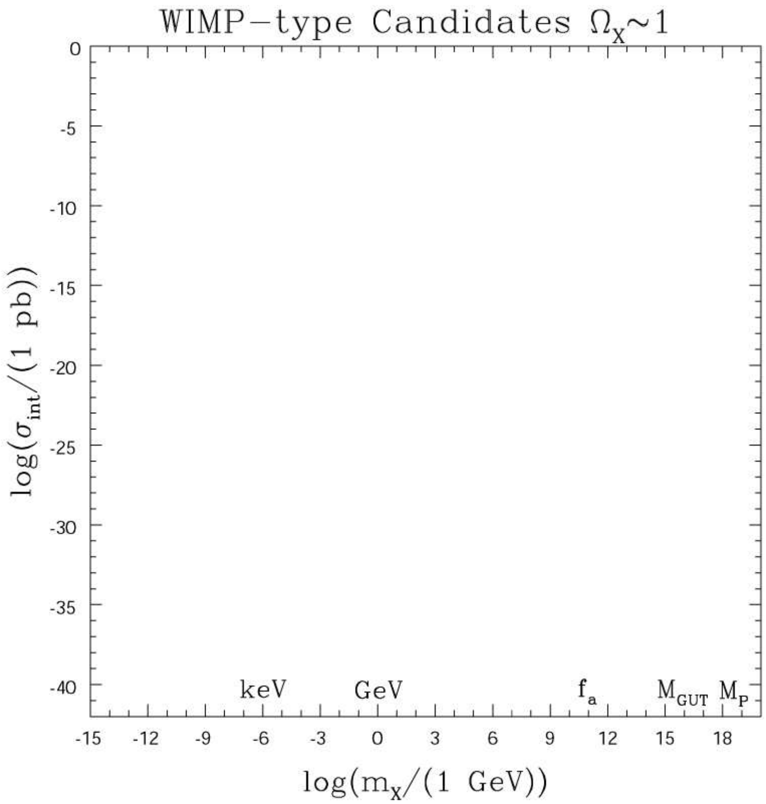
A hint? Possibly, but...

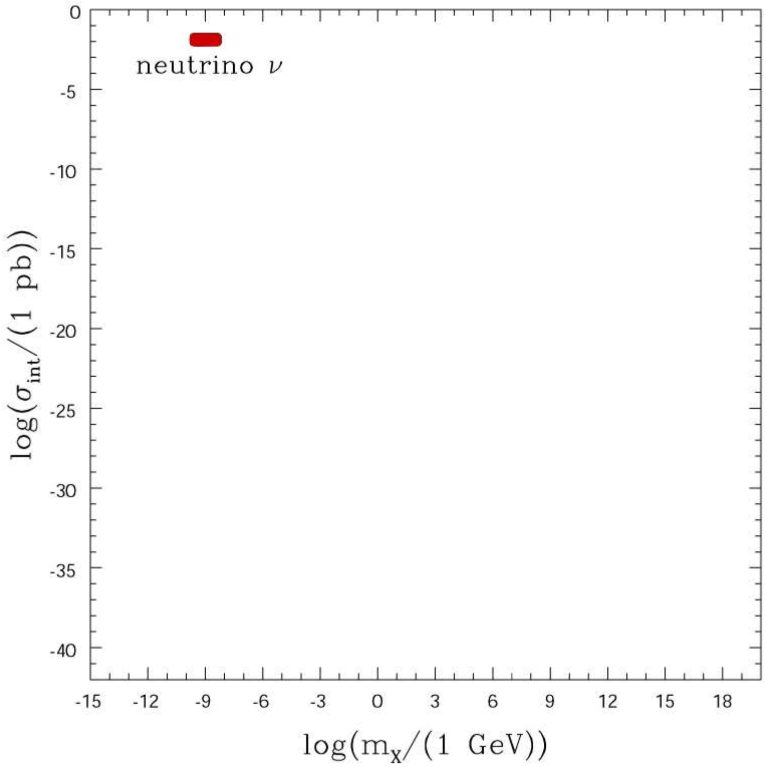
The Big Picture

well–motivated particle candidates s.t. $\Omega_{\mathrm{DM}} \sim 1$

The Big Picture



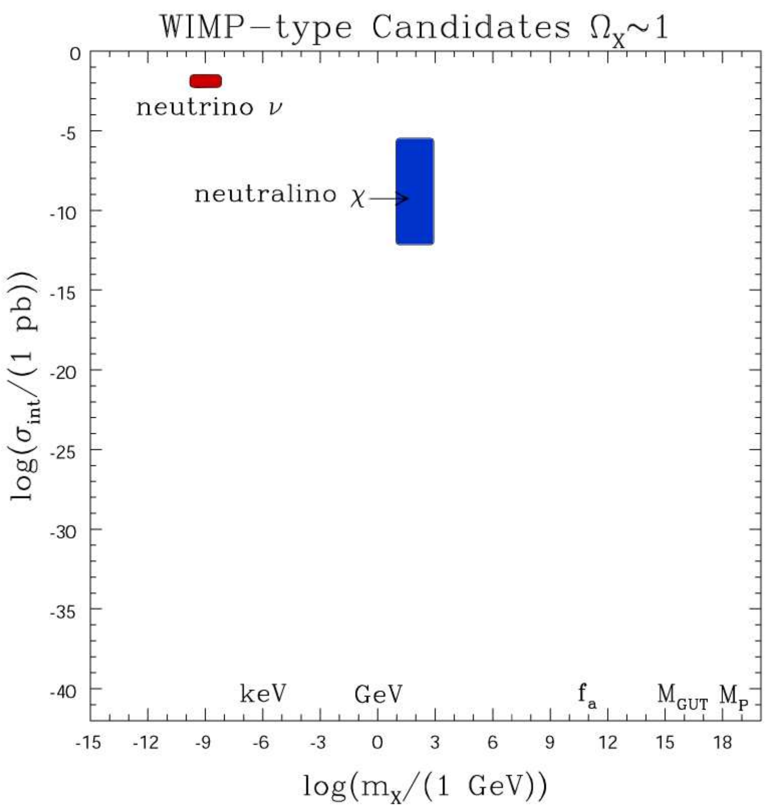
The Big Picture



- neutrino ν – hot DM

$$\mathcal{O}(0.01\,\mathrm{eV}) \lesssim m_\nu \lesssim \mathrm{few\,eV}, \quad \sigma \sim \sigma_{weak}$$

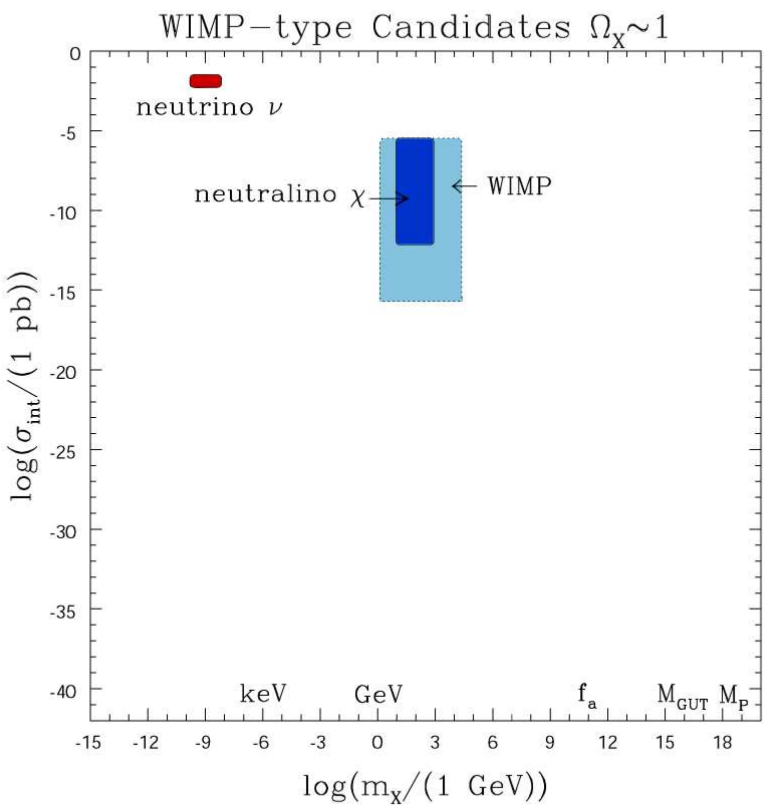
The Big Picture



- neutrino ν – hot DM
- neutralino χ

(LEP) $\mathcal{O}(100\,\mathrm{GeV}) \lesssim m_\chi \lesssim \mathcal{O}(1\,\mathrm{TeV})$, 10^{-5} pb $\gtrsim \sigma \gtrsim 10^{-12}$ pb, or less

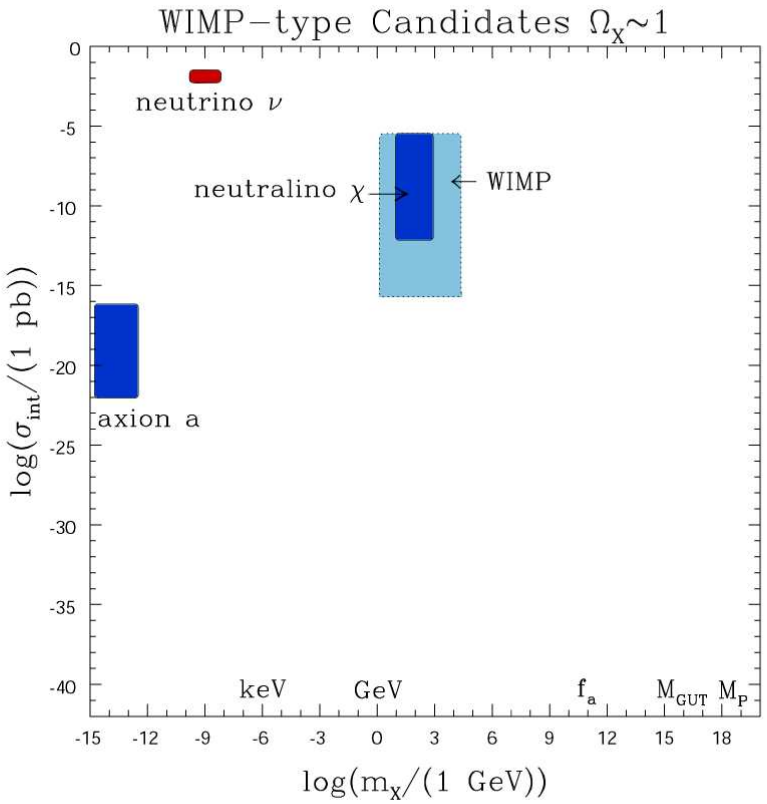
The Big Picture



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP

(“LW bound”) $\mathcal{O}(1\,\mathrm{GeV}) \lesssim m \lesssim \mathcal{O}(300\,\mathrm{TeV})$ (unitarity), $10^{-5}\,\mathrm{pb} \gtrsim \sigma \gtrsim ????$

The Big Picture



- neutrino ν – hot DM
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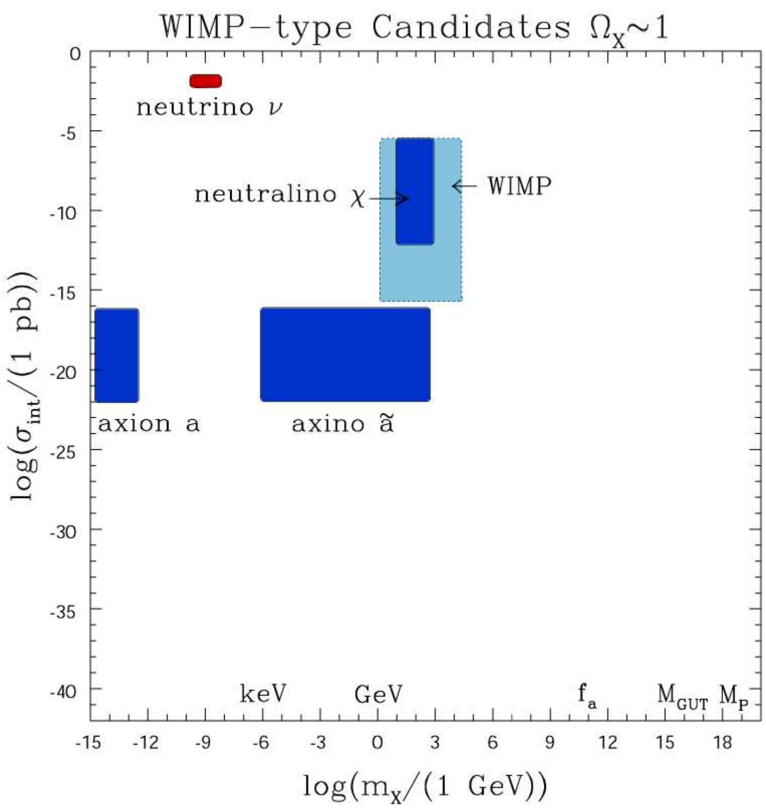
- “generic” WIMP
- axion a

$$m_a \sim \mathcal{O}(10^{-5}\,\text{eV}), \quad \sigma \sim (m_W/f_a)^2\,\sigma_{weak} \sim 10^{-16} - 10^{-22}\,\text{pb}$$

The Big Picture



- neutrino ν – hot DM
- neutralino χ
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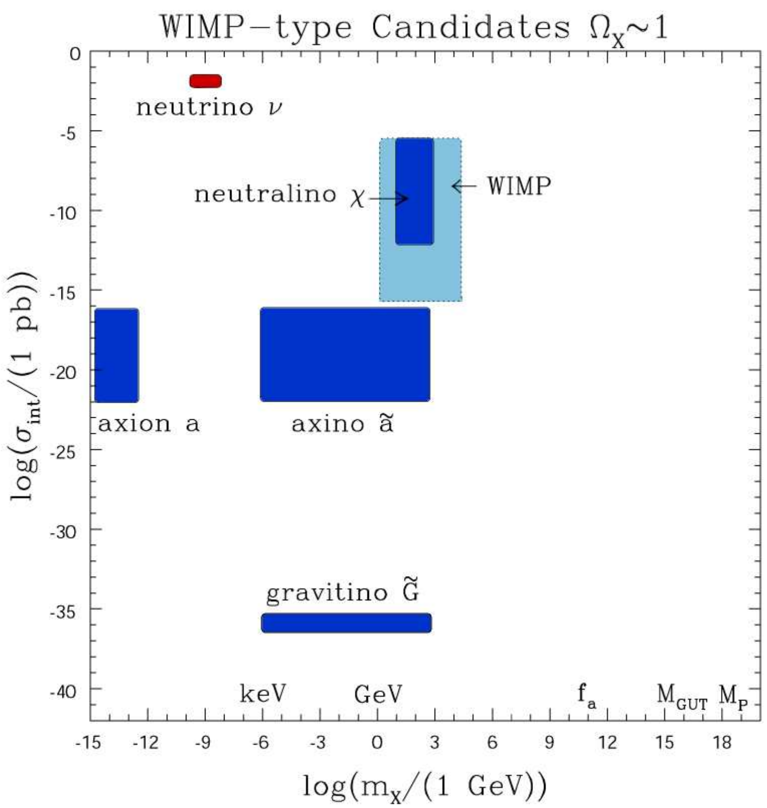
- axion a
- axino $\widetilde{a}$

$$\mathcal{O}(1\,\text{keV}) \lesssim m_{\widetilde{a}} \lesssim \mathcal{O}(1\,\text{TeV}), \quad \sigma \sim (m_W/f_a)^2 \, \sigma_{weak} \sim 10^{-16} - 10^{-22}\,\text{pb}$$

The Big Picture



- neutrino ν – hot DM
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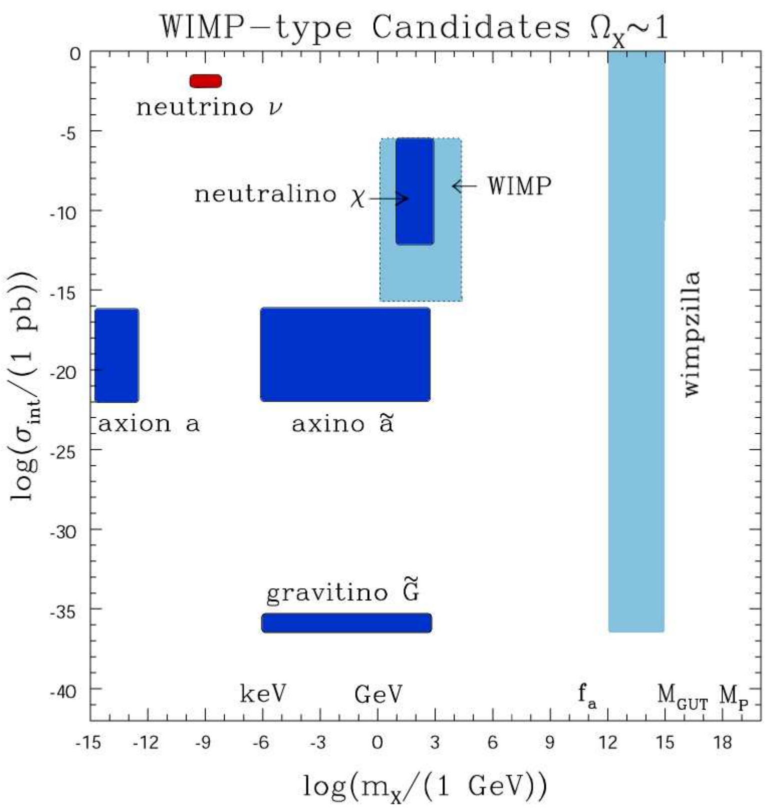
- axino $\widetilde{a}$
- gravitino $\widetilde{G}$

$\mathcal{O}(1)$ keV $\lesssim m_{\widetilde{G}} \lesssim \mathcal{O}(1)$ TeV, $(M_{\rm SUSY})$, $\quad \sigma \sim (m_W/M_{\rm P})^2\, \sigma_{weak} \sim 10^{-36}$ pb

The Big Picture



- neutrino ν – hot DM
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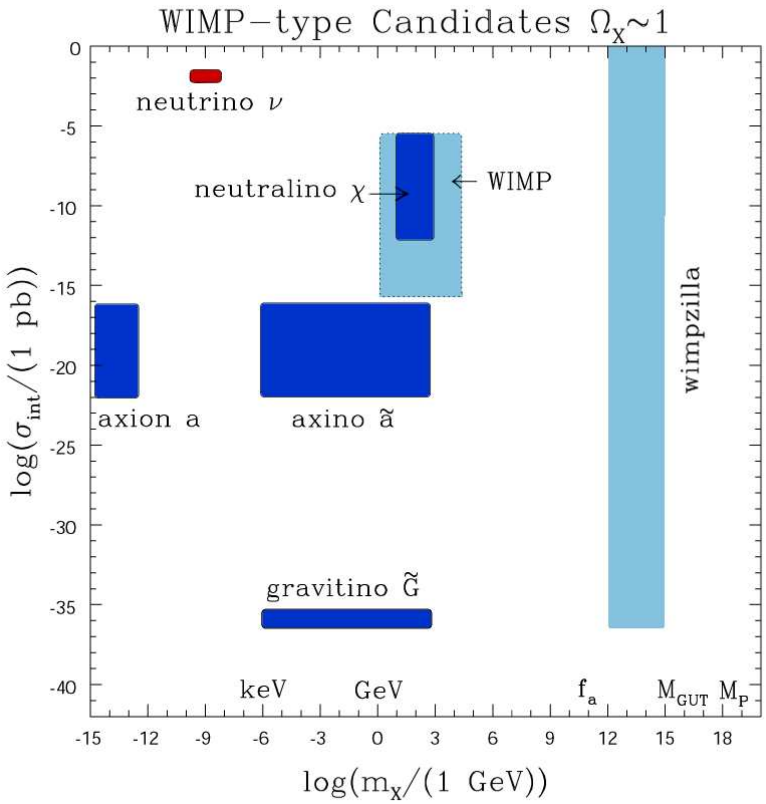
- wimpzilla

$m \sim \mathcal{O}(10^{13})$ GeV, σ unrestricted

The Big Picture



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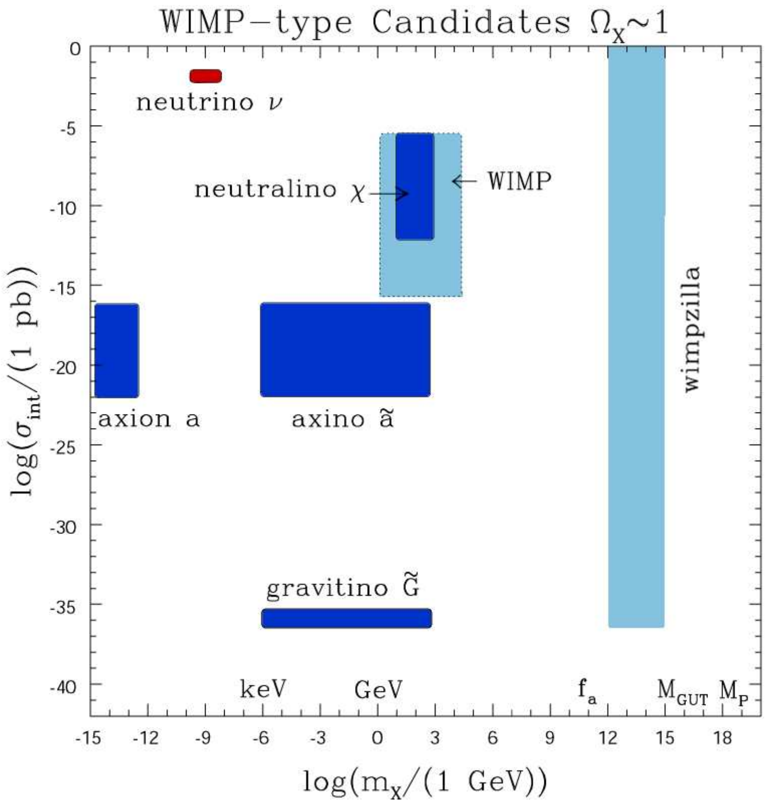
...plus: sterile (RH) neutrino or sneutrino, lightest Kałuża-Klein particle, etc, etc

The Big Picture



- neutrino ν – hot DM
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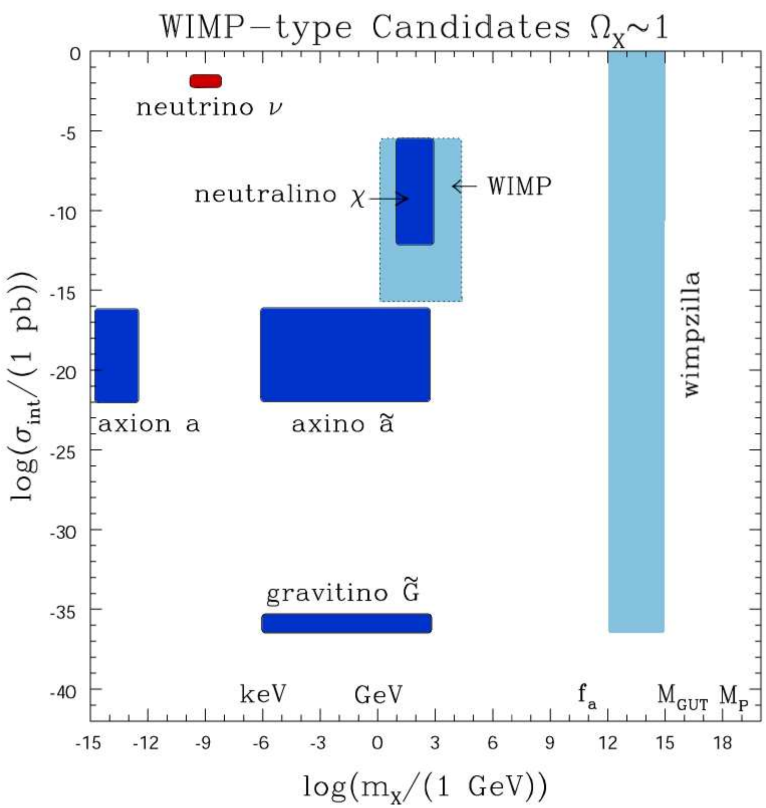
vastly different ranges of mass and σ, all give $\Omega \sim 1$

reason: different production mechanisms after the BB

The Big Picture



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solution of DM: must go beyond SM!

DM: What We Need to Know...

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- WIMP mass m_χ

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  $\Leftarrow$ f'n of model parameters

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  $\Leftarrow$ can now be computed accurately in terms of model's parameters

- detection: interaction rates

  $\Leftarrow$ likewise

DM: What We Need to Know...

- WIMP mass m_χ

  ⇐ f'n of model parameters

- relic abundance $\Omega_\chi h^2$

  ⇐ can now be computed accurately in terms of model's parameters

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  ⇐ likewise

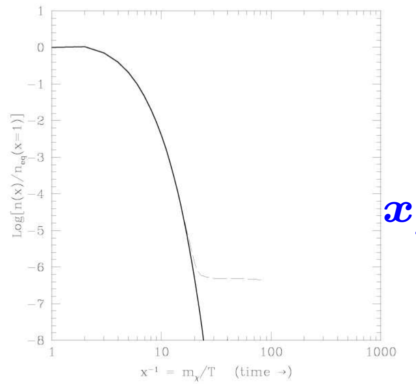
specific predictions strongly model–dependent

...may be a virtue

WIMP Relic Abundance

- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$

massive $\nu, \chi, \widetilde{G}, \widetilde{a}, \ldots$



$x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$

Boltzmann Eq.

$$\frac{d\,n_\chi}{d\,t} = -3Hn_\chi - \langle \sigma_{ann} v \rangle \left[n_\chi^2 - \left(n_\chi^{eq} \right)^2 \right]$$

---

n_χ– actual no. density of χ's

Hubble $H = 100\,h$ km/ s/ Mpc

(n_χ^{eq})– no. density of χ's in equil.

$n_\chi^{eq} \propto \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$

$\rho_\chi = m_\chi n_\chi$

v– relative velocity

$\rho_{crit} = 3H^2/8\pi G$

$\langle \ldots \rangle$– thermal average

$$\langle \sigma_{ann} v \rangle = \frac{\int d\,E_1 d\,E_2 (\sigma_{ann} v) e^{-E_1/T} e^{-E_2/T}}{\int d\,E_1 d\,E_2 e^{-E_1/T} e^{-E_2/T}}$$

$$\Omega_\chi = \rho_\chi / \rho_{crit}$$

Input from particle physics...

Input from particle physics...

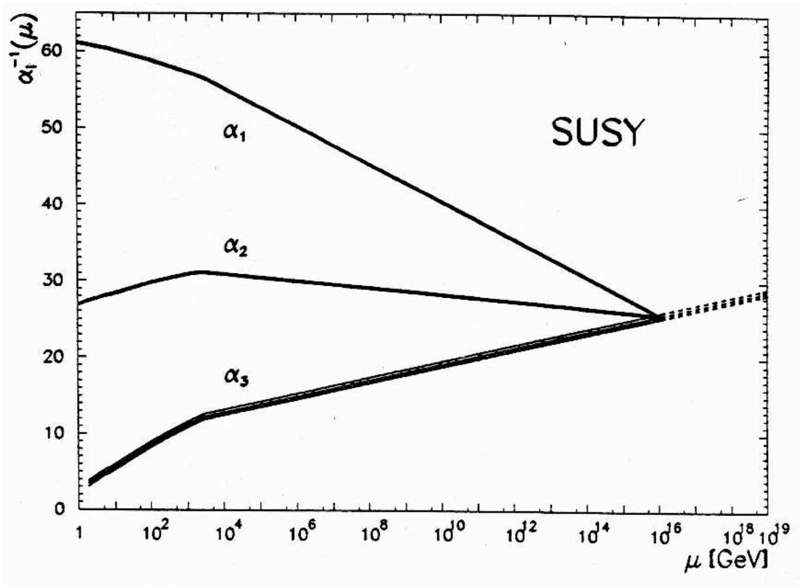
$$\sigma_{ann}$$

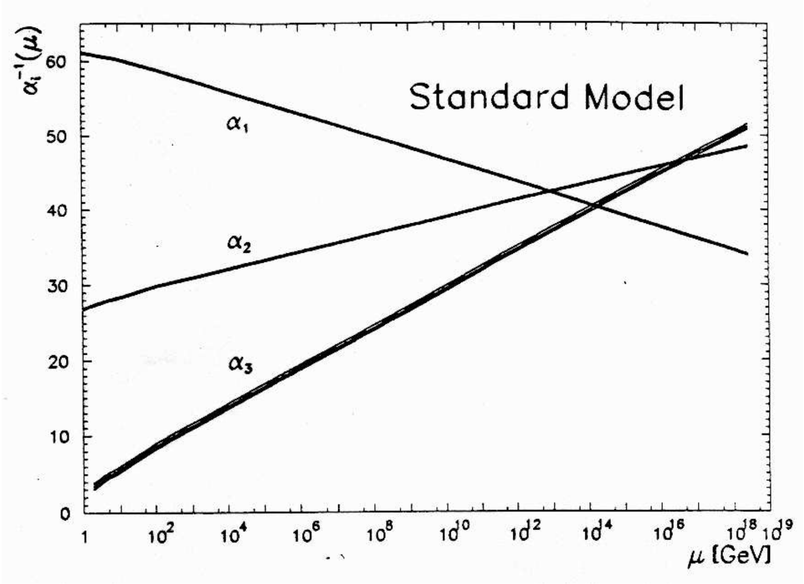
Input from particle physics...

$$\sigma_{ann}$$

$\Rightarrow$ need to select specific model

To SUSY or not to SUSY?





gauge couplings “run” with energy

SUSY Models

Two basic approaches:

SUSY Models

Two basic approaches:

- general MSSM

SUSY Models

Two basic approaches:

- general MSSM
- unification based:

SUSY Models

Two basic approaches:

- general MSSM
- unification based:
  - Constrained MSSM (CMSSM)

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- general MSSM
- unification based:
  - Constrained MSSM (CMSSM)
  - Non-unified Higgs mass (NUHM)
  - SO(10)–GUT
  - . . .

MSSM

...supersymmetrized SM + R–parity

MSSM

...supersymmetrized SM + R–parity

- gauginos $M_1 \overline{\widetilde{B}}\widetilde{B} + M_2 \overline{\widetilde{W}}_a \widetilde{W}_a + m_{\widetilde{g}} \overline{\widetilde{g}}_b \widetilde{g}_b$

At $Q = m_Z$: $M_1 \simeq 0.5 M_2$, $M_2 \simeq 0.3\, m_{\widetilde{g}}$

MSSM

...supersymmetrized SM + R–parity

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  At $Q = m_Z$: $M_1 \simeq 0.5 M_2$, $M_2 \simeq 0.3\, m_{\widetilde{g}}$

- higgsinos $\mu \widetilde{H}_b \widetilde{H}_t + h.c.$

MSSM

...supersymmetrized SM + R–parity

- gauginos $M_1 \overline{\widetilde{B}}\widetilde{B} + M_2 \overline{\widetilde{W}}_a \widetilde{W}_a + m_{\widetilde{g}} \overline{\widetilde{g}}_b \widetilde{g}_b$

  At $Q = m_Z$: $M_1 \simeq 0.5 M_2$, $M_2 \simeq 0.3\, m_{\widetilde{g}}$

- higgsinos $\mu \widetilde{H}_b \widetilde{H}_t + h.c.$
- Higgs $\mu^2 \left(H_b^2 + H_t^2\right) + \ldots$ $\tan\beta = \frac{\langle v_t \rangle}{\langle v_b \rangle}$

MSSM

...supersymmetrized SM + R–parity

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Majorana fermion ($\chi^c = \chi$)

stable, massive $\Rightarrow$ LSP

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(MSSM: over 500 annihilation channels...)

Spin–Independent Interactions

- elastic scatterings of WIMPs off target nuclei (SI=scalar)

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- Convenient quantity: c.s. at $q=0$: σ_p^{SI}

$\mu_p = \frac{m_\chi m_p}{m_\chi + m_p}$

$$\sigma_p^{SI} = \frac{4}{\pi}\mu_p^2 f_p^2$$

Relic Abundance vs. Detection Rates

$\Omega_\chi h^2 = \rho_\chi / \rho_{crit} \propto 1/\sigma_{ann} v$

$\sigma_{ann} \left(\chi\chi \to \bar{q}q, \bar{l}l, \ldots\right)$ $\sigma_{scat} \left(\chi q \to \chi q\right)$

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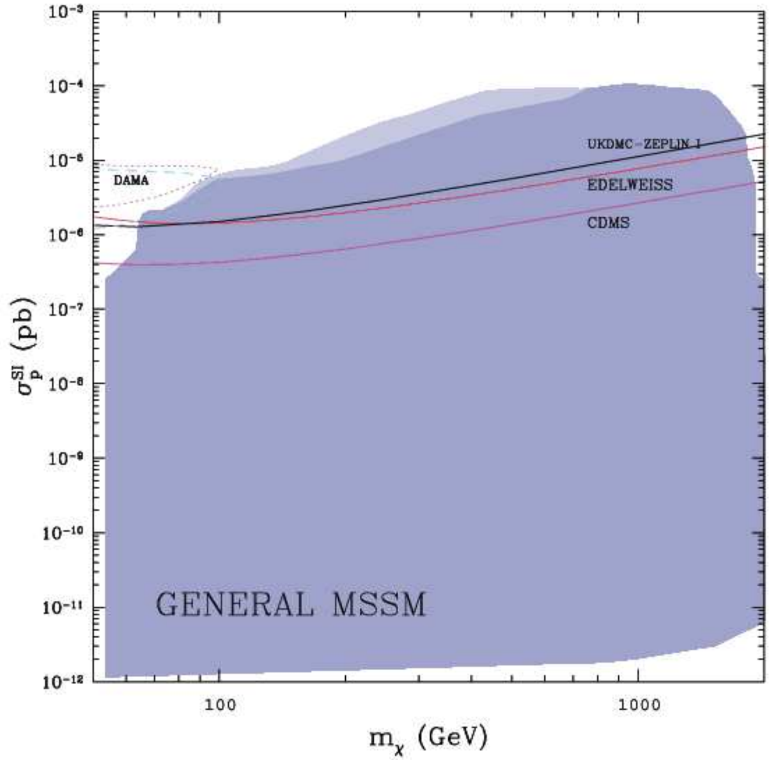
$\Rightarrow$ $\Omega_\chi h^2$ and σ_p^{SI} are controlled by different mass parameters

$\Rightarrow$ can have $\Omega_\chi h^2 \sim 0.1$ *and* $\sigma_p^{SI} \ll \sigma_{weak}$

MSSM: Expectations for σ_p^{SI}

general SUSY $\mu > 0$



σ_p^{SI} – WIMP–proton SI elastic scatt. c.s.

(elastic c.s. for $\chi p \longrightarrow \chi p$ at zero momentum transfer)

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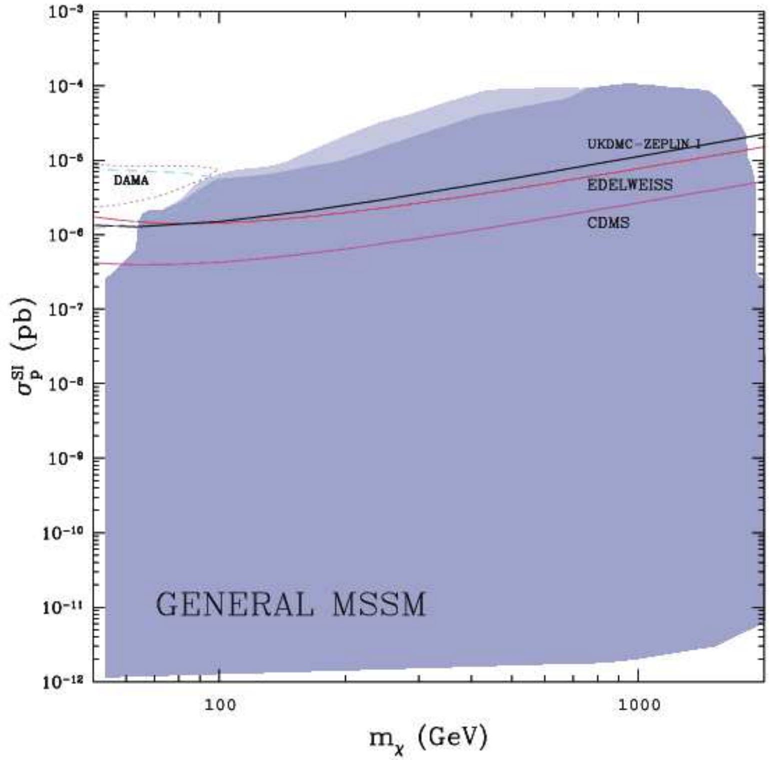

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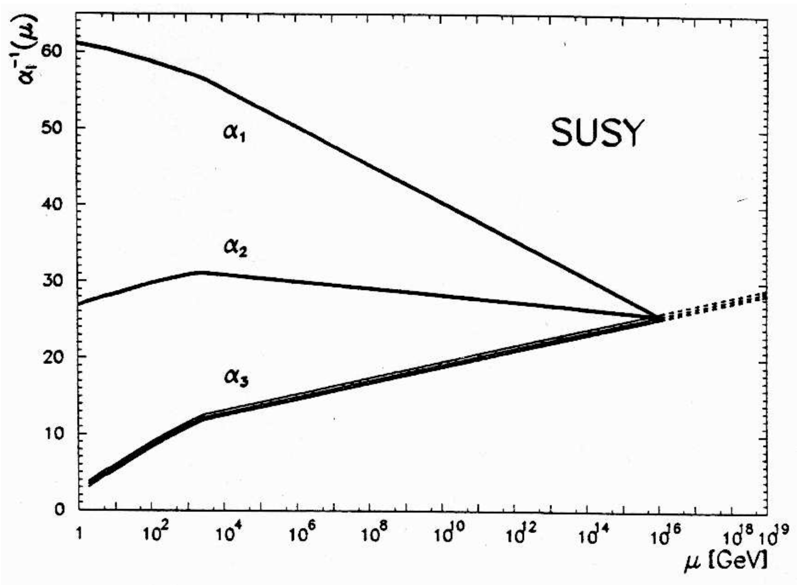
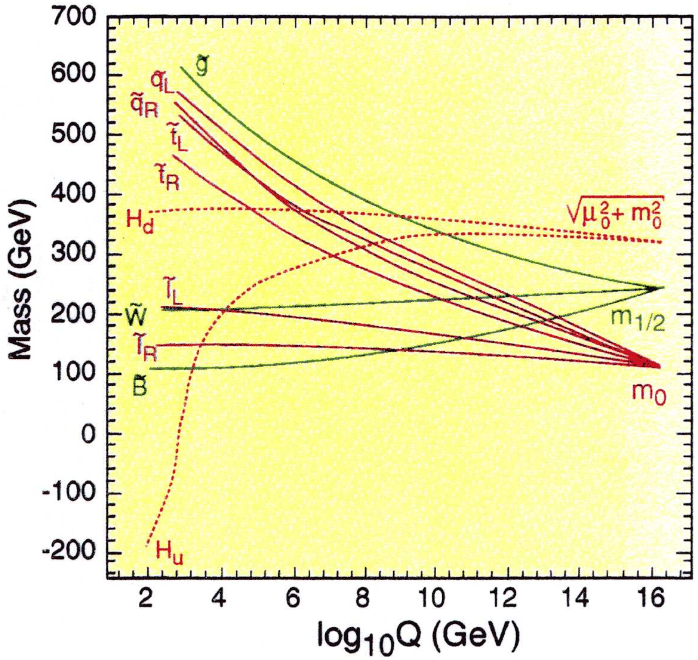
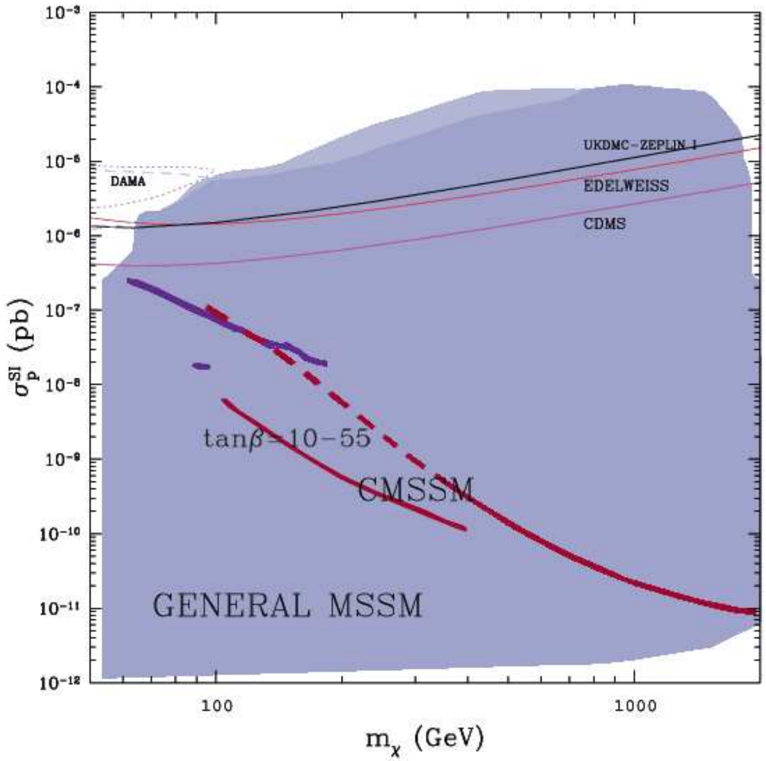
vast ranges!!!

Add grand unification...





Expectations for σ_p^{SI} with unification



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blue: general MSSM

red: Constrained MSSM

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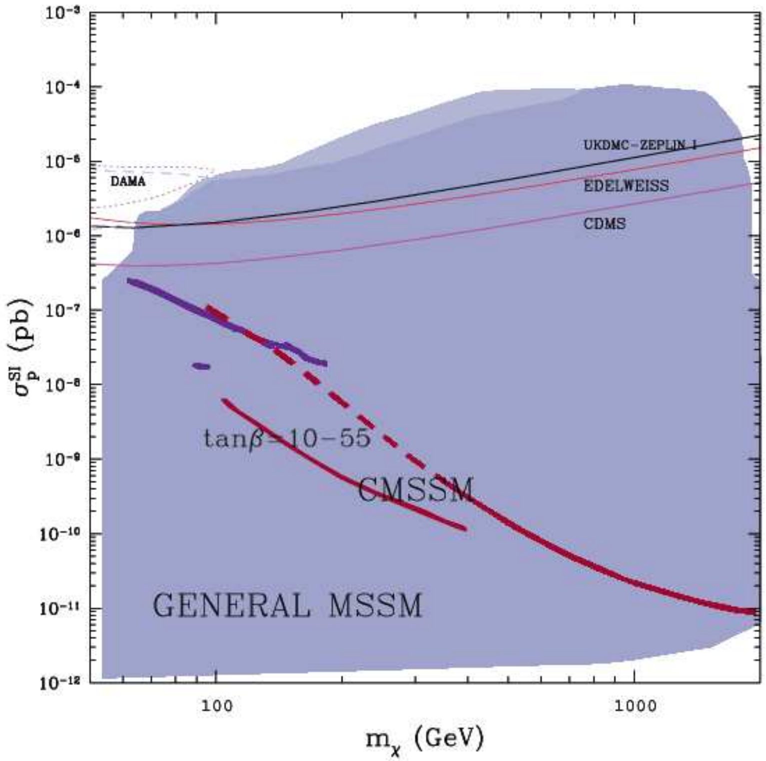

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much (!) more predictive

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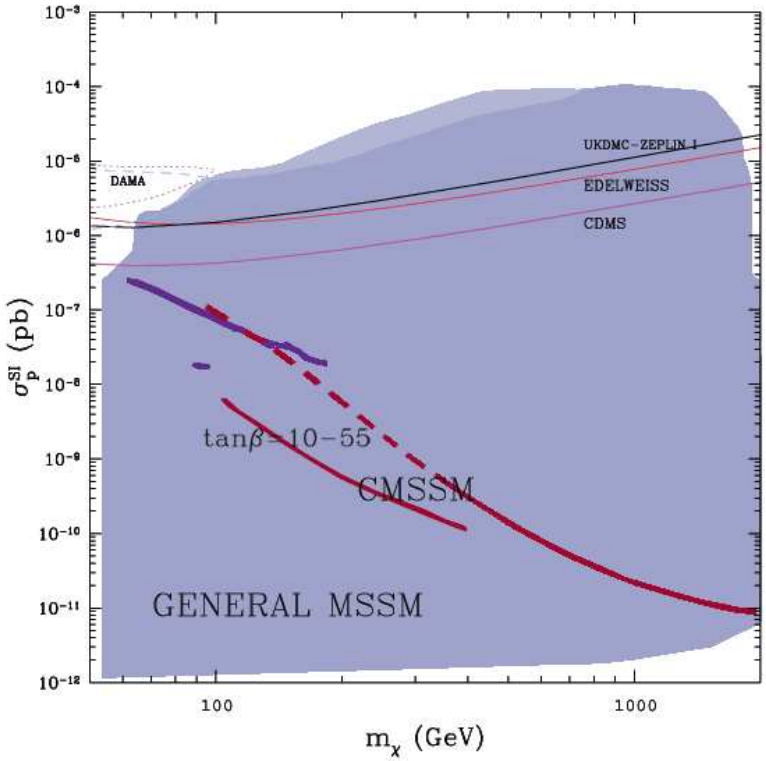

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outdated!

Constrained MSSM ...aka mSUGRA

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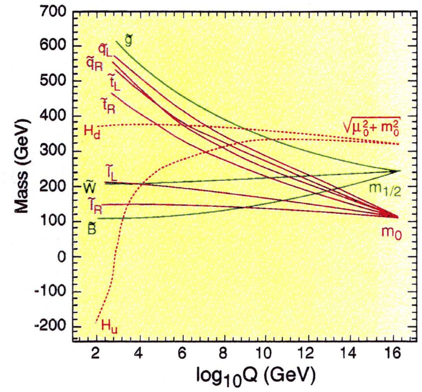
At $M_{\rm GUT} \simeq 2 \times 10^{16}$ GeV:



- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$ (c.f. MSSM)
- scalars $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m^2_0$
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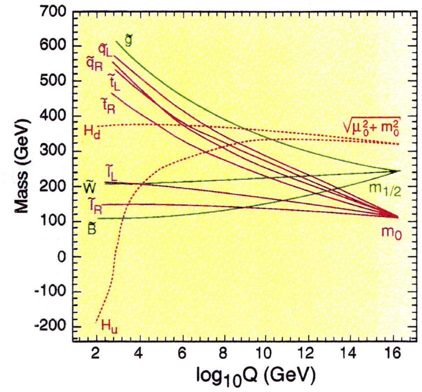

- radiative EWSB

$$\mu^2 = \frac{\left(m^2_{H_b}+\Sigma_b^{(1)}\right)-\left(m^2_{H_t}+\Sigma_t^{(1)}\right)\tan^2\beta}{\tan^2\beta-1} - \frac{m_Z^2}{2}$$

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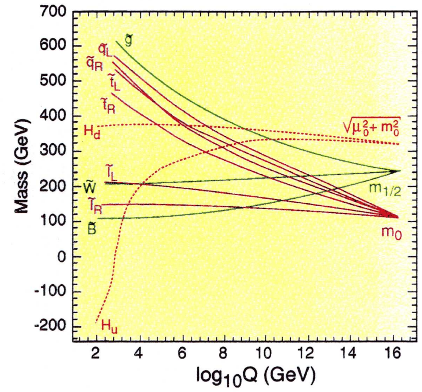

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- five independent parameters: $\tan\beta,\ m_{1/2},\ m_0,\ A_0,\ {\rm sgn}(\mu)$

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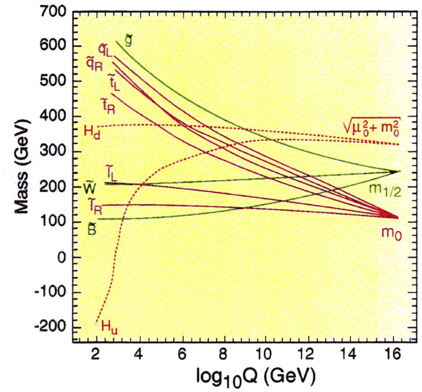

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- five independent parameters: $\tan\beta,\ m_{1/2},\ m_0,\ A_0,\ \mathrm{sgn}(\mu)$
- mass spectra at m_Z: run RGEs, 2–loop for g.c. and Y.c, 1-loop for masses
- some important quantities $(\mu, m_A, \ldots)$ very sensitive to procedure of computing EWSB & minimizing V_H

we use SoftSusy and FeynHiggs

CMSSM: allowed regions

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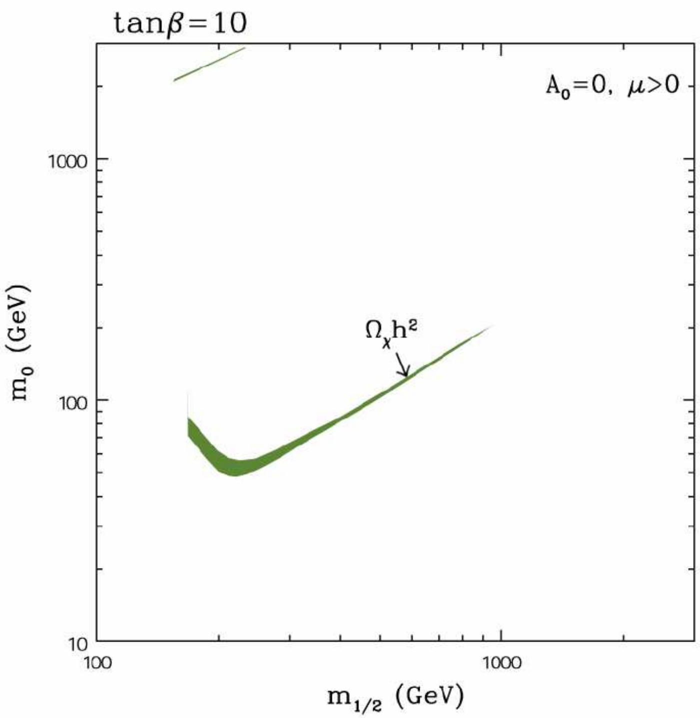
$\tan\beta \lesssim 45$



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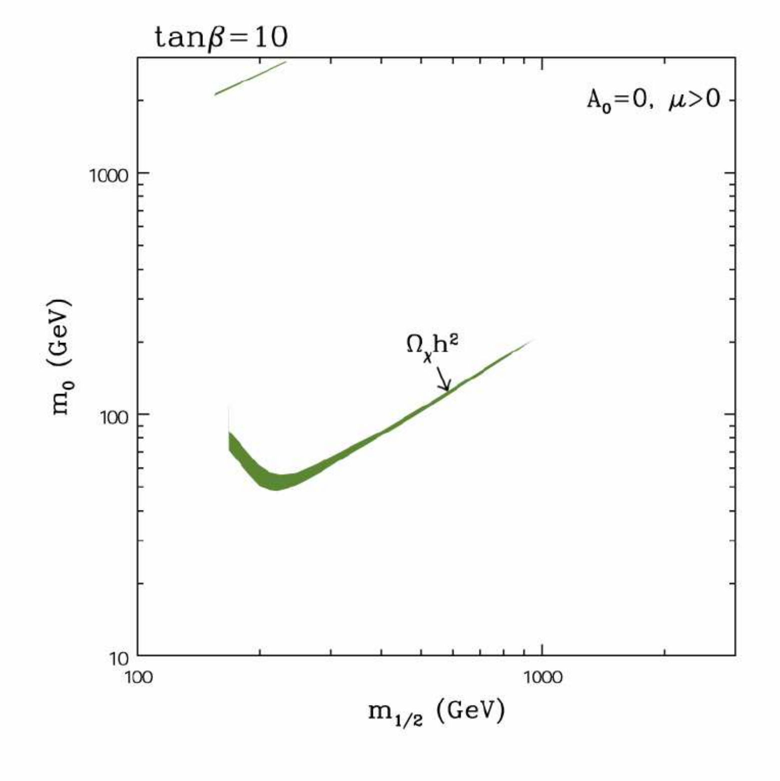

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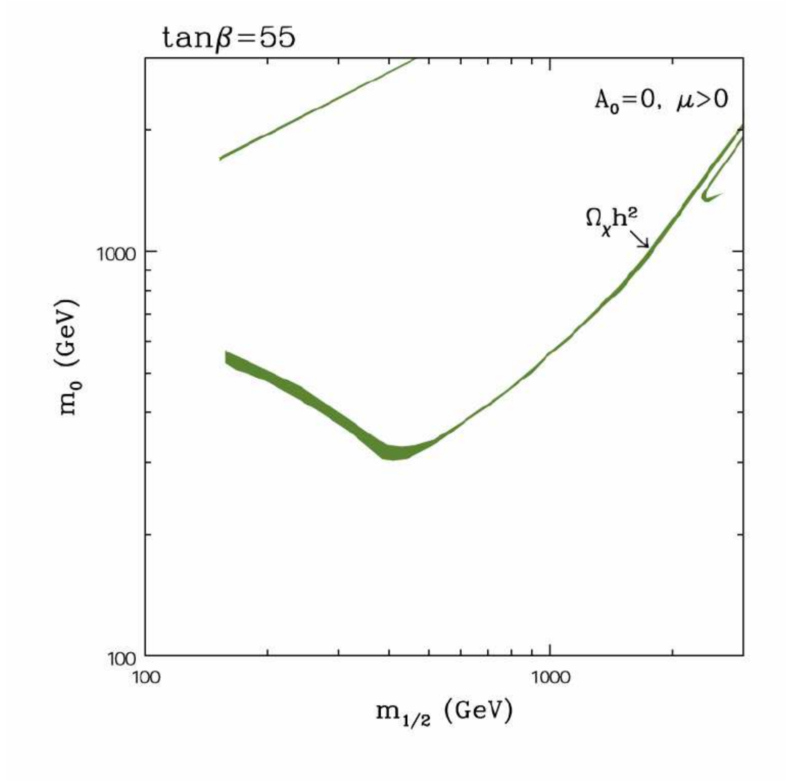

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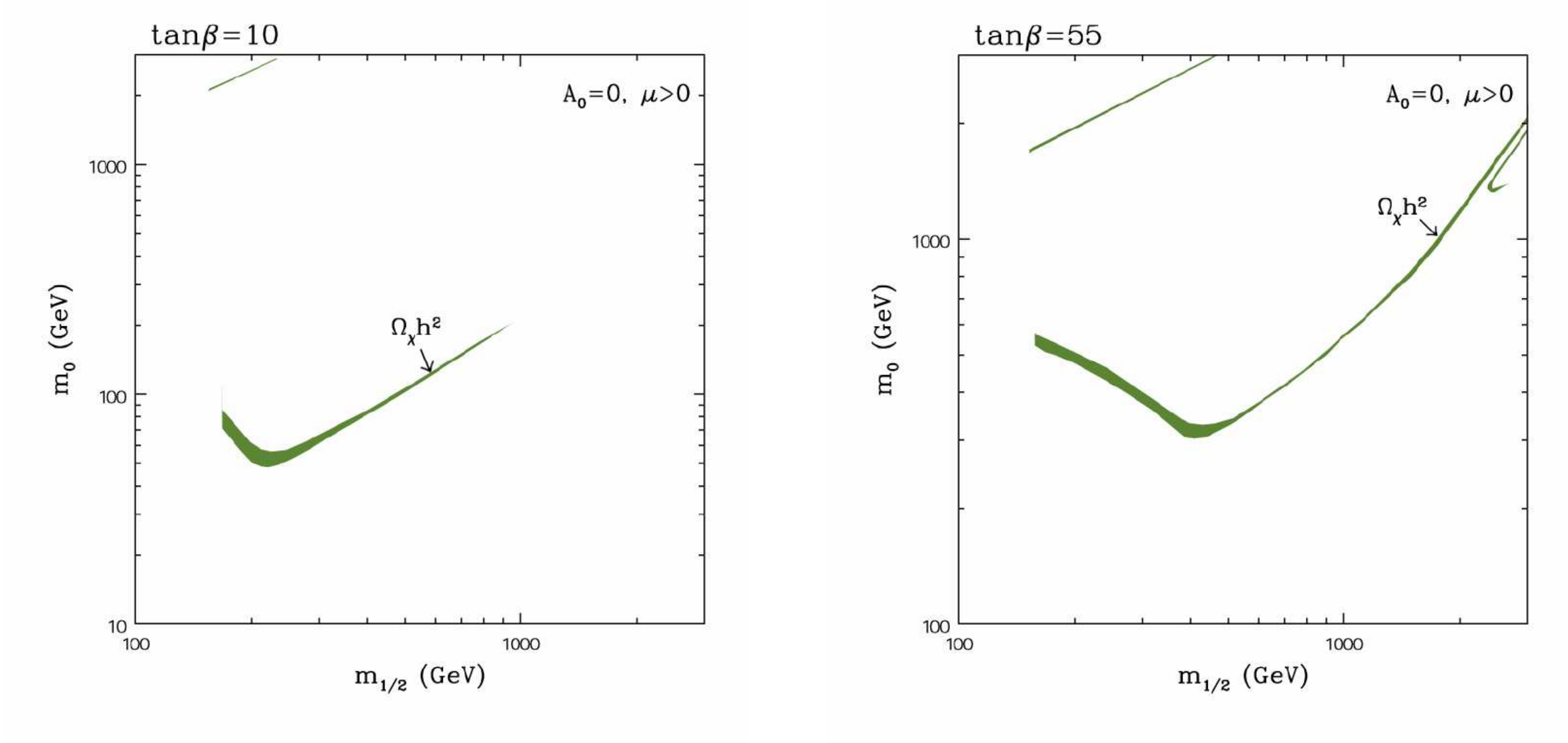

- fixed-grid scans, assuming rigid 1σ or 2σ ranges
- green: consistent with WMAP-3yr (at 2σ)
- all the rest excluded by LEP, $\mathbf{BR}(\bar{B} \to X_s\gamma)$, $\Omega_\chi h^2$, EWSB, charged LSP,...

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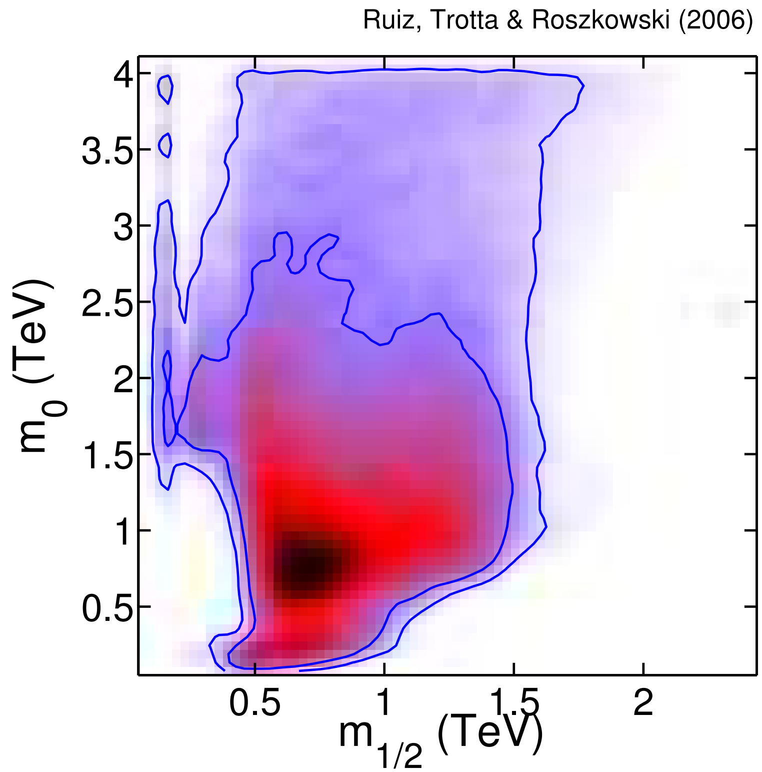

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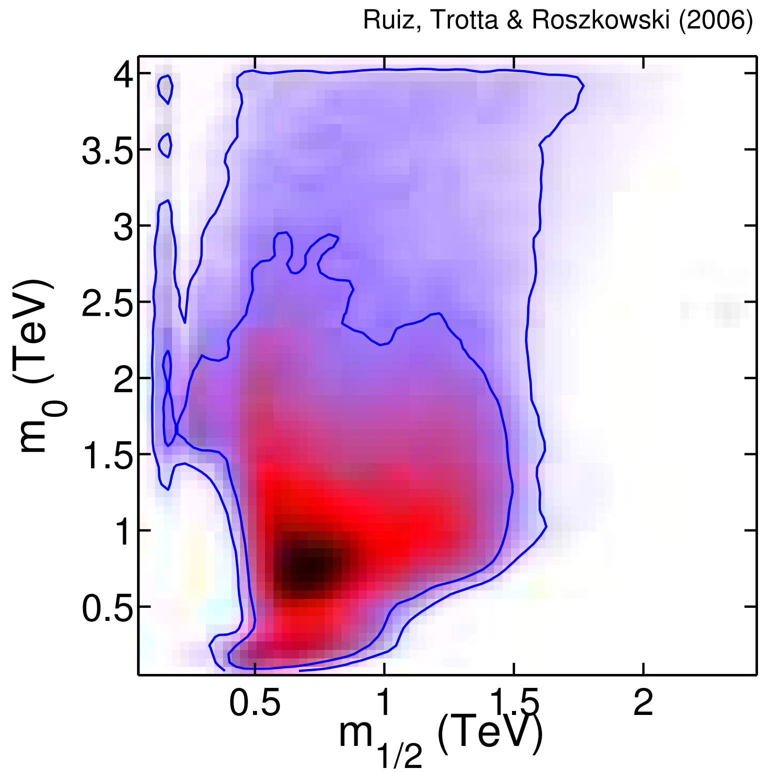

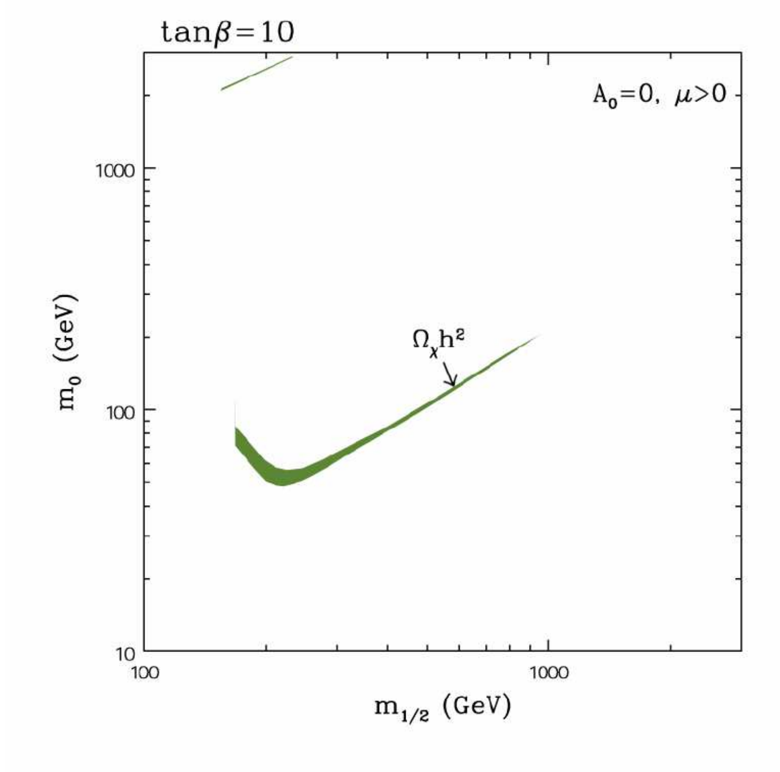

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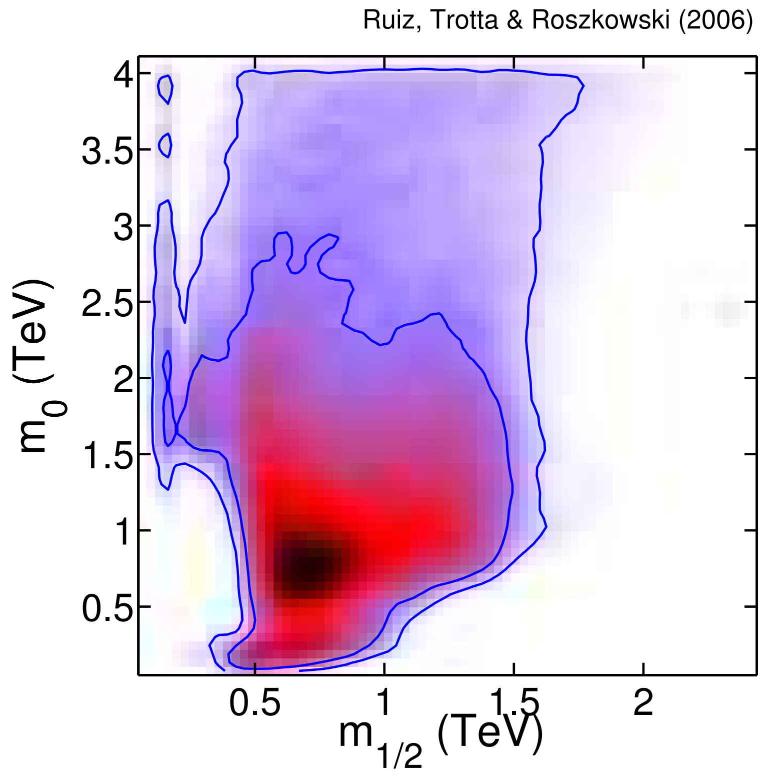

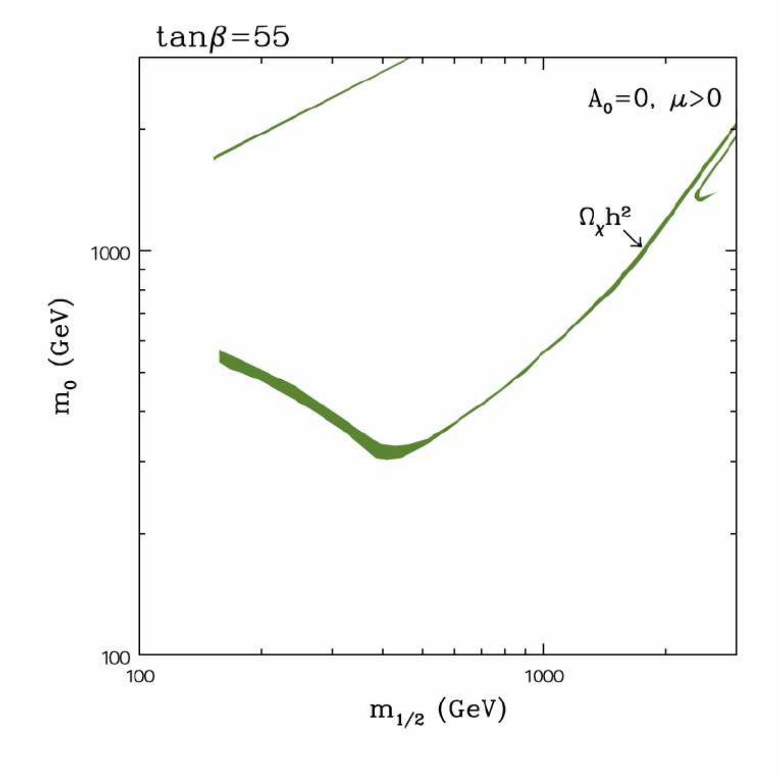

Note: In both an outdated SM value of $\mathbf{BR}(\bar{B} \longrightarrow X_s\gamma)$ used. See below.

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(MCMC=Markov Chain Monte Carlo)

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Disadvantages

- random scan of points (not strictly controlled)

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a probabilistic approach

Advantages

- efficient, nr of scan points $\propto N$
- easy to deal with additional parameters
- easy to deal with uncertainties (expt and theor)
- ‘allowed’ regions function of probability

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Powerful method of exploring multi–parameter models;

allows one to make global statements, expose correlations, etc.

Bayesian Analysis of the CMSSM

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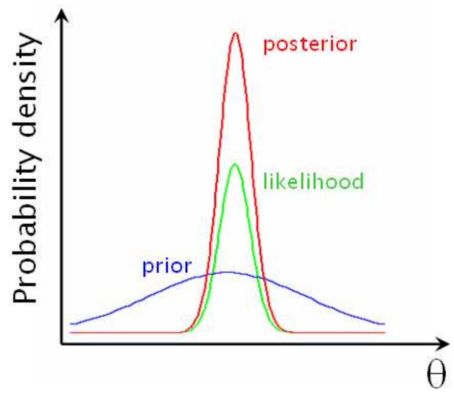

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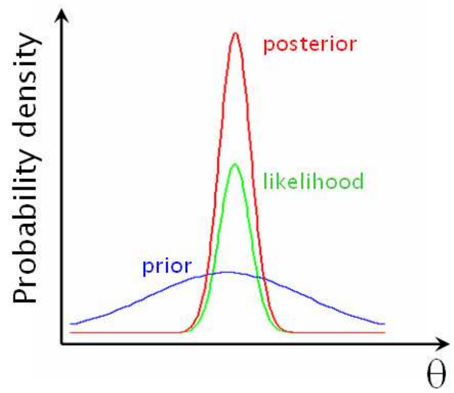

- Bayes' theorem: posterior pdf

$$p(\theta, \psi | d) = \frac{p(d|\xi)\pi(\theta,\psi)}{p(d)}$$

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{normalization factor}}$$

- $p(d|\xi)$: likelihood
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- $p(d)$: evidence (normalization factor)

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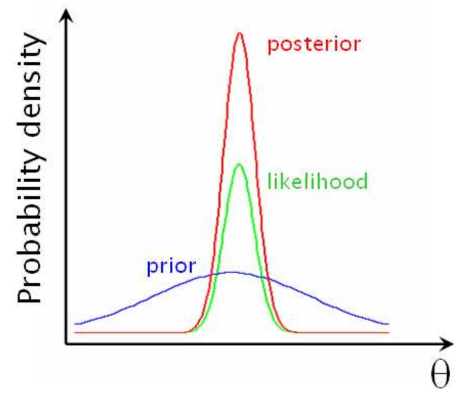

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- $p(d|\xi)$: likelihood
- $\pi(\theta, \psi)$: prior pdf
- $p(d)$: evidence (normalization factor)
- usually marginalize over SM (nuisance) parameters $\psi \Rightarrow p(\theta|d)$

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{normalization factor}}$$

Bayesian Analysis of the CMSSM

- $\theta = (m_0, m_{1/2}, A_0, \tan\beta)$: CMSSM parameters
- $\psi = (M_t, m_b(m_b)^{\overline{MS}}, \alpha_{\rm em}(M_Z)^{\overline{MS}}, \alpha_s^{\overline{MS}})$: SM (nuisance) parameters
- priors – assume flat distributions and ranges as:

CMSSM parameters θ
$50\,\mathrm{GeV} < m_0 < 4\,\mathrm{TeV}$
$50\,\mathrm{GeV} < m_{1/2} < 4\,\mathrm{TeV}$
$\lvert A_0 \rvert < 7\,\mathrm{TeV}$
$2 < \tan\beta < 62$

flat priors: SM (nuisance) parameters ψ
$160\,\mathrm{GeV} < M_t < 190\,\mathrm{GeV}$
$4\,\mathrm{GeV} < m_b(m_b)^{\overline{MS}} < 5\,\mathrm{GeV}$
$0.10 < \alpha_s^{\overline{MS}} < 0.13$
$127.5 < 1/\alpha_{\rm em}(M_Z)^{\overline{MS}} < 128.5$

- vary all 8 (CMSSM+SM) parameters simultaneously, apply MCMC
- include all relevant theoretical and experimental errors

Experimental Measurements

(assume Gaussian distributions)

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SM (nuisance) parameter	Mean μ	Error σ (expt)
M_t	171.4 GeV	2.1 GeV
$m_b(m_b)^{\overline{MS}}$	4.20 GeV	0.07 GeV
α_s	0.1176	0.002
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new $M_W = 80.413 \pm 0.048$ GeV (Jan 07, not yet included)
new $M_t = 170.9 \pm 1.8$ GeV (Mar 07, not yet included)
$\mathrm{BR}(\bar{B} \to X_s\gamma) \times 10^4$:
new SM: 3.15 ± 0.23 (Misiak & Steinhauser, Sept 06) used here

Derived observable	Mean μ	Errors σ (expt)	τ (th)
M_W	80.392 GeV	29 MeV	15 MeV
$\sin^2\theta_{\mathrm{eff}}$	0.23153	16×10^{-5}	15×10^{-5}
$\delta a_\mu^{\mathrm{SUSY}} \times 10^{10}$	28	8.1	1
$\mathrm{BR}(\bar{B} \to X_s\gamma) \times 10^4$	3.55	0.26	0.21
ΔM_{B_s}	17.33	0.12	4.8
$\Omega_\chi h^2$	0.119	0.009	$0.1\,\Omega_\chi h^2$

take as precisely known: $M_Z = 91.1876(21)$ GeV, $G_F = 1.16637(1) \times 10^{-5}$ GeV^{-2}

Experimental Limits

Derived observable	upper/lower limit	Constraints $\xi_{\rm lim}$	τ (theor.)
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	UL	1.5×10^{-7}	14%
m_h	LL	114.4 GeV (91.0 GeV)	3 GeV
$\zeta_h^2 \equiv g^2_{ZZh}/g^2_{ZZH_{\rm SM}}$	UL	$f(m_h)$	3%
m_χ	LL	50 GeV	5%
$m_{\chi_1^\pm}$	LL	103.5 GeV (92.4 GeV)	5%
$m_{\tilde{e}_R}$	LL	100 GeV (73 GeV)	5%
$m_{\tilde{\mu}_R}$	LL	95 GeV (73 GeV)	5%
$m_{\tilde{\tau}_1}$	LL	87 GeV (73 GeV)	5%
$m_{\tilde{\nu}}$	LL	94 GeV (43 GeV)	5%
$m_{\tilde{t}_1}$	LL	95 GeV (65 GeV)	5%
$m_{\tilde{b}_1}$	LL	95 GeV (59 GeV)	5%
$m_{\tilde{q}}$	LL	318 GeV	5%
$m_{\tilde{g}}$	LL	233 GeV	5%
(σ_p^{SI}	UL	WIMP mass dependent	$\sim 100\%$)

Note: DM direct detection σ_p^{SI} not applied due to astroph'l uncertainties (eg, local DM density)

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Take a single observable $\xi(m)$ that has been measured

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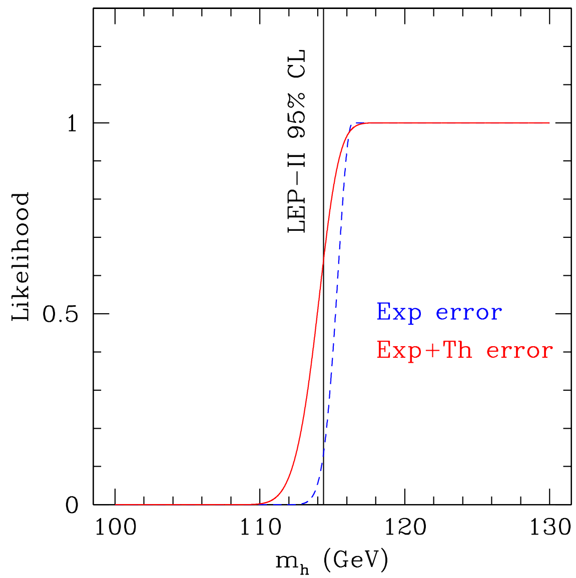
- for several uncorrelated observables (assumed Gaussian):

$$\mathcal{L} = \exp\left[-\sum_i \frac{\chi_i^2}{2}\right]$$

Example: Light Higgs mass

LEP: $m_h > 114.4$ GeV (95% CL) - if SM-like

- include both experimental and theoretical error:



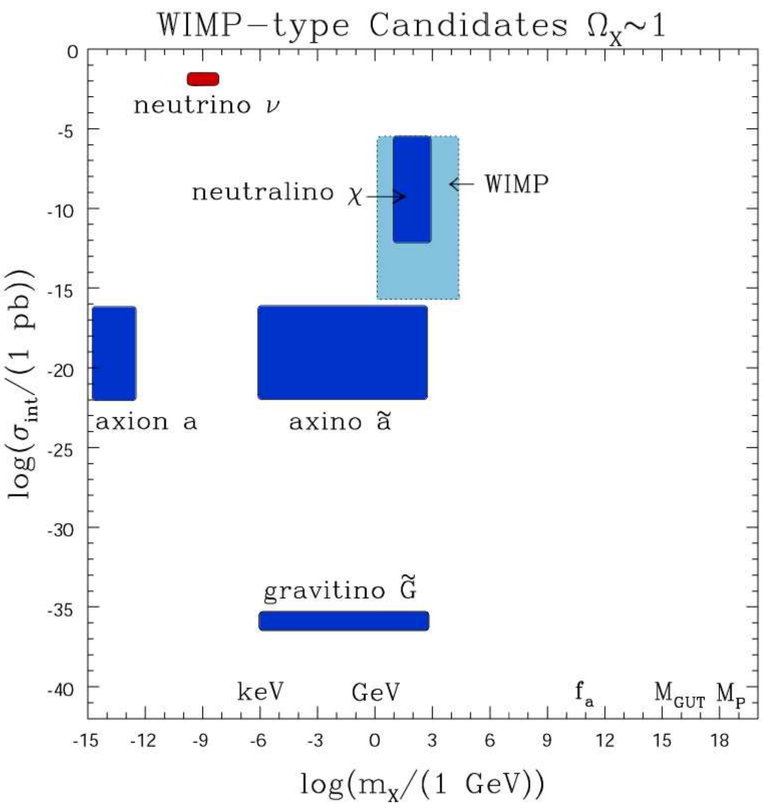
- we find $\zeta_h^2 \equiv \frac{g^2(m_h ZZ)_{\mathrm{MSSM}}}{g^2(m_h ZZ)_{\mathrm{SM}}} \simeq 1$

$\Rightarrow$ the light Higgs boson of the CMSSM is very SM-like

LEP-II limit applies

The Big Picture

well–motivated particle candidates such that $\mathbf{\Omega \sim 0.1}$



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- ????

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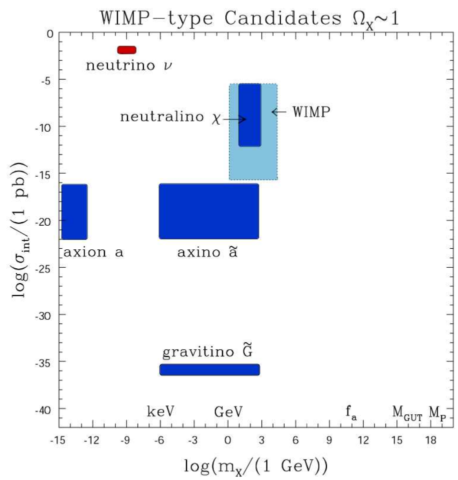

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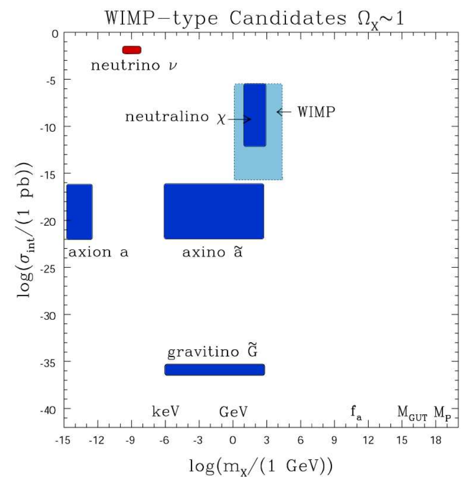

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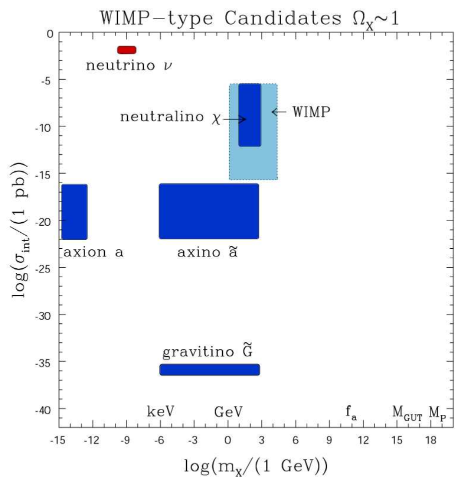

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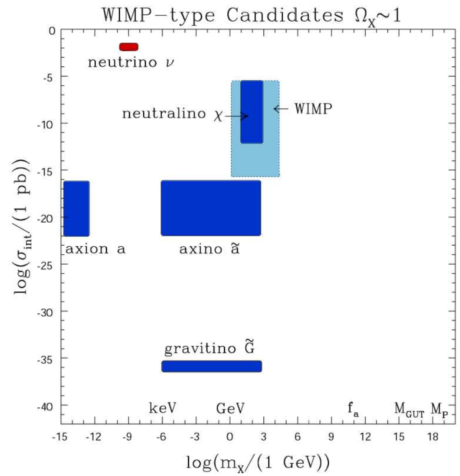

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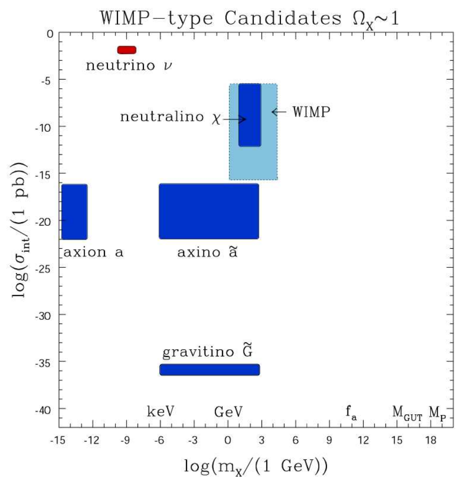

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- work them out and compare with search limits
- Bayesian analysis: powerful tool to do it properly
- CMSSM: light Higgs boson to be found at the Tevatron, or the model will be ruled out

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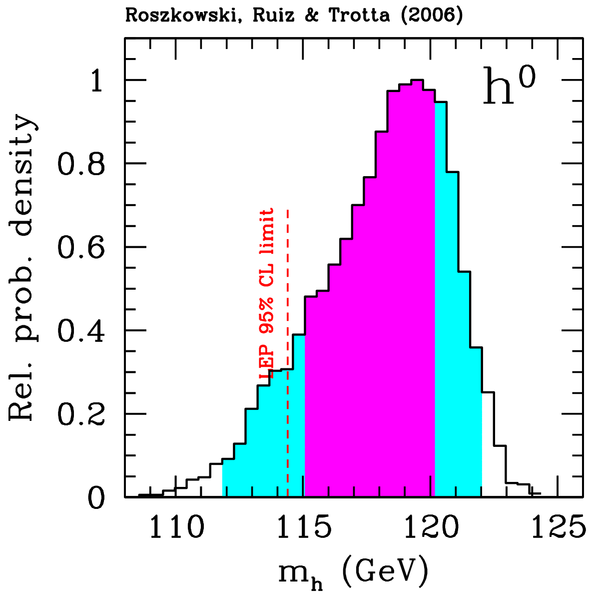

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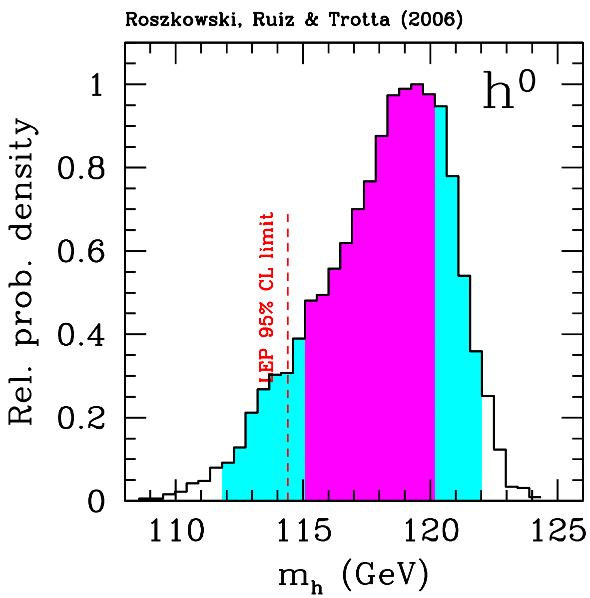
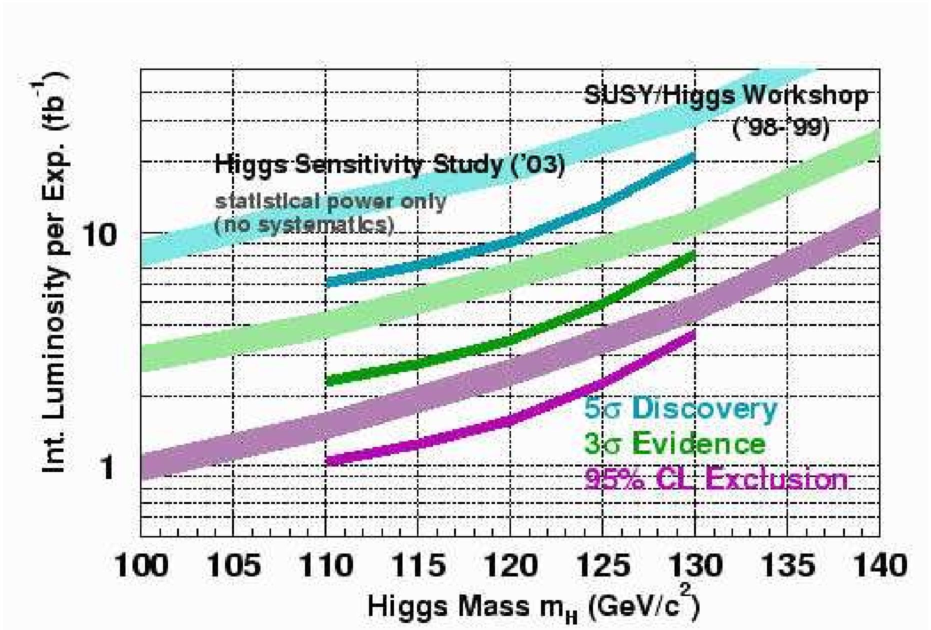


Tevatron reach (CDF and D0 WG (Oct 03))



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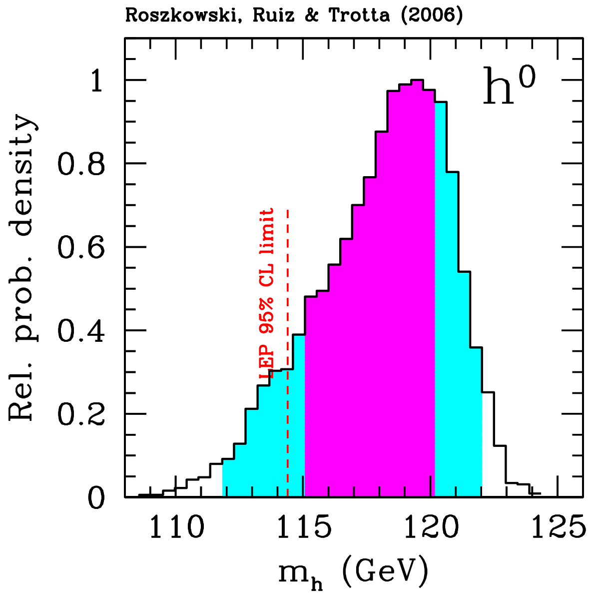

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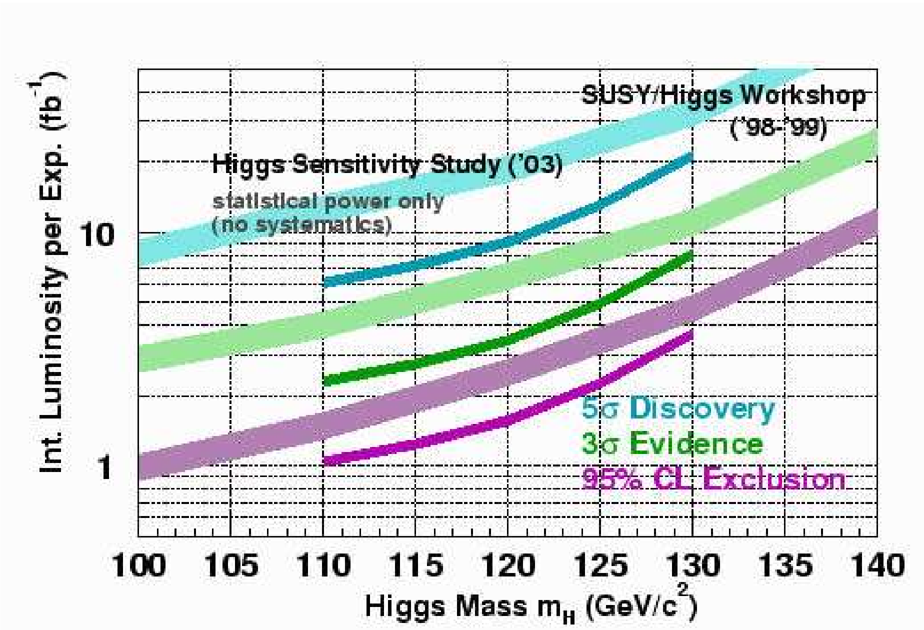

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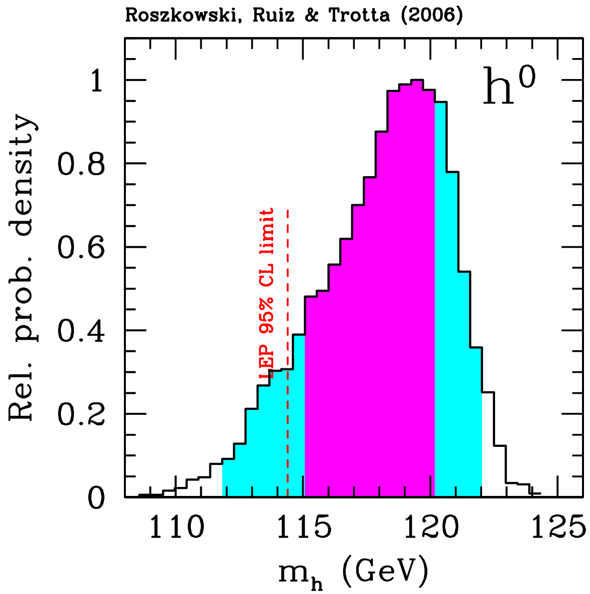

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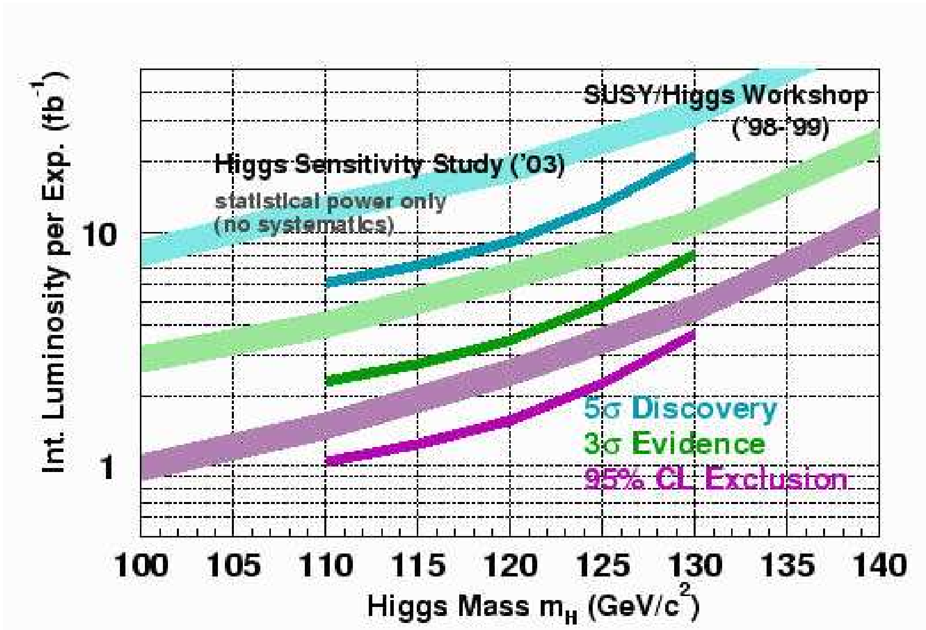

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...or else...

with ~ 4 fb^{-1}/expt: 3σ evidence over entire 95% range of m_h

with $\sim 10-12$ fb^{-1}/expt: 5σ discovery over entire 95% range of m_h

Tevatron: hope for up to ~ 8 fb^{-1}/expt

Probability maps of the CMSSM

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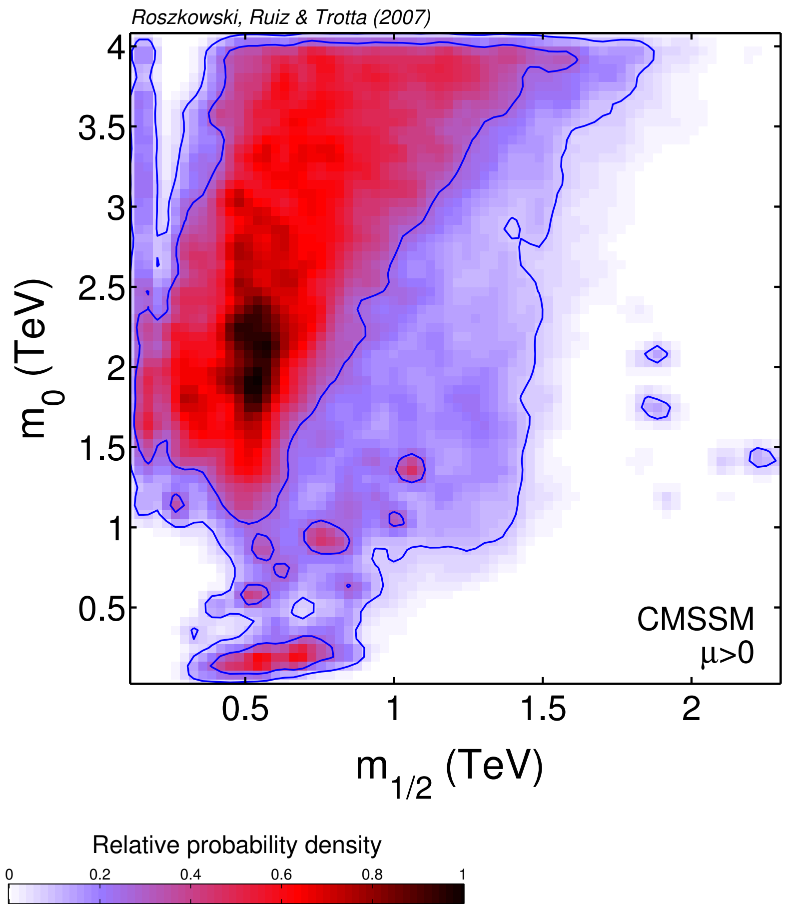
arXiv:0705.2012



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- relative probability density fn
- flat priors
- 68% total prob. – inner contours
- 95% total prob. – outer contours
- 2-dim pdf $p(m_0, m_{1/2}|d)$
- favored: $m_0 \gg m_{1/2}$ (FP region)

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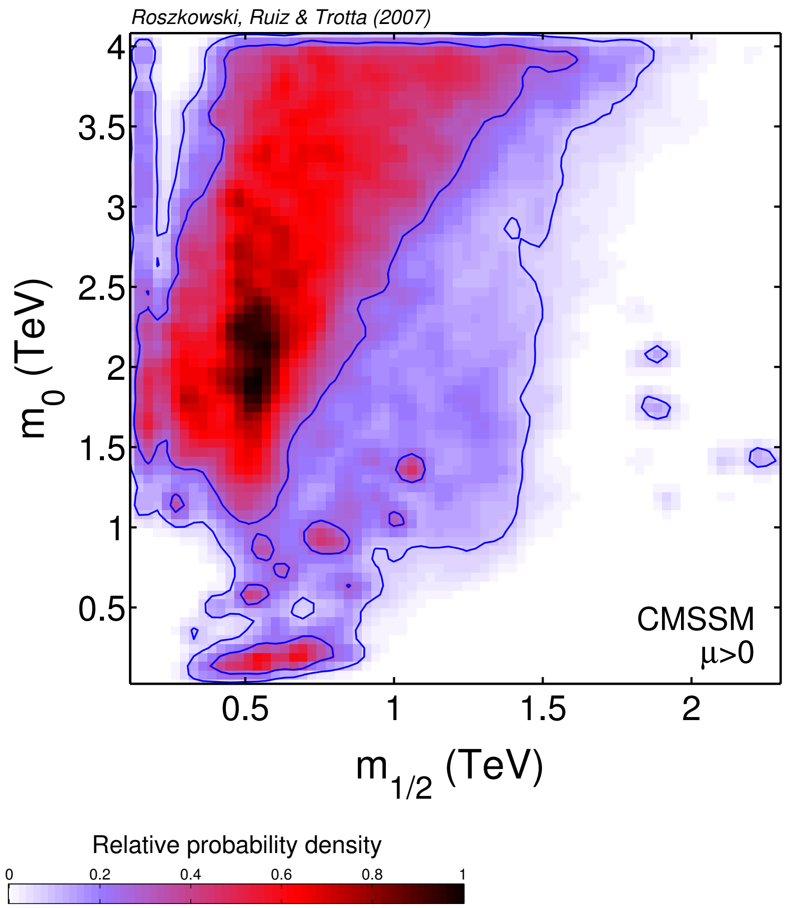

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similar study by Allanach+Lester(+Weber) (but no mean qof),
see also, Ellis et al (EHOW, χ^2 approach, no MCMC, they fix SM parameters!)

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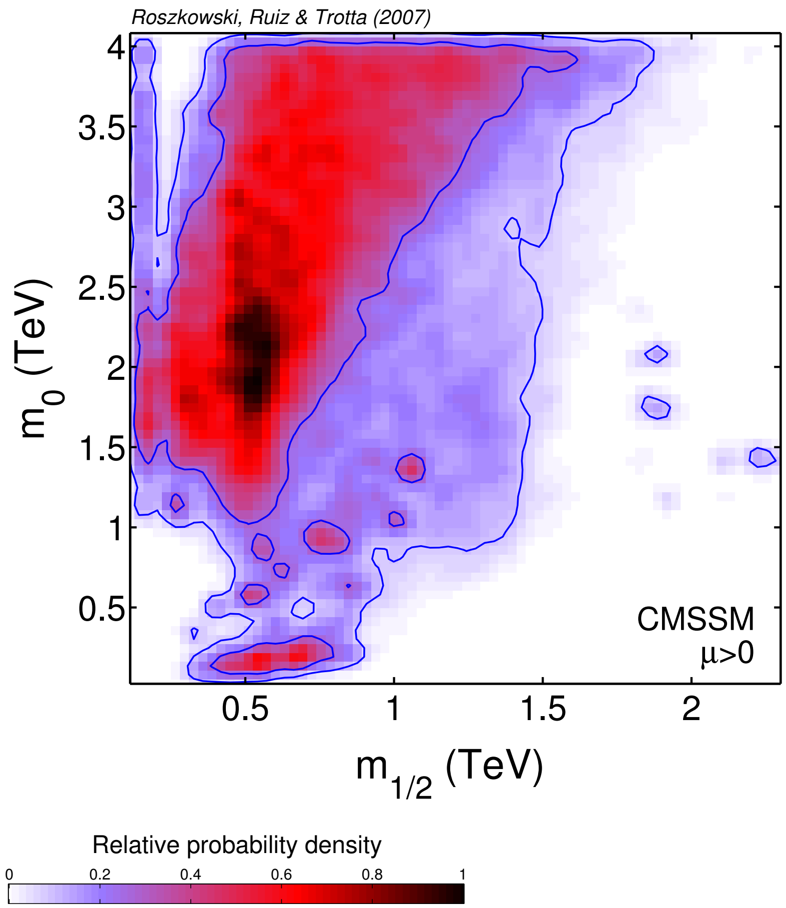

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unlike others (except for A+L), we vary also SM parameters

Impact of $b \longrightarrow s\gamma$

recall $BR(B \to X_s\gamma) = B(W^-/t) + B(H^-/t) - \mathrm{sgn}(\mu)\, B(\chi^-/\widetilde{t})$

compute SM: full NLO + NNLO of m_c (from M. Misiak); SUSY: dominant NLO $\propto \tan\beta, \log\left(M_S/m_W\right)$

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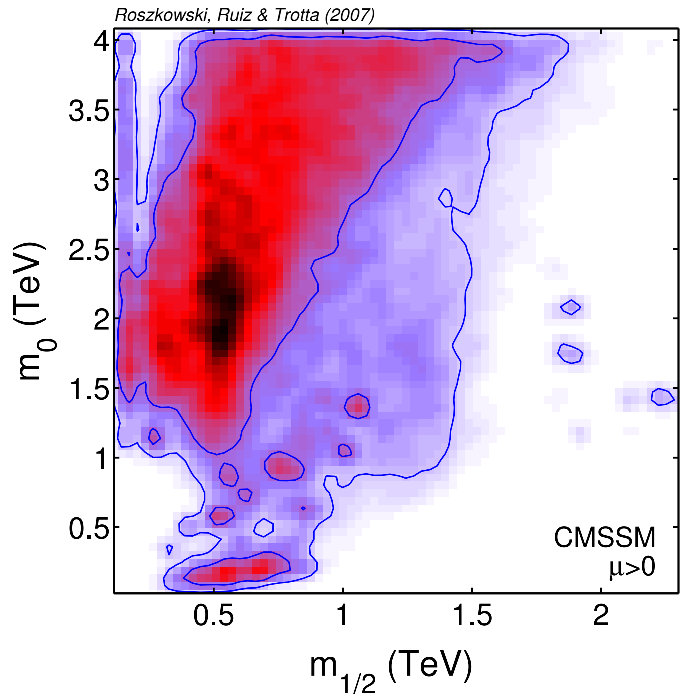
NEW: $BR(B \to X_s\gamma) \times 10^4$

EXPT: 3.55 ± 0.26, TH: 3.11 ± 0.21

(with our inputs), (May 07)



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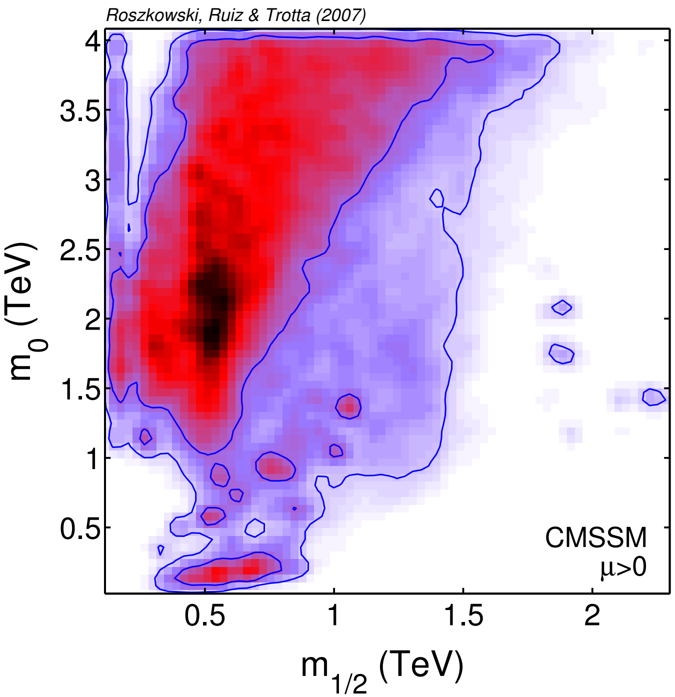

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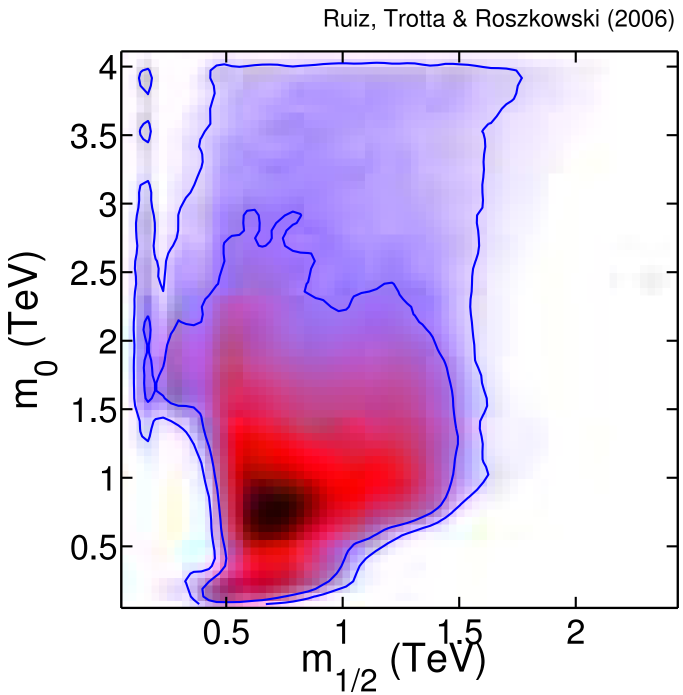

$\Rightarrow$ big shift towards large m_0, FP region!

How to catch the WIMP?

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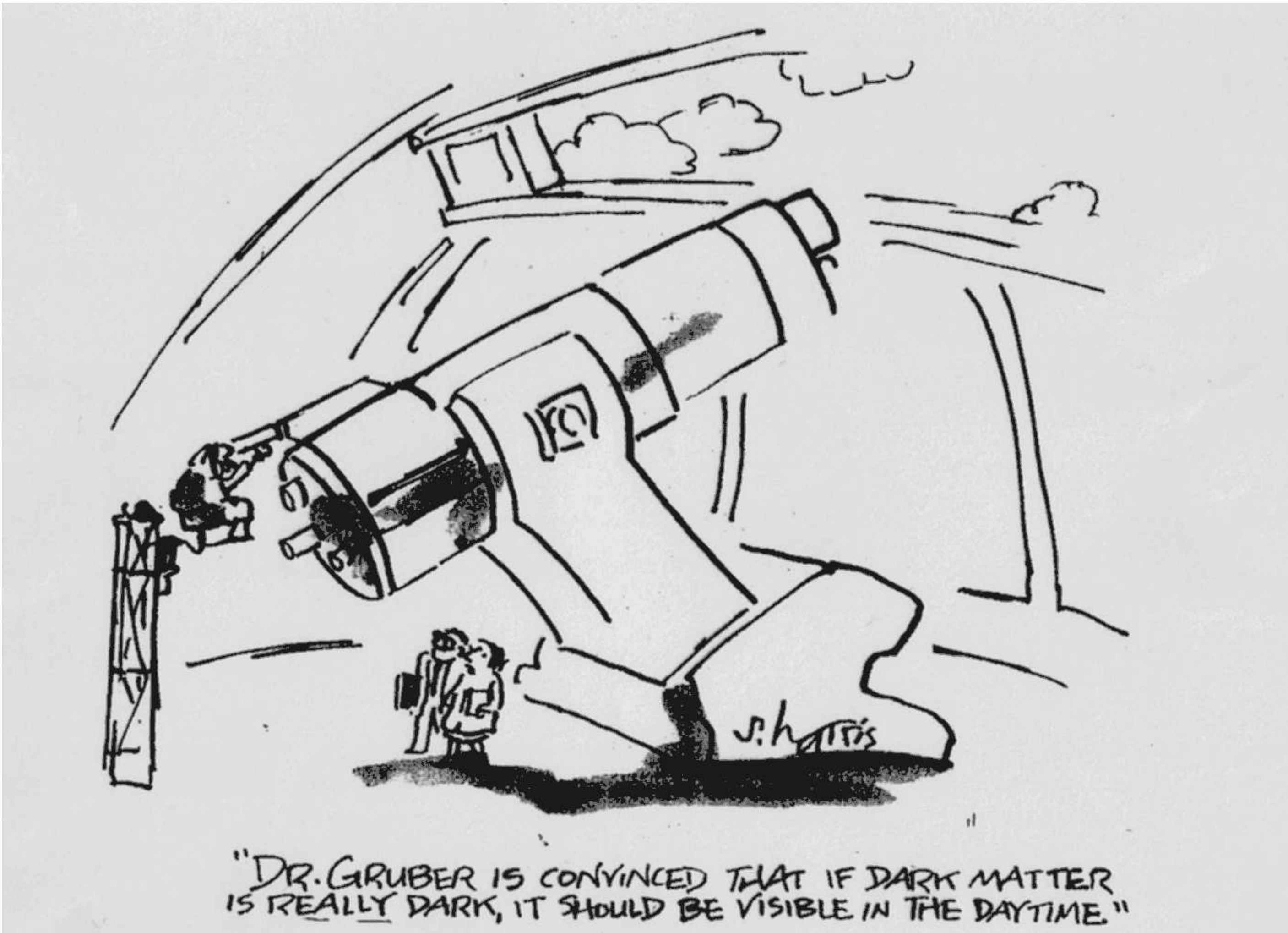

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    depending on DM distribution in the GC

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  - HE neutrinos from the Sun (or Earth)

    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape

  - antimatter (e^+, $\bar{p}$, $\bar{D}$) from WIMP pair-annihilation in the MW halo

    from within a few kpc

  - gamma rays from WIMP pair-annihilation in the Galactic center

    depending on DM distribution in the GC

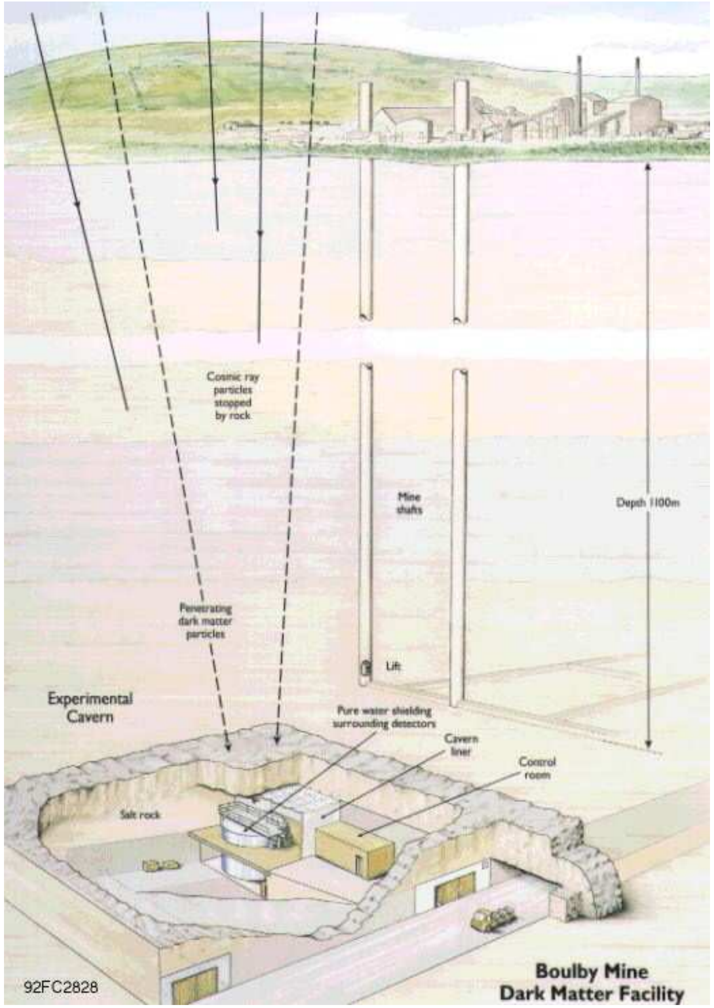
- other ideas: traces of WIMP annihilation in dwarf galaxies, in rich clusters, etc

  more speculative

Go underground/–ice/–water

... or to space

Go underground/–ice/–water



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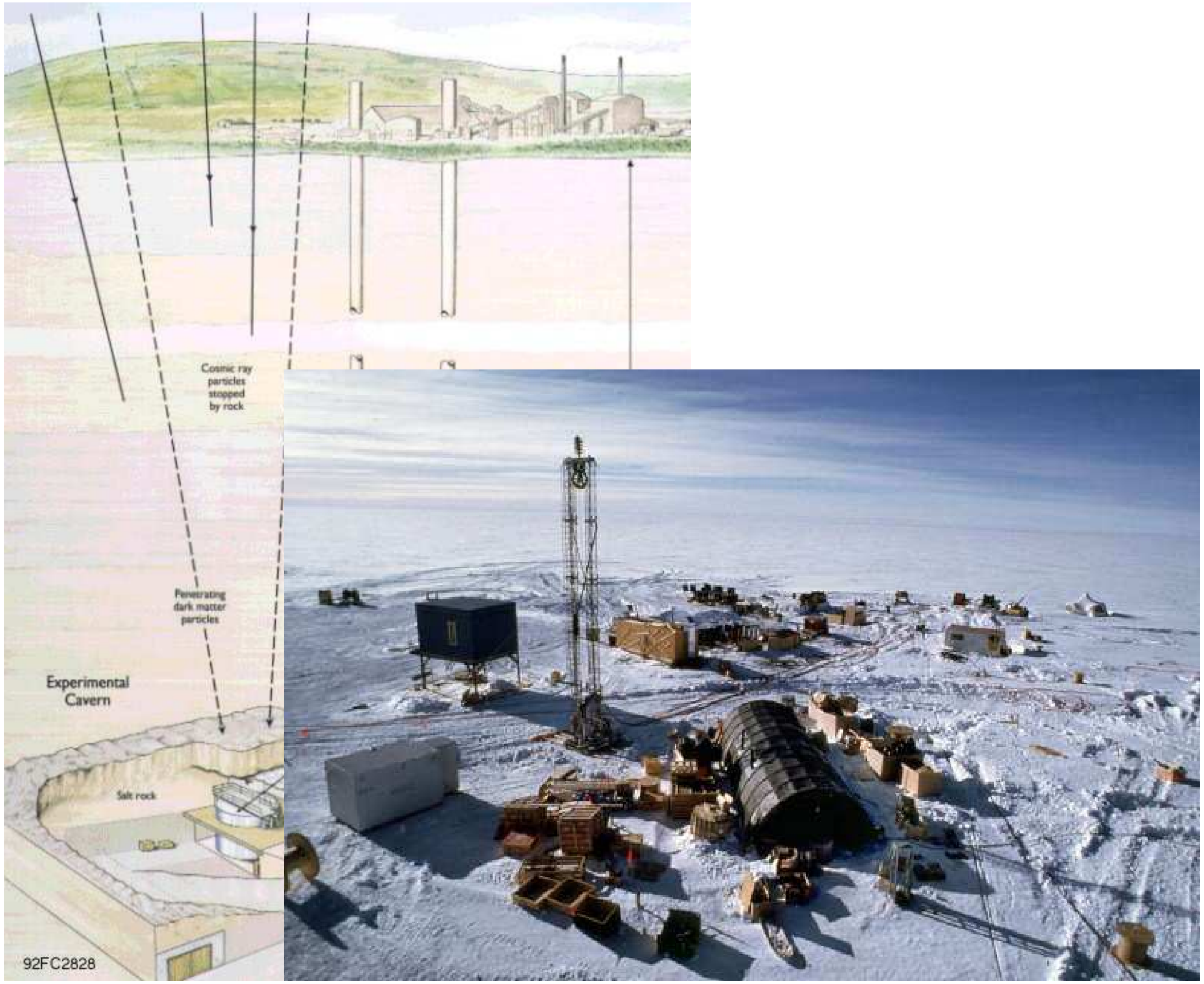

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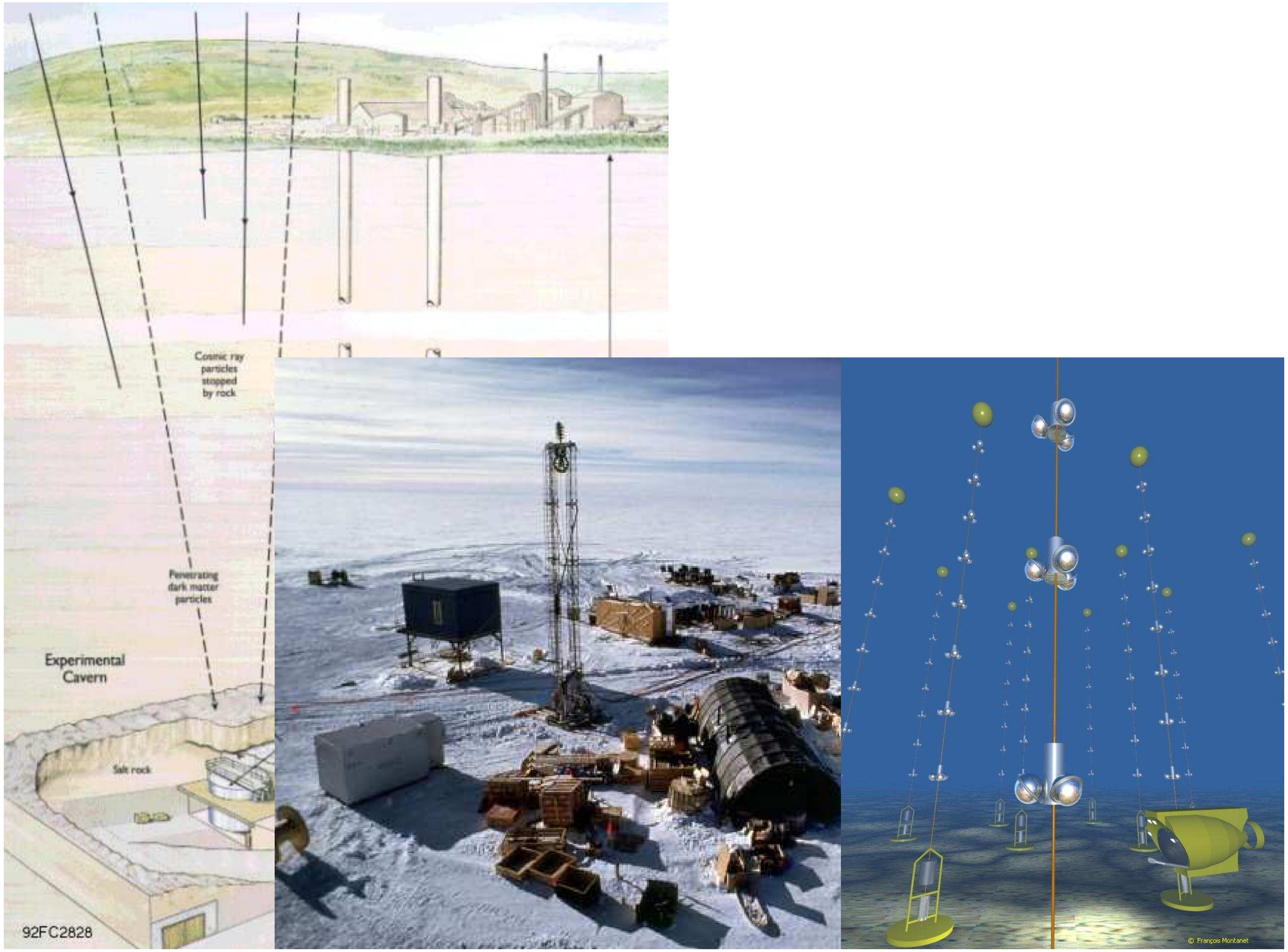

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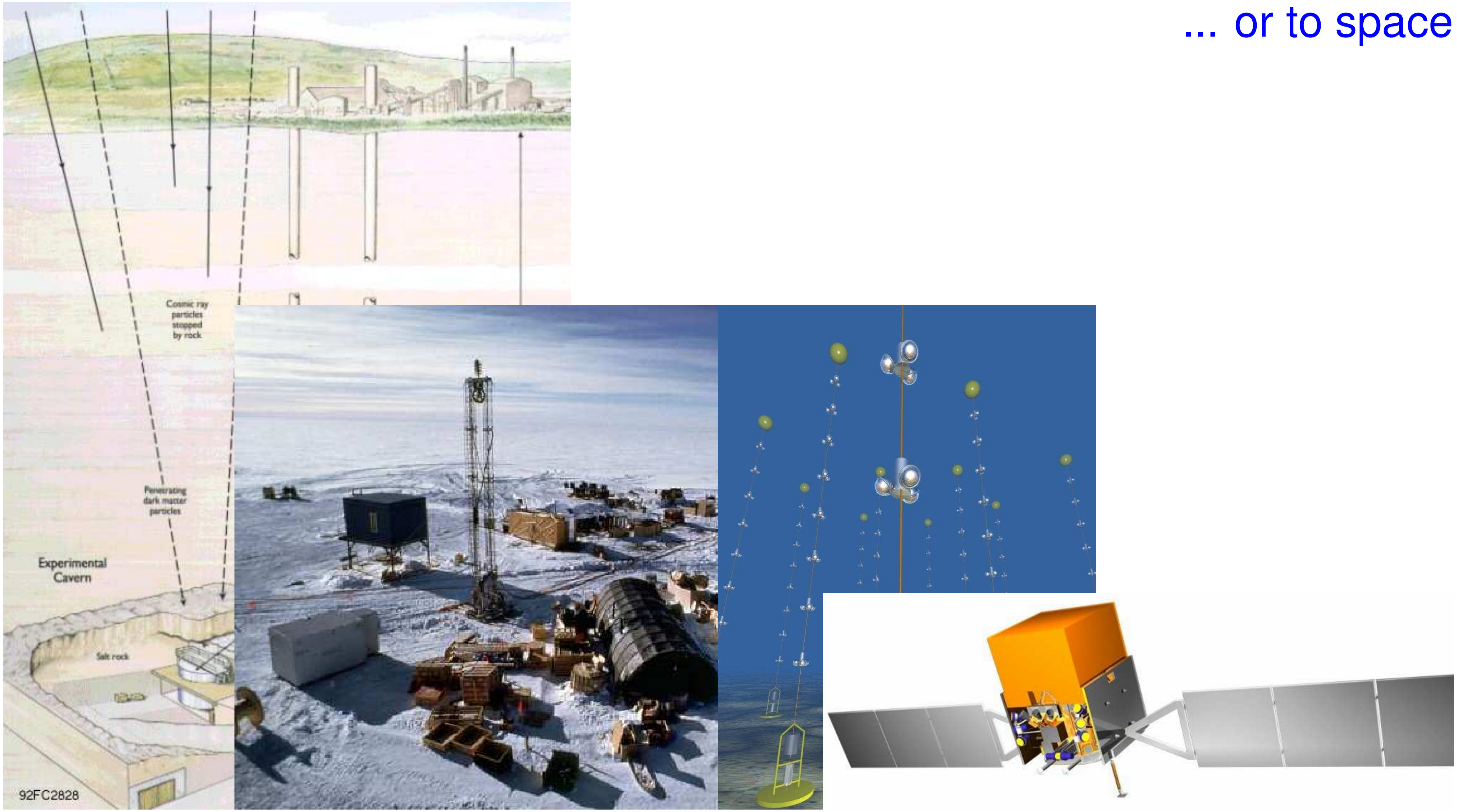

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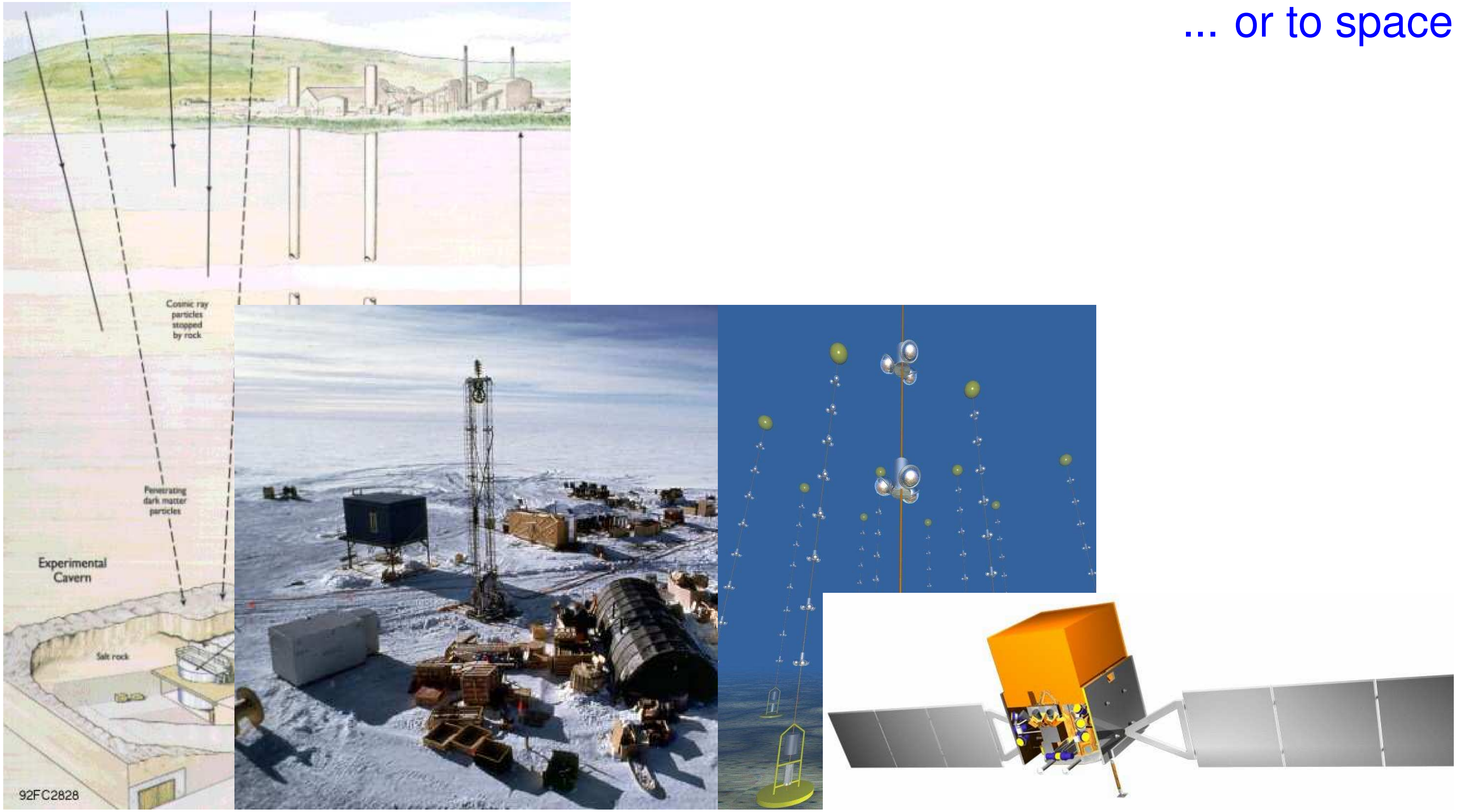
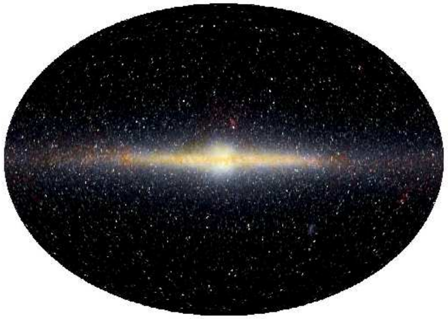


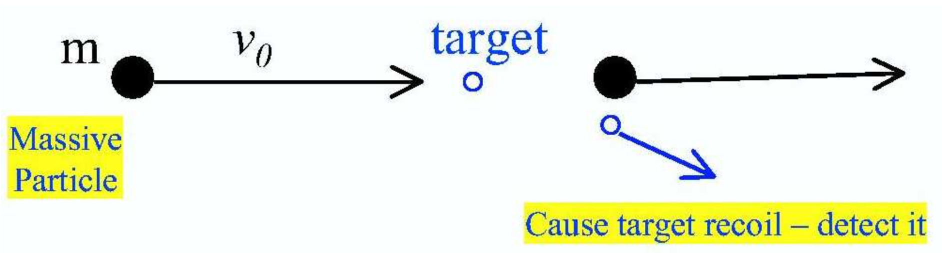
impressive experimental effort

Direct Detection

Direct Detection

MW is immersed in a halo of WIMPs





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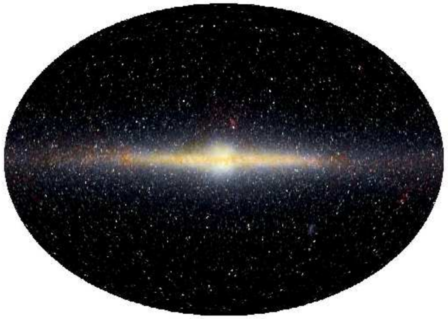

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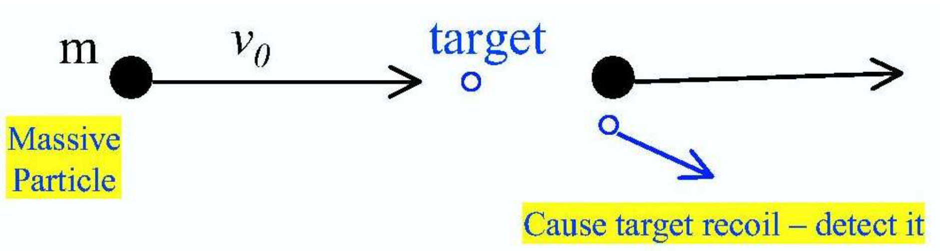
- velocity $v \sim 270\,\text{km}/\text{sec}$, Maxwellian



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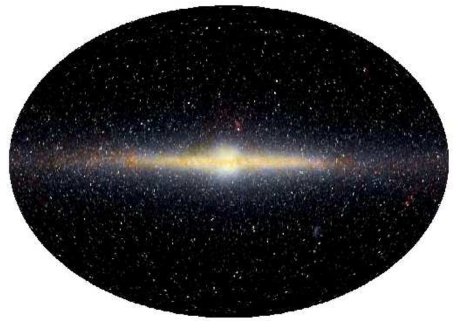

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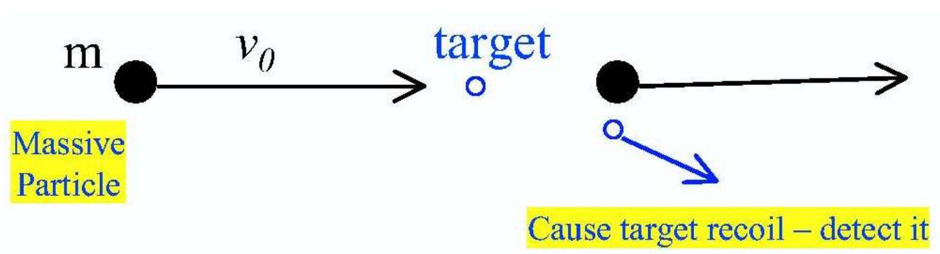

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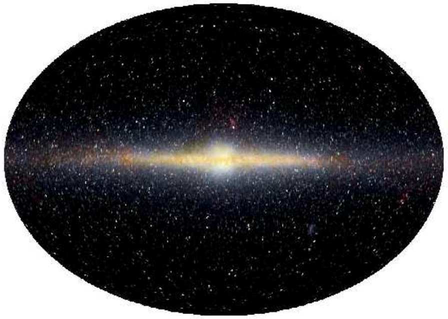

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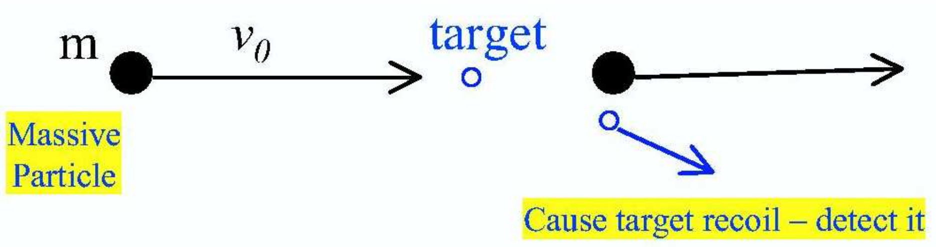
- energy deposit $\sim m_\chi v^2/2 \sim 100\,\mathrm{keV}$ tiny!!!



Dark matter detection: σ_p^{SI}

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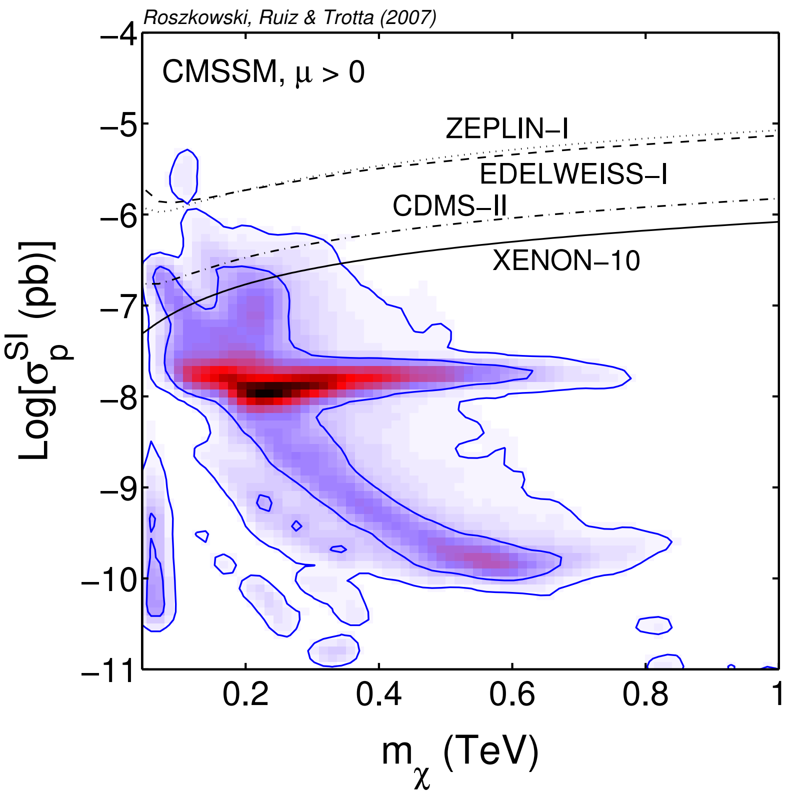
MCMC+Bayesian analysis



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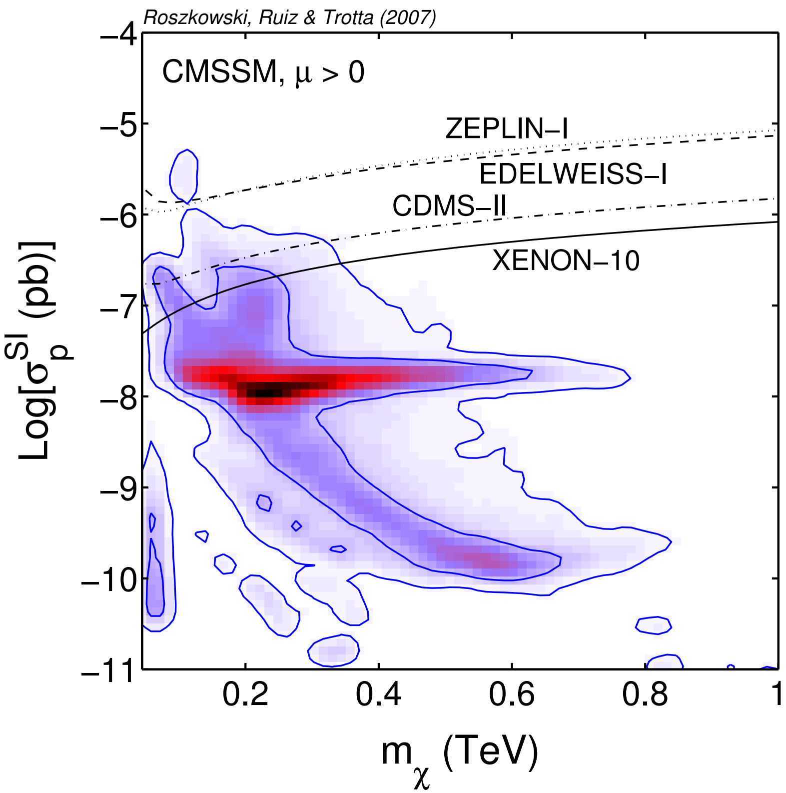
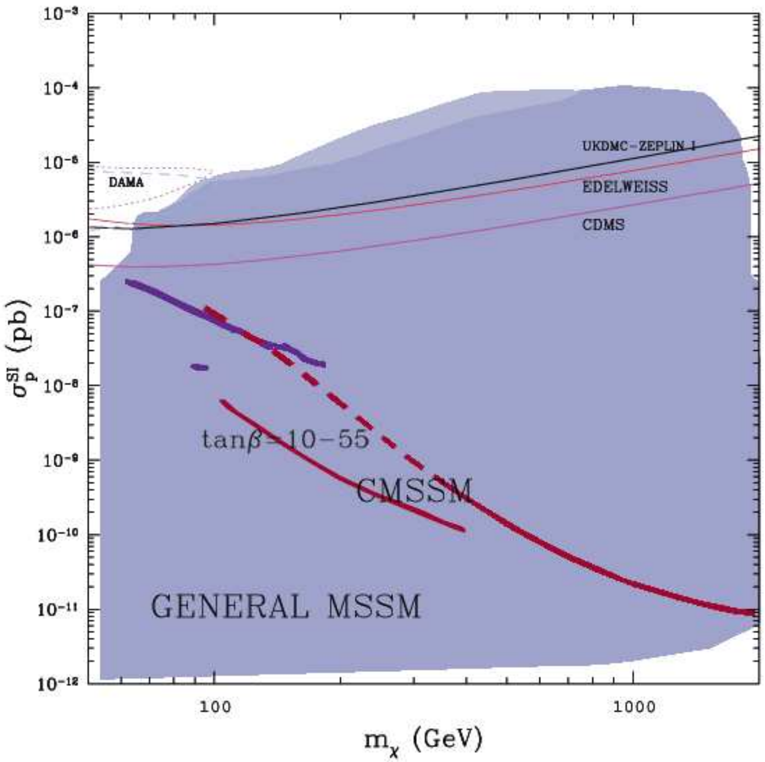
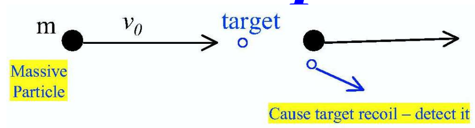
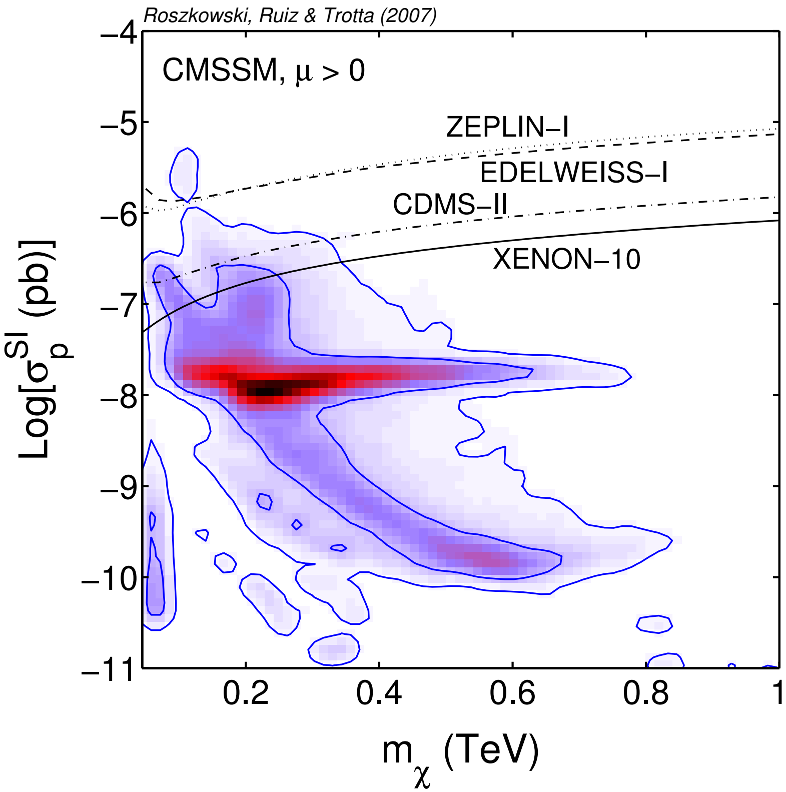


compare: fixed grid scan



Prospects for direct detection: σ_p^{SI}





Bayesian analysis, flat priors (MCMC)

internal (external): **68%** (**95%**) region

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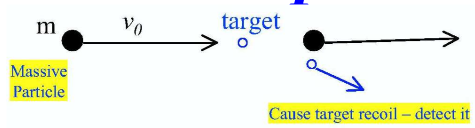

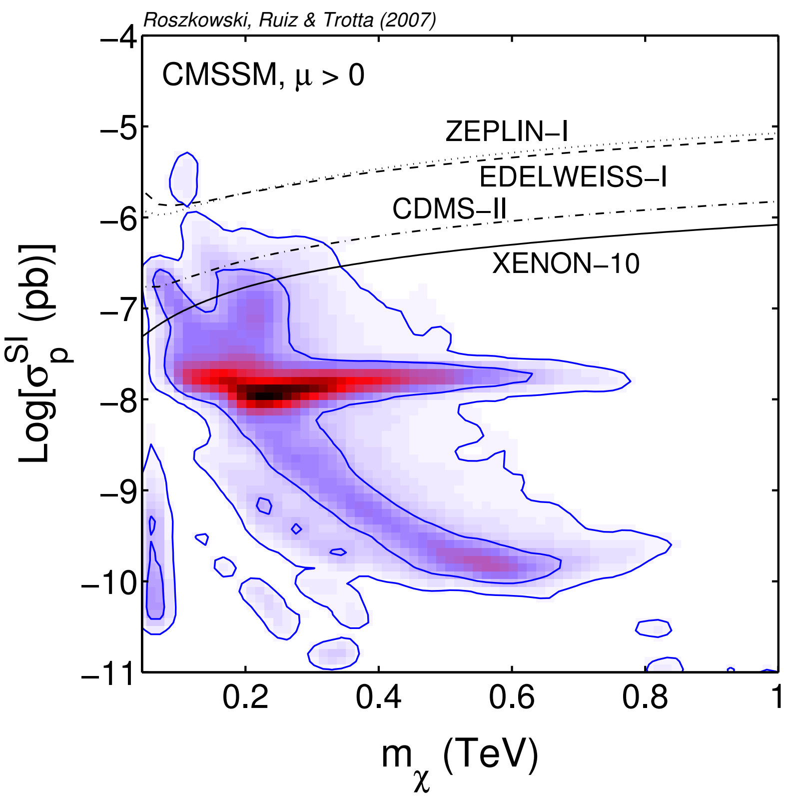

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XENON-10 (June 07):
new limit $\sigma_p^{SI} \lesssim 10^{-7}$ pb:

also CDMS–II (?)

$\Rightarrow$ explore the FP region

(large $m_0 \gg m_{1/2}$), outside of the LHC reach

ultimately: “1 tonne” detectors:
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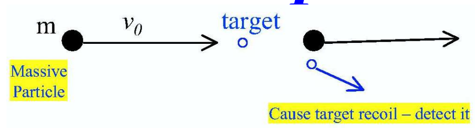

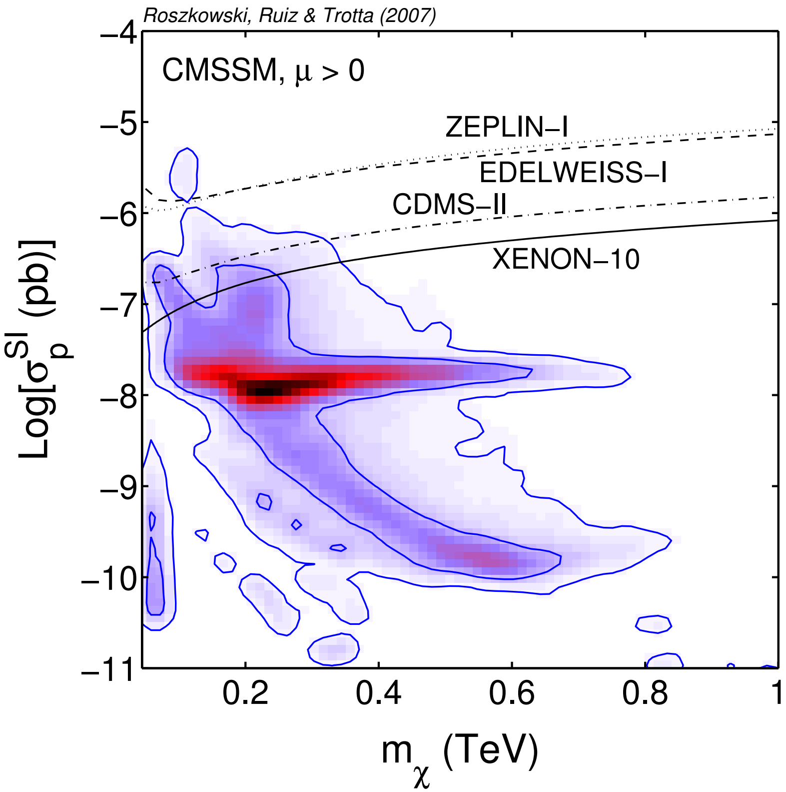

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most probable range: 10^{-7} pb $\lesssim \sigma_p^{SI} \lesssim 10^{-10}$ pb

partly outside of the LHC reach ($m_\chi \lesssim 400$ GeV)

CDM Halo Models

...not a settled matter

CDM Halo Models

fitting DM halo with a semi-heuristic formula: ...not a settled matter

$$\rho_{DM}(r) = \rho_c / \left(\frac{r}{a}\right)^{\gamma} \left[1 + \left(\frac{r}{a}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}$$

α, β, γ - adjustable parameters

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some most popular models:

halo model	a (kpc)	r_0 (kpc)	(α, β, γ)	small r: $\propto r^{-\gamma}$	large r: $\propto$
isothermal cored	3.5	8.5	$(2, 2, 0)$	flat	r^{-2}
NFW	20.0	8.0	$(1, 3, 1)$	r^{-1}	r^{-3}
NFW-c	20.0	8.0	$(1.5, 3, 1.5)$	$r^{-1.5}$	r^{-3}
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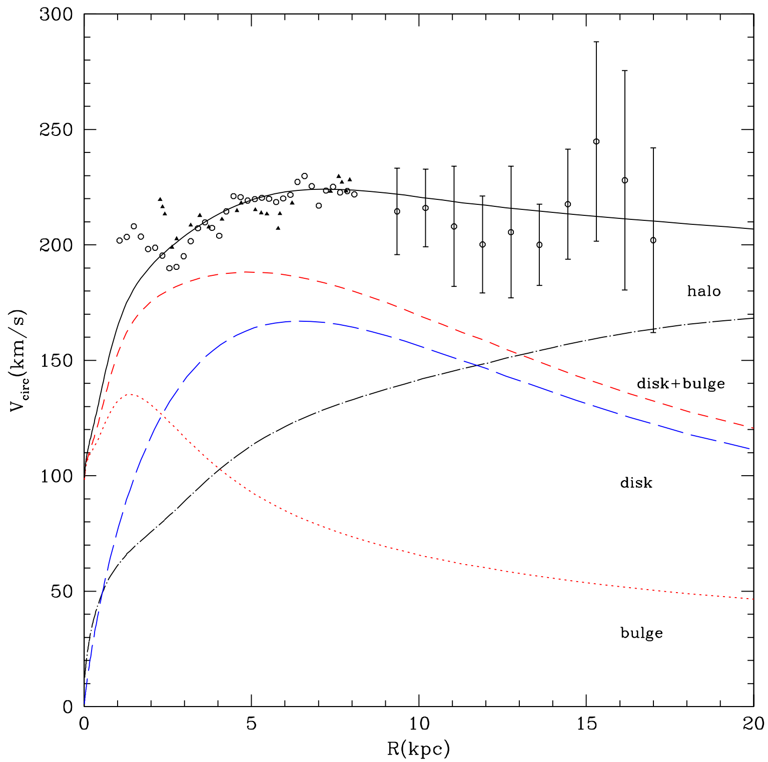
Many open questions: clumps??, central cusp??, spherical or tri–axial??,. . .

Our Milky Way

example of a reasonable model

(Klypin, et al., 2001)



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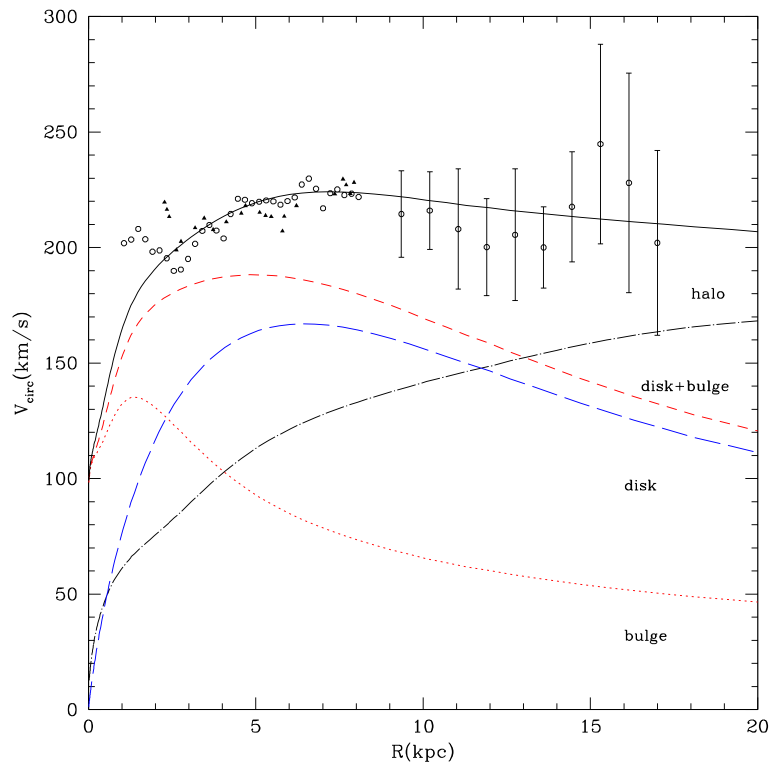

- based on NFW model with angular mom. exchange between baryons and DM
- DM dominates only at large r, well beyond the Solar radius
- DM likely to be subdominant in the inner regions
- if no exchange of angular mom.: more DM in the center (but problem with fast rotating bar?)

Gamma Rays from the Galactic Center

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- in the GC: ρ_{DM} is likely to be larger
- WIMP pair annihilation $\chi\chi \longrightarrow \mathbf{SMparticles} \propto \rho_\chi^2$ will be enhanced
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l.o.s - line of sight

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi) = \sum_i \frac{\sigma_i v}{8\pi m_\chi^2} \frac{dN_\gamma^i}{dE_\gamma} \int_{\mathrm{l.o.s.}} dl \rho_\chi^2(r(l,\psi))$$

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- separate particle physics and astrophysics inputs; define:

$$J(\psi) = \frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\mathrm{l.o.s.}} dl\, \rho_\chi^2(r(l,\psi))$$

and

$$\bar{J}(\Delta\Omega) = (1/\Delta\Omega) \int_{\Delta\Omega} J(\psi) d\Omega$$

$\Delta\Omega$ - finite angular resolution of a GR detector

Gamma Rays from the Galactic Center

- diff'l flux from the cone $\Delta\Omega$

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega) = \Phi_{\gamma,0} \sum_i \left(\frac{\sigma_i v}{10^{-29}\mathrm{cm}^3\ \mathrm{sec}^{-1}} \right) \frac{dN_\gamma^i}{dE_\gamma} \left(\frac{100\,\mathrm{GeV}}{m_\chi} \right)^2 (\bar{J}(\Delta\Omega)\Delta\Omega)$$

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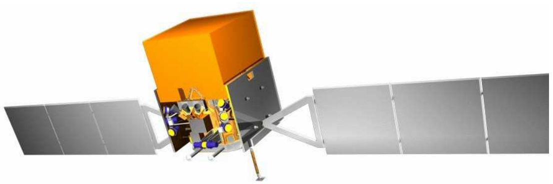
- all-sky survey
- effective energy range 20 MeV to 300 GeV, very good energy resolution
- angular resolution $\Delta\Omega \simeq 10^{-5}\mathrm{sr}$ (or ~ 0.15 deg for $E_\gamma > 10$ GeV)



GRs from the GC in the CMSSM

use GLAST parameters

Bayesian posterior probability maps

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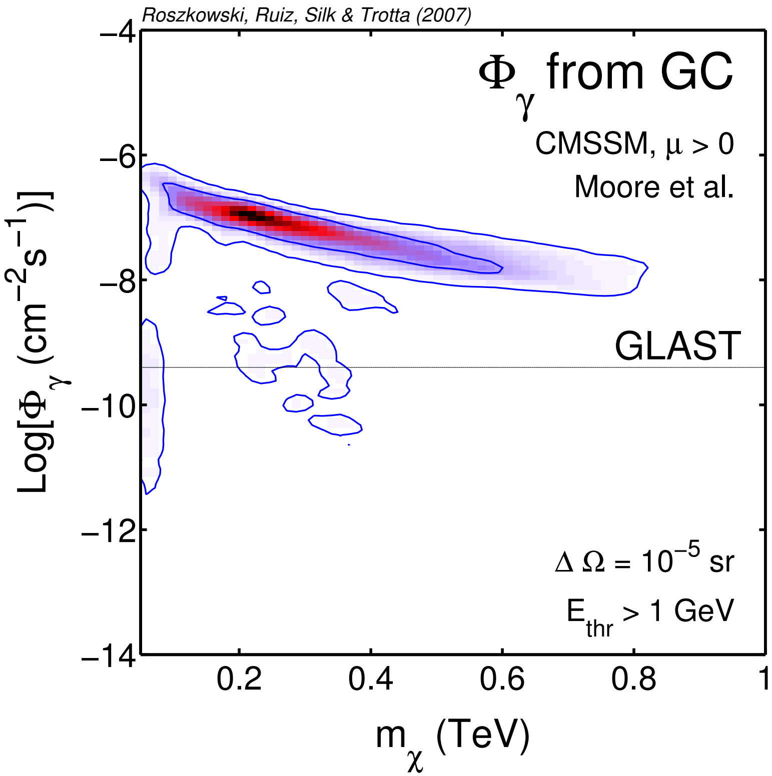
Moore model



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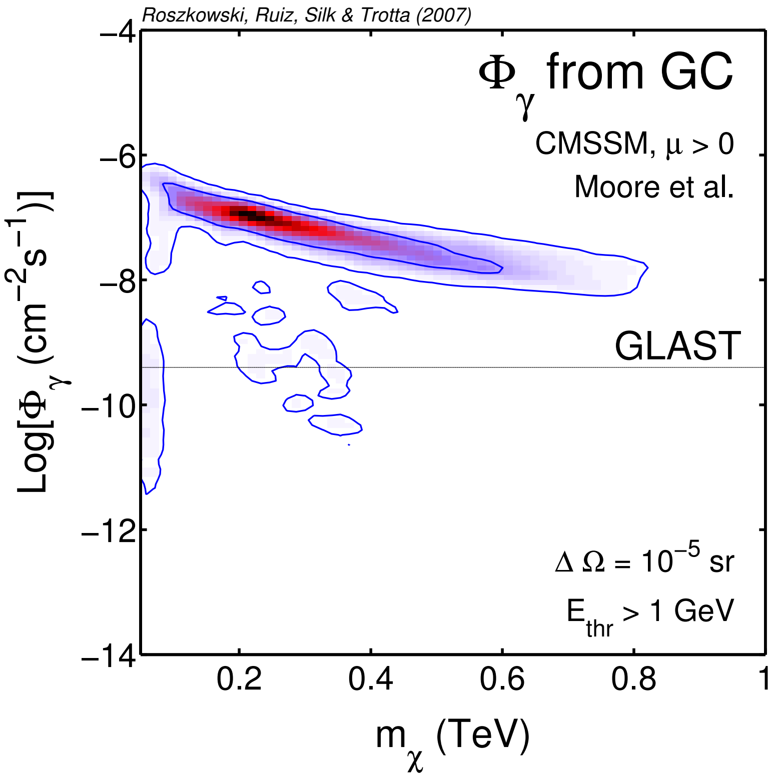
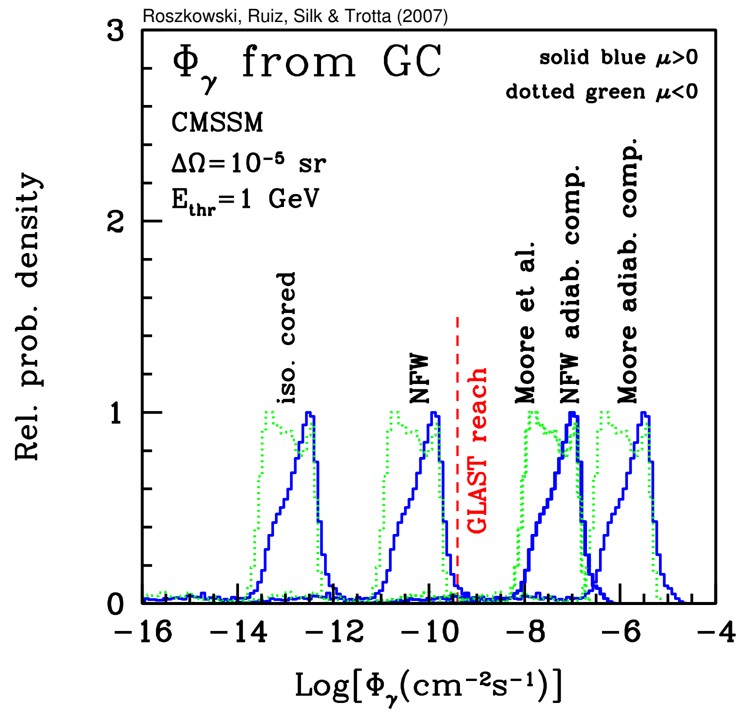


halo model dependence



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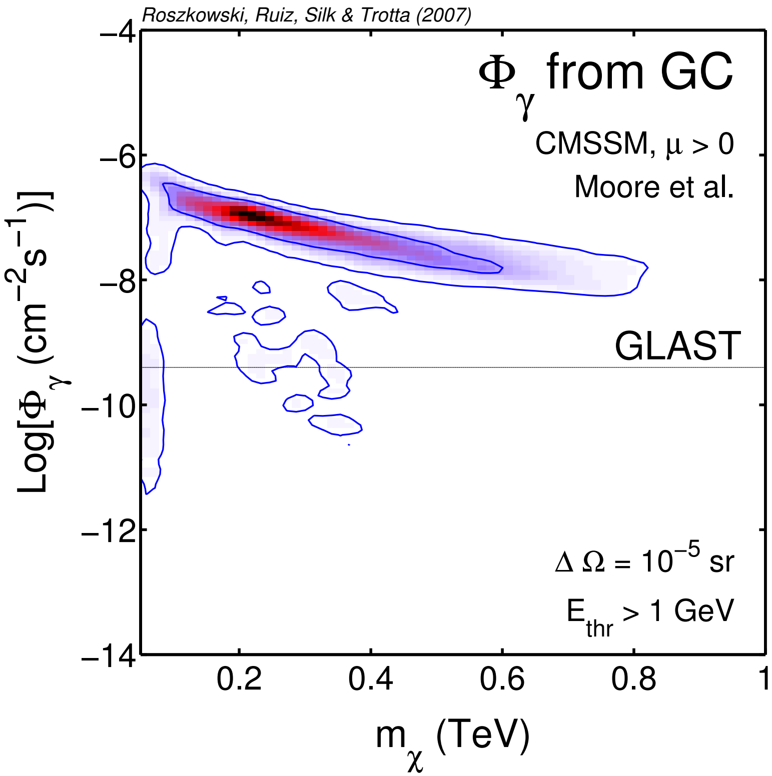

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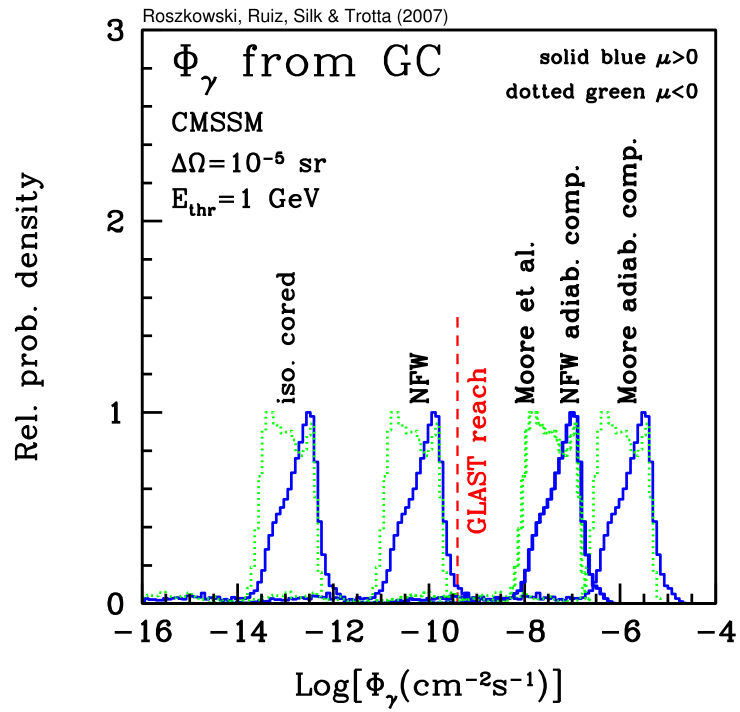

GLAST prospects critically depend on how cuspy the GC is

- more cuspy than NFW: all CMSSM range will be explored (at 95% CL)

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...What if Nature has made a different choice?

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- how to relax it w/o giving up CDM?

(...or screwing up cosmology)

Alternatives to Neutralino WIMP?

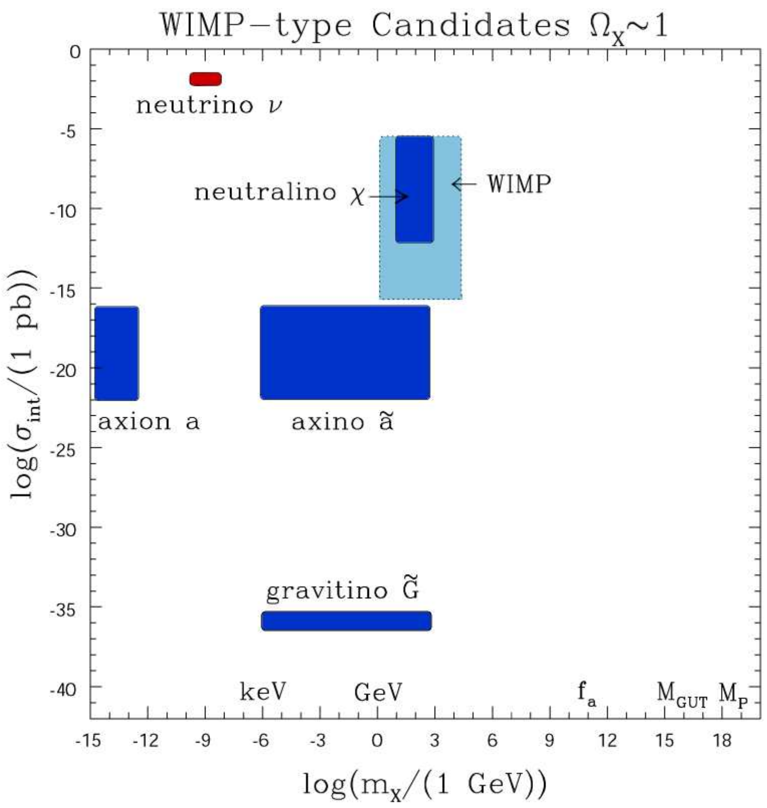
- $\Omega_\chi h^2 \simeq 0.1$: extremely strong constraint
- how to relax it w/o giving up CDM?

  (...or screwing up cosmology)
- need another WIMP

  (or another cosmology)

The Big Picture

well–motivated particle candidates such that $\Omega \sim 0.1$



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\widetilde{G}$

E–WIMPs: $\widetilde{G}$ and $\widetilde{a}$

(extremely weakly interacting massive particles)

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$\widetilde{G}$: Pagels+Primack, Weinberg ('82)

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(assume usual gravity mediated SUSY breaking)

	axino	gravitino
spin	1/2	3/2
interaction	$\sim 1/f_a^2$	$\sim 1/M_{\rm P}^2$
mass	$\not\propto M_{\rm SUSY}$	$\propto M_{\rm SUSY}$

- mass model dependent

  take it as free parameter

$f_a \sim 10^{9-12}$ GeV – PQ scale

$M_{\rm P} = 2.4 \times 10^{18}$ GeV – reduced Planck mass

$M_{\rm SUSY} \sim 100$ GeV $- 1$ TeV – soft SUSY mass scale

Axino E–WIMP as DM

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Covi+J.E. Kim+Roszkowski, PRL'99

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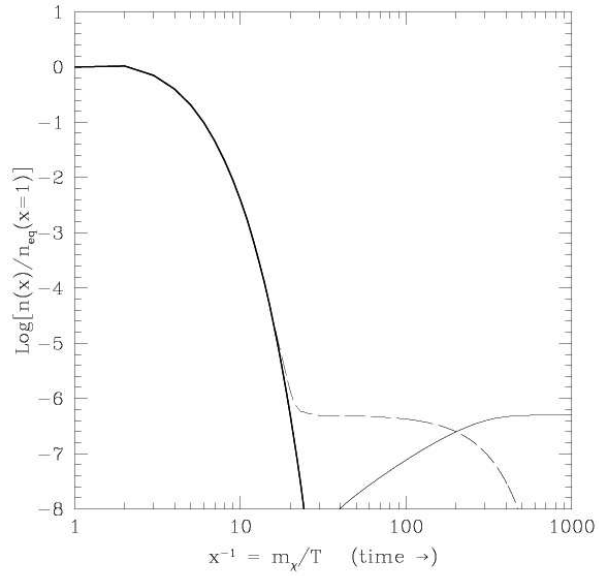

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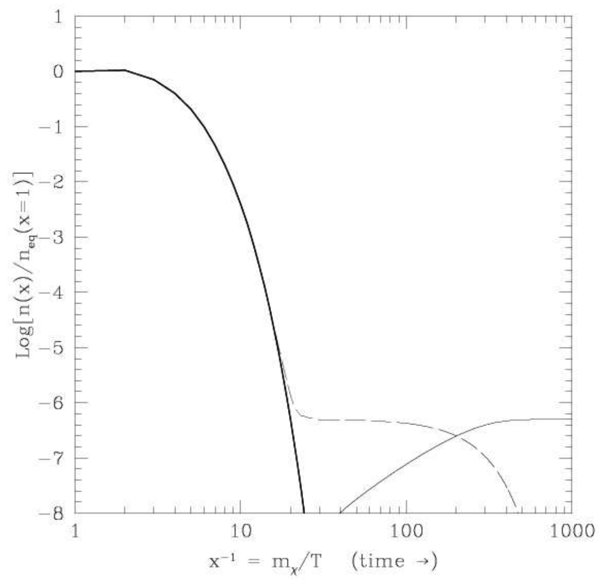
$(\chi \simeq \widetilde{B})$

...before BBN!



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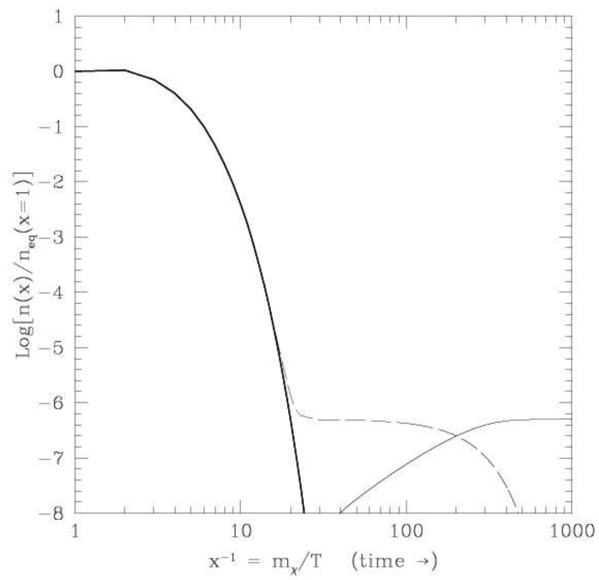

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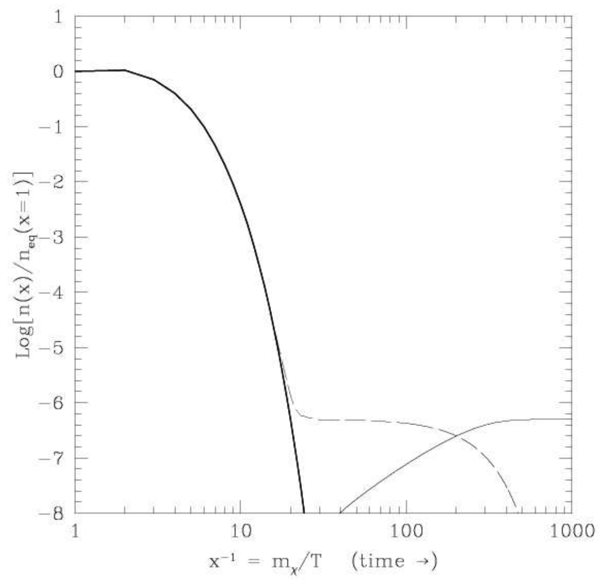

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NTP: non–thermal production

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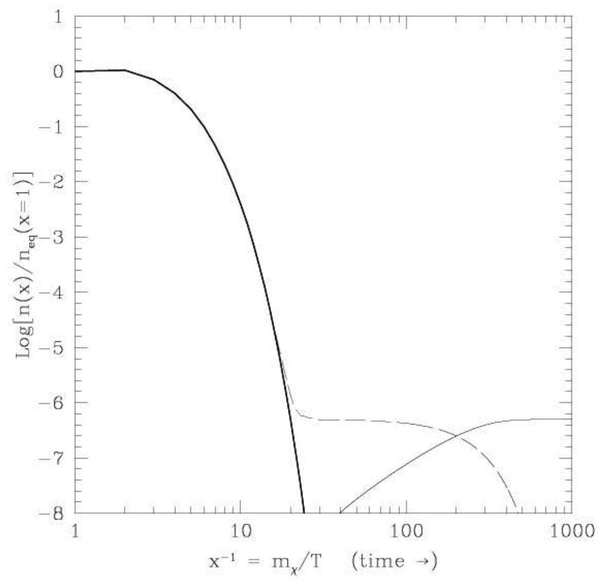

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NTP: non–thermal production

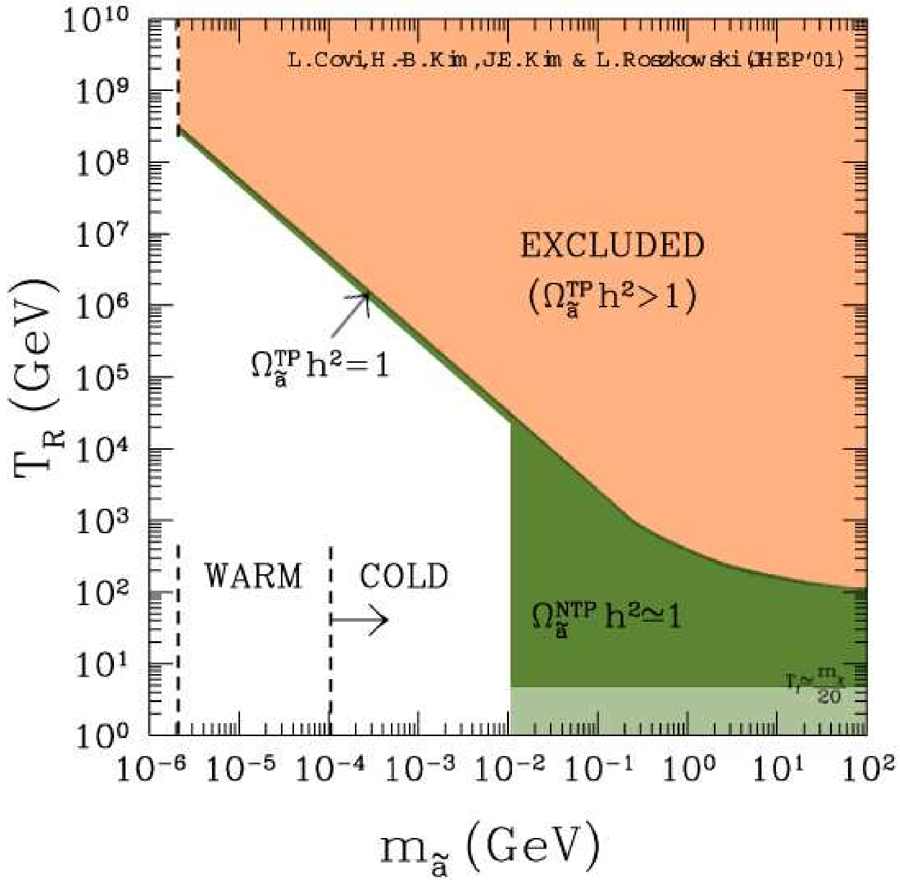
- plus TP processes: $q\,q \rightarrow \widetilde{a}\,\widetilde{g}, \quad \widetilde{q} \rightarrow \widetilde{a}\,q, \ldots$

TP: thermal production

NTP vs TP

Covi+H.-B. Kim+J.E. Kim+Roszkowski, JHEP '01 (hep-ph/0101009)

general MSSM:



...axino cold DM: $\Rightarrow$ low $T_R \lesssim 10^6$ GeV

Hints for axino DM from LHC?

Covi+LR+Ruiz de Austri+Small, JHEP'04 (hep-ph/0402240)

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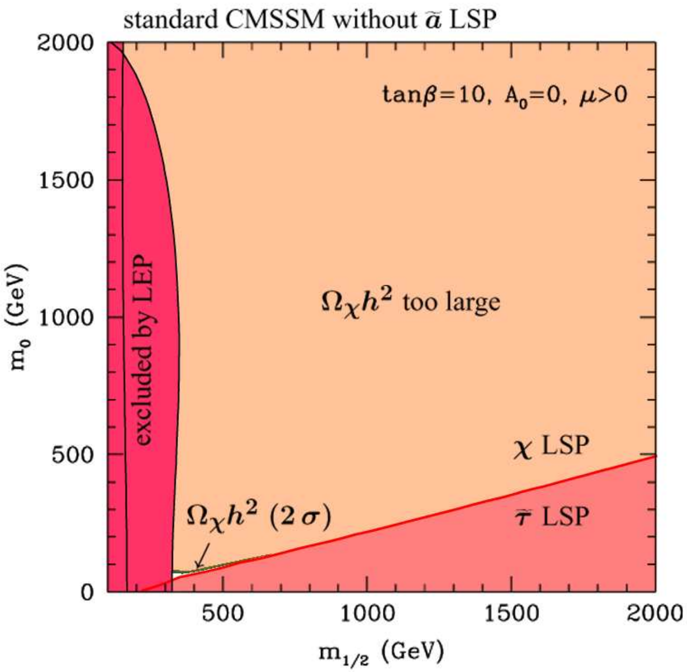

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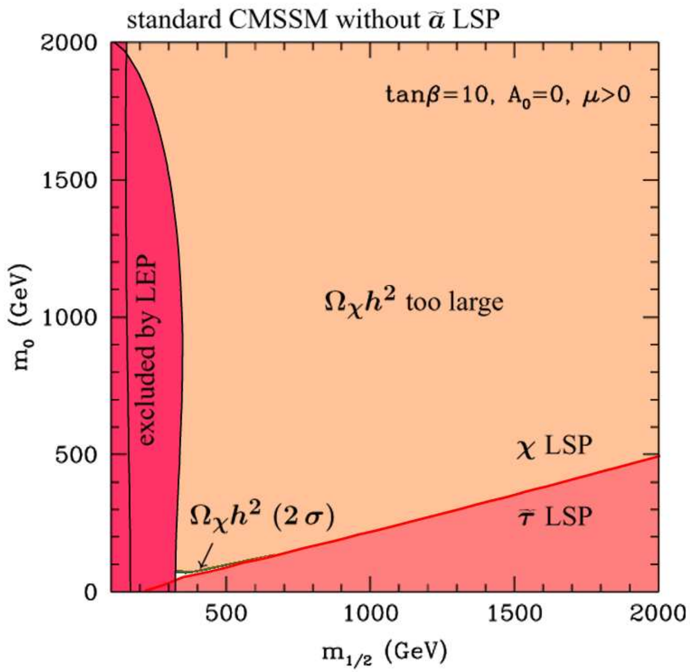

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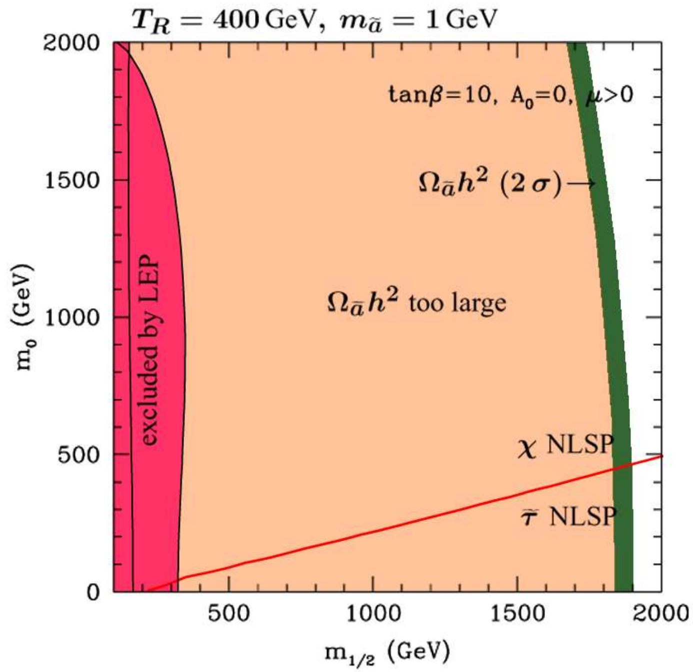

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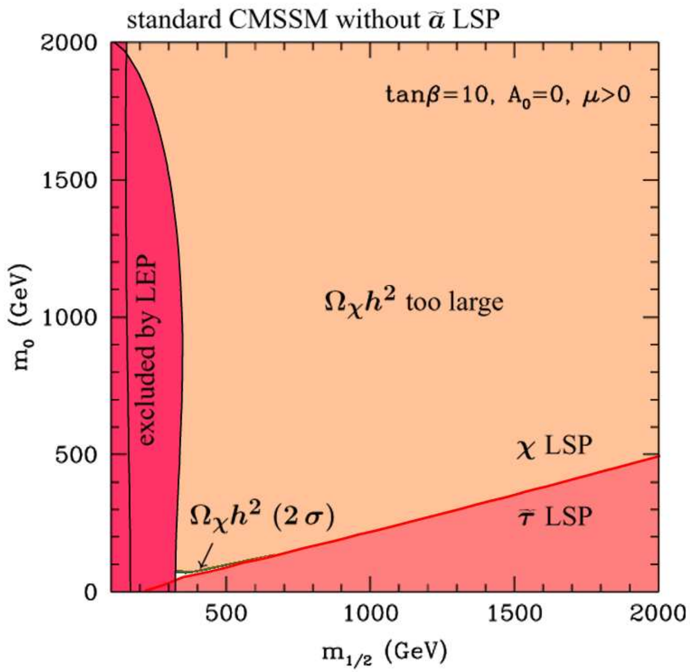

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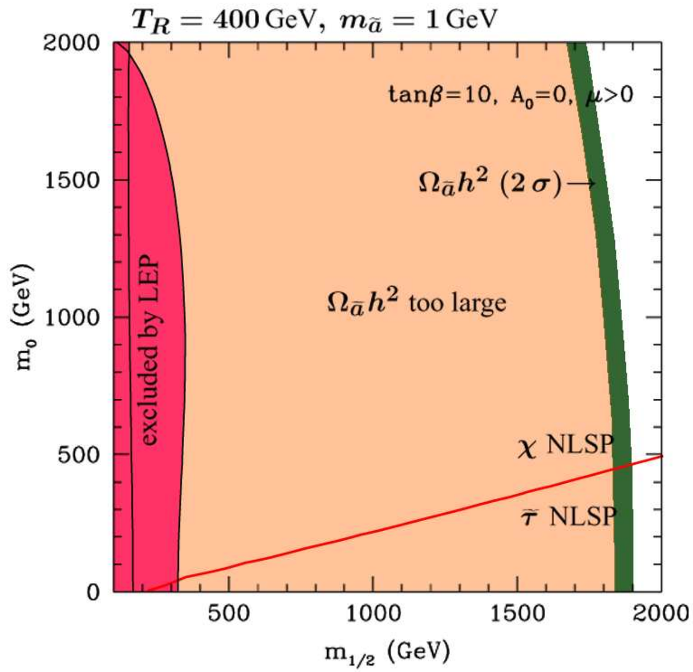

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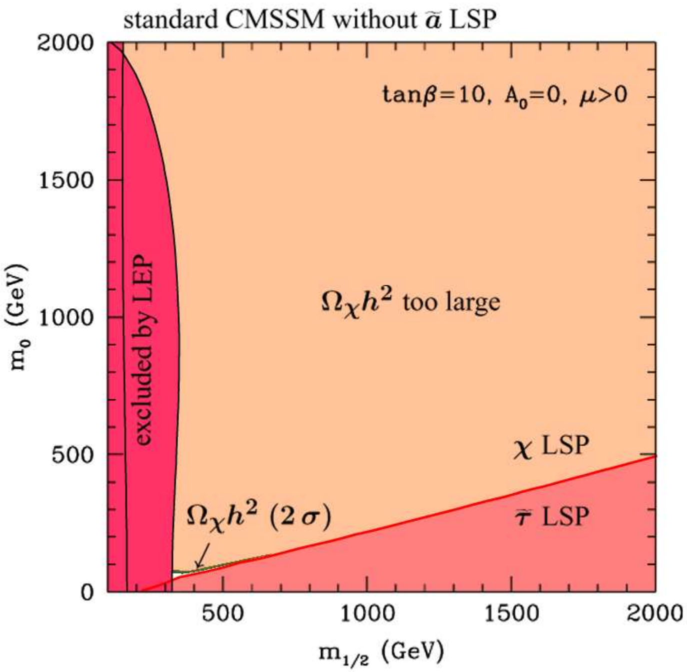

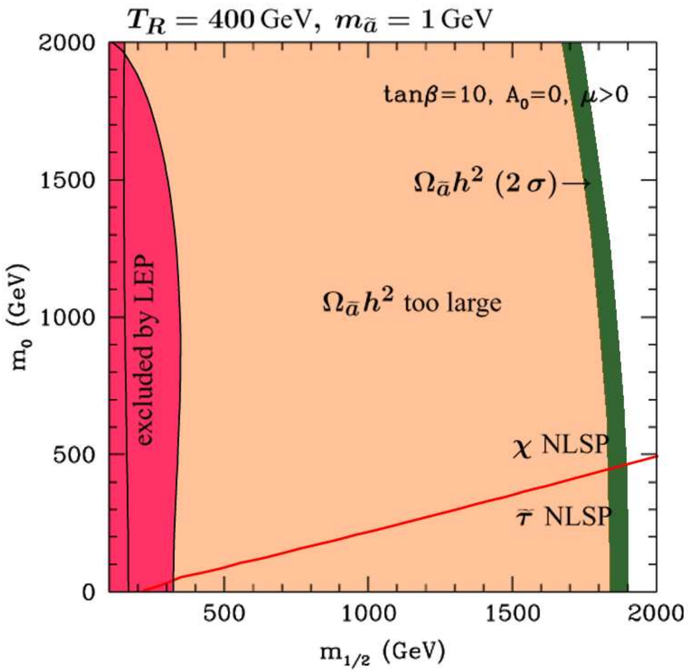

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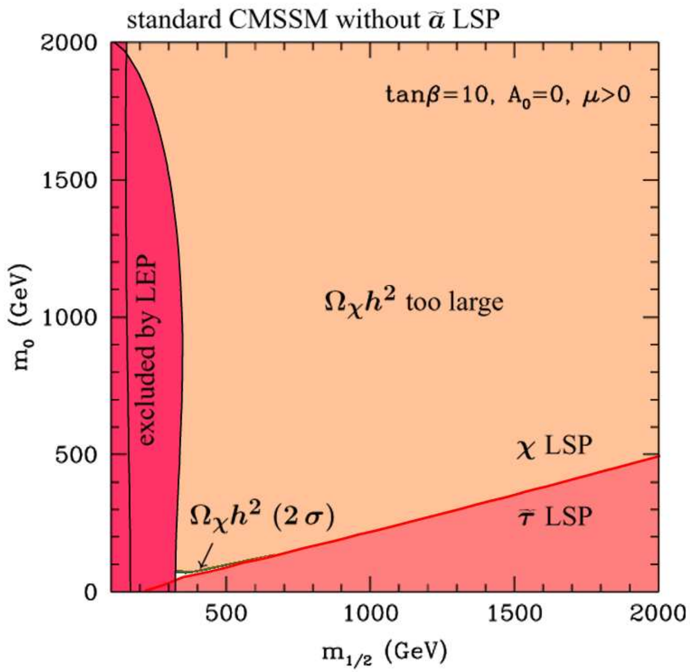

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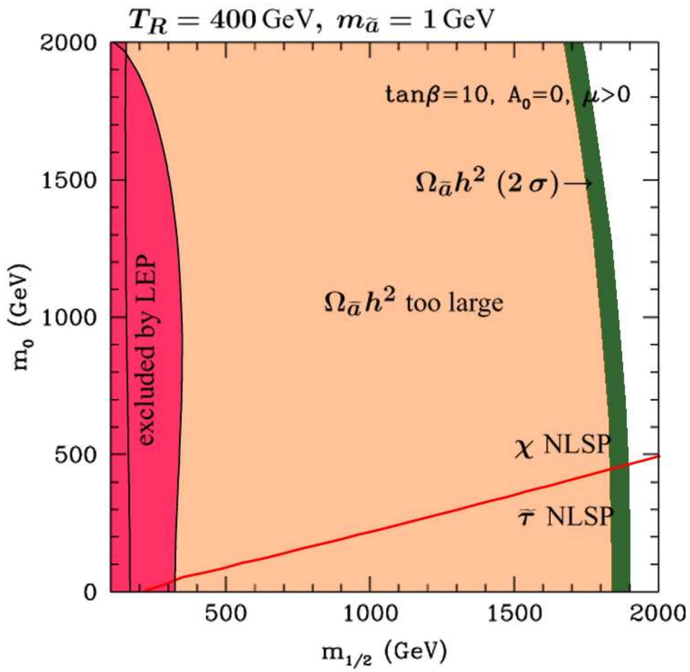

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- if χ NLSP: standard "missing energy" signature at LHC, but DM WIMP unsuccessful
- if $\tilde{\tau}_1$–NLSP: charged, apparently stable $\Rightarrow$ striking signature at LHC

The Gravitino $\widetilde{G}$

spin–$3/2$ partner of the graviton

- in gravity–mediated SUSY breaking models

$$m_{\widetilde{G}} = \frac{F}{\sqrt{3}M_{\mathrm{P}}}$$

$F \sim 10^{11}$ GeV – SUSY breaking scale
$M_{\mathrm{P}} = 2.4 \times 10^{18}$ GeV – reduced Planck mass
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- if it is the LSP…

can $\widetilde{G}$ give $\Omega_{\rm CDM}h^2 \sim 0.1$?

$\widetilde{G}$: cold (not warm) DM

Gravitino WIMP in the CMSSM

(analogous to $\widetilde{a}$ LSP)

Roszkowski+Ruiz de Austri+K.-Y. Choi, hep-ph/0408227

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$$\tau(\text{NLSP} \rightarrow \widetilde{G} + \gamma/\tau) \sim 10^8\,\text{sec}\left(\frac{100\,\text{GeV}}{m_{\text{NLSP}}}\right)^5 \left(\frac{m_{\widetilde{G}}}{100\,\text{GeV}}\right)^2 \ldots$$

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Feng, et al (FST 02-04), MSSM

Ellis, et al (EOSS 03), CMSSM

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$$\Omega^{\mathrm{TP}}_{\widetilde{G}} \simeq 0.2\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{G}}}\right)\left(\frac{m_{\widetilde{g}}(\mu)}{1\,\mathrm{TeV}}\right)^2$$

Bolz+Brandenburg+Buchmüller ('00)

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Bolz+Brandenburg+Buchmüller ('00)

At high $T_R \gtrsim 10^9$ GeV, TP is important

BBN Constraint

- apply $D/H + Y_p + {}^7Li/H + {}^3He/D + {}^6Li/{}^7Li$

Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, hep-ph/0509275
new, improved analysis
follow the initial hep-ph/0408227 (L.R.+Ruiz de Austri+K.-Y. Choi)

- self–consistent, both EM & HAD, vary B_h as f'n of SUSY parameters
- adopt abundances of light elements from observations (Jedamzik):

$$2.2 \times 10^{-5} < D/H < 5.3 \times 10^{-5}$$

$$0.232 < Y_p < 0.258$$

$$1.11 \times 10^{-10} < {}^7Li/H < 4.5 \times 10^{-10}$$

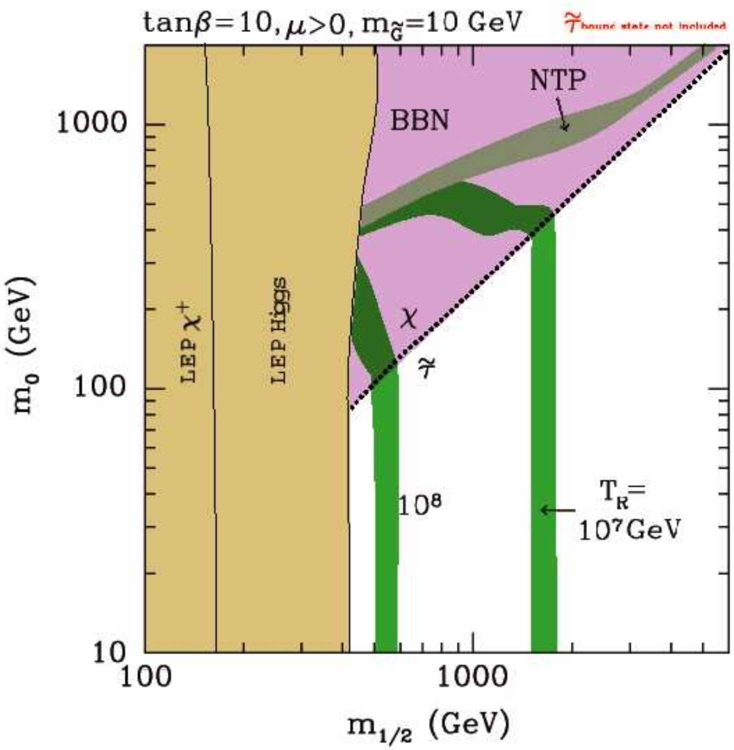
$${}^3He/D < 1.72$$

$${}^6Li/{}^7Li < 0.1875$$

Example: $m_{\widetilde{G}} = 10\,\mathrm{GeV}$

Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, hep-ph/0509275 and in prep.

apply all BBN: $D/H + Y_p + {}^7Li/H + {}^3He/D + {}^6Li/{}^7Li$



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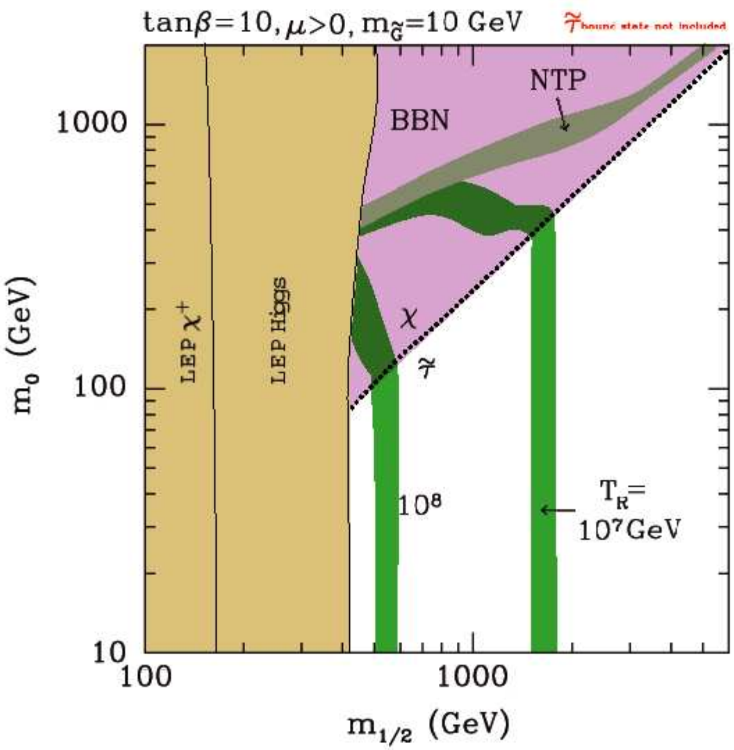

- only $\widetilde{\tau}_1$–NLSP region remains allowed

$\Rightarrow$ at LHC see charged "stable" LOSP $\widetilde{\tau}_1$ (instead of "expected" neutral χ)

confirmed Feng, et al (Apr 04)

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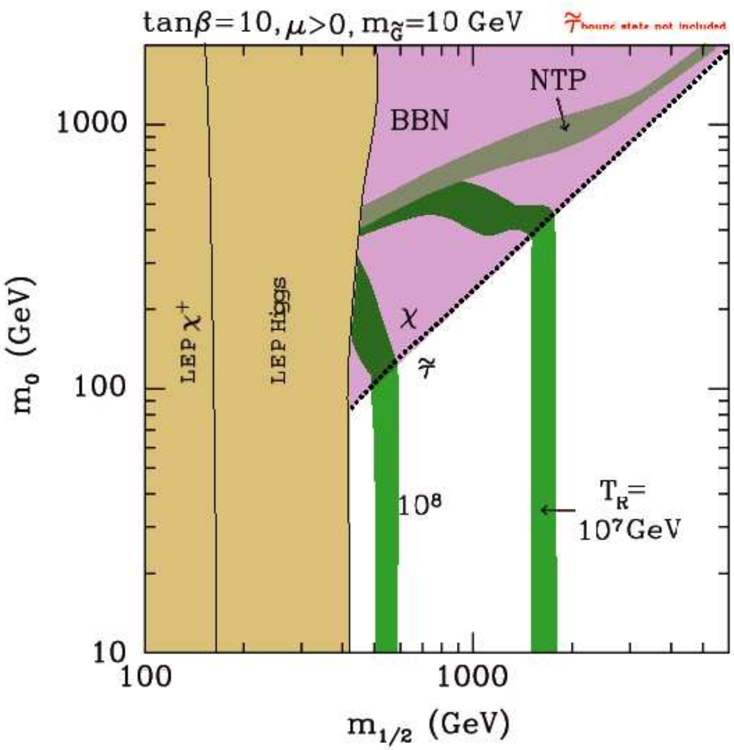

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- low T_R basically excluded (NTP part only), must include TP contribution to $\Omega_{\widetilde{G}} h^2$

  $\Rightarrow$ $m_{\widetilde{G}} = \mathcal{O}(100\,\mathrm{GeV})$: (typically) need high $T_R \sim 10^8$ GeV

$\widetilde{G}$ DM $\Rightarrow$ No High T Leptogenesis?

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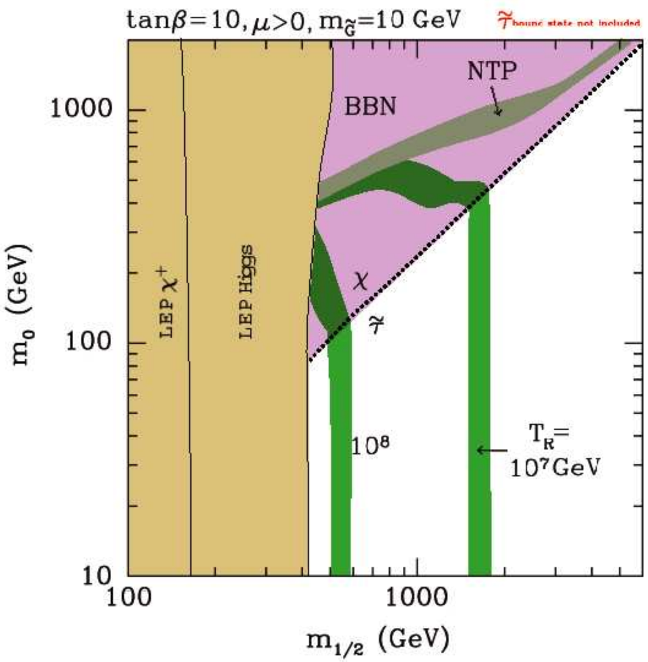
Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, hep-ph/0509275–> JCAP and in prep.

thermal leptogenesis: $T_R \gtrsim 2 \times 10^9$ GeV (Fukugida+Yanagida)



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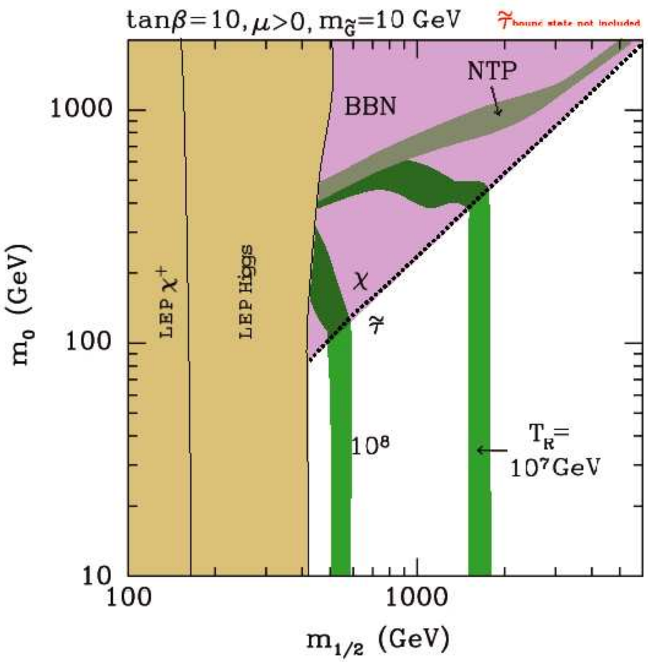

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$\Rightarrow$ $T_R \lesssim$ a few $\times 10^8$ GeV

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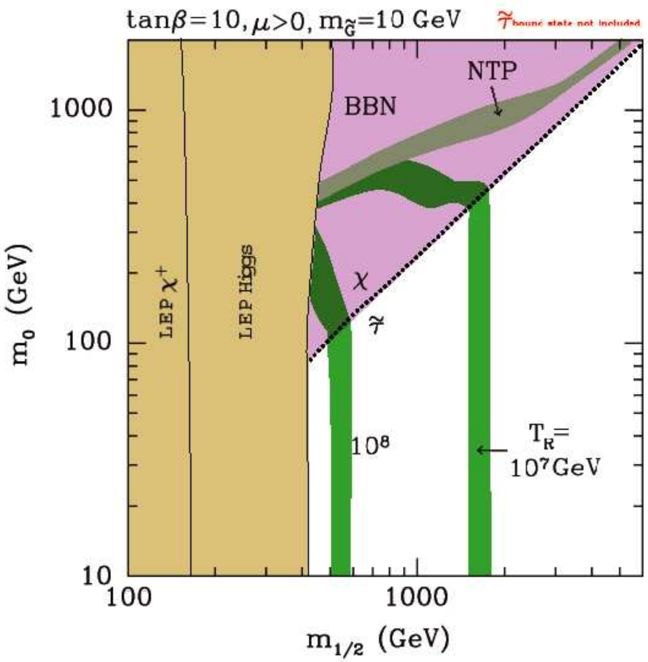

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NTP not enough

$\Rightarrow$ popular baryogenesis scenario strongly disfavored

...in the CMSSM

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  Brandenburg+Covi+Hamaguchi+L.R.+Steffen, hep-ph/0501287 $\longrightarrow$ PLB'05

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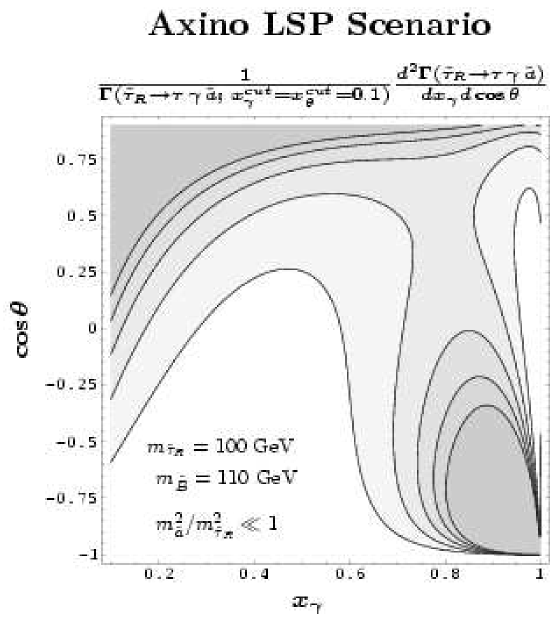
Brandenburg+Covi+Hamaguchi+L.R.+Steffen, hep-ph/0501287 ⟶ PLB'05



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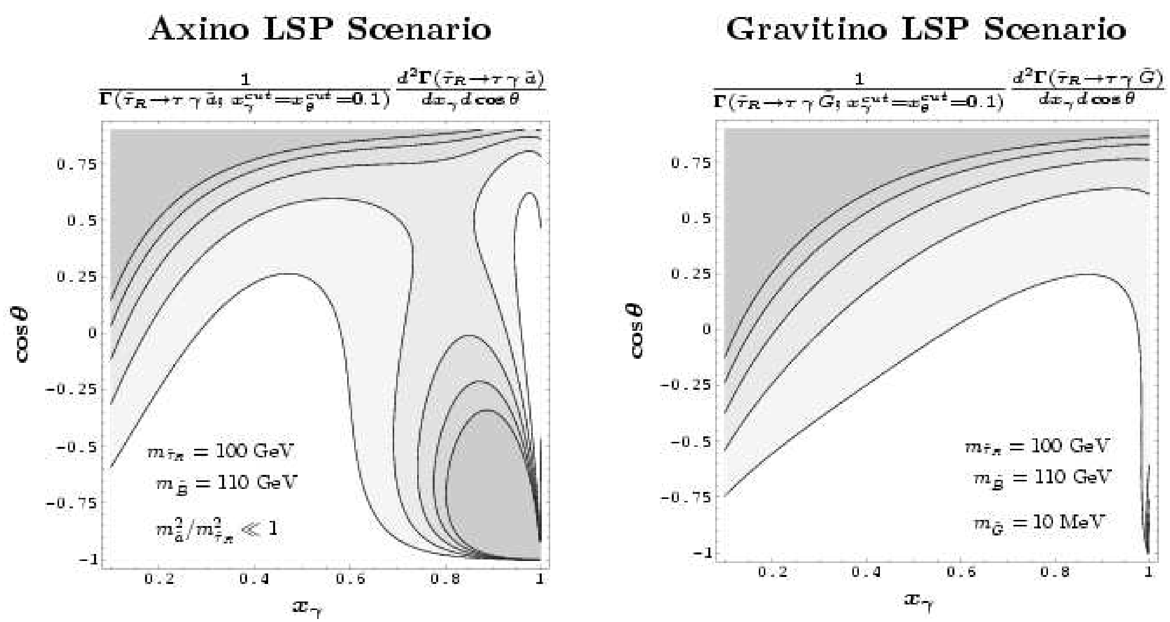
  Brandenburg+Covi+Hamaguchi+L.R.+Steffen, hep-ph/0501287 ⟶ PLB'05



$\widetilde{G}$ or $\widetilde{a}$: Will we ever know?

- If neutralino is NLSP: points towards $\widetilde{a}$ but hard to confirm

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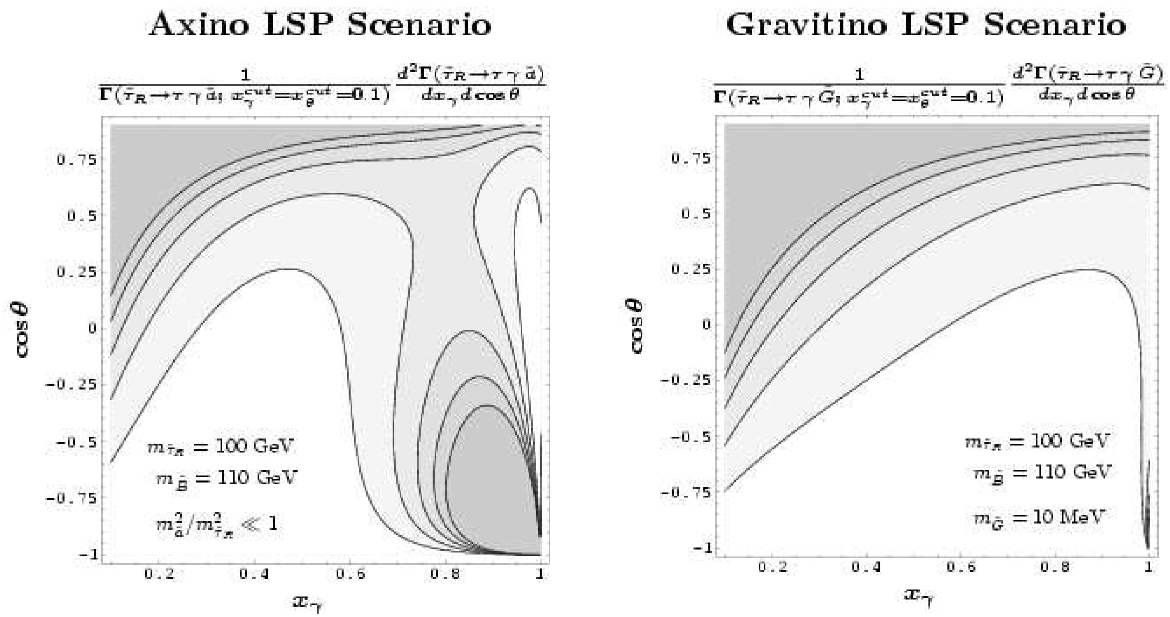
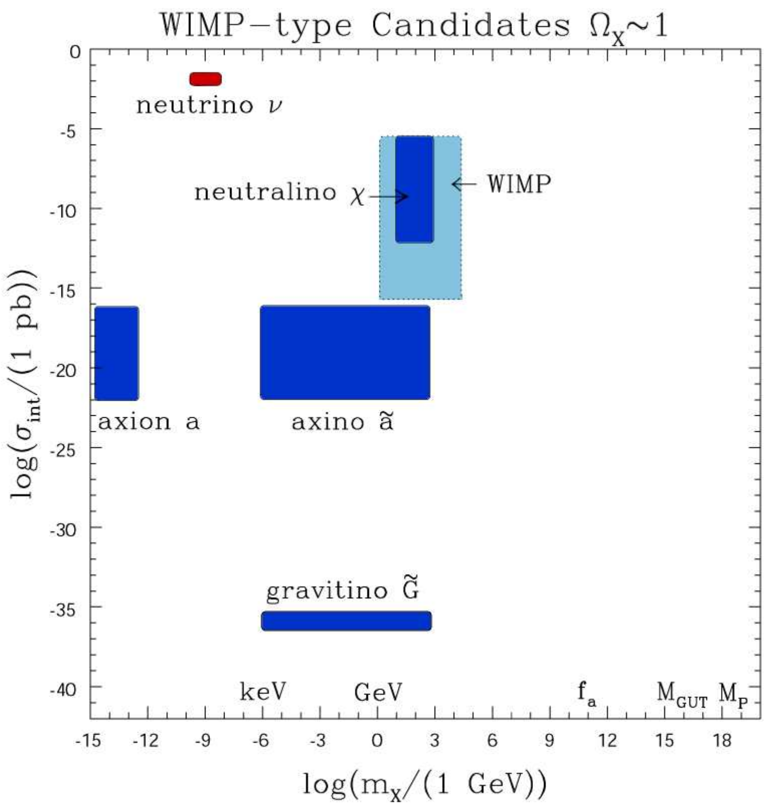


- different event distributions
- chance to distinguish at LHC

The Big Picture

well–motivated particle candidates such that $\Omega \sim 0.1$



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\widetilde{G}$
- ????

Summary

- dark matter: many possible candidates

  axion, neutralino, axino, gravitino, sterile (s)neutrino, lightest Kałuża-Klein particle, etc;

  (much harder to cook up a well-motivated, long-lived, underlying theory, like SUSY)

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- $\widetilde{a}$ and $\widetilde{G}$: partially testable at the LHC

The bottom line:

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DM WIMP will be discovered within a decade

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or else

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...STAY TUNED