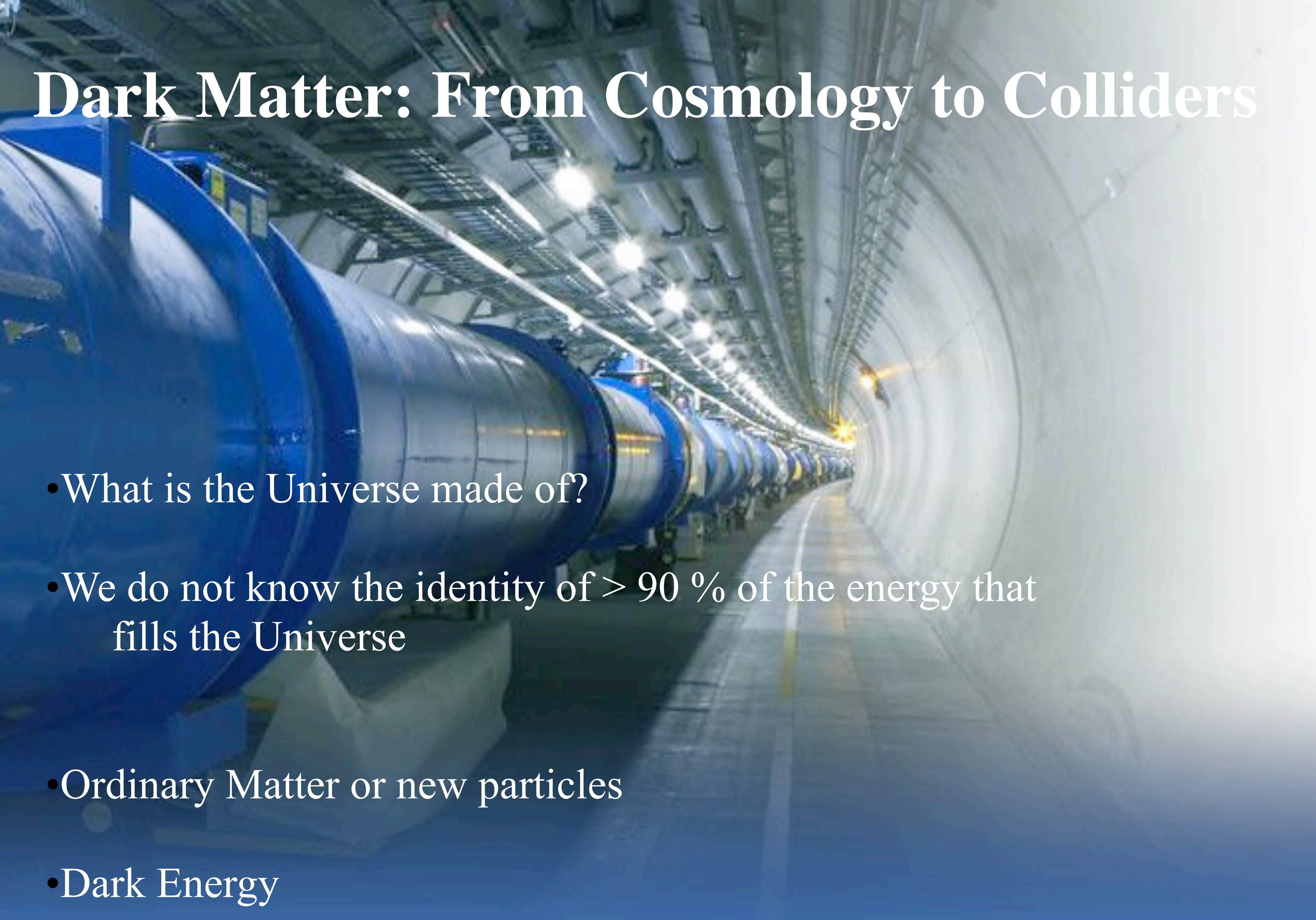


Dark Matter: From Cosmology to Colliders

- What is the Universe made of?
- We do not know the identity of > 90 % of the energy that fills the Universe
- Ordinary Matter or new particles
- Dark Energy

The Evidence:

- Observation:
  - Galactic Rotation Curves
  - Hot X-ray Gas
  - Gravitational Lensing
  - The CMB
- Theory
  - Growth of Galaxies
  - Nucleosynthesis
  - Inflation

Galactic Rotation Curves

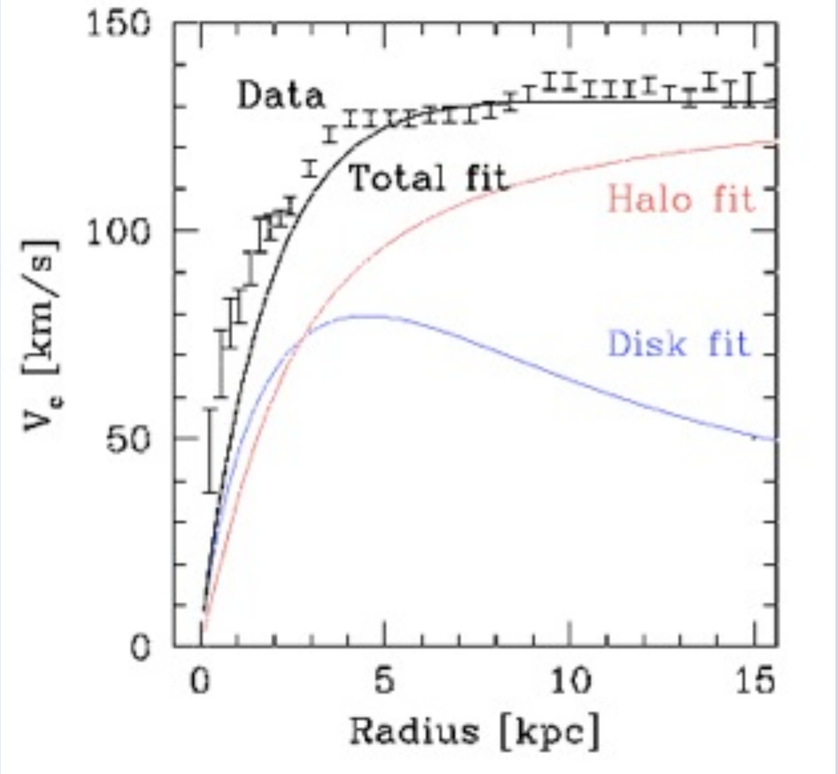
Doppler measurements in spiral galaxies

Observe: $v(r)$

Expect: $$\frac{GM^2}{r^2} = \frac{KMv^2}{r}$$

or $$M(<r) = \frac{Kv^2r}{G}$$

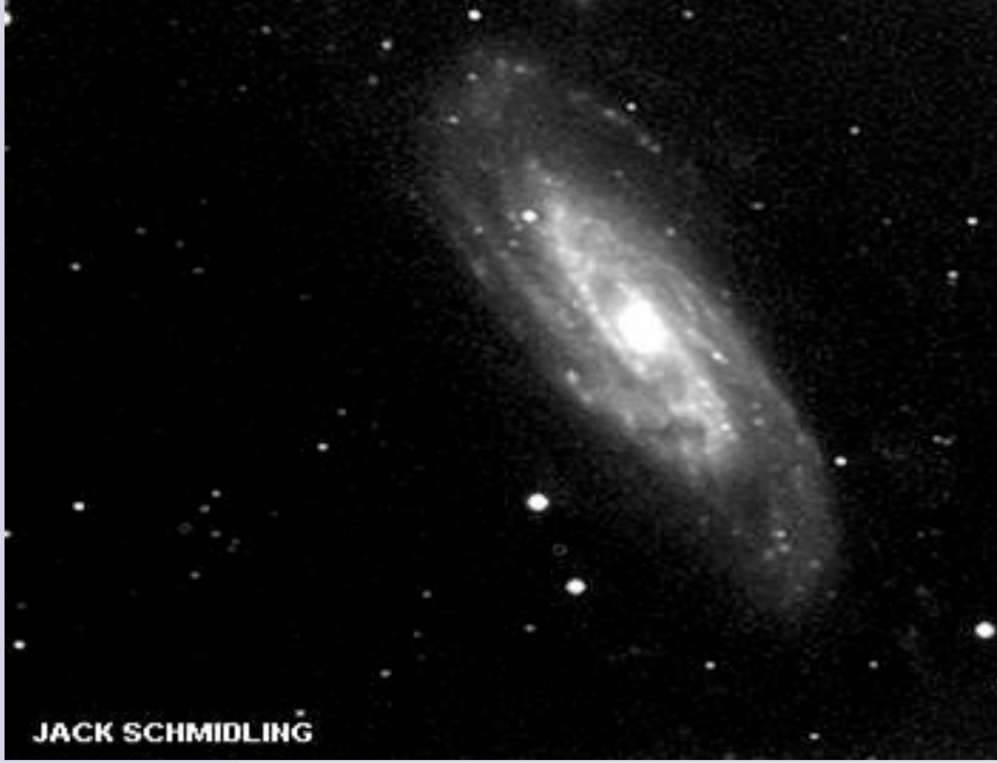
if M is constant $$v^2 \sim 1/r$$



NGC 2403

Expect: $$\frac{GM^2}{r^2} = \frac{KMv^2}{r}$$

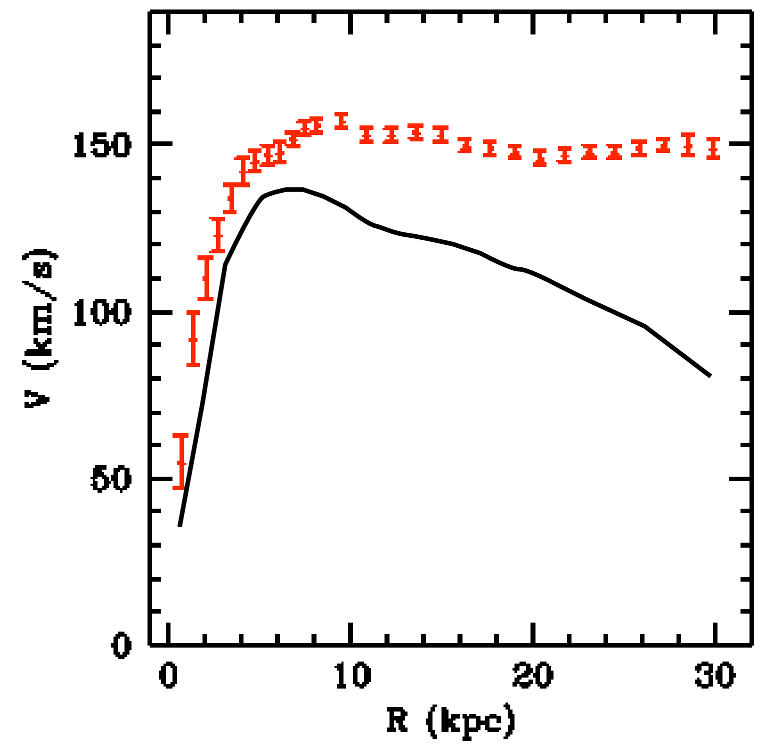
or $$M(<r) = \frac{Kv^2 r}{G}$$



if M is constant $$v^2 \sim 1/r$$

if v is constant $$M \sim r$$

$\Rightarrow$ **Existence of Dark Matter**

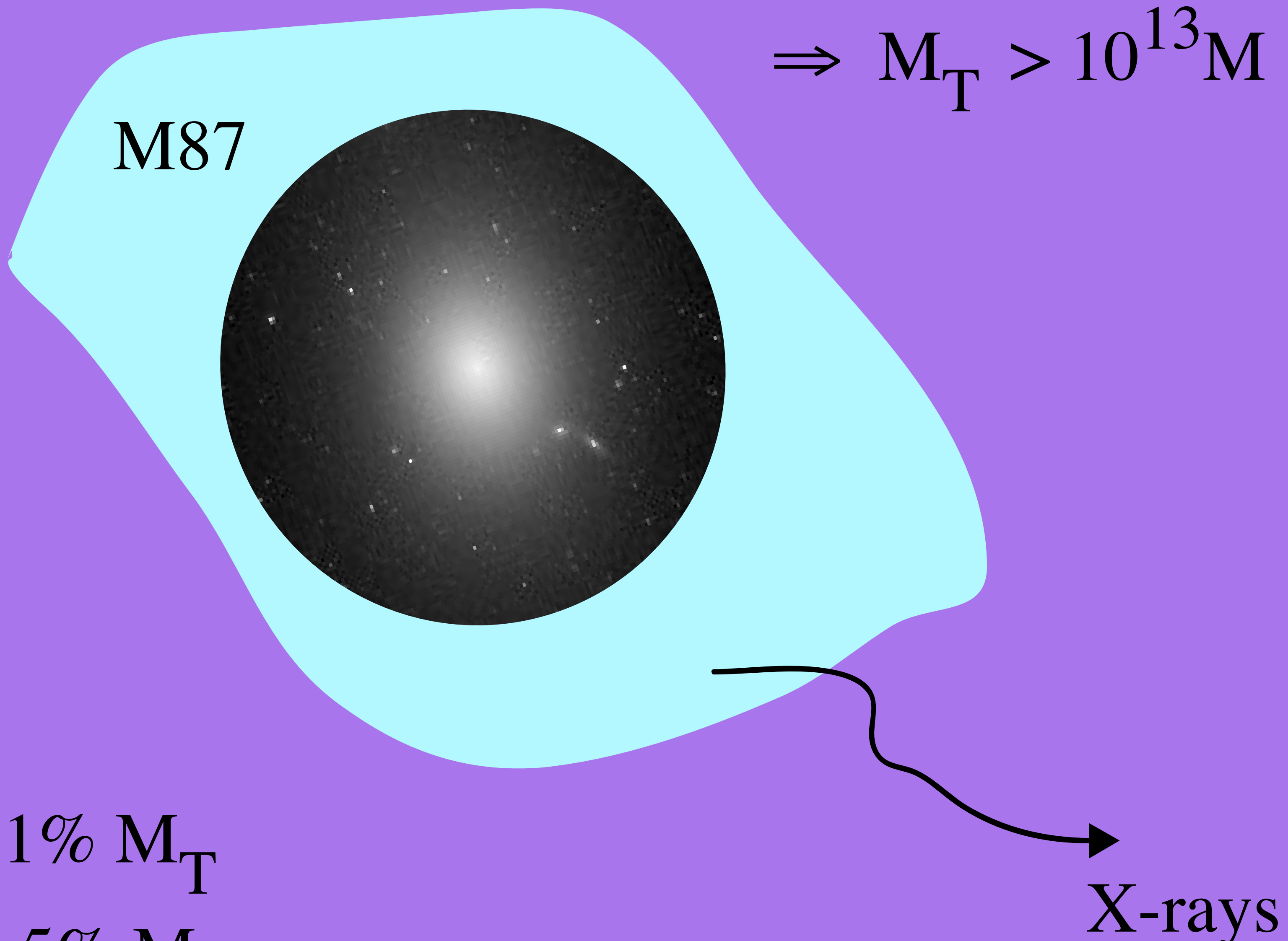


NGC 3198

Hot X-ray Gas

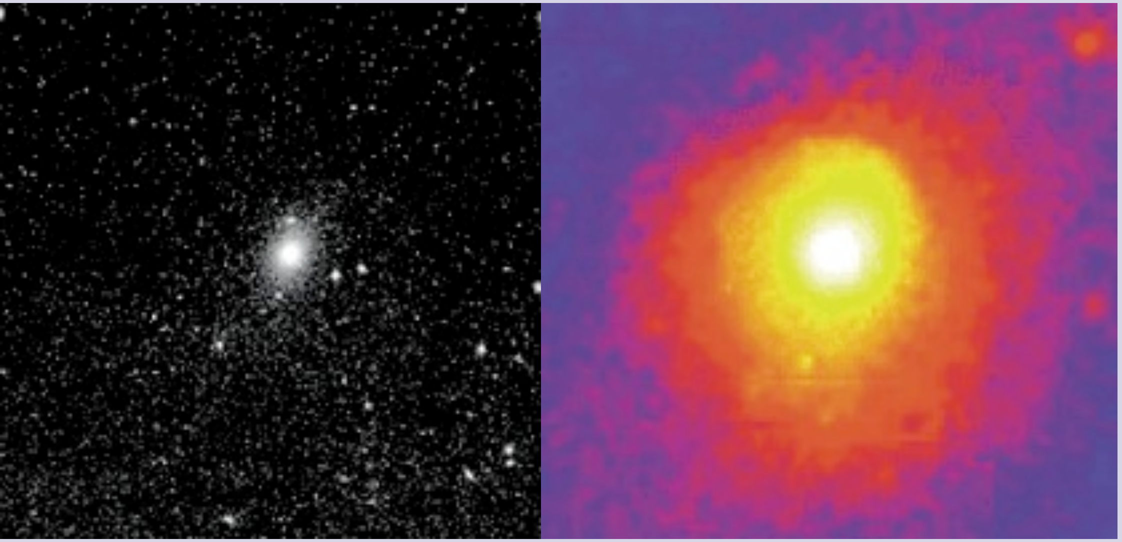
Bound Gas ($T > 10^6$ K)

$\Rightarrow M_T > 10^{13} M_\odot$

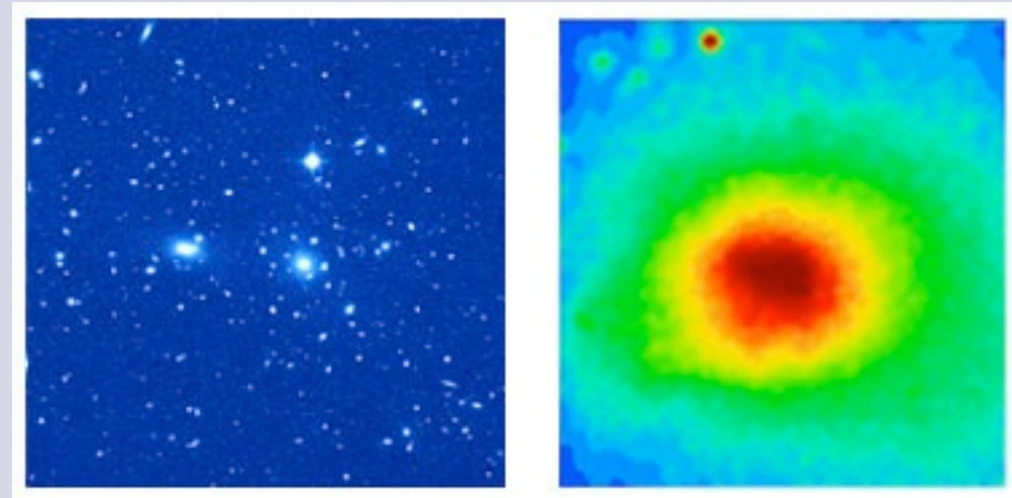


$M_{ell} < 1\% \, M_T$

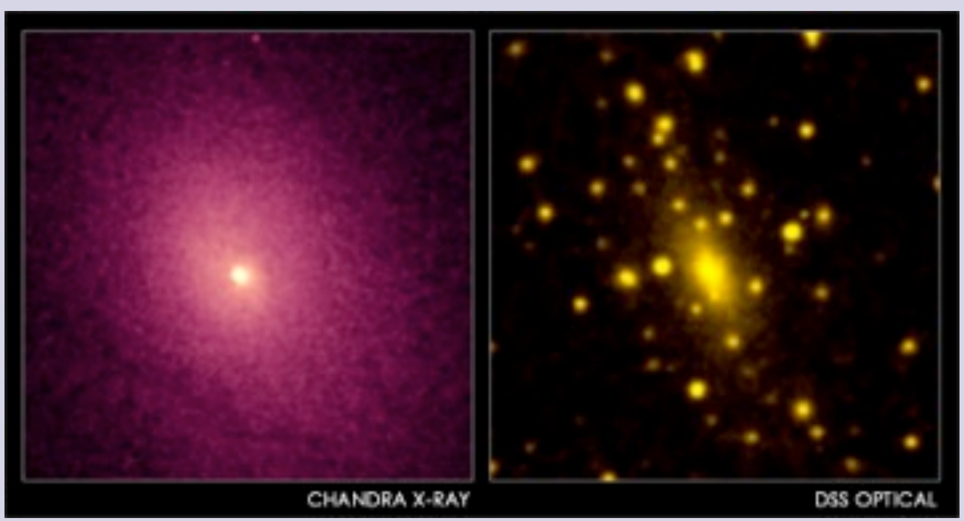
$M_{Gas} < 5\% \, M_T$



Virgo



Coma



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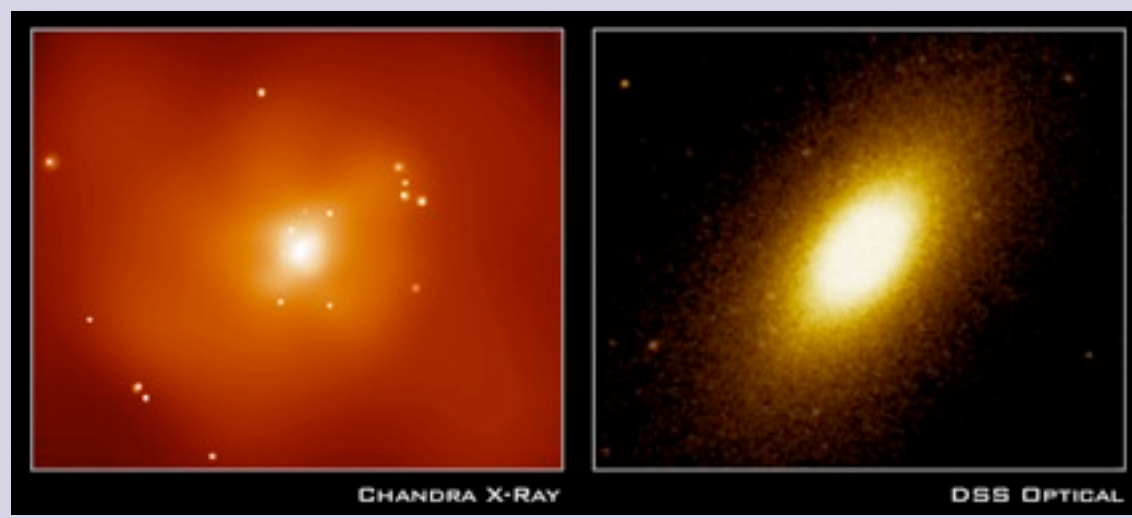
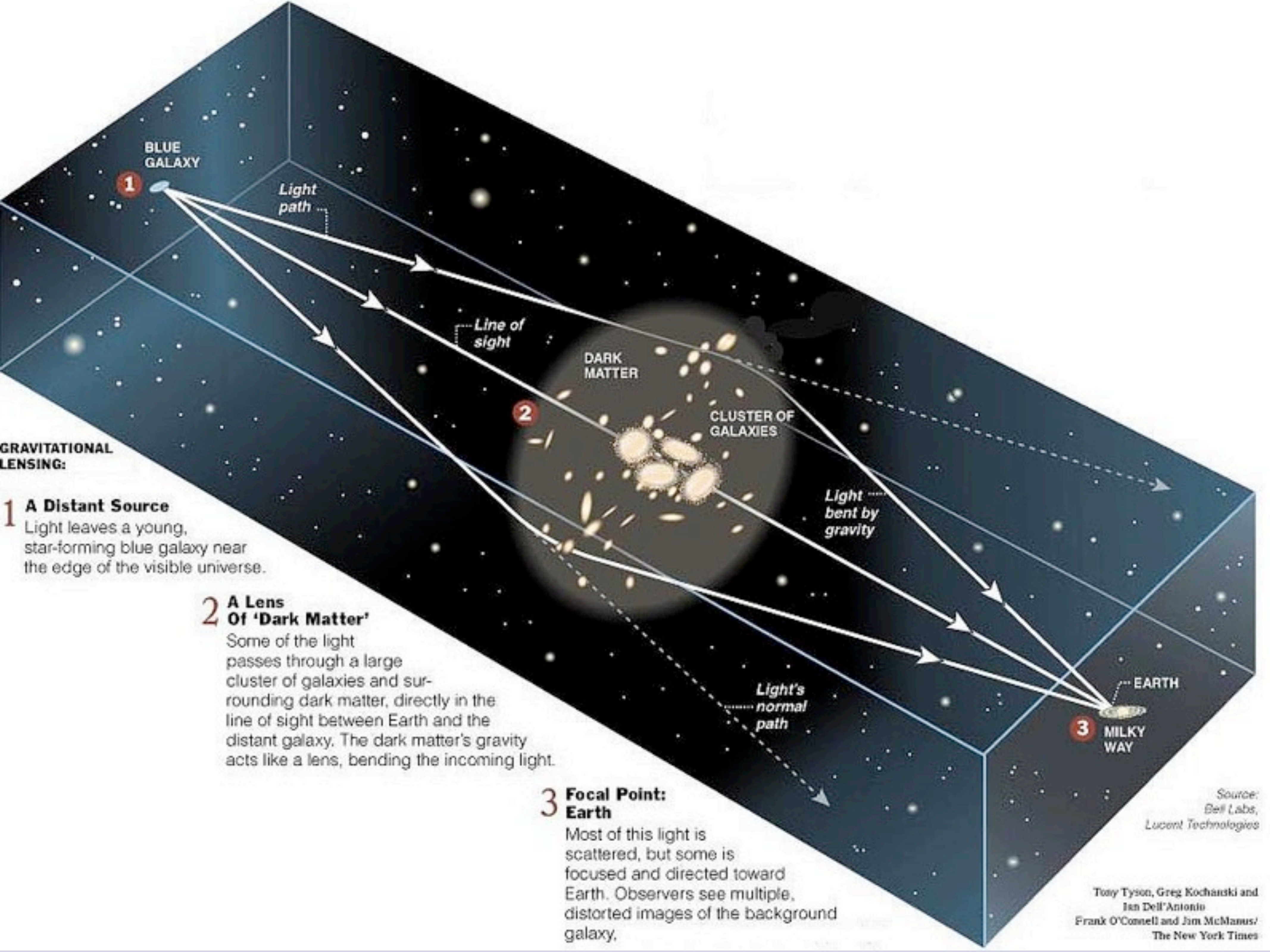
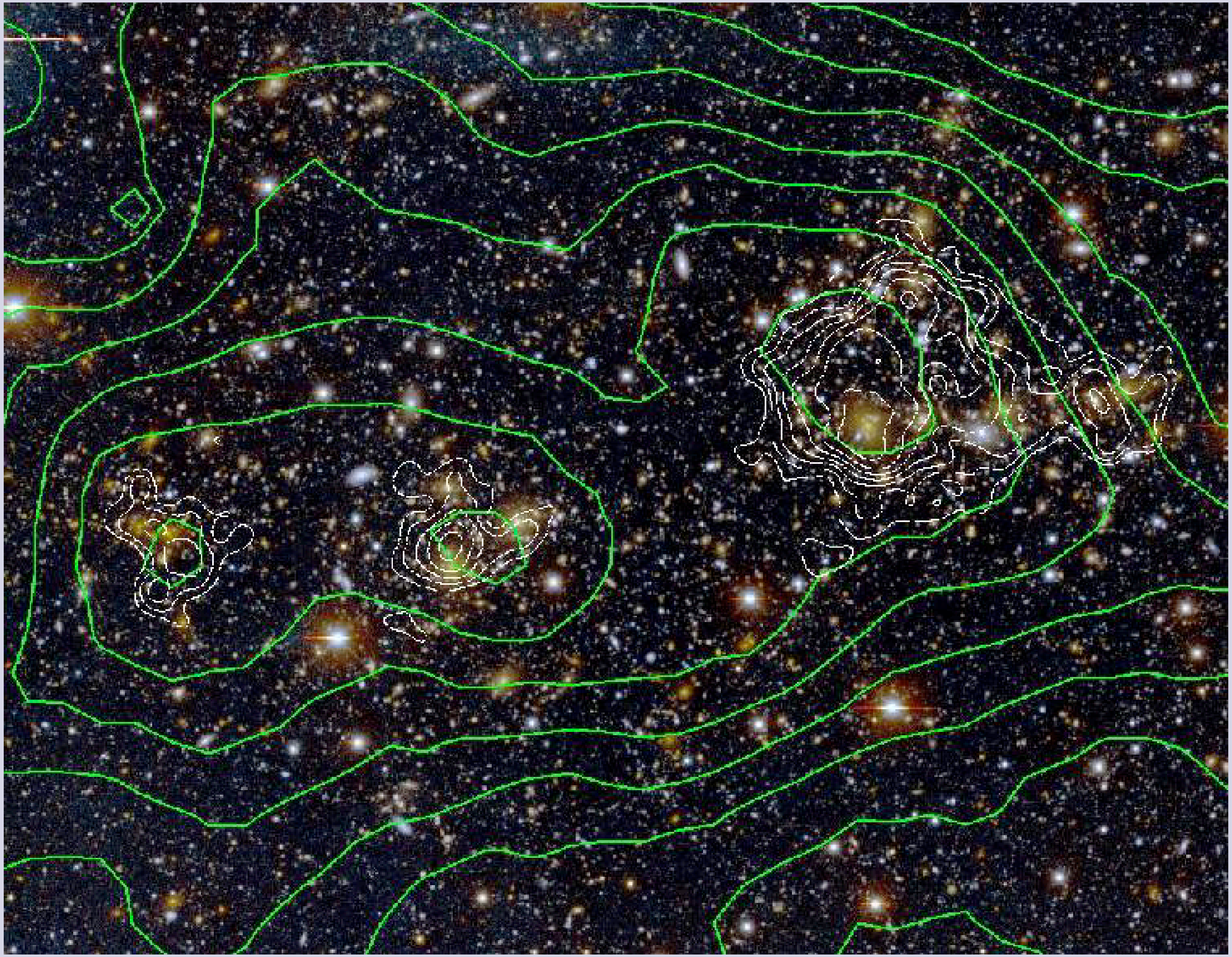


NGC720



BLUE GALAXY
1
Light path
Line of sight
DARK MATTER
2
CLUSTER OF GALAXIES
Light bent by gravity
Light's normal path
EARTH
3
MILKY WAY
GRAVITATIONAL LENSING:
1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.
2 A Lens Of 'Dark Matter'
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.
3 Focal Point: Earth
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.
Source: Bell Labs, Lucent Technologies
Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times

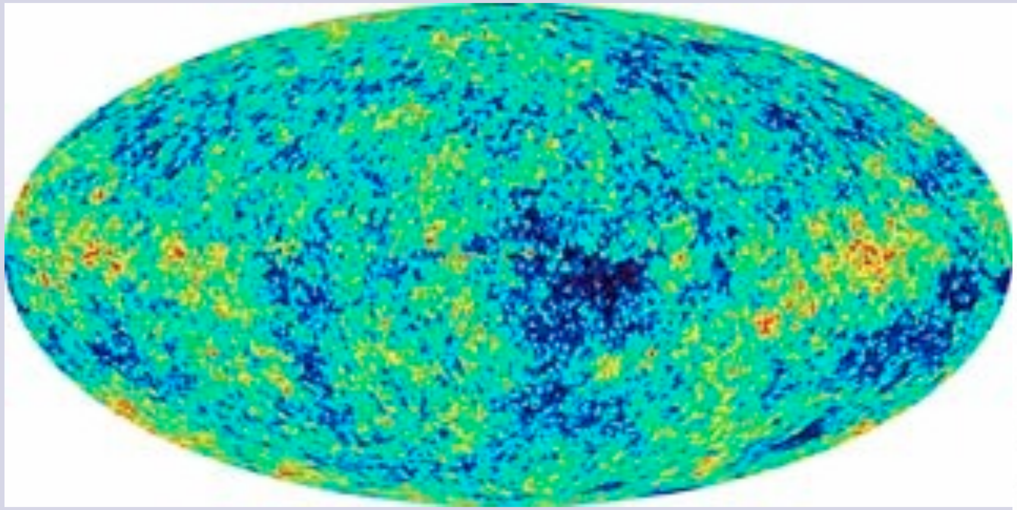
0024+1654

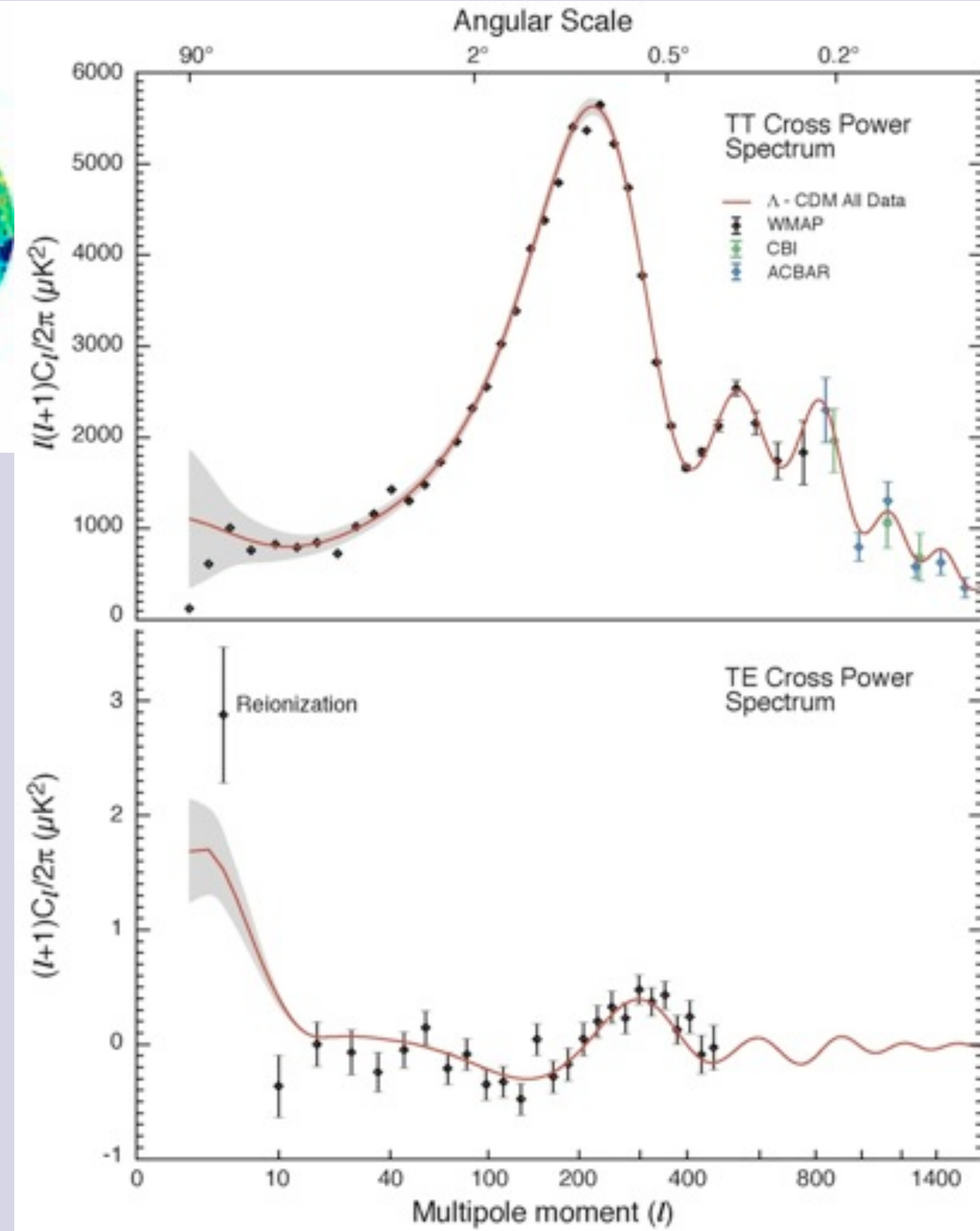


Abell 781 Wittman et al.

The Bullet Cluster

WMAP





Position of 1st peak

$\Rightarrow \quad \Omega = 1$

How Much Dark Matter

WMAP 5 Dunkley etal

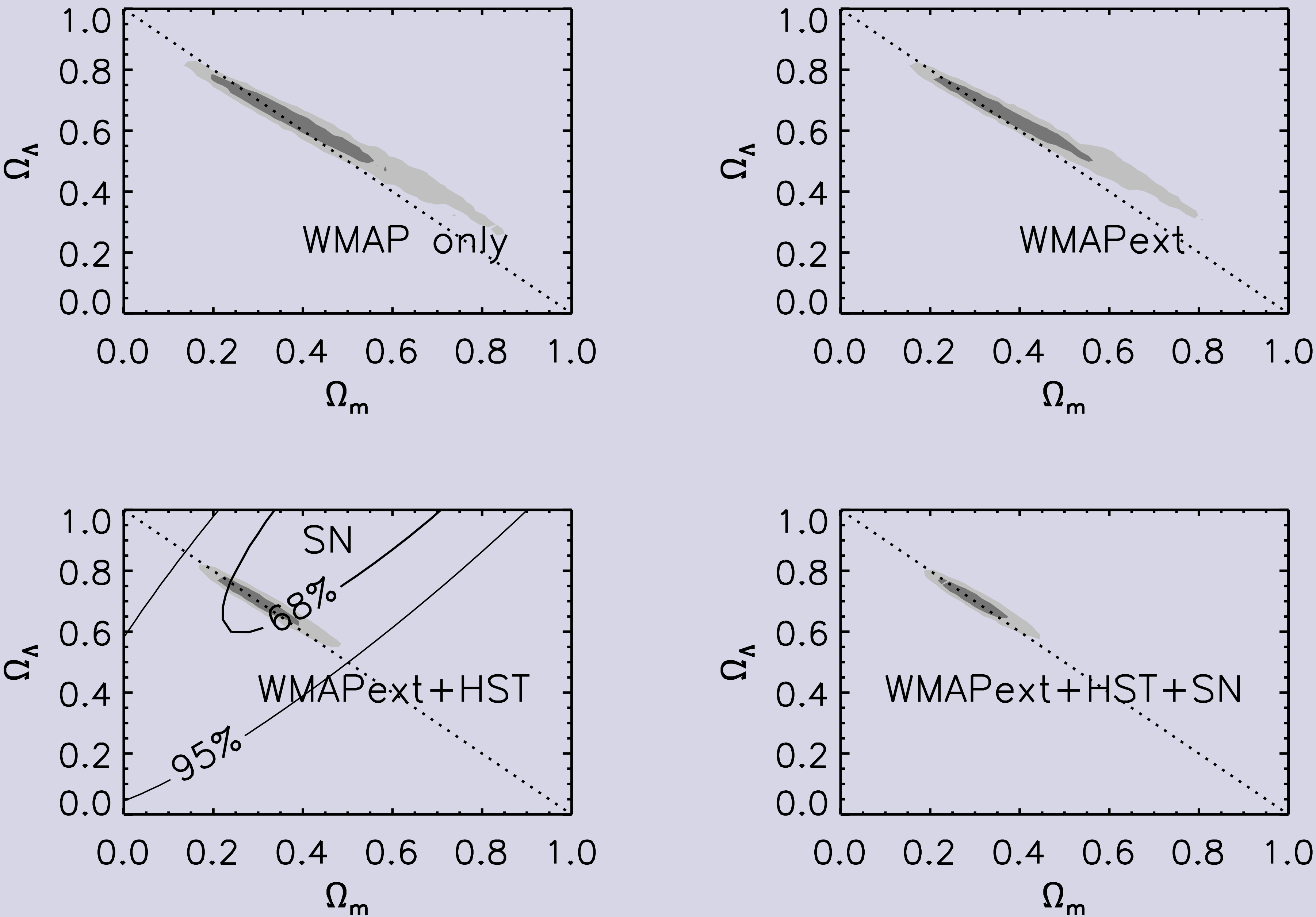
Precise bounds on matter content

$$\Omega_m h^2 = 0.1326 \pm 0.0063 \qquad \Omega_b h^2 = 0.0227 \pm 0.0006$$

$$\Omega_{cdm} h^2 = 0.1099 \pm 0.0062$$

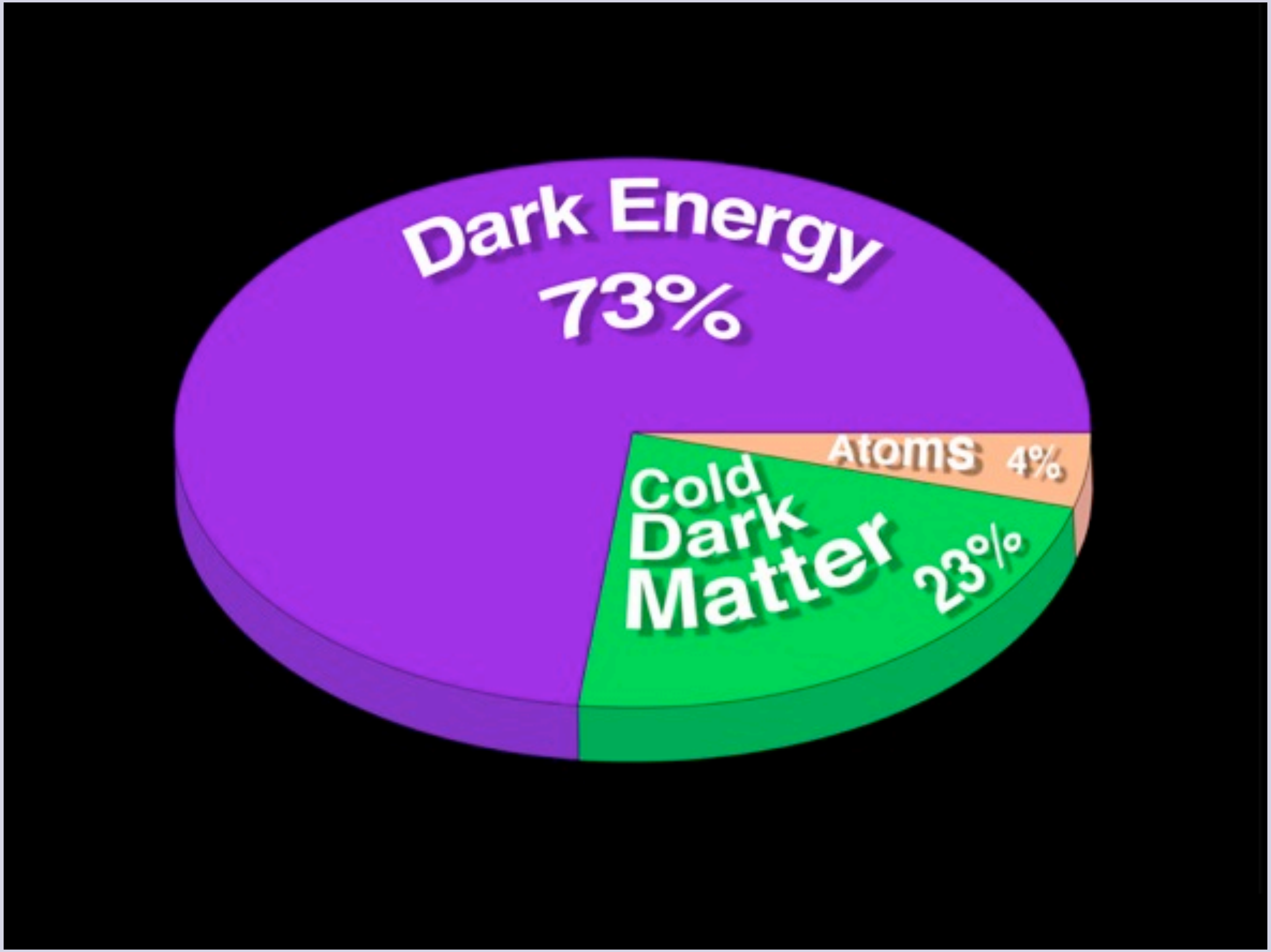
or

$$\Omega_{cdm}\, h^2 = 0.0975 - 0.1223 \quad (2\,\sigma)$$


WMAP only
WMAPext
SN
68%
95%
WMAPext+HST
WMAPext+HST+SN
Ω_Λ
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0

Cosmological Parameters:

$$\Omega = 1.011 \pm 0.012$$



Growth of Density Fluctuations

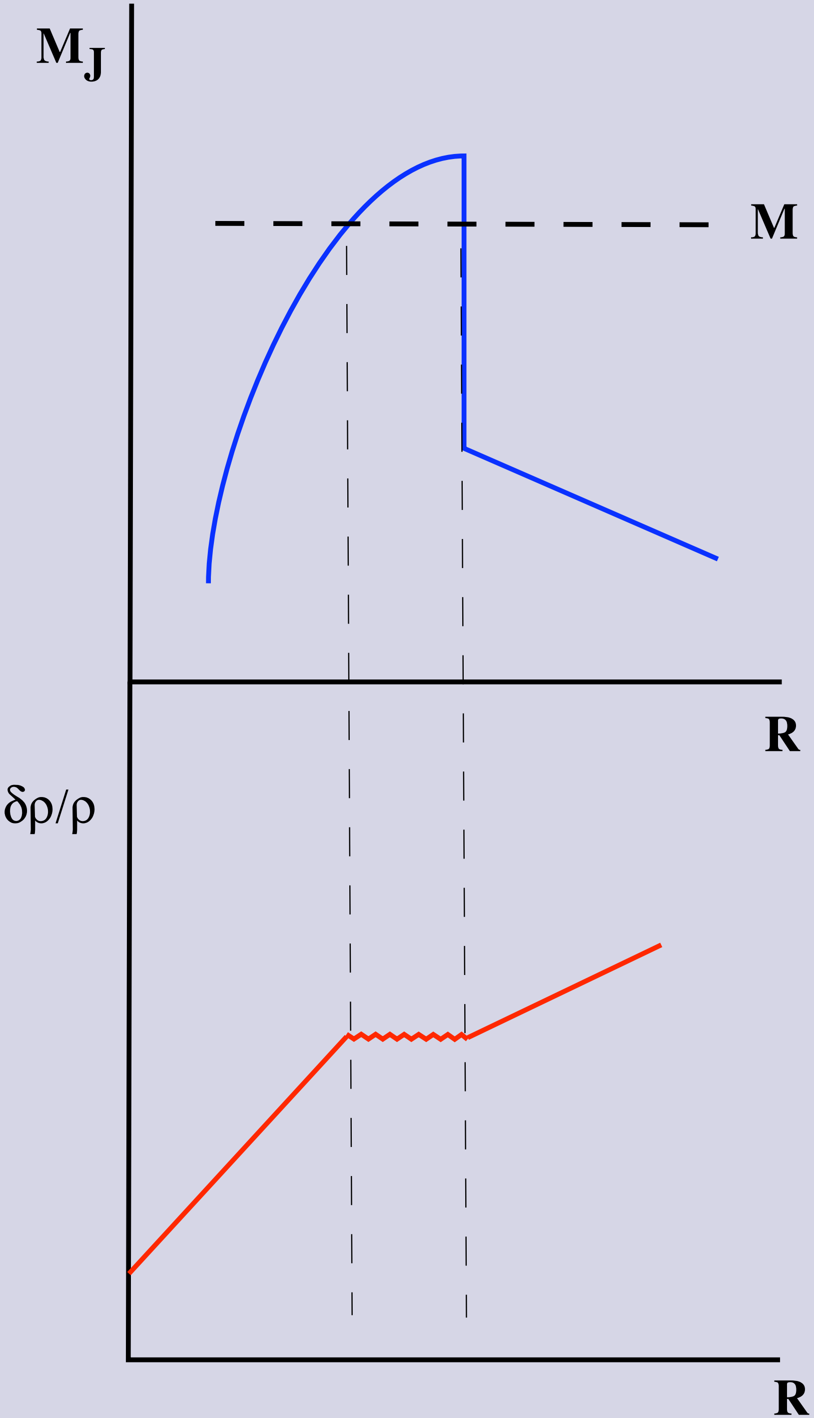
Density perturbation $\delta\rho$

Jean's criteria

Growth for $k > k_J$

Growth for $M > M_J$ Jean's Mass

Depends on Equation of State



- Dark Matter must be:
  - Stable (or very long-lived)
  - Neutral

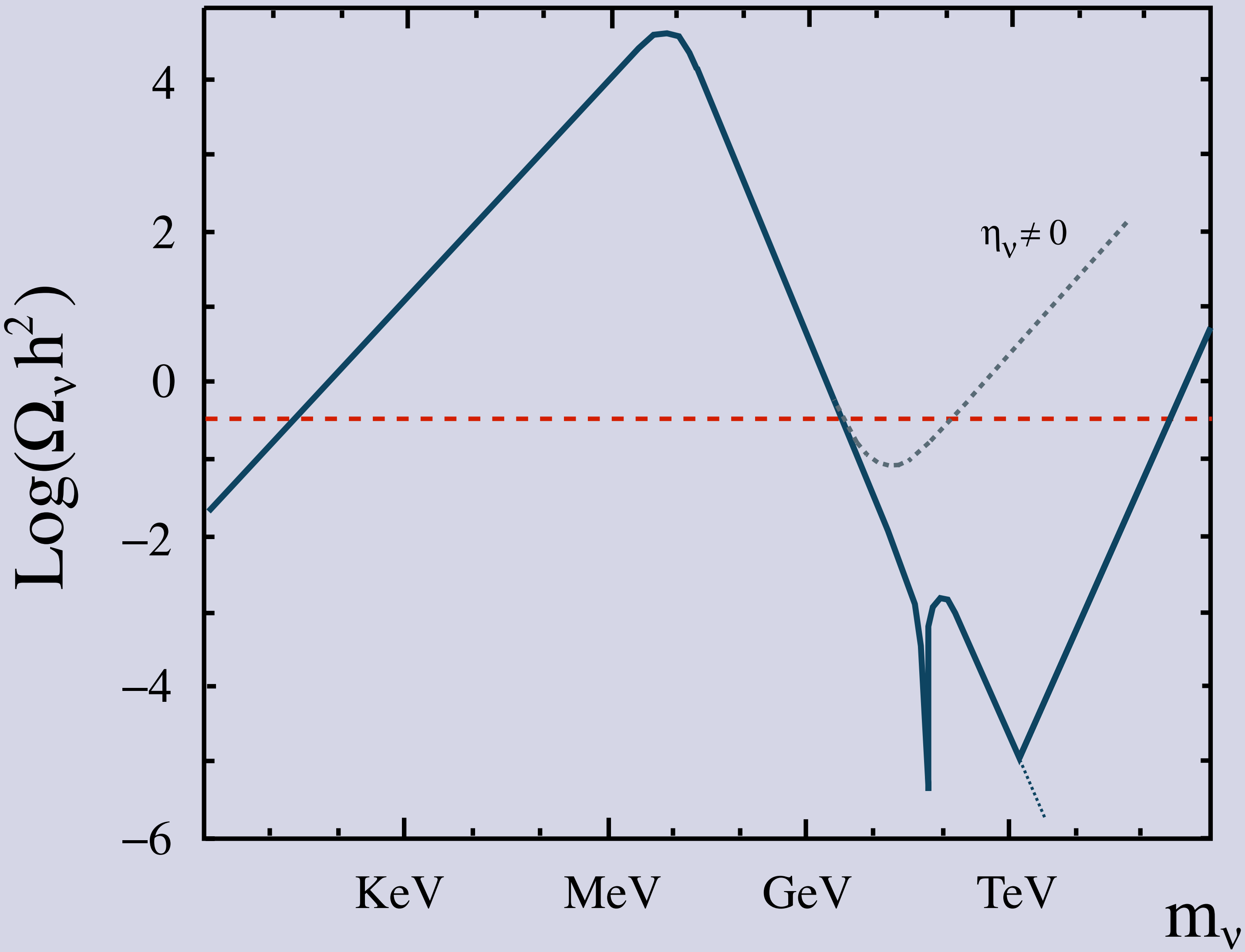
Candidates

- Baryons
  - Cluster, produce heavy elements, …$\Omega_B h^2 = 0.0224$
- Neutrinos
  - We know too much ($0.0005 < \Omega_\nu h^2 < 0.0076$)
- Axions
  - Solve the strong CP problem, scale is not well motivated
- LSP
  - Natural stable dark matter candidate with good relic density
- …

Neutrinos

Light ν's (m_ν < 1 MeV): Left over with $n_\nu \approx n_\gamma$

Heavy ν's (m_ν > 1 MeV): Left over from annihilations



Neutrinos

- Relic Density limit on light ν masses:

$$\rho_\nu = \frac{3}{11}\frac{g_\nu}{2} m_\nu n_\gamma$$

$$\Omega_\nu h^2 \simeq 0.01 m_\nu (eV) \frac{g_\nu}{2}$$

- WMAP +2df + limit

$$m_{tot} < 0.7 eV \Longrightarrow \Omega h^2 < 0.0076$$

- Heavy neutrinos (m > GeV) excluded as dark matter

Beyond the Standard Model

(add new symmetries, particles and/or interactions)

- Solutions to the strong CP problem
  - Axions
- Supersymmetry
  - Neutralinos

•

•

•

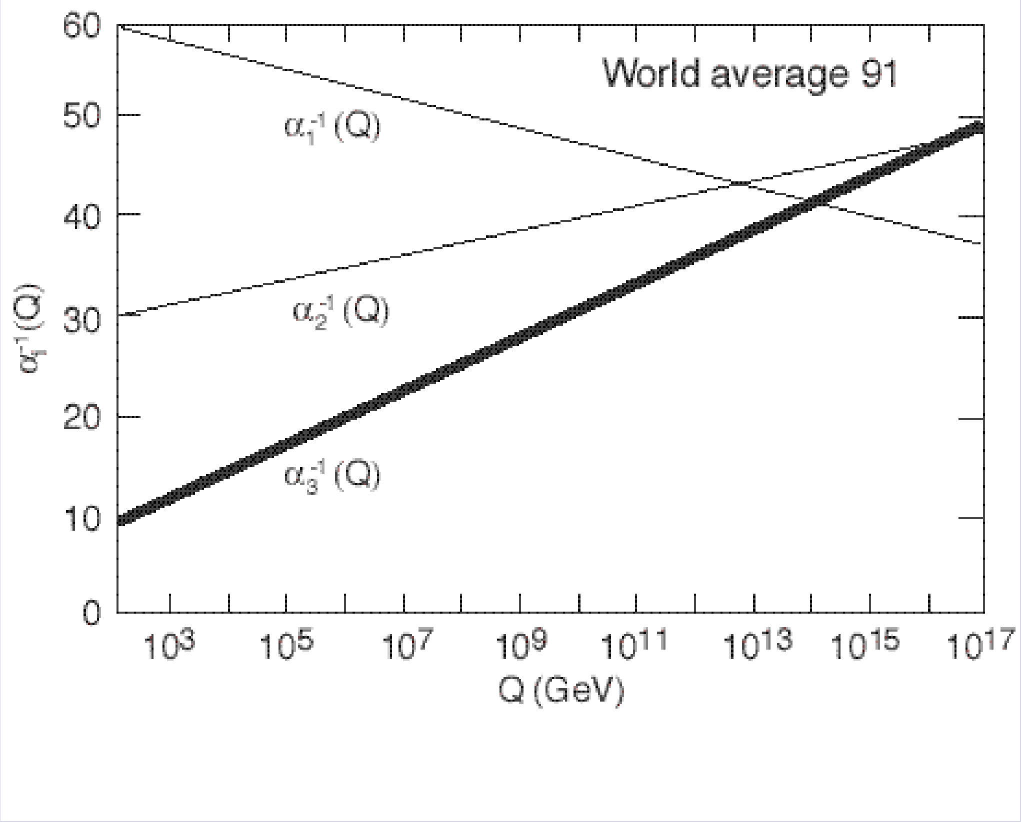
Guage Hierarchy Problem

$M_P \approx 10^{19}$ GeV

$M_X \approx 10^{16}$ GeV

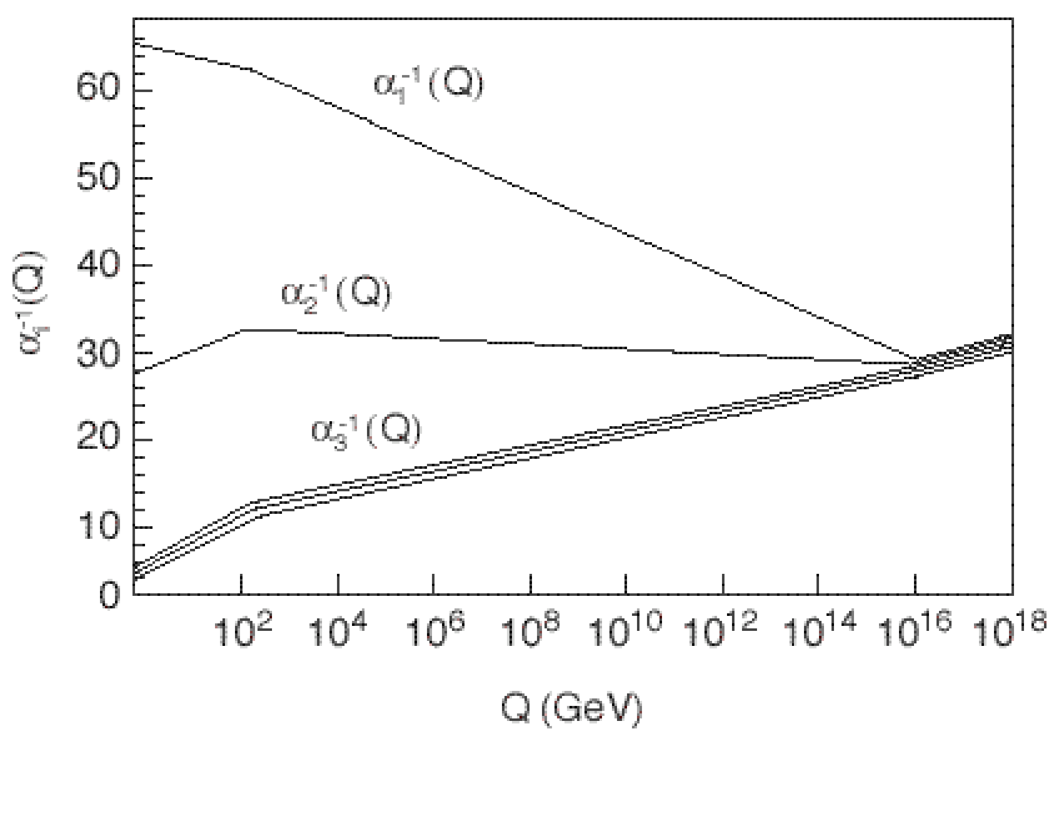
$M_W \approx 10^{2}$ GeV

Why are these scales different?
Do they stay different?



Running of the Gauge couplings
in the standard model

Running of the Gauge couplings
in the supersymmetric
standard model



What is the MSSM

1) Add minimal number of new particles:
Partners for all SM particles + 1 extra Higgs EW doublet.

2) Add minimal number of new interactions:
Impose R-parity to eliminate many UNWANTED interactions.

$$R = (-1)^{3B+L+2S}$$

The MSSM

$$
\begin{aligned}
Q_i &= \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \\
u_i^c &= u_L^c, \quad c_L^c, \quad t_L^c \\
d_i^c &= d_L^c, \quad s_L^c, \quad b_L^c \\
L_i &= \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \\
e_i^c &= e_L^c, \quad \mu_L^c, \quad \tau_L^c
\end{aligned}
$$

$$W = \epsilon_{ij}[y_e H_1^j L^i e^c + y_d H_1^j Q^i d^c + y_u H_2^i Q^j u^c] + W_\mu$$

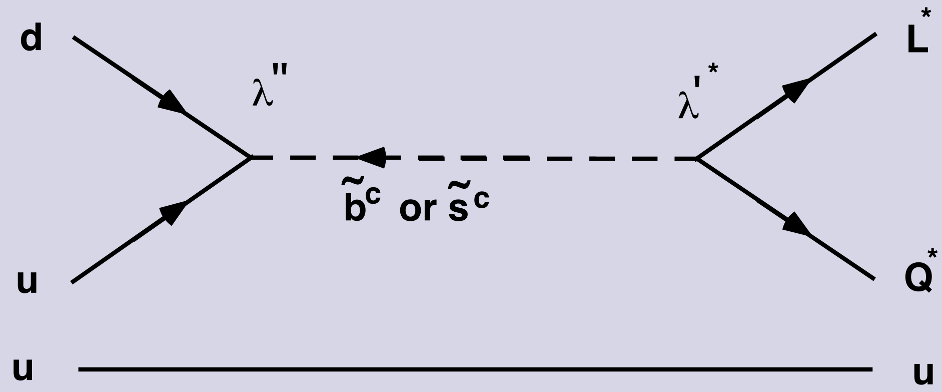
$$W_\mu = \epsilon_{ij} \mu H_1^i H_2^j$$

R-Parity:

$$W_R = \frac{1}{2}\lambda^{ijk} L_i L_j e_k^c + \lambda'^{ijk} L_i Q_j d_k^c + \frac{1}{2}\lambda''^{ijk} u_i^c d_j^c d_k^c + \mu'^i L_i H_u$$

Contains B and L violating operators

Proton decay



proton lifetime $\qquad \Gamma_p^{-1} \sim \frac{\tilde{m}^4}{m_p^5} \sim 10^8 \mathrm{GeV}^{-1}$

All New particles have R = -1

E.g.:

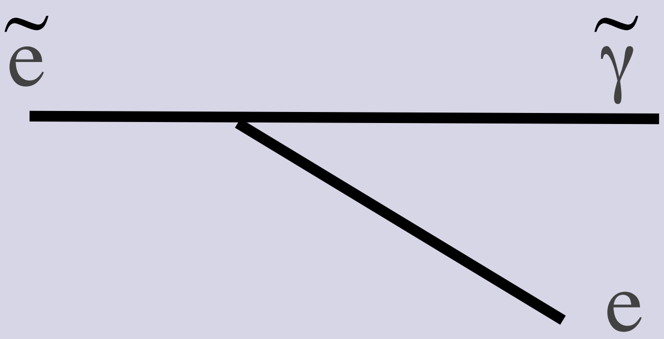
γ: S=1/2; B=L=0; $R=(-1)^{1} = -1$

e: S=0; B=0; L= -1; $R=(-1)^{-1} = -1$

u: S=0; B=1/3; L=0; $R=(-1)^{1} = -1$

R-Parity Conservation $\Rightarrow$

The Lightest Supersymmetric Particle (LSP) is stable



SUSY Dark Matter

MSSM and R-Parity $\Longrightarrow$ Stable DM candidate

1) Neutralinos

$$\chi_i = \alpha_i \widetilde{B} + \beta_i \widetilde{W} + \gamma_i \widetilde{H}_1 + \delta_i \widetilde{H}_2$$

2) Sneutrino

Excluded (unless add L-violating terms)

3) Other:

Axinos, Gravitinos, etc

Neutralinos

Mass matrix

$$(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0) \begin{pmatrix} M_1 & 0 & \frac{-g_1 v_1}{\sqrt{2}} & \frac{g_1 v_2}{\sqrt{2}} \\ 0 & M_2 & \frac{g_2 v_1}{\sqrt{2}} & \frac{-g_2 v_2}{\sqrt{2}} \\ \frac{-g_1 v_1}{\sqrt{2}} & \frac{g_2 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_1 v_2}{\sqrt{2}} & \frac{-g_2 v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

- Depends on $M_{1/2}$, μ, $\tan\beta$
- Assume $M_1 = M_2 = M_3$ @ GUT scale
- Relic density also depends on m_0 and m_A

Parameters

Higgs mixing mass: μ

Ratio of Higgs vevs: $\tan\beta$

Gaugino masses: M_i

Soft scalar masses: m_o

Bi and Trilinear Terms: B and A_i

Phases: θ_μ, θ_A

Unification Conditions

- Gaugino masses: $M_i = m_{1/2}$
- Scalar masses: $m_i = m_0$
- Trilinear terms: $A_i = A_0$

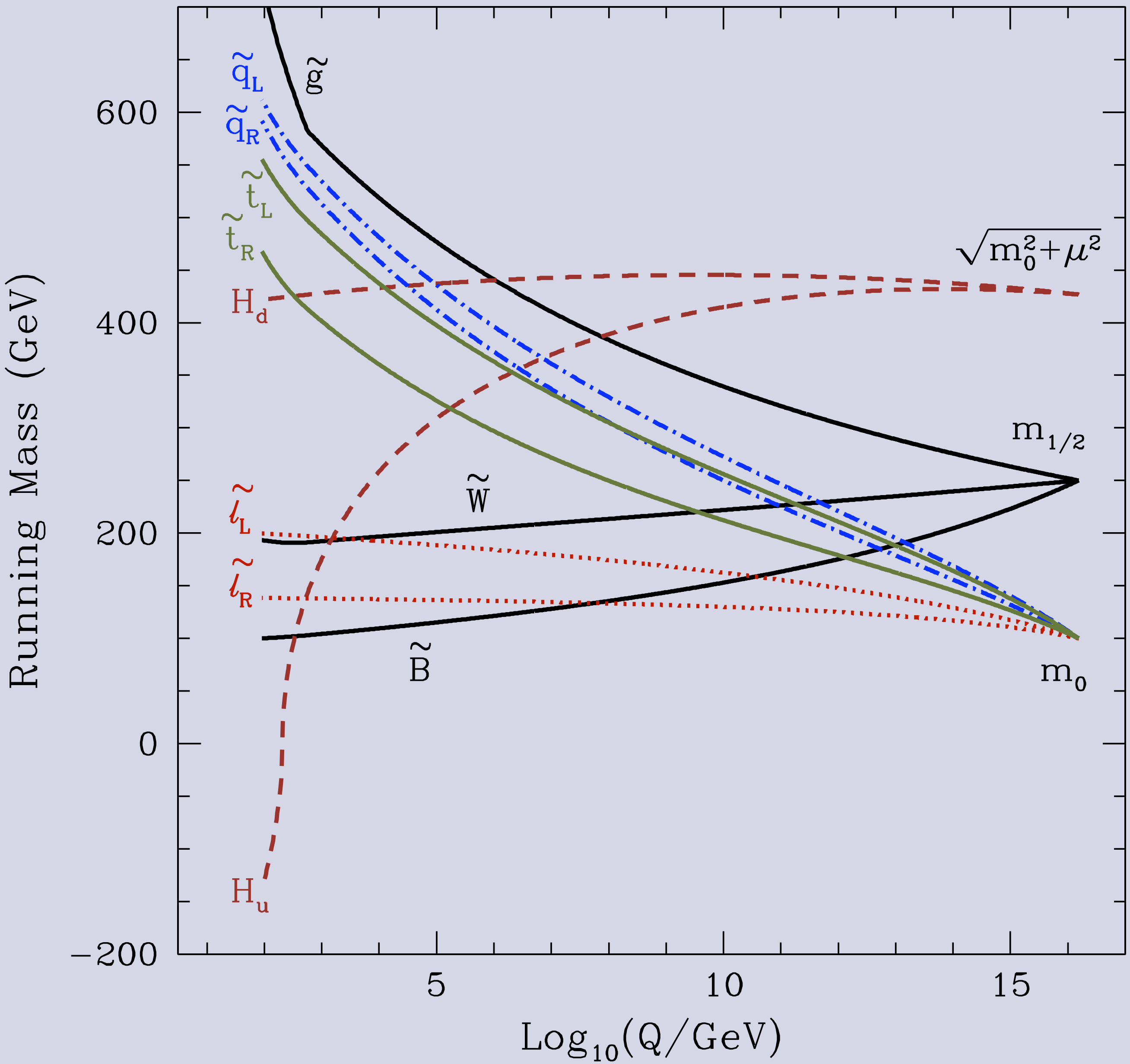
predict μ, B

mSugra Conditions

- Gravitino masses: $m_{3/2} = m_0$
- Bilinear term: $B_0 = A_0 - m_0$

predict μ, $\tan\beta$

CMSSM Spectra



Unification to rich spectrum
+
EWSB

Falk

The Relic Density

At high temperatures $T >> m_\chi$;

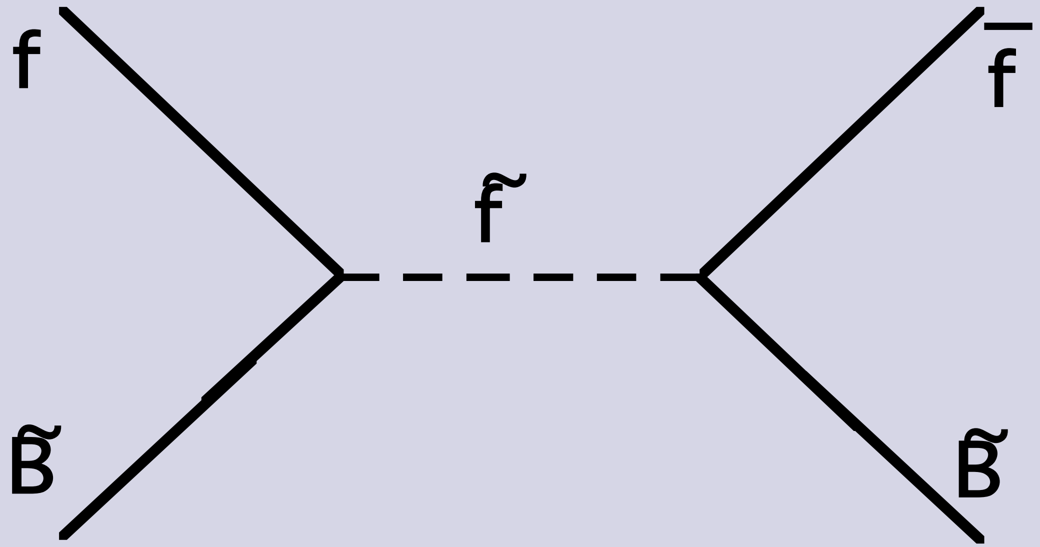
χ's in equilibrium $\Gamma > H$ $n_\chi \sim n_\gamma$

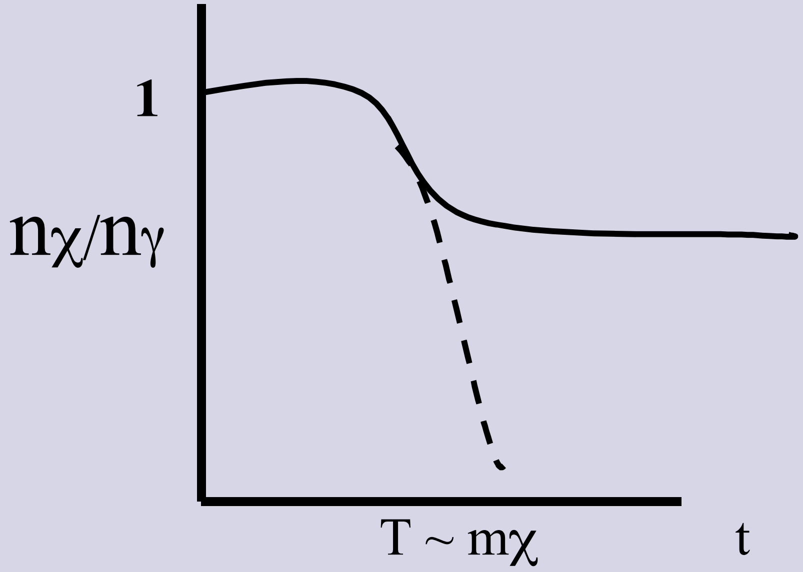
$\Gamma \sim n\sigma v \sim T^3\sigma v$; $HM_p \sim \sqrt{\rho} \sim T^2$

As $T < m_\chi$; annihilations drop n_χ

$n_\chi \sim e^{-m_\chi/T}\, n_\gamma$

Until freeze-out, $\Gamma < H$ $n_\chi/n_\gamma \sim$ constant





Annihilation Cross sections:

$$\tilde{B}\tilde{B} \longrightarrow f\bar{f}$$

$$\begin{aligned}
\langle \sigma v \rangle &= (1 - \frac{m_f^2}{m_{\tilde{B}}^2})^{1/2} \frac{g_1^4}{128\pi} \Big[(Y_L^2 + Y_R^2)^2 (\frac{m_f^2}{\Delta_f^2}) \\
&\quad + (Y_L^4 + Y_R^4)(\frac{4m_{\tilde{B}}^2}{\Delta_f^2})(1 + ...)\, x \Big] \\
&\equiv a + bx
\end{aligned}$$

$$\Delta_f \equiv m_{\tilde{f}}^2 + m_{\tilde{B}}^2 - m_f^2,$$

The Relic Density:

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

$$\frac{df}{dx} = m_\chi \left(\frac{1}{90} \pi^2 \kappa^2 N \right)^{1/2} (f^2 - f_0^2)$$

$$f = n/T^3$$

$$\Omega_\chi h^2 \simeq 1.9 \times 10^{-11} \left(\frac{T_\chi}{T_\gamma} \right)^3 N_f^{1/2} \left(\frac{\mathrm{GeV}}{a x_f + \frac{1}{2} b x_f^2} \right)$$

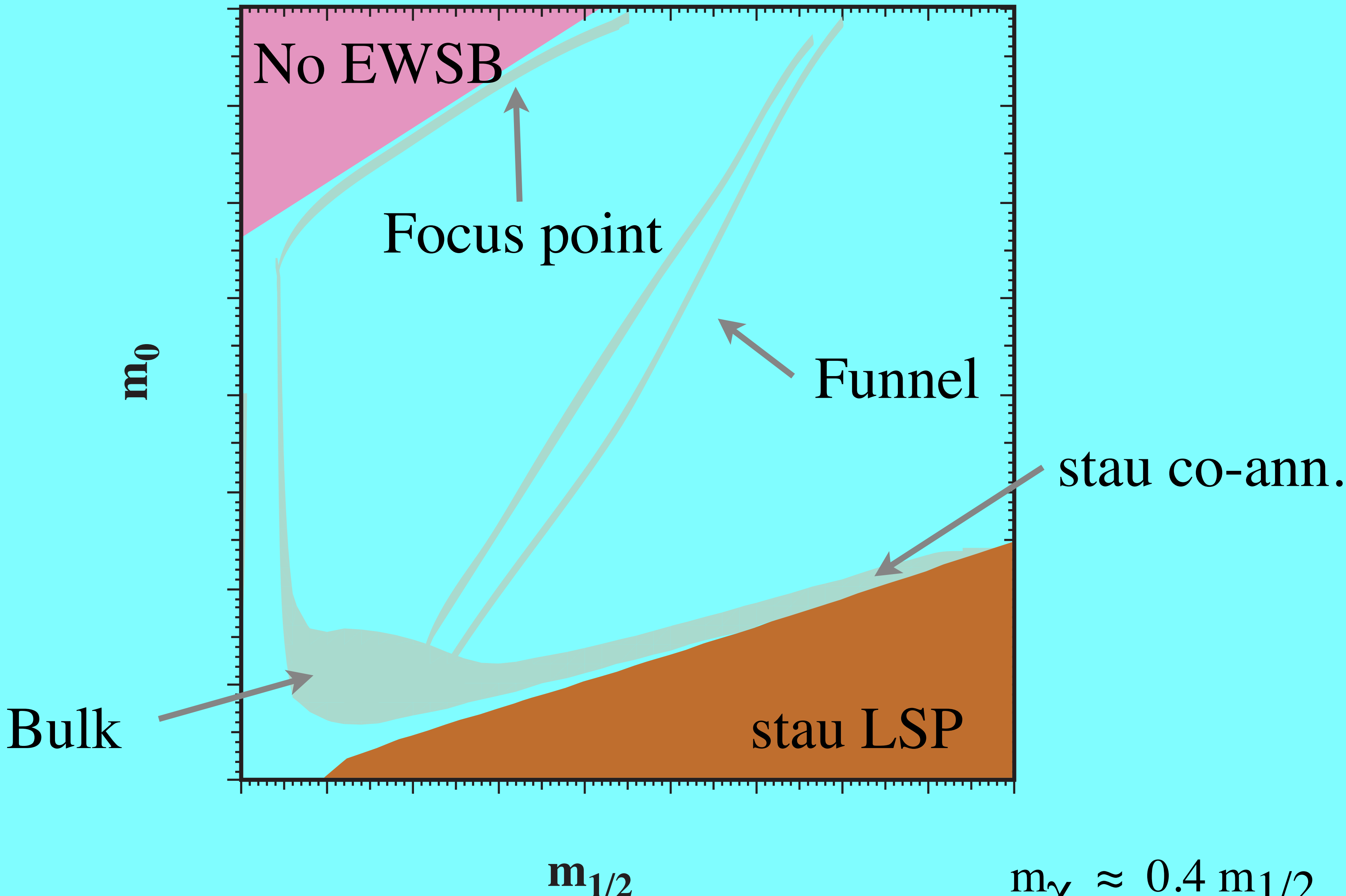
What is (T_χ/T_γ) ?

$$x_f \approx 1/20 \qquad N_f \approx N(m_\chi/20)$$

e.g., for $m_\chi = 100\ GeV$, $\quad T_f \approx 5GeV \quad N_f \approx 345/4$

$$(T_\chi/T_\gamma)^3 = (43/4N_f) \times (4/11)$$

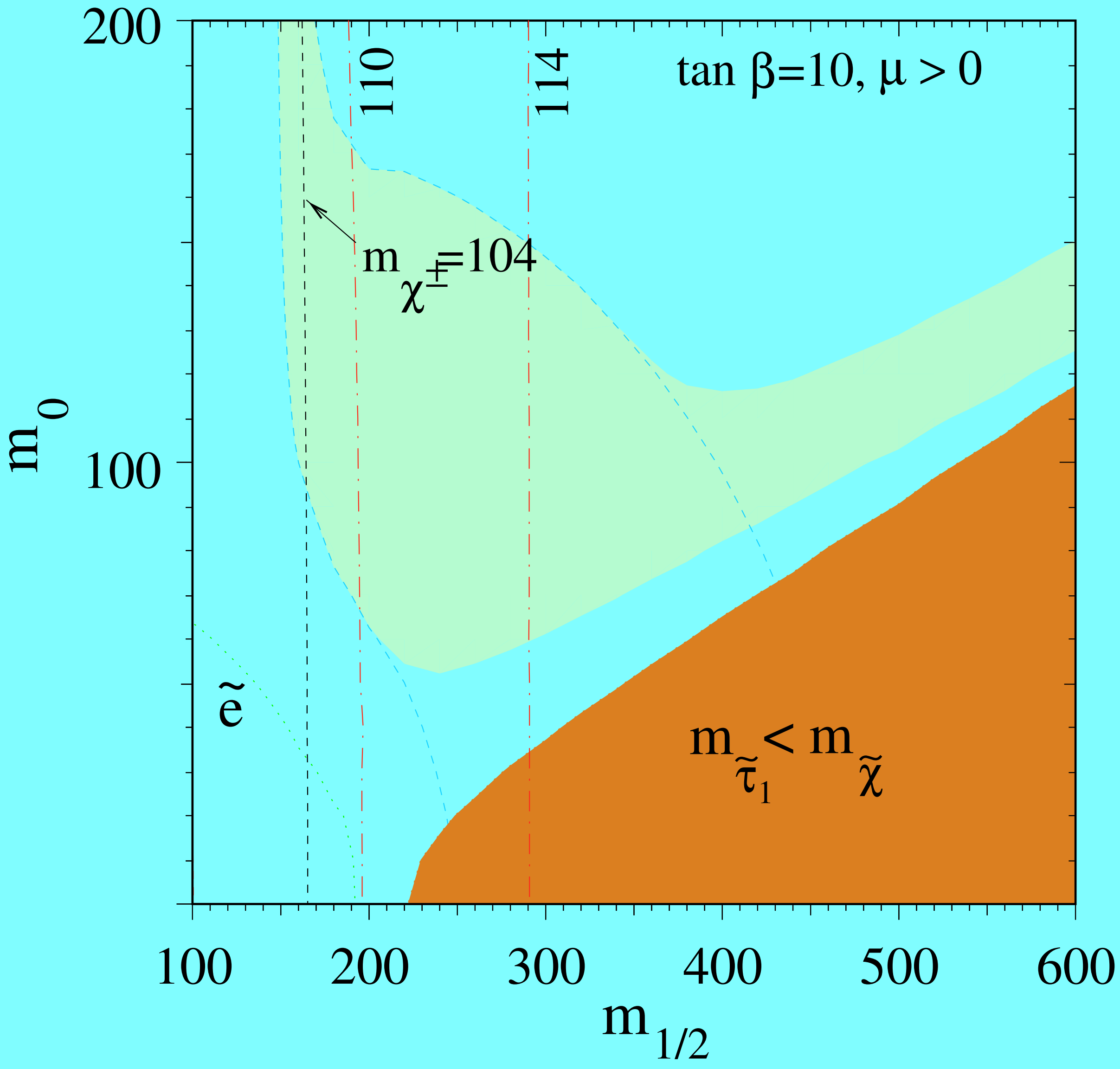
Typical Regions



$m_\chi \approx 0.4\, m_{1/2}$

Coannihilations

Important when stau mass close to neutralino mass



Coannihilations

total number density

$$n \equiv \sum_i n_i \ ,$$

and the effective annihilation cross section as

$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle \equiv \sum_{ij} \frac{n_{0,i} n_{0,j}}{n_0^2} \langle \sigma_{ij} v_{\rm rel} \rangle \ .$$

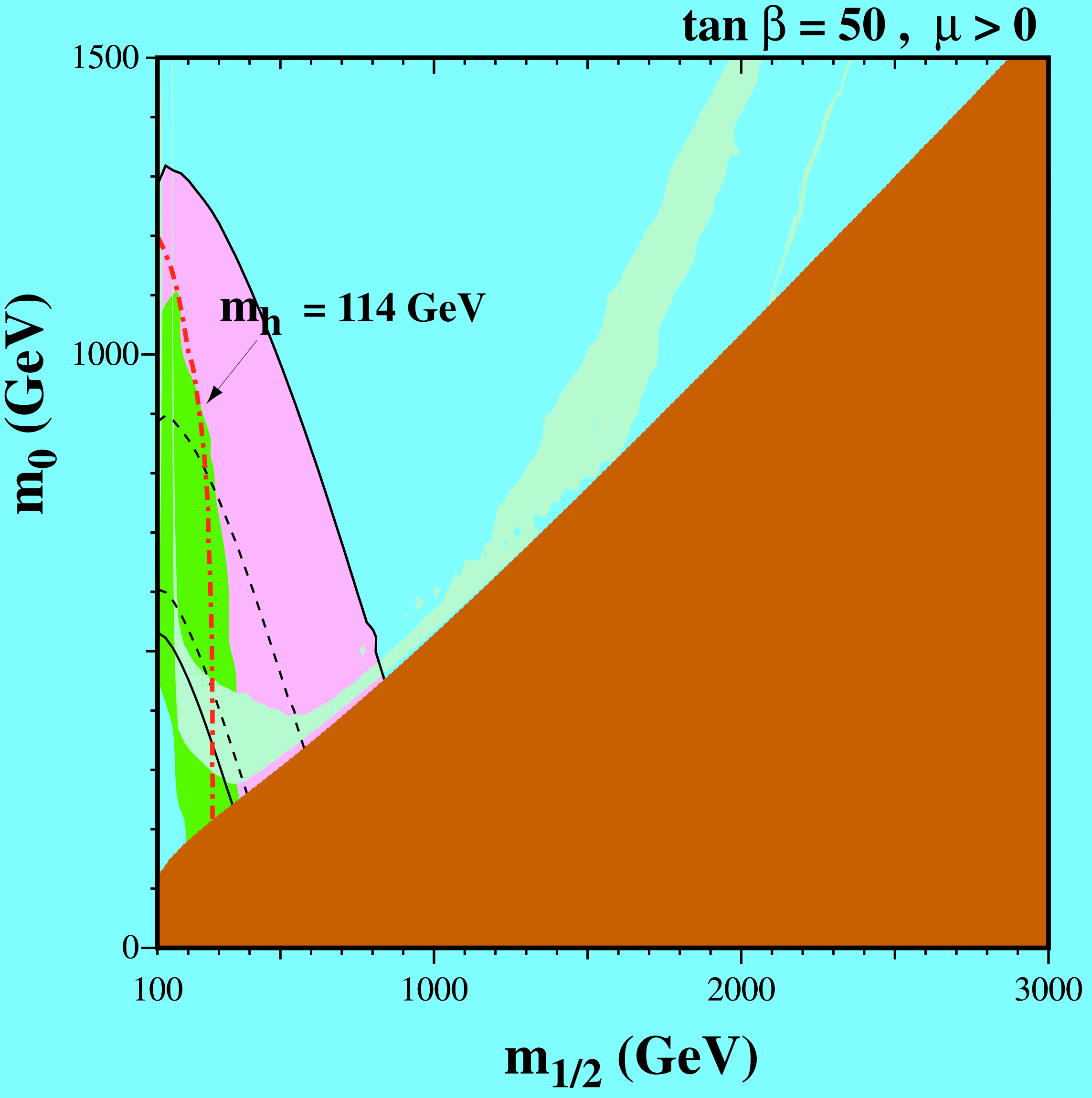
proportional to:

$$g_{\rm eff} \equiv \sum_i g_i (m_i/m_1)^{3/2} e^{-(m_i - m_1)/T}$$

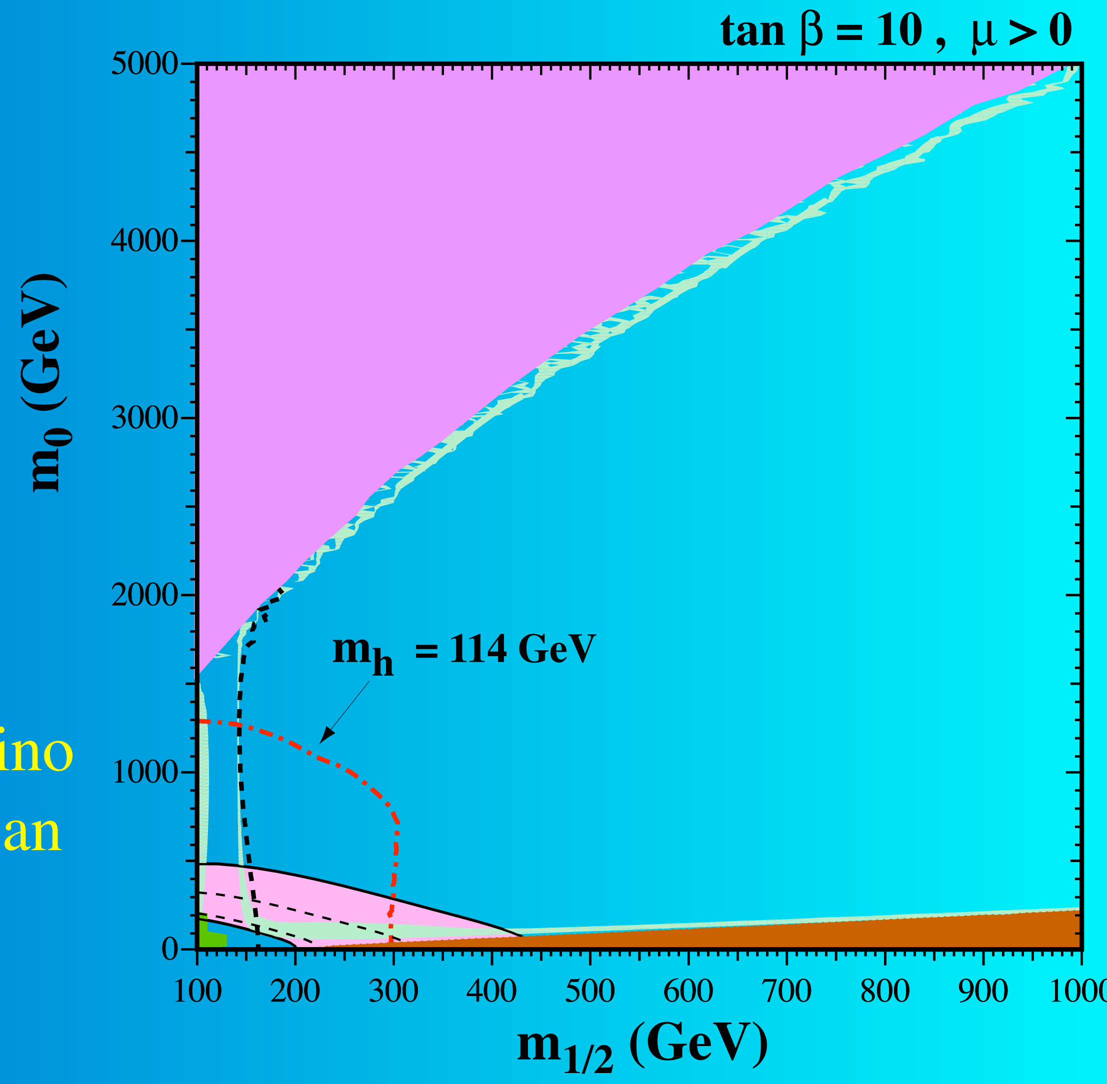
Griest & Seckel

Funnel Regions

Important when heavy Higgs mass is close to double the neutralino mass

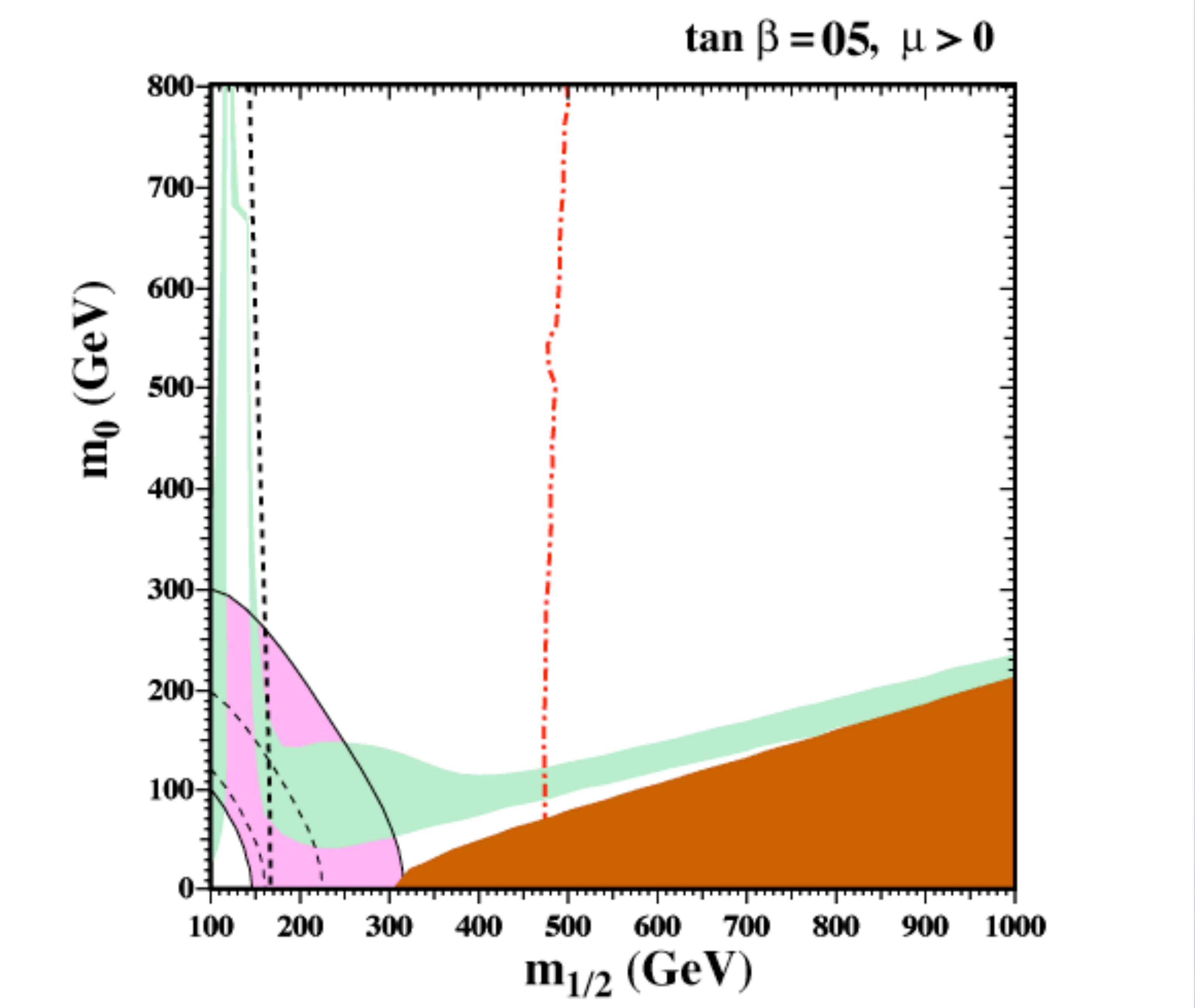


Focus Point Region

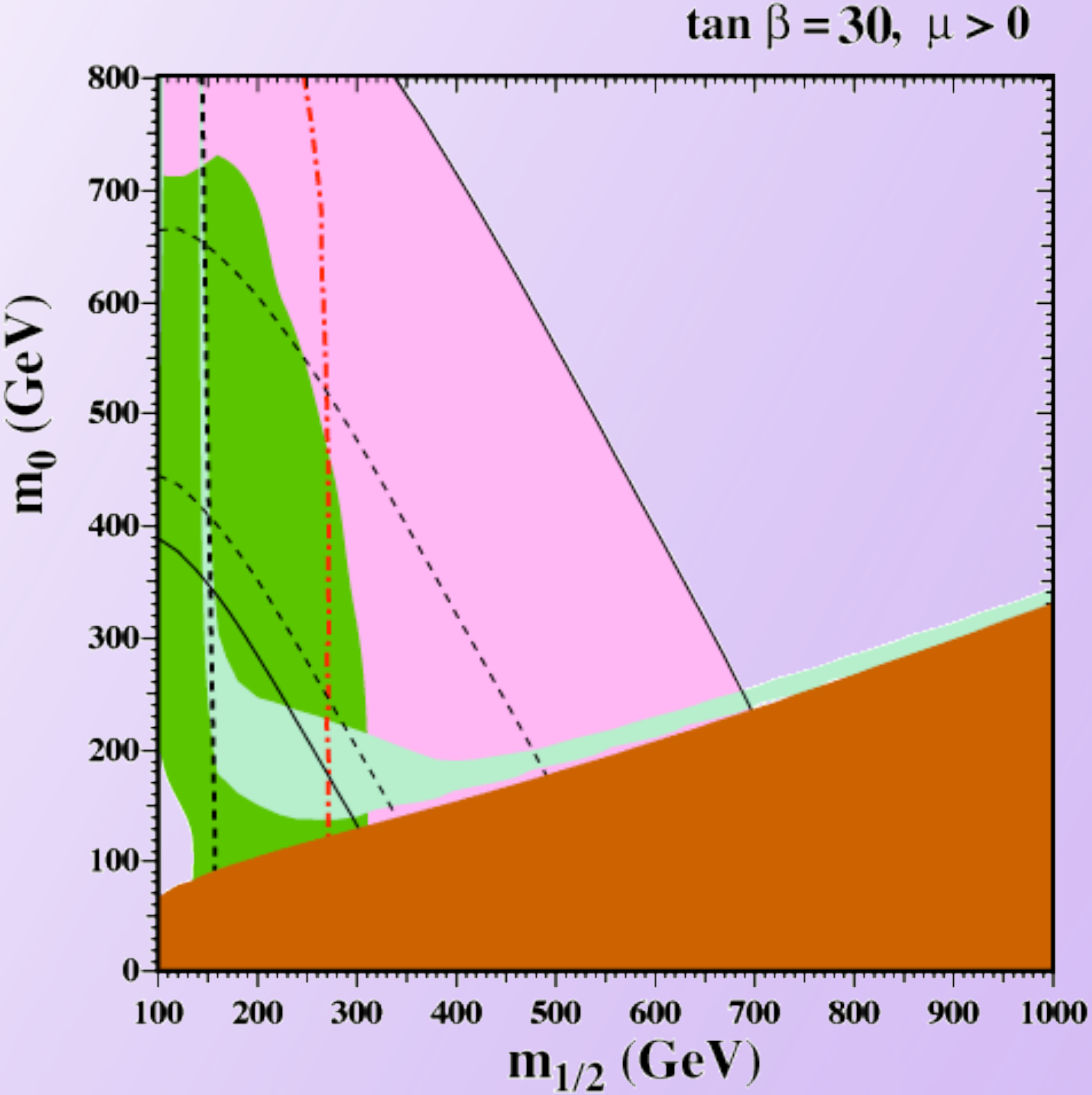


As m_0 gets very large, RGE's force μ to 0, allowing neutralino to become Higgsino like with an acceptable relic density.

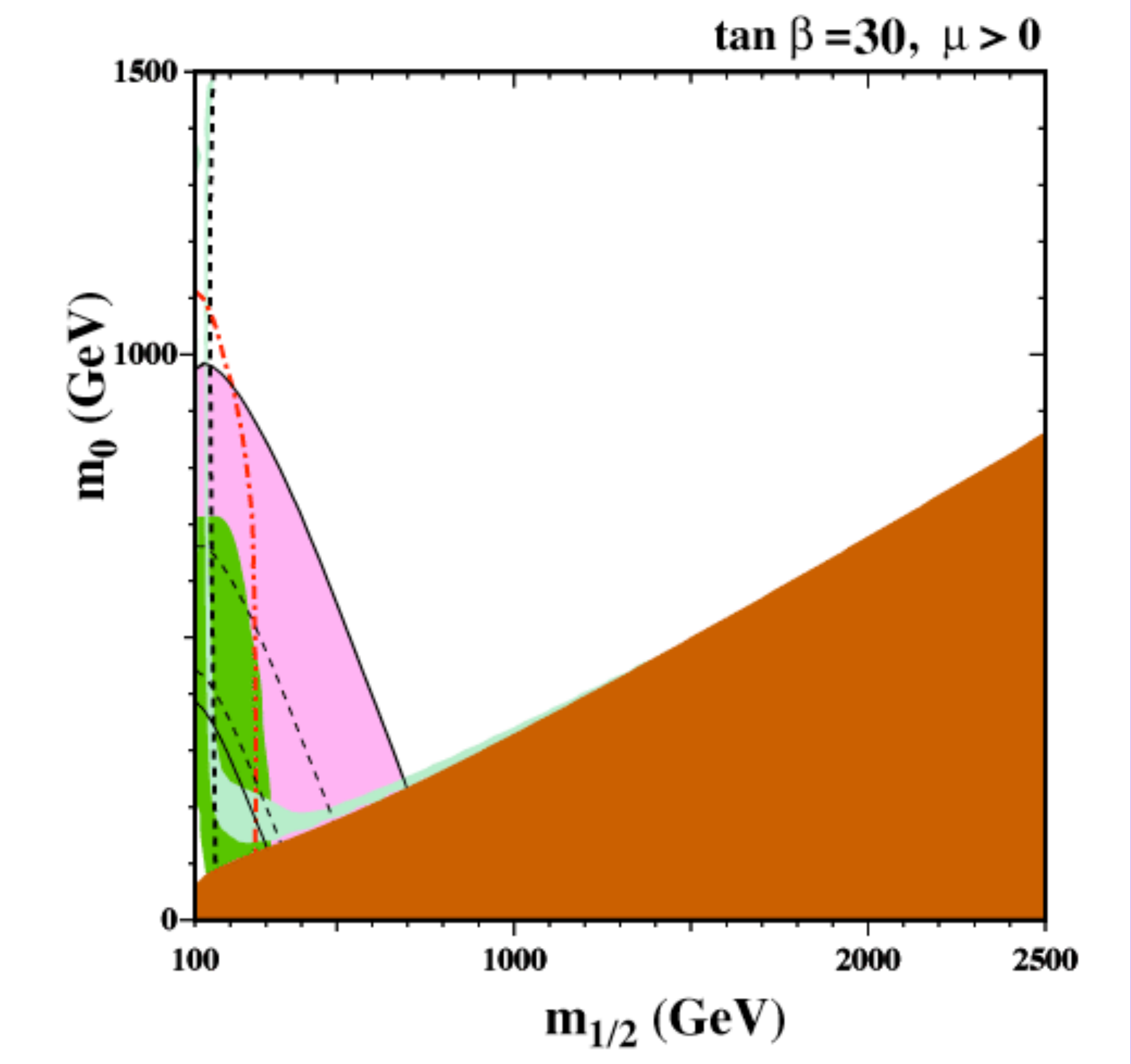
Feng, Matchev, Moroi

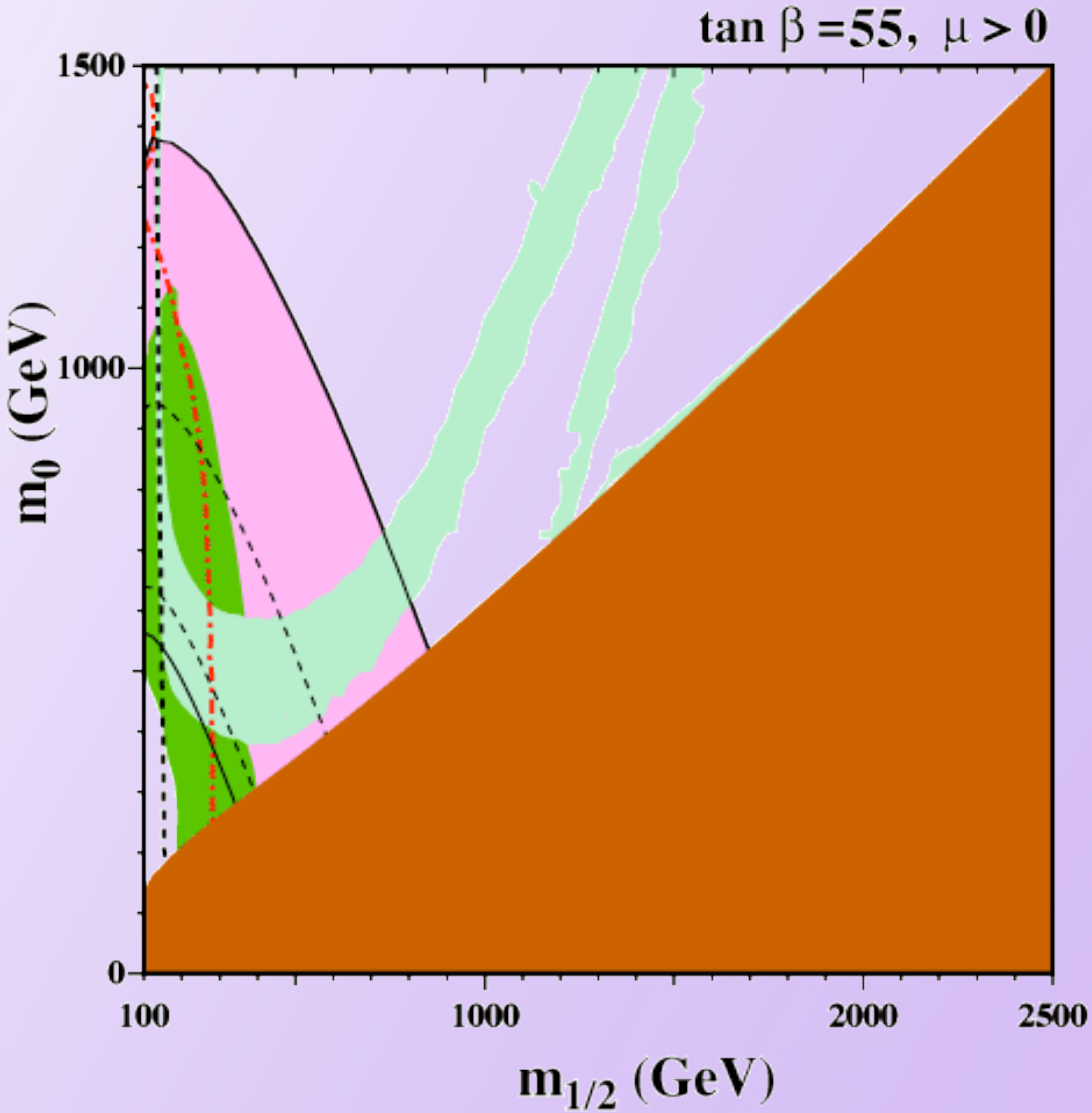


tan β = 05, μ > 0
m_0 (GeV)
m_1/2 (GeV)
0
100
200
300
400
500
600
700
800
100
200
300
400
500
600
700
800
900
1000



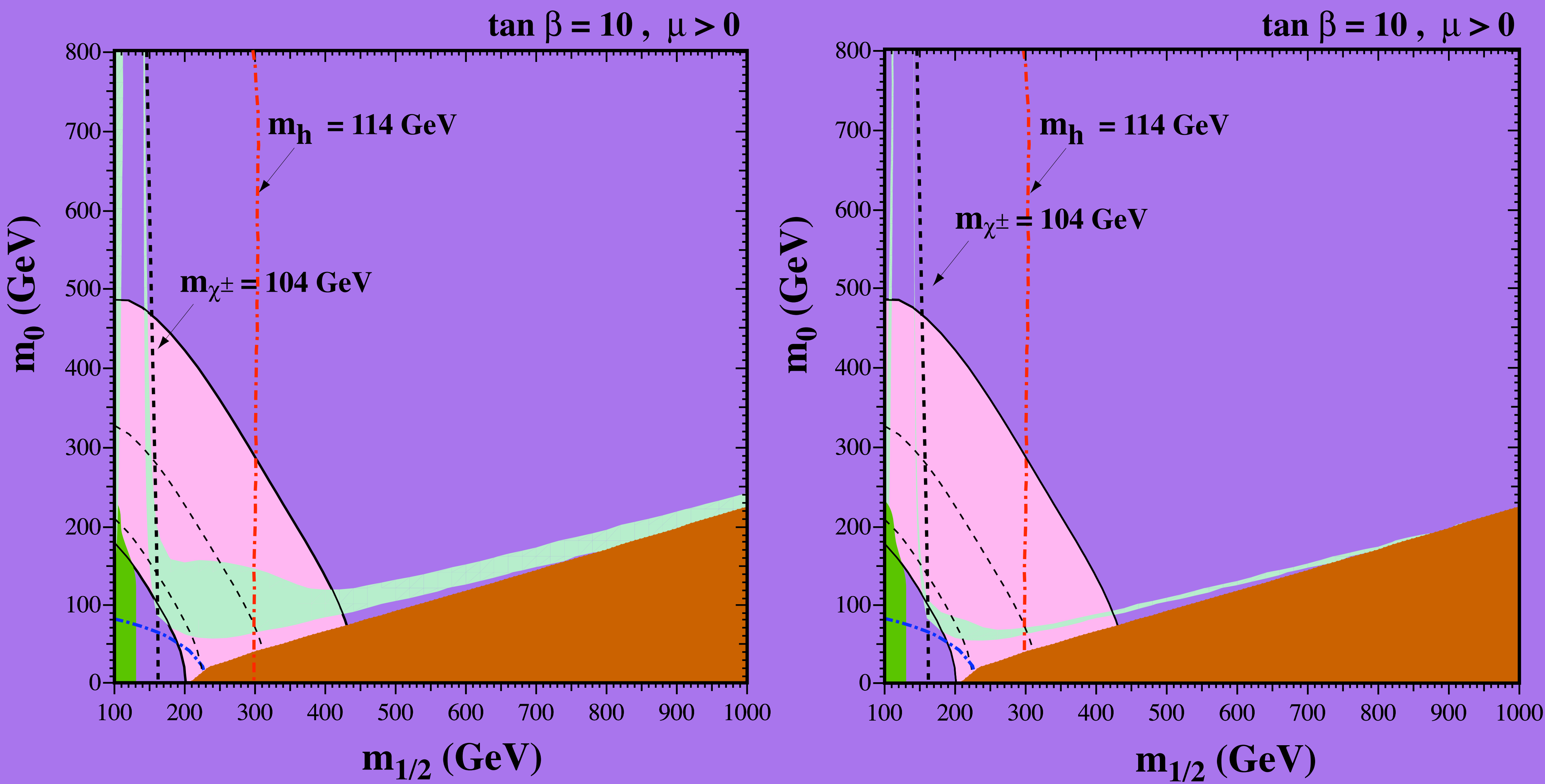
tan β = 30, μ > 0
m0 (GeV)
m1/2 (GeV)
0
100
200
300
400
500
600
700
800
100
200
300
400
500
600
700
800
900
1000


tan β =30, μ > 0
1500
1000
0
m0 (GeV)
100
1000
2000
2500
m1/2 (GeV)



tan β =55, μ > 0
1500
1000
0
m0 (GeV)
100
1000
2000
2500
m1/2 (GeV)

Effect of WMAP Densities

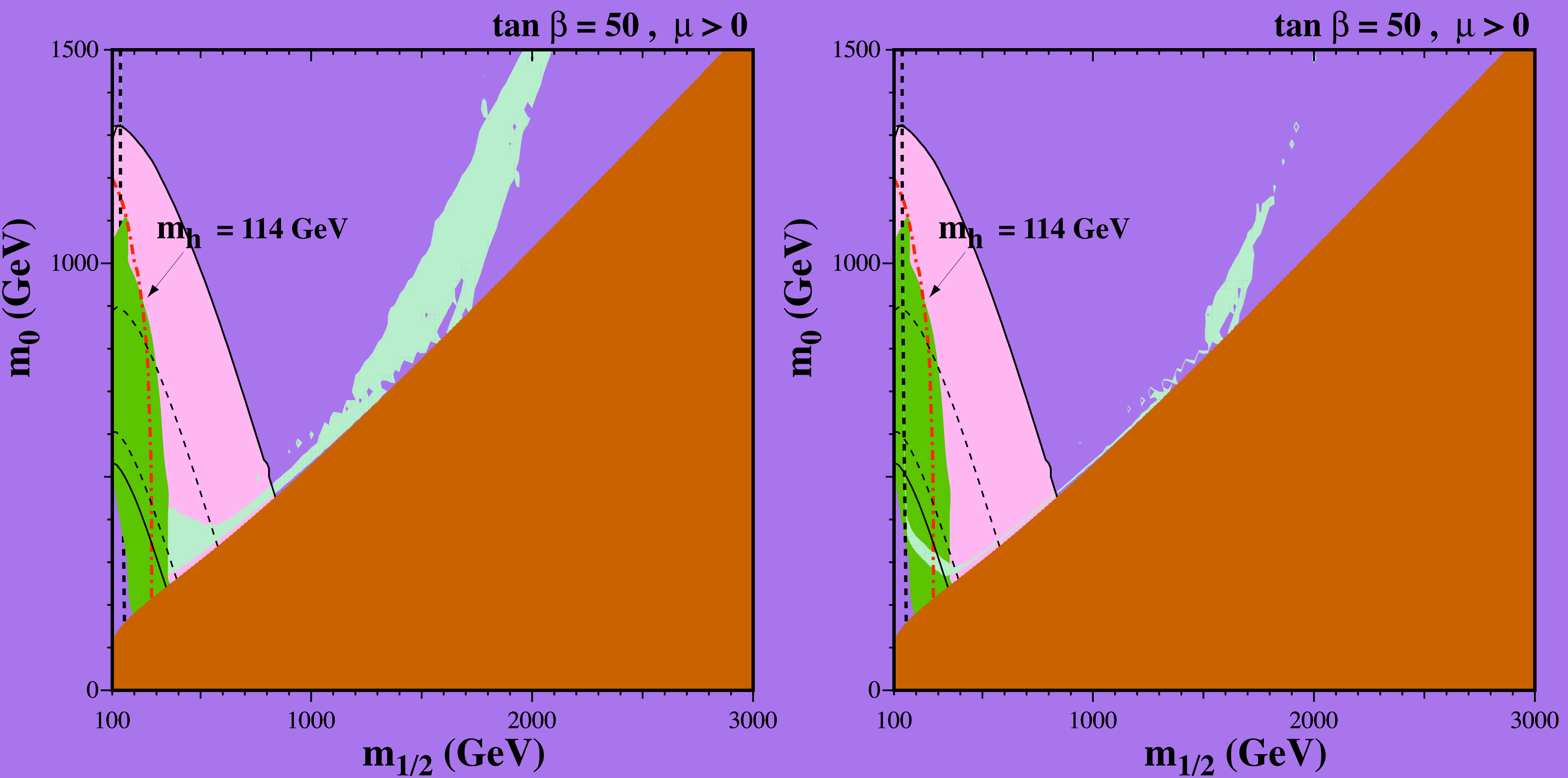


$\Omega h^2 = 0.1 - 0.3$

$\Omega h^2 = 0.09 - 0.13$

Ellis, Olive, Santoso, Spanos

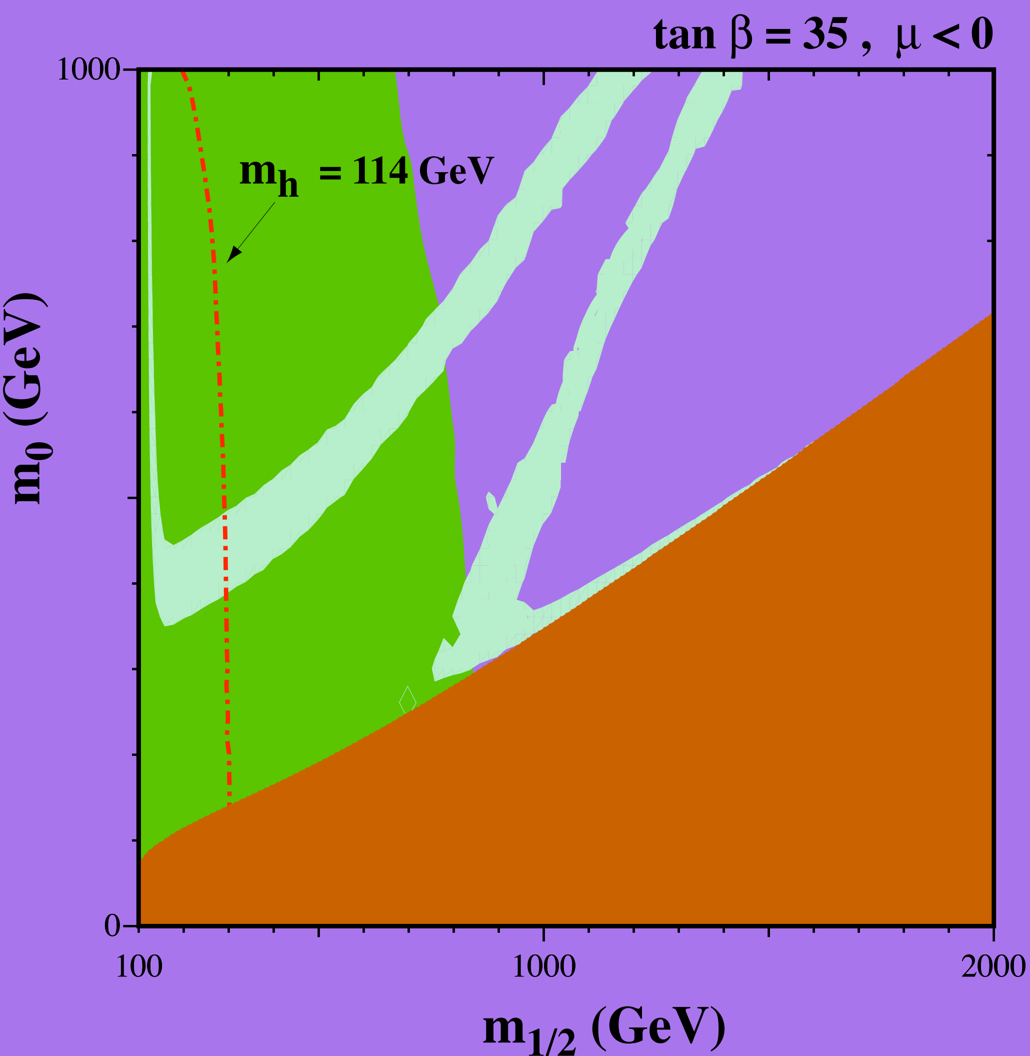
Effect of WMAP Densities



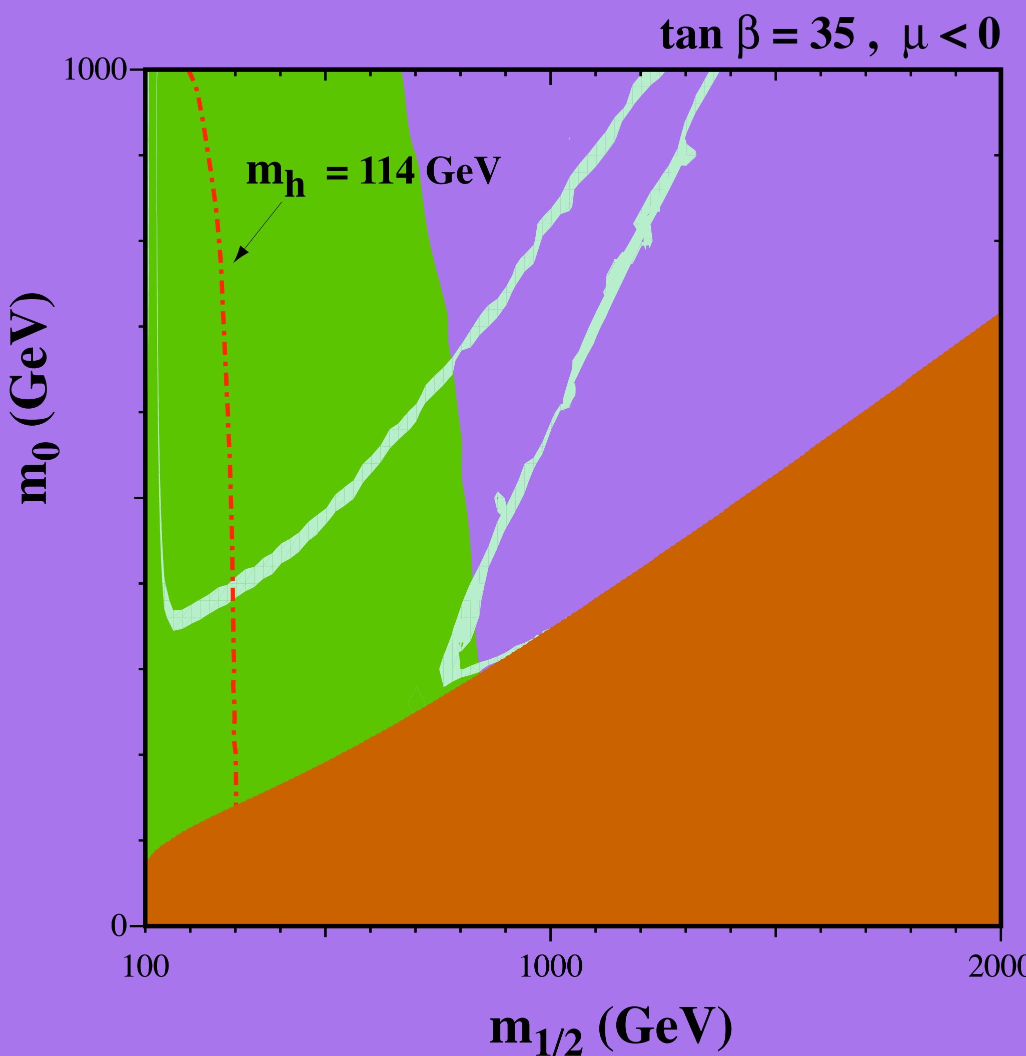
$\Omega h^2 = 0.1 - 0.3$ $\Omega h^2 = 0.09 - 0.13$

Ellis, Olive, Santoso, Spanos

Effect of WMAP Densities



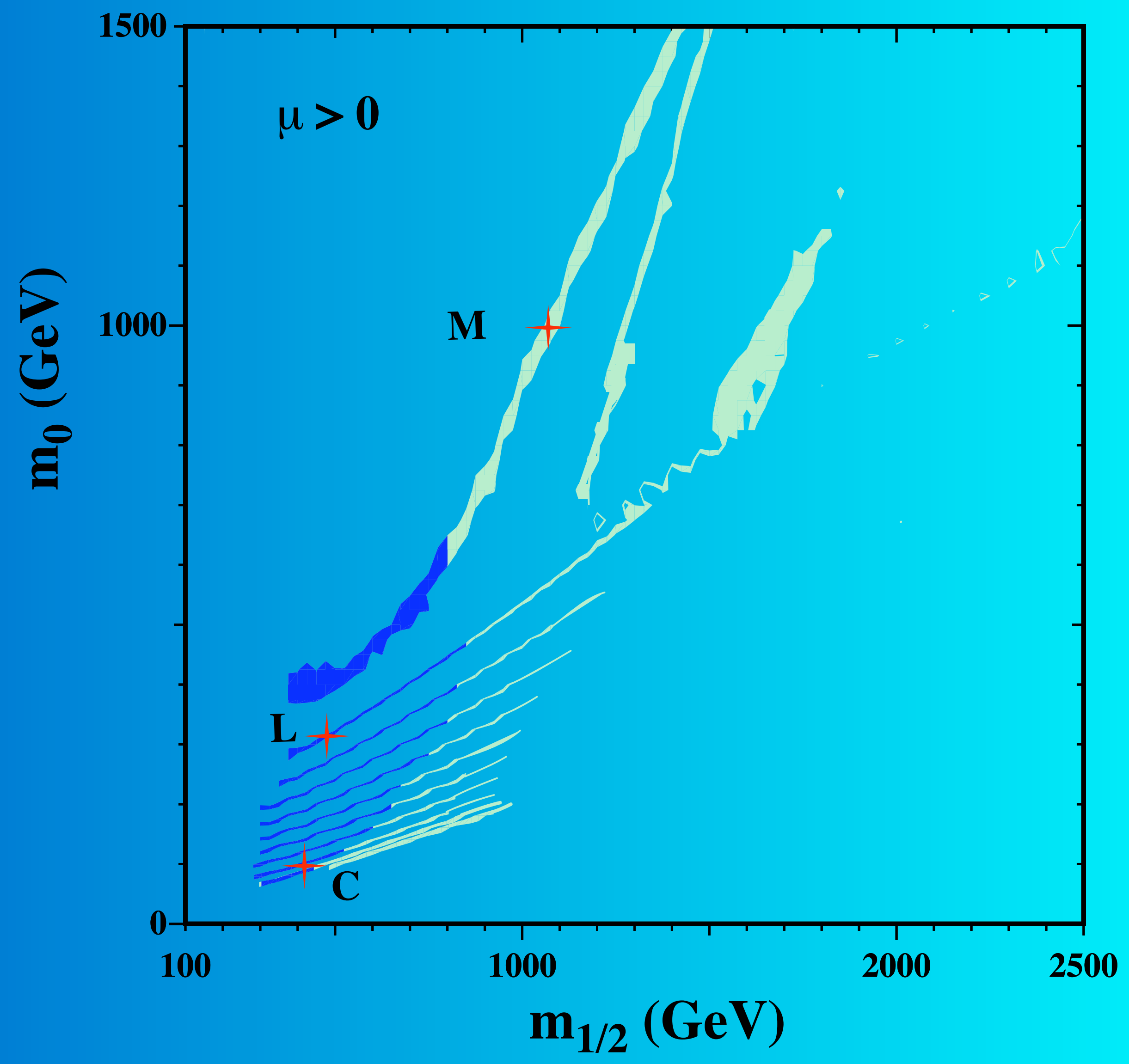
$\Omega h^2 = 0.1 - 0.3$



$\Omega h^2 = 0.09 - 0.13$

Ellis, Olive, Santoso, Spanos

Foliation in tan β



MCMC Analysis

Observable
$\Delta\alpha_{\mathrm{had}}^{(5)}(m_{\mathrm{Z}})$
m_{Z} $[\mathrm{GeV}/c^2]$
Γ_{Z} $[\mathrm{GeV}/c^2]$
σ_{had}^0 [nb]
R_l
$A_{\mathrm{fb}}(\ell)$
$A_\ell(P_\tau)$
R_{b}
R_{c}
$A_{\mathrm{fb}}(\mathrm{b})$
$A_{\mathrm{fb}}(\mathrm{c})$
A_{b}
A_{c}
$A_\ell(\mathrm{SLD})$
$\sin^2\theta_{\mathrm{w}}^\ell(Q_{\mathrm{fb}})$

Observable
m_{W} $[\mathrm{GeV}/c^2]$
$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$
m_{h} $[\mathrm{GeV}/c^2]$
$\mathrm{BR}_{\mathrm{b}\to\mathrm{s}\gamma}^{\mathrm{exp}}/\mathrm{BR}_{\mathrm{b}\to\mathrm{s}\gamma}^{\mathrm{SM}}$
m_{t} $[\mathrm{GeV}/c^2]$
$\Omega_{\mathrm{CDM}}h^2$
$\mathrm{BR}(B_s\to\mu^+\mu^-)$
$\mathrm{BR}_{\mathrm{B}\to\tau\nu}^{\mathrm{exp}}/\mathrm{BR}_{\mathrm{B}\to\tau\nu}^{\mathrm{SM}}$
$\mathrm{BR}_{B_d\to\ell\ell}^{\mathrm{exp}}/\mathrm{BR}_{B_d\to\ell\ell}^{\mathrm{SM}}$
$\mathrm{BR}_{B\to X_s\ell\ell}^{\mathrm{exp}}/\mathrm{BR}_{B\to X_s\ell\ell}^{\mathrm{SM}}$
$\mathrm{BR}_{K\to\mu\nu}^{\mathrm{exp}}/\mathrm{BR}_{K\to\mu\nu}^{\mathrm{SM}}$
$\mathrm{BR}_{K\to\pi\nu\bar{\nu}}^{\mathrm{exp}}/\mathrm{BR}_{K\to\pi\nu\bar{\nu}}^{\mathrm{SM}}$
$\Delta m_s^{\mathrm{exp}}/\Delta m_s^{\mathrm{SM}}$
$\frac{(\Delta m_s^{\mathrm{exp}}/\Delta m_s^{\mathrm{SM}})}{(\Delta m_d^{\mathrm{exp}}/\Delta m_d^{\mathrm{SM}})}$
$\Delta m_K^{\mathrm{exp}}/\Delta m_K^{\mathrm{SM}}$

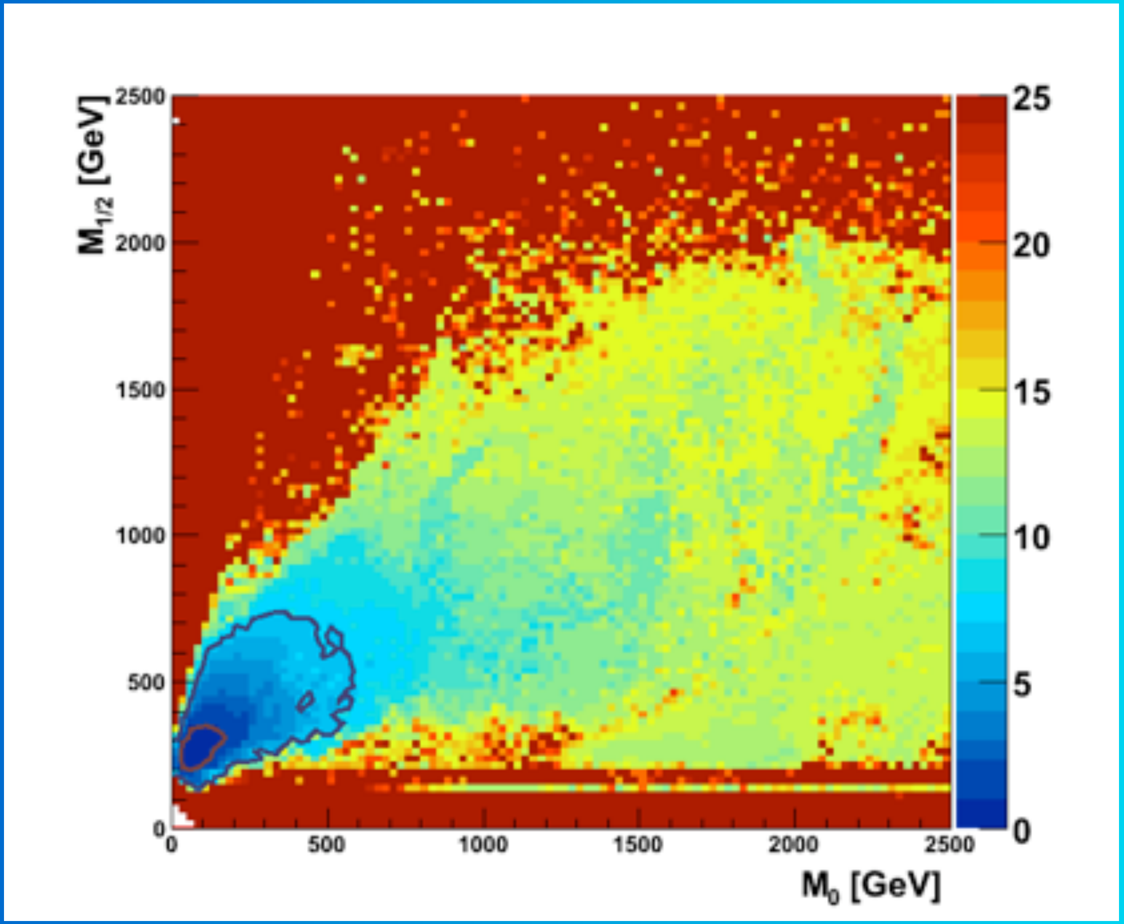
Long list of observables to constrain CMSSM parameter space

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Paradisi, Ronga, Weiglein

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i \frac{(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

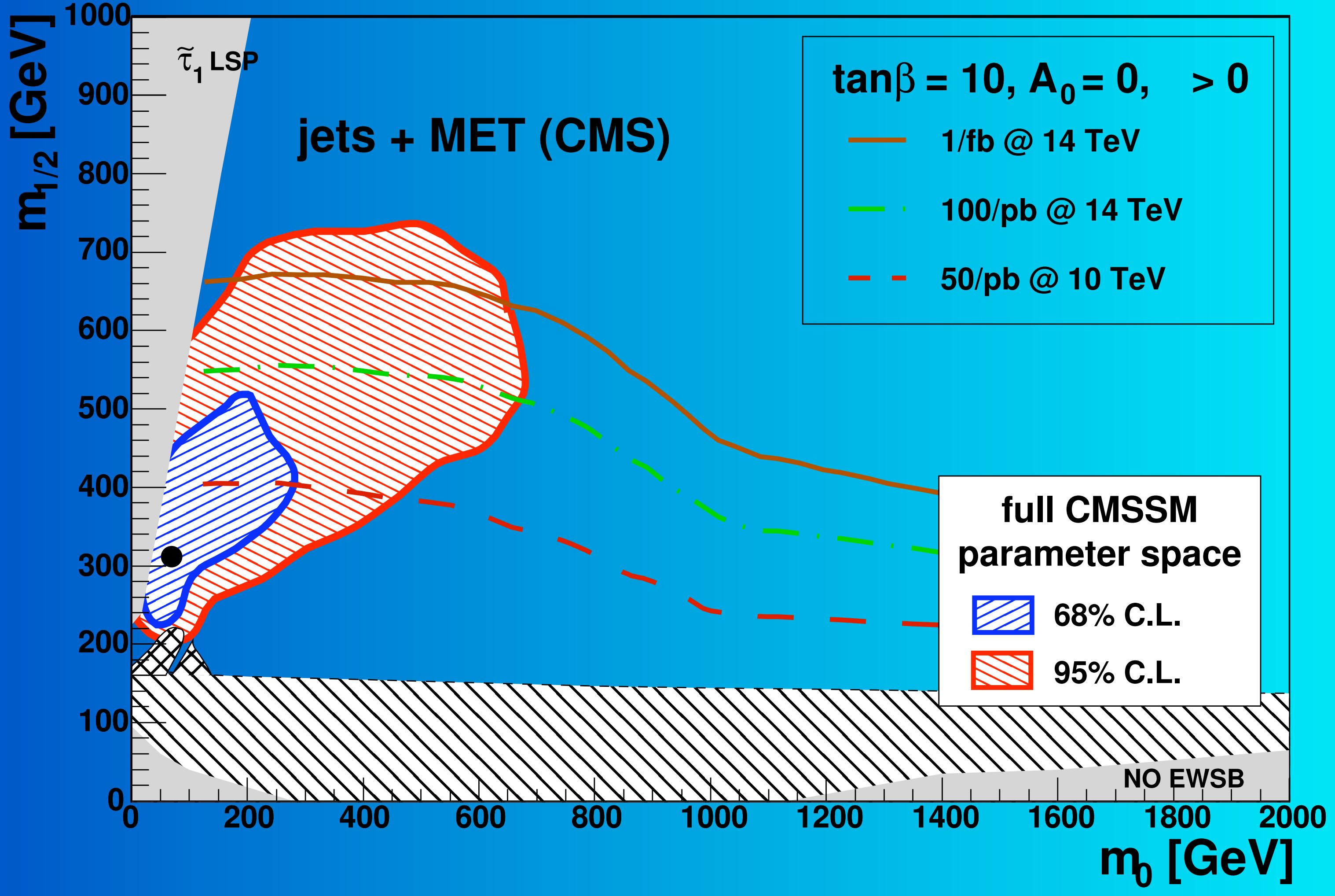
See also: Balz and Gondolo; Allanach, Lester, and Weber; deAustri, Trotta, and Roszkowski

Result for CMSSM



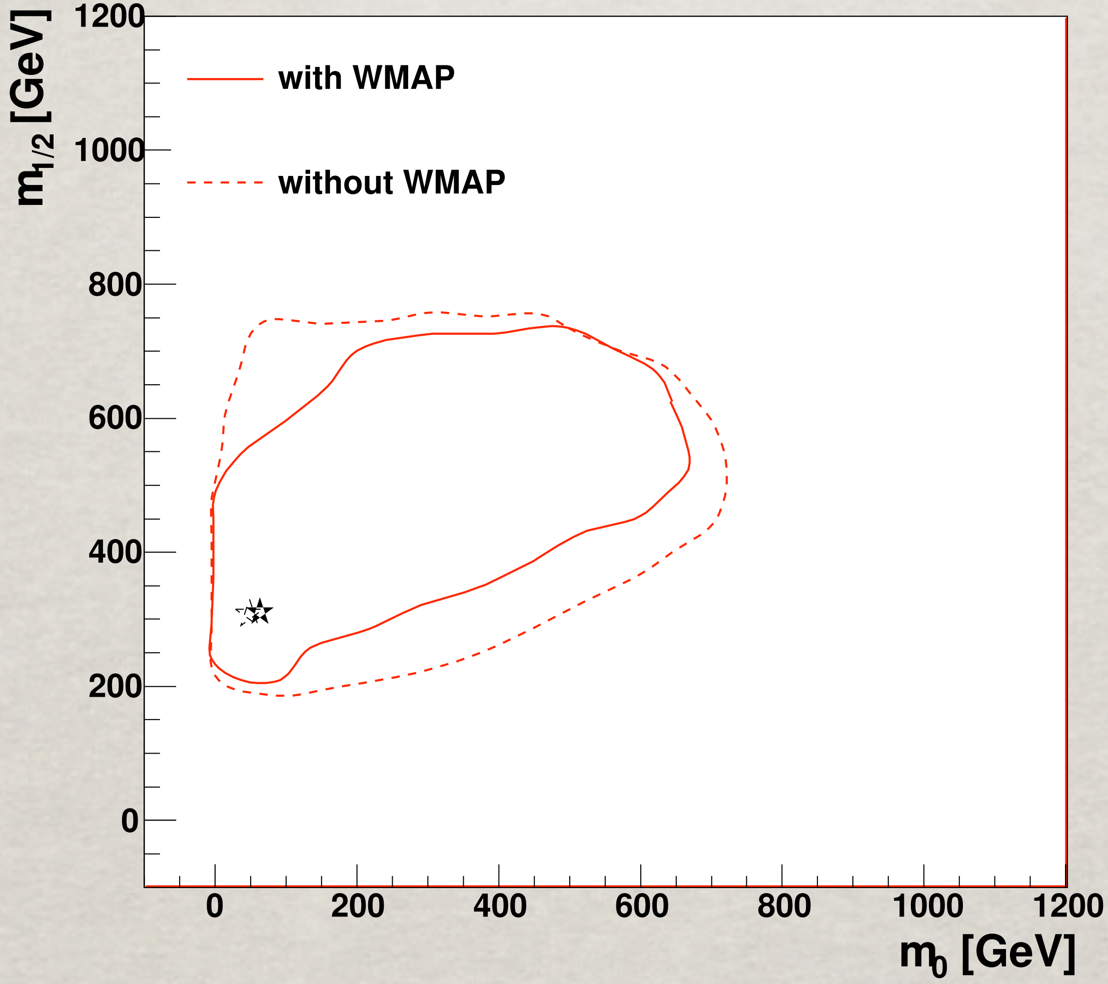
Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer,
Isidori, Olive, Paradisi, Ronga, Weiglein

LHC reach vs CMSSM



Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer,
Isidori, Olive, Paradisi, Ronga, Weiglein

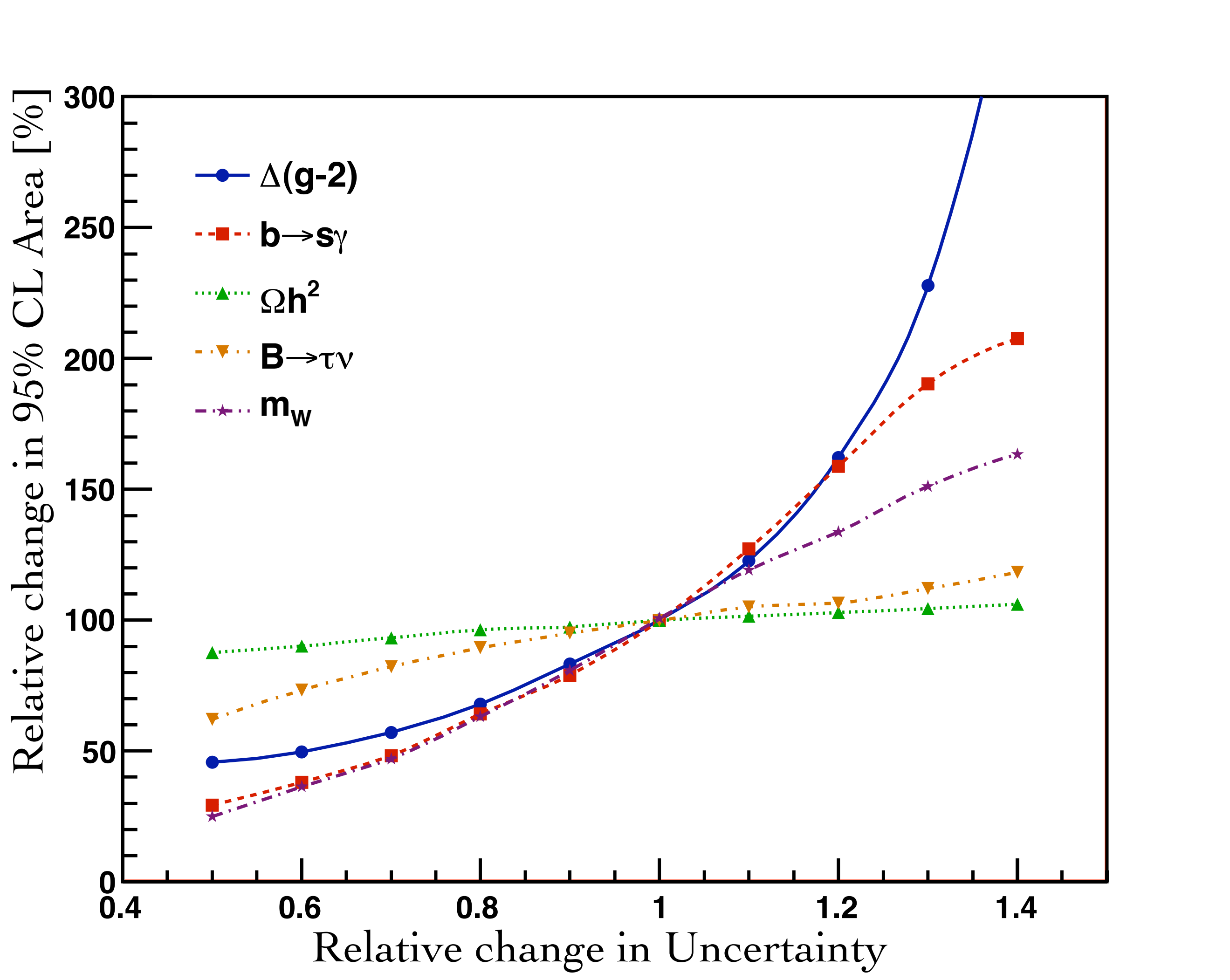
Impact of CDM



Recall foliation in tan β

Buchmueller et al.

Sensitivity to uncertainties

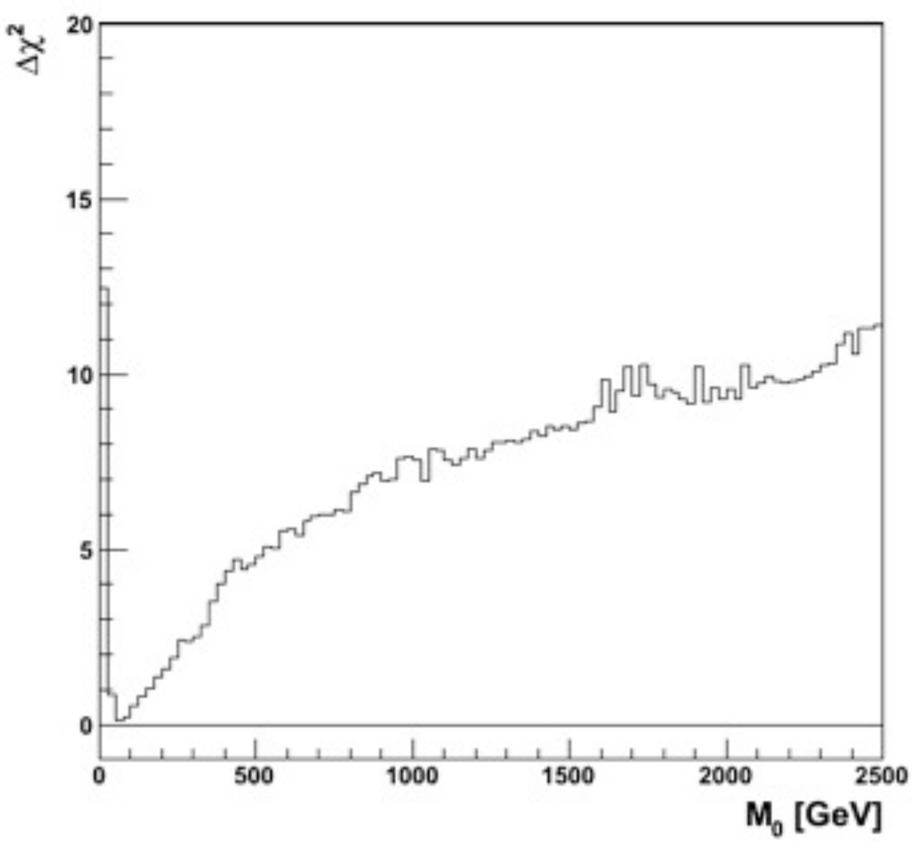


Buchmueller et al.

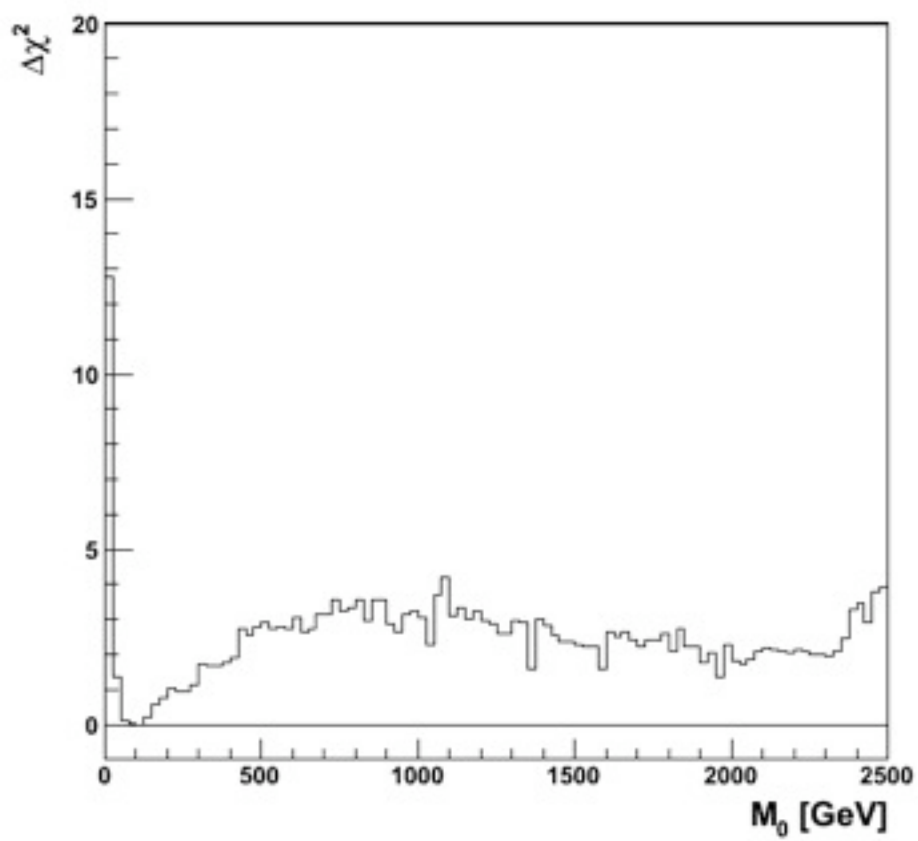
Where is the FP?

$\Delta\chi^2$ vs m_0

With g-2



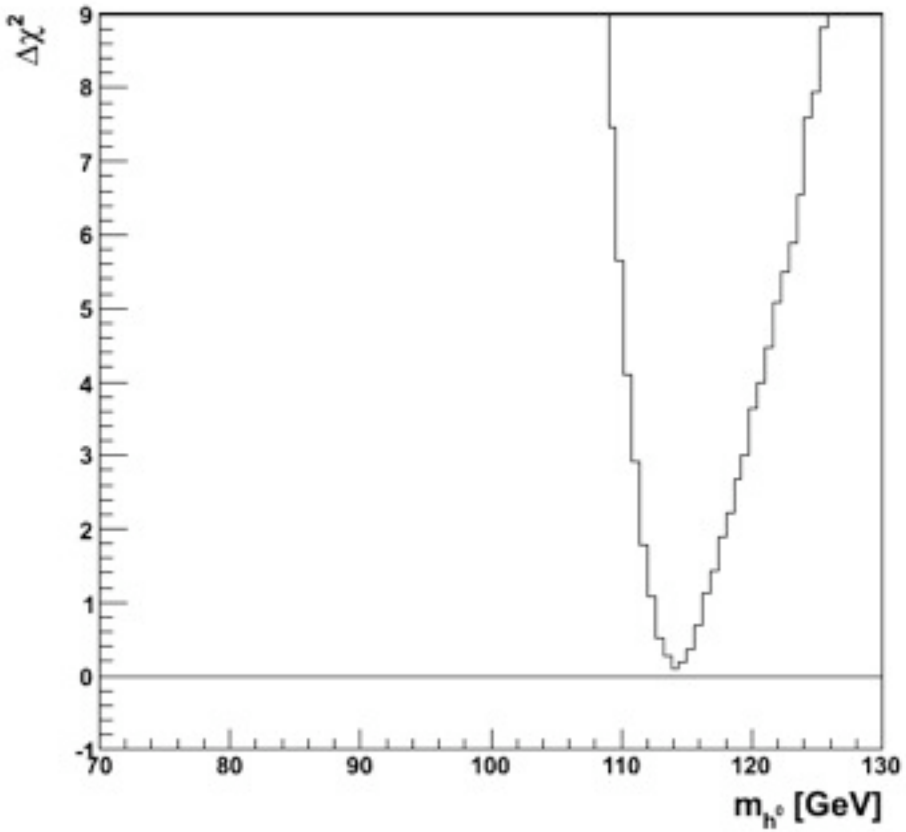
Without g-2



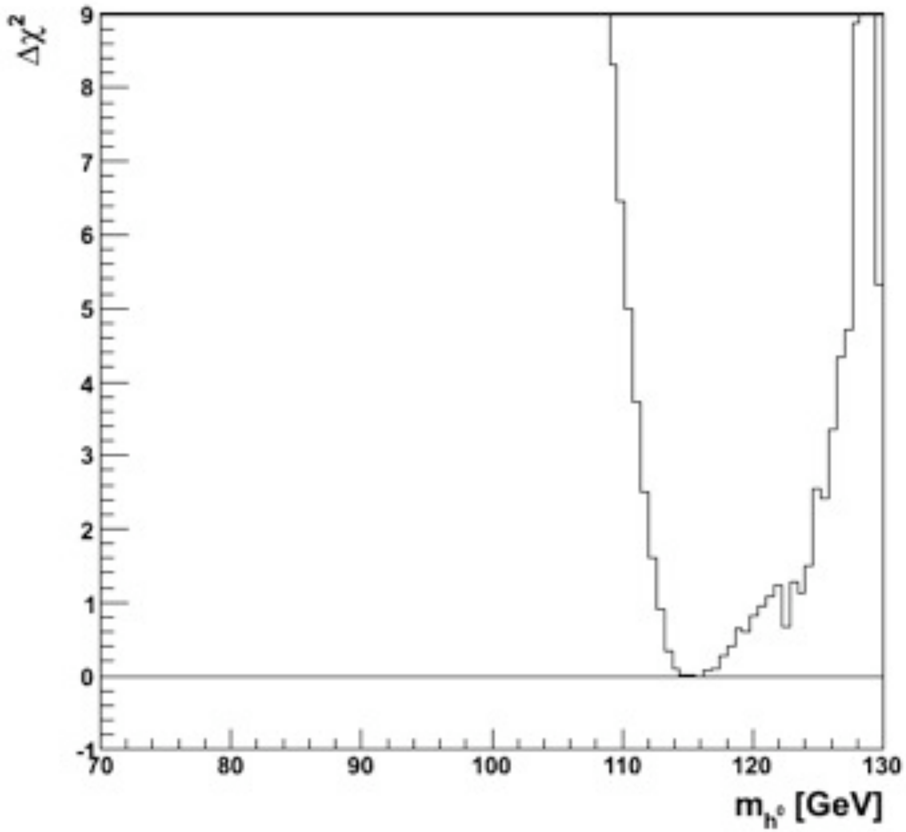
Buchmueller et al.

Δχ² vs m_h

With g-2



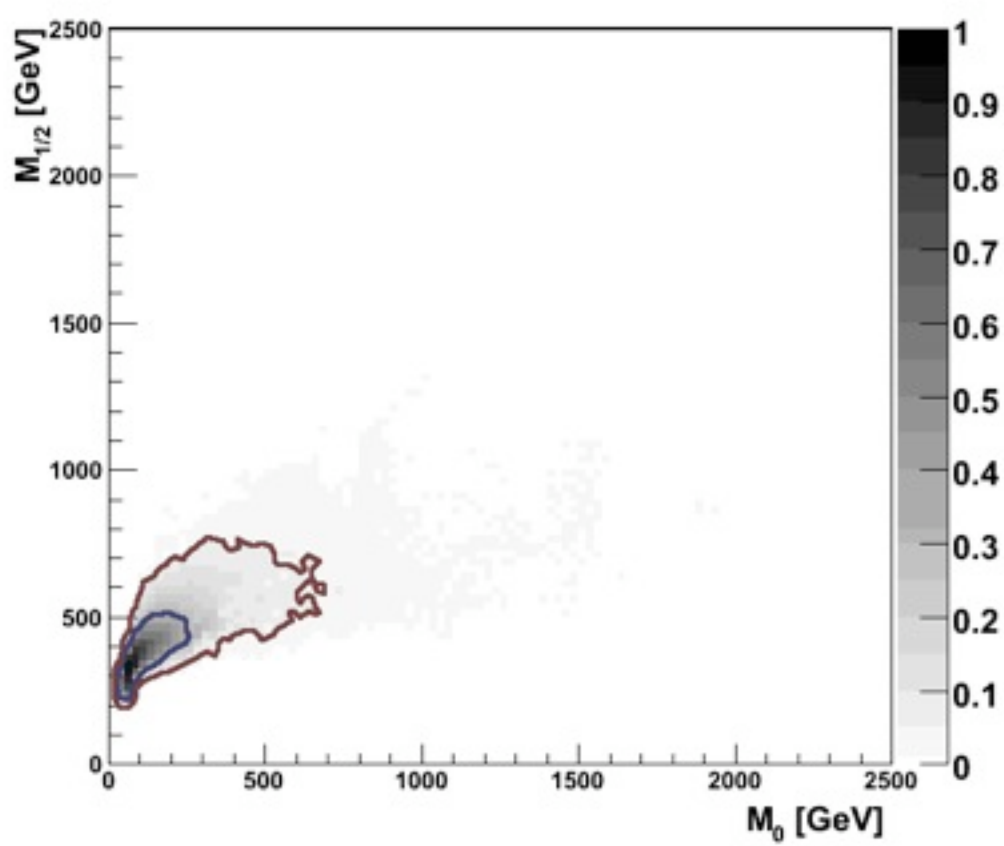
Without g-2



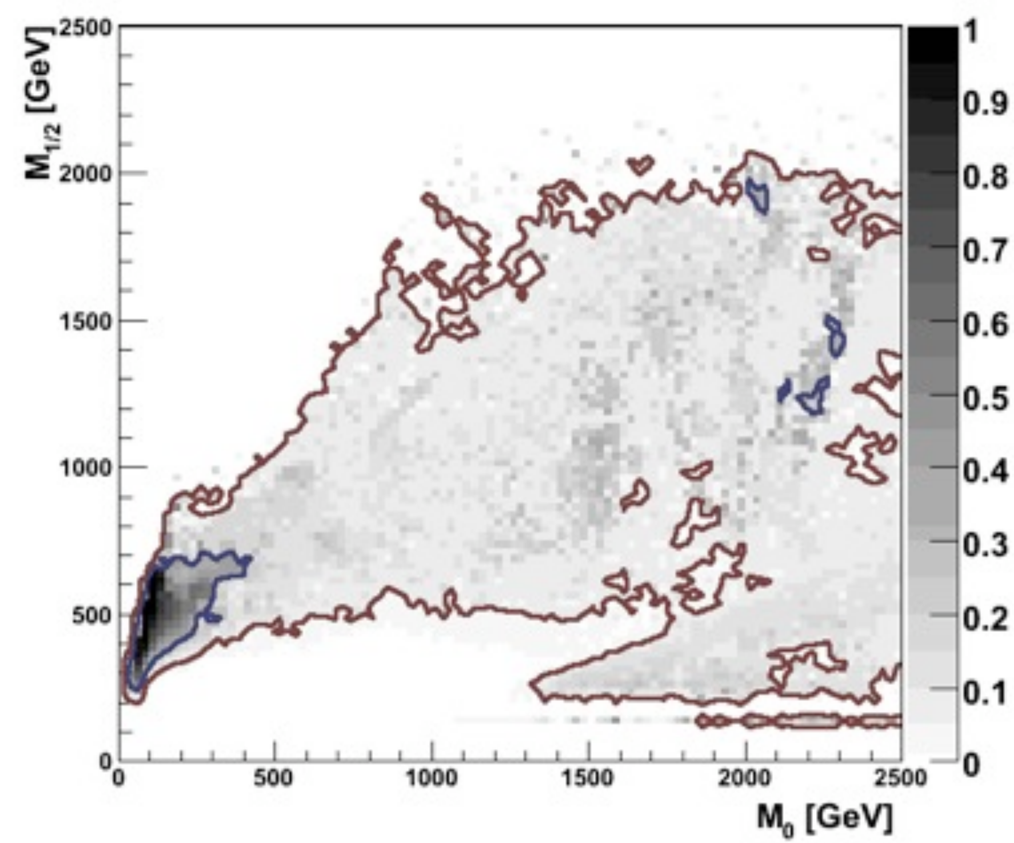
Buchmueller et al.

The CMSSM with and with g-2

With g-2



Without g-2



Buchmueller et al.

Effective Four Fermion Lagrangian

$$L = \bar{\chi}\,\gamma^{\mu}\gamma^{5}\chi\,\bar{q}_i\,\gamma^{\mu}(\alpha_{1i} + \alpha_{2i}\gamma^{5})\,q_i$$

$$+ \quad \alpha_{3i}\,\bar{\chi}\,\chi\,\bar{q}_i\,q_i + \alpha_{4i}\,\bar{\chi}\,\gamma^{5}\chi\,\bar{q}_i\,\gamma^{5}q_i$$

$$+ \quad \alpha_{5i}\,\bar{\chi}\,\chi\,\bar{q}_i\,\gamma^{5}q_i + \alpha_{6i}\,\bar{\chi}\,\gamma^{5}\chi\,\bar{q}_i\,q_i$$

The terms involving α_{1i}, α_{4i}, α_{5i}, and α_{6i} lead to velocity dependent elastic cross sections.

Remaining terms are:

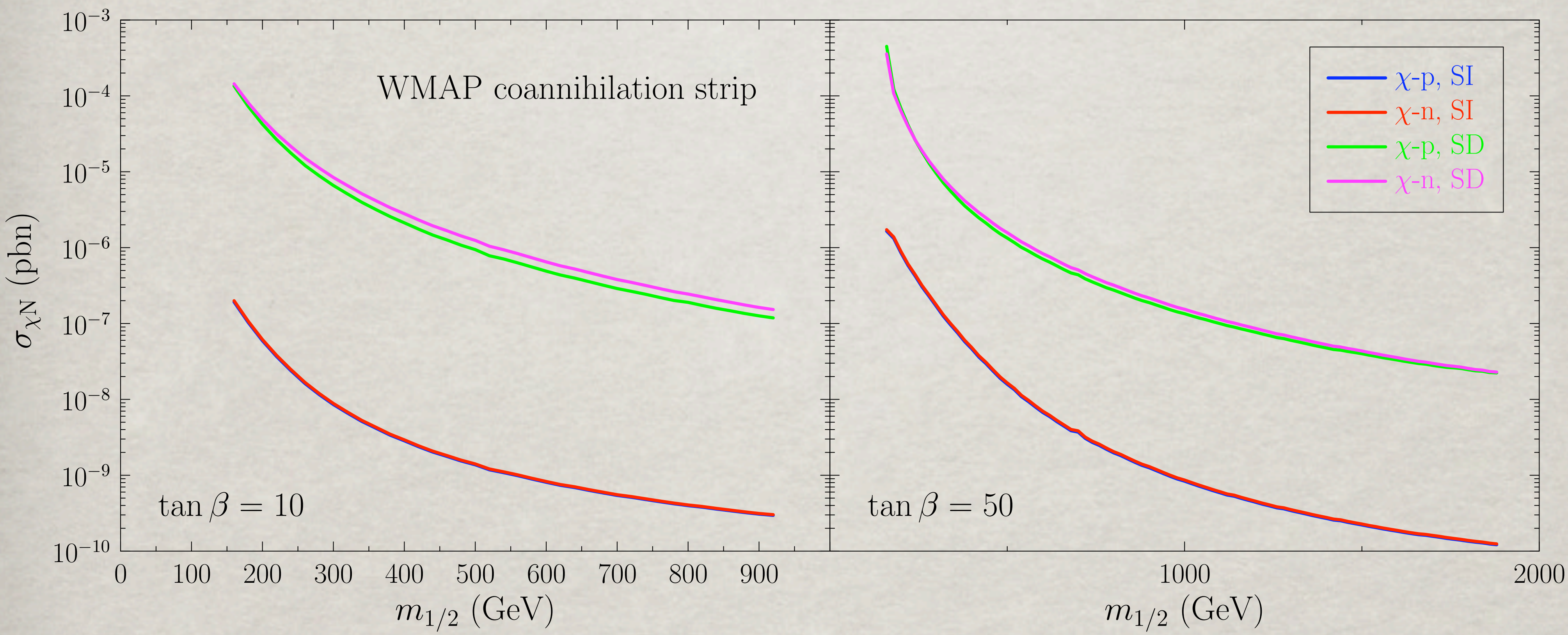
the spin dependent coefficient

$$\alpha_{2i}$$

and scalar coefficient

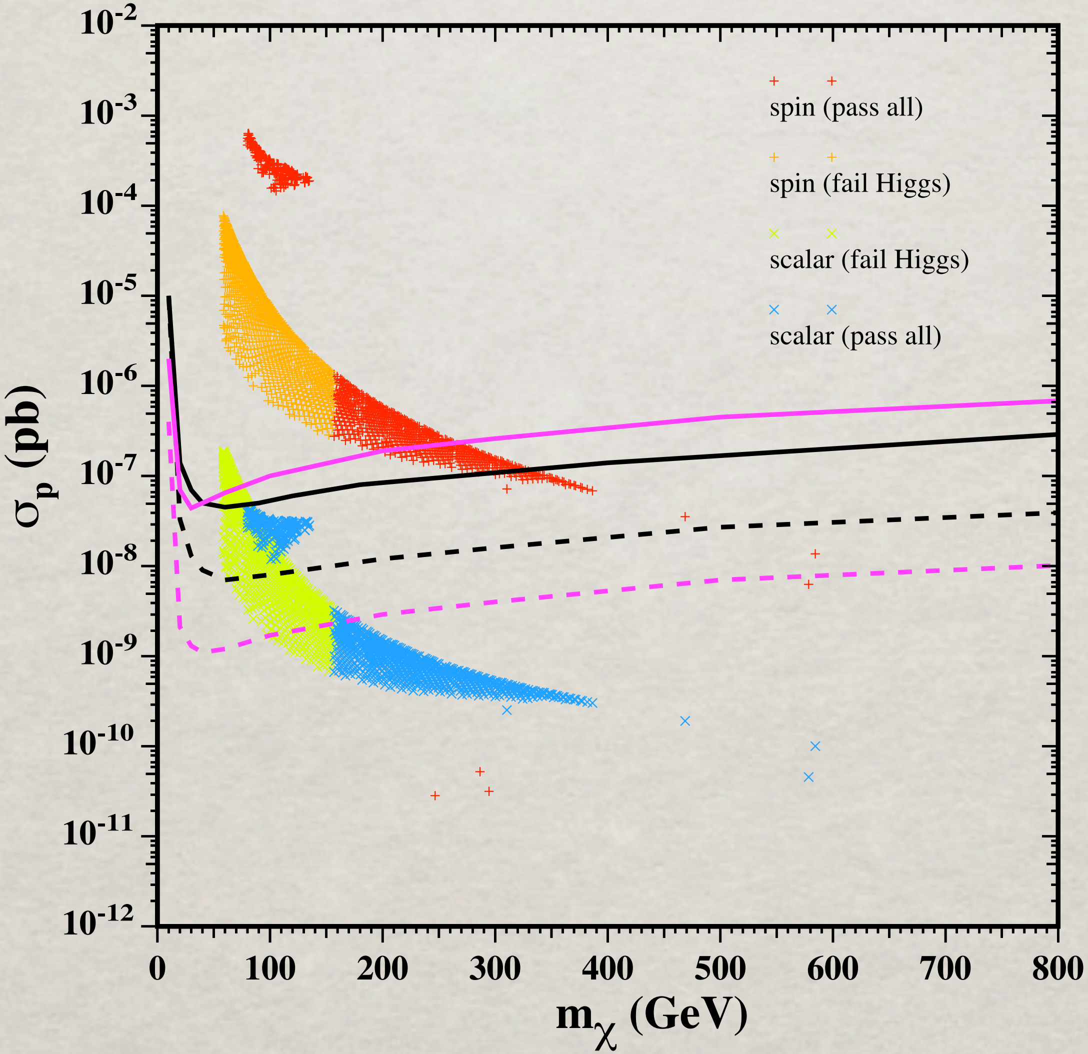
$$\alpha_{3i}$$

Direct Detection in the CMSSM



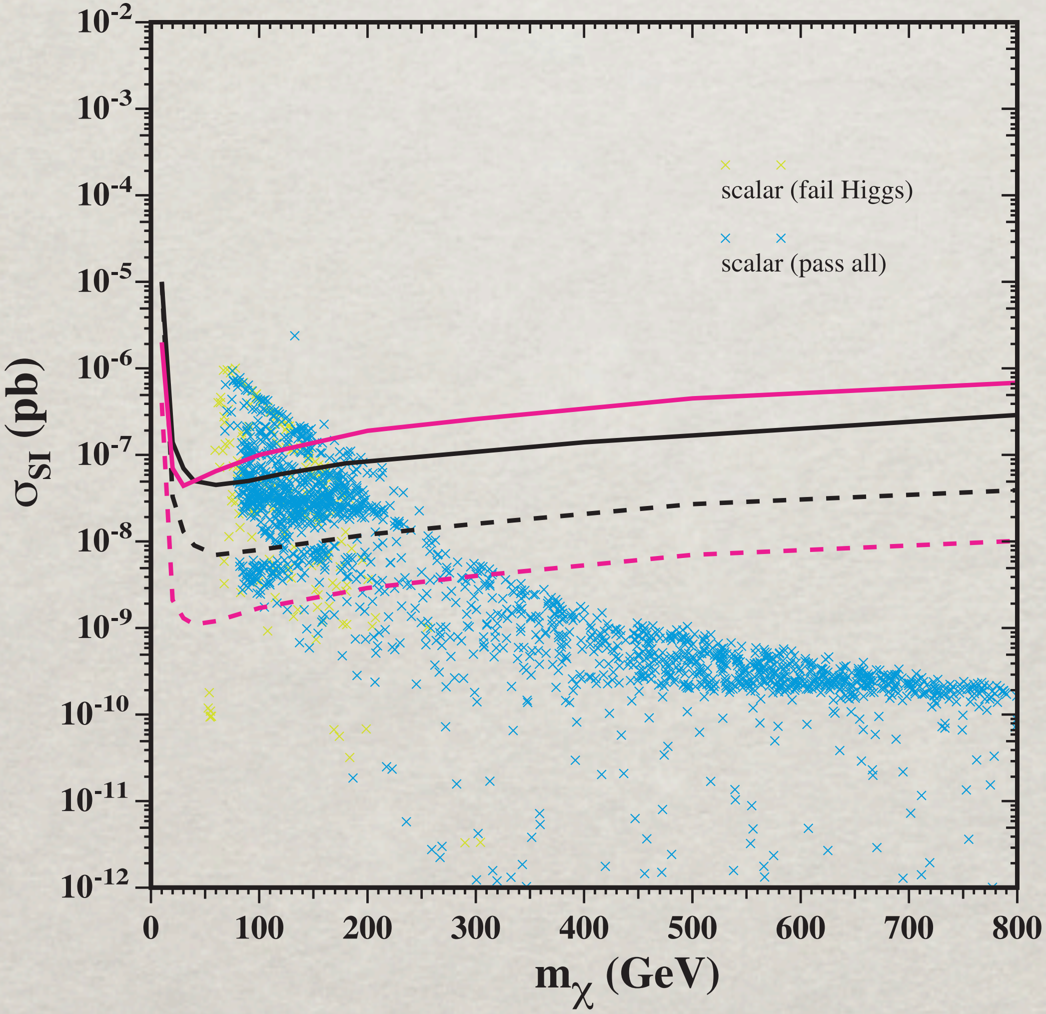
Ellis, Olive, Savage

Spin and Scalar cross sections at tan β = 10



Ellis, Olive, Sandick

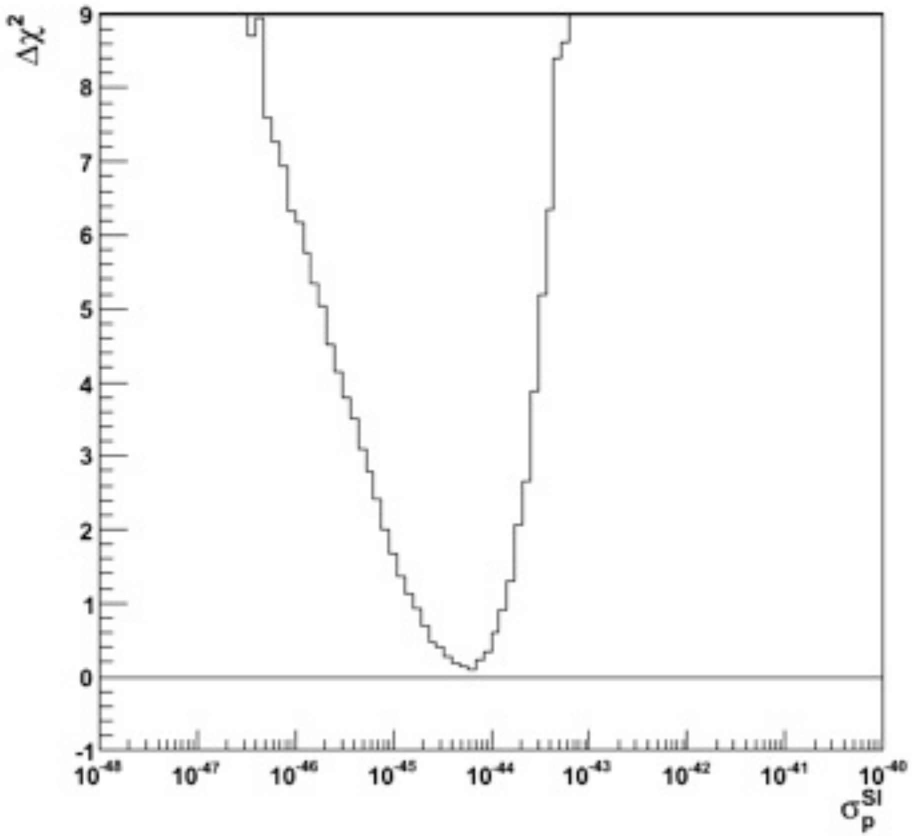
Direct Detection in the CMSSM



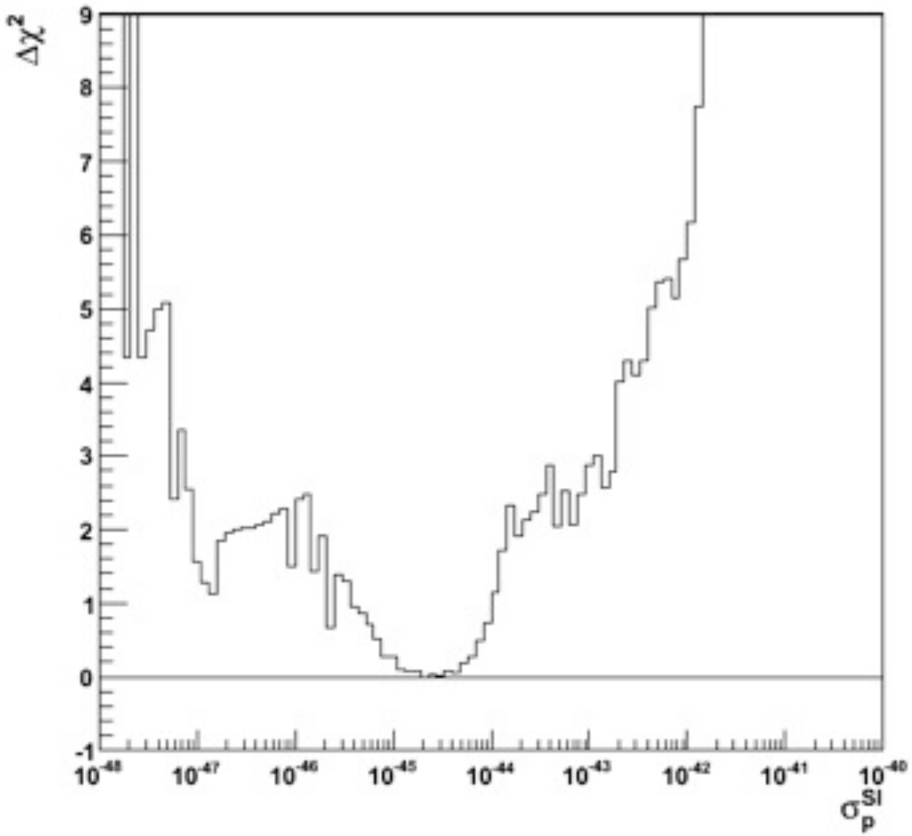
Ellis, Olive, Sandick

$\Delta\chi^2$ vs elastic scattering

With g-2



Without g-2



Buchmueller et al.

Uncertainties from hadronic matrix elements

The scalar cross section

$$\sigma_3 = \frac{4m_r^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2$$

where

$$\frac{f_p}{m_p} = \sum_{q=u,d,s} f_{Tq}^{(p)}\frac{\alpha_{3q}}{m_q} + \frac{2}{27}f_{TG}^{(p)}\sum_{c,b,t}\frac{\alpha_{3q}}{m_q}$$

and

$$m_p f_{Tq}^{(p)} \equiv \langle p|m_q\bar{q}q|p\rangle \equiv m_q B_q$$

determined by

$$\sigma_{\pi N} \equiv \Sigma = \frac{1}{2}(m_u + m_d)(B_u + B_d)$$

The strangeness contribution to the proton mass

$$y = \frac{2B_s}{B_u + B_d} = \frac{(m_u + m_d)\langle p|s\bar{s}|p\rangle}{\Sigma}$$

$$= 1 - \frac{\sigma_0}{\Sigma}$$

$\sigma_0 = 36 \pm 7$ MeV

For $\Sigma = 45$ MeV, y = 0.2

$$f_{T_u} = 0.020 \qquad f_{T_d} = 0.026 \qquad f_{T_s} = 0.117$$

For $\Sigma = 64$ MeV, y = 0.44

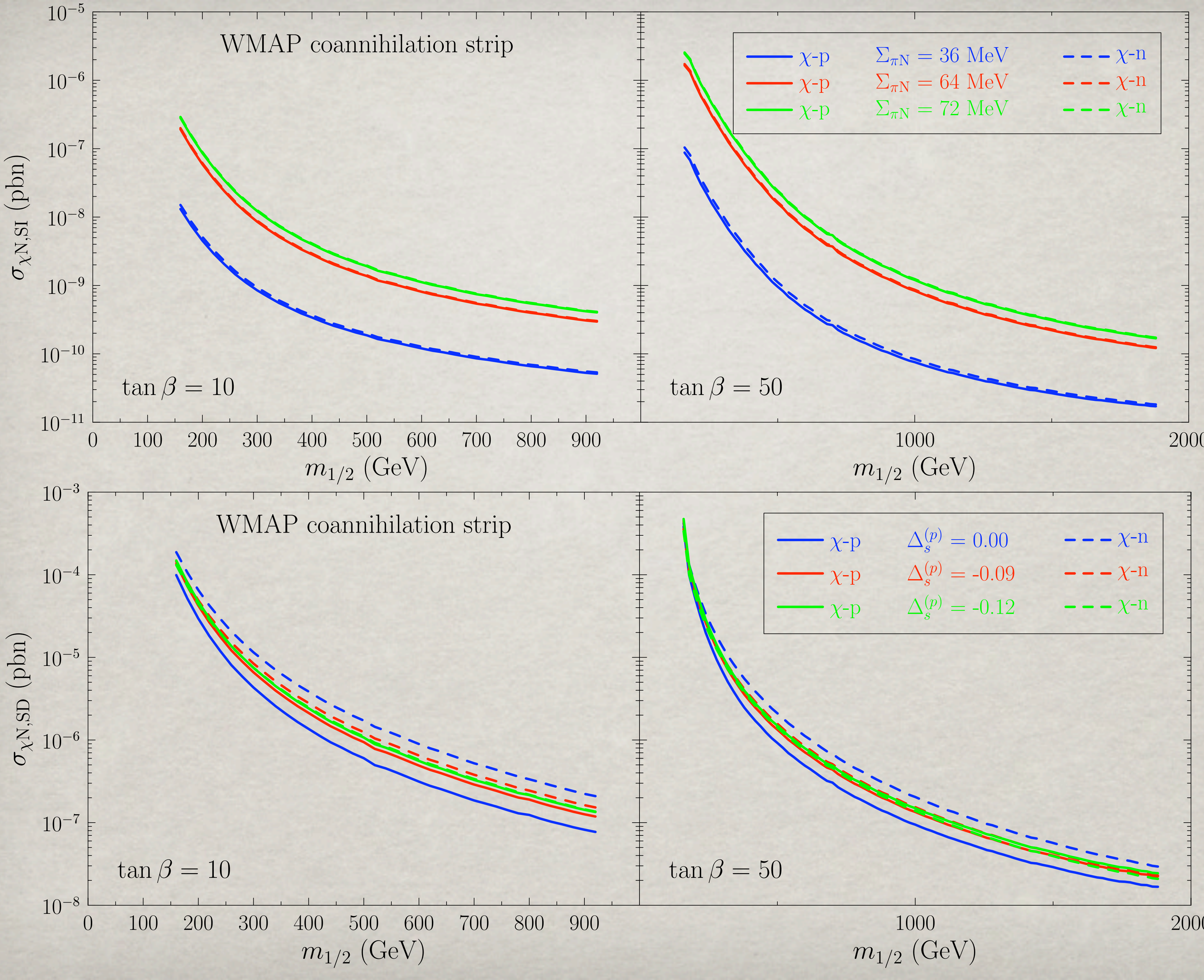
$$f_{T_u} = 0.027 \qquad f_{T_d} = 0.039 \qquad f_{T_s} = 0.363$$

For $\Sigma = 36$ MeV, y = 0

$$f_{T_u} = 0.016 \qquad f_{T_d} = 0.020 \qquad f_{T_s} = 0.$$

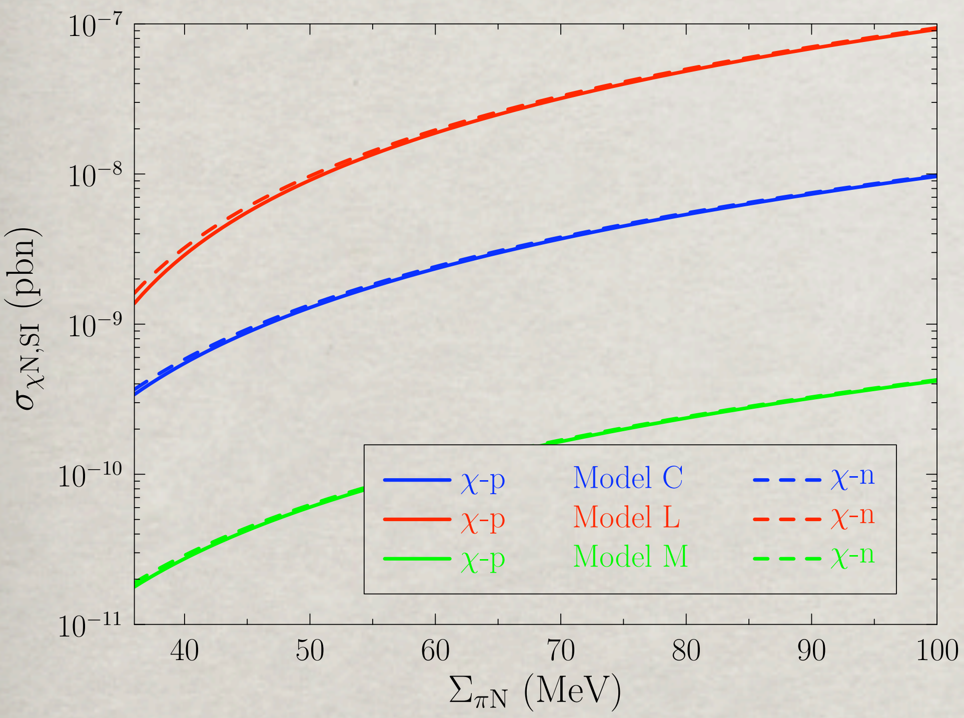
In addition,

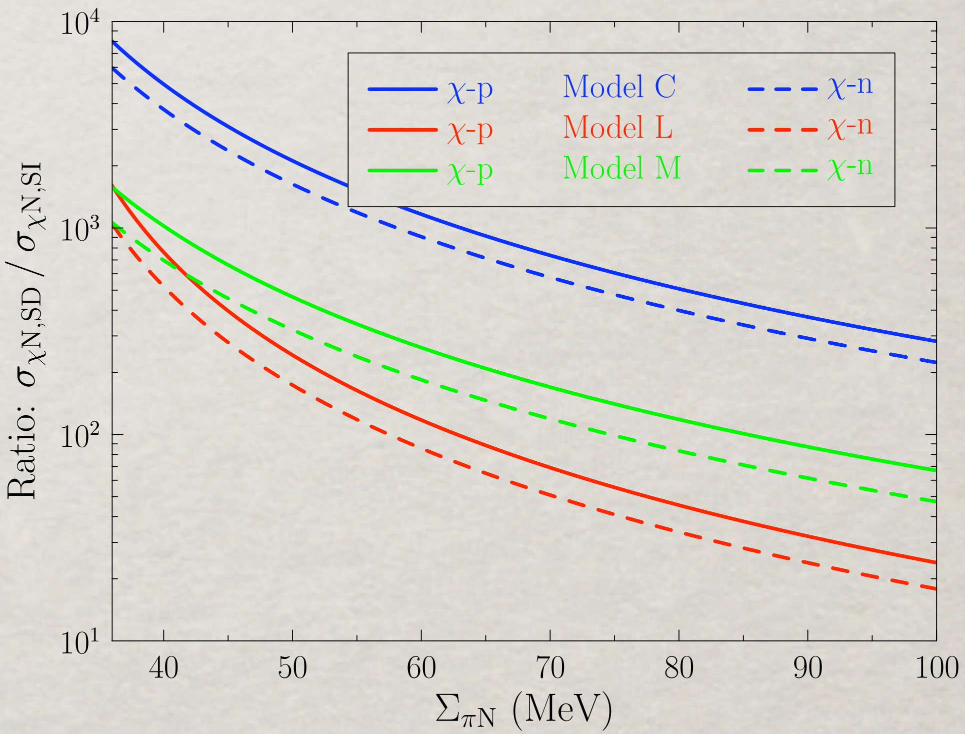
- Direct Detection signals are proportional to ϱ_0 $\sigma_{\chi N}$
- The local density is ϱ_0 typically assumed to be 0.3 GeV/cm^{-3}, but 0.2 - 0.4 GeV/cm^{-3} is reasonable.
- Models of galaxy formation may allow values as low as 0.04 GeV/cm^{-3}.



WMAP coannihilation strip
χ-p
$\Sigma_{\pi N}$ = 36 MeV
χ-n
χ-p
$\Sigma_{\pi N}$ = 64 MeV
χ-n
χ-p
$\Sigma_{\pi N}$ = 72 MeV
χ-n
$\sigma_{\chi N,SI}$ (pbn)
tan β = 10
tan β = 50
$m_{1/2}$ (GeV)
WMAP coannihilation strip
χ-p
$\Delta_s^{(p)}$ = 0.00
χ-n
χ-p
$\Delta_s^{(p)}$ = -0.09
χ-n
χ-p
$\Delta_s^{(p)}$ = -0.12
χ-n
$\sigma_{\chi N,SD}$ (pbn)
tan β = 10
tan β = 50
$m_{1/2}$ (GeV)

Benchmarks as a function of $\Sigma_{\pi N}$





Ellis, Olive, Savage

Summary

- Dark Matter component is large ($\Omega h^2 = 0.11$)
- CMSSM - 4+ parameter theory testable at LHC
- mSUGRA - 3+ parameter subset of the CMSSM
  - often predicts GDM
- CMSSM has several 'regions' in which the correct relic density is obtained
- χ^2 analysis (frequentist) shows strong preference for low (testable) values of $m_{1/2}$, m_0, and tan β