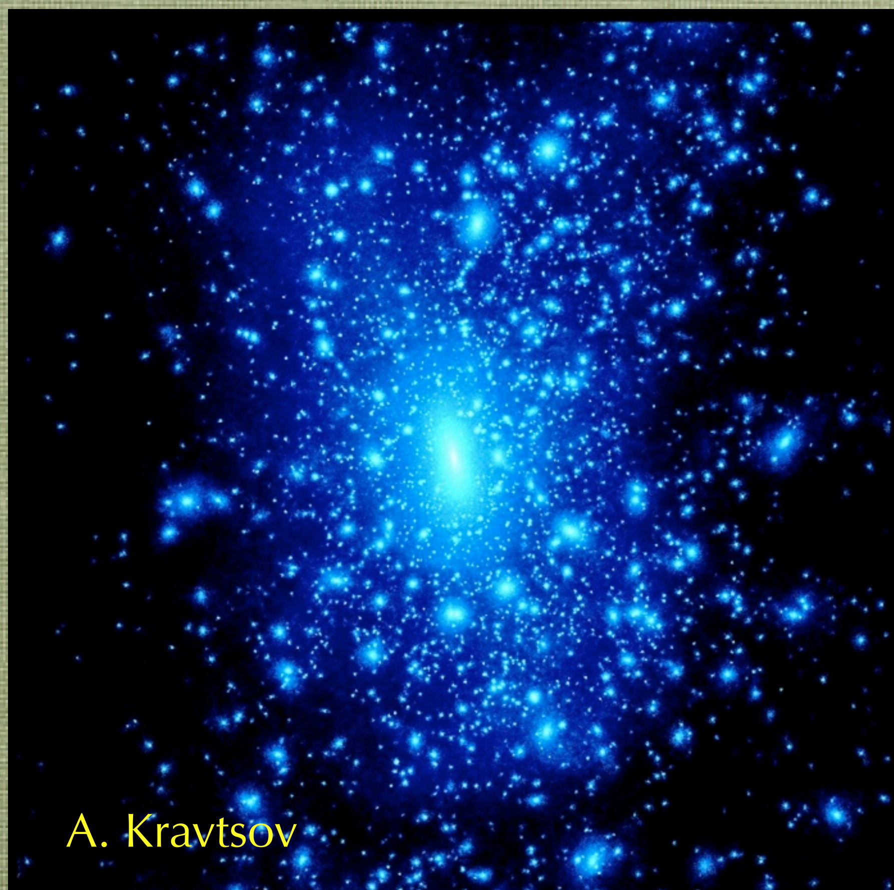
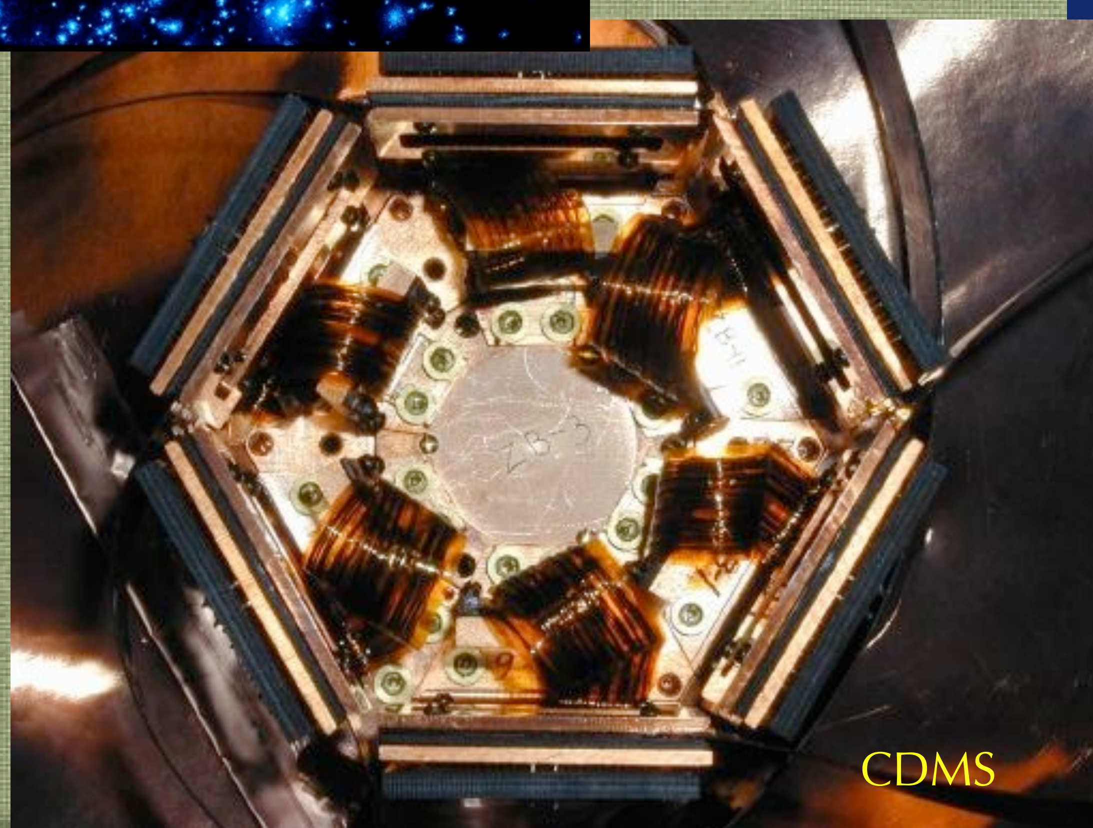
Dark Energy and Dark Matter


A. Kravtsov


CDMS

LEPTON
PHOTON
HAMBURG

$$\Omega = 1$$

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- What is Ω ?

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- What is Ω ?

$$\Omega = \rho/\rho_c \qquad \rho_c = 3H^2/8\pi G_N = 1.88 \times 10^{-29} h^2 \text{ g cm}^{-3}$$

and h = H/100 (km/Mpc/s)

$$H^2 \equiv \frac{\dot{R}^2}{R^2} = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3}$$

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  - $\Omega_r \sim 10^{-4}$; $\Omega_m \sim 0.26$; $\Omega_\Lambda \sim 0.74$

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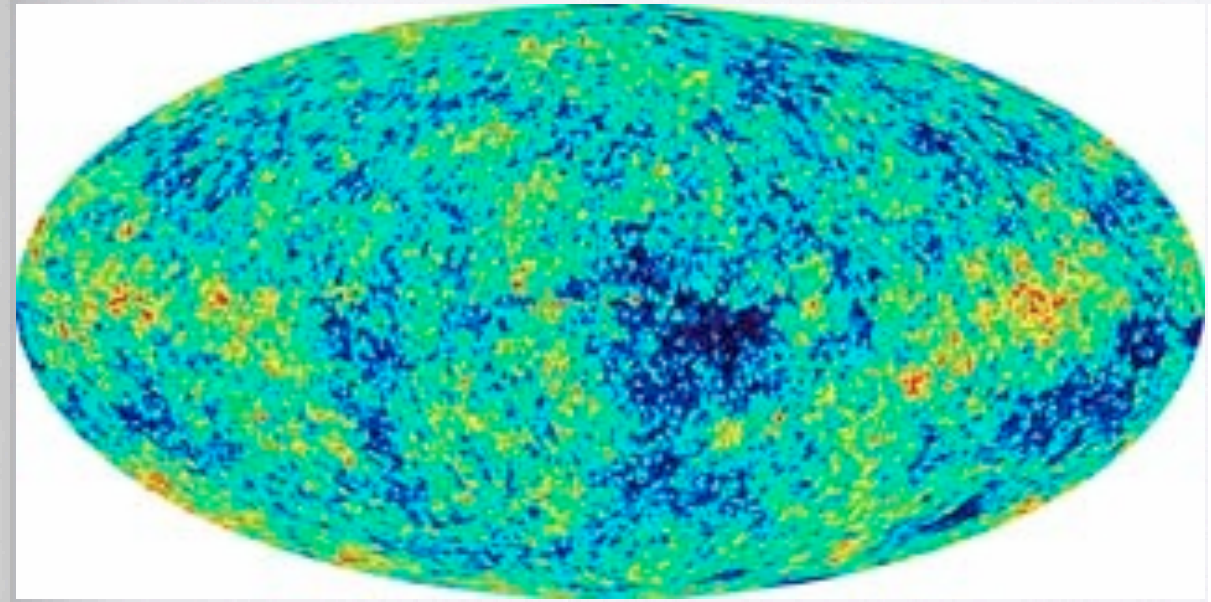
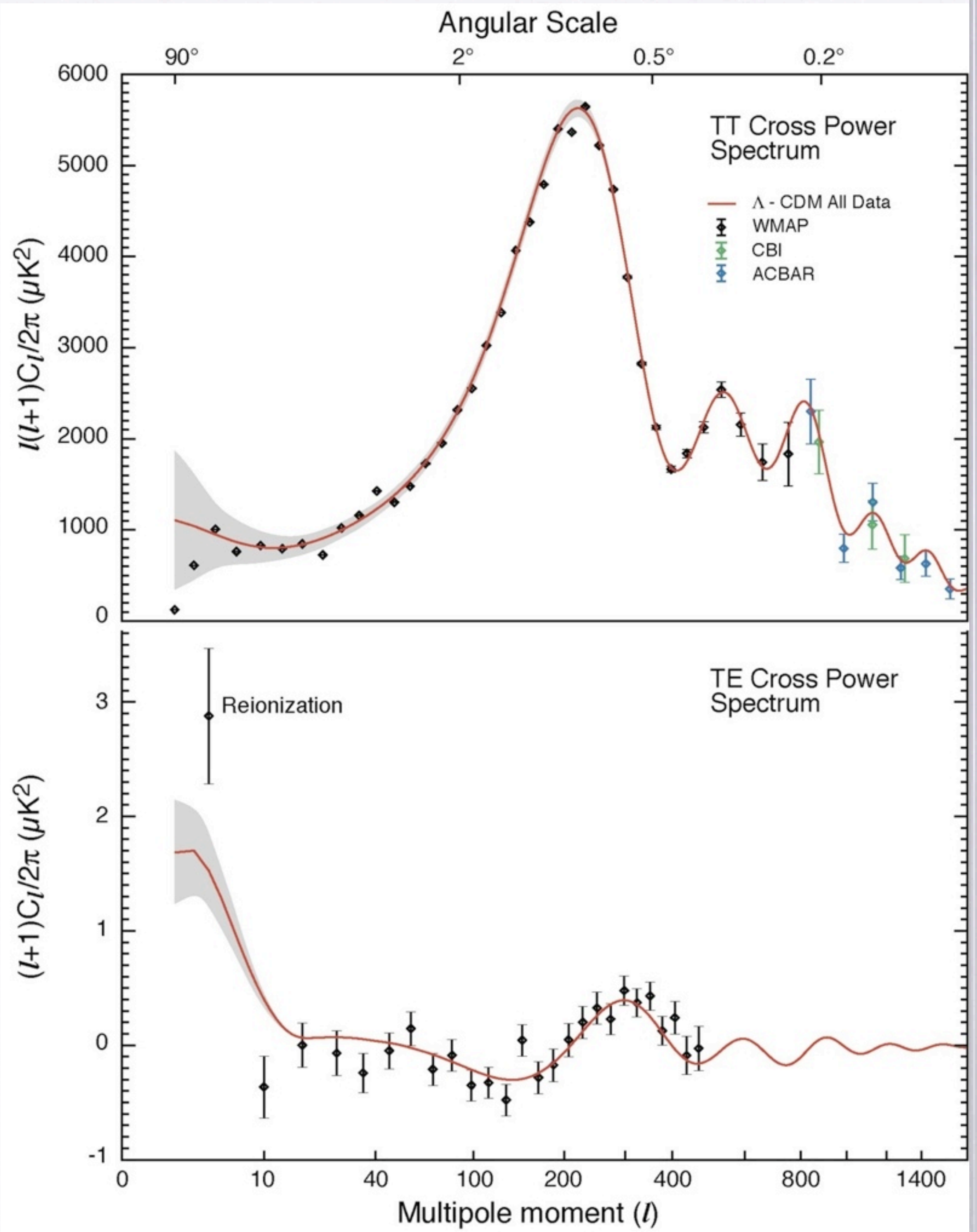
  - $\Omega_m = \Omega_B + \Omega_{cdm}$ also $0.0005 < \Omega_\nu h^2 < 0.0076$

WMAP

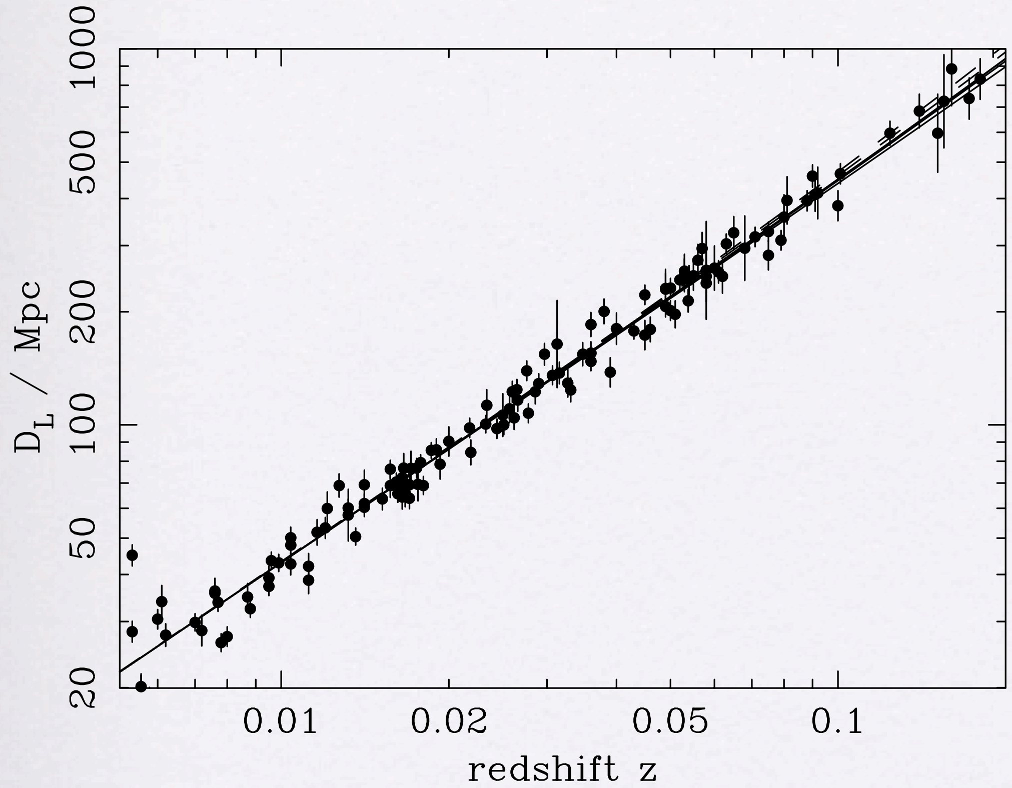


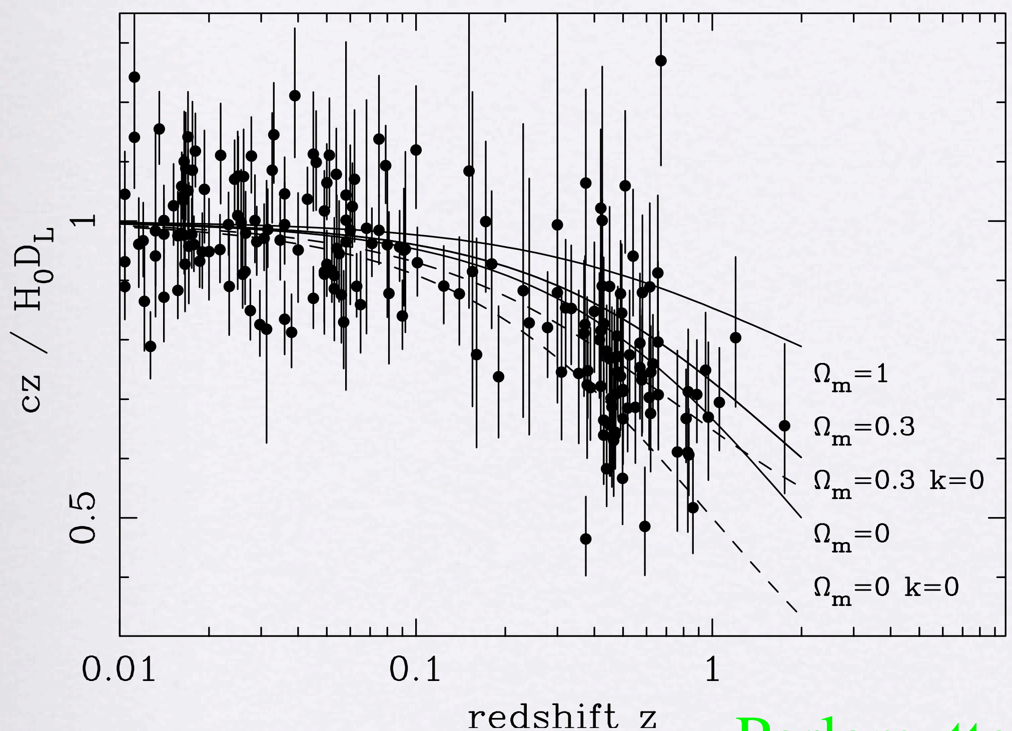


Position of 1st peak

$\Rightarrow \quad \Omega = 1$

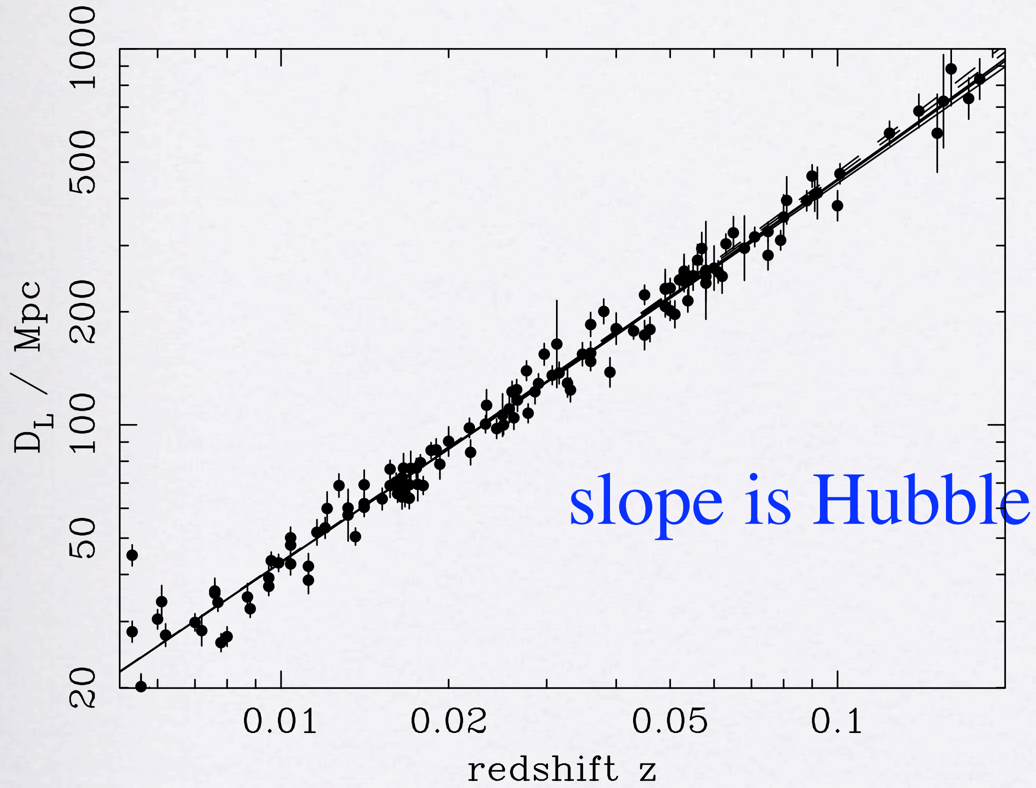
Type 1a Supernovae



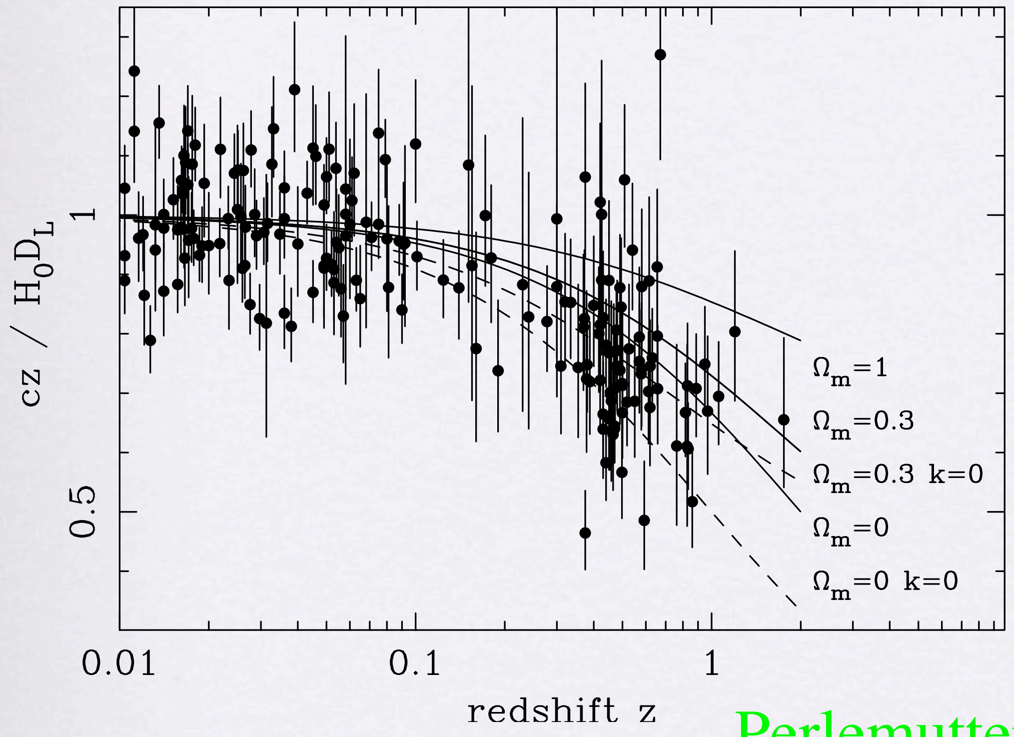


Perlemutter et al.
Riess et al.
Tonry et al.

Type 1a Supernovae



slope is Hubble law



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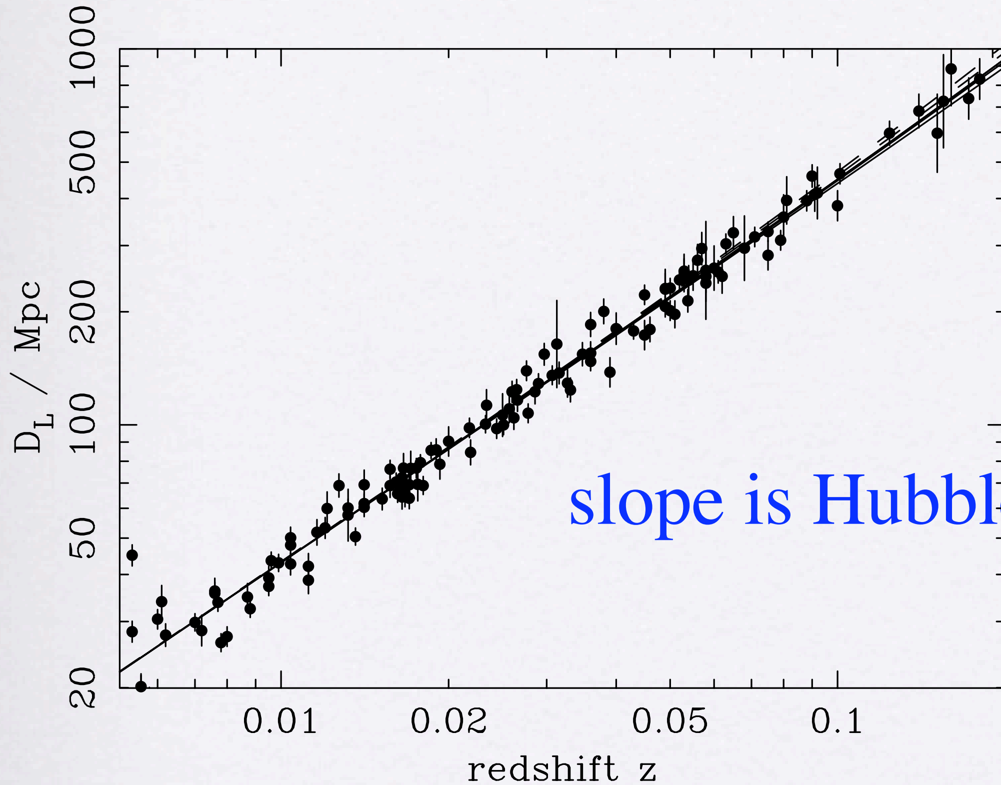
Type 1a Supernovae



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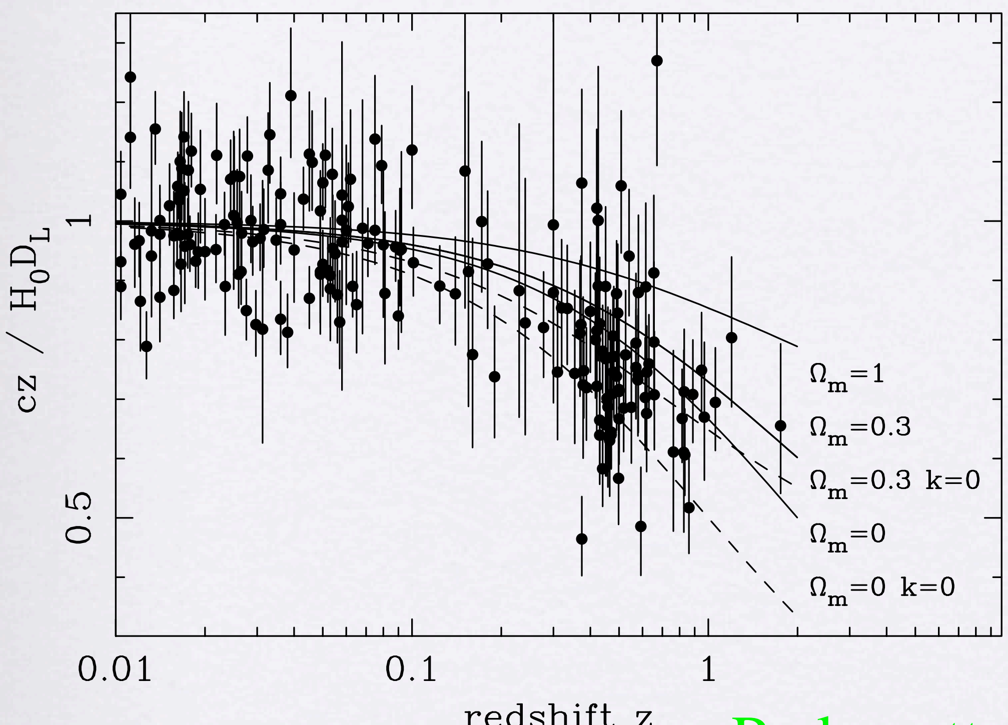

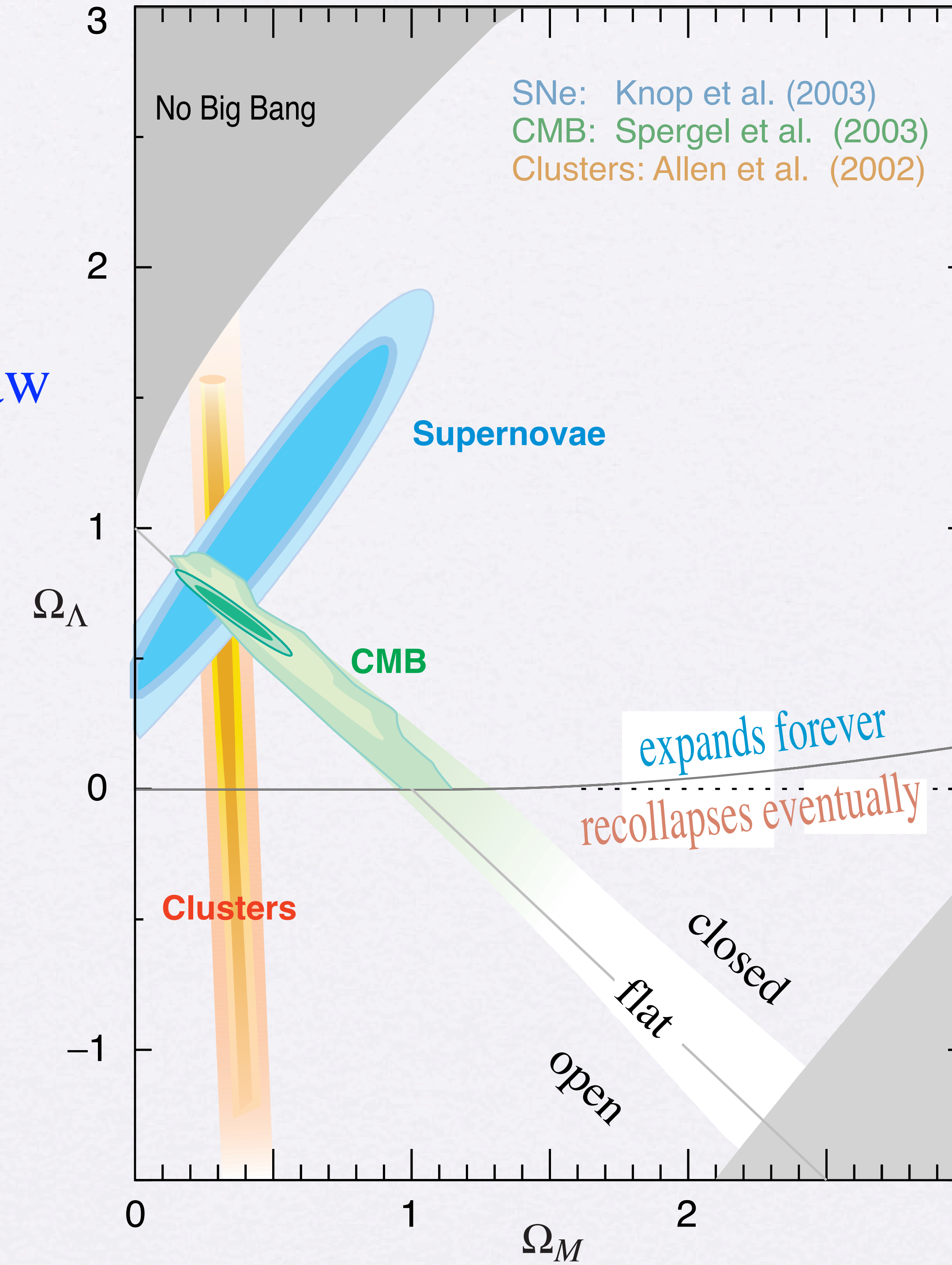

Perlemutter et al.

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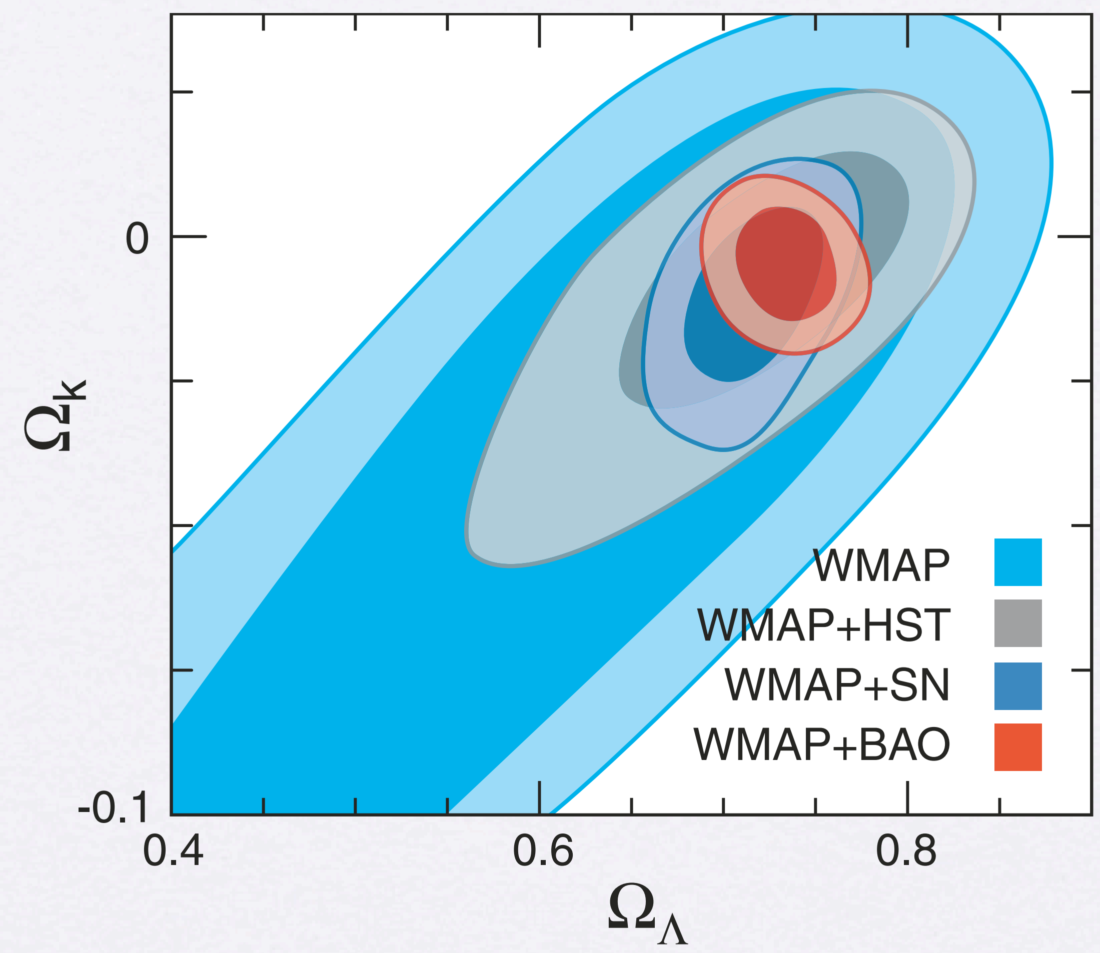
Dark Energy

- $\Omega_\Lambda \neq 0$

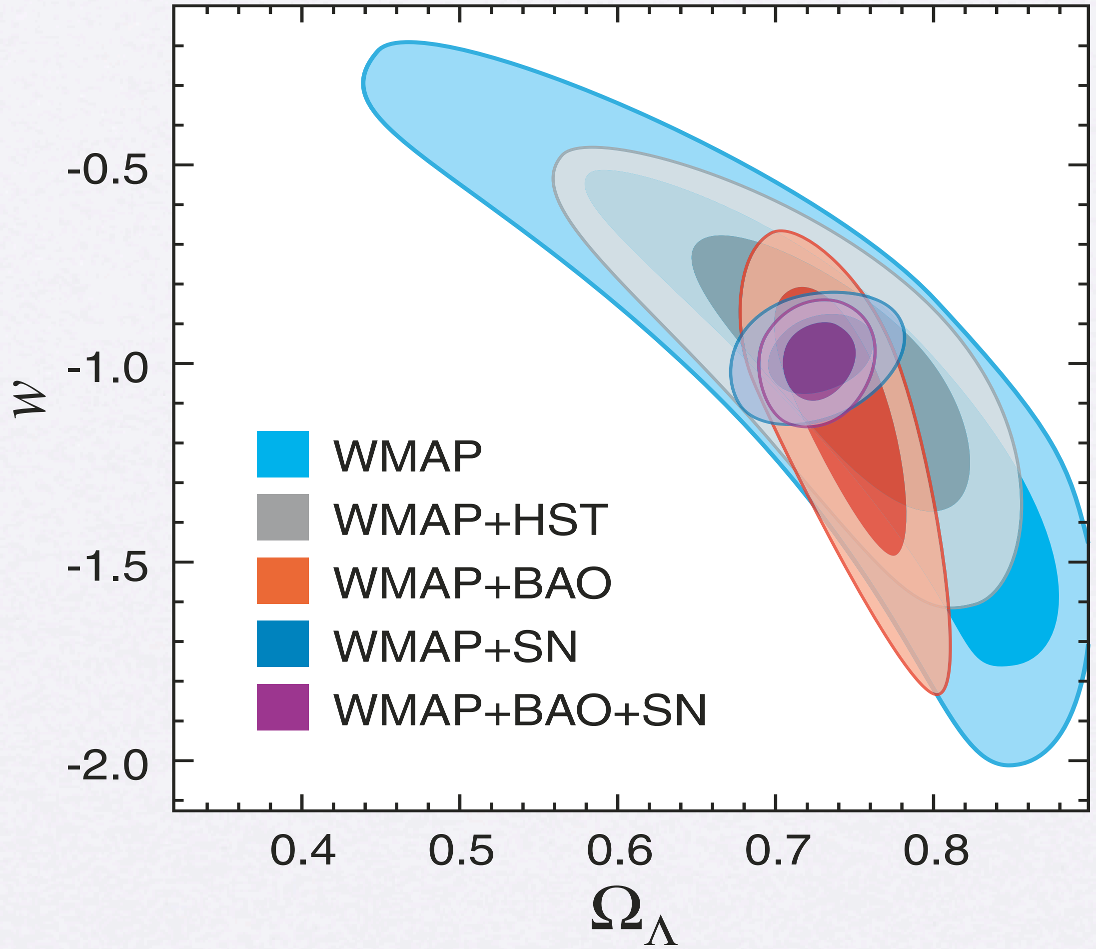


Komatsu et al.

Dark Energy

- $\Omega_\Lambda \neq 0$
- Simplest Solution:

- Λ = constant ($w = p/\rho = -1$)



Komatsu et al.

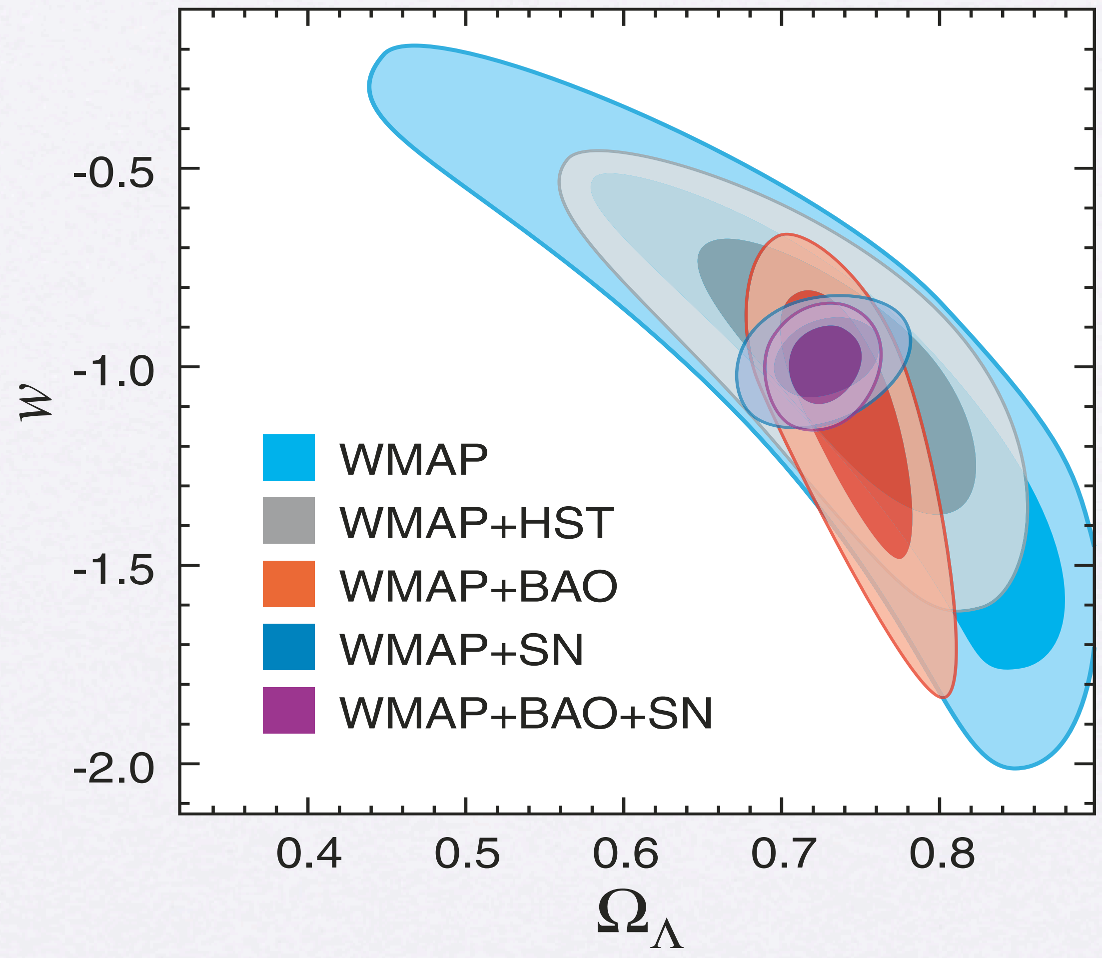
Dark Energy

- $\Omega_\Lambda \neq 0$

- Simplest Solution:

- Λ = constant ($w = p/\rho = -1$)

But require $\Lambda = 10^{-121}\, M_P^4$
Cosmological Constant Problem



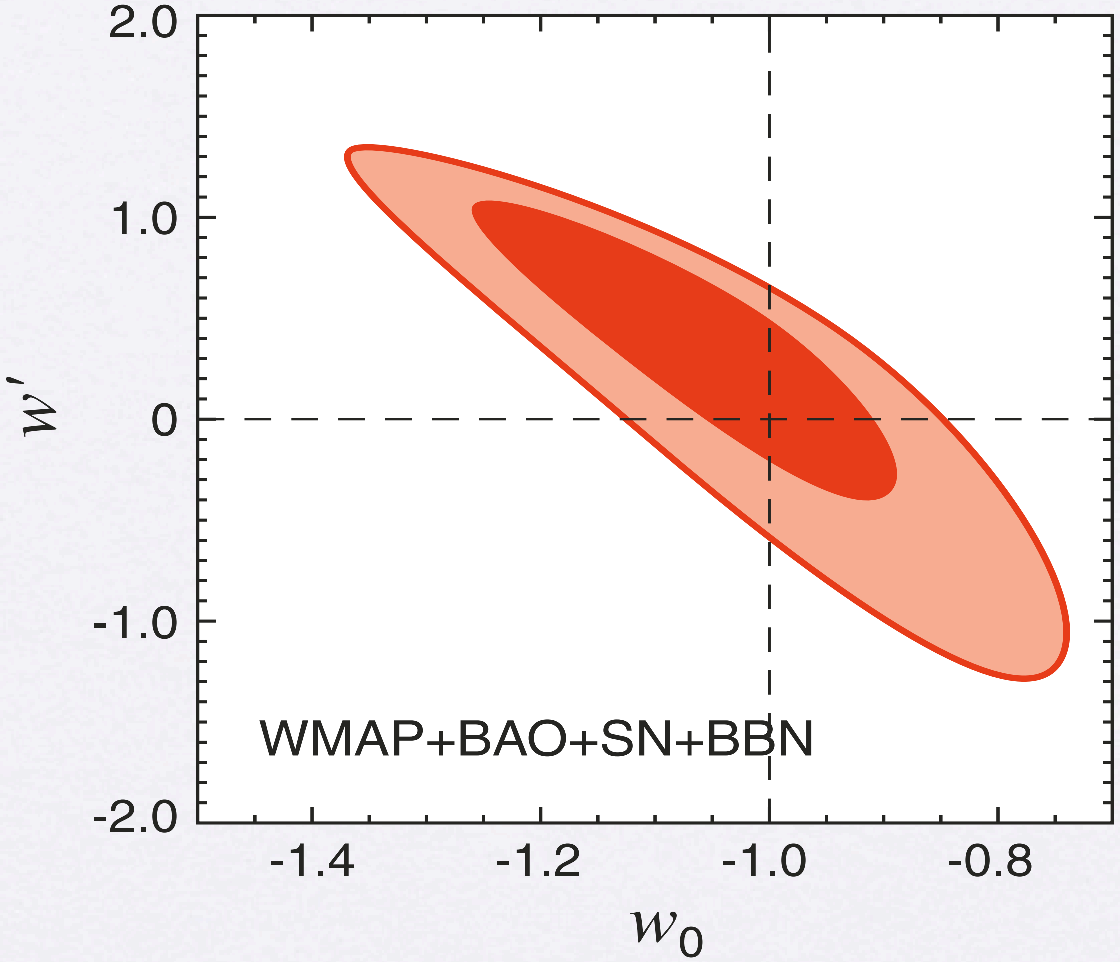
Komatsu et al.

Dark Energy

- $\Omega_\Lambda \neq 0$

- Simplest Solution:
- Λ = constant ($w = p/\rho = -1$)

- Other Solutions:
- Quintessence



Komatsu et al.

- Fine-Tuning

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    - $\Lambda = \Lambda_{GUT} + \Lambda_{EW} + \Lambda_{QCD} + \ldots$

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- Fine-Tuning
  - $\Lambda = \Lambda_{GUT} + \Lambda_{EW} + \Lambda_{QCD} + \dots$
- Coincidence
  - $\Omega_{\Lambda} \sim \Omega_{m}$
- Quintessence
  - Can be useful for solving the coincidence problem - Tracking -Variable couplings

How Much Dark Matter

WMAP 5

Dunkley etal

Precise bounds on matter content

How Much Dark Matter

WMAP 5 Dunkley etal

Precise bounds on matter content

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

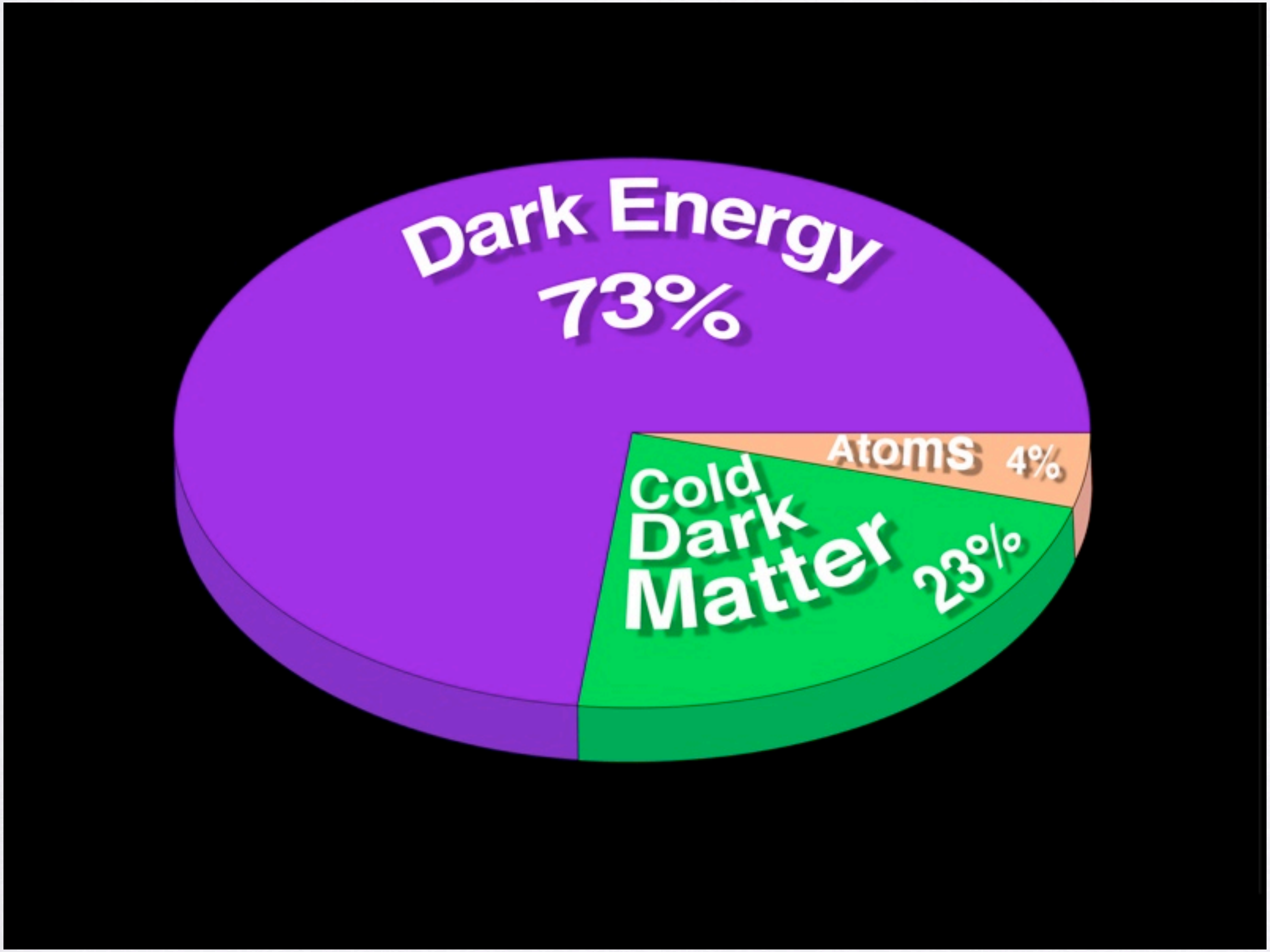
$\Omega_{cdm} h^2 = 0.1099 \pm 0.0062$

or

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

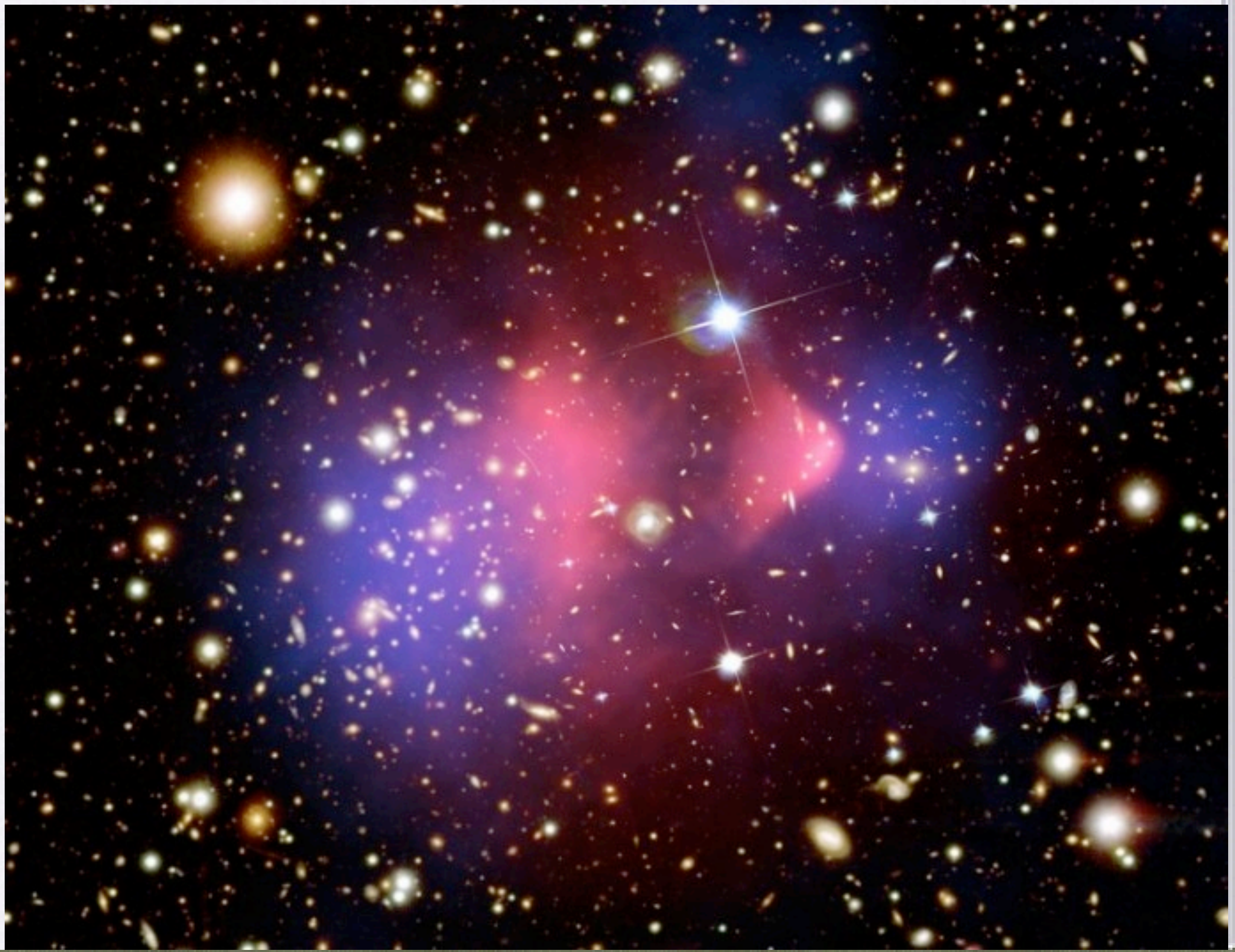
Cosmological Parameters:

$$\Omega = 1.011 \pm 0.012$$



The (other)Evidence:

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



Clowe et al.

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

Beyond the Standard Model

(add new symmetries, particles and/or interactions)

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

•

•

•

SUSY Dark Matter

MSSM and R-Parity → 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

Unification Conditions

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

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predict μ, B

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Constrained Minimal Supersymmetric Standard Model
CMSSM

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mSugra Conditions

- Gravitino mass: $m_{3/2} = m_0$
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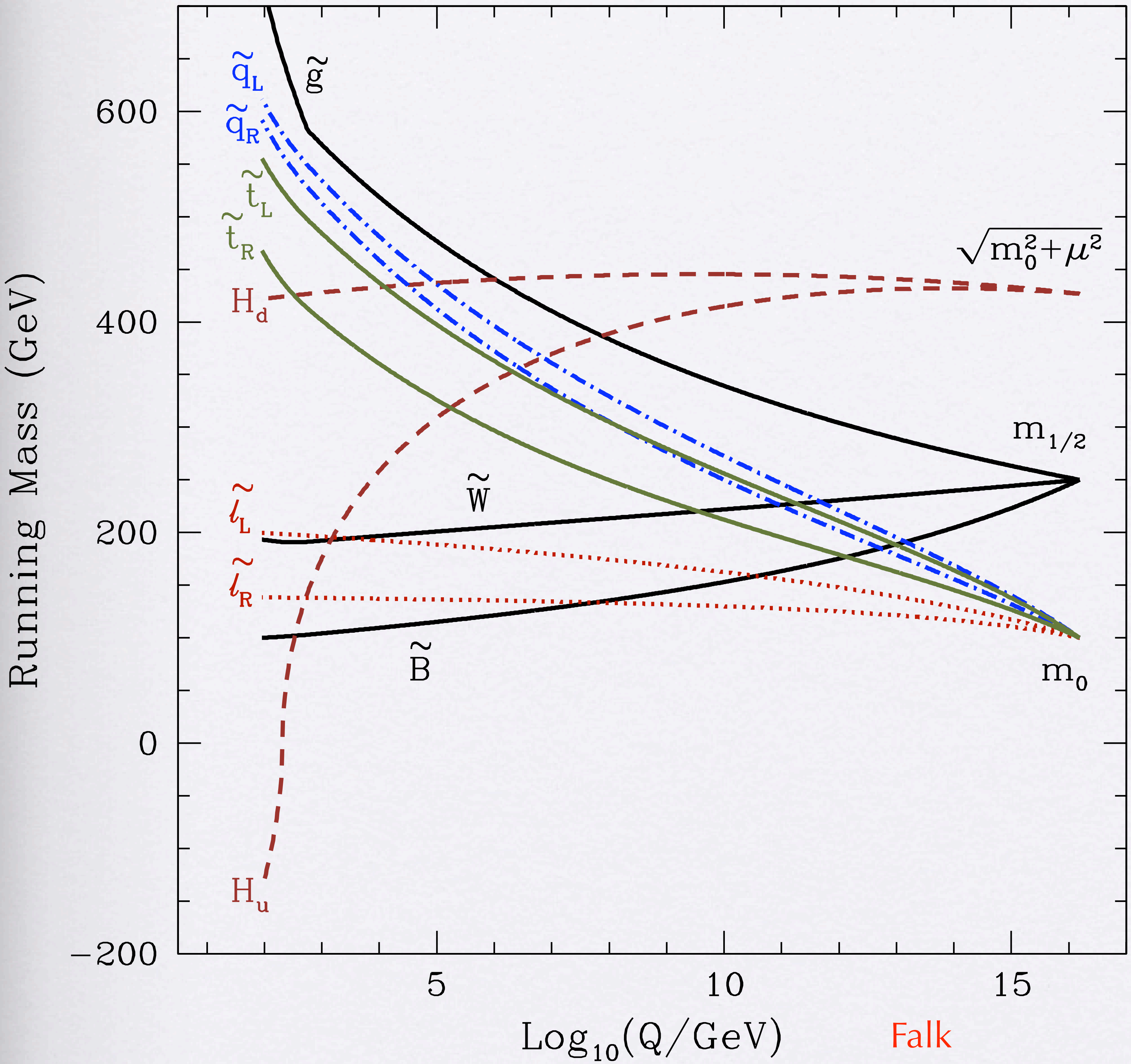
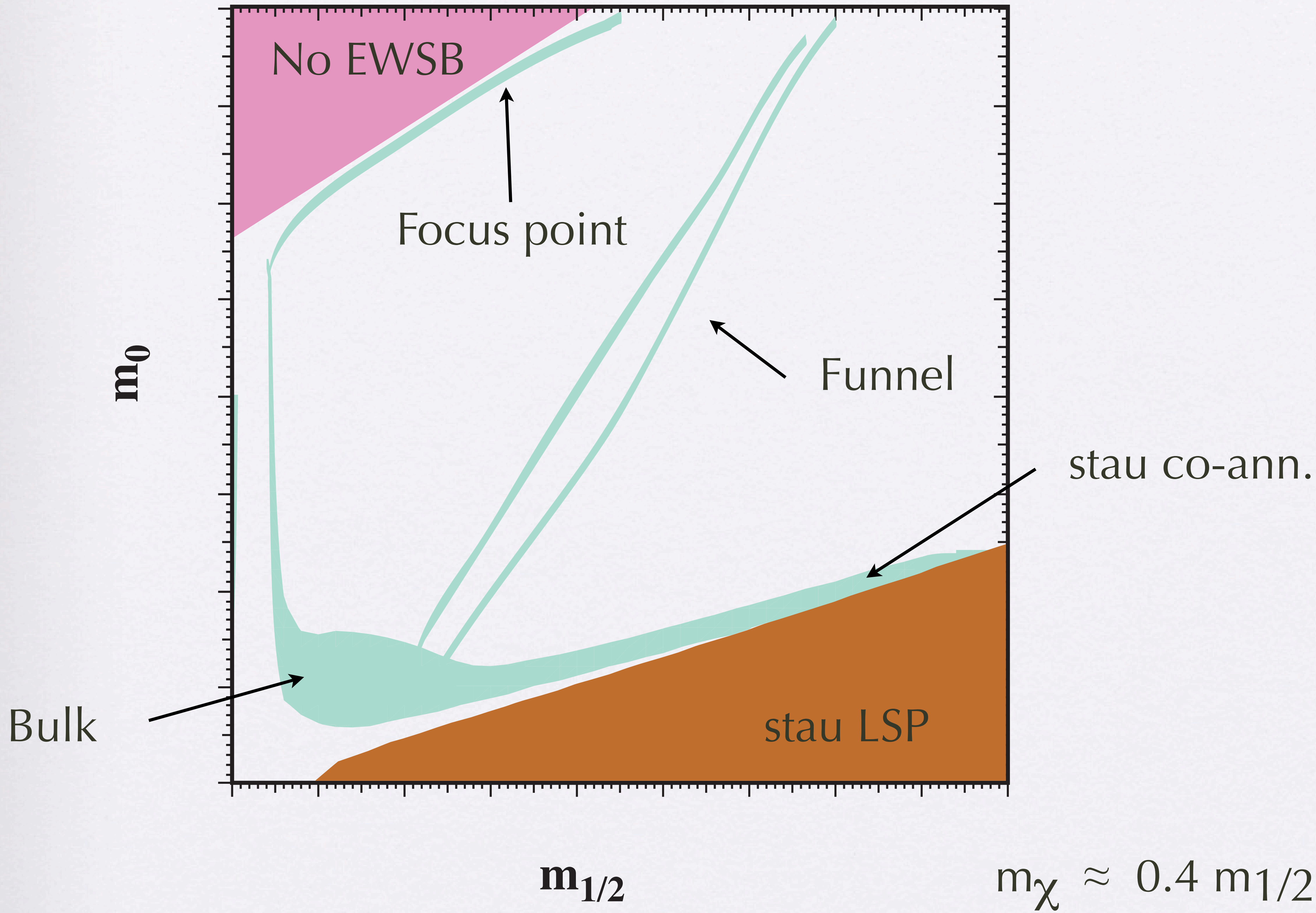
predict μ, $\tan\beta$

CMSSM Spectra



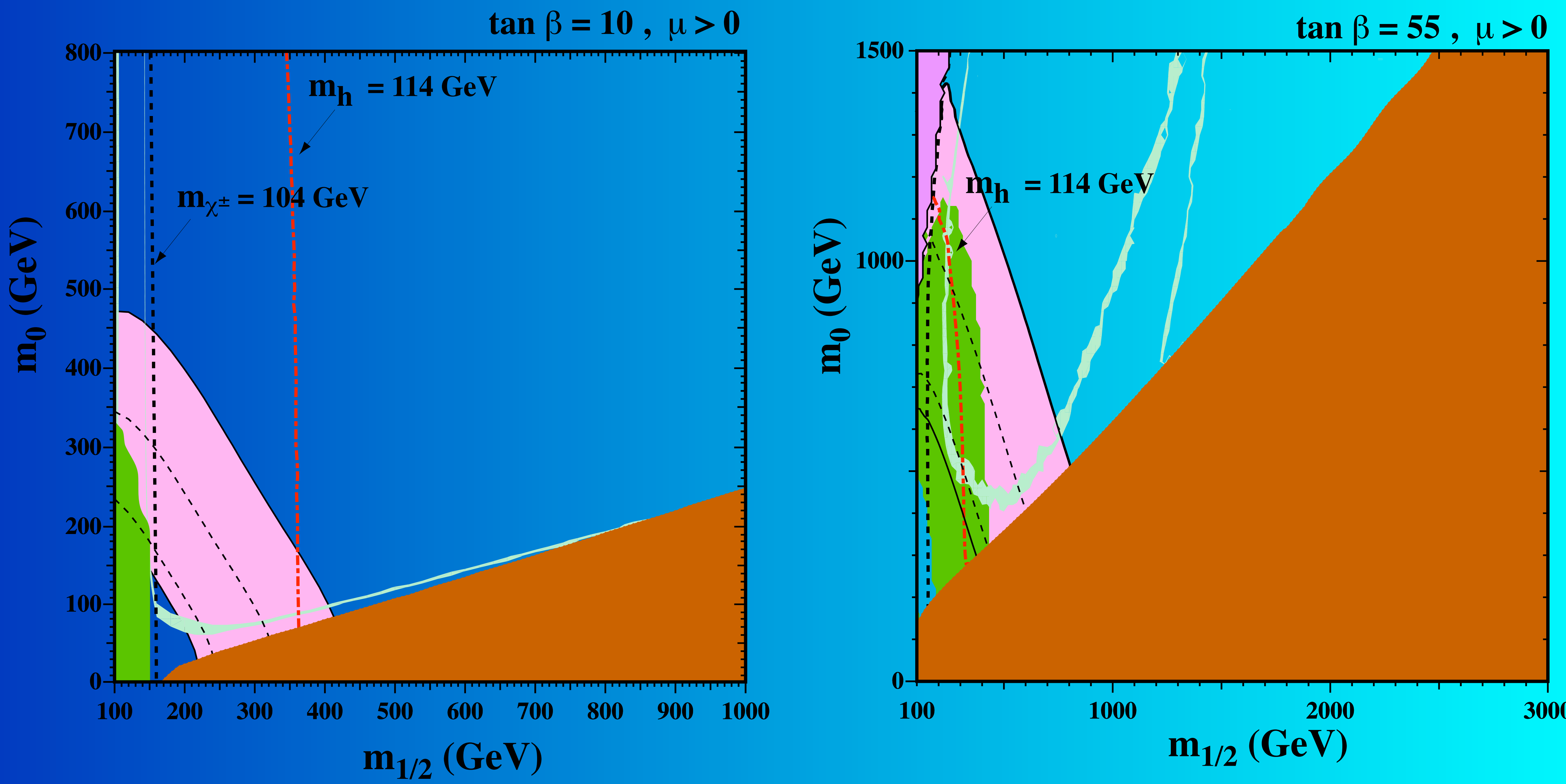
Unification to rich spectrum
+
EWSB

Typical Regions



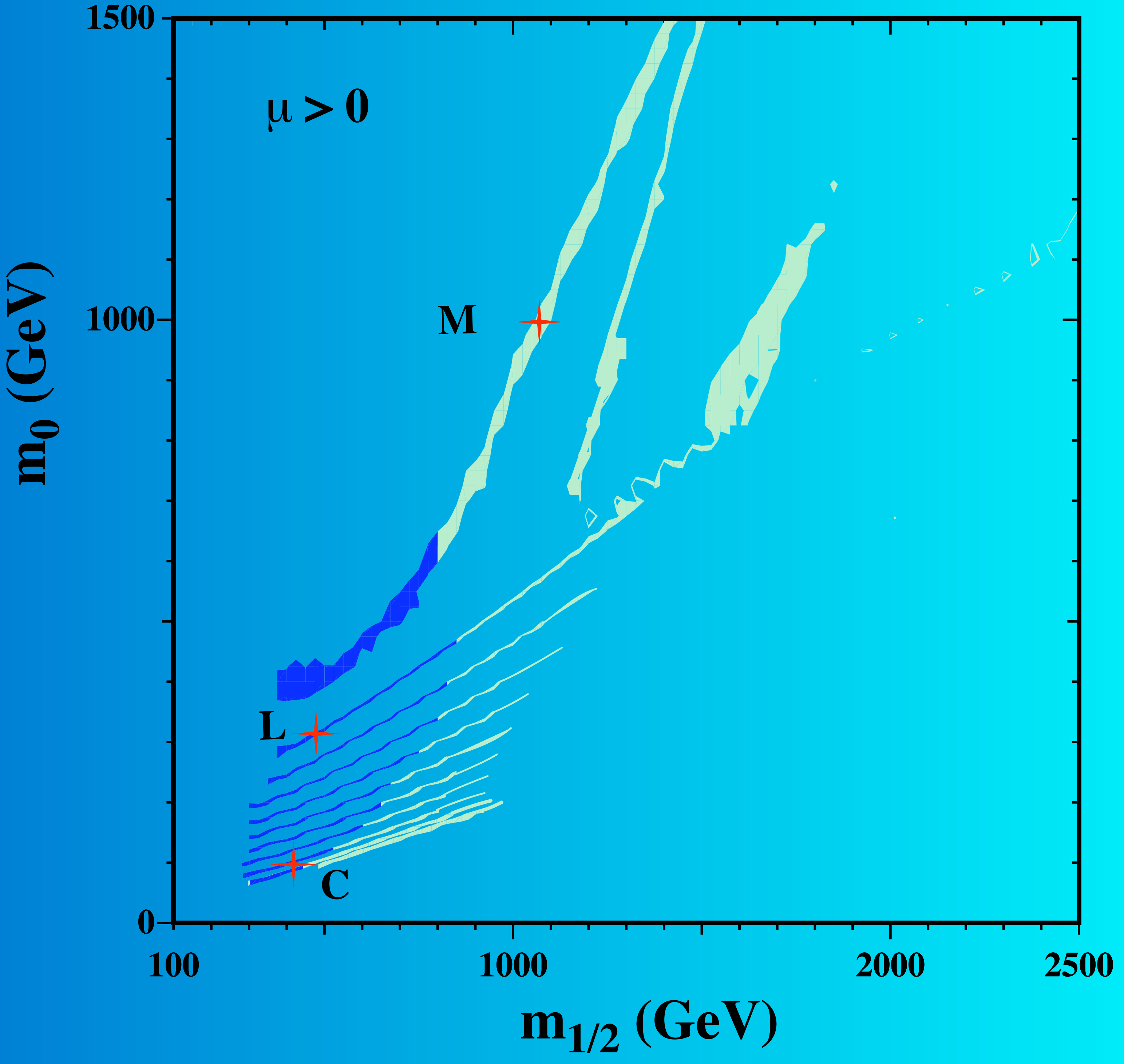
$m_\chi \approx 0.4\, m_{1/2}$

CMSSM



Ellis, Olive, Santoso, Spanos

Foliation in tan β



Ellis, Olive, Santoso, Spanos

MCMC Analysis

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

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

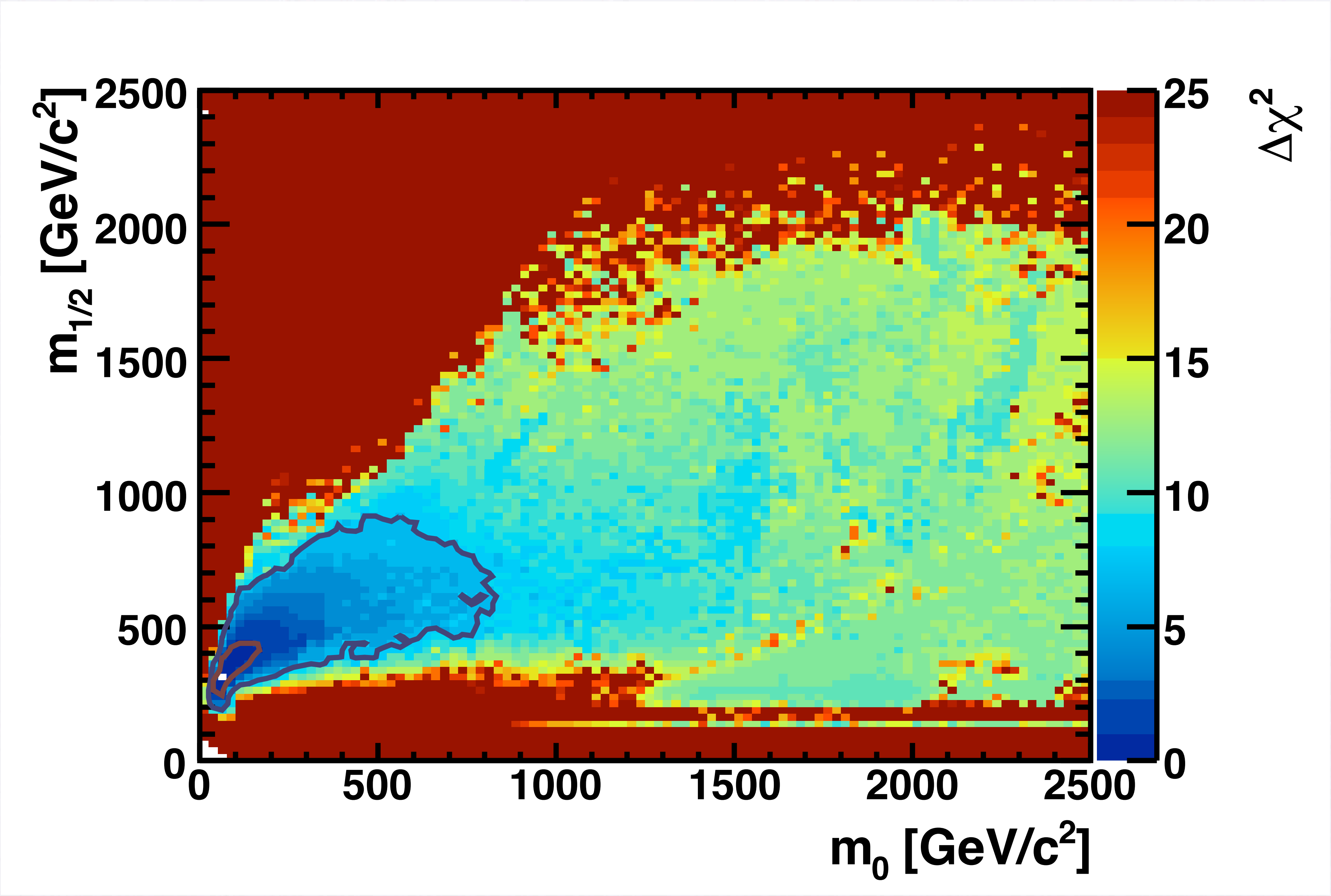
Long list of observables to constrain CMSSM parameter space

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

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2}$$
$$+ \chi^2(M_h) + \chi^2({\rm BR}(B_s \to \mu\mu))$$
$$+ \chi^2(\text{SUSY search limits})$$
$$+ \sum_i^M \frac{(f_{{\rm SM}_i}^{\rm obs} - f_{{\rm SM}_i}^{\rm fit})^2}{\sigma(f_{{\rm SM}_i})^2}$$

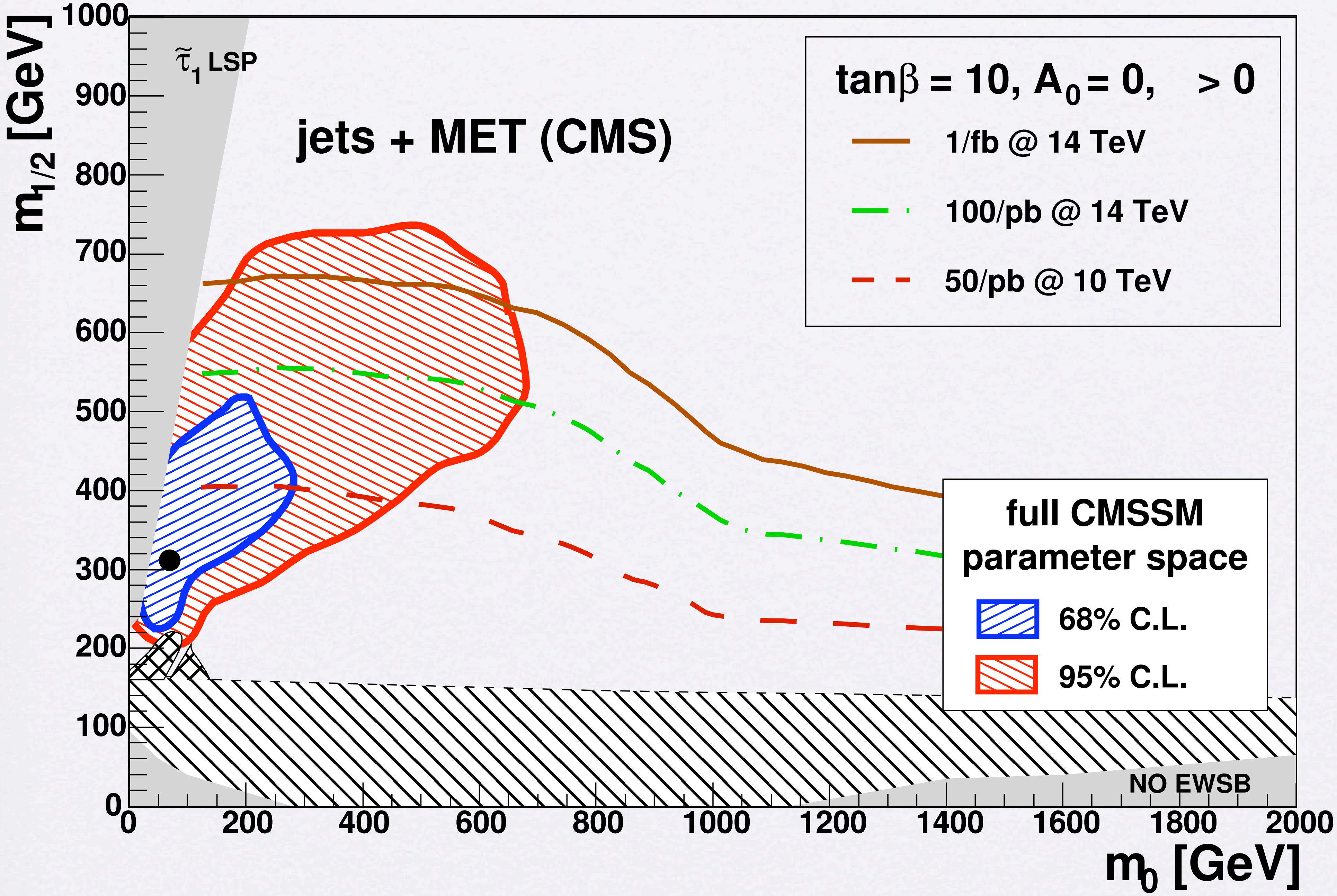
See also: Balz and Gondolo; Allanach, Lester, and Weber; deAustri, Trotta, and Roszkowski

Result for CMSSM



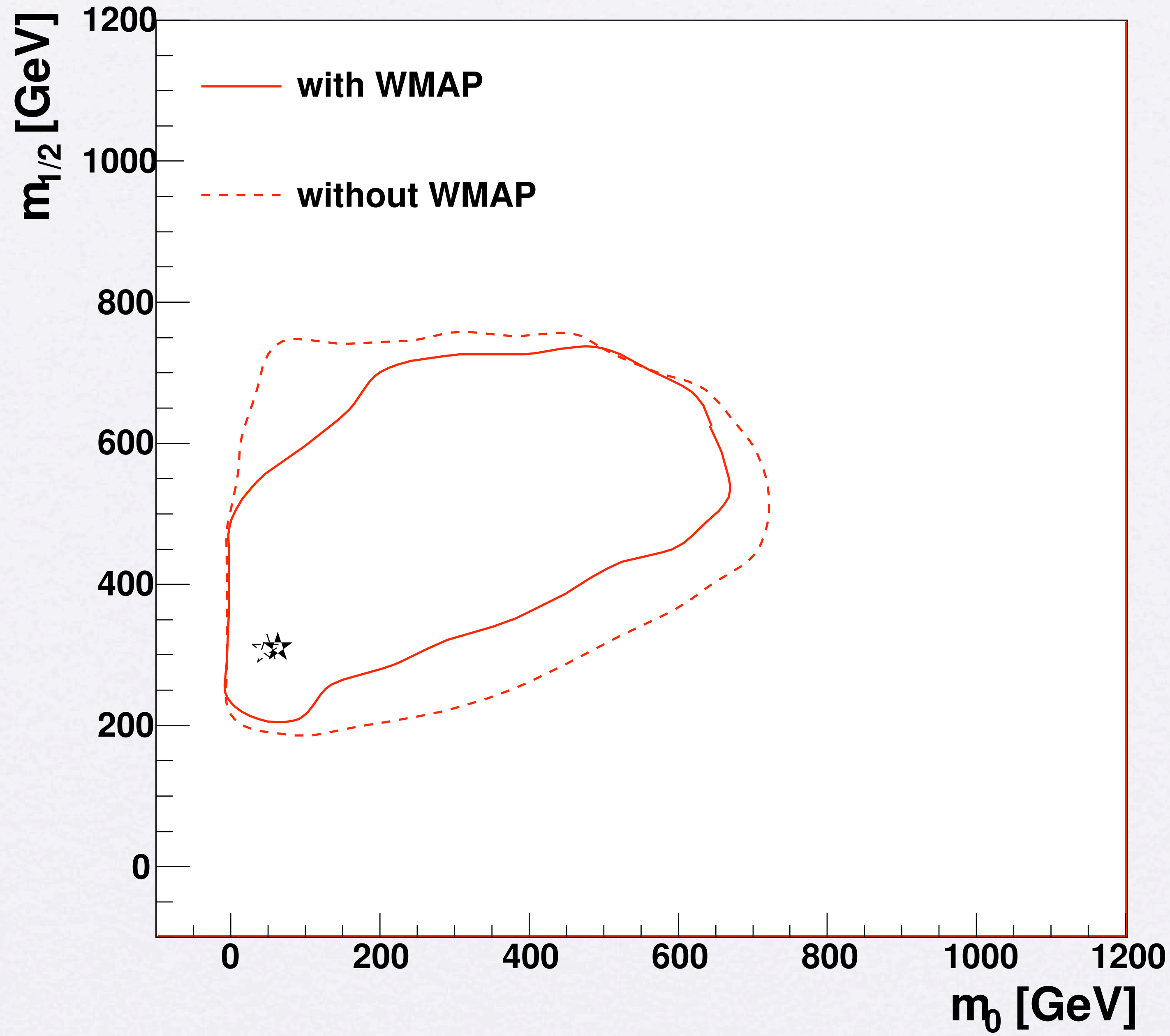
Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

LHC reach vs CMSSM



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

Impact of CDM



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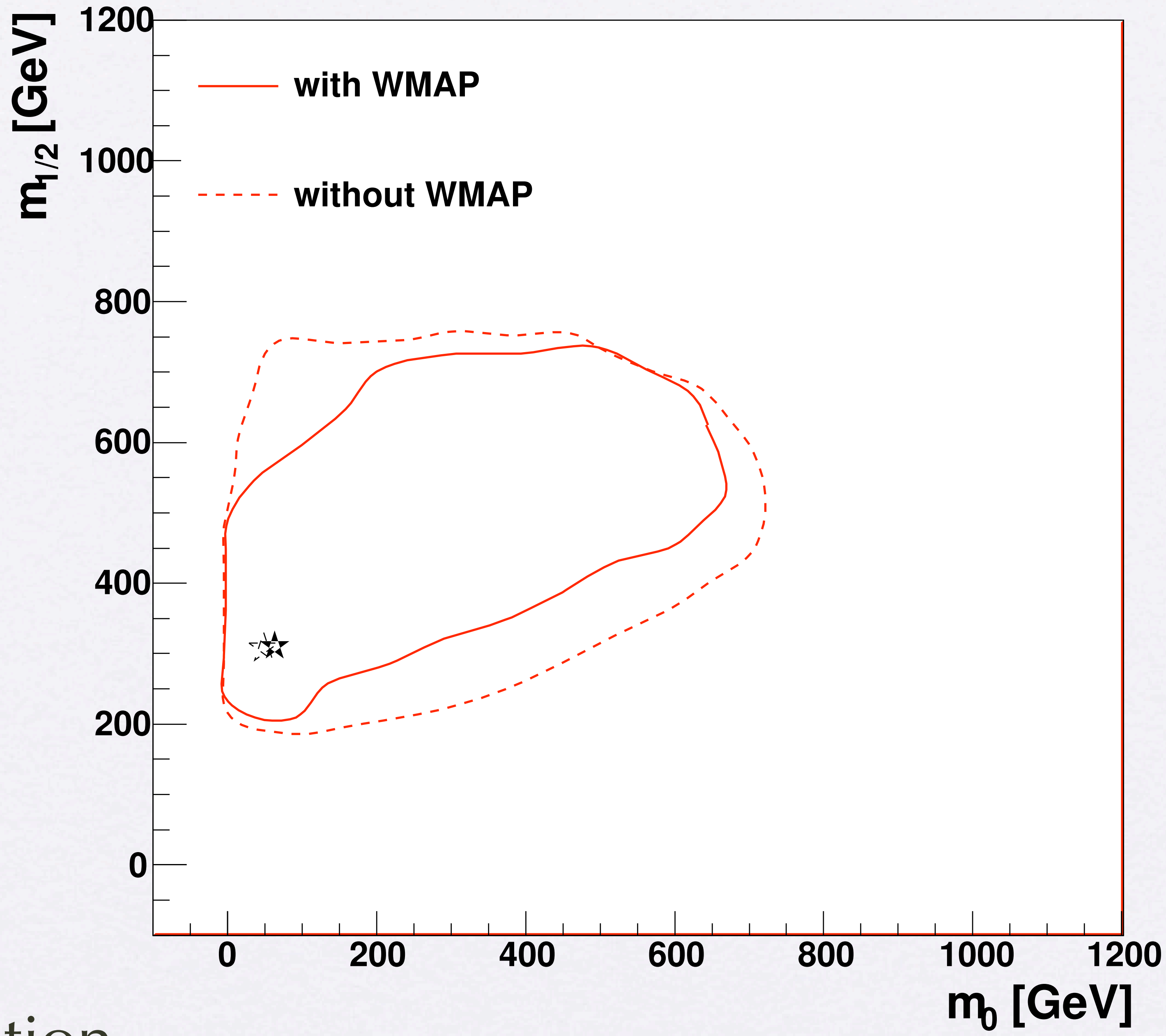
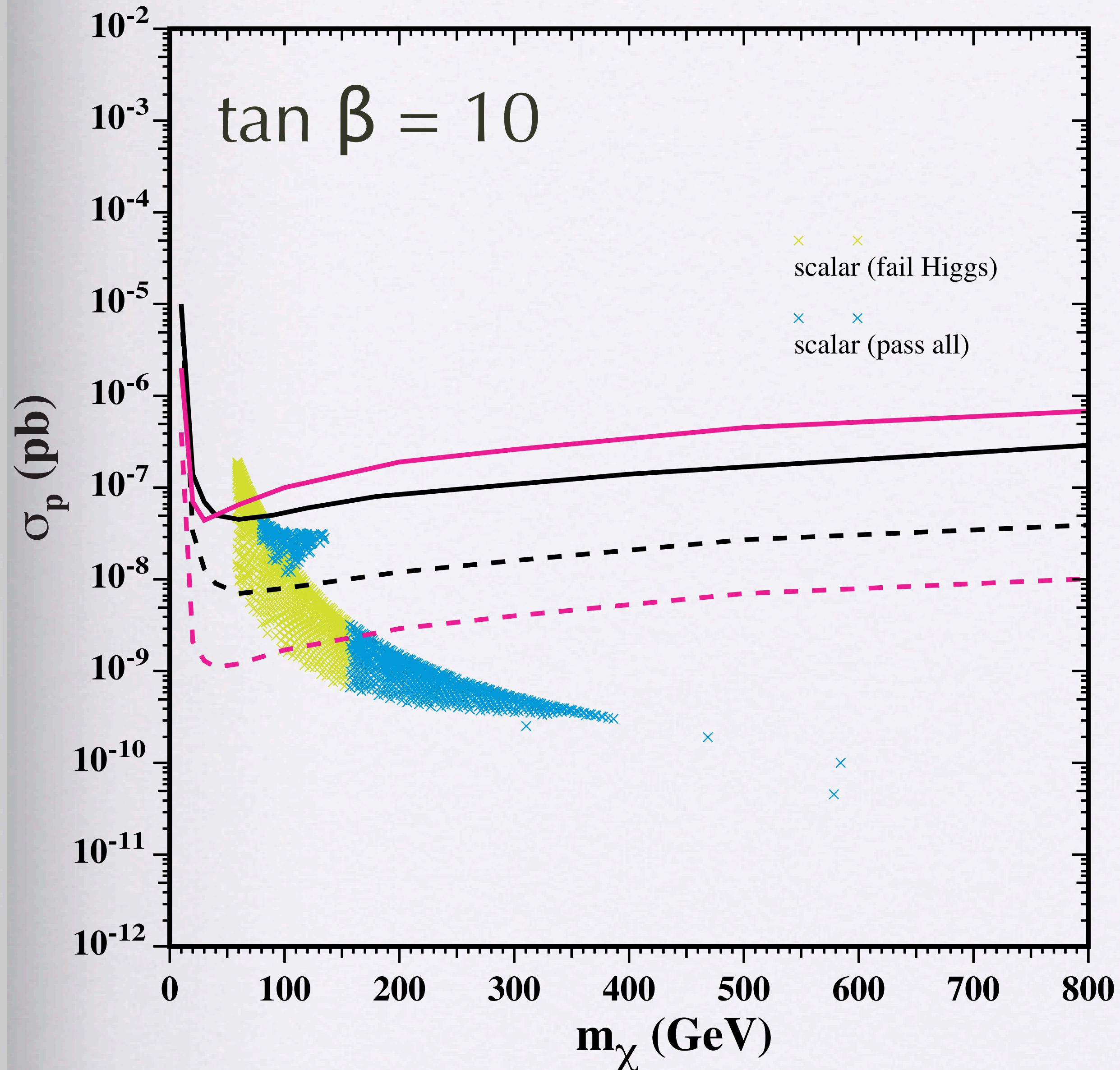
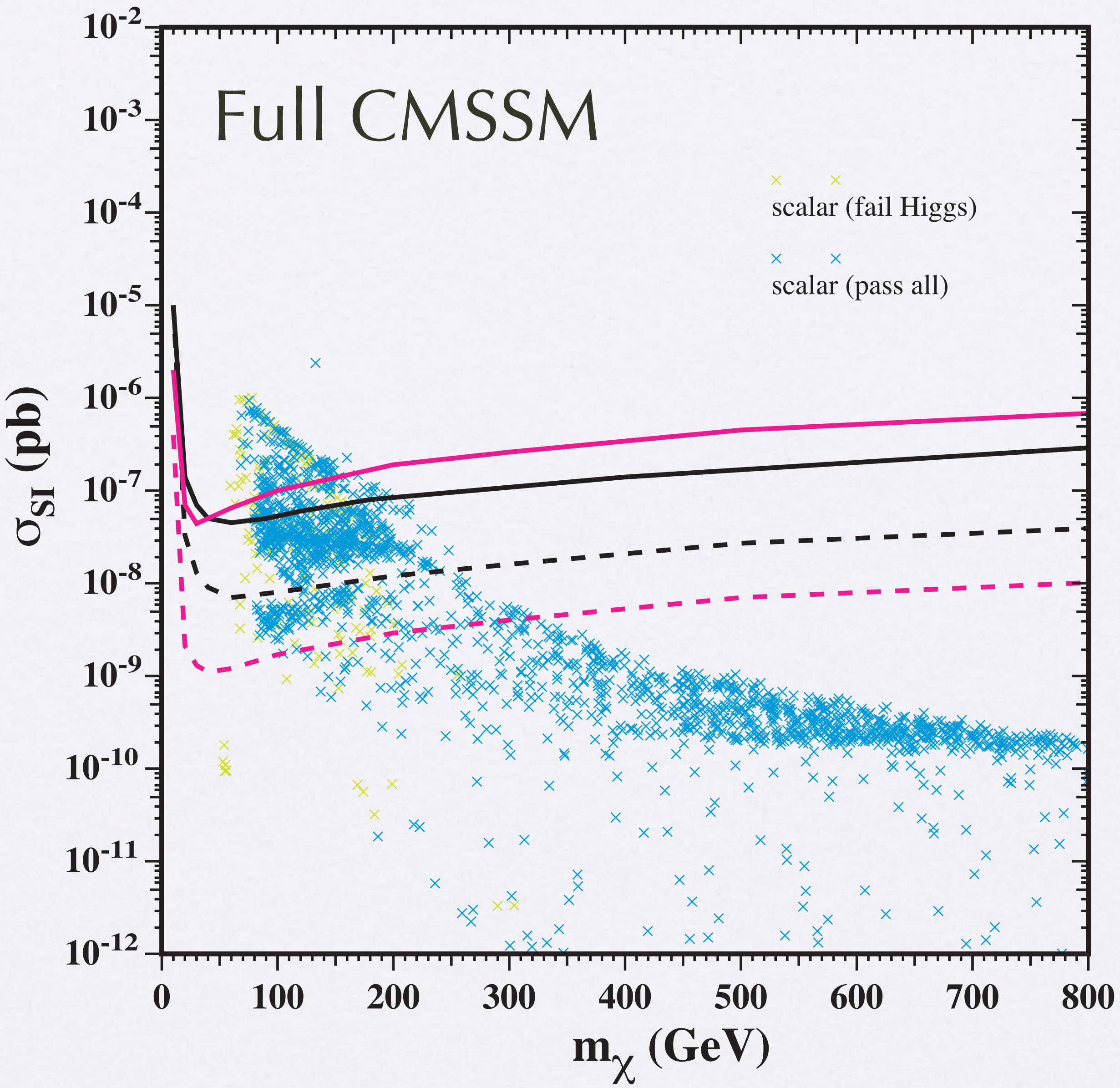


Recall foliation
in tan β

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

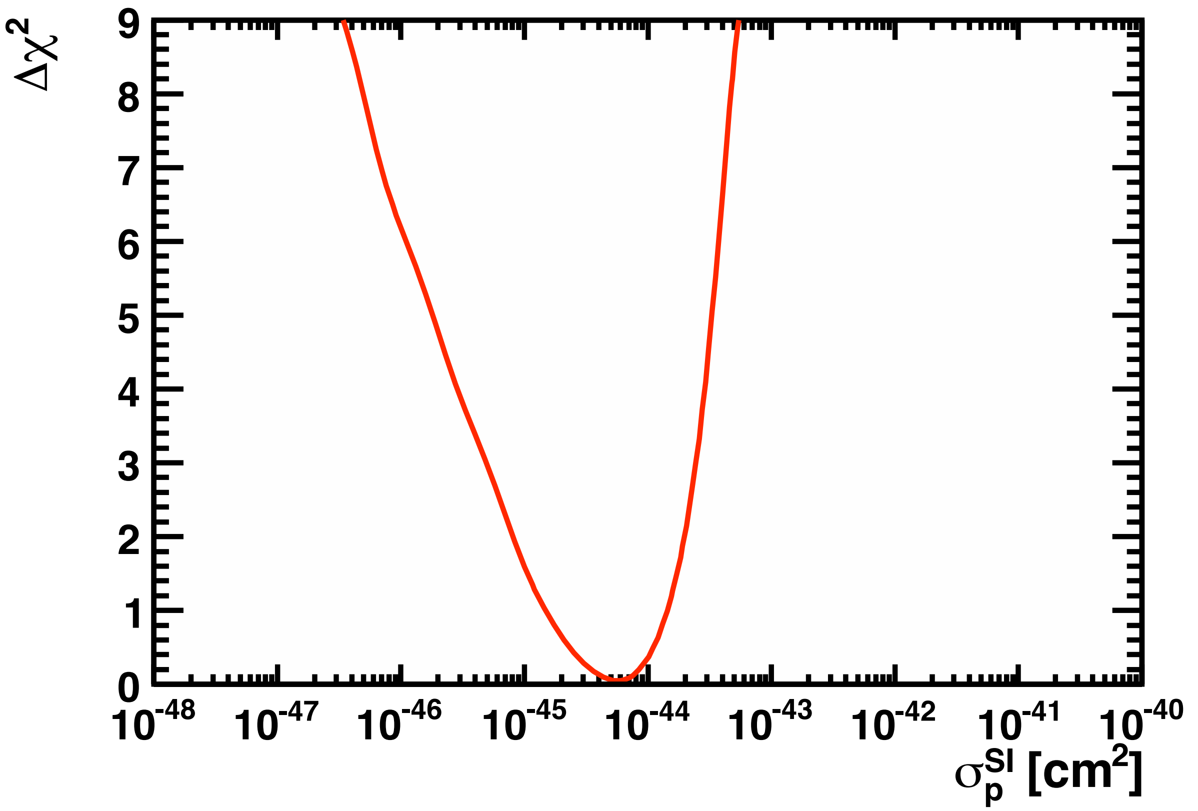
Direct Detection in the CMSSM

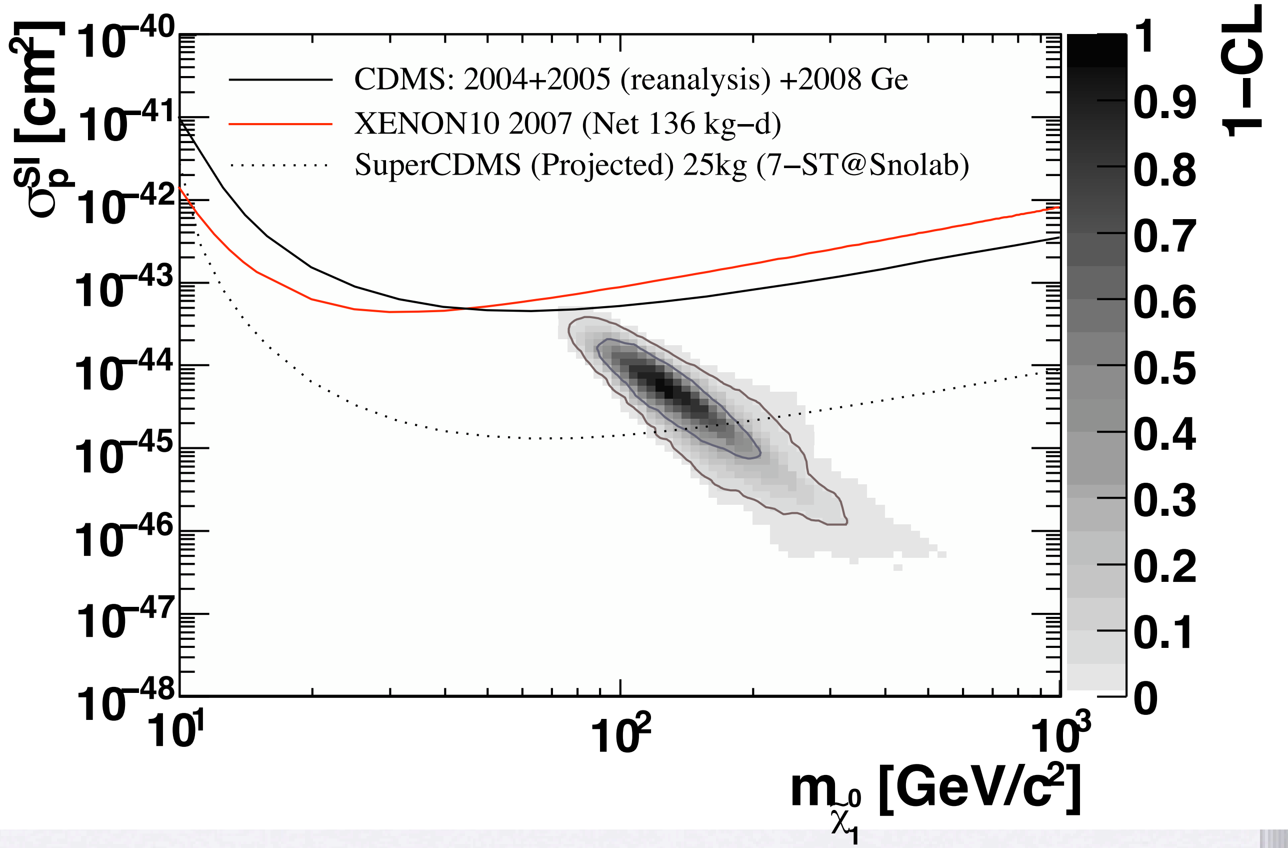




Ellis, Olive, Sandick

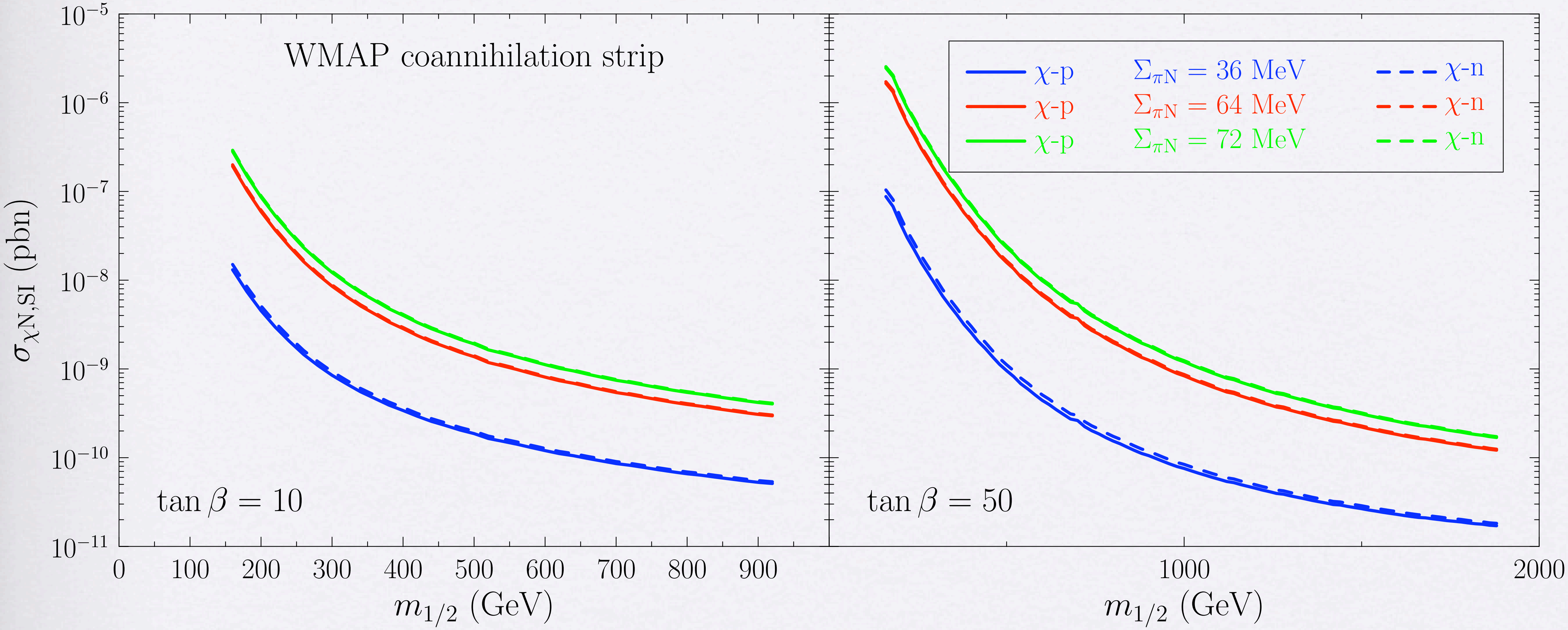
Direct Detection in the CMSSM





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

Uncertainties due to $\Sigma_{\pi N}$

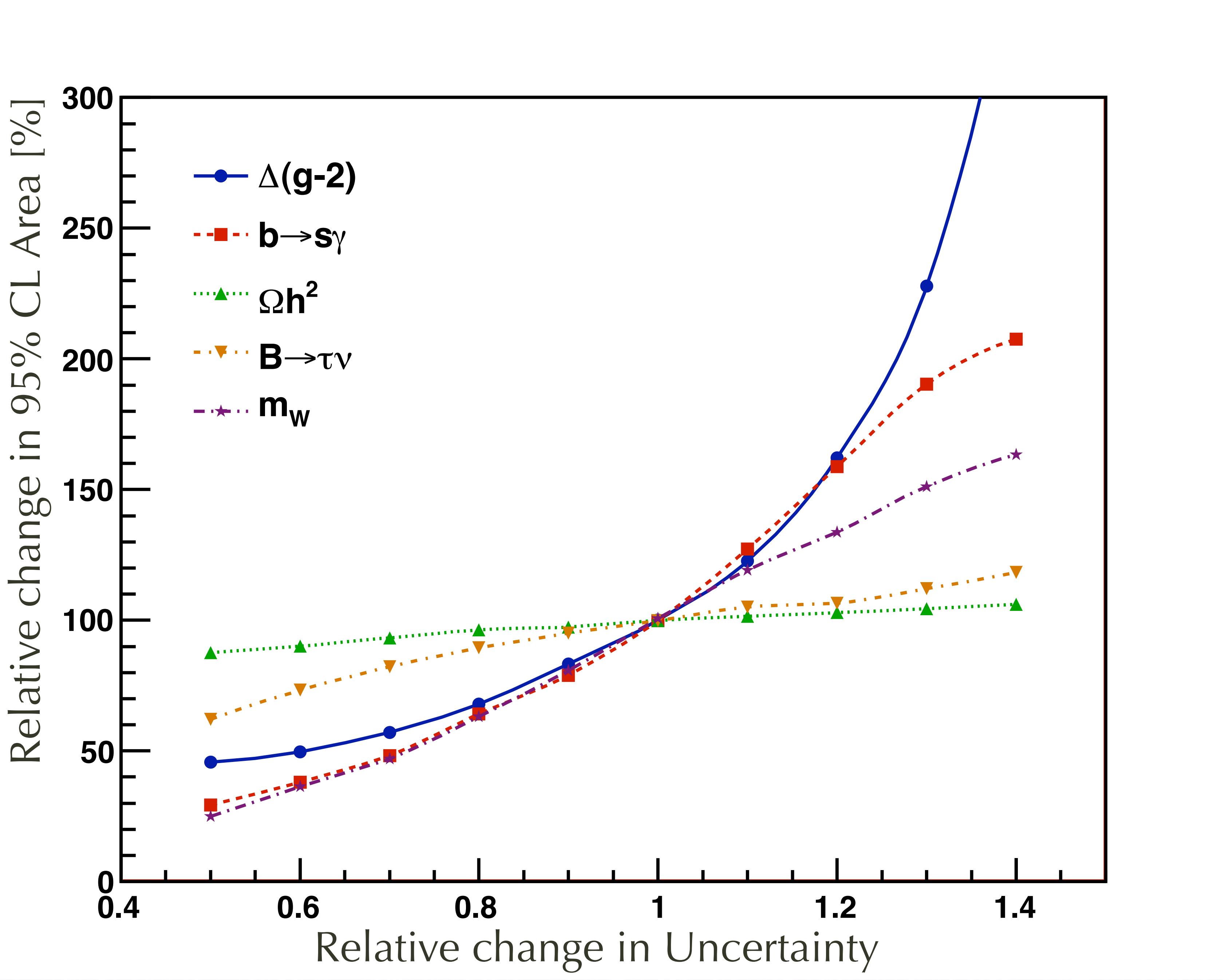


Ellis, Olive, Savage

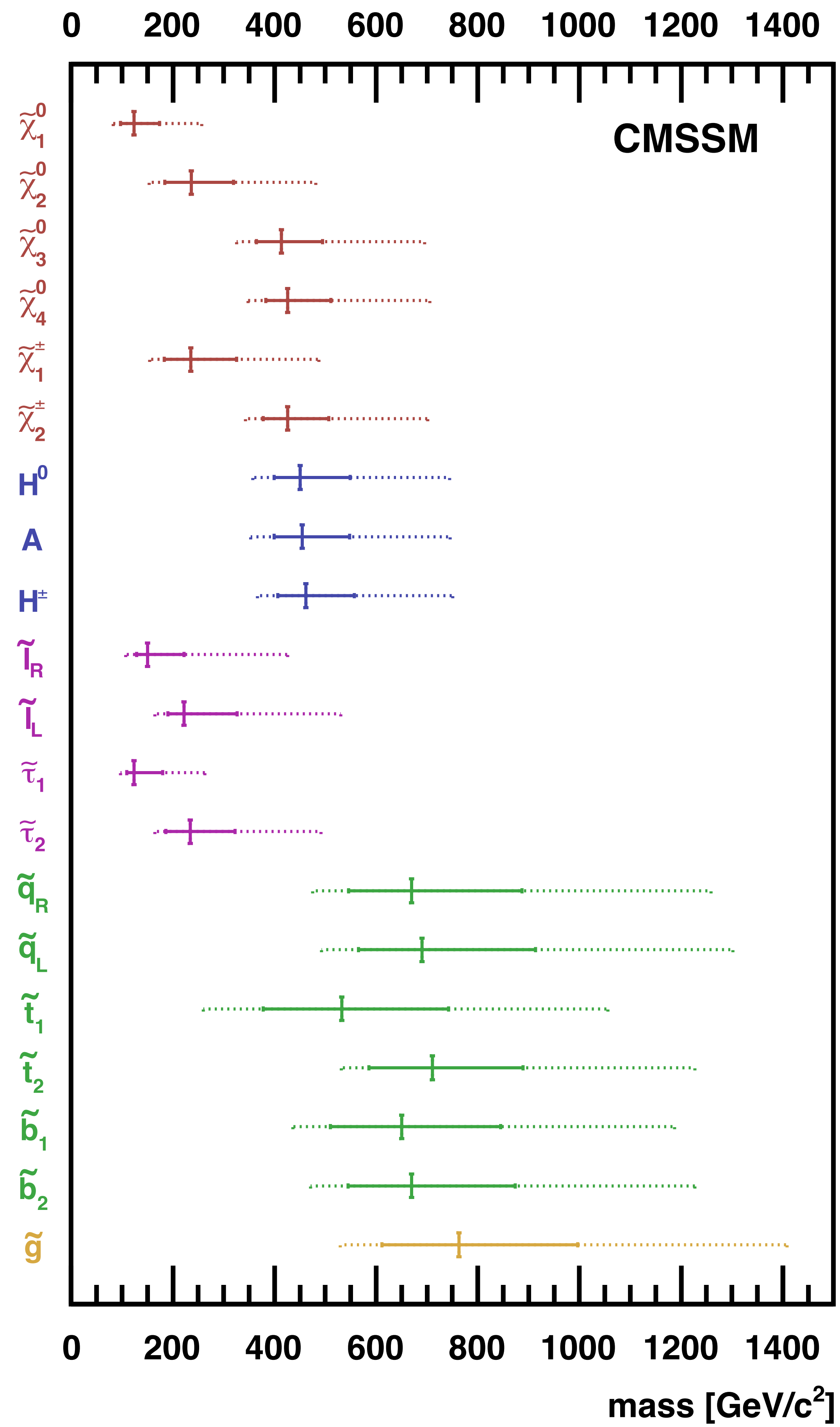
Summary

- Evidence is substantial for BOTH Dark Matter AND Dark Matter
- Dark Energy:
  - Simplest solution - Cosmological Constant which is consistent with all observations to date -
  - More complicated solutions such as quintessence also possible with consequences for new phenomena such as variable constants
- Dark Matter:
  - Requires Beyond the Standard Model Physics!
  - Neutralino Dark Matter exciting prospect from the points of view of the LHC and Direct Detection Experiments

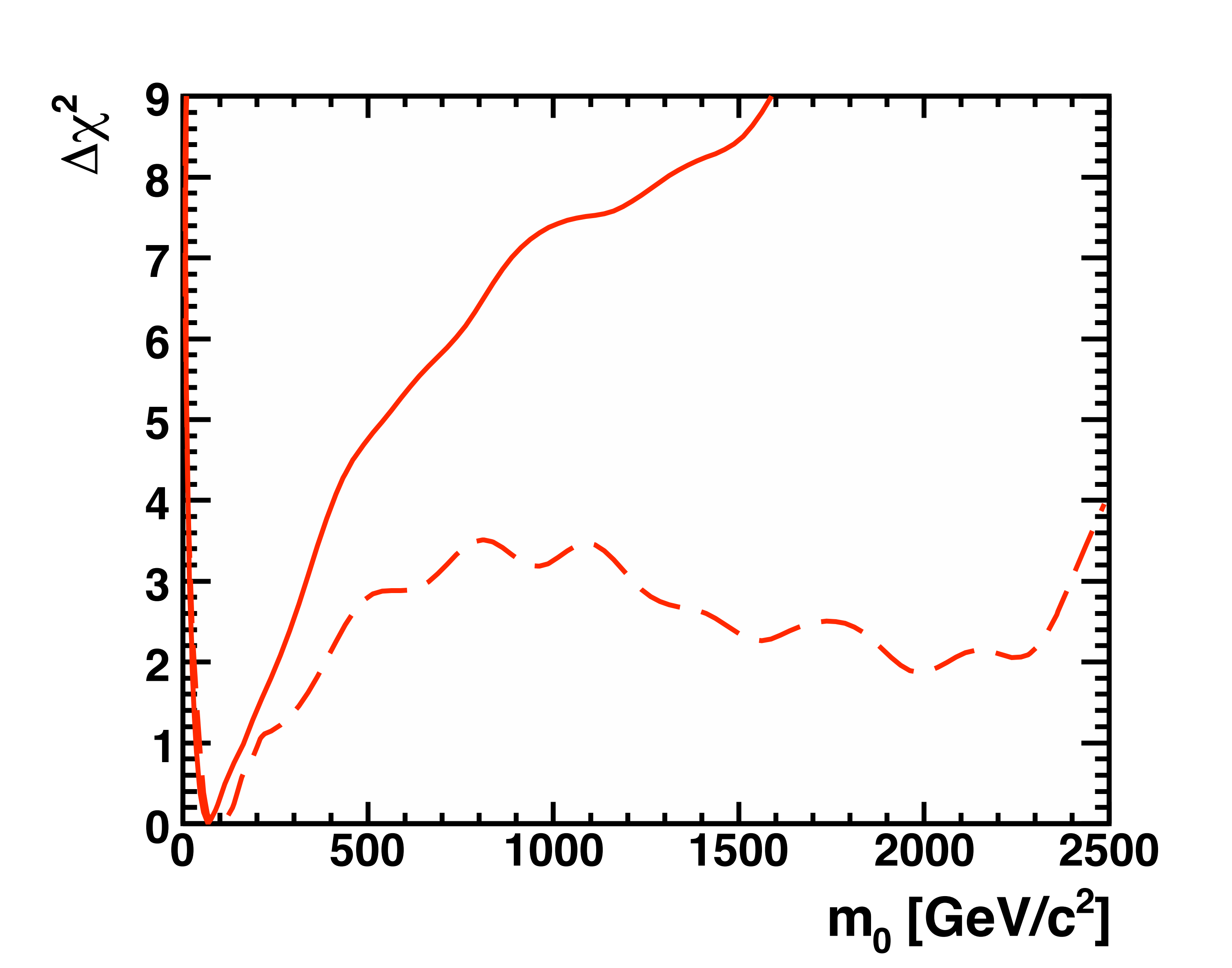
Sensitivity to uncertainties



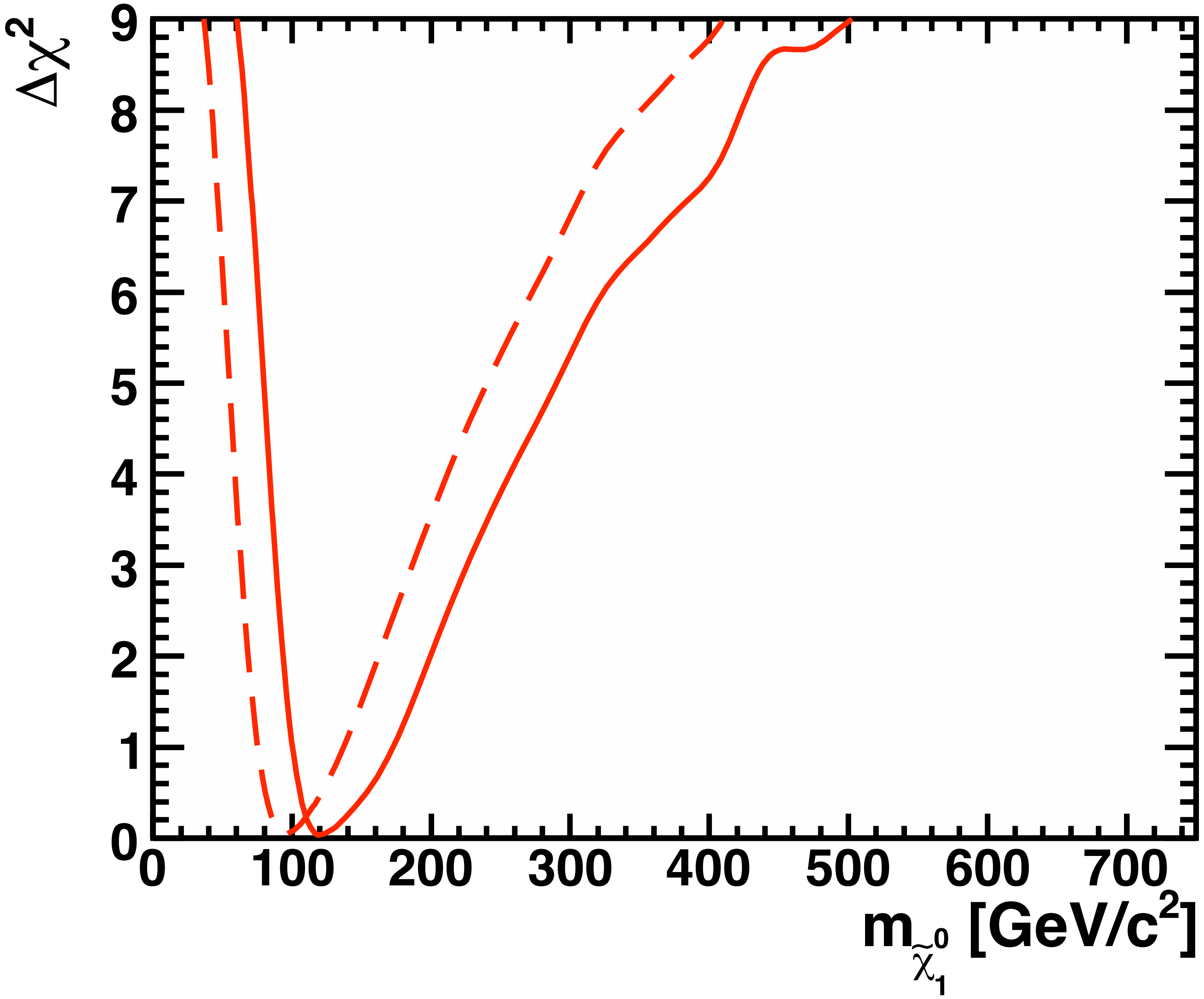
Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Paradisi, Ronga, Weiglein



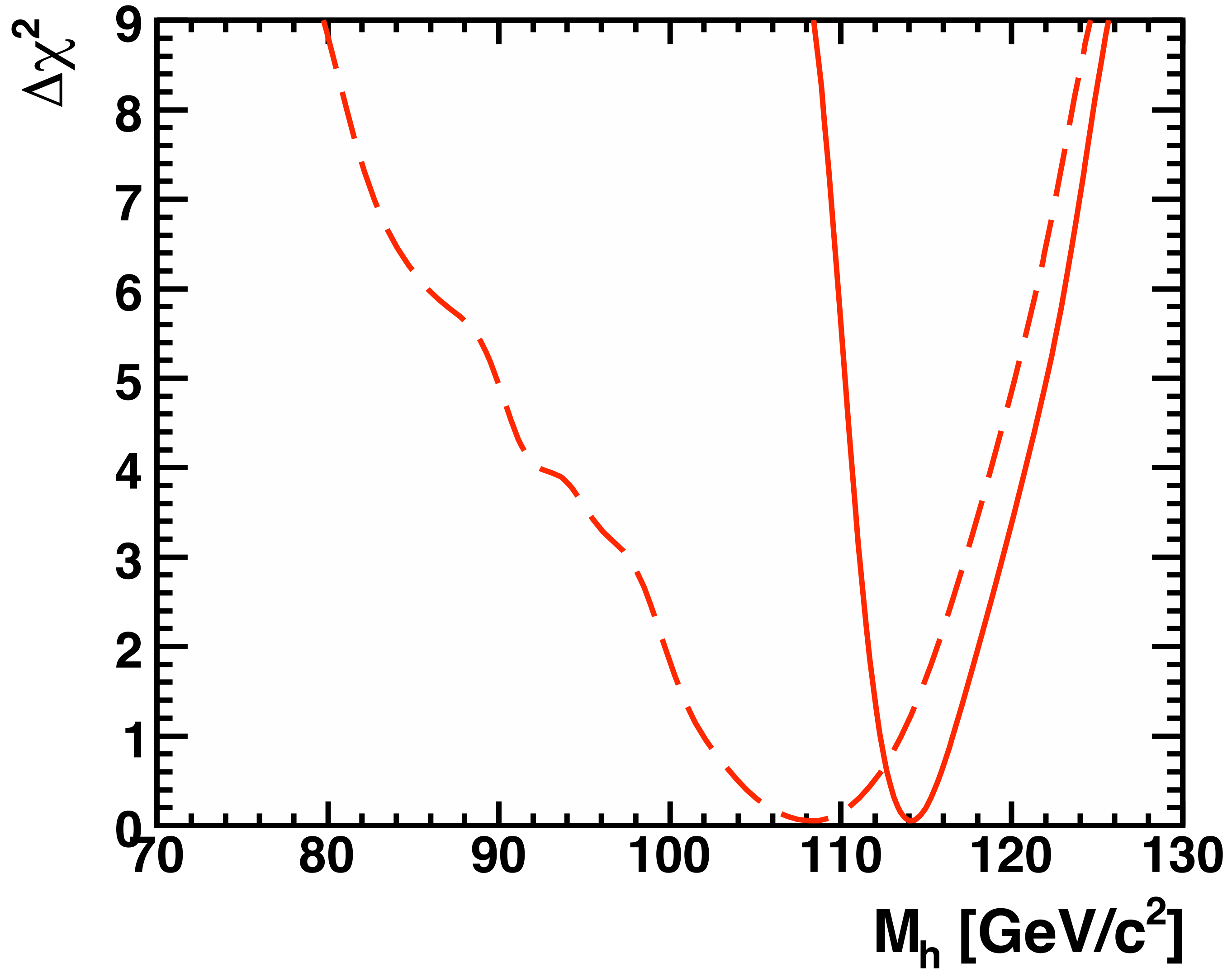
0
200
400
600
800
1000
1200
1400
CMSSM
$\tilde{\chi}_1^0$
$\tilde{\chi}_2^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_4^0$
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_2^\pm$
H^0
A
$H^\pm$
$\tilde{l}_R$
$\tilde{l}_L$
$\tilde{\tau}_1$
$\tilde{\tau}_2$
$\tilde{q}_R$
$\tilde{q}_L$
$\tilde{t}_1$
$\tilde{t}_2$
$\tilde{b}_1$
$\tilde{b}_2$
$\tilde{g}$
mass [GeV/c^2]



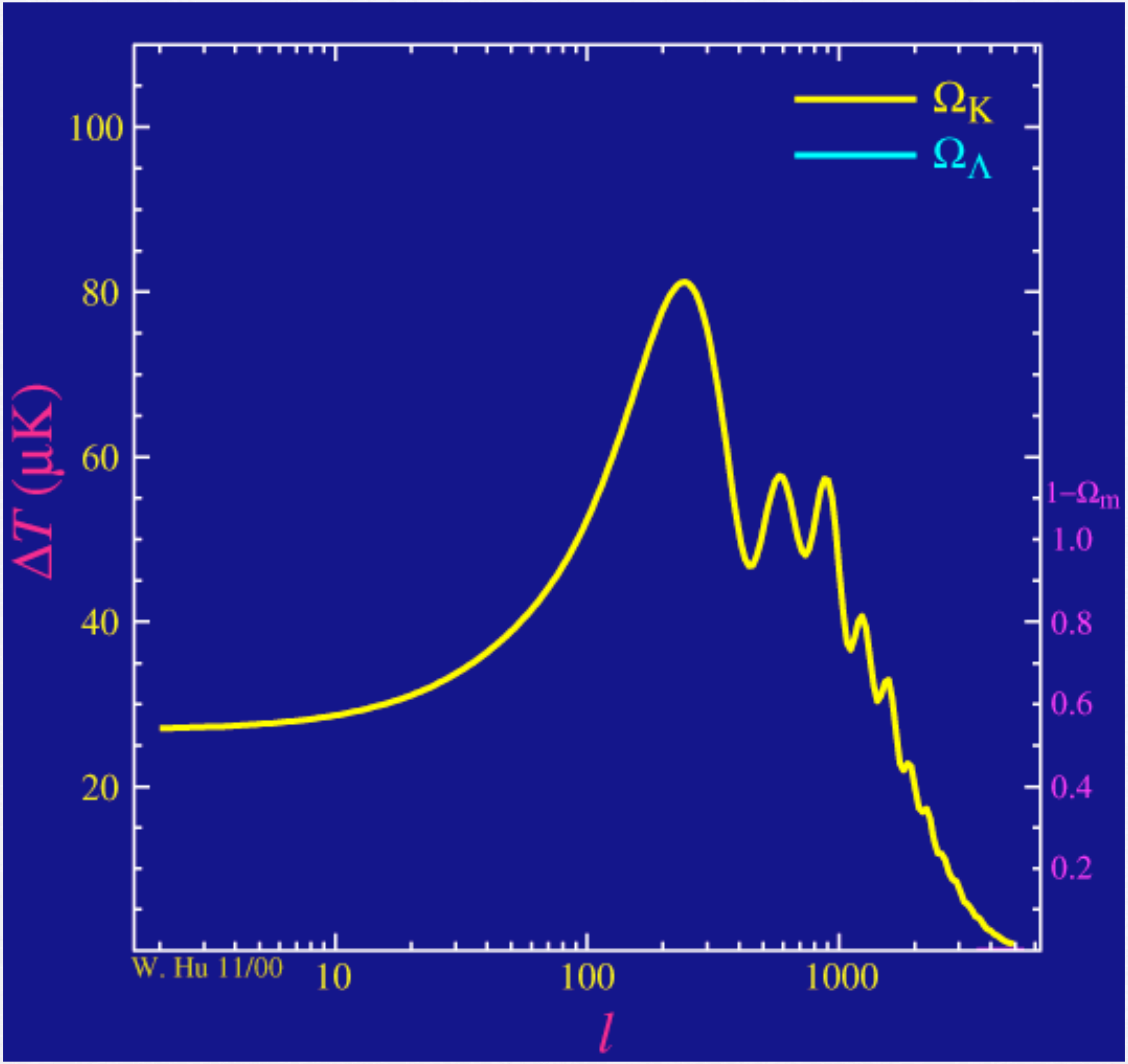
$\Delta\chi^2$
9
8
7
6
5
4
3
2
1
0
0
500
1000
1500
2000
2500
m_0 [GeV/c^2]



$\Delta\chi^2$
0
1
2
3
4
5
6
7
8
9
0
100
200
300
400
500
600
700
$m_{\tilde{\chi}_1^0}$ [GeV/c^2]

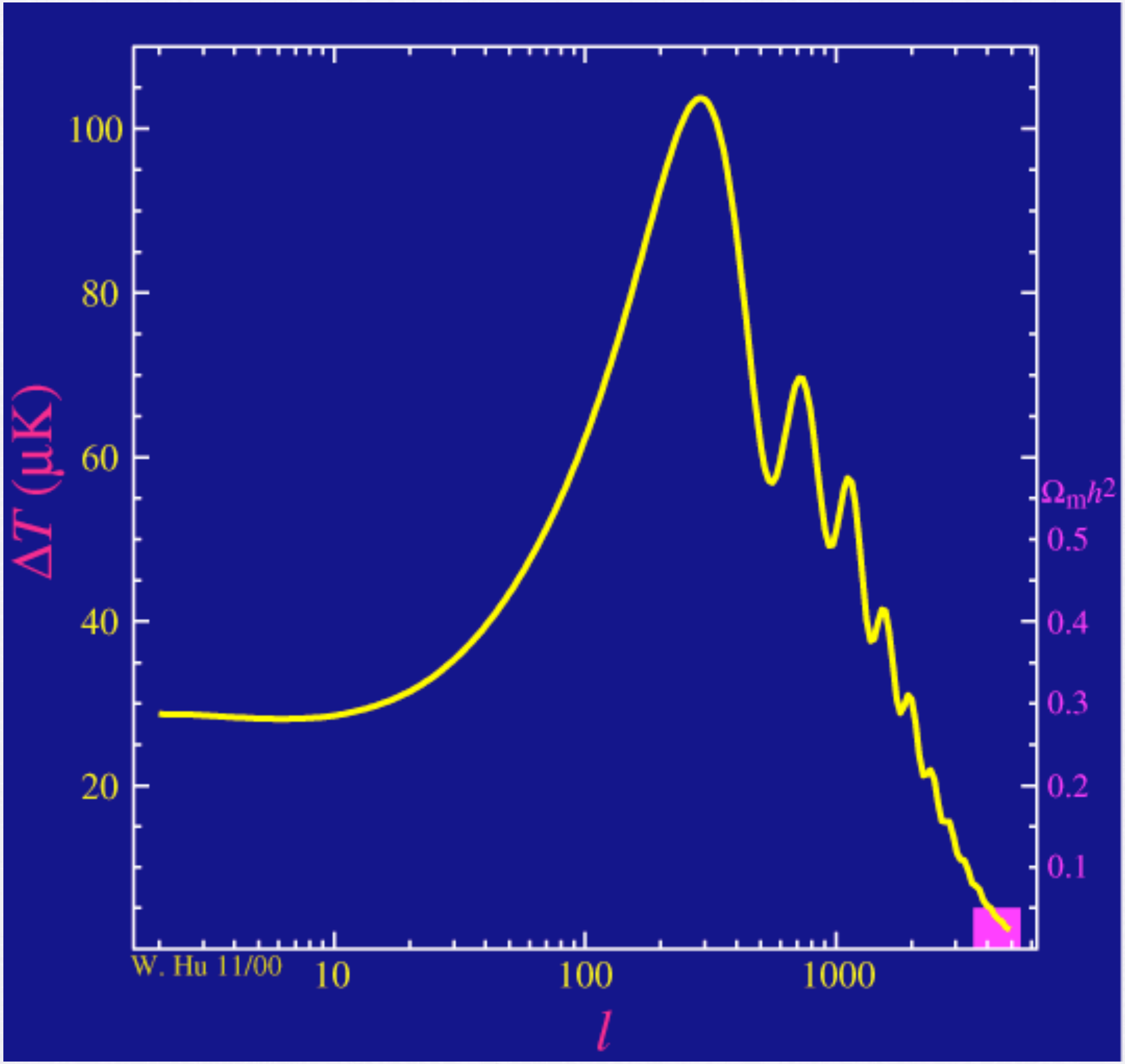


$\Delta\chi^2$
9
8
7
6
5
4
3
2
1
0
70
80
90
100
110
120
130
M_h [GeV/c^2]



ΔT (μK)
100
80
60
40
20
Ω_K
Ω_Λ
$1-\Omega_m$
1.0
0.8
0.6
0.4
0.2
W. Hu 11/00
10
100
1000
l

Wayne Hu



100
80
60
40
20
ΔT (μK)
$\Omega_m h^2$
0.5
0.4
0.3
0.2
0.1
W. Hu 11/00
10
100
1000
l

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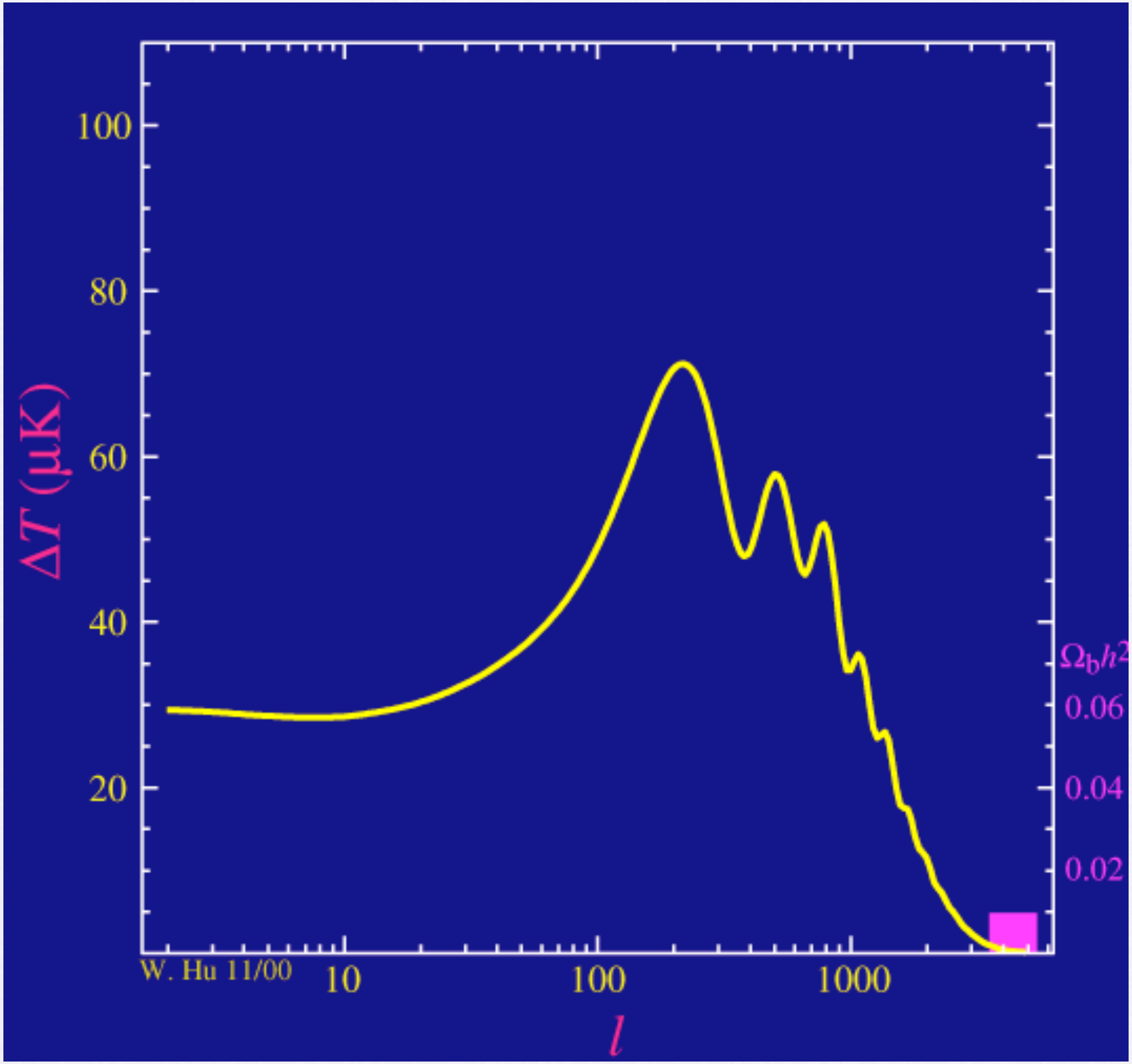

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Cosmological Parameters:

Hubble parameter	h
Cosmological constant	Ω_Λ
Dark matter density	$\Omega_{\rm dm}$
Baryon density	$\Omega_{\rm B}$
Radiation density	$\Omega_{\rm rad}$
Neutrino density	Ω_ν
Density perturbation amplitude	$\mathcal{P}_{\mathcal{R}}(k_*)$
Density perturbation spectral index	n
Tensor to scalar ratio	r
Ionization optical depth	τ

$\Omega = 1.011 \pm 0.012$

	WMAP alone	WMAP + 2dF	WMAP + all
$\Omega_{\rm m}h^2$	0.128 ± 0.008	0.126 ± 0.005	0.132 ± 0.004
$\Omega_{\rm b}h^2$	0.0223 ± 0.0007	0.0222 ± 0.0007	0.0219 ± 0.0007
h	0.73 ± 0.03	0.73 ± 0.02	$0.704^{+0.015}_{-0.016}$
n	0.958 ± 0.016	0.948 ± 0.015	0.947 ± 0.015
τ	0.089 ± 0.030	0.083 ± 0.028	$0.073^{+0.027}_{-0.028}$
σ_8	0.76 ± 0.05	0.74 ± 0.04	0.78 ± 0.03

Lahav + Liddle