PRECISION DARK MATTER PHYSICS

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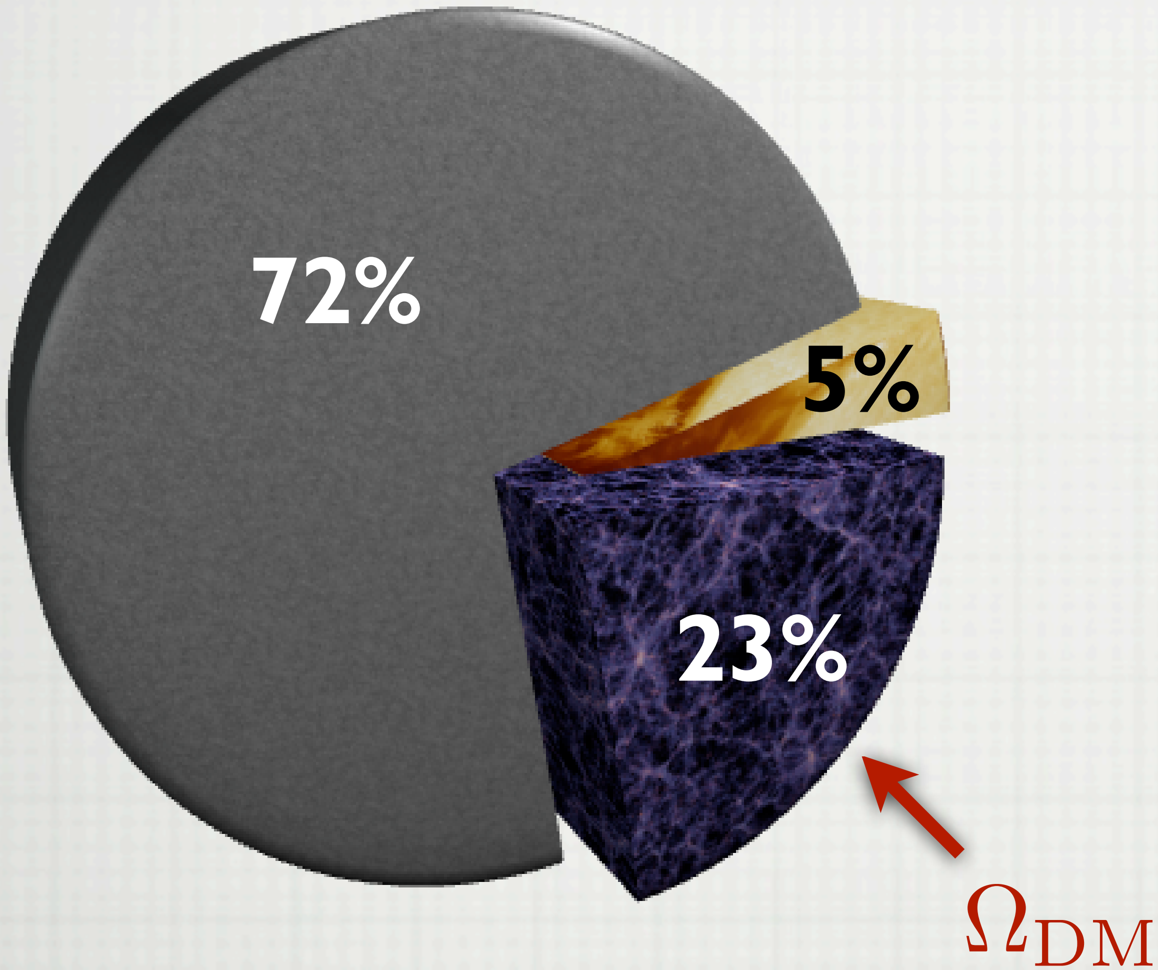
OUTLINE

1. Dark matter & particle physics
2. SUSY & dark matter
3. Precise predictions for DM annihilation
4. Summary

DARK MATTER

- What is the Universe made of ?



Matter density in the Universe

Dark Energy	$\Omega_{\rm DE} \sim 0.726$
Dark Matter	$\Omega_{\rm DM} \sim 0.228$
Ordinary Mat.	$\Omega_{\rm b} \sim 0.046$

$\Omega_{\rm tot} = 1$ ⇒ flat Universe

$$\Omega_x = \frac{\rho_x}{\rho_c} \qquad \rho_c = \frac{3H^2}{8\pi G_N}$$

- The knowledge on the content comes from a wide variety of sources

Cosmic Microwave Background - WMAP

Supernova Red Shifts - SN1a

Big Bang Nucleosynthesis

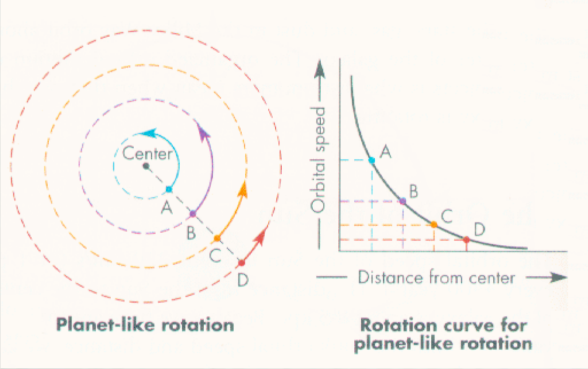
Baryonic Acoustic Oscillation

DARK MATTER

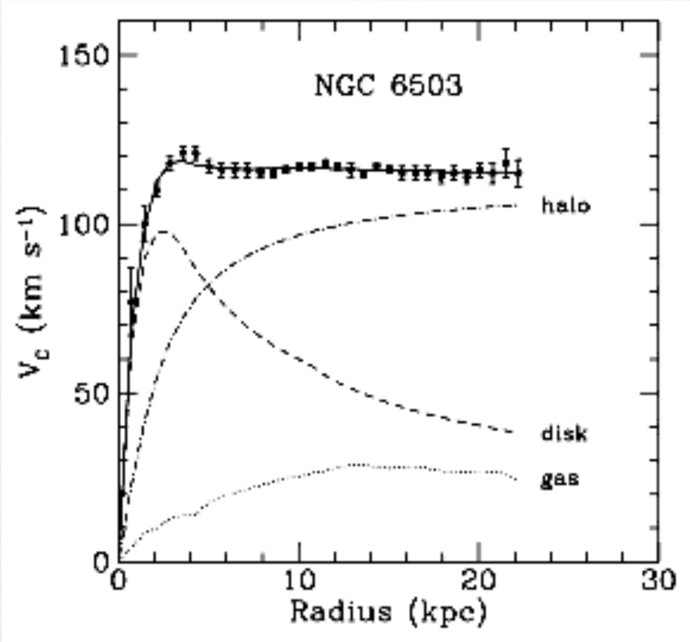
- A few hints /proofs of dark matter

1. Rotation curves of galaxies

Newtonian drop-off of stars' velocities with distance not supported by data



$$\frac{MG}{r^2} = \frac{v^2}{r} \Rightarrow v \sim \frac{1}{\sqrt{r}}$$



Two possible solutions to the flat curve profiles far off the centre of galaxy

1. Not-luminous heavy 'stuff ' making up halos of galaxies - DARK MATTER

2. Gravity works different at galaxy-like scales - Modified Newtonian Dynamics (MOND)

DARK MATTER

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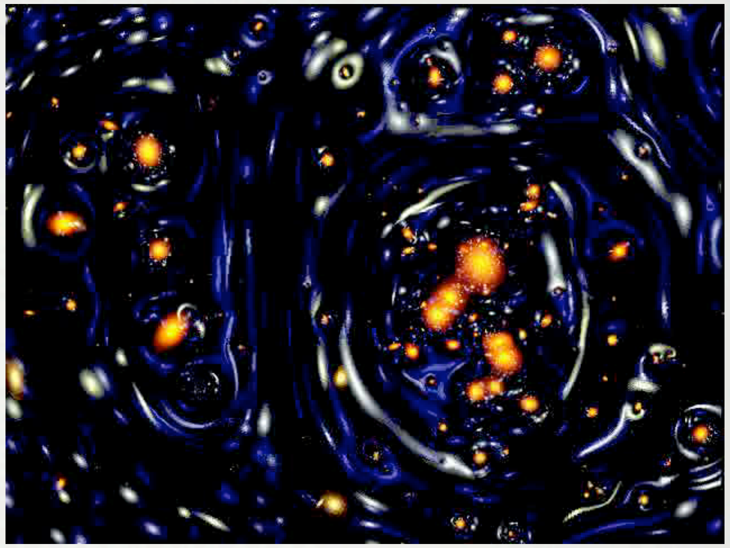
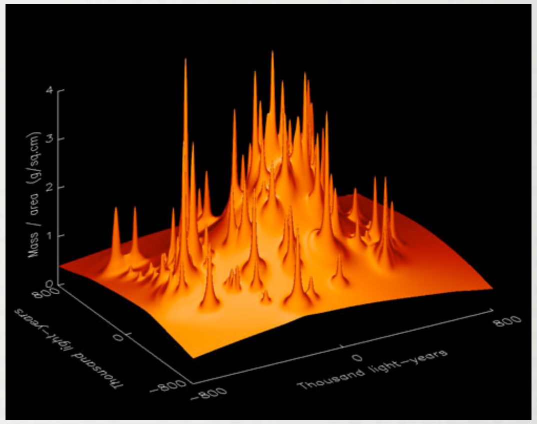


2. Gravitational lensing

Detecting mass in the Universe independent if you can see it or not

⇓

Ideal to search for dark matter even if we don't see it



Strong evidence for Dark Matter provided from combined measurement of galaxy cluster **1E0657-56 (bullet cluster)** by Chandra X-ray observatory & Hubble telescope & VLT

⇕

not only is there 'missing' matter but dark matter & luminous matter are displaced in the bullet cluster due to collision of 2 clusters

Important: no possible explanation with MOND!

DARK MATTER

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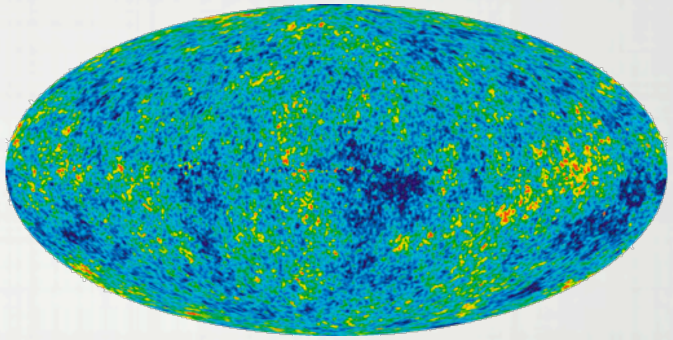
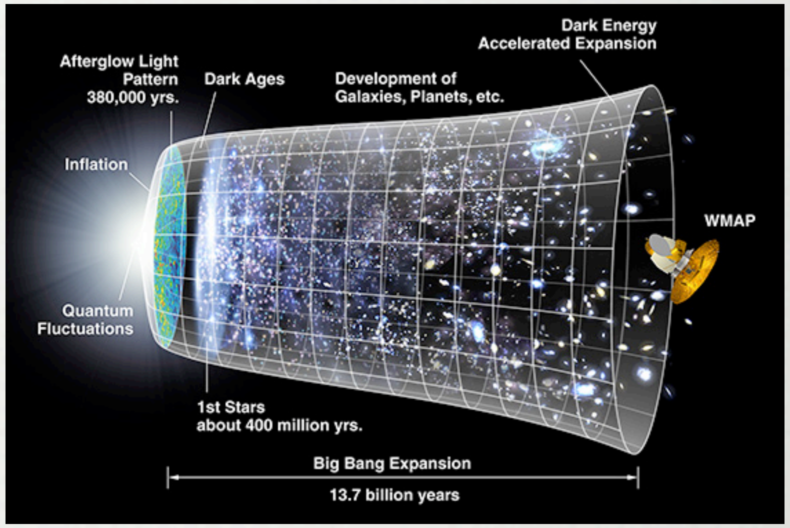
3. Cosmic Microwave Background & Baryonic Acoustic Oscillations



CMB & BAO measurements both test matter density anisotropies in the early Universe

CMB photons stem from 300'000 years after the Big Bang - provide picture of early Universe



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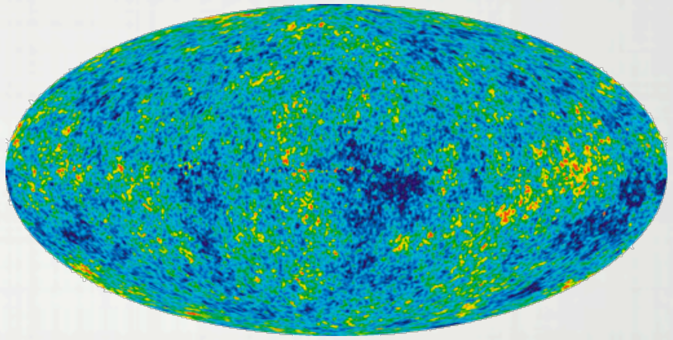

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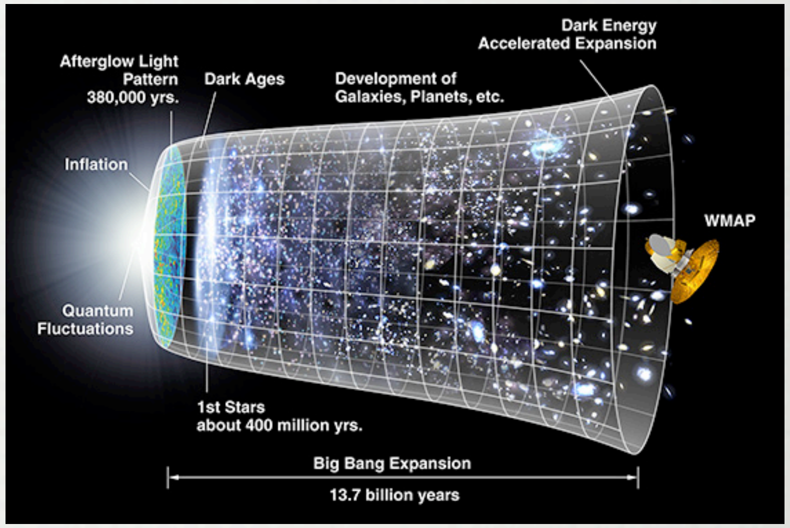

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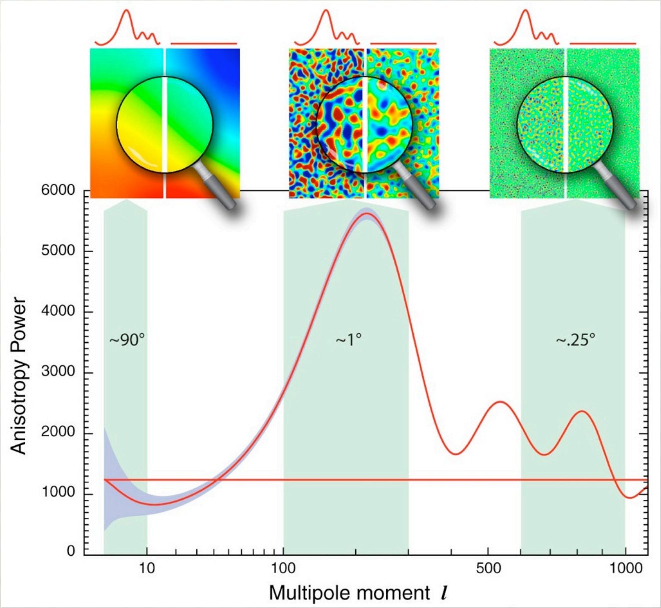
WMAP (Wilkinson Microwave Anisotropy Probe)
- relic radiation temperature maps of the sky
- higher temperature = higher density in the early Universe
- scale of anisotropies ...



Fitting data from WMAP with a Lambda CDM model
- the only quantitative measure of DARK MATTER density

$$\Omega_{\rm CDM}h^2 = 0.1123 \pm 0.0035$$

[WMAP 7-year data + BAO - Komatsu *et al.* arXiv: 1001.4538 (astro-ph)]

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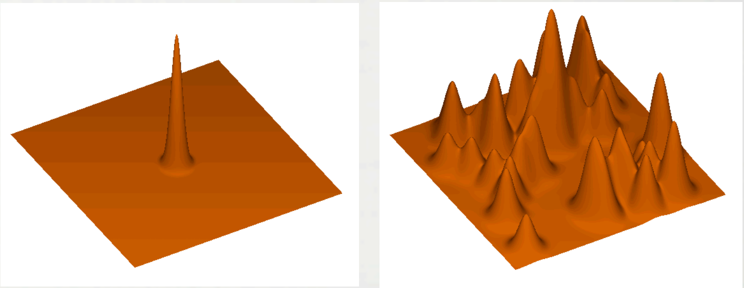
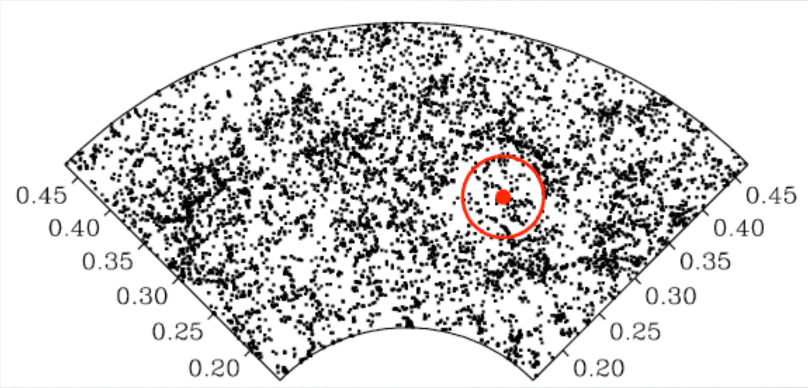
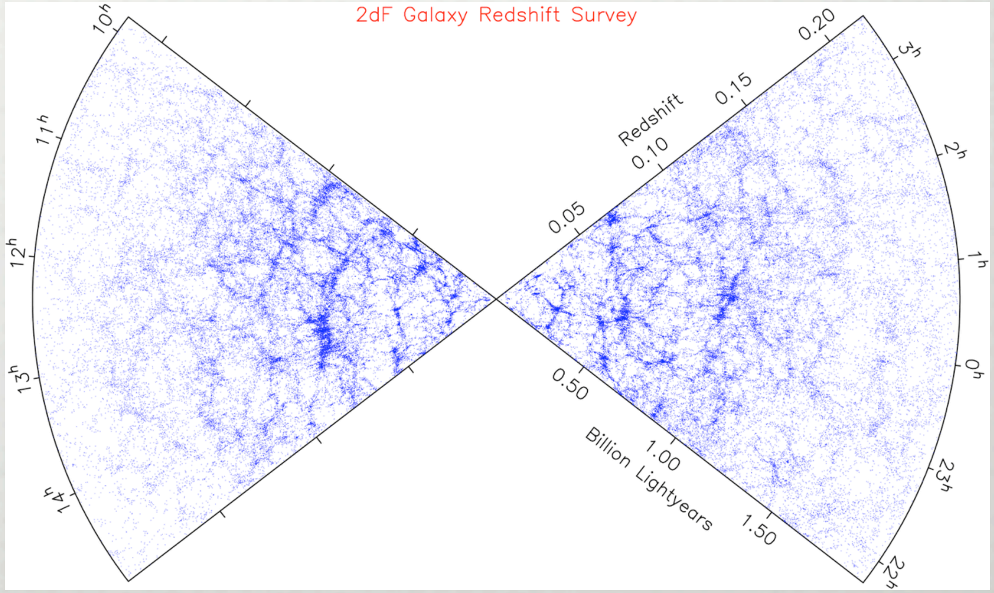


BAO - searching for acoustic peak coming from 'sound waves' in the early Universe in galaxy distributions



Sloan Digital Sky Survey & 2dF Galaxy Redshift Survey - large galaxy mapping efforts (>40000 galaxies each)



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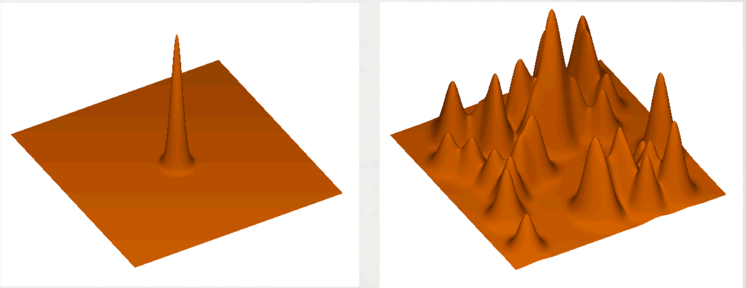

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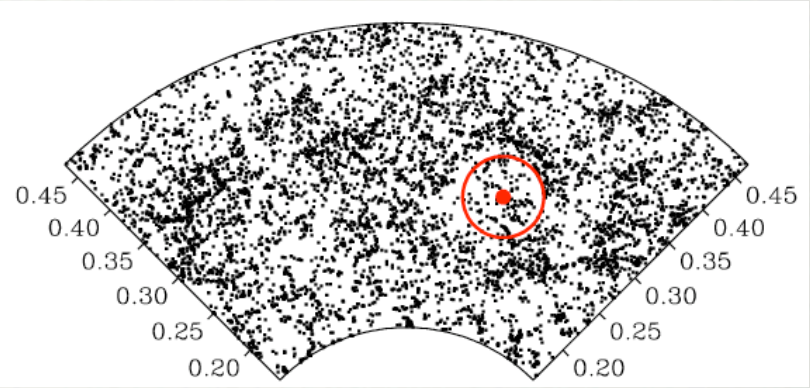
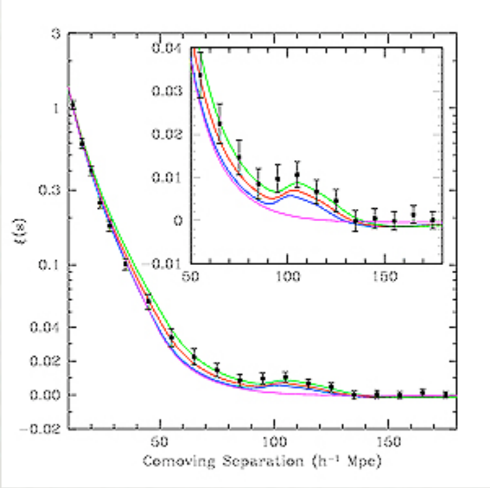
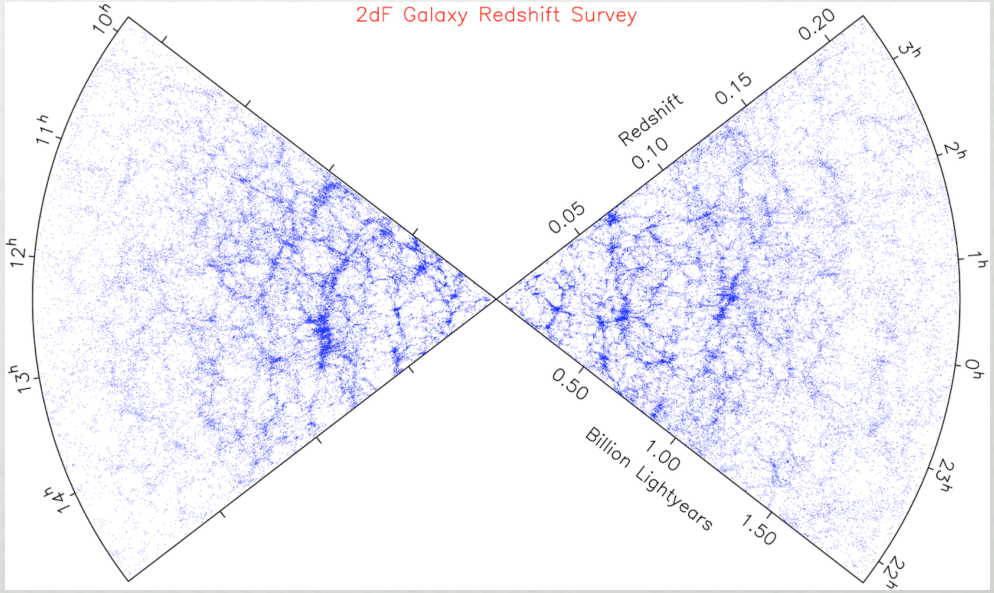


Sloan Digital Sky Survey & 2dF Galaxy Redshift Survey
- large galaxy mapping efforts (>40000 galaxies each)

Both SDSS & 2dF GRS **confirm** acoustic peak seen in CMB
- small preference for galaxies to be 150 Mpc apart





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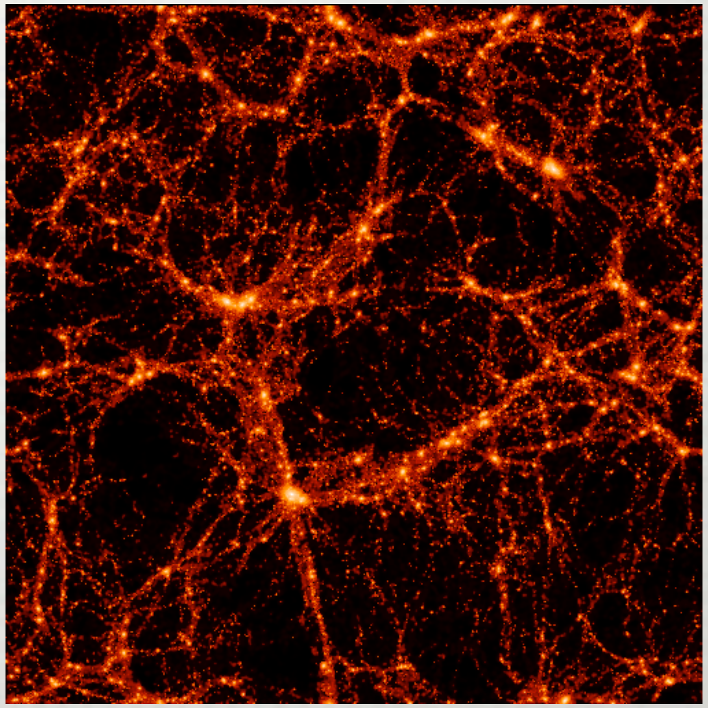
4. Large scale structure simulations

Computer models simulate effects of gravity on small perturbations in the early Universe - birth of galaxies
e.g. Virgo Consortium

Clustering of galaxies and galaxy clusters prefer
COLD DARK MATTER



Cold Dark Matter

- heavy particles with non-relativistic velocities
- slow enough to allow clustering
- in excellent agreement with all cosmological data

DARK MATTER

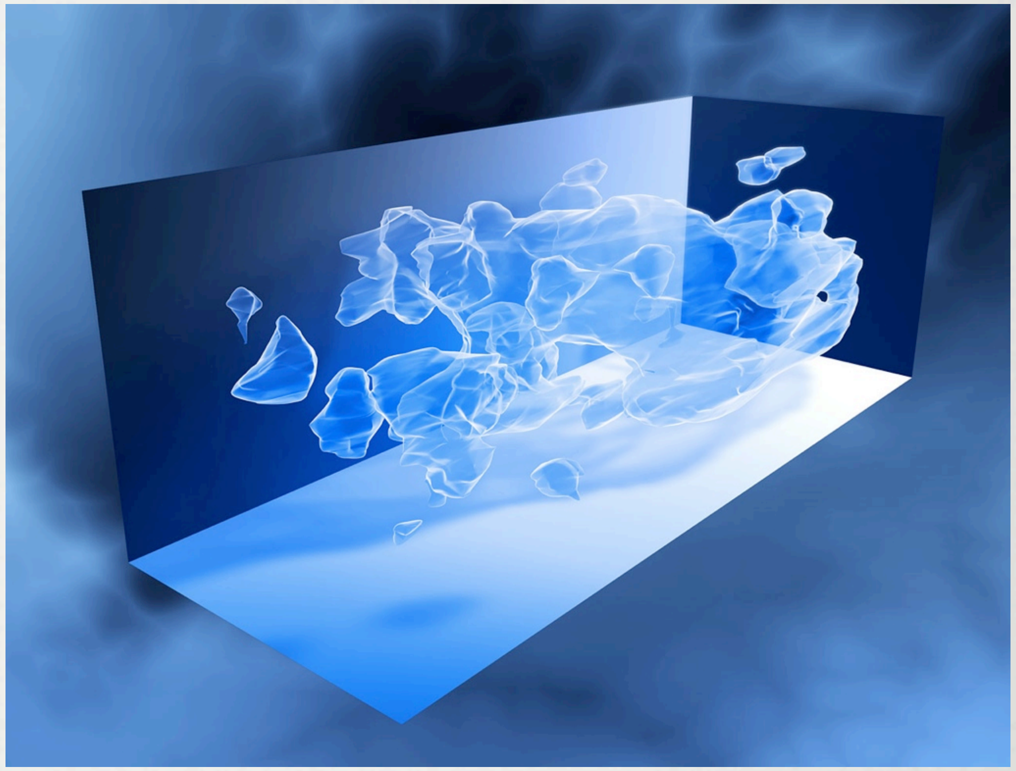
- Summary of what we know about Dark Matter

  - we know that it **exists** and it is present in the galaxies (rotational curves, gravitational lensing)

  - its relic density in the Universe is

$$\Omega_{\mathrm{CDM}} h^2 = 0.1123 \pm 0.0035$$

  - dark matter is cold - non-relativistic heavy particles



- What we don't know about Dark Matter

  - we have no information on exact distribution or local density of dark matter

  - no existing confirmed Dark Matter candidate

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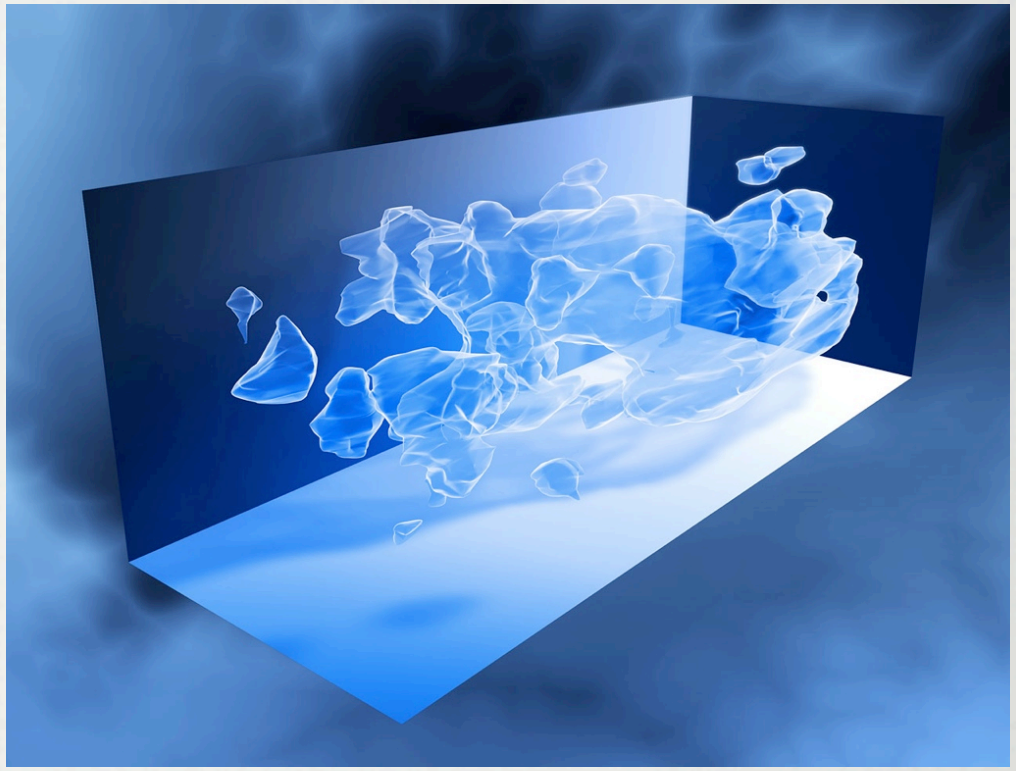

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DARK MATTER - SIGN OF BEYOND THE STANDARD MODEL PHYSICS

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- Dark matter related observables

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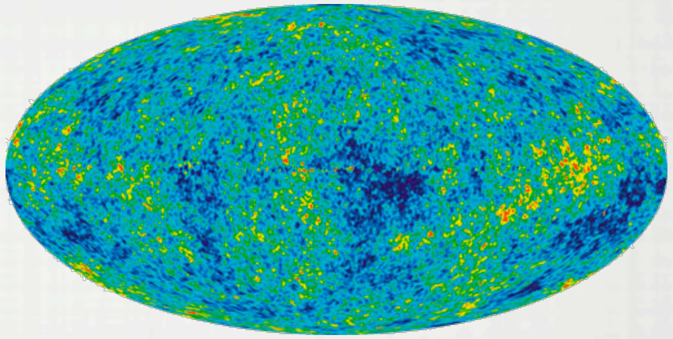
1. Dark matter relic density $\Omega_{\rm CDM}h^2$

   very indirect but precise observable
   - good for consistency check of DM candidates

   COBE, WMAP, Planck



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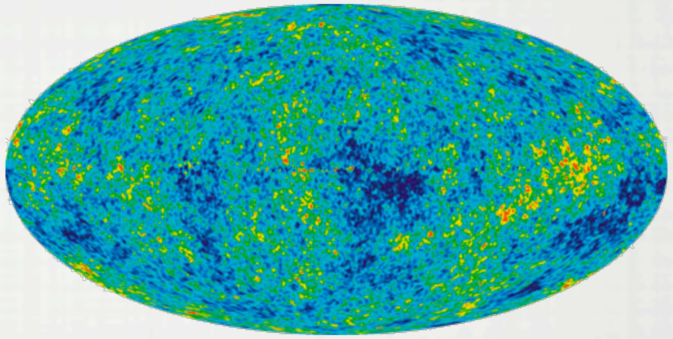


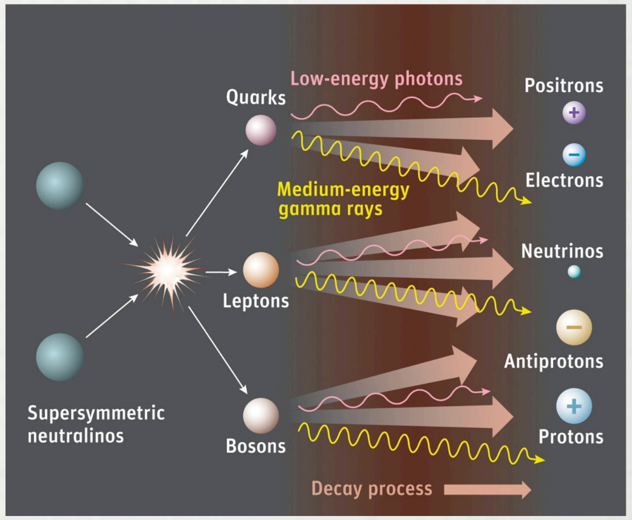
2. Indirect detection of dark matter

   observing products of DM annihilations in galactic halo

   $$e^{\pm}, p^{-}, \gamma, \nu, \bar{\nu}$$

   - difficult to use for a discovery due to huge uncertainties

   Pamela, Fermi/GLAST, AMS, ATIC, HESS, Magic, IceCube, Antares...



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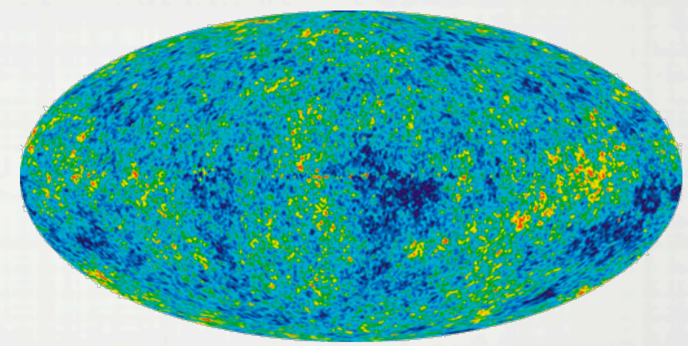

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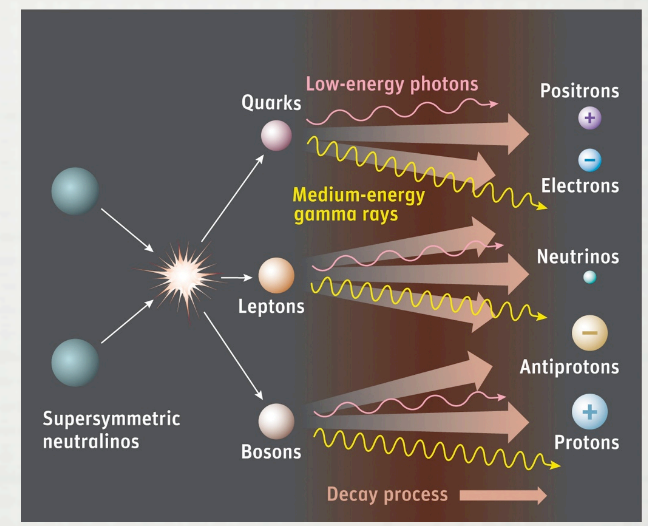
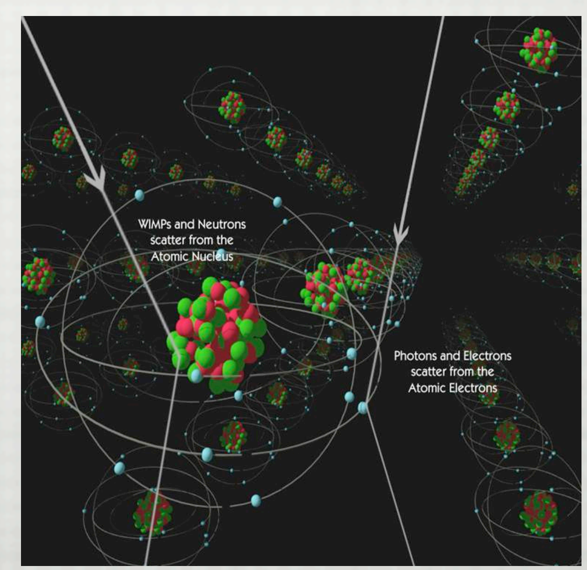


3. Direct detection of dark matter

   detection of nucleus recoil after scattering with DM
   - the only way how to access DM outside of colliders

   CDMS, Xenon, Edelweiss, ALPs, CAST



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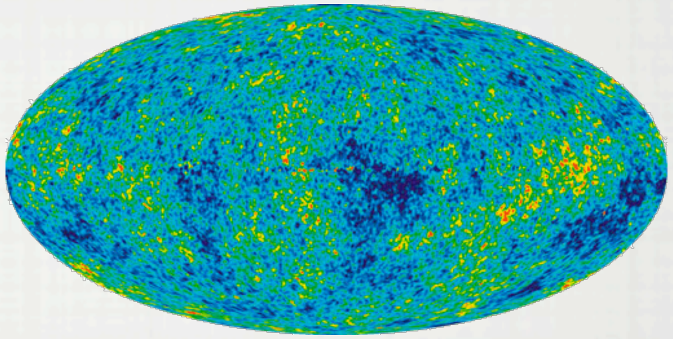

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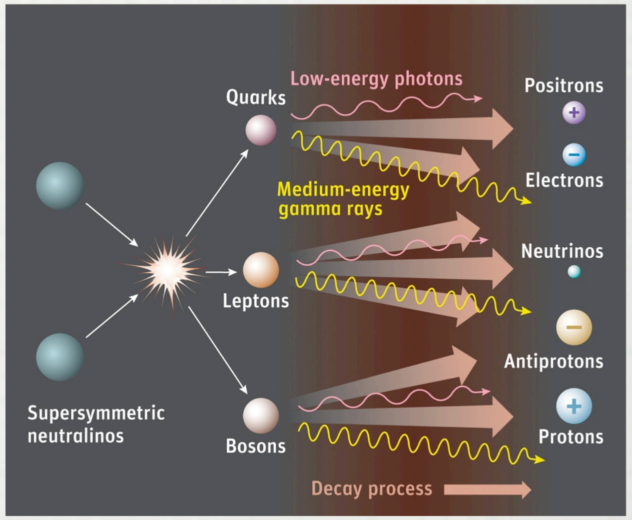

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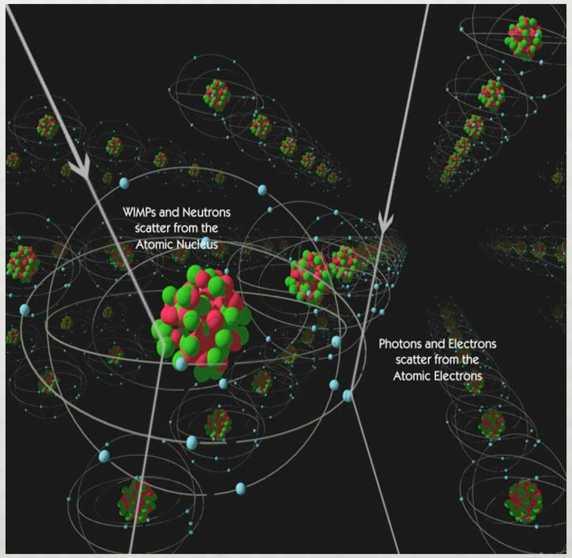
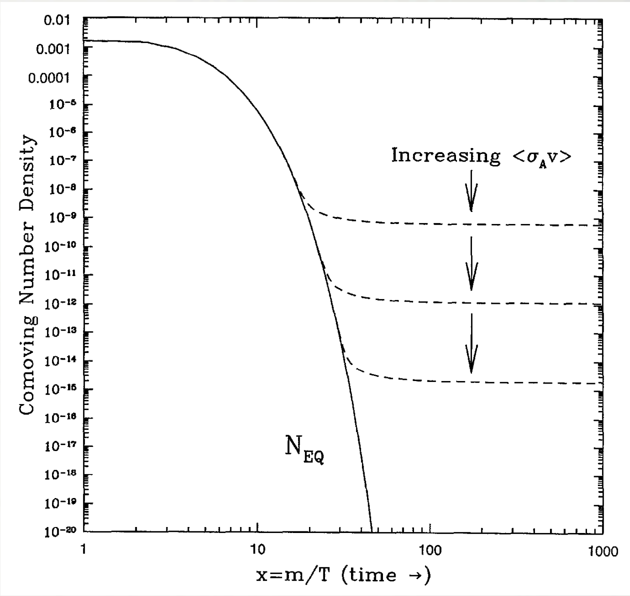


DM RELIC DENSITY

- Mechanism of dark matter survival in the Universe

  - DM density evolution is governed by Boltzmann equation

['90 Kolb & Turner]



$$\hat{\mathbf{L}}[f] = \mathbf{C}[f]$$

Liouville operator - time change for phase-space density

$$\hat{\mathbf{L}}[f] = E\frac{\partial f}{\partial t} - \frac{\dot{R}}{R}|\vec{p}|^2\frac{\partial f}{\partial E} \qquad n_\chi(t) = \frac{g}{(2\pi)^3}\int d^3p_\chi\, f_\chi(E,t)$$

Collision operator written in terms of annihilation & creation ME

$$\frac{g}{(2\pi)^3}\int \mathbf{C}[f]\,\frac{d^3p_\chi}{E_\chi} = -\int d\Pi_\chi (2\pi)^4\delta^4(p_{\chi_a} + p_{\chi_b} - p_i - p_j)$$

$$\times\left[|\mathcal{M}|^2_{\chi\chi\to X_iX_j} f_\chi f_\chi (1\pm f_i)(1\pm f_j) - |\mathcal{M}|^2_{X_iX_j\to\chi\chi} f_i f_j (1\pm f_\chi)(1\pm f_\chi)\right]$$

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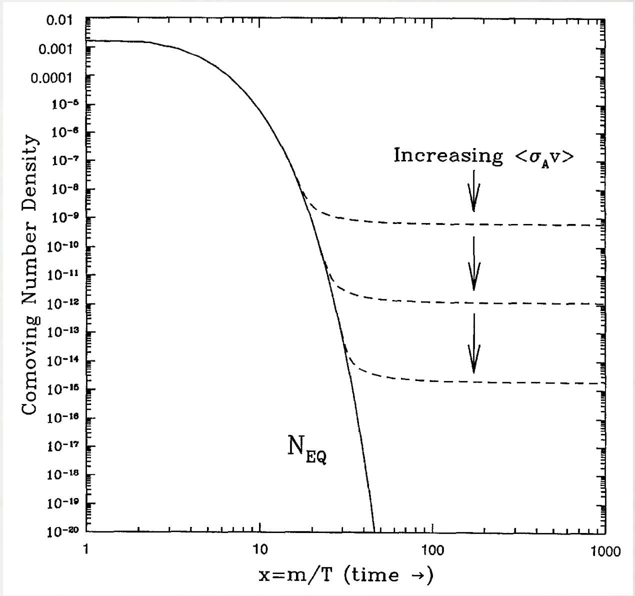

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Number density time (temperature) evolution - Boltzmann equation

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma_{\rm ann}v\rangle\left(n_\chi^2 - (n_\chi^{\rm EQ})^2\right) \qquad \text{Hubble parameter}\quad H = \frac{\dot{R}}{R}$$

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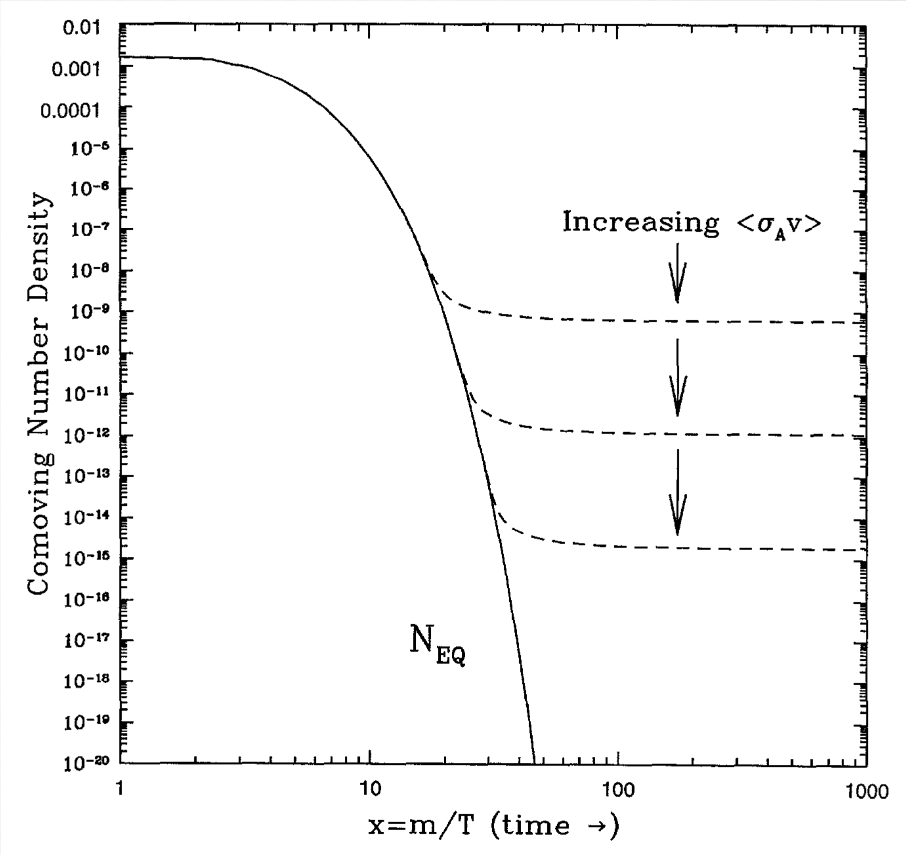
- Dark matter as a thermal relic

3 regimes given by the Boltzmann equation - $$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma_{\rm ann} v\rangle \big(n_\chi^2 - (n_\chi^{\rm EQ})^2\big)$$



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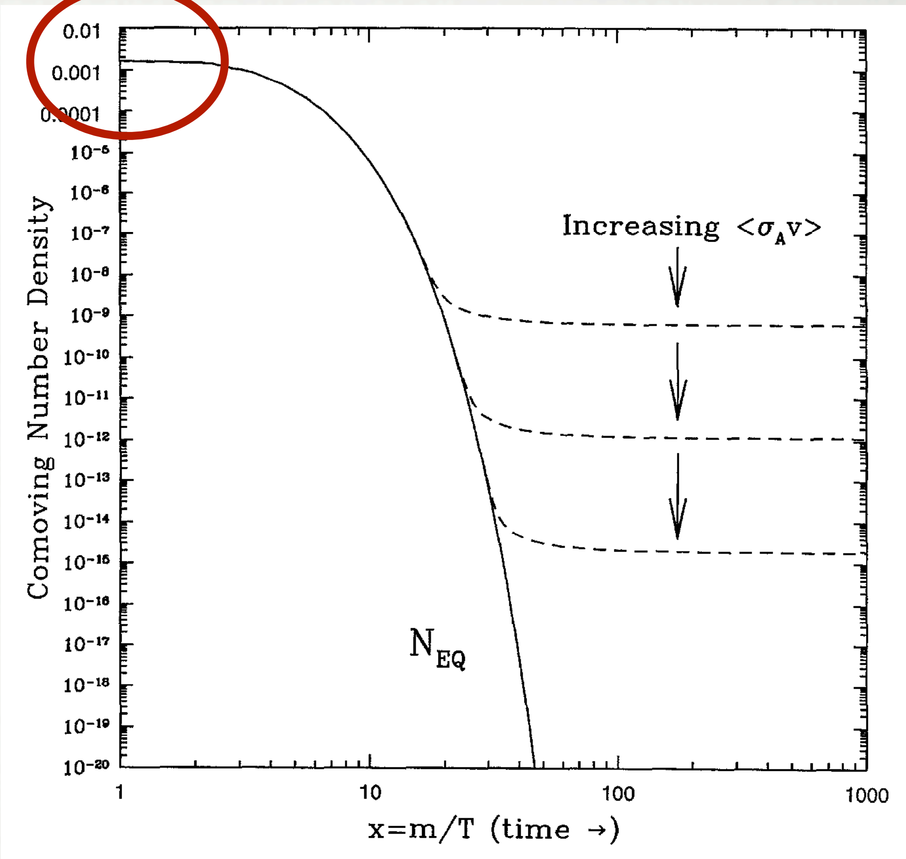
  1. thermal equilibrium stage - T≫m early in Universe annihilation and production processes compensate SM particles energetic enough to create DM



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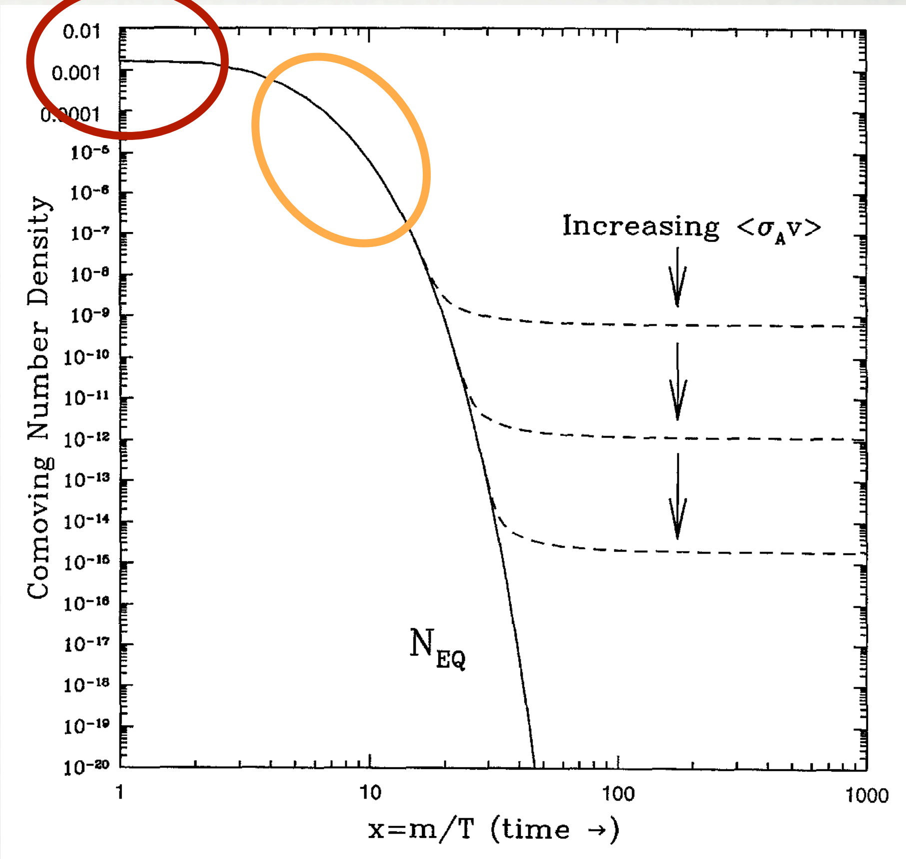

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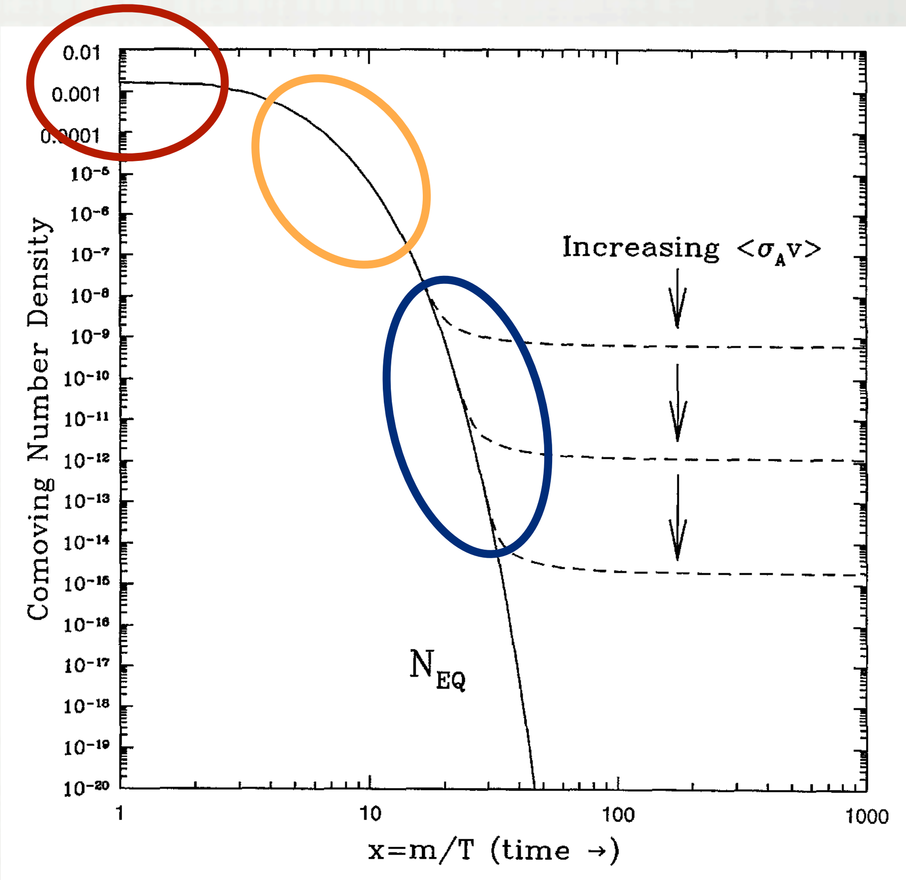

  2. **annihilation stage** - T~ m/10
     annihilation takes over as the SM particles not energetic enough to create DM (are in equilibrium with photons which cool down)

  3. **freeze-out** - T_F
     annihilation ineffective as the expansion diluted DM too much ⇒ DM survives in abundance

SUSY & DM

- Dark matter annihilation cross-section = weakly interacting massive particle

$$\Omega_\chi h^2 = \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{< \sigma v >}$$

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- **Minimal Supersymmetric Standard Model** (with R-parity)

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Superfield	Particle	Spin	Superpartner	Spin
$\hat{V}_1$	B_μ	1	$\tilde{B}$	$\frac{1}{2}$
$\hat{V}_2$	W^i_μ	1	$\tilde{W}^i$	$\frac{1}{2}$
$\hat{V}_3$	G^a_μ	1	$\tilde{g}^a$	$\frac{1}{2}$
$\hat{Q}$	$Q = (u_L, d_L)$	$\frac{1}{2}$	$\tilde{Q} = (\tilde{u}_L, \tilde{d}_L)$	0
$\hat{U}^c$	$U^c = \bar{u}_R$	$\frac{1}{2}$	$\tilde{U}^c = \tilde{u}^*_R$	0
$\hat{D}^c$	$D^c = \bar{d}_R$	$\frac{1}{2}$	$\tilde{D}^c = \tilde{d}^*_R$	0
$\hat{L}$	$L = (\nu_L, e_L)$	$\frac{1}{2}$	$\tilde{L} = (\tilde{\nu}_L, \tilde{e}_L)$	0
$\hat{E}^c$	$E^c = \bar{e}_R$	$\frac{1}{2}$	$\tilde{E}^c = \tilde{e}^*_R$	0
$\hat{H}_1$	$H_1 = (H^0_1, H^-_1)$	0	$\tilde{H}_1 = (\tilde{H}^0_1, \tilde{H}^-_1)$	$\frac{1}{2}$
$\hat{H}_2$	$H_2 = (H^+_2, H^0_2)$	0	$\tilde{H}_2 = (\tilde{H}^+_2, \tilde{H}^0_2)$	$\frac{1}{2}$

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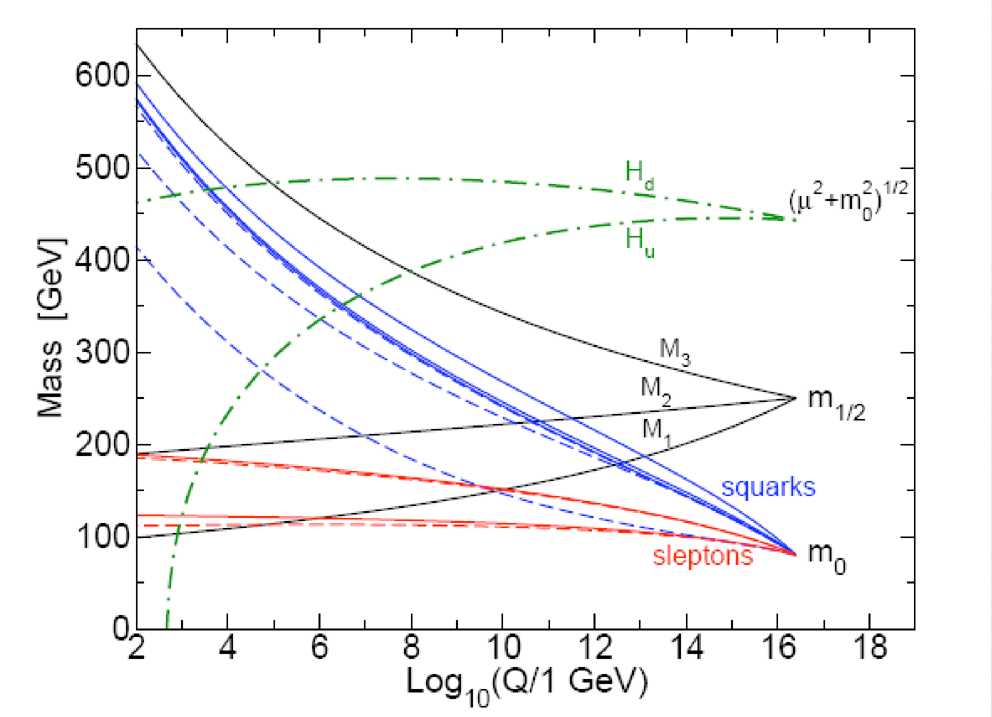


m_0 - universal scalar mass at the GUT scale

$m_{1/2}$ - universal fermion mass at the GUT scale

A_0 - universal trilinear scalar coupling at the GUT scale

tanβ - ratio of vevs at the GUT scale

μ - Higgs superpotential parameter

⇓ RGEs

SUSY mass spectrum at the EW scale + EWSB

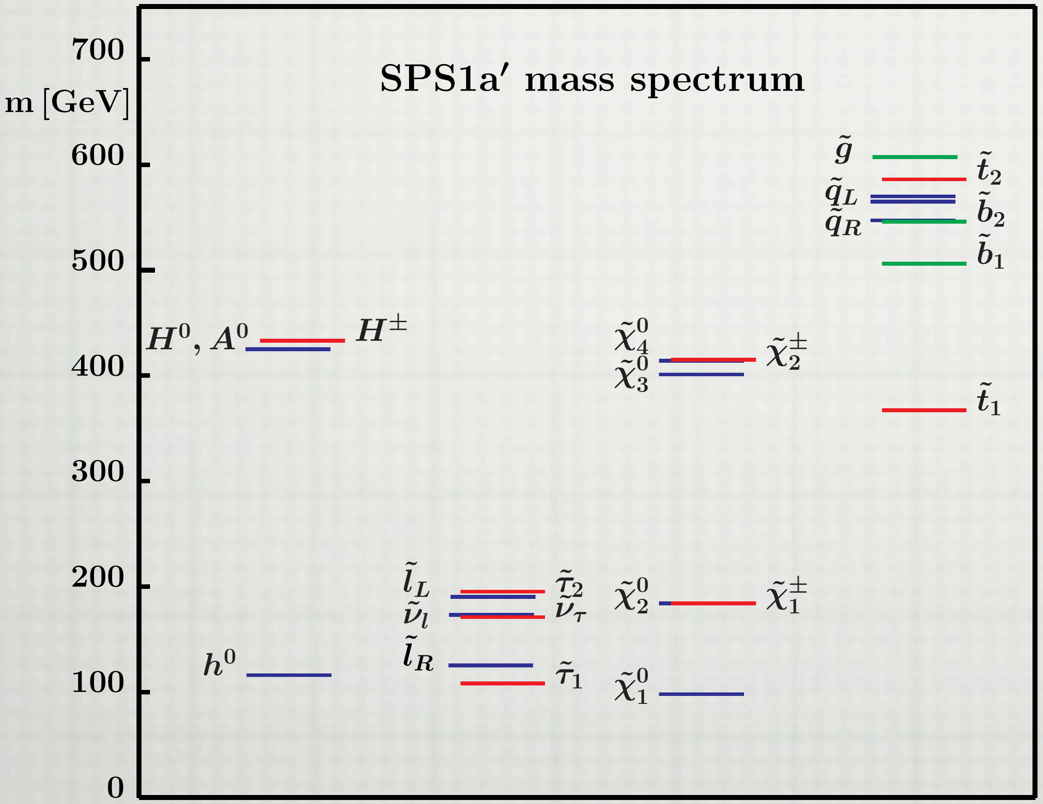
SUSY & DM

- Dark matter annihilation cross-section = weakly interacting massive particle

$$\Omega_\chi h^2 = \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma v>}$$

- No heavy neutral fermion in Standard Model ⇒ have to go beyond SM (MSSM)
- **Minimal Supersymmetric Standard Model** (with R-parity)

Typical MSSM mass spectrum



- light gauginos (lightest neutralino LSP)
- light scalar leptons (stau the lightest NLSP)
- heavy scalar quarks - big mass splittings

SUSY & DM

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  - other more exotic SUSY dark matter candidates possible

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- Supersymmetric DM candidates
  - **Sneutrino** possible MSSM dark matter candidate - ruled out by direct non-detection
  - **Neutralino** 'standard' MSSM dark matter candidate in majority of scenarios
    CDM with weak annihilation into quarks, leptons and gauge & Higgs bosons
  - **Gravitino** supergravity DM candidate, possible as hot, warm & cold DM
    nLSP in MSSM can be charged but it's constrained through decays in gravitinos
  - **Axino** in SUSY models with Peccei-Quinn solution to the strong CP problem

SUSY & DM

- Calculating DM abundance with particle physics methods

$$n(t_0) = \frac{1}{m}\left(\frac{t_0}{t_\gamma}\right)^3 t_\gamma^3 \sqrt{\frac{4\pi^3 g_* G_N}{45}} \left[\int_0^{x_F} \langle v\sigma \rangle dx\right]^{-1} \qquad x = \frac{T}{m}$$

thermally averaged total cross-section

$$\langle v\sigma \rangle = \frac{\int v\sigma\, e^{-E_1/T} e^{-E_2/T} \mathrm{d}^3 p_1\, \mathrm{d}^3 p_2}{\int e^{-E_1/T} e^{-E_2/T} \mathrm{d}^3 p_1\, \mathrm{d}^3 p_2}$$

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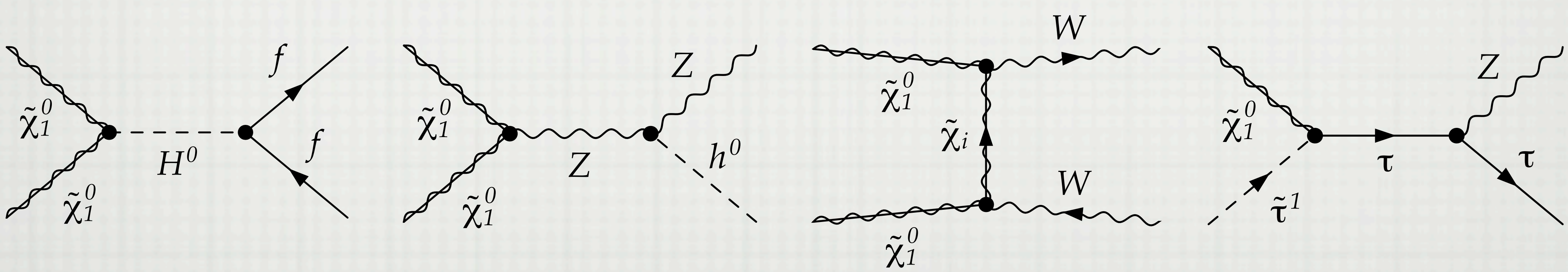
Total cross-section σ contains all SM final states



- Public codes perform a calculation of the relic density for given model (MSSM)

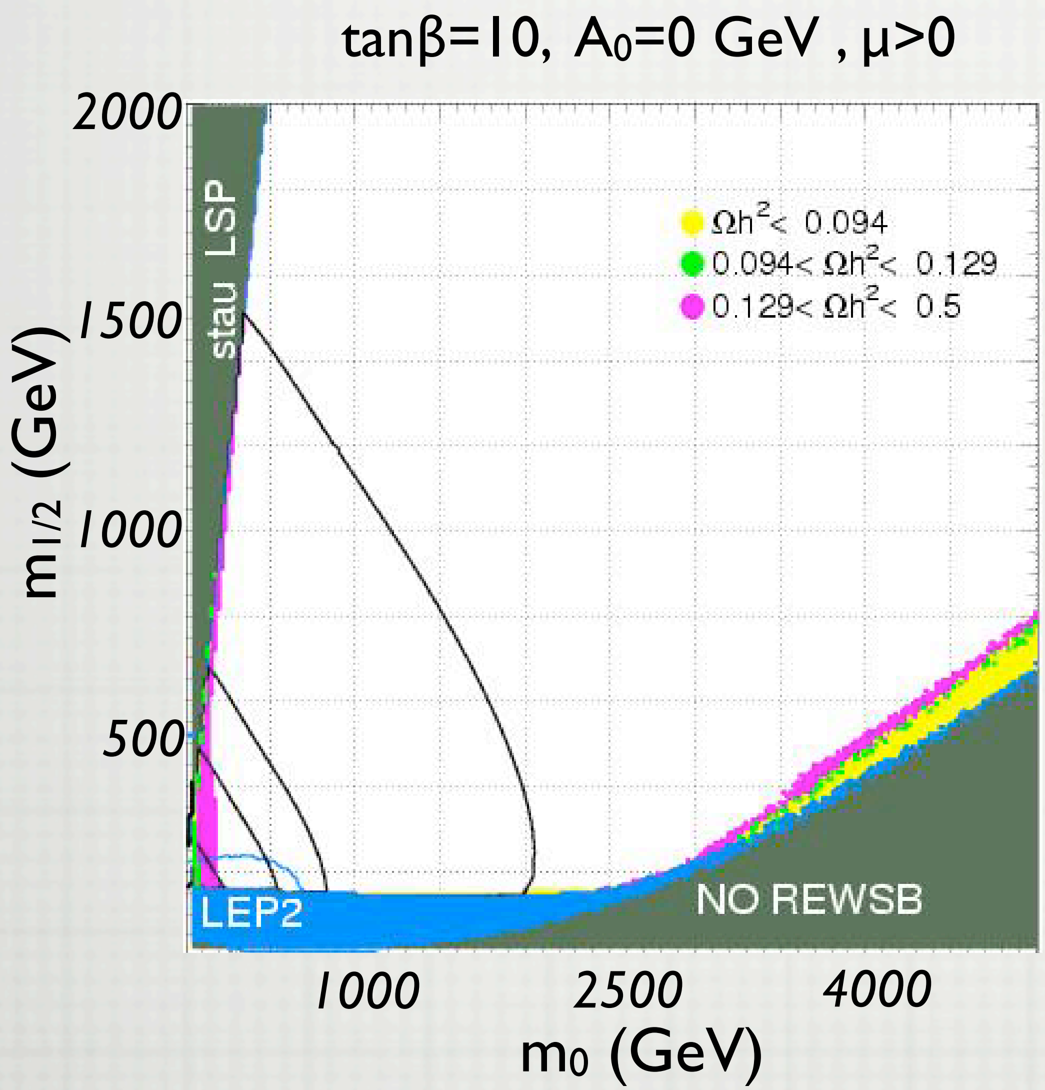
→ DarkSUSY [Gondolo *et al.* 2004]

→ micrOMEGAs [Bélanger *et al.* 2006]

→ SuperIso Relic [Arbey, Mahmoudi 2009]

SUSY & DM

- Typical mSUGRA scenarios with DM preferred regions

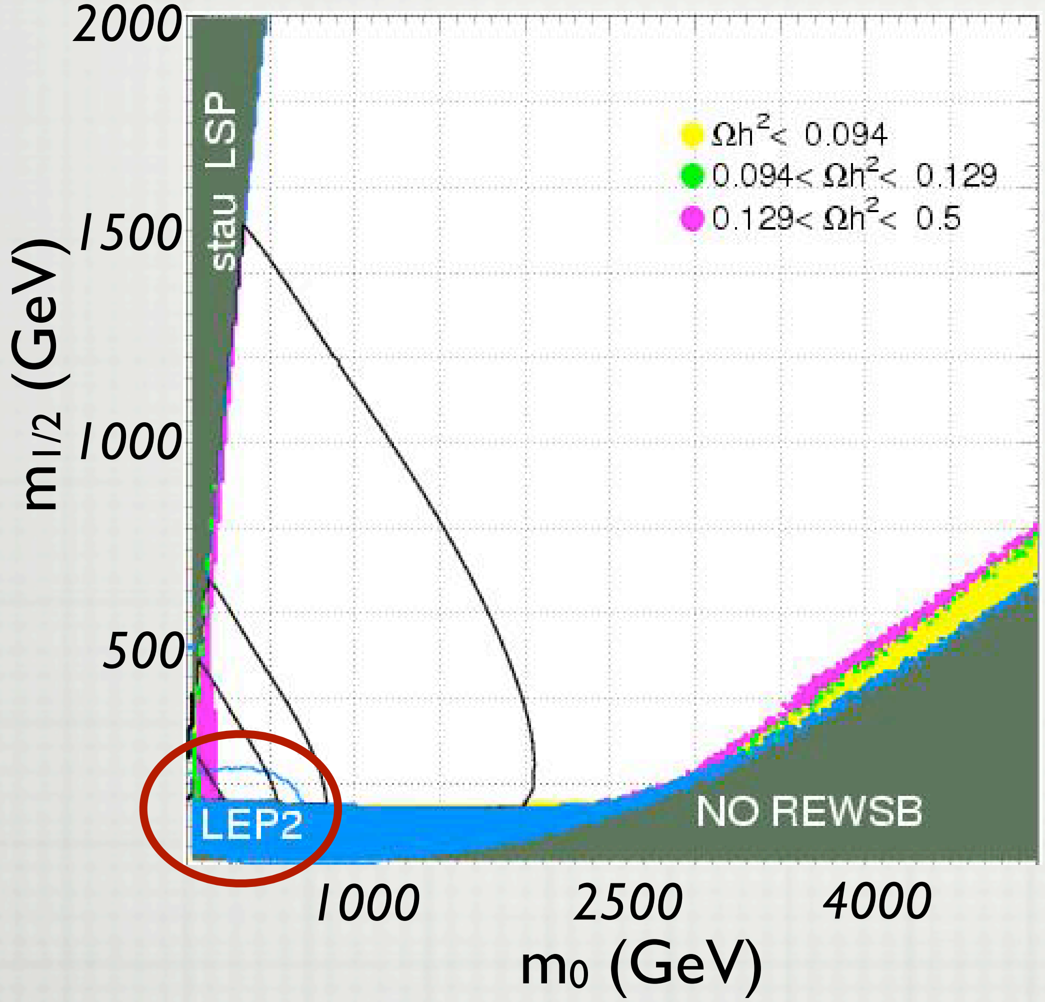


[Baer, Belyaev, Krupovnickas, Mustafayev hep-ph/0403214]

SUSY & DM

- Typical mSUGRA scenarios with DM preferred regions

tanβ=10, A_0=0 GeV , μ>0



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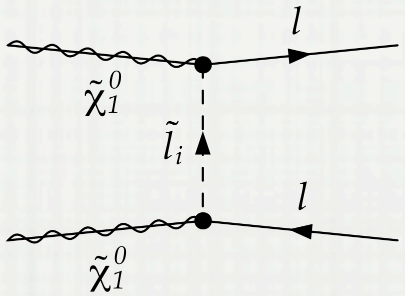
1. **bulk region** - low m_0-$m_{1/2}$, light sleptons



$$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \to l\,\bar{l} \quad \sim 39\%$$
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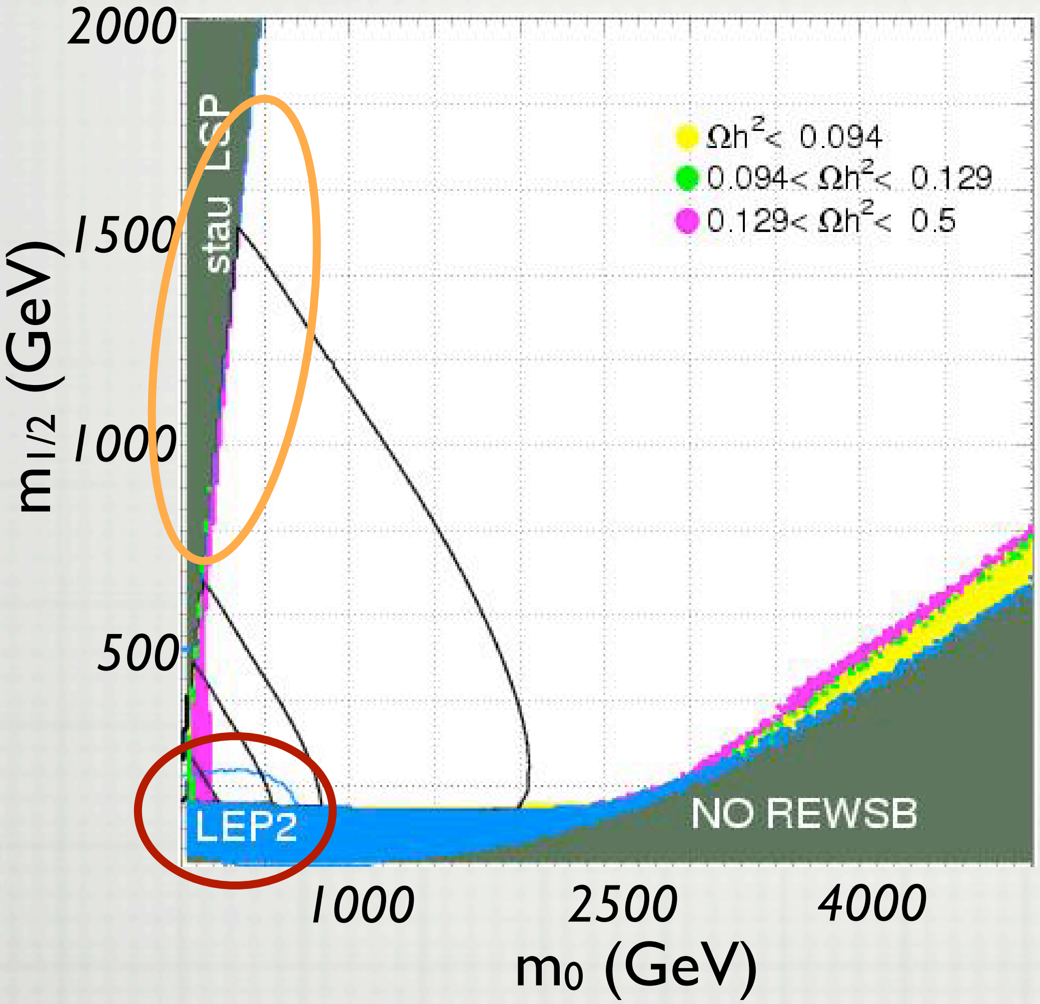

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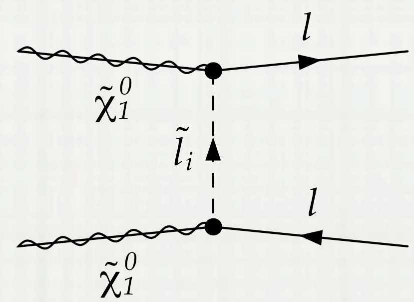

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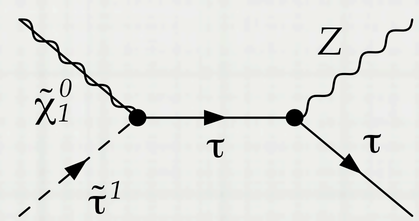

$$\tilde{\chi}_1^0\,\tilde{l}_1 \to A^0 l \quad \sim 37\%$$
$$\tilde{l}_i\,\tilde{l}_j \to l_i^+ l_j^- \quad \sim 29\%$$
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SUSY & DM

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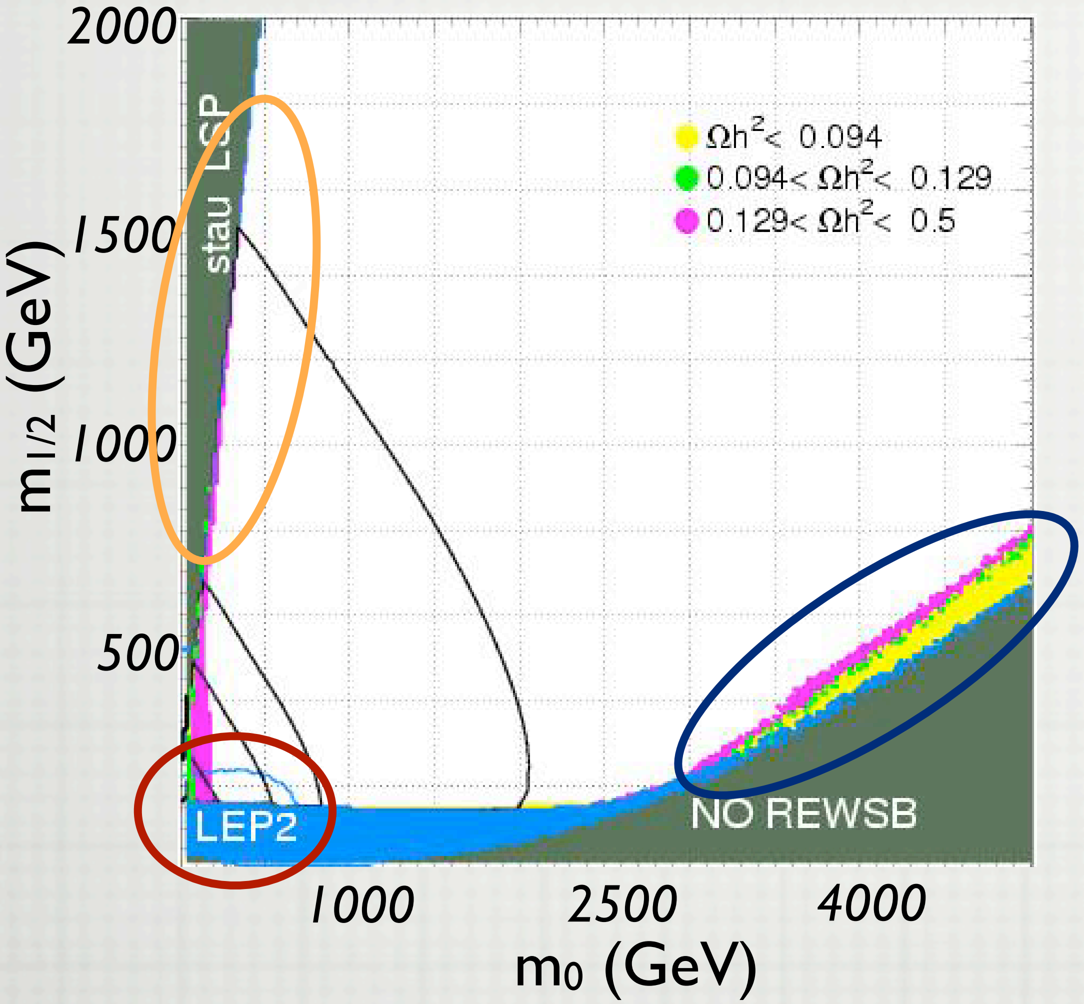

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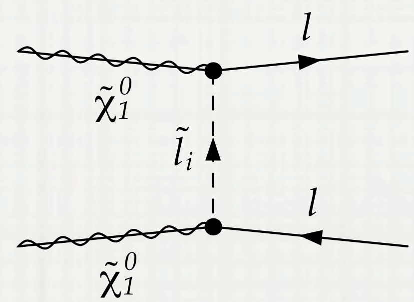

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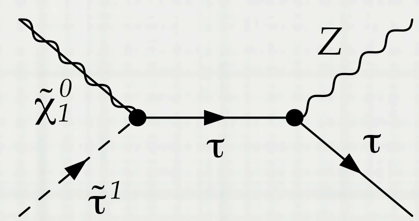

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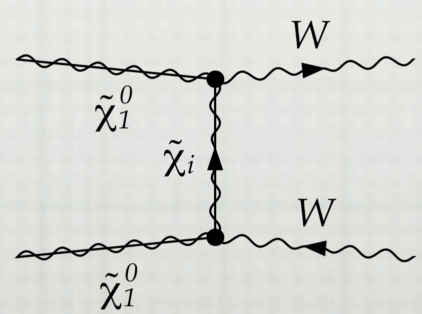
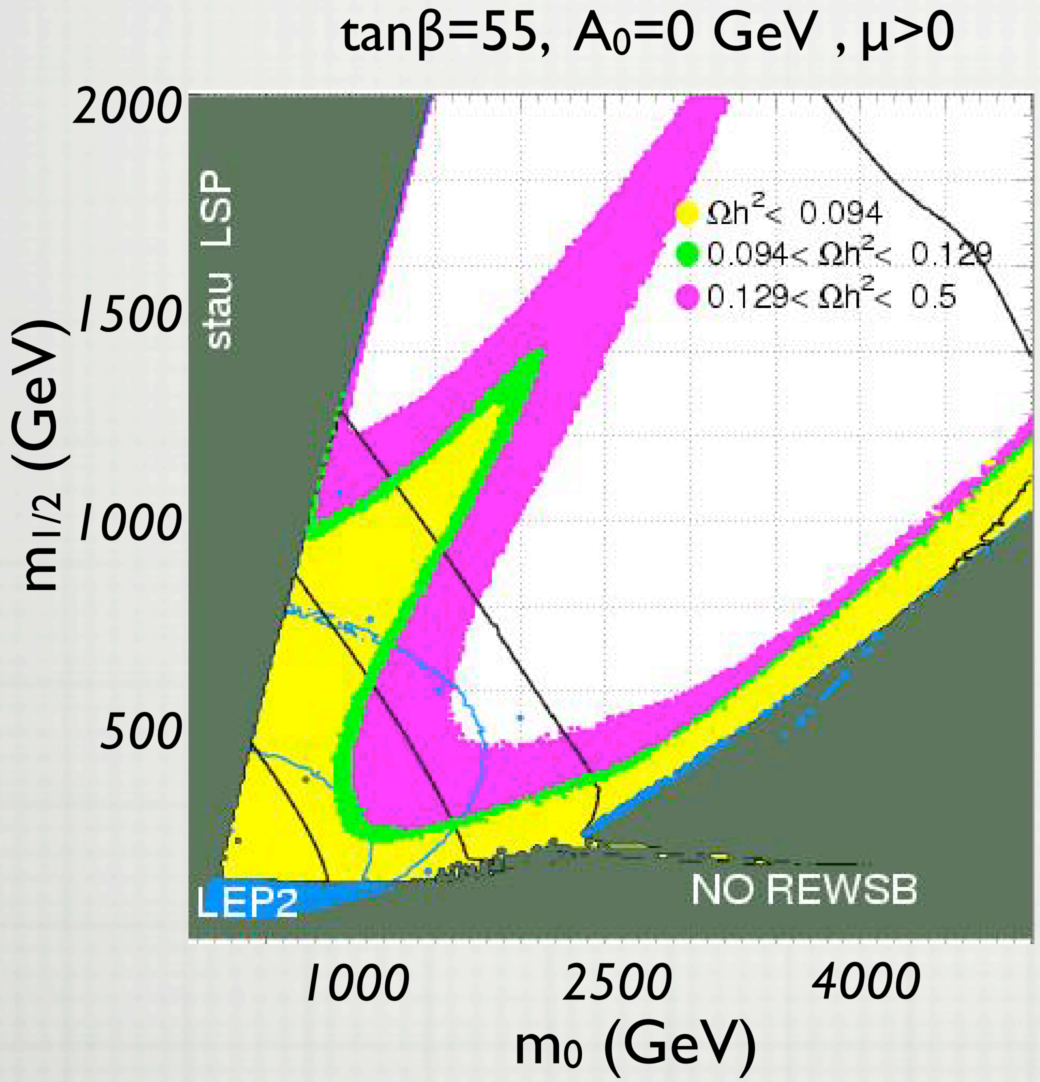
3. focus point region - large m_0 , near a region with no radiative EWSB



$$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \to W^+ W^- \;\sim 70\%$$
$$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \to Z^0 Z^0 \;\sim 16\%$$
$$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \to Z^0 h^0 \;\sim 7\%$$
$$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \to h^0 h^0 \;\sim 5\%$$

SUSY & DM

- Typical mSUGRA scenarios with DM preferred regions

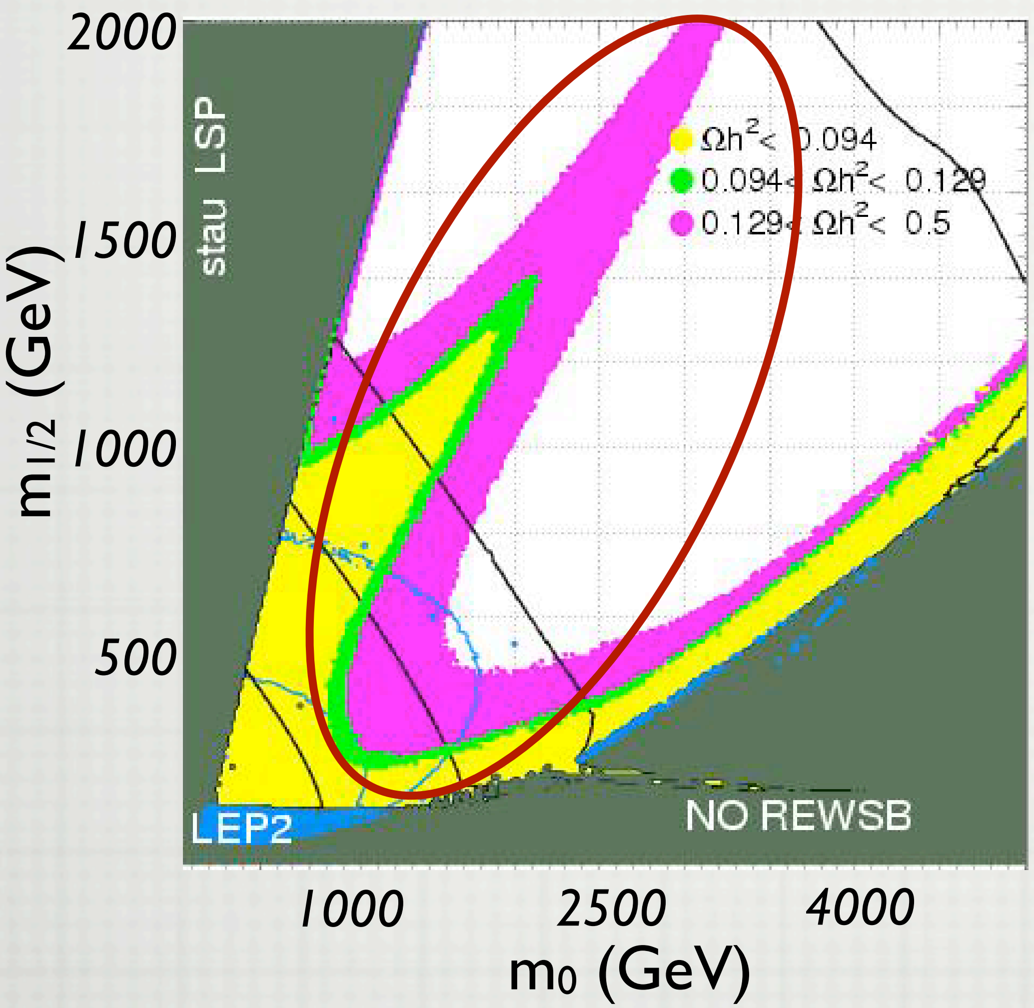


[Baer, Belyaev, Krupovnickas, Mustafayev hep-ph/0403214]

SUSY & DM

- Typical mSUGRA scenarios with DM preferred regions

tanβ=55, A_0=0 GeV , μ>0



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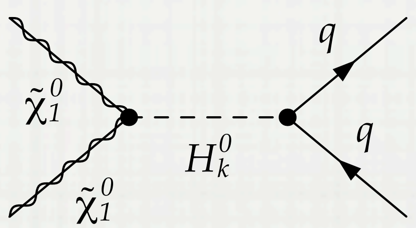
1. Higgs funnel region - Higgs resonances



$$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \to b\bar{b} \quad \sim 62\%$$
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$$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \to W^{\pm} H^{\mp} \sim 10\%$$
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SUSY & DM

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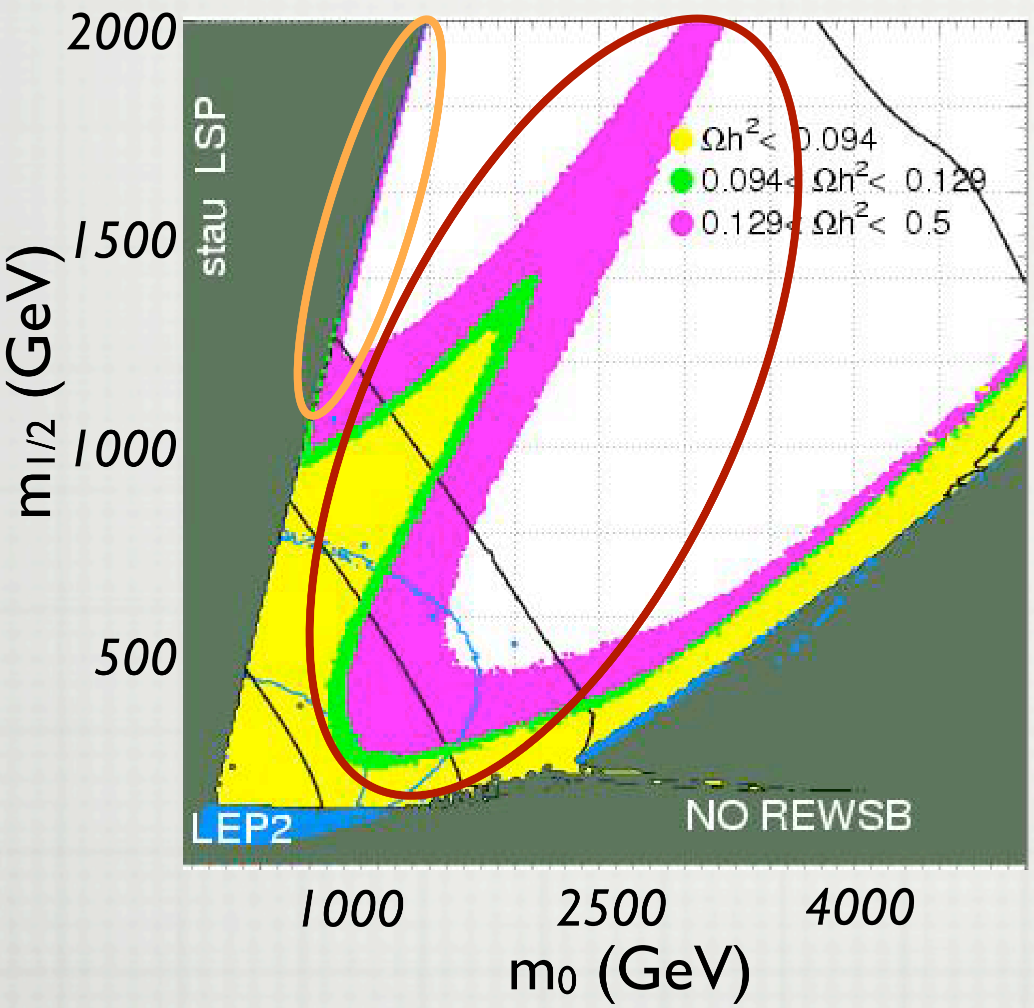

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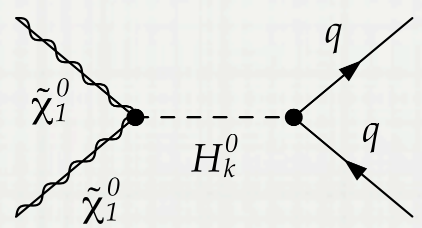

$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \to b\bar{b}$ $\sim 62\%$

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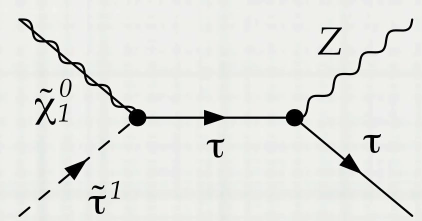

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SUSY & DM

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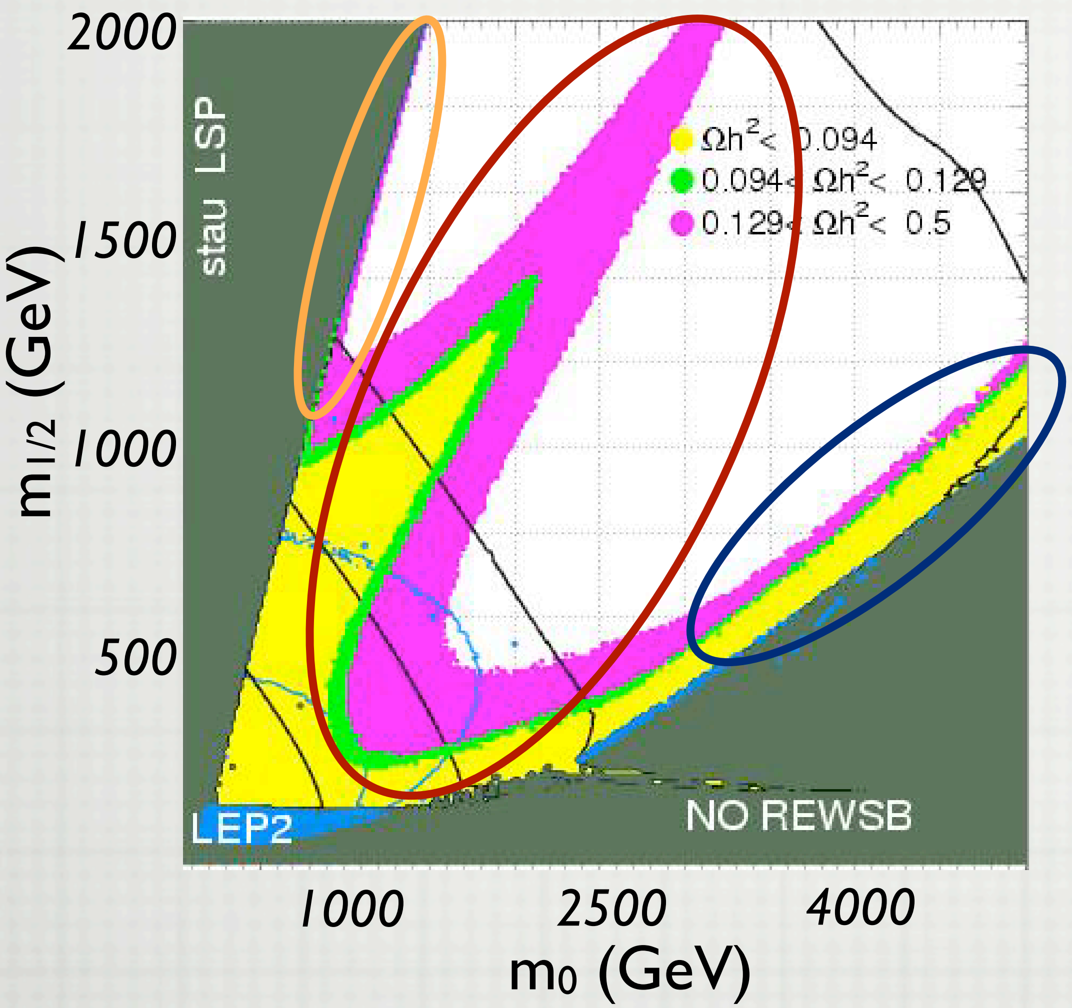

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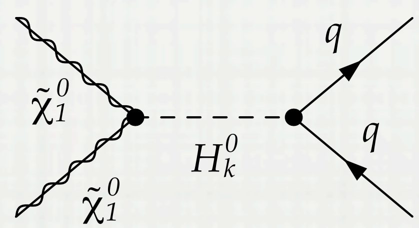

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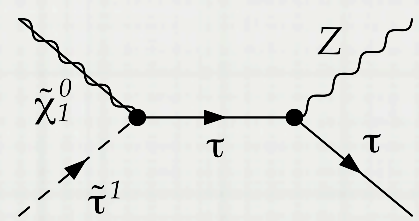

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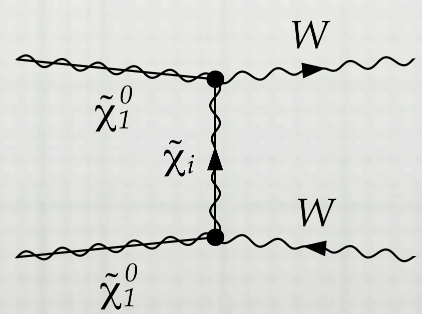


$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to t\bar{t}$ $\sim 64\%$

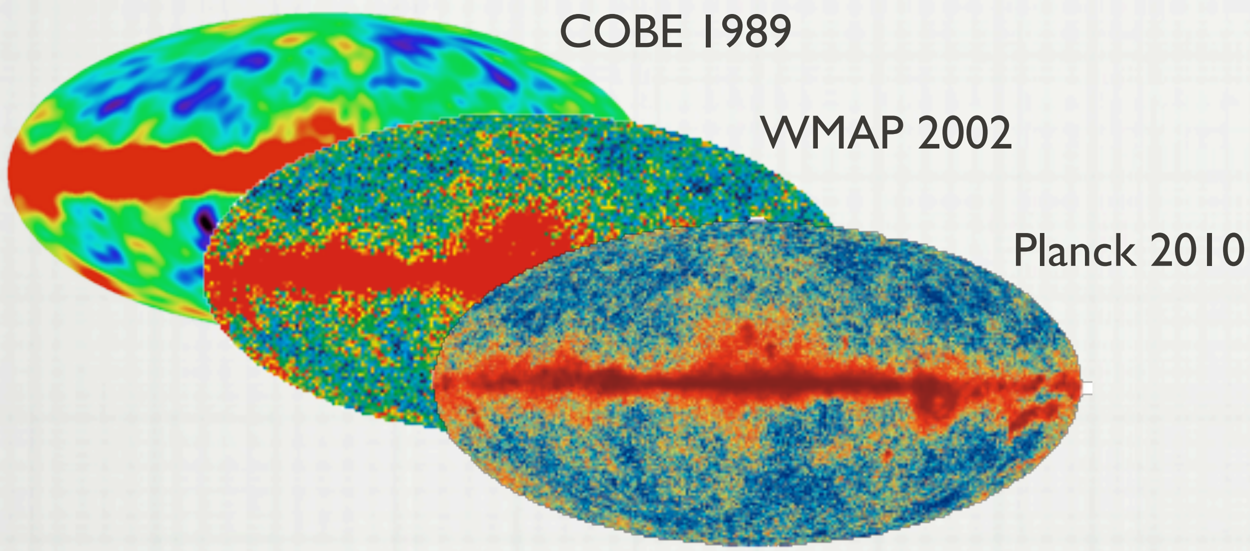
$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to b\bar{b}$ $\sim 15\%$

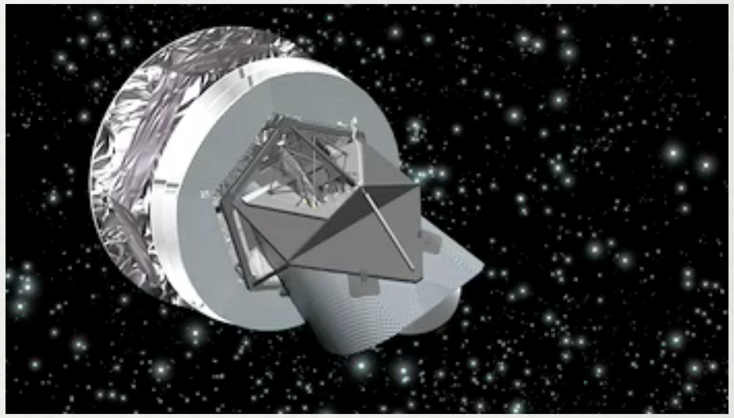
$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to W^+W^-$ $\sim 10\%$

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to Z^0Z^0$ $\sim 5\%$

PRECISE DM

- WMAP precision to be improved by Planck (launched in May 2009)





precision WMAP - 10% ➪ precision Planck - 2%

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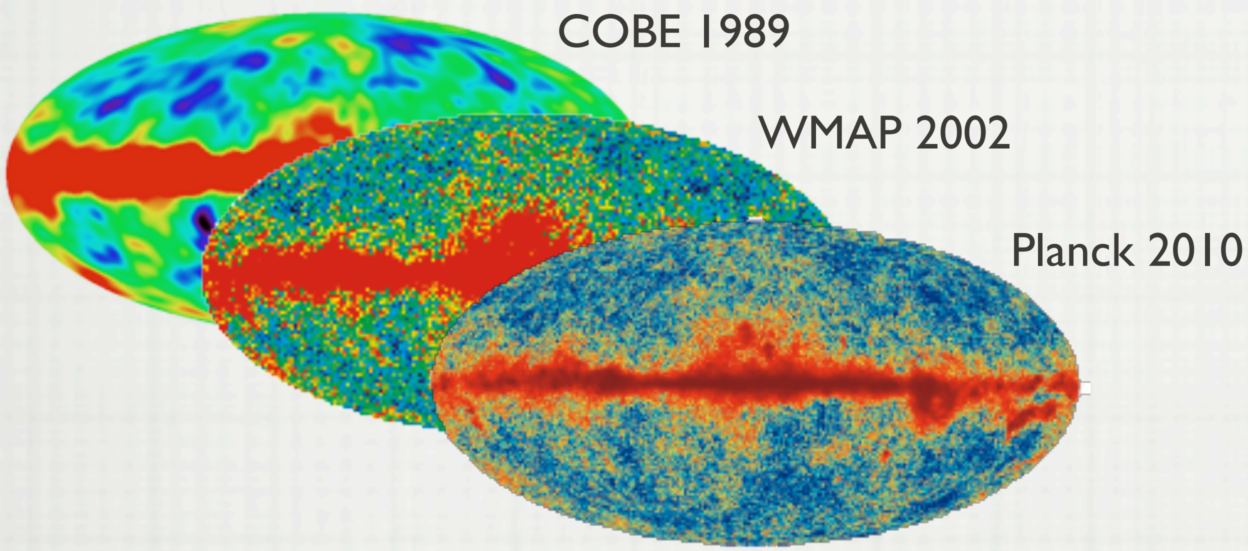

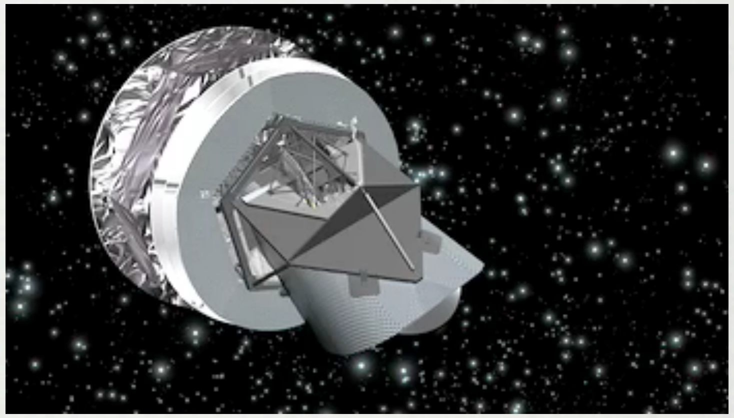

precision WMAP - 10% ➪ precision Planck - 2%

- Precise testing of consistency between cosmology & BSM physics
  - strict constraints & precise test of DM candidates (from LHC)
- **Higher order corrections important**
  - to make full use of experimental precision
  - modification of preferred parameter regions (before LHC results)

PRECISE DM

- QCD corrections

→ $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to q\bar{q}$ [Herrmann, Klasen, K.K., PRD79 (2009) 0901.0481 [hep-ph]]
[Herrmann, Klasen, K.K., PRD80 (2009) 0907.0030 [hep-ph]]

→ Co-annihilations with $\tilde{t}$ [Freitas, PRL652 (2007) 0705.4027 [hep-ph]]

- EW corrections

→ $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \gamma\gamma, Z\gamma, gg$ [Boudjema, Semenov, Temes, PRD72 (2005) hep-ph/0507127]

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PRECISE DM

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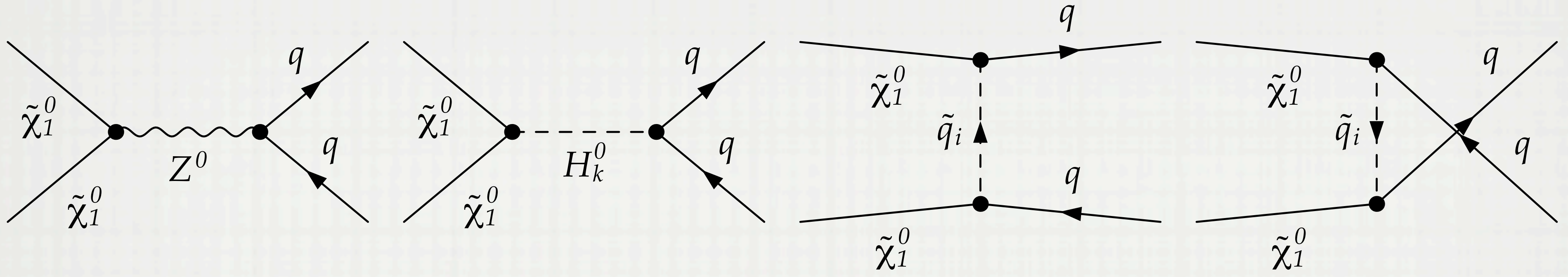
PRECISE DM

- Cross section includes s-channel Z-boson & Higgs boson, t & u-channel squark exchange



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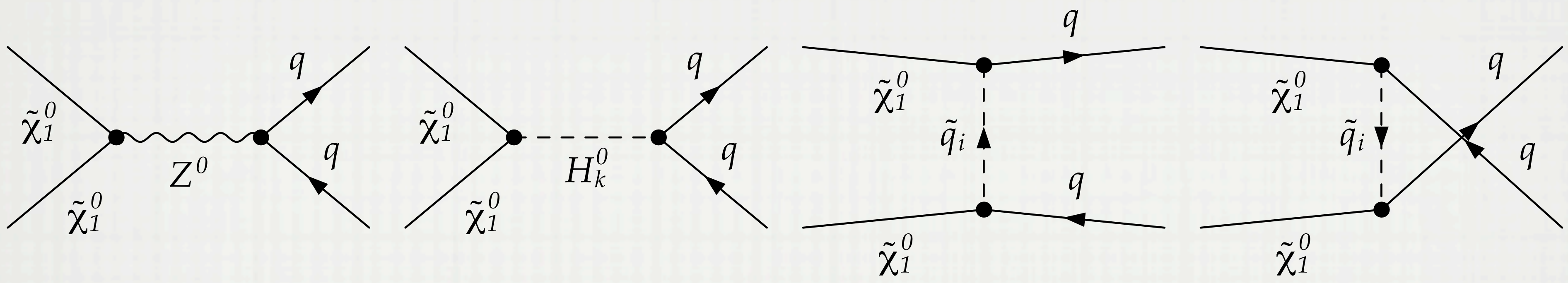

- Annihilation into light quarks (all except top) always kinematically allowed
  → dominant for light neutralino

- Non-relativistic limit of annihilation cross-section

$$\sigma v = a + b v^2 + \mathcal{O}(v^4)$$

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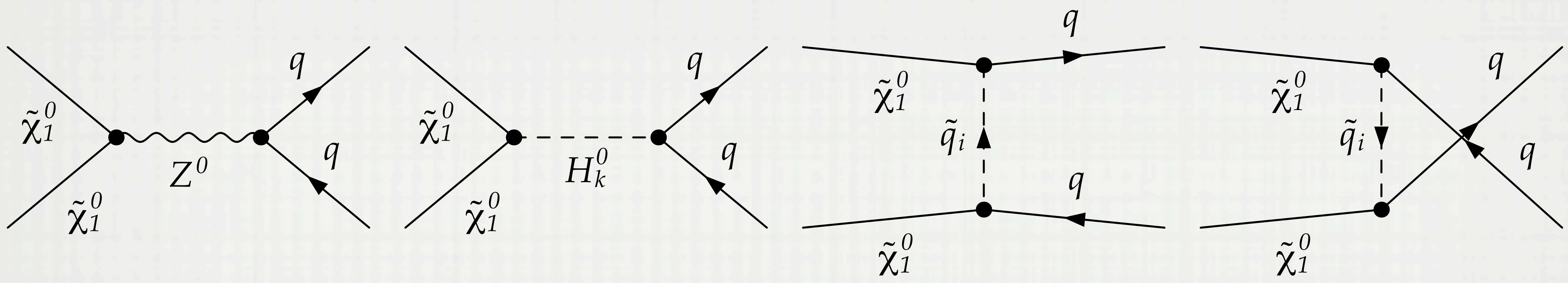

- Annihilation into light quarks (all except top) always kinematically allowed
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- Non-relativistic limit of annihilation cross-section

$$\sigma v = a + b v^2 + \mathcal{O}(v^4)$$

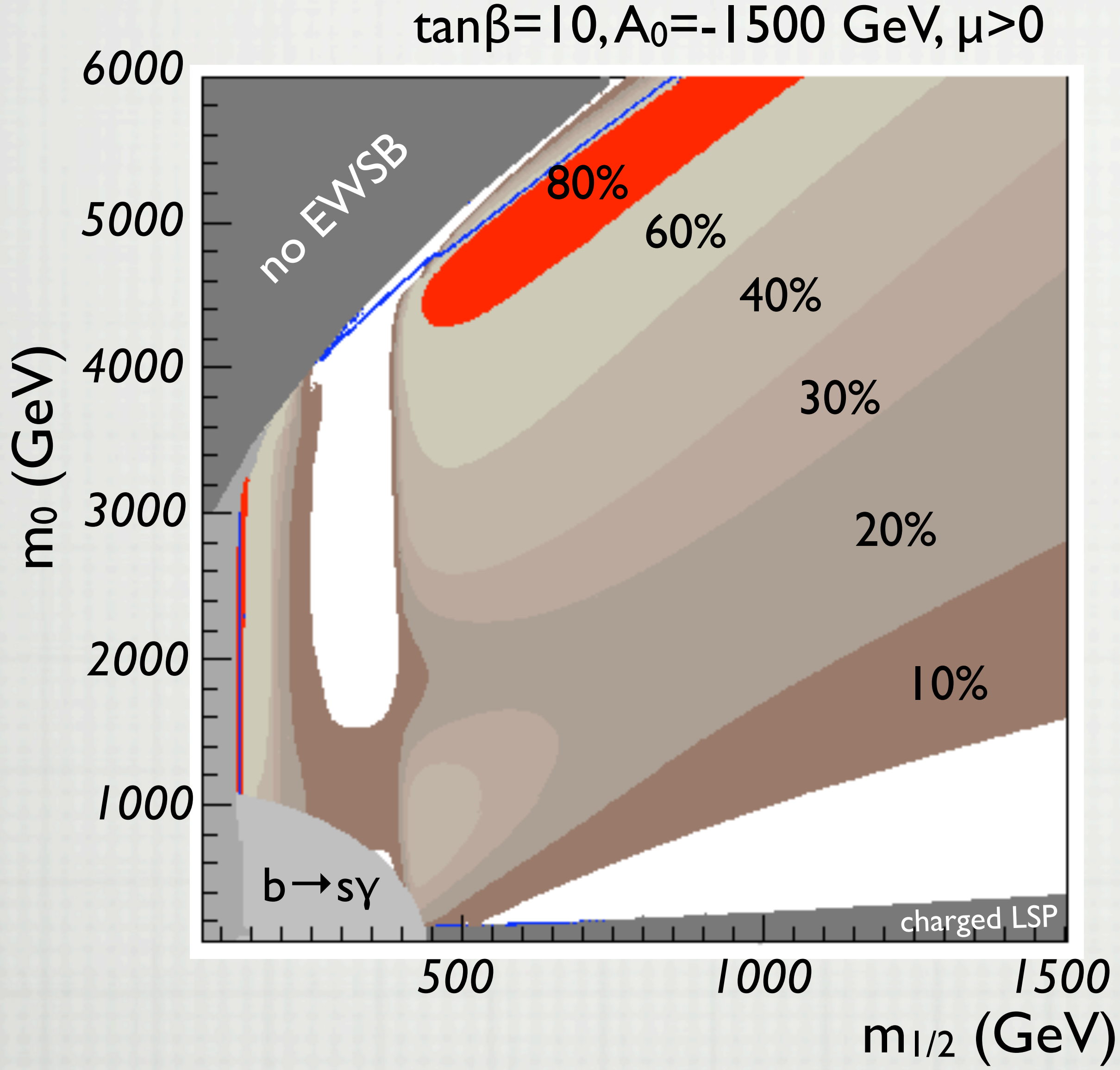
- Leading coefficient in annihilation to quarks proportional to the mass of the quark
  → light quarks of 1st & 2nd generation suppressed
  → top quark final states dominant if allowed

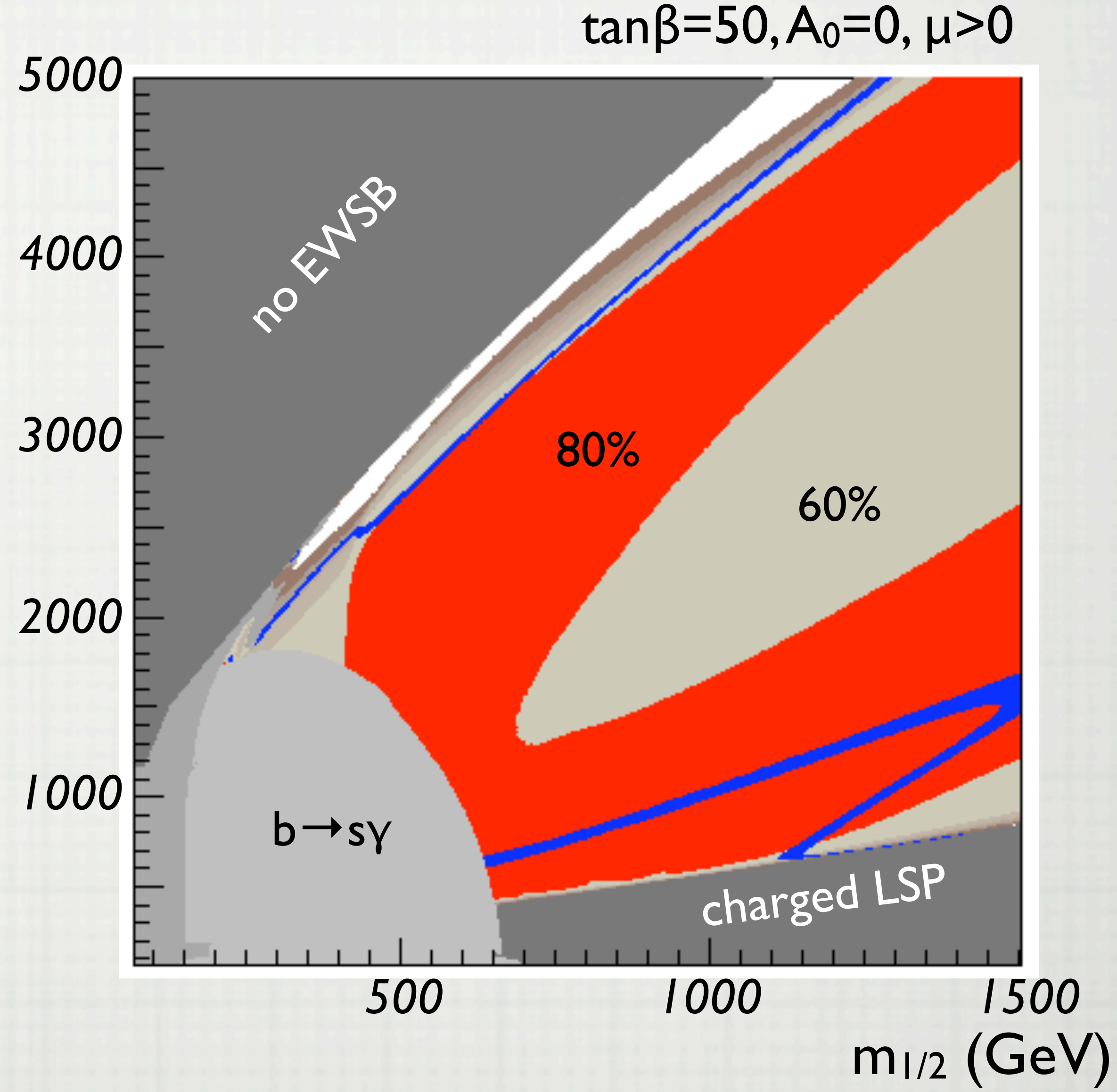
$$a \propto m_f$$

- Different scenarios lead to different dominant contributions
  → mSUGRA - Higgs exchange dominates & tanβ important parameter
  → beyond mSUGRA - also Z-boson or squark exchange can dominate

PRECISE DM

- Contribution of quark final states in mSUGRA m_0-$m_{1/2}$ planes





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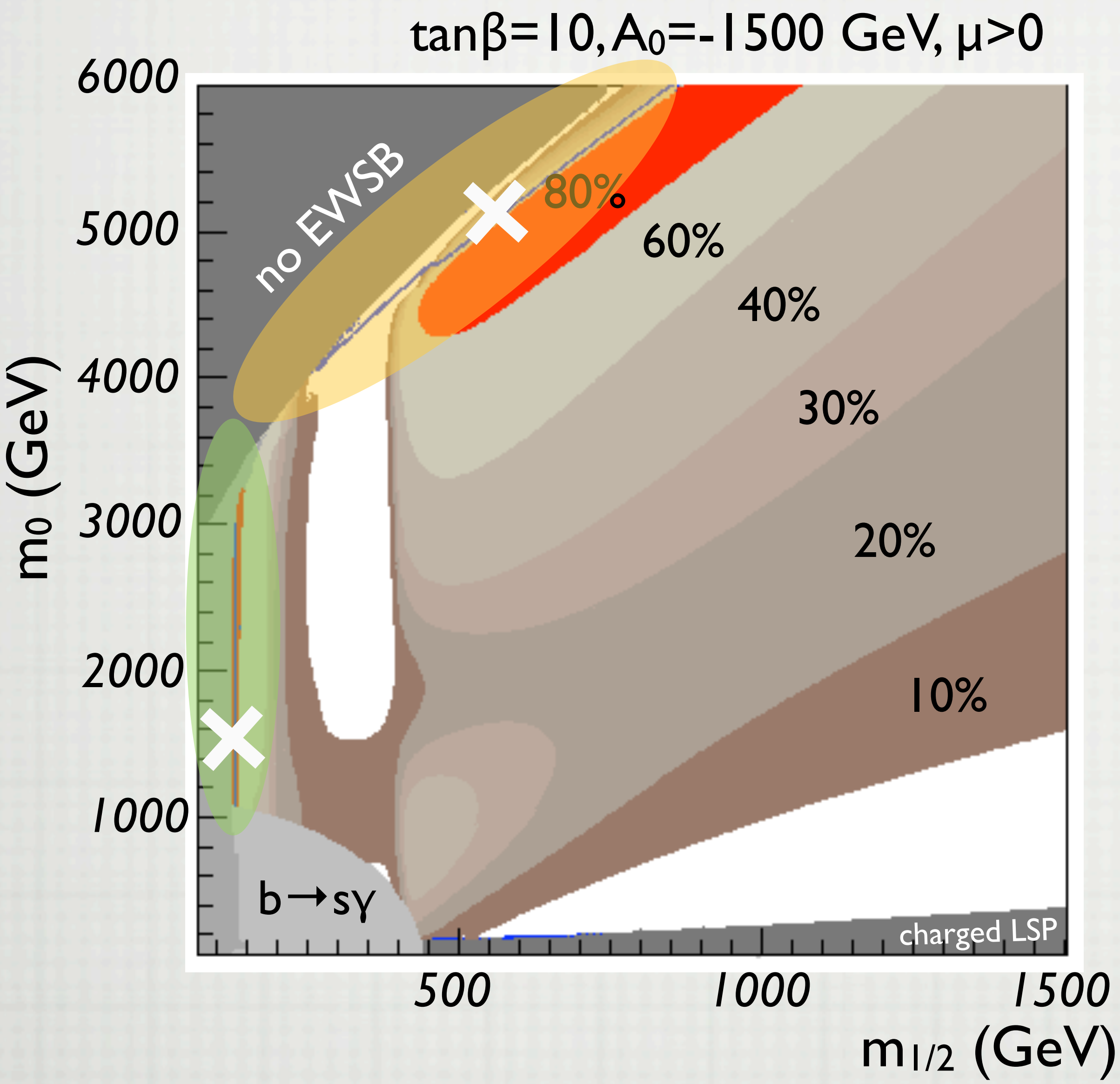

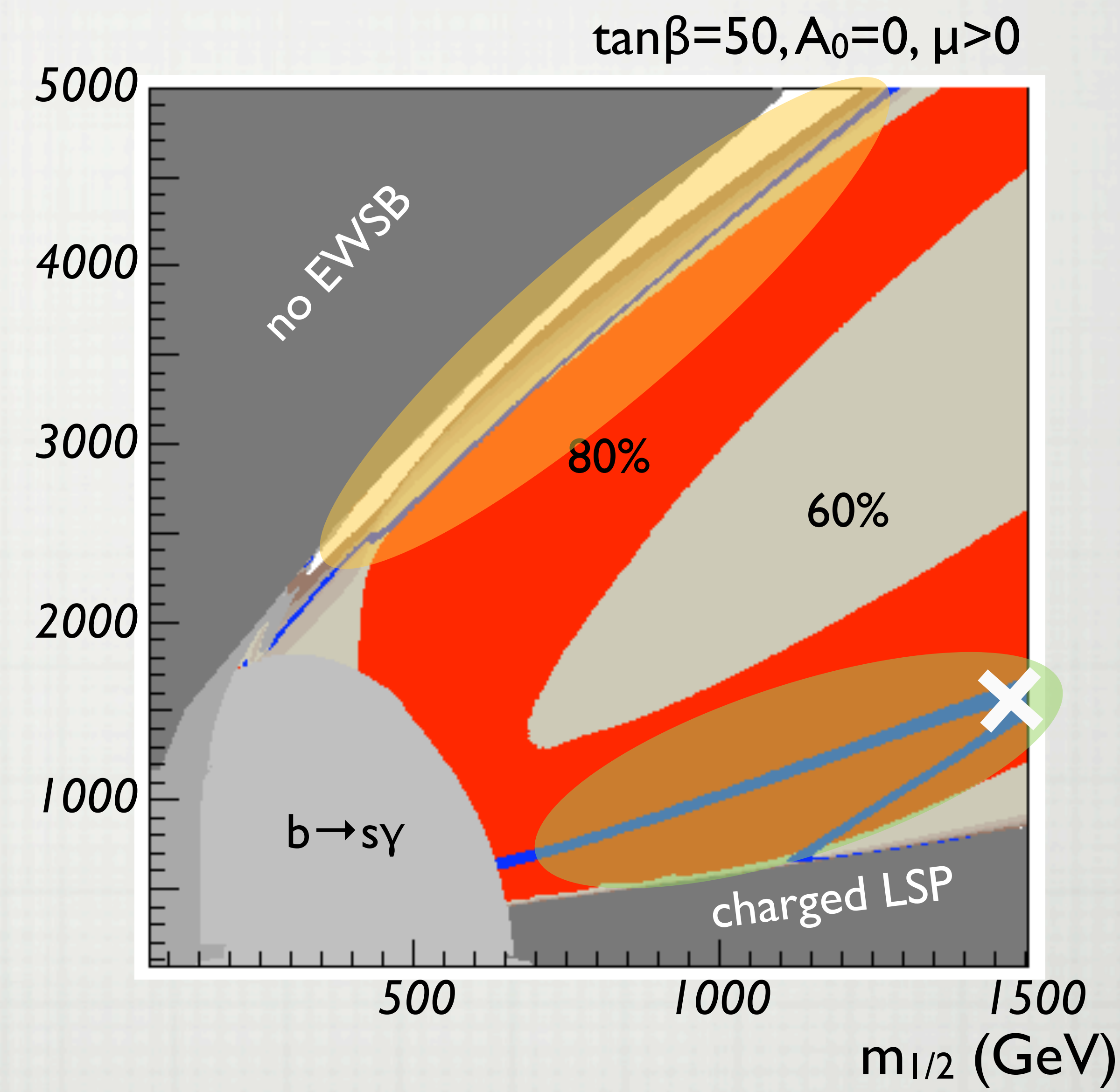

- Interesting regions:
  - Focus point region (tt dominated)
  - Bulk & A-funnel region (bb dominated)

PRECISE DM

- Relax unification conditions (still retain gauge coupling unification)
  - relax gaugino parameter unification M_1, M_2 , M_3
  - relax scalar parameter unification m_0, M_{Hu}, $M_{Hd,}$ (M_A, μ)

$$x_1 = \frac{M_1}{M_2} \quad x_3 = \frac{M_3}{M_2}$$

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$$x_1 = \frac{M_1}{M_2} \quad x_3 = \frac{M_3}{M_2}$$

- Higgs superpotential parameter **μ** important
  - **μ** influences higgsino fraction of neutralino

- Gluino parameter M_3 very influential
  - decrease in M_3 → decrease in M_{Hu} and squark masses
  - low M_{Hu} → low **μ** → larger higgsino fraction of $\tilde{\chi}_1^0$

PRECISE DM

- Relax unification conditions (still retain gauge coupling unification)
  - relax gaugino parameter unification M_1, M_2, M_3
  - relax scalar parameter unification m_0, M_{Hu}, M_{Hd}, (M_A, **μ**)

$$x_1 = \frac{M_1}{M_2} \qquad x_3 = \frac{M_3}{M_2}$$

- Higgs superpotential parameter **μ** important
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- Gluino parameter M_3 very influential
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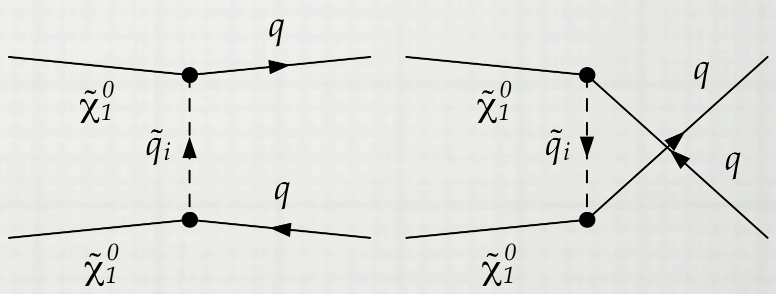
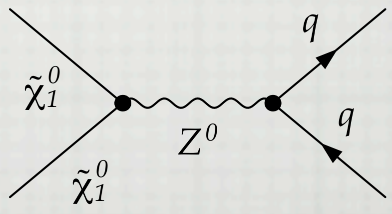
- **First scenario**
  - small squark masses & low tan**β** → squark exchange

[S.Martin 2007]



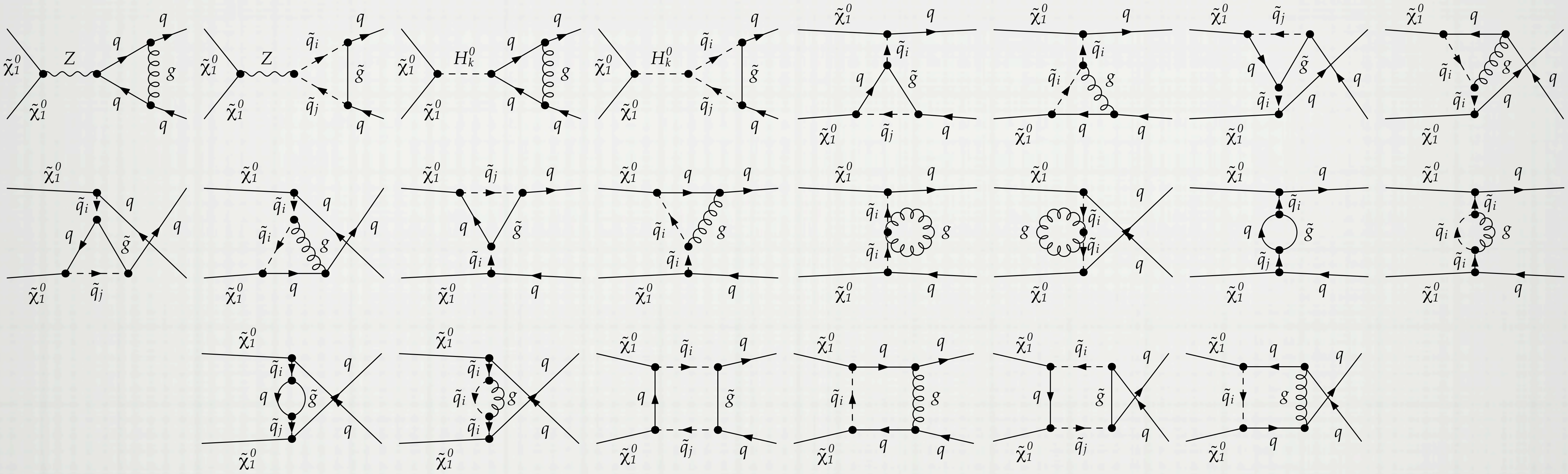
- **Second scenario**
  - large higgsino component of $\tilde{\chi}_1^0$ → Z exchange

[Bertin,Nezri,Orloff 2002]

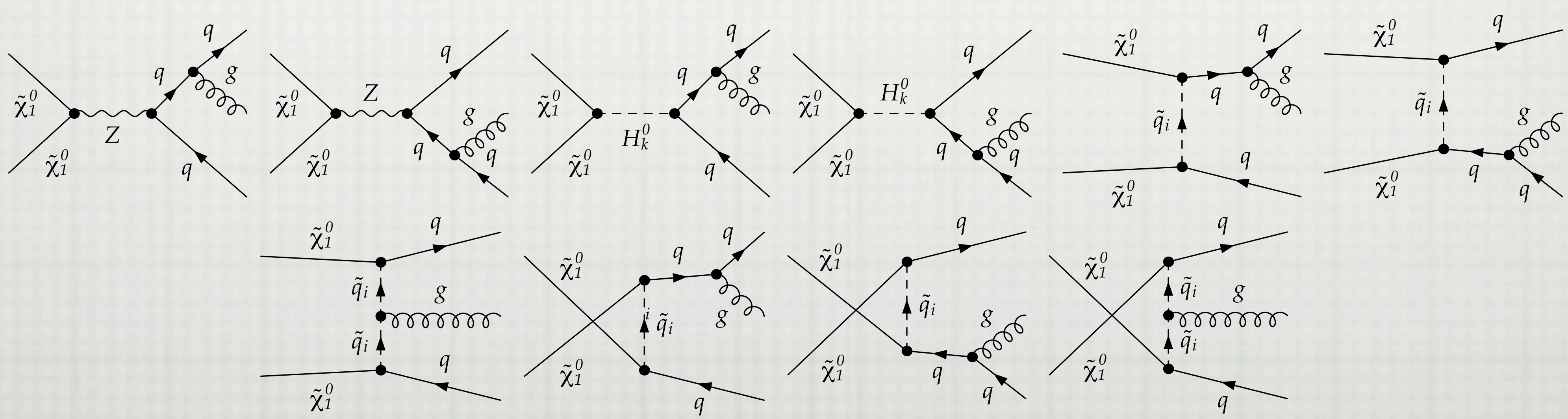


PRECISE DM

- Virtual loop corrections: On-shell renormalization



- Real emission corrections: Dipole subtraction method



PRECISE DM

- Virtual loop corrections:
  - → loops are calculated in $\overline{\text{DR}}$ regularization scheme
  - → UV divergence removed by On-shell & $\overline{\text{DR}}$ counterterms
  - → Yukawa coupl. & SUSY mixings $\overline{\text{DR}}$, the rest on-shell

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  - → UV divergence removed by On-shell & $\overline{\text{DR}}$ counterterms
  - → Yukawa coupl. & SUSY mixings $\overline{\text{DR}}$, the rest on-shell
- **Real corrections:**
  - → $\overline{\text{DR}}$ regularization scheme for IR divergence in loops & gluon radiation - poles
  - → Dipole subtraction method combines virtual & real part - cancel IR divergence

$$\sigma_{1-\text{loop}} = \left[\sigma_V + \int \mathrm{d}\sigma_{\text{aux}}\right]_{\varepsilon=0} + \int \left[\mathrm{d}\sigma_R - \mathrm{d}\sigma_{\text{aux}}\right]_{\varepsilon=0}$$

[Catani, Dittmaier, Seymour, Trocsanyi hep-ph/0201036]

PRECISE DM

- **Virtual loop corrections:**
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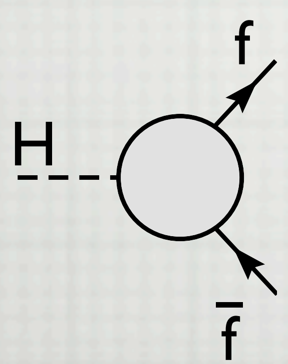
[Catani, Dittmaier, Seymour, Trocsanyi hep-ph/0201036]

- **Higgs exchange & Yukawa couplings**



→ Higgs boson decays to fermions well known
- QCD corrections up to $\mathcal{O}(\alpha_s^4)$ included

[Chertyrkin et al hep-ph/9505358, hep-ph/9608318, hep-ph/0511063]

→ SUSY-QCD corrections to bottom Yukawa coupling known to be important for large tanβ

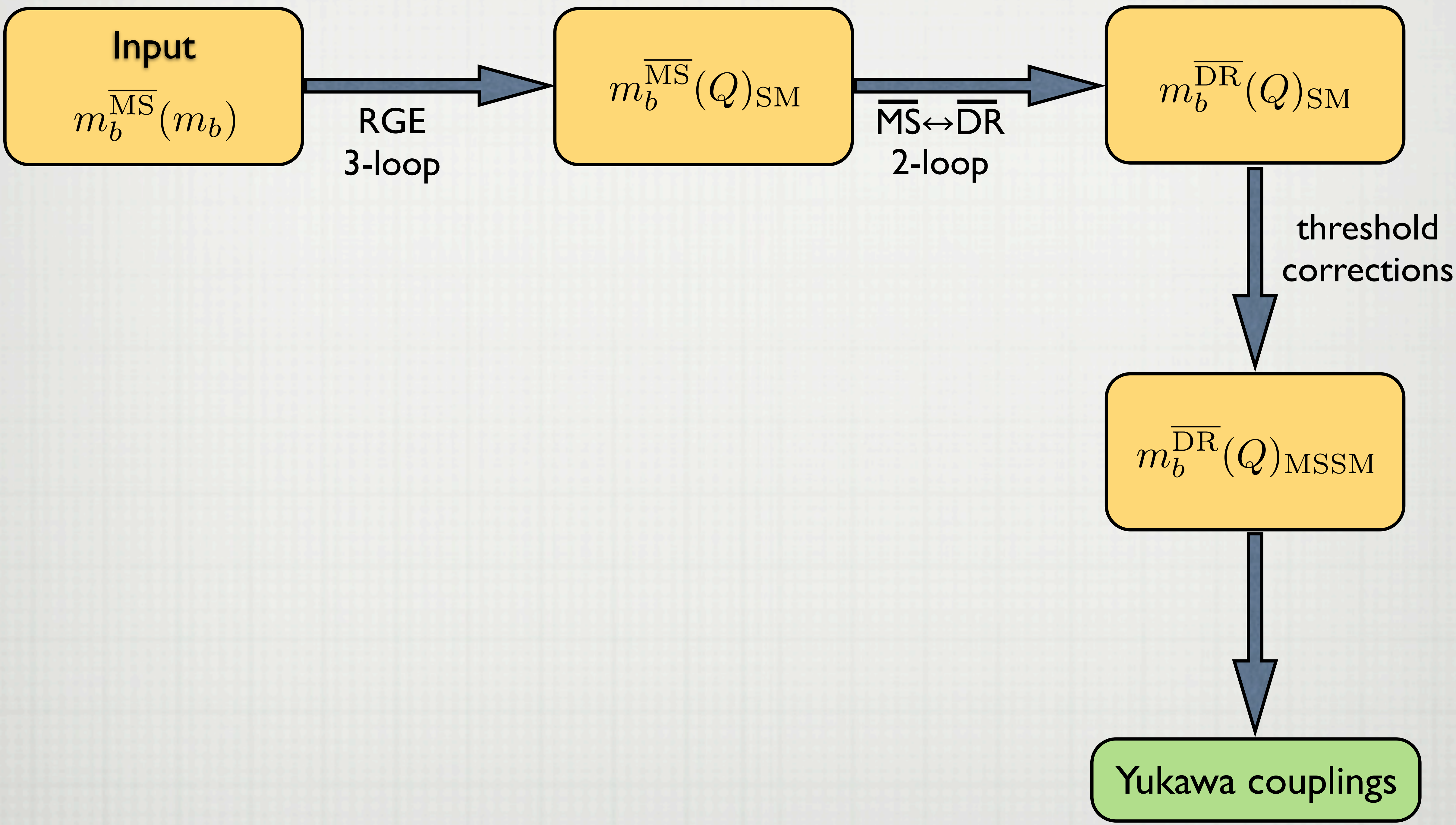
[Carena, Garcia, Nierste, Wagner hep-ph/9912516]

PRECISE DM

Input

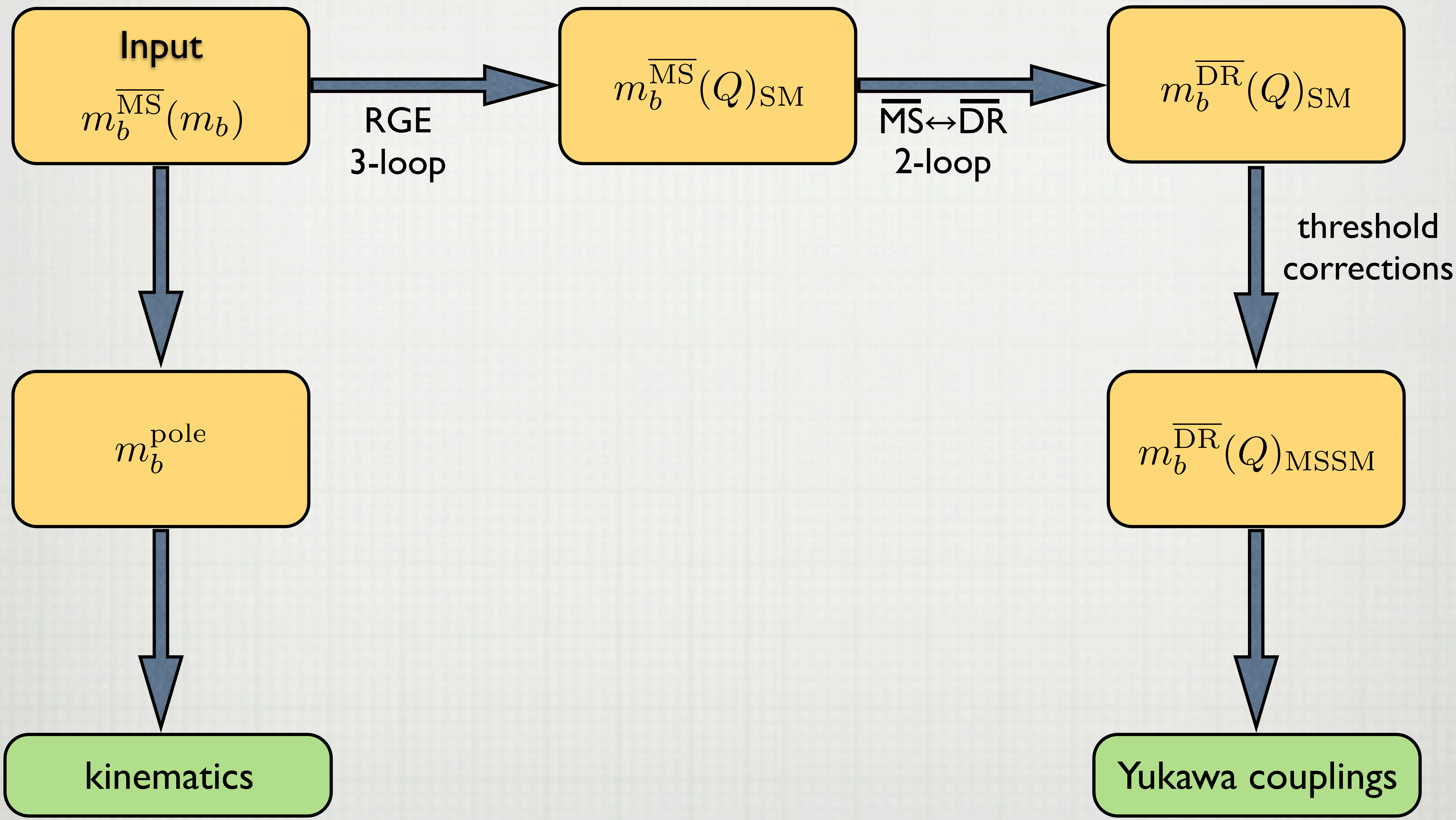
$m_b^{\overline{\mathrm{MS}}}(m_b)$

PRECISE DM

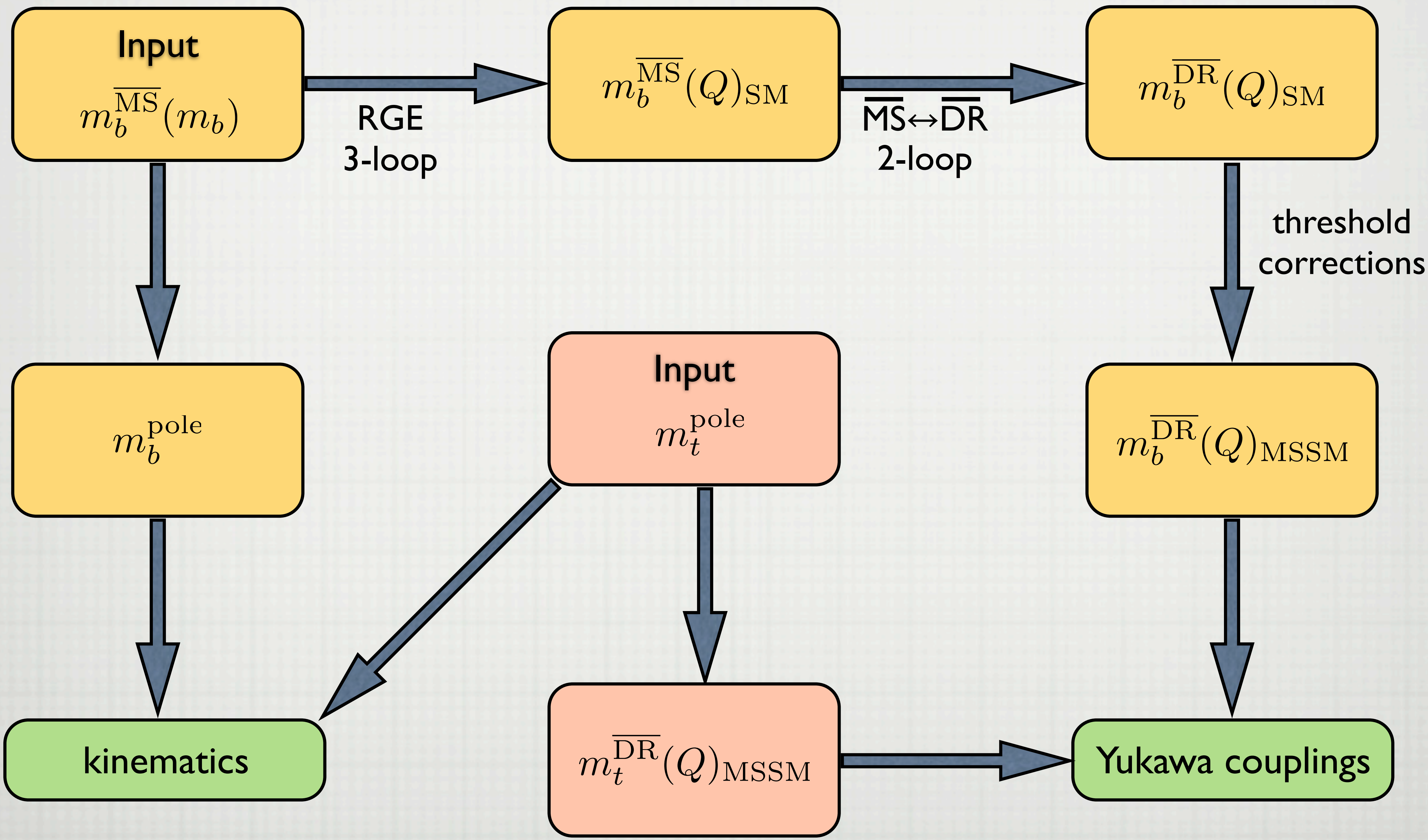


Input
$m_b^{\overline{\rm MS}}(m_b)$
RGE
3-loop
$m_b^{\overline{\rm MS}}(Q)_{\rm SM}$
$\overline{\rm MS}\leftrightarrow\overline{\rm DR}$
2-loop
$m_b^{\overline{\rm DR}}(Q)_{\rm SM}$
threshold
corrections
$m_b^{\overline{\rm DR}}(Q)_{\rm MSSM}$
Yukawa couplings

PRECISE DM


Input
$m_b^{\overline{\text{MS}}}(m_b)$
RGE
3-loop
$m_b^{\overline{\text{MS}}}(Q)_{\text{SM}}$
$\overline{\text{MS}}\leftrightarrow\overline{\text{DR}}$
2-loop
$m_b^{\overline{\text{DR}}}(Q)_{\text{SM}}$
threshold
corrections
m_b^{pole}
$m_b^{\overline{\text{DR}}}(Q)_{\text{MSSM}}$
kinematics
Yukawa couplings

PRECISE DM



Input
$m_b^{\overline{\rm MS}}(m_b)$
RGE
3-loop
$m_b^{\overline{\rm MS}}(Q)_{\rm SM}$
$\overline{\rm MS}\leftrightarrow\overline{\rm DR}$
2-loop
$m_b^{\overline{\rm DR}}(Q)_{\rm SM}$
threshold
corrections
$m_b^{\rm pole}$
Input
$m_t^{\rm pole}$
$m_b^{\overline{\rm DR}}(Q)_{\rm MSSM}$
kinematics
$m_t^{\overline{\rm DR}}(Q)_{\rm MSSM}$
Yukawa couplings

PRECISE DM

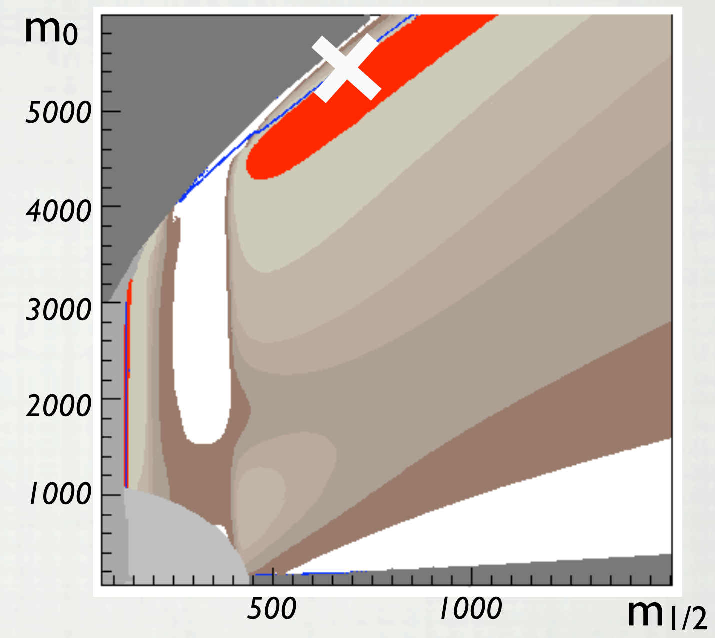
- mSUGRA parameter values:

  m_0 = 5300 GeV, $m_{1/2}$ = 625 GeV

  $\tan\beta$ = 10, A_0 = -1500 GeV, sgn μ = +

- Relic density:

  Ωh^2 = 0.110, $t\bar{t}$ = 72%



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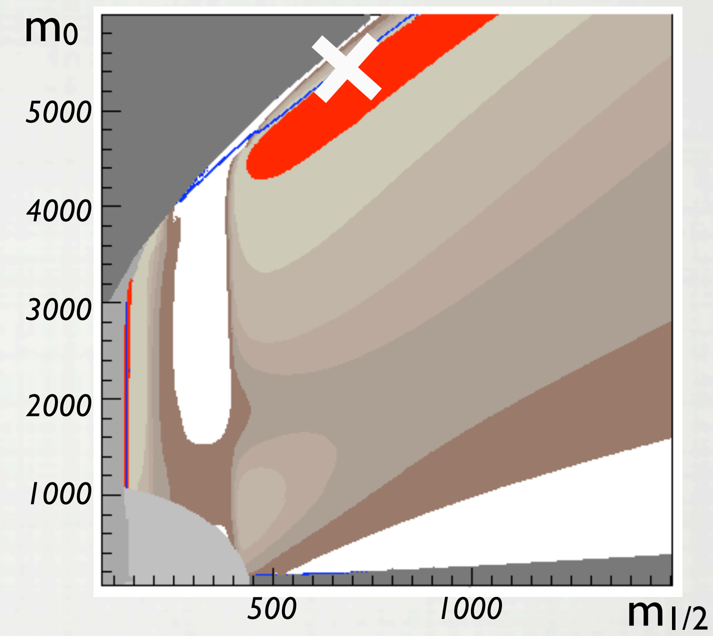
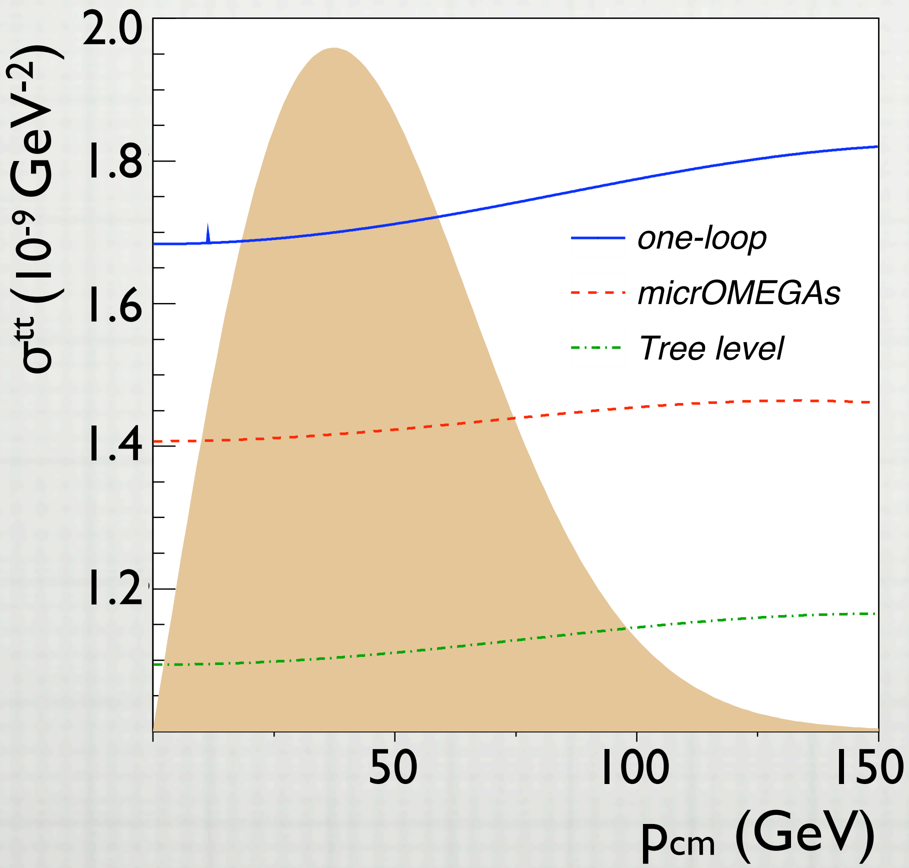
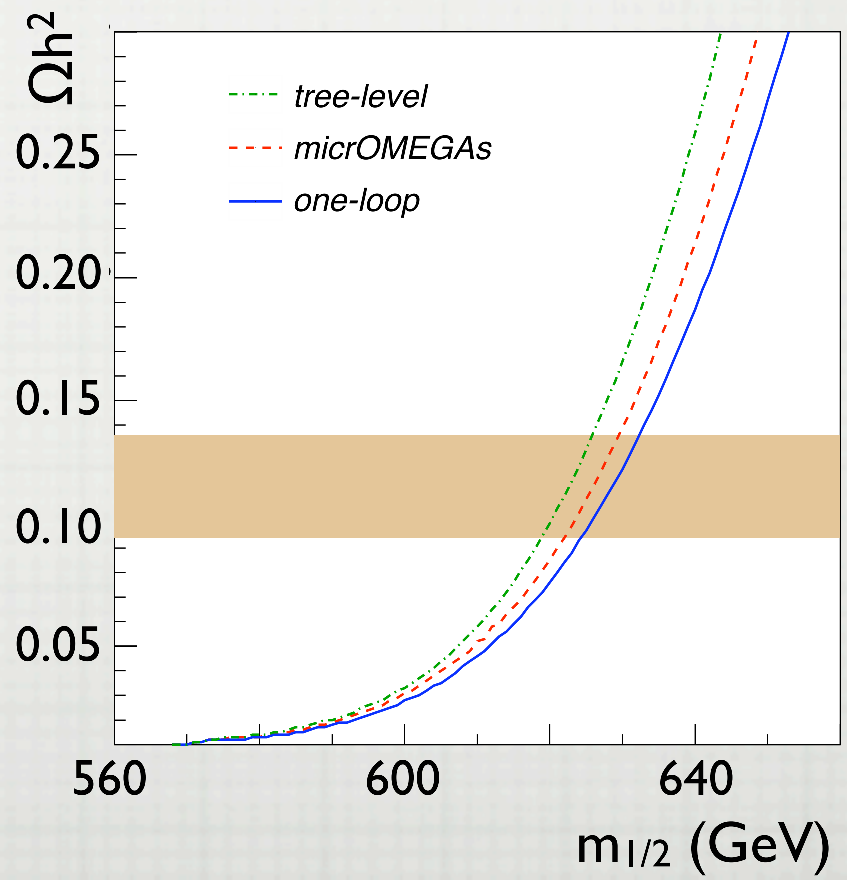






PRECISE DM

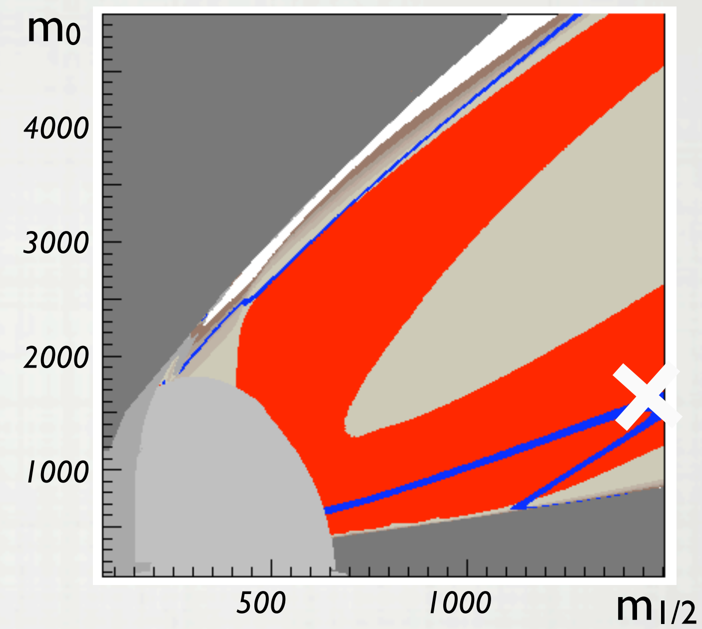
- mSUGRA parameter values:

  m_0 = 1500 GeV, $m_{1/2}$ = 1500 GeV

  $\tan\beta$ = 50, A_0 = 0 GeV, sgn μ = +

- Relic density:

  $\Omega h^2 = 0.117$, $b\bar{b}$ = 83%



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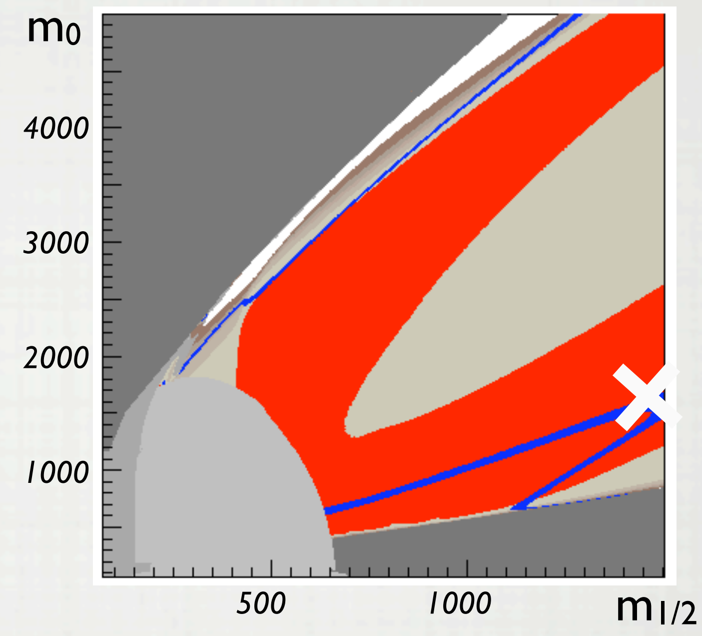

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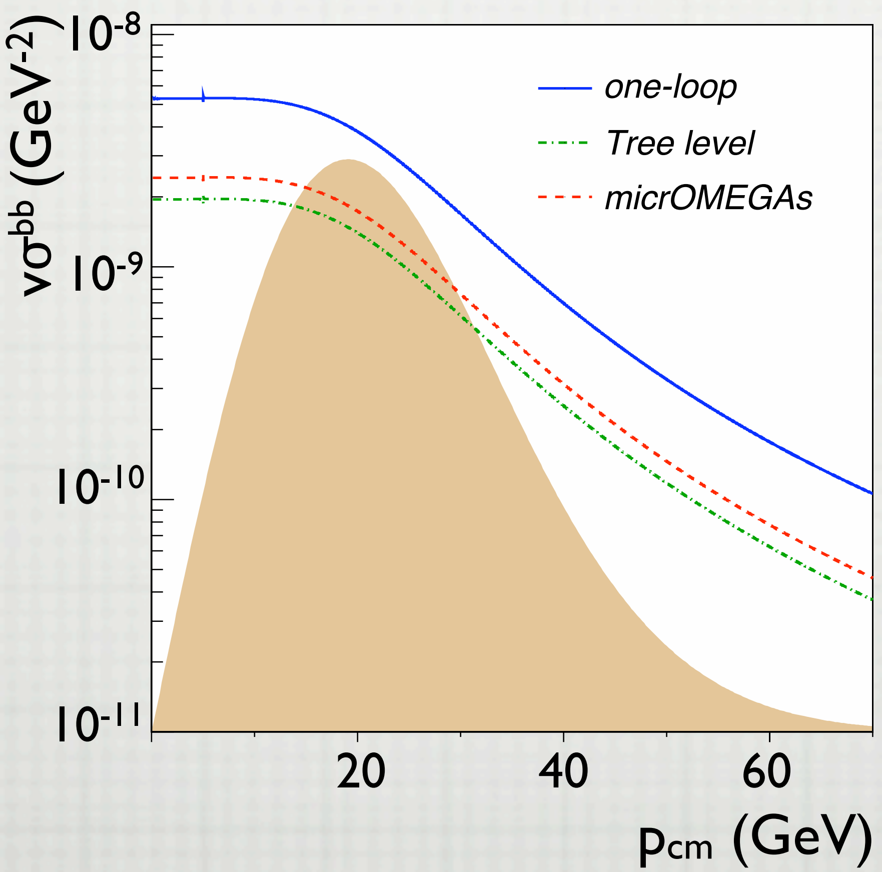
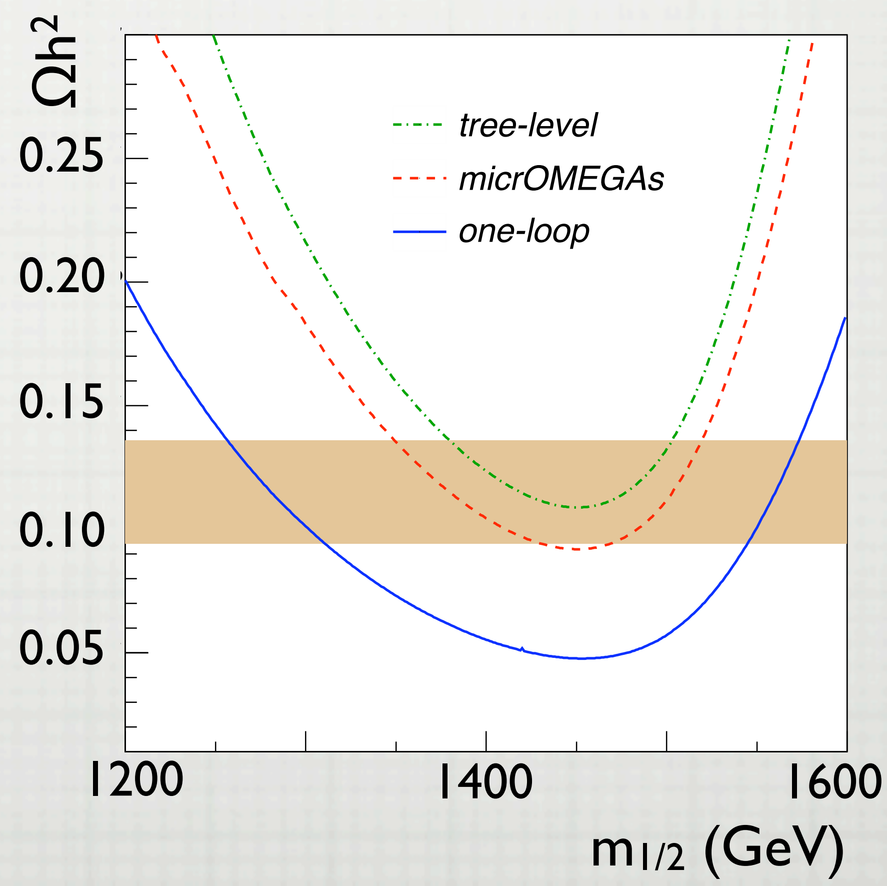




PRECISE DM

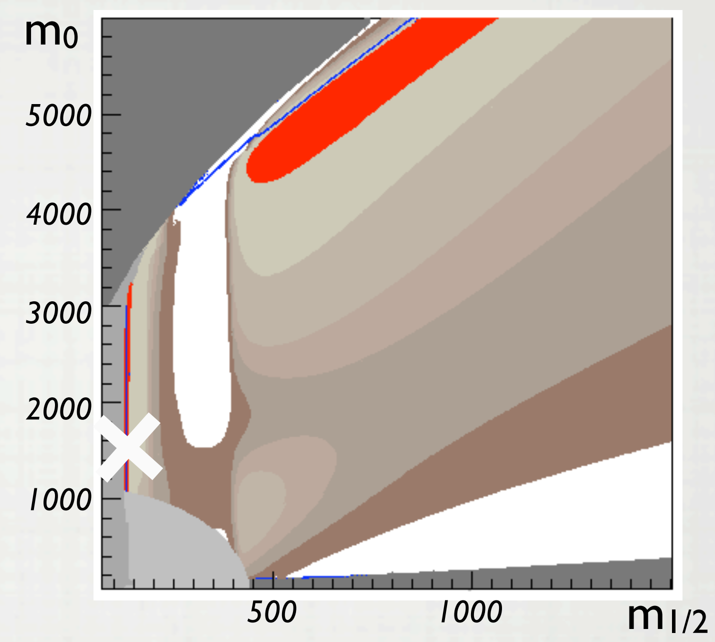
- mSUGRA parameter values:

  m_0 = 1500 GeV, $m_{1/2}$ = 130 GeV

  $\tan\beta$ = 10, A_0 = -1500 GeV, sgn μ = +

- Relic density:

  $\Omega h^2 = 0.116$, $b\bar{b}$ = 86%



PRECISE DM

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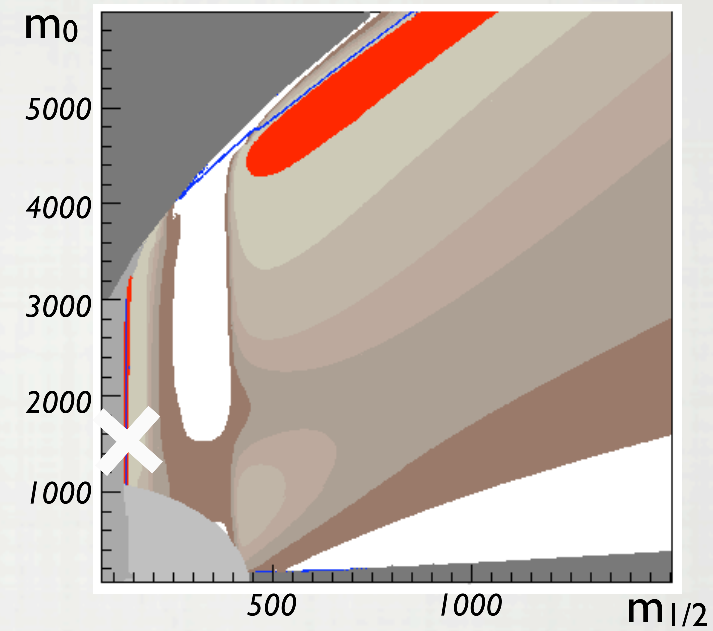

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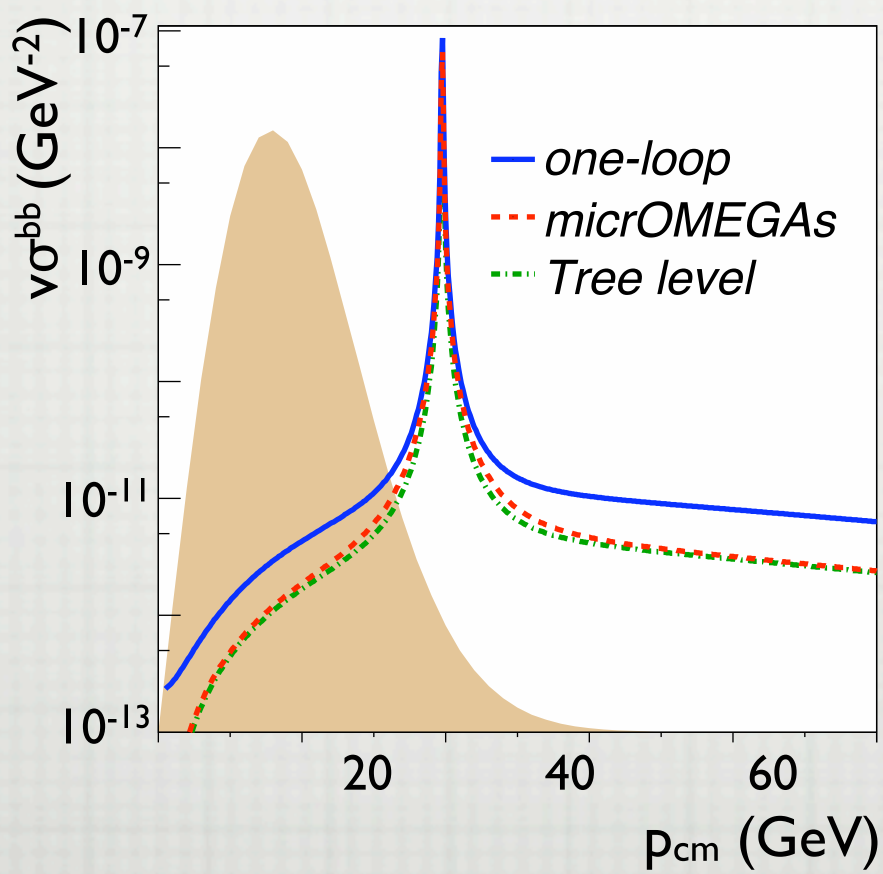
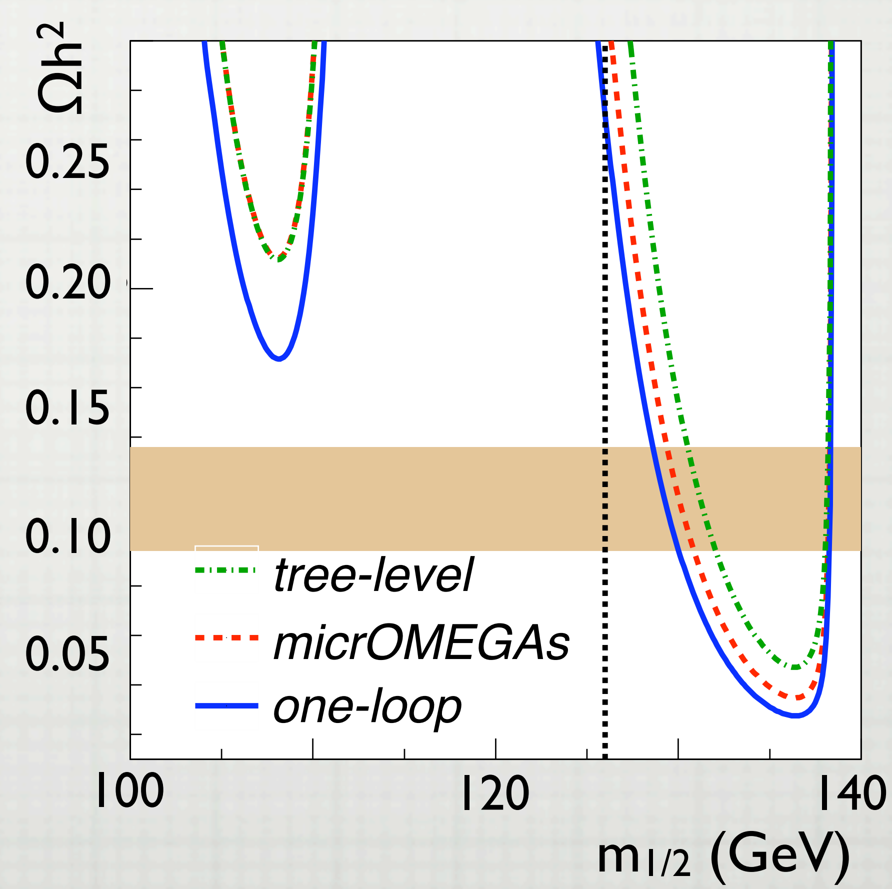
  $\Omega h^2 = 0.116$, $\quad b\bar{b} = 86\%$





PRECISE DM

- Parameter values:

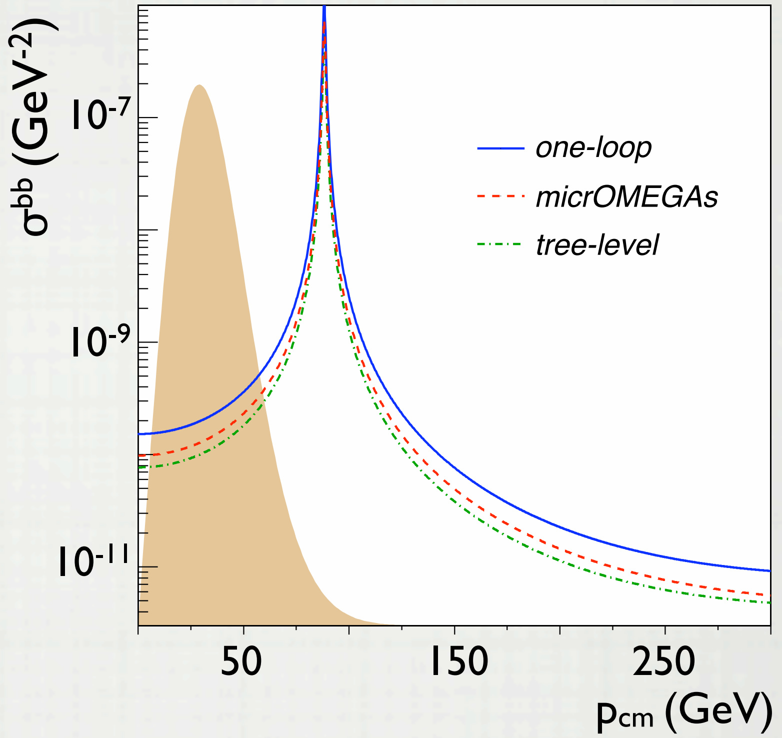
  m_0 = 500 GeV, M_2 = 500 GeV

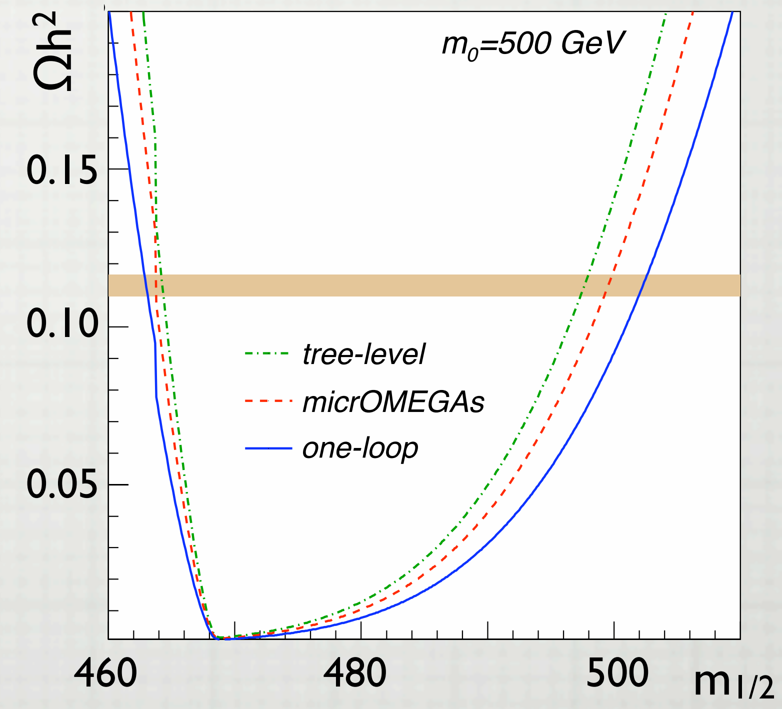
  $\tan\beta$ = 10, A_0 = 0, sgn μ = +

  M_{Hu} = 1500 GeV, M_{Hd} = 1000 GeV

- Relic density:

  $\Omega h^2 = 0.118$, $b\bar{b}$ = 64%, $t\bar{t}$ = 21%





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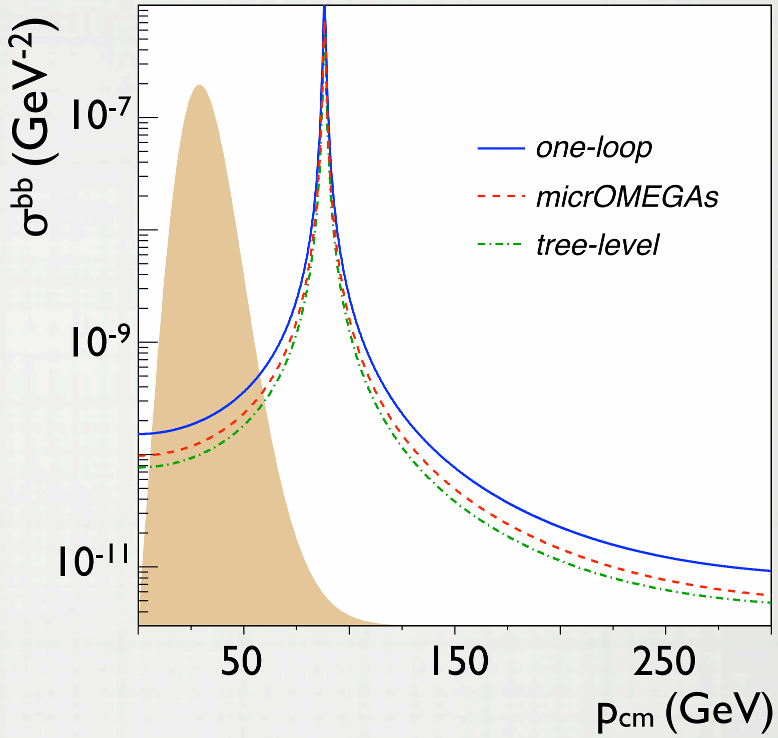
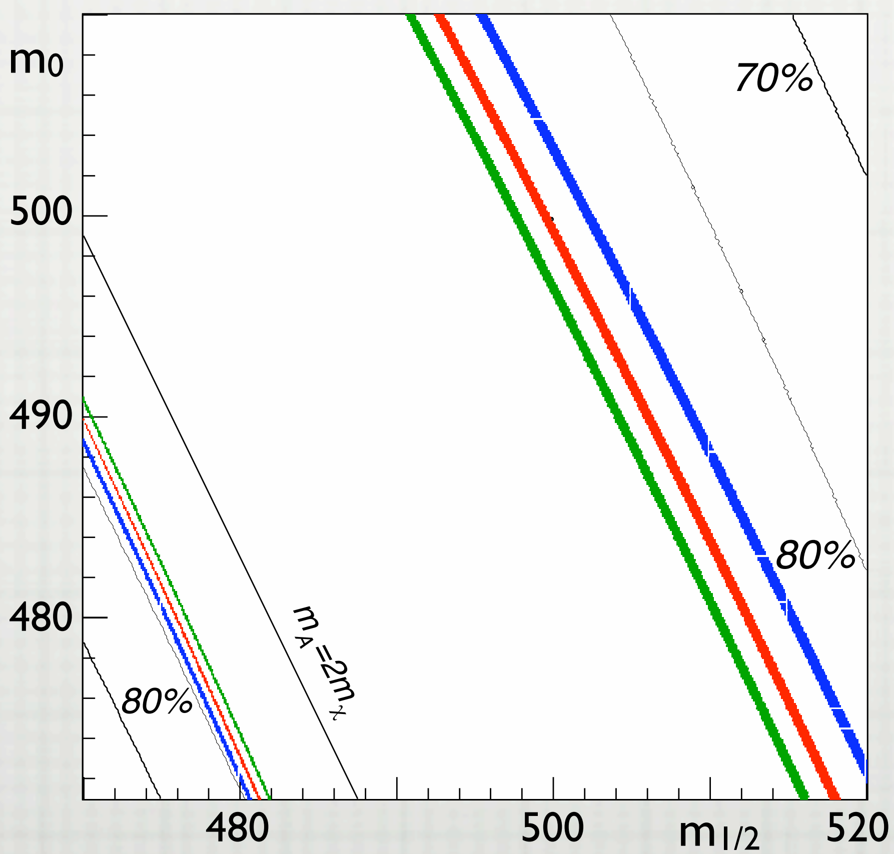
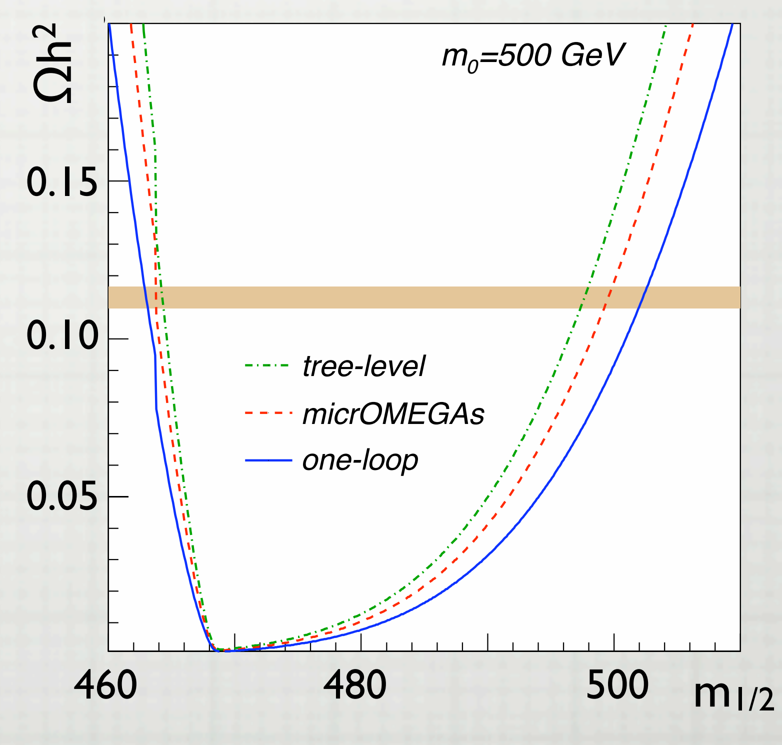






PRECISE DM

- Parameter values:

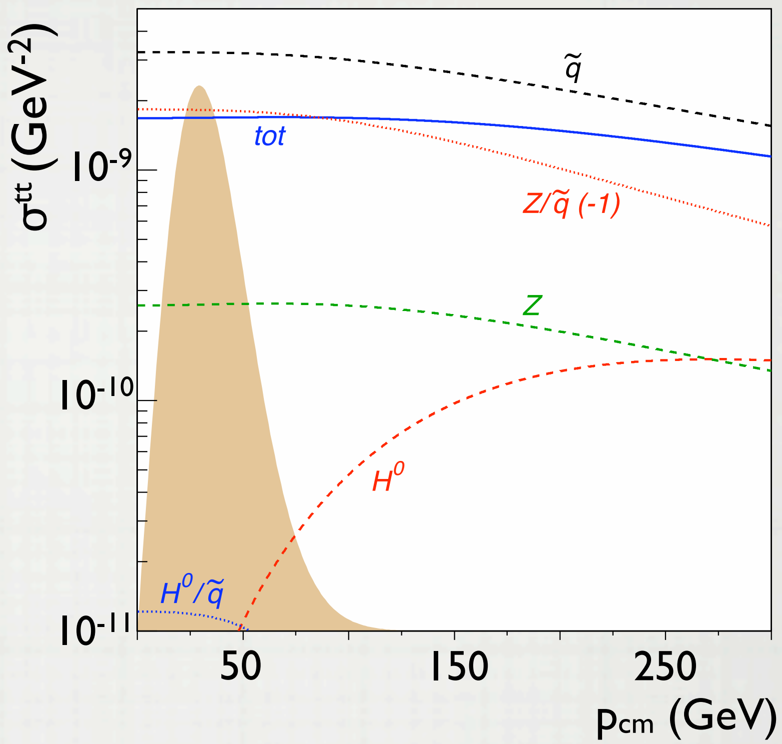
  m_0 = 500 GeV, M_2 = 500 GeV

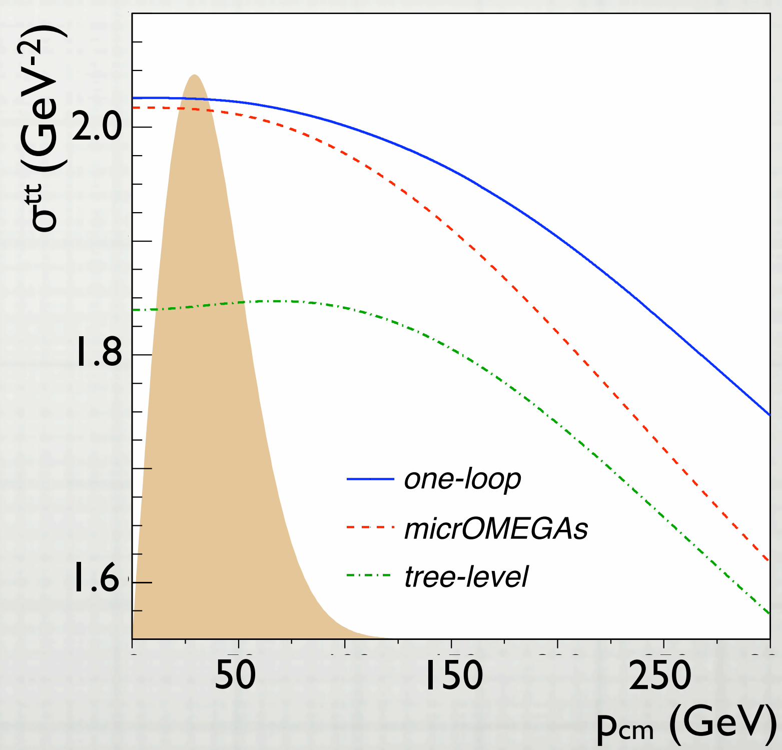
  $\tan\beta$ = 10, A_0 = -1200 GeV, sgn μ = +

  M_{Hu} = 1250 GeV, M_{Hd} = 2290 GeV

- Relic density:

  $\Omega h^2 = 0.113$, $\bar{t}t$ = 93%





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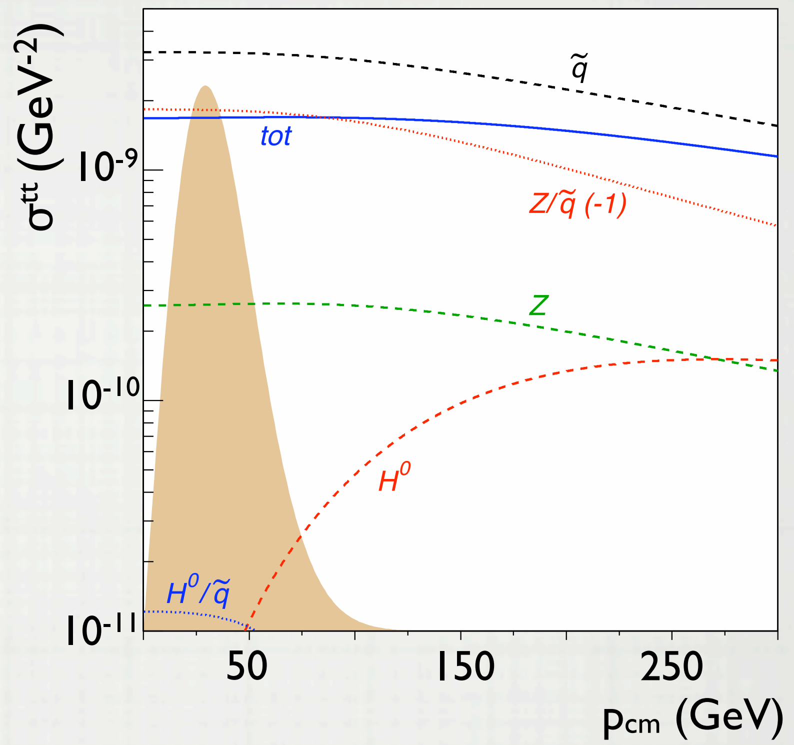
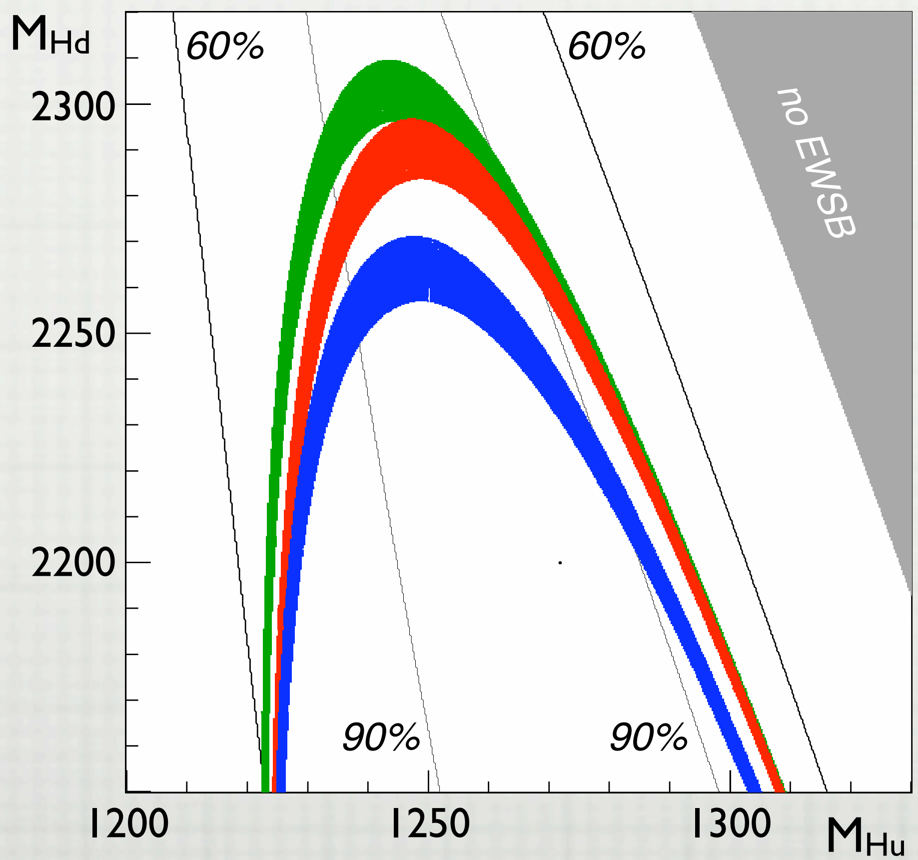
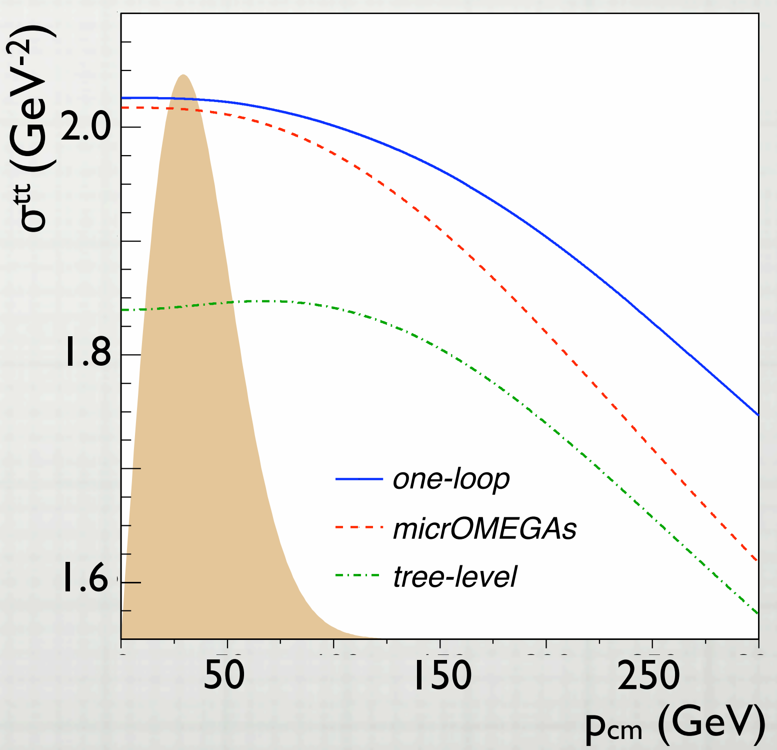






PRECISE DM

- Parameter values:

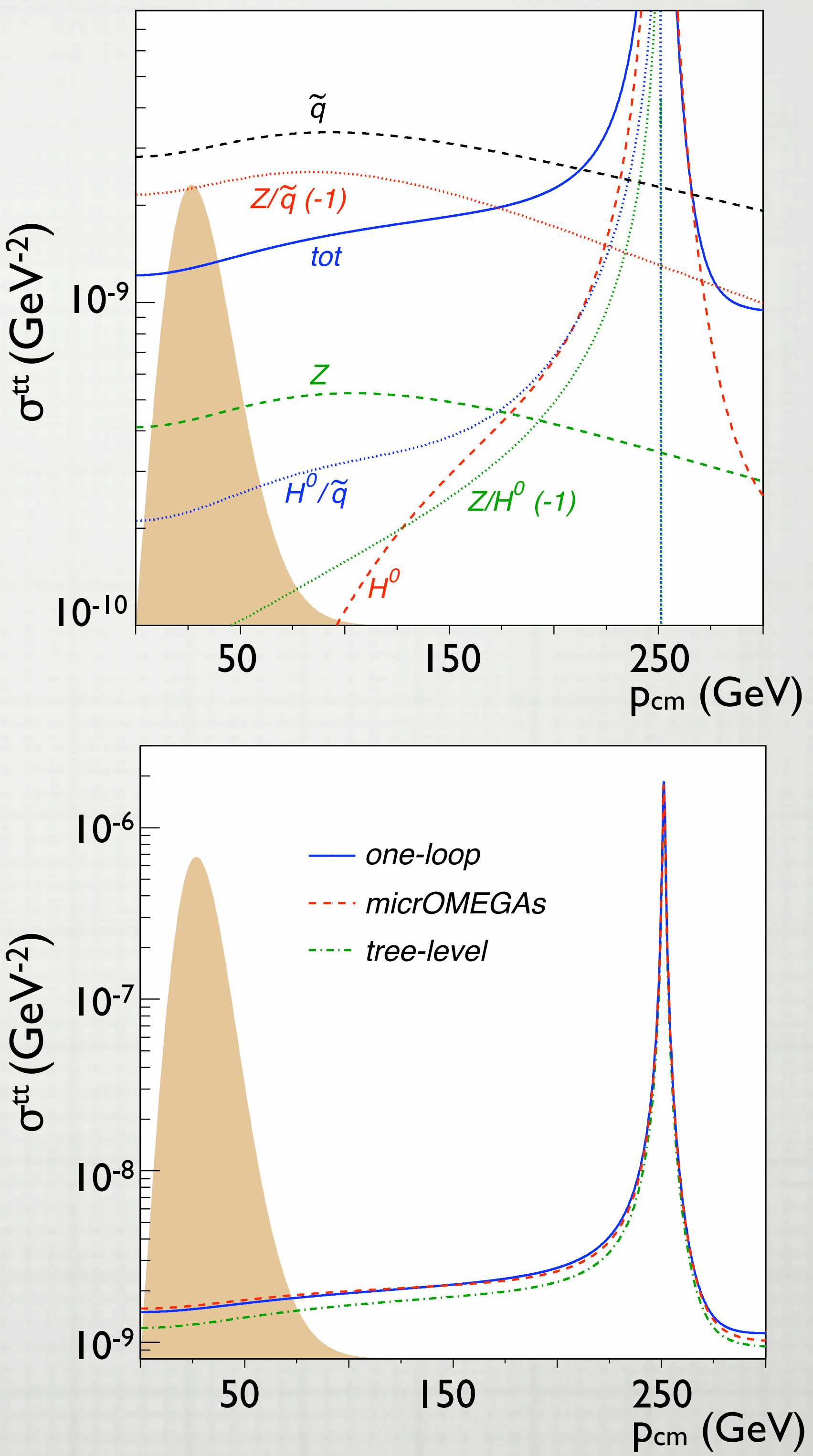
  m_0 = 320 GeV, M_2 = 700 GeV

  $\tan\beta$ = 10, A_0 = -350, sgn μ = +

  x_1 = 2/3, x_3 = 1/3

- Relic density:

  Ωh^2 = 0.114, $t\bar{t}$ = 79%



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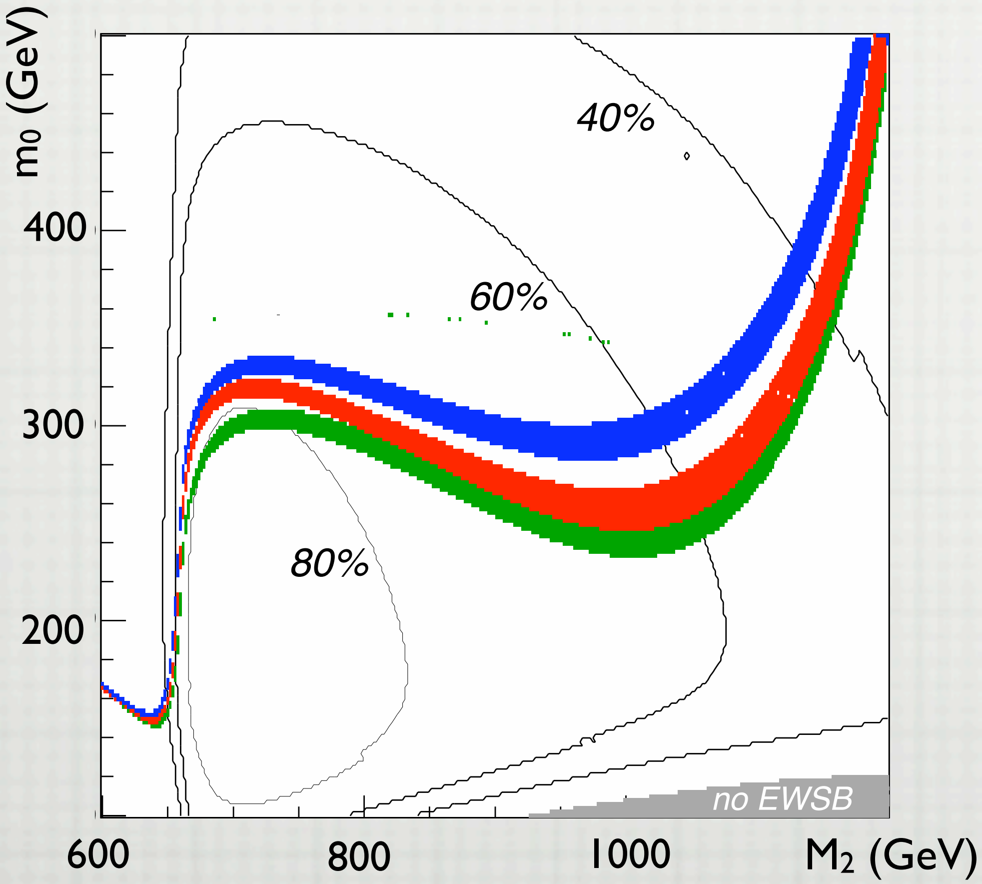
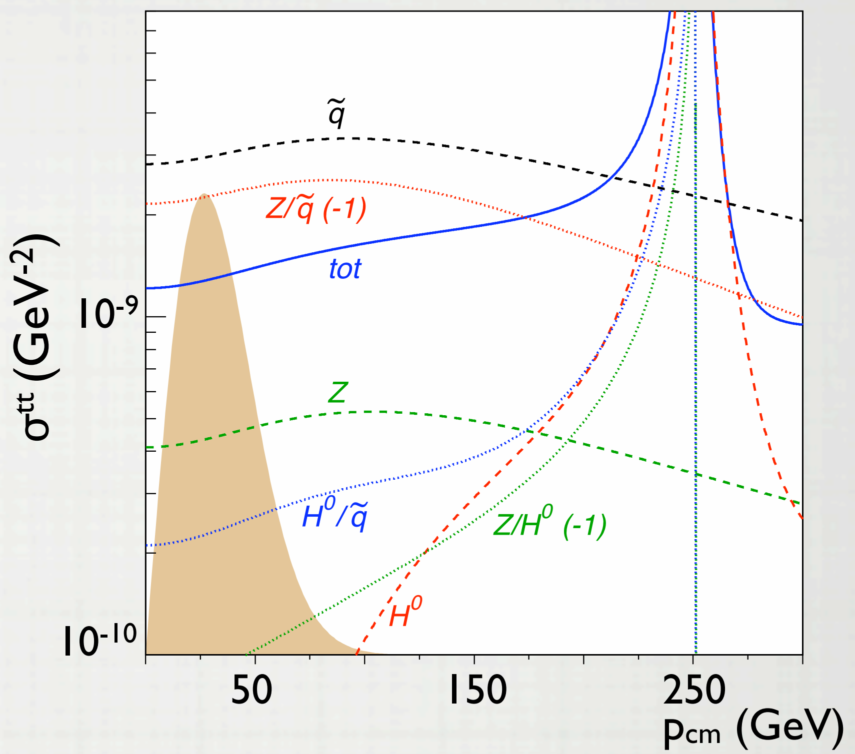
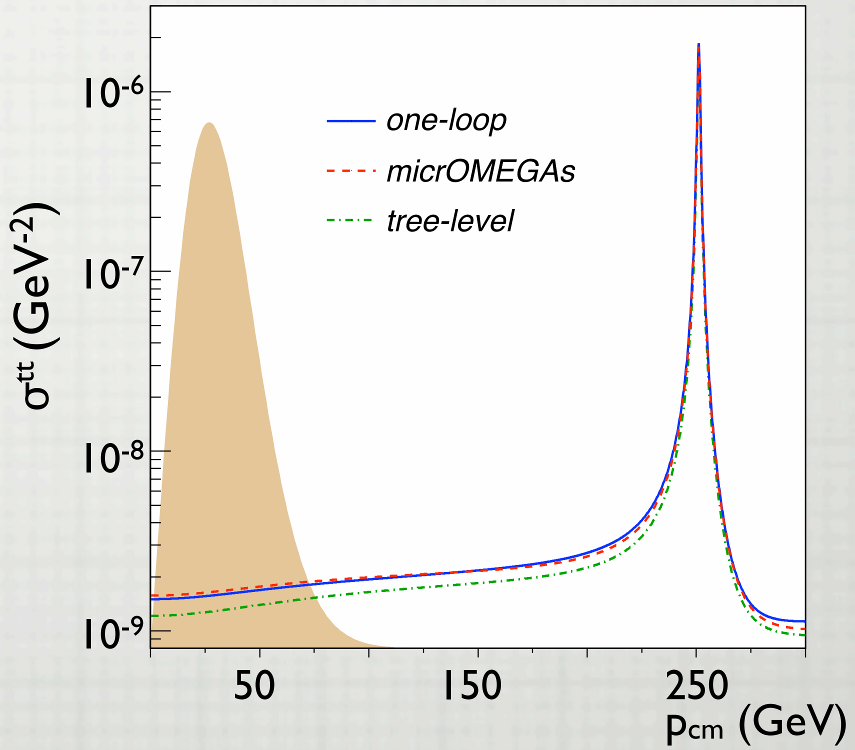






PRECISE DM

- Parameter values:

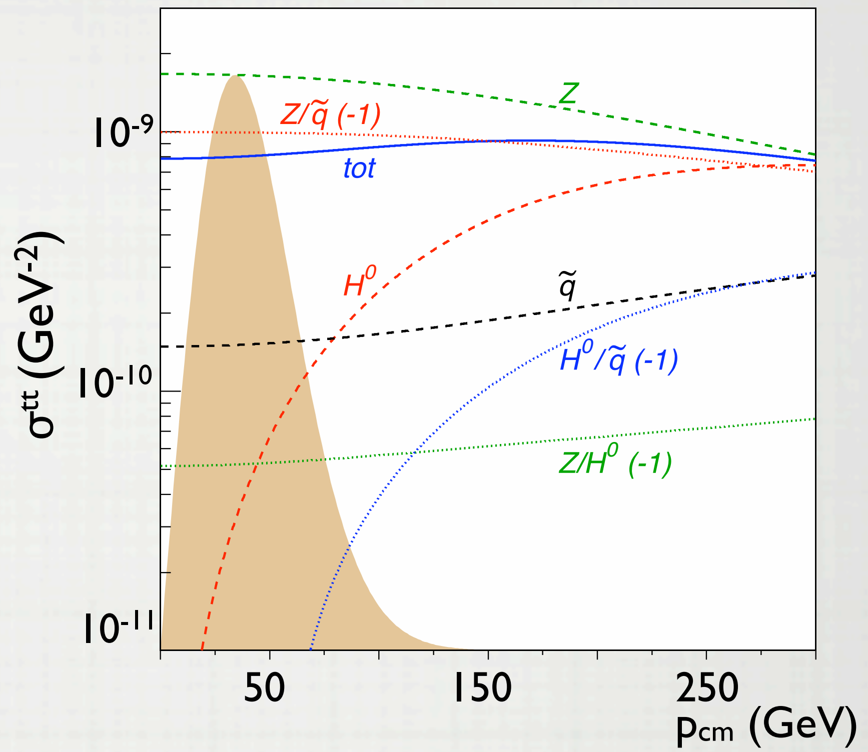
  m_0 = 1500 GeV, M_2 = 600 GeV

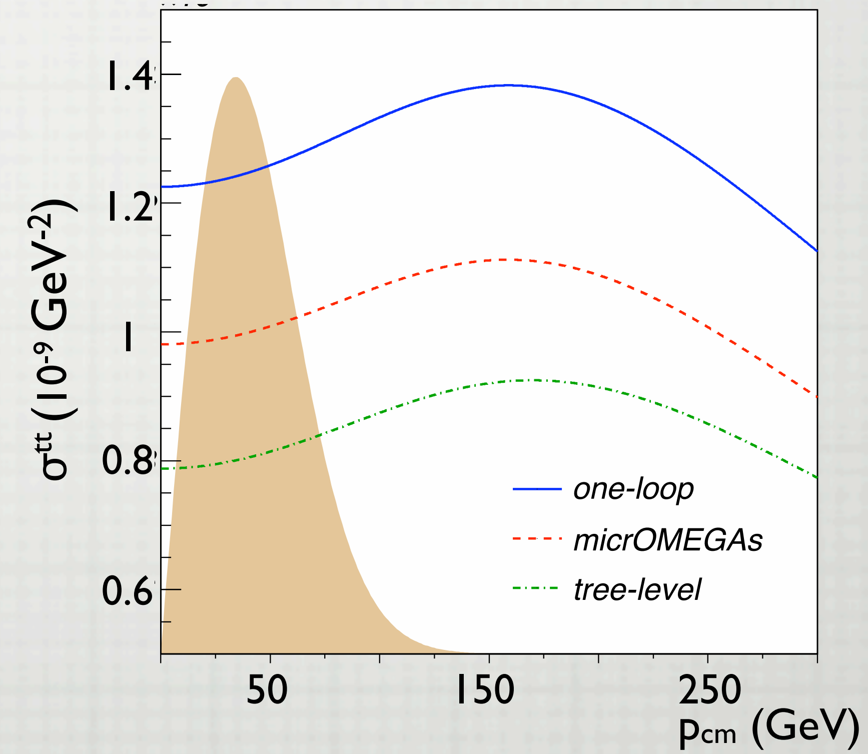
  $\tan\beta$ = 10, A_0 = 0, sgn μ = +

  x_1 = 1, x_3 = 4/9

- Relic density:

  Ωh^2 = 0.104, $t\bar{t}$ = 50%





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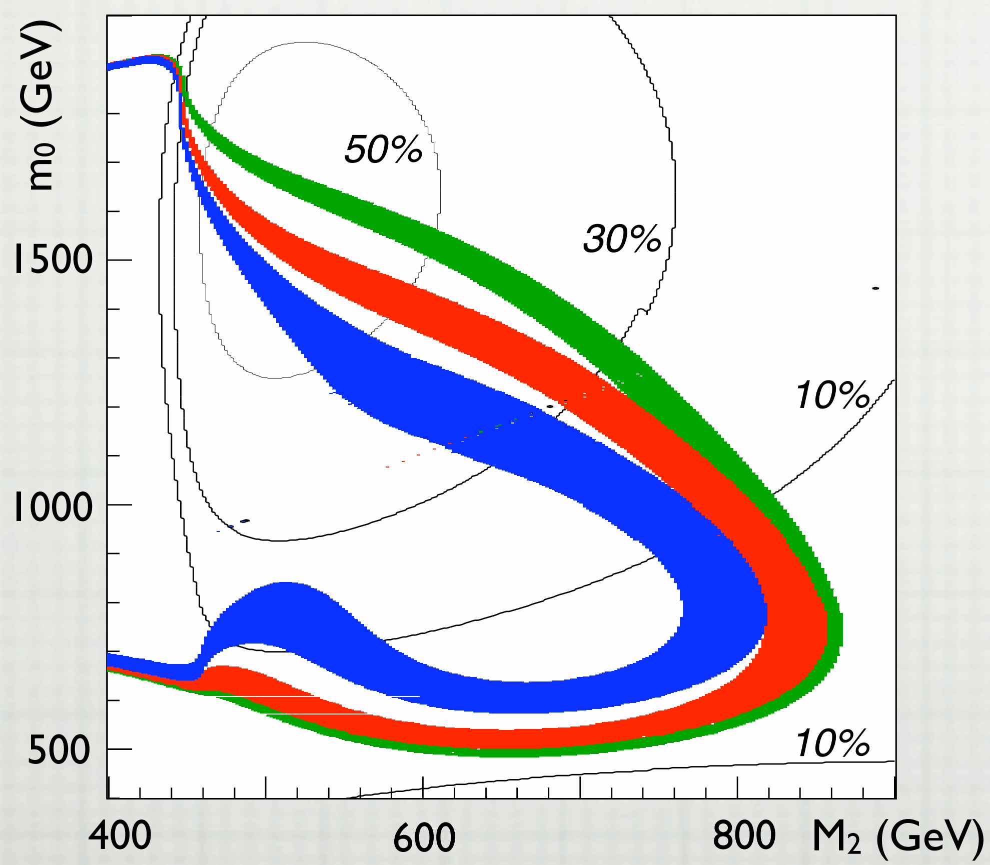
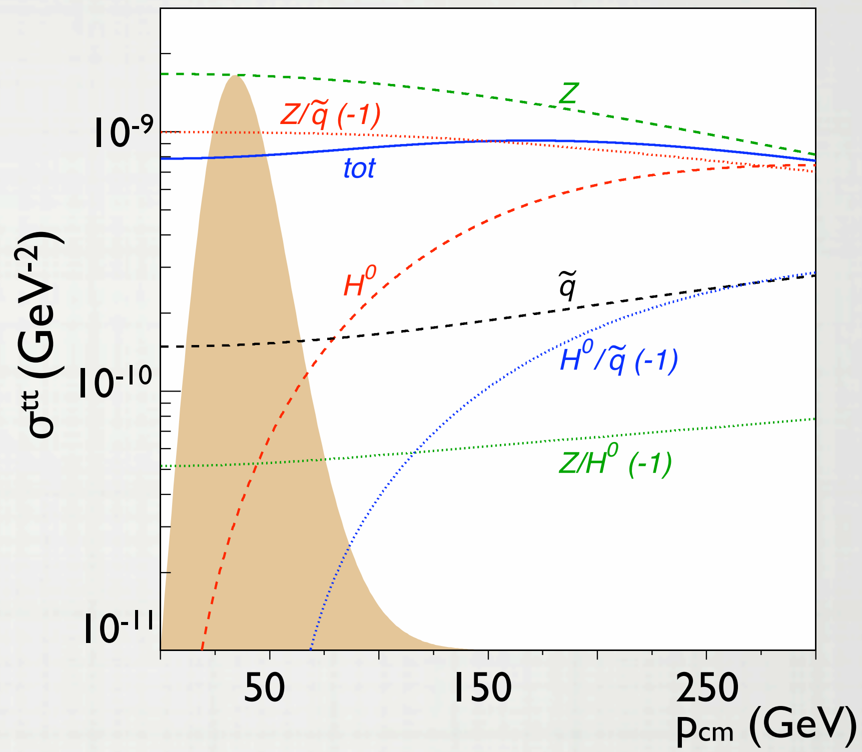
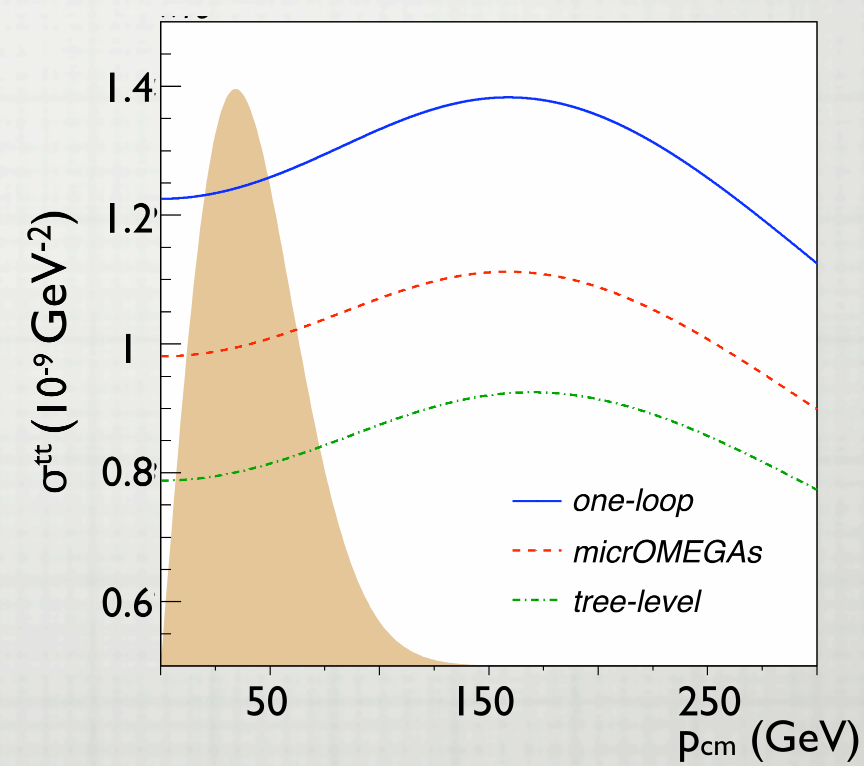
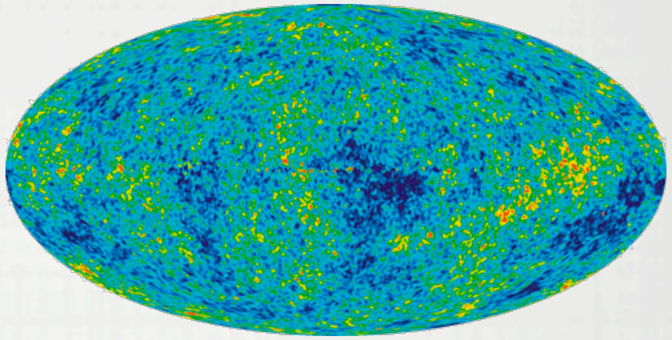






SUMMARY

- Precise astrophysical observations essential for particle physics at the LHC



- Higher-order corrections relevant for constraining SUSY parameter space using dark matter data

- SUSY-QCD corrections to neutralino annihilation to bottom & top quarks ~ 20-30%