Physics at the LHC
Lecture 10: Dark matter and the LHC

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Mass and geometry

Einstein equation:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G_N}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

$R_{\mu\nu}$**,** R**:** Ricci tensor, scalar

$g_{\mu\nu}$**:** Metric tensor

$T_{\mu\nu}$**:** energy-momentum tensor

Λ**:** cosmological constant

Line element:

$$ds^2 = -c^2 \mathrm{d}t^2 + a(t)^2 \left(\frac{\mathrm{d}r^2}{1 - kr^2} + r^2 \mathrm{d}\Omega^2 \right)$$

a =scale factor, $k = -1, 0, 1$

Friedmann equation (solution of Einstein equation with this metric):

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G_N}{3}\rho_{tot}$$

ρ_{tot}: average energy density of the universe

$H(t) = \frac{\dot{a}(t)}{a(t)}$: Hubble parameter. Today: $H_0 = 73 \pm 3$ km s^{-1} Mpc^{-1}

Critical density ($k = 0$, flat universe):

$$\rho_c \equiv \frac{3H^2}{8\pi G_N}$$

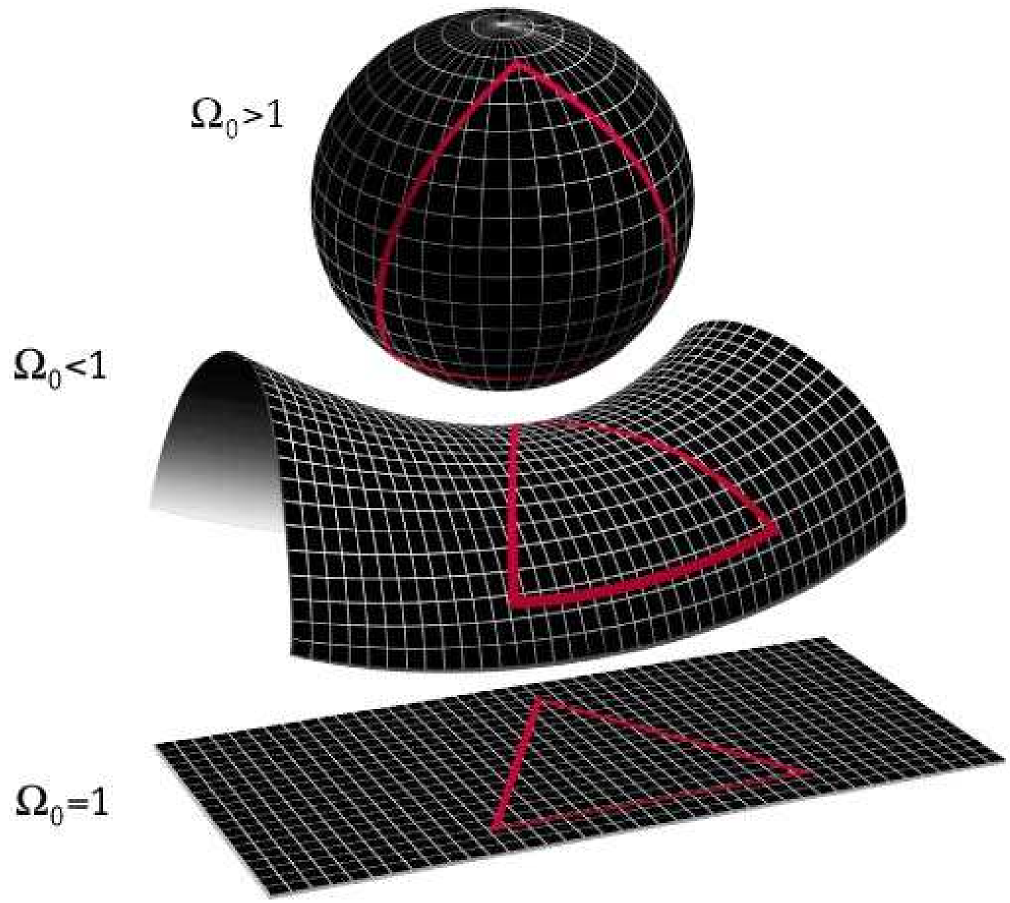
Express densities in terms of critical density:

$$\Omega_i \equiv \frac{\rho_i}{\rho_c}$$

$k = -1 : \Omega_{\rm tot} < 1$, open universe

$k = 0 : \Omega_{\rm tot} = 1$, flat universe

$k = 1 : \Omega_{\rm tot} > 1$, closed universe



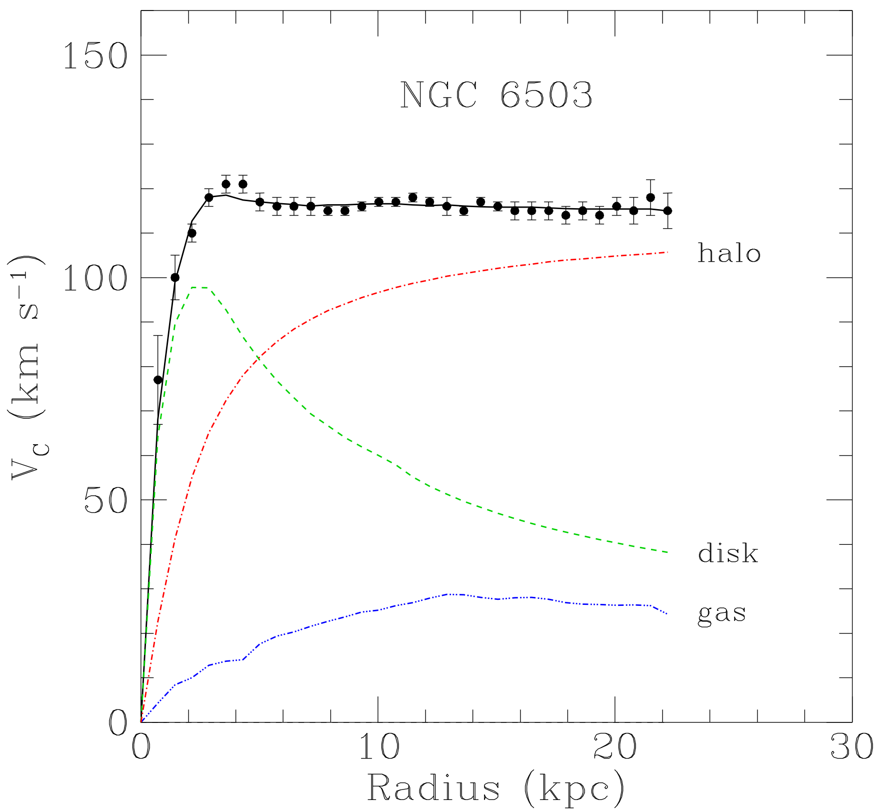
Why dark matter

Galactic scales:

Velocity distribution of objects at a distance r around the galaxy:

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

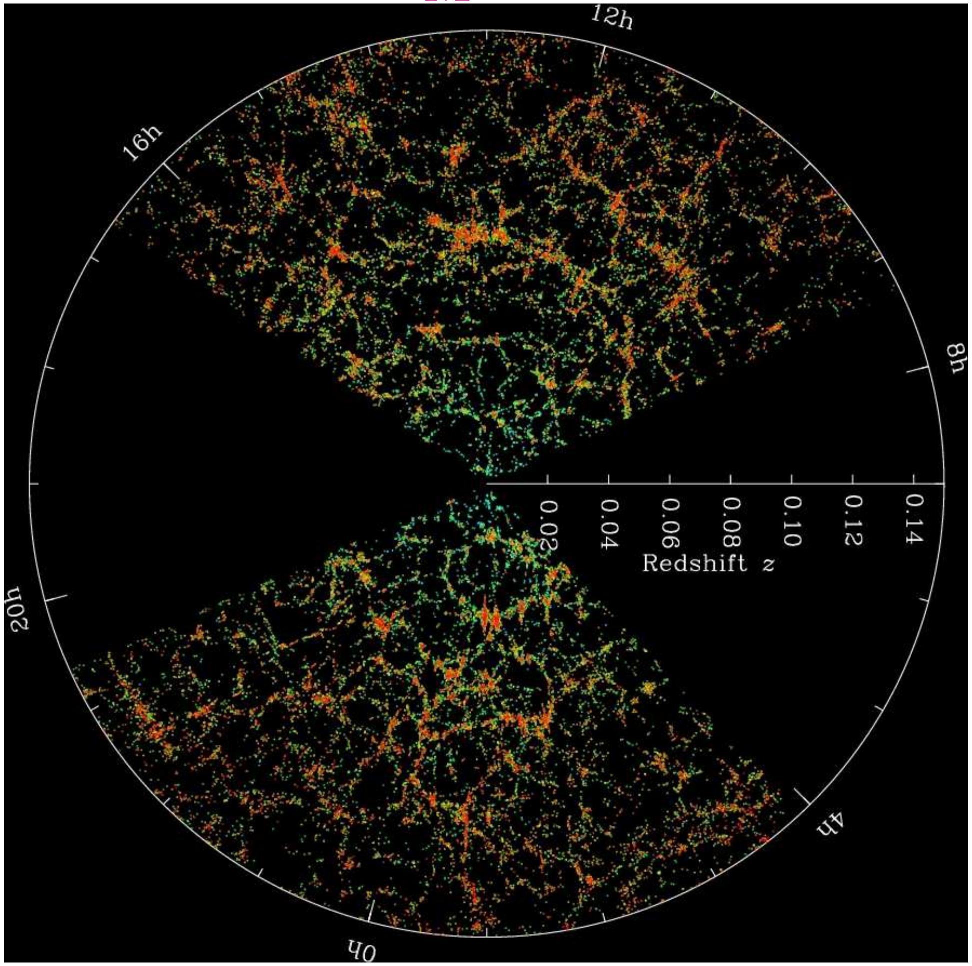
$M(r)$=mass inside radius r



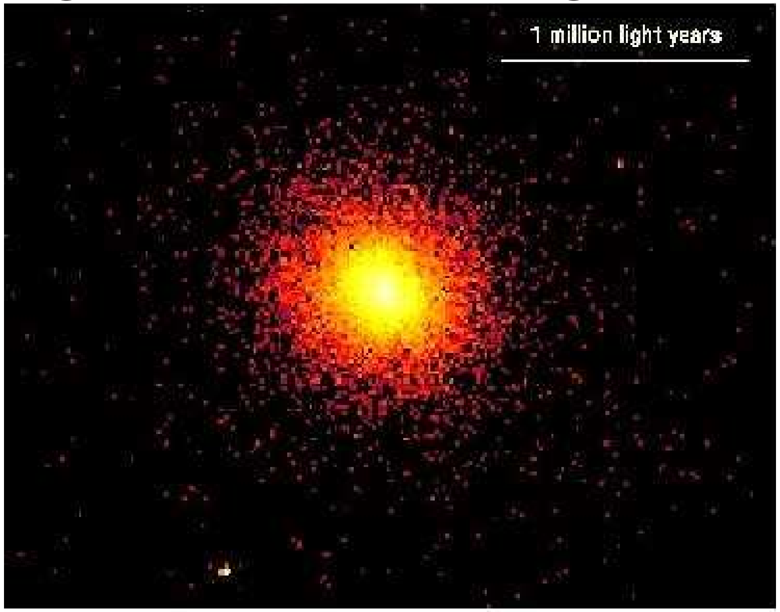
In the halo gas turns out to be much faster than predicted from visible (=baryonic) matter

Larger scales:

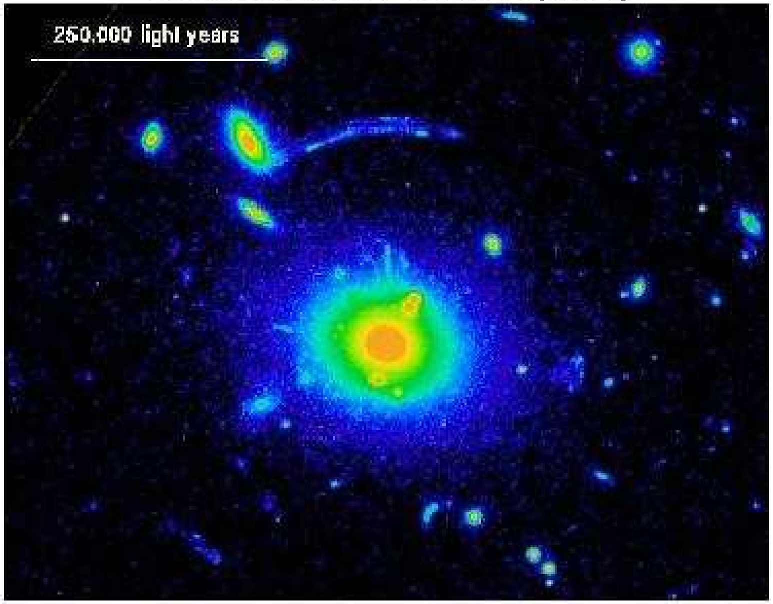
Detailed analysis of large scale structure and velocity distribution in galaxies gives $\Omega_M = 0.2 - 0.3$



This result is confirmed by results from gravitational lensing



MS2137.3-2353: Chandra (ACIS)

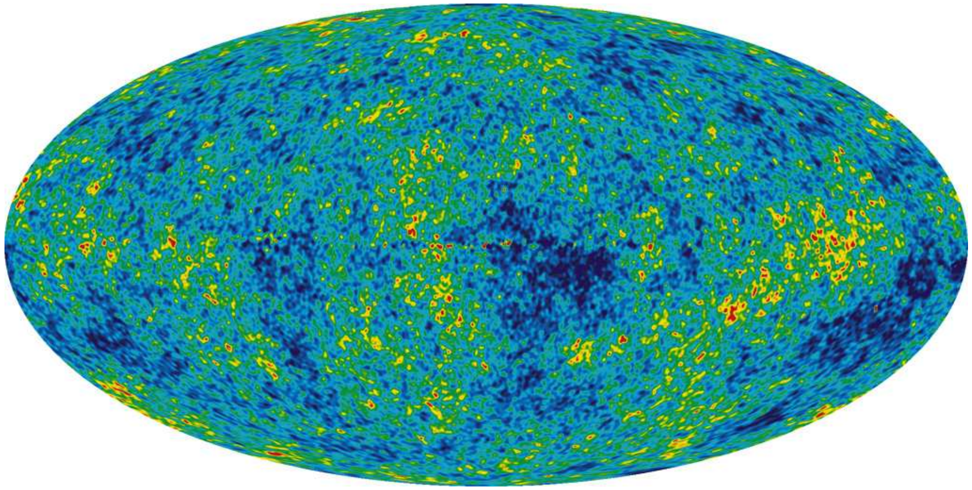


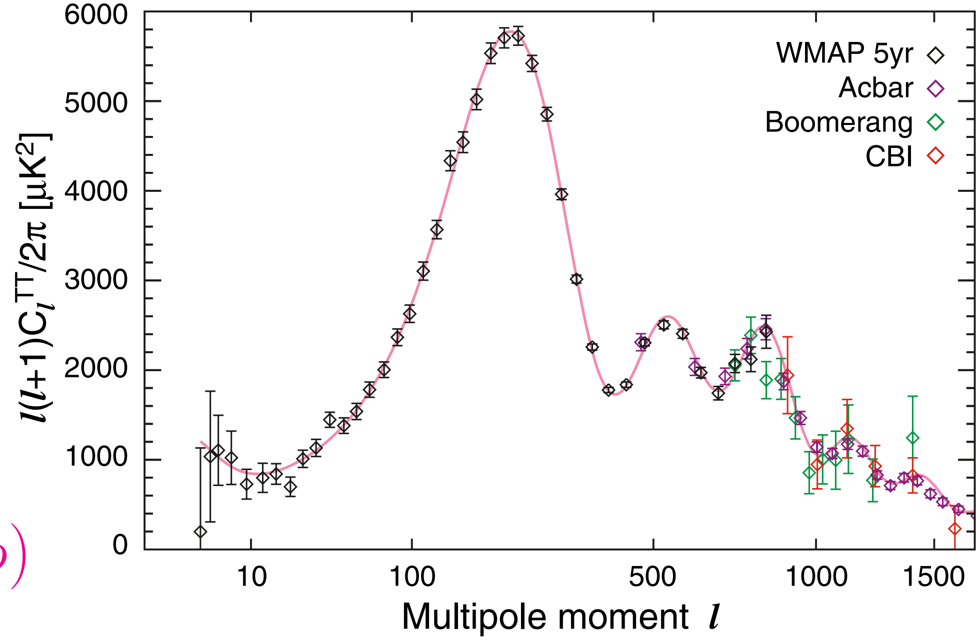
MS2137.3-2353: HST (WFPC2)

- 400000 years after the big bang atoms formed and the universe became transparent
- The photons decoupled at that time, cooled down and have the temperature of the universe (3 K)
- Any structure present at decoupling time can be seen in the CMB today
- The spectrum can be expanded in terms of spherical harmonics

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l=2}^{+\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta,\phi)$$

- The resulting power spectrum contains detailed information on the structure of the universe





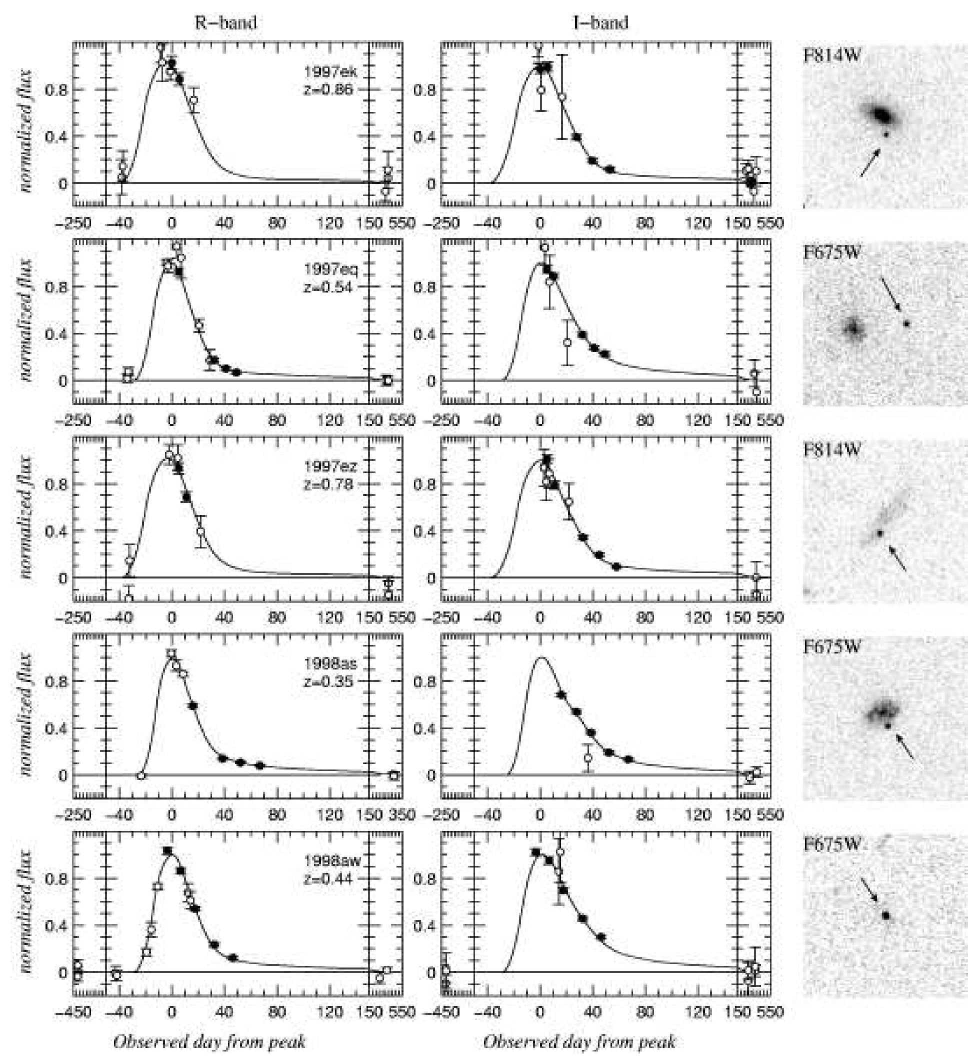
$$C_l \equiv < |a_{lm}|^2 > \equiv \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2.$$

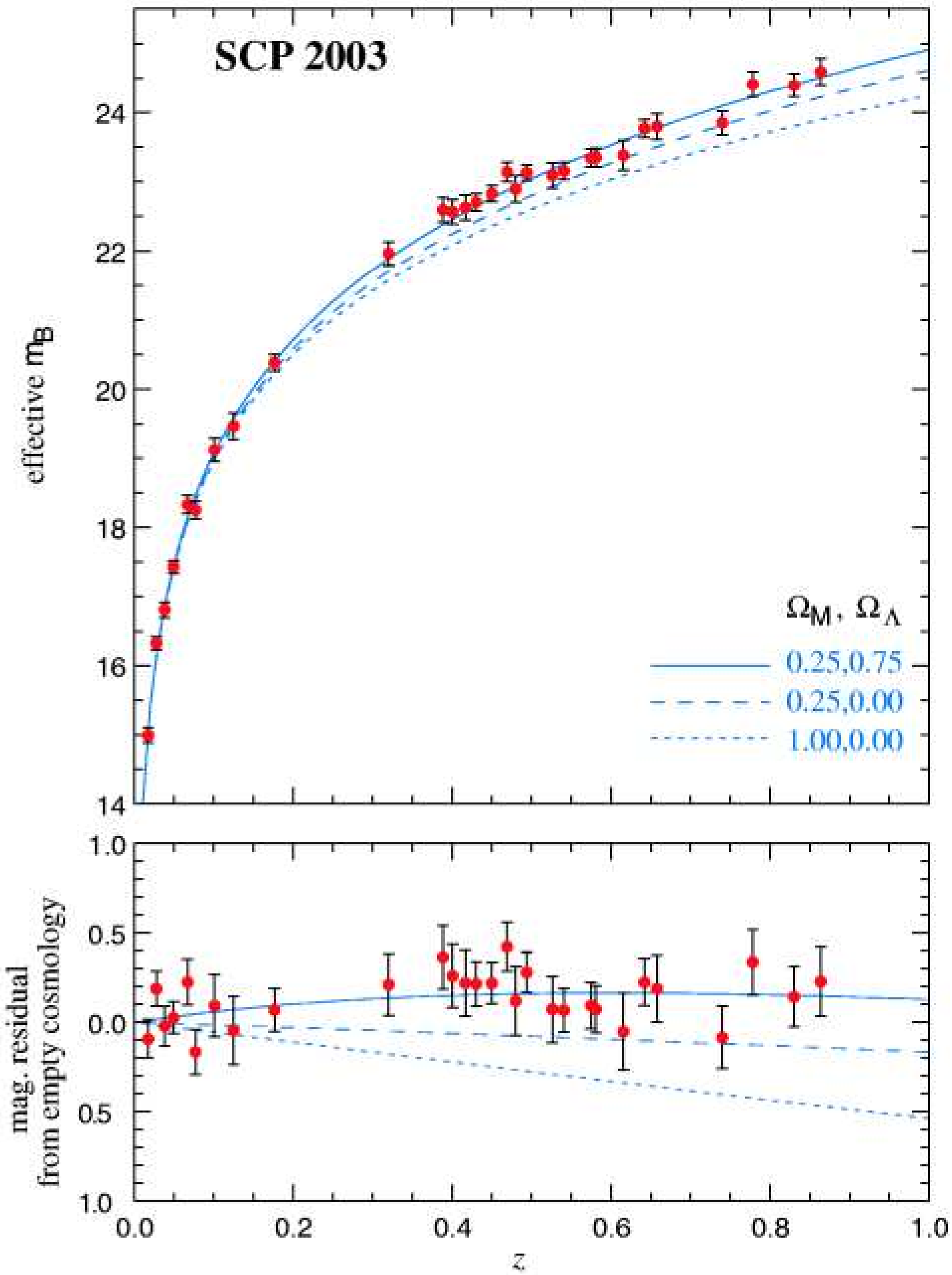
Information in the power spectrum:

- 1st peak: The size of the acoustic oscillations is well known. The peak position thus gives a precise measure of the geometry
- Other peaks: The ratio between the peak heights contains information on matter and baryon density

Supernovae:

- The absolute luminosity of type 1a supernovae is well known
- The apparent luminosity measures the distance of a supernova
- Its redshift measures the velocity
- With the Supernova Cosmology project the distance-velocity relation for many supernovae has been observed

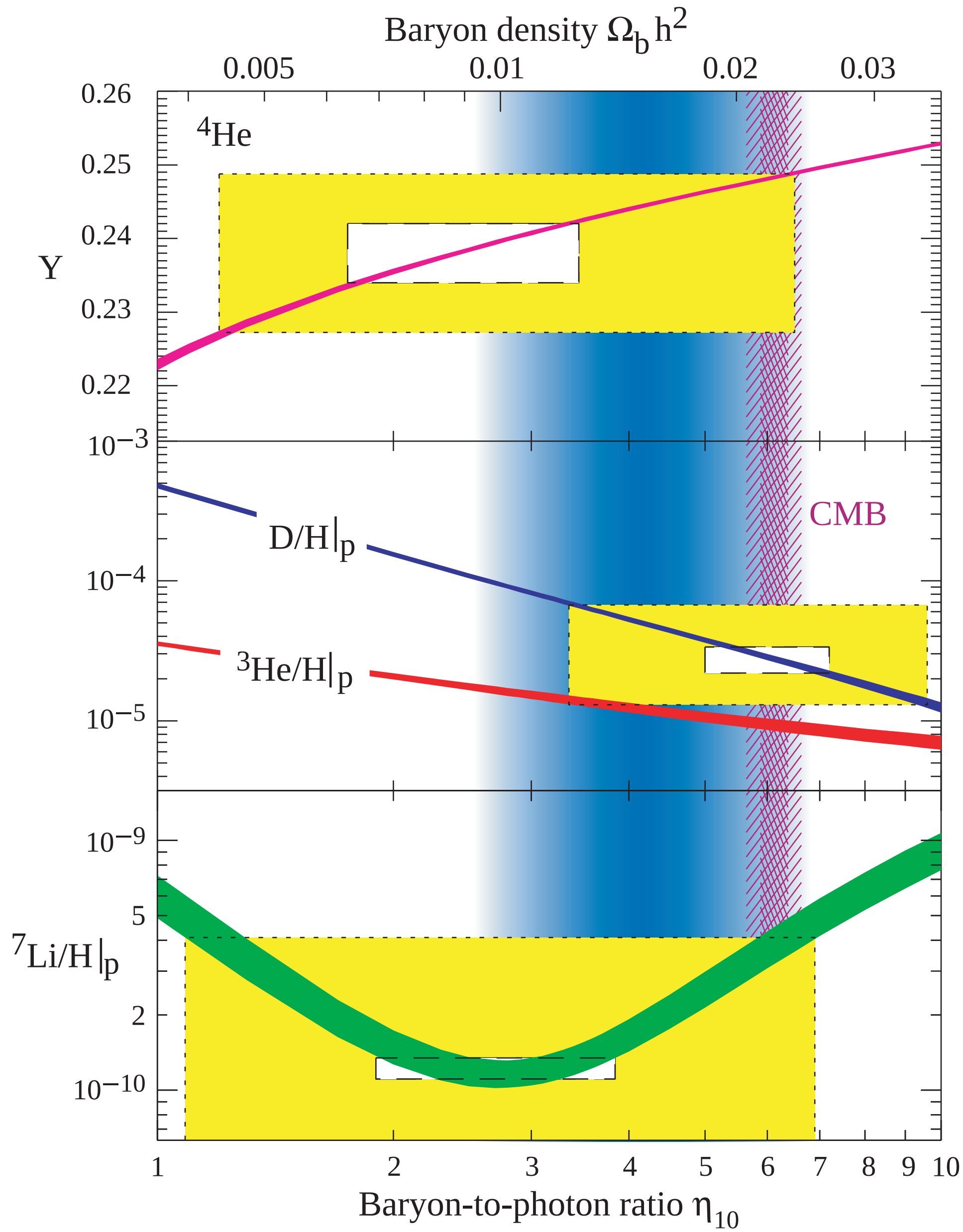




- It is expected that by gravitational force the expansion slows down
- However it is measured that the expansion accelerates
- This can be explained a dark energy with negative pressure
- E.g. this could be a non-vanishing cosmological constant

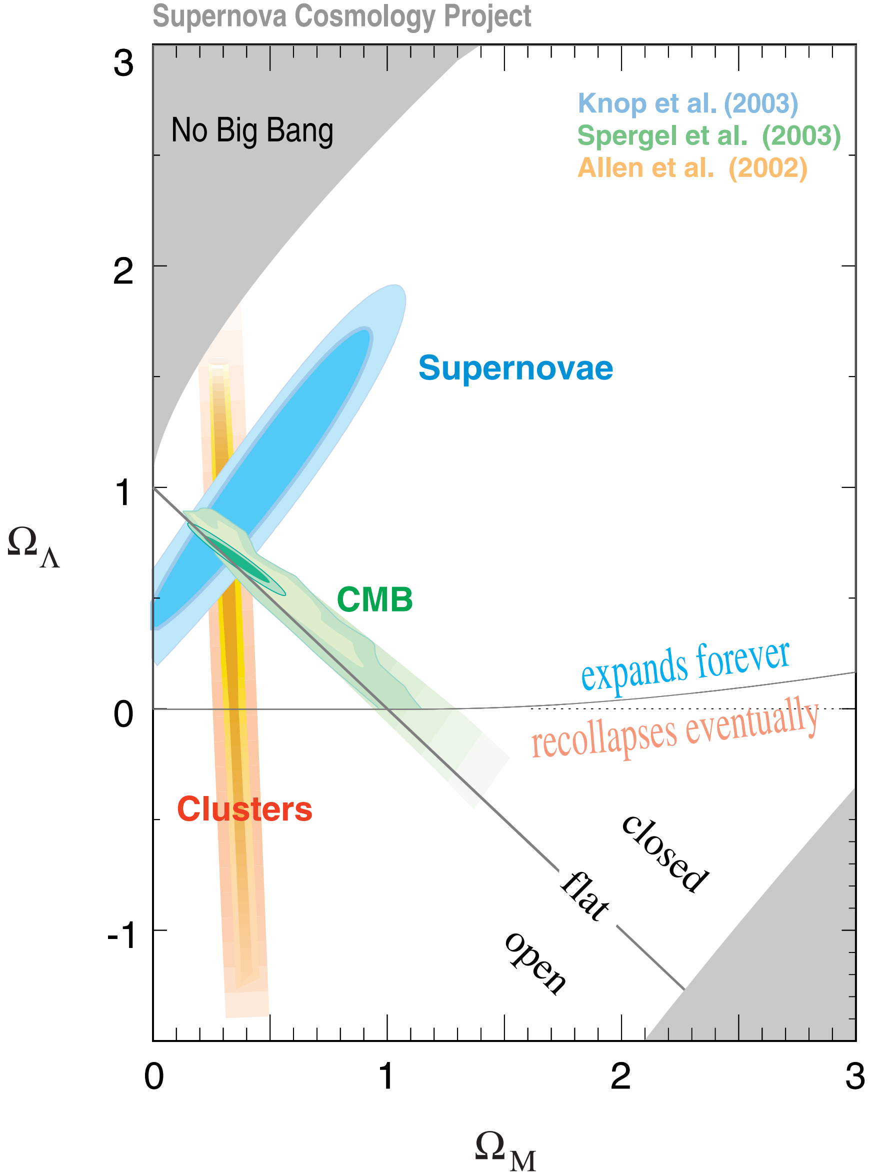
How do we know the baryonic matter density?

- The baryon density can be obtained measuring stars and dust in galaxies
- It follows from a detailed fit to the CMB power spectrum
- The abundance of primordial light elements after nucleosynthesis depends strongly on the baryon density
- All methods are consistent with $\Omega h^2 \approx 0.02$
  $(h = H_0/100\,\mathrm{km\,s^{-1}\,Mpc^{-1}})$



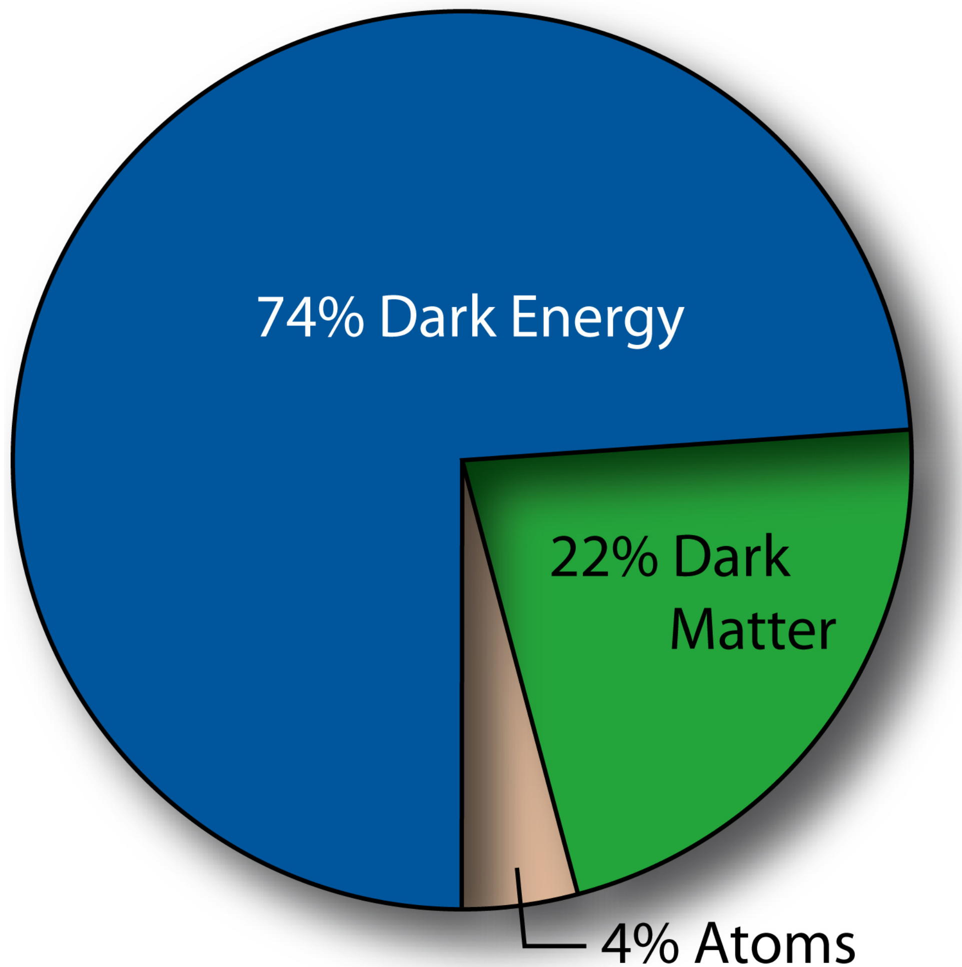
Global analysis of all data

All measurements give consistent results



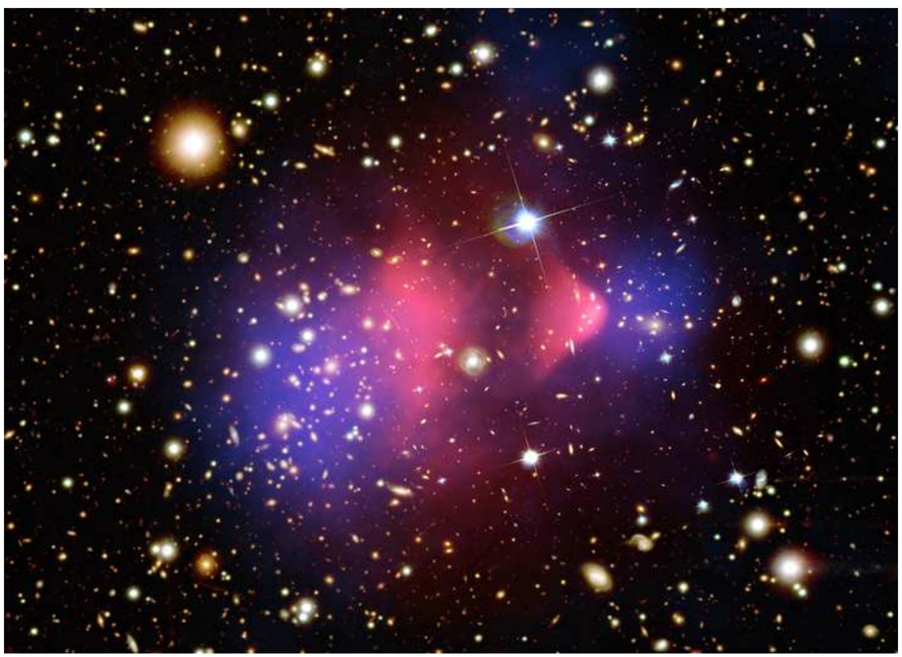
There is no way to get rid of the dark matter/energy

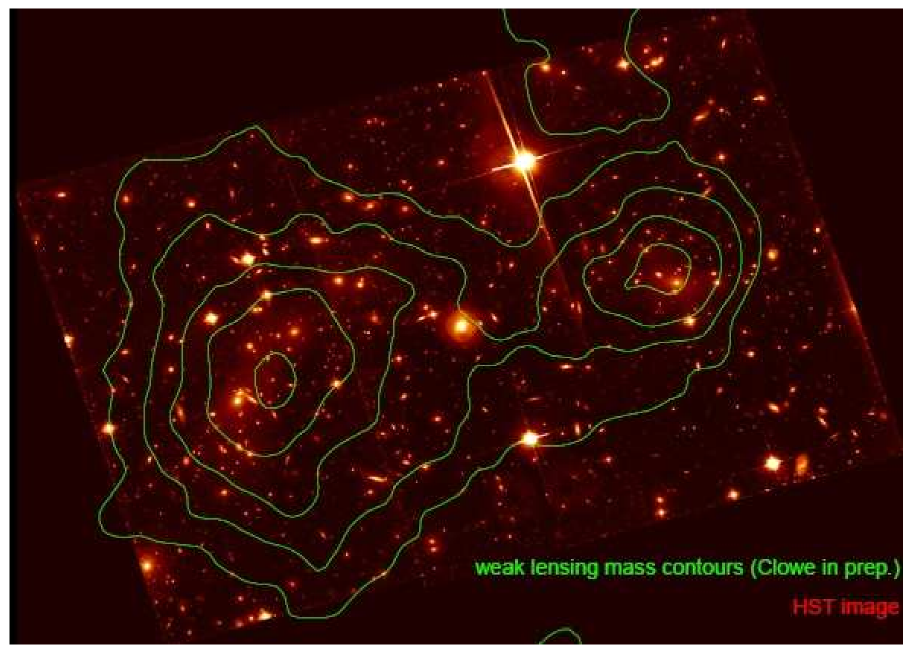
Our universe consists of



Can Newtonian gravity be wrong?

- There are theories that claim that gravity must be modified at large distances (MOND) avoiding dark matter
- This is in contradiction with the bullet-cluster observation:
  - Two galaxies collide
  - The stars (and the dark matter) pass without perturbation
  - The dust (majority of baryonic mass) is delayed because of interaction
  - Gravitational lensing shows that bulk of the matter is undisturbed





What is the nature of dark energy, dark matter?

Dark energy:

- Dark energy can be described by a cosmological constant
- Alternatively it can be a scalar field many orders of magnitude smaller than the Higgs field
- Particle physics probably cannot say anything about it

Dark matter:

- Dark matter can be ordinary particles (neutral and weakly interacting)
- Dark matter is responsible for the structure formation in the early universe
- To get the right amount of structure in the universe, the dark matter (or at least a component of it) should be cold ($M \sim 0.1 - 1\,\mathrm{TeV}$)

How to calculate the dark matter density?

- When the temperature of the universe was much higher than the dark matter mass, the dark matter was in thermal equilibrium
- When the temperature gets in the order of the mass the dark matter particles decouple
- The particles continue to annihilate until, due to the expansion of the universe, they don't meet anymore, then the number stays constant

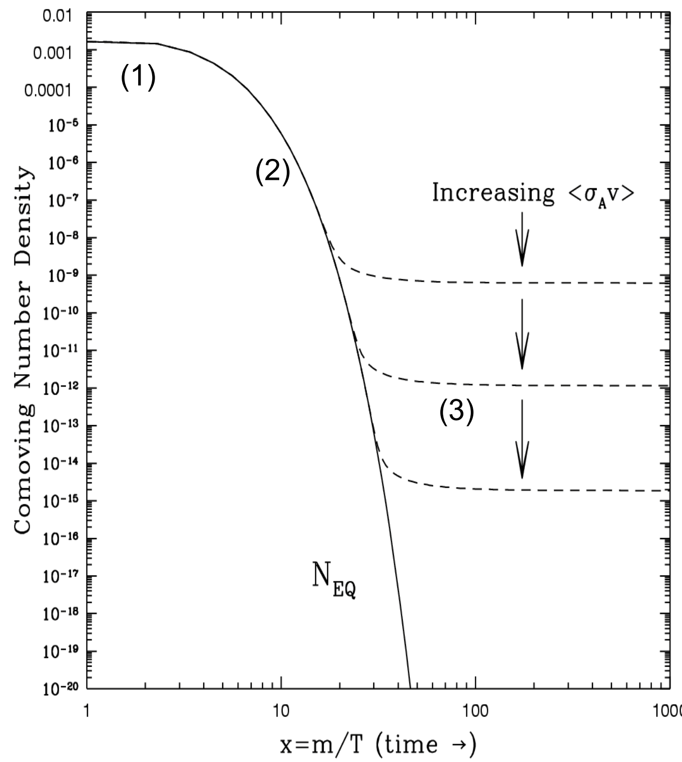
Number density in thermal equilibrium:

$$n^{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$$

Approx. number density after freezeout:

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

Need weak coss section to get the right density



Can neutrinos be the dark matter?

- The relic density of neutrinos is given by

$$\Omega_\nu h^2 = \sum_{i=1}^{3} \frac{m_i}{93\ \mathrm{eV}}$$

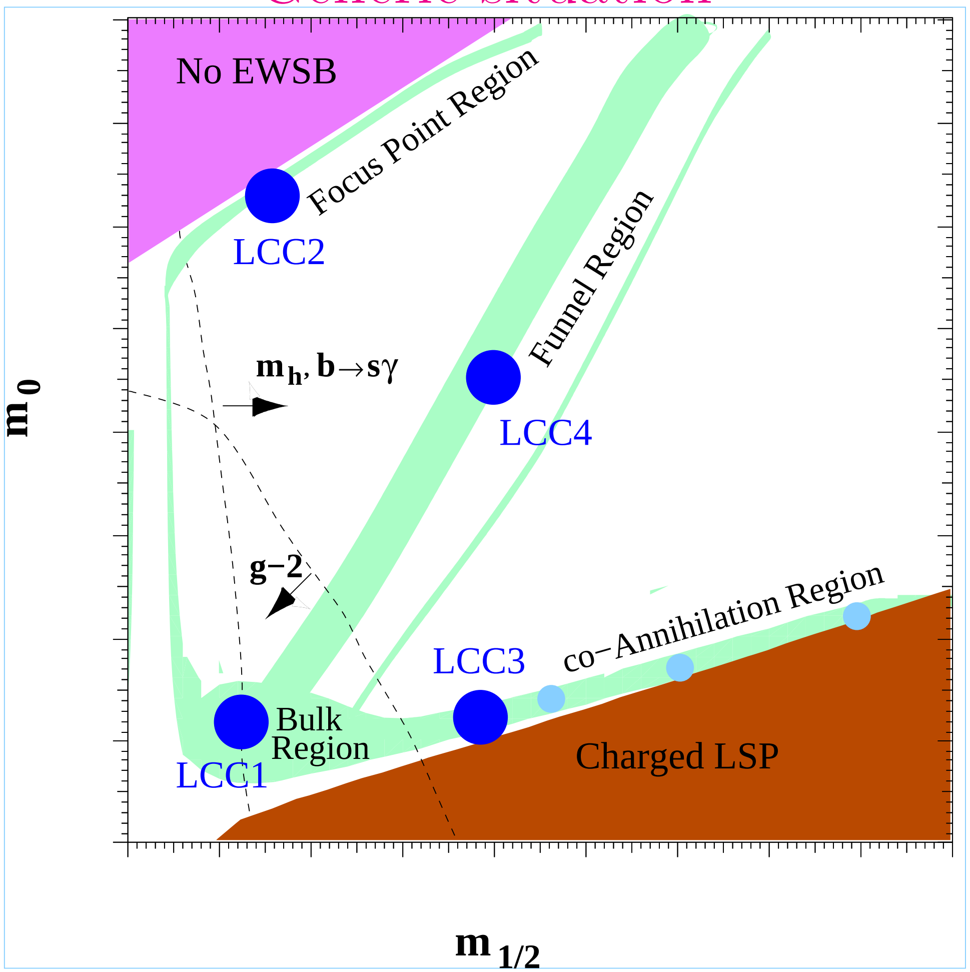
- We know experimentally $m_\nu < 2\,\mathrm{eV}$
- The small mass difference suggests that the neutrino mass is even much smaller
- This totally excludes neutrinos as dark matter
- In any case it would be difficult to explain the structure of the universe with a hot dark matter as neutrinos

Dark matter calculations in mSUGRA

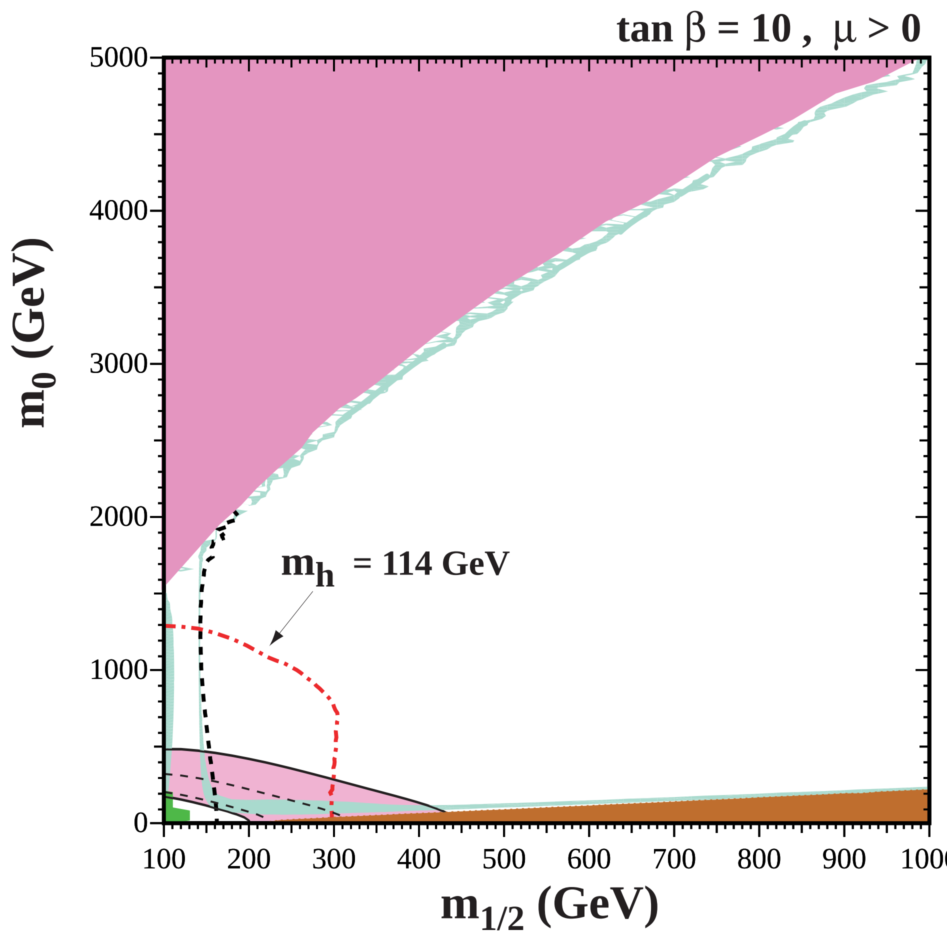
- In SUSY everything is known so that the dark matter density can be calculated
- (In most cases) it is enough to know the mass and annihilation cross section of the χ_1^0
- This means the composition of the χ_1^0 (photino, Zino, Higgsino) must be known
- In mSUGRA this quantity can be calculated as a function of the four parameters and one sign

Results:

Generic situation



Specific choice of $\tan\beta, \text{sign}(\mu)$



Several regions:

Bulk region: Region at low masses where the χ_1^0 annihilation cross section is large enough

Focus point region: m_0 is at the upper edge of its allowed range

- χ_1^0 has significant Higgsino component so that $\chi_1^0\chi_1^0 \to WW, ZZ$ gets relevant
  ➠ large enough annihilation cross section
- Scalars are very heavy and probably invisible at the LHC

Funnel regions: Special resonance conditions apply like $m(A) \approx 2m(\chi_1^0)$ so that the annihilation cross section gets enhanced by the decay through the resonance

Coannihilation region: m_0 is at the lower allowed edge

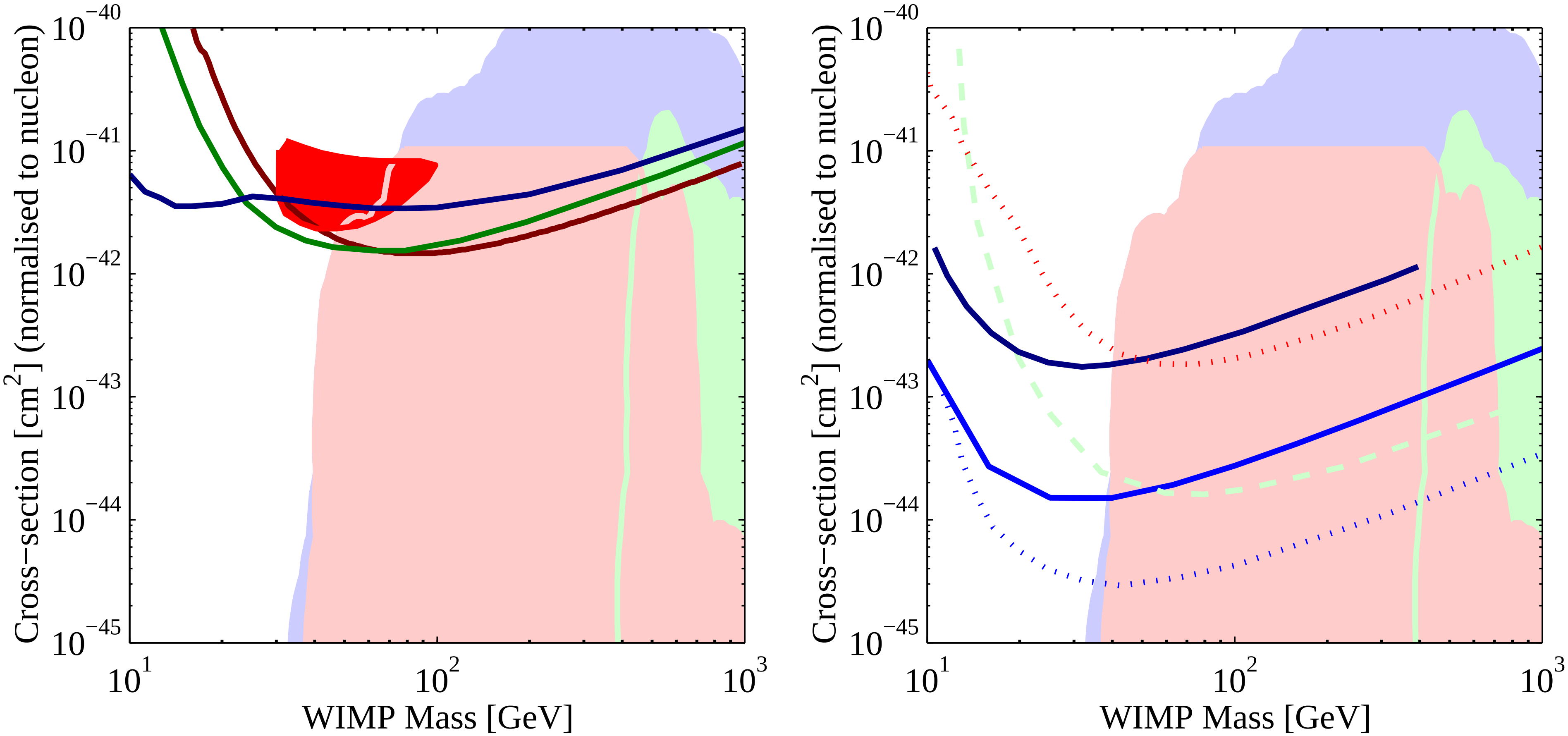
- The χ_1^0 and the $\tilde{\tau}$ are almost degenerate
- Apart from $\chi_1^0\chi_1^0$-annihilation also $\chi_1^0\tilde{\tau}$ -annihilation becomes relevant
- Together the two processes can reduce the χ_1^0 density enough

What can direct dark matter searches say?

- Dark matter searches look for elastic Xp scattering (X =dark matter)
- They are sensitive to the qX cross section times the local dark matter density
- In the bulk region the dominant annihilation process is $\chi_1^0\chi_1^0 \rightarrow \mathrm{f\bar{f}}$ which directly related to the qX elastic scattering
- In the other regions this relation doesn't exist so that the qX cross section can be different
- One experiment (DAMA) claims to see a signal in the seasonal variation of the counting rate
- This is however in contradiction to the results of low background experiments
- There are also searches looking for dark matter annihilation in the earth, the sun, the galactic halo
- Some experiments claim positive results, but they contradict each other

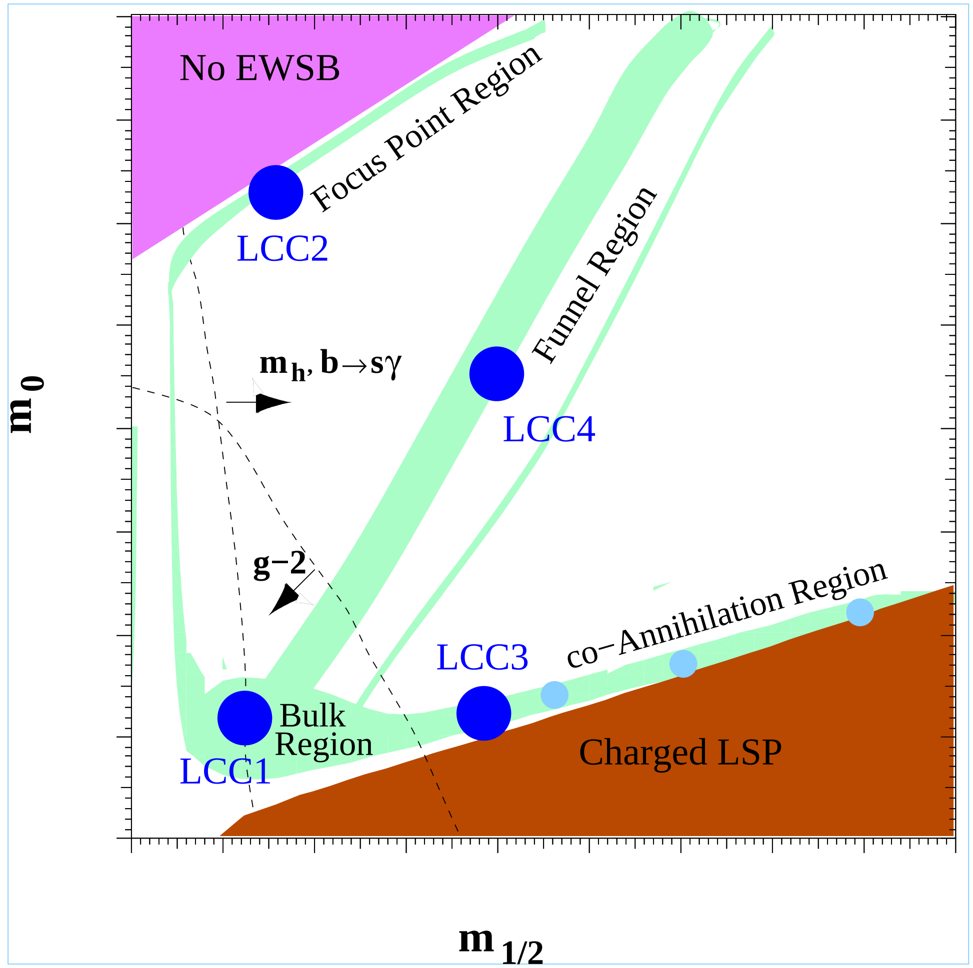
- Present searches just touch the interesting region
- In future a significant region will be covered

Comparison of dark matter searches to SUSY predictions



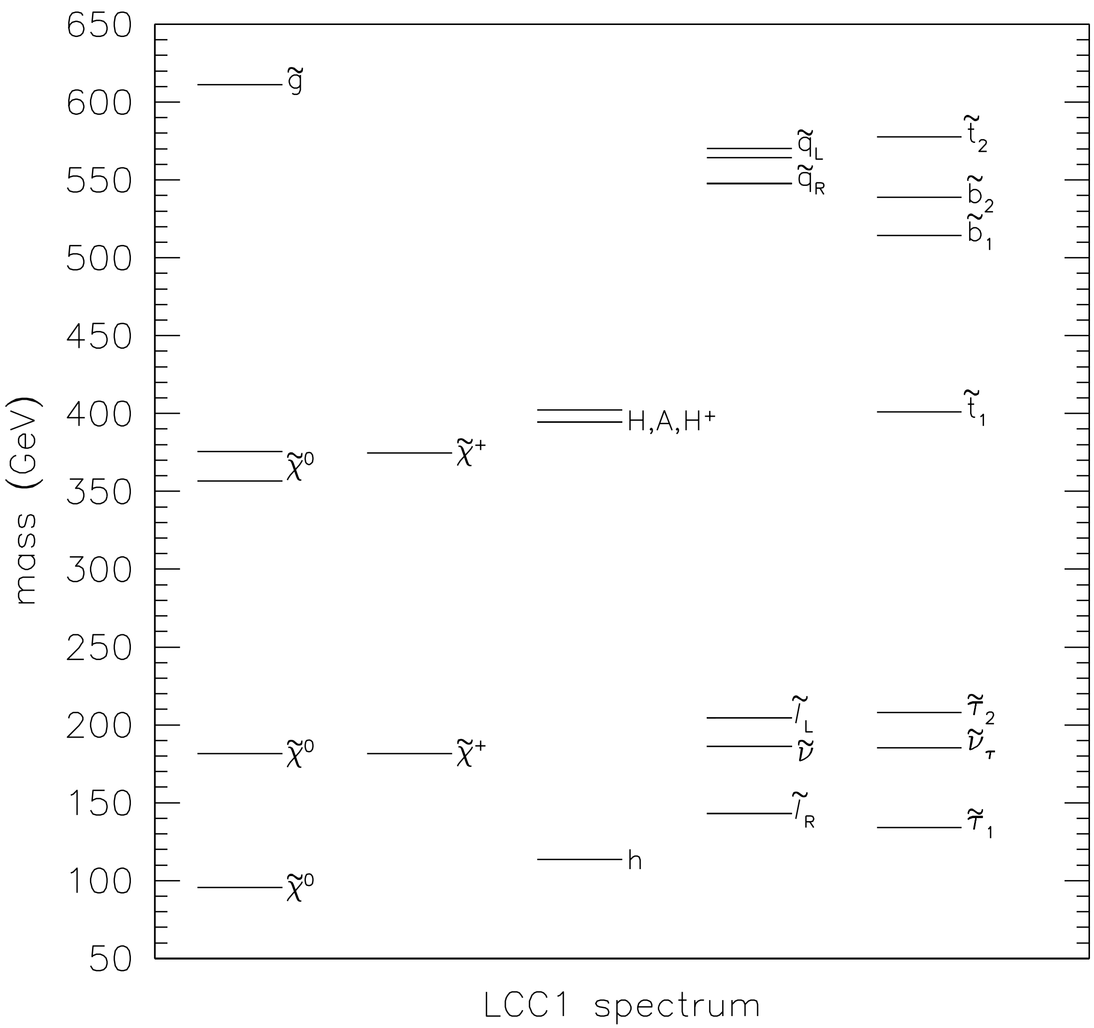
mSUGRA points at the LHC

- One benchmark point per region has been simulated for LHC and a future linear collider at $\sqrt{s} = 500\,\text{GeV}$ and $\sqrt{s} = 1\,\text{TeV}$
- For these points the measurement accuracy for SUSY parameters has been estimated
- From these accuracies the precision for the predictions on cosmologically relevant parameters has been calculated

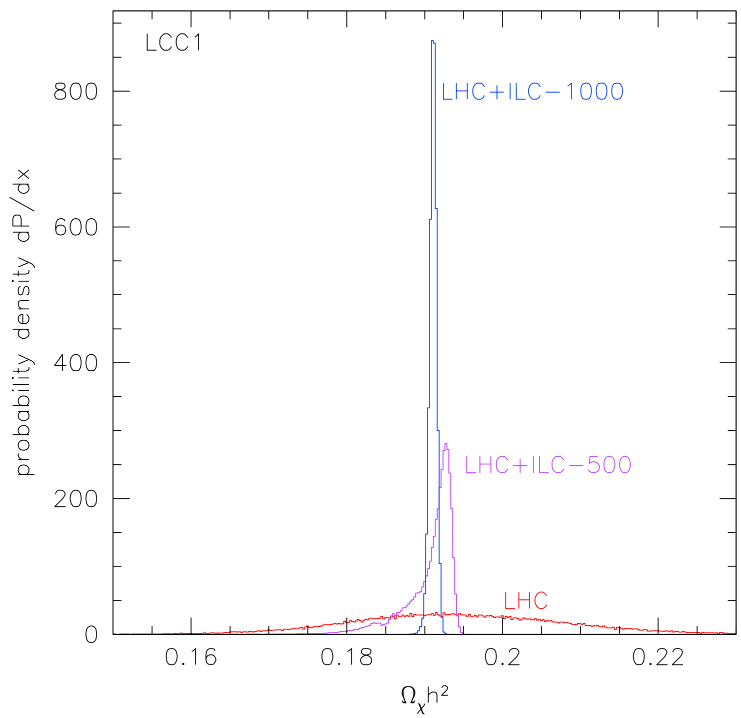


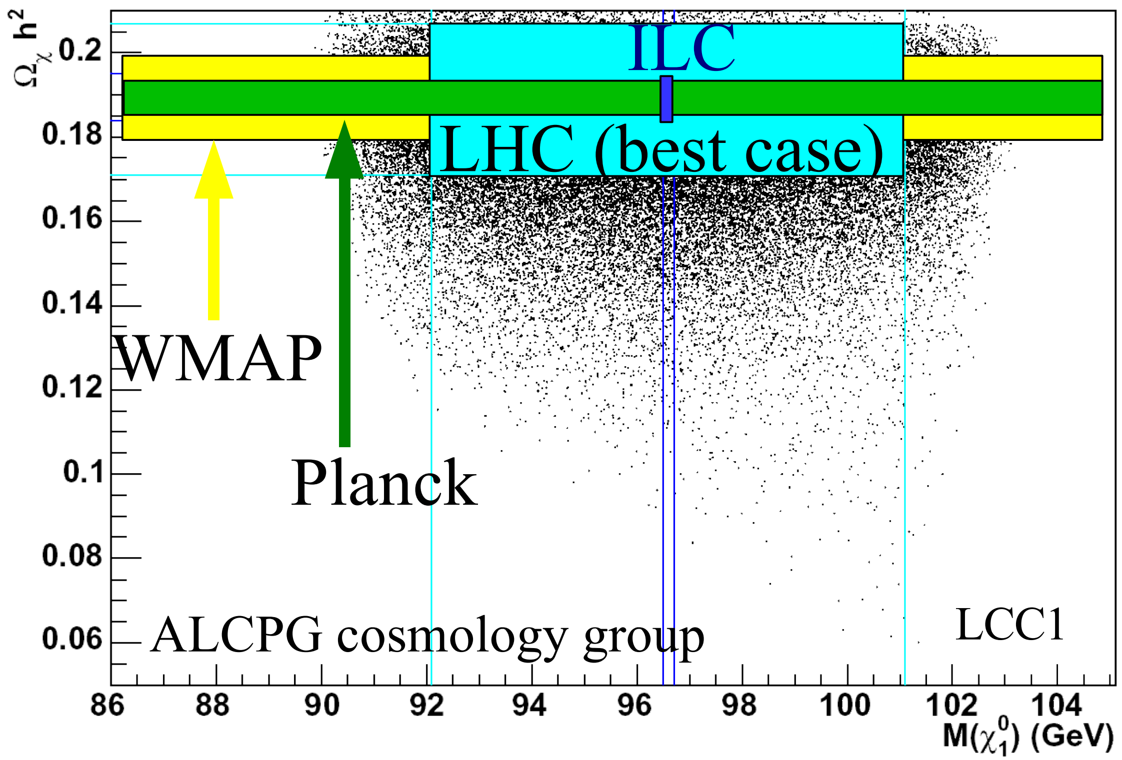
Bulk region

- Very light superpartners
- All masses can be measured with pretty good precision
- Only an ambiguity $\chi_3^0 - \chi_4^0$ remains
- A 1 TeV LC measures the full spectrum apart from squarks and gluinos with very good precision including the cross sections

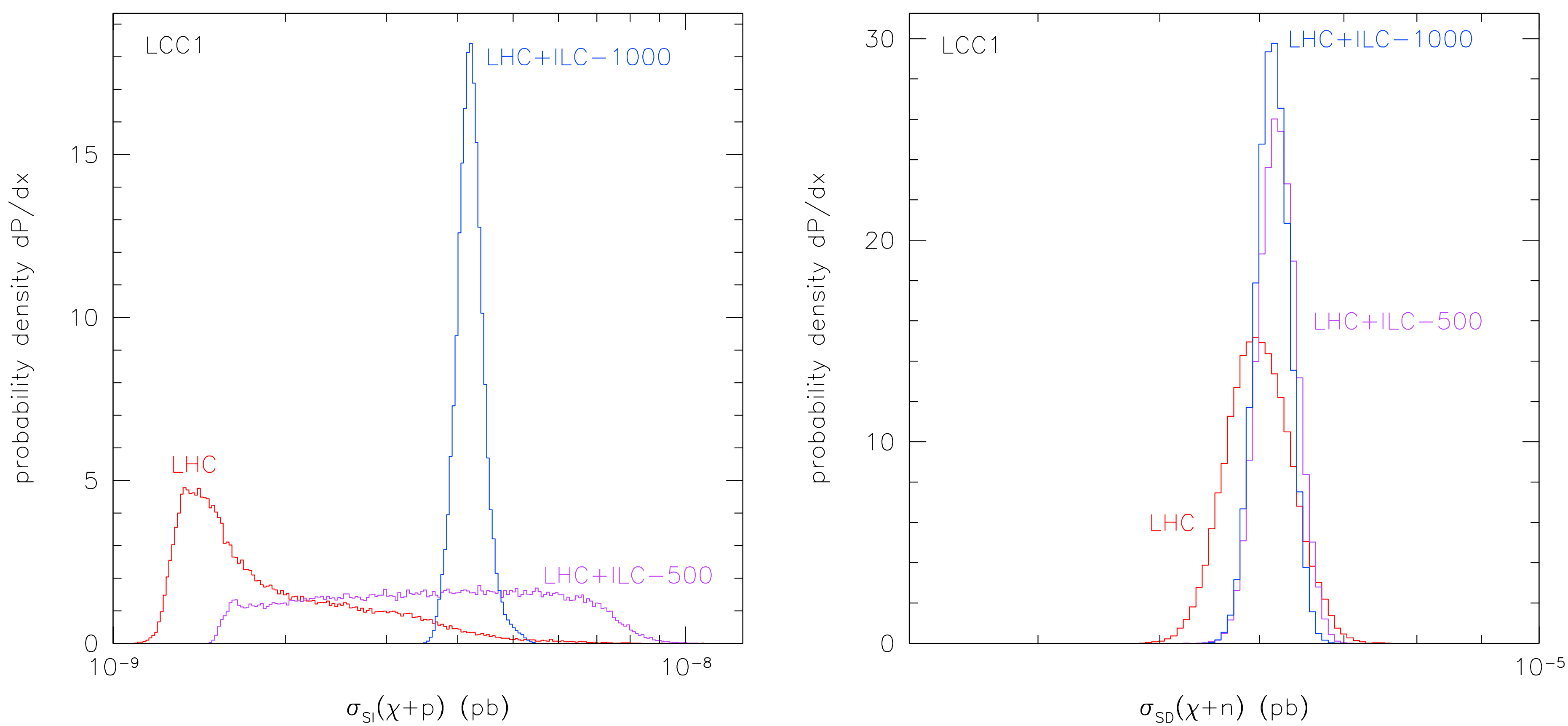


LHC measures Ωh^2 with $\sim$ 10% precision, LC matches the precision of the future Planck satellite



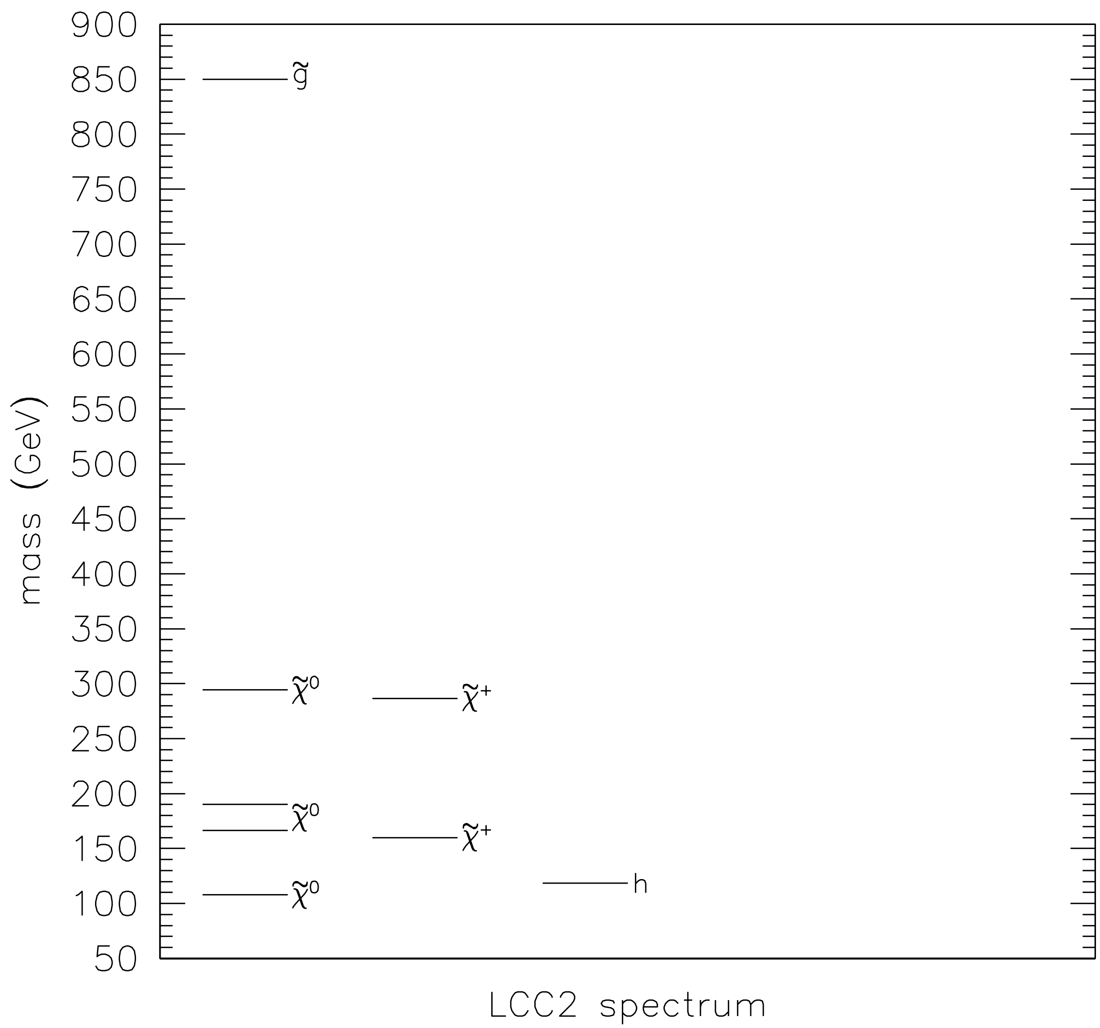


- Even at this point the prediction for the spin-independent cross section is quite imprecise for LHC and LHC+ILC500 (this cross section scales with A^2 in the direct searches)
- This is because of the missing H,A which mediate this cross section
- For the spin-dependent part the situation is much better (The spin dependent part only scales with $J(J+1)$ in the direct searches)



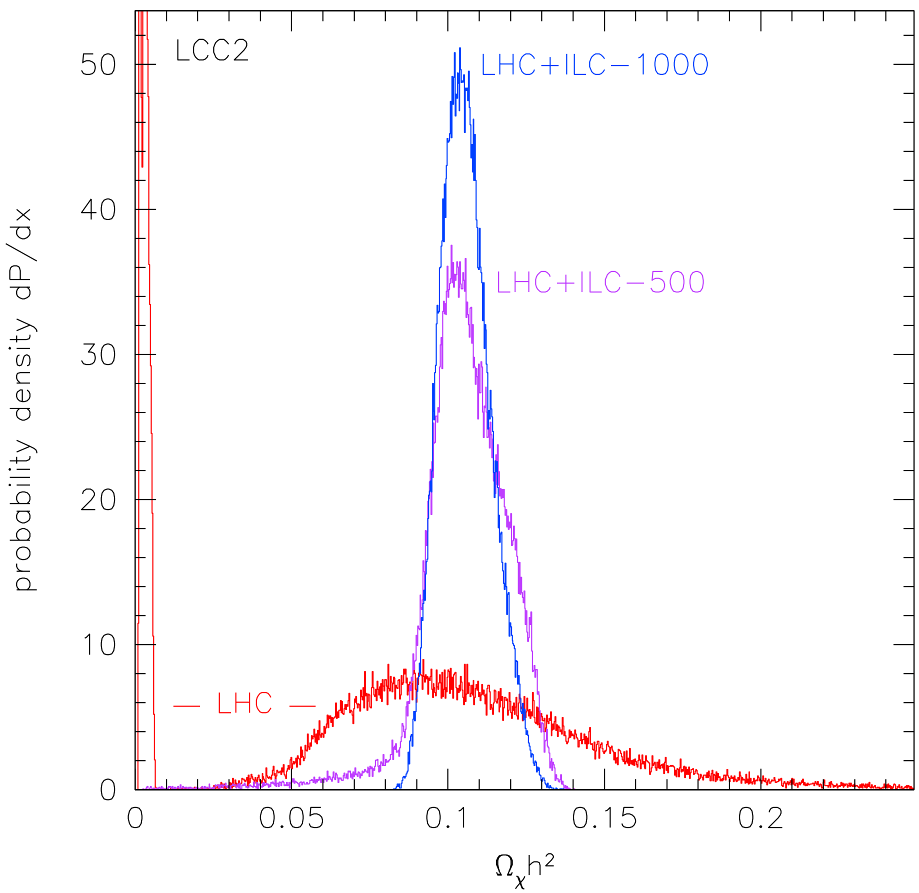
Focus-point region

- No scalars visible at any machine
- LHC only sees $\chi^0_{1,2,3}$ and gluino
- ILC sees charginos and χ^0_4 in addition
- However scalars decouple and are not important for the cosmological relevant properties

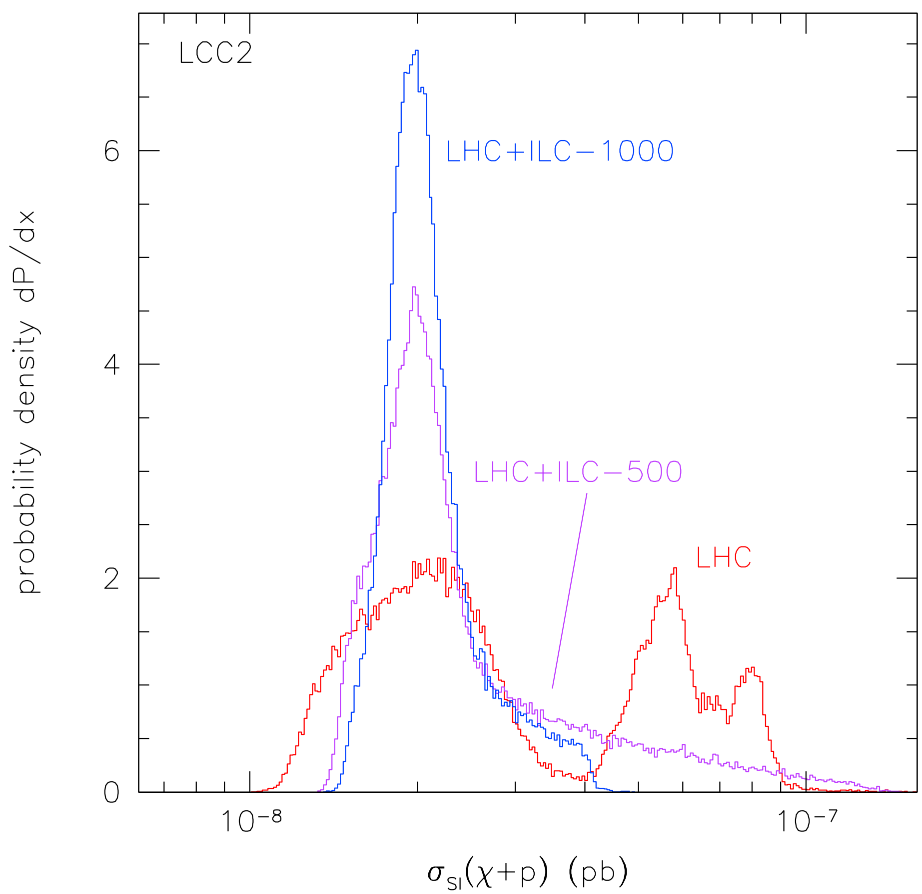


- The LHC can get the SUSY parameters only with a three-fold ambiguity (Bino/Wino/Higgsino solution) giving several peaks in the cosmological parameters
- They can be resolved by ILC measuring the chargino and cross sections

Dark matter density Ωh^2

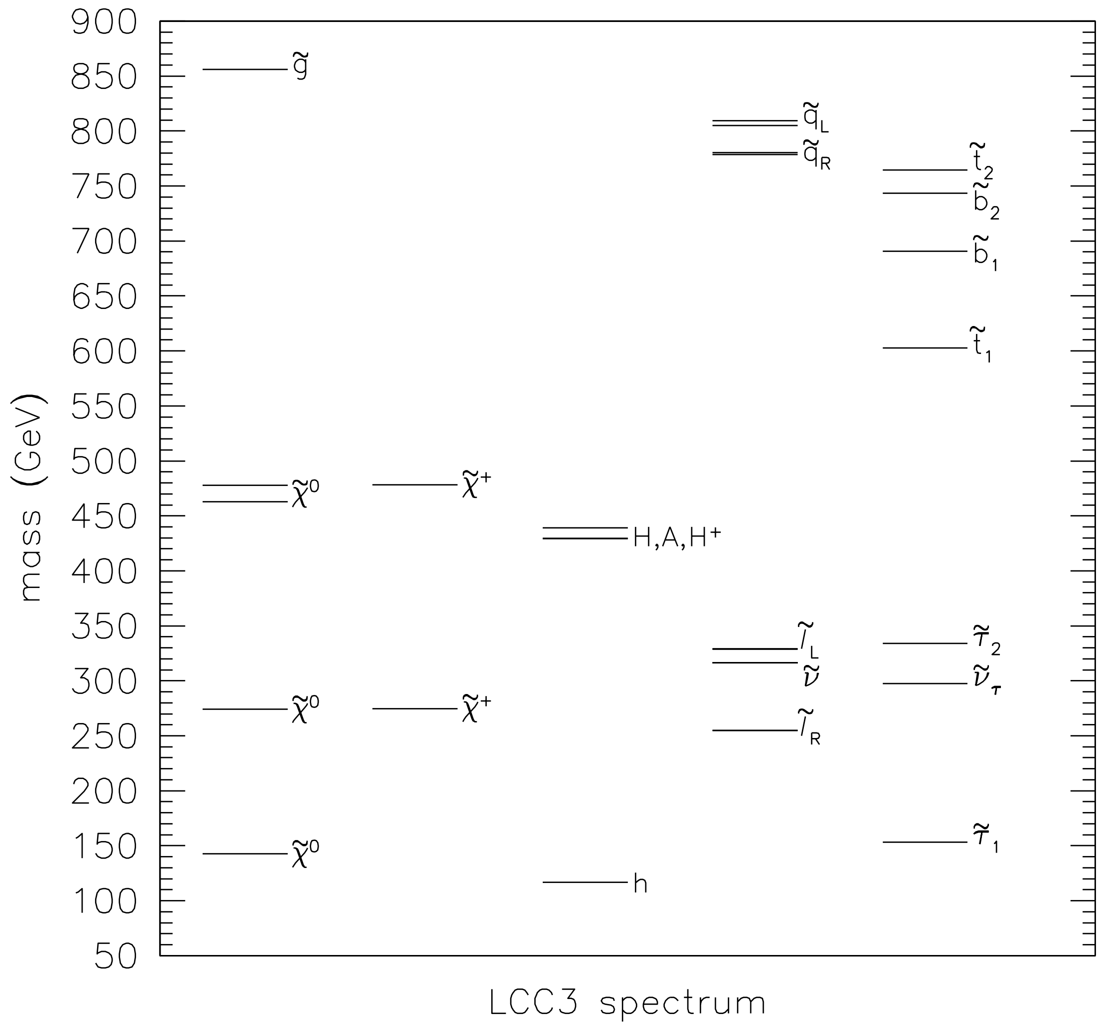


Spin independent Xp cross section



Coannihilation region

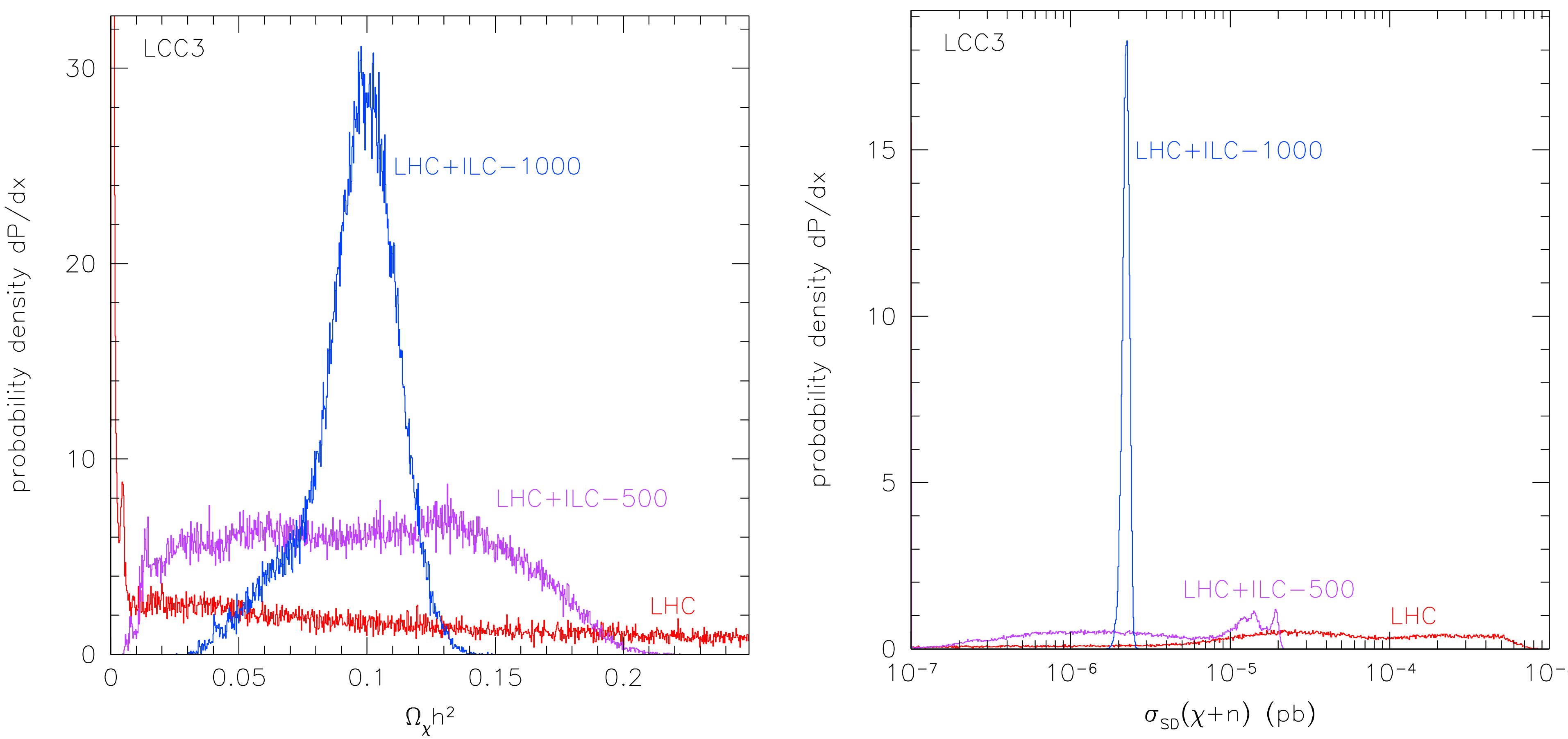
- SUSY can be relatively light
- With light scalars large $\tan\beta$ preferred to satisfy Higgs constraint
  ➡ most decays into τs
- $\tilde{\tau}$ and χ_1^0 almost degenerate
  ➡ $\tilde{\tau} \to \chi_1^0 \tau$ decay invisible at LHC



- Also the χ_2^0 decays via $\tilde{\tau}\tau$ so that the mass edge is invisible
  ➡ also very bad mass precision at LHC
- All this can be recovered at ILC

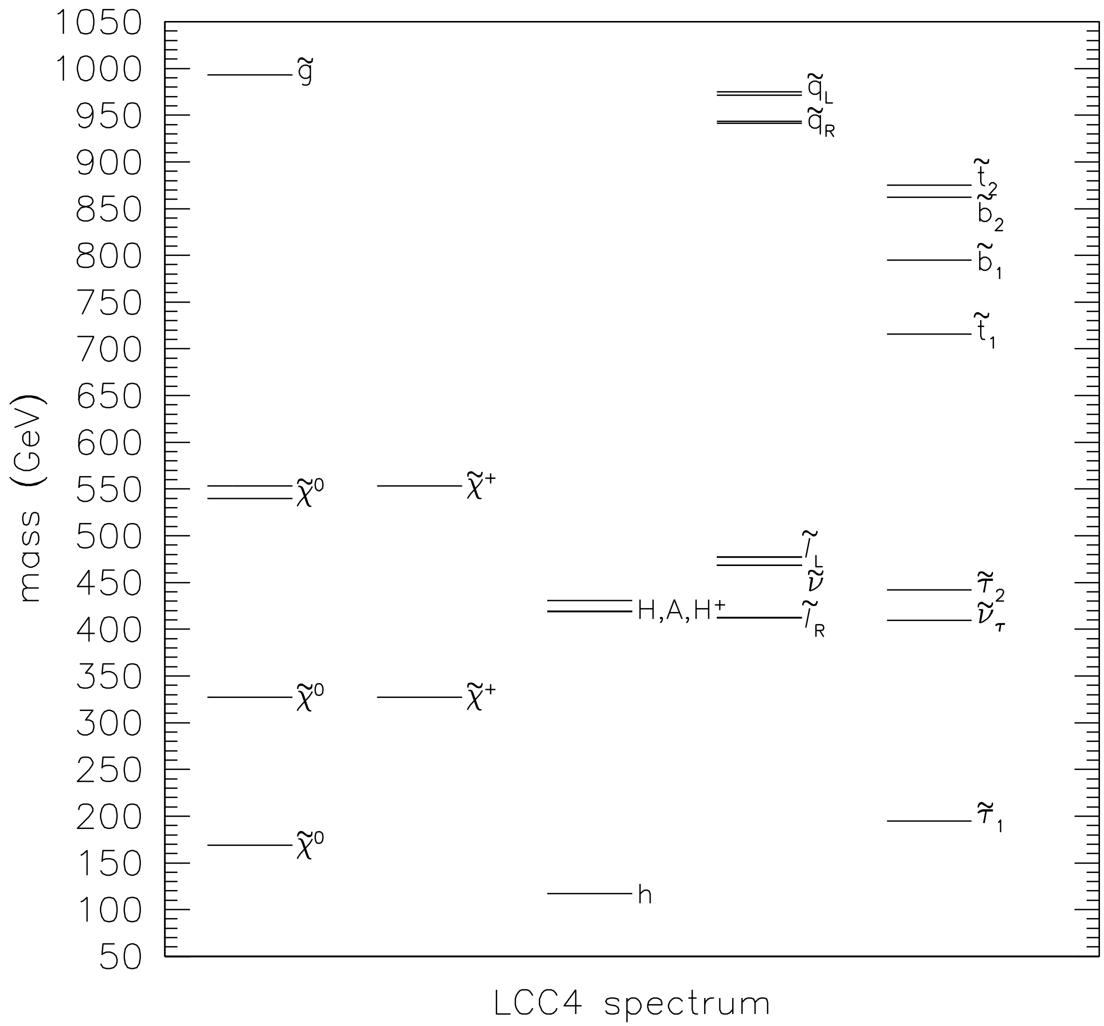
- LHC has very bad resolution and ambiguities on cosmological parameters
- ILC 500 solves this partly
- Only ILC 1000 can really solve the problem

Dark matter density Ωh^2 | Spin dependent Xn cross section



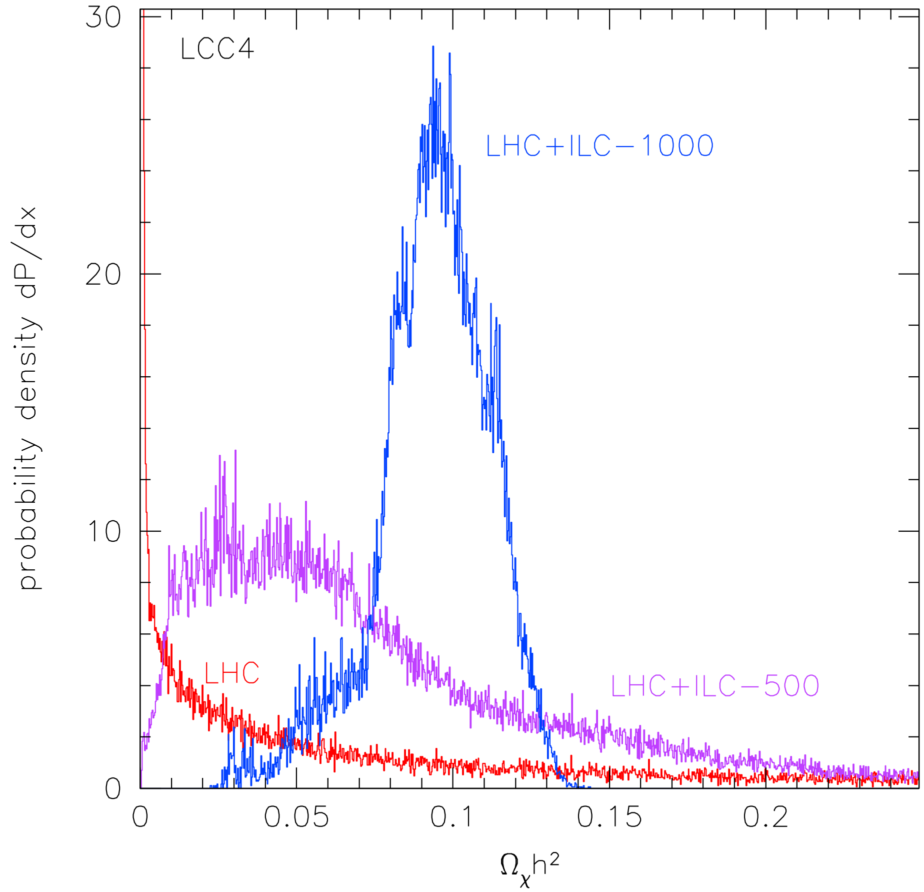
Funnel region

- Relic density brought down by resonance condition $2m(\chi_1^0) \sim m(A)$)
- Very strong sensitivity on exact masses and Γ_A
- Many τs due to large $\tan\beta$ so that measurement of neutralino properties will be difficult at LHC
- No chance to get Γ_A at LHC
- Need ILC 1000 to get these quantities

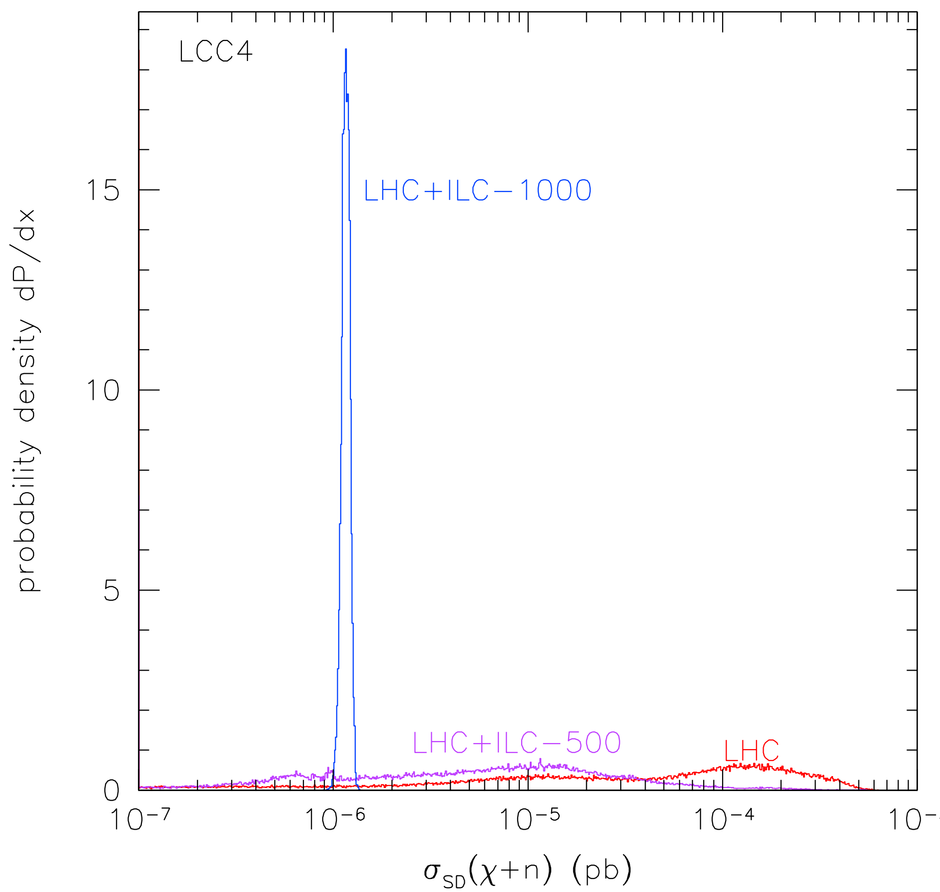


- No useful result from LHC
- ILC 1000 gives reasonable prediction

Dark matter density Ωh^2



Spin dependent Xn cross section

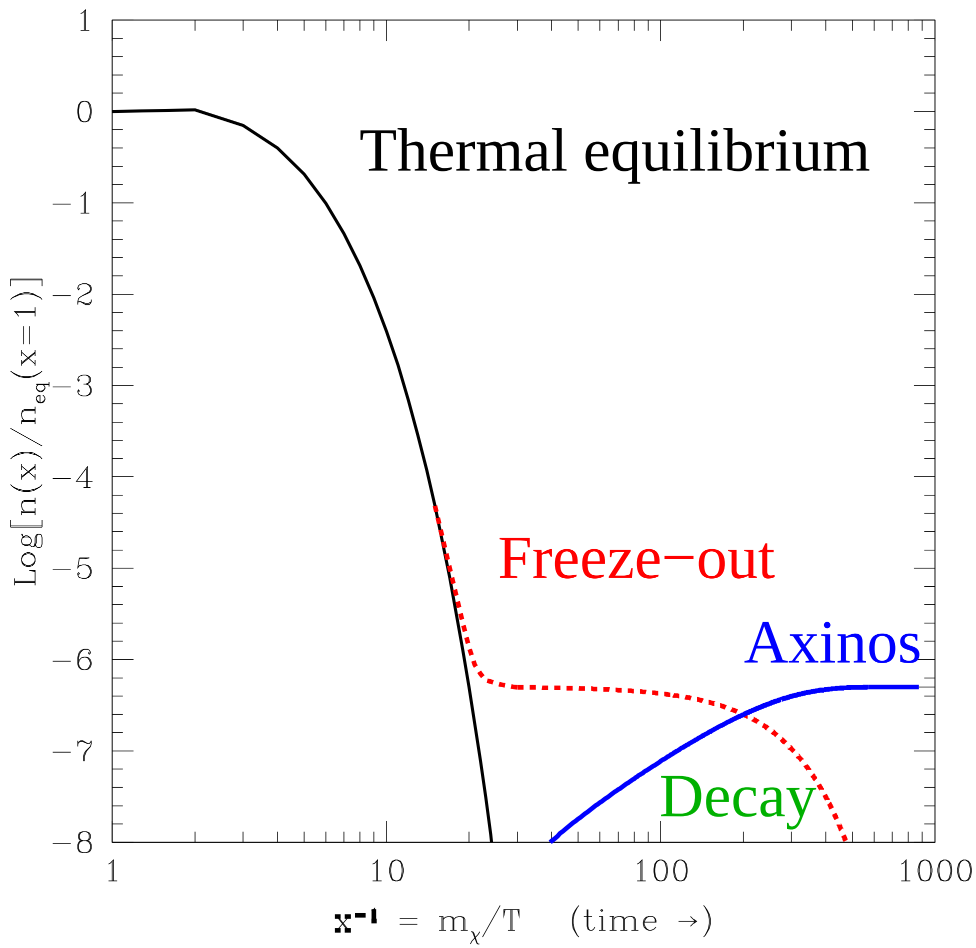


Other Dark Matter possibilities in SUSY

- In SUSY also the gravitino or axino can be the LSP
- Both particles are very weakly coupling (super-WIMP)
- The NLSP will be long lived and normally decay outside the detector
- The NLSP can be neutral or charged
- The NLSP lifetime can be from seconds to years
- Especially for the graviton the lifetime can be very long
- However if the lifetime is longer than about 1 min. there are problems with nucleosynthesis:
  - The primordial elements are formed after about one minute
  - When the NLSP decay produces hadrons (e.g. in τ decays) these elements get destroyed again
  - This is in contradiction with todays measurements
- The elastic scattering cross section is very low, so that super-WIMPs will not be seen in direct dark matter searches

Primordial creation of super-WIMPs

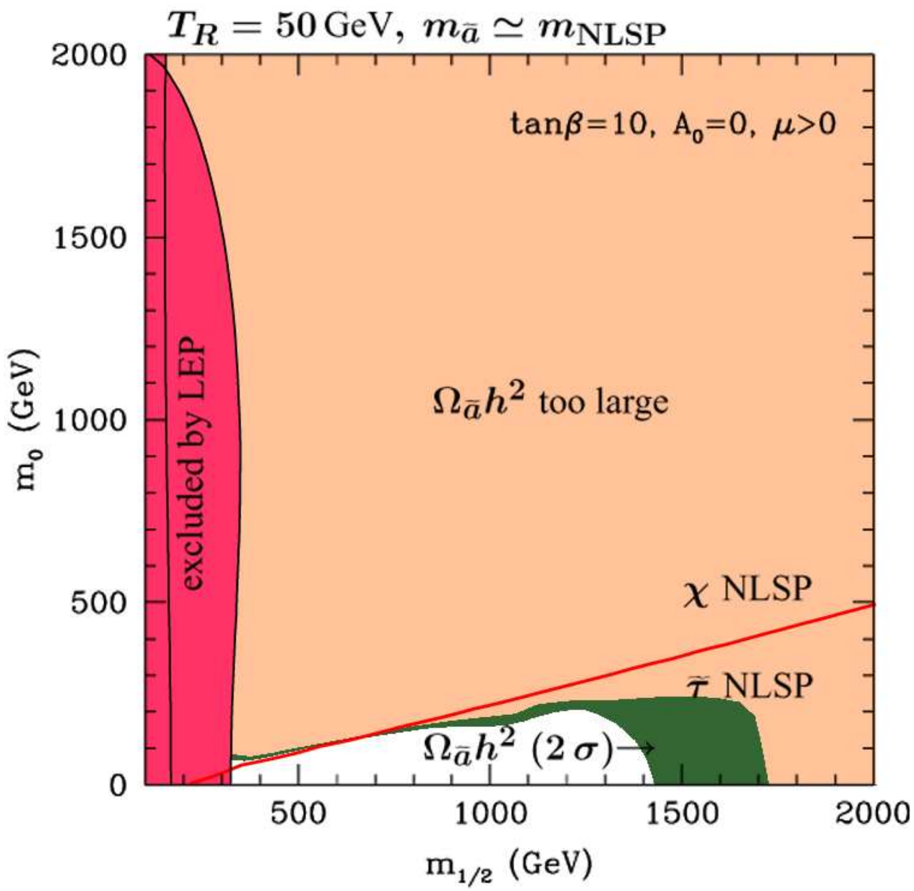
- If super-WIMPs are created in thermal equilibrium depends on the details of the inflation model
- However in any case the NLSP will be produced in the normal mechanism
- After decoupling the NLSP will decay to the LSP
- The dark matter density will thus be reduced by $\frac{M(LSP)}{M(NLSP)}$



super-WIMPs in the LHC

Neutralino NLSP:

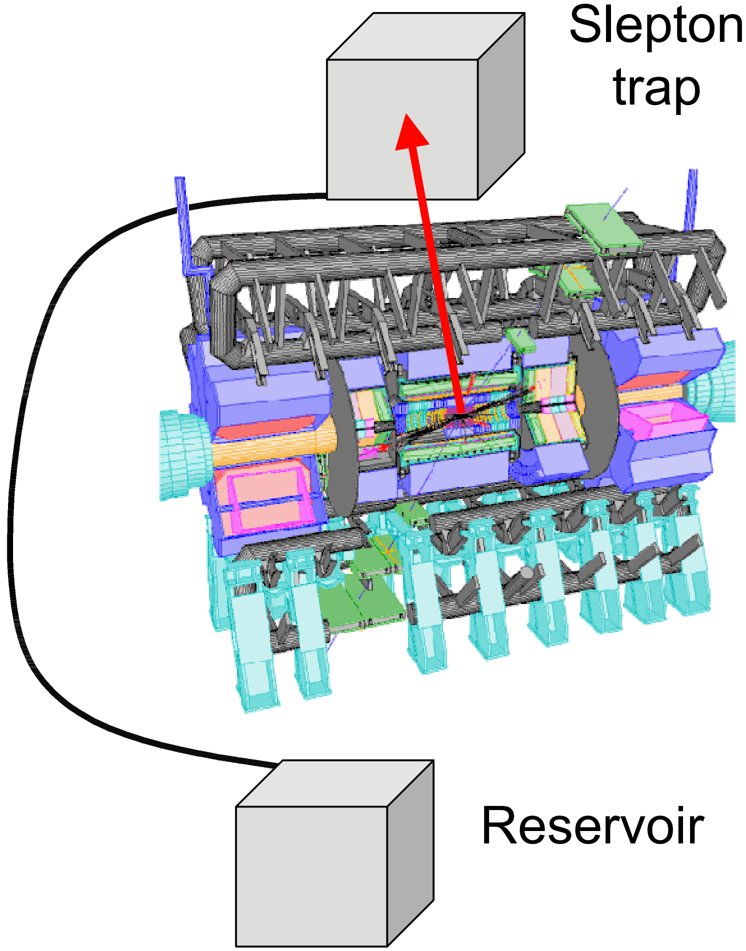
- When the NLSP-lifetime is longer than the detector length there is no way to see that the NLSP is not the LSP
- Analysing the SUSY parameters one will get a wrong (too high) dark matter density
- One will also predict a much too high scattering cross section
- If the prediction is in the range of the direct searches this can give a hint where the wrong prediction comes from



In most of the parameter space the $\tilde{\tau}$ NLSP seems to be preferred

Charged ($\tilde{\tau}$) NLSP

- A heavy stable lepton will be identified in the detector, showing the scenario
- The NLSP mass can be measured from time of flight or dE/dx
- If the scenario is assumed (gravitino, axino...) the LSP mass can be obtained from the NLSP lifetime



Crazy(?) idea:

- Put large water tanks around detector
- Some $\tilde{\tau}$s will be stopped in tanks by dE/dx
- The $\tilde{\tau}$-lifetime can be measured watching the tanks with photo-multipliers
- Need about 1 kton of water to get $\mathcal{O}(100)$ trapped $\tilde{\tau}$s per year

Recent alternative: sneutrino NLSP

- No really good justification of Higgs mass to unify with other scalar masses

➠ Can choose different Higgs masses

➠ Sneutrino can become NLSP in a gravitino-LSP scenario

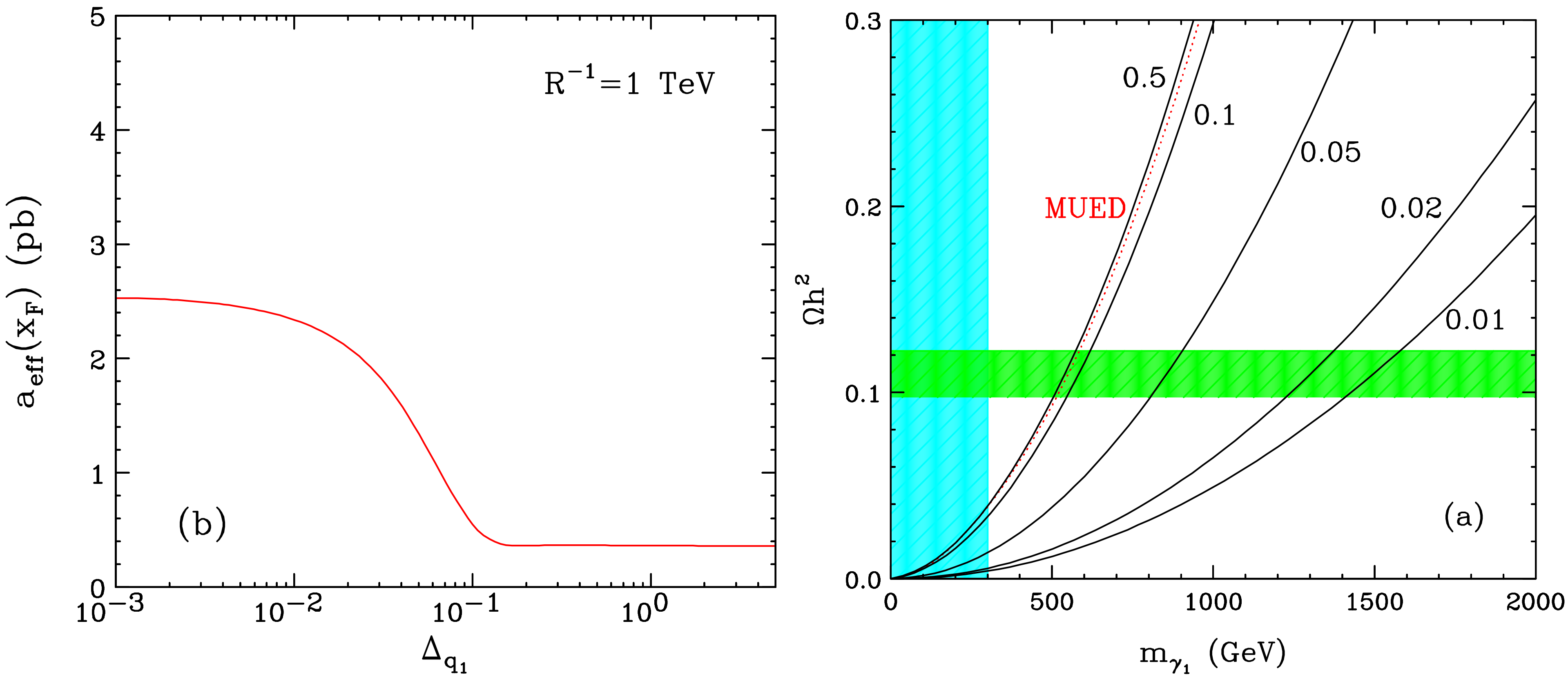
- Sneutrino decay: $\tilde{\nu} \rightarrow \tilde{G}\nu$
- Nothing in the final state that can destroy nucleons

➠ No problems with $\tilde{\nu}$-lifetime

Dark matter in Universal Extra Dimensions

- If compactified extra dimensions exist where all particles live in the extra dimensions all particles have Kaluza Klein excitations
- To be consistent with present data the size of the extra dimensions must be at least a few hundred GeV
- A KK parity can be defined which is 1 for even excitations and -1 for odd excitations
- If KK-parity is conserved the lightest KK-resonance is stable, being a dark matter candidate
- This is most probably the 1st KK excitation of the photon
- The KK-resonances are degenerate and the degeneracy is broken by loop corrections ➟ can be small
- Coannihilation can be important

As in Supersymmetry, the dark matter density gets smaller for smaller mass splitting

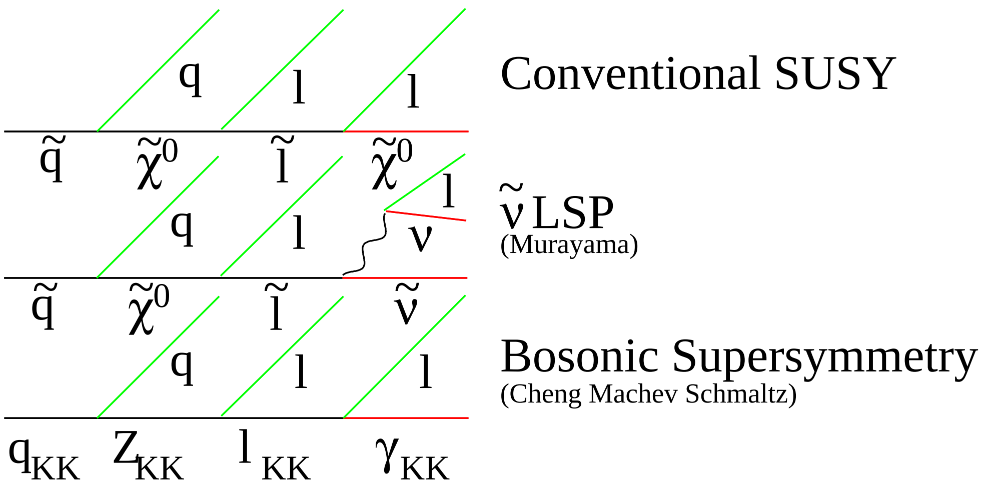


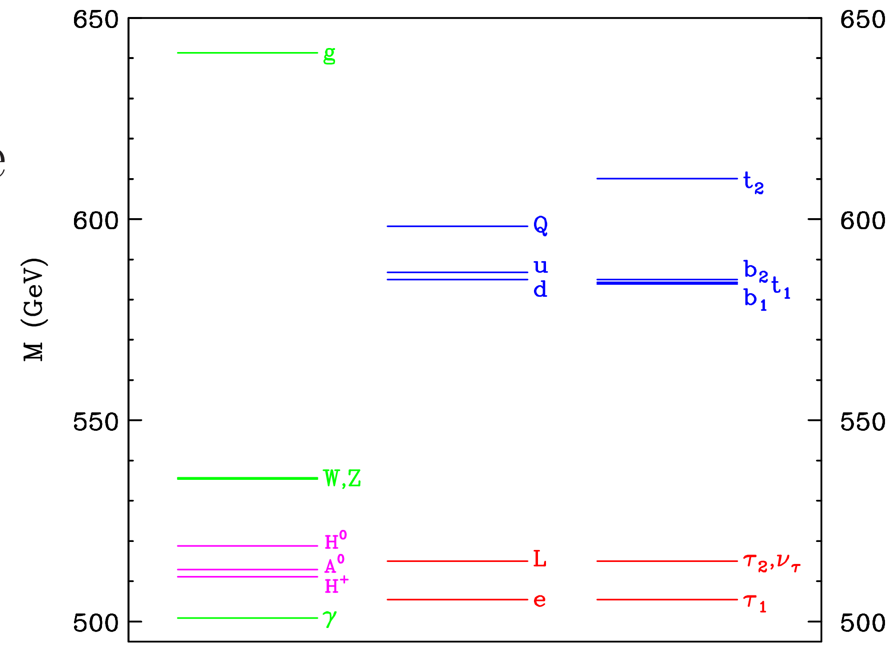
Correspondingly the DM-particle mass must be larger

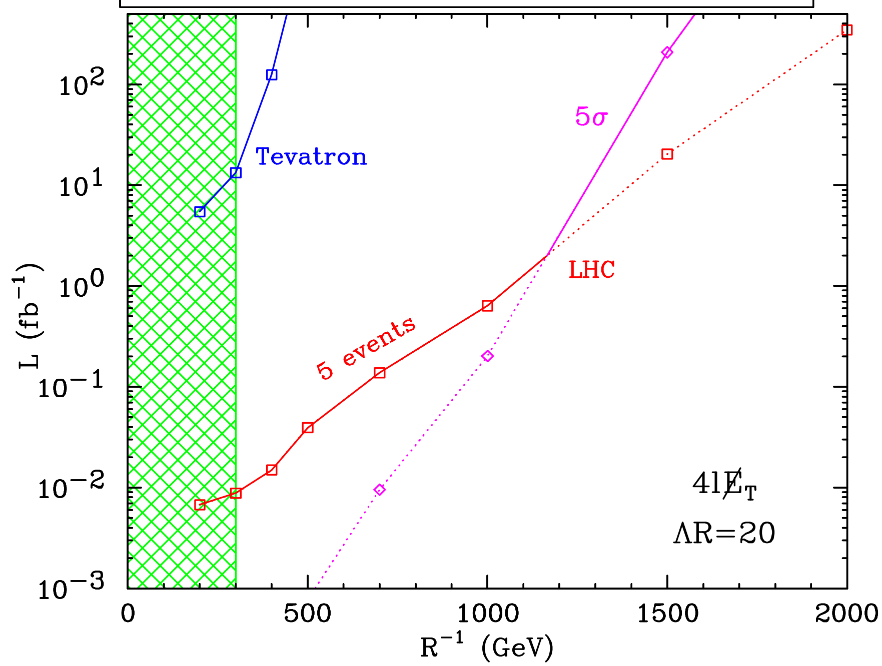
UED at the LHC

- UED at the LHC look very much like SUSY

M. Peskin, Victoria

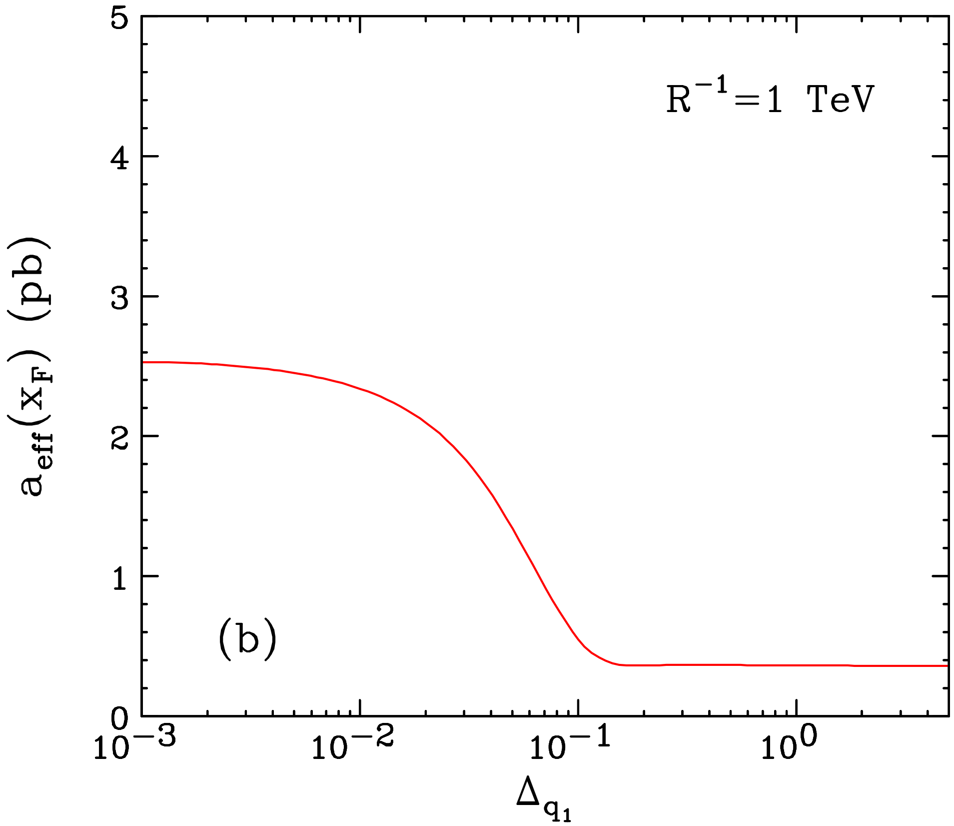


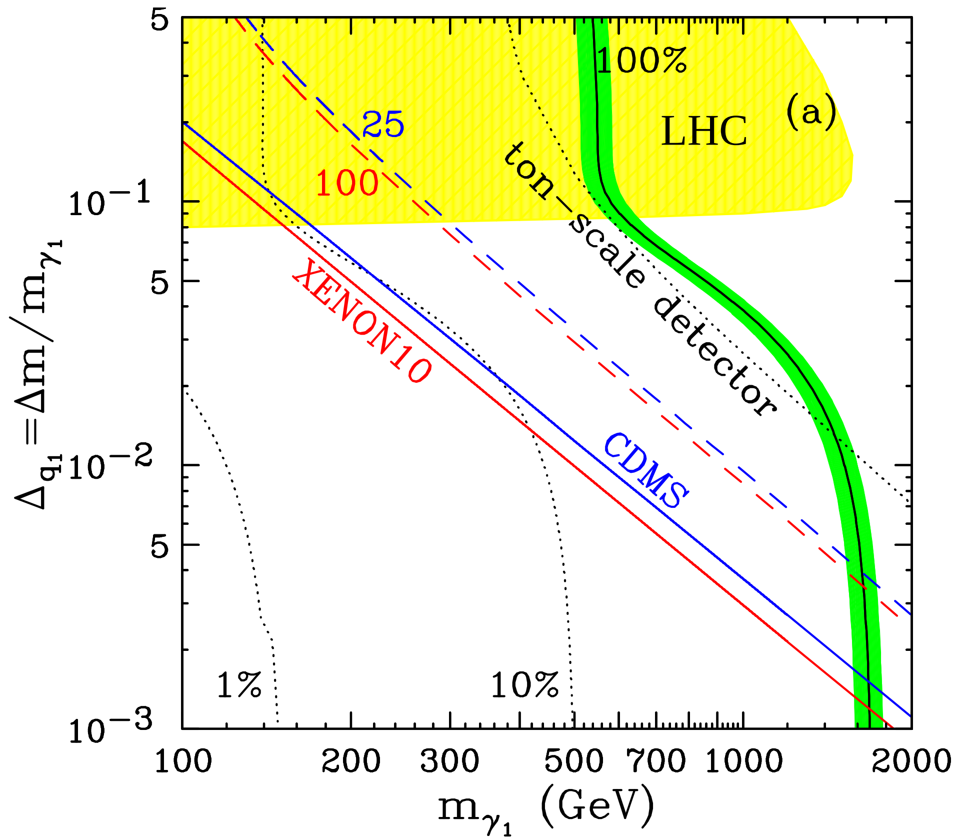




- A model with moderate mass splitting has been studied
- In the $4\ell E_T$(miss) mode the LHC reach is around 1.5 TeV

- The LHC sees the signal only if the mass difference is large enough
- On the contrary the $p\gamma_{KK}$ cross section rises with smaller mass difference enlarging the sensitivity of direct searches
- The combination of future direct search experiments and the LHC spans basically the whole region

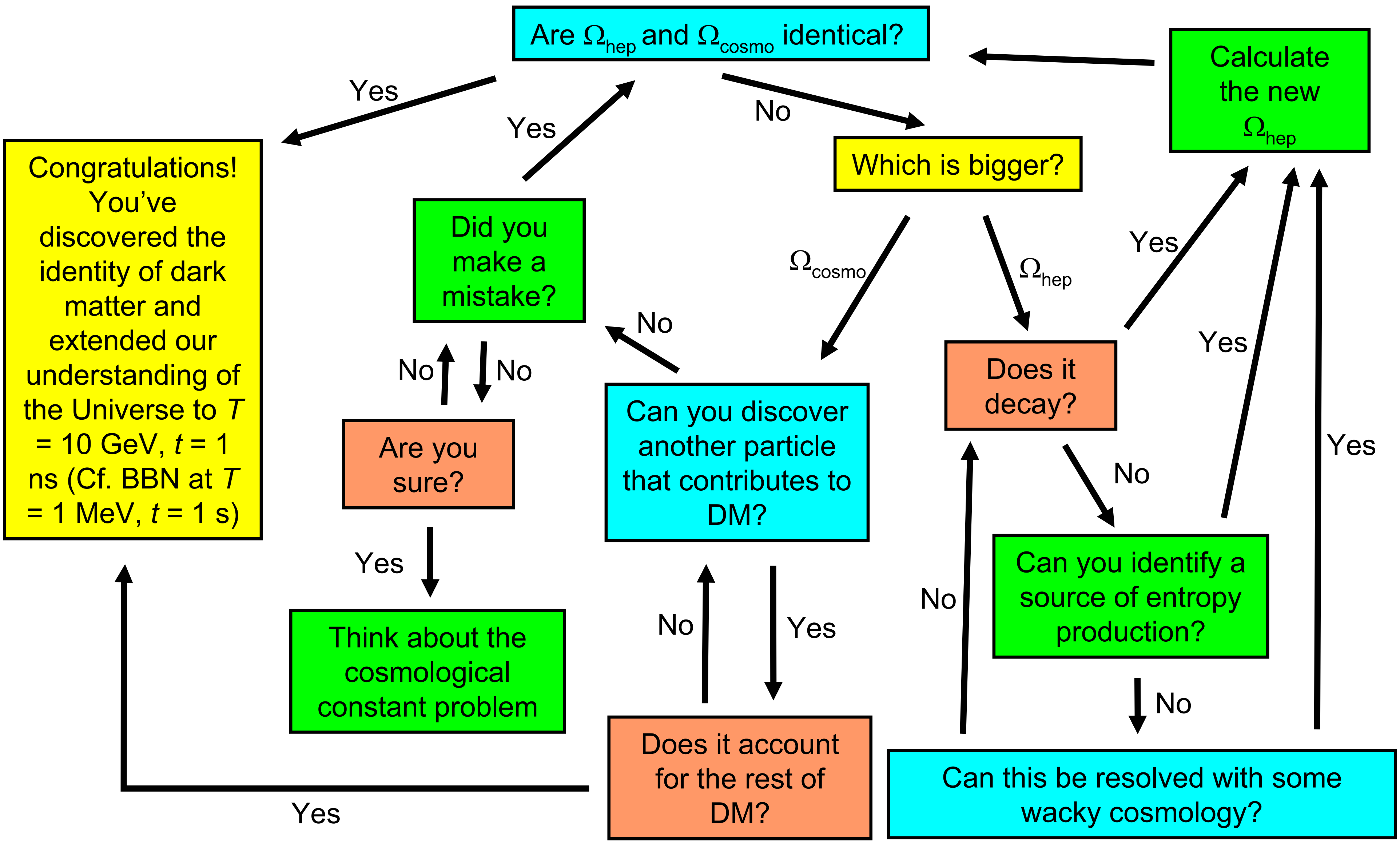




Dark matter in other models

- Dark matter can be present in several other models: little Higgs, Randall Sundrum, ...
- In all cases the stable particle is generated by a new conserved parity
- Since the cross sections are given by Big-bang cosmology the search reach is similar in all cases
- The dark matter always generates missing E_T in the detector
- Details of the search of course depend on the model

IDENTIFYING DARK MATTER



(J.Feng)

Conclusions

- Big-bang cosmology and astrophysical observations predict a weakly interacting dark-matter particle in the 100-1000 GeV region
- LHC has a high chance to find this particle
- If the LHC information is sufficient to calculate the dark-matter density and other properties depends on the details of the models