Using Collider Data to Constrain the Early Universe Properties

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Outline

Dark Matter Problem

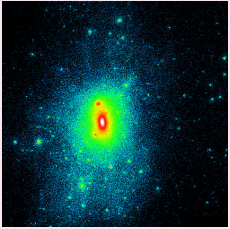
Different scales involved

- Galactic scale
  - Galaxy Rotation Curves
  - Galaxy Collisions
- Cluster Scale
  - X-Ray Observations
  - Weak Lensing
  - Bullet Cluster
- Cosmological Scale
  - Supernovæ of type Ia
  - Cosmic Microwave Background
  - ...

Dark matter candidates: WIMPs

Weakly Interacting Massive Particles

- No direct detection yet
- Good cosmological behaviour and good galaxy formation
- Clumpiness problems? (clumps formation, cuspy core, ...)



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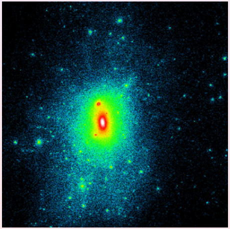
Minimal Supersymmetric Standard Model (MSSM)

- Standard Model extension
- Large mass stable particles: cold dark matter
- Not verified yet



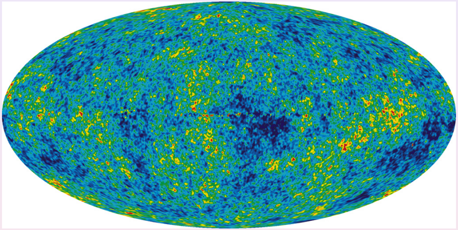
Many other cosmological questions

- Inflation
- Particle-Antiparticle Asymmetry
- Leptogenesis
- Baryogenesis
- Nucleosynthesis and ^{7}Li
- Dark energy
- ...

Relic density

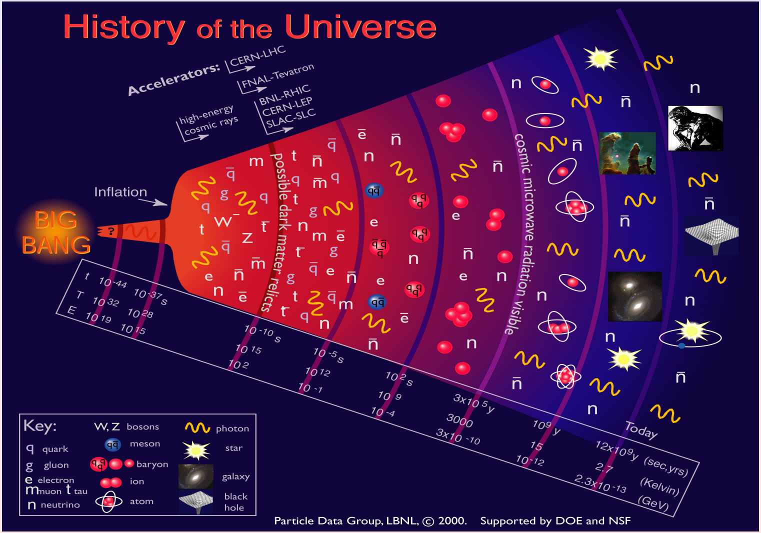
The recent observations of the WMAP satellite, combined with other cosmological data impose the dark matter density range at 95% C.L.:

$$0.088 < \Omega_{DM} h^2 < 0.123$$



Considering supersymmetry, it is possible to make prediction for the dark matter density, assuming the LSP is the only dark matter component

$\rightarrow$ relic density, to be compared to the WMAP range


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s 10^15 10^2
10^-5 s 10^12 10^-1
10^2 s 10^9 10^-4
3x10^5 y 3000 3x10^-10
10^9 y 15 10^-12
Today 12x10^9 y (sec,yrs) 2.7 (Kelvin) 2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Relic density: standard calculation

In the Standard Model of Cosmology:

- before and at nucleosynthesis time, the expansion is dominated by radiation

$$H^2 = 8\pi G/3 \times \rho_{\rm rad}$$

- the evolution of the number density of supersymmetric particles follows the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

n: number density of relic particles.

Relic density: standard calculation

Effective invariant annihilation rate W_{eff}:

(ij: coannihilating SUSY particles / kl: SM outgoing particles)

$$\frac{dW_{\mathrm{eff}}}{d\cos\theta} = \sum_{ijkl} \frac{p_{ij} p_{kl}}{32\pi p_{\mathrm{eff}} S_{kl} \sqrt{s}} \sum_{\mathrm{helicities}} \left| \sum_{\mathrm{diagrams}} \mathcal{M}(ij \to kl) \right|^2$$

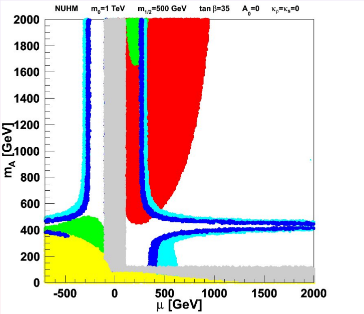
Thermal average of effective cross section:

$$\langle \sigma_{\mathrm{eff}} v \rangle = \frac{\int_0^\infty dp_{\mathrm{eff}} p_{\mathrm{eff}}^2 W_{\mathrm{eff}} K_1 \left(\frac{\sqrt{s}}{T} \right)}{m_1^4 T \left[\sum_i \frac{g_i}{g_1} \frac{m_i^2}{m_1^2} K_2 \left(\frac{m_i}{T} \right) \right]^2}$$

($K_{1,2}$: modified Bessel functions)

Relic density: standard calculation

By comparing the calculated relic density to the cosmological dark matter density, constraints on SUSY parameters can be derived.



Green: area disfavored by BR($B \to X_s\gamma$)
Red: area disfavored by the isospin asymmetry of $B \to K^*\gamma$
Blue: area favored by WMAP

Relic density: sensitivity to the cosmological model

Caveat!

The cosmological standard model is a simple model, and many unobservable phenomena could have happened during the pre-BBN era.

Relic density: influence of a modified expansion rate

For example, the expansion rate can be modified.
We can parametrize the modification by adding a new density ρ_D:

$$H^2 = 8\pi G/3 \times (\rho_{\text{rad}} + \rho_D) \text{ with } \rho_D(T) = \rho_D(T_{BBN})(T/T_{BBN})^{n_D}$$

- $n_D = 4$: radiation-like behavior
- $n_D = 6$: behavior of a scalar field dominated by its kinetic term
- $n_D > 6$: extra-dimension effects

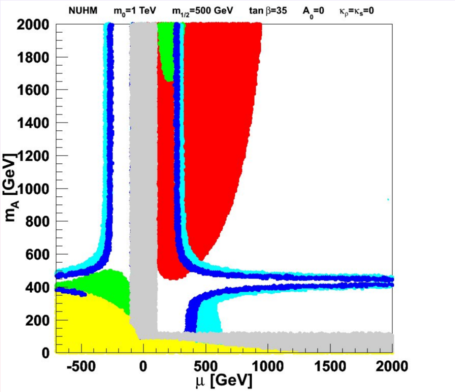
Let's introduce $\kappa_D = \rho_D(T_{BBN})/\rho_{\text{rad}}(T_{BBN})$

The modified expansion is in agreement with the observations provided $n_D > 4$ and $\kappa_D < 1$

Such a modification can drastically change the obtained relic density!

Relic density: influence of a modified expansion rate

Displacement of the WMAP limits in NUHM: Standard model



Large even for a very small expansion rate modification!

Arbey & Mahmoudi, Phys. Lett. B669 (2008); Arbey & Mahmoudi, arXiv:0909.0266 [hep-ph]

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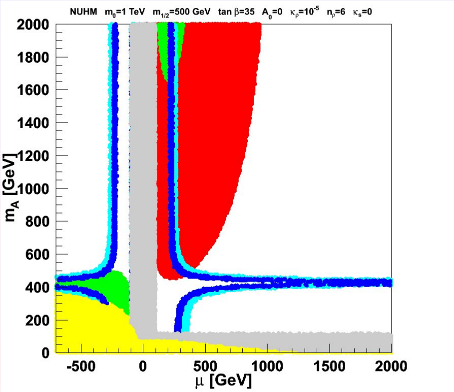

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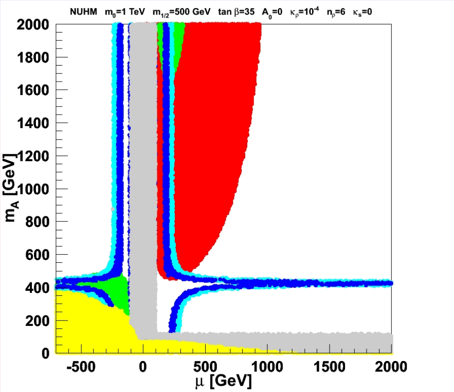

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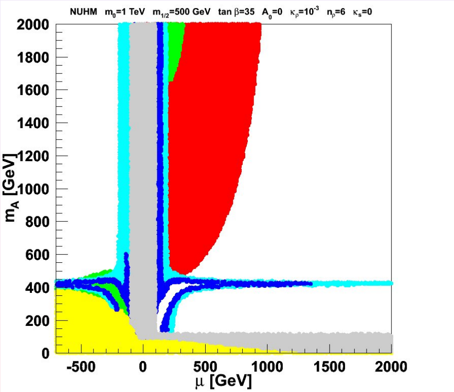

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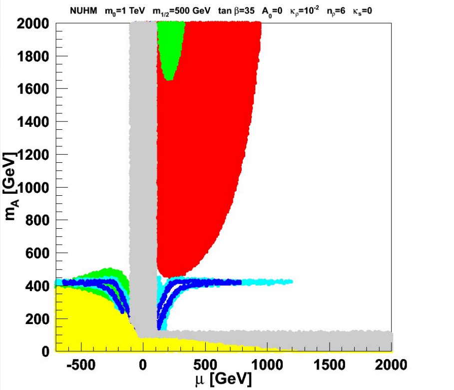

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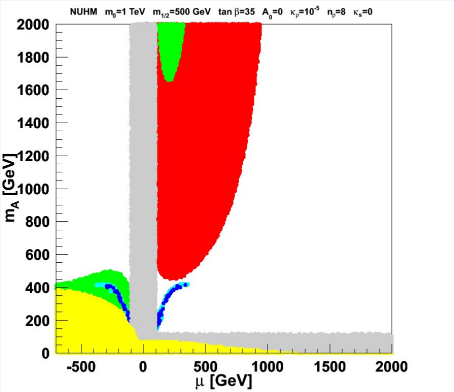

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Relic density: influence of a modified entropy content

The entropy content of the Universe can also be altered!

$\Rightarrow$ Modified relation between time, expansion rate and temperature!

Parametrization consists in adding a new entropy density s_D to the total entropy density:

$$s_D(T) = s_D(T_{BBN})(T/T_{BBN})^{n_s}$$

- $n_s = 3$: radiation-like behavior
- $n_s \sim 4$: entropy evolution of a decaying scalar field

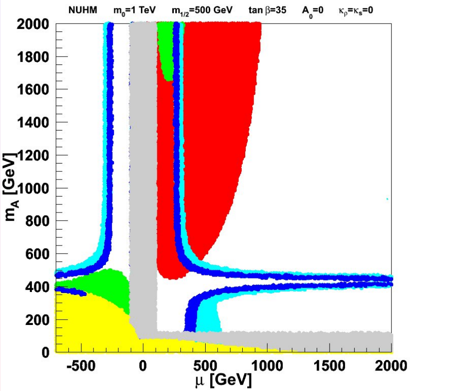
Let's introduce $\kappa_s = s_D(T_{BBN})/s_{\rm rad}(T_{BBN})$

The modified expansion is in agreement with the observations provided $n_s > 3$ and $\kappa_s < 1$

This modification changes the relic density in the other direction!

Relic density: influence of a modified entropy content

Displacement of the WMAP limits in NUHM: Standard model



The WMAP constraints can move in any direction!

Arbey & Mahmoudi, arXiv:0906.0368 [hep-ph]; Arbey & Mahmoudi, arXiv:0909.0266 [hep-ph]

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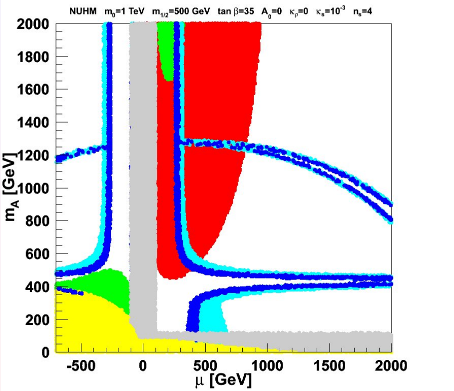

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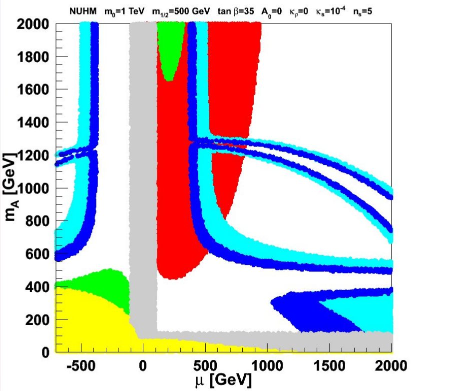

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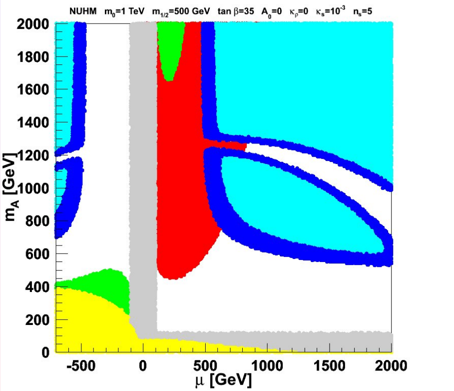

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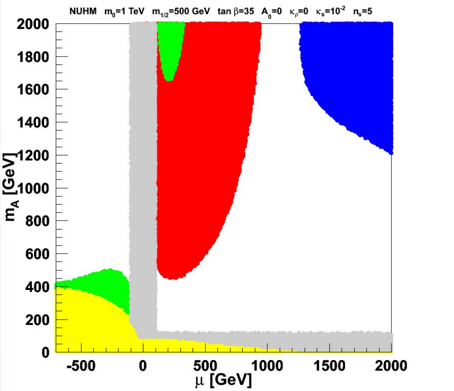

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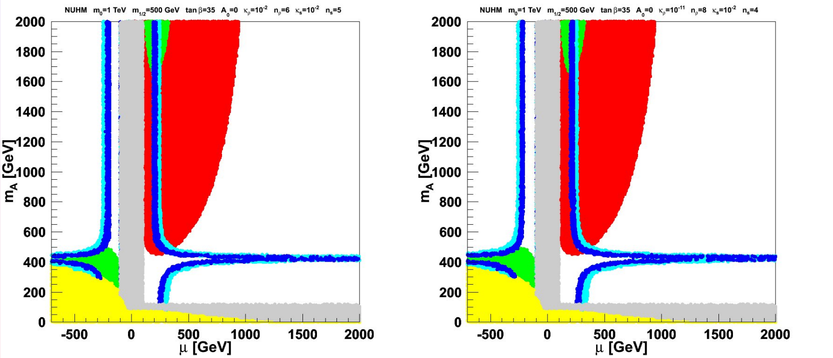
Relic density: sensitivity to the cosmological model

The use of WMAP limits in the context of the relic density is highly questionable!!!

Inverse problem...

If we know the particle physics scenario, can we deduce the Early Universe properties?

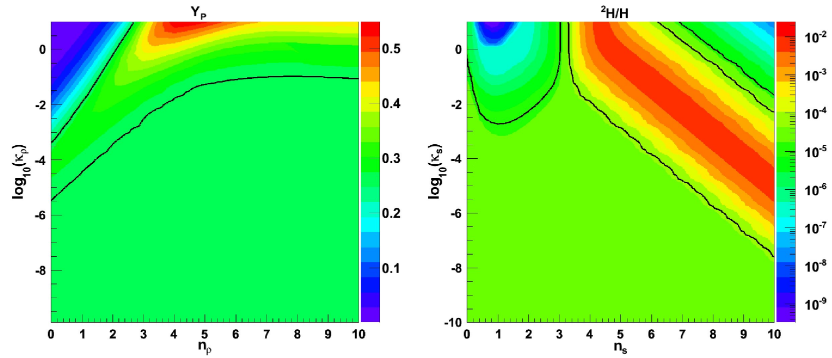


Need to find ways to remove degeneracy...

Arbey & Mahmoudi, arXiv:0909.0266 [hep-ph]

Inverse problem...

BBN constraints on energy and entropy densities



Need to find ways to remove degeneracy... e.g. with BBN...

Arbey & Mahmoudi, arXiv:0909.0266 [hep-ph]

Relic density calculation in alternative cosmological models: SuperIso Relic

SuperIso Relic = SuperIso (flavour physics calculations)
+ relic density calculation

F. Mahmoudi, Comput. Phys. Commun. 180 (2009)   A. Arbey and F. Mahmoudi, arXiv:0906.0369 [hep-ph]

Concept of the code

- Automatized computation of flavour observables and relic density in SUSY
- Flexible particle physics model implementation (mSUGRA, NUHM, AMSB, ...)
- Flexible cosmological model implementation (dark energy, reheating, ...)
- Publicly available on http://superiso.in2p3.fr/relic

SuperIso Relic

Structure of the code

- Generation of a SLHA file with Isajet or Softsusy
- Initialization of the variables using the SLHA file
- Generation of additional Higgs sector variables with FeynHiggs
- Calculation of W_{eff} with Fortran functions
- Calculation of $\langle \sigma_{\rm eff} v \rangle$ with C functions
- Solving of the Boltzmann equation with C functions
- Computation of the other SuperIso observables

Arbey & Mahmoudi, arXiv:0906.0369 [hep-ph]

SuperIso Relic

Fortran and diagram generation

- Analytical calculation of the amplitudes with Mathematica / FeynArts / FormCalc / FORM
- FormCalc-generated Fortran code interfaced with the SuperIso C-functions
- Use of LoopTools (if needed) to compute loop amplitudes
- Possibility to use of FeynArts model file generators (FeynRules, LanHEP, ...)

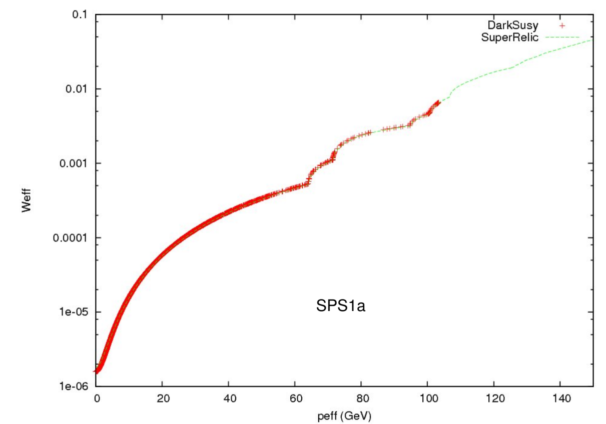
Arbey & Mahmoudi, arXiv:0906.0369 [hep-ph]

SuperIso Relic

Status

- Calculation of amplitudes within MSSM with MFV at tree level fully implemented (more than 3000 processes involved)
- Good agreement with Micromegas and DarkSusy
- Publicly available in two versions:
  - a statically linked version, fast at execution, but requiring the compilation of all the processes before the first run (around 1-2 hours) $\rightarrow$ advised for intensive use.
  - a version with shared libraries, which compiles the processes “on the fly”, slower at execution, but faster at compilation $\rightarrow$ advised for a quick start.
- Well tested under Linux machines with GNU and Intel compilers
- Package including LoopTools v2.4 and FeynHiggs v2.6.5.

SuperIso Relic



Good agreement with DarkSusy!

SuperIso Relic

Status: Alternative cosmological models

- Relic density within the cosmological standard model fully implemented
- Possible to use different QCD equation of state for radiation
- Possible to modify the expansion of the early Universe through the presence of an effective dark density

$$\rho_D(T) = \rho_D^0 T^{n_\rho}$$

- Possible to modify the thermal properties of the Universe through the presence of an effective dark entropy

$$s_D(T) = s_D^0 T^{n_s}$$

Conclusion and perspectives

Inverse problem?

- dangerous to use the relic density to constrain SUSY!
- dangerous to combine collider data and relic density to determine a new particle physics model!

Inverted problem?

- possible to use the collider data and the relic density to constrain Cosmology!
- possible to combine collider data and the relic density to determine the early universe physics!

SuperIso Relic: perspectives

- Addition of BBN constraints on the cosmological models
- Extension to more cosmological scenarios
- Extension to more particle physics models