Cosmological Constraints on Supersymmetric Models

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Cosmology at the Beach, Jan 14, 2011

The Standard Model

forces

GAUGE	Gauge bosons	$(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$
B-boson	$A_\mu^{(1)} = B_\mu$	$(\mathbf{1}, \mathbf{1})_0$
W-bosons	$A_\mu^{(2)\,a} = W_\mu^a$	$(\mathbf{1}, \mathbf{3})_0$
gluon	$A_\mu^{(3)\,a} = G_\mu^a$	$(\mathbf{8}, \mathbf{1})_0$

matter

MATTER	Fermions	$(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$
leptons $I = 1, 2, 3$	$L^I = \begin{pmatrix} \nu_L^I \\ e_L^{-\,I} \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{-1}$
	$E^{c\,I} = e_R^{-\,c\,I}$	$(\mathbf{1}, \mathbf{1})_{+2}$
quarks $I = 1, 2, 3$ $(\times$ 3 colors)	$Q^I = \begin{pmatrix} u_L^I \\ d_L^I \end{pmatrix}$	$(\mathbf{3}, \mathbf{2})_{+\frac{1}{3}}$
	$U^{c\,I} = u_R^{c\,I}$	$(\overline{\mathbf{3}}, \mathbf{1})_{-\frac{4}{3}}$
	$D^{c\,I} = d_R^{c\,I}$	$(\overline{\mathbf{3}}, \mathbf{1})_{+\frac{2}{3}}$

HIGGS	Higgs Boson	$(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$
Higgs	$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{+1}$

Supersymmetry

GAUGE	Gauge bosons	Gauginos	$(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$
B-boson, bino	$A_\mu^{(1)} = B_\mu$	$\lambda^{(1)} = \widetilde{B}$	$(\mathbf{1}, \mathbf{1})_0$
W-bosons, winos	$A_\mu^{(2)\,a} = W_\mu^a$	$\lambda^{(2)\,a} = \widetilde{W}^a$	$(\mathbf{1}, \mathbf{3})_0$
gluon, gluino	$A_\mu^{(3)\,a} = G_\mu^a$	$\lambda^{(3)\,a} = \widetilde{g}^a$	$(\mathbf{8}, \mathbf{1})_0$

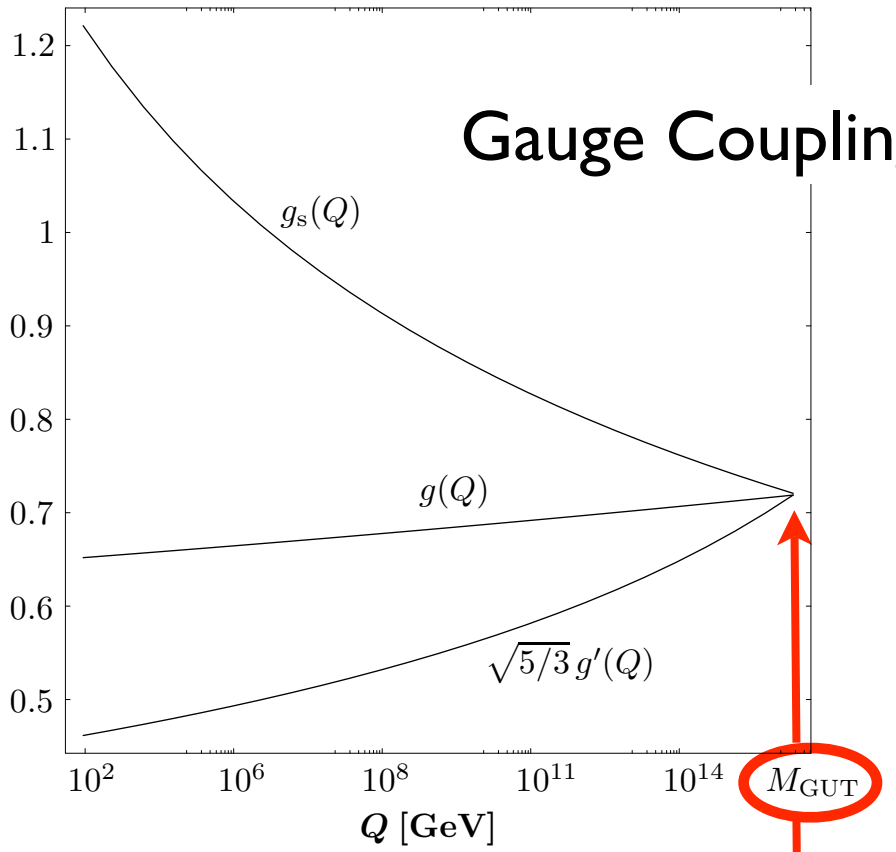
MATTER	Sfermions	Fermions	$(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$
sleptons, leptons $I = 1, 2, 3$	$\widetilde{L}^I = \begin{pmatrix} \widetilde{\nu}_L^I \\ \widetilde{e}_L^{-\,I} \end{pmatrix}$	$L^I = \begin{pmatrix} \nu_L^I \\ e_L^{-\,I} \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{-1}$
	$\widetilde{E}^{*I} = \widetilde{e}_R^{-\,*\,I}$	$E^{c\,I} = e_R^{-\,c\,I}$	$(\mathbf{1}, \mathbf{1})_{+2}$
squarks, quarks $I = 1, 2, 3$ ($\times$ 3 colors)	$\widetilde{Q}^I = \begin{pmatrix} \widetilde{u}_L^I \\ \widetilde{d}_L^I \end{pmatrix}$	$Q^I = \begin{pmatrix} u_L^I \\ d_L^I \end{pmatrix}$	$(\mathbf{3}, \mathbf{2})_{+\frac{1}{3}}$
	$\widetilde{U}^{*I} = \widetilde{u}_R^{*I}$	$U^{c\,I} = u_R^{c\,I}$	$(\overline{\mathbf{3}}, \mathbf{1})_{-\frac{4}{3}}$
	$\widetilde{D}^{*I} = \widetilde{d}_R^{*I}$	$D^{c\,I} = d_R^{c\,I}$	$(\overline{\mathbf{3}}, \mathbf{1})_{+\frac{2}{3}}$
Higgs, higgsinos	$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\widetilde{H}_d = \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{-1}$
	$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\widetilde{H}_u = \begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{+1}$

Minimal Supersymmetric Extension of the Standard Model

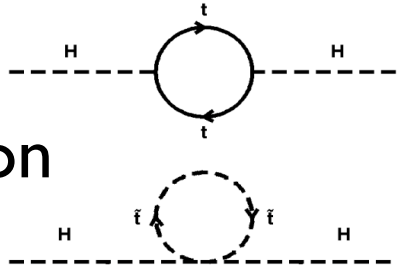
Every Particle of the Standard Model has a Superpartner

Why Supersymmetry?

Extension of Space-Time Symmetry



Gauge Coupling Unification



Hierarchy Stabilization
[Lecture by Mark Trodden]

(Super-) Gravity

Consistent String Theory

Dark Matter

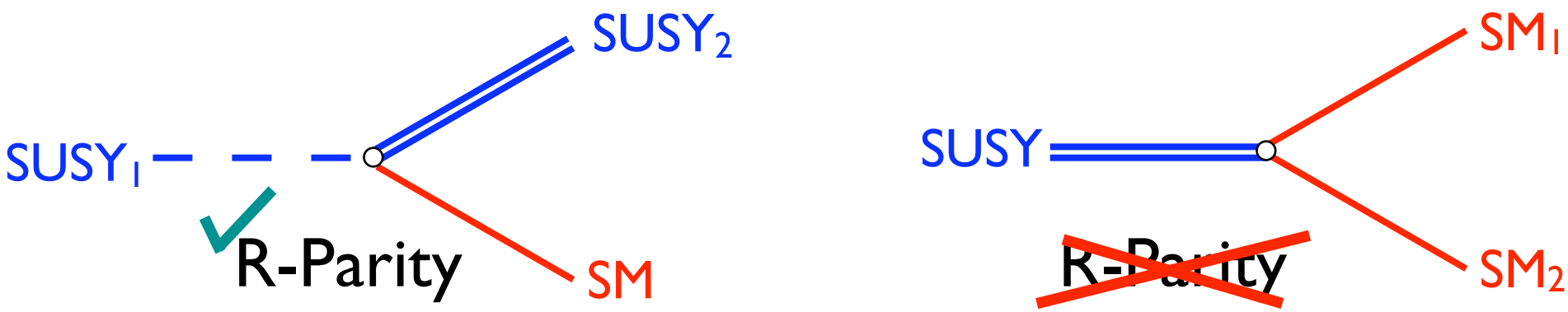
Gauge Coupling Unification at $M_{GUT} \simeq 2 \times 10^{16}\,\mathrm{GeV}$

[Lecture by Mark Trodden]

Conservation of R-Parity

- superpotential: $W_{\mathrm{MSSM}} \leftarrow W_{\Delta L} + W_{\Delta B}$
- non-observation of L & B violating processes (proton stability, ...)
- postulate conservation of R-Parity $\leftarrow$ multiplicative quantum number

$$P_{\mathrm{R}} = (-1)^{3(B-L)+2S} = \begin{cases} +1 & \text{for } \mathrm{SM}, H_u, H_d \\ -1 & \text{for } \widetilde{X} \leftarrow \text{superpartners} \end{cases}$$



The lightest supersymmetric particle (LSP) is stable!!!

Cosmological Constraints

- Dark Matter Density
- Structure Formation
- Big Bang Nucleosynthesis
- Baryogenesis / Leptogenesis

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LSP Density ≤ DM Density

photons

$\Omega_\gamma = 0.005\ \%$

baryons

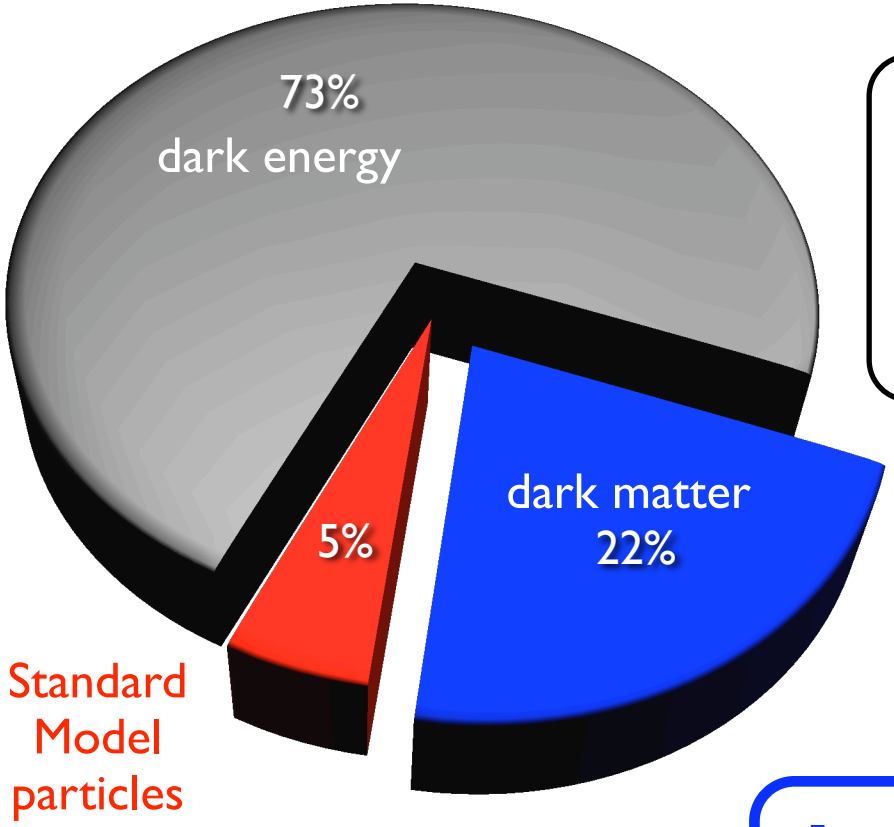
$\Omega_B = 4\ \%$

? baryon asymmetry ?

neutrinos

$0.1\ \% \leq \Omega_\nu \leq 1.5\ \%$

? neutrino mass ?



dark energy

$\Omega_{DE} = 73\ \%$

? vacuum energy ?

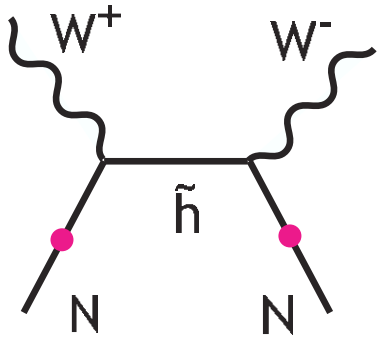
dark matter

$\Omega_{DM} = 22\ \%$

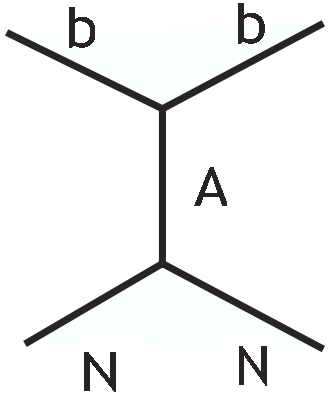
? identity ?

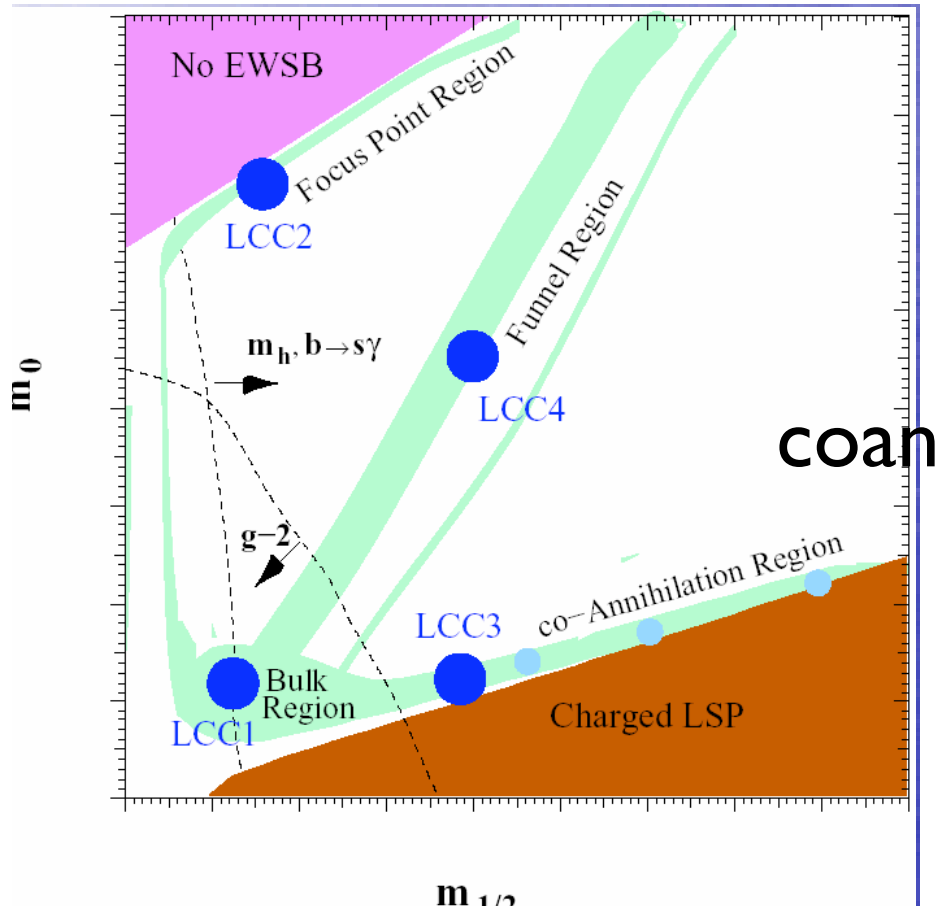
Neutralino LSP Case

focus point region

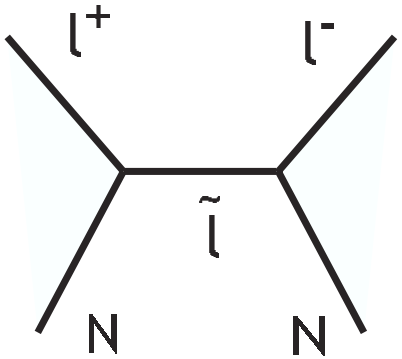


annihilation funnel

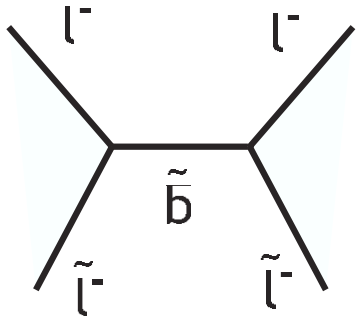




bulk region

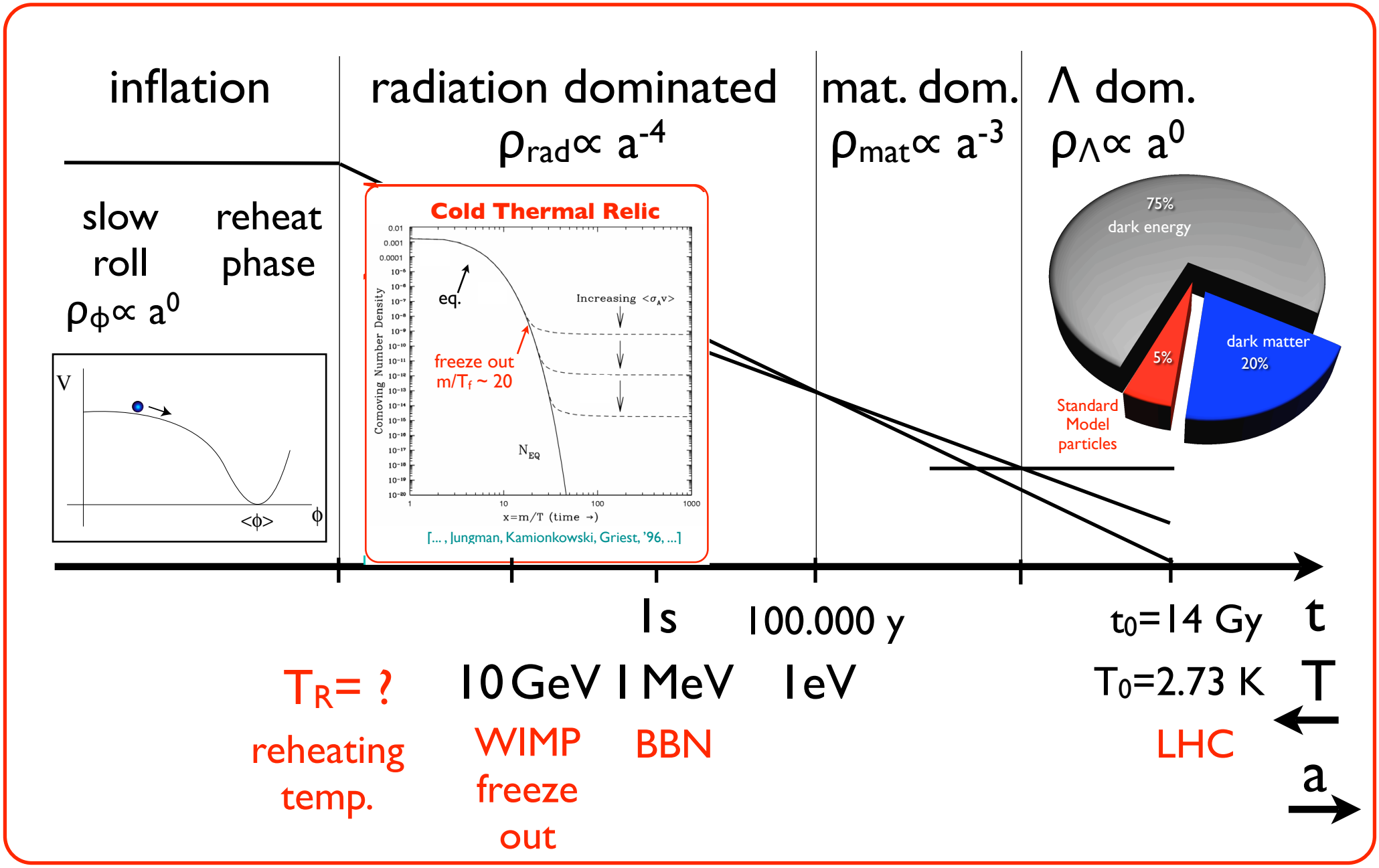


coannihilation region



[see Baltz, Battaglia, Peskin, Wizansky, '06]

Standard Thermal History of the Universe



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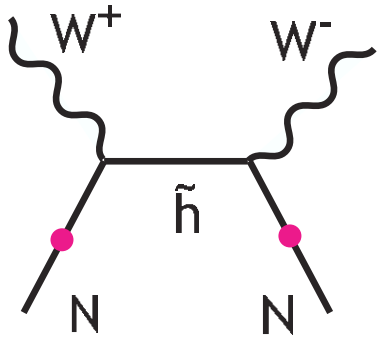

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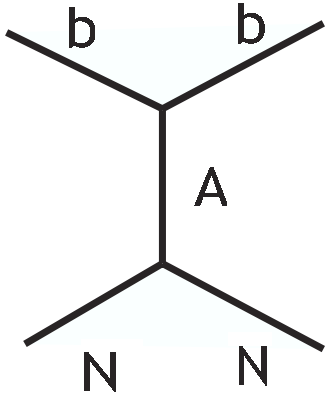

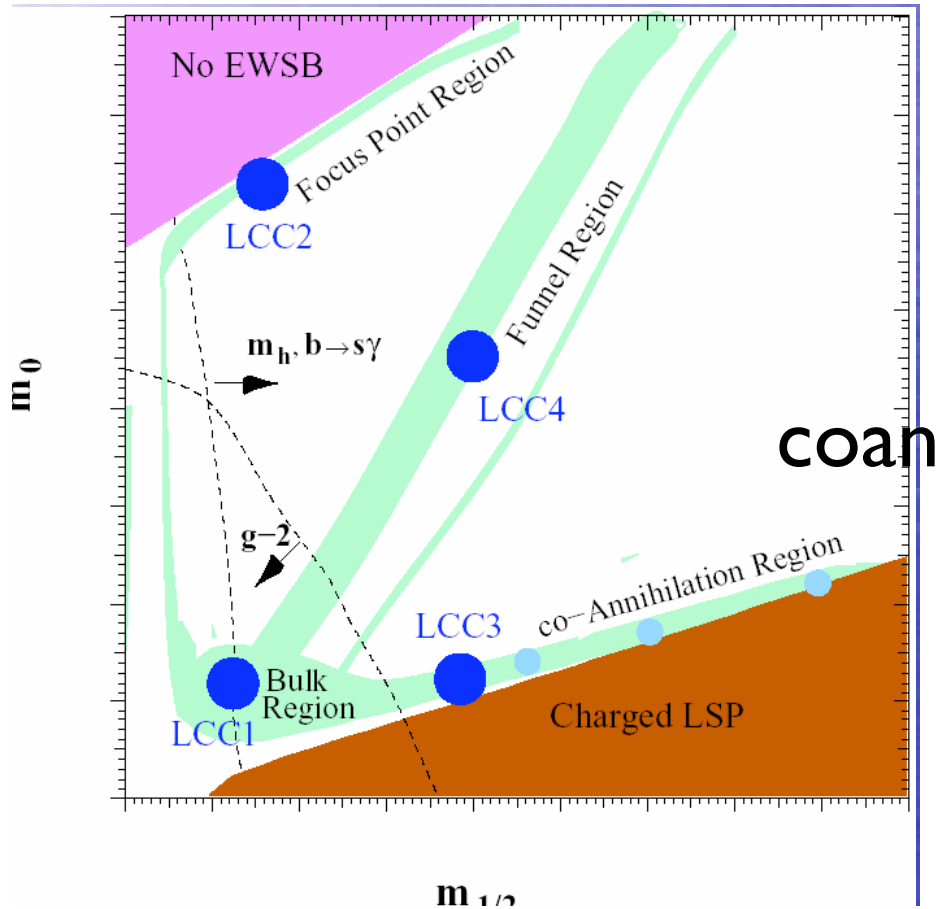

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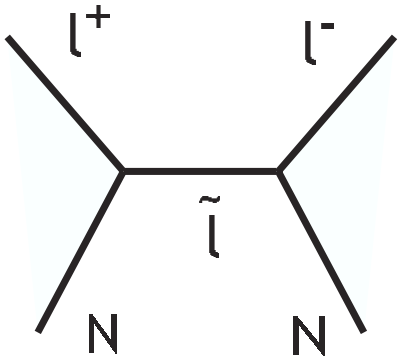

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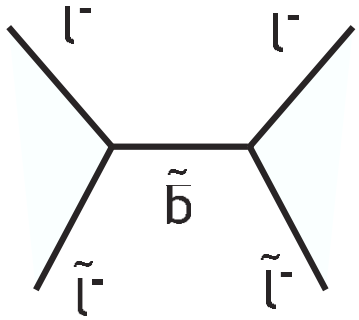

[see Baltz, Battaglia, Peskin, Wizansky, '06]

Neutralino LSP Case

poster by Jonas Lindert

Other well-motivated candidates

Extremely Weakly Interacting Particles (EWIPs)

Extensions of the Standard Model

Peccei-Quinn Symmetry & Supersymmetry

	Axions $f_a > 10^9$ GeV	Axinos $f_a > 10^9$ GeV	Gravitinos $M_{Pl} = 2.4 \times 10^{18}$ GeV
spin	0	1/2	3/2
mass	<10 meV	?	eV-TeV
int.	$\propto (p/f_a)^n$	$\propto (p/f_a)^n$	$\propto (p/M_{Pl})^n$

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poster by Peter Graf

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Axino & Gravitino LSP Cases

↓

Extremely Weakly Interacting Particles (EWIPs)

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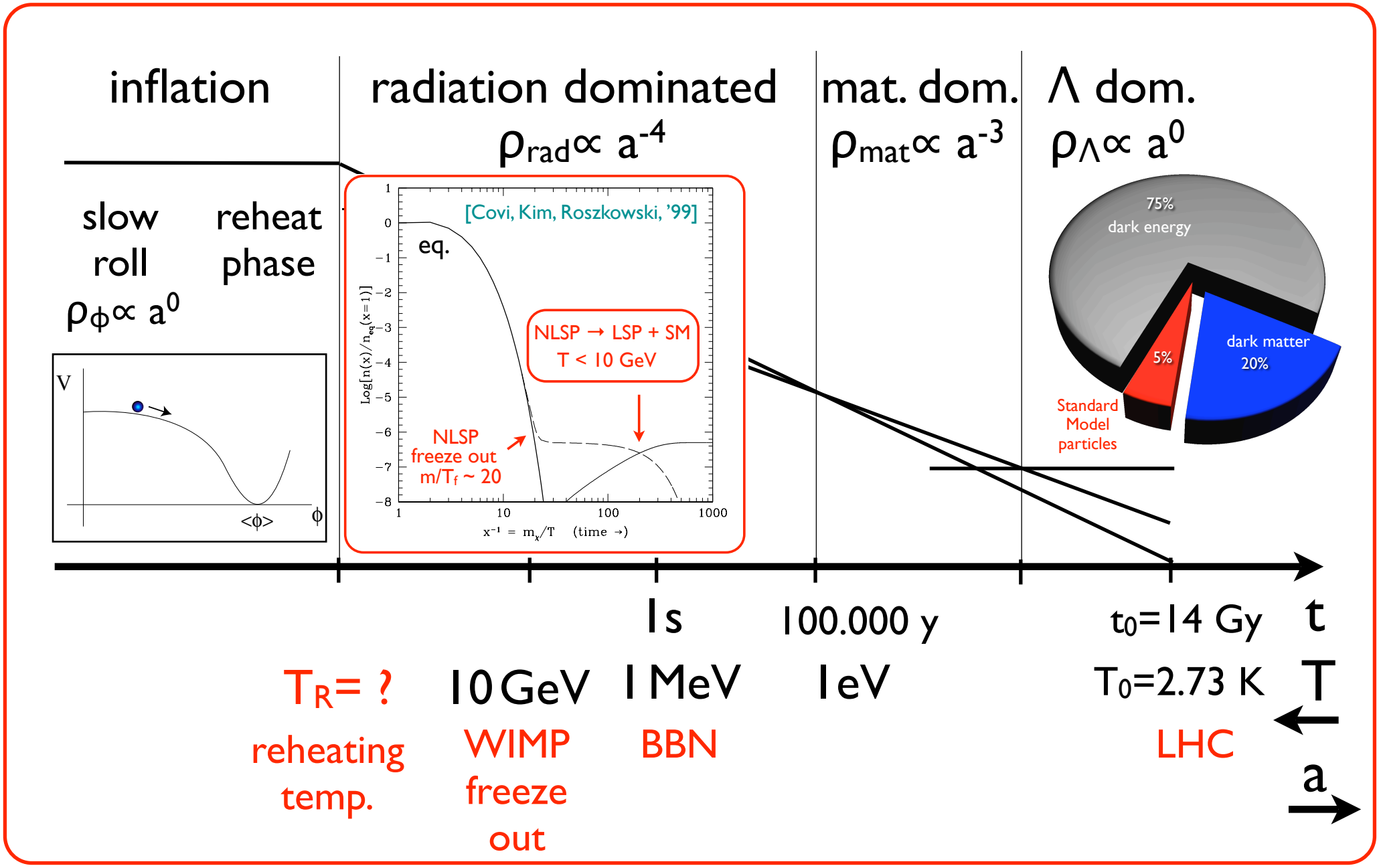
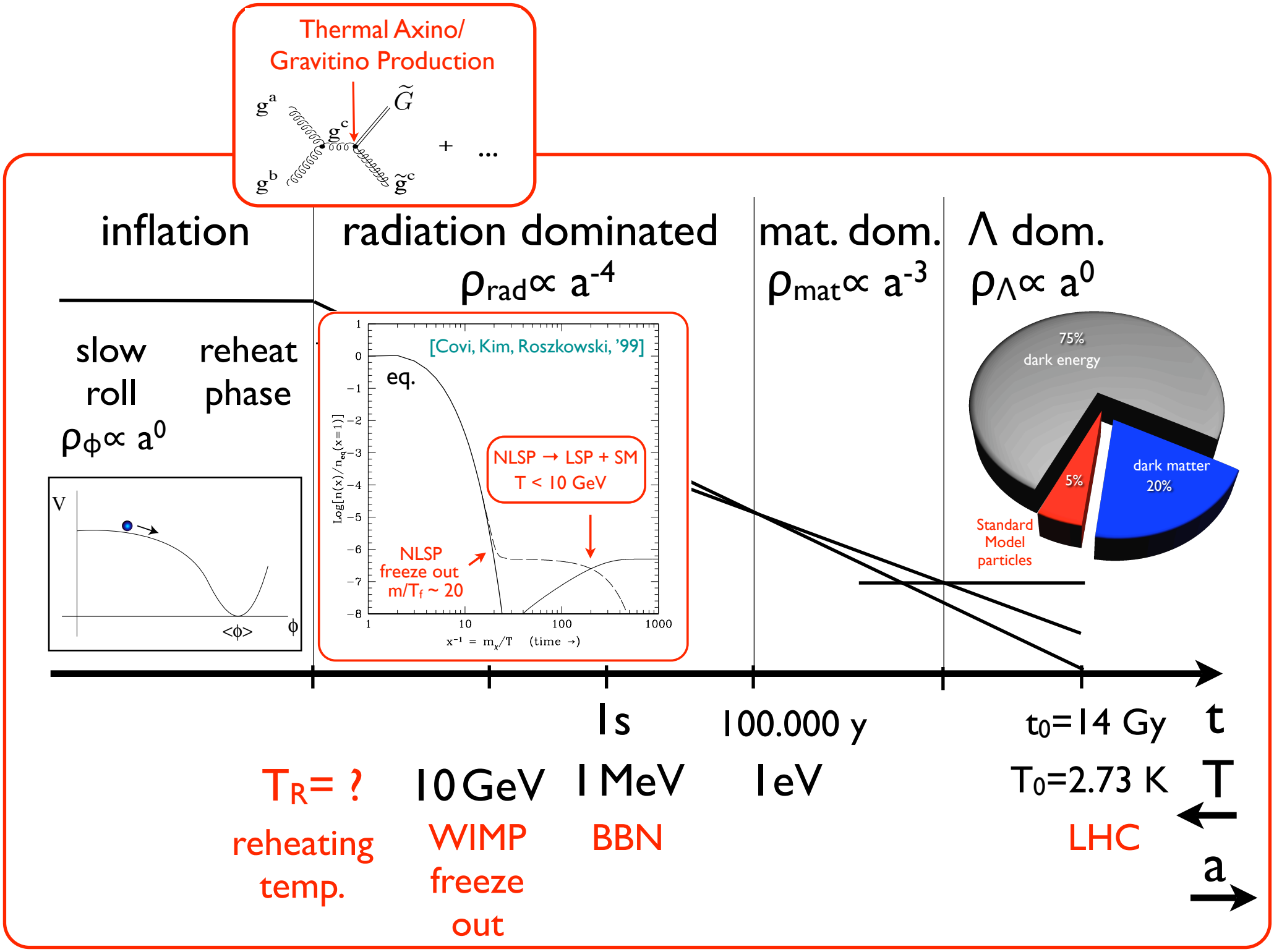

inflation
radiation dominated
$\rho_{rad} \propto a^{-4}$
mat. dom.
$\rho_{mat} \propto a^{-3}$
Λ dom.
$\rho_\Lambda \propto a^0$
slow roll
reheat phase
$\rho_\phi \propto a^0$
V
<φ>
φ
[Covi, Kim, Roszkowski, '99]
eq.
NLSP → LSP + SM
T < 10 GeV
NLSP freeze out
m/T_f ~ 20
Log[n(x)/n_eq(x=1)]
x⁻¹ = m_χ/T (time →)
75% dark energy
5%
dark matter 20%
Standard Model particles
1 s
100.000 y
t₀=14 Gy
t
T_R= ?
10 GeV
1 MeV
1 eV
T₀=2.73 K
T
reheating temp.
WIMP freeze out
BBN
LHC
a


Thermal Axino/
Gravitino Production
+ ...
inflation
radiation dominated
$\rho_{rad} \propto a^{-4}$
mat. dom.
$\rho_{mat} \propto a^{-3}$
Λ dom.
$\rho_\Lambda \propto a^0$
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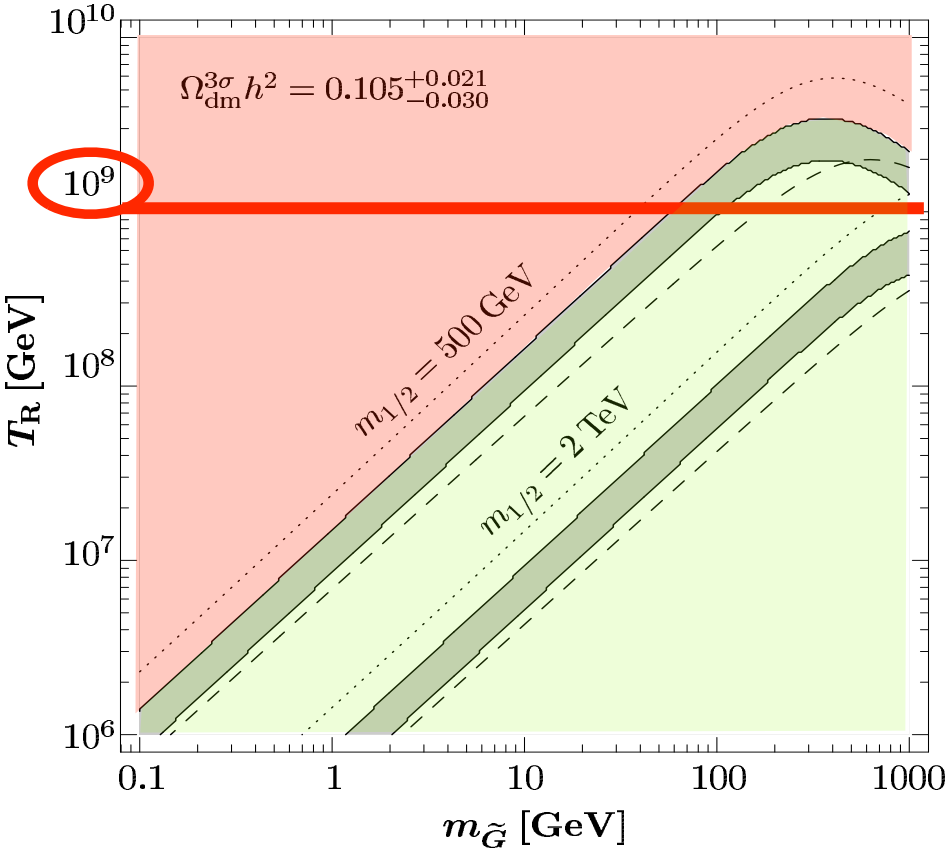
LHC
a

Gravitino LSP Case

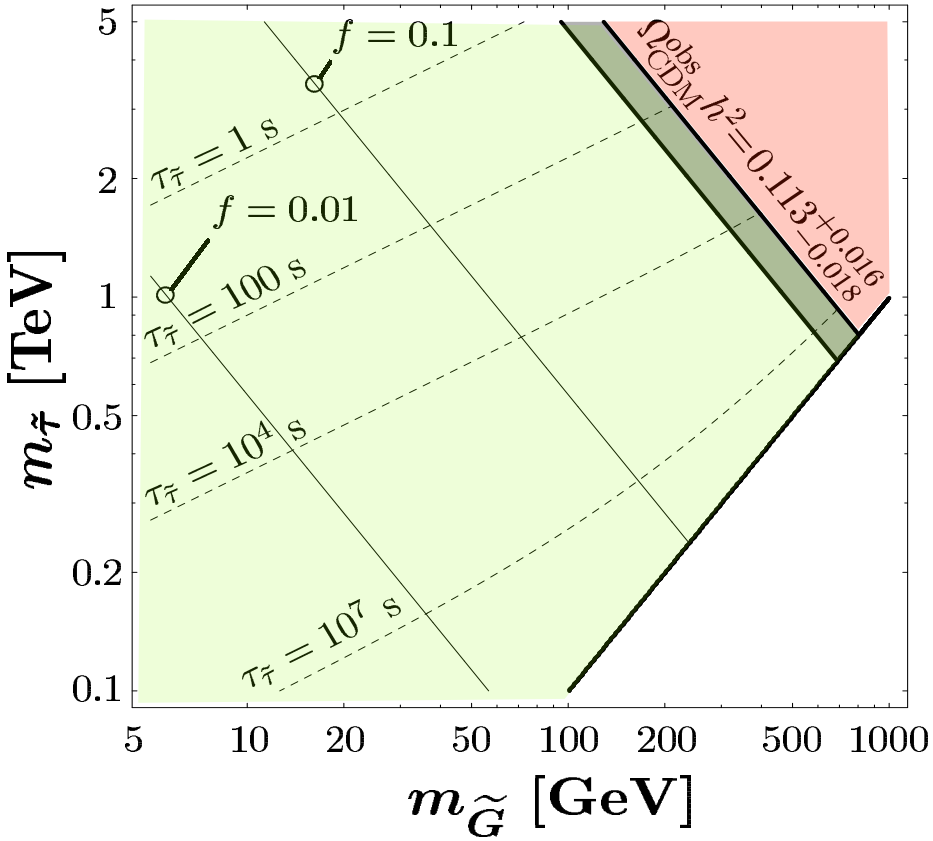
Thermal $\widetilde{G}$ Production



[Pradler, FDS, '07]

see also [Moroi, Murayama, Yamguchi, '93, Asaka, Hamaguchi, Suzuki, '00, Roszkowski et al., '05, Cerdeno et al., '06, FDS '06, Rychkov, Strumia, '07]

$\widetilde{\tau}$ NLSP $\longrightarrow \widetilde{G} + \tau$

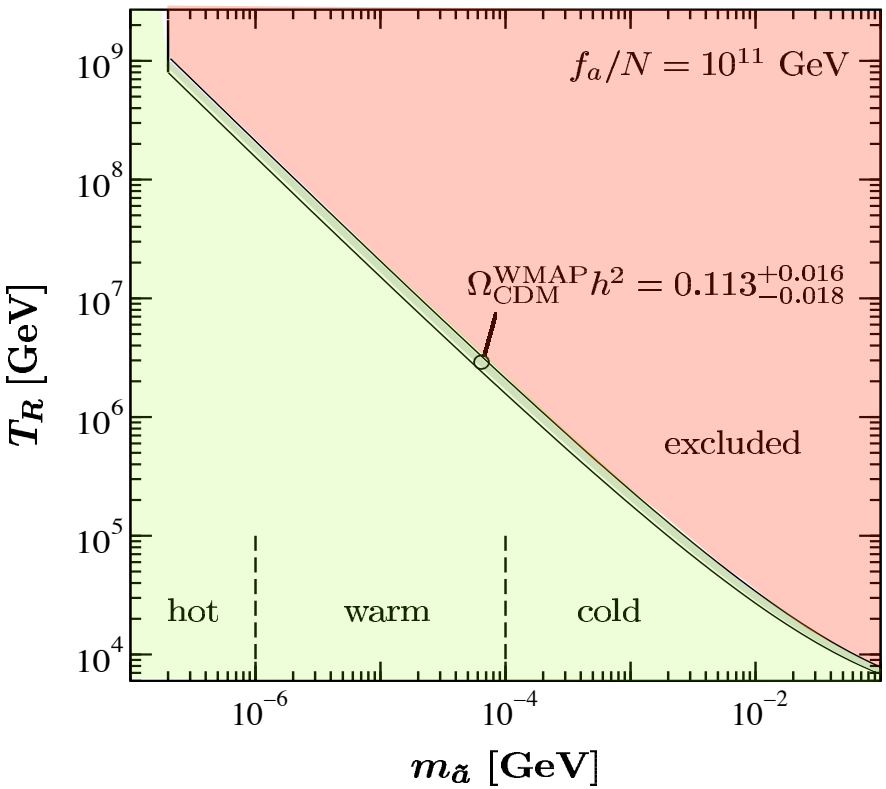


[FDS '06]

see also [Borgani, Masiero, Yamguchi, '96, Asaka, Hamaguchi, Suzuki, '00, Ellis et al., '04, Feng, Su, Takayama, '04]

Axino LSP Case

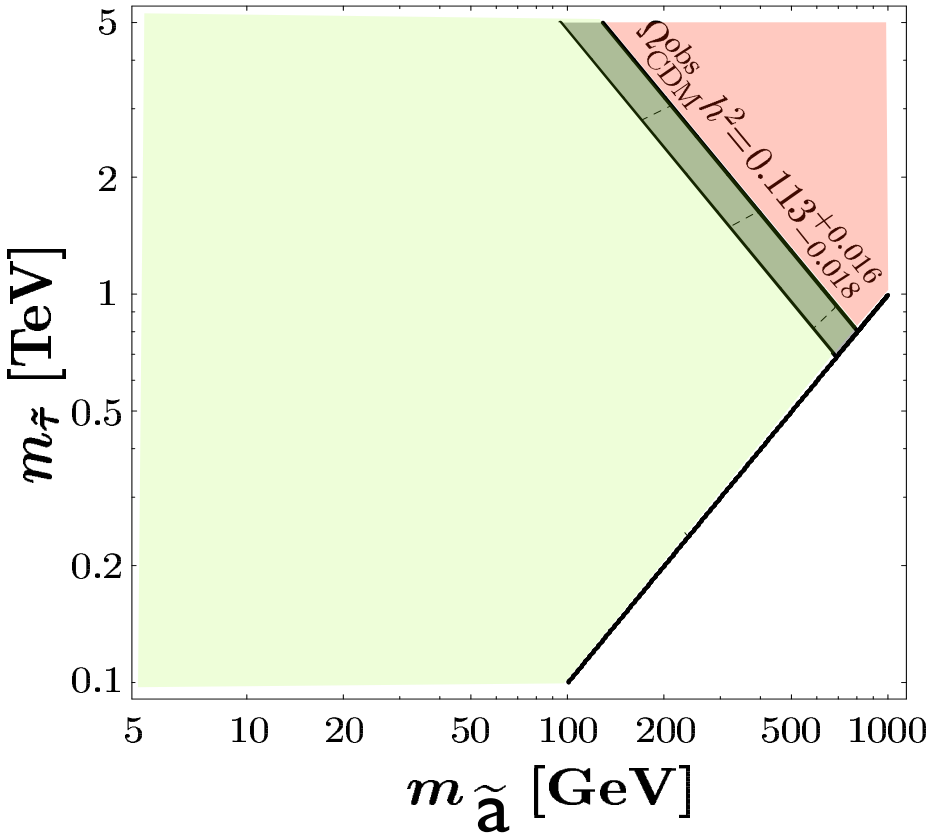
Thermal $\tilde{a}$ Production



[Brandenburg, FDS, '04]

see also [Covi et al., '01]

$\tilde{\tau}$ NLSP $\longrightarrow$ $\tilde{a} + \tau$



identical to the gravitino case

Cosmological Constraints

- Dark Matter Density
- Structure Formation
- Big Bang Nucleosynthesis
- Baryogenesis / Leptogenesis

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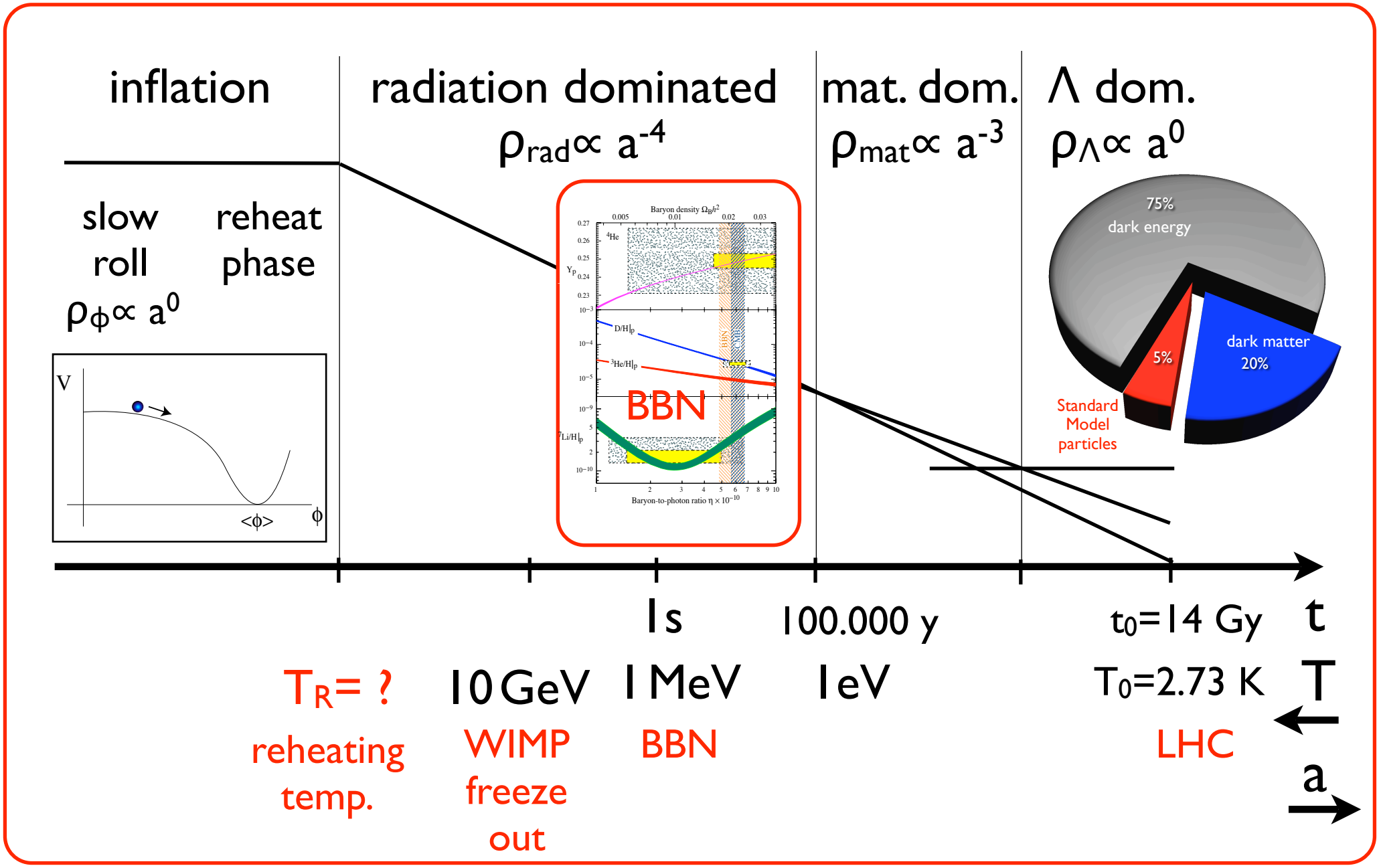
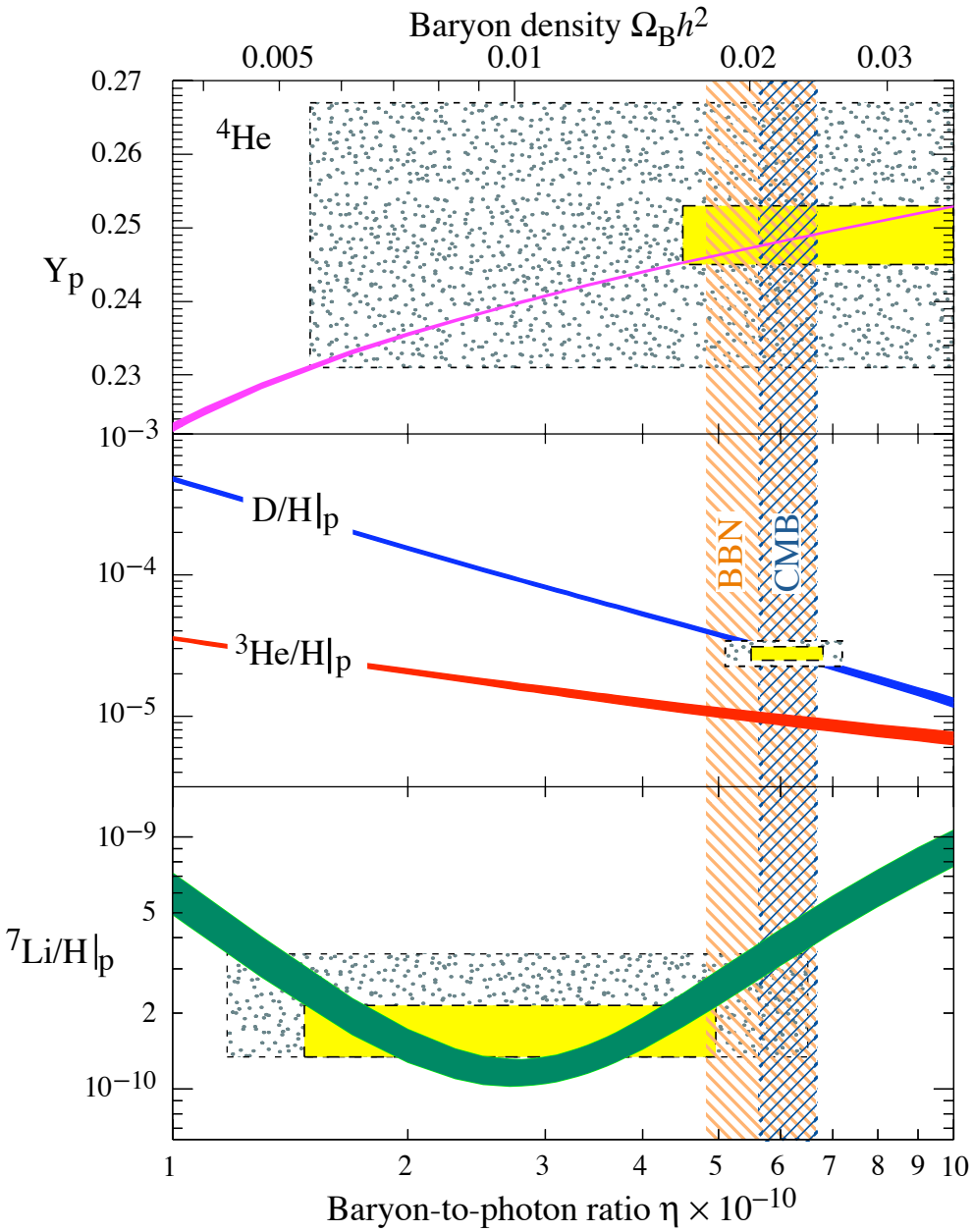
Big Bang Nucleosynthesis

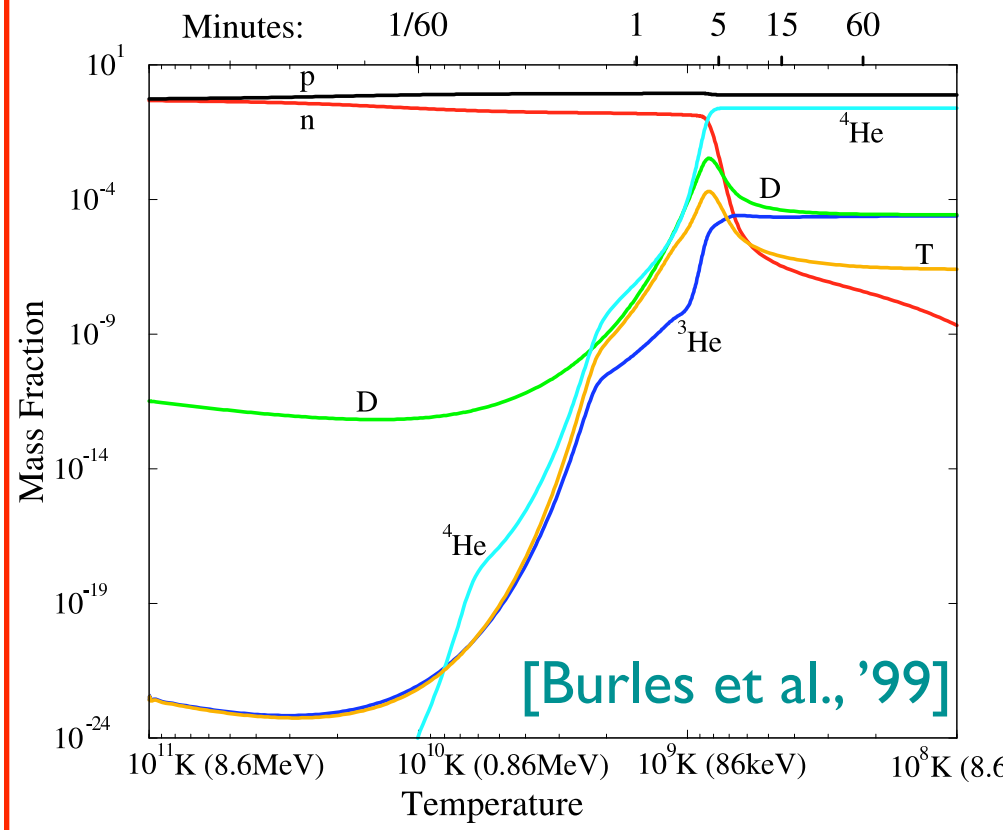


Big-Bang Nucleosynthesis

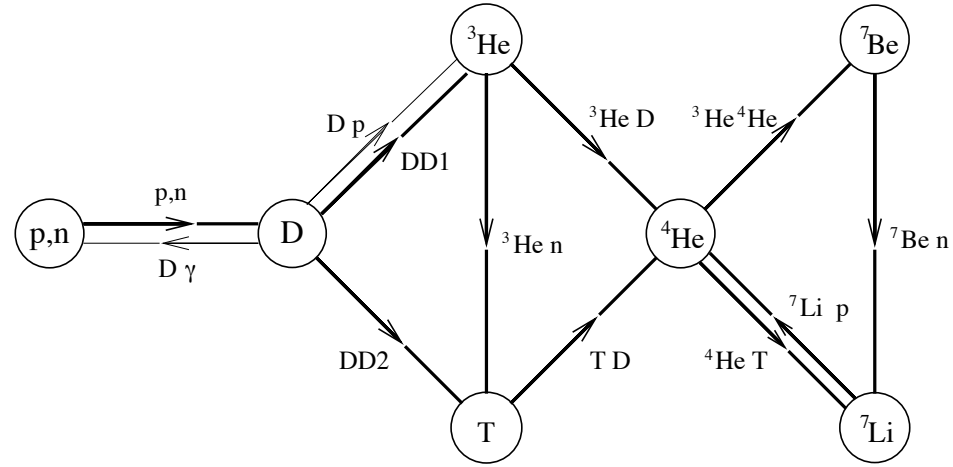


[Particle Data Book 2006]

SBBN

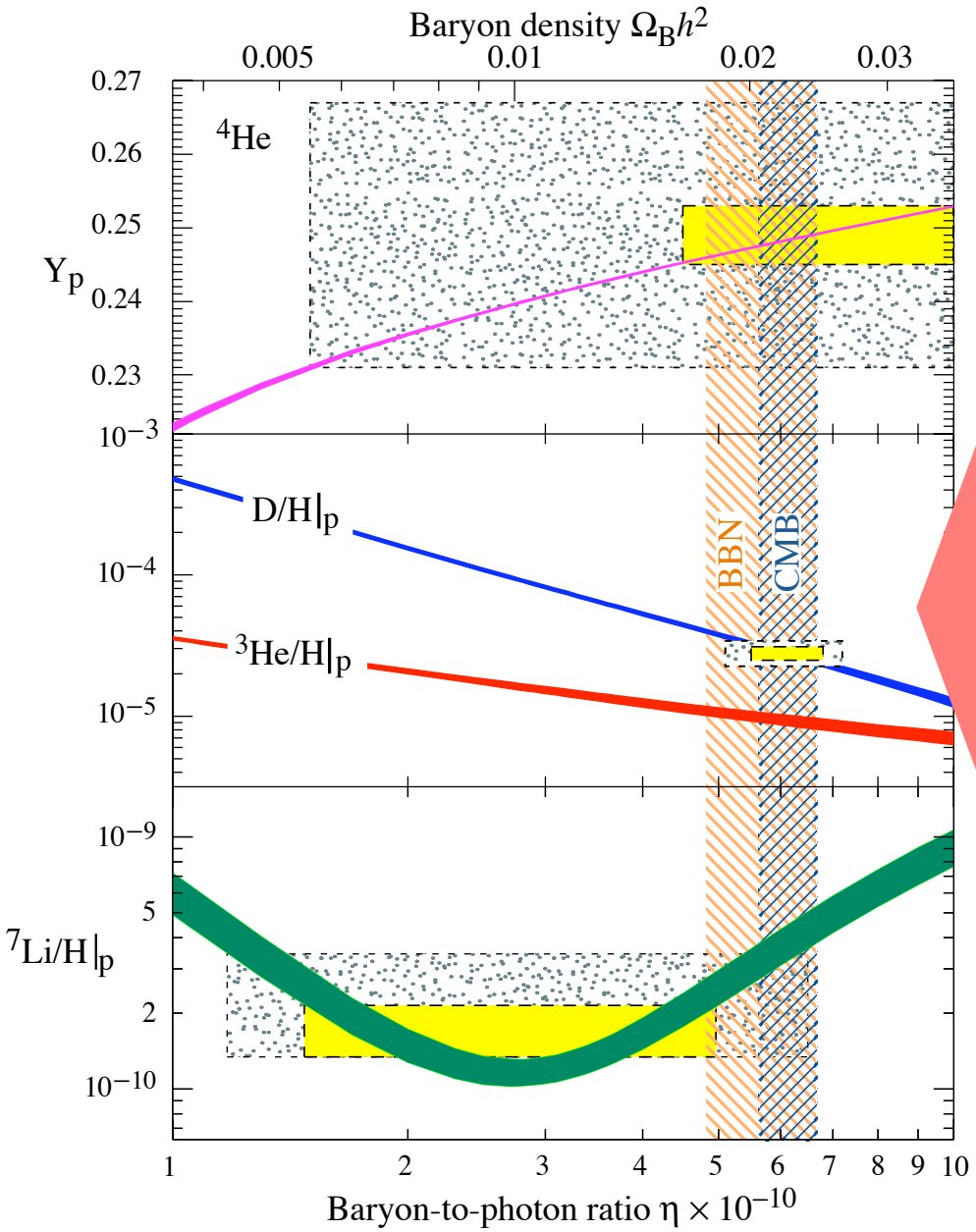


[Burles et al., '99]

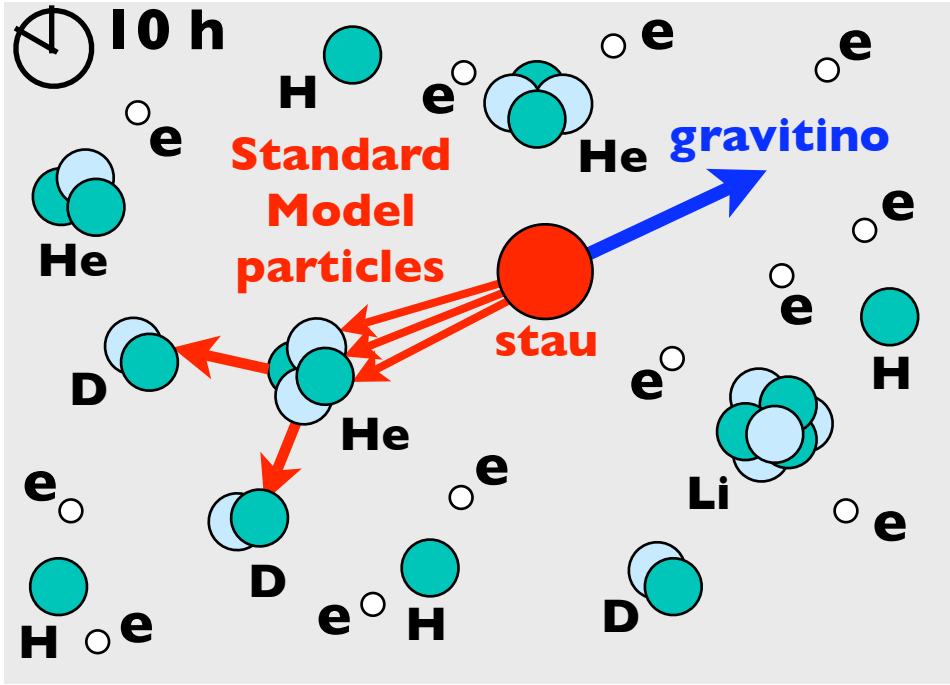


[V. Mukhanov, '04]

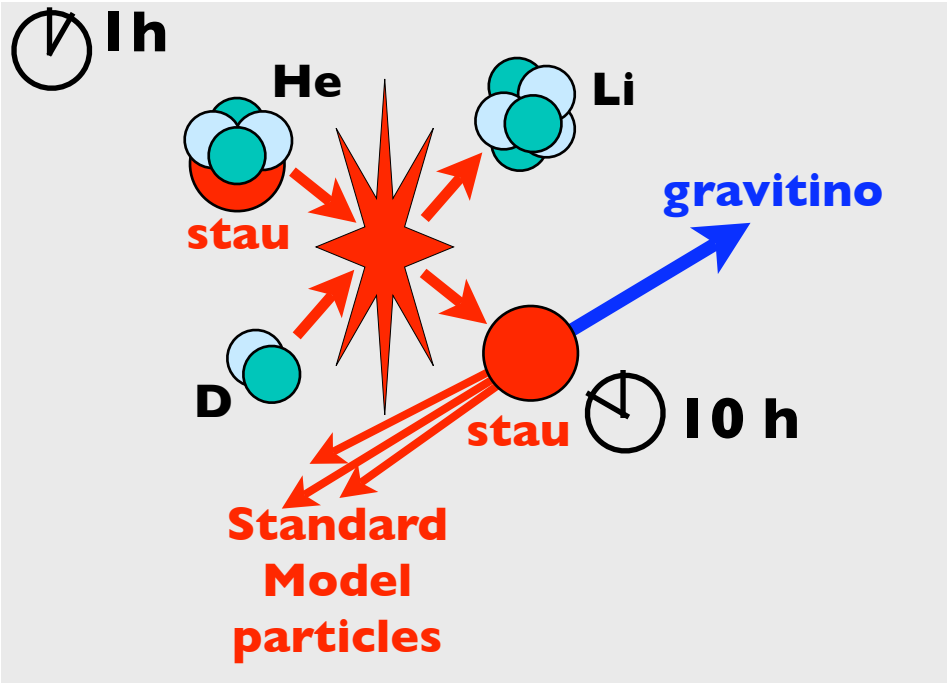
Big-Bang Nucleosynthesis



[Particle Data Book 2006]



Catalyzed BBN [Pospelov, '06]



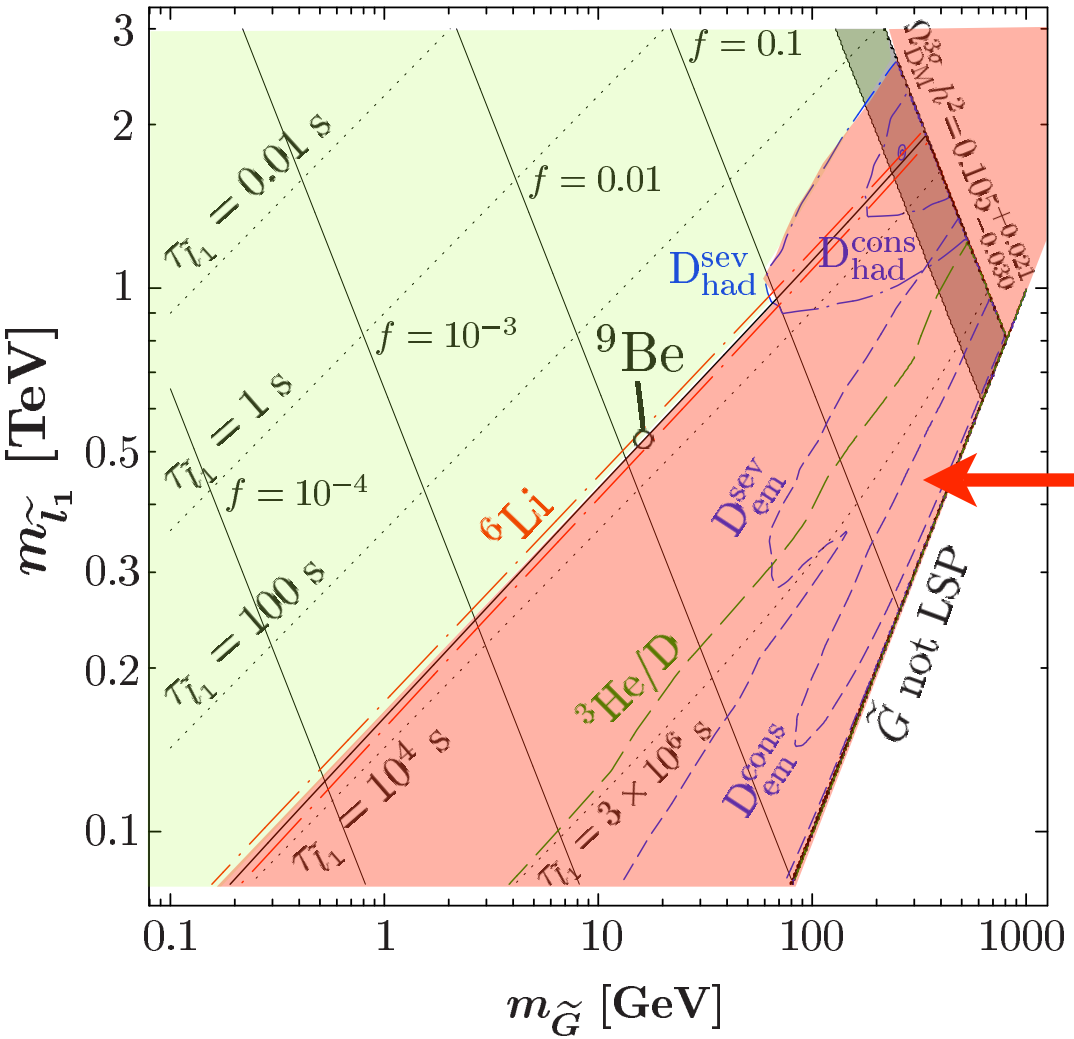
[Cyburt et al., '06; FDS, '06; Pradler, FDS, '07; Hamaguchi et al., '07; Kawasaki, Kohri, Moroi, '07; Takayama, '07; Jedamzik, '07; Pradler, FDS, '08]

CBBN of ^{9}Be: [Pospelov, '07; Pospelov, Pradler, FDS, '08]

Gravitino LSP Case with a Charged Slepton NLSP

(C)BBN Constaints

[Pospelov, Pradler, FDS, '08]

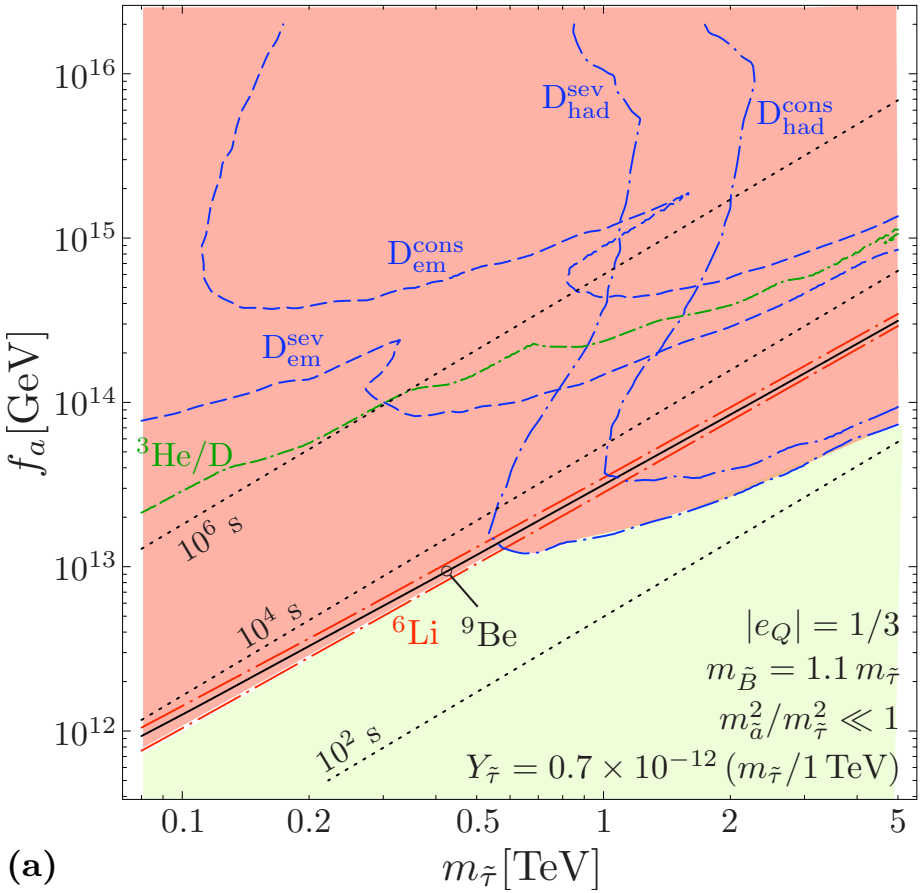


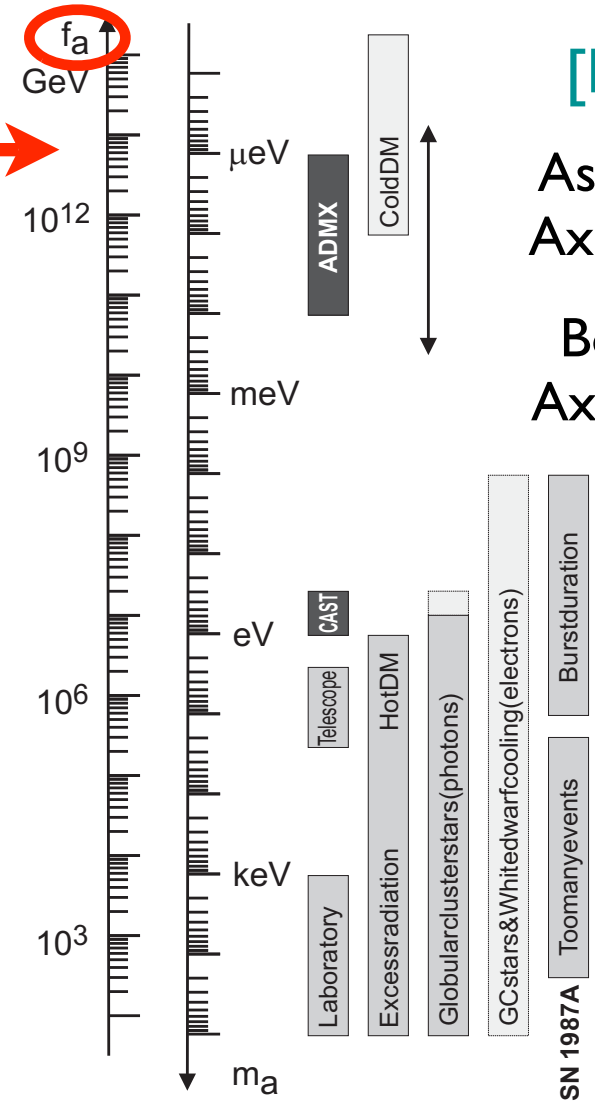
disfavored by cosmological constraints

see also
[FDS, hep-ph/0611027]

[Freitas, FDS, Tajuddin, Wyler, 0909.3293]

Axino LSP Case with a Charged Slepton NLSP





[Raffelt, '06]

Astrophysical Axion Bounds

Bounds from Axion Searches

Upper Limits on the Peccei-Quinn Scale

Cosmological Constraints

- Dark Matter Density
- Structure Formation
- Big Bang Nucleosynthesis
- Baryogenesis / Leptogenesis

Supersymmetric Dark Matter Candidates

LSP	interaction	production	constraints	experiments
$\widetilde{\chi}_1^0$	g, g'	WIMP	$\leftarrow$ cold	indirect detection (EGRET, GLAST, ...)
	weak	freeze out		direct detection (CRESST, EDELWEISS, ...)
	$M_{\mathrm{W}} \sim 100$ GeV			prod.@colliders (Tevatron, LHC, ILC, ...)
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	$\leftarrow$ warm	$+\ \widetilde{\tau}$ collection
	$\mathrm{M_{Pl}} = 2.44 \times 10^{18}$ GeV	...	BBN	$+\ \widetilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, $\mathrm{M_{Pl}}$ (?)
$\widetilde{a}$	$\left(\frac{p}{f_a}\right)^n$	therm. prod.	$\leftarrow$ cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	$\leftarrow$ warm	$+\ \widetilde{\tau}$ collection
	$f_a \gtrsim 10^9$ GeV	...	BBN	$+\ \widetilde{\tau}$ decay analysis: $m_{\tilde{a}}$, f_a

Supersymmetric Dark Matter Candidates

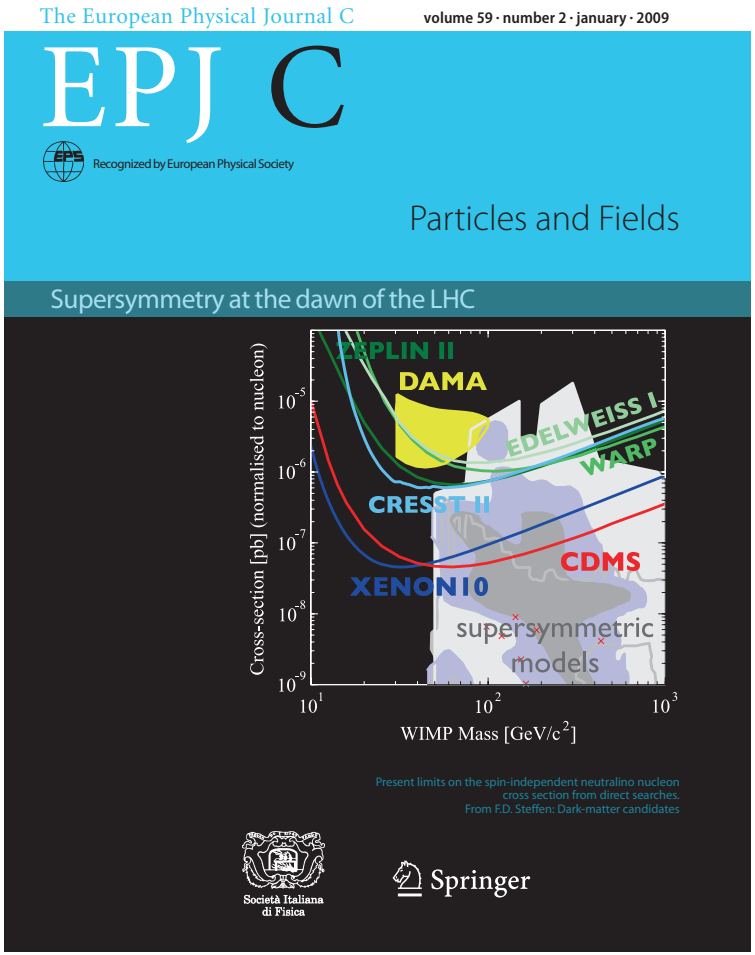
LSP	interaction	production	constraints	experiments
$\widetilde{\chi}_1^0$				
$\widetilde{G}$				
$\widetilde{a}$				

For a review (including an extensive list of references),

see

[FDS, *Dark Matter Candidates*, Eur. Phys. J. C59 (2009) 557, arXiv:0811.3347]

in



Supersymmetric Dark Matter Candidates

LSP	interaction	production	constraints	experiments
$\widetilde{\chi}_1^0$	g, g'	WIMP	$\leftarrow$ cold	indirect detection (EGRET, GLAST, ...)
	weak	freeze out		direct detection (CRESST, EDELWEISS, ...)
	$M_{\mathrm{W}} \sim 100$ GeV			prod.@colliders (Tevatron, LHC, ILC, ...)
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	$\leftarrow$ warm	$+\ \widetilde{\tau}$ collection
	$\mathrm{M_{Pl}} = 2.44 \times 10^{18}$ GeV	...	BBN	$+\ \widetilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, $\mathrm{M_{Pl}}$ (?)
$\widetilde{a}$	$\left(\frac{p}{f_a}\right)^n$	therm. prod.	$\leftarrow$ cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	$\leftarrow$ warm	$+\ \widetilde{\tau}$ collection
	$f_a \gtrsim 10^9$ GeV	...	BBN	$+\ \widetilde{\tau}$ decay analysis: $m_{\tilde{a}}$, f_a

Bonus Material

Cosmological Constraints

- Dark Matter Density
- Structure Formation
- Big Bang Nucleosynthesis
- Baryogenesis / Leptogenesis

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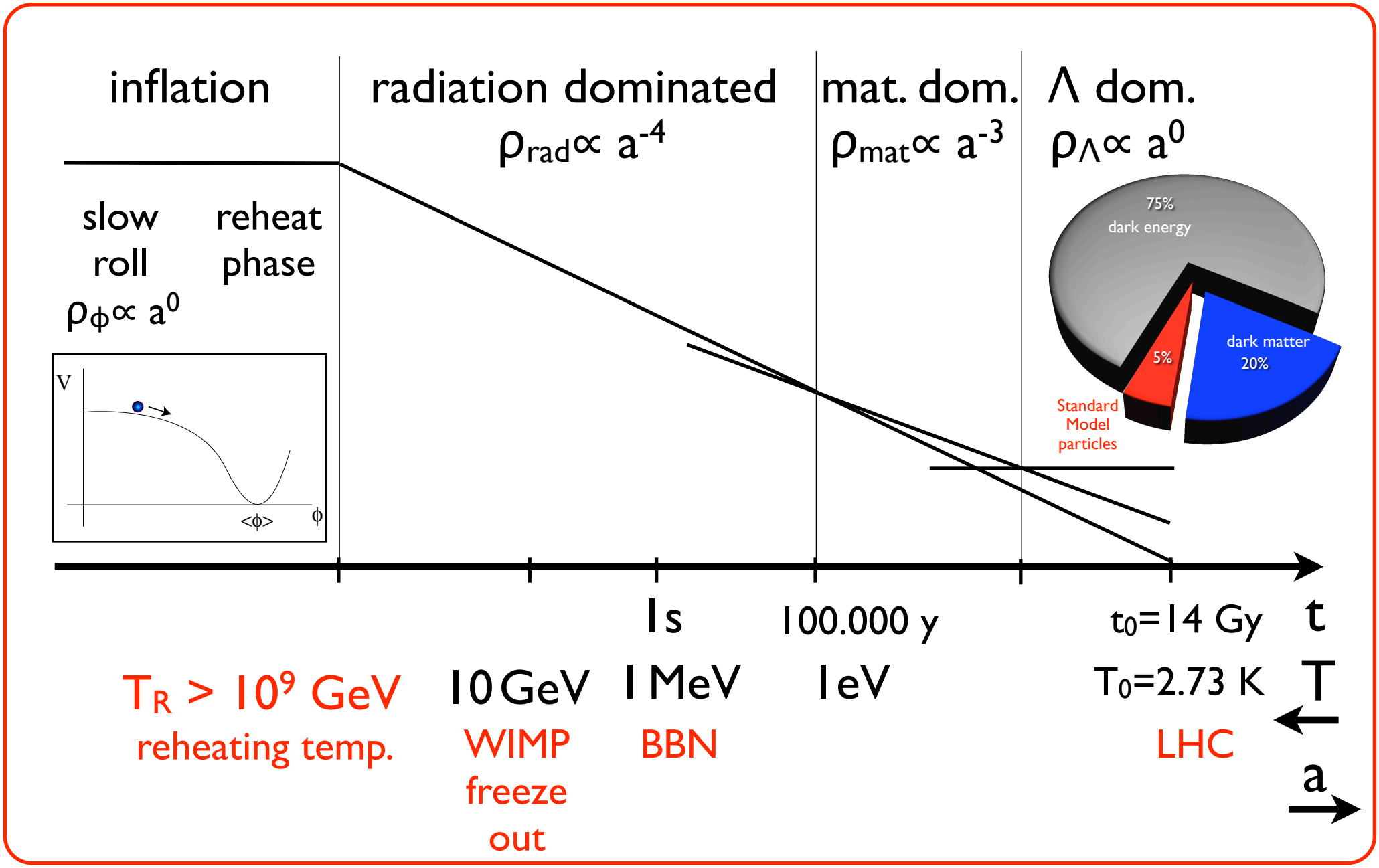
Thermal Leptogenesis



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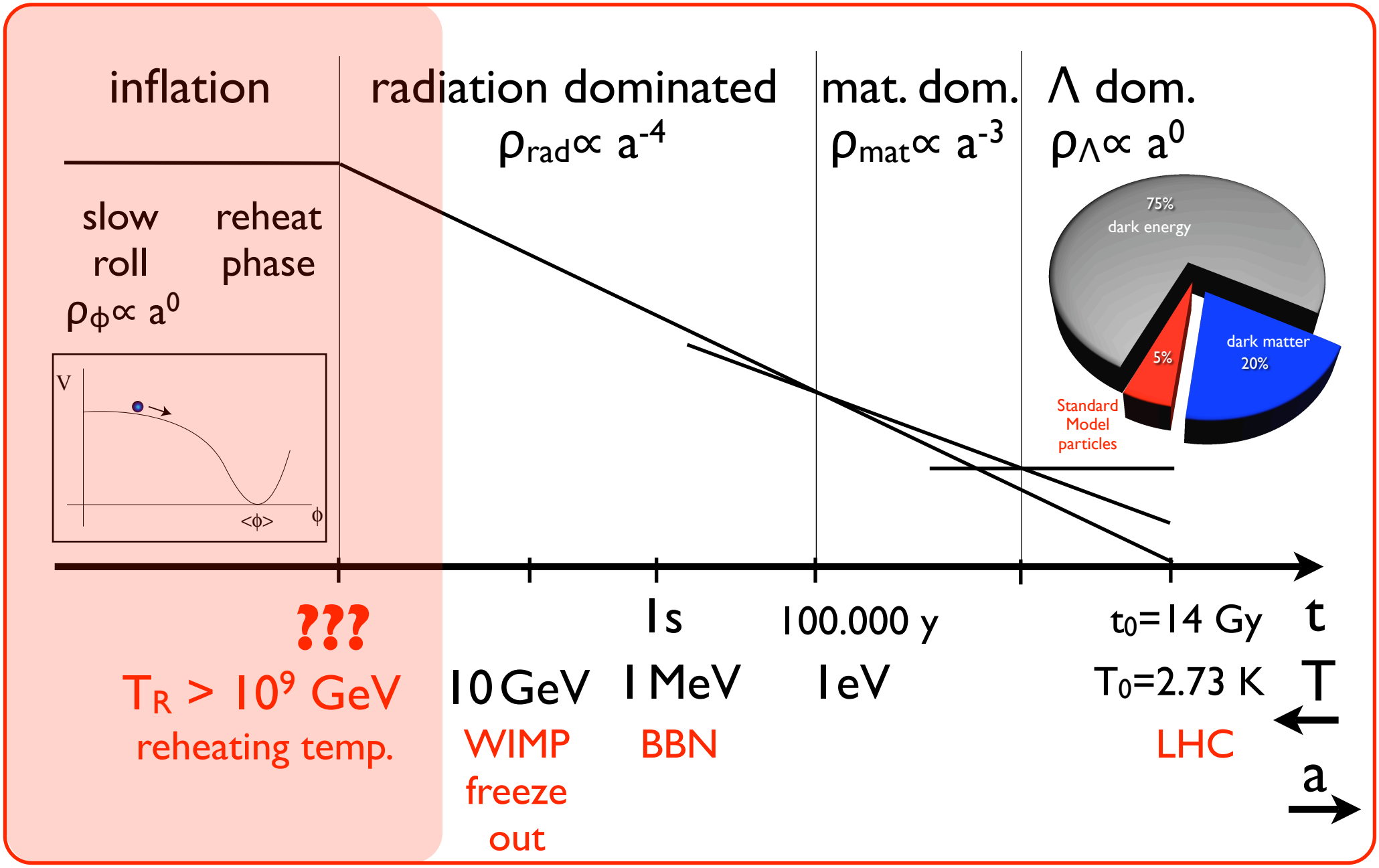
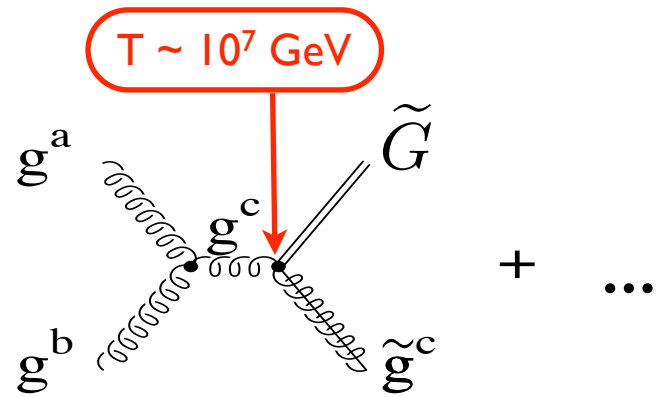


The gravitino can become a problem ...

Thermal Gravitino Production

gauge-field of
local SUSY
(supergravity)

Very Hot Early Universe



gauge-invariant treatment
(hard thermal loop resummation)

SUSY QCD
[Bolz, Brandenburg, Buchmüller, '01]

+ electroweak contributions
[Pradler, Steffen, '06 & '07]

Thermal Gravitino Production

gauge-field of local SUSY (supergravity)

Stable Gravitino

gravitino LSP

- gravitino DM
- late NLSP decays
- NLSP bound states

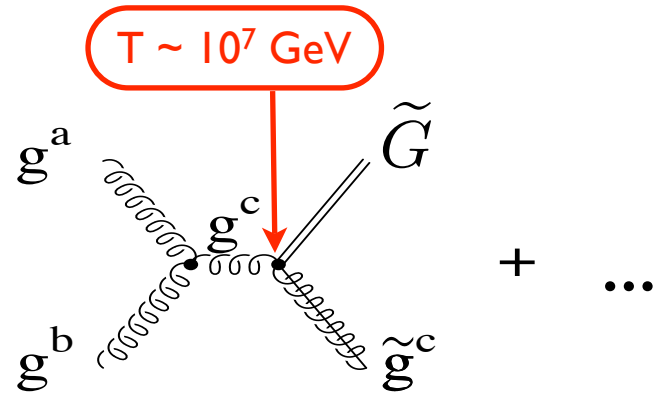
Unstable Gravitino

neutralino LSP

- neutralino DM
- late gravitino decays

BBN constraints

Very Hot Early Universe



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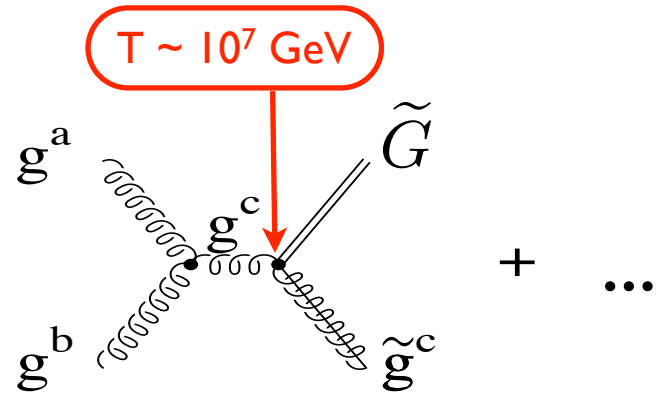

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Upper Limits on the Reheating Temperature

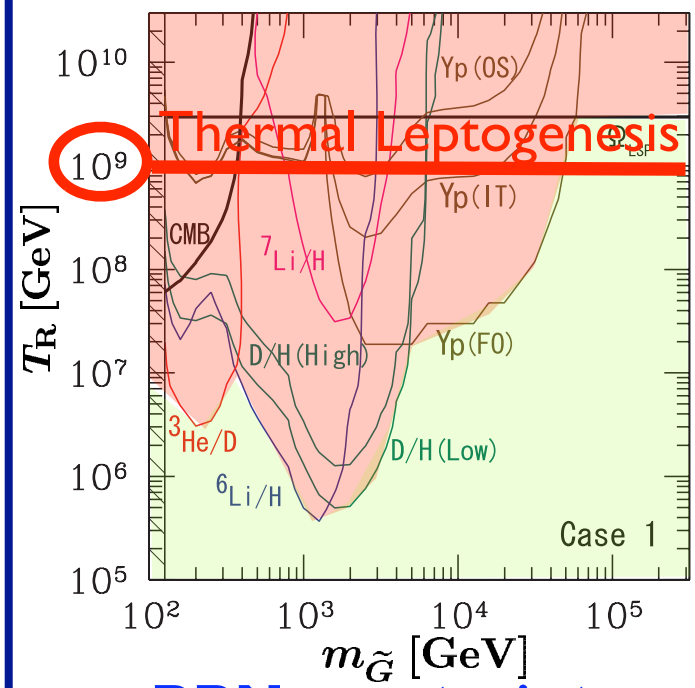
Neutralino LSP

Late Decaying Gravitinos from Thermal Production

$$Y_{\tilde{G}}^{\mathrm{TP}}(T_{\mathrm{low}}) \equiv \frac{n_{\tilde{G}}^{\mathrm{TP}}(T_{\mathrm{low}})}{s(T_{\mathrm{low}})} \approx \frac{C_{\tilde{G}}(T_{\mathrm{R}})}{s(T_{\mathrm{R}})H(T_{\mathrm{R}})}$$
$$= \sum_{i=1}^{3} y_i g_i^2(T_{\mathrm{R}}) \left(1 + \frac{M_i^2(T_{\mathrm{R}})}{3m_{\tilde{G}}^2}\right)$$
$$\times \ln\left(\frac{k_i}{g_i(T_{\mathrm{R}})}\right)\left(\frac{T_{\mathrm{R}}}{10^{10}\ \mathrm{GeV}}\right),$$

[Pradler, FDS, '07]

Unstable Gravitino



BBN constraints

+ Ω_{DM} constraint for neutralino DM

[Kohri, Moroi, Yotsuyanagi, '05]

Thermal Leptogenesis requires T >10^9 GeV

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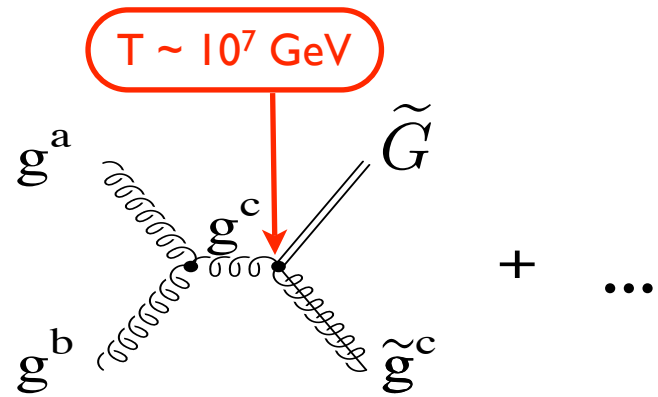

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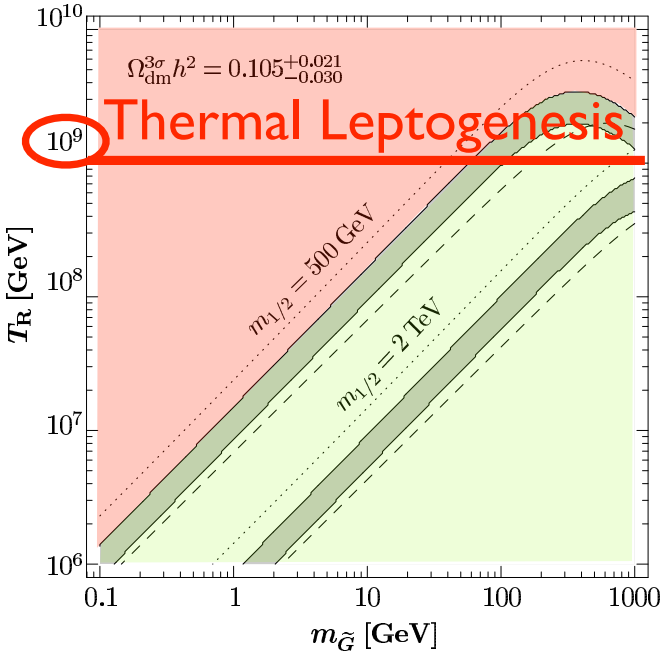
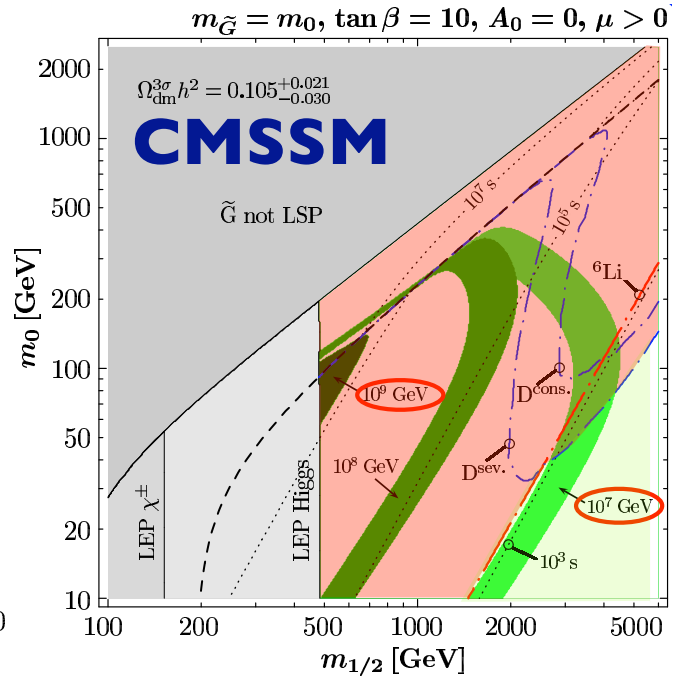




Ω_{DM} constraint for gravitino DM

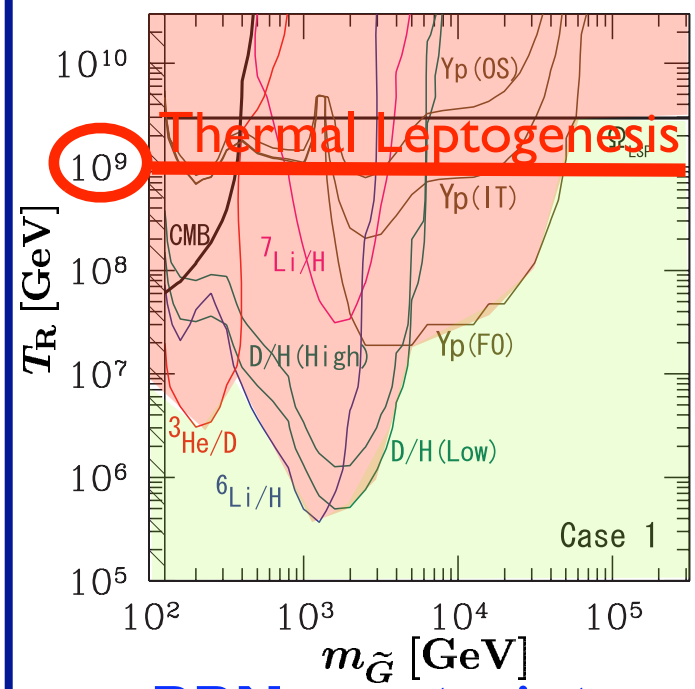
[Pradler, FDS, '07]

+ BBN constraints

$$T_R \lesssim 4.9 \times 10^7 \text{ GeV} \left(\frac{m_{\tilde{G}}}{10 \text{ GeV}}\right)^{1/5}$$

[Pradler, FDS, arXiv:0710.2213]

Unstable Gravitino



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