Dark Matter Computations

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TUM
LMU
Excellence Cluster
Universe

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Pre-SUSY 2010
Bonn, August 20th, 2010

Contents

photons

$\Omega_\gamma = 0.005\ \%$

baryons

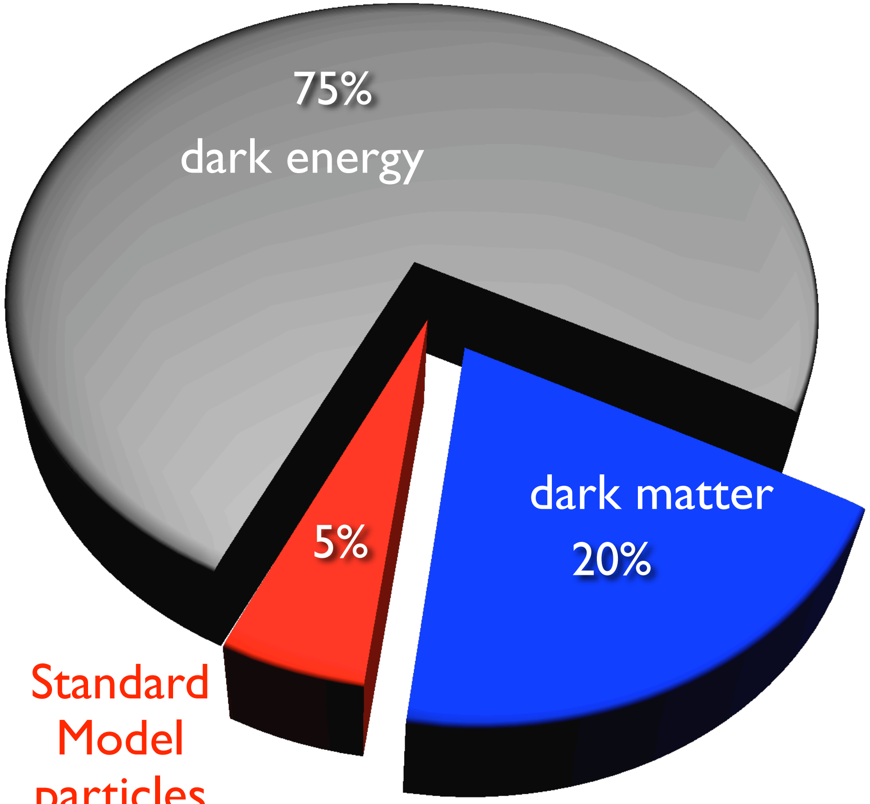
$\Omega_B = 4\ \%$

? baryon asymmetry ?

neutrinos

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

? neutrino mass ?



Standard Model particles

dark energy

$\Omega_{DE} = 75\ \%$

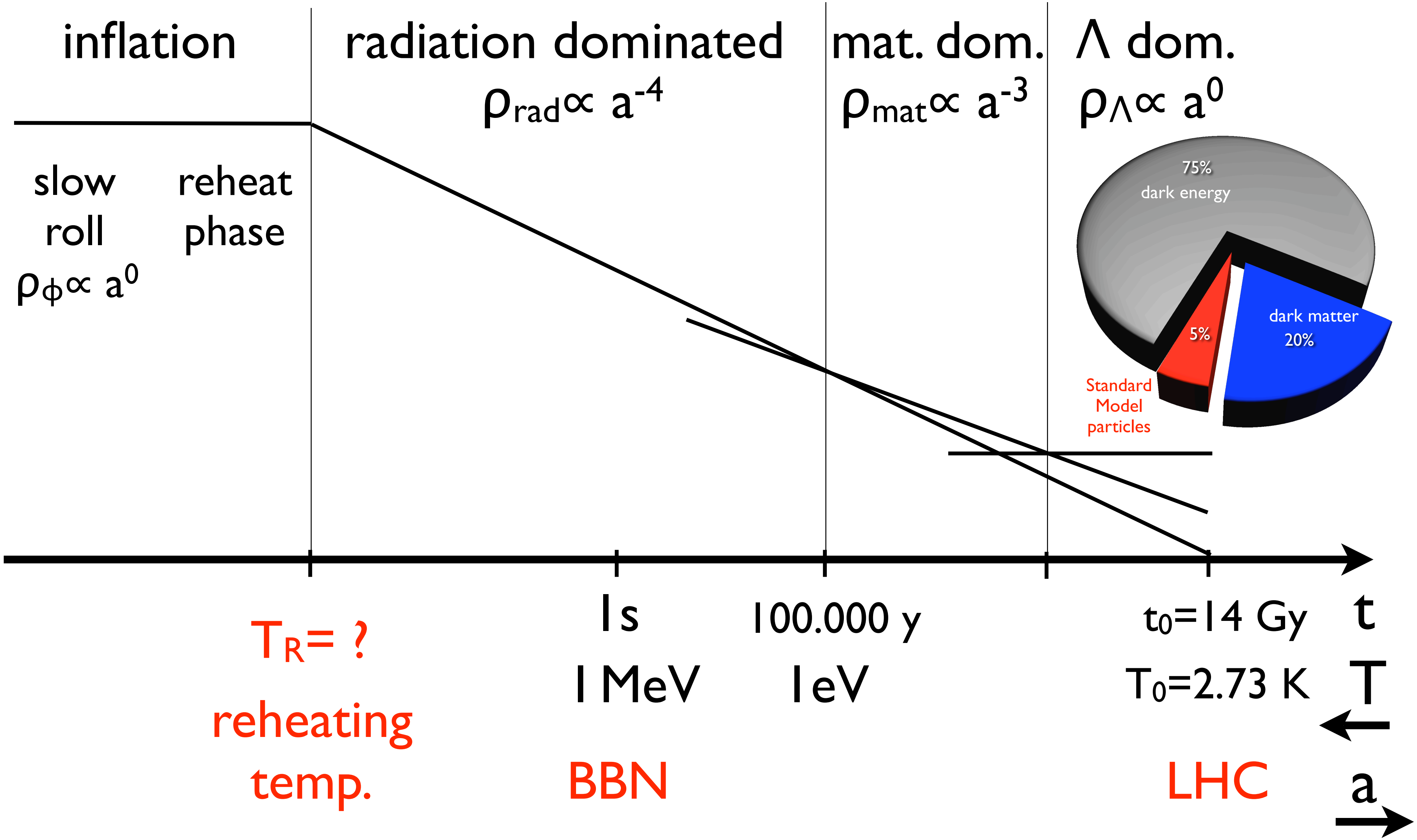
? vacuum energy ?

dark matter

$\Omega_{DM} = 20\ \%$

? identity ?

Standard Thermal History of the Universe



inflation

slow roll $\rho_\phi \propto a^0$

reheat phase

radiation dominated $\rho_{rad} \propto a^{-4}$

mat. dom. $\rho_{mat} \propto a^{-3}$

Λ dom. $\rho_\Lambda \propto a^0$

T_R= ?

reheating temp.

1 s

1 MeV

BBN

100.000 y

1 eV

t_0=14 Gy

T_0=2.73 K

LHC

t

T ←

a →

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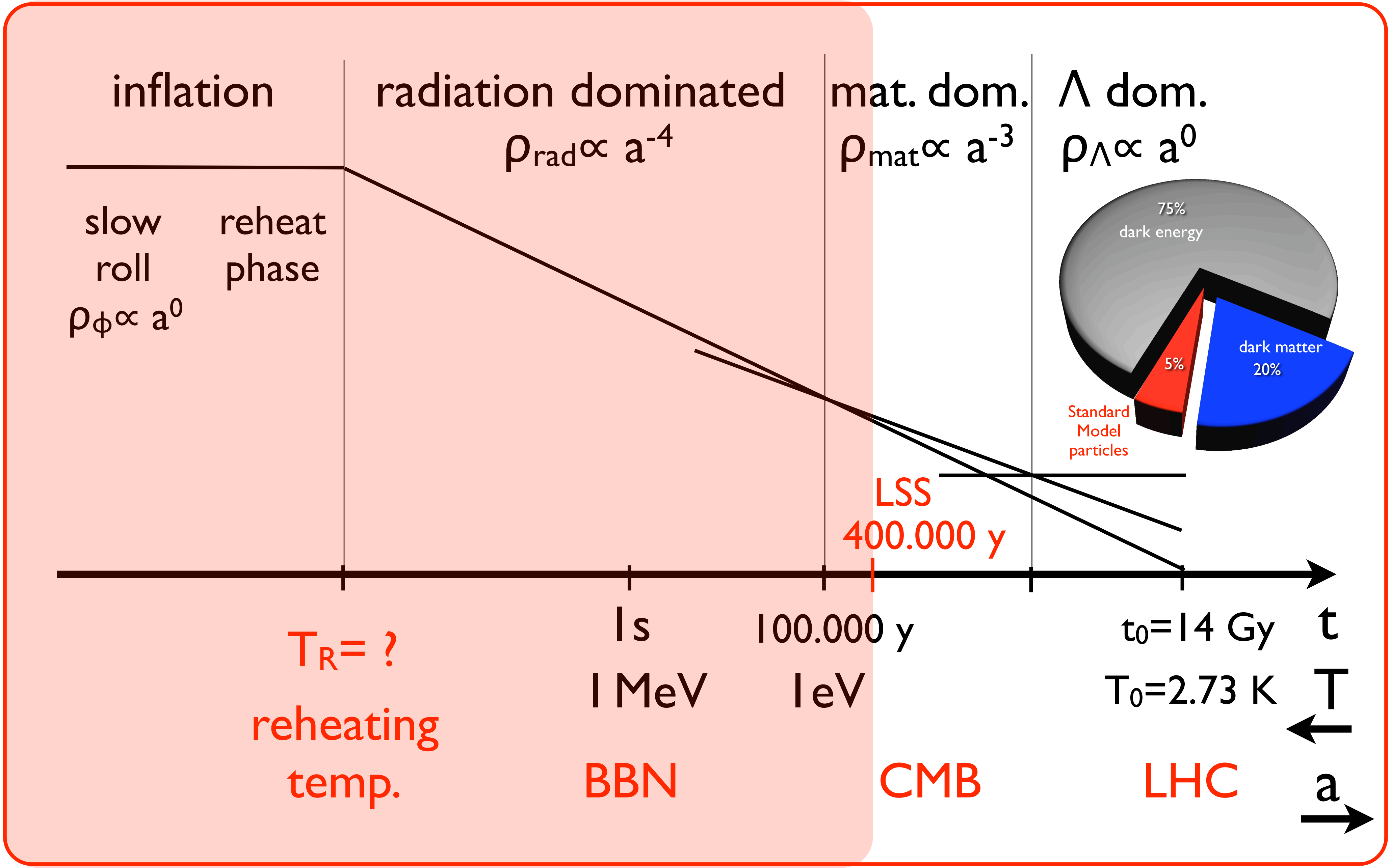

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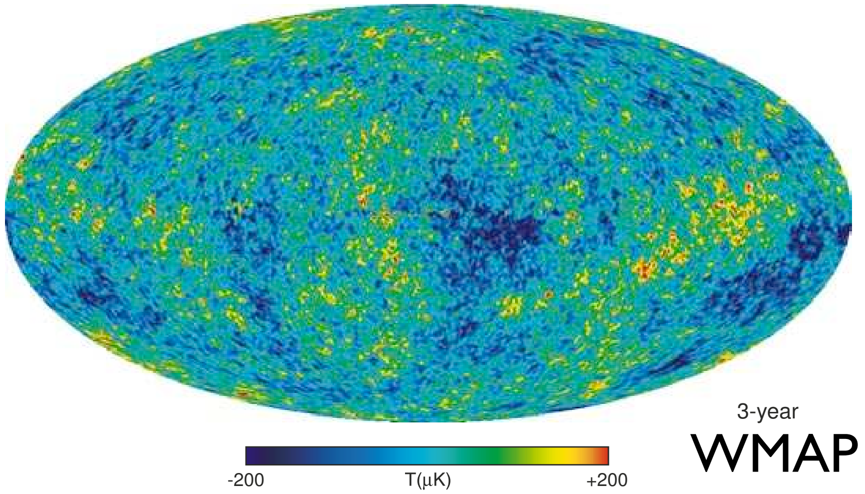
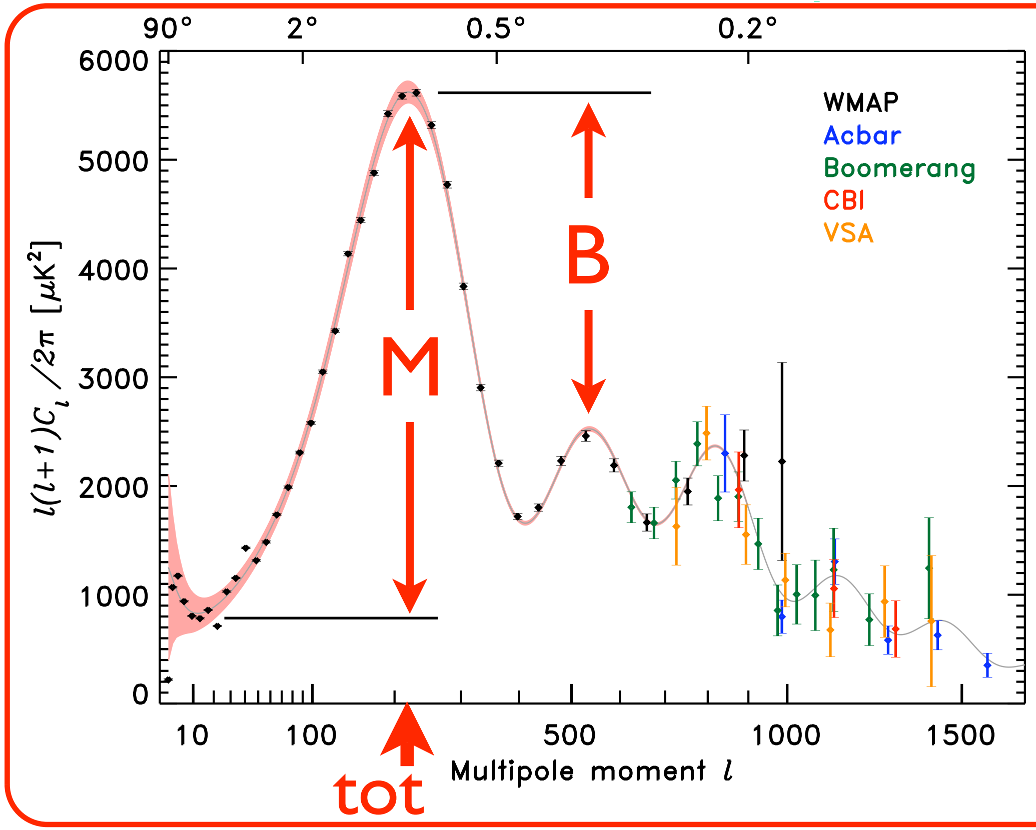
Photons

$\Omega_\gamma = 0.005\ \%$
photon density

Cosmic
Microwave
Background
Radiation



Looking forward to see data from Planck!!!



$\Omega_{tot} = 100\ \%$
critical density

$\Omega_M = 24\ \%$
matter density

$\Omega_B = 4\ \%$
baryon density

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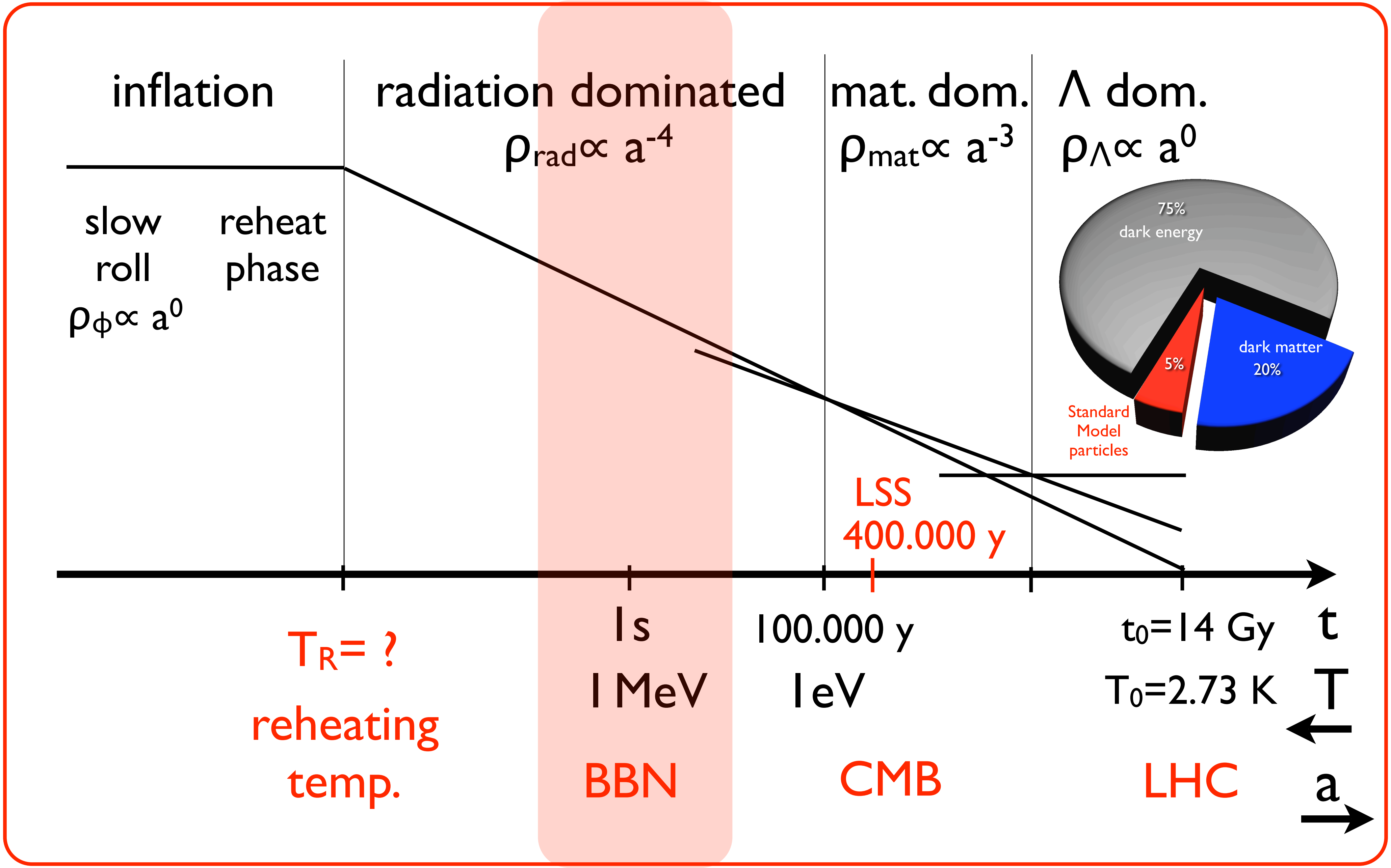

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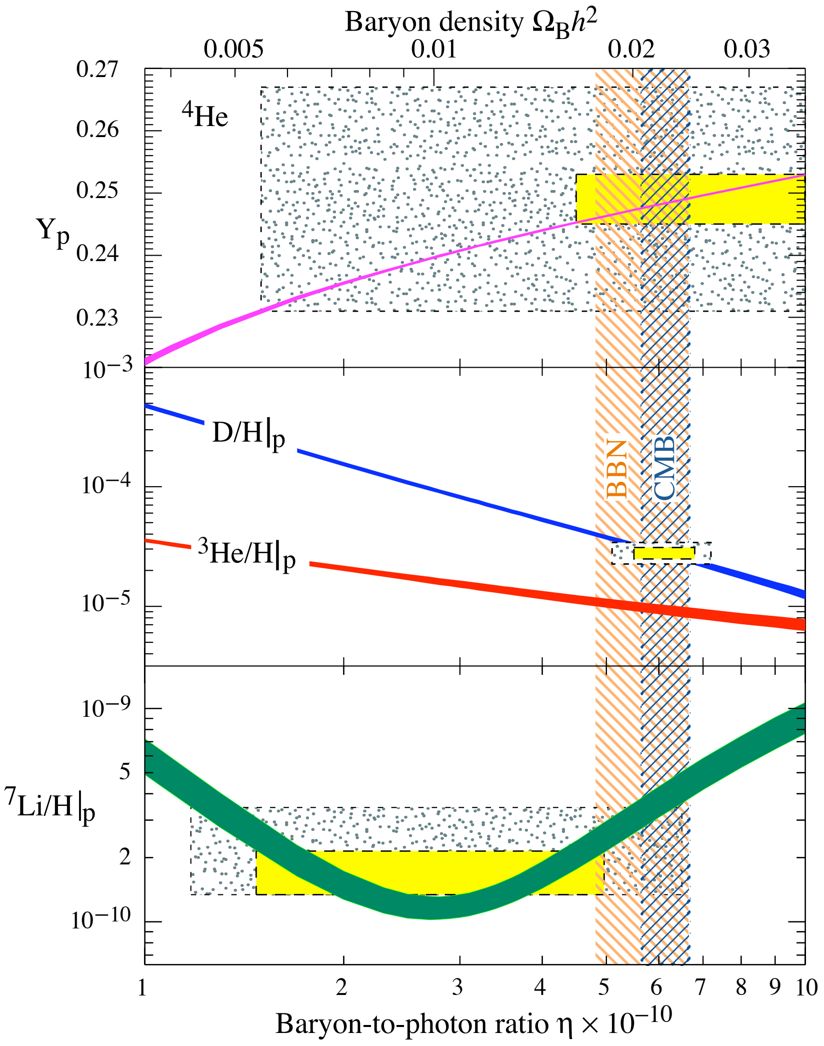
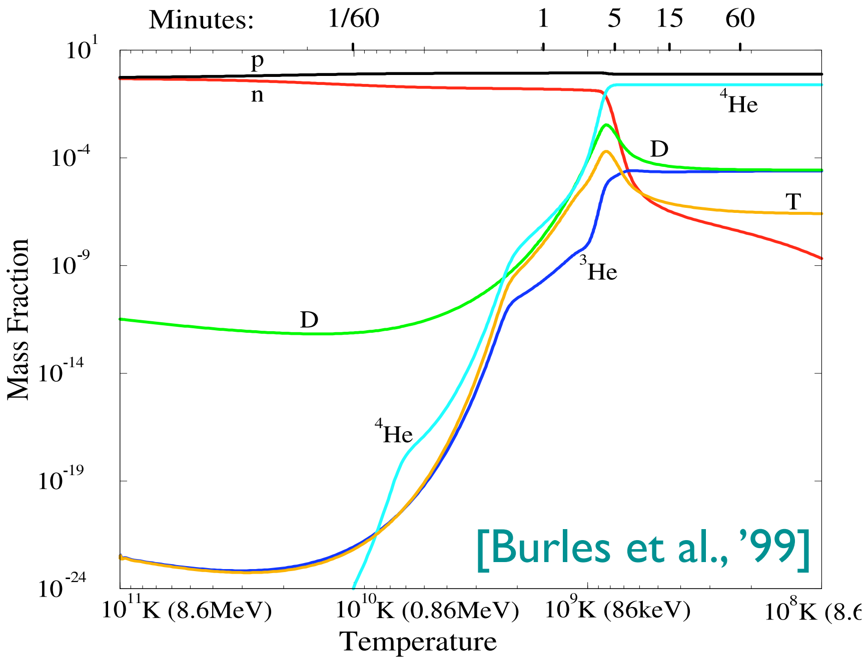
Baryons

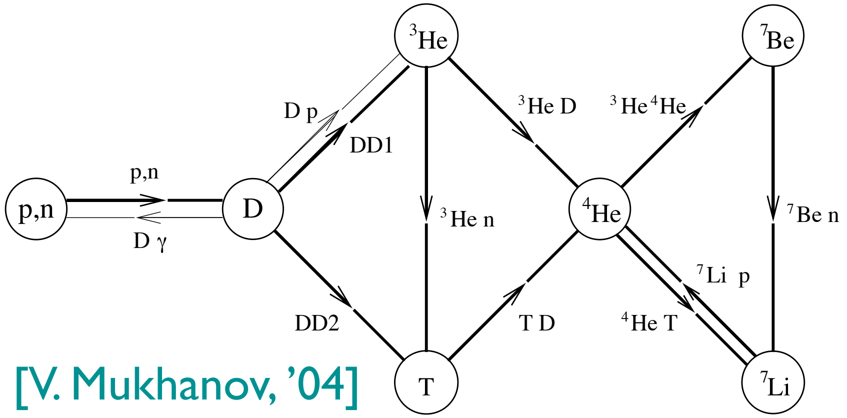
Big Bang Nucleosynthesis



[Particle Data Book 2006]



[Burles et al., '99]



[V. Mukhanov, '04]

Baryons

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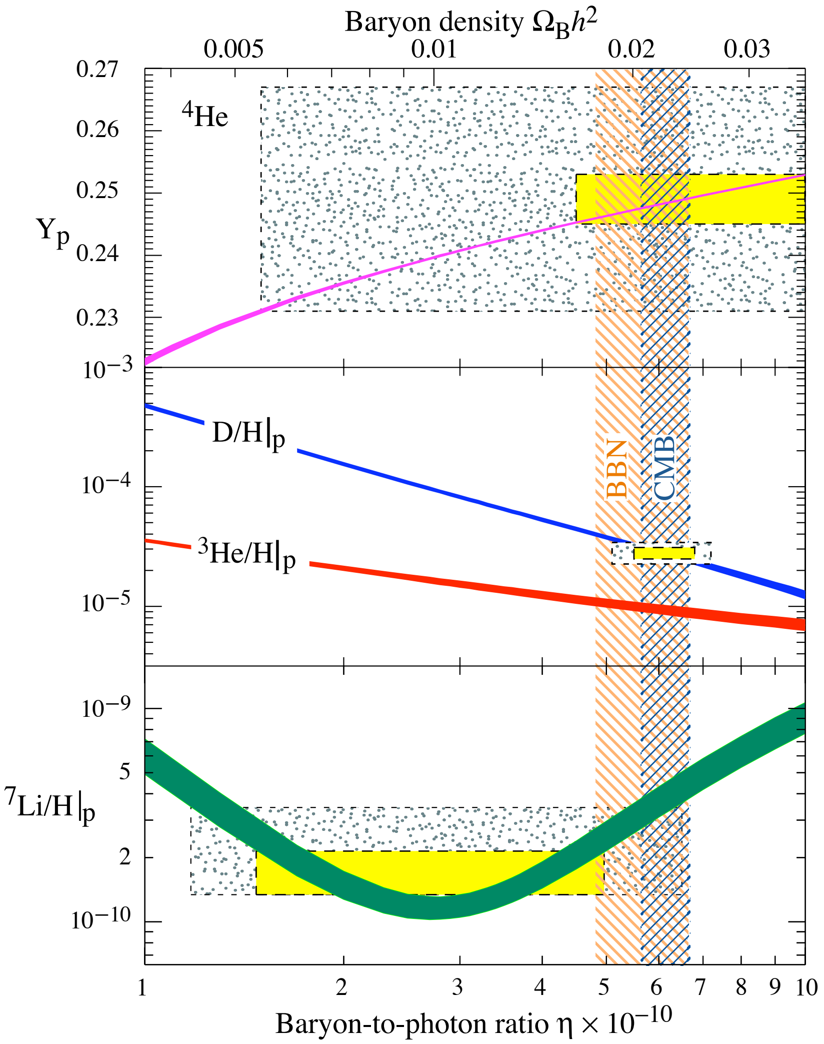
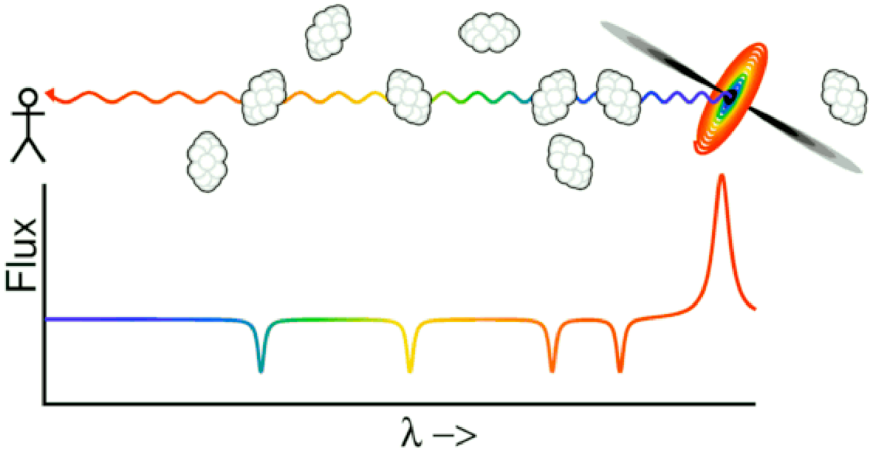
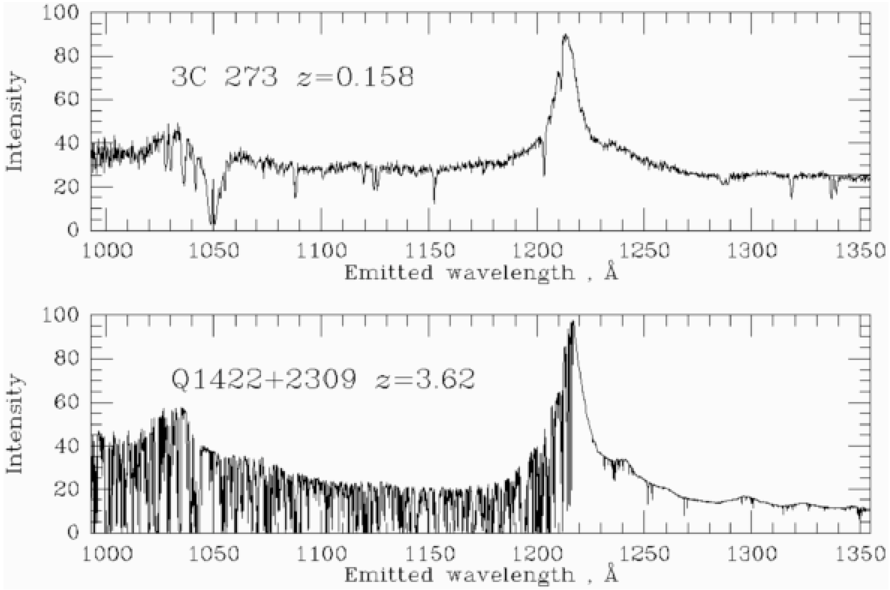


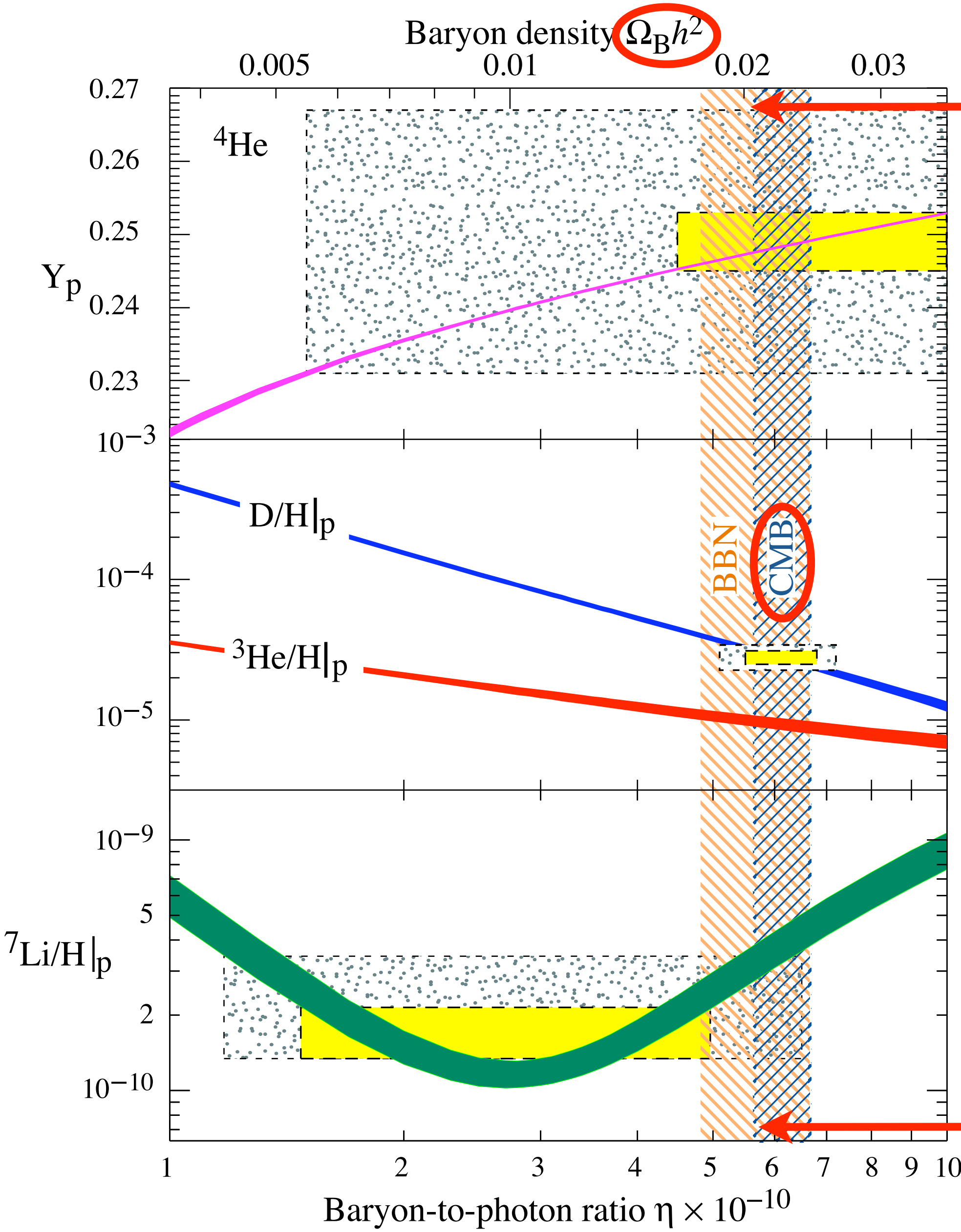
[Particle Data Book 2006]

Lyman α Forrest





Baryons



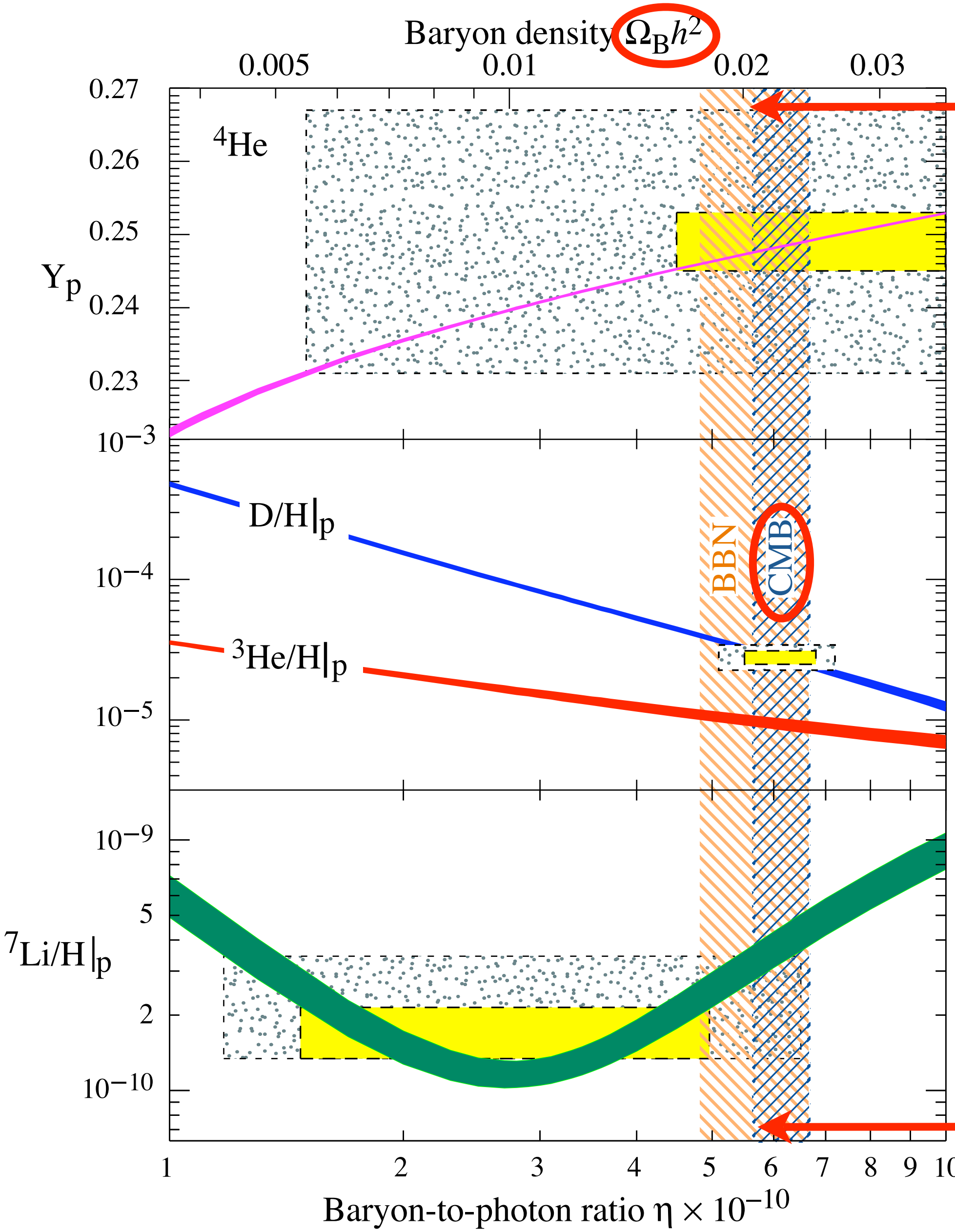
Ω_B = 4 %

baryon density

$\eta = 6\times10^{-10}$

baryon asymmetry

Baryons



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baryon density

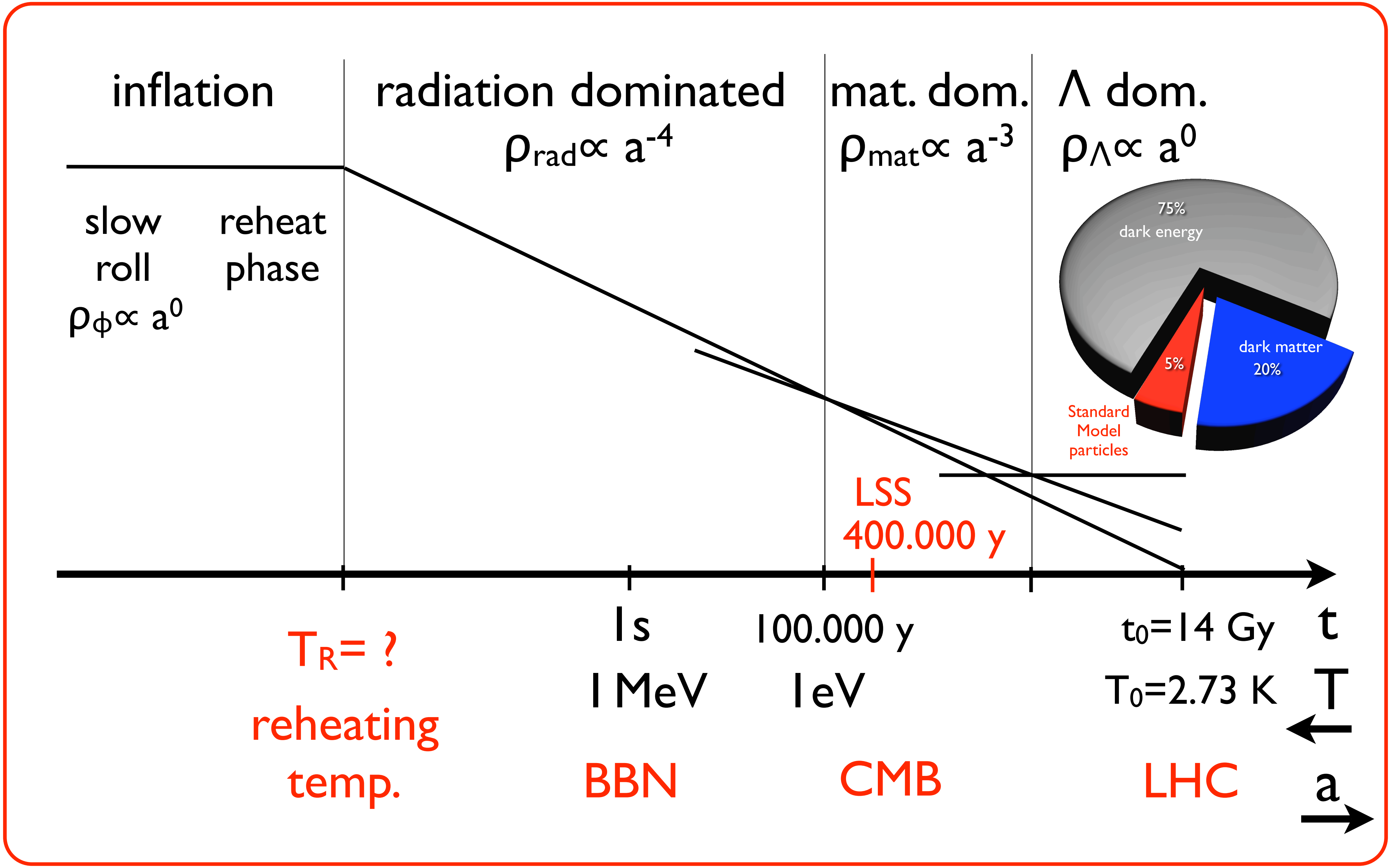
What is the origin of the baryon asymmetry ?

Electroweak Baryogenesis
m_H < 120 GeV
[Talks by Carlos Wagner]

Thermal Leptogenesis
$T_R > 10^9$ GeV

η = 6×10^{-10}
baryon asymmetry

Standard Thermal History of the Universe



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BBN

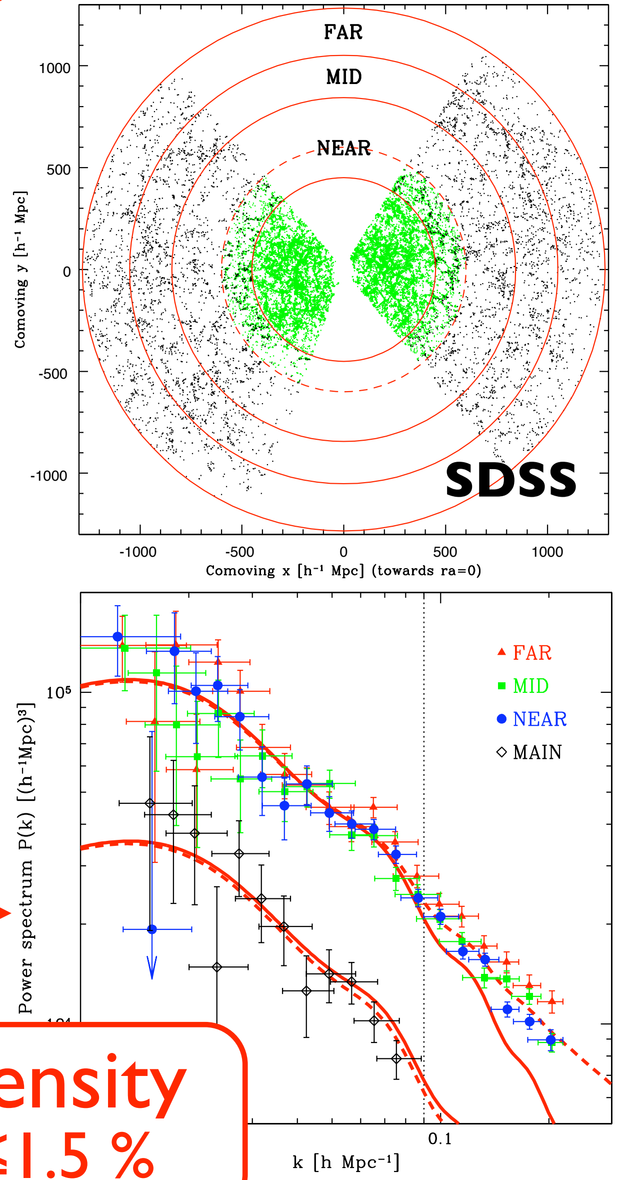
CMB

LHC

Neutrinos

- weakly interacting
- hot thermal relics
- neutrino oscillations
- hot dark matter

$$\sum_i m_{\nu_i} \lesssim \mathcal{O}(1\ \mathrm{eV})$$



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

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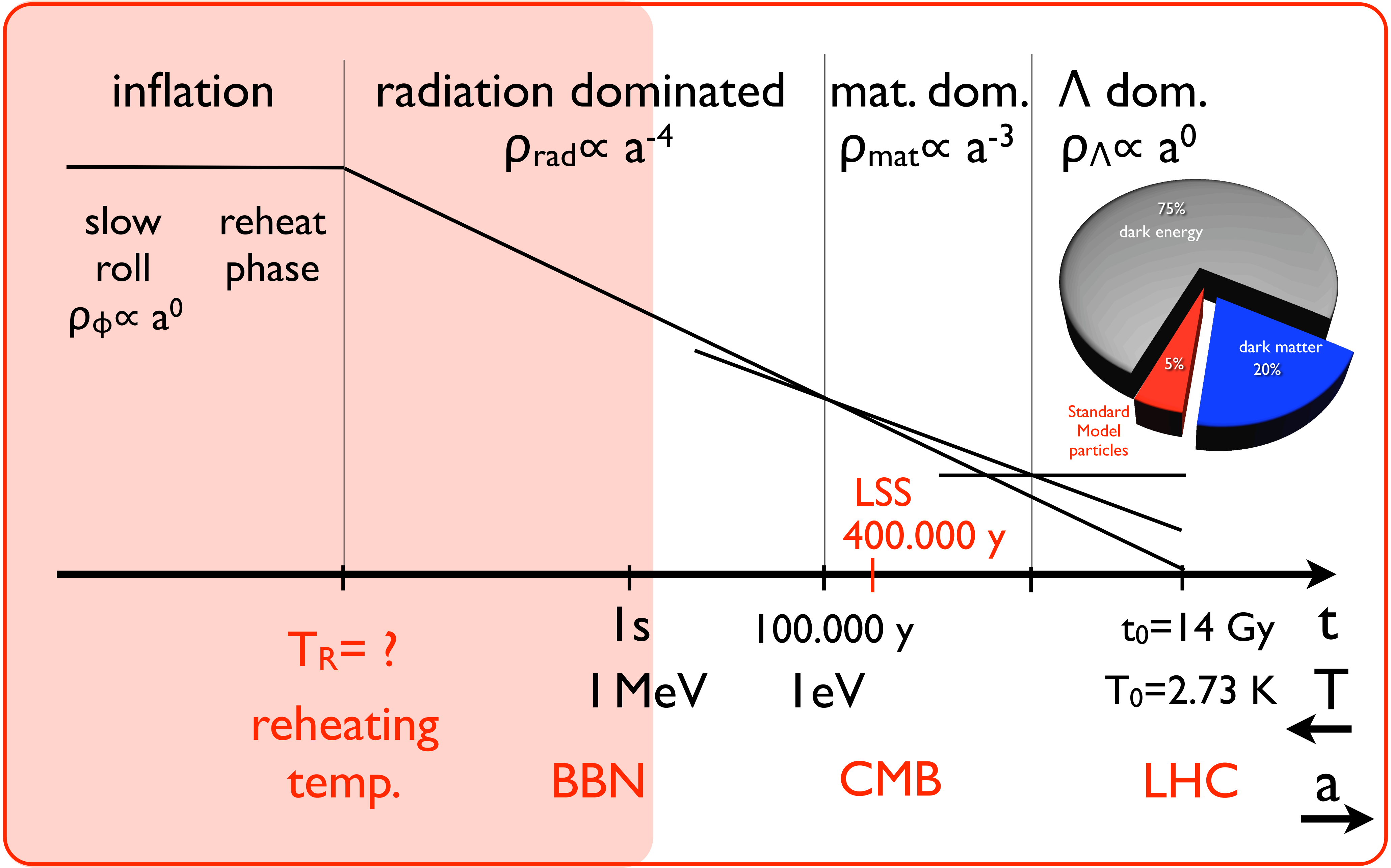

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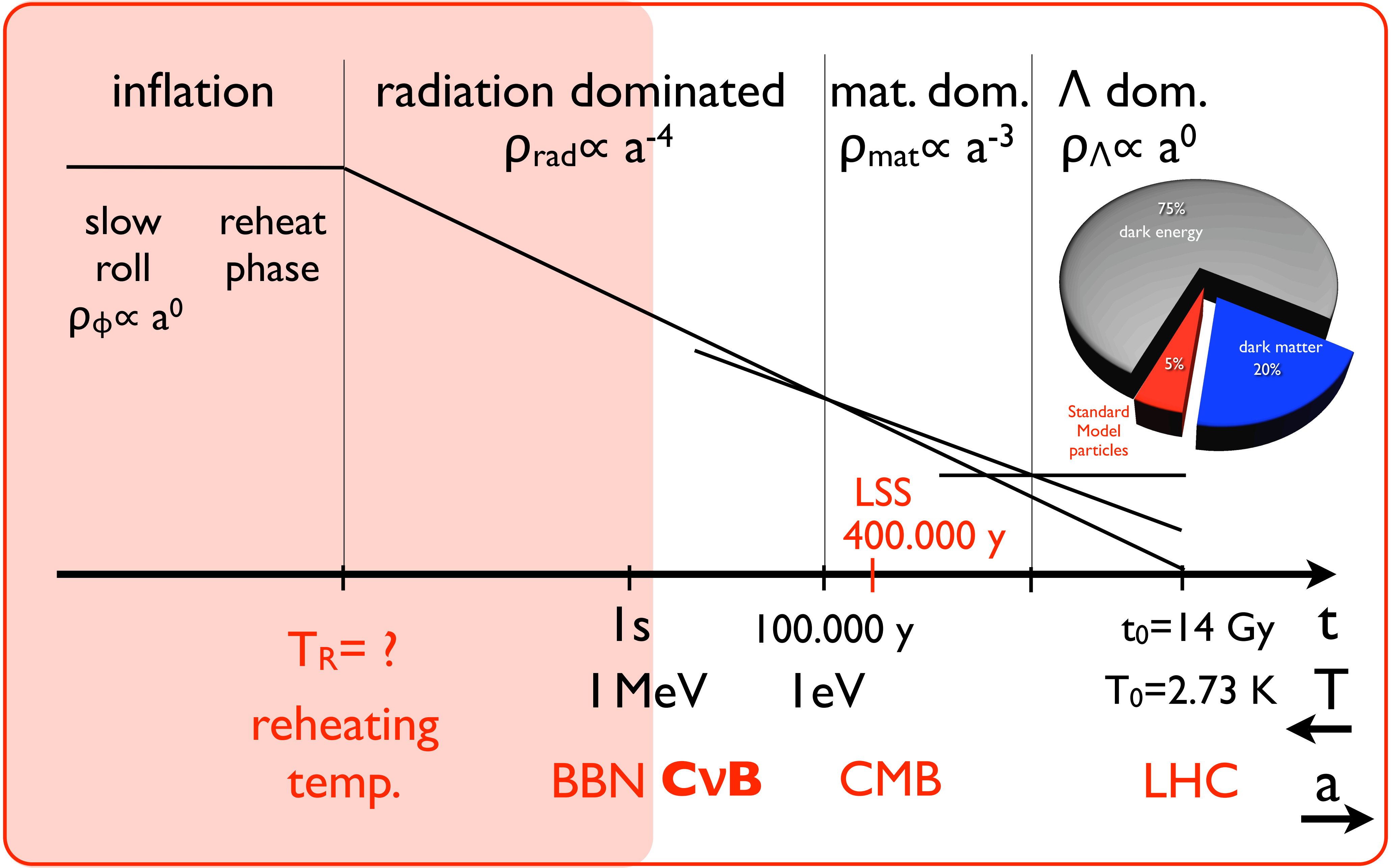

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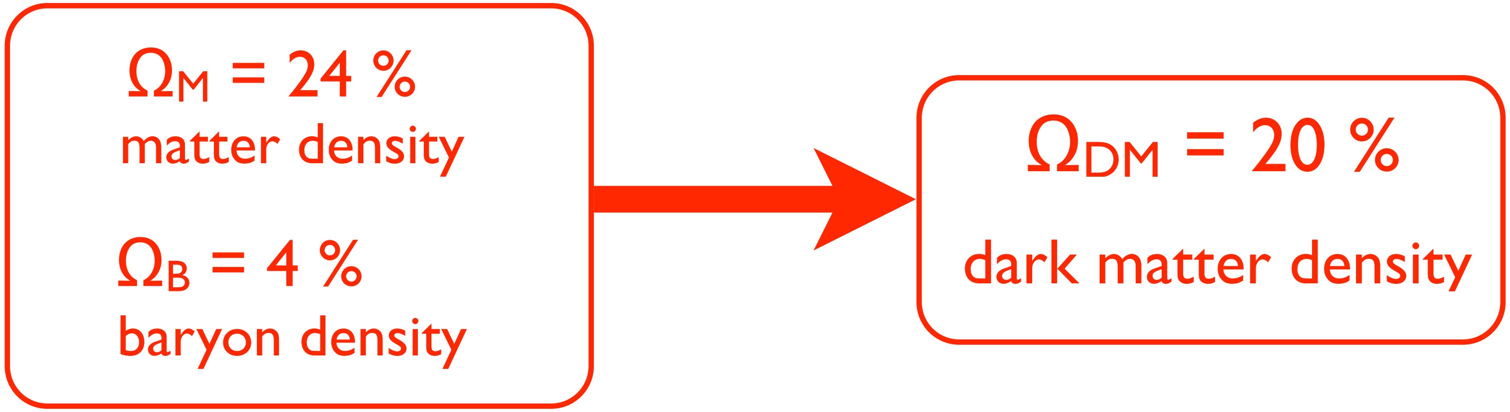
Dark Matter



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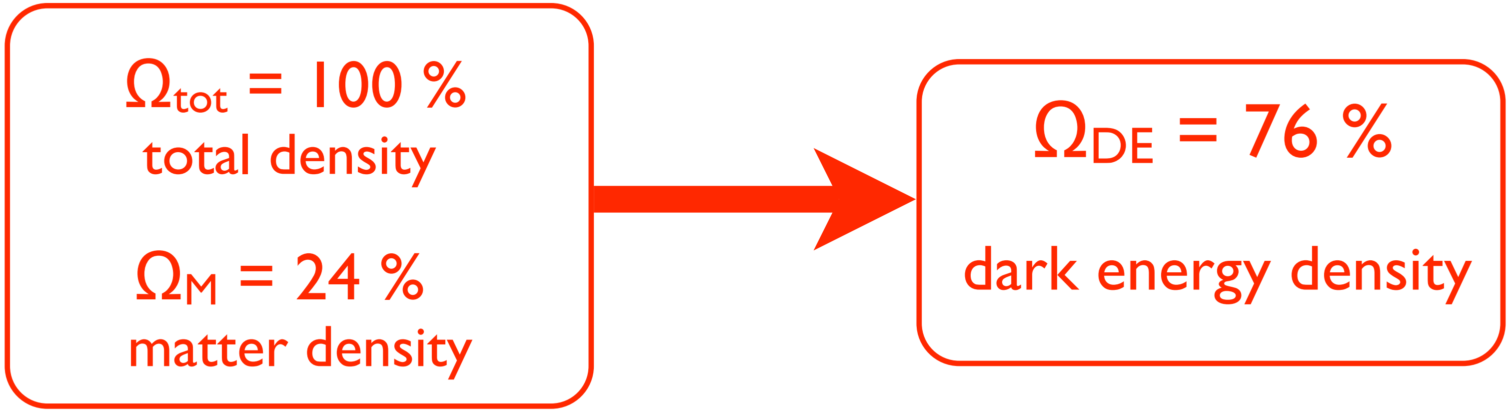
matter density

$\Omega_B = 4\ \%$
baryon density

$\Omega_{DM} = 20\ \%$
dark matter density

Dark Energy



Ω_{tot} = 100 %

total density

Ω_{M} = 24 %

matter density

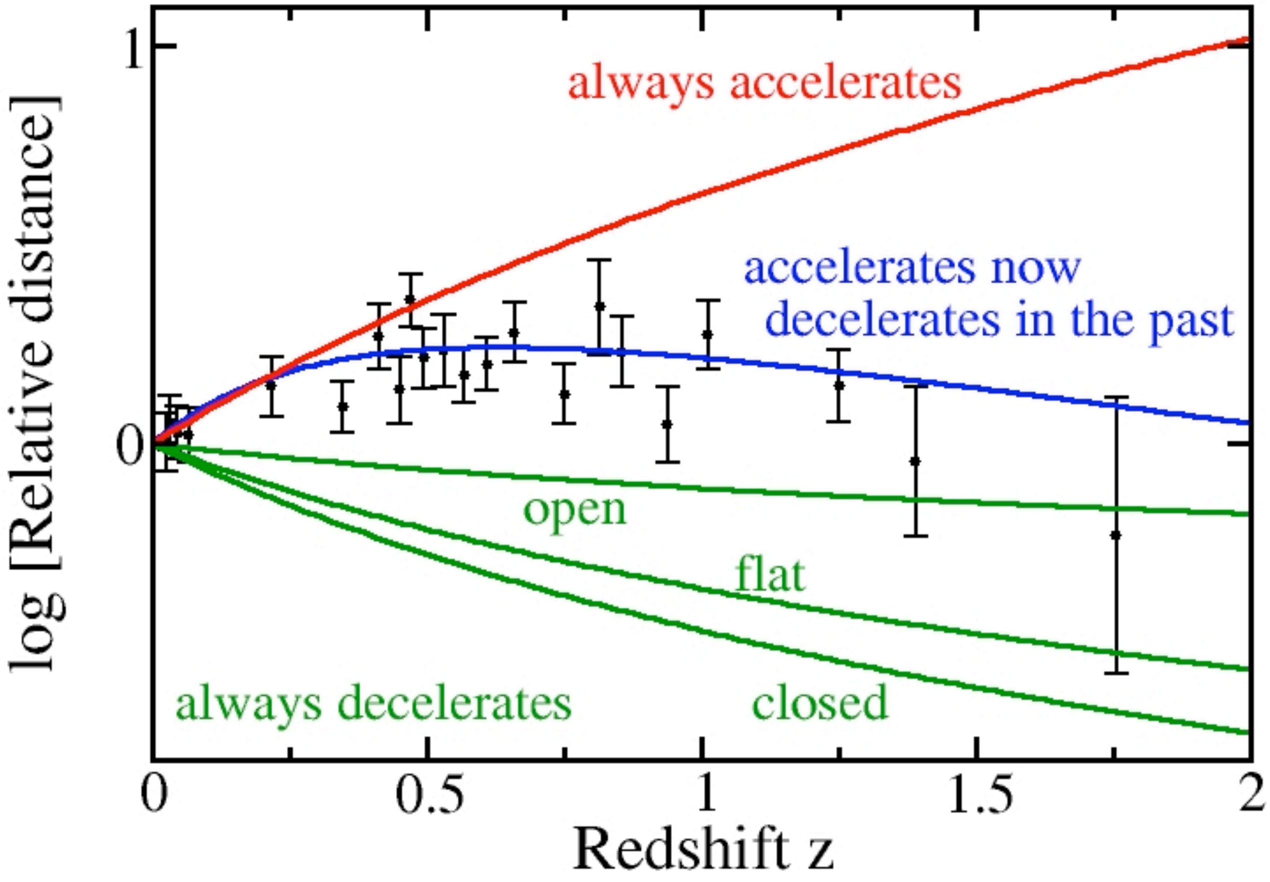
Ω_{DE} = 76 %

dark energy density

Cosmological Constant Problem

Dark Energy

Supernovae Ia



[from Huterer's Talk at PONTAvignon 2008]

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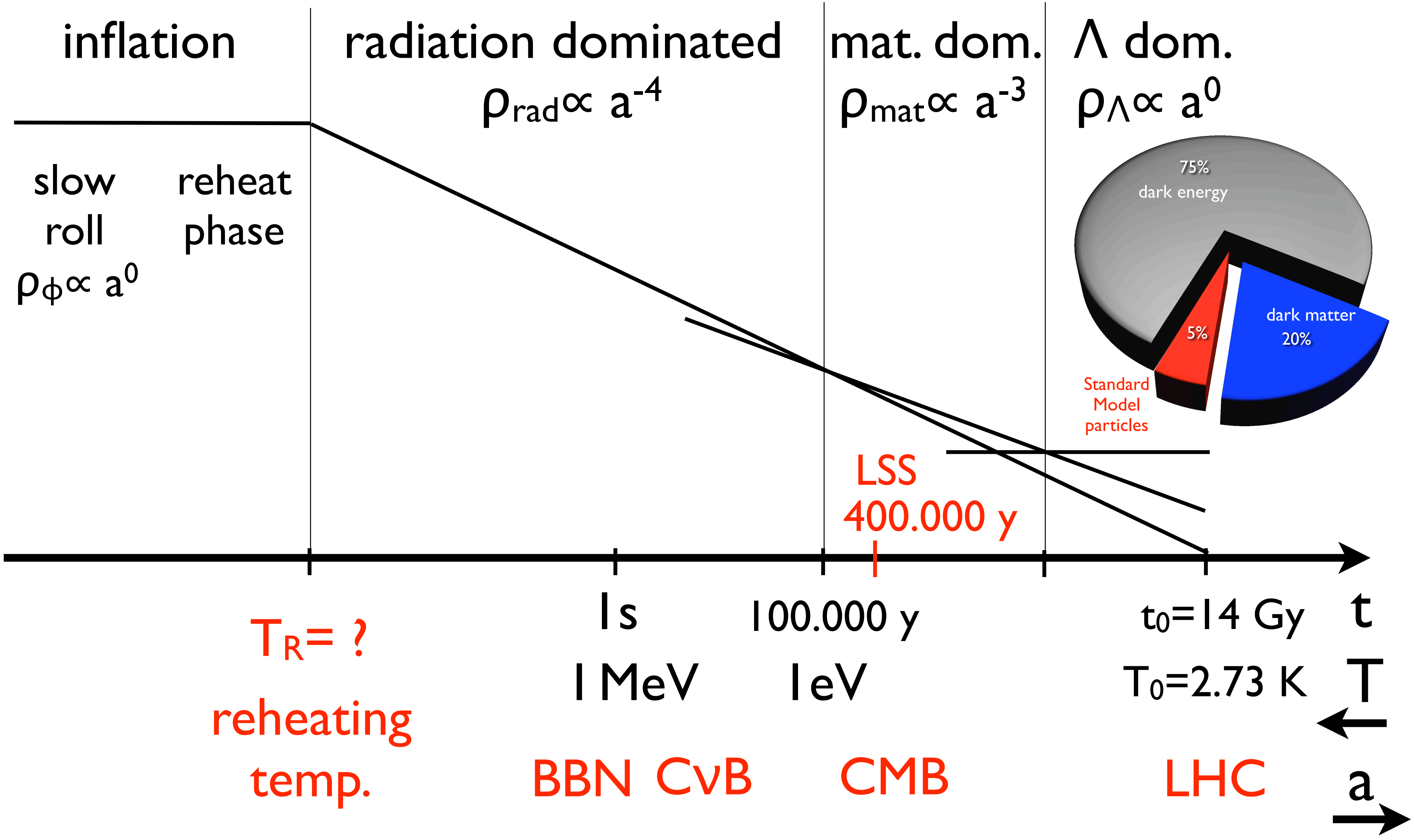

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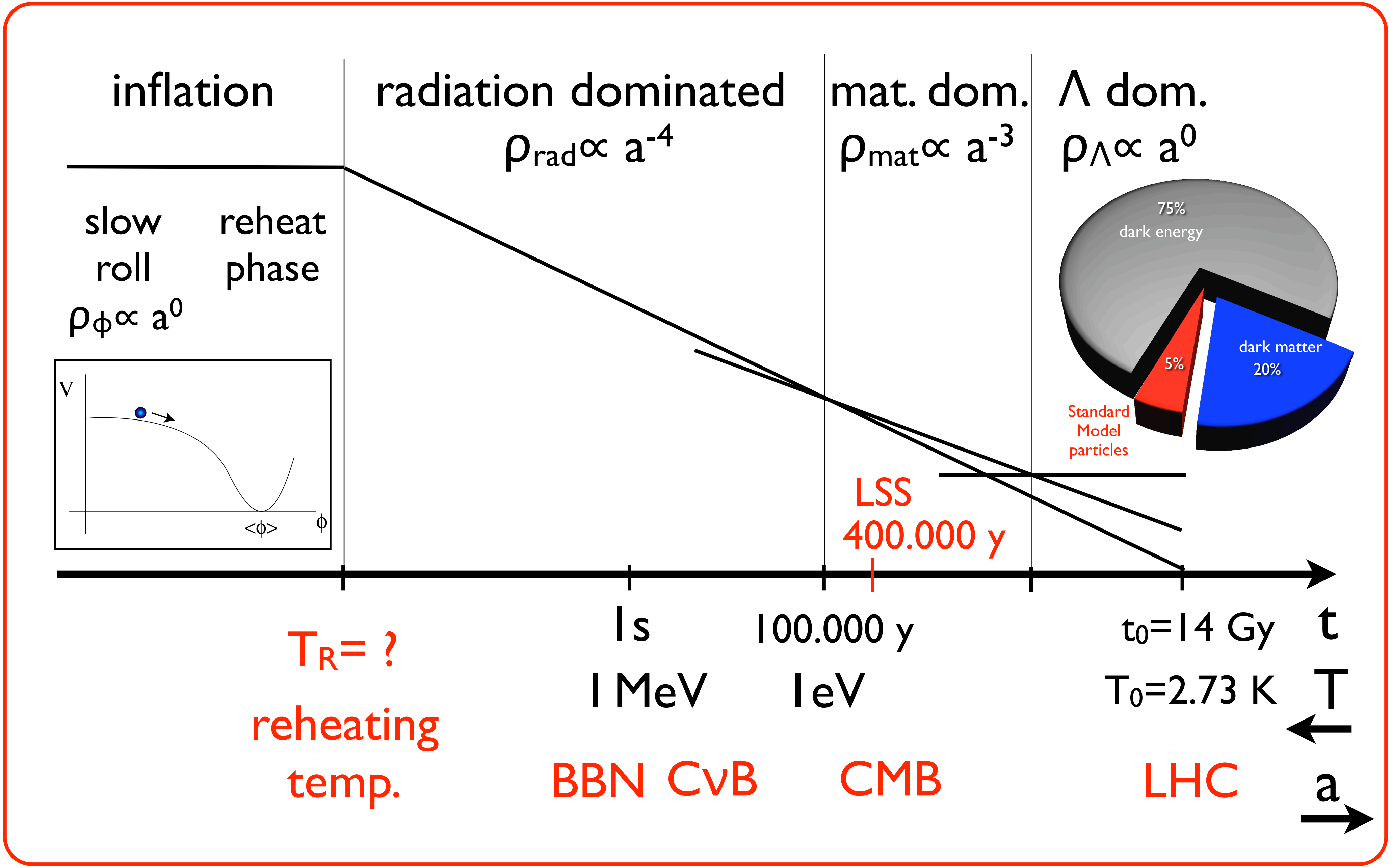

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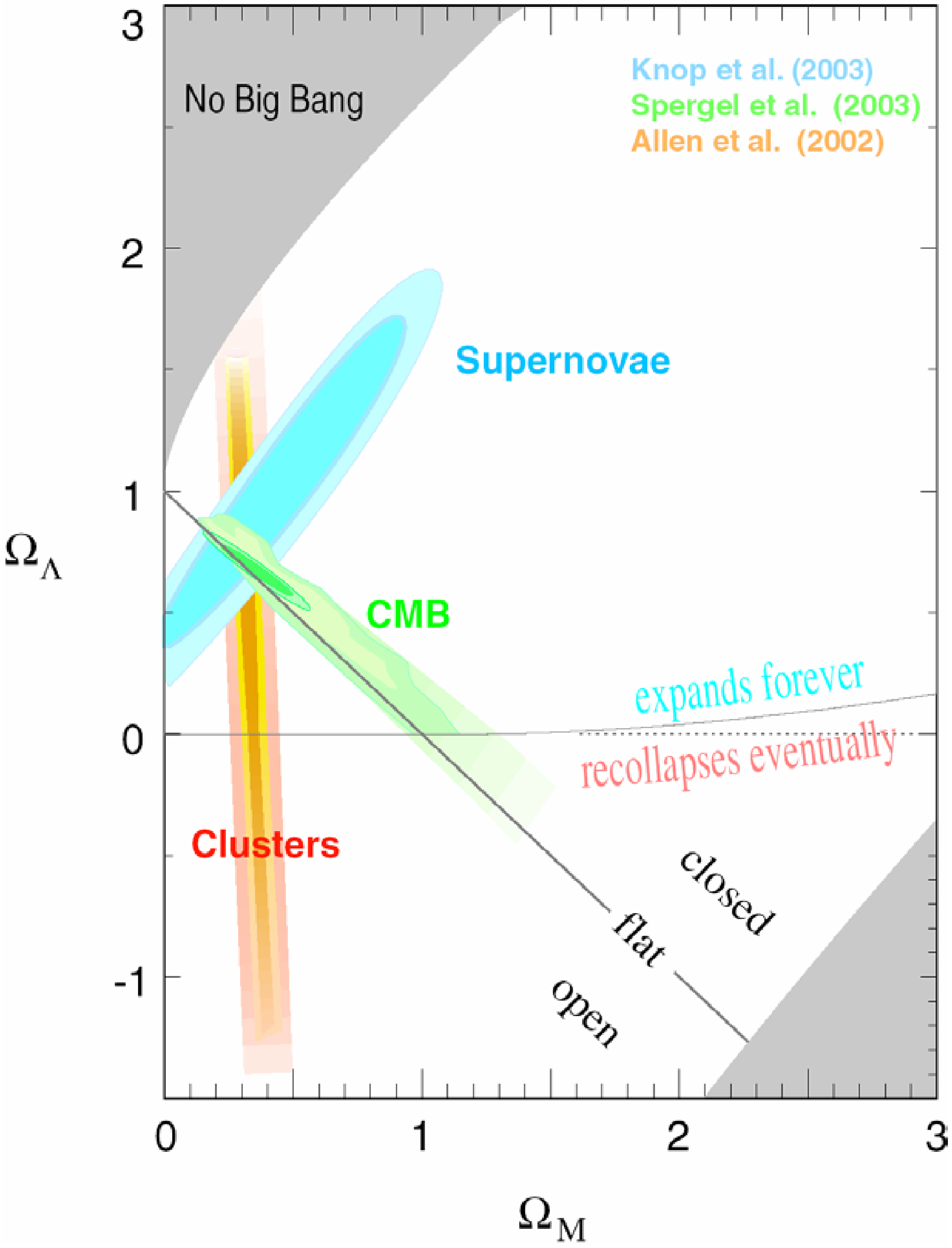
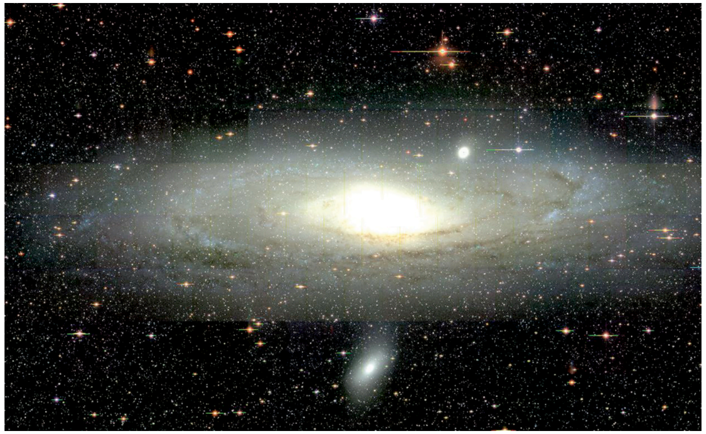
The Cosmic Concordance Model

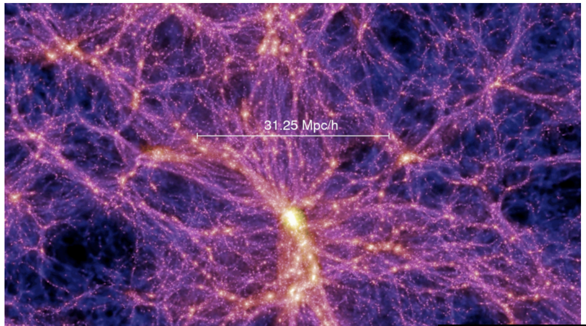


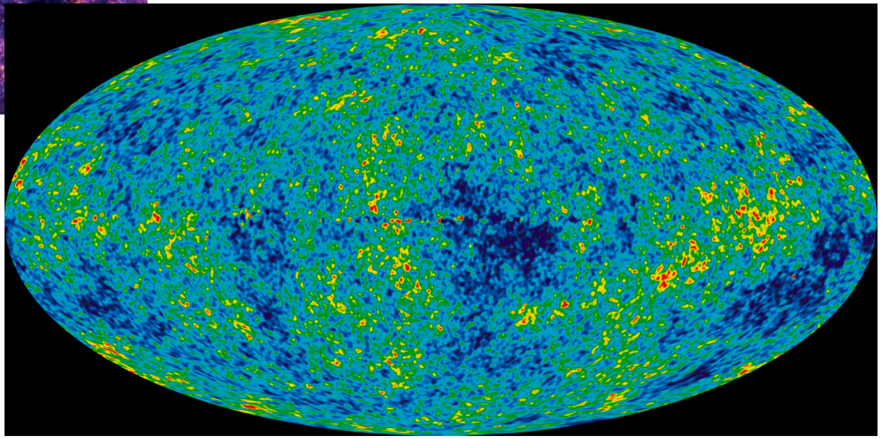
What is
the (particle ?) identity
of dark matter???

Properties of Dark Matter

- stable or lifetime well above the age of our Universe
- electrically neutral
- clusters ⟶
- “cold”
- dissipationless
- color neutral







The Standard Model

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	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	$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{+1}$

Dark Matter

↓

Physics beyond the Standard Model

Supersymmetry

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

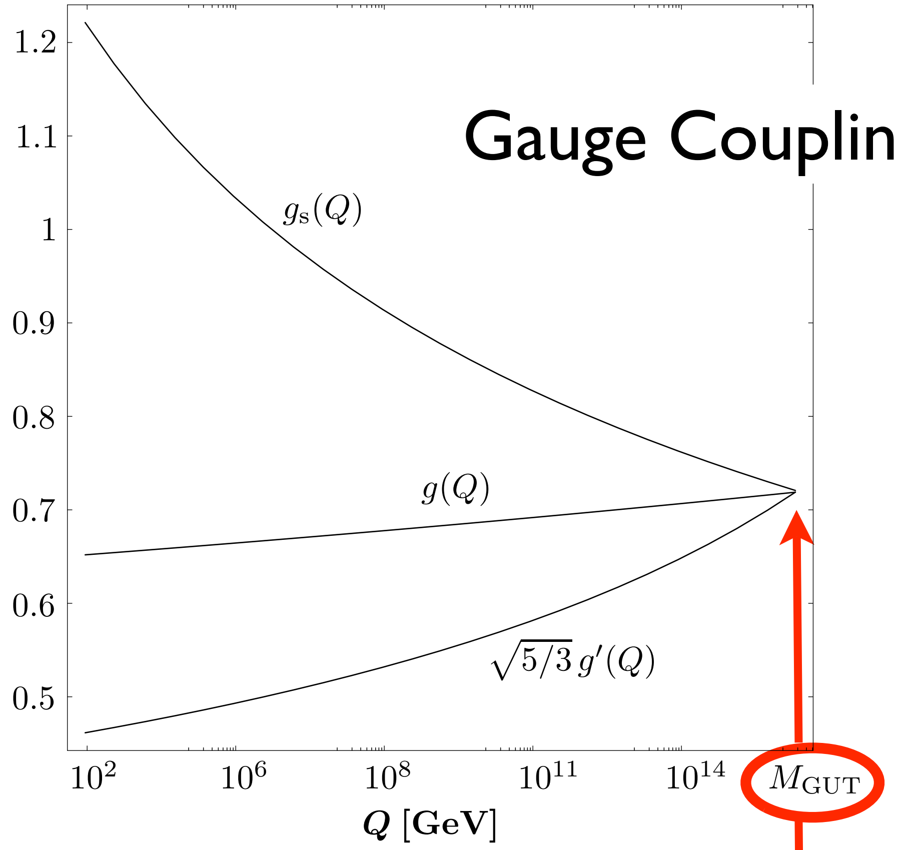
MATTER	Sfermions	Fermions	$(\mathrm{SU}(3)_C, \mathrm{SU}(2)_L)_Y$
sleptons, leptons $I = 1, 2, 3$	$\widetilde{L}^I = \begin{pmatrix} \widetilde{\nu}^I_L \\ \widetilde{e}^{-\,I}_L \end{pmatrix}$	$L^I = \begin{pmatrix} \nu^I_L \\ e^{-\,I}_L \end{pmatrix}$	$(\mathbf{1},\mathbf{2})_{-1}$
	$\widetilde{E}^{*I}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

Minimal
Supersymmetric
Extension
of the
Standard Model

**Every Particle
of the
Standard Model
has a
Superpartner**

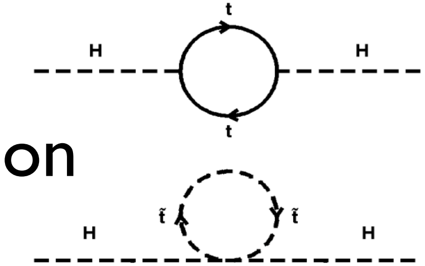
Why Supersymmetry?

Extension of Space-Time Symmetry



Gauge Coupling Unification

Hierarchy Stabilization



(Super-) Gravity

Consistent String Theory

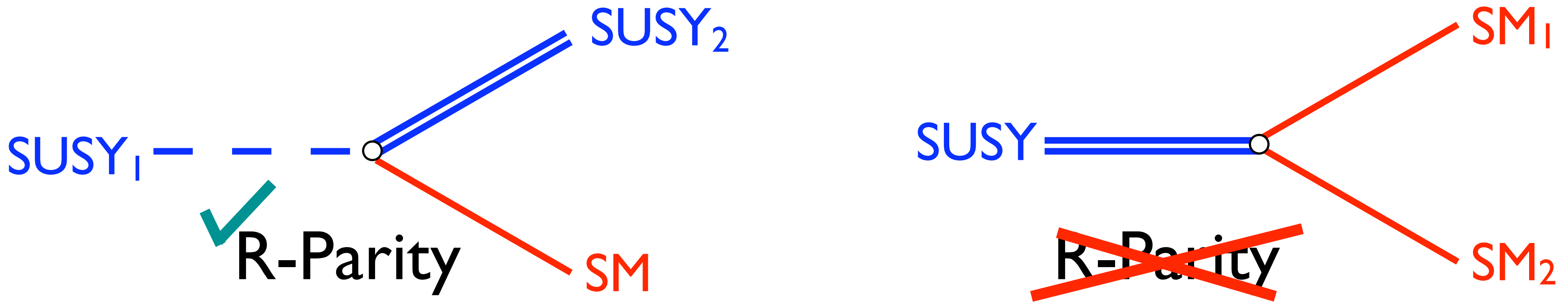
Dark Matter

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

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 ← multiplicative quantum number

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



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

Supersymmetric Dark Matter Candiates

	LSP	ID	spin	mass	interaction
lightest neutralino	$\widetilde{\chi}^0_1$	$\widetilde{B}, \widetilde{W}, \widetilde{H}^0_u, \widetilde{H}^0_d$	$\frac{1}{2}$	$\mathcal{O}(100\ \mathrm{GeV})$	g, g'
$\in$ MSSM		mixture		$M_1, M_2, \mu, \tan\beta$	weak

Weakly
Interacting
Massive
Particle

[“Heavy Neutrino”]

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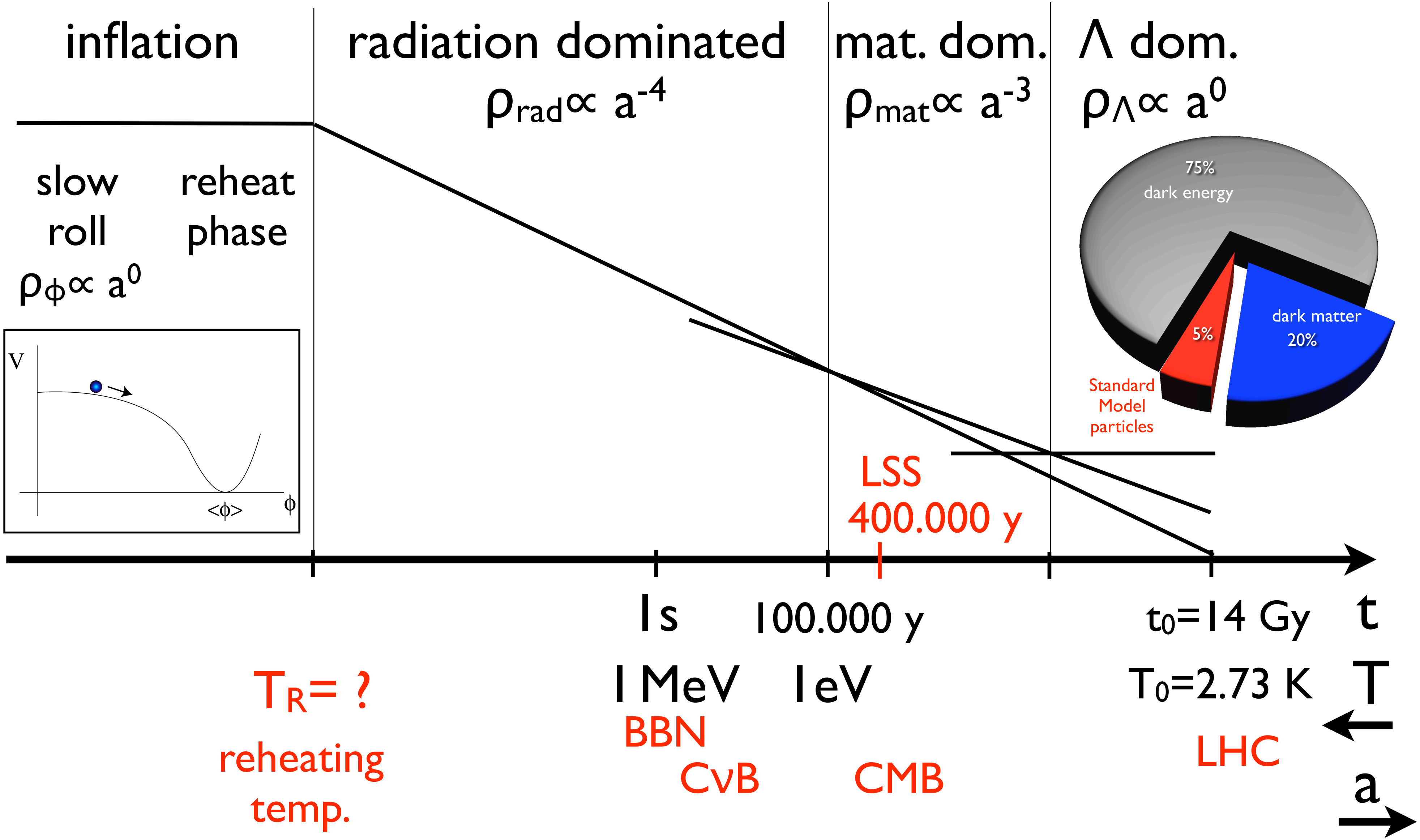

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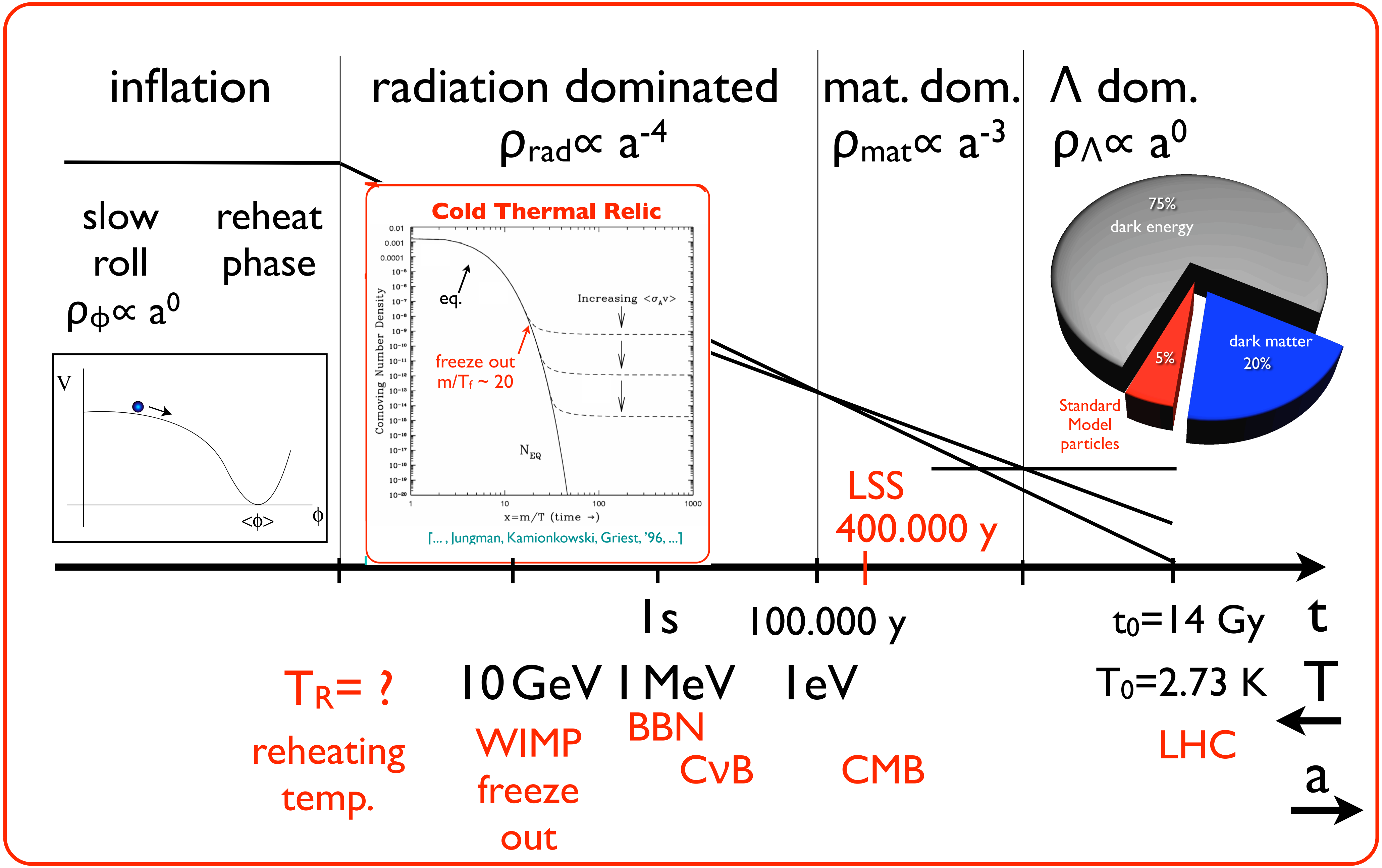

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Cold Thermal Relic

[… , Jungman, Kamionkowski, Griest, ’96, …]

LSS

400.000 y

1 s

100.000 y

t_0=14 Gy

t

T_R= ?

reheating temp.

10 GeV

WIMP freeze out

1 MeV

BBN

CνB

1 eV

CMB

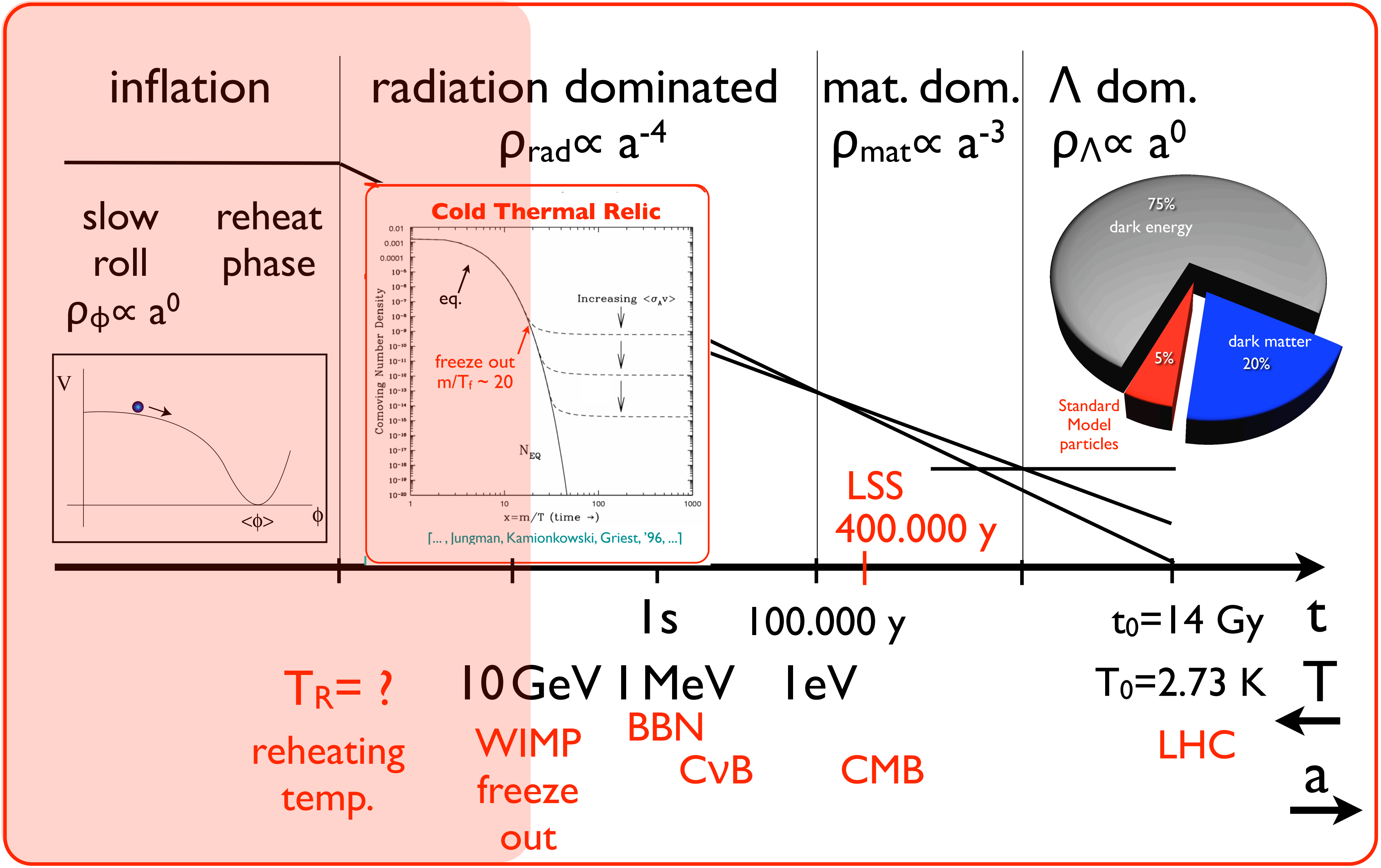
T_0=2.73 K

LHC

T

a

Standard Thermal History of the Universe



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Boltzmann Eqs. for WIMP freeze out

$$\frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45}} M_p < \sigma v > (Y(T)^2 - Y_{eq}(T)^2)$$

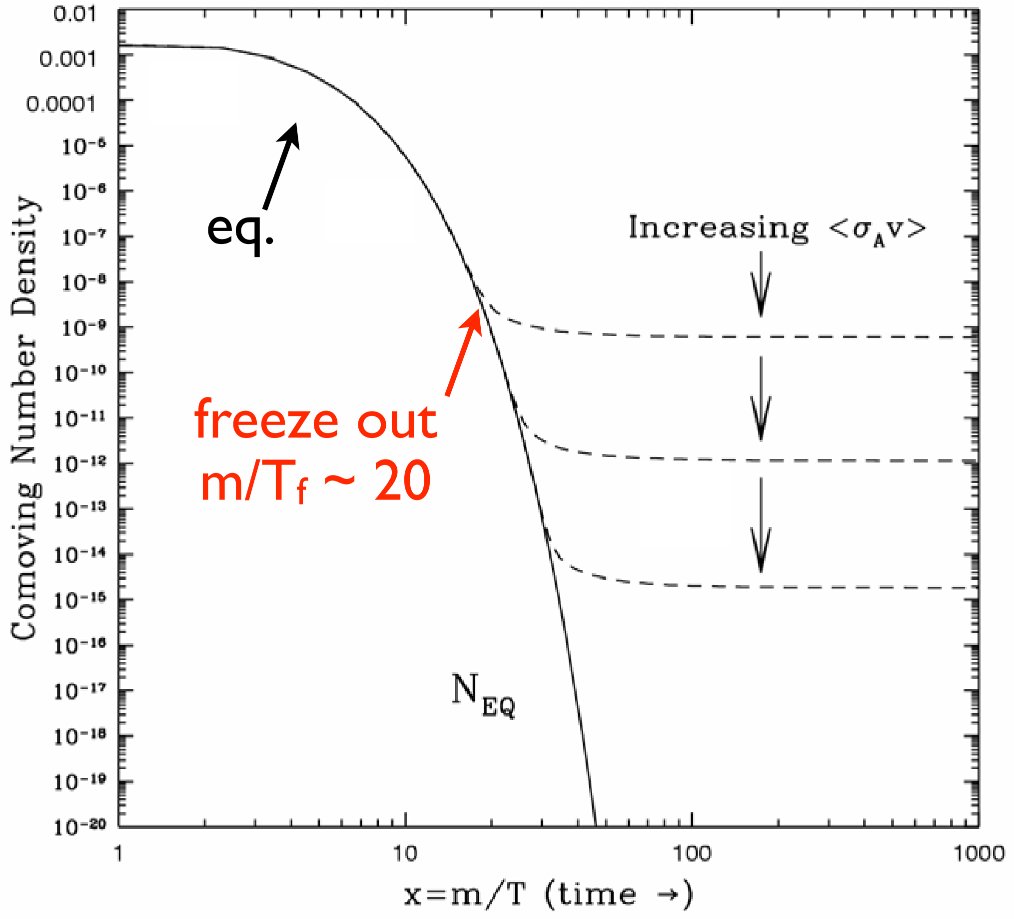
$$< \sigma v >= \frac{\sum\limits_{i,j} g_i g_j \int\limits_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T(\sum\limits_i g_i m_i^2 K_2(m_i/T))^2}$$

$\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints

LSP	interaction	production	constraints
$\widetilde{\chi}_1^0$	g, g’	WIMP	← cold
	weak	freeze out	

$$\Omega_{\widetilde{\chi}_1^0} h^2 = m_{\widetilde{\chi}_1^0}\, Y^{\rm dec}_{\widetilde{\chi}_1^0}\, s(T_0)\, h^2/\rho_c$$

Cold Thermal Relic



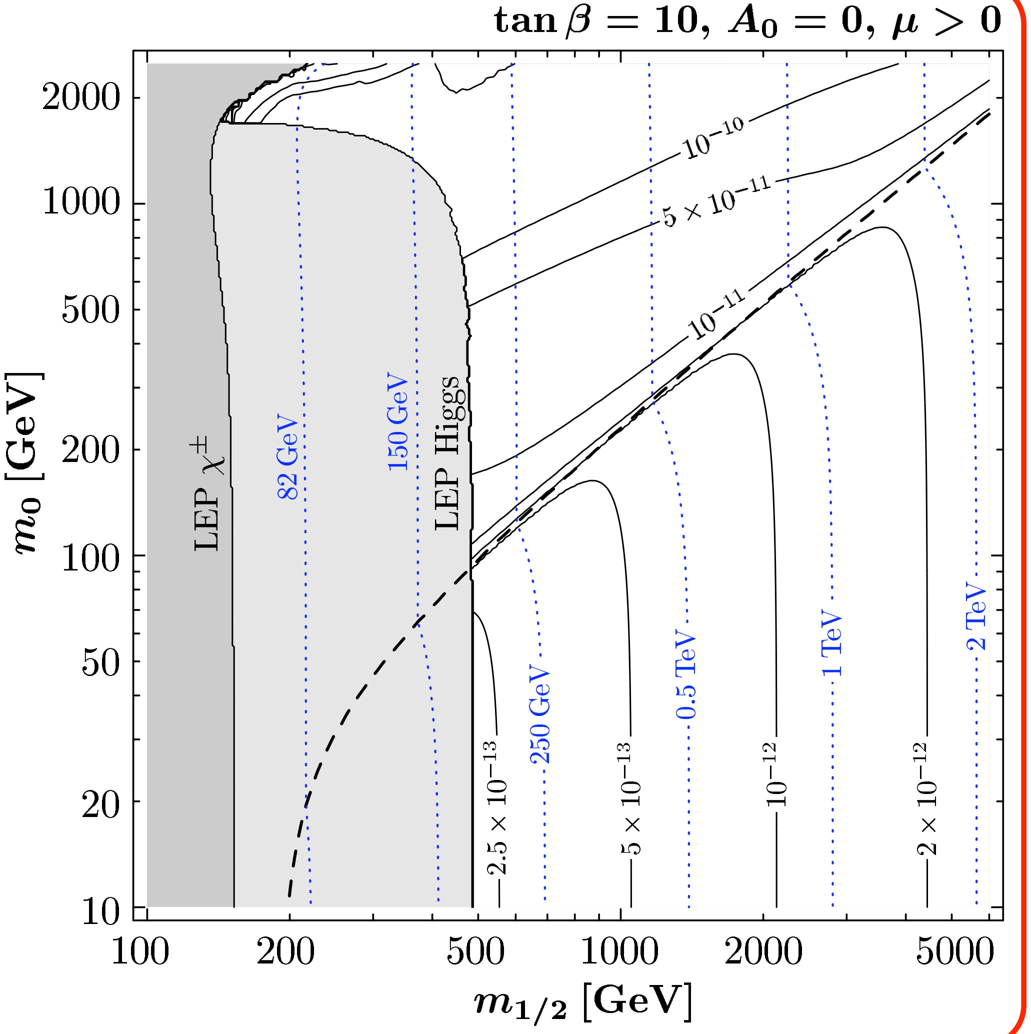
[... , Jungman, Kamionkowski, Griest, ’96, ...]

$\Omega_{\widetilde{\chi}_1^0} = \Omega_{\rm DM}$ **is possible!!!**

$\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints

LSP	interaction	production	constraints
$\widetilde{\chi}_1^0$	g, g'	WIMP	← cold
	weak	freeze out	

$$\Omega_{\widetilde{\chi}_1^0} h^2 = m_{\widetilde{\chi}_1^0}\, Y^{\mathrm{dec}}_{\widetilde{\chi}_1^0}\, s(T_0)\, h^2/\rho_c$$



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$\widetilde{\chi}^0_1$ LSP Dark Matter: Production, Constraints

LSP	interaction	production	constraints
$\widetilde{\chi}^0_1$	g, g'	WIMP	← cold
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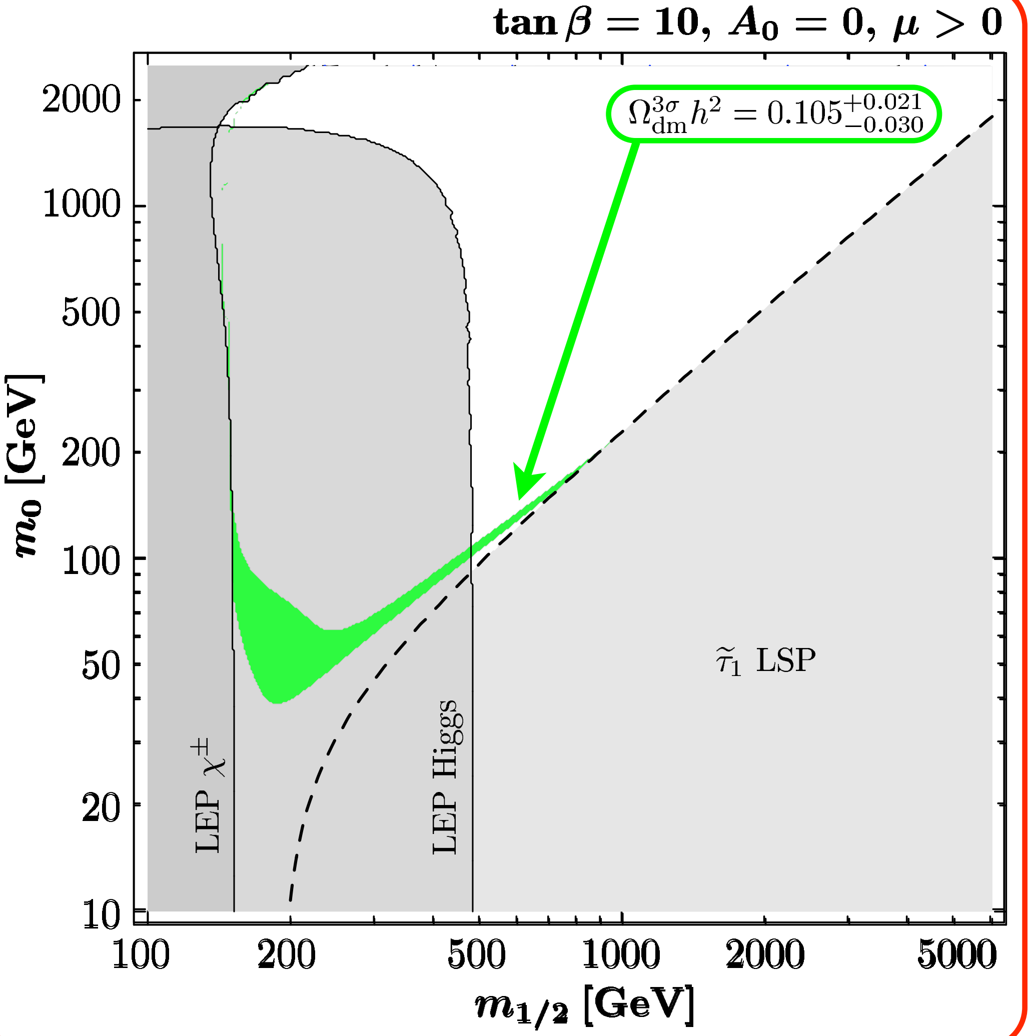
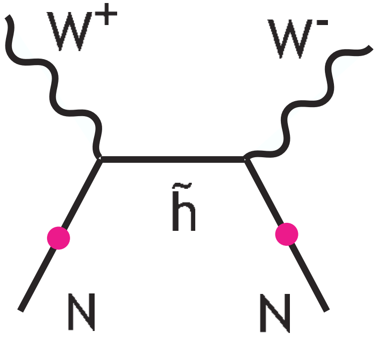


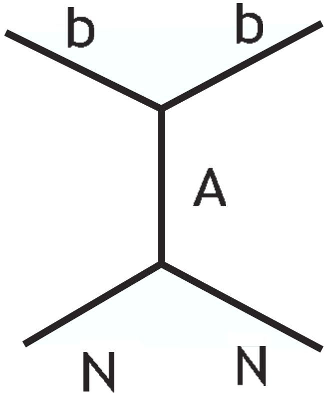
$\Omega_{\widetilde{\chi}^0_1} = \Omega_{\mathrm{DM}}$ is possible!!!

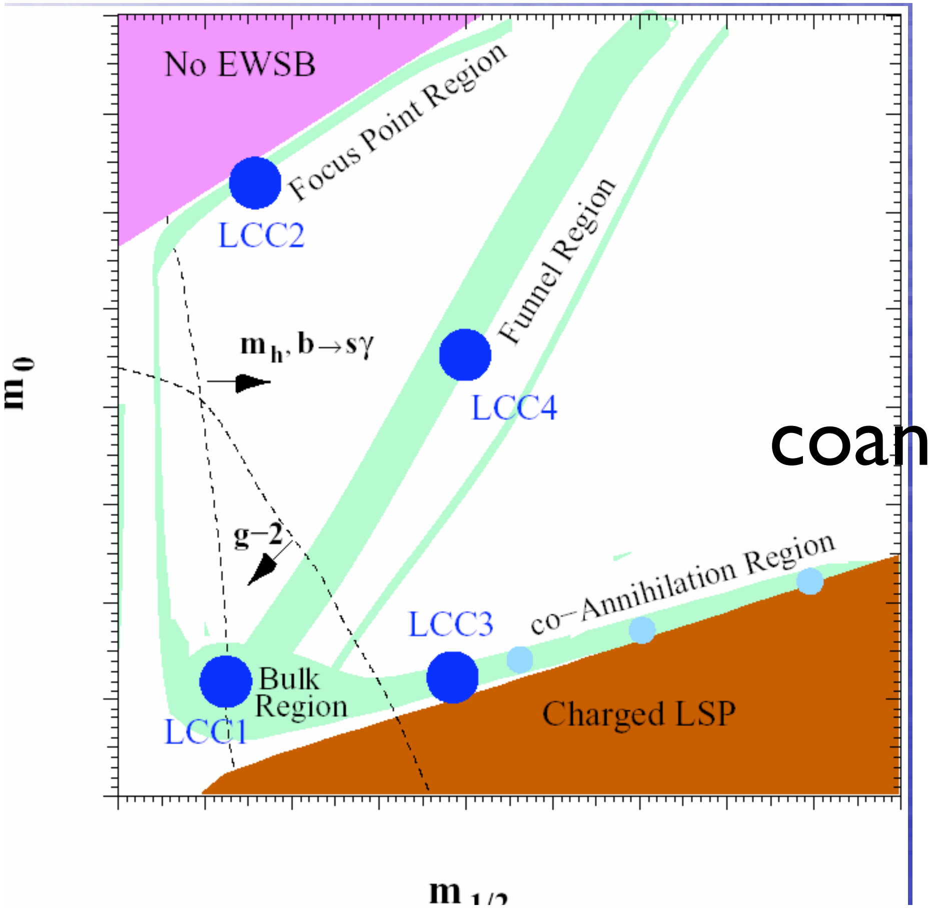
Neutralino LSP Case

focus point region

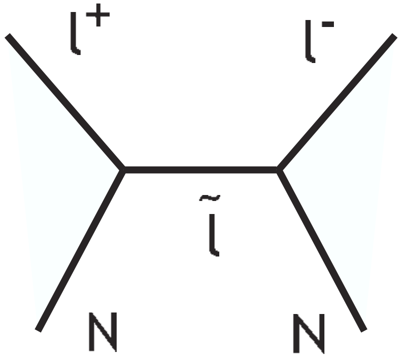


annihilation funnel

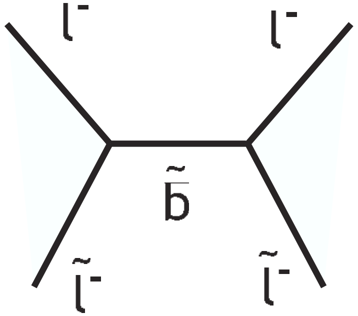




bulk region



coannihilation region



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

$\widetilde{\chi}^0_1$ LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
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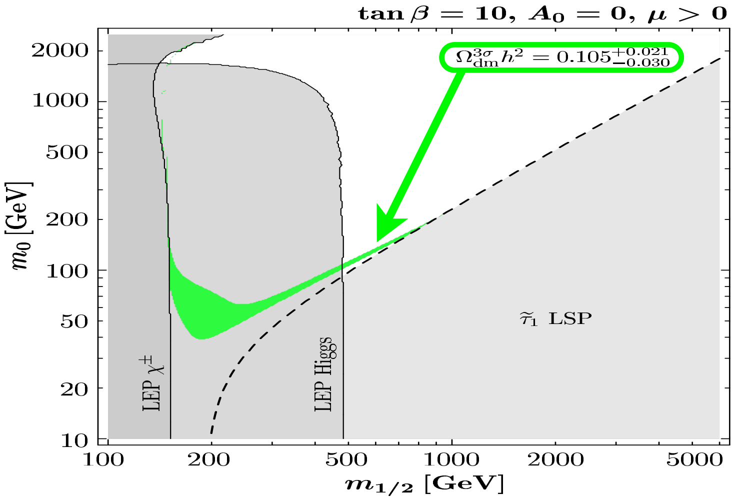
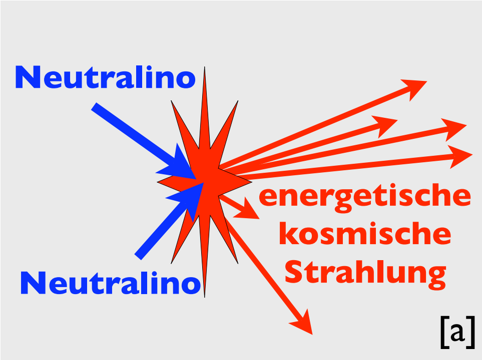
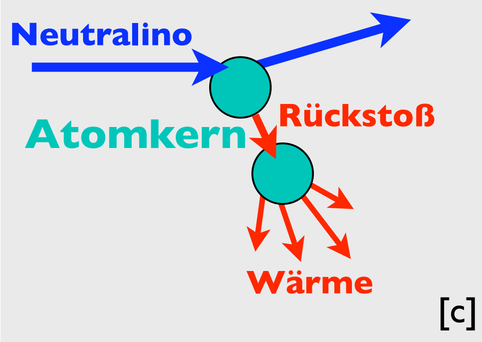
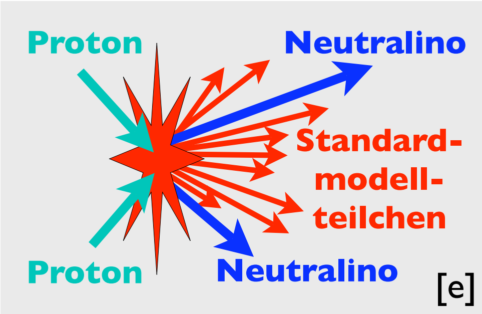
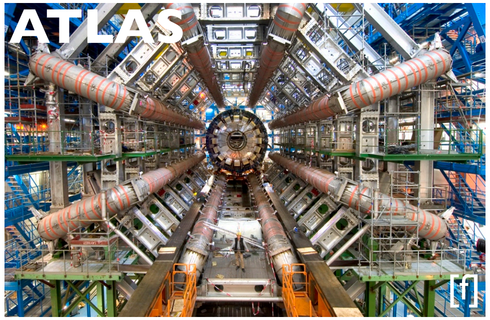




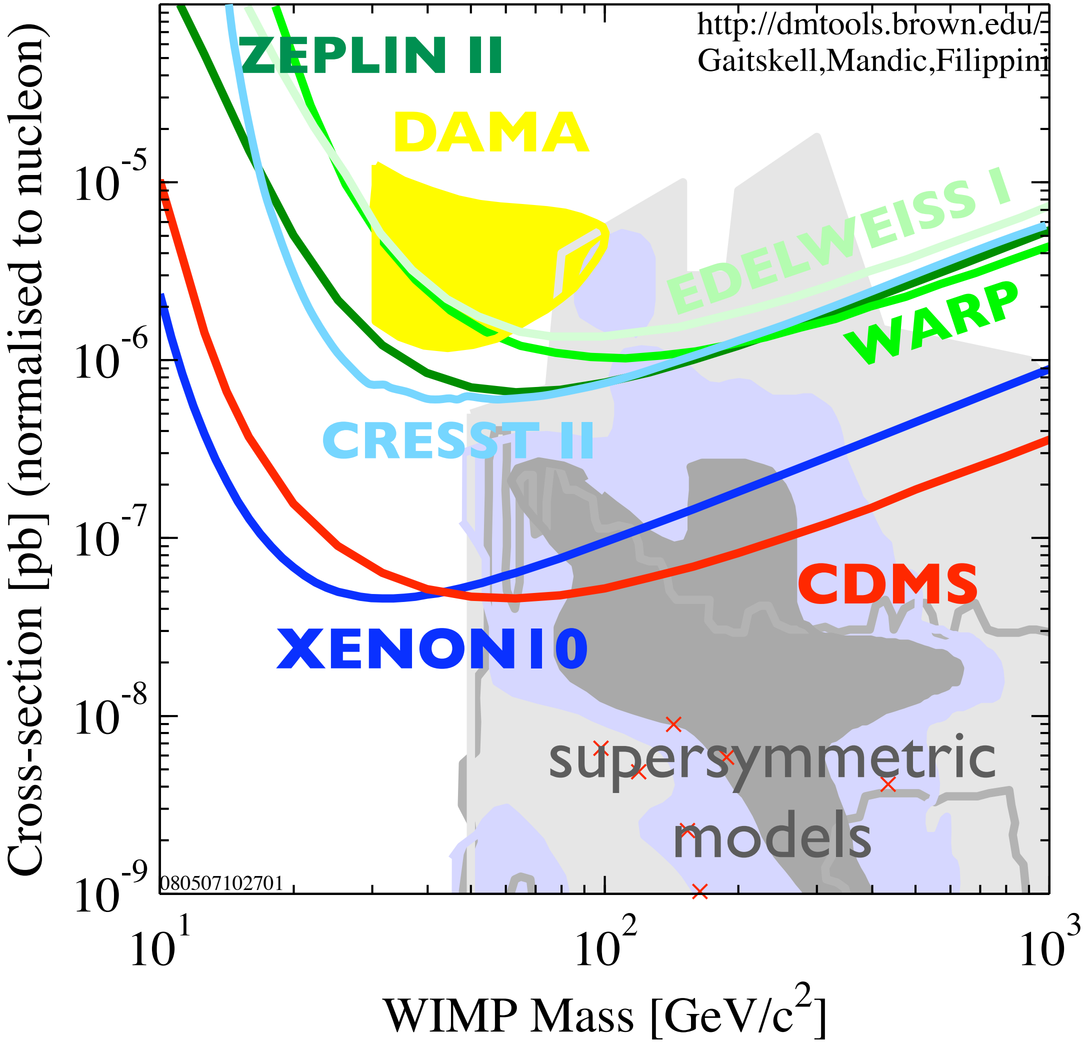






promising experimental prospects

Upper limits on the neutralino-nucleon interaction strength



$\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

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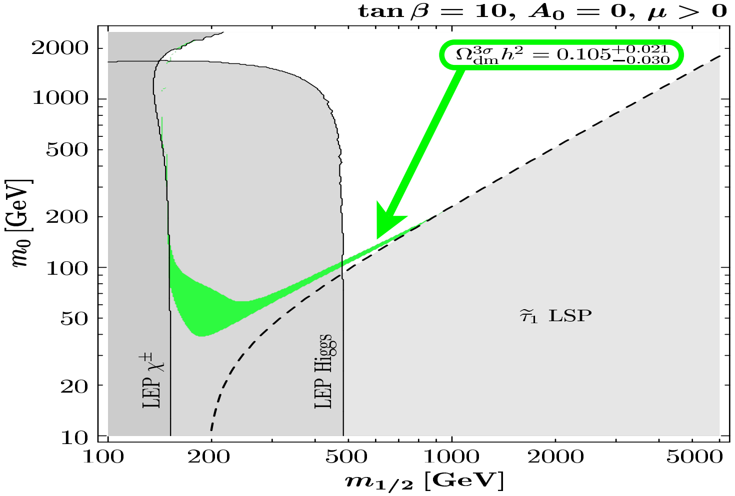
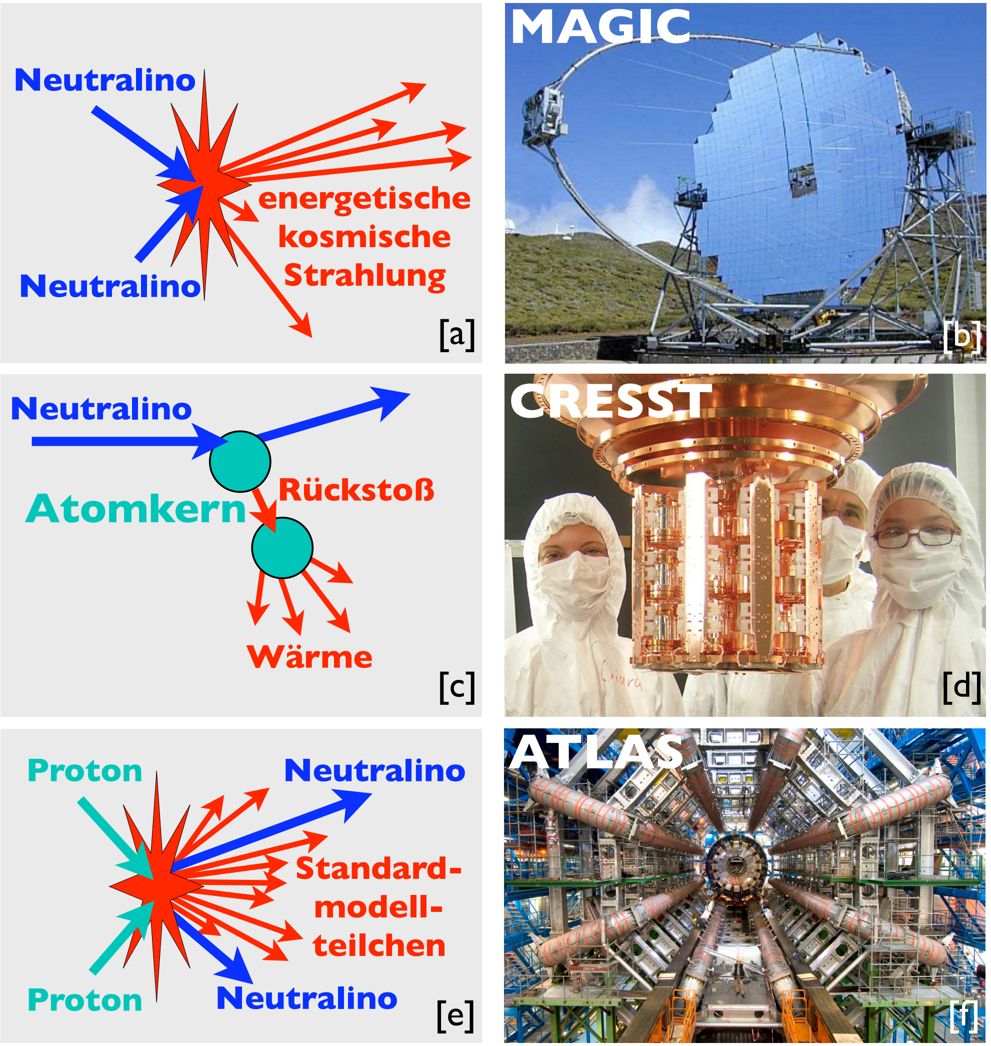
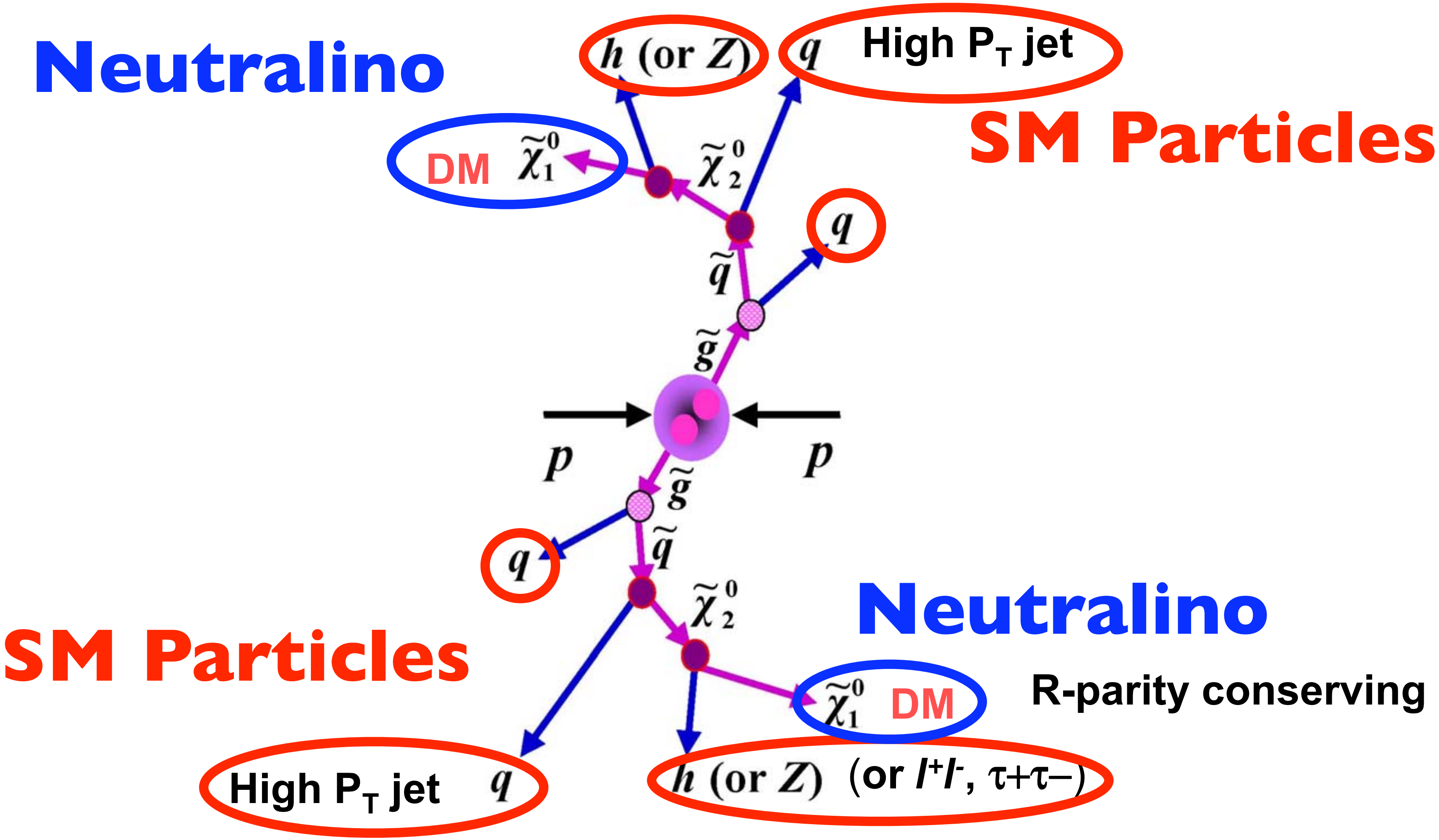




promising experimental prospects

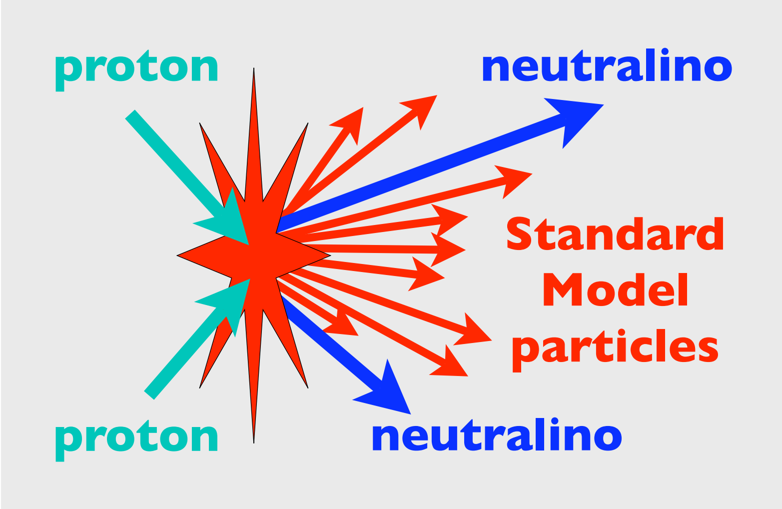
Neutralino DM Production at the LHC



The signal : jets + leptons + missing E_T

[from B. Dutta's Talk, SUSY 2007]

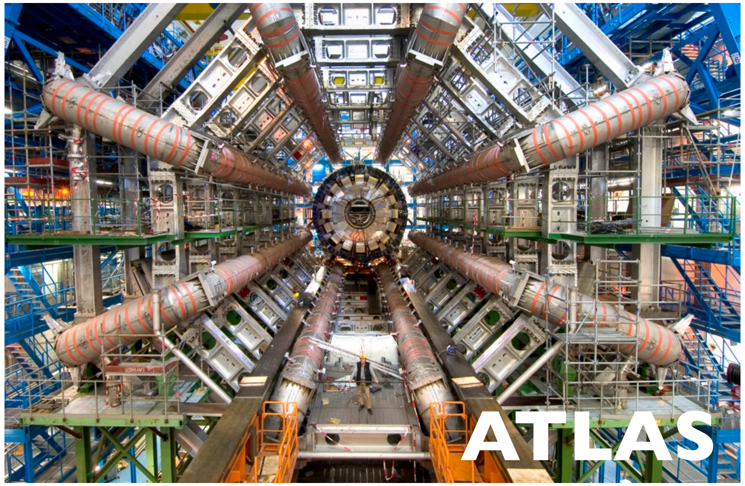
Collider Searches

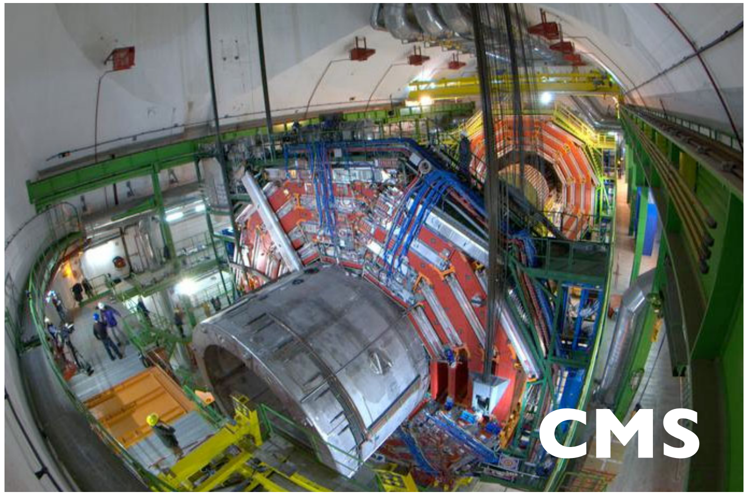


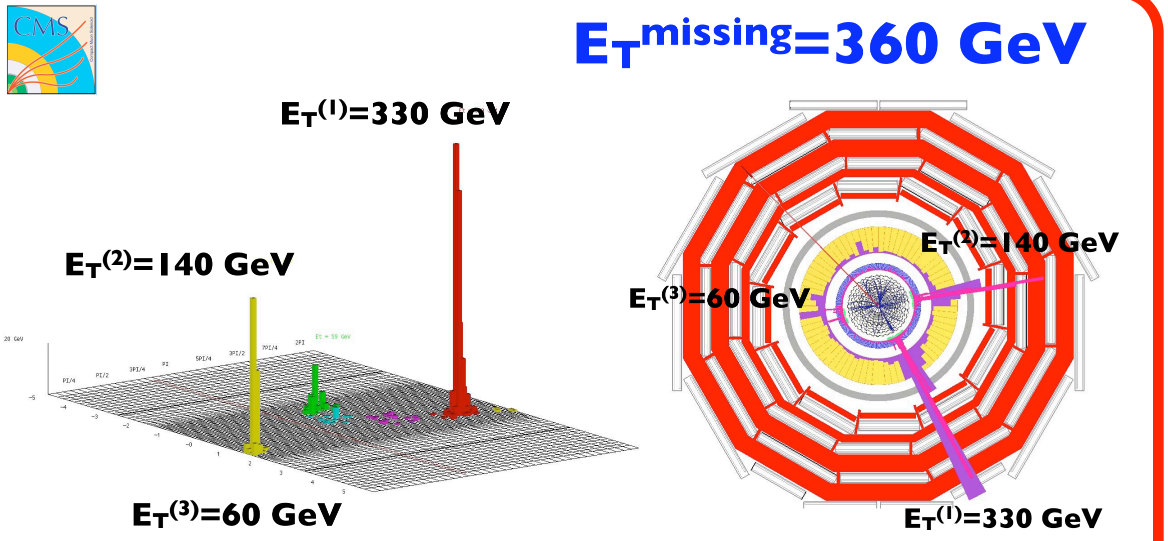
ongoing searches at Tevatron

pp @ 2 TeV

CDF D0







The signal:

jets + leptons + large E_T^{miss}

Warning

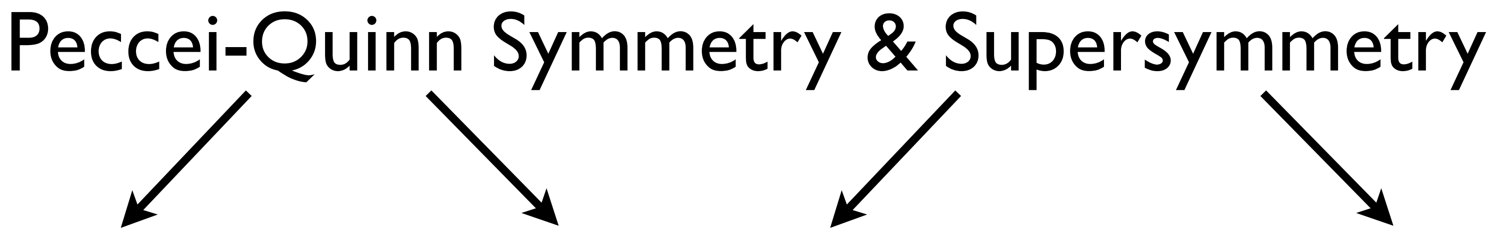
Things might turn out to be very different …

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.	$\propto (p/f_a)^n$	$\propto (p/f_a)^n$	$\propto (p/M_{Pl})^n$

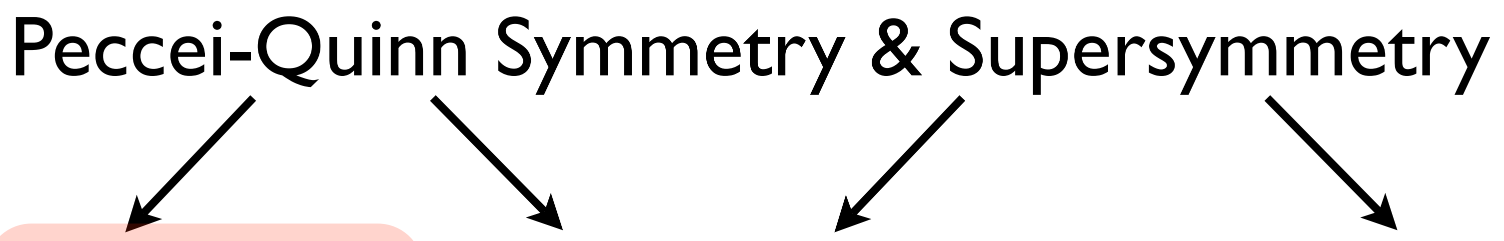
[Talk by Jihn E. Kim]

Other well-motivated candidates

↓

Extremely Weakly Interacting Particles (EWIPs)

Extensions of the Standard Model



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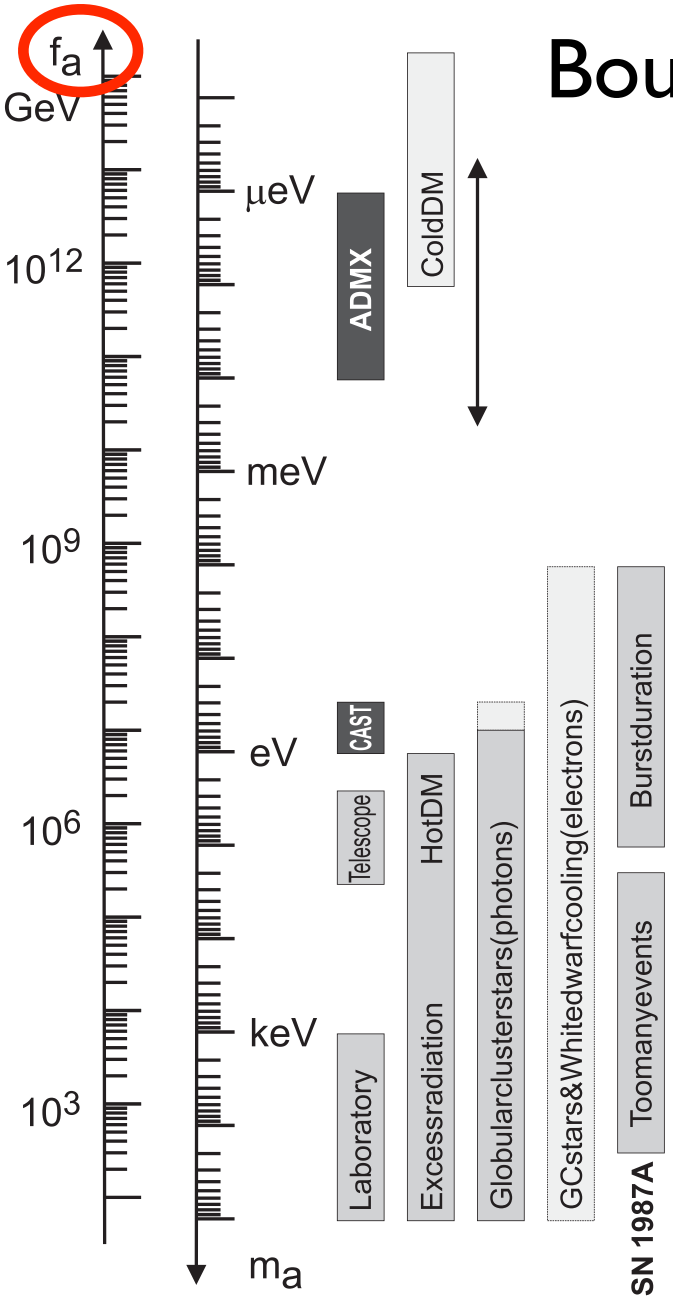
[Talk by Jihn E. Kim]

[Raffelt, ’06]

Bounds on the Peccei-Quinn Scale



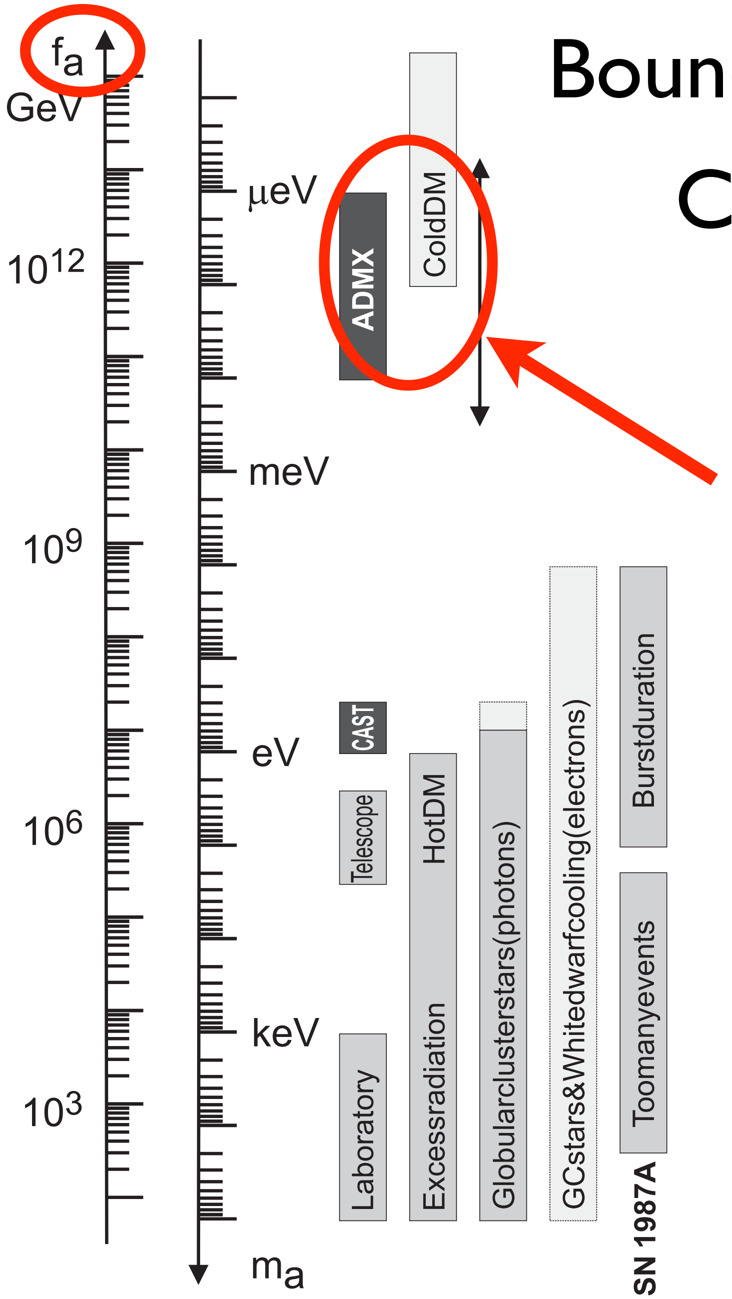
Bounds from Axion Searches

Cosmological Axion Bounds

Astrophysical Axion Bounds

[Raffelt, ’06]

Bounds on the Peccei-Quinn Scale



Bounds from Axion Searches

Cosmological Axion Bounds

Astrophysical Axion Bounds

only 1 Axion CDM Search Experiment

[Raffelt, ’06]

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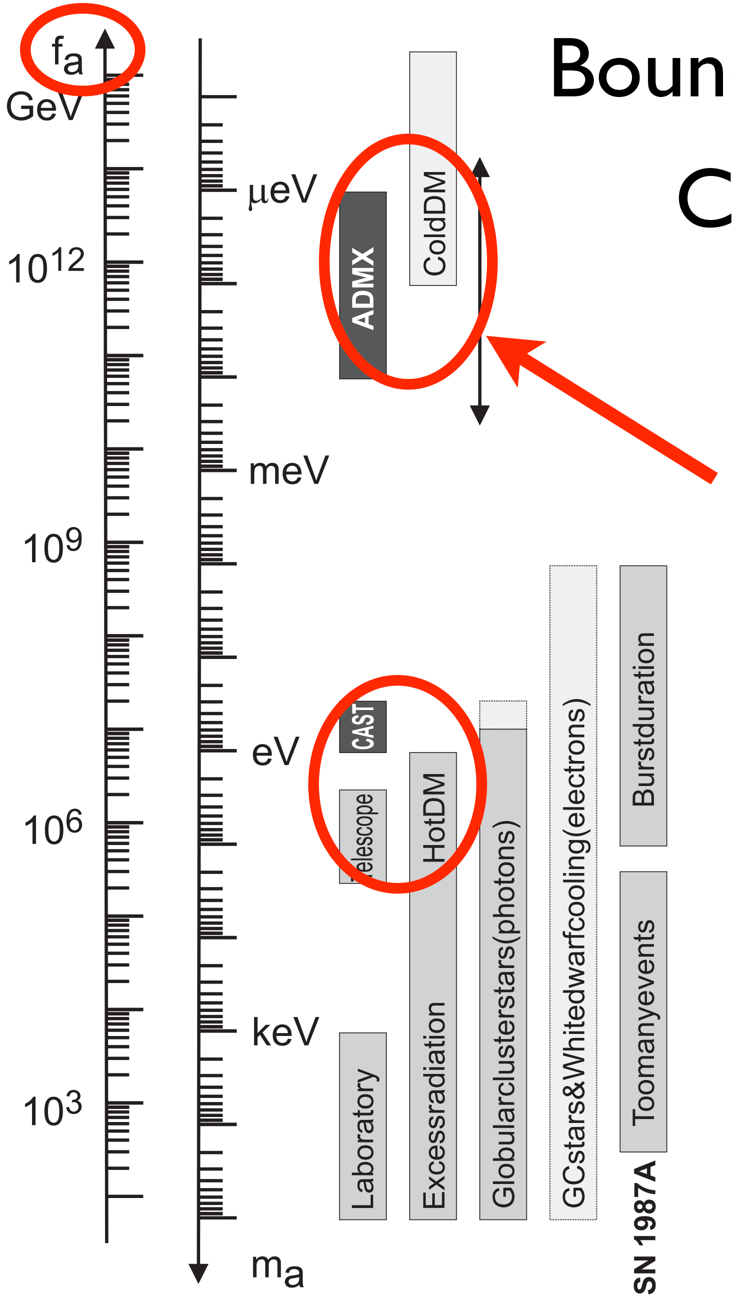


Bounds from Axion Searches

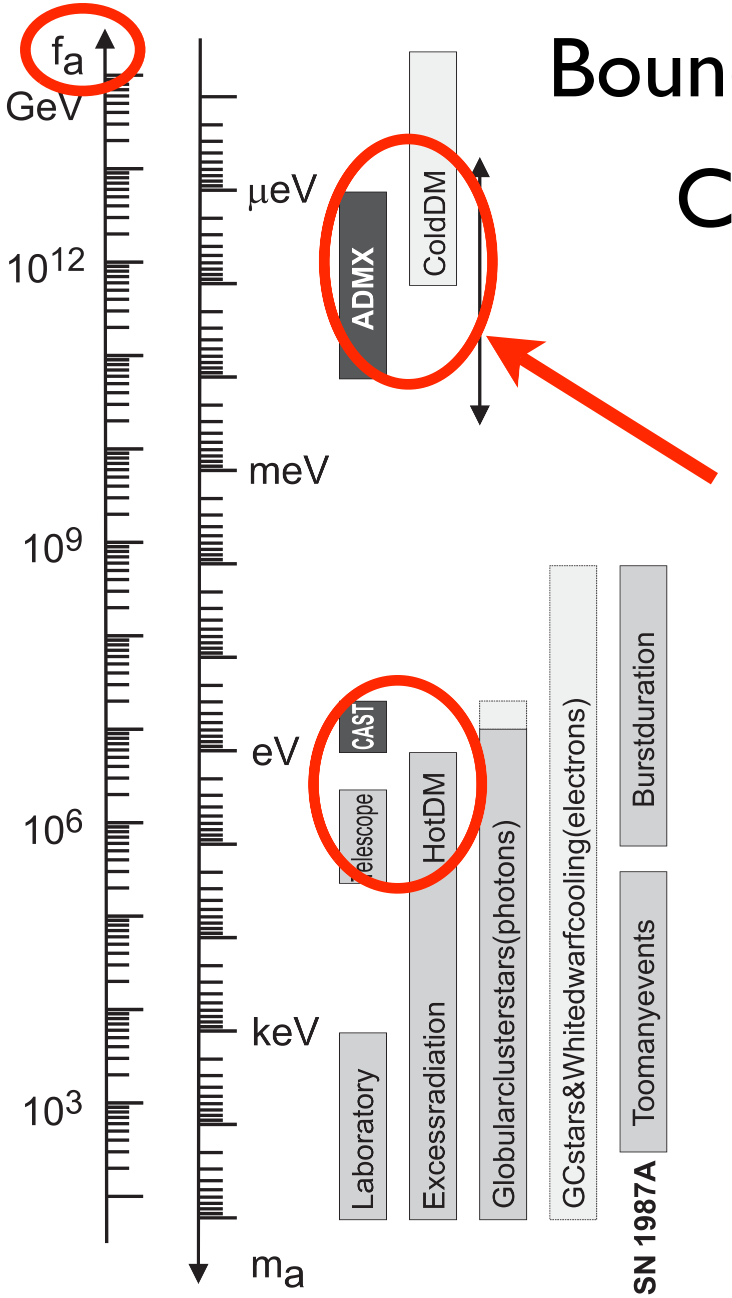
Cosmological Axion Bounds

Astrophysical Axion Bounds

only 1 Axion **C**DM Search Experiment

[Raffelt, ’06]

Bounds on the Peccei-Quinn Scale



Bounds from Axion Searches

Cosmological Axion Bounds

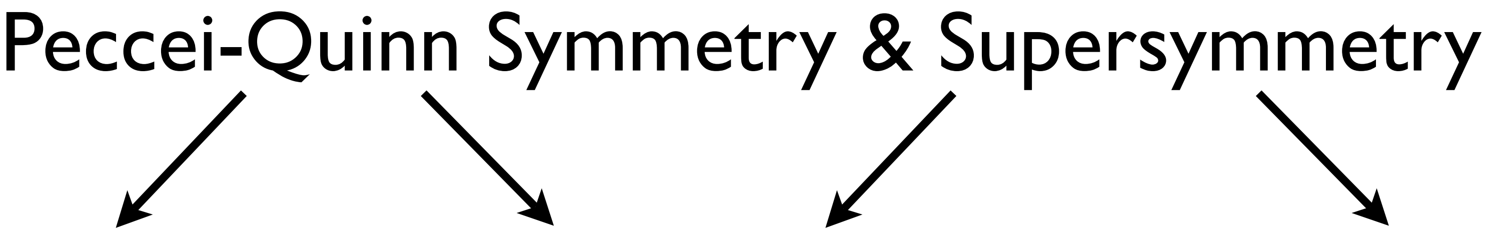
Astrophysical Axion Bounds

only 1 Axion CDM Search Experiment

Axion DM and Neutralino DM might coexist!

Extremely Weakly Interacting Particles (EWIPs)

Extensions of the Standard Model



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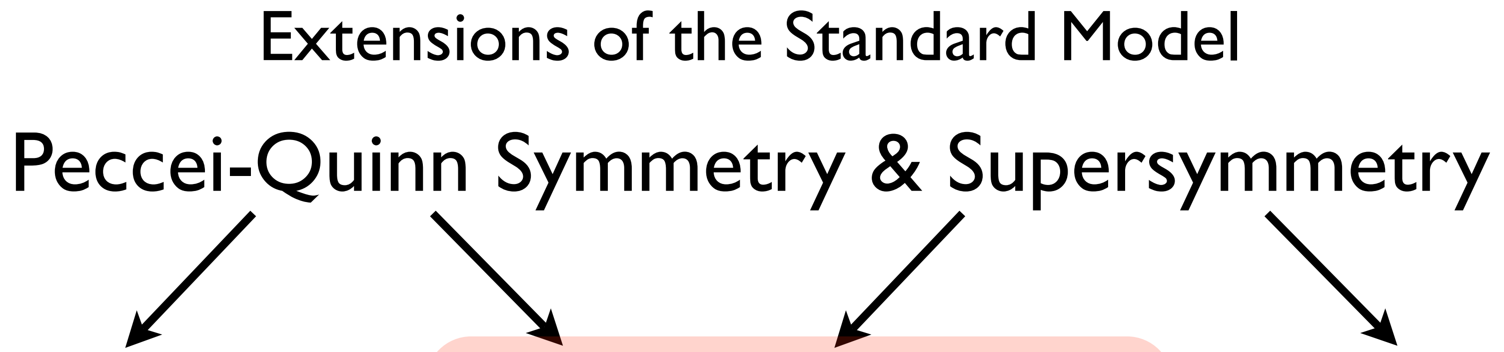

Extensions of the Standard Model

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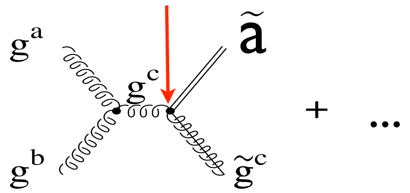
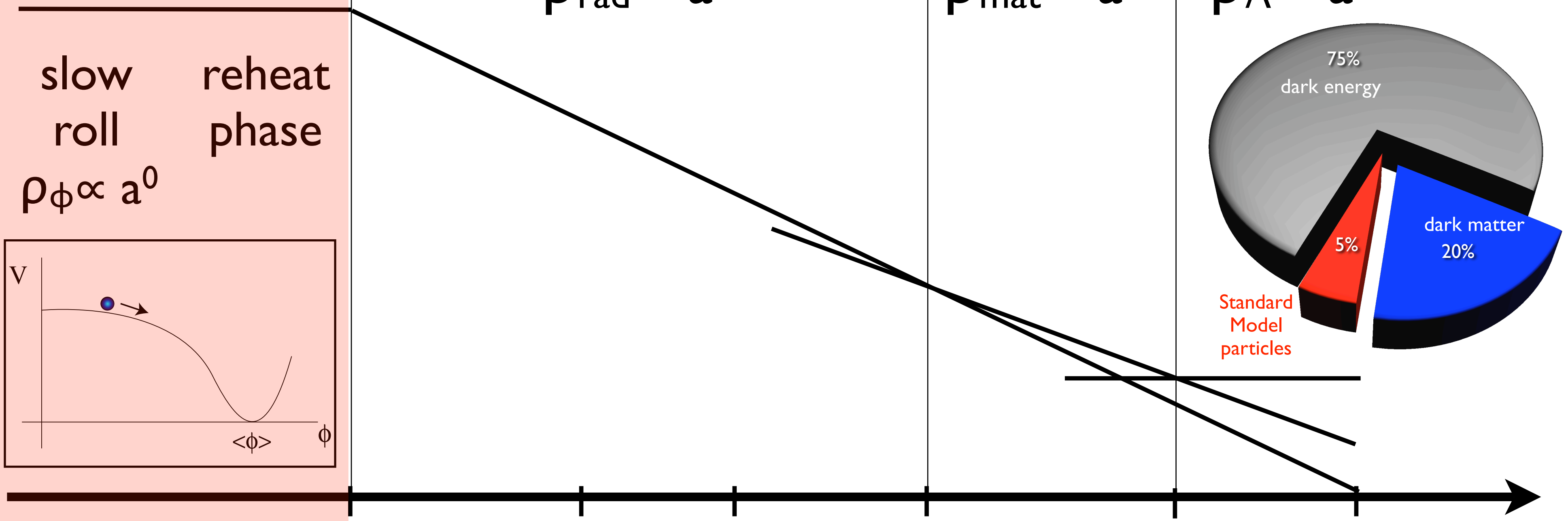
Thermal Axino Production



inflation | radiation dominated $\rho_{rad} \propto a^{-4}$ | mat. dom. $\rho_{mat} \propto a^{-3}$ | Λ dom. $\rho_{\Lambda} \propto a^0$

slow roll $\rho_{\phi} \propto a^0$

reheat phase



		1 s	100.000 y	t_0=14 Gy	t
T_R= ?	10 GeV	1 MeV	1 eV	T_0=2.73 K	T ←
reheating temp.	WIMP freeze out	BBN CνB	CMB	LHC	a →

[Brandenburg, FDS, ’04]

Thermal Production of

Axino Dark Matter

in the Early Universe

Axino Number Density for $f_a > T_D > T_R \gtrsim 10^4$ GeV

- Boltzmann equation: time evolution of axino density $n_{\tilde{a}}$ in the thermal bath

$$\frac{dn_{\tilde{a}}}{dt} + 3Hn_{\tilde{a}} = C_{\tilde{a}} = \int d^3p \, \frac{d\Gamma_{\tilde{a}}}{d^3p} \quad \longleftarrow \quad \text{generation of } \tilde{a} - \text{annihilation of } \tilde{a}$$

- collision term for $a(p_1) + b(p_2) \to c(p_3) + \tilde{a}(p)$: $\qquad (C_{a+b\to c+\tilde{a}} \in C_{\tilde{a}})$

$$C_{a+b\to c+\tilde{a}} = \int \frac{d^3p}{(2\pi)^3 2E} \int \left[\prod_{i=1}^{3} \frac{d^3p_i}{(2\pi)^3 2E_i} \right] (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p)$$
$$\times \left[|M_{a+b\to c+\tilde{a}}|^2 f_a f_b (1 \pm f_c)(1 - f_{\tilde{a}}) - |M_{c+\tilde{a}\to a+b}|^2 f_c f_{\tilde{a}} (1 \pm f_a)(1 \pm f_b) \right]$$

- phase space densities: $f_i \quad \longrightarrow \quad$ number densities: $n_i = \int \frac{d^3p_i}{(2\pi)^3 2E_i} g_i f_i(E_i)$

a, b, and c: $f_i = f_i^{\text{eq}} = f_{B/F} = \frac{1}{\exp(E_i/T) \mp 1}$, $\qquad$ axino: $f_{\tilde{a}} \approx 0$

[Kim, '79; Shifman, Vainshtein, Zakharov, '80]

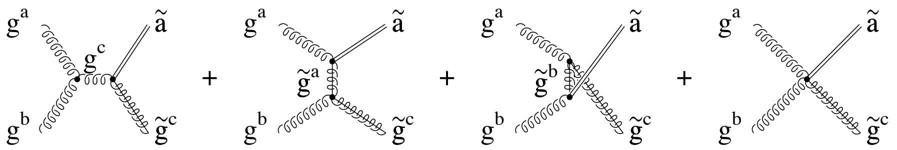
Axino Interactions ⟵ Hadronic (KSVZ) Axion Models

- axino–gluino–gluon interaction:

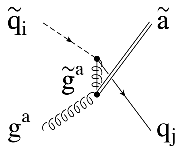
$$\mathcal{L}_{\tilde{a}\tilde{g}g} = i \, \frac{\alpha_{\rm s}}{16\pi(f_a/N)} \, \bar{\tilde{a}} \, \gamma_5 \, [\gamma^\mu, \gamma^\nu] \, \tilde{g}^a \, G^a_{\mu\nu}$$

Thermal Axino Production in SUSY QCD

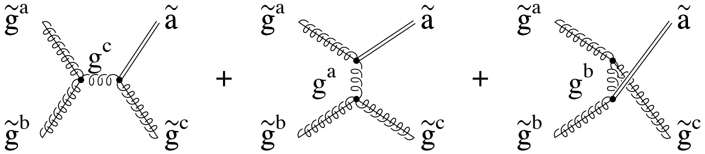
- A: $g^a + g^b \to \tilde{g}^c + \tilde{a}$



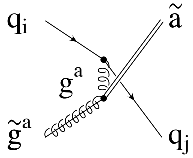
- B: $g^a + \tilde{g}^b \to g^c + \tilde{a}$ (crossing of A)
- C: $\tilde{q}_i + g^a \to \tilde{q}_j + \tilde{a}$



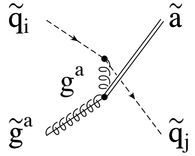
- D: $g^a + q_i \to \tilde{q}_j + \tilde{a}$ (crossing of C)
- E: $\bar{\tilde{q}}_i + q_j \to g^a + \tilde{a}$ (crossing of C)
- F: $\tilde{g}^a + \tilde{g}^b \to \tilde{g}^c + \tilde{a}$



- G: $q_i + \tilde{g}^a \to q_j + \tilde{a}$



- H: $\tilde{q}_i + \tilde{g}^a \to \tilde{q}_j + \tilde{a}$



- I: $q_i + \bar{q}_j \to \tilde{g}^a + \tilde{a}$ (crossing of G)
- J: $\tilde{q}_i + \bar{\tilde{q}}_j \to \tilde{g}^a + \tilde{a}$ (crossing of H)

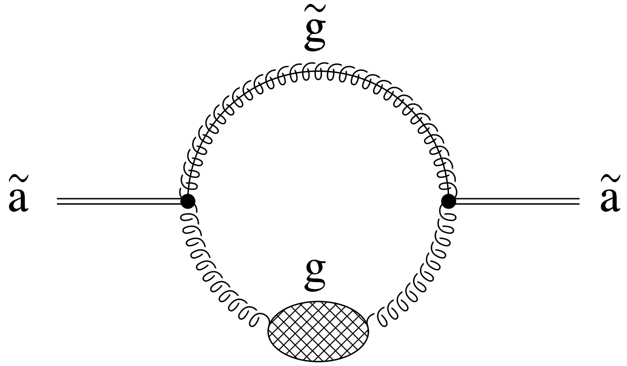
Axino Production in 2 → 2 Processes

	process i	$\lvert\mathcal{M}_i\rvert^2 / \frac{g^6}{128\pi^4 (f_a/N)^2}$
A	$g^a + g^b \to \tilde{g}^c + \tilde{a}$	$4(s + 2t + 2\frac{t^2}{s})\lvert f^{abc}\rvert^2$
B	$g^a + \tilde{g}^b \to g^c + \tilde{a}$	$-4(t + 2s + 2\frac{s^2}{t})\lvert f^{abc}\rvert^2$
C	$\tilde{q}_i + g^a \to q_j + \tilde{a}$	$2s\lvert T^a_{ji}\rvert^2$
D	$g^a + q_i \to \tilde{q}_j + \tilde{a}$	$-2t\lvert T^a_{ji}\rvert^2$
E	$\bar{\tilde{q}}_i + q_j \to g^a + \tilde{a}$	$-2t\lvert T^a_{ji}\rvert^2$
F	$\tilde{g}^a + \tilde{g}^b \to \tilde{g}^c + \tilde{a}$	$-8\frac{(s^2+st+t^2)^2}{st(s+t)}\lvert f^{abc}\rvert^2$
G	$q_i + \tilde{g}^a \to q_j + \tilde{a}$	$-4(s + \frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
H	$\tilde{q}_i + \tilde{g}^a \to \tilde{q}_j + \tilde{a}$	$-2(\frac{t}{2} + 2s + 2\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
I	$q_i + \bar{q}_j \to \tilde{g}^a + \tilde{a}$	$-4(t + \frac{t^2}{s})\lvert T^a_{ji}\rvert^2$
J	$\tilde{q}_i + \bar{\tilde{q}}_j \to \tilde{g}^a + \tilde{a}$	$2(\frac{s}{2} + 2t + 2\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$

B, F, G, & H: Logarithmic IR Singularity

- Separation of Scales: $gT \ll \Lambda \ll T \quad \leftarrow \quad g \ll 1$ [Braaten, Yuan, 1991]

- Soft Part: Axino Self-Energy

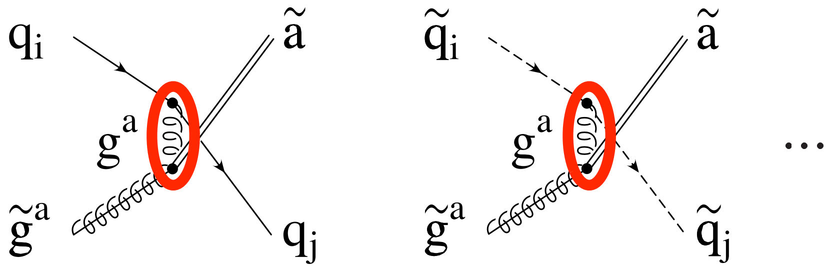


→ eff. HTL resummed propagator

$$E\,\frac{d\Gamma_{\tilde{a}}}{d^3p}\bigg|_{\text{soft}} = -f_F(E)\,\frac{\text{Im}\Sigma(E+i\epsilon,\mathbf{p})}{(2\pi)^3}\bigg|_{|\mathbf{p}_1-\mathbf{p}_3|<\Lambda}$$

$$= A_{\text{soft}} + B\ln\left[\frac{\Lambda}{gT}\right]$$

- Hard Part: Relativ. Kin. Theory



→ bare propagator

$$E\,\frac{d\Gamma_{\tilde{a}}}{d^3p}\bigg|_{\text{hard}} = \frac{1}{2}\int\prod_{i=1}^{3}\ldots|M|^2\,\Theta(|\mathbf{p}_1-\mathbf{p}_3|-\Lambda)$$

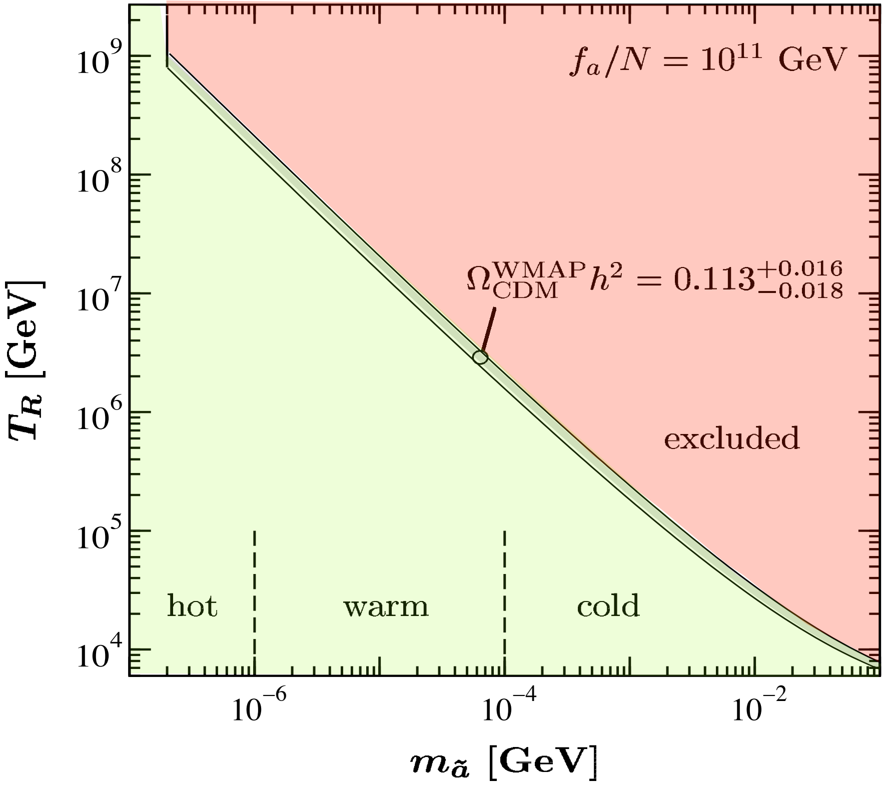
$$= A_{\text{hard}} + B\ln\left[\frac{T}{\Lambda}\right]$$

- Thermal Production Rate: $*$ complete to LO in g , $*$ finite , $*$ indep. of Λ

$$E\,\frac{d\Gamma_{\widetilde{G}}}{d^3p}\bigg|_{\text{LO in }g} = E\,\frac{d\Gamma_{\widetilde{G}}}{d^3p}\bigg|_{\text{soft}} + E\,\frac{d\Gamma_{\widetilde{G}}}{d^3p}\bigg|_{\text{hard}} = A_{\text{soft}} + A_{\text{hard}} + B\ln\left[\frac{1}{g}\right]$$

Axino LSP Case

Thermal $\tilde{a}$ Production



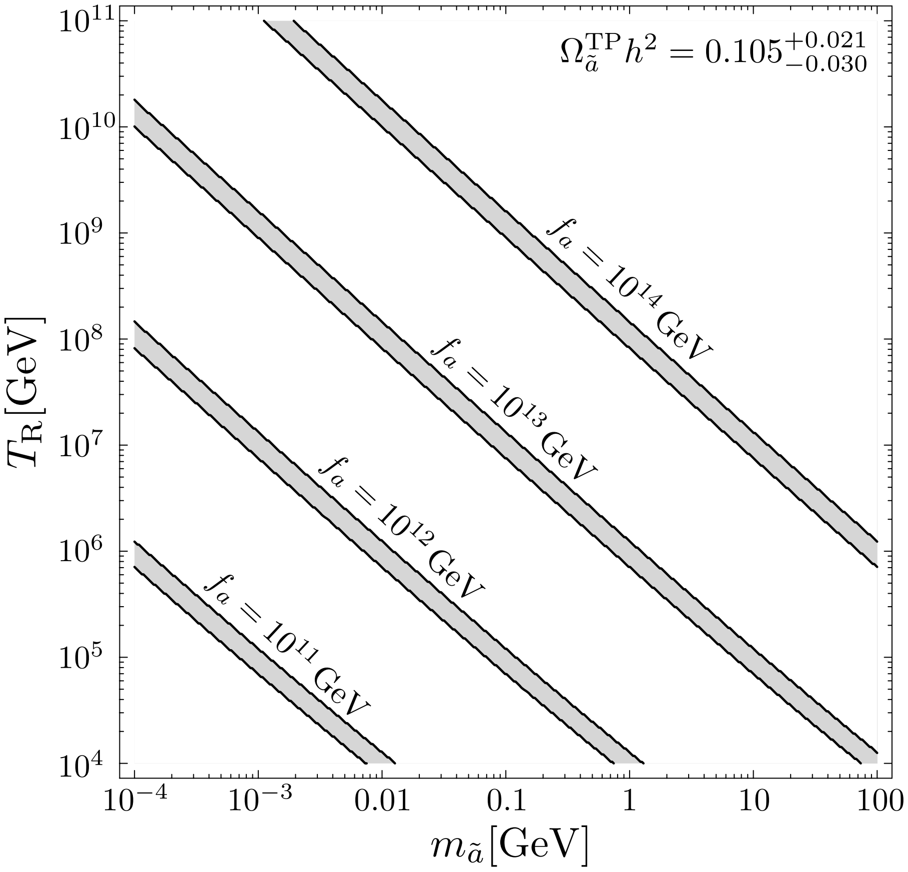
[Brandenburg, FDS, '04]

see also [Covi et al., '01]

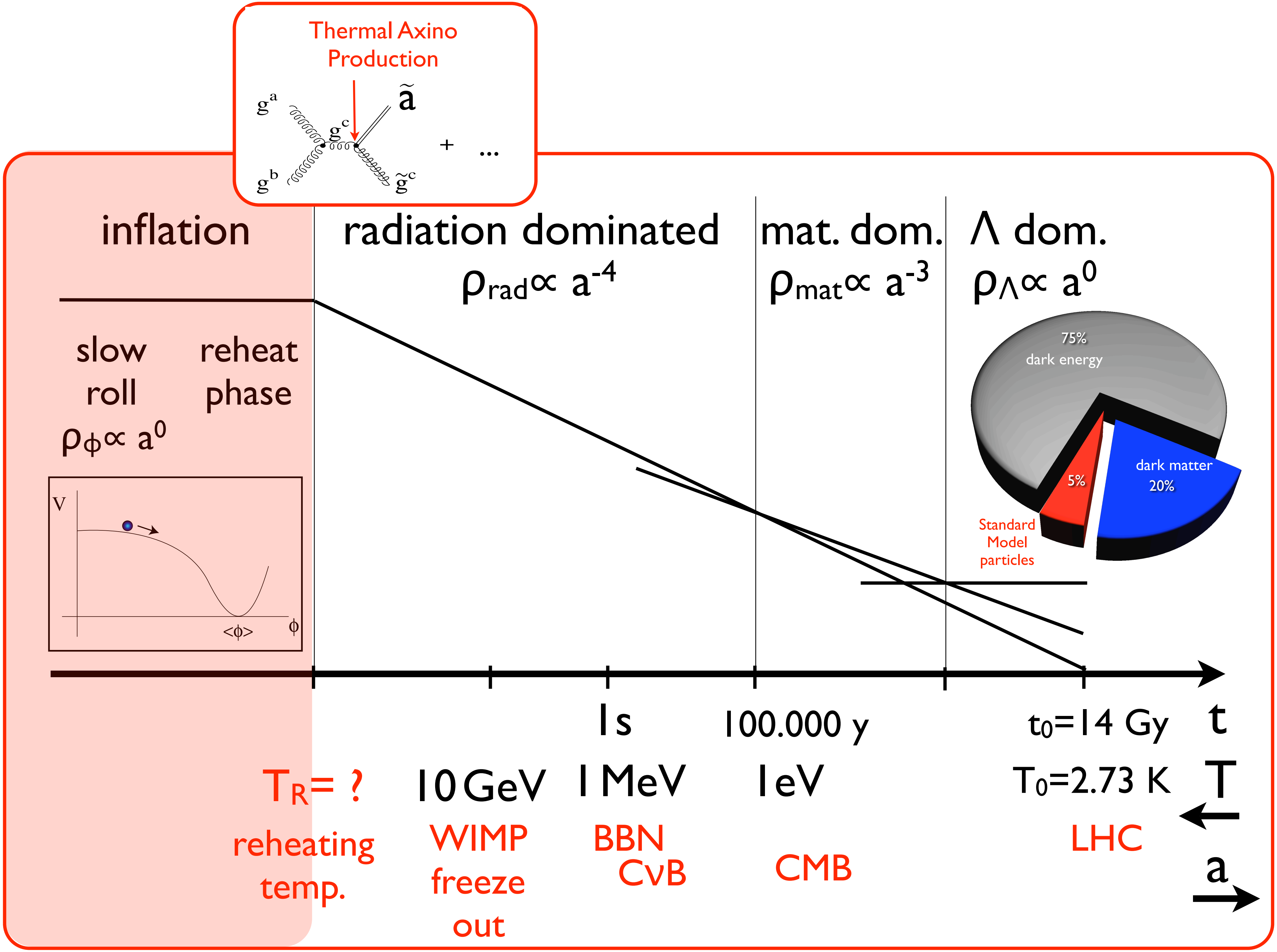
and [Strumia, '10]

Axino LSP Case

Thermal $\widetilde{a}$ Production



[Freitas, FDS, Tajuddin, Wyler, '09]



Thermal Axino Production

inflation

slow roll
$\rho_\phi \propto a^0$

reheat phase

radiation dominated
$\rho_{rad} \propto a^{-4}$

mat. dom.
$\rho_{mat} \propto a^{-3}$

Λ dom.
$\rho_\Lambda \propto a^0$

1s

100.000 y

t_0=14 Gy

t

T_R= ?

10 GeV

1 MeV

1 eV

T_0=2.73 K

T ←

reheating temp.

WIMP freeze out

BBN

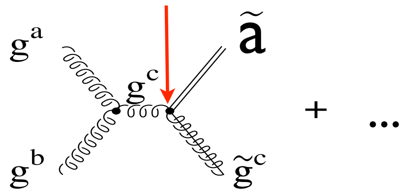
CνB

CMB

LHC

a →

Thermal Axino Production

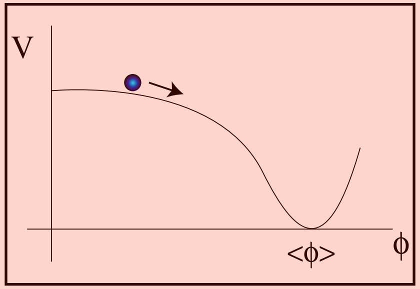


inflation

slow roll

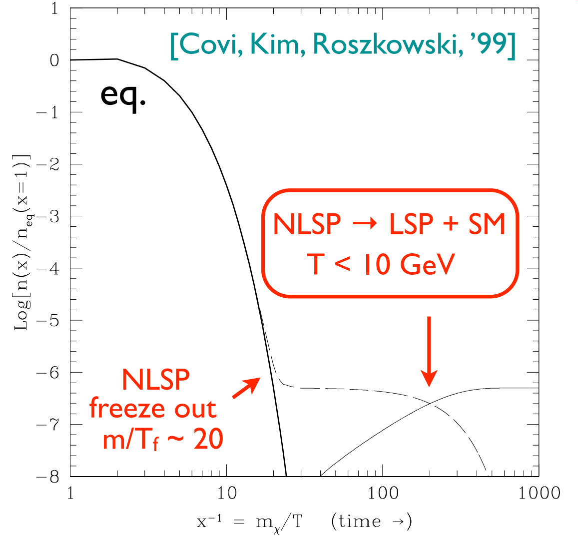
$\rho_\phi \propto a^0$

reheat phase



radiation dominated

$\rho_{rad} \propto a^{-4}$

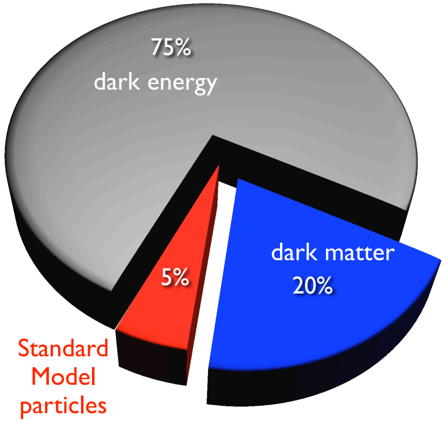


mat. dom.

$\rho_{mat} \propto a^{-3}$

Λ dom.

$\rho_\Lambda \propto a^0$



1 s

100.000 y

t_0=14 Gy

t

T_R= ?

reheating temp.

10 GeV

WIMP freeze out

1 MeV

BBN

CνB

1 eV

CMB

T_0=2.73 K

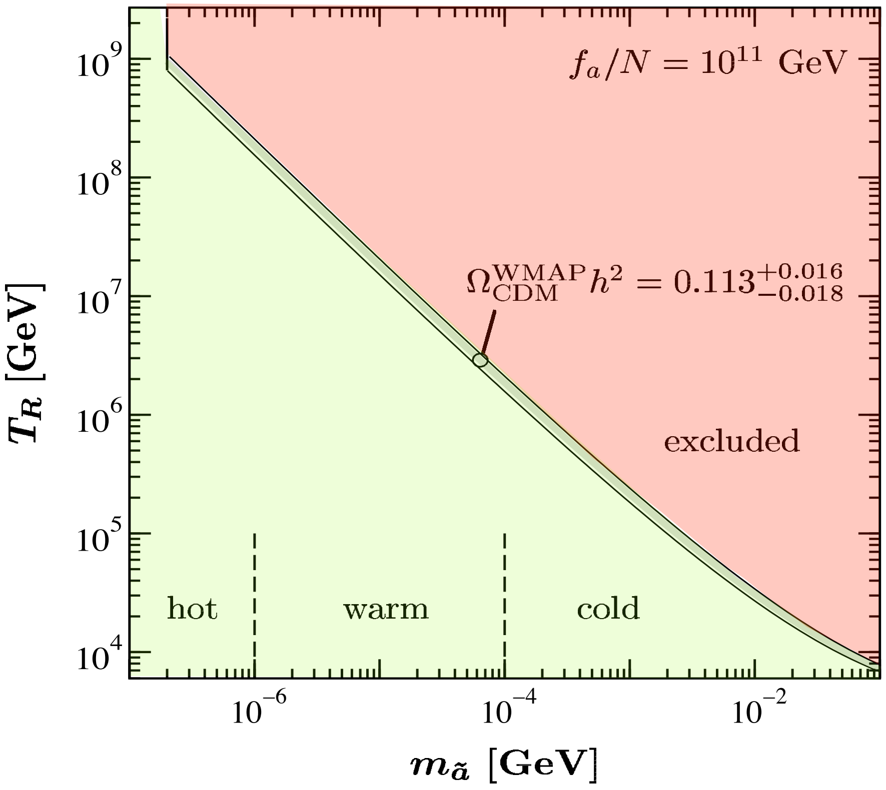
T ←

LHC

a →

Axino LSP Case

Thermal $\widetilde{a}$ Production

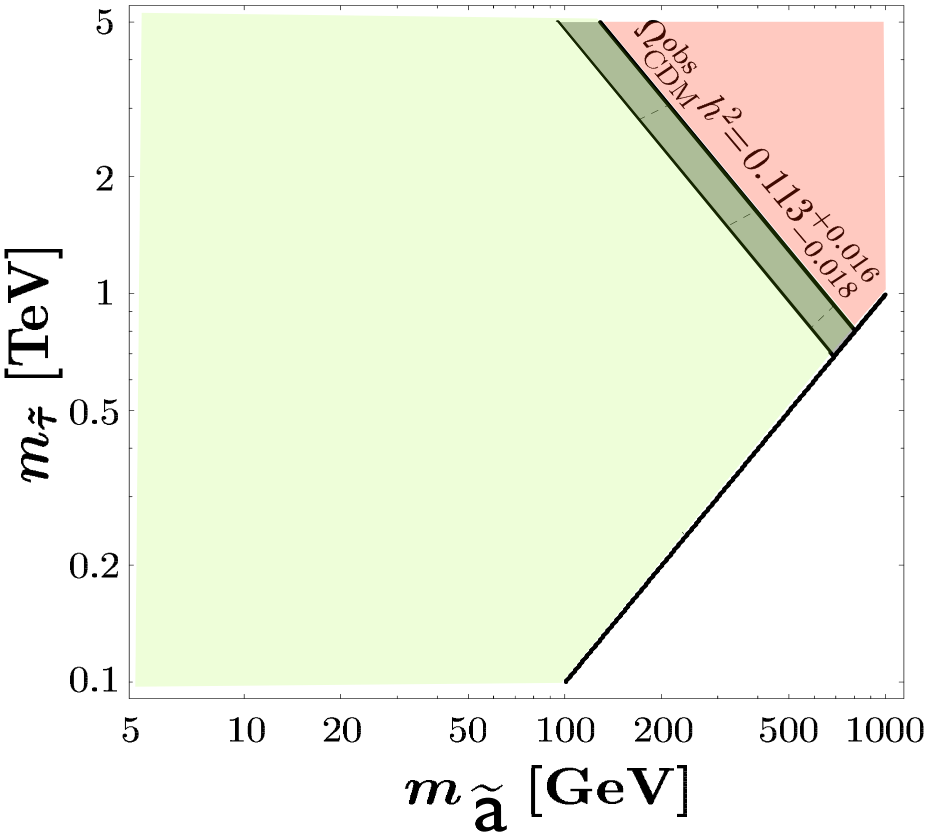


[Brandenburg, FDS, '04]

see also [Covi et al., '01]

and [Strumia, '10]

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



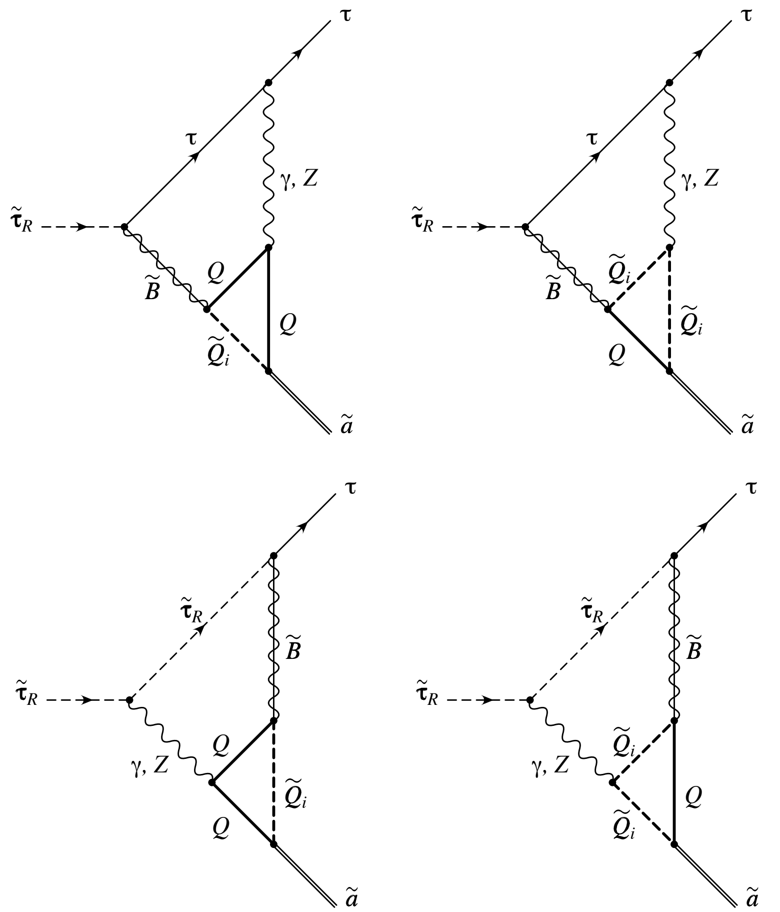
Probing axinos experimentally ???

↓

If we are lucky ...

[Freitas, Tajuddin, FDS, Wyler, '09]

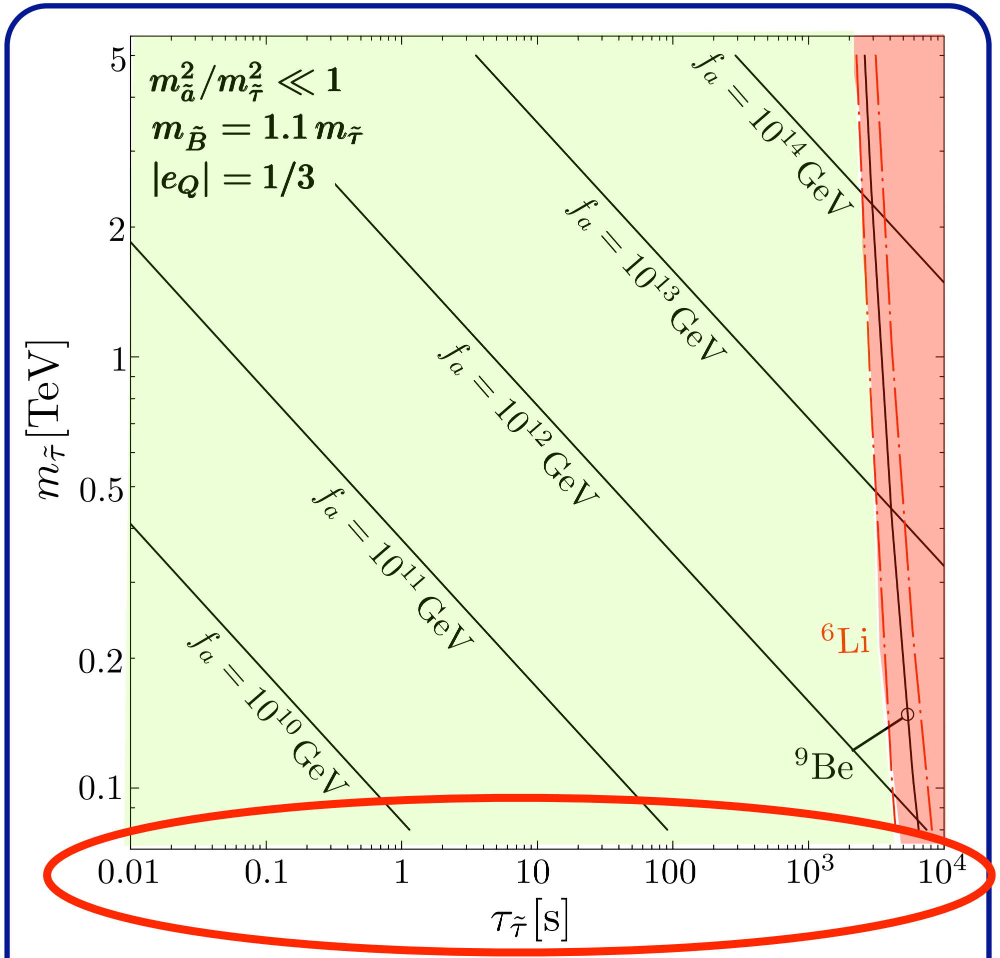
Stau Decays into Axinos



$W_{\mathrm{PQ}} = y\Phi Q_1 Q_2 \qquad M_{\tilde{Q}_{1,2}} = M_{\mathrm{Q}} = y\langle\phi\rangle = y f_a/\sqrt{2}$

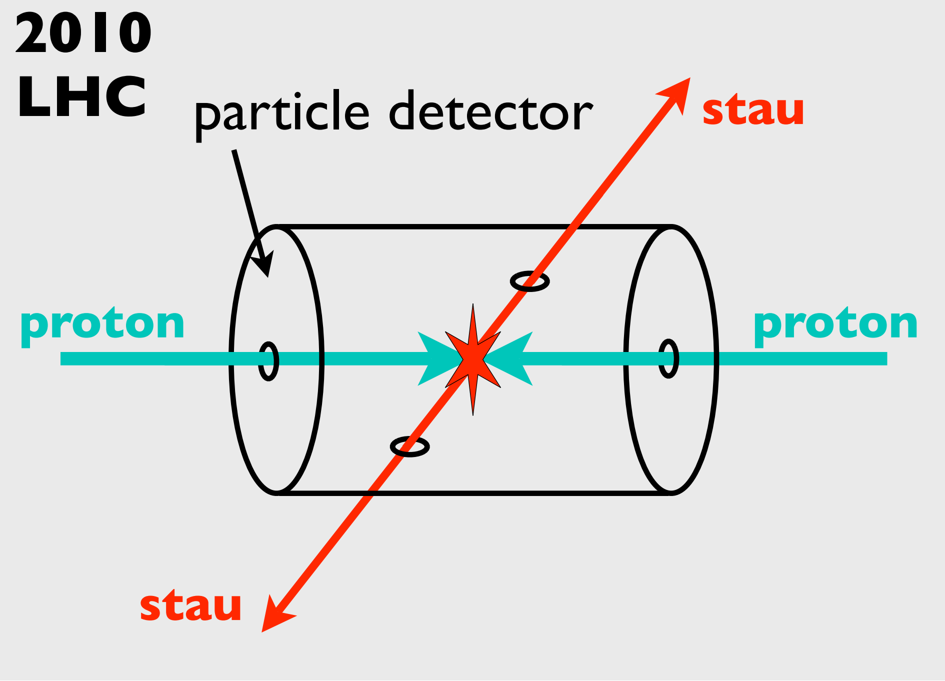
Chiral multiplet	$\mathrm{U(1)_{PQ}}$	$(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_{\mathrm{Y}}$
$\Phi = \phi + \sqrt{2}\chi\theta + F_\Phi\theta\theta$	$+1$	$(\mathbf{1},\mathbf{1})_0$
$Q_1 = \tilde{Q}_1 + \sqrt{2}q_1\theta + F_1\theta\theta$	$-1/2$	$(\mathbf{3},\mathbf{1})_{+e_Q}$
$Q_2 = \tilde{Q}_2 + \sqrt{2}q_2\theta + F_2\theta\theta$	$-1/2$	$(\mathbf{3}^*,\mathbf{1})_{-e_Q}$

BBN

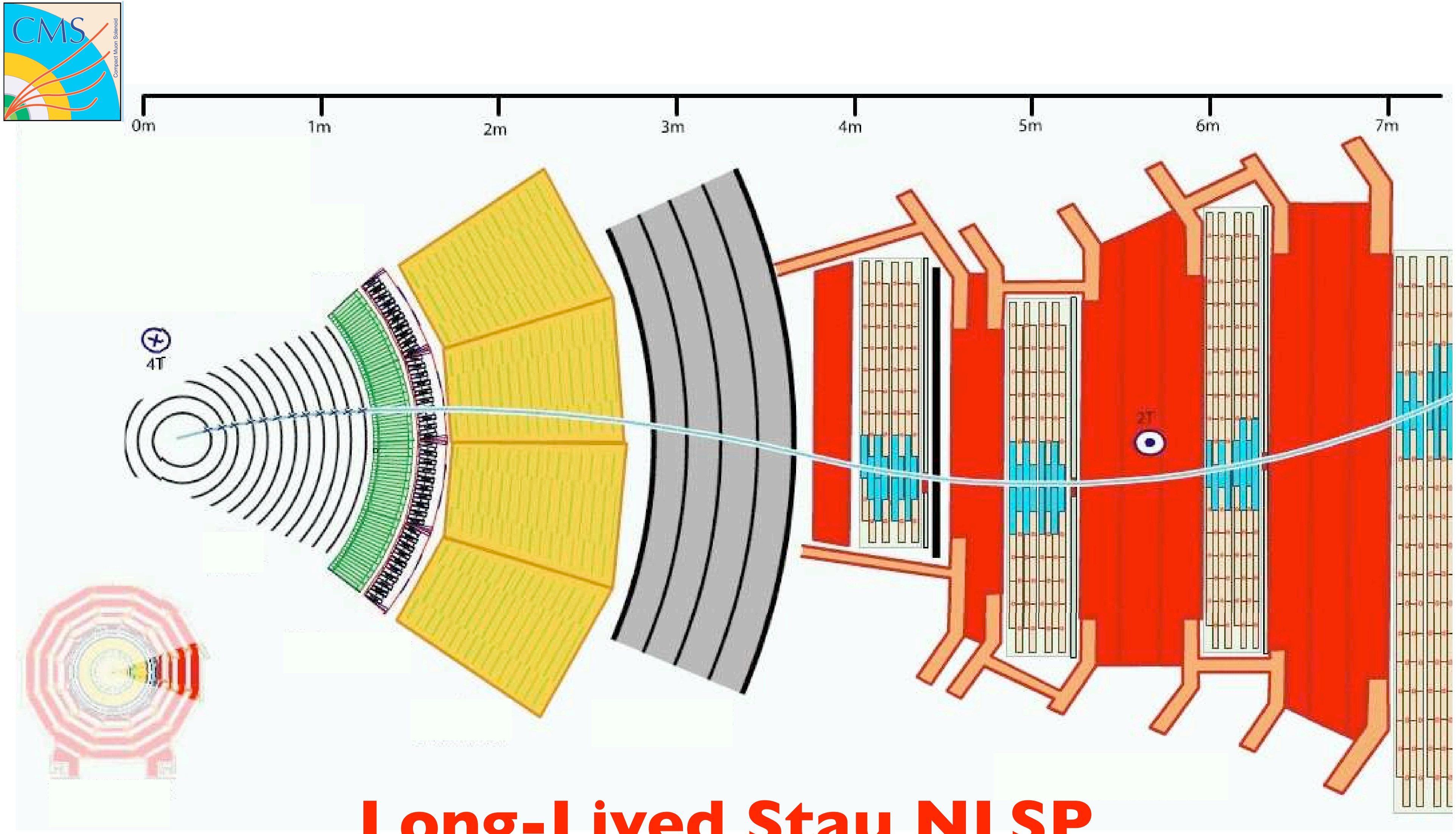


$$\Gamma^{\tilde\tau_{\mathrm{R}}}_{\mathrm{tot}} \approx \Gamma(\tilde\tau_{\mathrm{R}} \to \tau\tilde a)_{\mathrm{LL}}$$

$$= \frac{81\alpha^4 e_Q^4}{128\pi^5 \cos^8\theta_W}\,\frac{m_{\tilde\tau} m_{\tilde B}^2}{f_a^2}\left(1-\frac{m_{\tilde a}^2}{m_{\tilde\tau}^2}\right)^2 \ln^2\left(\frac{y f_a}{\sqrt{2}\, m_{\tilde\tau}}\right)$$

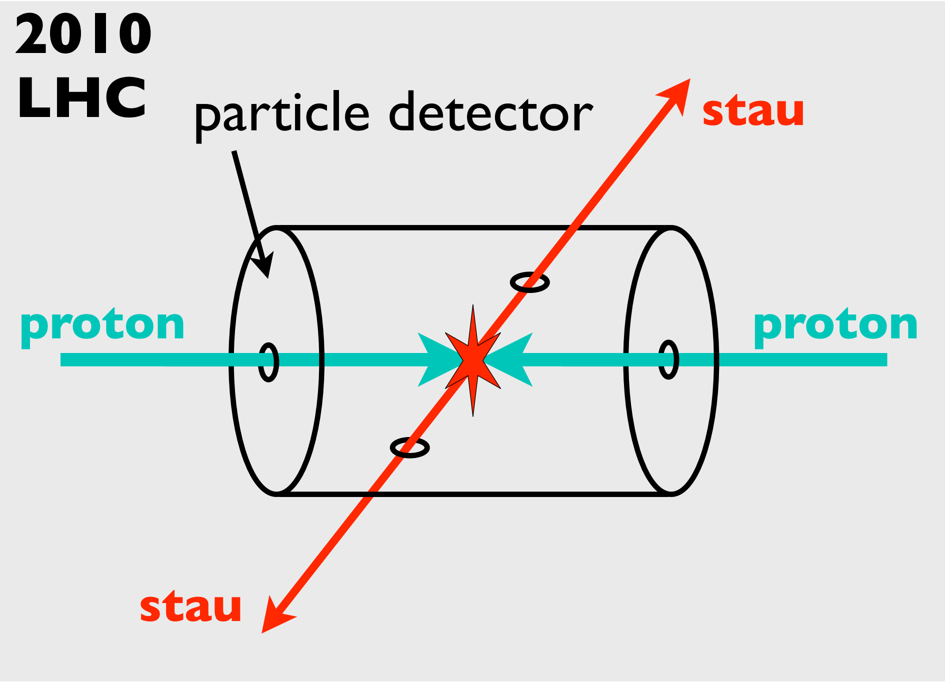

2010
LHC
particle detector
stau
proton
proton
stau

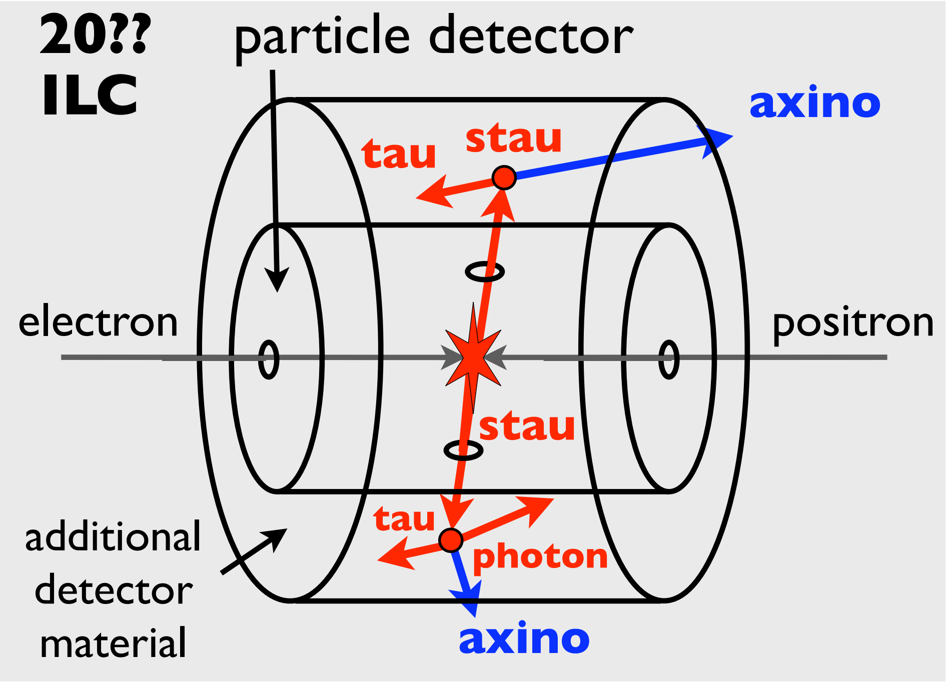
“Stable” Charged Massive Particle @ LHC



Long-Lived Stau NLSP

[from P. Zalewski’s Talk, SUSY 2007]



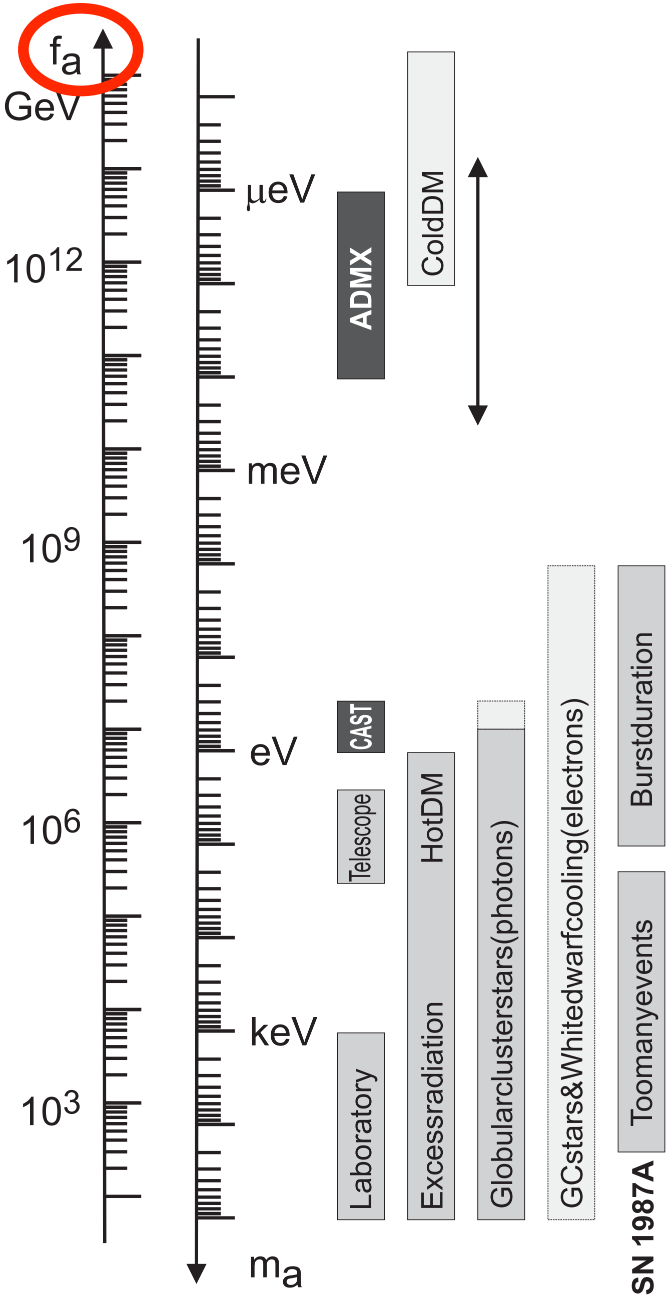


Probing f_a @ Colliders

[Brandenburg et al., ’05]

[Raffelt, '06]

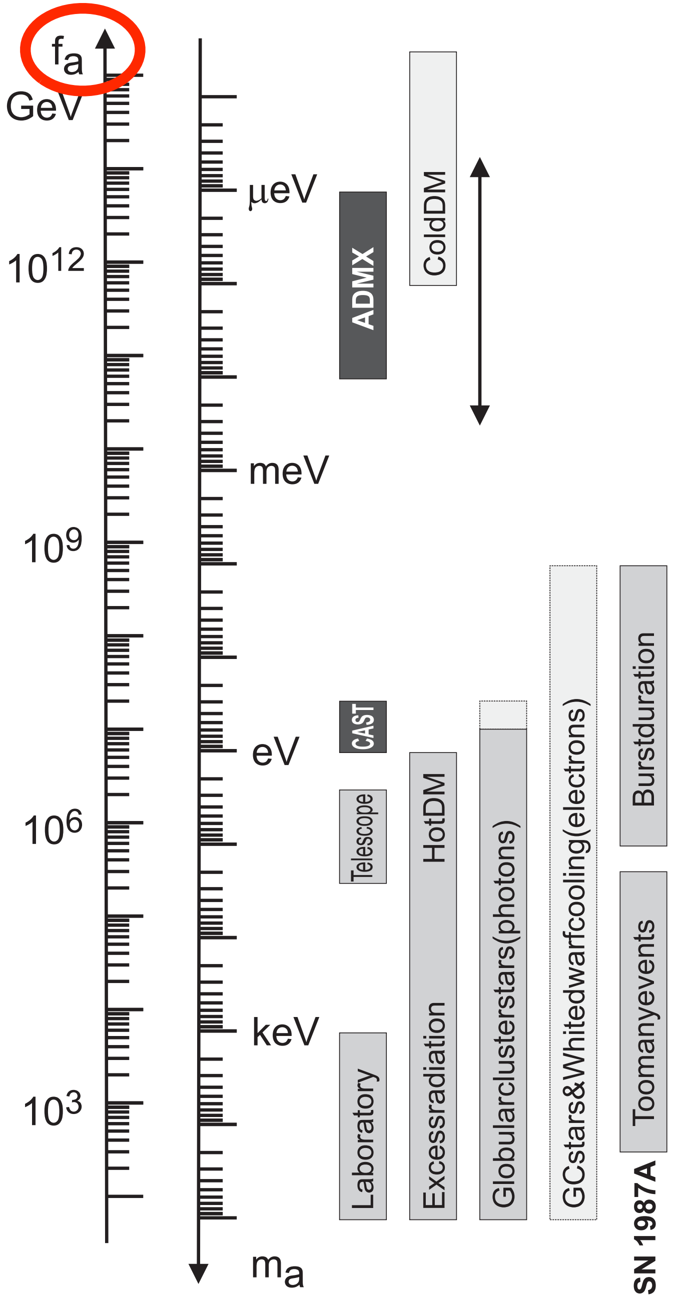
Bounds on the Peccei-Quinn Scale



Is the value of the Peccei-Quinn scale inferred from axino searches consistent with astrophysical axion bounds and results from axion searches?

[Raffelt, '06]

Bounds on the Peccei-Quinn Scale



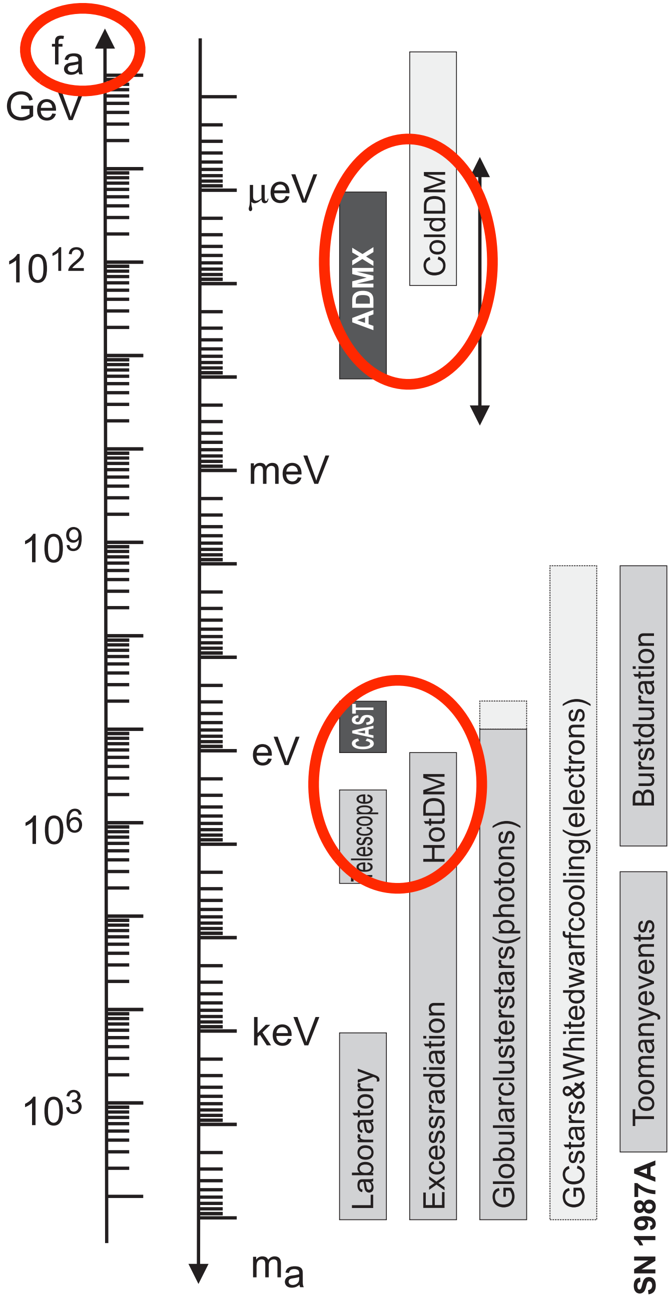
Agreement between Axion & Axino Searches

↓

Strong Hint for the Axino LSP

[Raffelt, ’06]

Bounds on the Peccei-Quinn Scale



Agreement between Axion & Axino Searches

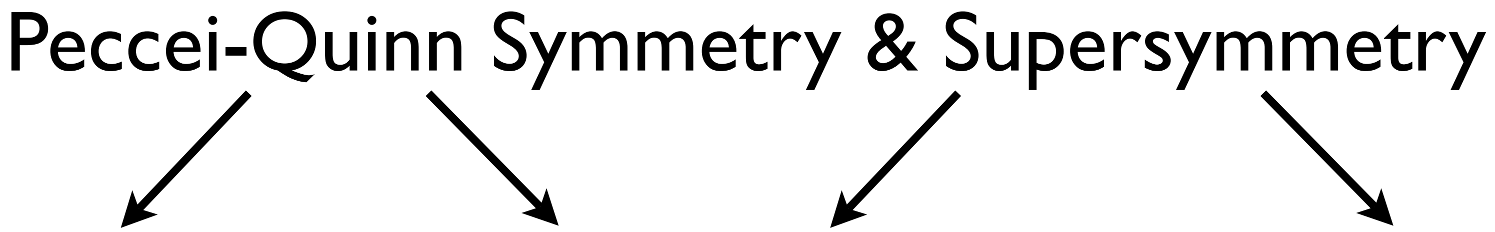
↓

Strong Hint for the Axino LSP

Axion DM & Axino DM might coexist!

Extremely Weakly Interacting Particles (EWIPs)

Extensions of the Standard Model

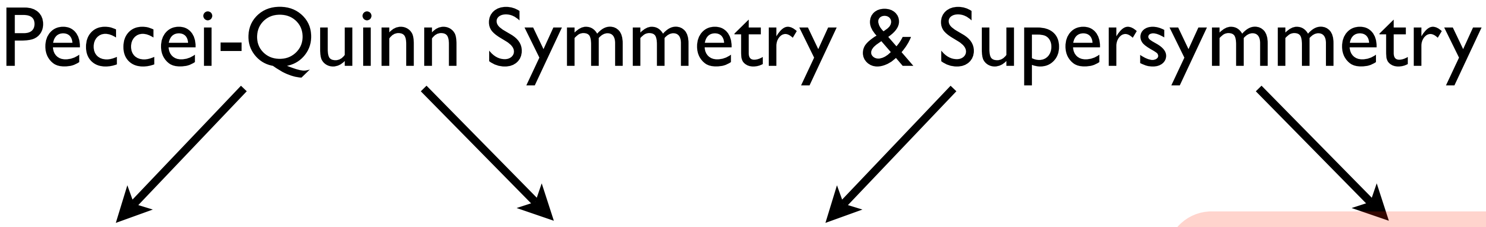


Peccei-Quinn Symmetry & Supersymmetry

	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.	$\propto (p/f_a)^n$	$\propto (p/f_a)^n$	$\propto (p/M_{Pl})^n$

Extremely Weakly Interacting Particles (EWIPs)

Extensions of the Standard Model



	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
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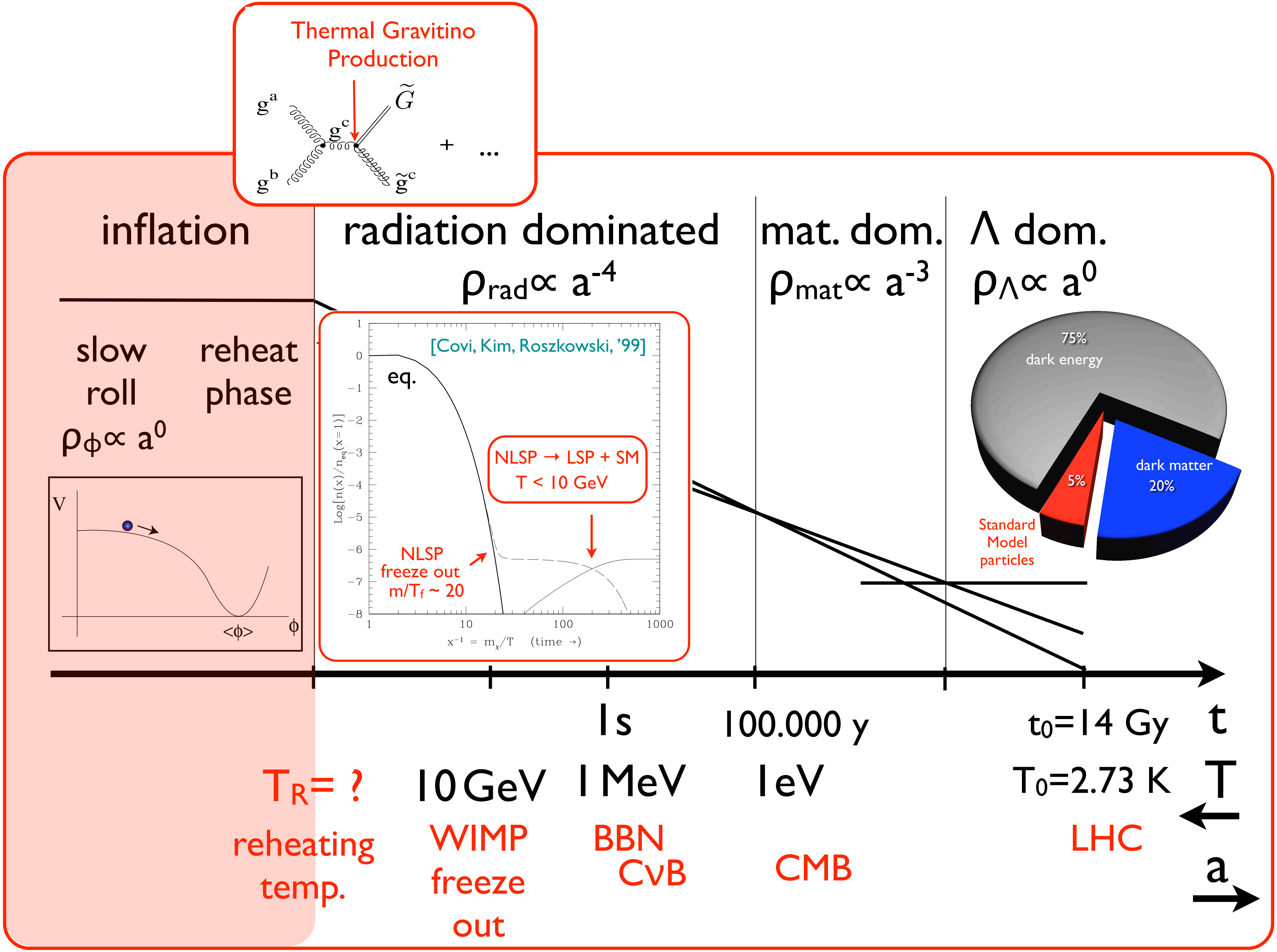


Thermal Gravitino Production

inflation

slow roll

$\rho_\phi \propto a^0$

reheat phase

radiation dominated

$\rho_{rad} \propto a^{-4}$

mat. dom.

$\rho_{mat} \propto a^{-3}$

Λ dom.

$\rho_\Lambda \propto a^0$

[Covi, Kim, Roszkowski, '99]

NLSP → LSP + SM

T < 10 GeV

NLSP freeze out $m/T_f \sim 20$

1 s

100.000 y

t_0=14 Gy

t

T_R= ?

10 GeV

1 MeV

1 eV

T_0=2.73 K

T

a

reheating temp.

WIMP freeze out

BBN

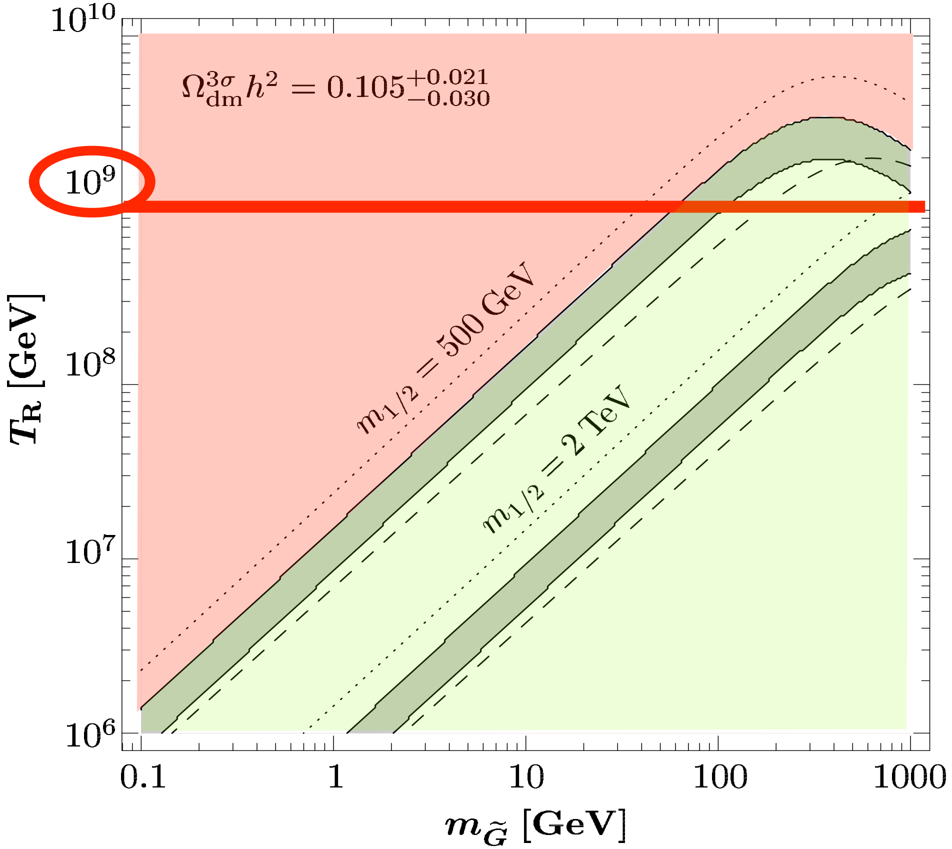
CνB

CMB

LHC

Gravitino LSP Case

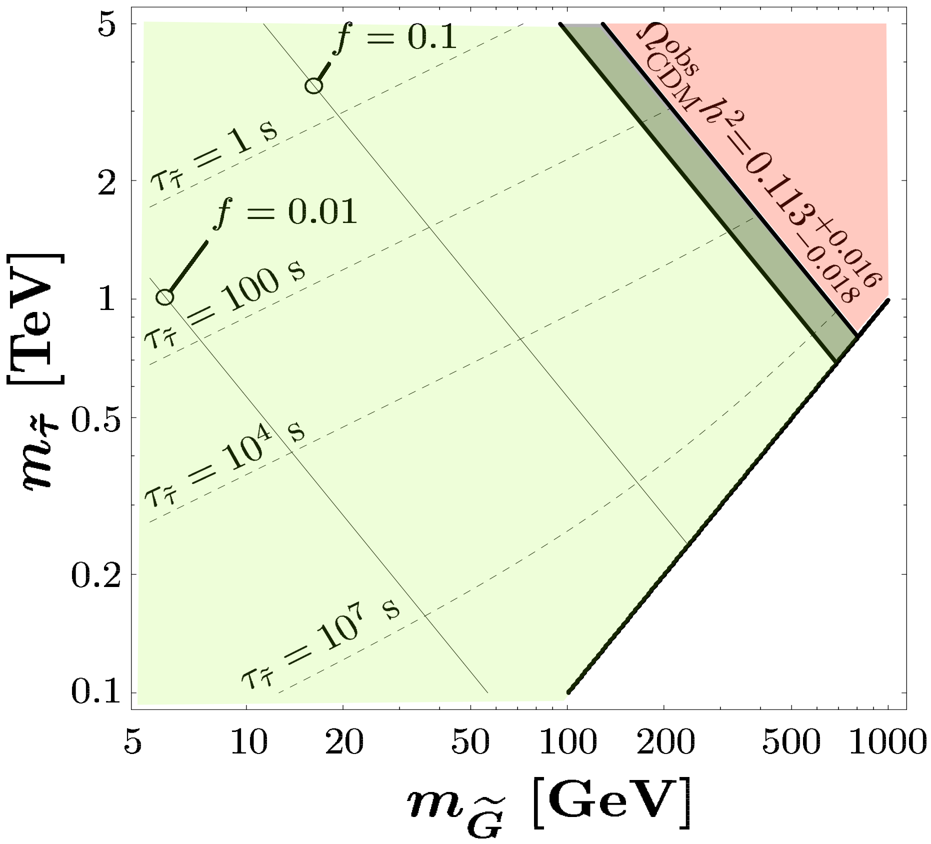
Thermal $\widetilde{G}$ Production



[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]

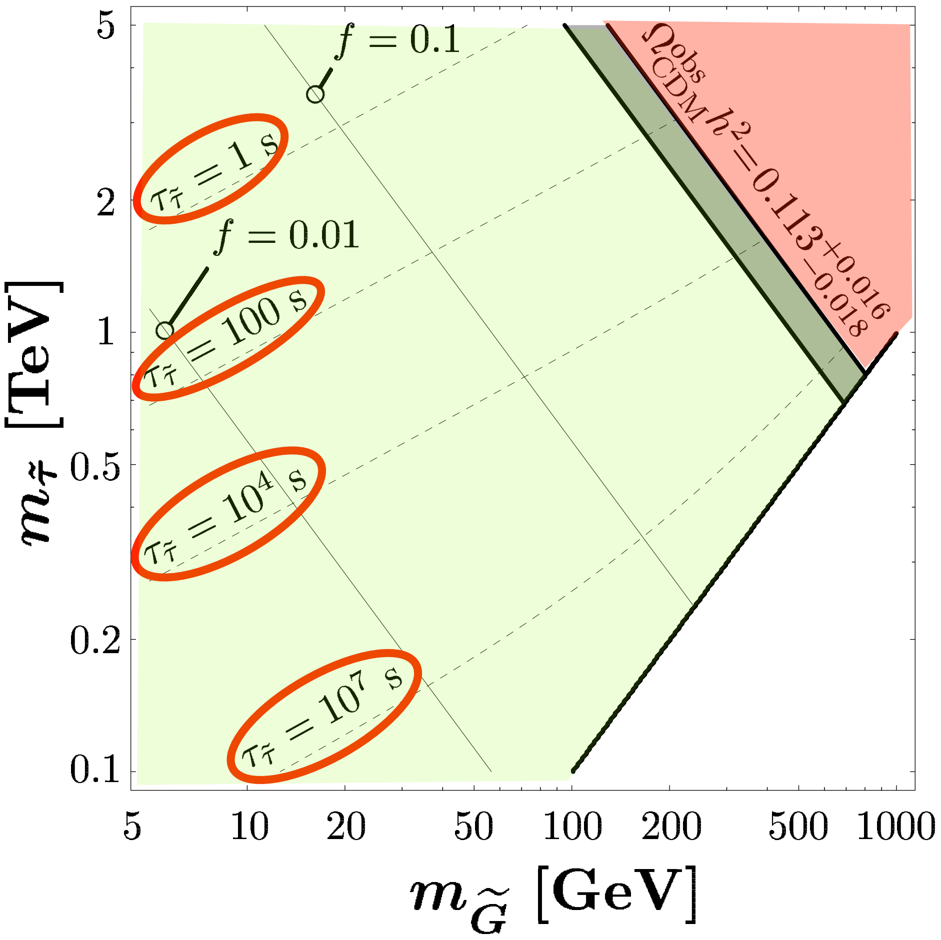
Probing gravitinos experimentally ???

↓

If we are lucky ...

long-lived NLSP

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

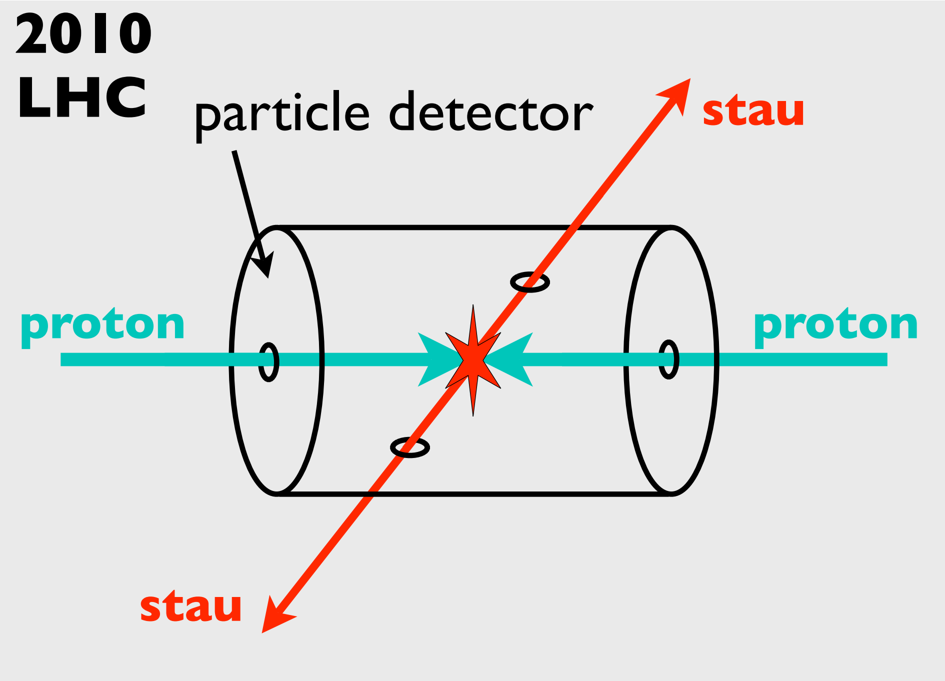


Signatures of Gravitinos in Experiments

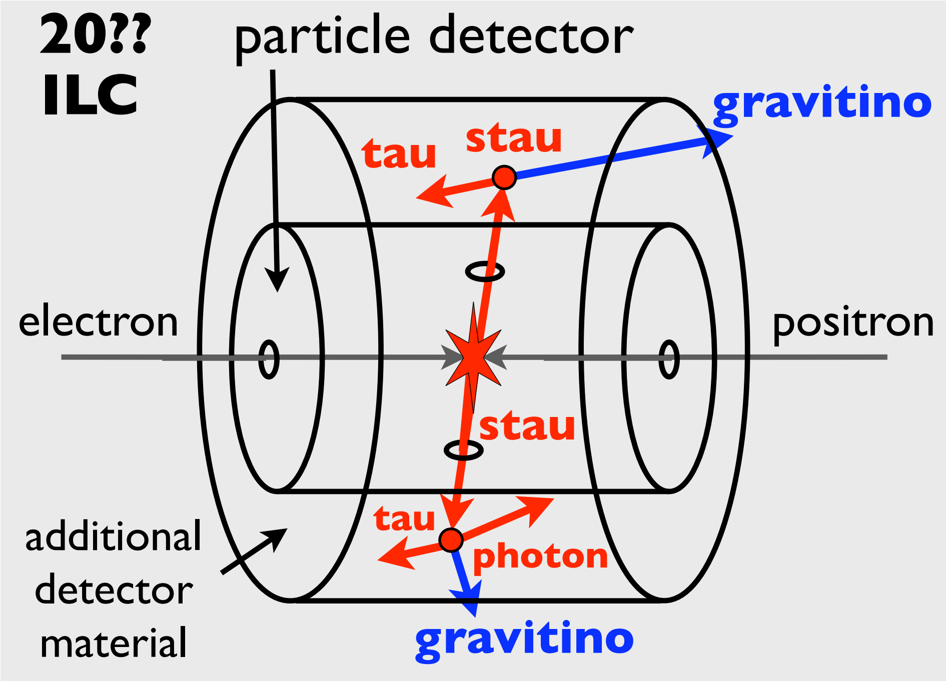
- Direct Detection of $\widetilde{G}$

- Direct Production of $\widetilde{G}$

⁎ “stable” charged sparticles



⁎ long-lived charged sparticles



[... ; Buchmüller et al., ’04; Hamaguchi et al., ’04; Feng, Smith, ’05; Martyn, ’06; ...]

Summary - Well-motivated DM Candidates

candidate	identity	mass	interactions	production	constraints	experiments
a	axion	< 0.01 eV	$(p/f_a)^n$	misalign. mech.	← cold	direct searches with
	(spin 0)		extremely weak			microwave cavities
	N.-Goldst. boson		$f_a \gtrsim 6 \times 10^8$ GeV			$\hookrightarrow m_a,\ f_a,\ g_{a\gamma\gamma}$
	PQ symm. break.				CMB	
$\widetilde{\chi}^0_1$ LSP	lightest neutralino	$\mathcal{O}(100\,\mathrm{GeV})$	g, g', y_i	therm. relic	← cold	indirect searches
	(spin 1/2)		weak	$\widetilde{G}$ decay	← warm/hot	direct searches
	mixture of		$M_{\mathrm{W}} \sim 100$ GeV			collider searches
	$\widetilde{B},\ \widetilde{W},\ \widetilde{H}^0_u,\ \widetilde{H}^0_d$				BBN	$\hookrightarrow m_{\widetilde{\chi}^0_1},\ \widetilde{\chi}^0_1$ coupl.
$\widetilde{G}$ LSP	gravitino	eV–TeV	$(p/\mathrm{M_P})^n$	therm. prod.	← cold	$\widetilde{\tau}_1$ prod. at colliders
	(spin 3/2)		extremely weak	NLSP decay	← warm	$+\ \widetilde{\tau}_1$ collection
	superpartner		$\mathrm{M_P} = 2.4 \times 10^{18}$ GeV			$+\ \widetilde{\tau}_1$ decay analysis
	of the graviton				BBN	$\hookrightarrow m_{\widetilde{G}},\ \mathrm{M_P}\ (?),\ T_{\mathrm{R}}$
$\widetilde{a}$ LSP	axino	eV–GeV	$(p/f_a)^n$	therm. prod.	← cold/warm	$\widetilde{\tau}_1$ prod. at colliders
	(spin 1/2)		extremely weak	NLSP decay	← warm/hot	$+\ \widetilde{\tau}_1$ collection
	superpartner		$f_a \gtrsim 6 \times 10^8$ GeV			$+\ \widetilde{\tau}_1$ decay analysis
	of the axion				BBN	$\hookrightarrow m_{\widetilde{a}}\ (?),\ f_a,\ T_{\mathrm{R}}\ (?)$

Summary - Well-motivated DM Candidates

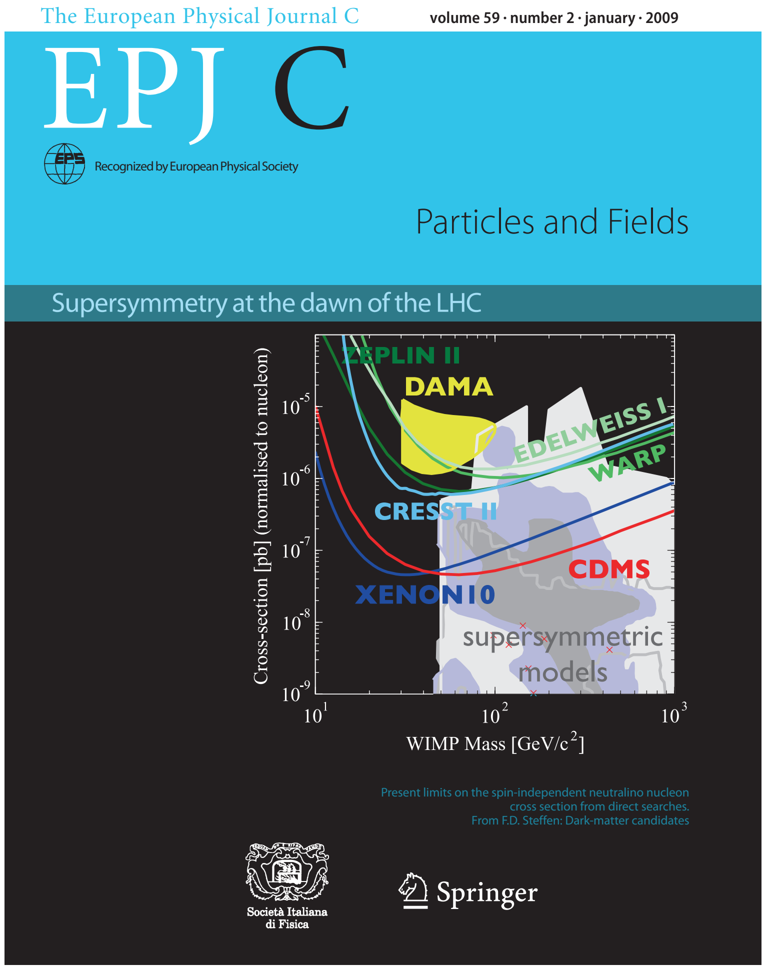
candidate	identity	mass	interactions	production	constraints	experiments
a						
$\widetilde{\chi}^0_1$ LSP						
$\widetilde{G}$ LSP						
$\widetilde{a}$ LSP						

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

see

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

in



The European Physical Journal C volume 59 · number 2 · january · 2009

EPJ C

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Particles and Fields

Supersymmetry at the dawn of the LHC

Present limits on the spin-independent neutralino nucleon cross section from direct searches. From F.D. Steffen: Dark-matter candidates

Società Italiana di Fisica

Springer

Summary - Well-motivated DM Candidates

candidate	identity	mass	interactions	production	constraints	experiments
a	axion	< 0.01 eV	$(p/f_a)^n$	misalign. mech.	← cold	direct searches with
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	PQ symm. break.				CMB	
$\widetilde{\chi}^0_1$ LSP	lightest neutralino	$\mathcal{O}(100\,\mathrm{GeV})$	g, g', y_i	therm. relic	← cold	indirect searches
	(spin 1/2)		weak	$\widetilde{G}$ decay	← warm/hot	direct searches
	mixture of		$M_{\mathrm{W}} \sim 100$ GeV			collider searches
	$\widetilde{B},\ \widetilde{W},\ \widetilde{H}^0_u,\ \widetilde{H}^0_d$				BBN	$\hookrightarrow m_{\widetilde{\chi}^0_1},\ \widetilde{\chi}^0_1$ coupl.
$\widetilde{G}$ LSP	gravitino	eV–TeV	$(p/\mathrm{M_P})^n$	therm. prod.	← cold	$\widetilde{\tau}_1$ prod. at colliders
	(spin 3/2)		extremely weak	NLSP decay	← warm	$+\ \widetilde{\tau}_1$ collection
	superpartner		$\mathrm{M_P} = 2.4 \times 10^{18}$ GeV			$+\ \widetilde{\tau}_1$ decay analysis
	of the graviton				BBN	$\hookrightarrow m_{\widetilde{G}},\ \mathrm{M_P}\ (?),\ T_{\mathrm{R}}$
$\widetilde{a}$ LSP	axino	eV–GeV	$(p/f_a)^n$	therm. prod.	← cold/warm	$\widetilde{\tau}_1$ prod. at colliders
	(spin 1/2)		extremely weak	NLSP decay	← warm/hot	$+\ \widetilde{\tau}_1$ collection
	superpartner		$f_a \gtrsim 6 \times 10^8$ GeV			$+\ \widetilde{\tau}_1$ decay analysis
	of the axion				BBN	$\hookrightarrow m_{\widetilde{a}}\ (?),\ f_a,\ T_{\mathrm{R}}\ (?)$

Scenario I - Axion CDM (+ SUSY DM)

events

candidate	identity	mass	interactions	production	constraints	experiments
a	axion	< 0.01 eV	$(p/f_a)^n$	misalign. mech.	← cold	direct searches with
	(spin 0)		extremely weak			microwave cavities
	N.-Goldst. boson		$f_a \gtrsim 6 \times 10^8$ GeV			$\hookrightarrow m_a,\ f_a,\ g_{a\gamma\gamma}$
	PQ symm. break.				CMB	
$\widetilde{\chi}^0_1$ LSP	lightest neutralino	$\mathcal{O}(100\,\mathrm{GeV})$	g, g', y_i	therm. relic	← cold	indirect searches
	(spin 1/2)		weak	$\widetilde{G}$ decay	← warm/hot	direct searches
	mixture of		$M_{\mathrm{W}} \sim 100$ GeV			collider searches
	$\widetilde{B},\ \widetilde{W},\ \widetilde{H}^0_u,\ \widetilde{H}^0_d$				BBN	$\hookrightarrow m_{\widetilde{\chi}^0_1},\ \widetilde{\chi}^0_1$ coupl.
$\widetilde{G}$ LSP	gravitino	eV–TeV	$(p/\mathrm{M_P})^n$	therm. prod.	← cold	$\widetilde{\tau}_1$ prod. at colliders
	(spin 3/2)		extremely weak	NLSP decay	← warm	$+\ \widetilde{\tau}_1$ collection
	superpartner		$\mathrm{M_P} = 2.4 \times 10^{18}$ GeV			$+\ \widetilde{\tau}_1$ decay analysis
	of the graviton				BBN	$\hookrightarrow m_{\widetilde{G}},\ \mathrm{M_P}$ (?), T_{R}
$\widetilde{a}$ LSP	axino	eV–GeV	$(p/f_a)^n$	therm. prod.	← cold/warm	$\widetilde{\tau}_1$ prod. at colliders
	(spin 1/2)		extremely weak	NLSP decay	← warm/hot	$+\ \widetilde{\tau}_1$ collection
	superpartner		$f_a \gtrsim 6 \times 10^8$ GeV			$+\ \widetilde{\tau}_1$ decay analysis
	of the axion				BBN	$\hookrightarrow m_{\widetilde{a}}$ (?), f_a, T_{R} (?)

Scenario I - Axion CDM (+ SUSY DM)

events

candidate	identity	mass	interactions	production	constraints	experiments
a	axion (spin 0) N.-Goldst. boson PQ symm. break.	< 0.01 eV	$(p/f_a)^n$ extremely weak $f_a \gtrsim 6 \times 10^8$ GeV	misalign. mech.	← cold CMB	direct searches with microwave cavities $\hookrightarrow m_a,\ f_a,\ g_{a\gamma\gamma}$
$\widetilde{\chi}_1^0$ LSP	lightest neutralino (spin 1/2) mixture of $\widetilde{B},\ \widetilde{W},\ \widetilde{H}_u^0,\ \widetilde{H}_d^0$	$\mathcal{O}(100\,\mathrm{GeV})$	g, g', y_i weak $M_{\mathrm{W}} \sim 100$ GeV	therm. relic $\widetilde{G}$ decay	← cold ← warm/hot BBN	indirect searches direct searches collider searches $\hookrightarrow m_{\widetilde{\chi}_1^0},\ \widetilde{\chi}_1^0$ coupl.
$\widetilde{G}$ LSP	gravitino (spin 3/2) superpartner of the graviton	eV–TeV	$(p/\mathrm{M_P})^n$ extremely weak $\mathrm{M_P} = 2.4 \times 10^{18}$ GeV	therm. prod. NLSP decay	← cold ← warm BBN	$\widetilde{\tau}_1$ prod. at colliders $+\ \widetilde{\tau}_1$ collection $+\ \widetilde{\tau}_1$ decay analysis $\hookrightarrow m_{\widetilde{G}},\ \mathrm{M_P}$ (?), T_{R}
$\widetilde{a}$ LSP	axino (spin 1/2) superpartner of the axion	eV–GeV	$(p/f_a)^n$ extremely weak $f_a \gtrsim 6 \times 10^8$ GeV	therm. prod. NLSP decay	← cold/warm ← warm/hot BBN	$\widetilde{\tau}_1$ prod. at colliders $+\ \widetilde{\tau}_1$ collection $+\ \widetilde{\tau}_1$ decay analysis $\hookrightarrow m_{\widetilde{a}}$ (?), f_a, T_{R} (?)

still viable

Scenario 2 - WIMP DM (+ Axion DM)

candidate	identity	mass	interactions	production	constraints	experiments
a	axion (spin 0) N.-Goldst. boson PQ symm. break.	< 0.01 eV	$(p/f_a)^n$ extremely weak $f_a \gtrsim 6 \times 10^8$ GeV	misalign. mech.	← cold CMB	direct searches with microwave cavities $\hookrightarrow m_a,\ f_a,\ g_{a\gamma\gamma}$
$\widetilde{\chi}^0_1$ LSP	lightest neutralino (spin 1/2) mixture of $\widetilde{B},\ \widetilde{W},\ \widetilde{H}^0_u,\ \widetilde{H}^0_d$	$\mathcal{O}(100\,\mathrm{GeV})$	g, g', y_i weak $M_W \sim 100$ GeV	therm. relic $\widetilde{G}$ decay	← cold ← warm/hot BBN	indirect searches events direct searches collider searches $\hookrightarrow m_{\widetilde{\chi}^0_1},\ \widetilde{\chi}^0_1$ coupl.
$\widetilde{G}$ LSP	gravitino (spin 3/2) superpartner of the graviton	eV–TeV	$(p/\mathrm{M_P})^n$ extremely weak $\mathrm{M_P} = 2.4 \times 10^{18}$ GeV	therm. prod. NLSP decay	← cold ← warm BBN	$\widetilde{\tau}_1$ prod. at colliders + $\widetilde{\tau}_1$ collection + $\widetilde{\tau}_1$ decay analysis $\hookrightarrow m_{\widetilde{G}},\ \mathrm{M_P}$ (?), T_R
$\widetilde{a}$ LSP	axino (spin 1/2) superpartner of the axion	eV–GeV	$(p/f_a)^n$ extremely weak $f_a \gtrsim 6 \times 10^8$ GeV	therm. prod. NLSP decay	← cold/warm ← warm/hot BBN	$\widetilde{\tau}_1$ prod. at colliders + $\widetilde{\tau}_1$ collection + $\widetilde{\tau}_1$ decay analysis $\hookrightarrow m_{\widetilde{a}}$ (?), f_a, T_R (?)

Scenario 2 - WIMP DM (+ Axion DM)

candidate	identity	mass	interactions	production	constraints	experiments
a	axion (spin 0) N.-Goldst. boson PQ symm. break.	< 0.01 eV	$(p/f_a)^n$ extremely weak $f_a \gtrsim 6 \times 10^8$ GeV	misalign. mech.	← cold CMB	direct searches with microwave cavities $\hookrightarrow m_a,\ f_a,\ g_{a\gamma\gamma}$ still viable
$\widetilde{\chi}_1^0$ LSP	lightest neutralino (spin 1/2) mixture of $\widetilde{B}, \widetilde{W}, \widetilde{H}_u^0, \widetilde{H}_d^0$	$\mathcal{O}(100\,\mathrm{GeV})$	g, g', y_i weak $M_W \sim 100$ GeV	therm. relic $\widetilde{G}$ decay	← cold ← warm/hot BBN	indirect searches events direct searches collider searches $\hookrightarrow m_{\widetilde{\chi}_1^0},\ \widetilde{\chi}_1^0$ coupl.
$\widetilde{G}$ LSP	gravitino (spin 3/2) superpartner of the graviton	eV–TeV	$(p/\mathrm{M_P})^n$ extremely weak $\mathrm{M_P} = 2.4 \times 10^{18}$ GeV	therm. prod. NLSP decay	← cold ← warm BBN	$\widetilde{\tau}_1$ prod. at colliders + $\widetilde{\tau}_1$ collection + $\widetilde{\tau}_1$ decay analysis $\hookrightarrow m_{\widetilde{G}},\ \mathrm{M_P}$ (?), T_R
$\widetilde{a}$ LSP	axino (spin 1/2) superpartner of the axion	eV–GeV	$(p/f_a)^n$ extremely weak $f_a \gtrsim 6 \times 10^8$ GeV	therm. prod. NLSP decay	← cold/warm ← warm/hot BBN	$\widetilde{\tau}_1$ prod. at colliders + $\widetilde{\tau}_1$ collection + $\widetilde{\tau}_1$ decay analysis $\hookrightarrow m_{\widetilde{a}}$ (?), f_a, T_R (?)

Scenario 3 - EWIP DM (+ Axion DM)

candidate	identity	mass	interactions	production	constraints	experiments
a	axion (spin 0) N.-Goldst. boson PQ symm. break.	< 0.01 eV	$(p/f_a)^n$ extremely weak $f_a \gtrsim 6 \times 10^8$ GeV	misalign. mech.	← cold CMB	direct searches with microwave cavities $\hookrightarrow m_a,\, f_a,\, g_{a\gamma\gamma}$
$\widetilde{\chi}^0_1$ LSP	lightest neutralino (spin 1/2) mixture of $\widetilde{B},\, \widetilde{W},\, \widetilde{H}^0_u,\, \widetilde{H}^0_d$	$\mathcal{O}(100\,\mathrm{GeV})$	g, g', y_i weak $M_W \sim 100$ GeV	therm. relic $\widetilde{G}$ decay	← cold ← warm/hot BBN	indirect searches direct searches collider searches $\hookrightarrow m_{\widetilde{\chi}^0_1},\, \widetilde{\chi}^0_1$ coupl.
$\widetilde{G}$ LSP	gravitino (spin 3/2) superpartner of the graviton	eV–TeV	$(p/\mathrm{M_P})^n$ extremely weak $\mathrm{M_P} = 2.4 \times 10^{18}$ GeV	therm. prod. NLSP decay	← cold ← warm BBN	events $\widetilde{\tau}_1$ prod. at colliders + $\widetilde{\tau}_1$ collection + $\widetilde{\tau}_1$ decay analysis $\hookrightarrow m_{\widetilde{G}},\, \mathrm{M_P}$ (?), T_R
$\widetilde{a}$ LSP	axino (spin 1/2) superpartner of the axion	eV–GeV	$(p/f_a)^n$ extremely weak $f_a \gtrsim 6 \times 10^8$ GeV	therm. prod. NLSP decay	← cold/warm ← warm/hot BBN	$\widetilde{\tau}_1$ prod. at colliders + $\widetilde{\tau}_1$ collection events + $\widetilde{\tau}_1$ decay analysis $\hookrightarrow m_{\widetilde{a}}$ (?), f_a, T_R (?)

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$\widetilde{\chi}^0_1$ LSP	lightest neutralino (spin 1/2) mixture of $\widetilde{B}$, $\widetilde{W}$, $\widetilde{H}^0_u$, $\widetilde{H}^0_d$	$\mathcal{O}(100\,\mathrm{GeV})$	g, g', y_i weak $M_\mathrm{W} \sim 100$ GeV	therm. relic $\widetilde{G}$ decay	← cold ← warm/hot BBN	indirect searches direct searches collider searches ↪ $m_{\widetilde{\chi}^0_1}$, $\widetilde{\chi}^0_1$ coupl.
$\widetilde{G}$ LSP	gravitino (spin 3/2) superpartner of the graviton	eV–TeV	$(p/\mathrm{M_P})^n$ extremely weak $\mathrm{M_P} = 2.4 \times 10^{18}$ GeV	therm. prod. NLSP decay	← cold ← warm BBN	$\widetilde{\tau}_1$ prod. at colliders + $\widetilde{\tau}_1$ collection + $\widetilde{\tau}_1$ decay analysis ↪ $m_{\widetilde{G}}$, $\mathrm{M_P}$ (?), T_R
$\widetilde{a}$ LSP	axino (spin 1/2) superpartner of the axion	eV–GeV	$(p/f_a)^n$ extremely weak $f_a \gtrsim 6 \times 10^8$ GeV	therm. prod. NLSP decay	← cold/warm ← warm/hot BBN	$\widetilde{\tau}_1$ prod. at colliders + $\widetilde{\tau}_1$ collection + $\widetilde{\tau}_1$ decay analysis ↪ $m_{\widetilde{a}}$ (?), f_a, T_R (?)

still viable

events

events

still viable

Conclusion

To clarify the (particle ?) identity
of dark matter,
it will be crucial to have
experimental & obs. data from the
many complementary approaches:
direct, indirect & collider dm searches