Dark Matter, Particle Physics and the LHC

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Excellence Cluster Universe

International School of Nuclear Physics
Erice, September 19th, 2010

Contents today

photons

$\Omega_\gamma = 0.005\ \%$

baryons

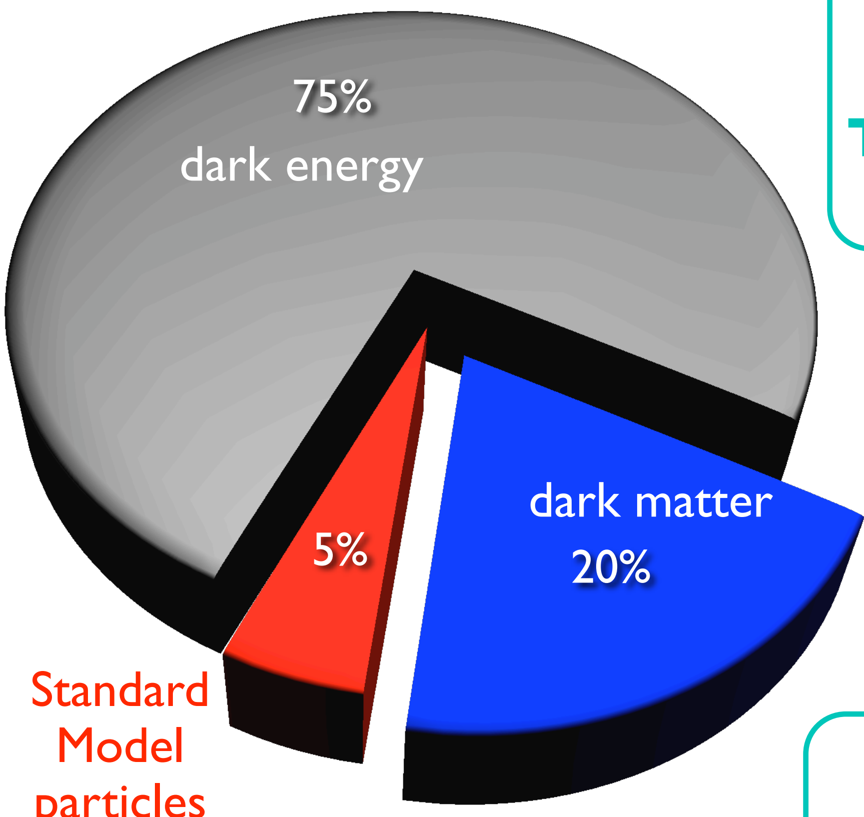
$\Omega_B = 4\ \%$

? baryon asymmetry ?

neutrinos

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

? neutrino mass ?



dark energy

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

? vacuum energy ?

Evidence for DE

↓

Talks by Reynald Pain, Dominik Schwarz

dark matter

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

? identity ?

Evidence for DM

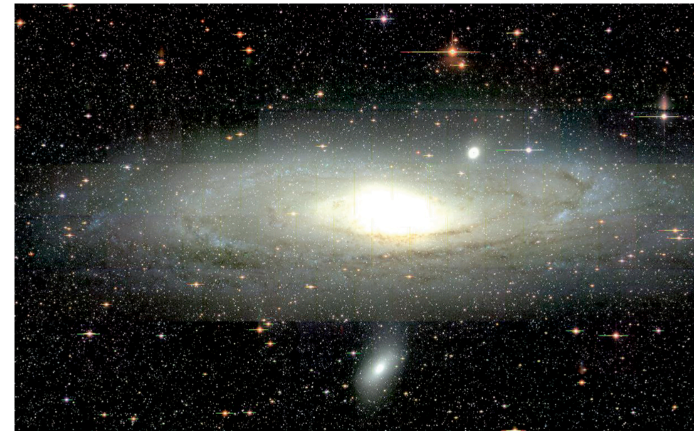
↓

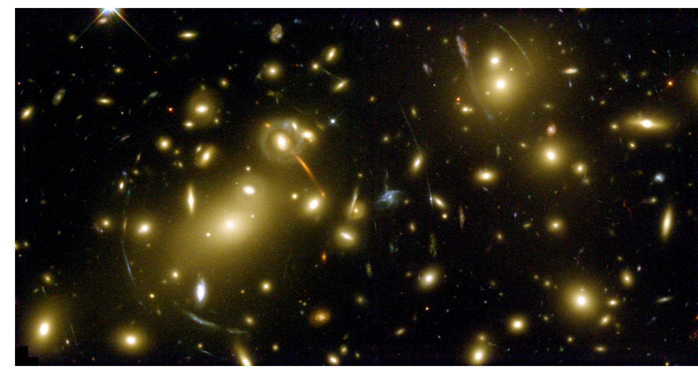
Talks by Josef Jochum, Christian Weinheimer

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

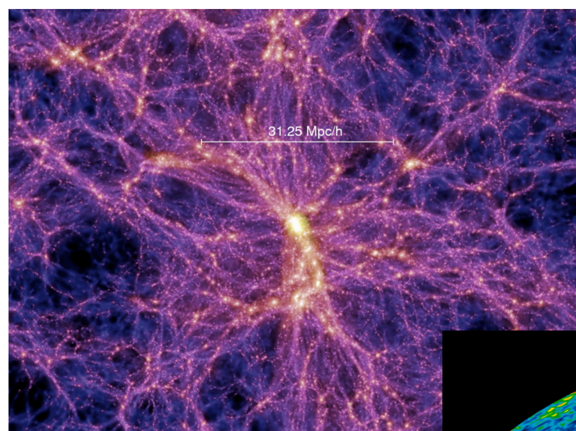
Properties of Dark Matter

- stable or lifetime well above the age of our Universe

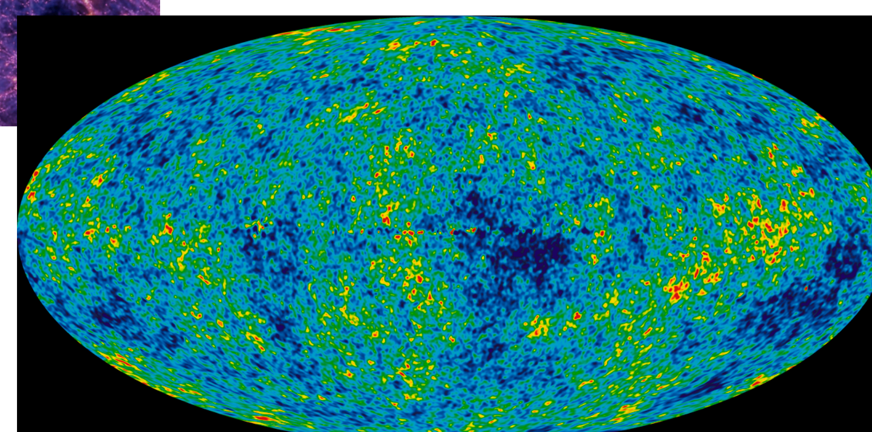




- electrically neutral
- clusters →



- "cold"
- dissipationless
- color neutral



The Standard Model

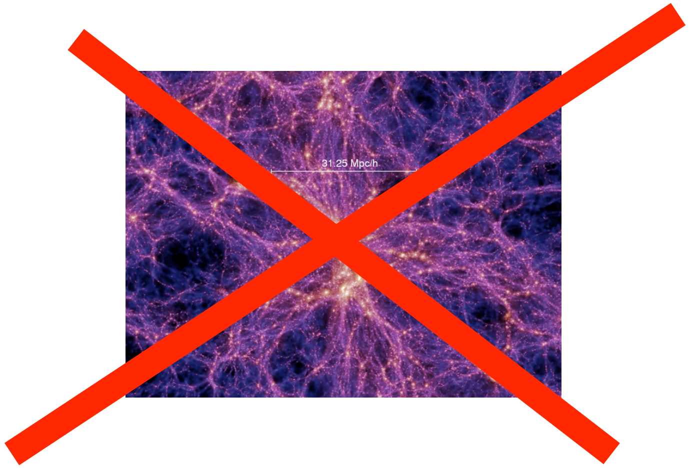
GAUGE	Gauge bosons	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
B-boson	$A_\mu^{(1)} = B_\mu$	$(\mathbf{1}, \mathbf{1})_0$
W-bosons	$A_\mu^{(2)\,a} = W_\mu^a$	$(\mathbf{1}, \mathbf{3})_0$
gluon	$A_\mu^{(3)\,a} = G_\mu^a$	$(\mathbf{8}, \mathbf{1})_0$

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

Properties of Neutrino Dark Matter

- stable $\rightarrow \tau_{\mathrm{DM}} \gtrsim$ age of our Universe
- clusters $\leftarrow$ gravitation
- fast – "hot"
- electrically neutral
- color neutral



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

Neutrino Dark Matter = Hot Dark Matter

in conflict with Large Scale Structure

The Standard Model

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

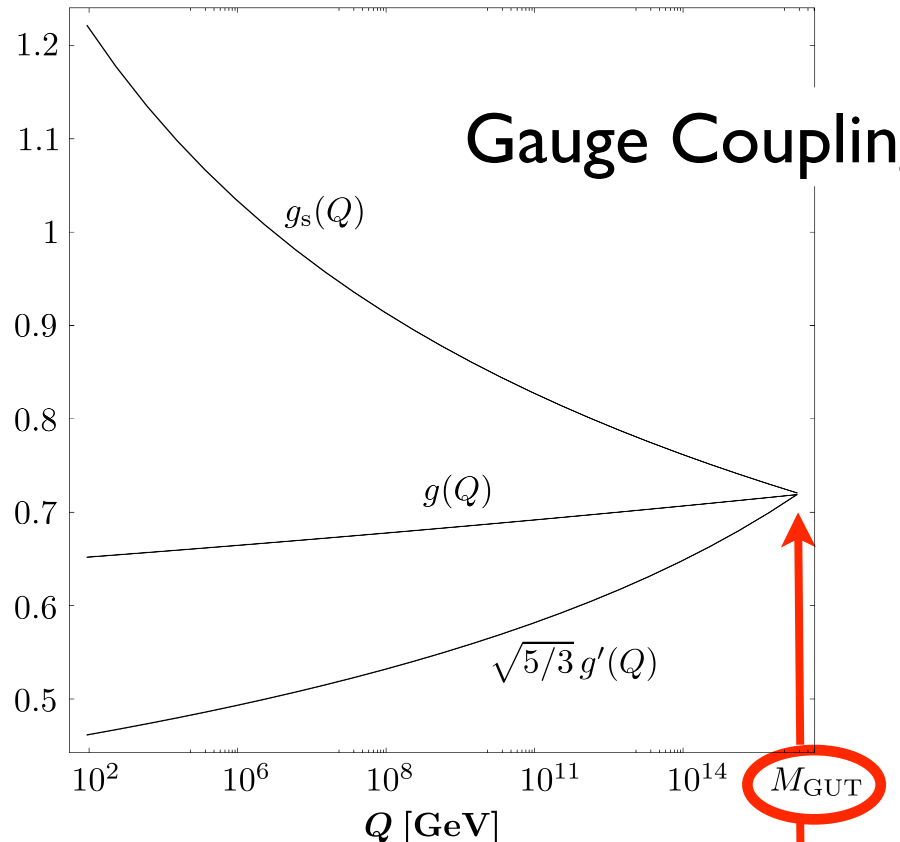
MATTER	Sfermions	Fermions	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
sleptons, leptons $I = 1, 2, 3$	$\widetilde{L}^I = \begin{pmatrix} \widetilde{\nu}_L^I \\ \widetilde{e}_L^{-\,I} \end{pmatrix}$	$L^I = \begin{pmatrix} \nu_L^I \\ e_L^{-\,I} \end{pmatrix}$	$(\mathbf{1},\mathbf{2})_{-1}$
	$\widetilde{E}^{*I} = \widetilde{e}_R^{-\,*\,I}$	$E^{c\,I} = e_R^{-\,c\,I}$	$(\mathbf{1},\mathbf{1})_{+2}$
squarks, quarks $I = 1, 2, 3$ (× 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

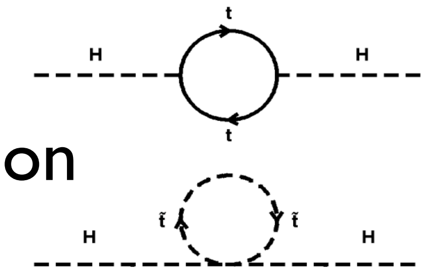
Why Supersymmetry?

Extension of Space-Time Symmetry



Gauge Coupling Unification

Hierarchy Stabilization



(Super-) Gravity

Consistent String Theory

Dark Matter

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

Supersymmetry

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$(\times\ 3$ colors)	$\widetilde{U}^{*I} = \widetilde{u}_R^{*I}$	$U^{c\,I} = u_R^{c\,I}$	$(\overline{\mathbf{3}},\mathbf{1})_{-\frac{4}{3}}$
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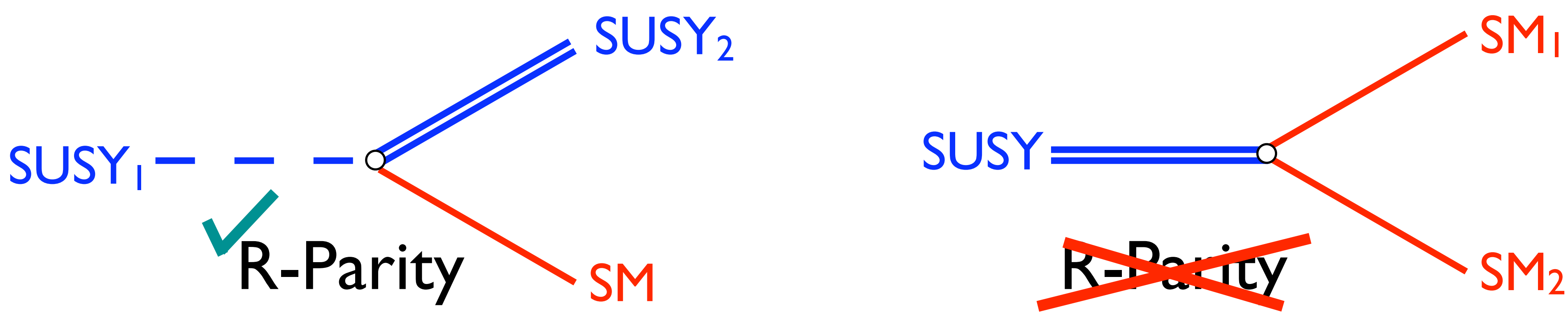
Minimal
Supersymmetric
Extension
of the
Standard Model

Every Particle
of the
Standard Model
has a
Superpartner

Conservation of R-Parity

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

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



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

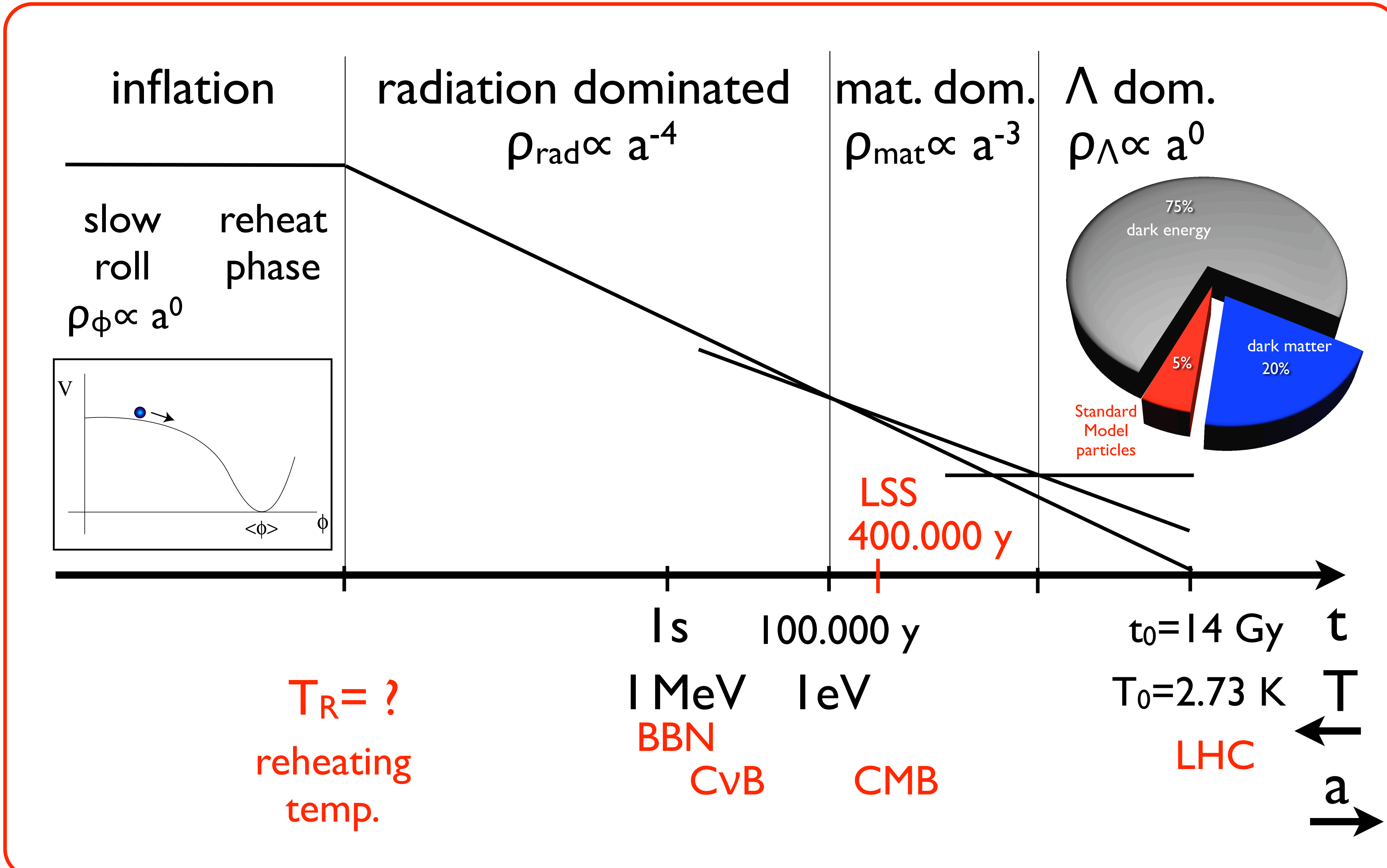
Supersymmetric Dark Matter Candiates

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

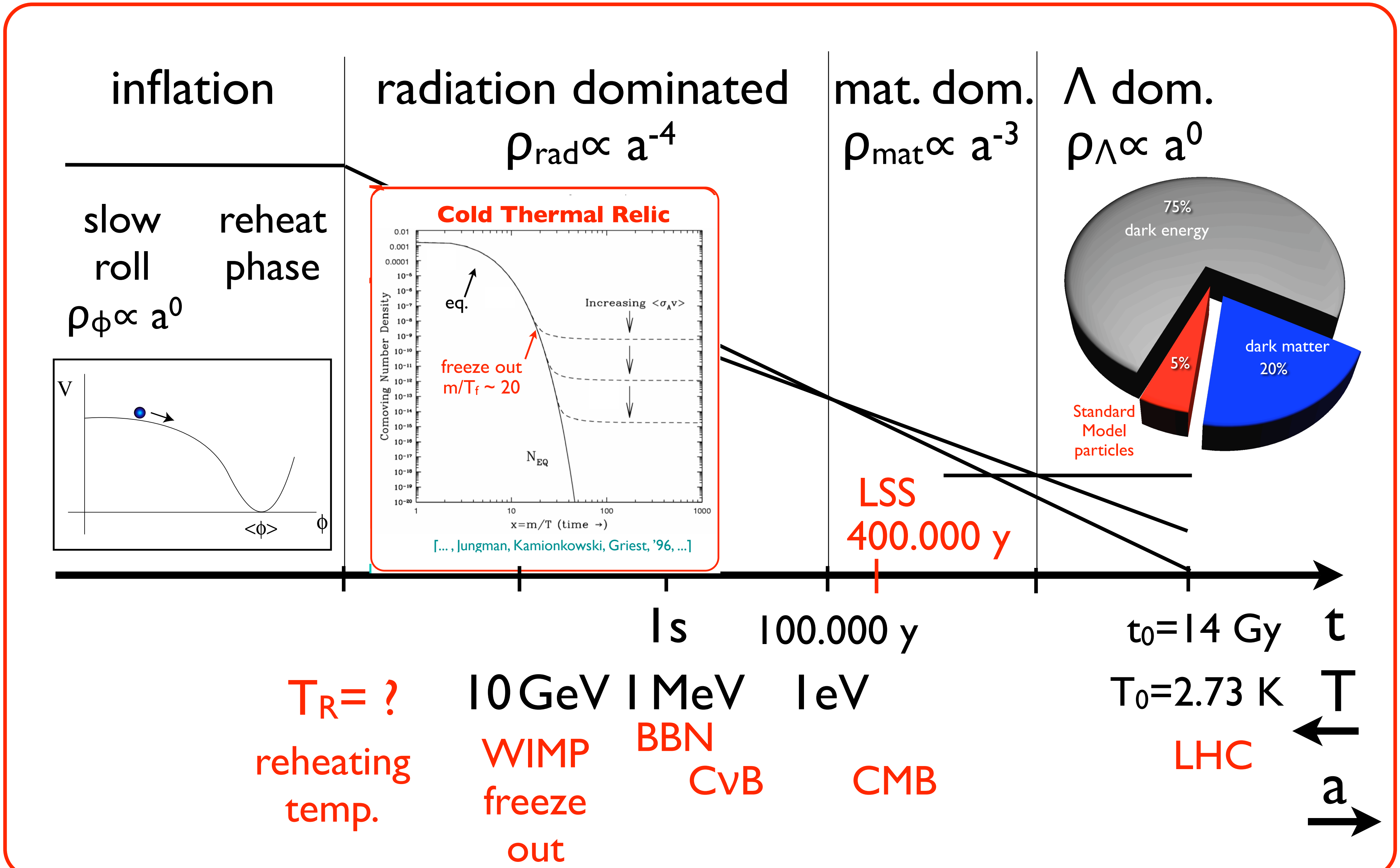
Weakly
Interacting
Massive
Particle

["Heavy Neutrino"]

Standard Thermal History of the Universe



Standard Thermal History of the Universe

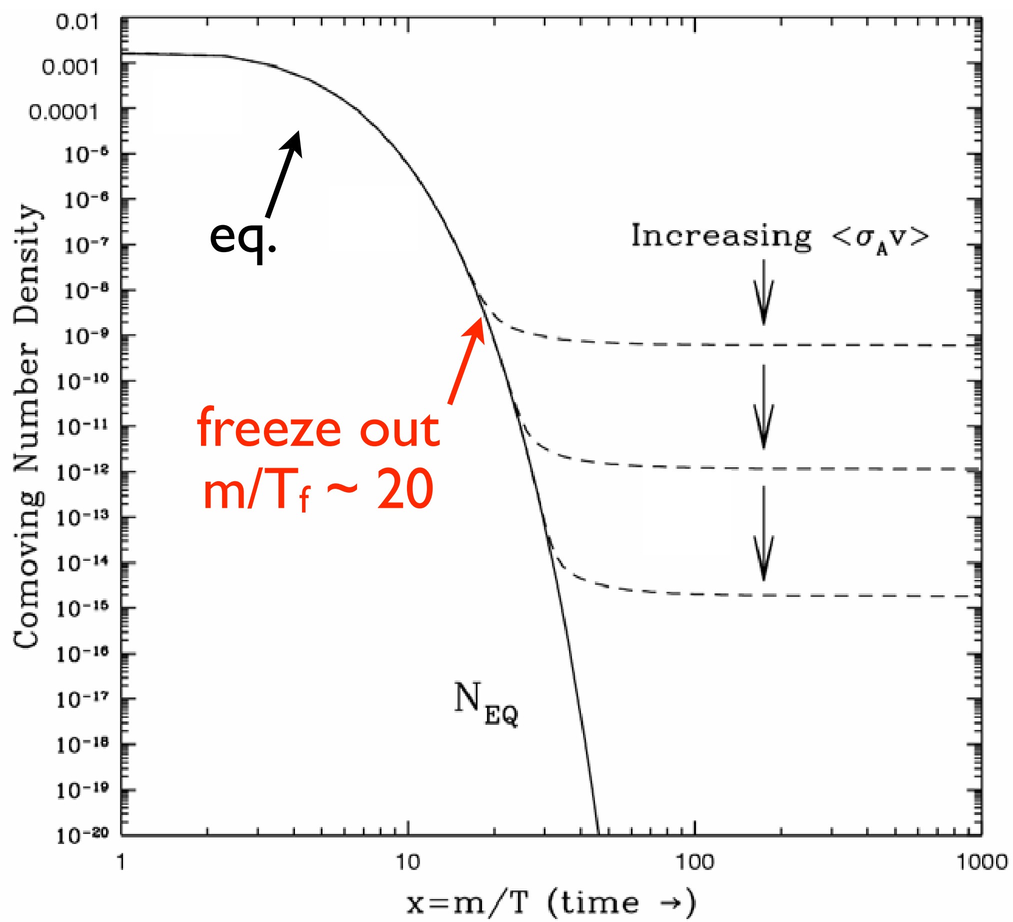


$\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints

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

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

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' weak	WIMP freeze out	← cold

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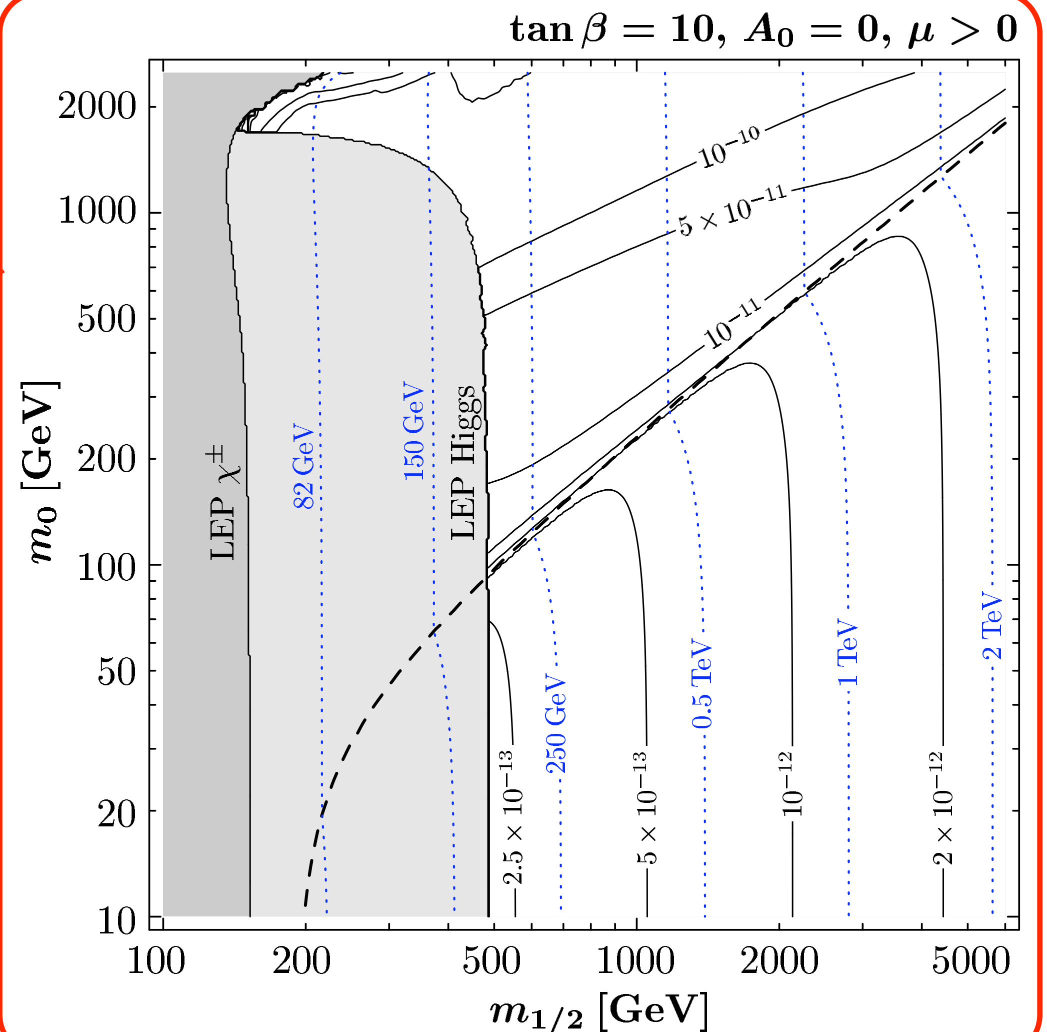
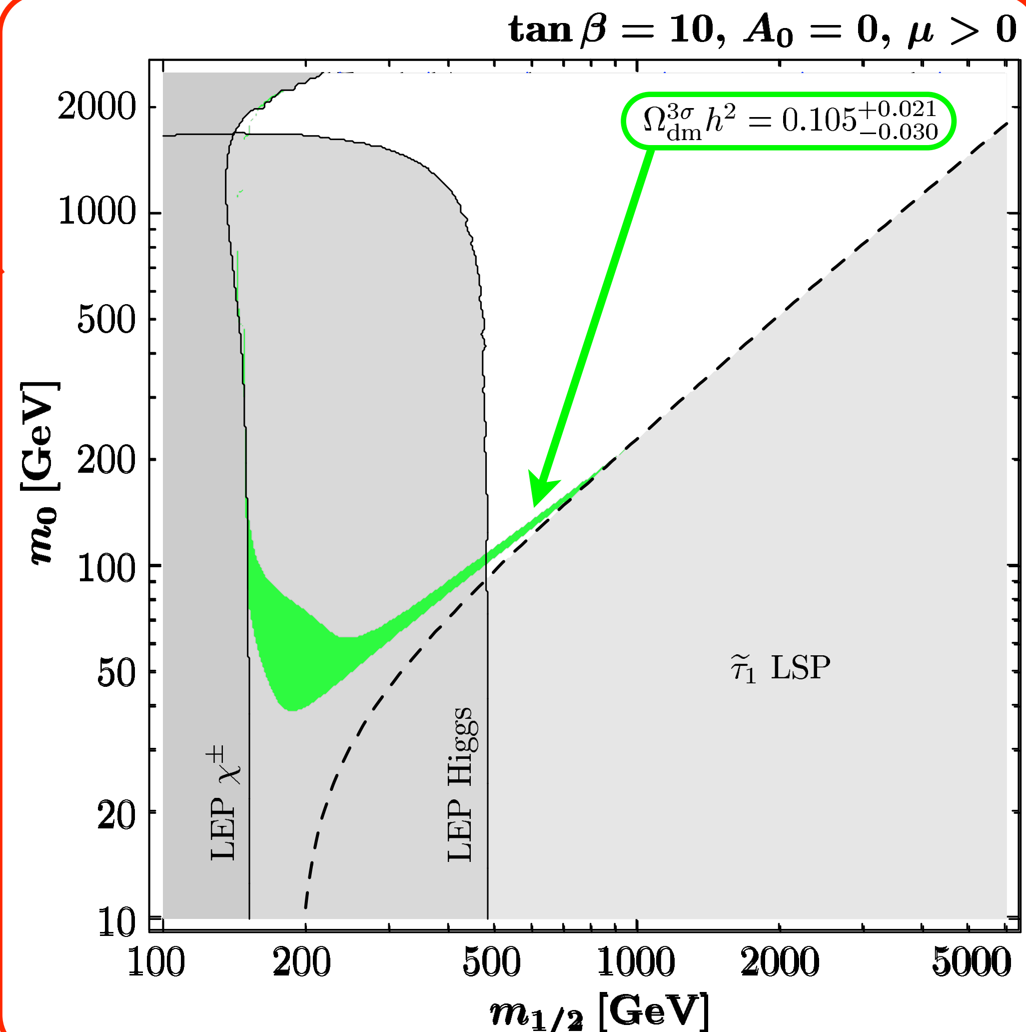


$\Omega_{\widetilde{\chi}_1^0} = \Omega_{\rm DM}$ **is possible!!!**

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

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

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



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

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

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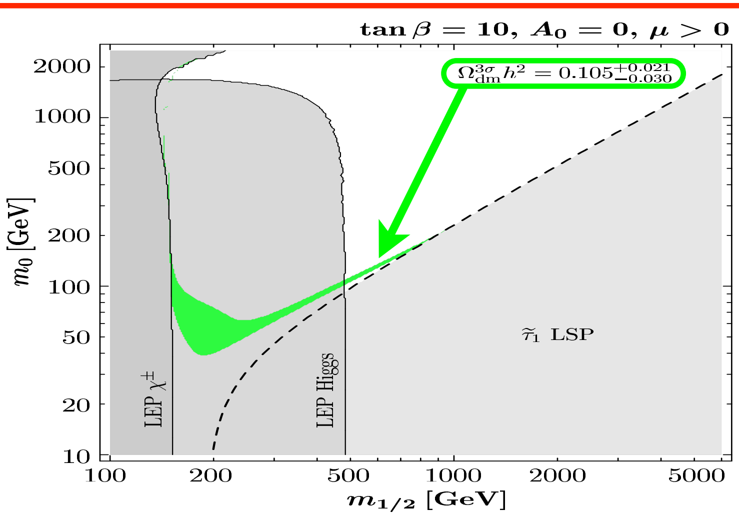

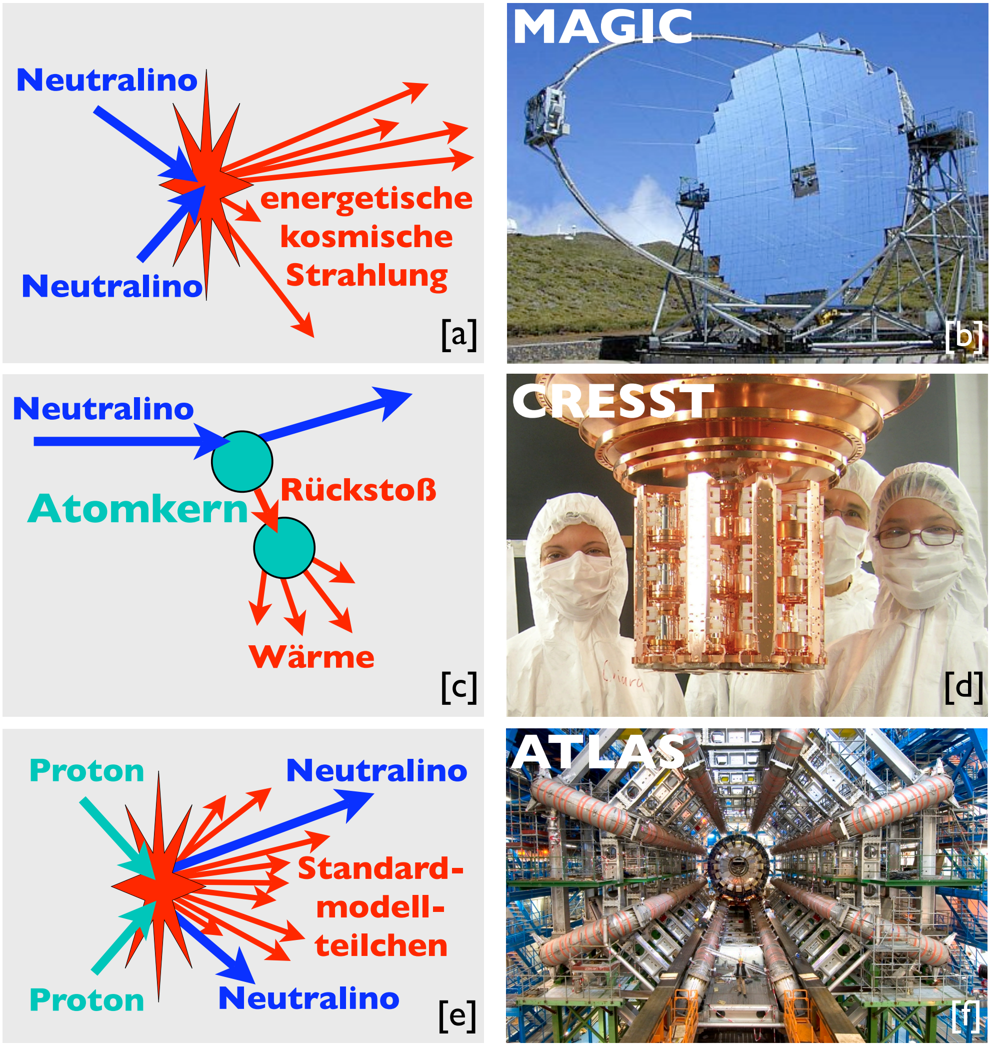

promising experimental prospects

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

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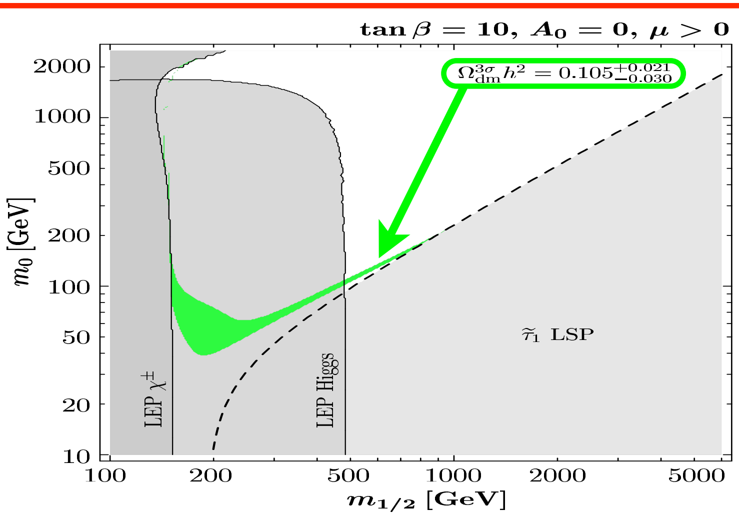

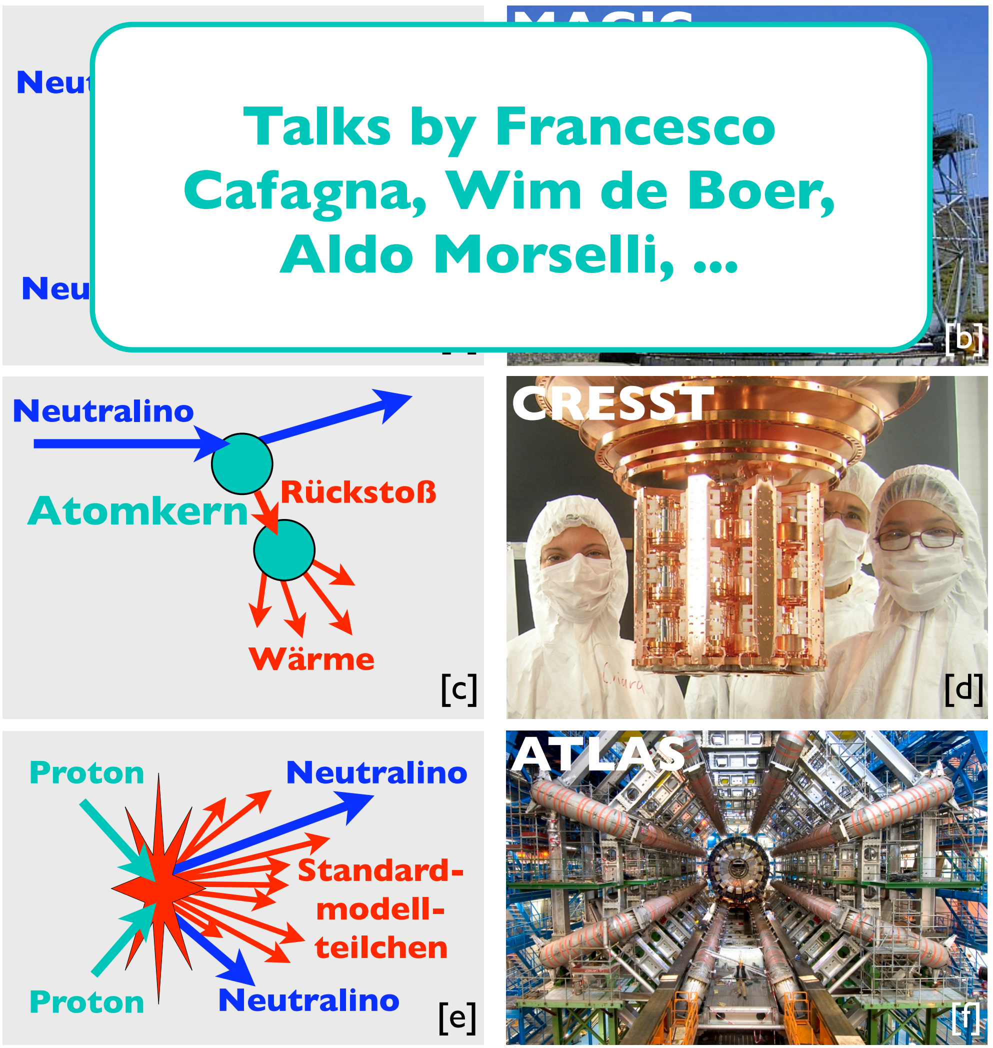

Talks by Francesco Cafagna, Wim de Boer, Aldo Morselli, ...

promising experimental prospects

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

LSP	interaction	production	constraints	experiments
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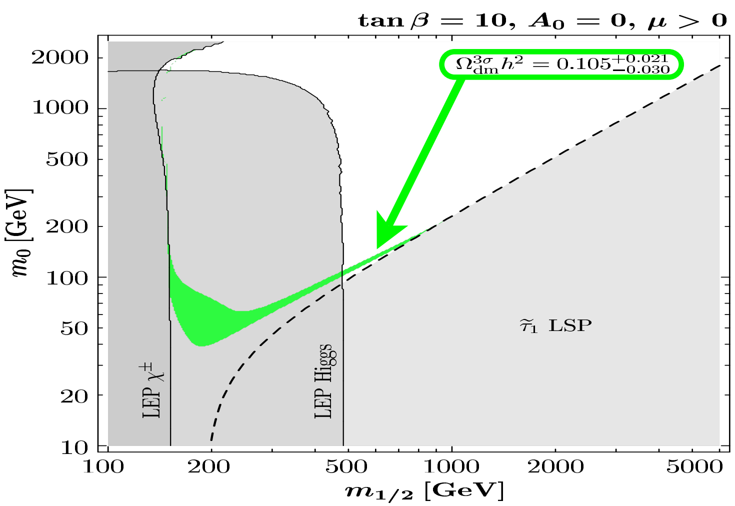

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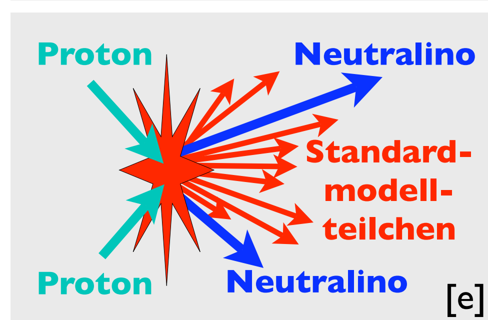
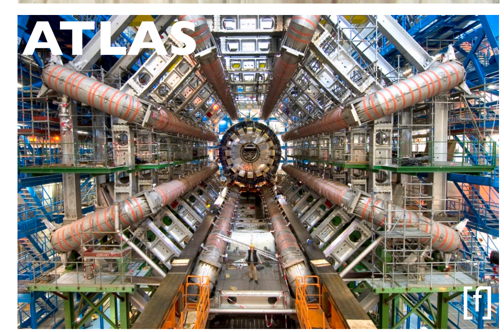
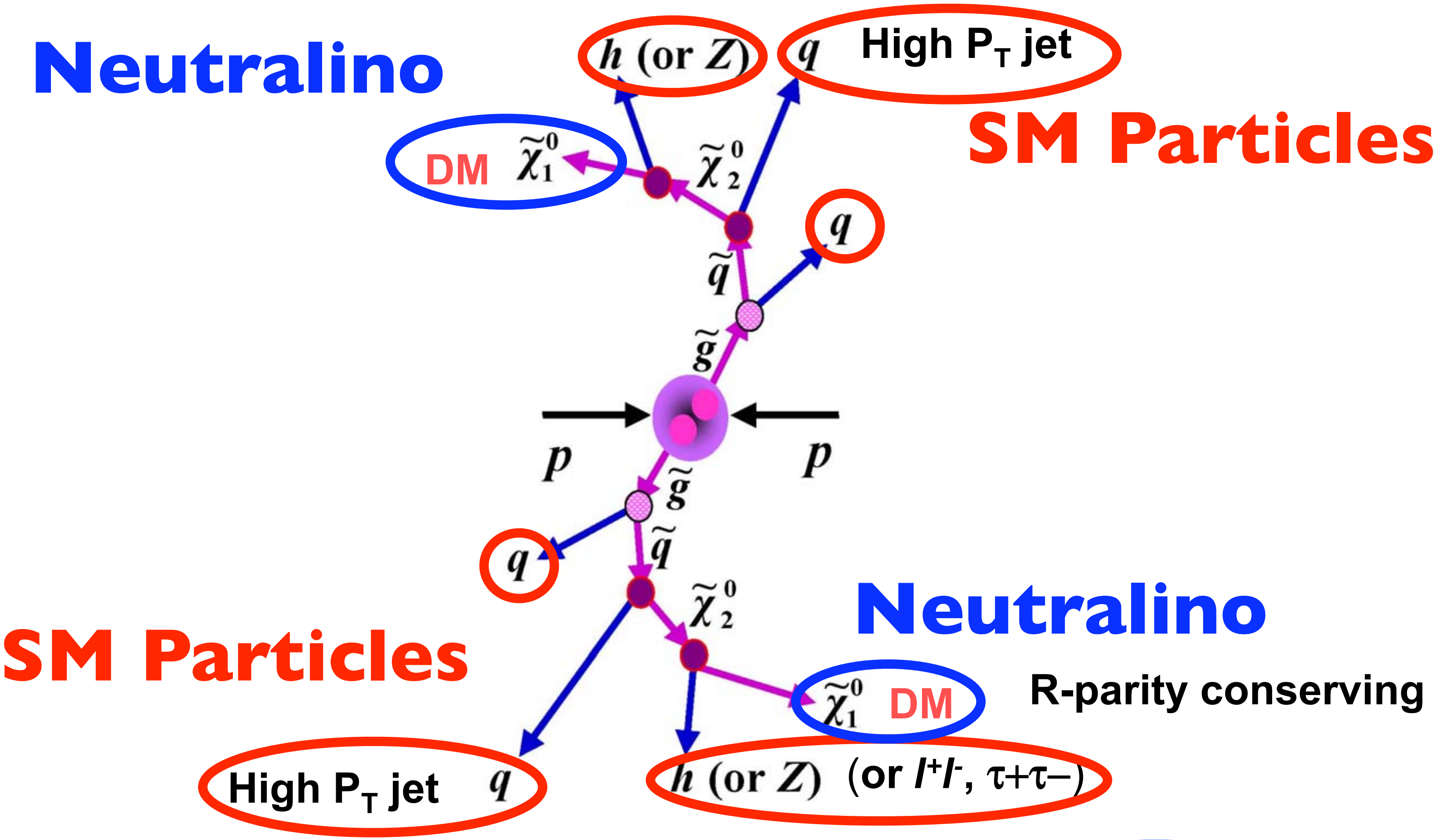
Talks by Josef Jochum, Rita Bernabei, Enectali Fiugueroa-Feliciano, Christian Weinheimer





promising experimental prospects

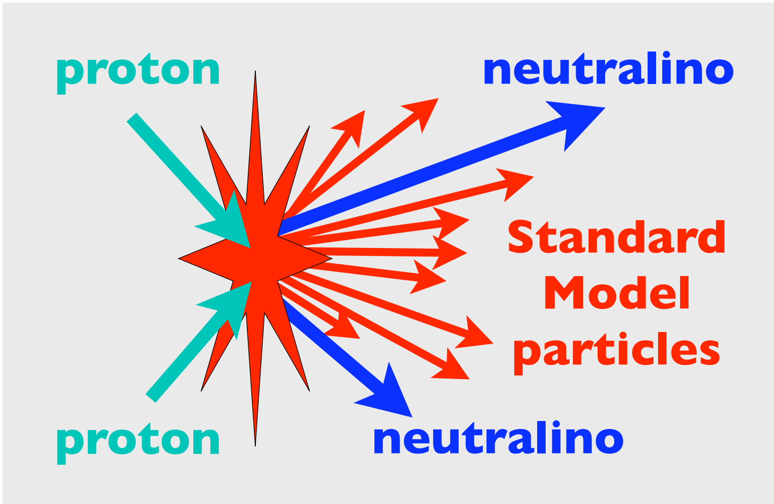
Neutralino DM Production at the LHC



The signal : jets + leptons + missing E_T

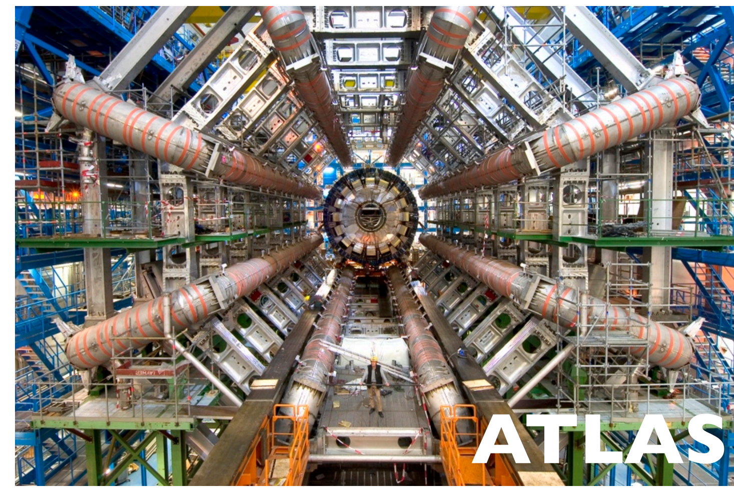
[from B. Dutta's Talk, SUSY 2007]

Collider Searches

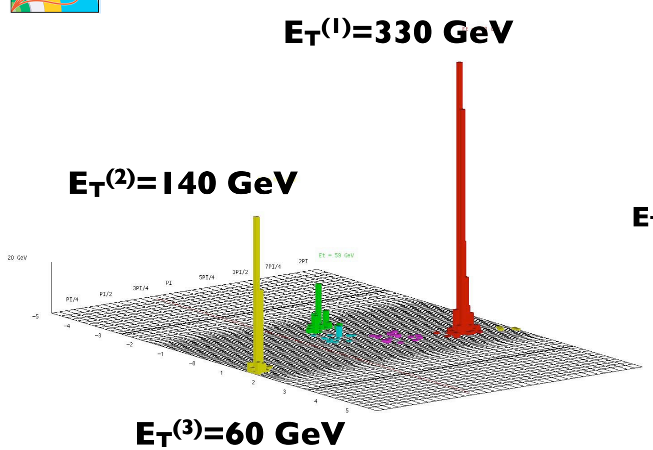


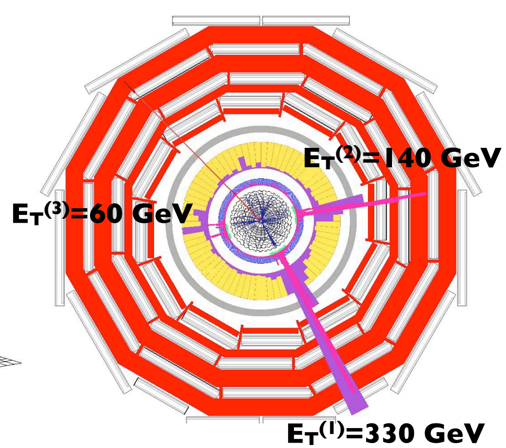
ongoing searches at Tevatron
pp @ 2 TeV

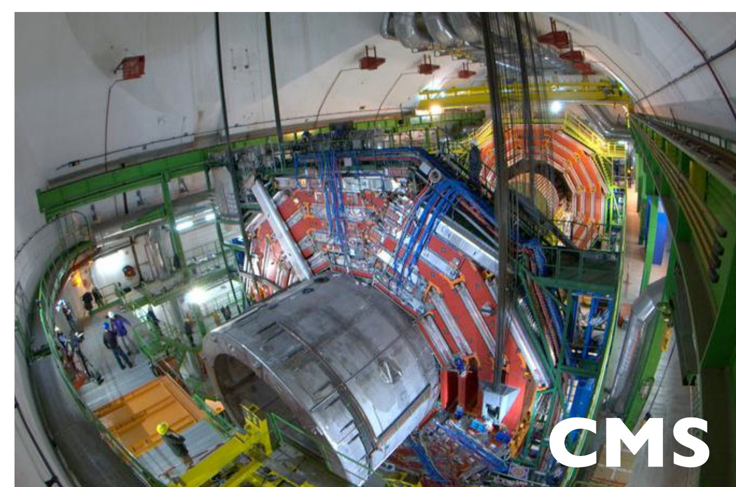
CDF D0



$E_T^{missing}$=360 GeV





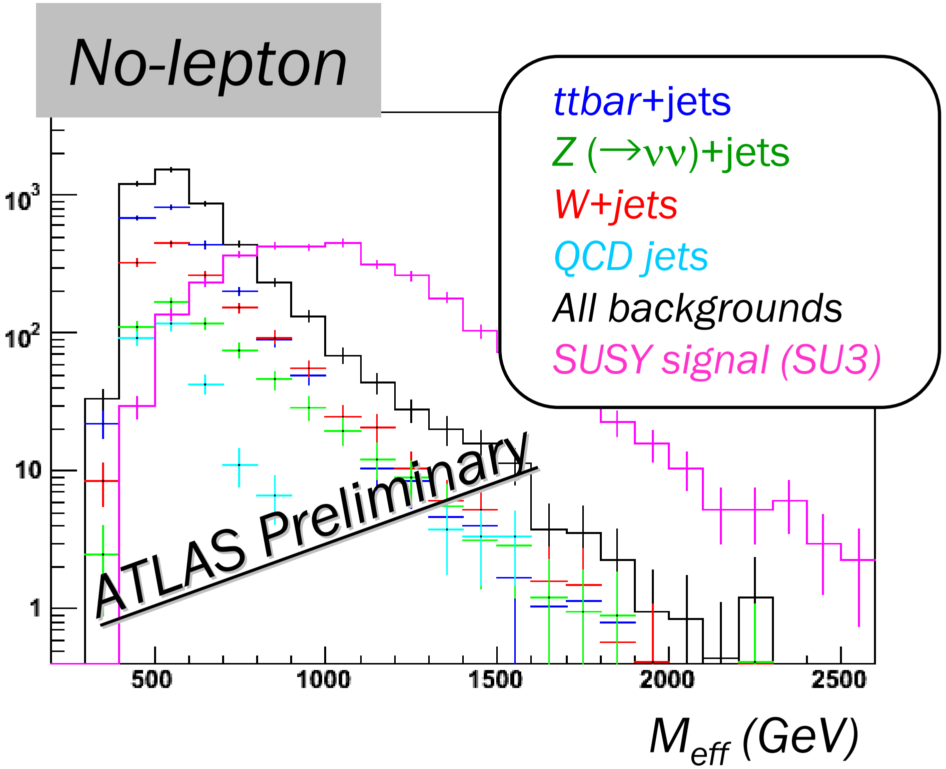


The signal:

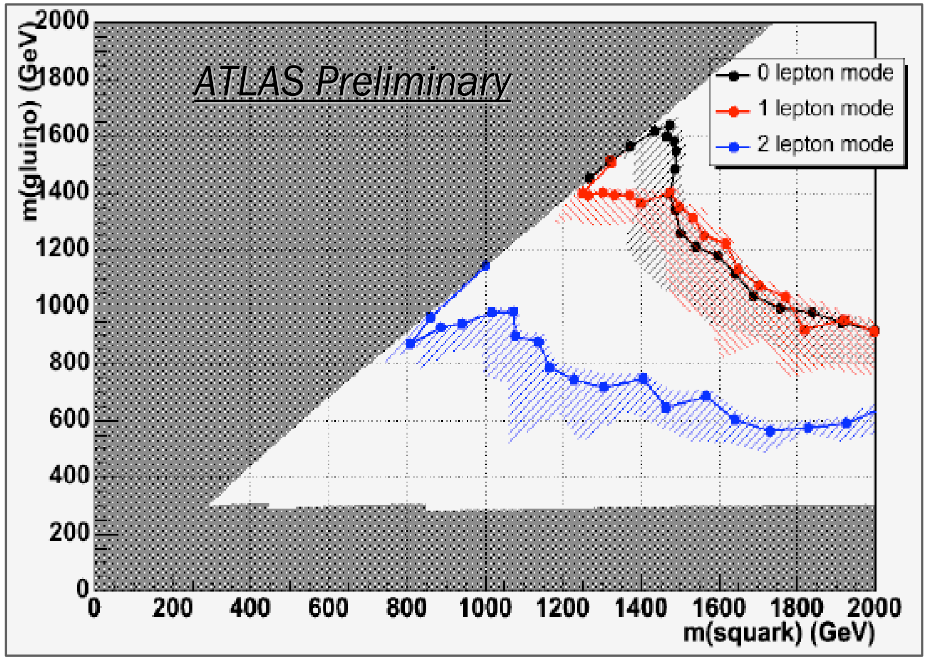
jets + leptons + large E_T^{miss}

Early SUSY Searches @ ATLAS

Benchmark point SU3:
m_0=100GeV, $m_{1/2}$=300GeV, A_0=-300, tanβ=6, sign(μ)=+



Discovery potential with L~1fb^{-1}

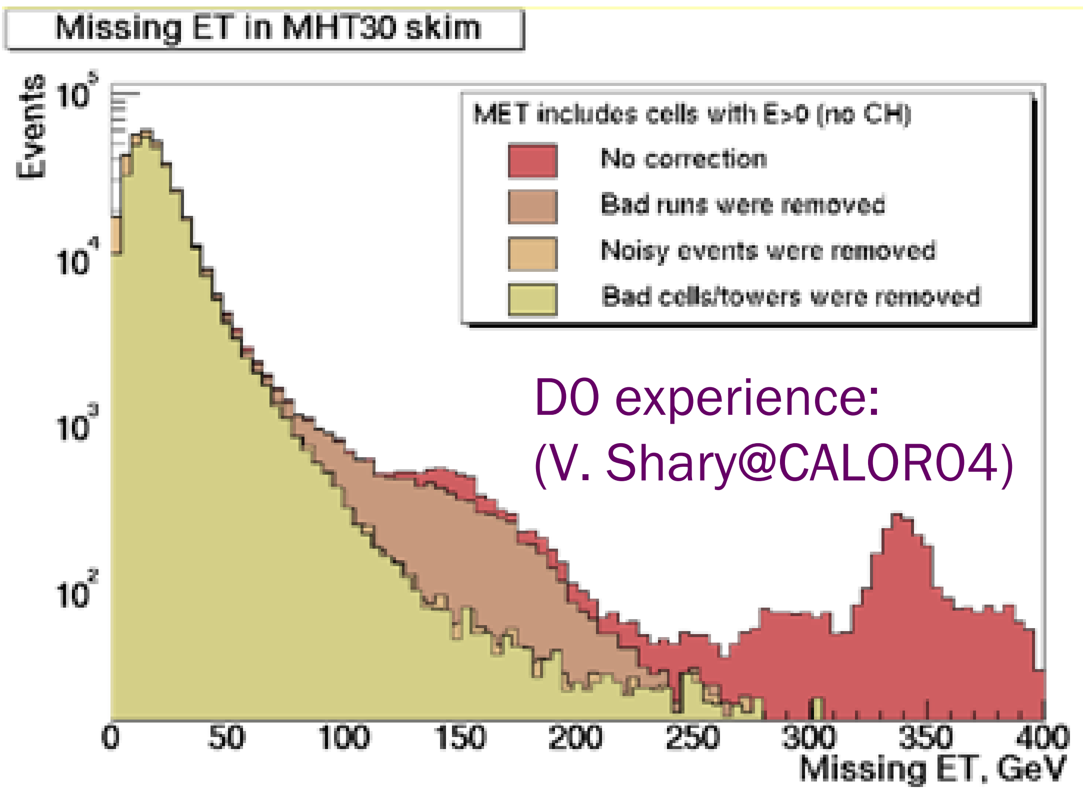


Effective mass $(M_{eff} = \Sigma_i\, p_T^i + E_T^{miss})$

E_T^{miss}>100 GeV

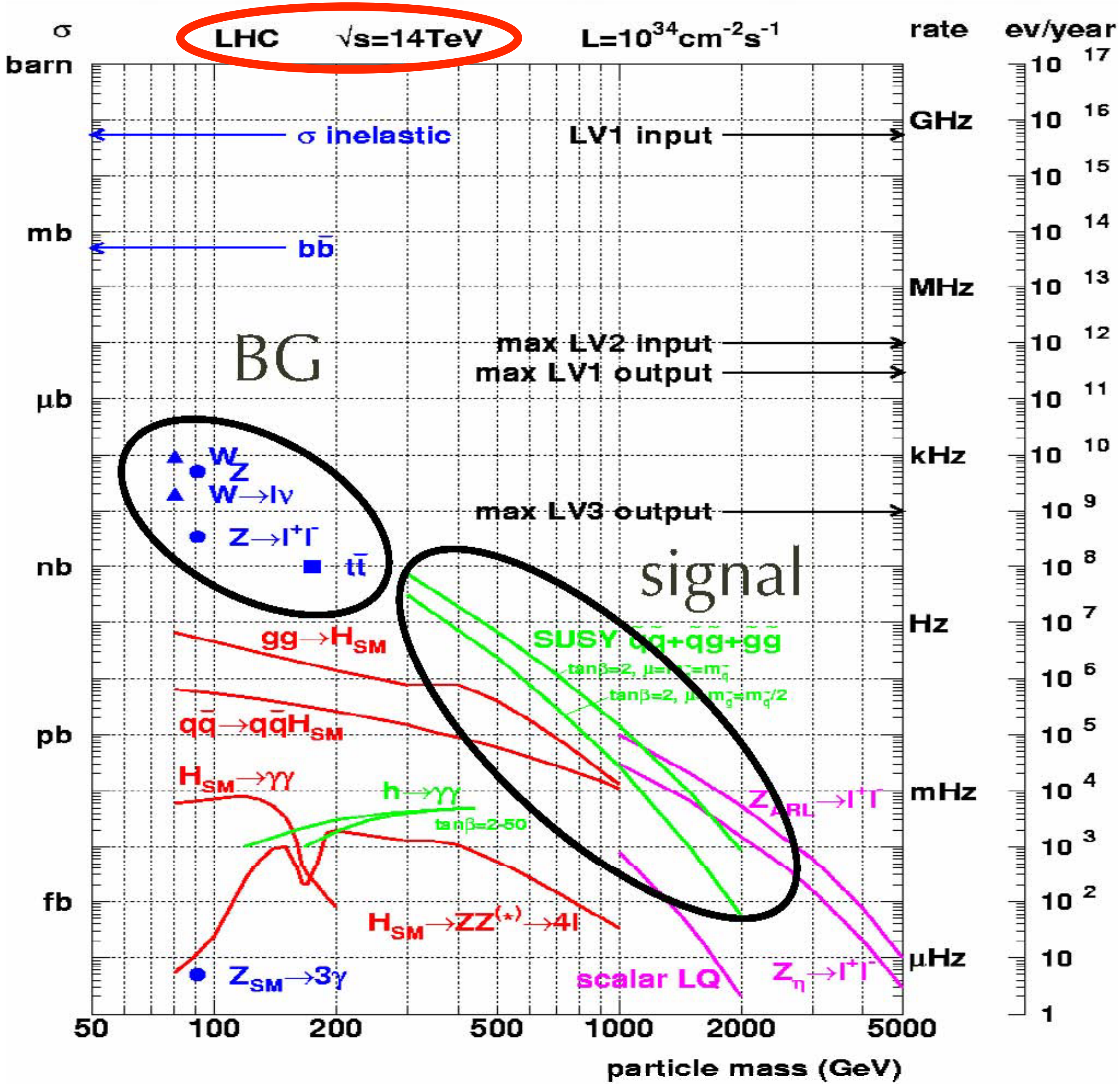
[from S. Yamamoto's Talk, SUSY 2007]

Controlling Energy Scale and Resolution of E_T^{miss} ...



... is very difficult !!!

CMS



σ barn
LHC √s=14TeV
L=10^34 cm^-2 s^-1
rate
ev/year
σ inelastic
LV1 input
GHz
mb
bb̄
MHz
BG
max LV2 input
max LV1 output
μb
kHz
W
Z
W→lν
Z→l+l-
max LV3 output
nb
tt̄
signal
Hz
gg→H_SM
SUSY q̃q̃+q̃g̃+g̃g̃
qq̄→qq̄H_SM
pb
H_SM→γγ
h→γγ
tanβ=2-50
mHz
fb
H_SM→ZZ(*)→4l
Z_SM→3γ
scalar LQ
μHz
50
100
200
500
1000
2000
5000
particle mass (GeV)

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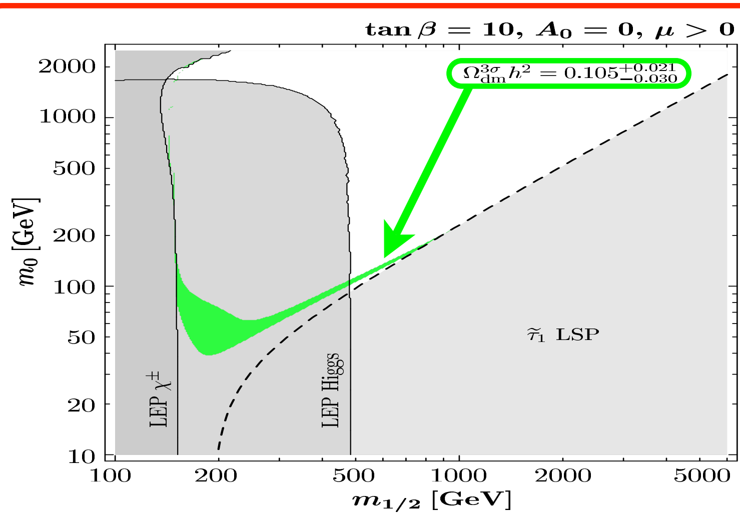
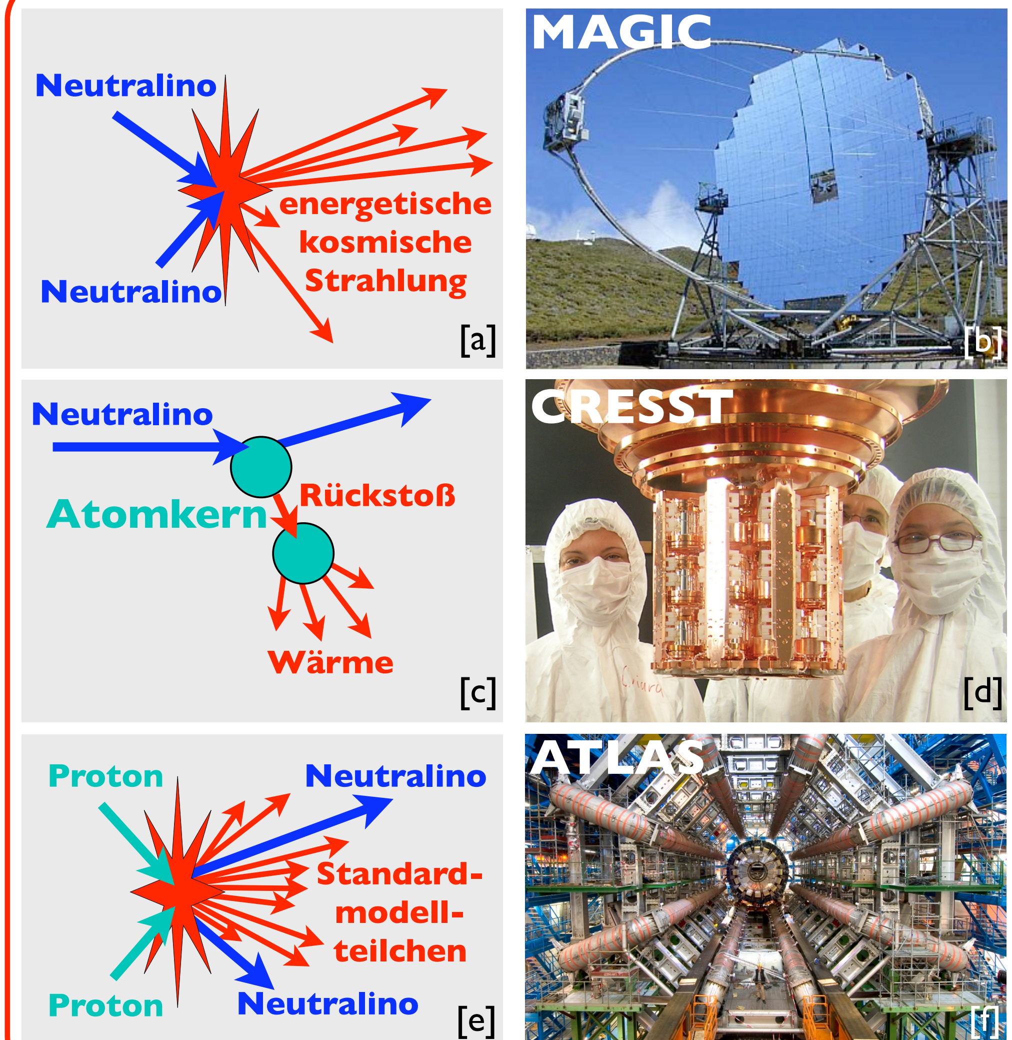
$$\Omega_{\widetilde{\chi}_1^0} = \Omega_{\mathrm{DM}} \text{ is possible!!!}$$





promising experimental prospects

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

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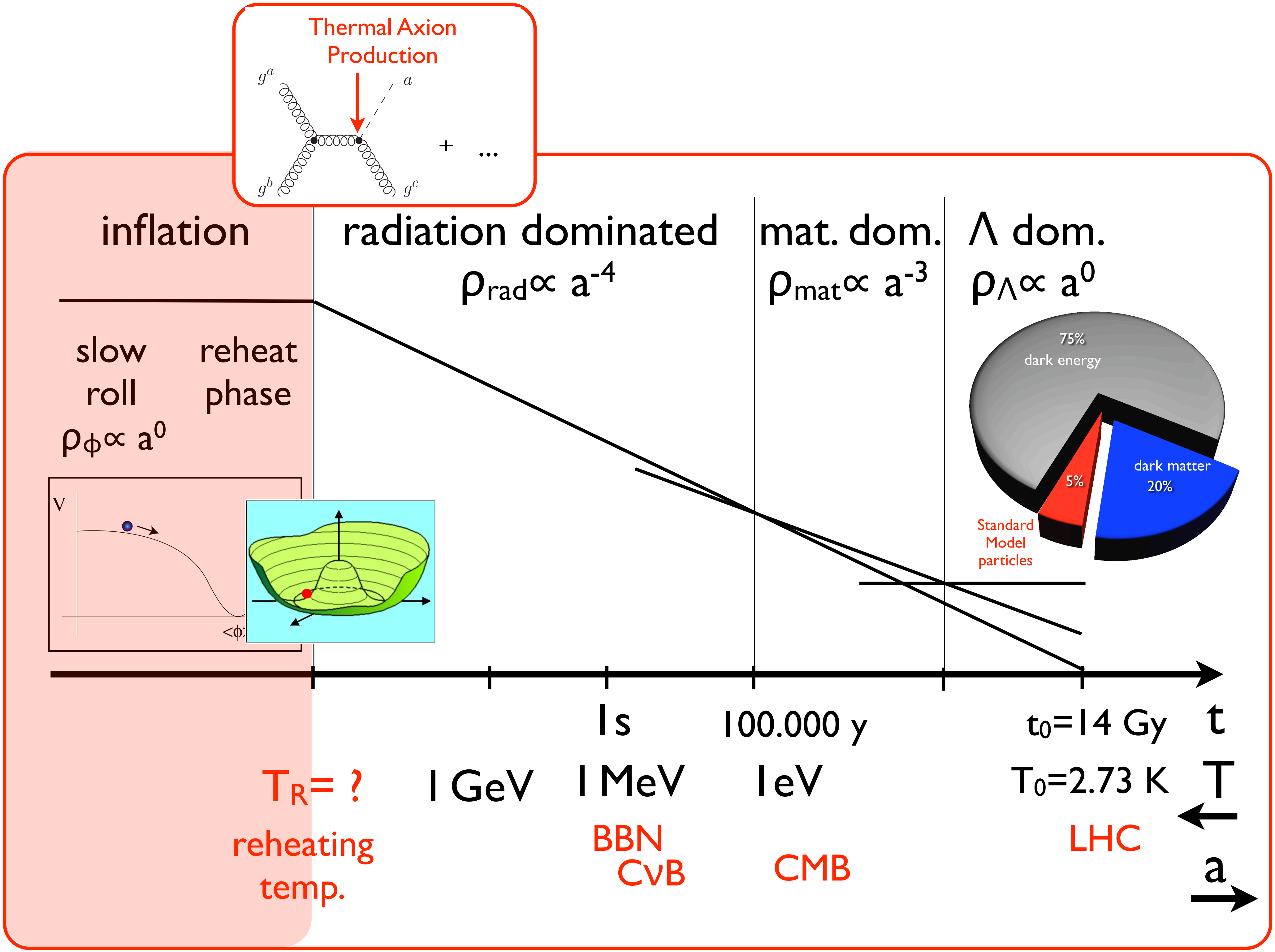
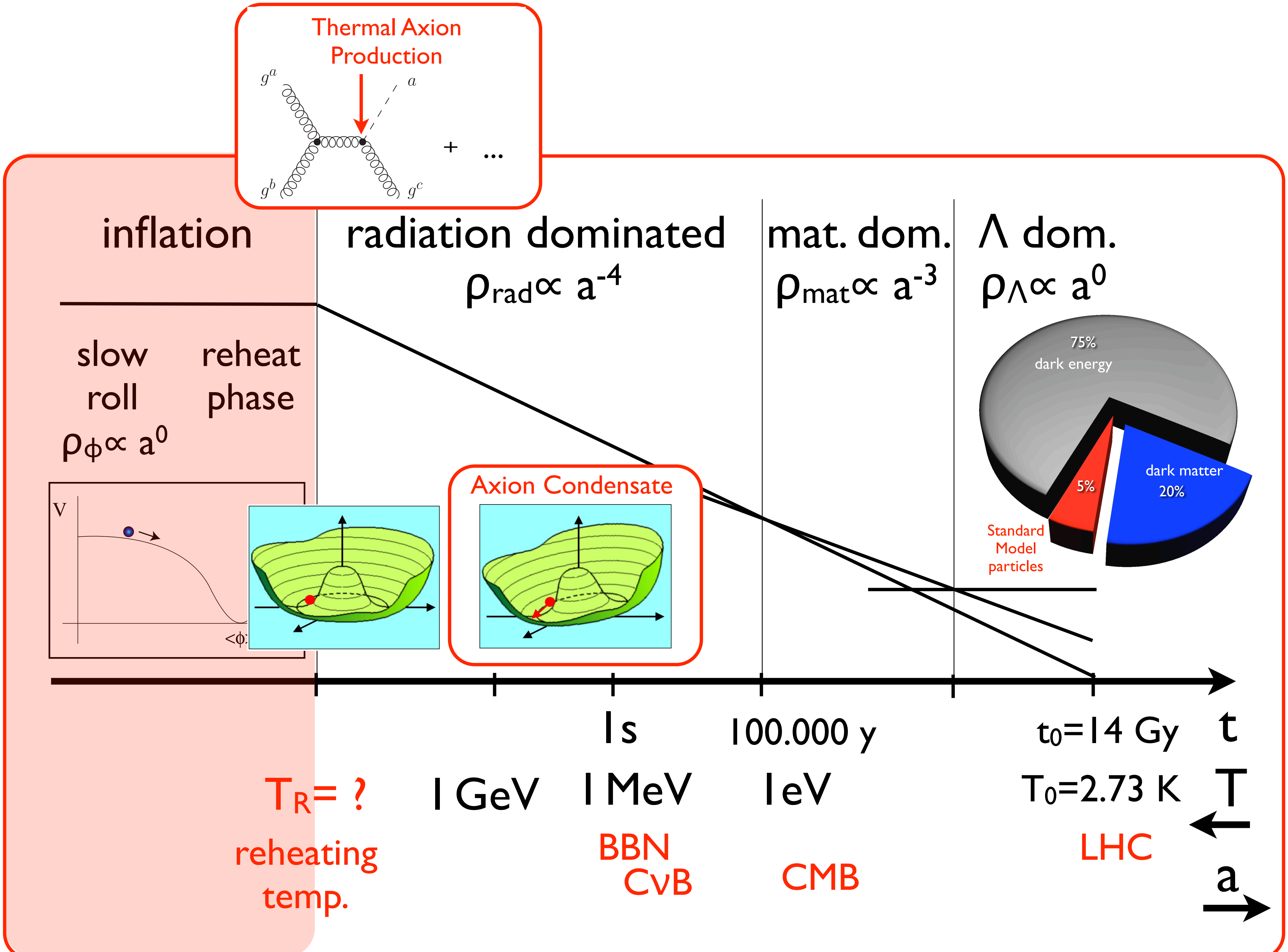

Thermal Axion Production
g^a
a
g^b
g^c
+ ...
inflation
slow roll
$\rho_\phi \propto a^0$
reheat phase
V
radiation dominated
$\rho_{rad} \propto a^{-4}$
mat. dom.
$\rho_{mat} \propto a^{-3}$
Λ dom.
$\rho_\Lambda \propto a^0$
75% dark energy
dark matter 20%
5%
Standard Model particles
1 s
100.000 y
t_0=14 Gy
t
T_R= ?
reheating temp.
1 GeV
1 MeV
1 eV
T_0=2.73 K
T
BBN
CνB
CMB
LHC
a



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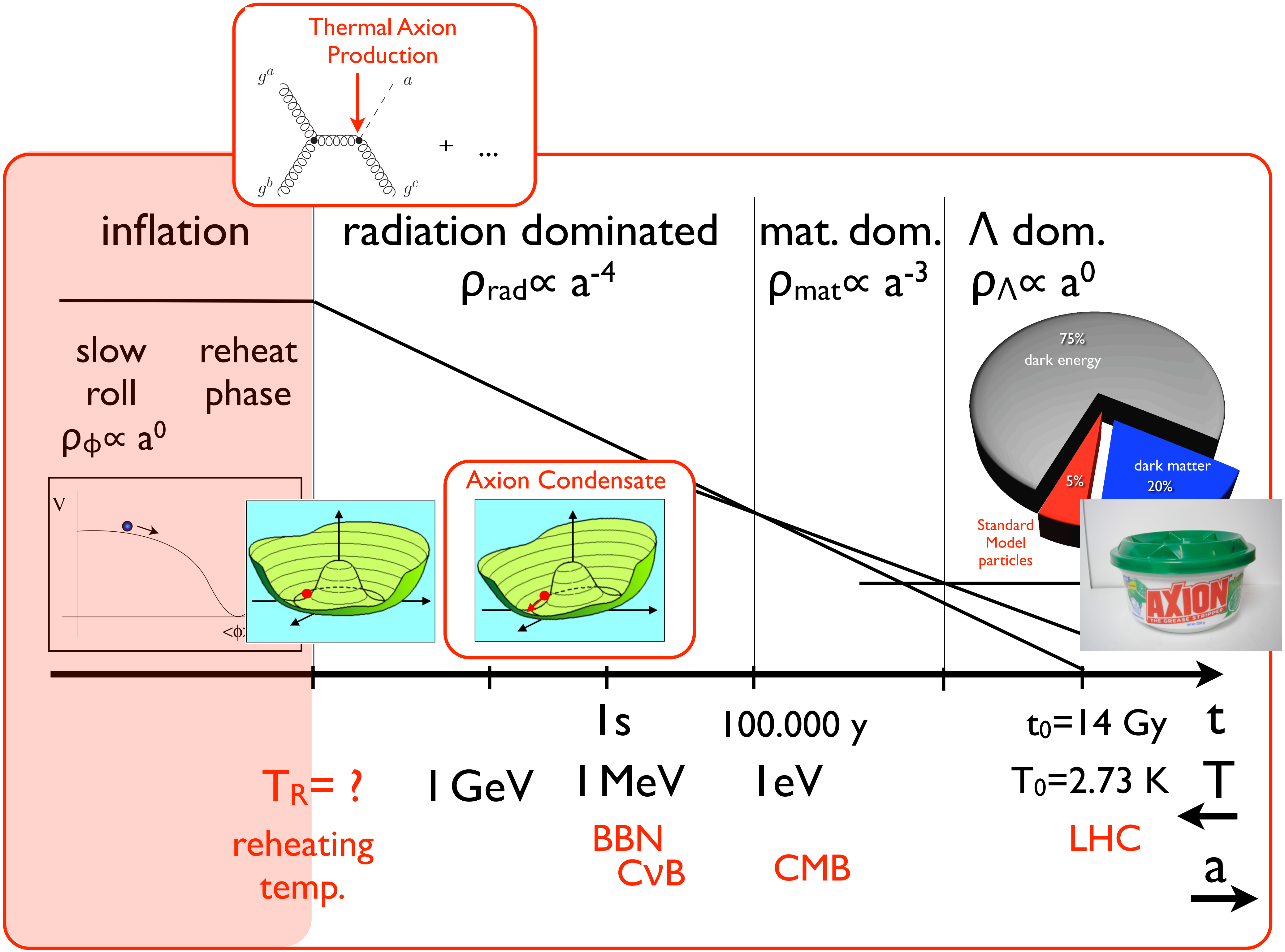
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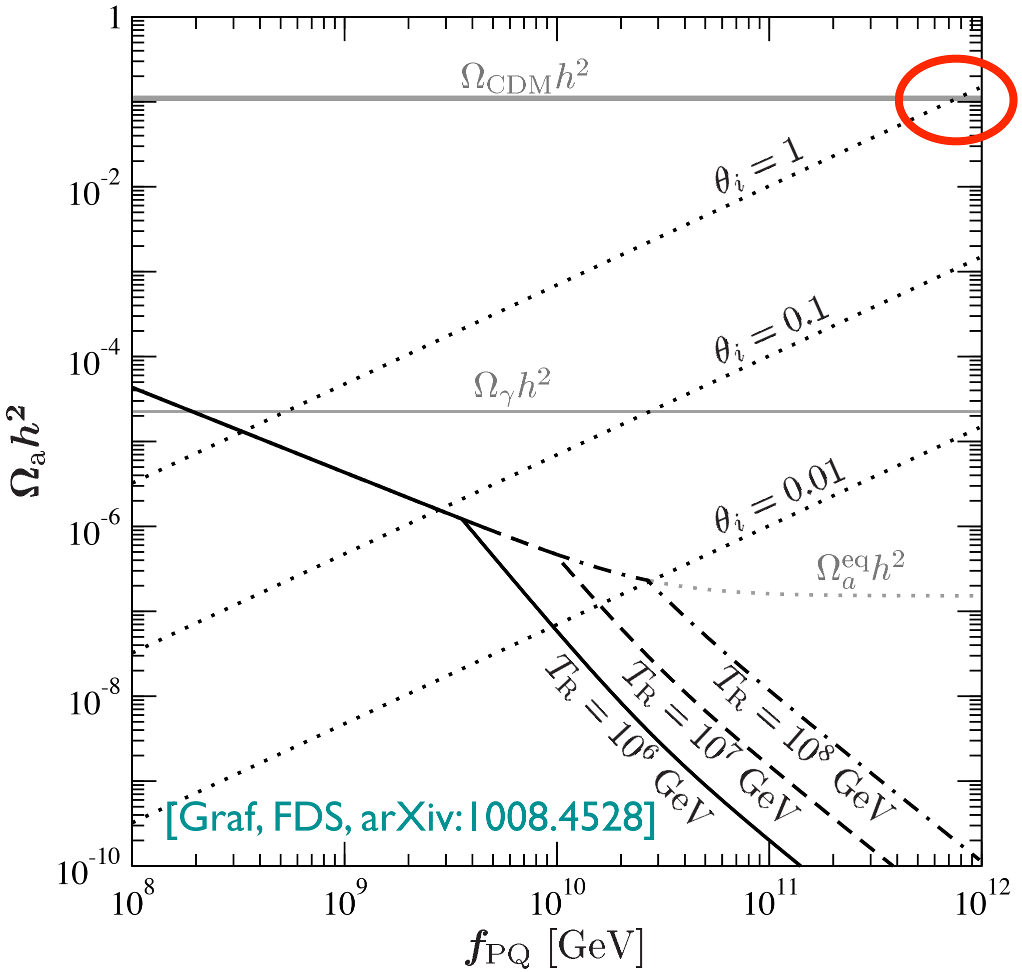
LHC
a

Axion Dark Matter



Axion Condensate: CDM

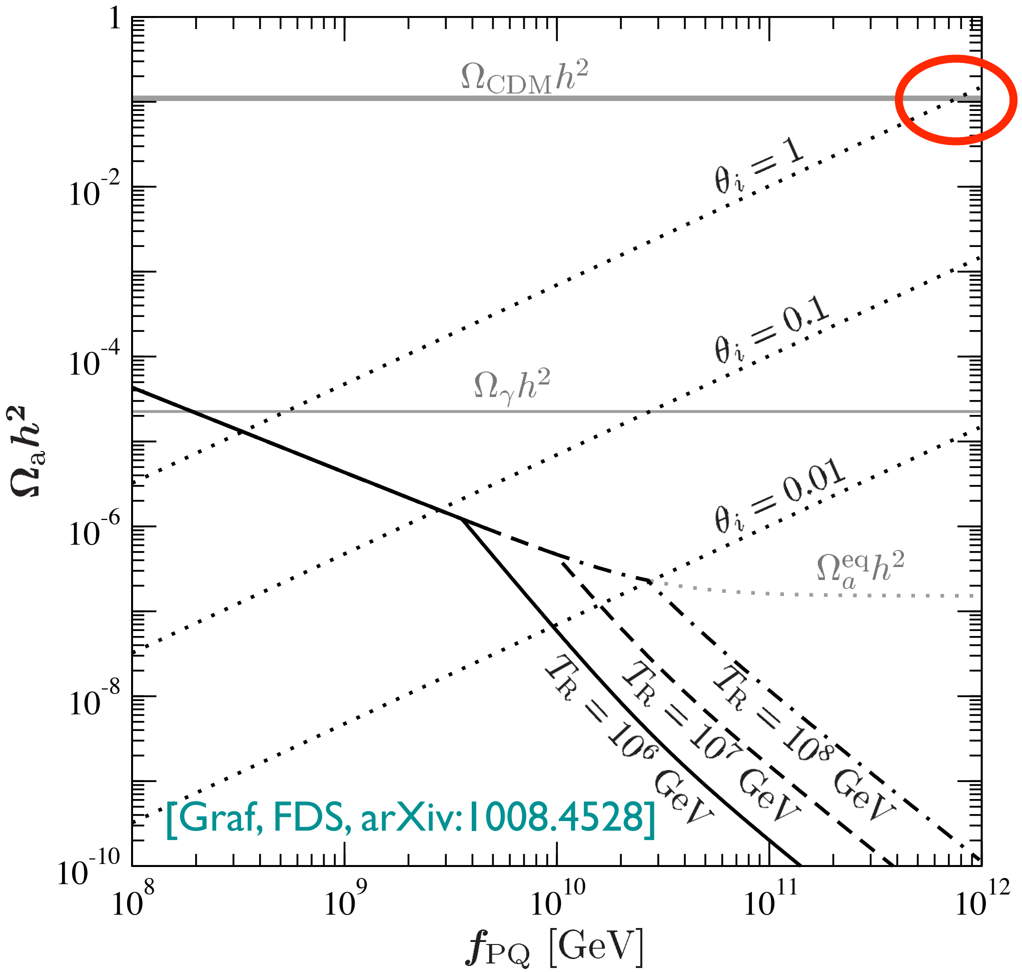
$$\Omega_a^{\rm MIS} h^2 \sim 0.15\, \theta_i^2 (f_{\rm PQ}/10^{12}\,{\rm GeV})^{7/6}$$

[... , Sikivie, '08; Kim, Carosi, '08, ...]

Axion Mass

$$m_a \simeq 0.6 \;\; {\rm meV}\,(10^{10}\,{\rm GeV}/f_{\rm PQ})$$

Axion Dark Matter



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[... , Sikivie, '08; Kim, Carosi, '08, ...]

Thermal Axions: WDM/HDM

$$\Omega_a^{\rm TP/eq} h^2 \simeq \sqrt{\langle p_{a,0}\rangle^2 + m_a^2}\, Y_a^{\rm TP/eq}\, s(T_0) h^2/\rho_c$$

$$18.6 g_s^6 \ln\left(\frac{1.501}{g_s}\right)\left(\frac{10^{10}\,{\rm GeV}}{f_{\rm PQ}}\right)^2\left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right)$$

[Graf, FDS, arXiv:1008.4528]

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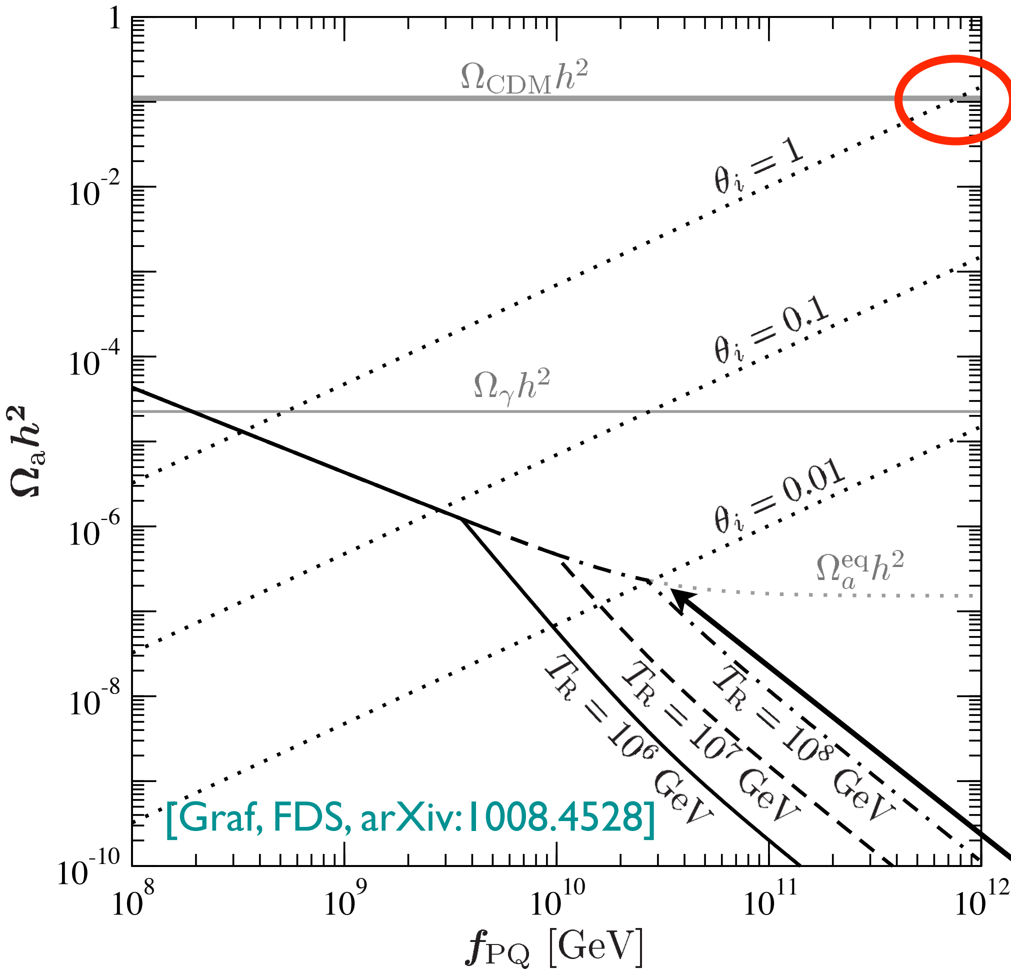

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[Graf, FDS, arXiv:1008.4528]

Axion Decoupling Temperature

$$T_{\rm D} \approx 9.6\times 10^6\,{\rm GeV}\left(\frac{f_{\rm PQ}}{10^{10}\,{\rm GeV}}\right)^{2.246}$$

[Masso et al., '02; Sikivie, '08; Graf, FDS, '10]

Axion Mass

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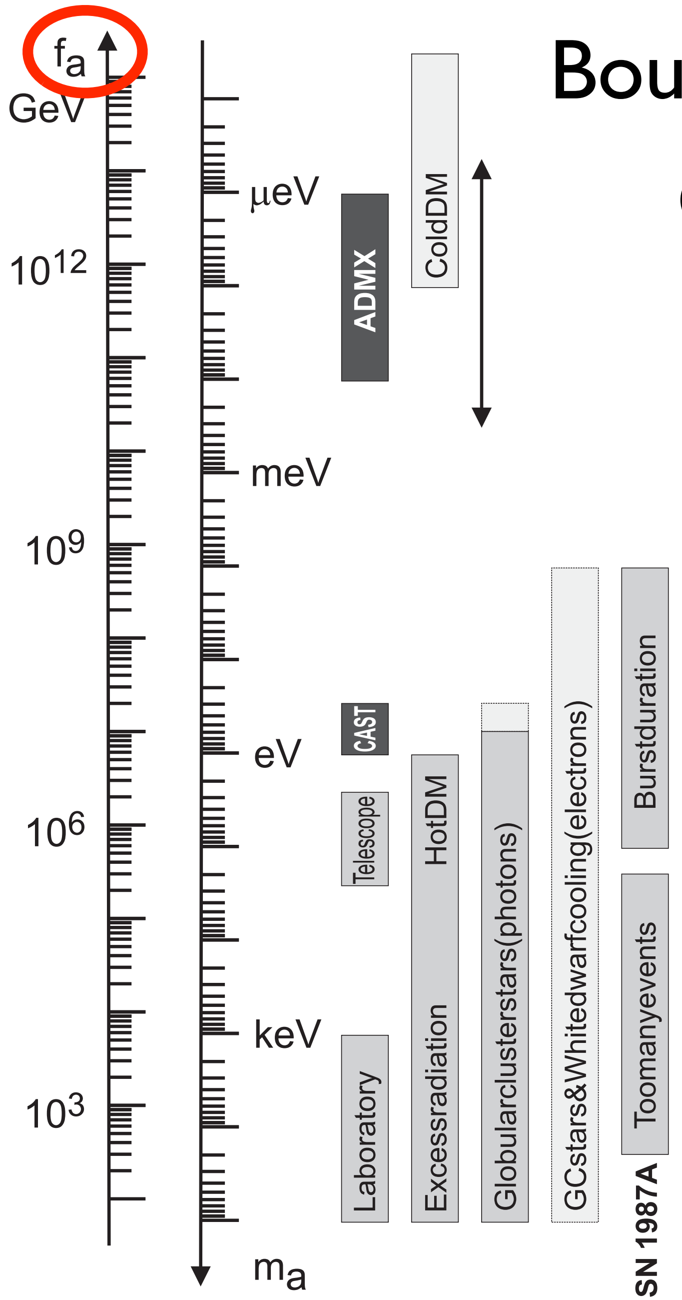
[Raffelt, '06]

Bounds on the Peccei-Quinn Scale



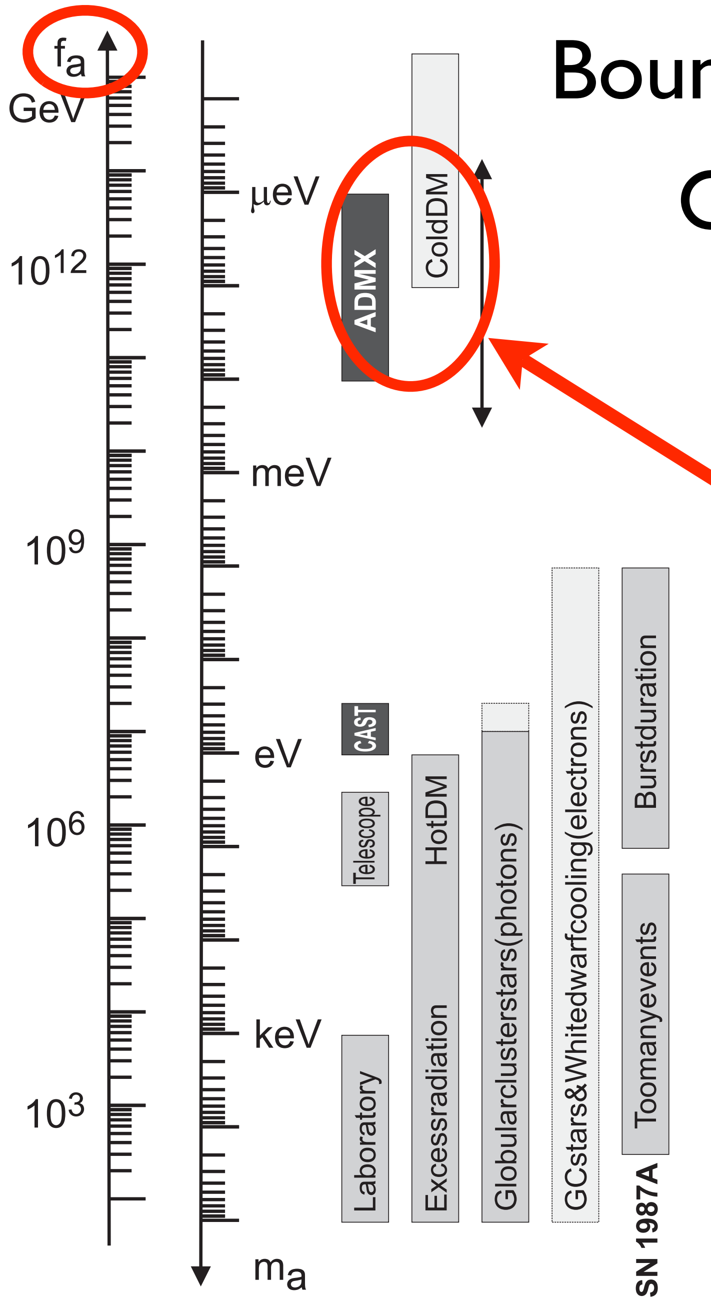
Bounds from Axion Searches

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 **C**DM Search Experiment

[Raffelt, '06]

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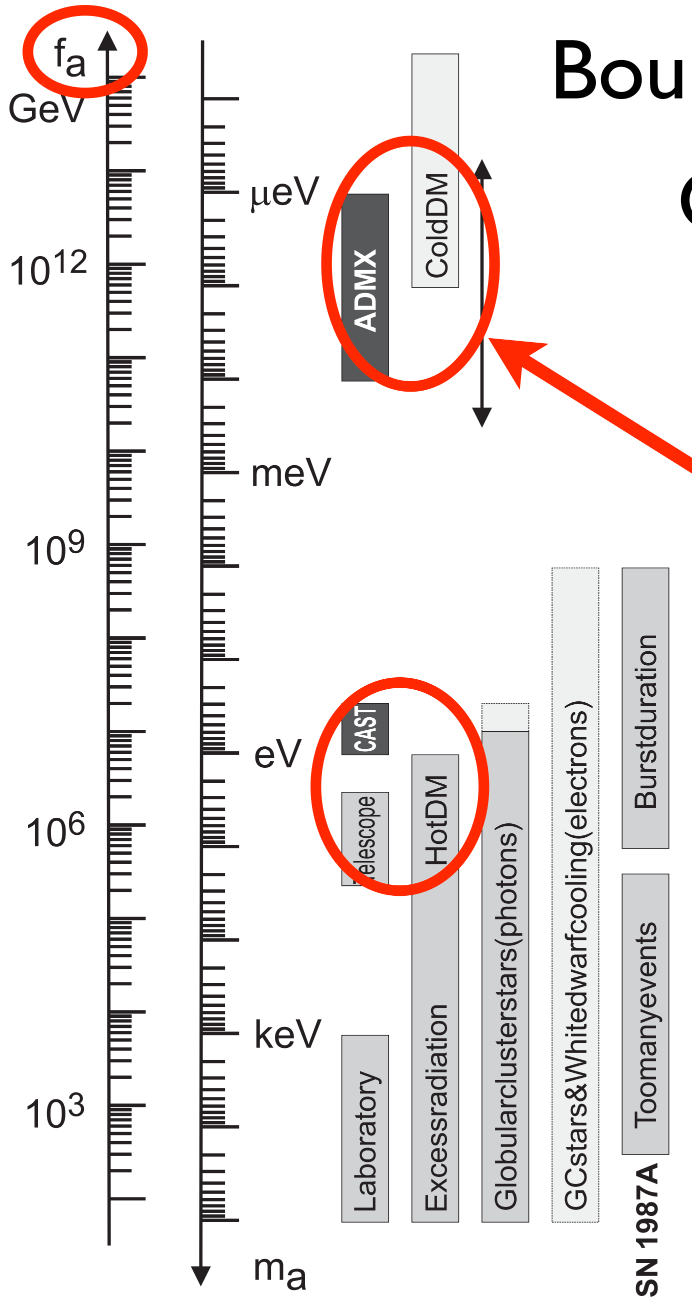

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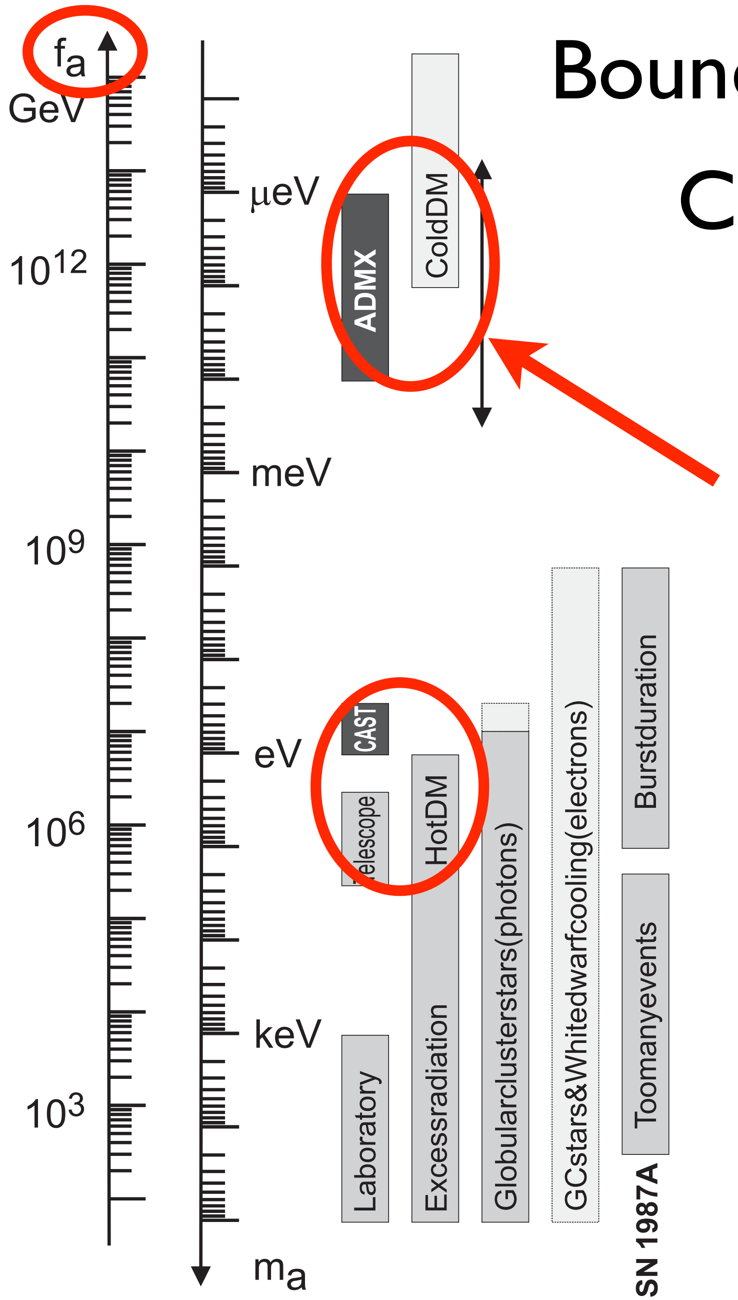
[Raffelt, '06]

Bounds on the Peccei-Quinn Scale



Bounds from Axion Searches

Cosmological Axion Bounds

Astrophysical Axion Bounds

only 1 Axion **C**DM Search Experiment

Axion DM and Neutralino DM might coexist!

Extremely Weakly Interacting Particles (EWIPs)

Extensions of the Standard Model

Peccei-Quinn Symmetry & Supersymmetry

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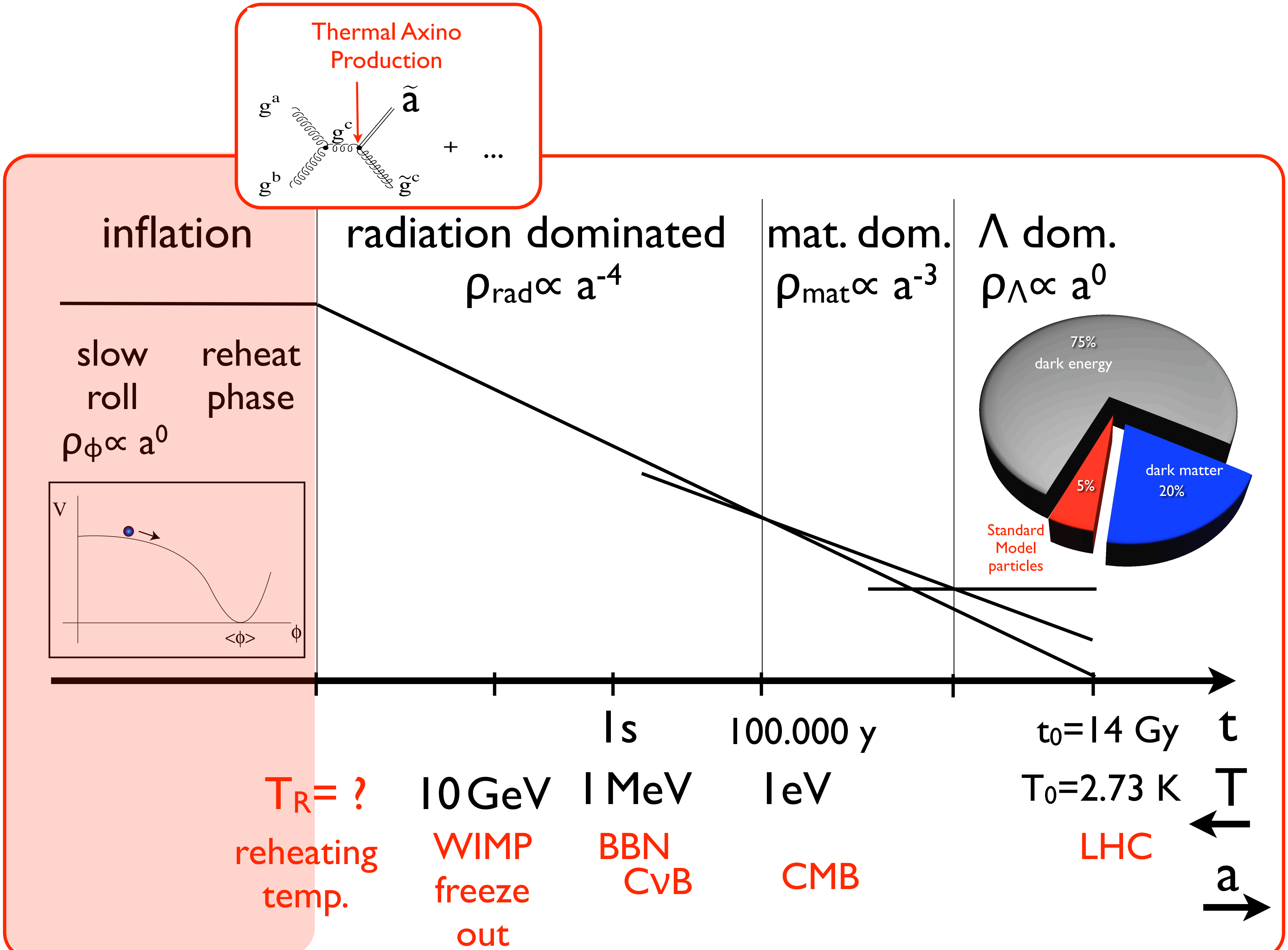
Thermal Axino Production
g^a
g^b
g^c
$\tilde{a}$
$\tilde{g}^c$
+ ...
inflation
radiation dominated
$\rho_{rad} \propto a^{-4}$
mat. dom.
$\rho_{mat} \propto a^{-3}$
Λ dom.
$\rho_{\Lambda} \propto a^{0}$
slow roll
$\rho_{\phi} \propto a^{0}$
reheat phase
V
<φ>
φ
75%
dark energy
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20%
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Standard Model particles
1 s
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t_0=14 Gy
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reheating temp.
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WIMP freeze out
1 MeV
BBN
CνB
1 eV
CMB
T_0=2.73 K
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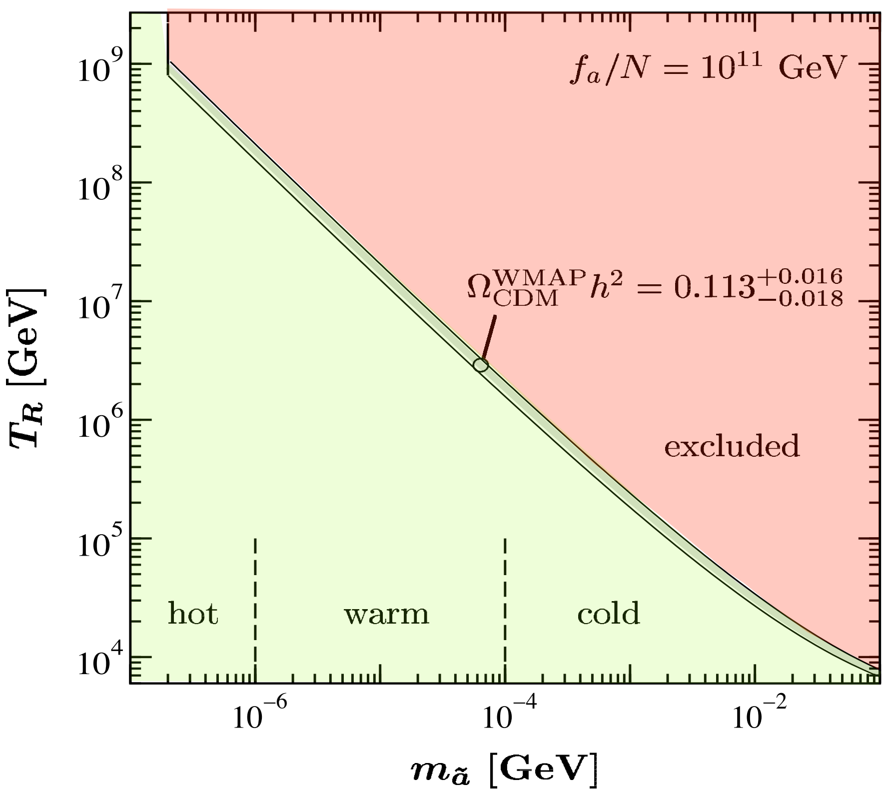
LHC
a

Axino LSP Case

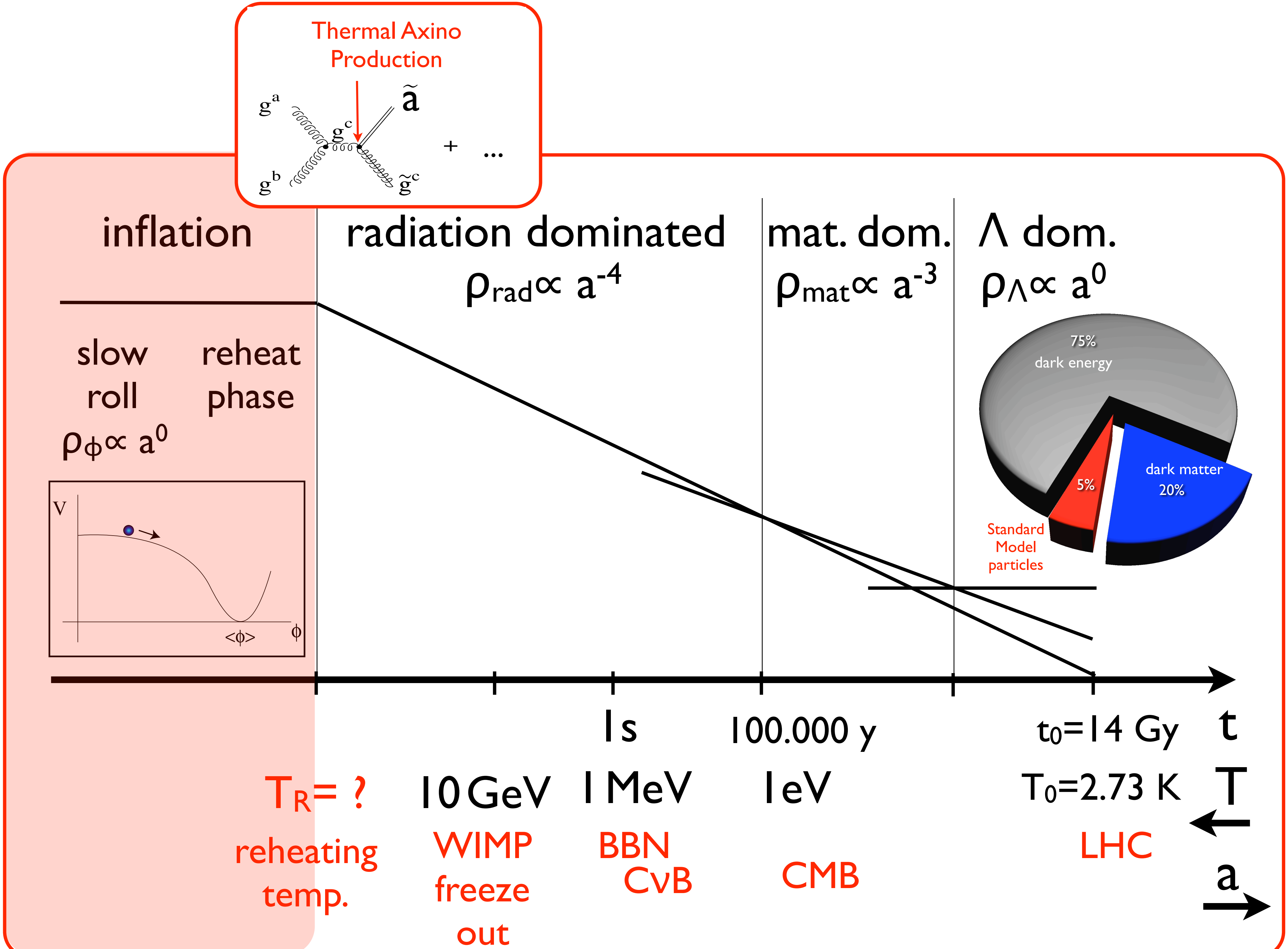
Thermal $\tilde{a}$ Production



[Brandenburg, FDS, '04]

see also [Covi et al., '01]

and [Strumia, '10]


Thermal Axino Production
g^a
g^b
g^c
ã
g̃^c
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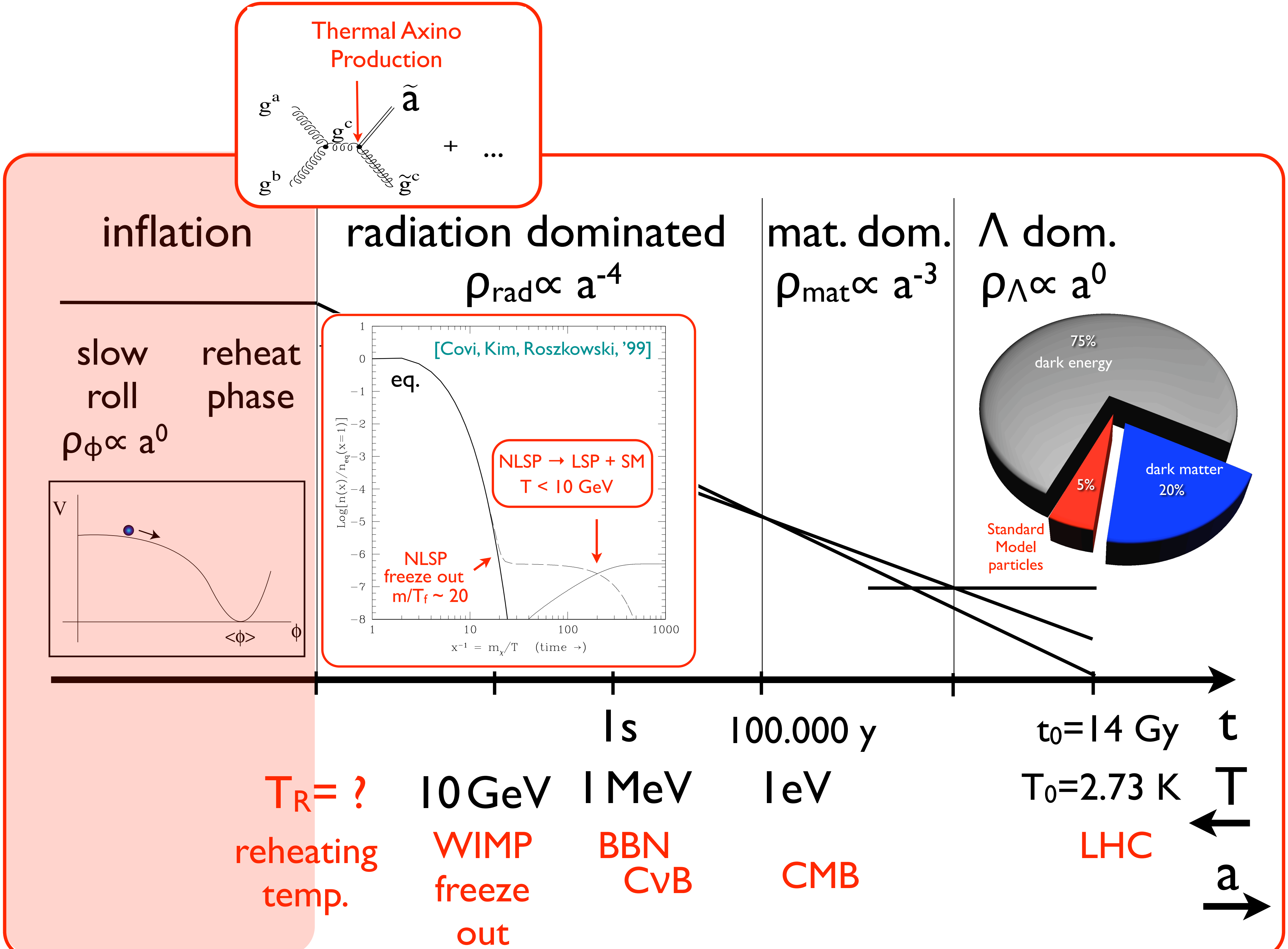
Thermal Axino Production
+ ...
inflation
radiation dominated
mat. dom.
Λ dom.
ρrad∝ a-4
ρmat∝ a-3
ρΛ∝ a0
slow roll
reheat phase
ρφ∝ a0
[Covi, Kim, Roszkowski, '99]
eq.
NLSP → LSP + SM
T < 10 GeV
NLSP freeze out m/Tf ~ 20
x-1 = mχ/T (time →)
75% dark energy
dark matter 20%
5%
Standard Model particles
1 s
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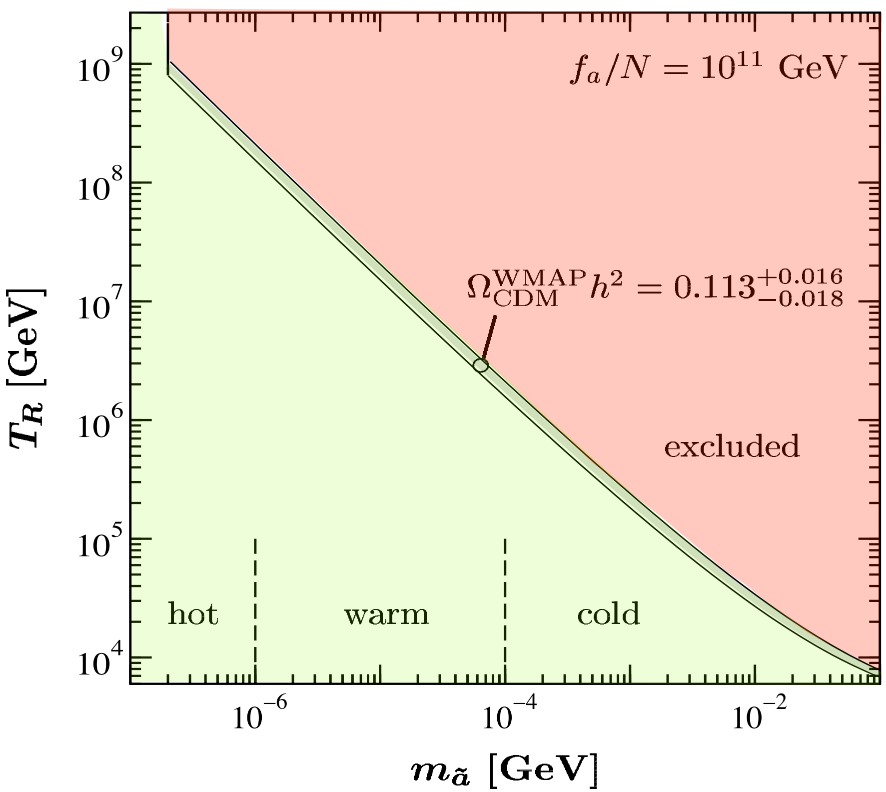
Thermal $\widetilde{a}$ Production

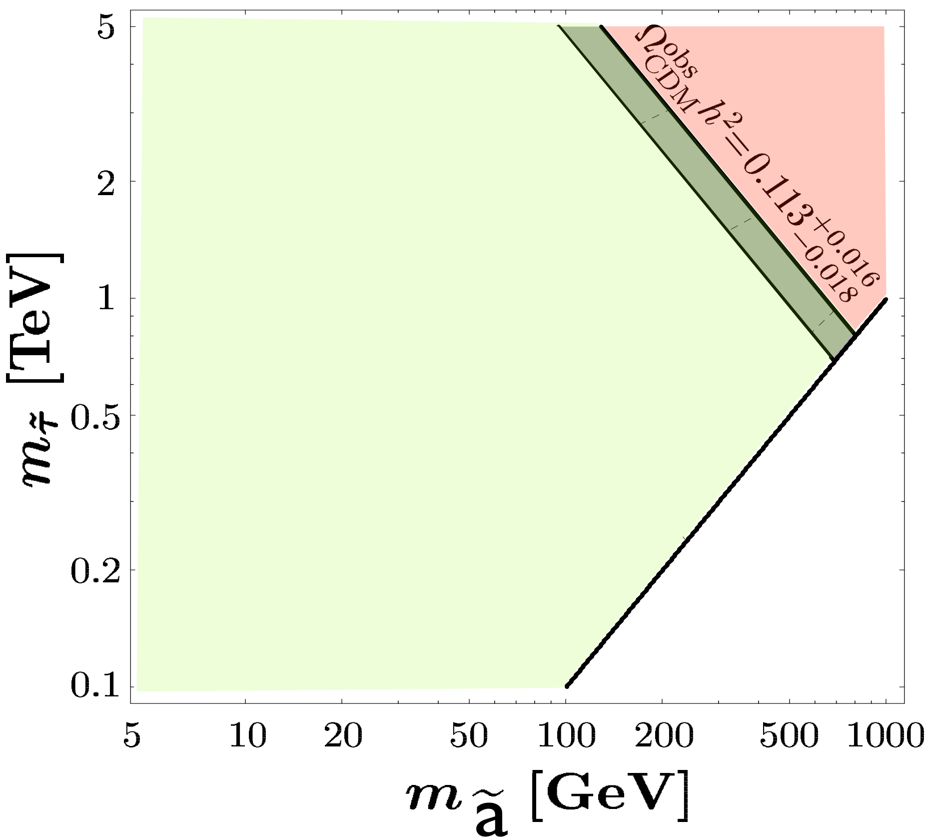


[Brandenburg, FDS, ‘04]

see also [Covi et al., ’01]

and [Strumia, ’10]

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



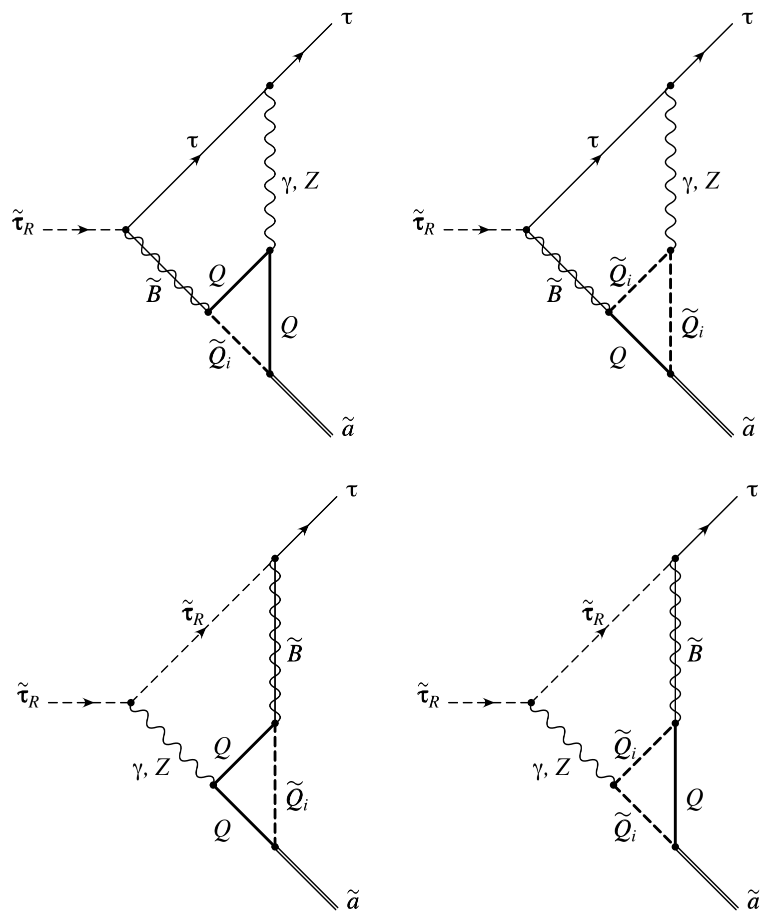
Probing axinos experimentally ???

↓

If we are lucky ...

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

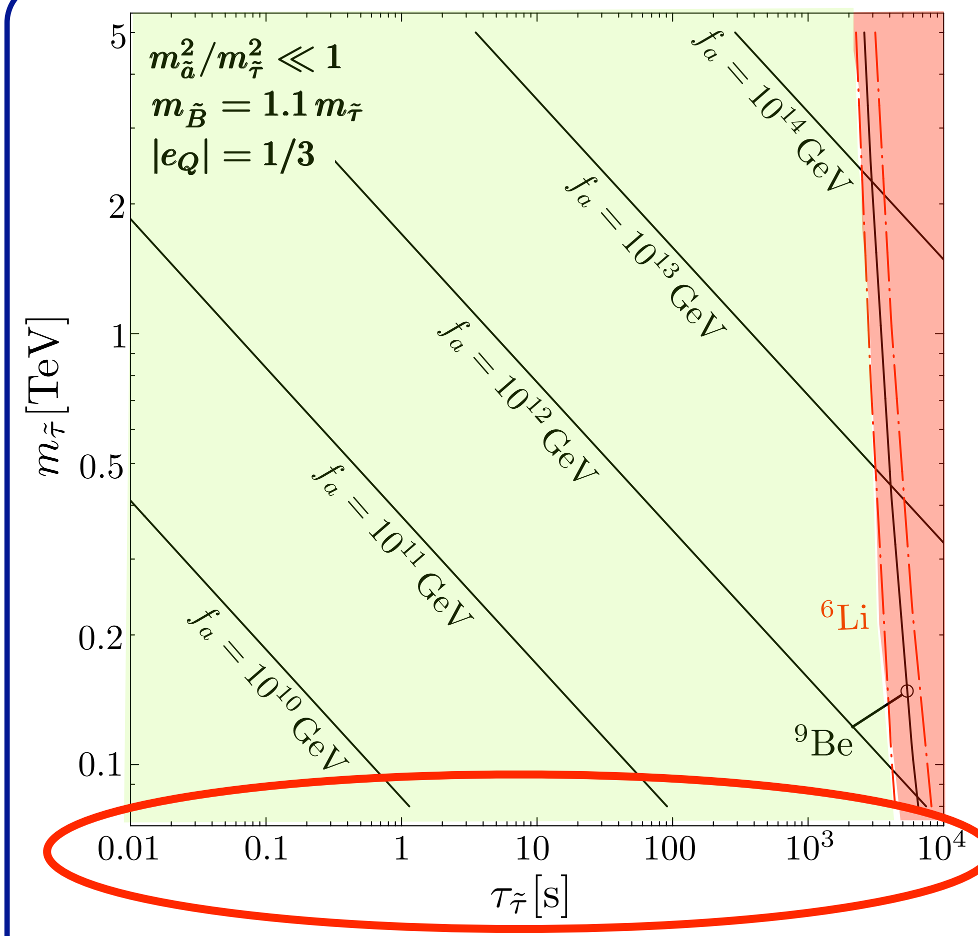
Stau Decays into Axinos



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

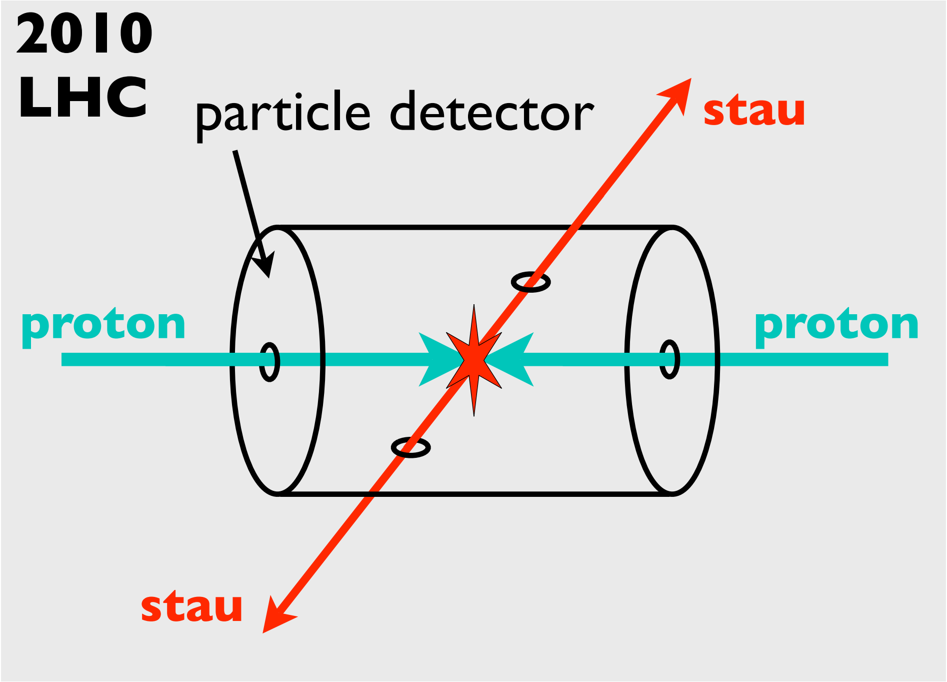
Chiral multiplet	$U(1)_{PQ}$	$(SU(3)_c, SU(2)_L)_Y$
$\Phi = \phi + \sqrt{2}\chi\theta + F_\Phi\theta\theta$	+1	$(\mathbf{1},\mathbf{1})_0$
$Q_1 = \tilde{Q}_1 + \sqrt{2}q_1\theta + F_1\theta\theta$	−1/2	$(\mathbf{3},\mathbf{1})_{+e_Q}$
$Q_2 = \tilde{Q}_2 + \sqrt{2}q_2\theta + F_2\theta\theta$	−1/2	$(\mathbf{3}^*,\mathbf{1})_{-e_Q}$

BBN

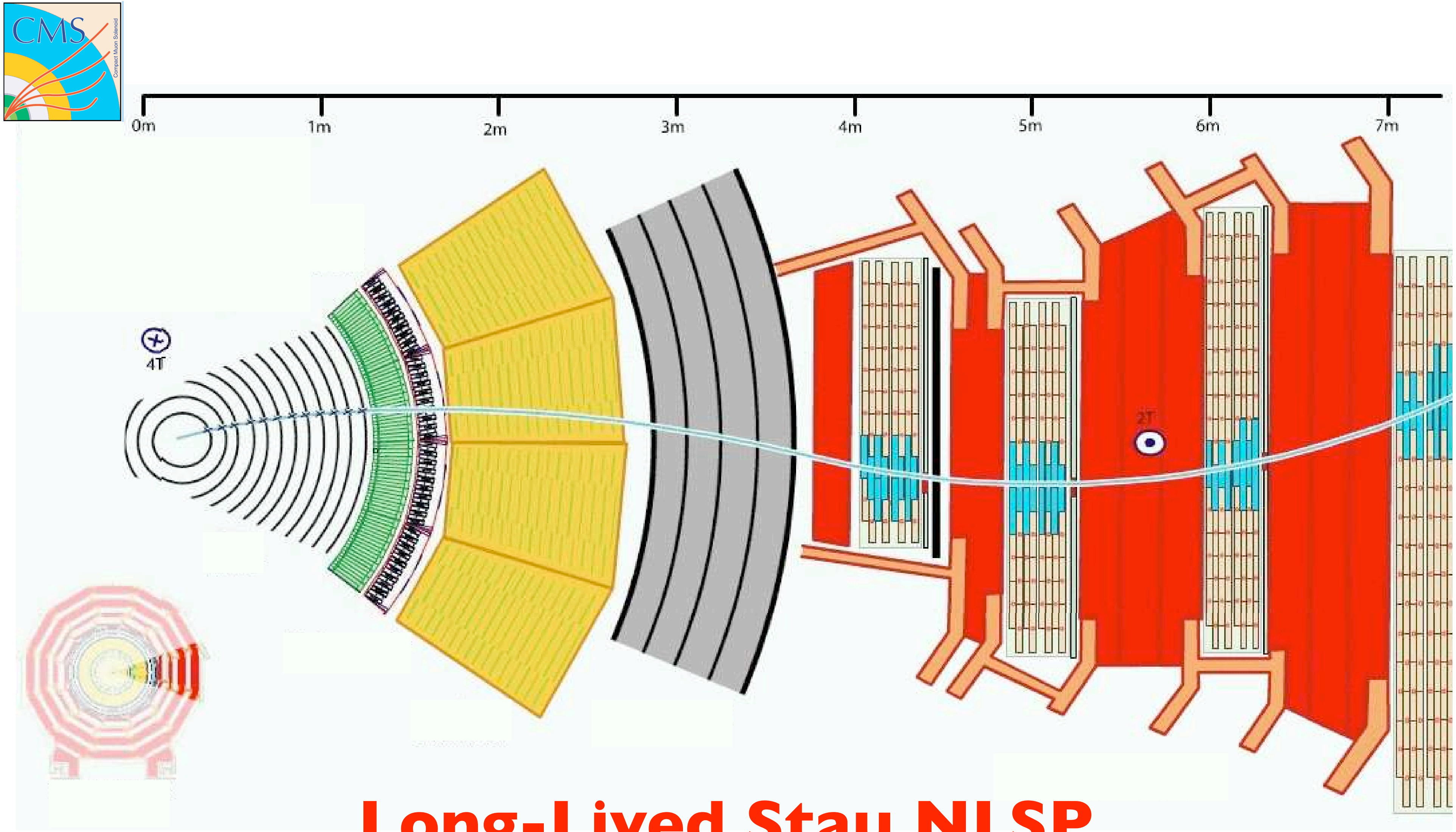


$$\Gamma_{\rm tot}^{\tilde{\tau}_R} \approx \Gamma(\tilde{\tau}_R \to \tau\tilde{a})_{LL}$$

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

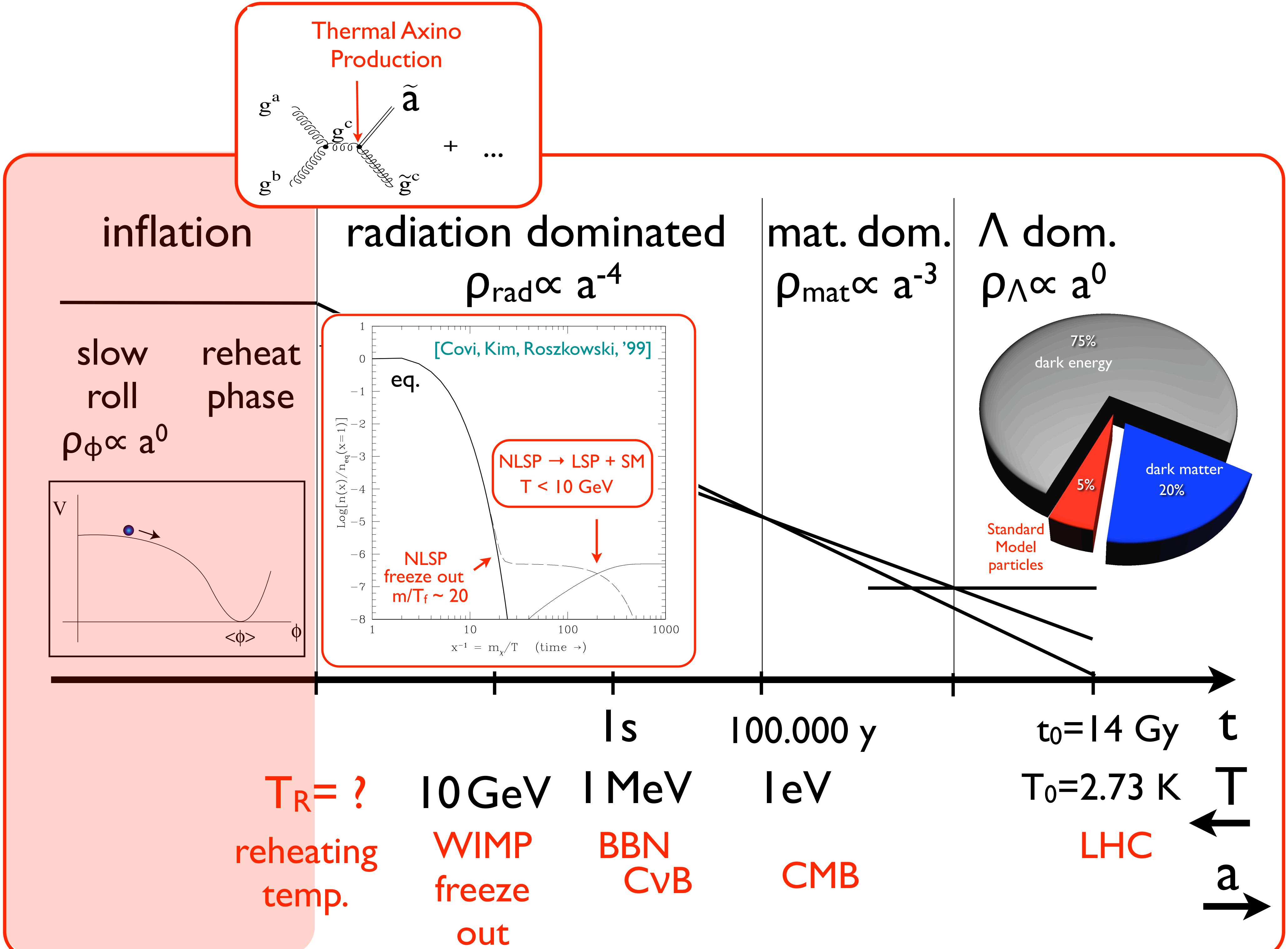

2010
LHC
particle detector
stau
proton
proton
stau

“Stable” Charged Massive Particle @ LHC



Long-Lived Stau NLSP

[from P. Zalewski’s Talk, SUSY 2007]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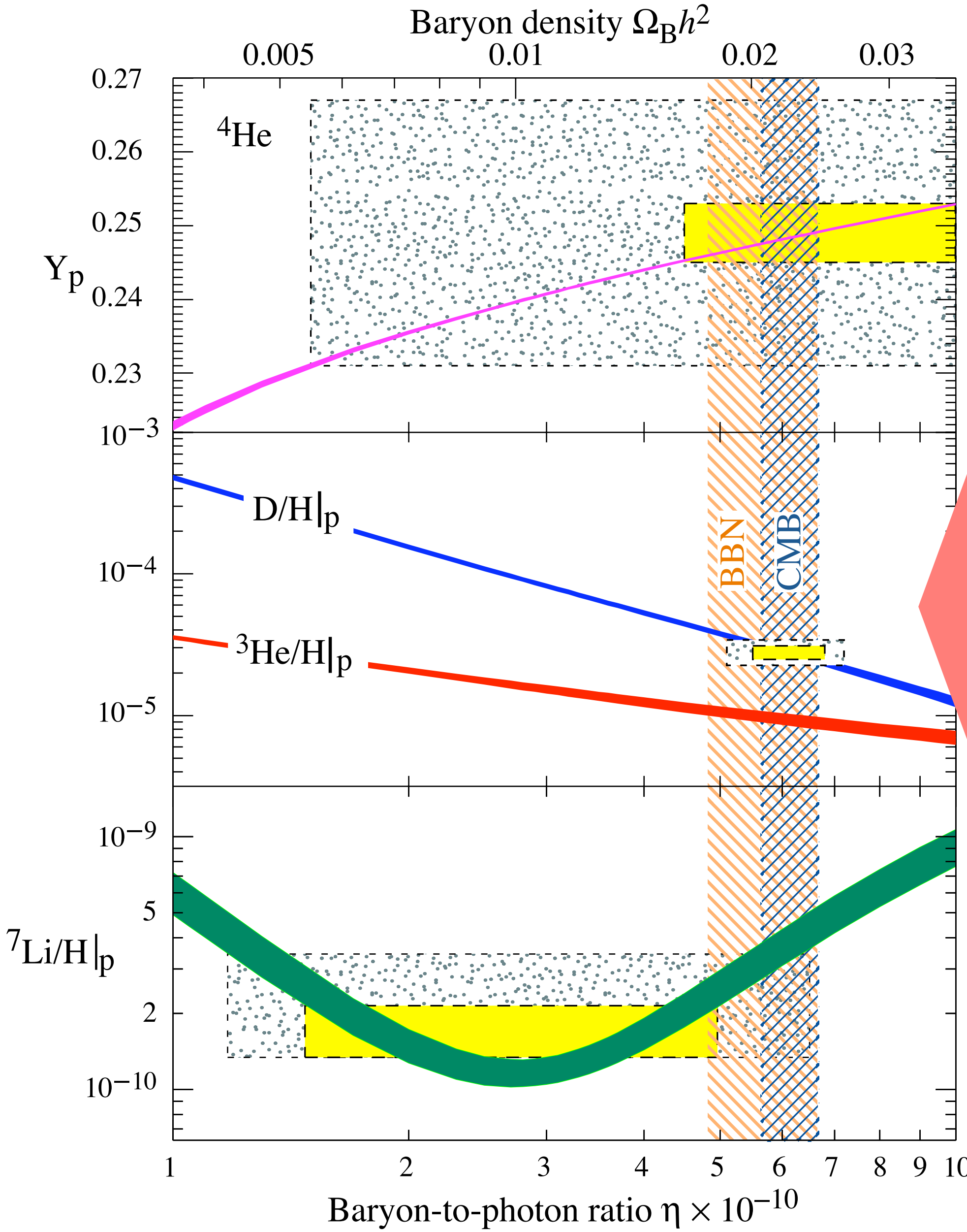
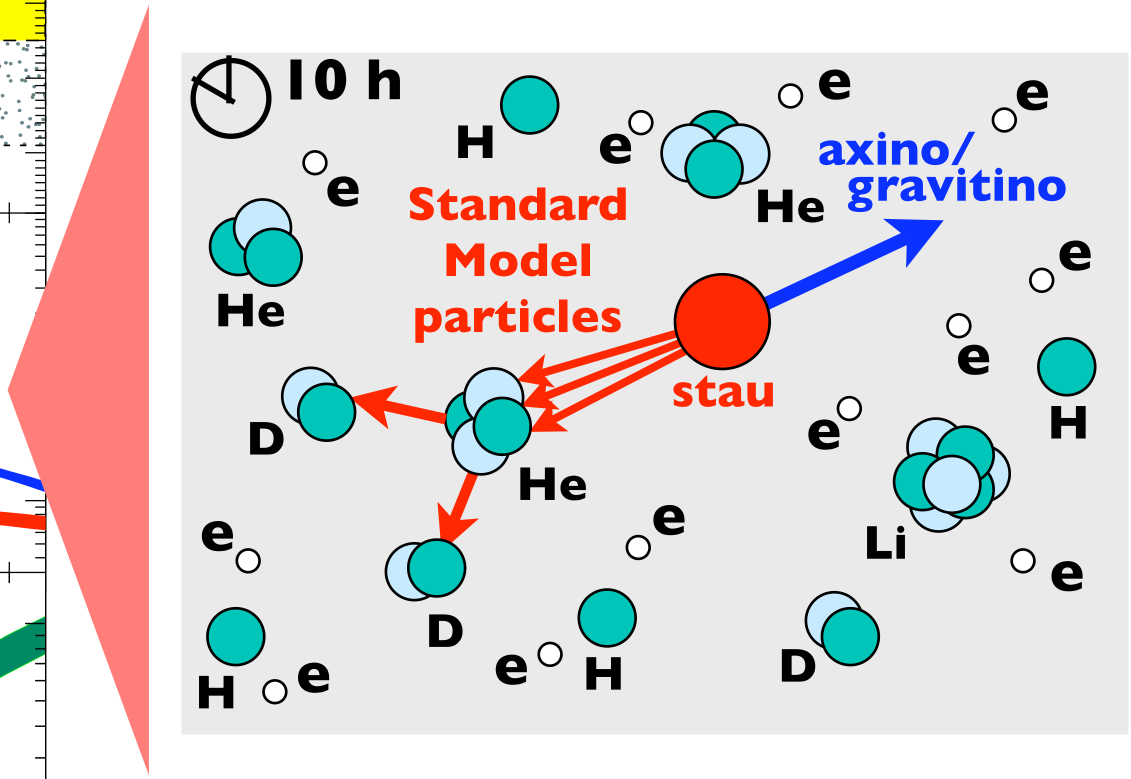
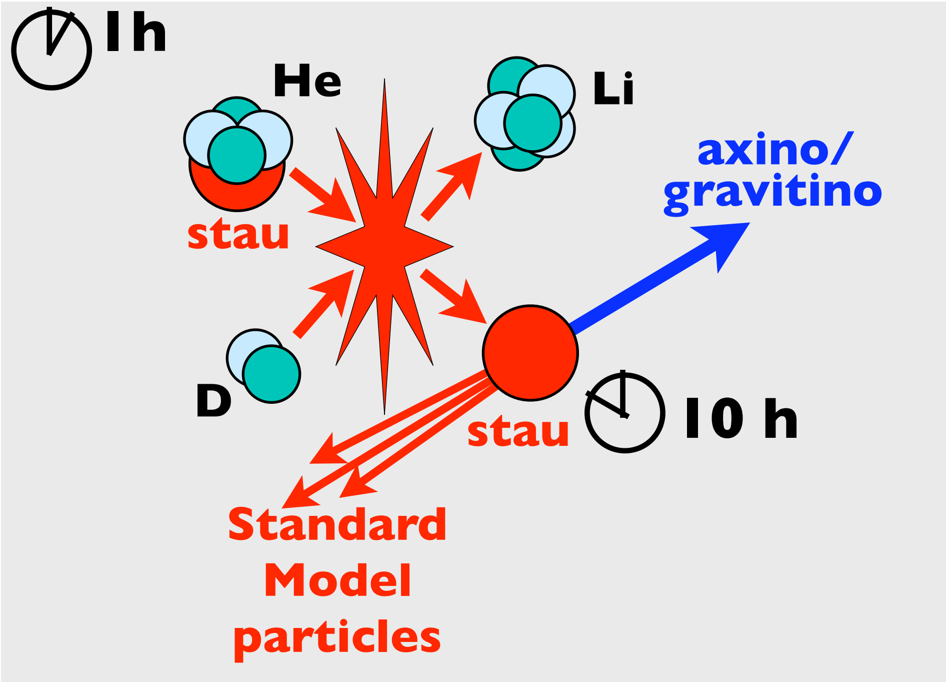
Big-Bang Nucleosynthesis



[Particle Data Book 2006]



Catalyzed BBN [Pospelov, '06]

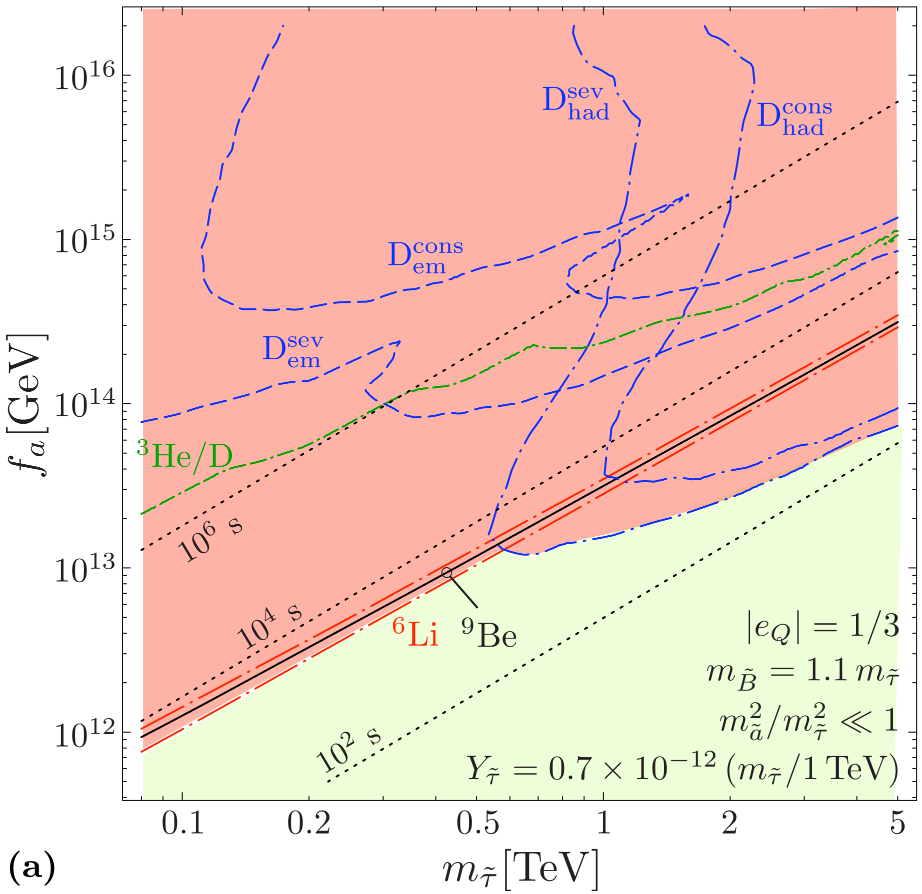


[Cyburt et al., ‘06; FDS, ’06; Pradler, FDS, ’07; Hamaguchi et al., ’07; Kawasaki, Kohri, Moroi, ’07; Takayama, ’07; Jedamzik, ’07; Pradler, FDS, ’08]

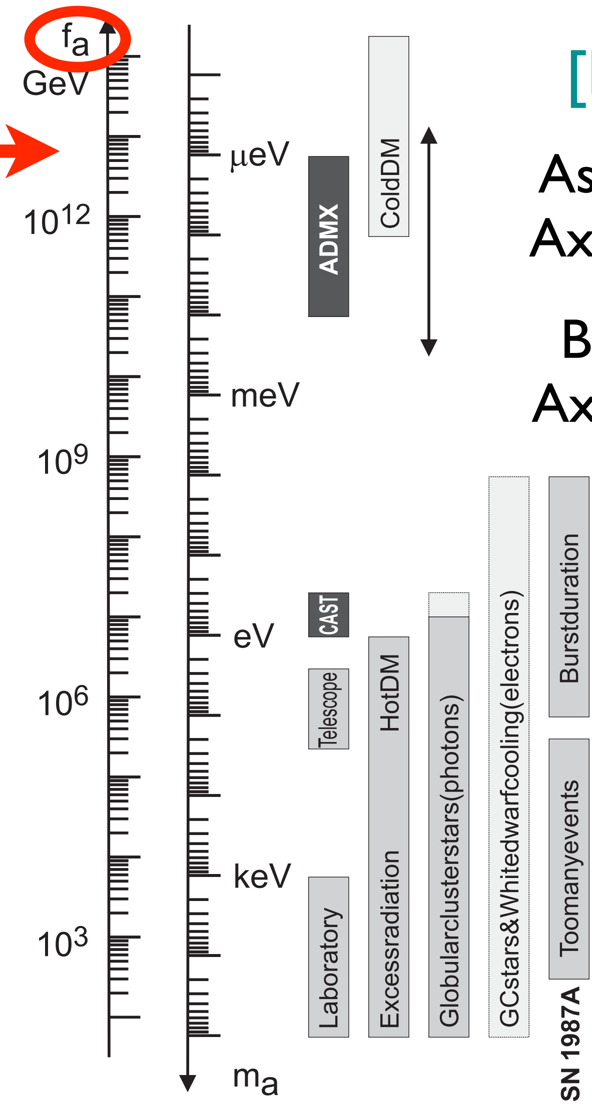
CBBN of ^{9}Be: [Pospelov, ’07; Pospelov, Pradler, FDS, ’08]

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

Axino LSP Case with a Charged Slepton NLSP



BBN

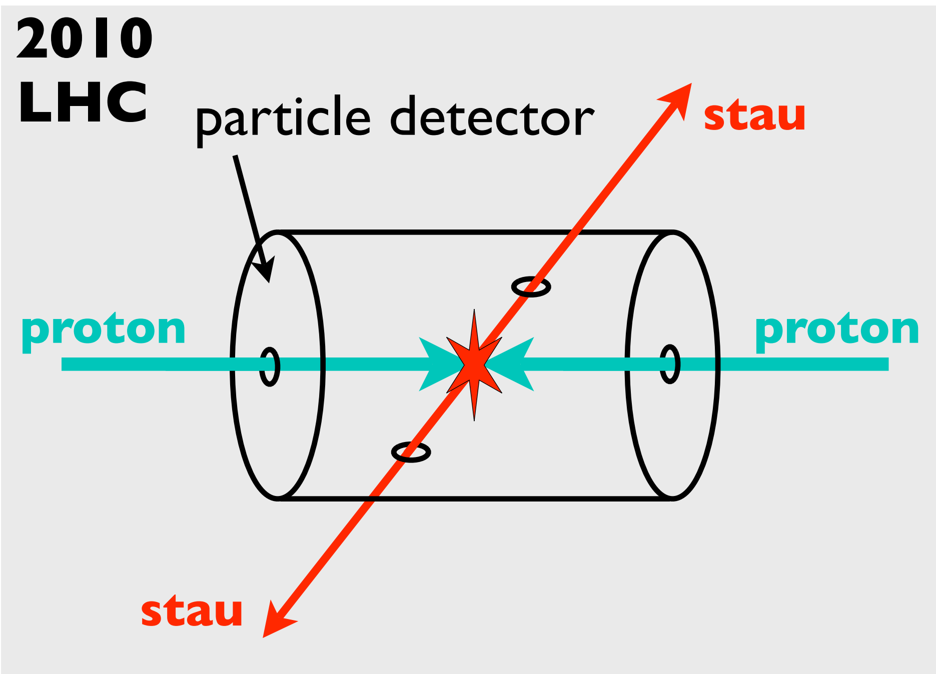


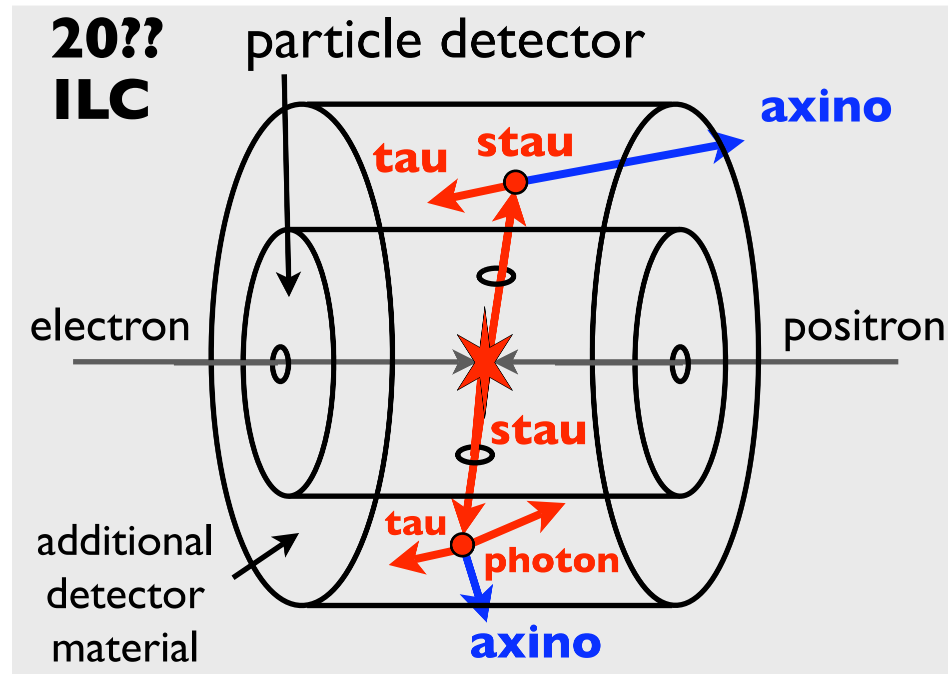
[Raffelt, '06]

Astrophysical Axion Bounds

Bounds from Axion Searches

Upper Limits on the Peccei-Quinn Scale



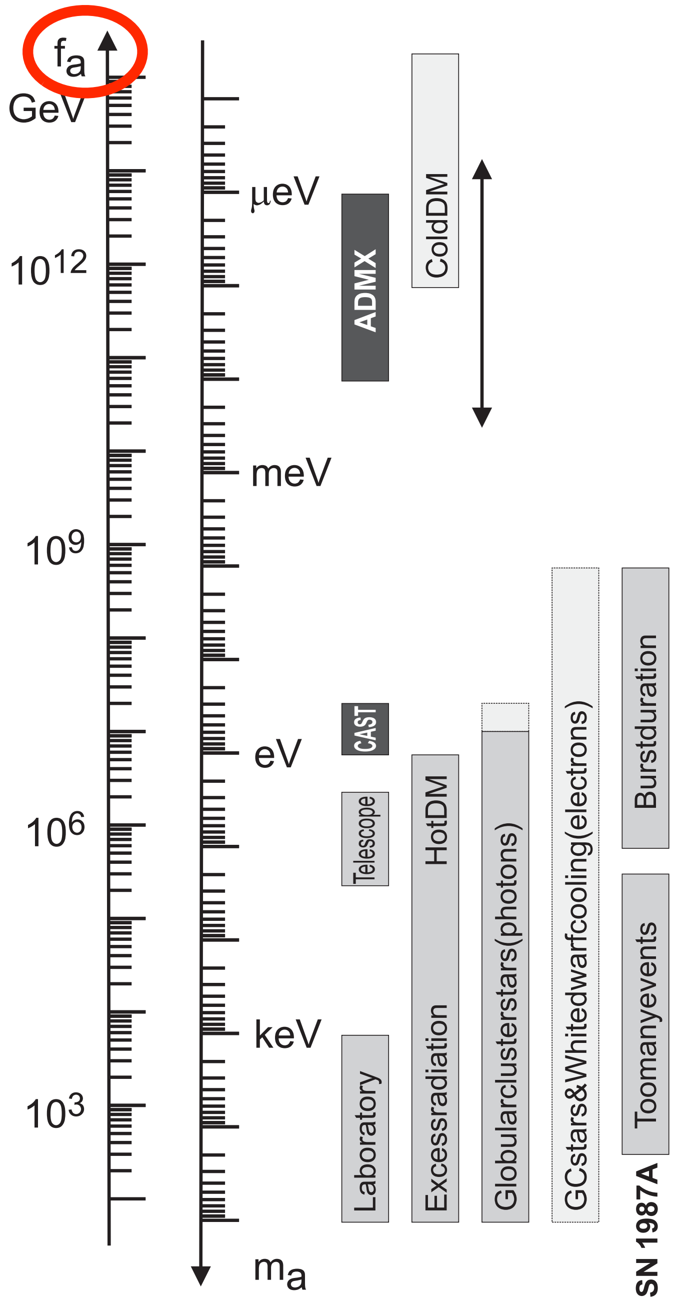


Probing f_a @ Colliders

[Brandenburg et al., '05]

[Raffelt, '06]

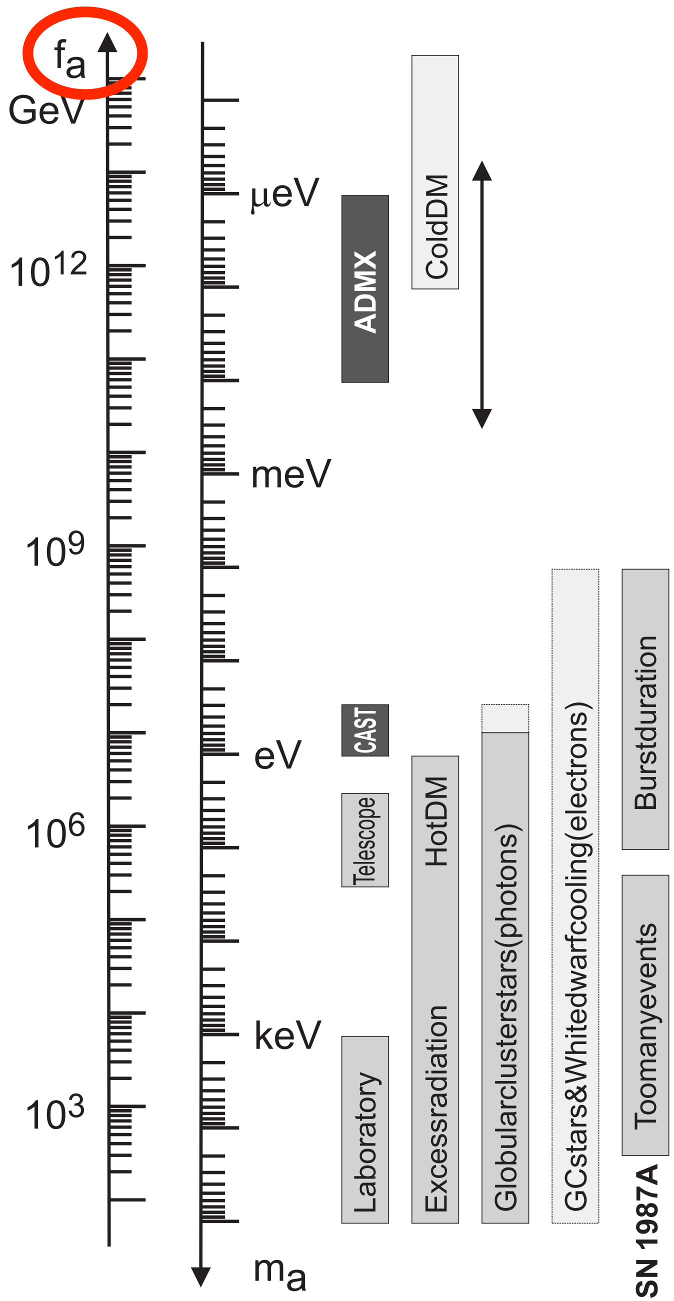
Bounds on the Peccei-Quinn Scale



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



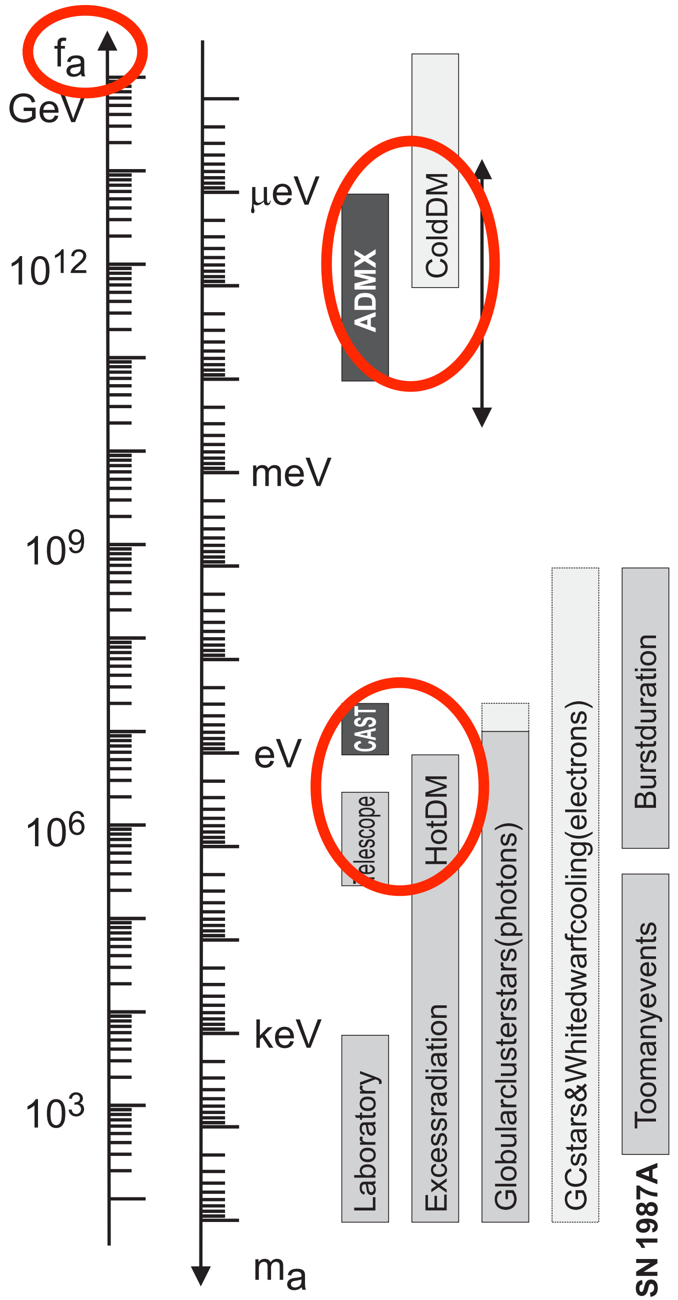
Agreement between Axion & Axino Searches

↓

Strong Hint for the Axino LSP

[Raffelt, ’06]

Bounds on the Peccei-Quinn Scale



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Axion DM & Axino DM might coexist!

Extremely Weakly Interacting Particles (EWIPs)

Extensions of the Standard Model

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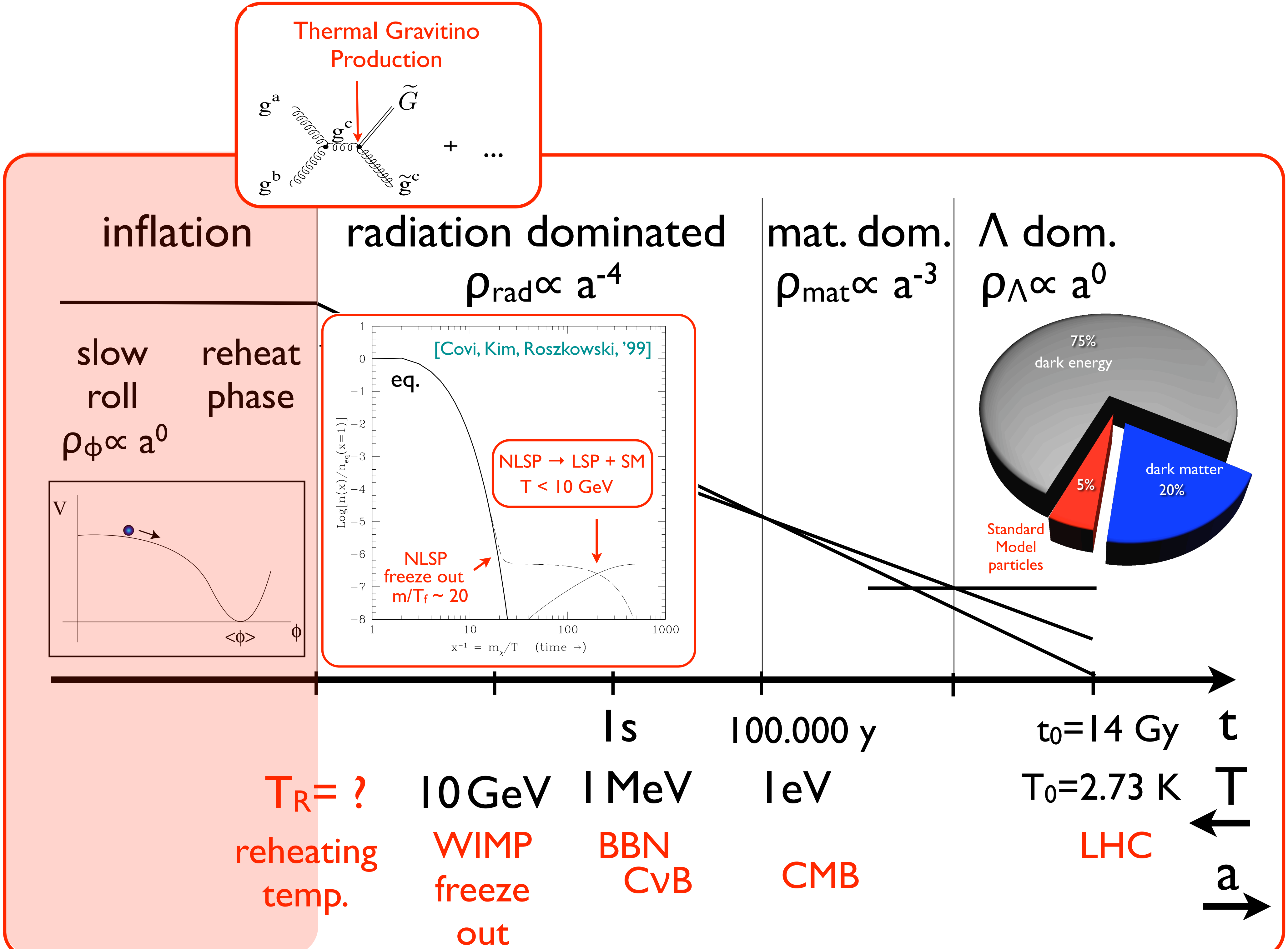
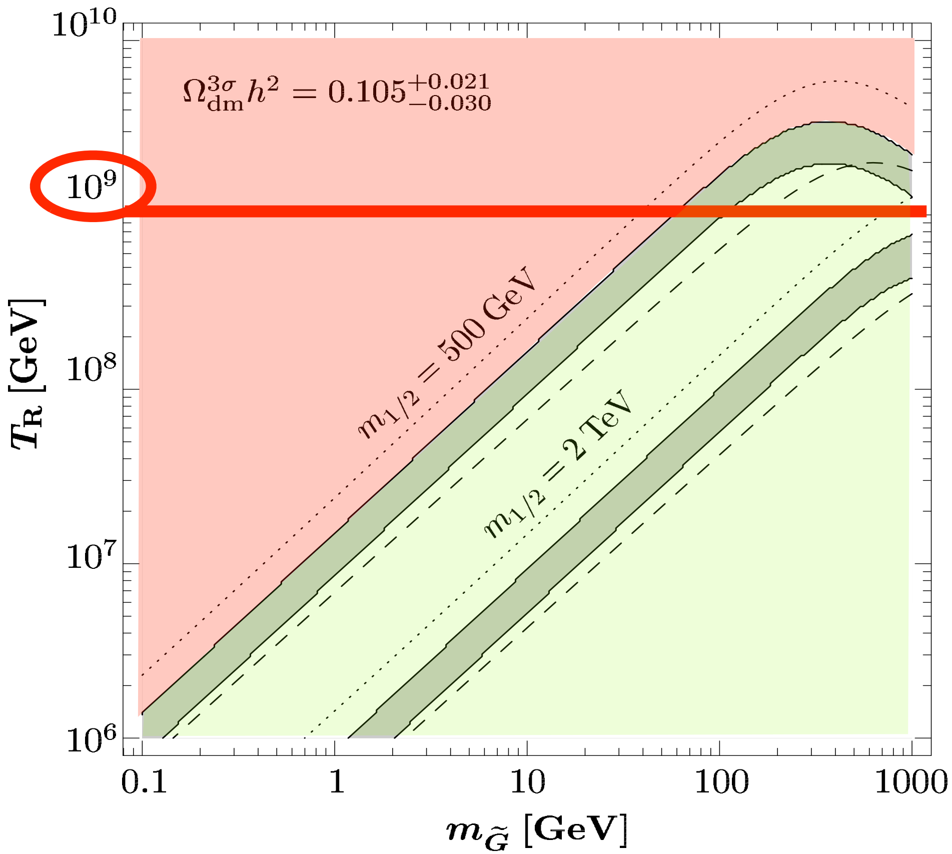
mass	< 10 meV	?	eV-TeV
int.	$\propto (p/f_a)^n$	$\propto (p/f_a)^n$	$\propto (p/M_{Pl})^n$


Thermal Gravitino
Production
g^a
g^b
g^c
$\widetilde{G}$
$\widetilde{g}^c$
+ ...
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
V
<φ>
φ
[Covi, Kim, Roszkowski, '99]
eq.
NLSP → LSP + SM
T < 10 GeV
NLSP
freeze out
$m/T_f \sim 20$
$\mathrm{Log}[n(x)/n_{eq}(x=1)]$
$x^{-1} = m_\chi/T$ (time →)
75%
dark energy
dark matter
20%
5%
Standard
Model
particles
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

Gravitino LSP Case

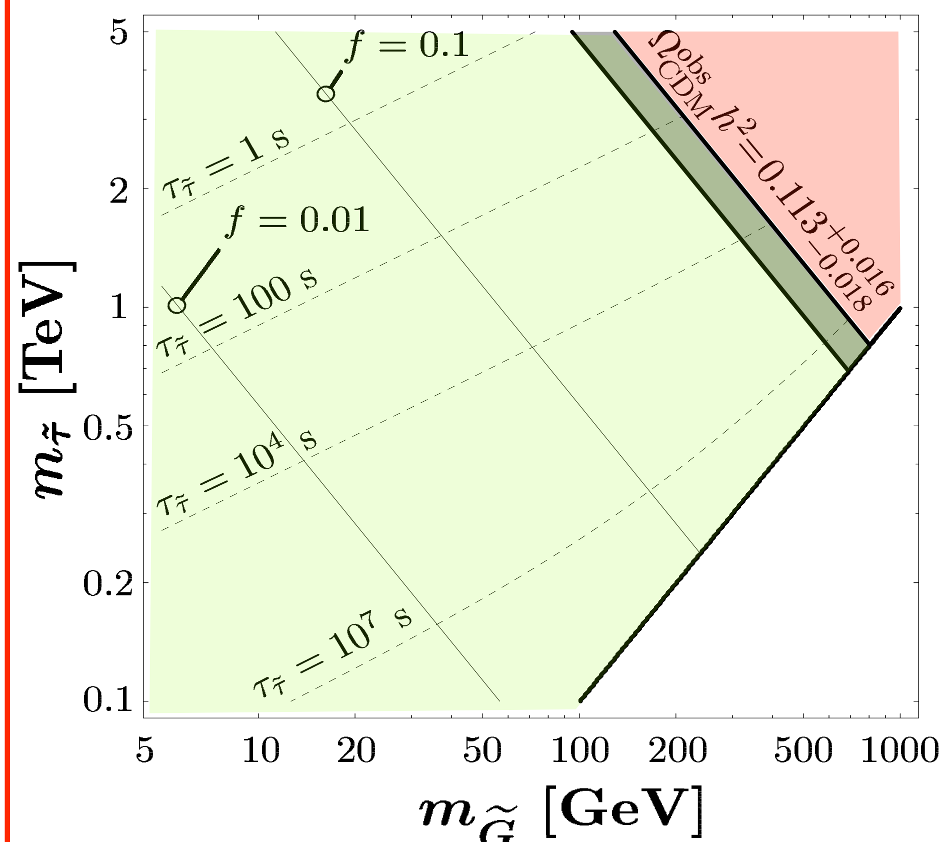
Thermal $\widetilde{G}$ Production



[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]

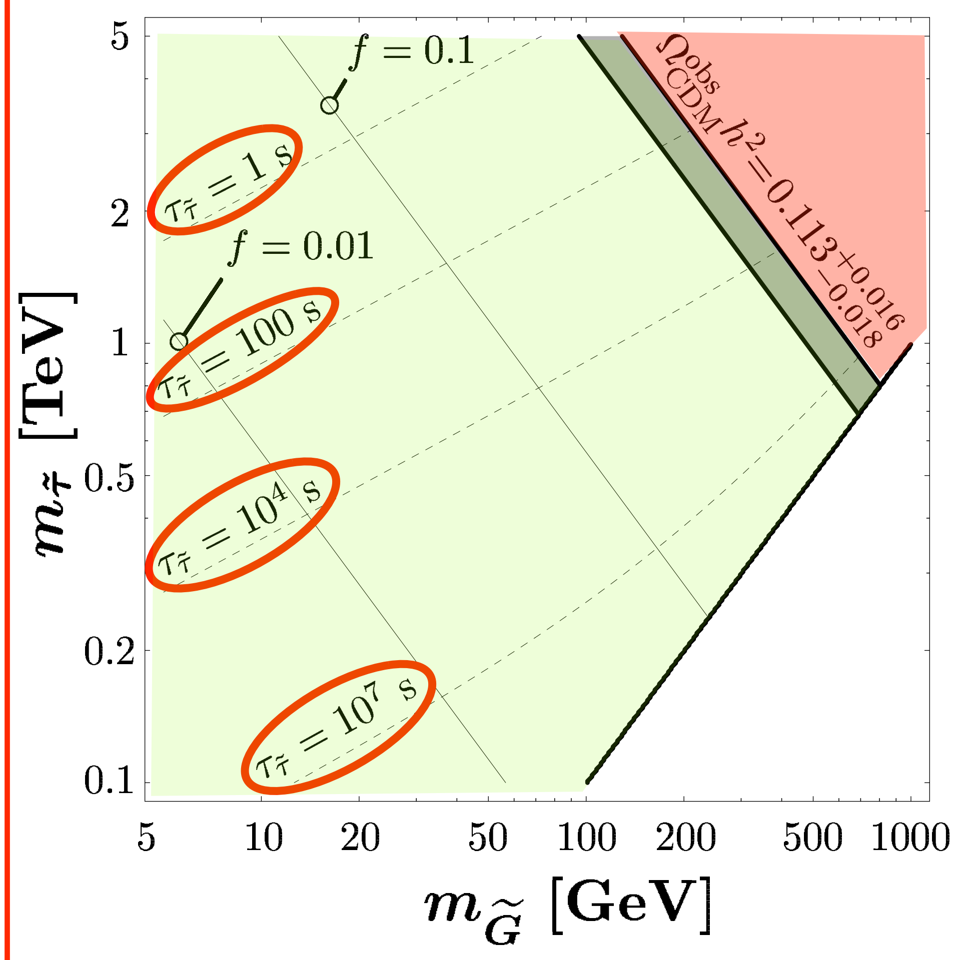
Probing gravitinos experimentally ???

↓

If we are lucky ...

long-lived NLSP

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

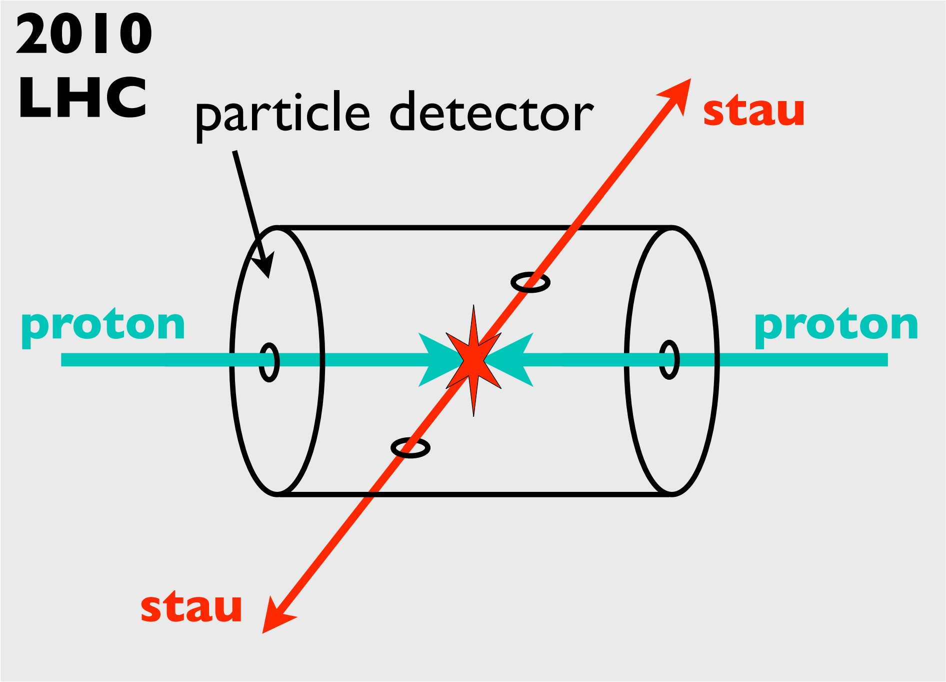


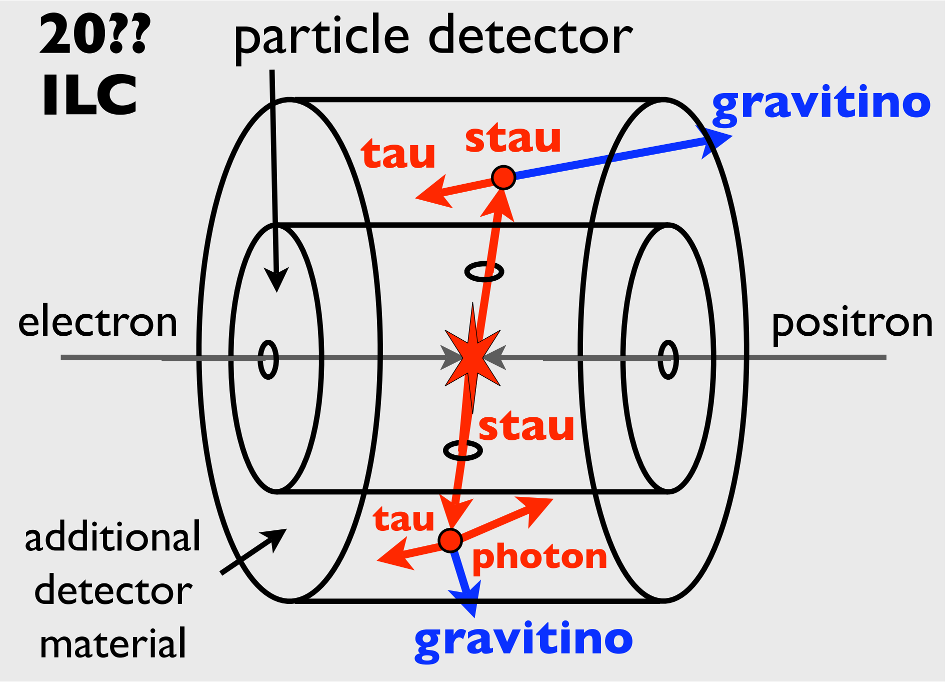
Signatures of Gravitinos in Experiments

– Direct Detection of $\widetilde{G}$

– Direct Production of $\widetilde{G}$

⁎ "stable" charged sparticles **⁎ long-lived charged sparticles**



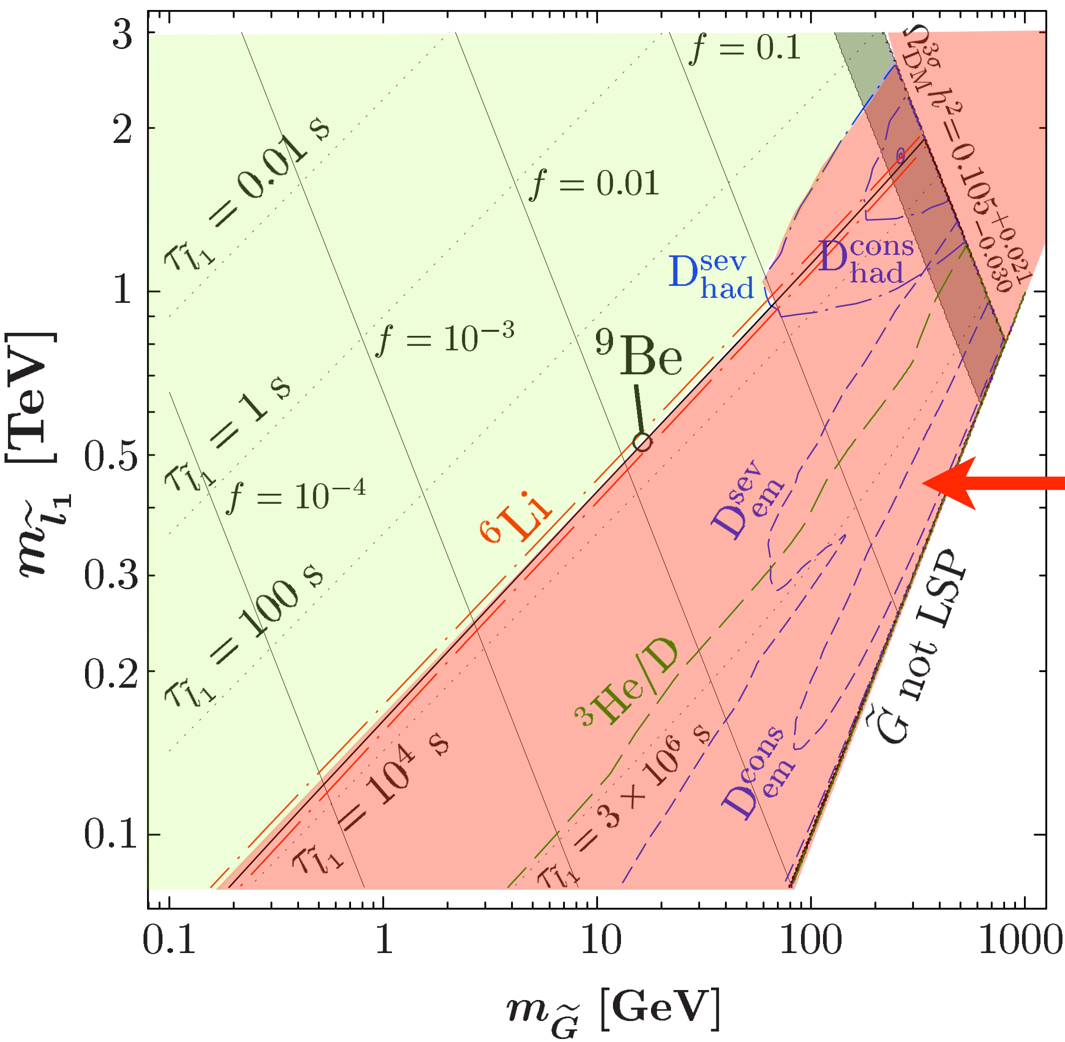


[... ; Buchmüller et al., '04; Hamaguchi et al., '04; Feng, Smith, '05; Martyn, '06; ...]

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]

Summary - Well-motivated DM Candidates

candidate	identity	mass	interactions	production	constraints	experiments
a	axion	< 0.01 eV	$(p/f_a)^n$	misalign. mech.	$\leftarrow$ 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	$\leftarrow$ cold	indirect searches
	(spin 1/2)		weak	$\widetilde{G}$ decay	$\leftarrow$ 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.	$\leftarrow$ cold	$\widetilde{\tau}_1$ prod. at colliders
	(spin 3/2)		extremely weak	NLSP decay	$\leftarrow$ 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.	$\leftarrow$ cold/warm	$\widetilde{\tau}_1$ prod. at colliders
	(spin 1/2)		extremely weak	NLSP decay	$\leftarrow$ 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} (?)

Summary - Well-motivated DM Candidates

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

Summary - Well-motivated DM Candidates

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.	$\leftarrow$ 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 $M_{\mathrm{W}} \sim 100$ GeV	therm. relic $\widetilde{G}$ decay	$\leftarrow$ cold $\leftarrow$ 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	$\leftarrow$ cold $\leftarrow$ 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	$\leftarrow$ cold/warm $\leftarrow$ 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 I - Axion CDM (+ SUSY 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.	$\leftarrow$ cold CMB	events 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 $M_\mathrm{W} \sim 100$ GeV	therm. relic $\widetilde{G}$ decay	$\leftarrow$ cold $\leftarrow$ 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	$\leftarrow$ cold $\leftarrow$ 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	$\leftarrow$ cold/warm $\leftarrow$ 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 I - Axion CDM (+ SUSY 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.	$\leftarrow$ 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 $M_\mathrm{W} \sim 100$ GeV	therm. relic $\widetilde{G}$ decay	$\leftarrow$ cold $\leftarrow$ 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	$\leftarrow$ cold $\leftarrow$ 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	$\leftarrow$ cold/warm $\leftarrow$ 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 (?)

events

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 $\hookrightarrow m_a,\ f_a,\ g_{a\gamma\gamma}$
$\widetilde{\chi}_1^0$ 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 events 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 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.	$\leftarrow$ 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	$\leftarrow$ cold $\leftarrow$ 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	$\leftarrow$ cold $\leftarrow$ 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	$\leftarrow$ cold/warm $\leftarrow$ 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	< 0.01 eV	$(p/f_a)^n$	misalign. mech.	$\leftarrow$ 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	
$\widetilde{\chi}_1^0$ LSP	lightest neutralino	$\mathcal{O}(100\,\mathrm{GeV})$	g, g', y_i	therm. relic	$\leftarrow$ cold	indirect searches
	(spin 1/2)		weak	$\widetilde{G}$ decay	$\leftarrow$ warm/hot	direct searches
	mixture of		$M_{\mathrm{W}} \sim 100$ GeV			collider searches
	$\widetilde{B},\ \widetilde{W},\ \widetilde{H}_u^0,\ \widetilde{H}_d^0$				BBN	$\hookrightarrow m_{\widetilde{\chi}_1^0},\ \widetilde{\chi}_1^0$ coupl.
$\widetilde{G}$ LSP	gravitino	eV–TeV	$(p/\mathrm{M_P})^n$	therm. prod.	$\leftarrow$ cold	events: $\widetilde{\tau}_1$ prod. at colliders
	(spin 3/2)		extremely weak	NLSP decay	$\leftarrow$ 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.	$\leftarrow$ cold/warm	$\widetilde{\tau}_1$ prod. at colliders
	(spin 1/2)		extremely weak	NLSP decay	$\leftarrow$ warm/hot	$+\ \widetilde{\tau}_1$ collection (events)
	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 3 - EWIP DM (+ Axion DM)

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

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,
BBN studies, ...