Dark Matter in $\not{C}P$ Supersymmetry

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Outline

- Introduction
- DM searches
- $\not{C}\!P$ in Supersymmetry
- Susy DM and $\not{C}\!P$
- Summary

Early Universe and DM

Evidence for DM

Various astrophysical sources have confirmed the existence of Dark Matter (DM)

- Binding of Galaxies in Clusters (F. Zwicky, 1933)
- Rotation curves of Galaxies (V.C. Rubin and W.K. Ford, 1970)
- Bindings of hot gases in clusters
- Gravitational Lensing observations
- Large Scale Stucture simulations
- High z - Supernovae
- Observations of colliding clusters of Galaxies

The most direct and accurate evidence comes from WMAP by measuring anisotropies of the CMB power spectrum

$$\sim 73\% \ \mathrm{DarkEnergy}, \sim 23\% \ \mathrm{DarkMatter}, 4\% \ \mathrm{Baryons}$$

$\Lambda\mathrm{CDM}$ in agreement with astrophysical data

$$\Omega_{DM} h_0^2 = 0.111^{+0.011}_{-0.015} \ 2\sigma$$

N. Spergel et al., WMAP collaboration, Astrophys. J. Suppl. 170 (2007) 377

Hot or Cold Dark Matter ?

HDM is almost ruled out (like SM neutrinos !)

Super - K (1998) $\Longrightarrow \Delta m_\nu \neq 0$, Neutrinos are massive

$$\Omega_\nu h_0^2 \simeq 0.1 \Longrightarrow \sum m_\nu \simeq 10\ eV$$

- Too small for dwarf halos requiring: $\sum m_\nu > 120\ eV$. By Pauli Principle cannot cluster in dwarf halos (Tremaine and Gunn)
- $10\ eV$ too large for structure formation which puts upper limits, $\sum m_\nu < 1.0\ eV$

Non - SM like neutrinos are not ruled out !

CDM established by various observations

- Via Lactea II simulations for the study of DM halo in Milky Way
  J. Diemand et al, 2008 - arxiV: 0805.1244 [astro-ph]
- Observations of proto-galaxies (*Very Large Telescope*)
- ...

Candidates for Dark Matter

Thermal, or non-thermal, relics created in the early Universe may constitute part or all of the observed DM

WIMPs

Weakly Interacting Massive Particles in the mass range $3\ \text{GeV} < M_\chi < 50\ \text{TeV}$ naturally yield

$$\Omega_{DM} h_0^2 \sim 0.1\ ,\ \text{(WIMP miracle)}$$

- LSP - neutralinos in SUSY theories
- Heavy ν - like particles
- KK excitations in ED theories
- Lightest T-odd particles in little Higgs models
- Other exotic

superWIMPs

Interact with smaller strength (gravitationally,...) than WIMPs

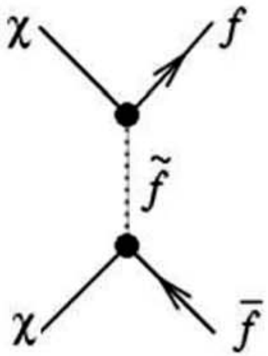
- Gravitino (superpartner of graviton)
- KK gravitons
- Axino (superpartner of axion)
- ...

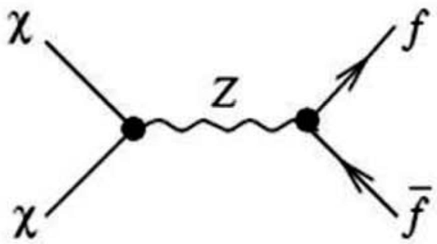
Other Candidates

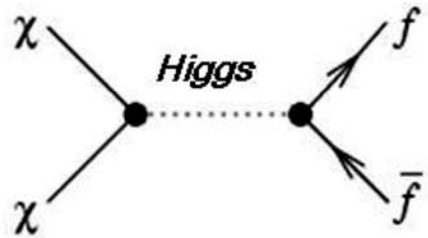
- Axion ($m_a \simeq 10^{-6} - 10^{-3}\ eV$)
- Wimpzillas, Cryptons
- Q - balls
- BH remnants and other very massive astrophysical objects
- Moduli fields of String Theory
- ...

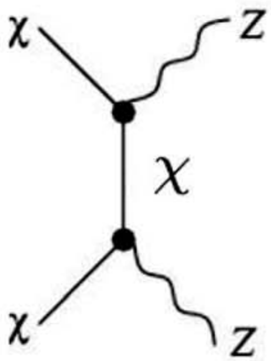
■ **SUPERSYMMETRY , with conserved R - parity, offers an ideal WIMP candidate ! The LSP neutralino (if the lightest sparticle). Also gravitino, axino or superpartner of a sterile neutrino.**

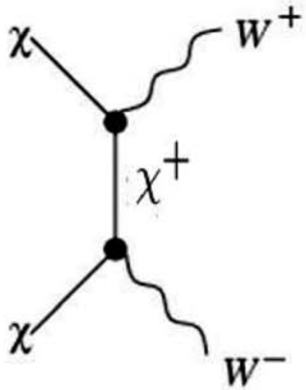
Neutralino pair annihilation











+ more

Boltzmann equation: (No co-annihilations)

$$\frac{dn}{dt} = -3\,\frac{\dot{a}}{a}\,n - \langle v\,\sigma \rangle \left(n^2 - n_{eq}^2 \right)$$

Neutralino matter density :

$$\rho_{\tilde\chi} = \left(\frac{4\pi^3}{45} \right)^{1/2} \left(\frac{T_{\tilde\chi}}{T_\gamma} \right)^3 \frac{T_\gamma^3}{M_{Planck}} \frac{\sqrt{g_{eff}(T_f)}}{\mathbf{J}}$$

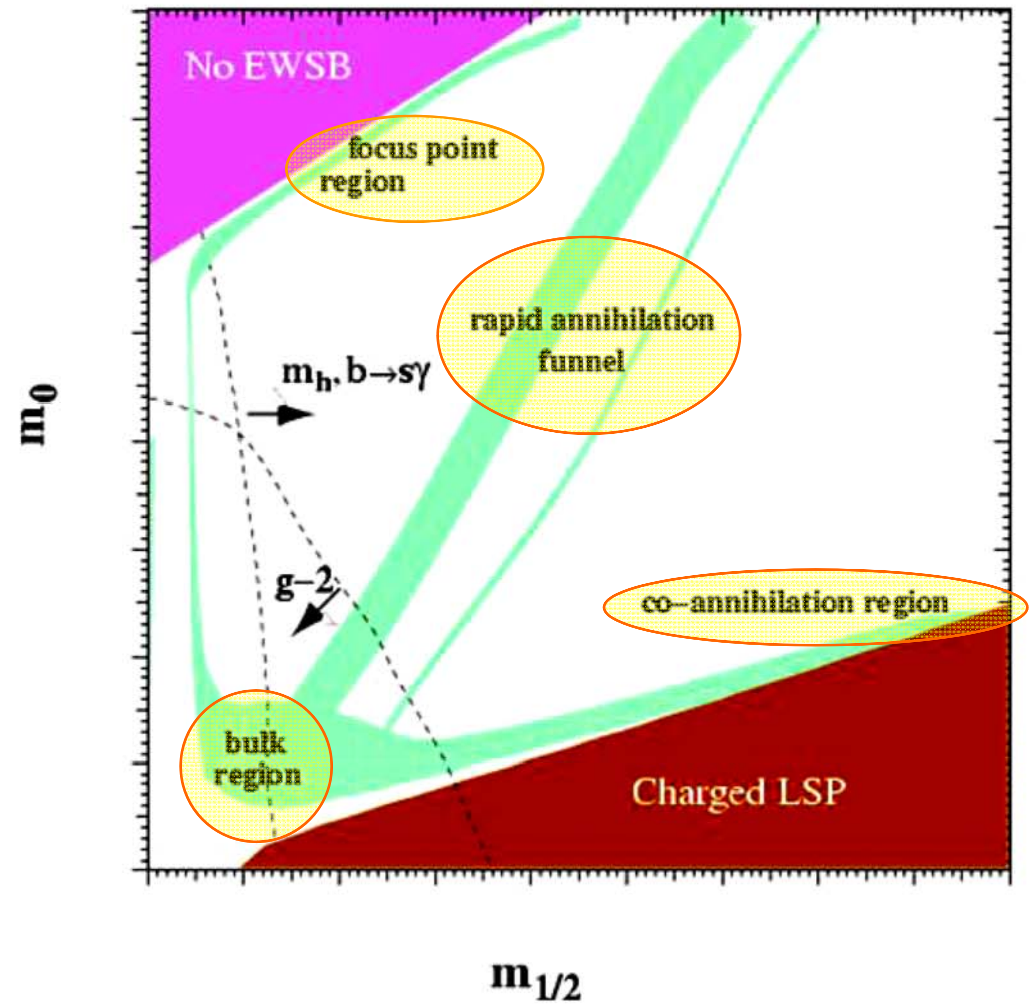
with $$\left(\frac{T_{\tilde\chi}}{T_\gamma} \right)^3 = \frac{4}{11} \cdot \frac{g_{eff}(T_\nu)}{g_{eff}(T_f)} = \frac{3.91}{g_{eff}(T_f)}$$

Relic Density :

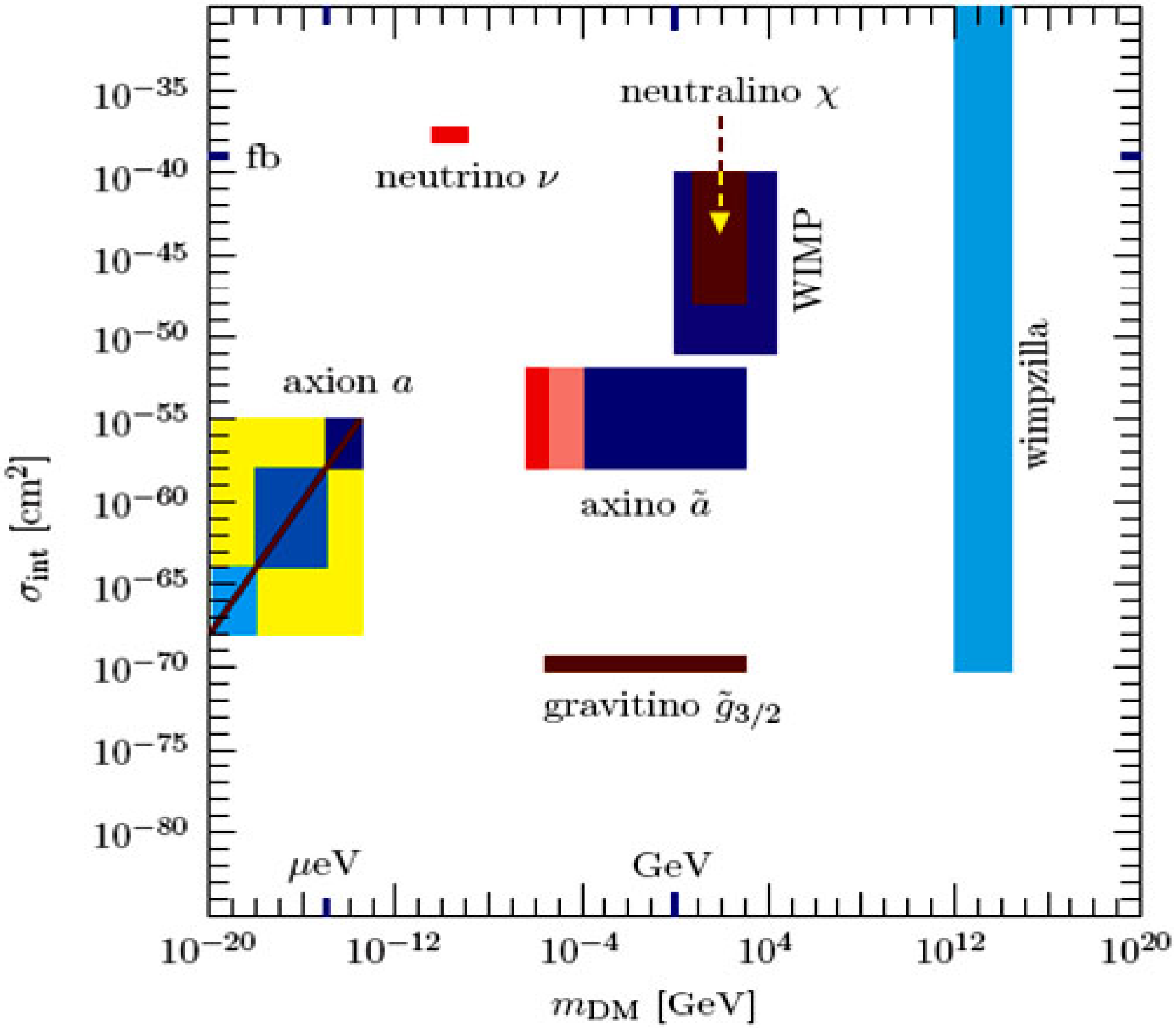
$$\Omega_{\tilde\chi}\, h_0{}^2 = \frac{1.066 \times 10^9\ GeV^{-1}}{M_{Planck}\ \sqrt{g_{eff}(T_f)}\ \mathbf{J}}$$

$\mathbf{J} \equiv \int_0^{x_f} \langle v\sigma \rangle\ dx$ **with** $x_f = T_f / m_{\tilde\chi}$

Cosmologically allowed regions

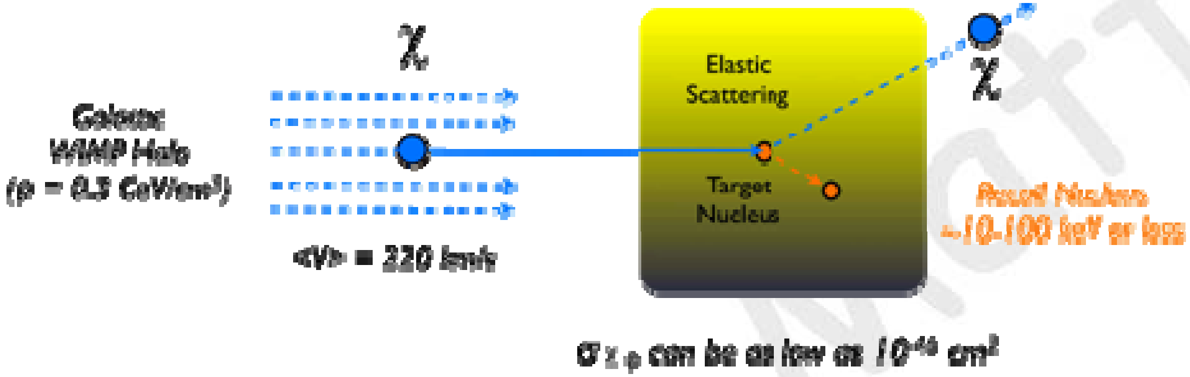


hep-ph/0106204, Battaglia et al.


neutralino χ
neutrino ν
fb
WIMP
wimpzilla
axion a
axino $\tilde{a}$
gravitino $\tilde{g}_{3/2}$
μeV
GeV
$\sigma_{\rm int}$ [cm^2]
$m_{\rm DM}$ [GeV]
10^{-35}
10^{-40}
10^{-45}
10^{-50}
10^{-55}
10^{-60}
10^{-65}
10^{-70}
10^{-75}
10^{-80}
10^{-20}
10^{-12}
10^{-4}
10^{4}
10^{12}
10^{20}

Direct Detection of DM

DM is detectable from its elastic scattering with Nuclei



(K. Ni, Erice 2008)

CDMS, CDMS II 2008 Ge, XENON, ...
have put limits on the spin-independent elastic cross-section.

DAMA / Libra (Yearly modulation)
Detected signal consistent with DM in the galactic halo ! Not confirmed by other experiments, but their results cannot be directly compared in a model independent way.

In **mSUGRA** the spin-independent X-section falls with m_{LSP}

$$\sigma_{SI} \simeq 10^{-8} - 10^{-10}\ pb \quad (m_{LSP} \simeq 200 - 800\ GeV)$$

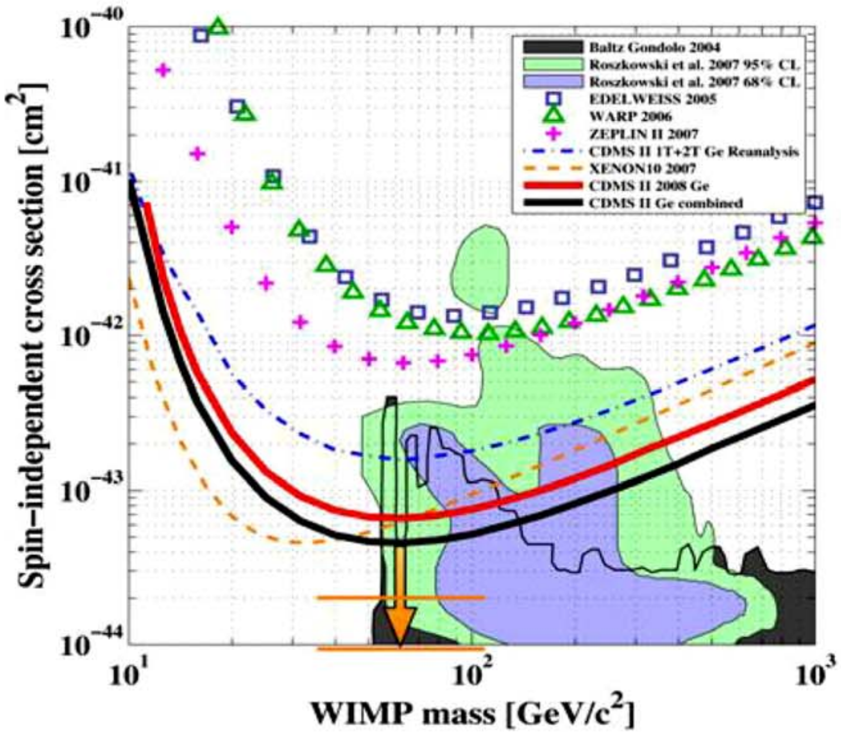
In models predicting DM with enhanced Higgsino component the X-section is large, $\sim 10^{-8}\ pb$, even for larger m_{LSP}.

- The projected sensitivity of coming experiments **superCDMS, XENON-100, XENONIT, LUX, WARP,...** will reach $\sim 10^{-9} - 10^{-10}\ pb$ for $m_{LSP} < 800\ GeV$.
- Some experiments will use materials sensitive to spin-dependent X-sections (fluorine,...).

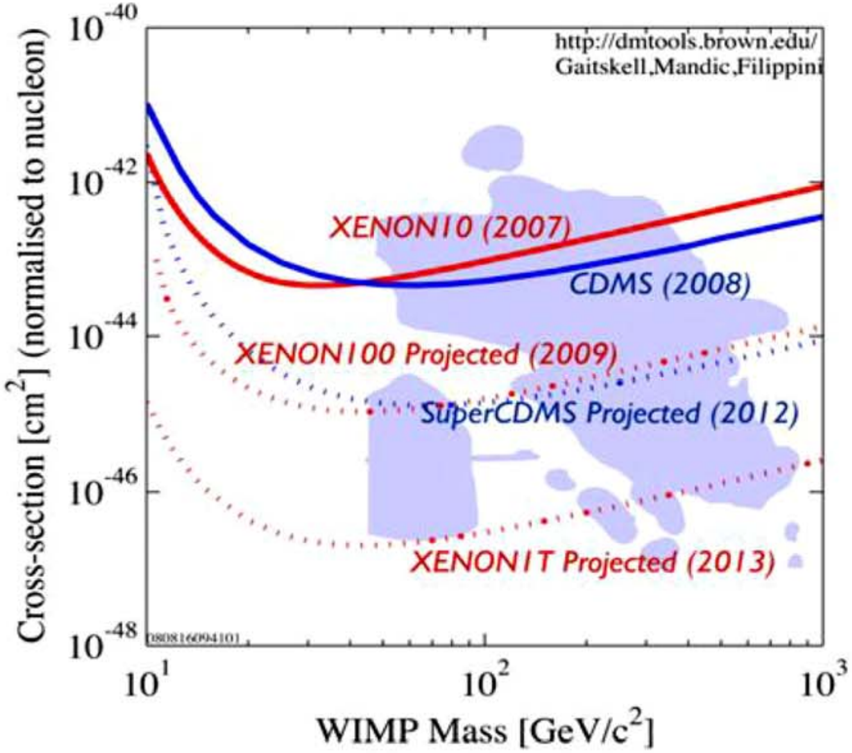
If DM has supersymmetric origin it is likely to be detected in DD experiments in the coming years.

Current and future DD limits

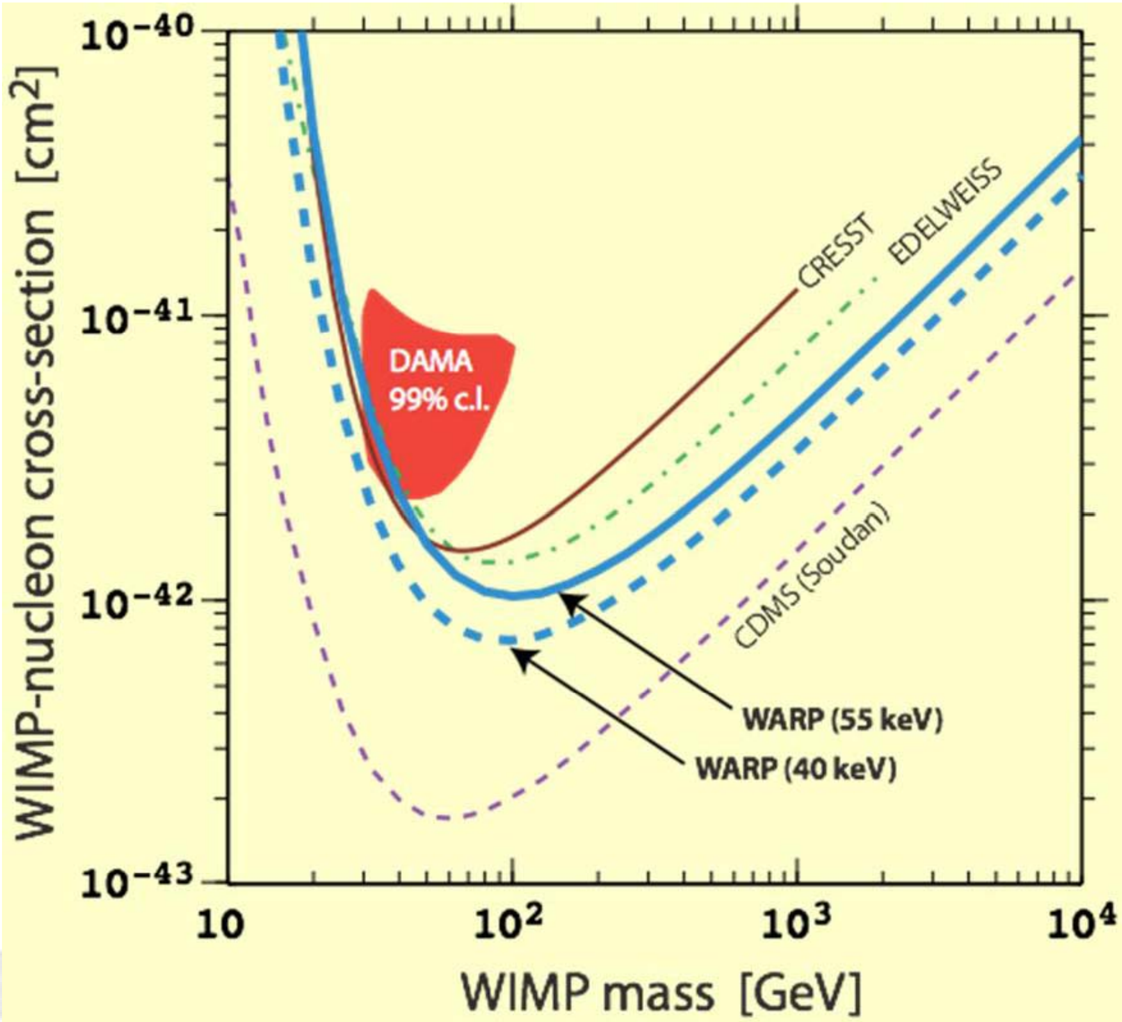
Also A. RUBBIA, This conference



CDMS WIMP limits
B. Sadoulet, arxiV: 0802.3530,
Moriond, 19 March 2008



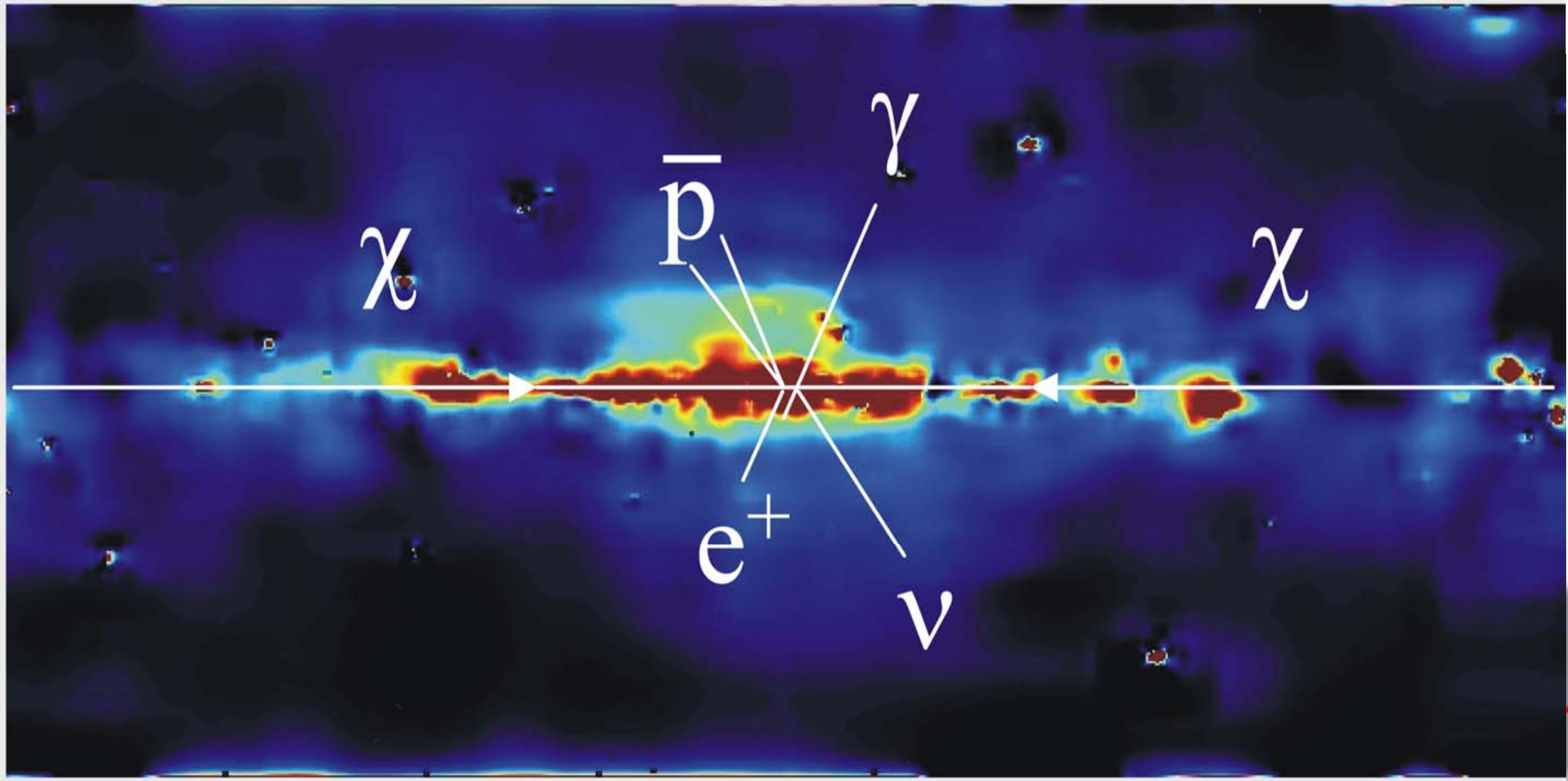
XENON10 limits
N. Kaixuan,
Erice, 29 August 2008



WIMP-nucleon cross-section [cm^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10
10^2
10^3
10^4
WIMP mass [GeV]
DAMA
99% c.l.
CRESST
EDELWEISS
CDMS (Soudan)
WARP (55 keV)
WARP (40 keV)

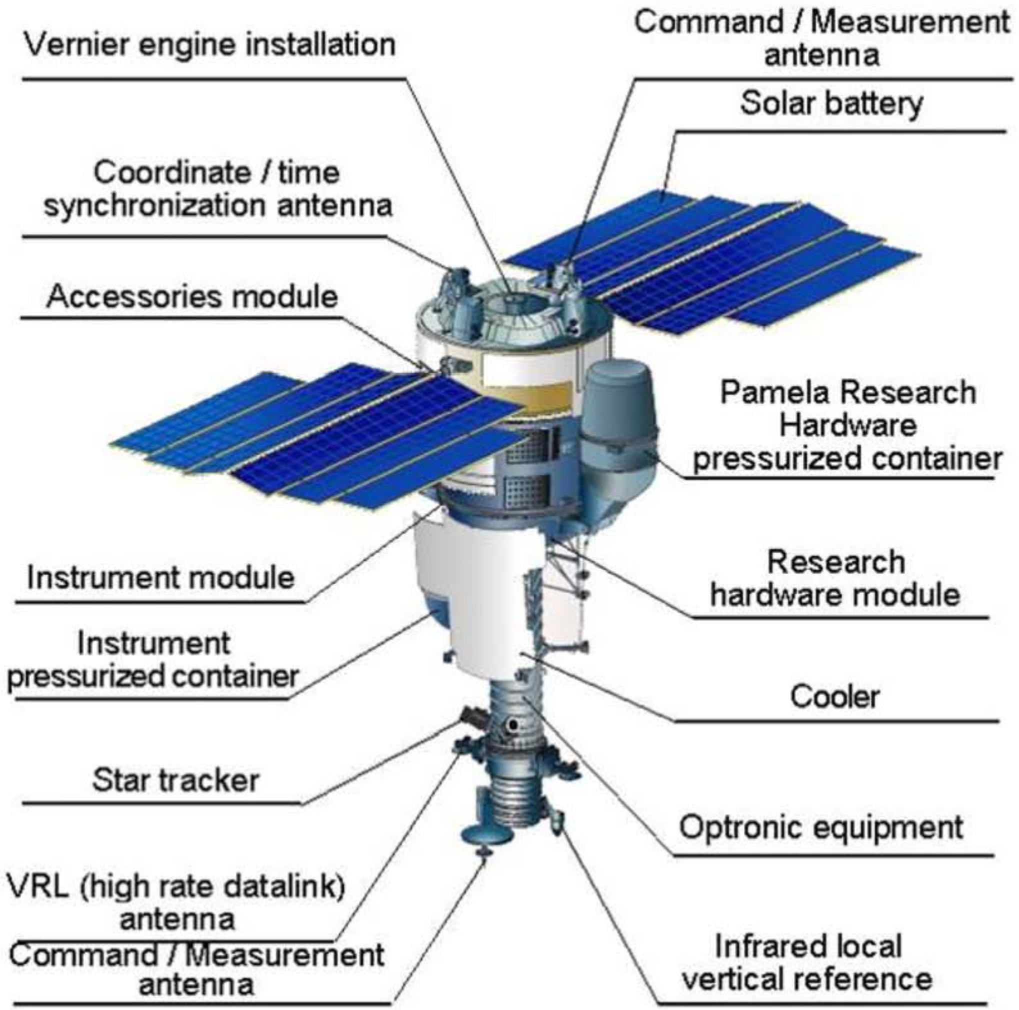
Indirect Detection of DM

- **WIMP-WIMP annihilation in the galactic halos may be detected through production of γ, neutrinos, anti-matter.**

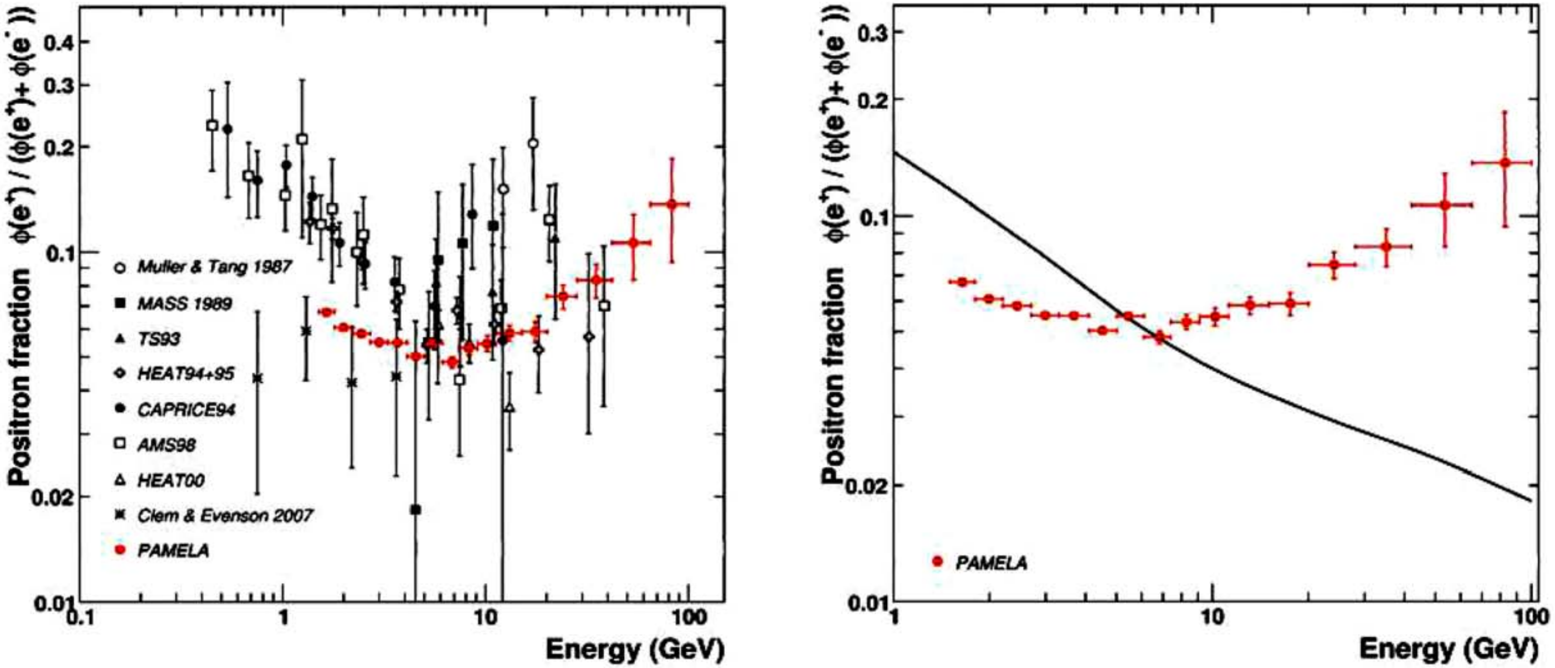


?

PAMELA

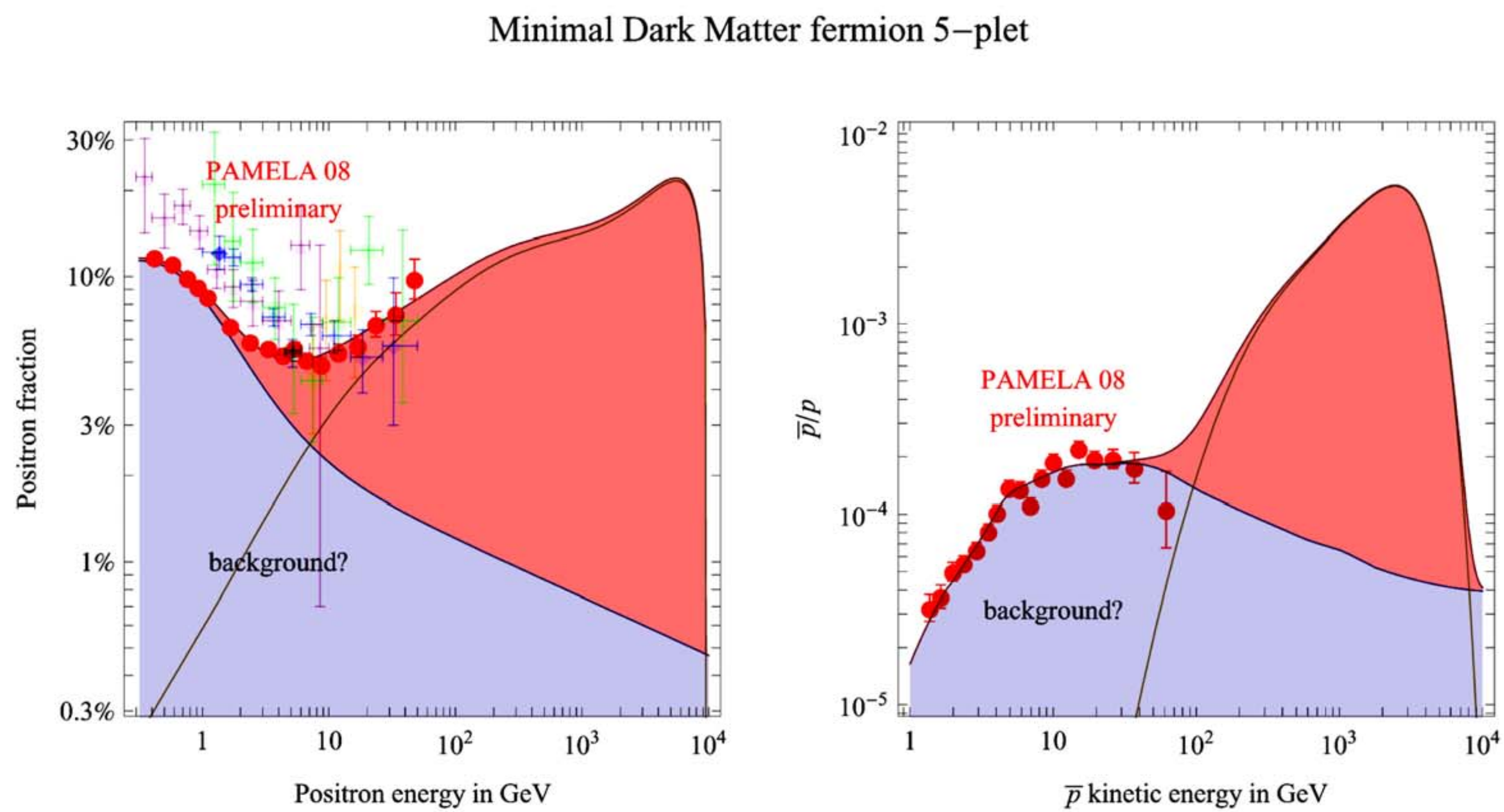


Vernier engine installation
Command / Measurement antenna
Solar battery
Coordinate / time synchronization antenna
Accessories module
Pamela Research Hardware pressurized container
Research hardware module
Instrument module
Instrument pressurized container
Cooler
Star tracker
Optronic equipment
VRL (high rate datalink) antenna
Command / Measurement antenna
Infrared local vertical reference



Fraction of e^+ measured by PAMELA compared with other experimental data (left). Comparison with theoretical model for secondary production of e^+ during the propagation of cosmic - rays in our Galaxy (right).

O. Andriani et al arXiv: 0810.4995 [astro-ph].

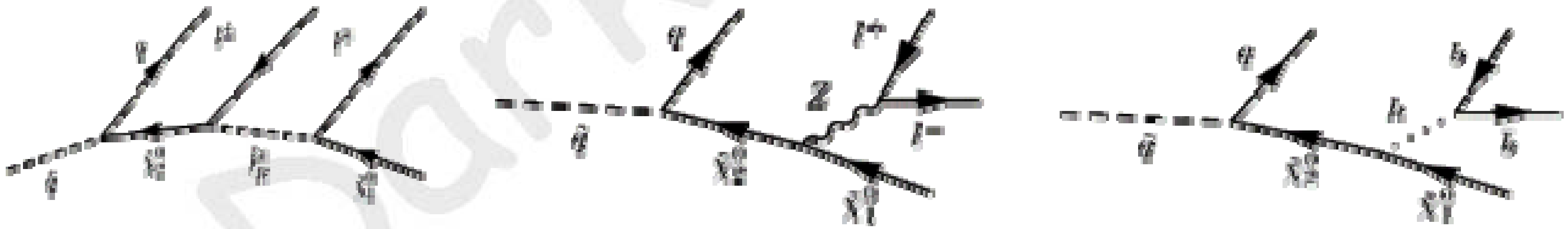


Also other proposals :
V. Barger, W. Keung, D. Marfatia, G. Shaugnessy, arXiv:0809.0162 [hep-ph]
R. Harnik, G. Kribs, arXiv:0810.5557 [hep-ph]
D. Feldman, Z. Liu, P. Nath, arXiv:0810.5762 [hep-ph]
…

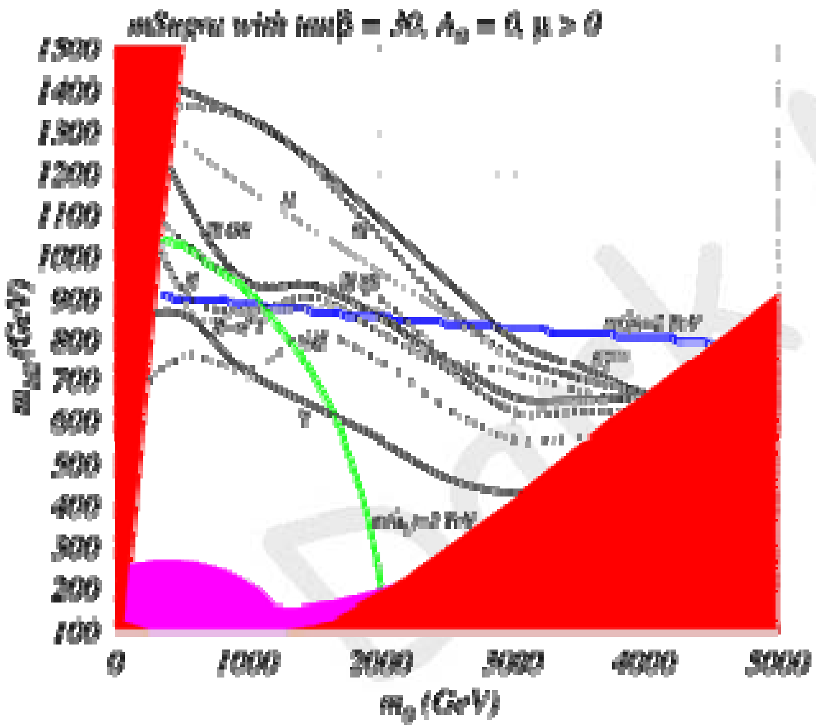
Supersymmetric DM in colliders

The LSP neutralino, if exists, is a leading CDM candidate and may be detected in collider searches.

- Heavier than the LSP states decay via multi-step-cascade processes to LSP.
- $\tilde{q}, \tilde{g}$ are among the heavy states, strongly interacting, and if not extremely heavy will have large production X-sections with $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{g}$ in the final state.



- In mSUGRA, with 100 fb^{-1} integrated luminosity, the LHC reach for low m_0 extends to $M_{1/2} < 1.4\ TeV$ corresponding to $m_{\tilde{q},\tilde{g}} \simeq 3\ TeV$.
- For large m_0, sfermions are too heavy to be produced and the LHC reach comes only from $\tilde{g}$ pair production for $M_{1/2}$ up to $\sim 700\ GeV$ equivalent to $m_{\tilde{g}} \simeq 2\ TeV$



The 100 fb^{-1} reach of LHC for mSUGRA.
H. Baer and X. Tata, arXiv:0805.1905

If DM has supersymmetric origin will be observed in Direct and Indirect Dark Matter searches and, in a coplementary way, in LHC experiments. Its detection will mark the beginning of a new exciting era in Astroparticle and Particle Physics.

The popular models MSSM, CMSSM, mSUGRA ... have been extensively studied. Leading SUSY DM candidates :

- $\tilde{\chi}$, LSP - neutralino (CDM, can yield $\mathbf{\Omega_{\tilde{\chi}} h_0^2 \sim 0.1}$).
- $\tilde{G}$, Gravitino (Mixture of Cold and Warm / Hot DM)
  Poses problems for BBN due to late decays of NLSP which dissociate light nuclei. This is avoided if NLSP is a stau or if R - parity is broken.
- $\tilde{a}$, Axino (Mixture of Cold and Warm / Hot DM)
  Revived interest, reconciles Yukawa - unification models, that predict over-abundance of neutralino DM, with WMAP data.
  (H. Baer, S. Kraml, S. Sekmen, H. Summy, arXiv:0801.1831v2 [hep-ph])

Supersymmetric models encompassing CP - violation, have not been studied to the same extent ! Sources of CP - violations, other than this in the CKM-matrix, possess interesting features :

- Important for EW Baryogenesis
- Affect the predictions for LSP relic densities
- Produce EDMs for elementary fermions and Atoms
- Affect the sparticle mass spectrum
- Have large impact on Higgs-boson phenomenology
- Have impact on $B_s \to \mu^+\mu^-$ and $B \to K\phi$
- SUSY $\not{C}P$ phases can be observed in collider physics :
  Through $\tilde{q}, \tilde{g}$ production
  Squark decays ($\tilde{t} \to t + l^+ l^- + \tilde{\chi}$, observable at LHC)
  $e^+e^- \to f\bar{f}$ (observable at ILC)

O. KITTEL, This conference

$\not{C}P$ and Baryogenesis

CKM phase too small to account for the observed Baryon asymmetry ⟹ Include additional $\not{C}P$ sources !
Large phases accomodated in SUSY parameters are welcome for Baryogenesis which takes place via first order EW phase transition
(Leptogenesis is an alternarive :

A. PILAFTSIS, This conference

M. Fukugita

- $\tilde{q}, \tilde{l}$ d … $< m_t$.
  Phas… ⟹
  Leave… effect.
- $\tilde{\chi}^+, \tilde{\chi}$ … enario. The
  …ct… …t phases are
  arg(…

SUSY CP - problem !

$$\delta_{CP} \times \left(\frac{1\ \text{TeV}}{M_{\text{SUSY}}}\right) << 1$$

Phase $\delta_{CP} << 1$

Scale $M_{\text{SUSY}} >> \text{TeV}$

Small phases overproduce EDMs which put stringent constraints !

EDMs are probes of $\not{C}P$ and new physics. Upper limits on them translate into constraints on $\not{C}P$ phases.

EDM	Bound
^{205}Tl (paramagnetic)	$\lvert d_{Tl}\rvert < 9 \times 10^{-25}$ e · cm
^{199}Hg (diamagnetic)	$\lvert d_{Hg}\rvert < 2 \times 10^{-28}$ e · cm
neutron	$\lvert d_n\rvert < 2.9 \times 10^{-26}$ e · cm

Future expts will impose additional constraints by measuring Deuteron EDM with a projected sensitivity

$$|d_D| < (1-3) \times 10^{-27}$$

EDM collaboration - Y.K. Semertzidis et al. AIP Conf. Proc. 200 (2004)

The dependencies of EDMs from the $\not{C}P$ sources is through :

- CP - odd effective interactions at the QCD scale $\sim 1\ GeV$, involving θ_{QCD}, fermion EDMs, quark chromoelectric moments, Weinberg operator and 4-f couplings

$$\mathcal{L}_{\rm dim=4} = \frac{g_s^2}{32\pi^2}\,\theta\; G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a}$$

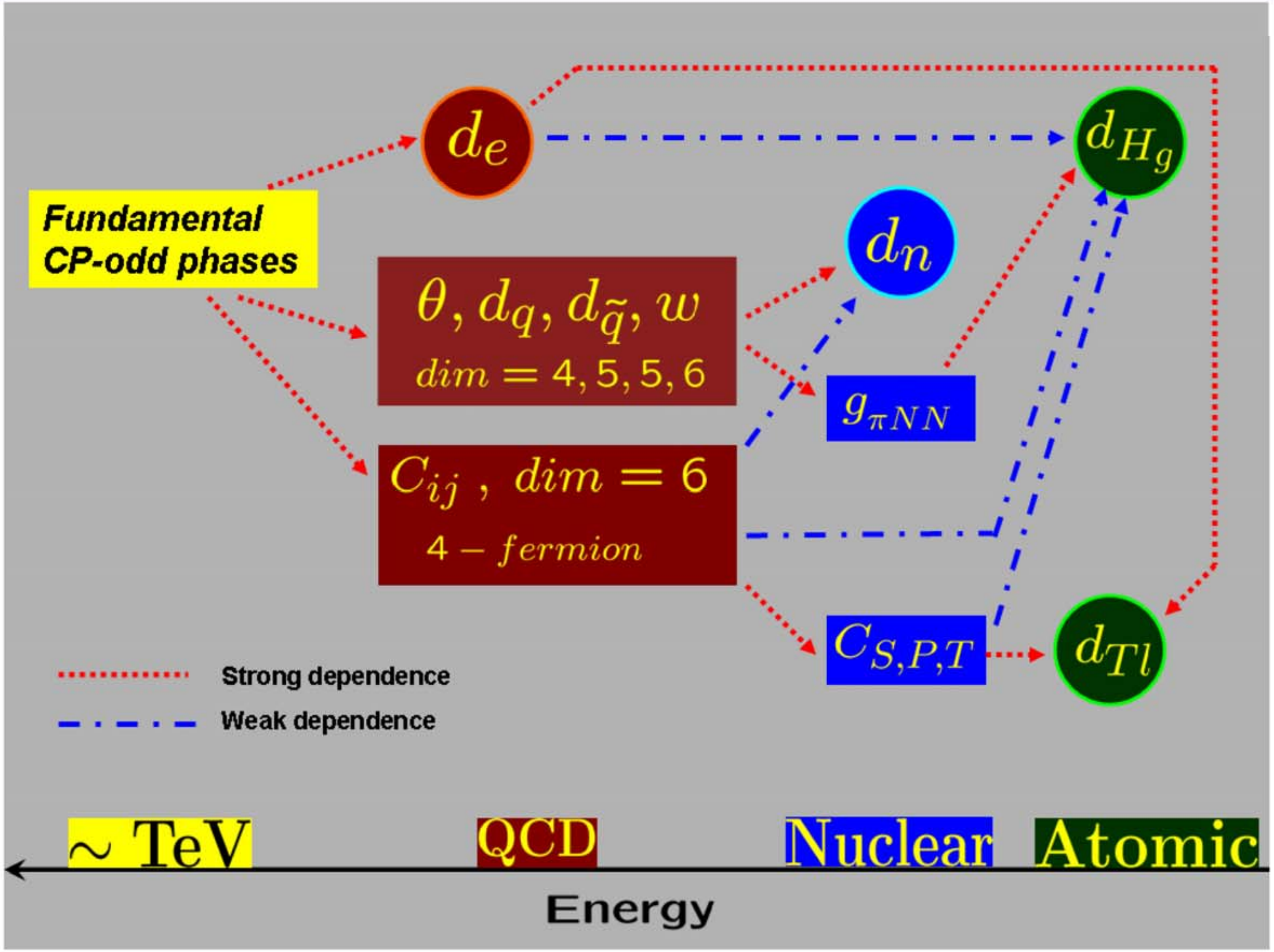
$$\mathcal{L}_{\rm dim=5} = -\frac{i}{2}\sum_{l=u,d,s,e,\mu} d_l\;\overline{\psi}_l(F\sigma)\gamma_5\psi_l - \frac{i}{2}\sum_{l=u,d,s} g_s\;\widetilde{d}_l\;\overline{\psi}_l(G\sigma)\gamma_5\psi_l$$

$$\mathcal{L}_{\rm dim=6} = \frac{1}{3}w\;f^{abc}G^a_{\mu\nu}\widetilde{G}^{\nu\beta,b}G_\beta{}^{\mu,c} + \sum_{l,j} C_{lj}\;(\bar{\psi}_l\psi_l)(\bar{\psi}_j i\gamma_5\psi_j) + \cdots$$

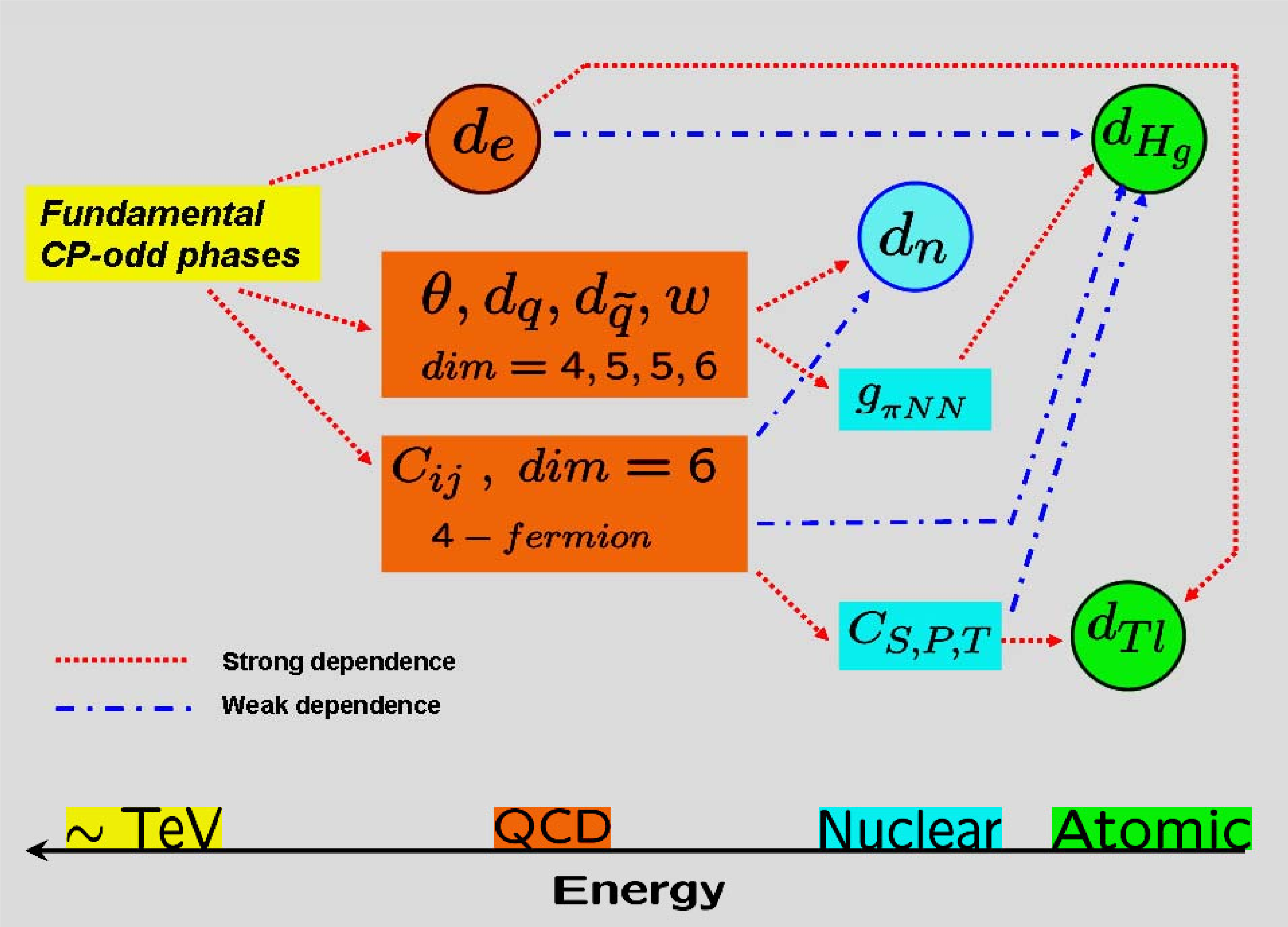
- CP - odd πNN and $eeNN$ effective interactions at the nuclear scale

$$\mathcal{L}_{\pi NN} = g^{(0)}_{\pi NN}\bar{N}\tau^a N\pi^a + g^{(1)}_{\pi NN}\bar{N}N\pi^0 + g^{(2)}_{\pi NN}(\bar{N}\tau^a N\pi^a - 3\bar{N}\tau^3 N\pi^0)$$

$$\mathcal{L}_{eN} = C_S\;\bar{e}\gamma_5 e\bar{N}N + C_P\;\bar{e}e\bar{N}\gamma_5 N + C_T\;\epsilon_{\mu\nu\alpha\beta}\bar{e}\sigma^{\mu\nu}e\bar{N}\sigma^{\alpha\beta}N$$



Dependence tree of EDMs on the fundamental CP-odd sources
M. Pospelov and A. Ritz, arXiv:hep-ph/0504231.


Fundamental CP-odd phases
d_e
$\theta, d_q, d_{\tilde{q}}, w$
$dim = 4, 5, 5, 6$
C_{ij} , $dim = 6$
$4 - fermion$
d_n
$g_{\pi NN}$
$C_{S,P,T}$
d_{Hg}
d_{Tl}
Strong dependence
Weak dependence
~ TeV
QCD
Nuclear
Atomic
Energy

Thallium, Mercury and neutron EDMs :

Bound on Tl edm translates into bound on electron edm

$$d_{\mathrm{Tl}} = -585\, d_e - 43\, e\, (C_S^{(sing)} - 0.2 C_S^{(trip)})\ GeV$$

$$d_{\mathrm{Hg}} = 10^{-2} d_e - 1.8 \times 10^{-4}\, e\, g_{\pi NN}^{(ispin=1)}\ GeV^{-1}$$

$$- 1.4 \times 10^{-5}\, e \left[\frac{0.5 C_{dd}}{m_d} + 3.3k \frac{C_{sd}}{m_s} + (1 - 0.25k)\frac{C_{bd}}{m_b}\right] GeV^2$$

$$+ e\,(3.5 \times 10^{-3} C_S^{(sing)} + 4 \times 10^{-4} C_P^{(sing)})\ GeV$$

$$d_n = 2\left[0.7\,(d_d - 0.25 d_u) + 0.55\, e\,(\tilde{d}_d + 0.5\,\tilde{d}_d)\right]$$

$$+ e\,(20.0\ w\ MeV + 0.65 \times 10^{-3} \frac{C_{bd}}{m_b}\ GeV^2)$$

with

$$k \equiv \frac{< N|m_s \bar{s}s|N >}{220\ MeV} \simeq 0.3 - 1$$

Demir, Lebedev, Olive, Pospelov, Ritz hep-ph/0311314 ; Olive, Pospelov, Ritz, Santoso, hep-ph/0506106 ; J. Ellis and A. Pilaftsis, arXiv:0808.1819 [hep-ph]

Extend MSSM to include $\not{CP}$ sources.

$$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{soft}$$

$\mathcal{L}_{soft}$ encodes supersymmetry breaking terms.

- Global $U(3)$ - symmetries eliminate redundant phases from the quark and lepton Yukawa sector $\Longrightarrow$ One CKM complex phase is left.
- In the limit of zero Higgs mixing, $\mu = 0$, $\mathcal{L}_{SUSY}$ is symmetric under

$U_{PQ}(1)$, **Global Peccei-Quinn symmetry**
$U_R(1)$, **Global R-symmetry**

Customary to trade $U_R(1)$ for $U_{R-PQ}(1)$

Multiplet	PQ-charge	R-charge		(R-PQ) - charge	
	boson-fermion	boson-fermion		boson-fermion	
Higgs	1	1	0	0	-1
Quark-Lepton	- $\frac{1}{2}$	$\frac{1}{2}$	- $\frac{1}{2}$	1	0
Vector	0	0	-1	0	-1

These rotations eliminate further phases !

Phases and Invariants

- Focus on **CPMFV** models - flavor mixing in the CKM matrix
- Pursue a top-down approach with boundary conditions imposed at the Unification scale - pertinent to a unified picture that determines dynamics at Planckian energies. The number of low enegy parameters is reduced, like in mSUGRA.
- **PQ** and **R** - symmetries eliminate redundant phases. Which ones is a matter of choice !
  Physical quantities depend on twelve invariant combinations !

$$\arg(\mu M_a m_3^{2*}) \ , \ \arg(\mu A_i m_3^{2*})$$

M_a = Gaugino masses, $a = 1, 2, 3$

A_i = Trilinear couplings ($i = e, \mu, \tau, u, c, t, d, s, b$)

m_3^2 = Higgs mixing parameter

- **cmSUGRA** (*complex mSUGRA*)
  Two phases, basis usually adopted $\phi_\mu = \arg(\mu)$, $\phi_A = \arg(A_0)$.
  ϕ_μ is tightly constrained by EDMs.
- **CPMFV**
  Twelve phases, more options available, rich phenomenology !

The phases of gauginos, trilinear couplings and m_3^2 are different at GUT and EW scales !

The phases run with energy scale !

Exception is the μ phase

RGE running of phases

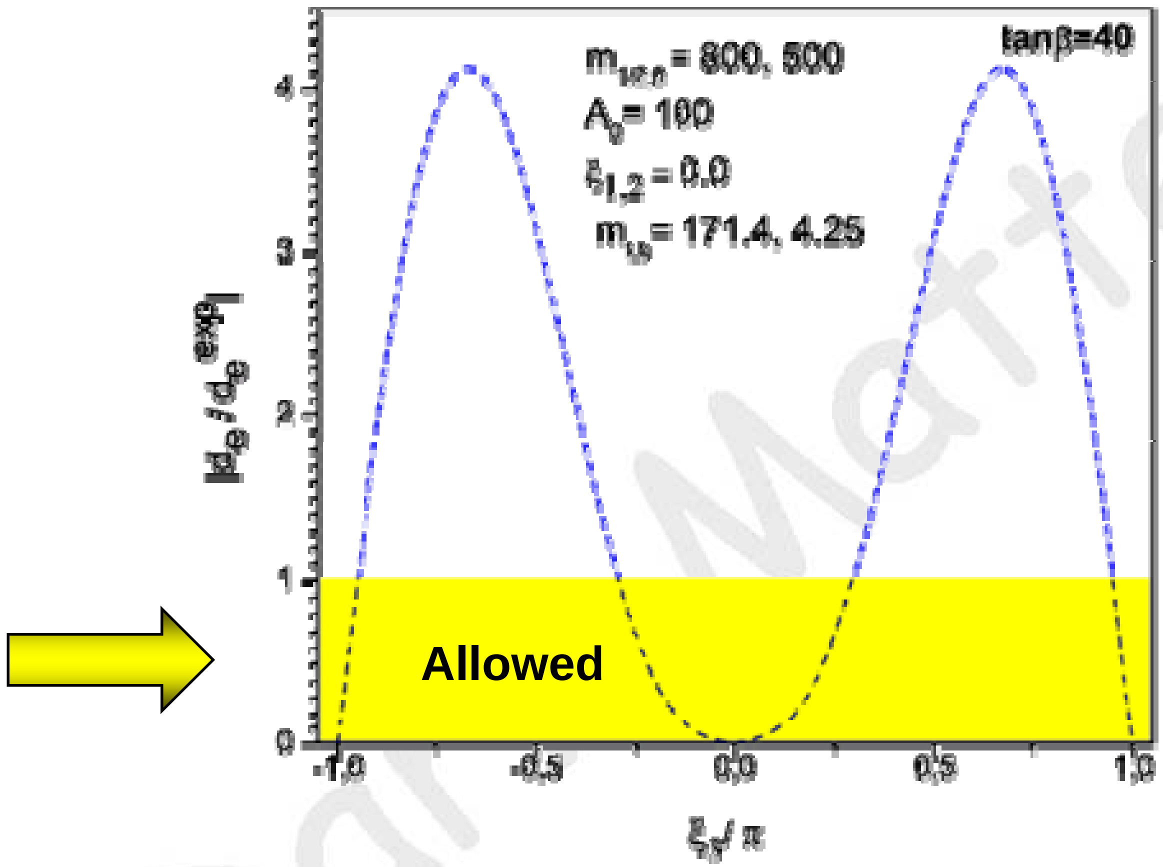
Gaugino mass phases do not run at 1-loop. At 2-loop they run and EW-strong interaction contributions to RGEs for M_1, M_2 have large group factors ! $\Longrightarrow$

$$\frac{dM_1}{d\ln Q} = \ldots - \frac{1}{(4\pi)^2}\frac{\mathbf{176}}{\mathbf{5}}\,\alpha_1\alpha_3\,(M_3 + M_1)\ldots$$

$$\frac{dM_2}{d\ln Q} = \ldots - \frac{1}{(4\pi)^2}\,\mathbf{48}\;\alpha_2\alpha_3\,(M_3 + M_2)\ldots$$

At low energies phases $arg(M_{1,2}) \sim 10^{-2}$ are produced, from the gluino phase $arg(M_3)$, even if absent at the GUT scale !
Due to RGE running gluino phase affects electron's EDM.

- $arg(M_3)$ affects relic densities through its impact on bottom mass corrections for large $\tan\beta$.
- Gluino phase is observable in gluino production and is important for the cancellation mechanism.

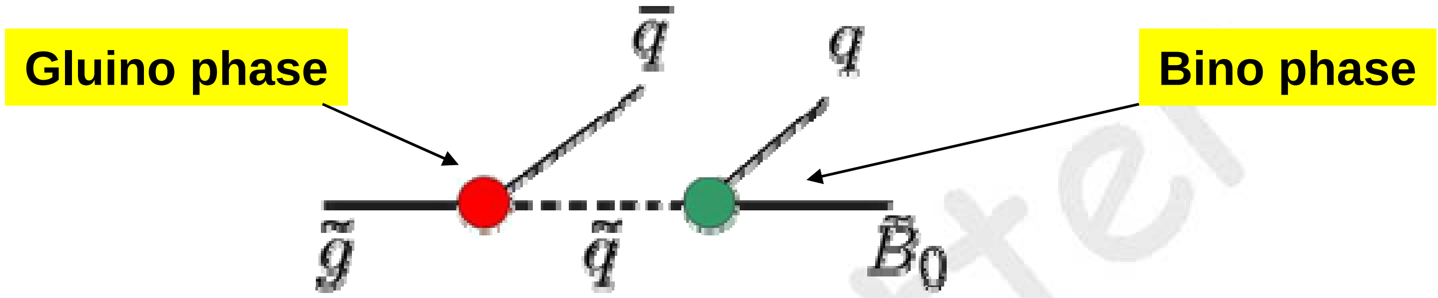


$m_{1/2}, m_0, A_0 =$

magnitudes

The ratio of the electron EDM to its experimental limit as function of the gluino phase ξ_3 (at M_{GUT}). The remaining phases are zero.

Gluino production



If LSP=Bino, CP phase absent in squark sector

$$\frac{d\sigma}{dx} \sim \left(\frac{1}{m^4_{\tilde{q}_L}} + \frac{1}{m^4_{\tilde{q}_R}}\right) m^4_{\tilde{g}}$$
$$\times\sqrt{x^2 - y^2}\left(x - \frac{4}{3}x^2 - \frac{2}{3}y^2 + xy^2 + y(1 - 2x + y^2)\cos(\xi_3 - \xi_1)\right)$$

$x \equiv E_{\tilde{B}}/m_{\tilde{g}}$, $y \equiv m_{\tilde{B}}/m_{\tilde{g}}$

$\xi_3 =$ **gluino phase,** $\xi_1 =$ **Bino phase**

$e^+e^- \longrightarrow t\bar{t}$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 + C\,\frac{\alpha_s}{\pi}\sin(\phi_{A_t} - \phi_{\tilde{g}})\,\frac{\vec{J}\cdot\vec{p}\times\vec{k}}{|\vec{p}\times\vec{k}|}\right)$$

$\vec{J}$ = Unit polarization vector perpendicular to production plane
$\vec{k}$ = C.M. momentum of e^-
$\vec{p}$ = C.M. momentum of t
C = depends on SUSY inputs (10 % for typical SUSY inputs)

E. Christova and M. Fabbrichesi, PLB315 (338) 1993

The importance of SUSY $\not{C}P$ in conjunction with the DM observation by WMAP3 has been the subject of several works:

for a review: T. Ibrahim, P. Nath, Rev. Mod. Phys. 80 arXiv:0705.2008 [hep-ph]

- **MSSM** models with $\not{C}P$ have been studied and large phases can be in agreement with electron and neutron **EDM** and **WMAP** data.
  $\not{C}P$ modifies $\Omega_{\tilde{\chi}} h_0^2$ up to 100 % or more !

G. Belanger, F. Boudjema, S. Kraml, A. Pukhov, A. Semenov, PRD73 (2006) 115007, arXiv:hep-ph/0604150

- **CPMFV** is the most ecomomic and more predictive. If we impose universal b.c. for magnitudes but not phases it conforms with **FCNC** and minimally extends **cmSUGRA** .

M. Argyrou, A,B,L. and V. Spanos, JHEP 0805:026,2008 arXiv:0804.2613 [hep-ph]

  Such models with Yukawa unification studied in

M. Gomez, T. Ibrahim, P. Nath, S. Skadhauge, PRD72 (2005) 095008, arXiv:hep-ph/0604150;

Additional source of $\not{C}P$

Higgs vevs are misaligned !

$$\langle H_d \rangle = v_1 \; , \; \langle H_u \rangle = v_2 \, e^{i\,\theta}$$

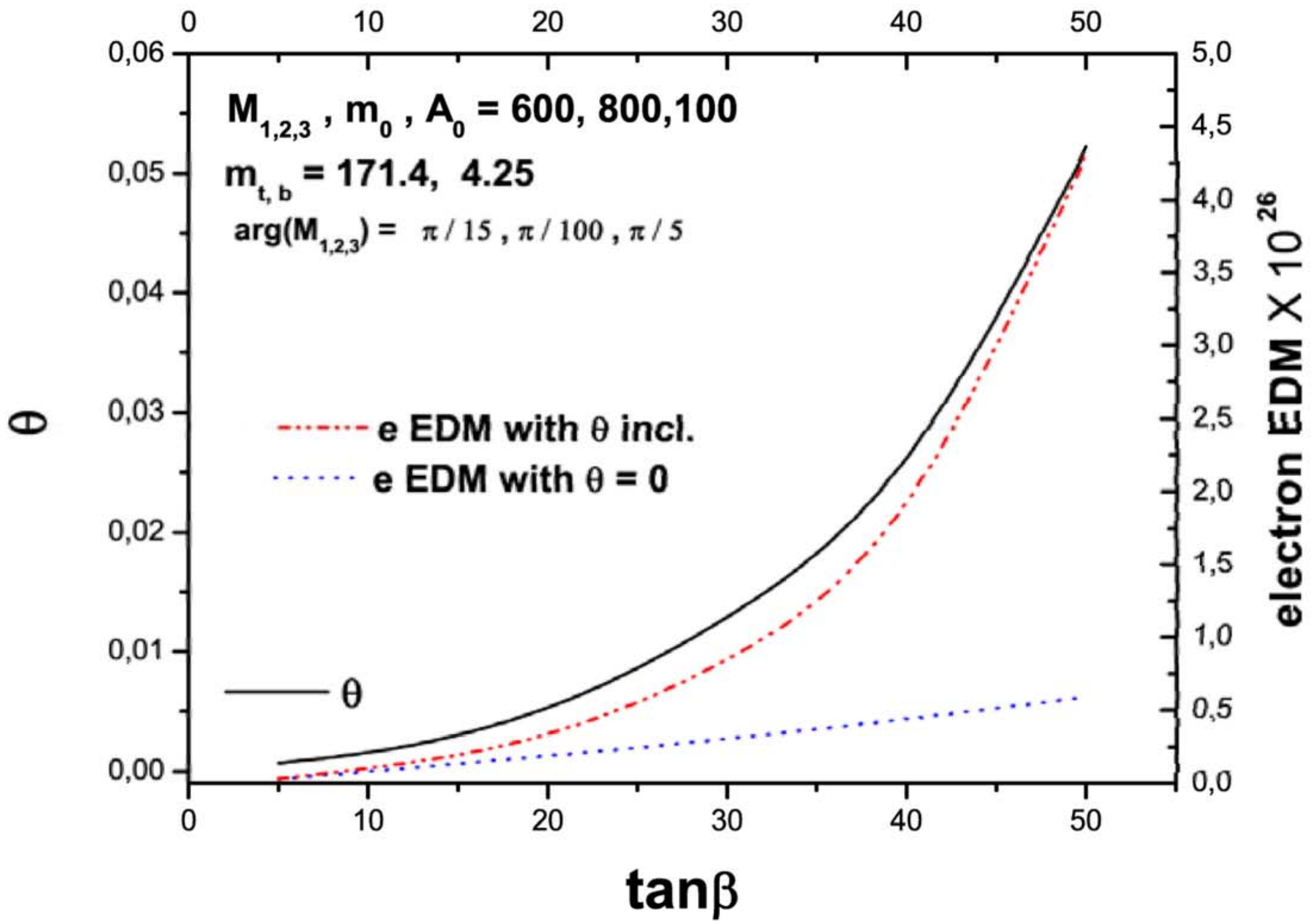
θ is calculable determined from the minimization conditions

D. A. Demir, Phys. Rev. D 60, 095007 (1999) [arXiv:hep-ph/9905571]

- Chargino / Neutralino / Sfermion mass matrices, EDMs, Chromoelectric moments, depend on it through the $\theta + \arg(\mu)$.
- Certain couplings depend on θ .
- Enhances Higgs decay widths $H_0 \to b\bar{b}$ affecting relic density for LSP pair annihihation through a Higgs resonance.

T. Ibrahim and P. Nath, Phys. Rev. D 58, 111301 (1998) [Erratum-ibid. D 60, 099902 (1999)] [arXiv:hep-ph/9807501].

D. A. Demir, Phys. Rev. D 60, 055006 (1999) [arXiv:hep ph/9901389]


$M_{1,2,3}$, m_0 , A_0 = 600, 800,100
$m_{t,b}$ = 171.4, 4.25
arg($M_{1,2,3}$) = π / 15 , π / 100 , π / 5
e EDM with θ incl.
e EDM with θ = 0
θ
tanβ
electron EDM X 10^{26}
0
10
20
30
40
50
0,00
0,01
0,02
0,03
0,04
0,05
0,06
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
5,0

For DM relic abundances and EDM calculations need :

- 2-loop RGE running from GUT to EW scale induces large phases with large impact on **EDMs** saturating the experimental bounds.
  Impact of trilinear phases to gaugino mass phases studied in :
  K. A. Olive, M. Pospelov, A. Ritz and Y. Santoso, Phys. Rev. D 72, 075001 (2005) [arXiv:hep-ph/0506106].
- Higgs masses and widths which depend on $\not{C}\not{P}$ phases and are sensitive to m_t, which is now lower than that used in earlier works.
  Updated analysis on CP-conserving CMSSM : *A. Belyaev, S. Dar, I. Gogoladze, A. Mustafayev and Q. Shafi, arXiv:0712.1049 [hep-ph].*
- Vacuum misalignement angle θ, having large impact on **EDMs**, and Higgs widths, especially for large $\tan\beta$ and non-zero gluino phase.
- SUSY threshold corrections to m_b which depend on $\not{C}\not{P}$ phases and have a large impact on the cosmologically allowed domains.
  M. E. Gomez, T. Ibrahim, P. Nath and S. Skadhauge, arXiv:hep-ph/0410007; Phys. Rev. D 70, 035014 (2004) [arXiv:hep-ph/0404025]

Reconciling EDM and WMAP constraints

LSP pair annihilation into $\mathbf{f\bar{f}}$ through a Higgs resonance spans a large amount of the parameter space satisfying WMAP data. These "funnel" regions open for large $\tan\beta$, extend to large $\mathbf{m_0, M_{1/2} < 2}$ **TeV**, where **EDMs** are possibly mass suppressed, and may be accessible to **LHC** !

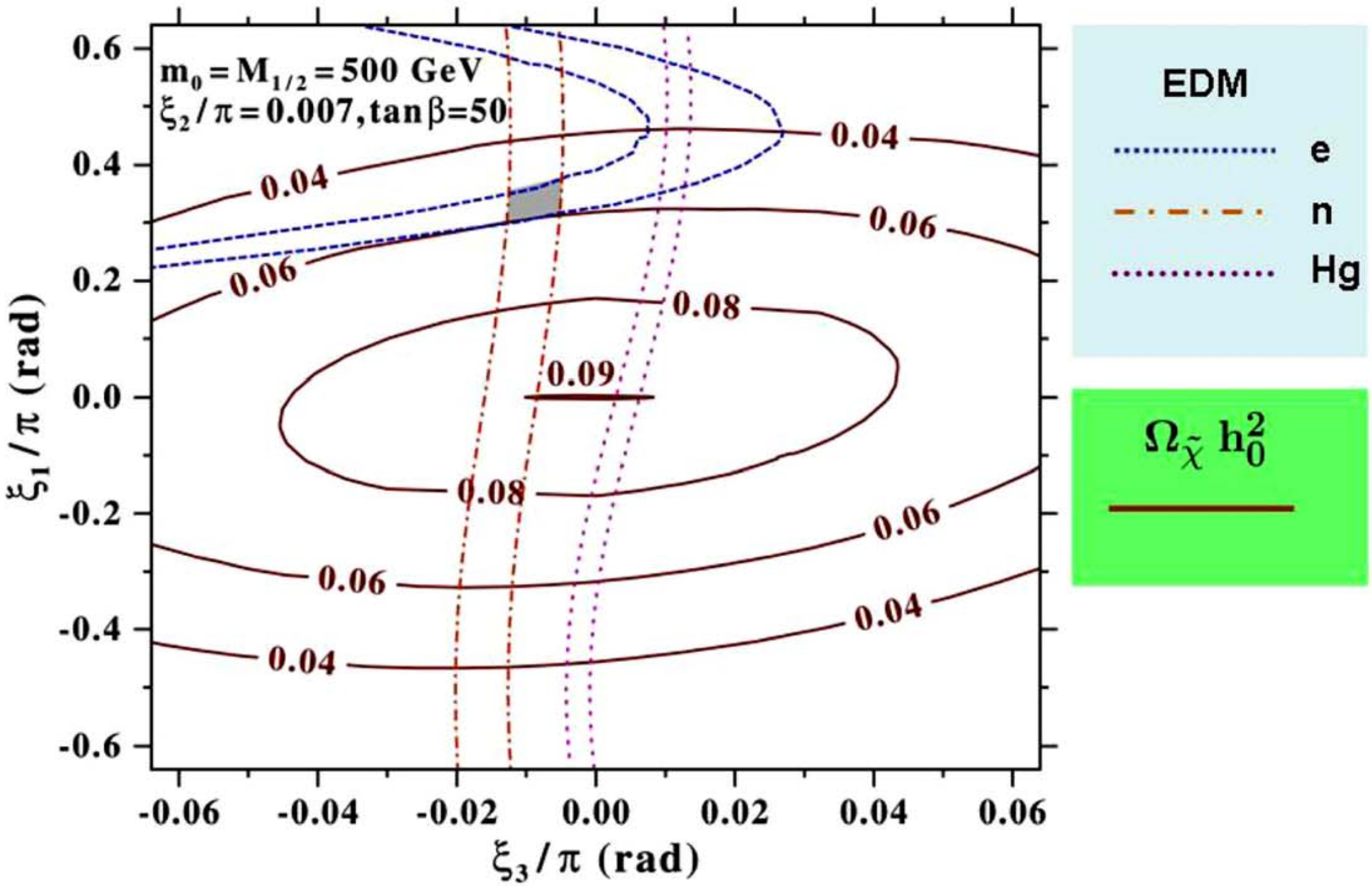
Funnels track the line

$$\frac{M_{Higgs}}{2\, m_{\tilde{\chi}}} = 1$$

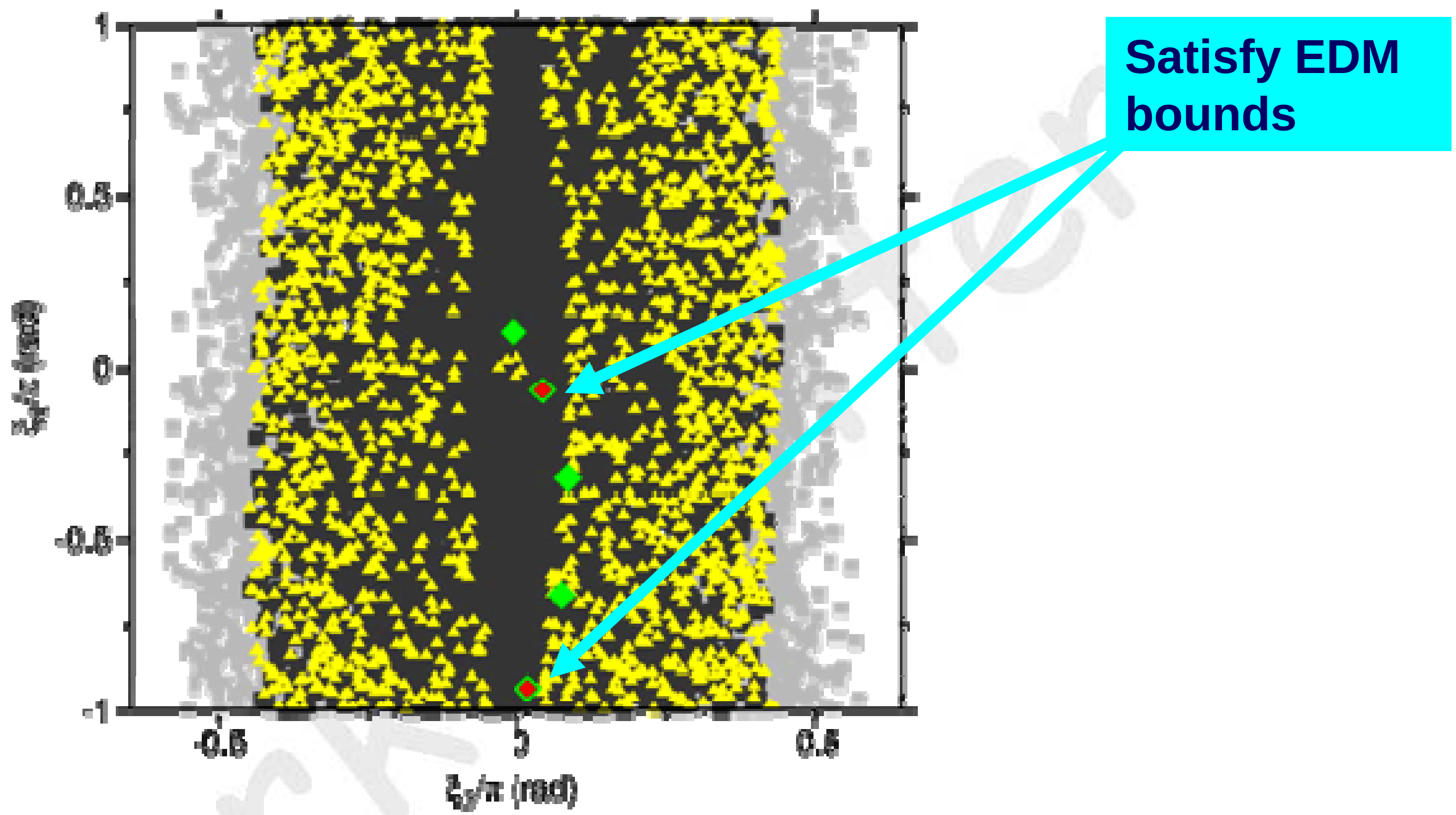
The shape and location of these regions depend sensitively on:

- $\mathbf{M_{Higgs}}$, which are sensitive to $\mathbf{m_t}$.
- Higgs widths Γ_H, which depend on the CP-odd phases.
- Bottom mass $\mathbf{m_b}$, whose threshold corrections depend on the CP-odd phases.

Difficult to satisfy all EDM bounds and WMAP constraints !



$\xi_{1,2,3}$ = phases of $M_{1,2,3}$ at M_{GUT}



Projection on the ξ_1, ξ_3 plane of a random sample of ξ_1, ξ_2, ξ_3 with all other phases taken zero. $M_{1/2} = 480\ GeV$, $m_0 = 500\ GeV$, $A_0 = 100\ GeV$ and $\tan\beta = 50$.

Grey points = all accelerator bounds. Black points = in addition $\Omega_{\tilde{\chi}} h_0^2 < 0.122$.

Yellow points = $0.096 < \Omega_{\tilde{\chi}} h_0^2 < 0.122$. Green diamonds = d_e, d_n are satisfied.
Red / Green diamonds = all EDM bounds are satisfied.

The EDM constraints & the cancellation mechanism

Contributions of the various Feynman graphs may cancel each other to render EDMs of electron and neutron small. This allows for small $m_0, M_{1/2}$ values.

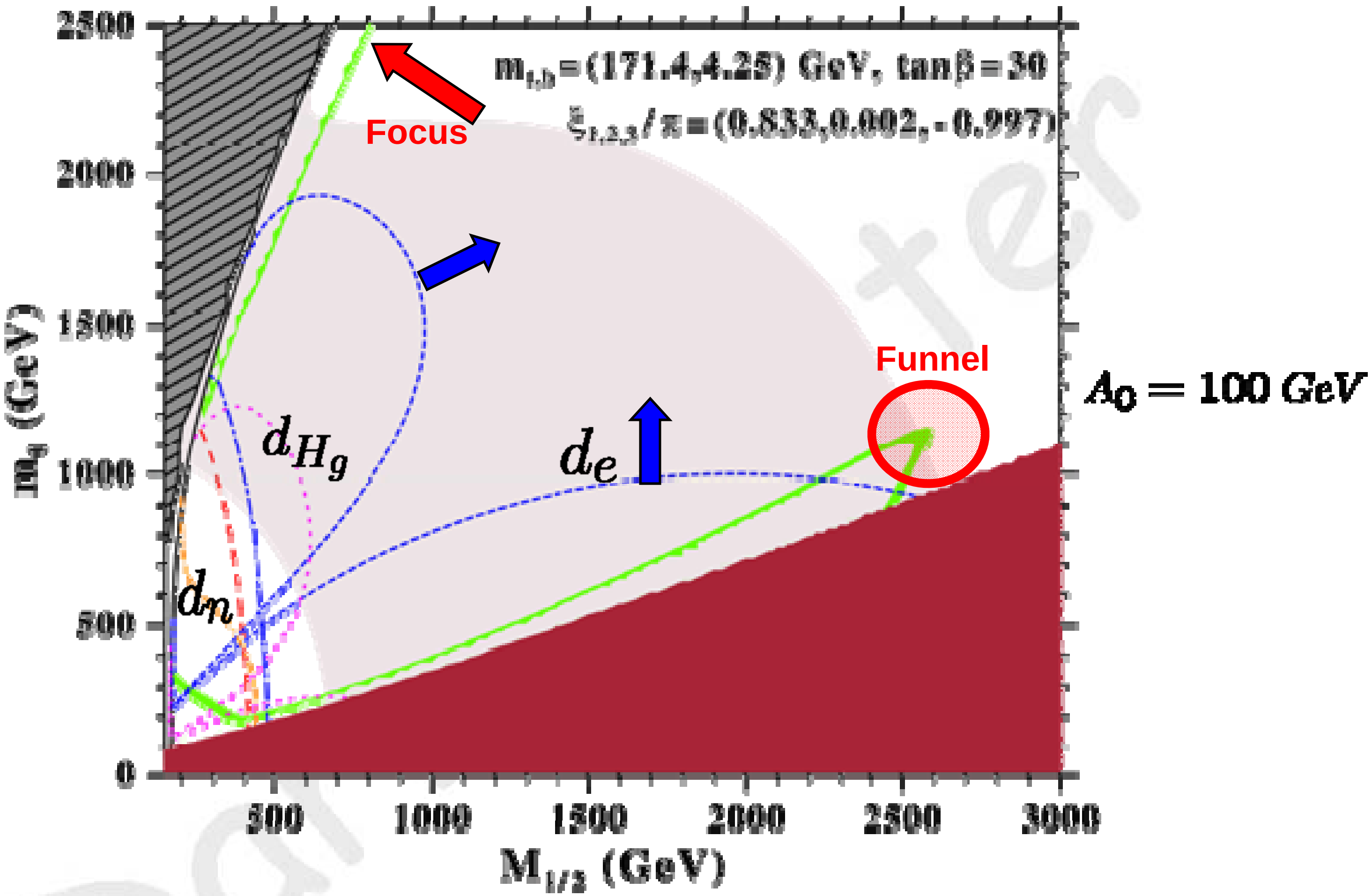
T. Ibrahim and P. Nath, Phys. Rev. D 61, 093004 (2000) [arXiv:hep-ph/9910553].

For given $m_0, M_{1/2}$ and remaining inputs :

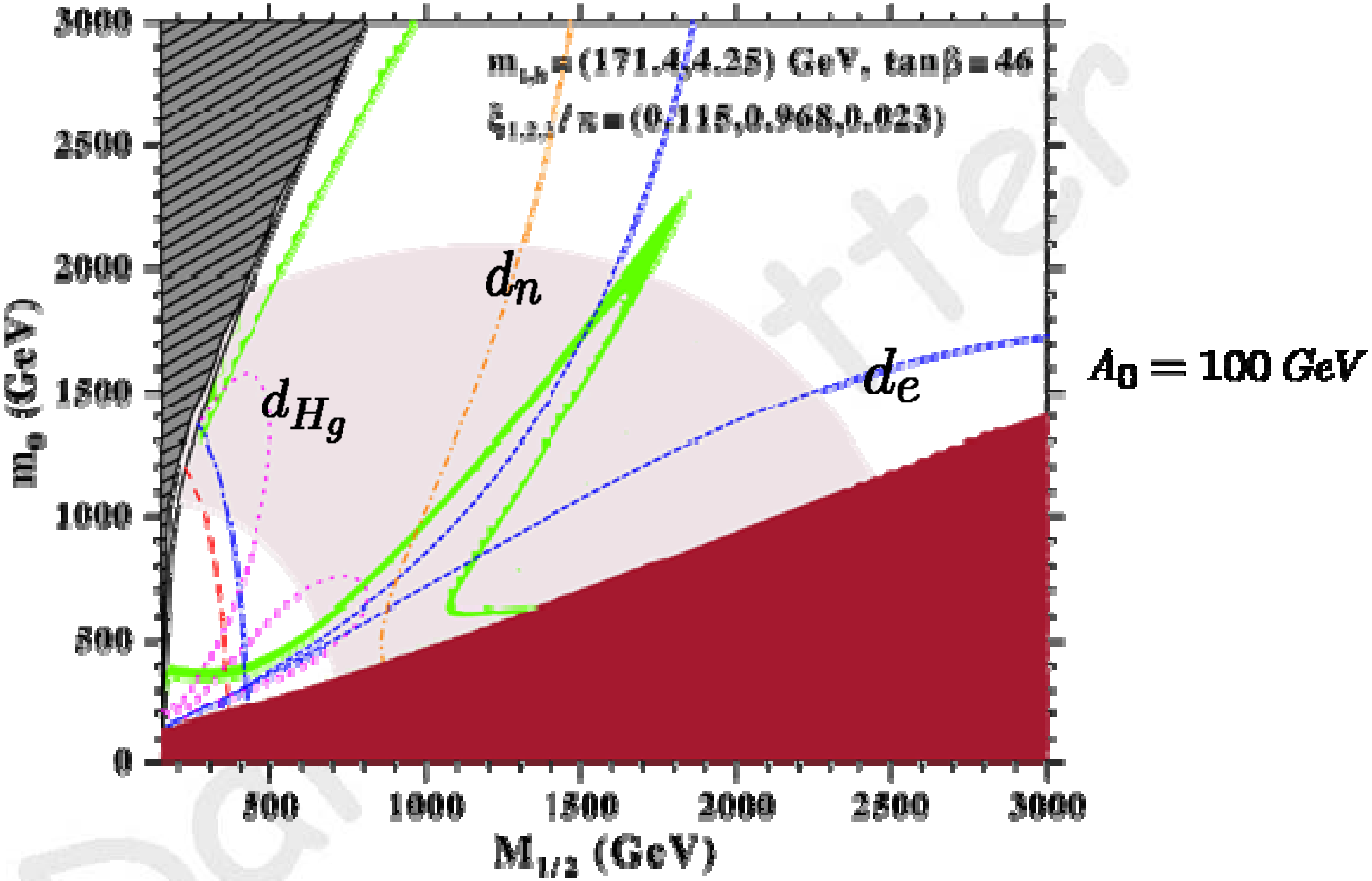
- Rotate $\xi_1(M_{GUT})$ until neutralino contributions (ξ_1 - dependent) cancell chargino (ξ_1 - independent) contributions to d_e.
- Rotate $\xi_3(M_{GUT})$ until d_n becomes small.

Mercury EDM not guaranteed to be small !

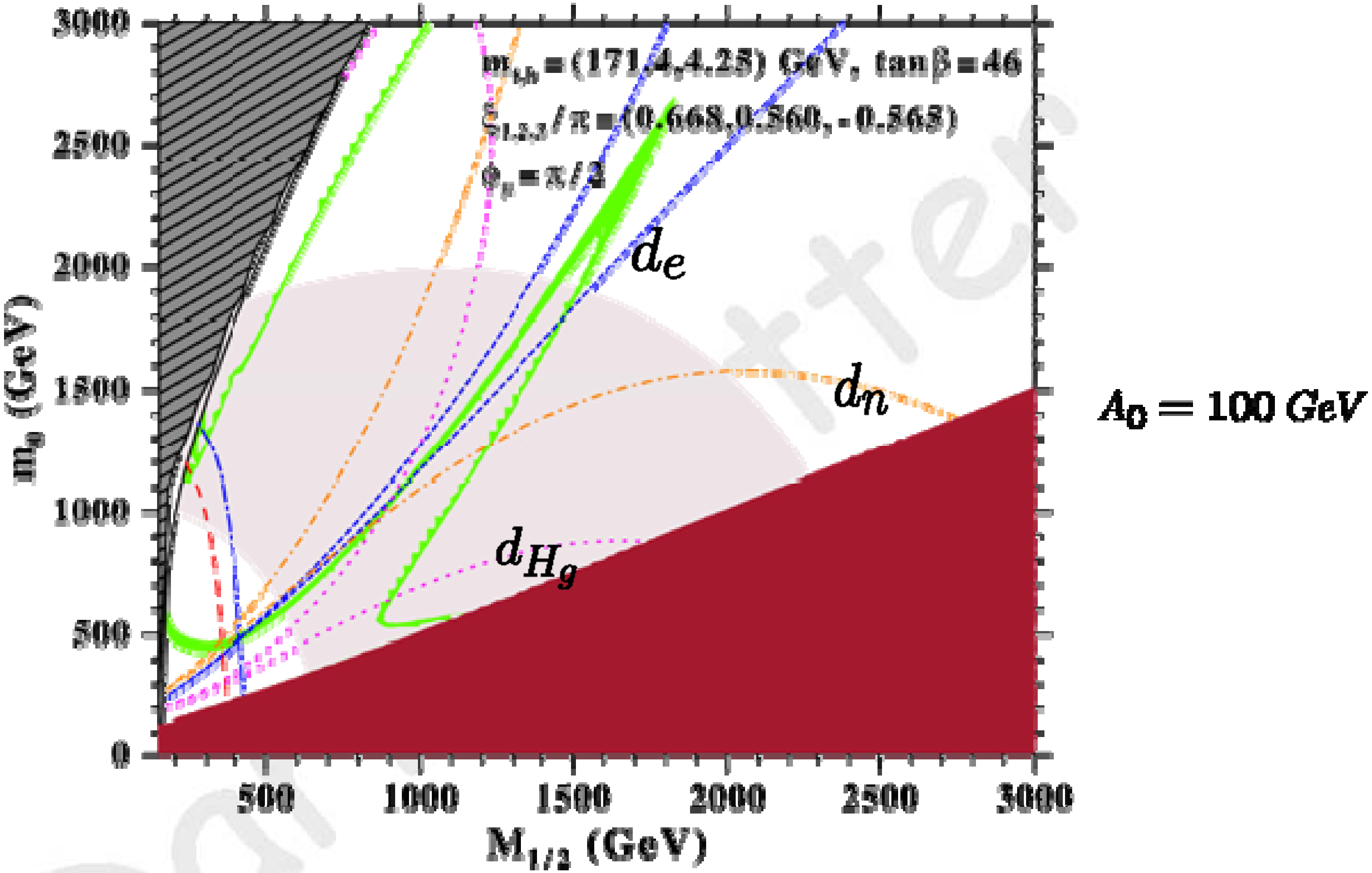
Cumbersome but feasible ! With the obtained phases scan the entire $m_0, M_{1/2}$ parameter space.



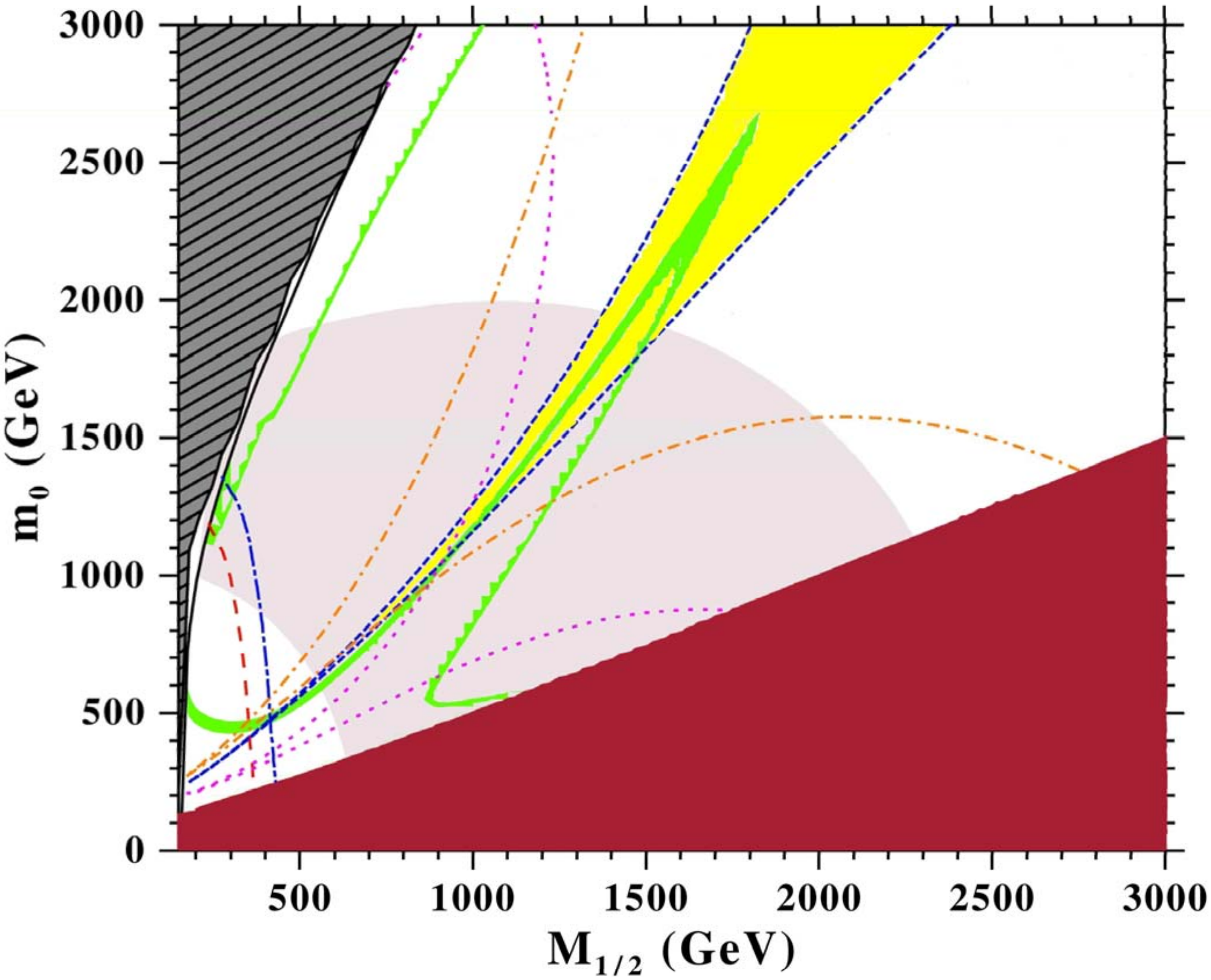
Large tan $\beta = 30$. Part of Focus point region compatible with all data and accessible to LHC ($M_{1/2} < 700$ GeV). Small funnel, started being formed, inaccessible to LHC ($M_{1/2} > 2.2$ TeV , $m_0 \sim 1$ TeV). In shadowed region $0.8 < |M_2/\mu| < 1.0$ as required in Higgsino/Gaugino driven Baryogenesis.



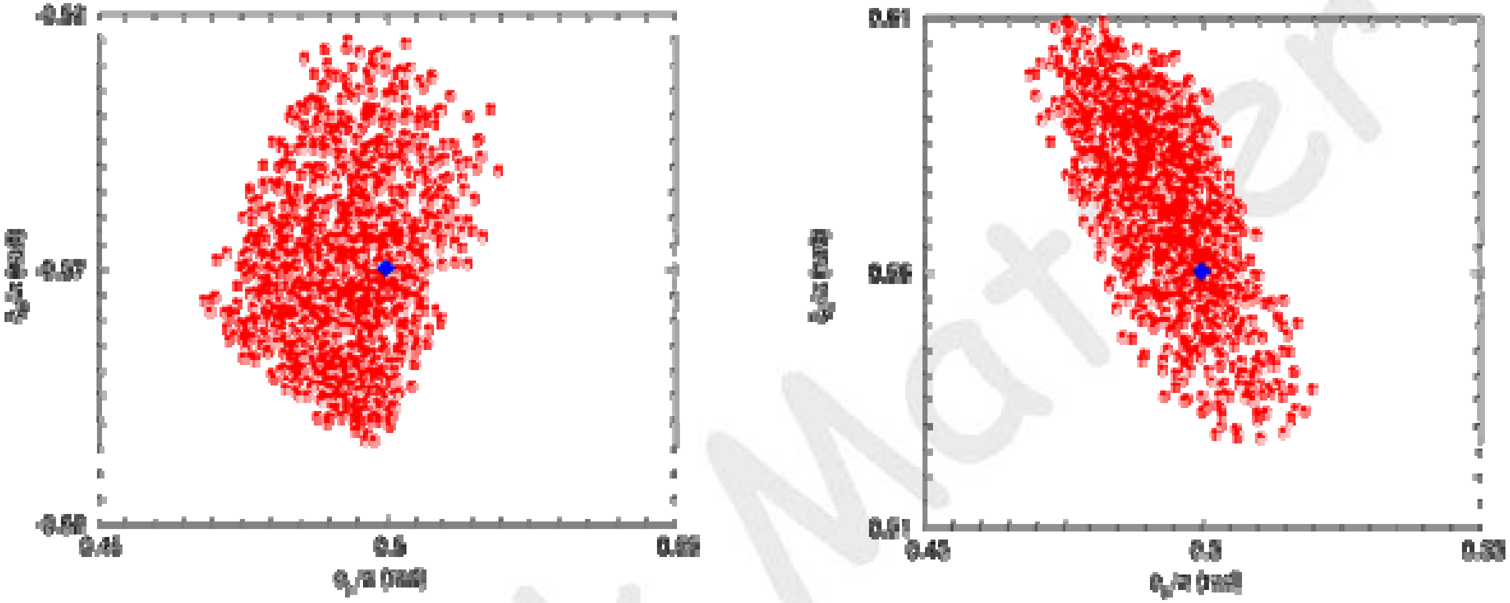
Large $\tan\beta = 46$. Focus point region inaccessible to LHC ($m_0 > 8$ TeV by d_e bound). Part of funnel region accessible to LHC. In shadowed region $0.8 < |M_2/\mu| < 1.0$ as required in Higgsino/Gaugino driven Baryogenesis.



Large $\tan\beta = 46$, $\phi_\mu = \pi/2$. Focus point region inaccessible to LHC. Part of funnel region accessible to LHC. In shadowed region $0.8 < |M_2/\mu| < 1.0$ as required in Higgsino/Gaugino driven Baryogenesis)



3000
2500
2000
1500
1000
500
0
m0 (GeV)
500
1000
1500
2000
2500
3000
M1/2 (GeV)



How much the phases are fine tuned ?

Blue diamond: point $m_0 = 2000\ GeV, M_{1/2} = 1520\ GeV, A_0 = 100\ GeV$ selected from previous figure. The red diamonds satisfy all constraints. The amount of tuning for the phases ϕ_μ, $\xi_{2,3}$ is $\mathcal{O}(0.05\pi)$. Bino phase ξ_1 is less fine tuned $\mathcal{O}(0.1\pi)$ (not shown).

Summary

- mSUGRA with $\not{C}P$ too restrictive by EDM data.
- $\not{C}P$ models with non-universal boundary conditions include additional phases and are phenomenologically rich.
- The cancellation mechanism is an important tool to delineate regions with large phases, within LHC reach, reconciling EDM and WMAP data.
- RGE scale dependencies of the phases induce sizable effects and should be counted for.
- Large phases can be measured in future experiments and models with $\not{C}P$ deserve further detailed investigation.

Origin of phases ?
GUT physics, Familons or ? ← **G. G. ROSS, This conference**

Alternative Cosmological scenarios

Changing the Cosmological assumptions modifies the predicted WIMPs relic densities !

non - Standard Cosmological Scenarios :

- Inflationary models with low reheat temperature.
- Models with late entropy production which dilutes relic densities.
- Modified Universe expansion rate or Early Universe dynamics.
- ...

In non - standard scenarios the relic density may differ from that obtained in conventional approaches, in some cases by many orders of magnitudes !

Relic Densities with modified expansion rate

If Universe is not radiation dominated after inflation and extra component ρ_ϕ contributes to matter - energy density

$$3\,H^2 = 8\pi G_N\,(\rho_r + \rho_\phi)$$

then $Y \equiv n/s$ satisfies a modified Boltzmann equation,

$$\frac{dY}{dT} = \xi < \sigma v > (Y^2 - Y_{eq}^2)\left[\frac{45 G_N}{\pi} g_{eff}\right]^{-1/2} (h + \frac{T}{3}\frac{dh}{dT})$$

The factor ξ accounts for the modified expansion rate !

$$\xi = \left(1 - \frac{\rho_\phi}{\rho_r}\right)^{-1/2}$$

- **In Quintessence models the maximal enhancement to relic density, compatible with BBN bounds**

$$\Delta\Omega \equiv (\Omega - \Omega_{no\,\phi})/\Omega_{no\,\phi} \sim 10^6$$

S. Profumo and P. Ullio, JCAP 0311 (2003) 006, hep-ph/0309220 ;

Supercritical String Cosmology - SSC

The situation of modified expansion rate is encountered in SSC models where a rolling dilaton provides with a smoothly evolving Dark Energy and it couples to matter density

$$\frac{d\rho_m}{dt} = -3H(\rho_m + p_m) + \dot{\phi}(\rho_m - 3p_m)$$

then Y varies as

$$\frac{dY}{dT} = \xi < \sigma v > (Y^2 - Y_{eq}^2) \left[\frac{45 G_N}{\pi} g_{eff}\right]^{-1/2} (h + \frac{T}{3}\frac{dh}{dT}) - \frac{\dot{\phi} Y}{HT}$$

→

$$\Omega = R \times \Omega_0$$

Ω_0 = Density obtained by ordinary calculations.
R = Cosmological correction factor.

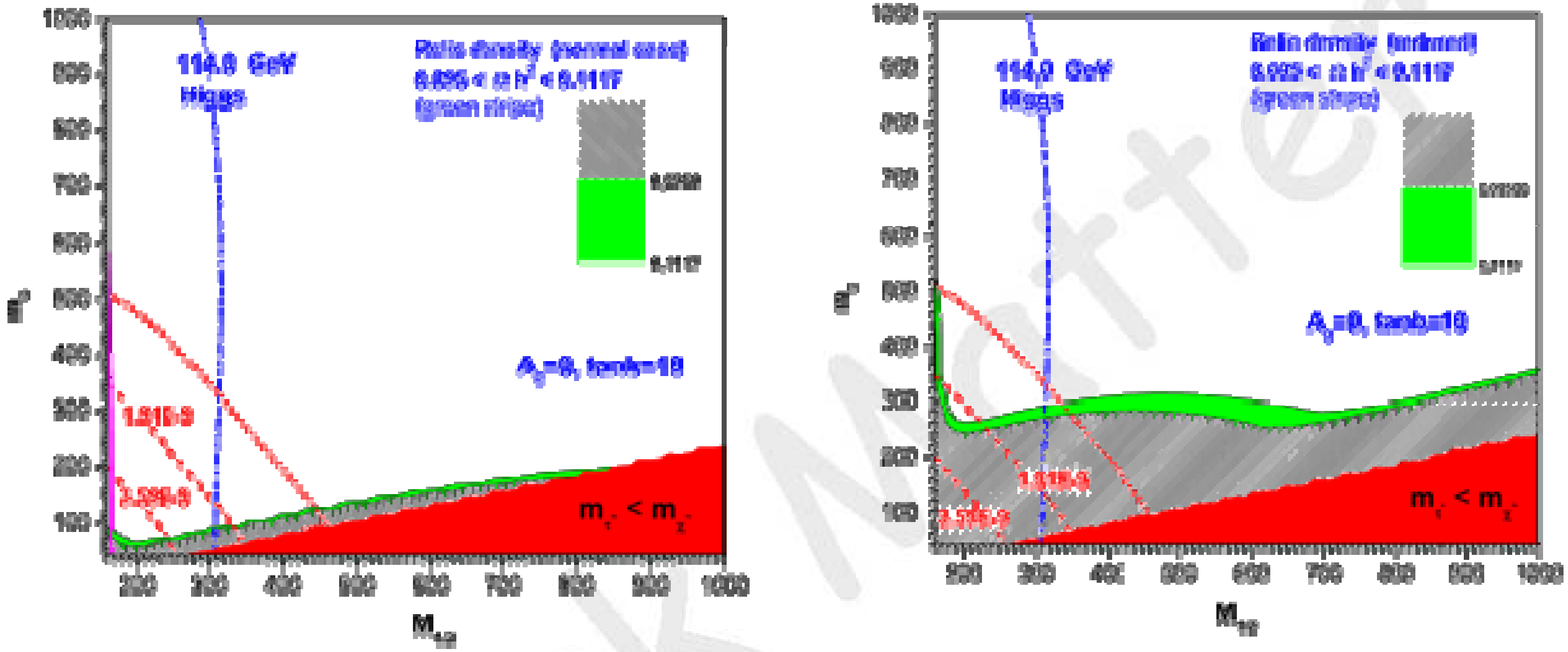
$$R = \xi^{-1}(T_f) \; \exp\left(\int_{T_0}^{T_f} \frac{\dot{\phi}}{HT}\, dT\right)$$

A.B.L, N. E. Mavromatos and D. V. Nanopoulos, Phys. Lett. B 649 (2007) 83, hep-ph/0612152.

- **For an LSP neutralino $R \sim \mathcal{O}(1/10)$ for dilaton solutions which are in agreement with an accelerating Universe, $q_0 = -0.61$, and smooth evolution of the DE in the regime $0 < z < 1.6$.**
- **LSP relic density is diluted by a factor of ten and regions of MSSM with too much DM are allowed !**
- **For a baryon $R \sim \mathcal{O}(1)$, leaving the predictions for conventional matter relic abundances unaffected !**

The phenomenological consequences for LHC studied in :

B. Dutta, A. Gurrola, T. Kamon, A. Krislock, A. B. Lahanas, N. E. Mavromatos and D. V. Nanopoulos, arXiv:0808.1372 [hep-ph]



The effect of the factor R for the neutralino relic density, $\Omega_{\tilde{\chi}} h_0^2$ in the mSUGRA.

The cosmologically allowd region moves to highier m_0 values.

Coannihilation region :

The dominant decay chain for a squark is

$$\tilde{q}_L \to q\, \tilde{\chi}_2^0 \to q\, \tau\, \tilde{\tau} \to \; q\tau\tau\, \tilde{\chi}_1^0$$

with low-energy τ's.

$$\text{Dominant signal}: \quad 2\tau + \text{jet} + \not{E}_T$$

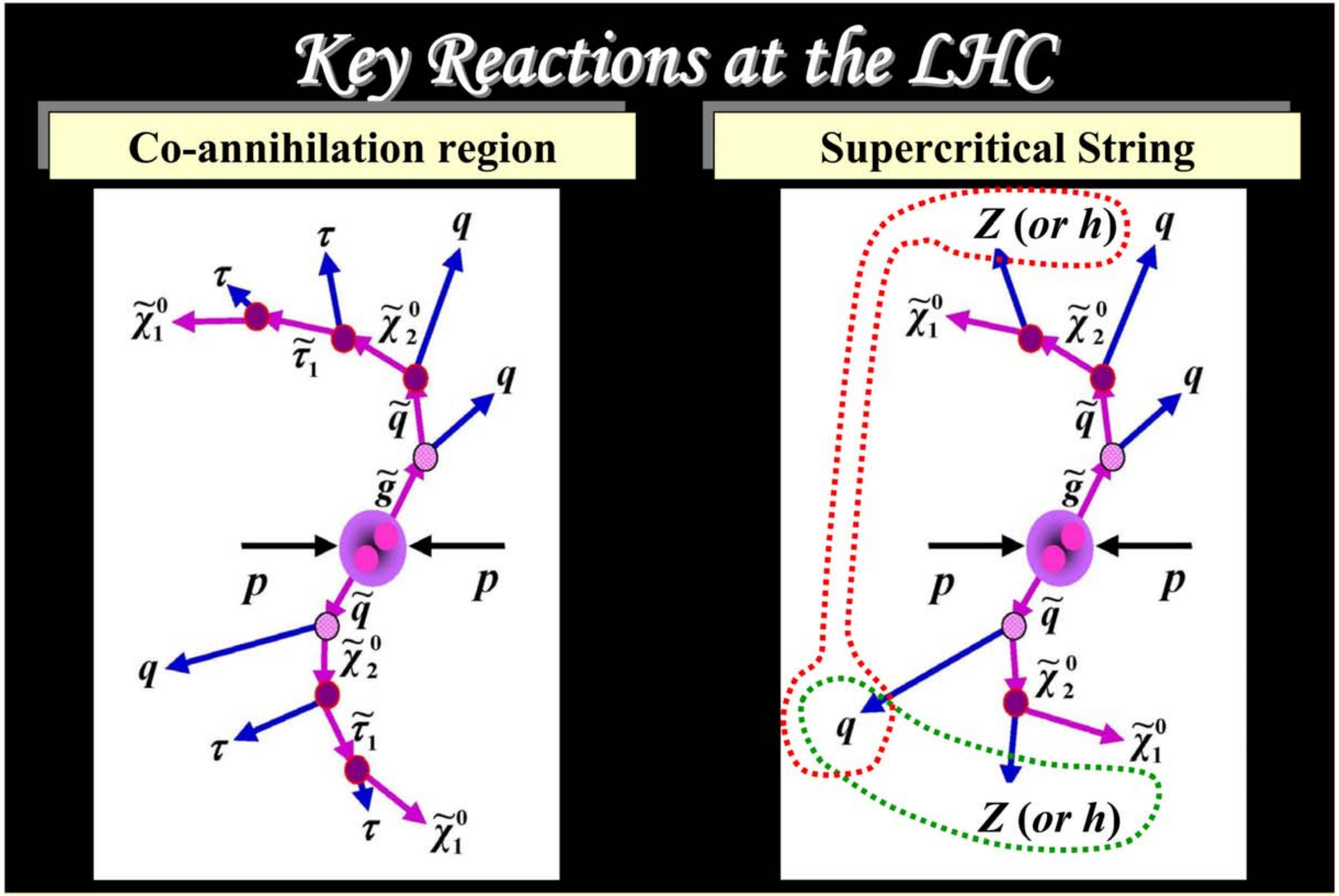
SSC region :

Three possible $\tilde{\chi}_2^0$ decays

$$\tilde{\chi}_2^0 \to \; h_0 + \tilde{\chi}_1^0\,,\ \tilde{\chi}_2^0 \to \; Z + \tilde{\chi}_1^0\,,\ \tilde{\chi}_2^0 \to \; \tau\, \tilde{\tau}$$

$$\text{Possible signals} \quad : \quad \begin{array}{l} Z + \text{jet} + \not{E}_T \\ h_0 + \text{jet} + \not{E}_T \\ 2\tau + \text{jet} + \not{E}_T \end{array}$$

with high-energy τ's (for $M_{1/2} > 500\ GeV$).



Signals of SSC at the LHC. Z and/or Higgses are expected in the final state.

Summary

- Modification of the Early Universe evolution may dramaticaly affect the predictions for DM abundances.
- SUSY DM predictions are not as robust as we think !