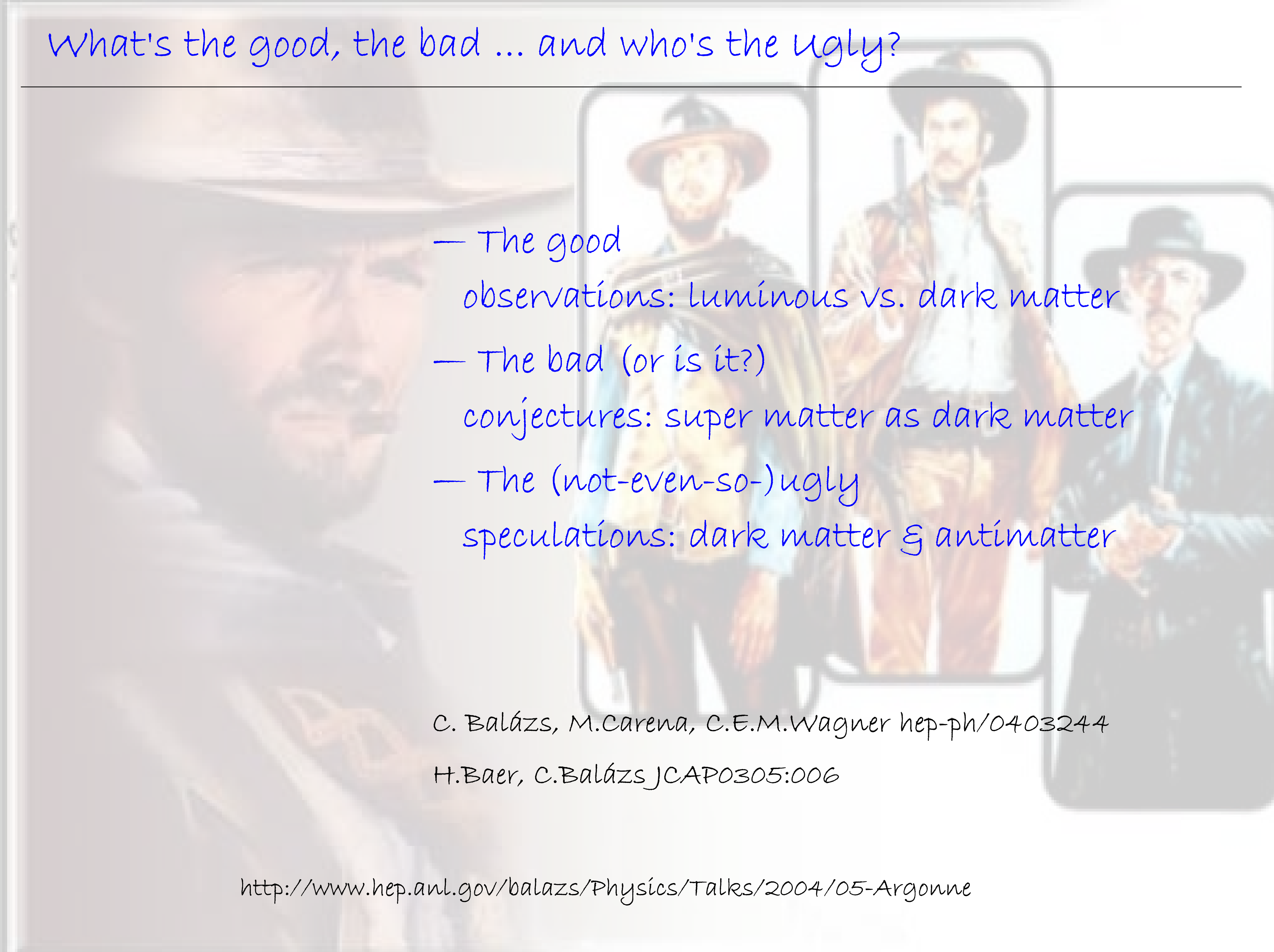

Super-
anti-
dark
matter

What's the good, the bad ... and who's the ugly?



— The good

observations: luminous vs. dark matter

— The bad (or is it?)

conjectures: super matter as dark matter

— The (not-even-so-)ugly

speculations: dark matter & antimatter

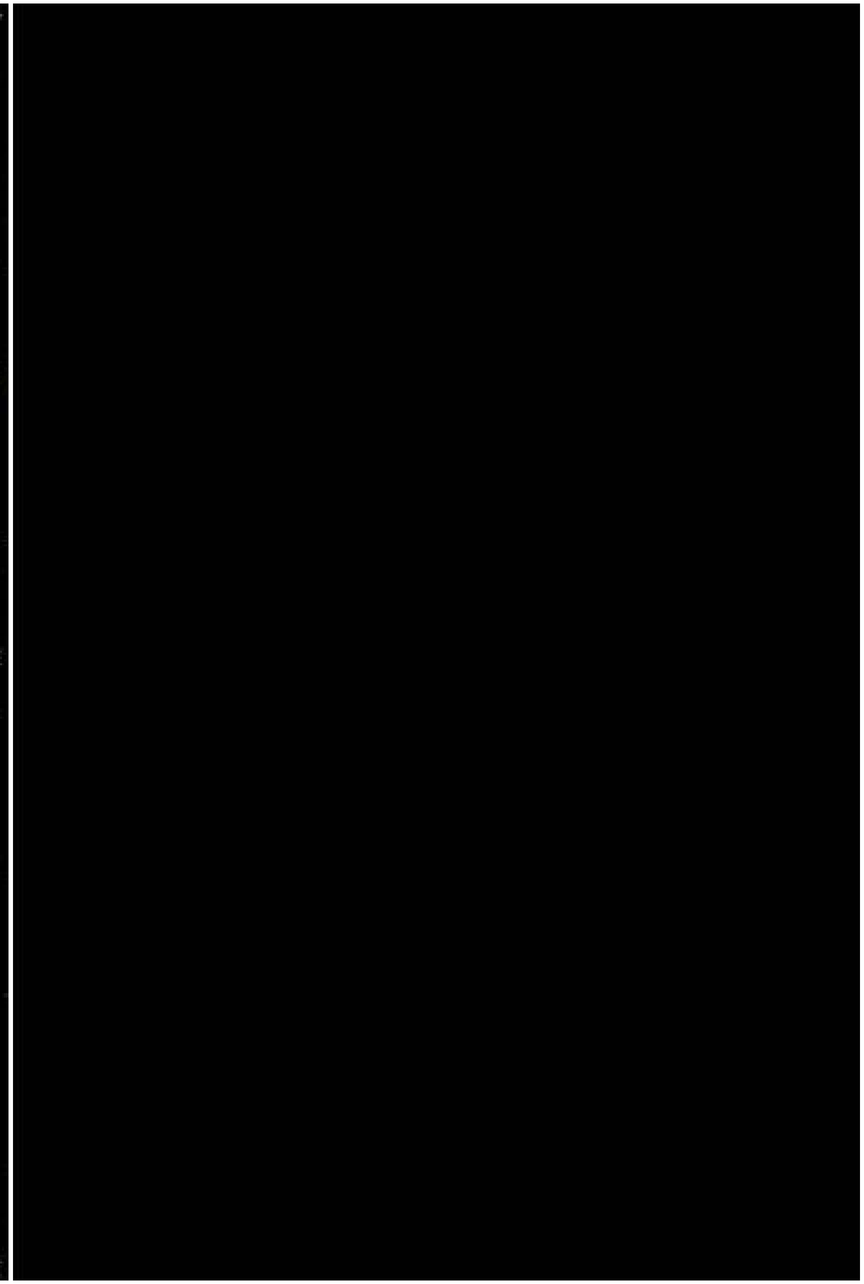
C. Balázs, M.Carena, C.E.M.Wagner hep-ph/0403244

H.Baer, C.Balázs JCAP0305:006

http://www.hep.anl.gov/balazs/Physics/Talks/2004/05-Argonne

What's dark matter?

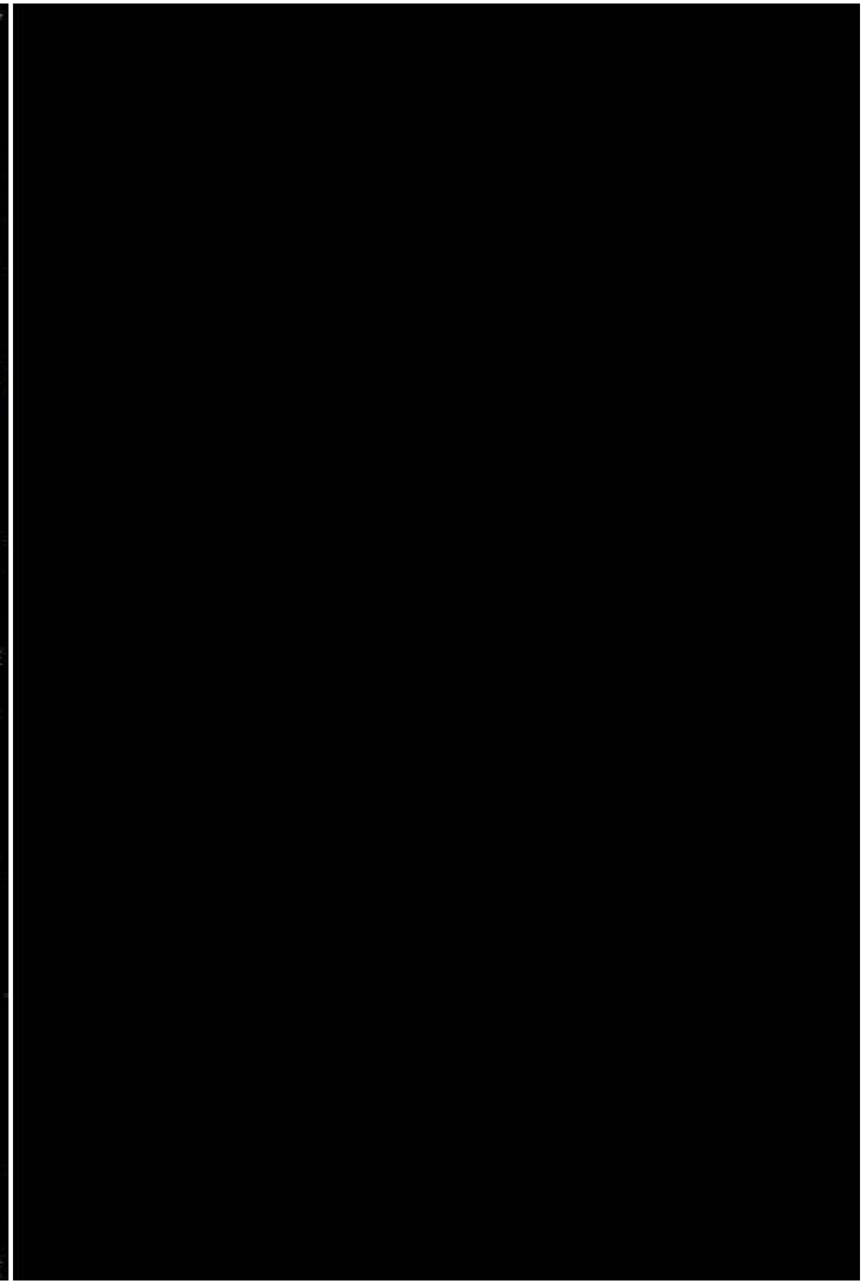
Luminous matter (M81 & 82)



Dark matter

What's dark matter?

Old matter

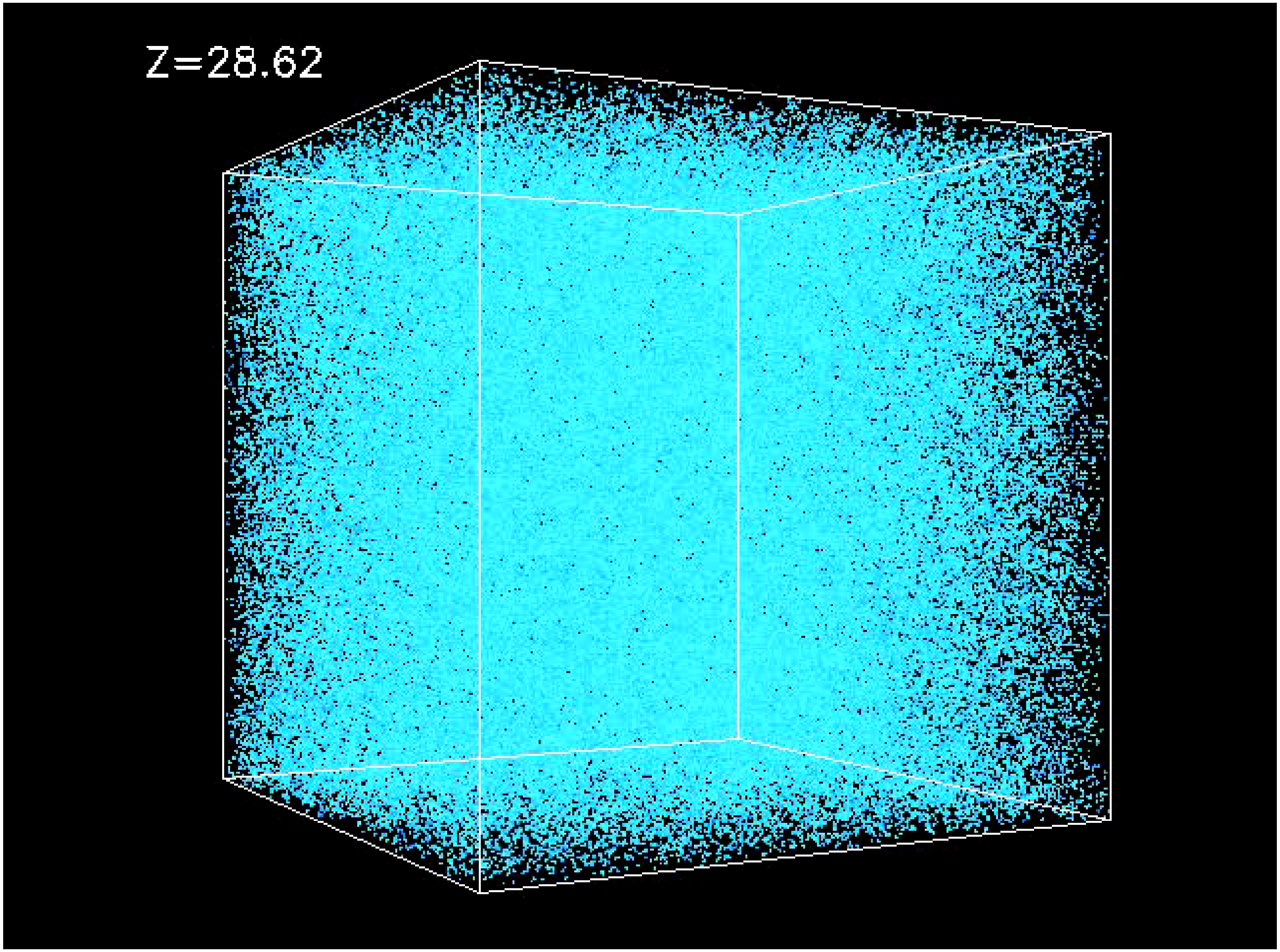


New matter

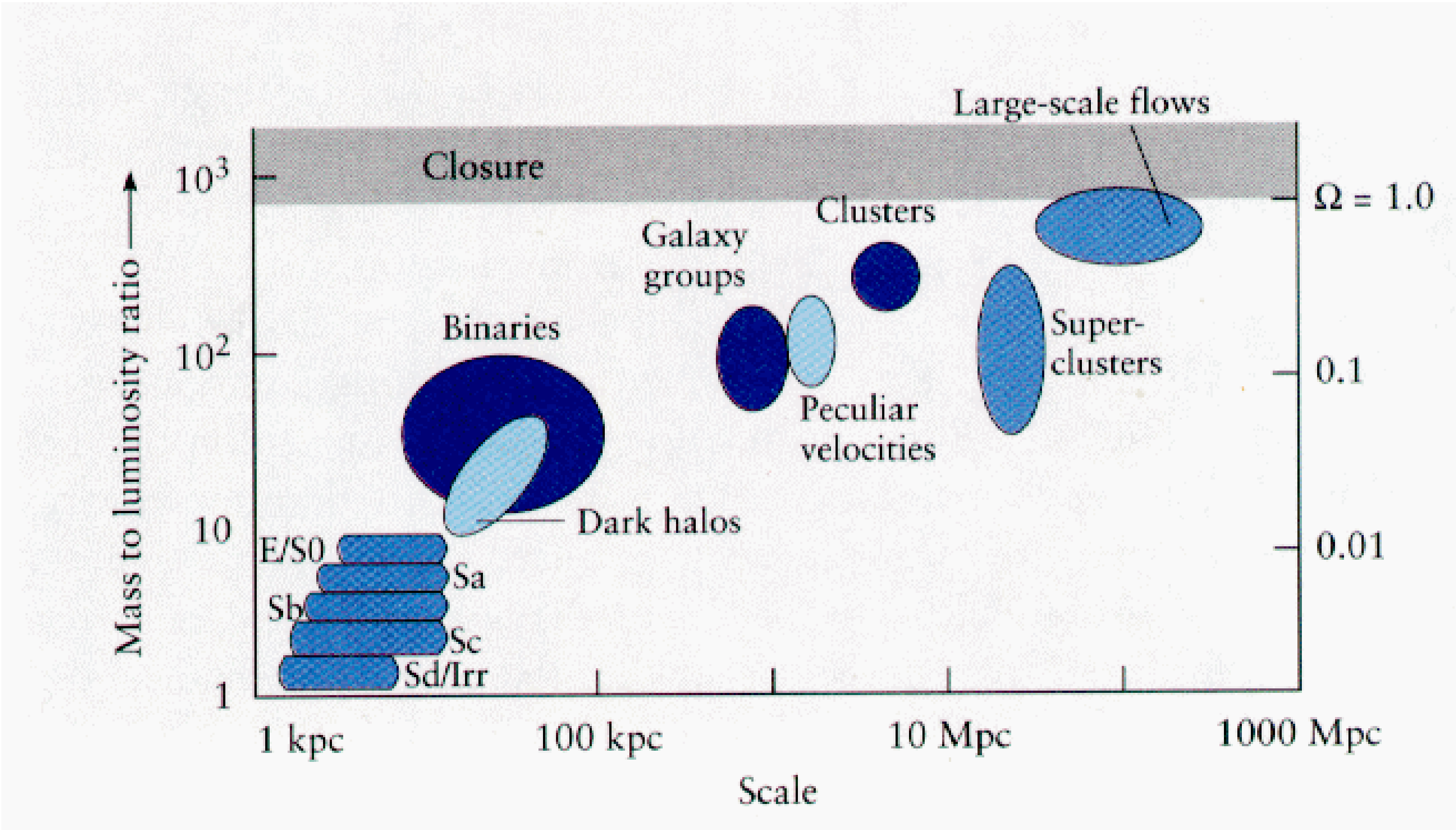
Do we need new matter?

– Presence of CDM in early universe is essential for structure formation

- CDM collapses first, attracting matter later   cfcp.uchicago.edu/lss/filaments.htm



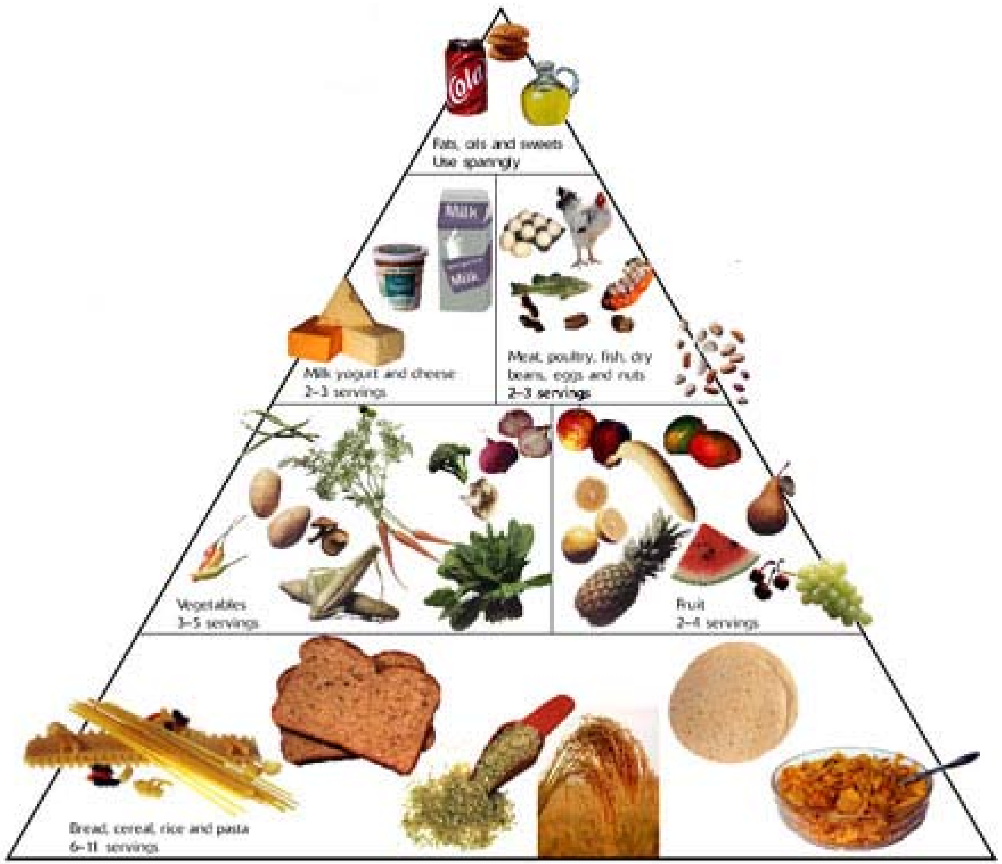
Mass/luminosity problem at all scales



— Can this gravitational anomaly be solved by modifying gravity?

- no solution consistent with all data and GR (but see MOND Bekenstein astro-ph/0403694, or Moffat astro-ph/0403266, gr-qc/0404076, etc.)
- alternative: dark matter

How much new matter is there in the Universe?

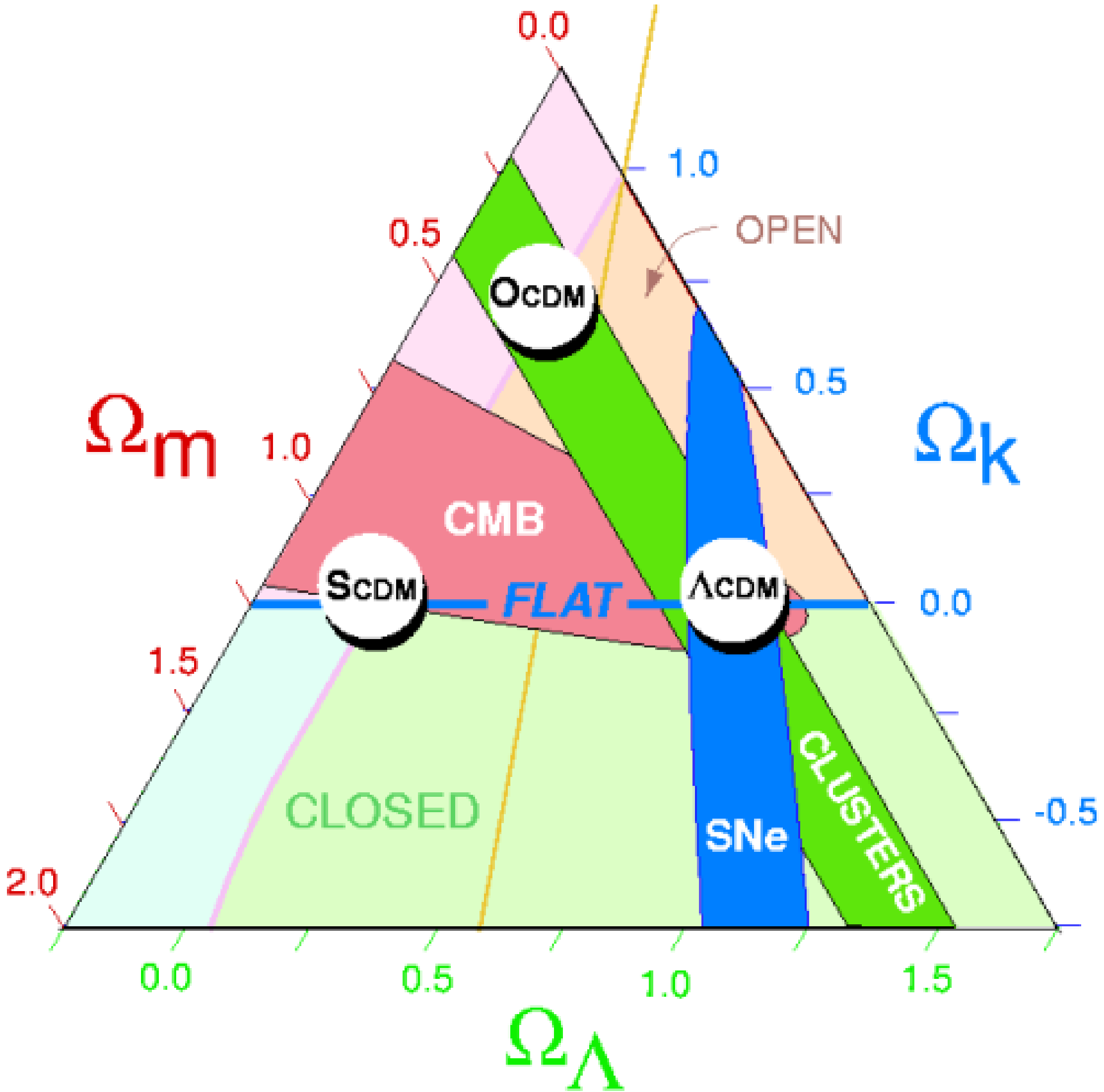


food pyramid

How much new matter is there in the universe?

– E balance a 'la FRW: $\frac{\rho}{\rho_c} = \Omega_M + \Omega_\Lambda + \Omega_k$ $\rho_c = 3H_0^2/8\pi G_N$, $H_0 = 70$km/s/Mpc

- supernovae, WMAP, SDSS $\Rightarrow$ $\Omega_M \approx 0.3$, $\Omega_\Lambda \approx 0.7$, $\Omega_k \approx 0 \rightarrow \Omega_{tot} \approx 1$



Bahcall et al. 1999

How much dark matter is in the Universe?

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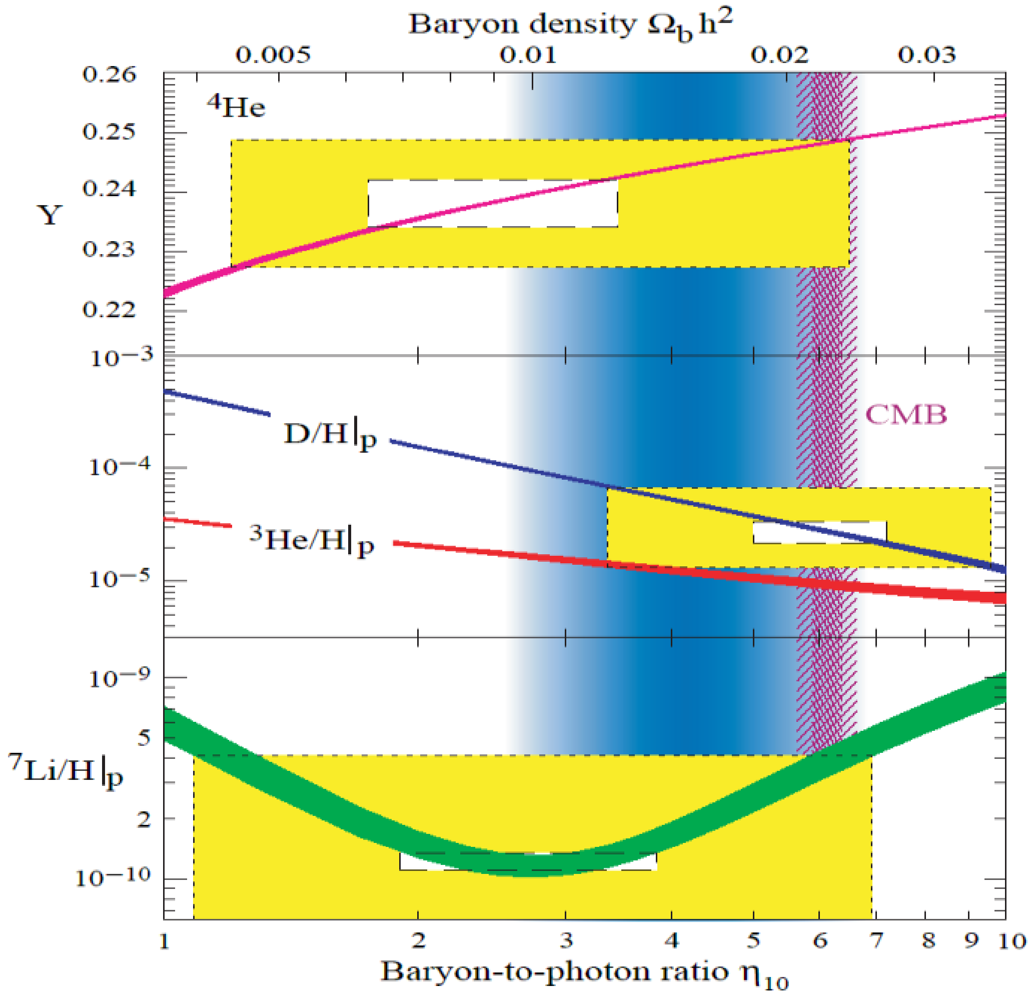
- supernovae, WMAP, SDSS $\Rightarrow$ $\Omega_M \approx 0.3$, $\Omega_\Lambda \approx 0.7$, $\Omega_k \approx 0 \rightarrow \Omega_{tot} \approx 1$
- BBN & CMB ("cosmic concordance") $\Rightarrow$ $\Omega_B \approx 0.04$ $\longrightarrow$ $\Omega_{DM} \approx 0.25$



PDB 2002

Can CDM be neutralinos?

— $\tilde{Z}_1$ excellent CDM candidate: neutral, stable, has right mass & xsections!

— Thermal history: $T < T_F \rightarrow$ LSP only (co-)annihilates into SM particles

- LSP n density described by Boltzmann eq.

$$\dot{n} = -3\,H\,n - \langle \sigma_{eff}\, v \rangle \,(n^2 - n_{eq}^2)$$

- Contribution to Ω in terms of thermally averaged effective xsection

$$\Omega_{LSP} \sim 1 \Big/ \int_0^{x_F} \langle \sigma_{eff}\, v \rangle \, dx \qquad (x_F = m_{\tilde{Z}_1} / T_F)$$

- $\langle \sigma_{eff}\, v \rangle$ gets contribution from $\tilde{Z}_{1,2}$, $\tilde{W}_1$, $\tilde{l}$, $\tilde{q}$ (co-)annihilation

$$\langle \sigma_{eff}\, v \rangle = \frac{\int_2^{\infty} K_1(ax) \sum_{j,k=1}^{N} g_j\, g_k\, \sigma_{jk}(a)\, \lambda(a, b_j, b_k)\, da}{4 \left(\sum_{i=1}^{N} K_2(b_i\, x)\, b_i^2\, g_i\right)^2 / x}$$

$$\left(b_i = \frac{m_i}{m_{\tilde{Z}_1}},\ \ K_1(x) \sim e^{-x}\right)$$

- about 10.000 (co-)annihilation diagrams can be evaluated with

  CompHEP → ISAReD or MicrOmegas   Reduce → DarkSUSY

- SUSY model generated with ISASUGRA

- good agreement between these codes & Ellis et al, Drees et al., Nanopoulos et al.

TABLE I. A tabulation of Feynman diagrams contributing to our neutralino annihilation cross section calculation.

Process	Particles exchanged: s channel	t channel	u channel
$\widetilde{Z}_1\widetilde{Z}_1 \to Z^0Z^0$	h, H	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to W^+W^-$	h, H, Z^0	$\widetilde{W}^{\pm}_{1,2}$	$\widetilde{W}^{\pm}_{1,2}$
$\widetilde{Z}_1\widetilde{Z}_1 \to Z^0h$	Z^0, A	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to Z^0H$	Z^0, A	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to Z^0A$	h, H	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to W^-H^+$	h, H, A	$\widetilde{W}^{\pm}_{1,2}$	$\widetilde{W}^{\pm}_{1,2}$
$\widetilde{Z}_1\widetilde{Z}_1 \to W^+H^-$	h, H, A	$\widetilde{W}^{\pm}_{1,2}$	$\widetilde{W}^{\pm}_{1,2}$
$\widetilde{Z}_1\widetilde{Z}_1 \to hh$	h, H	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to HH$	h, H	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to hH$	h, H	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to AA$	h, H	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to hA$	Z^0, A	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to HA$	h, H	$\widetilde{Z}_{1,2,3,4}$	$\widetilde{Z}_{1,2,3,4}$
$\widetilde{Z}_1\widetilde{Z}_1 \to H^+H^-$	h, H, Z^0	$\widetilde{W}^{\pm}_{1,2}$	$\widetilde{W}^{\pm}_{1,2}$
$\widetilde{Z}_1\widetilde{Z}_1 \to f\bar{f}$	Z^0, h, H, A	$\tilde{f}^{\pm}_{1,2}$	$\tilde{f}^{\pm}_{1,2}$

Baer,Balazs,Belyaev JHEP0203,042(`02)

SUSY breaking?

— $\tilde{Z}_1$ CDM became an important constraint in SUSY model building

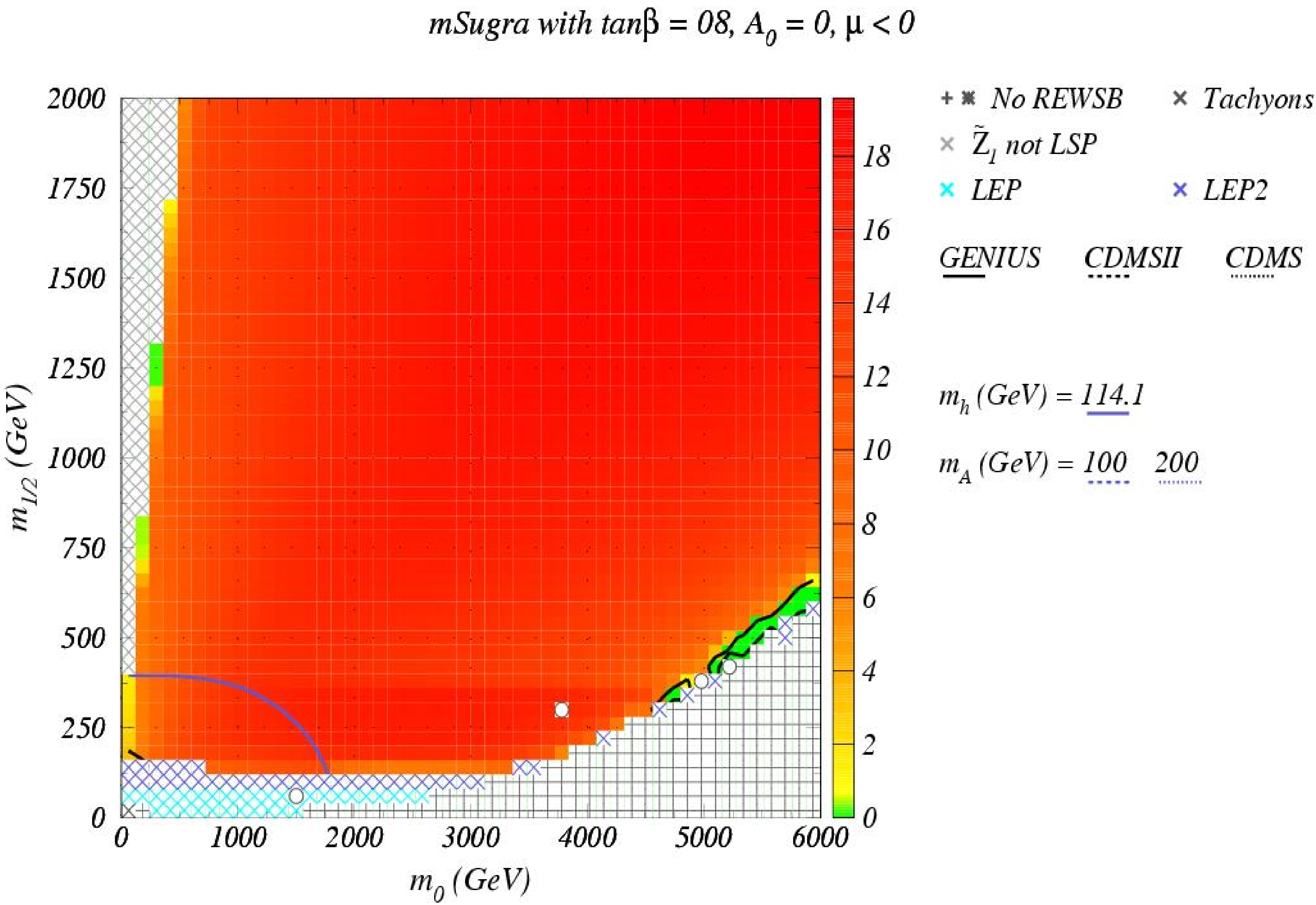
- tight exp't limits on CDM relic density translate into constraints on SSB
- cosmological properties are determined by spectrum

	mSUGRA	inoMSB	AMSB
LSP	$\tilde{Z}_1$	$\tilde{Z}_1$	$\tilde{Z}_1$
(fix	no fix needed	$M_C > M_{GUT}$ or NUGM	D-terms)
NLSP	$\tilde{W}_1$, $\tilde{\tau}_1$, $\tilde{t}_1$	$\tilde{\tau}_1$	$\tilde{\tau}_1$
typical $\tilde{Z}$ mix	$\tilde{B}$	$\tilde{B}$-$\tilde{W}$	$\tilde{W}$
annihilation	ineffective	effective	very effective
CDM density	high	about right or low	very low
co-ann.	$\tilde{Z}_1\,\tilde{W}_1$, $\tilde{Z}_1\,\tilde{f}_1$	$\tilde{Z}_1\,\tilde{l}_1$, $\tilde{Z}_1\,\tilde{W}_1$	$\tilde{Z}_1\,\tilde{W}_1$
CDM	strongly constr.	constrained	unconstr.

- CDM constraints are even important for MSSM

Arnowitt et al.; Baer et al.; Belanger et al.; Djouadi et al.; Ellis et al., Nanopoulos et al., ...

How much dark matter is in mSUGRA?



How much antimatter is in the MSSM?

— Observation: $N_B \gg N_{\bar{B}}$ (antimatter only seen in cosmic rays)

— Conditions (Sakharov): discreet symmetries have to be broken

1. $\not{B}$ to allow asymmetry: efficient in the early universe

2. $\not{C}$ & $\not{CP}$ to generate asymmetry

3. $\not{T}$ to preserve asymmetry: universe falls out of thermal equilibrium, when B switches from being violated to being conserved

— EWBG (Shaposhnikov): SM can satisfy Sakharov conditions, if

1. $\not{B}$ (satisfied at quantum level: in SM anomalies only conserve B—L)

2. there's enough $\not{CP}$ in CKM (not satisfied in SM, but possible in MSSM)

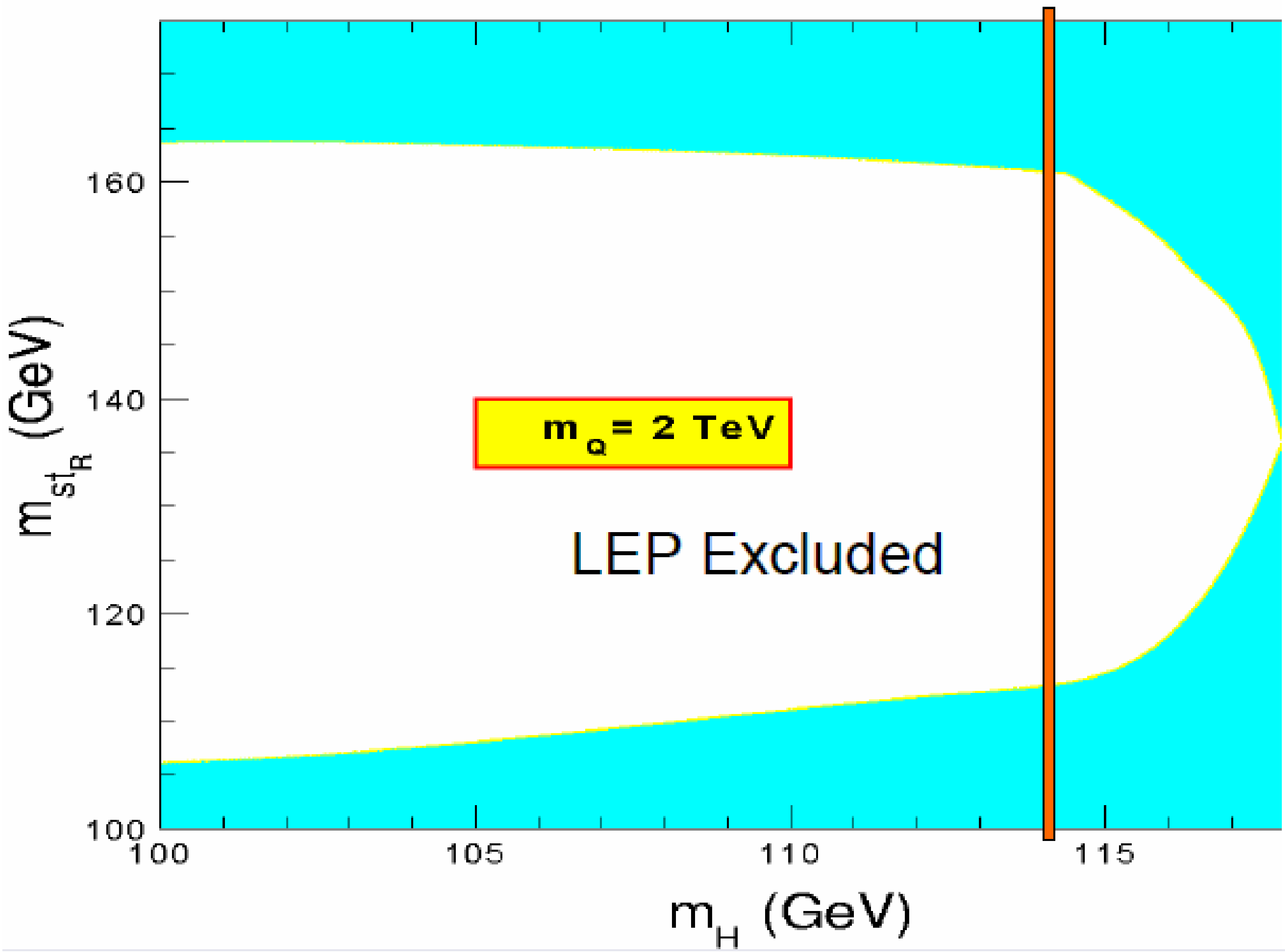
3. EW phase transition strongly first order (in SM $\leftrightarrow$ $m_h < 40$ GeV)

— EW baryogenesis in the MSSM: possible if

- h is light, $\tilde{t}_1$ is light, $\tilde{t}_2$ is heavy, X_t small(ish),

  μ (and/or M_1) has a complex phase

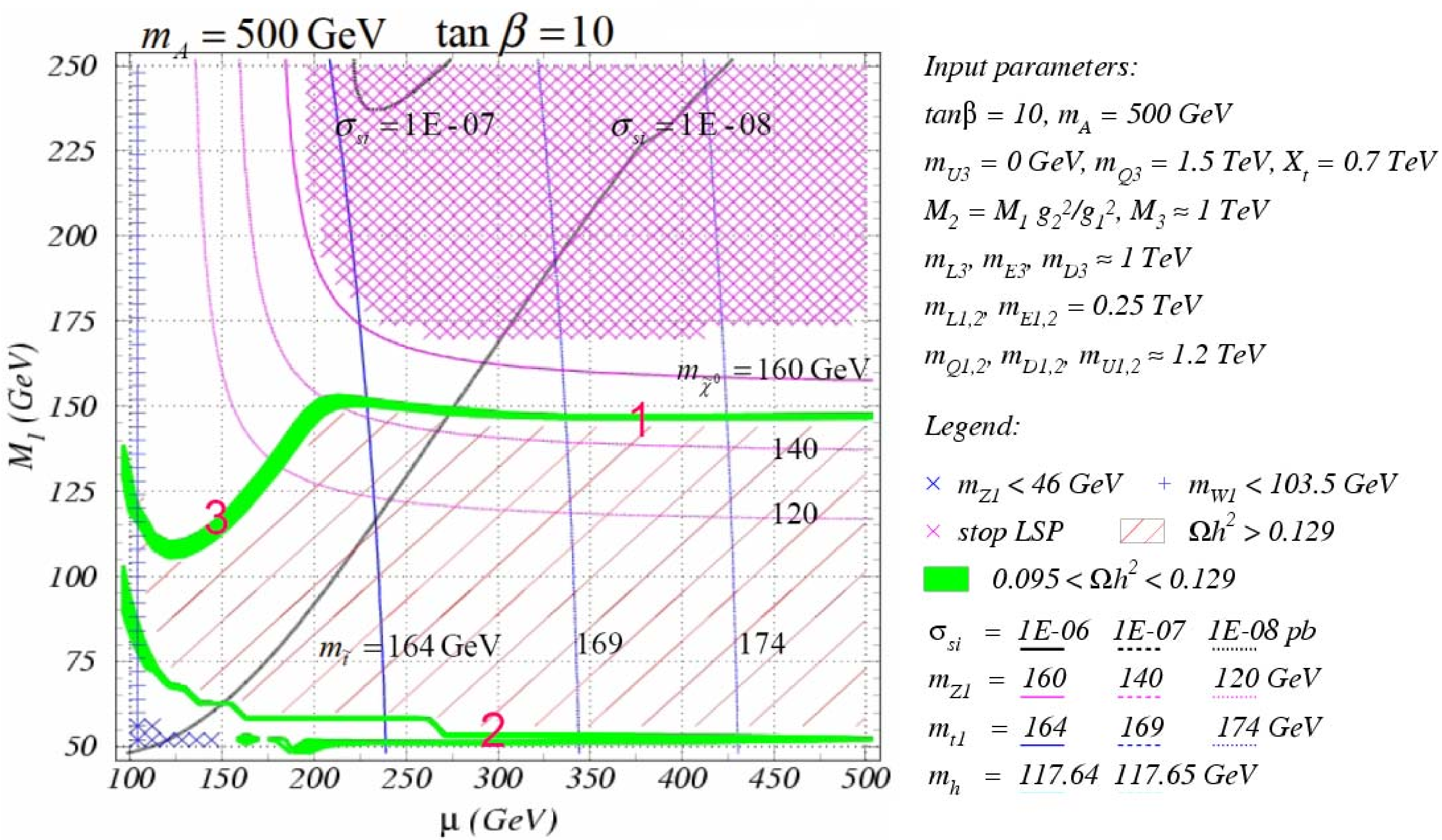
— EW baryogenesis constraints



Carena,Quiros,Wagner

Baryogenesis & DM in the MSSM

— Can the conditions for EW baryogenesis & right amount of neutralino DM be simultaneously satisfied in the MSSM?

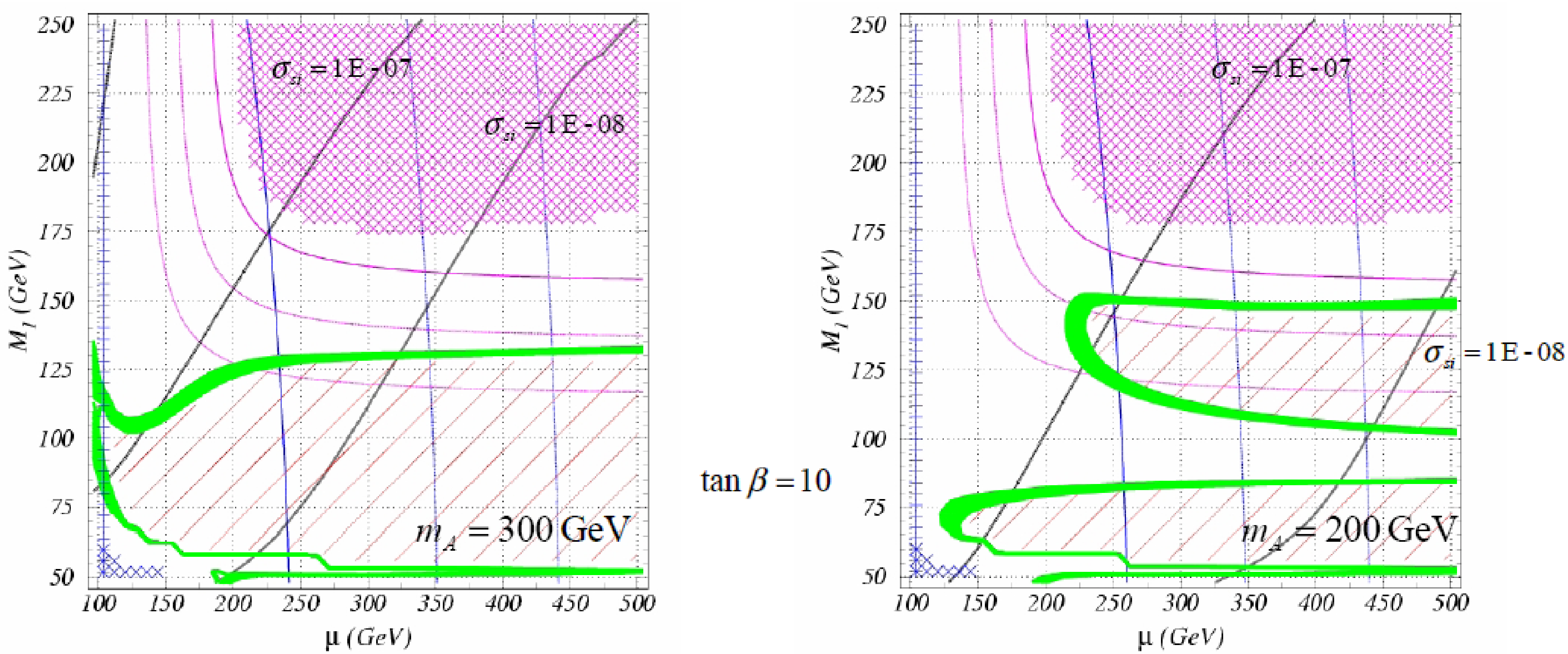


Balazs,Carena,Wagner 2004

Baryogenesis & DM in the MSSM

— Effect of annihilations via heavy Higgs resonances

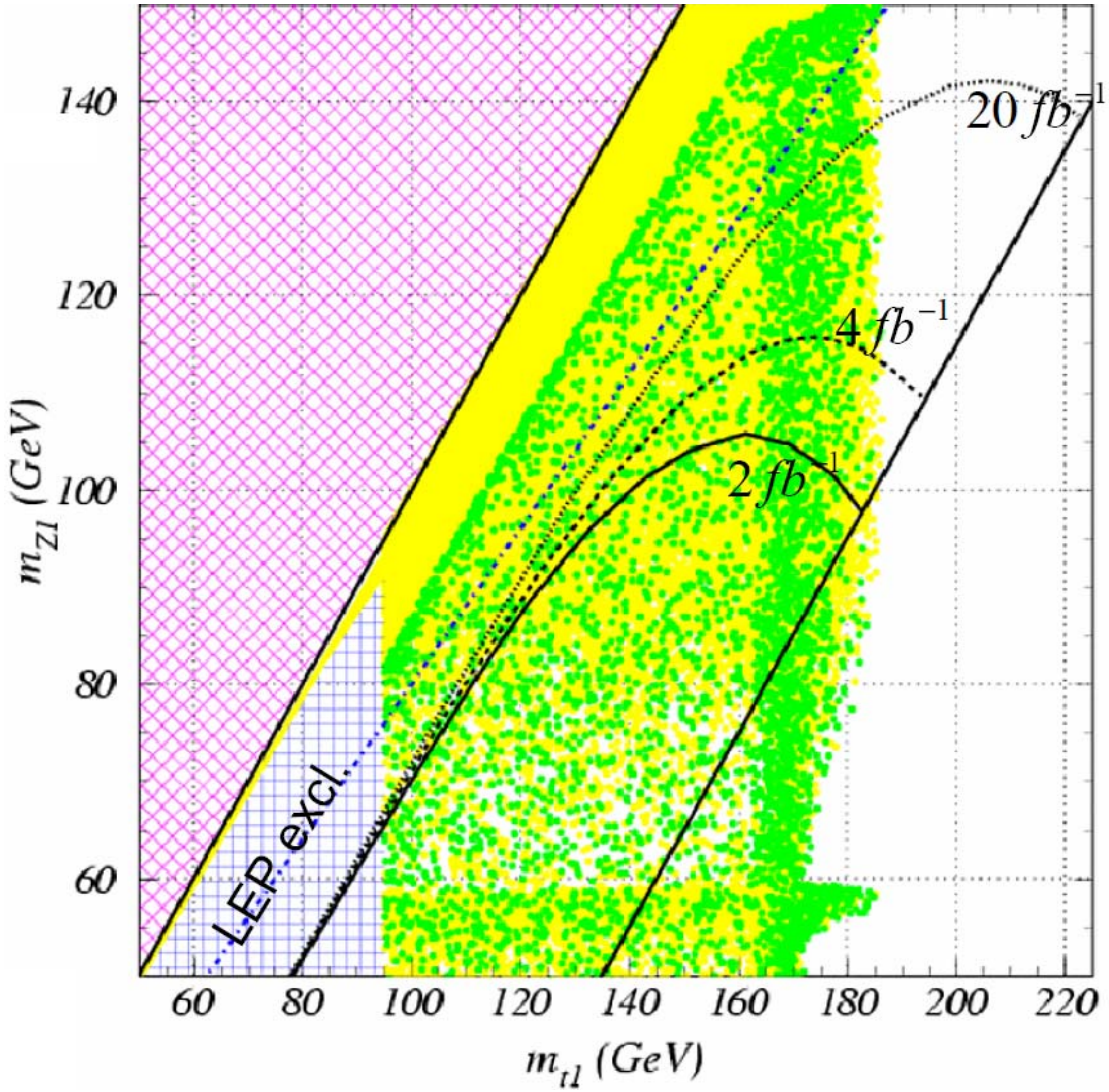
- $m_A = 300$ GeV: the cosmologically preferred region shifts to lower $m_{\tilde{Z}_1}$
- $m_A = 200$ GeV: new (heavy) Higgs-resonance corridor opens up



Balazs,Carena,Wagner 2004

— Neutralino-nucleon elastic xsection is promising for near future exp.s

Can the Tevatron reach this?

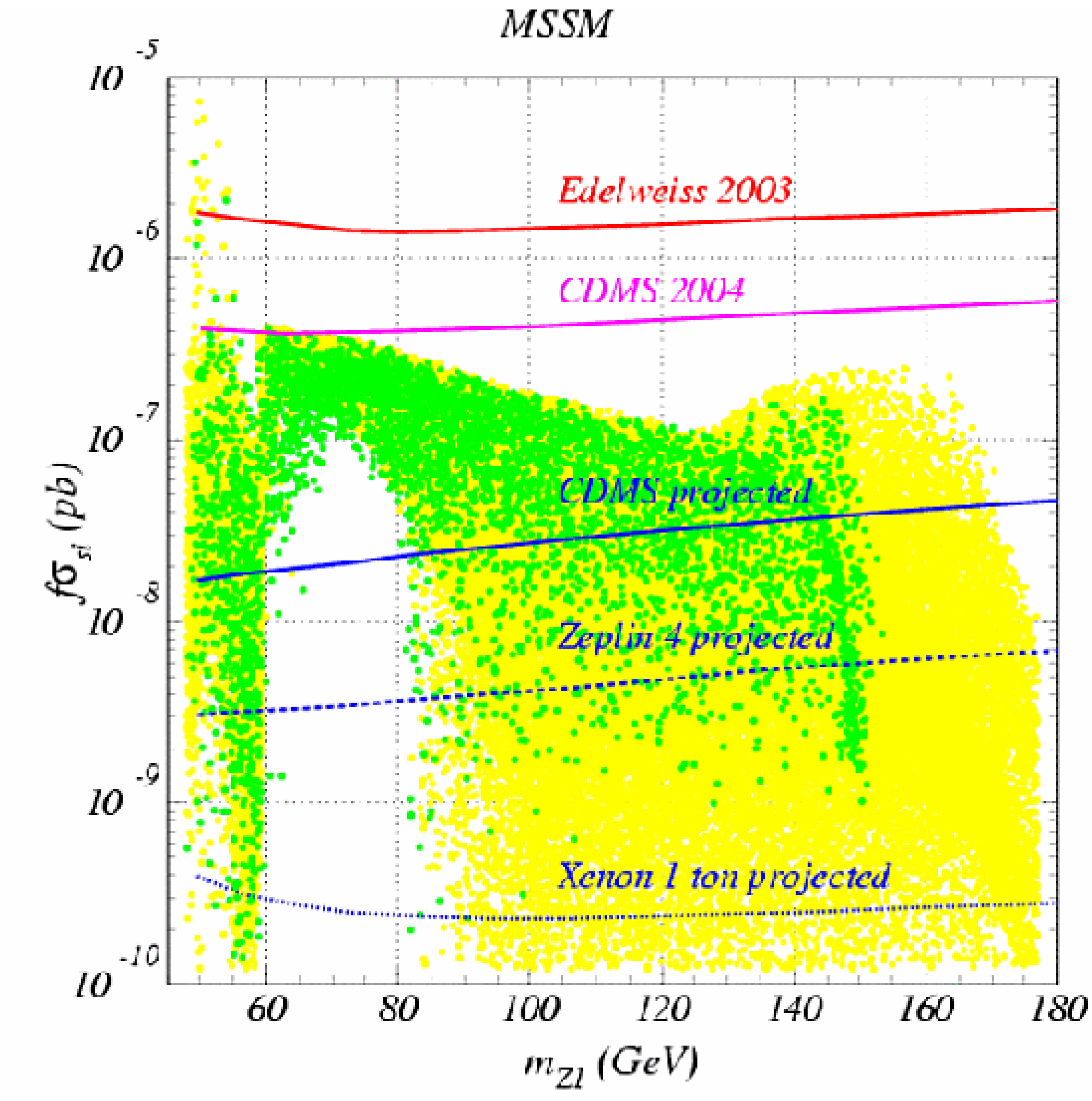


– If $\tilde{t}_1 \to c\tilde{Z}_1$ dominant

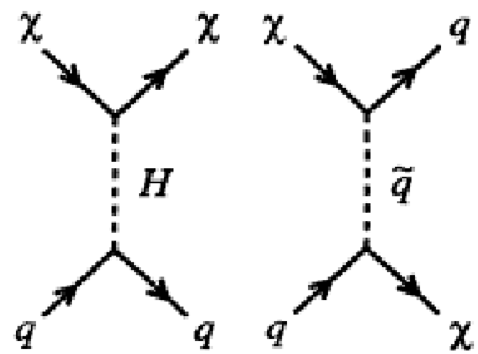
- considerable part of examined para space is observable
- if $m_{\tilde{t}_1} \lesssim 1.25\, m_{\tilde{Z}_1}$ coannihilation region $\Rightarrow$ no reach; same at LHC
- if $m_{\tilde{t}_1} > m_{\tilde{Z}_1} + m_Z + m_b$ Higgs resonance region & $m_{\tilde{t}_1} \gtrsim 140$ GeV $\Rightarrow$ 3 body decay $\leftrightarrow$ no reach

Balazs, Carena, Wagner 2004

Complementarity with direct CDM detection experiments



– Future WIMP nucleon elastic scattering exp.s will probe large part of all regions



- coannihilation region probed
- XENON promises to explore the whole relevant para region

Balazs, Carena, Wagner 2004

Is it a bird? Is it a plane? No, it's super...

— Phases aside, can the necessary low-energy spectrum be generated in mSUGRA, GMSB, AMSB or in inoMSB?

— Simultaneous EWSB & CDM constraints are strong on MSSM

- assuming gaugino mass unification, some (1-loop) RGEs can be 'inverted':

$$m^2_{H_1}(M_{GUT}) \sim m^2_A - \frac{1}{12}M_1^2 - \mu^2 + m^2_Z$$
$$m^2_{H_2}(M_{GUT}) \sim m^2_{\tilde{Q}_3} + 3A_t^2 + 15A_t M_1 - 20M_1^2 + \ldots$$
$$m^2_{\tilde{U}_3}(M_{GUT}) \sim \frac{2}{3}m^2_{\tilde{Q}_3} + 2A_t^2 + 11A_t M_1 - 53M_1^2 + \ldots$$
$$m^2_{\tilde{Q}_3}(M_{GUT}) \sim \frac{4}{3}m^2_{\tilde{Q}_3} + A_t^2 + 5A_t M_1 - 46M_1^2 + \ldots$$
$$A_t(M_{GUT}) \sim 3A_t + \frac{27}{2}M_1 + \ldots$$

- $m^2_{\tilde{Q}_3}$, A_t, M_1 strongly constrained by EWBG $\Rightarrow$ no scalar unification
- EWBG & NCDM doesn't work in mSUGRA, minoMSB or mAMSB (+phases)

Summary: The good, the bad and the ugly

– Good: CDM seems to be out there and it might be made of neutralinos

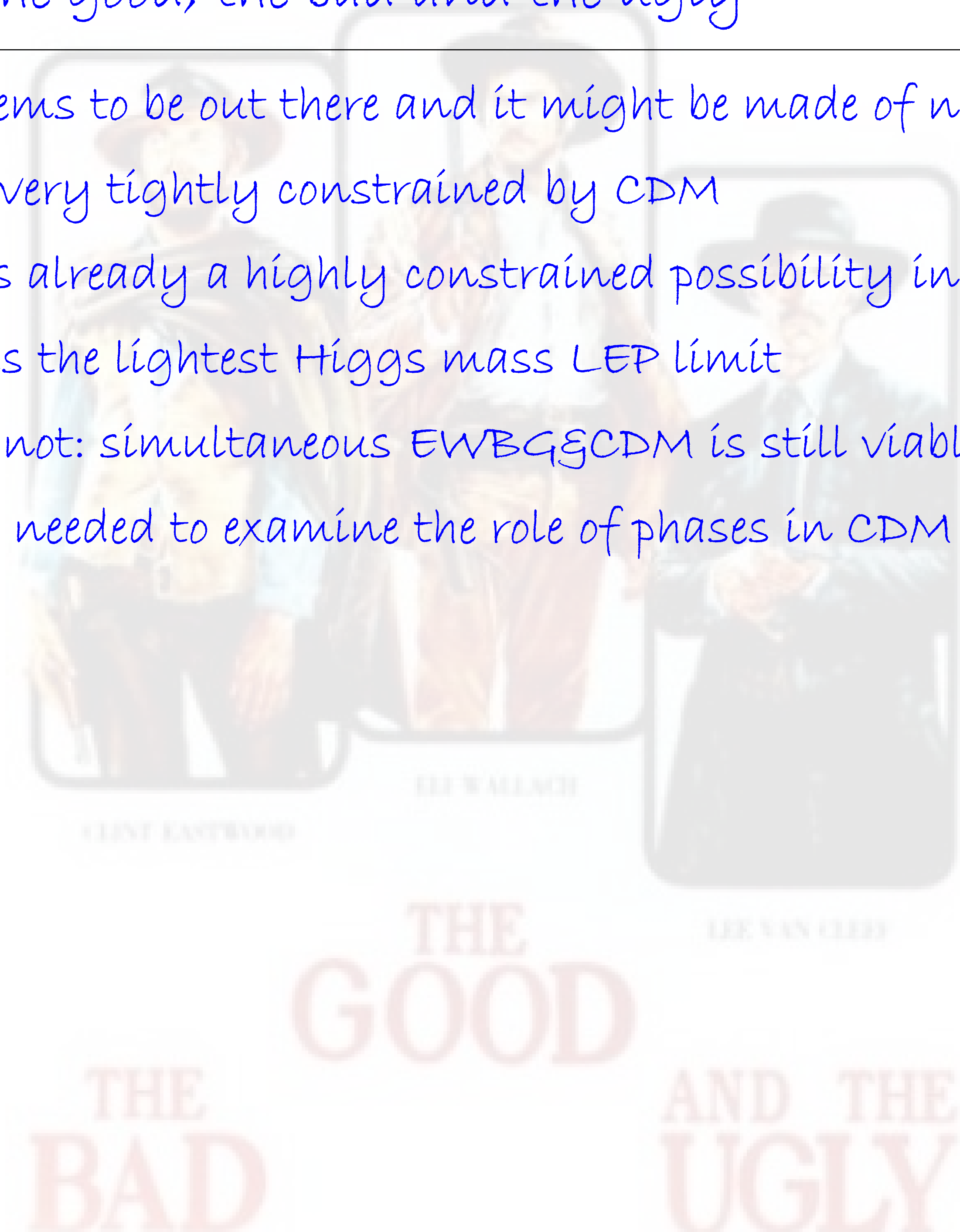
- mSUGRA is very tightly constrained by CDM

– Bad: EWBG is already a highly constrained possibility in the MSSM

- it just survives the lightest Higgs mass LEP limit

– Ugly? Maybe not: simultaneous EWBG&CDM is still viable in the MSSM

- further study needed to examine the role of phases in CDM (in progress)



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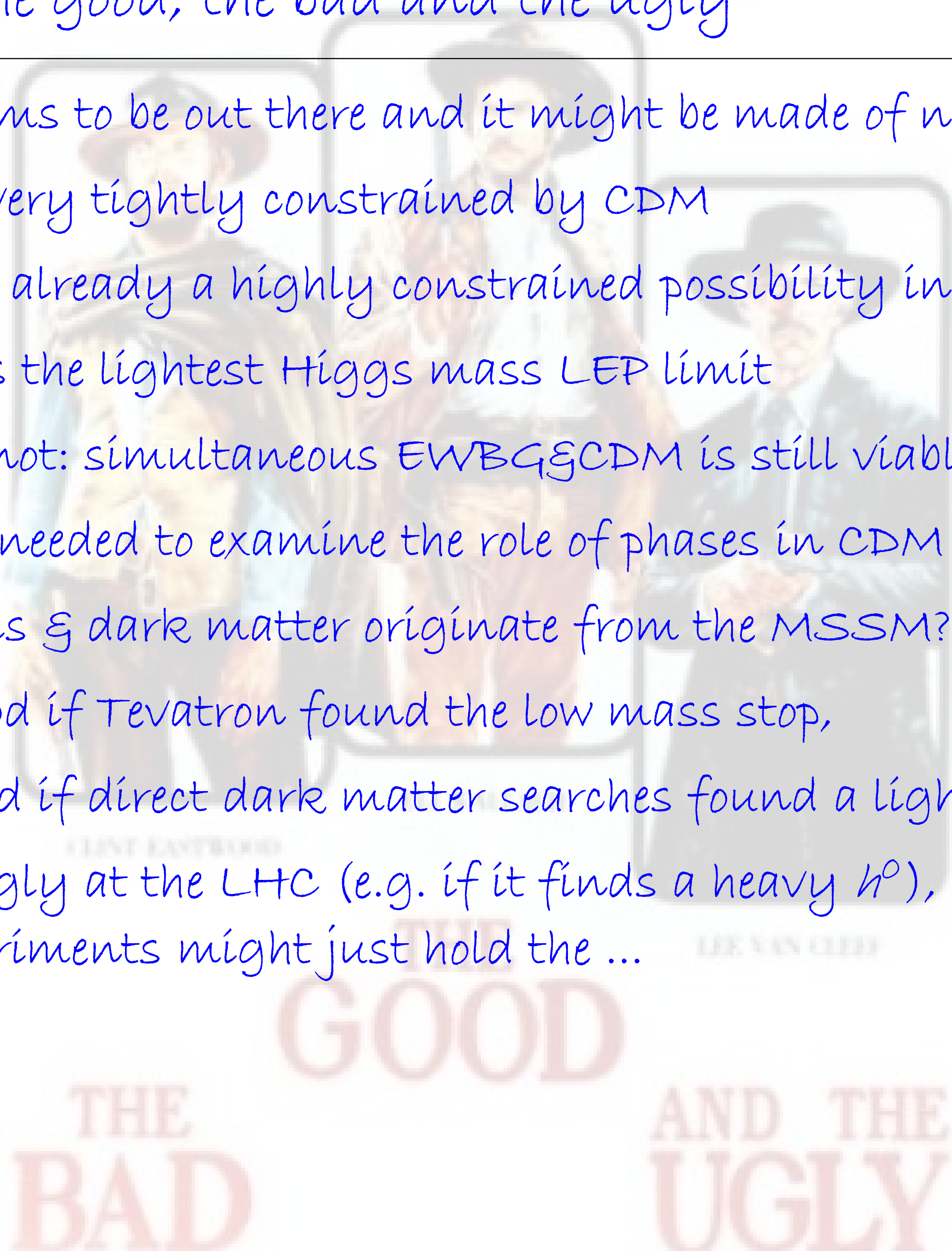
— Do baryogenesis & dark matter originate from the MSSM?

- it would be good if Tevatron found the low mass stop,
- wouldn't be bad if direct dark matter searches found a light WIMP, either
- it might get ugly at the LHC (e.g. if it finds a heavy h^0), but at the end one of these three experiments might just hold the ...



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... smoking gun!