THEORY SUMMARY

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ICREA/IFAE Barcelona

44th Rencontres de Moriond
Electroweak Session,
La Thuile, March 7-14 2009

OUTLINE

- Strong interactions
- Flavor physics
- Extra dimensions
- Dark Matter
- Baryons
- Perspectives in theory

The Standard Model of strong and electroweak interactions is based on the gauge group

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

- $SU(3)_c$ describes the physics of strong interactions: QCD (see next week conference)
- $SU(2)_L \times U(1)_Y$ describes the physics of weak and electromagnetic interactions
- It has to be spontaneously broken to QED by the Higgs mechanism
- The Standard Model describes the experimental data with high accuracy

THE STRONG SECTOR

- The theory of strong interactions is well confirmed but the theory becomes non-perturbative at low energies
- It is essential to understand the QCD background at LHC for any discovery: Higgs, new physics,...
- Used techniques are different: pQCD, NRQCD, HQET, chiral Lagrangians, non-perturbative methods (lattice),..., or a combination of all

PERTURBATIVE METHODS:

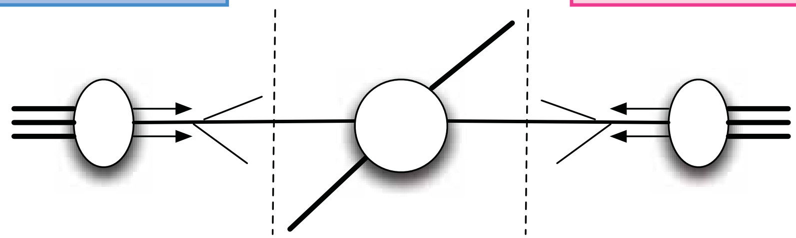
Giulia Zanderighi

Prerequisite: factorization

$$\frac{d\sigma_{\mathrm{pp}\to\mathrm{hadrons}}}{dX} = \sum_{a,b}\int dx_1 dx_2 f_a(x_1,\mu_F) f_b(x_2,\mu_F) \times \frac{d\hat{\sigma}_{\mathrm{ab}\to\mathrm{partons}}(\alpha_s(\mu_R),\mu_R,\mu_F)}{dX} + \mathcal{O}\left(\frac{\Lambda^n_{\mathrm{QCD}}}{Q^n}\right)$$

Extracted from data, but evolution is perturbative

Expansion in the coupling constant (LO, NLO, NNLO...)



NB: factorization used in many contexts without proof

Giulia Zanderighi

Parton densities: recent progress

Recent major progress:

- full NNLO evolution (previous only approximate NNLO)
- full treatment of heavy flavors near the quark mass

  [Numerically: e.g. (6-7)% effect on Drell-Yan at LHC]
- more systematic use of uncertainties/correlations
- Neural Network (NN) PDFs

splitting functions at NNLO: Moch, Vermaseren, A. Vogt '04
[+ much related theory progress '04 -'08]
Alekhin, CTEQ, MSTW (new MSTW '09), NN collaboration

Recently on the market: toolkits for NNLO DGLAP evolution of PDFs

PEGASUS A. Vogt '04; QCDNUM Botje '07
CANDIA Cafarella et al. '08; HOPPET Salam & Rojo '08

⇒ Description of PDFs reaching precision, but still some work ahead

Impressive progress in the last years

Giulia Zanderighi

- precision in parton densities
- higher orders (LO, NLO, NNLO & resummations)
- jets: many new ideas, impressive level of sophistication
- ... [much more, I did not have time to mention]

Progress driven by

- automation/flexibility/public codes
- good communication with experimentalists & common papers

Still many challenges ahead but QCD theory will provide solid basis for a successful physics program at the LHC

Rainer Sommer

The principle

First principle "solution" of QCD

experiments, hadrons

$$m_p = 938.272\,\mathrm{MeV}$$
$$M_\pi = 139.570\,\mathrm{MeV}$$
$$m_\mathrm{K} = 493.7\,\mathrm{MeV}$$
$$m_\mathrm{D} = 1896\,\mathrm{MeV}$$
$$m_\mathrm{B} = 5279\,\mathrm{MeV}$$

- **The Lagrangian**
- **Non-perturbative regulator: lattice with spacing a**
- **Technology**

continuum limit $a \to 0$

fundamental parameters & hadronic matrix elements

$$\alpha(\mu)$$
$$m_\mathrm{u}(\mu)\,,\ m_\mathrm{s}(\mu)$$
$$m_\mathrm{c}(\mu)\,,\ m_\mathrm{b}(\mu)$$
$$F_\mathrm{B}\,,\ F_{\mathrm{B_s}}\,,\ \xi\ \ldots$$

Some sample results from the literature

Review of E. Gamiz lattice 2008

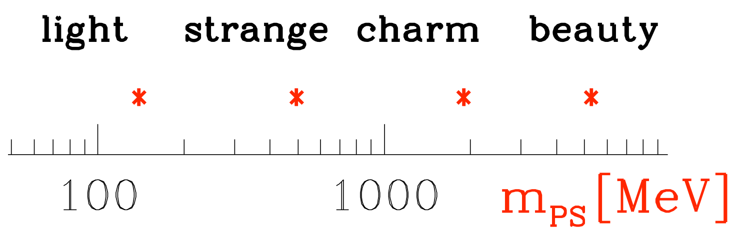
examples of results

$m_c^{\overline{\mathrm{MS}}}(3\,\mathrm{GeV})$	$=$	$0.986(10)\,\mathrm{GeV}$	HPQCD
$m_b^{\overline{\mathrm{MS}}}(m_b)$	$=$	$4.20(4)\,\mathrm{GeV}$	HPQCD
$\xi = \frac{F_{B_s}\sqrt{m_{B_s}}}{F_B\sqrt{m_B}}$	$=$	$1.211(38)(24)$	FNAL/MILC
F_{B_s}	$=$	$243(11)\,\mathrm{MeV}$	FNAL/MILC
F_{D_s}	$=$	$241(3)\,\mathrm{MeV}$	HPQCD

Precision up to 1 % is claimed

The challenge

multiple scale problem
always difficult
for a numerical treatment



lattice cutoffs:

$$\Lambda_{\rm UV} = a^{-1}$$
$$\Lambda_{\rm IR} = L^{-1}$$

$$\begin{array}{ccccc} L^{-1} & \ll & m_\pi\,,\ \ldots\ ,m_{\rm D}\,,m_{\rm B} & \ll & a^{-1} \\ {\rm O}({\rm e}^{-LM_\pi}) & & & & m_{\rm D}\,a \lesssim 1/2 \\ \downarrow & & & & \downarrow \\ L \gtrsim 4/M_\pi \sim 6\,{\rm fm} & & & & a \approx 0.05\,{\rm fm} \end{array}$$

$$L/a \gtrsim 120$$

beauty not yet accomodated: effective theory, $\Lambda_{\rm QCD}/m_{\rm b}$ expansion

$N_{\mathrm{f}} = 2$ QCD: Coordinated Lattice Simulations

Teams

* Berlin (team leader Ulli Wolff)
* CERN (L. Giusti, M. Lüscher)
* DESY-Zeuthen (Rainer Sommer)
* Madrid (Carlos Pena)
* Mainz(Hartmut Wittig)
* Rome (Roberto Petronzio)
* Valencia (Pilar Hernández)

Physics planned at present

* Fundamental parameters up to M_{b}
* Pion interactions
* Baryon physics
* Kaon physics

also with mixed actions

β	a[fm]	lattice	L[fm]	masses	
5.30	0.08	48×24^3	1.9	6 masses	CERN, Rome
5.30	0.08	64×32^3	2.6	6 masses	CERN, Rome
5.50	0.06	64×32^3	1.9	5 masses	DESY,Berlin,Madrid
5.70	0.04	96×48^3	1.9	2 masses	DESY,Berlin
5.70	0.04	128×64^3	2.6	2 masses	DESY,Berlin, started

Promising for charm (and beauty)

Very good agreement with precision data

Fit Input

- usage of latest experimental results:
  - **Z-pole observables**: LEP/SLD results [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - **M_W and Γ_W**: LEP/Tevatron [ADLO, hep-ex/0612034] [CDF, Phys Rev. D77, 112001 (2008)] [CDF, Phys. Lett. 100, 071801 (2008)] [CDF+D0, Phys. Rev. D 70, 092008 (2004)]
  - **m_t**: Tevatron [arXivx:0808.1089 [hep-ex]]
  - **$\Delta\alpha_{had}^{(5)}(M_Z^2)$**: including α_S dependency [Hagiwara et al., Phys. Lett. B649, 173 (2007)]
  - **m_c, m_b**: world averages [PDG, J. Phys. G33,1 (2006)]
- theoretical uncertainties: M_W (δM_W=4-6GeV), $\sin^2\theta^l_{eff}$ ($\delta\sin^2\theta^l_{eff}$ =4.7·10^{-5})
- floating fit parameters: M_Z, M_H, m_t, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\alpha_S(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$
- fits are performed in two versions:
  - standard fit: all data except results from direct Higgs searches
  - complete fit: all data including results from direct Higgs searches at LEP [ADLO: Phys. Lett. B565, 61 (2003)] and Tevatron [CDF+D0: arXiv:0804.3423, CDF+D0: arXiv:0808.0534]

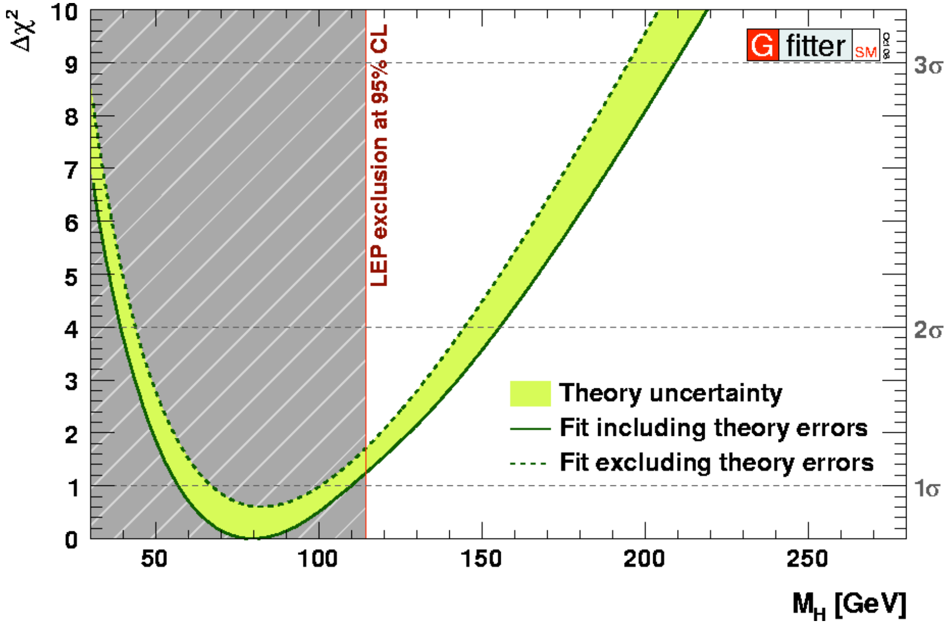
Parameter	Input value
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010
A_ℓ $^{(\star)}$	0.1499 ± 0.0018
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012
M_H [GeV] $^{(\circ)}$	Likelihood ratios
M_W [GeV]	80.399 ± 0.025
Γ_W [GeV]	2.098 ± 0.048
$\overline{m}_c$ [GeV]	1.25 ± 0.09
$\overline{m}_b$ [GeV]	4.20 ± 0.07
m_t [GeV]	172.4 ± 1.2
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2768 ± 22
$\alpha_s(M_Z^2)$	–

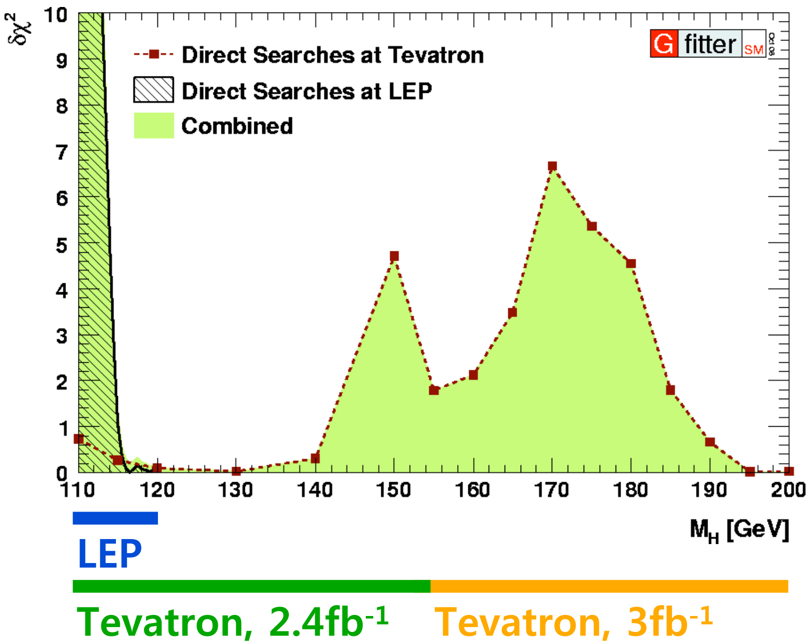
† in units of 10^{-5}

Higgs Mass Constraints

Martin Goebel

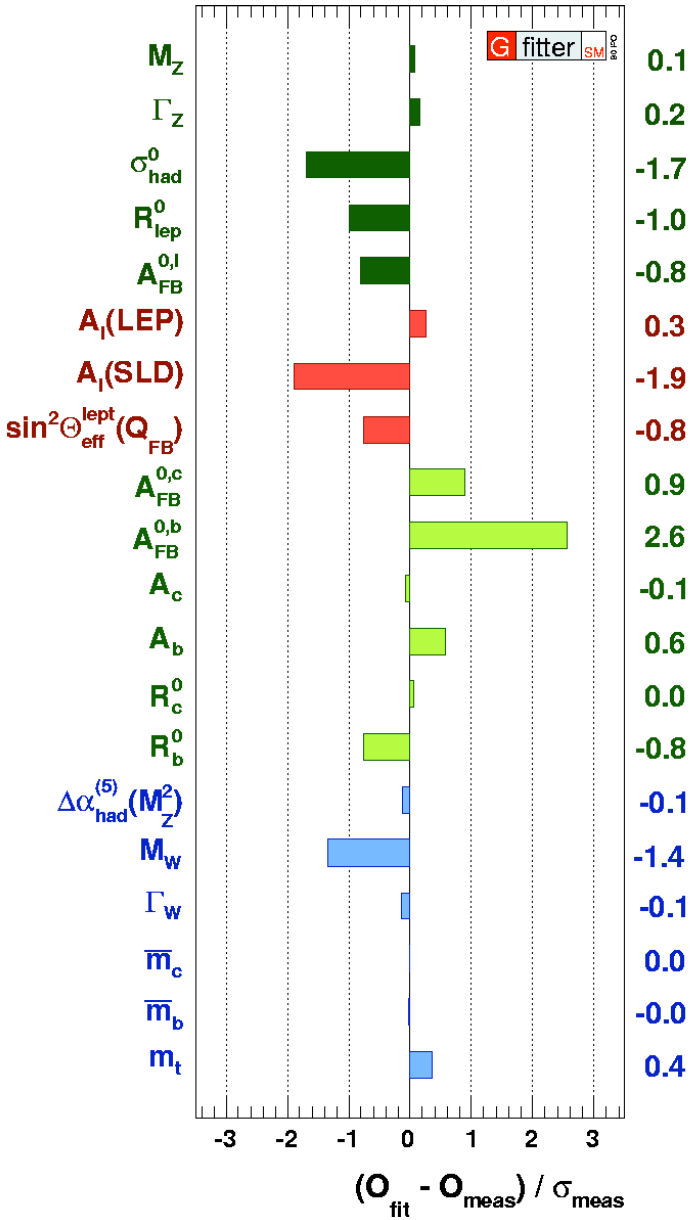
- standard fit:
  - from MC toy: p-value=0.225±0.004$_{-0.02}$
  - Higgs mass
    - central value ±1σ: $\boxed{M_H = 80^{+30}_{-23}\ \mathrm{GeV}}$
    - 2σ interval: [39, 155] GeV
    - 3σ interval: [26, 209] GeV
- green error band
  - theory uncertainties directly included in χ^2 ("flat likelihood")
- direct Higgs searches from LEP and Tevatron
  - resulting contribution added to the χ^2 during the fit





Pulls and Results for Complete Fit

Martin Goebel



- pull values of complete fit
  - no value exceeds 3σ
  - FB asymmetry of bottom quarks → largest contribution to χ^2

- α_S from complete fit:

$$\alpha_S(M_Z^2) = 0.1193^{+0.0028}_{-0.0027} \pm 0.0001$$

  - including N³LO of the massless QCD Adler function
  - first error is experimental fit error
  - second error due to missing QCD orders:
    - incl. variation of renorm. scale from $M_Z/2$ to $2M_Z$ and massless terms of order/beyond $\alpha_S^5(M_Z)$ and massive terms of order/beyond $\alpha_S^4(M_Z)$

There are a number of problems that the SM cannot resolve and requires NEW PHYSICS

- The Higgs sector is sensitive to the UV cutoff: hierarchy problem $\Rightarrow$ Supersymmetry, Warped extra-dimensions
- No explanation of the flavor structure, including the existence of 3 generations
- No Dark Matter candidate
- No explanations for baryons
- No unification of strong and electroweak couplings
- No unification with gravity

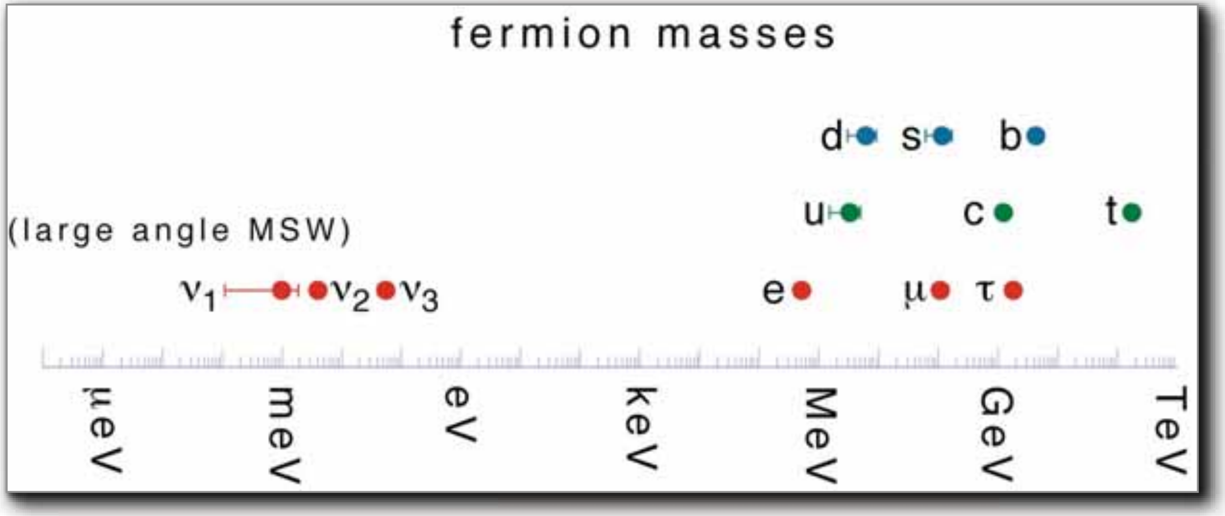
FLAVOR

- Solution to the flavor problem is finding a rationale for the structure of masses and mixing angles for quarks and leptons
- Normally it involves introducing a flavor symmetry under which flavor transforms and which breaks at some high scale leaving behind the flavor structure
- An example is the Froggatt-Nielsen mechanism with scalar fields coupled to Yukawa couplings as different powers according to quantum numbers

Puzzles of the electroweak sector

Matthias Neubert

- Unexplained hierarchies of fermion masses:



- Unexplained hierarchies of fermion mixings (e.g. quark sector):

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

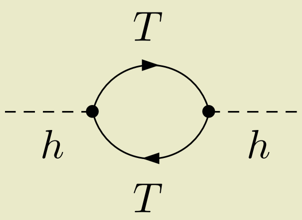
Matthias Neubert

Beyond SM there is another problem of flavor ...

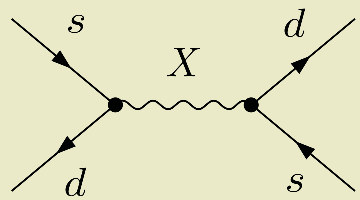
$$\mathcal{L}_{\rm EFT} = \underbrace{\Lambda_{\rm UV}^2\,\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2}_{} + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \underbrace{\frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2}}_{} + \dots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass

large FCNCs $\Downarrow$ generic flavor structure



$$\sim \frac{g_T^2}{16\pi^2}\,\Lambda_{\rm UV}^2$$



$$\sim \frac{g_X^2}{\Lambda_{\rm UV}^2}$$

no fine-tuning $\Downarrow$

bounds on flavor mixing $\Downarrow$

$\Lambda_{\rm Higgs} \lesssim 1$ TeV $\longrightarrow$ increasing energy scale $\longrightarrow$ $\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

- Solutions to flavor problem explaining $\Lambda_{\rm Higgs} << \Lambda_{\rm flavor}$:

  (i) $\Lambda_{\rm UV} >> 1$ TeV: new particles too heavy to be discovered at LHC

  (ii) $\Lambda_{\rm UV} \approx 1$ TeV: quark flavor mixing protected by flavor symmetry

- The global symmetry can give rise to a discrete one
- Much simpler to find models based on discrete groups
- In the quark sector there is strong relation with B-physics:
- Amarijit Soni finds that several sizable effects in B CP asymmetries are better fitted with a 4th generation and t' and b' around 400-600 GeV and a heavy Higgs
- Aoife Bharucha presented a detailed calculation of the process $B \to K^* \mu^+ \mu^- \to K^- \pi^+ \mu^+ \mu^-$ that can probe SM and NP at LHC
- In the leptonic sector the knowledge of neutrino masses and neutrino mixing angles can well fit the tri-bi-maximal texture

Federica Bazzocchi

2008

Neutrinos
& Lepton mixing

$$\begin{aligned}
\Delta m^2_{sol} &= 8.1(7.5-8.7)\cdot 10^{-5}\mathrm{eV}^2\\
\Delta m^2_{atm} &= 2.2(1.7-2.9)\cdot 10^{-3}\mathrm{eV}^2\\
\sin^2\theta_{12} &= 0.30(0.25-0.34)\\
\sin^2\theta_{23} &= 0.50(0.38-0.64)\\
\sin^2\theta_{13} &= 0(\leq 0.028)
\end{aligned}$$

(? $\sin\theta_{13}\neq 0$ see Palazzo's talk on friday)

M.Maltoni et al. New J.Phys.6:122,2004

Harrison, Perkins, Scott, PLB530 (2002)

$$U^T_{TB}\, M_\nu\, U_{TB} = M_\nu^{diag}$$

$$\boxed{U_{TB} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}}$$

$$M_l^{diag}$$

TRI-maximal

BI-maximal

$$\sin^2\theta_{12} = 1/3, \sin^2\theta_{23} = 1/2, \sin^2\theta_{13} = 0$$

Discrete flavor symmetries

@ LO exact TBM!

Ma & Rajasekaran PRD64,
Babu et al. PLB552 (A4)
Ma PLB632 (2006),
Hagerdon et al. JHEP 06 042 (S4)

A4

★ even permutations of 4 objects (subgroup of S_4, tethraedral symmetries)
★4!/2=12 elements
★generated by two basic permutations: S=(4321) & T=(2314)
★$S^2=T^3=(ST)^3=1$ -> a representation of the group
★12 elements belong to 4 equivalence classes
★4 inequivalent representations 1,1',1'' & 3

S4

★ permutations of 4 objects (tethraedral symmetries)
★ 4!=24 elements
★$S^4=T^3=1$, $ST^2S=T$ -> a representation of the group
★24 elements belong to 5 equivalence classes
★5 inequivalent representations 1_1, 1_2, 2, 3_1, 3_2

Federica Bazzocchi

A4, S4

Z3
charged leptons

Z2 , Z2xZ2
neutrinos

$$G_{Z_3}^T M_l M_l^\dagger G_{Z_3} = M_l M_l^\dagger$$

(or $G_{Z_3}^T M_l G_{Z_3} = M_l$)

$$G_{Z_2}^T M_\nu G_{Z_2} = M_\nu$$

$$U_{Z_3}$$

$$U_{Z_2}$$

$$U_{lep} = U_{Z_3}^\dagger U_{Z_2} = U_{TB}$$

the group splits differently in charged lepton and neutrino sector not to get trivial mixing !

A4 for SU(5) constructed by Alfredo Urbano (YSF2)

Federica Bazzocchi

choose a basis for the A4,S4 generators in which the charged lepton are diagonal

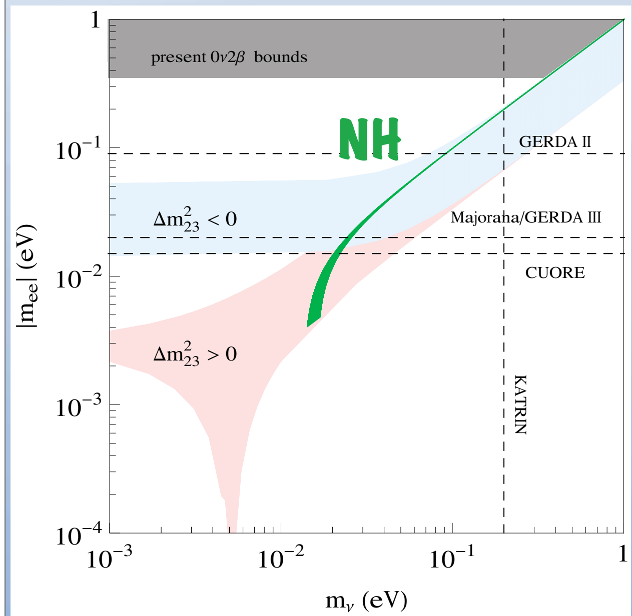
neutrinos can get a mass in different ways		flavour symmetry
effective operator (EF)	$\frac{1}{\Lambda} L L h_u h_u$	$\frac{1}{\Lambda} L L h_u h_u \frac{\phi_i}{\Lambda_F}$
type I see-saw (SSI)	$M_\nu \sim -m_D\, M_R^{-1} m_D^T$	$m_D \sim L h_u \nu^c \frac{\phi_i}{\Lambda_F}$ $M_R \sim \nu^c \nu^c \phi_i$
type II see-saw (SSII)	$L L \Phi$	$L L \Phi \frac{\phi_i}{\Lambda_F}$
type III see-saw (SSIII)	$M_\nu \sim -m_{l\Sigma}\, M_\Sigma^{-1} m_{l\Sigma}^T$	$m_{l\Sigma} \sim L h_u \Sigma \frac{\phi_i}{\Lambda_F}$ $M_\Sigma \sim \Sigma \Sigma \phi_i$

Comparing models: A4

Federica Bazzocchi

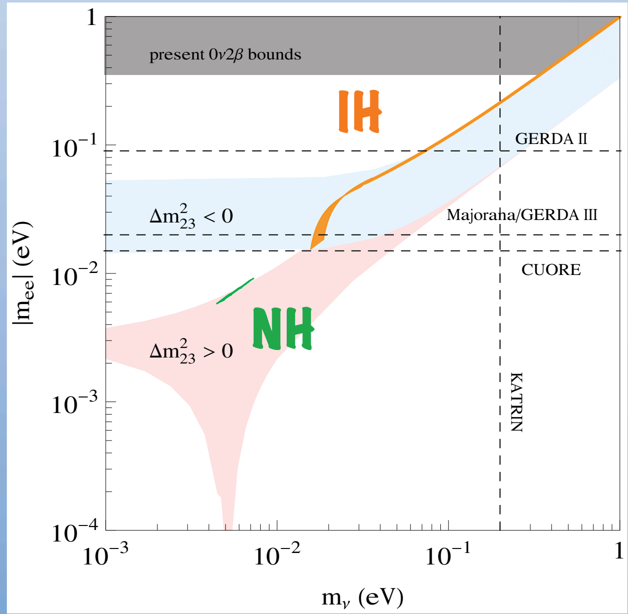
AF-EF

$$M_\nu = v\begin{pmatrix} a+2c & -c & -c \\ -c & 2c & a-c \\ -c & a-c & 2c \end{pmatrix}$$



AF-SSI

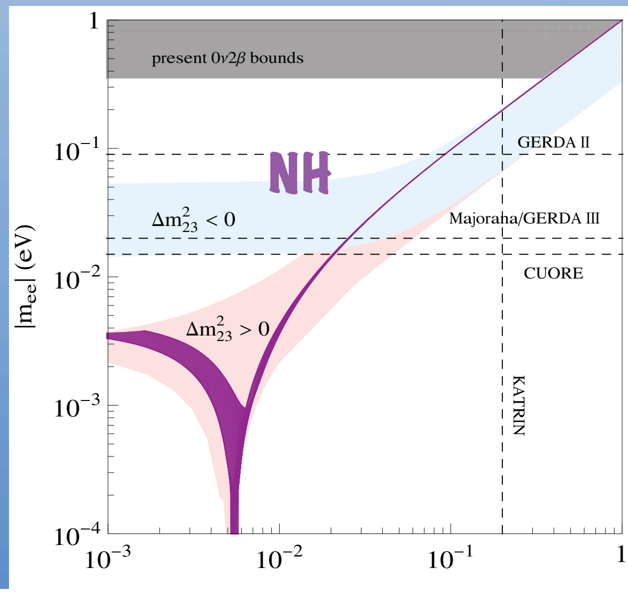
$$M_\nu = v\begin{pmatrix} \frac{1}{3a}+\frac{2}{3}\frac{1}{(a+3c)} & \frac{1}{3a}-\frac{1}{3}\frac{1}{(a+3c)} & \frac{1}{3a}-\frac{1}{3}\frac{1}{(a+3c)} \\ \frac{1}{3a}-\frac{1}{3}\frac{1}{(a+3c)} & \frac{1}{3a}+\frac{2}{3}\frac{1}{(a+3c)} & \frac{1}{3a}-\frac{1}{3}\frac{1}{(a+3c)} \\ \frac{1}{3a}-\frac{1}{3}\frac{1}{(a+3c)} & \frac{1}{3a}-\frac{1}{3}\frac{1}{(a+3c)} & \frac{1}{3a}+\frac{2}{3}\frac{1}{(a+3c)} \end{pmatrix}$$



FI-structure one in MR the other in mD

HMV

$$M_\nu = v\begin{pmatrix} \frac{2}{3}a^2+\frac{1}{3}b^2 & -\frac{1}{3}a^2+\frac{1}{3}b^2 & -\frac{1}{3}a^2+\frac{1}{3}b^2 \\ -\frac{1}{3}a^2+\frac{1}{3}b^2 & \frac{1}{6}a^2+\frac{1}{3}b^2+\frac{1}{2}c^2 & \frac{1}{6}a^2+\frac{1}{3}b^2-\frac{1}{2}c^2 \\ -\frac{1}{3}a^2+\frac{1}{3}b^2 & \frac{1}{6}a^2+\frac{1}{3}b^2-\frac{1}{2}c^2 & \frac{1}{6}a^2+\frac{1}{3}b^2+\frac{1}{2}c^2 \end{pmatrix}$$

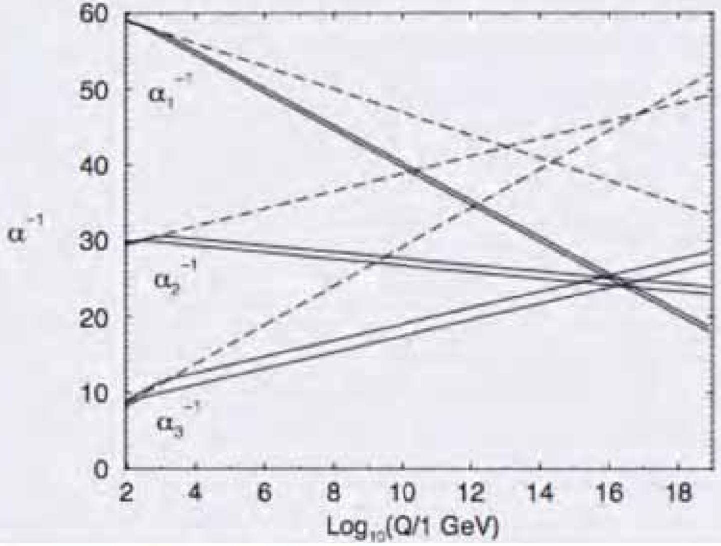


SUPERSYMMETRY

- Supersymmetry is the simplest and more elegant solution to the hierarchy problem: quadratic divergences generated by bosons are canceled by fermions
- In its minimal version (MSSM) the SM-like Higgs mass is very strongly bound and then the theory can be ruled out at the LHC
- In the MSSM there is a natural candidate for CDM: the lightest neutralino provided R-parity is conserved
- Gauge coupling unification happens without imposing it
- Radiative electroweak breaking is a nice feature of minimal SUGRA
- The stability/triviality problem of the SM are naturally solved by the relation between quartic and gauge coupling

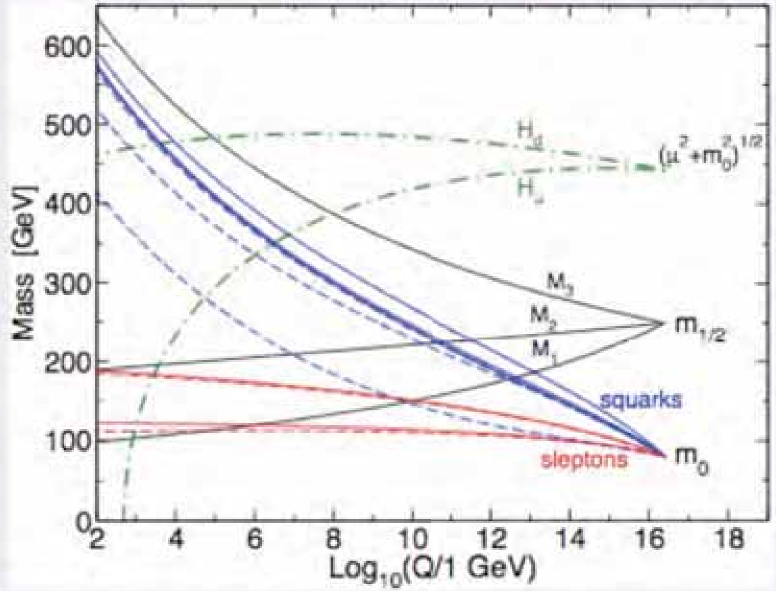
Gauge coupling unification

Consistently with LEP measurements and if superparticles are at $\sim$ TeV scale gauge couplings unify at a scale $M_{GUT} \sim 2 \times 10^{16}$ GeV



Electroweak breaking

If soft breaking parameters are generated at M_{GUT} a tachyonic mass can be triggered by RGE at the weak scale



Stability/triviality problems

- The stability ($\lambda < 0$) and triviality/Landau pole ($\lambda \to \infty$) problems are solved because of the supersymmetric relation

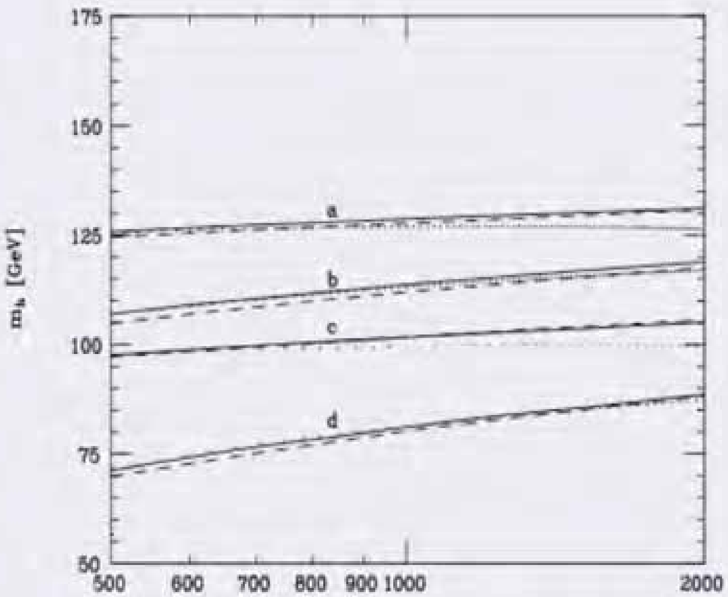
$$\lambda = \frac{1}{8}(g^2 + g'^2)$$

- Because the gauge couplings remain perturbative (and positive) up to M_{GUT} there is no stability and/or triviality problem in the MSSM
- As a consequence: the Higgs mass (unlike in the SM) is NOT a free parameter. For the SM-like Higgs

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{M_S^2}\left(1 - \frac{A_t^2}{12 M_S^2}\right)\right]$$

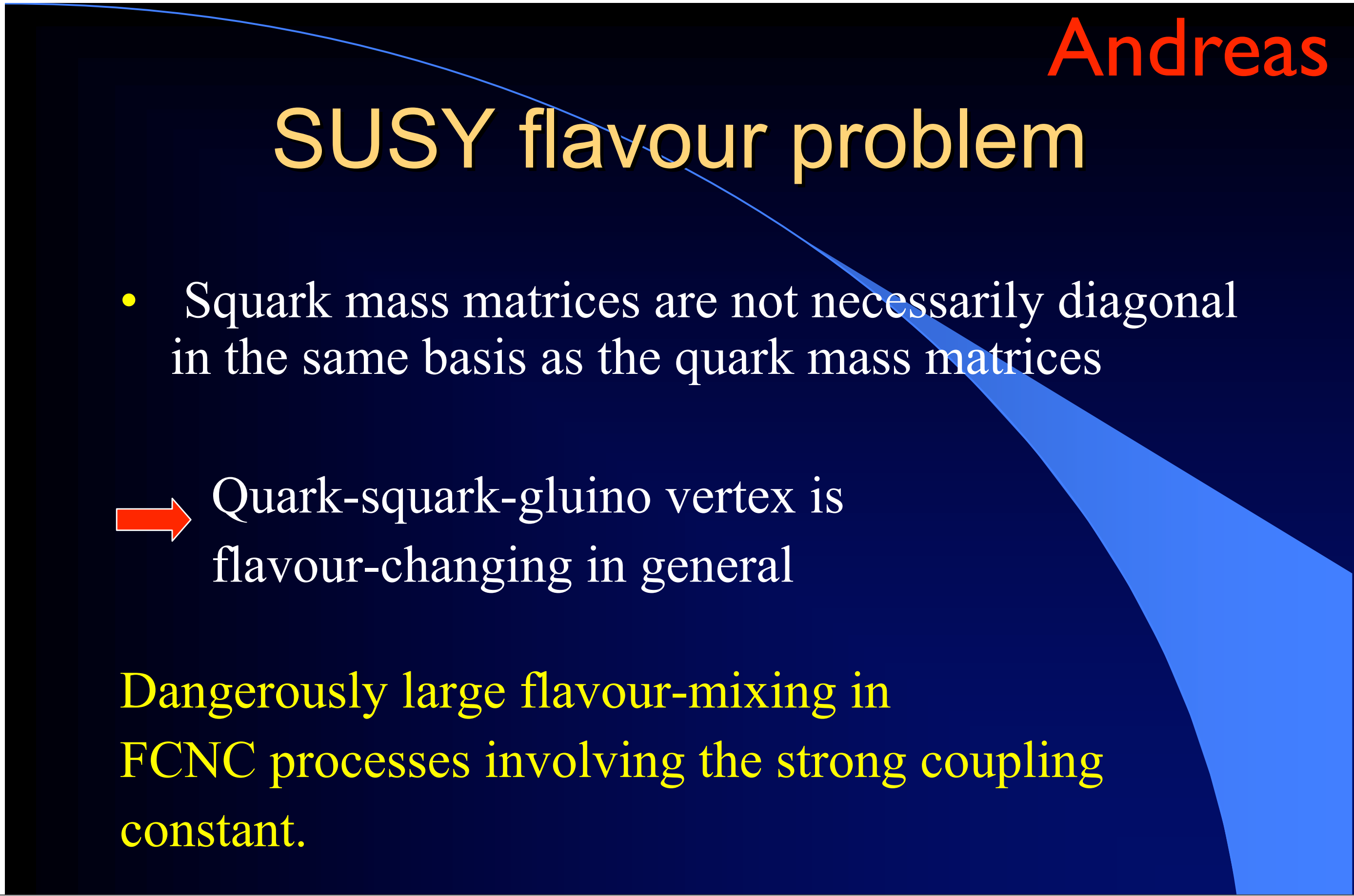
- The Higgs mass is a prediction in a supersymmetric theory $\Rightarrow$ theoretical constraints

m_h Vs. M_{SUSY} [$m_A \sim 1$ TeV, (a,b) $\tan\beta = 15$ $A_t/M_{SUSY} = (\sqrt{6}, 0)$; (c,d) $\tan\beta = 2$]



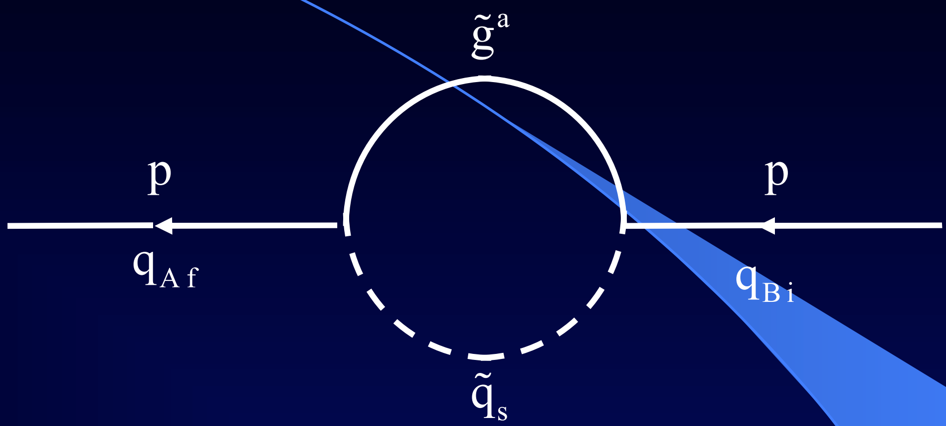
- The key problem in supersymmetric theories is the generation of soft breaking terms: gravity mediation, gauge mediation, gaugino mediation, anomaly mediation
- In general supersymmetry suffers from the so-called supersymmetric flavor problem: if there is a mismatch between quark and squark diagonalization

Andreas Crivellin



Flavour-changing self energy:

$$-i\Sigma(p)^{q\,AB}_{fi} =$$



Mass insertion approximation

$$\Sigma(0)^q_{fi} = g_s^2 \frac{m_{\tilde{g}}}{6\pi^2}\left(\Delta^{\tilde{q}\,LR}_{fi} P_R + \Delta^{\tilde{q}\,RL}_{fi} P_L\right) C_0\left(m_{\tilde{g}}^{\ 2}, M^{\tilde{q}}_{f\,A}, M^{\tilde{q}}_{i\,B}\right)$$

Exact diagonalization

$$\Sigma(0)^q_{fi} = g_s^{\ 2} \frac{m_{\tilde{g}}}{6\pi^2} \sum_{s=1}^{6} \left(\left(V^s_{RL}\right)_{fi} P_R + \left(V^s_{LR}\right)_{fi} P_L\right) B_0\left(m_{\tilde{g}}^{\ 2}, m_{q_s}^{\ 2}\right) \text{ with}$$

dimensonless

$$\left(V^s_{LR}\right)_{fi} \equiv \sum_{j,k=1}^{6} U^{qL*}_{jf} W^{\tilde{q}}_{js} U^{qR}_{ki} W^{\tilde{q}\ *}_{k+3,s}, \quad \left(V^s_{RL}\right)_{fi} \equiv \sum_{j,k=1}^{6} U^{qR*}_{jf} W^{\tilde{q}}_{j+3,s} U^{qL}_{ki} W^{\tilde{q}\ *}_{ks}$$

$\Rightarrow$ $\Sigma(0)\sim M_{SUSY}$ for constant δ

Andreas Crivellin

Results and comparison

quantity	our bound	bound from FCNC	bound from vacuum stability
$\delta^{d\,LR}_{12}$	0.0011	0.006, K mixing	0.00015
$\delta^{d\,LR}_{13}$	0.001	0.15, B_d mixing	0.005
$\delta^{d\,LR}_{23}$	0.01	0.06, $b\rightarrow s\gamma$	0.05
$\delta^{d\,LL}_{13}$	0.032	0.5, B_d mixing	--
$\delta^{u\,LR}_{12}$	0.0047	0.016, D mixing	0.0012
$\delta^{u\,LR}_{13}$	0.027	--	0.22
$\delta^{u\,LR}_{23}$	0.27	--	0.22

Bounds calculated with $m_{squark}=m_{gluino}=1000GeV$

Too many parameters: a simplification is Minimal Flavor Violation

What does MFV imply for SUSY? Simplification !

$\ast$ The superpotential ($N=1$, unbroken R-parity) is MFV !

$W_{MSSM} = Q Y_u H_u U + Q Y_d H_d D + L Y_e H_d E + \mu H_d H_u$

$\ast$ SUSY-breaking with MFV-generational structure:

$\tilde{Q}^\dagger \tilde{m}_Q^2 \tilde{Q} + \tilde{U}^\dagger \tilde{m}_U^2 \tilde{U} + \tilde{D}^\dagger \tilde{m}_D^2 \tilde{D} + (A_u \tilde{Q} H_u \tilde{U}^* + A_d \tilde{Q} H_d \tilde{D}^* + h.c.)$

$$\begin{aligned}
\tilde{m}_Q^2 &= \tilde{m}^2 (a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger) \\
\tilde{m}_U^2 &= \tilde{m}^2 (a_2 \mathbf{1} + b_5 Y_u^\dagger Y_u) \\
\tilde{m}_D^2 &= \tilde{m}^2 (a_3 \mathbf{1} + b_6 Y_d^\dagger Y_d) \\
A_u &= A (a_4 \mathbf{1} + b_7 Y_d Y_d^\dagger) Y_u \\
A_d &= A (a_5 \mathbf{1} + b_8 Y_u Y_u^\dagger) Y_d
\end{aligned}$$

D'Ambrosio et al '02

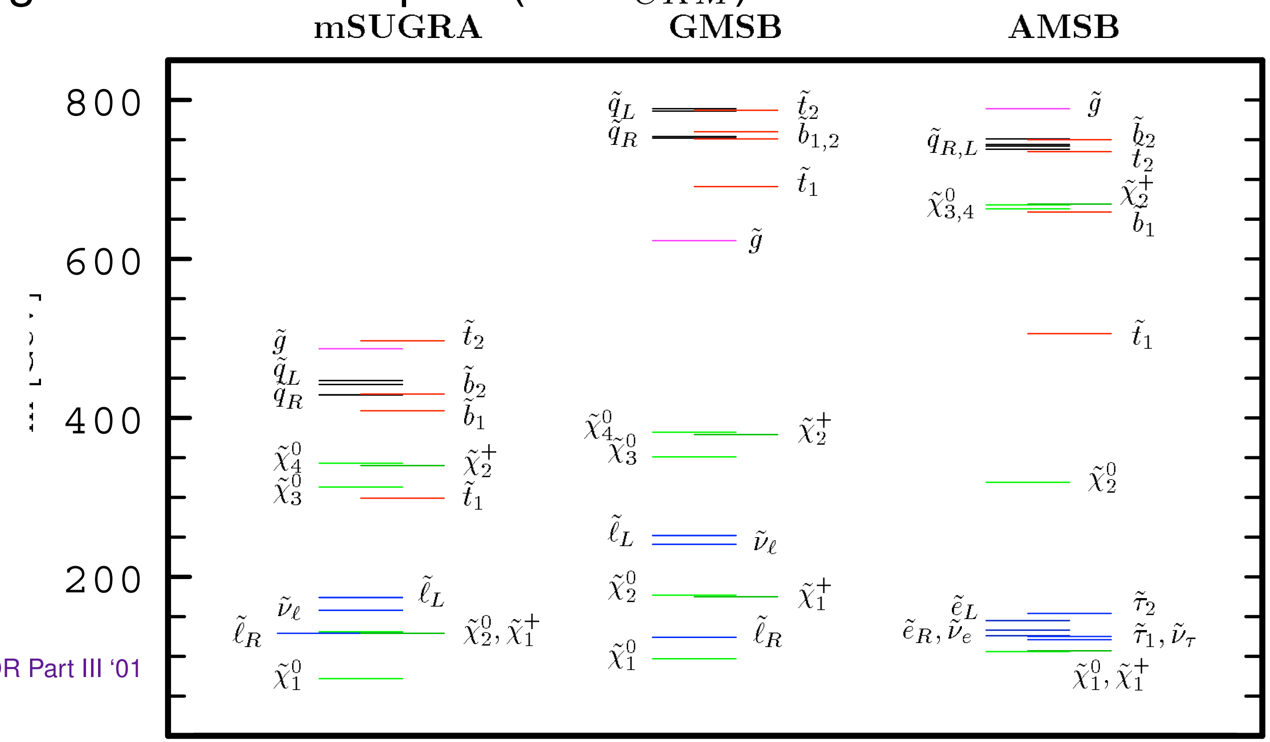
$b_i \equiv 0$: SUSY breaking is flavor blind

MFV Predictions for the MSSM

* Highly degenerate squarks of 1st and 2nd generation:

$\Delta m/m_0 \sim \lambda_c^2/2; \quad \Delta m < 1$ GeV

* 3rd generation decoupled (via V_{CKM}).



TESLA TDR Part III '01

Marco Nardecchia (YSF1)

Another simplification: 1st and 2nd generations heavy

Hierarchical Soft Terms

- In the Hierarchical scenario the LL and RR soft terms have the following structure:

$$\tilde{m}^2 = \begin{pmatrix} h_{11} & h_{12} & a_1 \\ h_{21} & h_{22} & a_2 \\ \bar{a}_1 & \bar{a}_2 & l_3 \end{pmatrix}$$

Where the "h" block is heavy and the remaining entries are much lighter.

The first two families can be naturally heavier with respect to the 3rd one.

Motivations:

- Complementary to degenerate assumption
- If we start with a degenerate condition at very high energy, we end up to a split situation at low energy because of the Yukawa coupling of the 3rd family
- Welcome to alleviate SUSY flavor problem

$$A(\Delta F = 1) = f(x)\hat{\delta}_{ij}$$
$$A(\Delta F = 2) = g^{(1)}(x)\hat{\delta}^2_{ij}$$

$$x = \frac{\tilde{m}_3^2}{M^2}$$

$$\hat{\delta}^{LL}_{ds} \equiv \hat{\delta}^{LL}_{db}\hat{\delta}^{LL}_{bs}$$

Suppression in the 1-2 sector

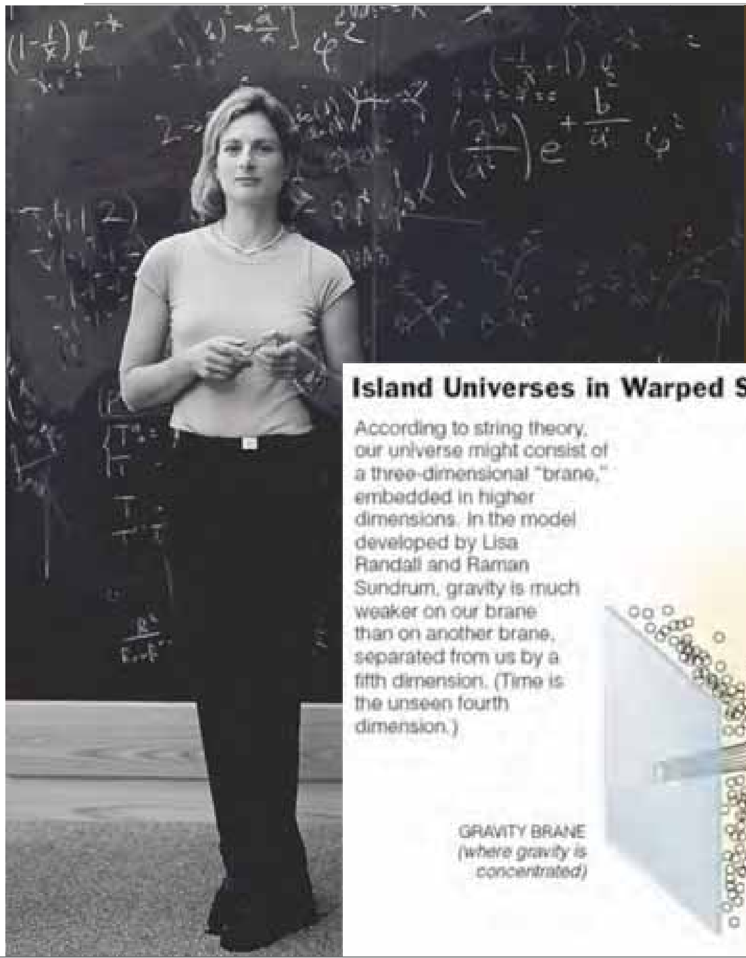
There are only 4 flavor violating insertions: $\hat{\delta}^{LL}_{bd}, \hat{\delta}^{LL}_{bd}, \hat{\delta}^{RR}_{bd}, \hat{\delta}^{RR}_{bd}$

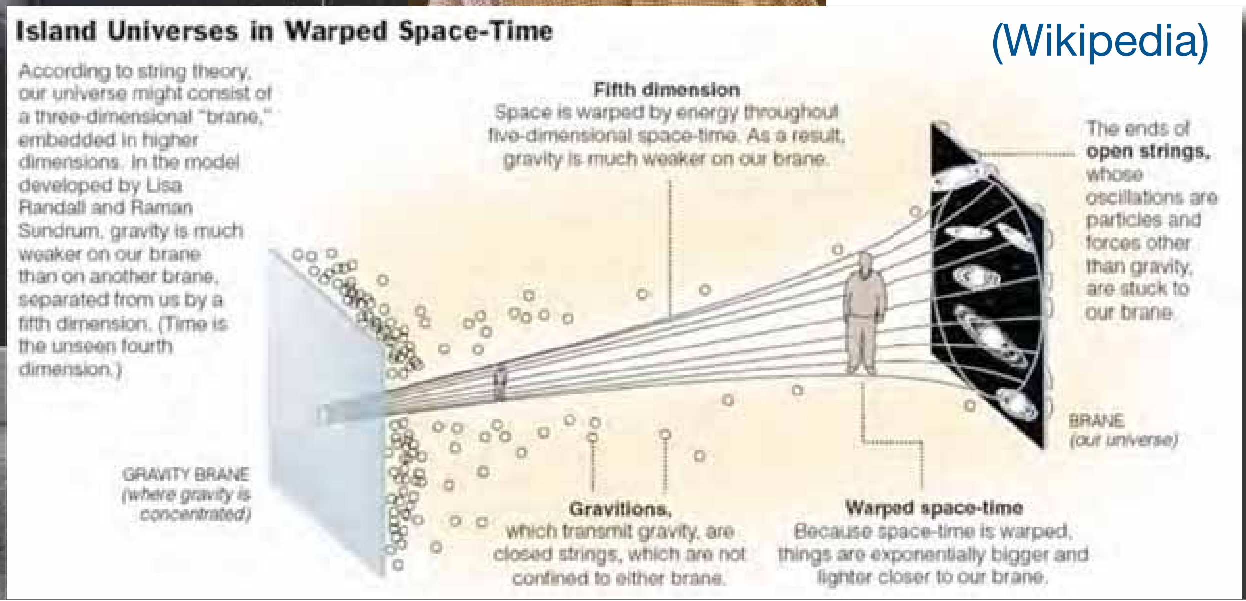
WARPED EXTRA DIMENSIONS

- It is a solution to the hierarchy problem that involves gravity: it was proposed by Randall and Sundrum

The Randall-Sundrum (RS) idea

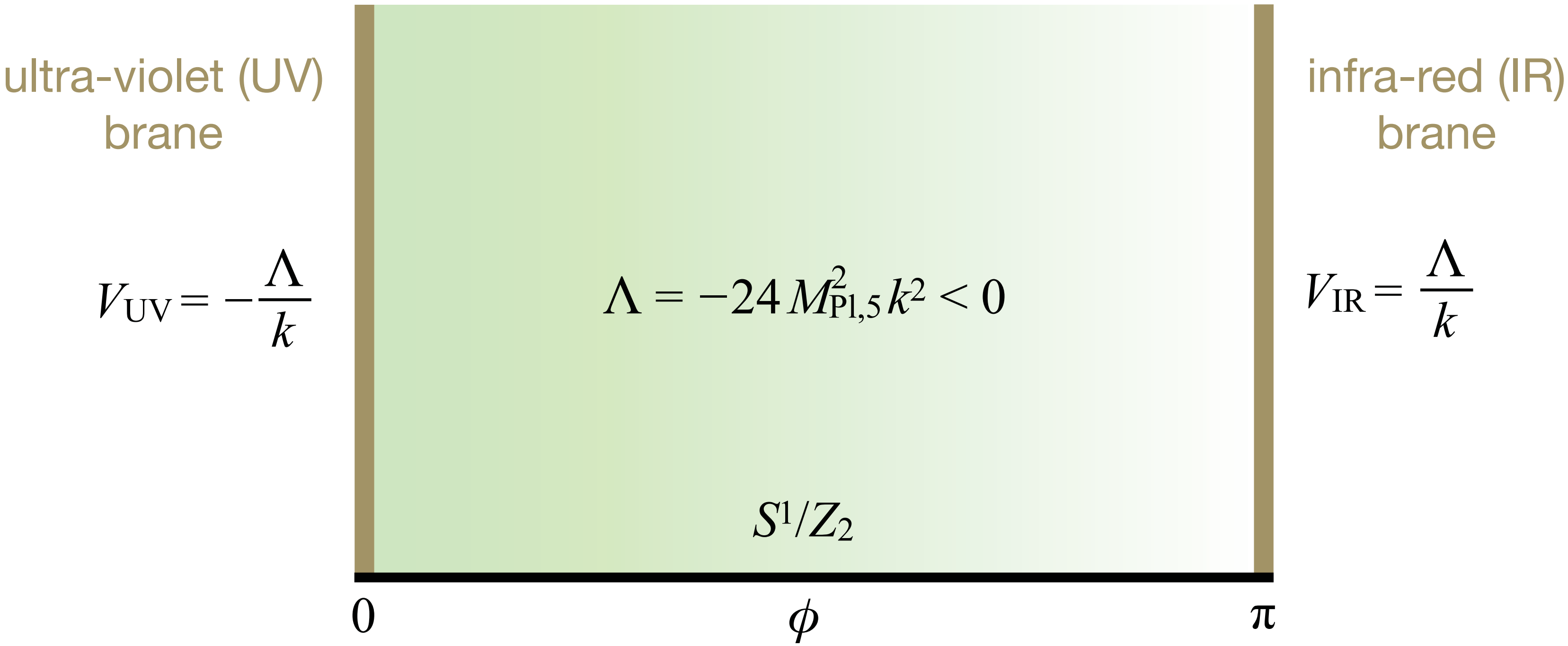
Matthias Neubert





(Wikipedia)

Hierarchies from geometry: RS model*



<u>Slice of AdS₅ with curvature k:</u>

warp factor
(solution to Einstein's equations)

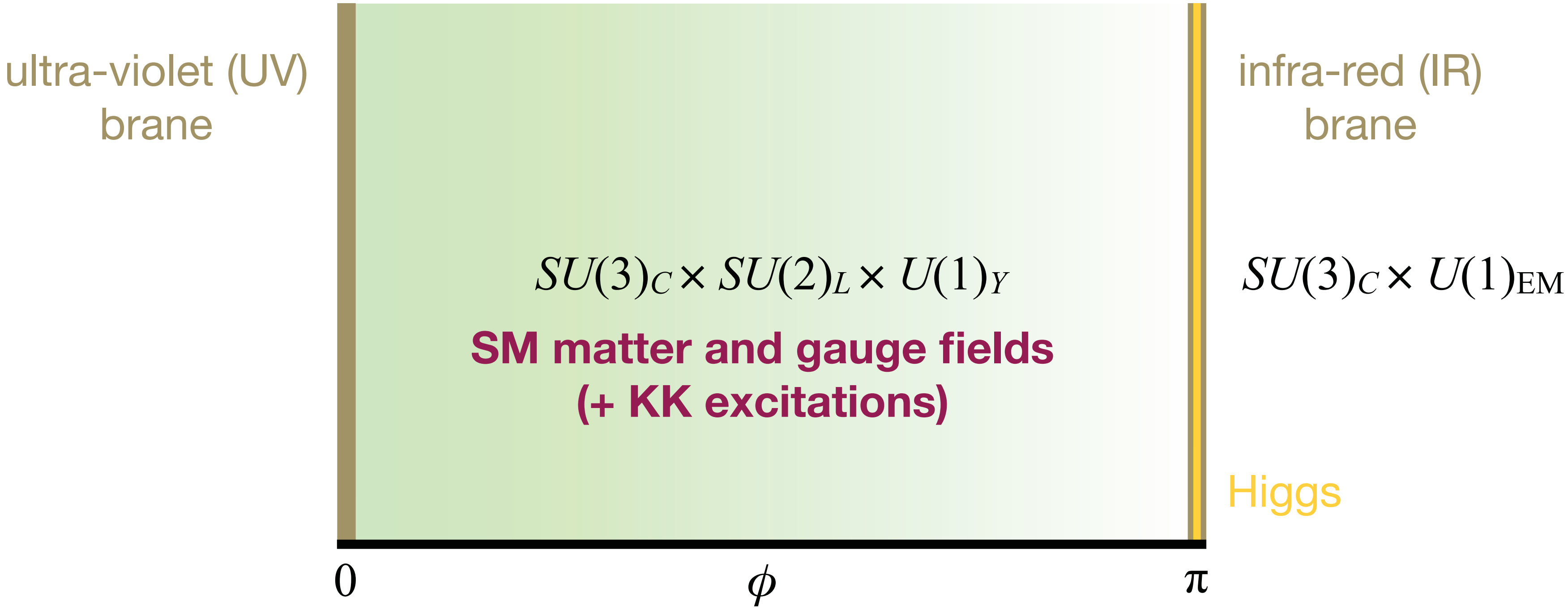
$$ds^2 = e^{-2\sigma}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2\,, \qquad \sigma = kr|\phi|$$

$$\epsilon = \frac{M_W}{M_{\rm Pl}} = e^{-kr\pi} \approx 10^{-16}\,, \qquad L = -\ln\epsilon \approx 37\,, \qquad M_{\rm KK} = k\epsilon = \text{few TeV}$$

*Randall and Sundrum, hep-ph/9905221, hep-th/9906064

Matthias Neubert

Hierarchies from geometry: RS model



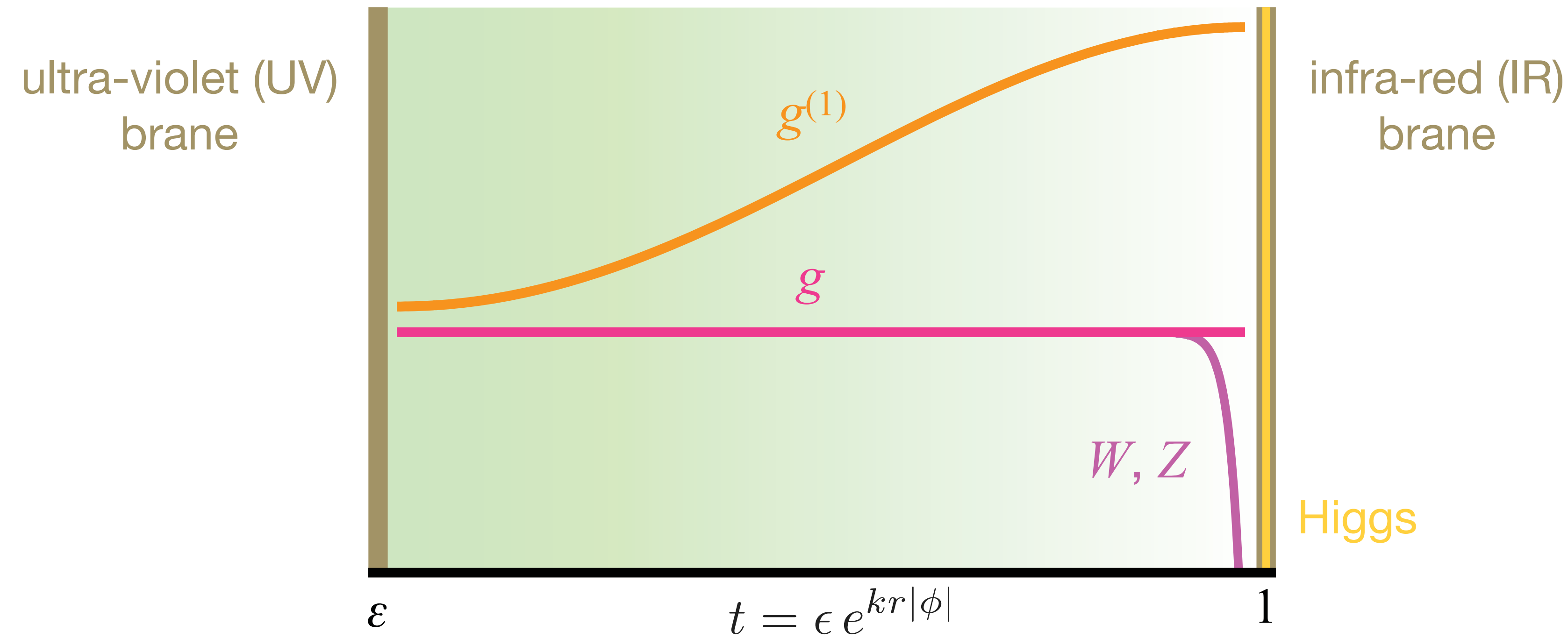
Pattern of gauge-symmetry breaking:

- bulk gauge group $SU(2)_L \times U(1)_Y$ broken by IR brane-localized Higgs to $U(1)_{EM}$
- more complicated patterns (with custodial symmetry) also considered in literature*

*Agashe, Delgado, May, Sundrum, hep-ph/0308036; Agashe, Contino, Da Rold, Pomarol, hep-ph/0605341

Matthias Neubert

RS model: Gauge boson profiles*



<u>Profiles of gauge fields:</u>

- while profiles of photon and gluon are flat, wave functions of heavy gauge bosons and KK modes are peaked near IR brane

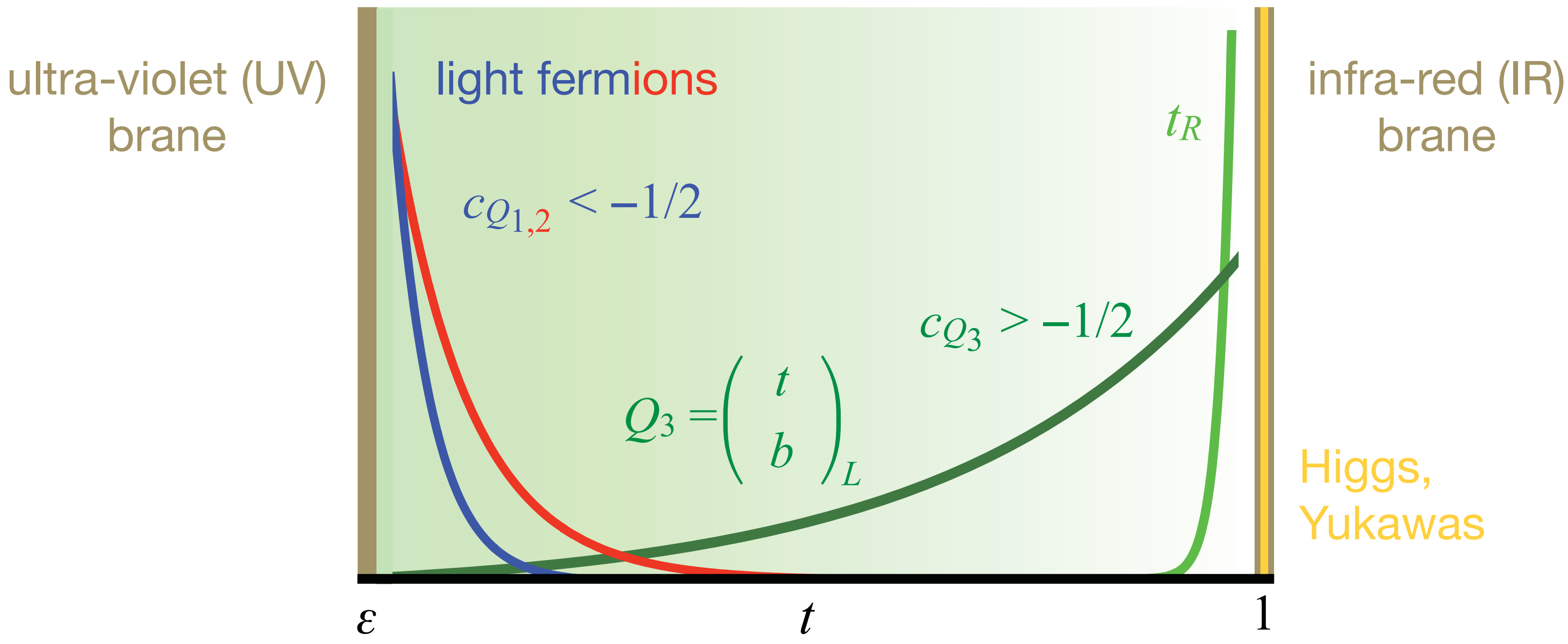
$$\chi_{g,\gamma}(\phi) = \frac{1}{\sqrt{2\pi}}\,, \qquad \chi_{W,Z}(\phi) \approx \frac{1}{\sqrt{2\pi}}\left[1 + \frac{m_{W,Z}^2}{M_{\mathrm{KK}}^2}\left(1 - \frac{1}{L} + t^2\left(1 - 2L - 2\ln t\right)\right)\right]$$

*Davoudiasl *et al.*, hep-ph/9911262; Pomarol, hep-ph/9911294; Chang *et al.*, hep-ph/9912498

RS setup allows a "theory of flavor"

RS model: Fermion profiles*

Matthias Neubert



<u>Profiles of fermion fields:</u>

- localization of fermion profiles in extra dimension controlled by bulk mass parameters $c_{Q,q} = \pm M_{Q,q}/k$
- top quark lives in IR to generate its large mass, while light fermions live in UV

Quark masses and mixings in RS model*

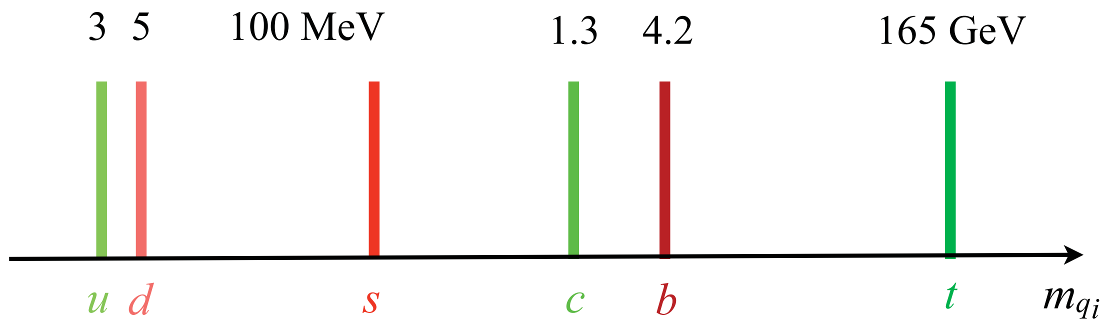
Scaling laws:

$$m_{q_i} = \mathcal{O}(1)\,\frac{v}{\sqrt{2}}\,F_{c_{Q_i}}F_{c_{q_i}}$$

$$\lambda = \mathcal{O}(1)\,\frac{F_{c_{Q_1}}}{F_{c_{Q_2}}}$$

$$A = \mathcal{O}(1)\,\frac{F^3_{c_{Q_2}}}{F^2_{c_{Q_1}}F_{c_{Q_3}}}$$

$$\bar\rho - i\bar\eta = \mathcal{O}(1)$$



$$\boxed{\begin{array}{lll} c_{Q_1} = -0.579\,, & c_{Q_2} = -0.517\,, & c_{Q_3} = -0.473 \\ c_{u_1} = -0.742\,, & c_{u_2} = -0.558\,, & c_{u_3} = +0.339 \\ c_{d_1} = -0.711\,, & c_{d_2} = -0.666\,, & c_{d_3} = -0.553 \end{array}}$$

(+ anarchic Yukawa matrices)

- Hierarchy in quark masses and mixings can be naturally generated from anarchic complex 3×3 matrices $Y_q = \mathcal{O}(1)$ entering $Y_q^{\text{eff}} = F_{c_{Q_i}}\,(Y_q)_{ij}\,F_{c_{q_j}}$

Matthias Neubert

Warped-space Froggatt-Nielsen mechanism*

Bulk fermions in RS:

$$(Y_q^{\text{eff,RS}})_{ij} \propto (Y_q)_{ij}\, e^{-kr\pi(c_{Q_i}-c_{q_j})}$$

- bulk parameter c_{Q_i,q_i}
- warp factor $\epsilon = e^{-kr\pi}$

Froggatt-Nielsen (FN) symmetry:

$$(Y_q^{\text{eff,FN}})_{ij} \propto (Y_q)_{ij}\, \epsilon^{a_{Q_i}-b_{q_j}}$$

- $U(1)_F$ charges $Q_F = a_{Q_i},\, b_{q_j}$
- model parameter $\epsilon \ll 1$ set by VEVs

- Models with warped spatial extra dimension provide compelling geometrical interpretation of flavor symmetry

RS is a **theory** of flavor!

(to a good extent)

*Froggatt and Nielsen, Nucl. Phys, B147 (1979) 277; Casagrande *et al.*, arXiv:0807.4537; Blanke *et al.*, arXiv:0809.1073

Mixing matrices: Scaling relations

Matthias Neubert

- In all cases one finds:

$$
(\Delta_Q^{(\prime)})_{ij} \sim F_{c_{Q_i}} F_{c_{Q_j}} \,, \qquad (\delta_Q)_{ij} \sim \frac{m_{q_i} m_{q_j}}{M_{\mathrm{KK}}^2} \frac{1}{F_{c_{q_i}} F_{c_{q_j}}} \sim \frac{v^2 Y_q^2}{M_{\mathrm{KK}}^2} F_{c_{q_i}} F_{c_{q_j}} \,,
$$

$$
(\Delta_q^{(\prime)})_{ij} \sim F_{c_{q_i}} F_{c_{q_j}} \,, \qquad (\delta_q)_{ij} \sim \frac{m_{q_i} m_{q_j}}{M_{\mathrm{KK}}^2} \frac{1}{F_{c_{Q_i}} F_{c_{Q_j}}} \sim \frac{v^2 Y_q^2}{M_{\mathrm{KK}}^2} F_{c_{Q_i}} F_{c_{Q_j}}
$$

Implications of scaling relations:

- all effects are proportional to $F_{c_{A_i}} F_{c_{A_j}}$, so that all flavor-violating vertices involving light, UV-localized fermions are suppressed
- this suppression of dangerous FCNCs involving light quarks reflects the RS-GIM mechanism

- Flavor-changing tree-level transitions of K and B_s mesons particularly interesting as their sensitivity to KK scale extends beyond LHC reach

DARK MATTER

$$\Omega_{DM} h^2 = 0.105(8)$$

The most popular candidate is a neutral stable weakly interacting massive particle (WIMP)

The WIMP S annihilates and its particle density obeys the Boltzmann equation

$$\frac{dn_S}{dt} = -3Hn_S - \langle \sigma_{\rm ann} v \rangle \left(n_S^2 - n_{S,eq}^2 \right)$$

$$n_{S,eq} = T^3 \left(\frac{M_S}{2\pi T} \right)^{3/2} e^{-M_S/T}$$

Equilibrium distribution

$$f = n/T^3 \qquad \frac{df_S}{dT} = \frac{\langle \sigma_{\rm ann} v \rangle}{H/T^2} (f_S^2 - f_{S,eq}^2)$$

An approximate solution

$$\frac{M_S}{\hat{T}} = \log\left(\frac{M_S \langle \sigma_{\rm ann} v \rangle}{H/\hat{T}^2}\right) + \frac{1}{2}\log\left(\frac{8\pi^3 \hat{T}}{M_S}\right)$$

Freeze out temp.

$$f(T \ll M_S) \approx \frac{H/\hat{T}^2}{\hat{T}\langle \sigma_{\rm ann} v \rangle}$$

Final particle density

Total energy density of WIMPS at present $T = T_\gamma$

$$\Omega_{DM} = \frac{2}{g_*}\frac{M_S n_S(T_\gamma)}{\rho_{\rm crit}} = \frac{2}{g_*}\frac{H/T^2}{\hat{T}\langle \sigma_{\rm ann} v \rangle}\frac{M_S T_\gamma^3}{\rho_{crit}}$$

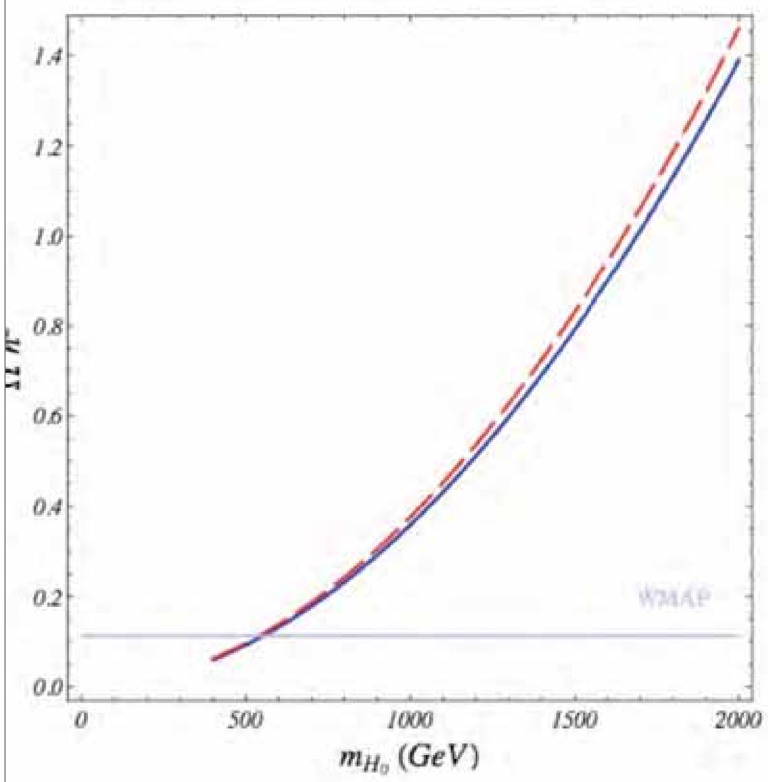
- Direct searches: elastic scattering of DM off nuclei in a low background detector (recoil energy of nucleus)
- Indirect searches: signals due to DM annihilation in Sun, Earth, where it has been captured and accumulated and in the Galactic Halo

It is relatively easy to have candidates for DM satisfying the energy density constraint

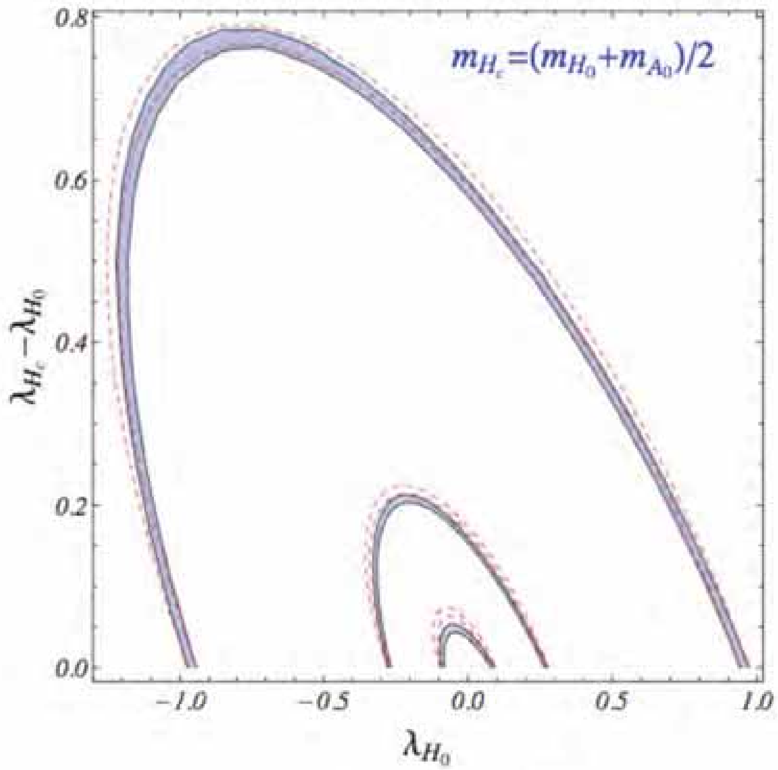
Some possibilities studied by Fu-Sin Ling

- Singlet coupled to the Higgs (simplest)
- Inert doublet (Higgs with no VEV)

Pure gauge limit



With quartic couplings



m_{H_0} = 600, 1000, 3000 GeV

- Constraints on solar system DM has been pointed out in the talks of Stephen Adler and Annika Peter

DARK MATTER CAN BE GRAVITATIONALLY BOUND ON DIFFERENT SCALES

Stephen Adler

- GALACTIC HALO DARK MATTER

MASS DENSITY $\rho \sim 0.3\ \mathrm{GeV}/c^2\ \mathrm{cm}^{-3}$

MAXWELLIAN VELOCITY DISTRIBUTION

$$f \propto v^2 e^{-3v^2/2\bar{v}^2} \qquad \bar{v} \sim 270\ \mathrm{km/s}$$

$$v = W_{\mathrm{DARK\ MATTER}} + v_{\oplus}$$

EARTH MOTION VELOCITY

DRUKIER, FREESE + SPERGEL; FREESE, FRIEMAN + GOULD } ANNUAL MODULATION EFFECT; DAMA/LIBRA SIGNAL

Stephen Adler

- SOLAR SYSTEM-BOUND DARK MATTER?

FROM STUDY OF PLANETARY ORBITS -

FRÊRE, LING + VERTONGEN

SERENO + JETZER

IORIO

KHRIPLOVICH + PITJEVA

$\rho < 10^5\ GeV/c^2\ cm^{-3}$

COULD PRODUCE A DAILY (SIDEREAL TIME) MODULATION IN DAMA/LIBRA → 24 HOUR PERIOD

EARTH (PLANET-BOUND) DARK MATTER?

IF BOUND WERE ATTAINED, AND IF MASS WERE UNIFORMLY DISTRIBUTED BELOW THE MOON'S ORBIT, DENSITY WOULD BE

$$\rho \sim 6 \times 10^{10}\ GeV/c^2\ cm^{-3} \gg \rho_{HALO},\ \rho_{SUN\text{-}BOUND\ LIMIT}$$

Stephen Adler

CONSTRAINTS ⇒

- DARK MATTER LOCALIZED WELL WITHIN MOON ORBIT AND NOT TOO NEAR EARTH
- DARK MATTER MASS << GeV
- σ_{DM-N} HIGH: 10^{-33} cm^2 TO 10^{-27} cm^2
- DARK MATTER <u>NON</u>-SELF-ANNIHILATING AND STABLE IN ABSENCE OF NUCLEONS

POSSIBLE APPLICATIONS OF EARTH AND PLANET-BOUND DARK MATTER (SPECULATIVE!)

Stephen Adler

- JOVIAN PLANET ANOMALIES

[ADLER PHYS. LETT. B 671 (2009) 203
ARXIV: 0808.2823]

SURFACE HEAT FLUX H $\frac{erg}{cm^2 s}$	PLANET
5440	JUPITER
2010	SATURN
<42	URANUS
433	NEPTUNE

(de Pater + Lissauer)

(?) ACCRETION OF PLANET-BOUND DARK MATTER COULD ACCOUNT FOR UNEXPLAINED INTERNAL HEAT PRODUCTION (REQUIRES LOW ENERGY RELEASE EFFICIENCY)

(?) URANUS AXIS ON ITS SIDE RELATIVE TO ECLIPTIC - COLLISION CAUSING THIS COULD HAVE KNOCKED URANUS OUT OF ITS DARK MATTER CLOUD

Stephen Adler

• FLYBY ANOMALY

INCOMING ASYMPTOTE V_{IN}

NEAR-EARTH TRAJECTORY CAN'T BE TRACKED

OUTGOING ASYMPTOTE V_{OUT}

ANDERSON ET AL
PRL 100 (2008) 091102

$\Downarrow$

V_{OUT} EXTRAPOLATED FROM V_{IN} DOES NOT AGREE WITH OBSERVATION

	GALILEO II	NEAR
DATE	12/8/92	1/23/98
ΔV_∞ $\frac{mm}{s}$	-4.6	13.46
σV_∞ $\frac{mm}{s}$	1.0	0.01

EFFECT IS $\sim 10^{-6} V_\infty$
EITHER SIGN

The

Dynamics of dark matter bound to the solar system

(and why it matters for indirect detection)

has been studied by Annika Peter who focussed on standard WIMPs

Indirect Detection of Dark Matter in the Solar System

- ν's in the Sun
- ν's from the Earth
- γ's outside the Sun (if time)

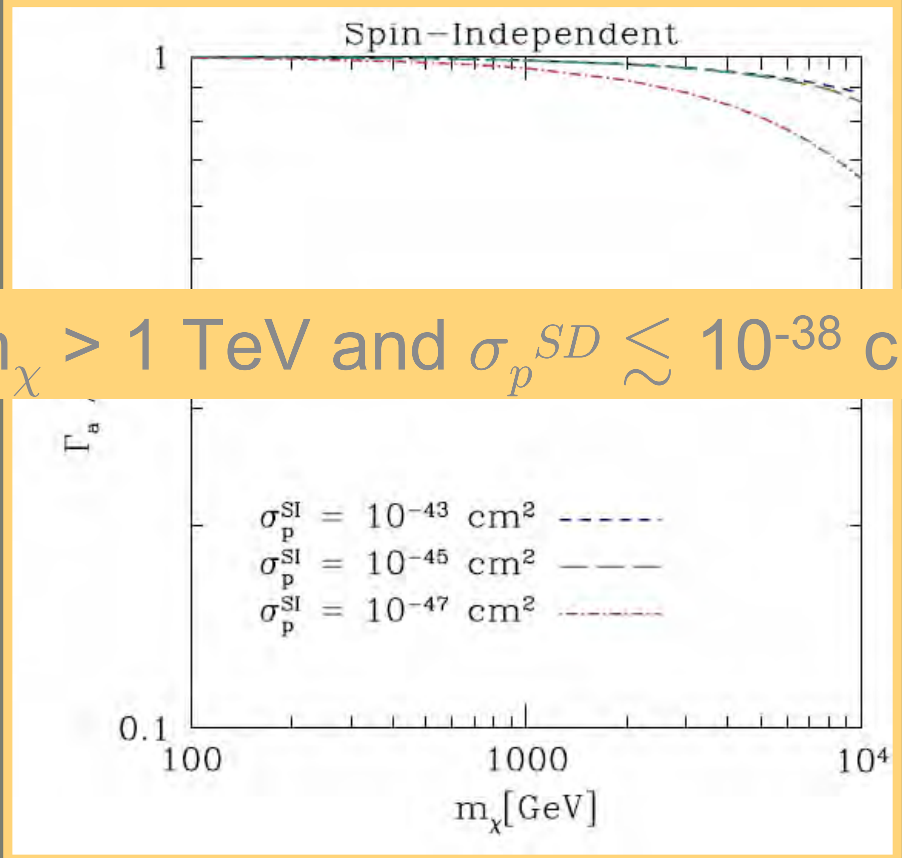
all of these probes depend on what happens to the dark matter after it becomes bound to the solar system!

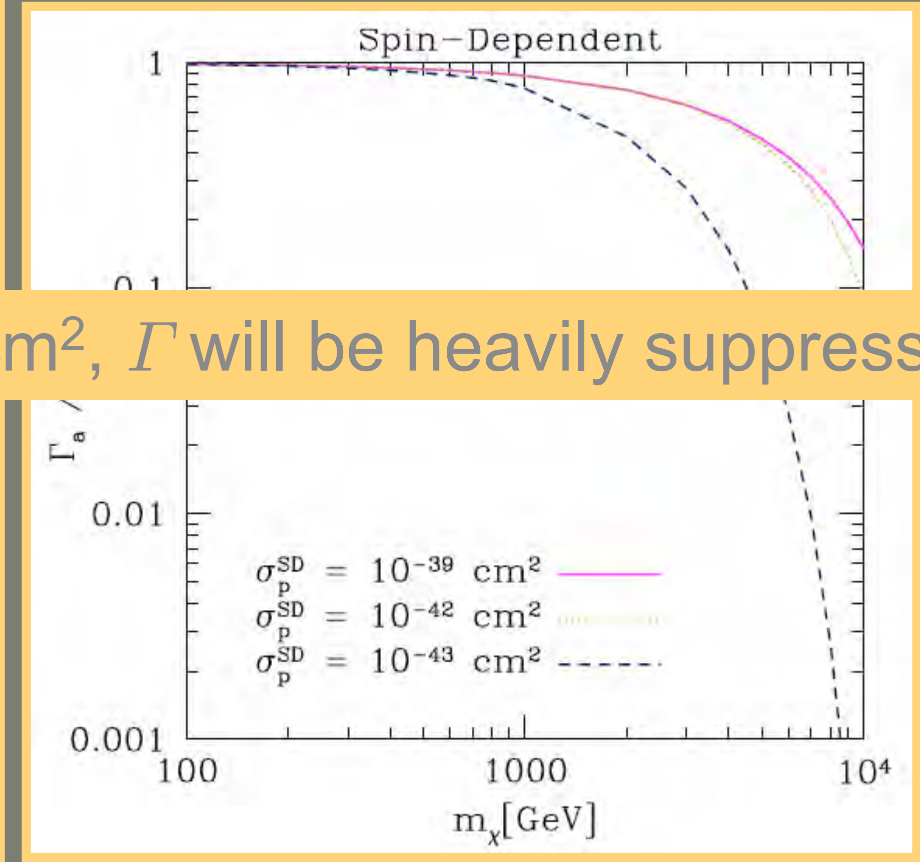
Suppression of the Annihilation Rate

(Standard Halo Model)

Annika Peter

Neutrinos from WIMPs in the Sun





If m_χ > 1 TeV and $\sigma_p{}^{SD} \lesssim 10^{-38}$ cm², Γ will be heavily suppressed

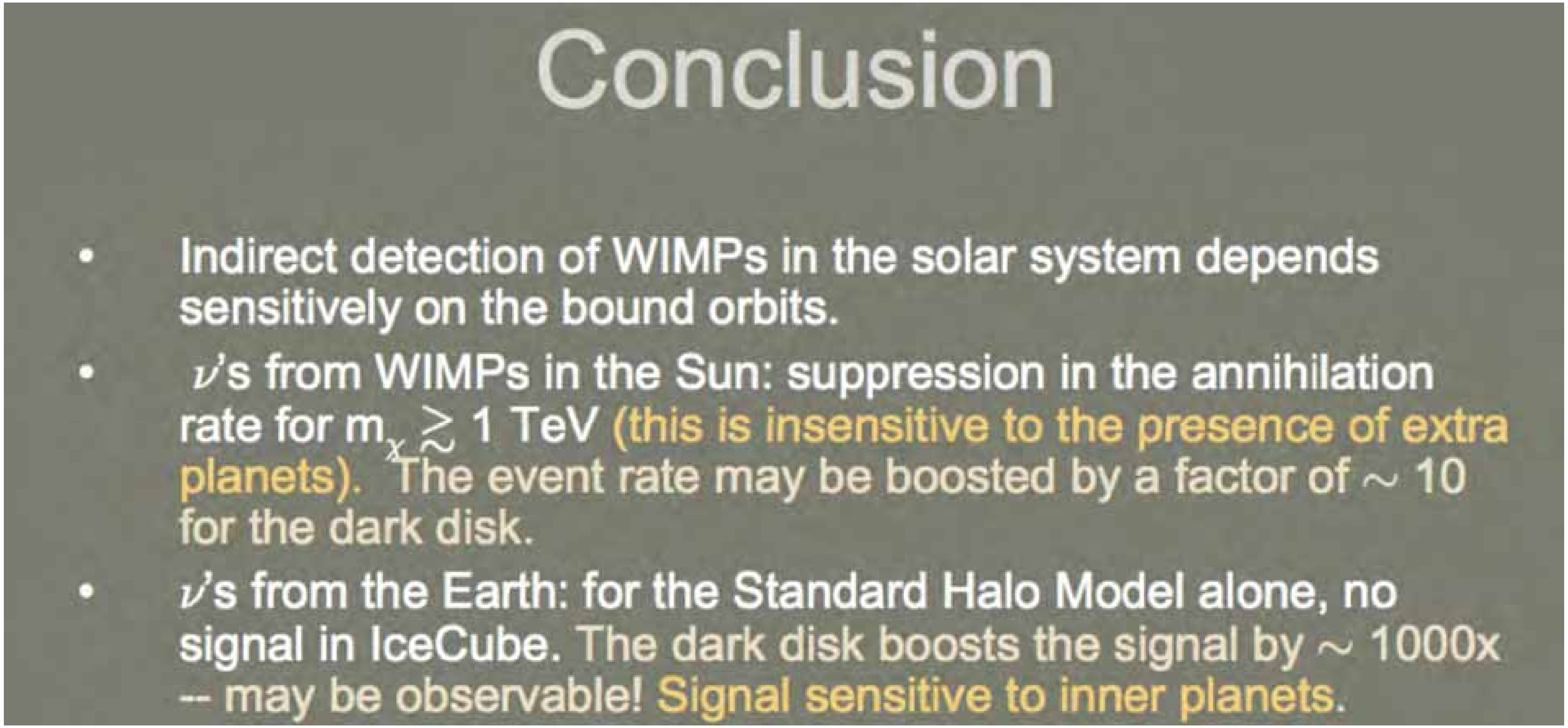
One Huge Astrophysical Systematic: The Dark Disk

Annika Peter

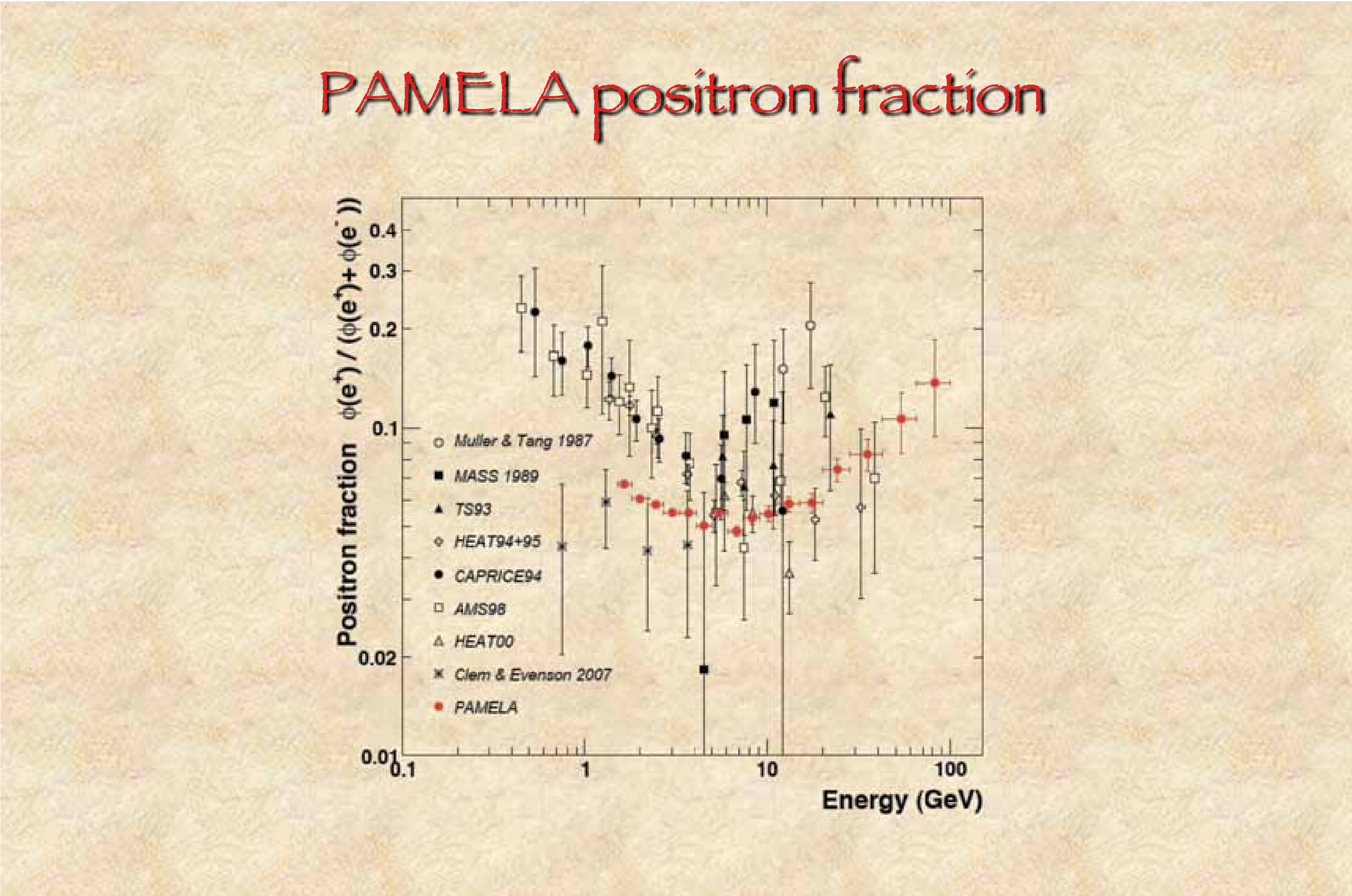
- Standard Halo Model (approximate multivariate Gaussian, $\sigma \approx v_{\odot}/2^{1/2}$) based on N-body simulations of dark matter-only galaxies.
- Simulations that include baryons show that the stellar disk drags satellites into the disk plane, where they dissolve.
- This yields a DARK DISK with properties similar to the stellar disk generated by these satellites.
- The dark disk properties are extremely sensitive to the merger history of the Galaxy.
- Typically, speeds wrt to the solar system are MUCH smaller--much easier to capture.

(Read et al. 2008, 2009)

Annika Peter

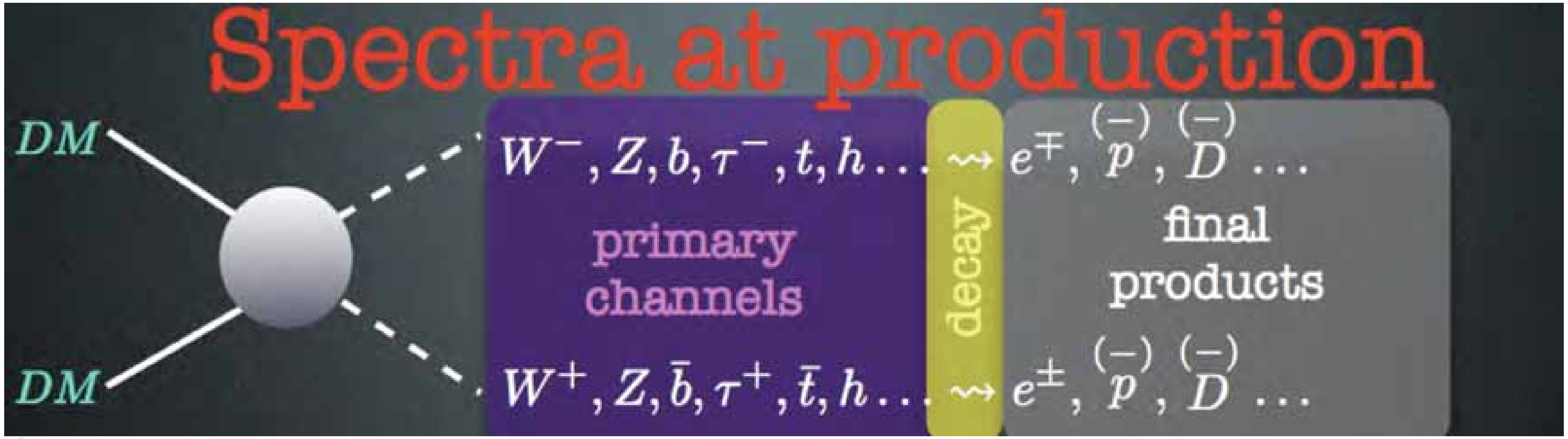


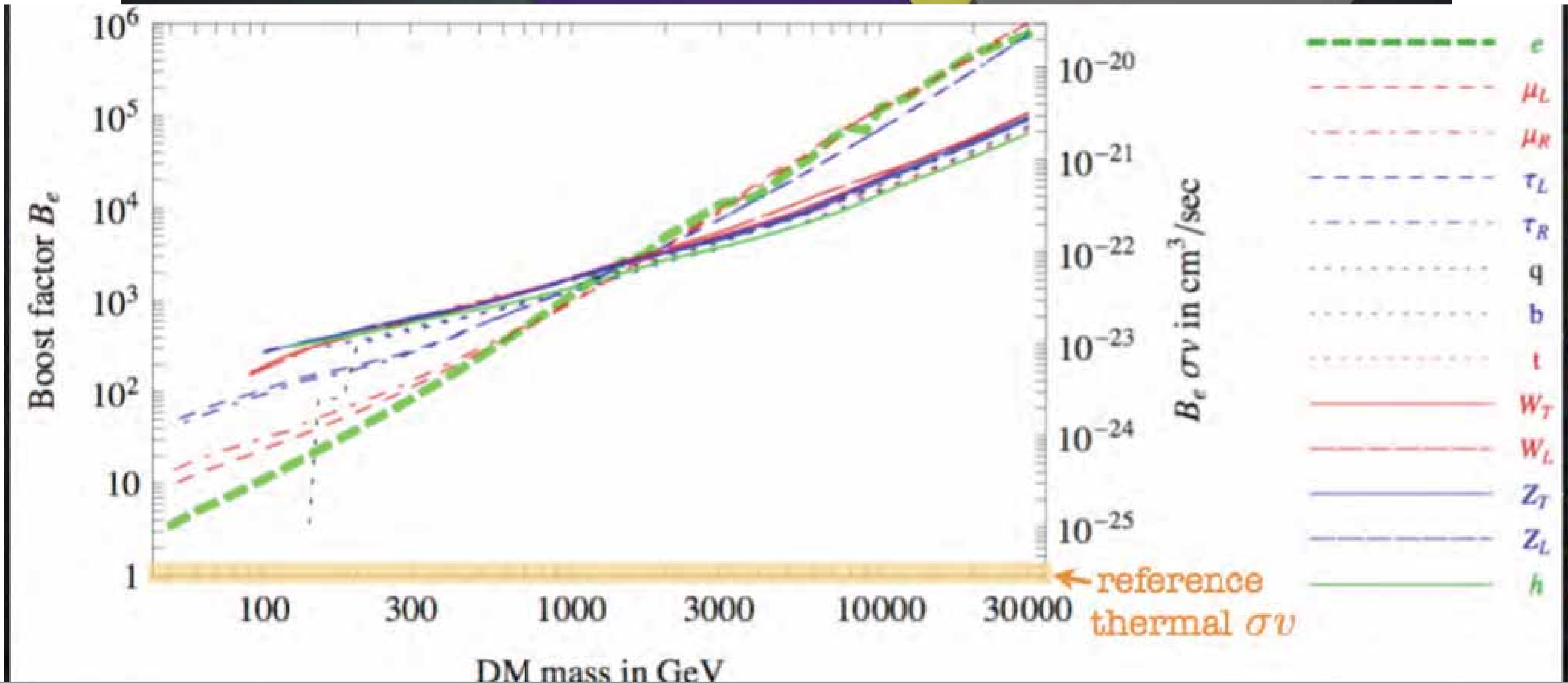
Question: is the PAMELA positron excess from DM ?



This question was dealt with in a DM independent way

Marco Cirelli

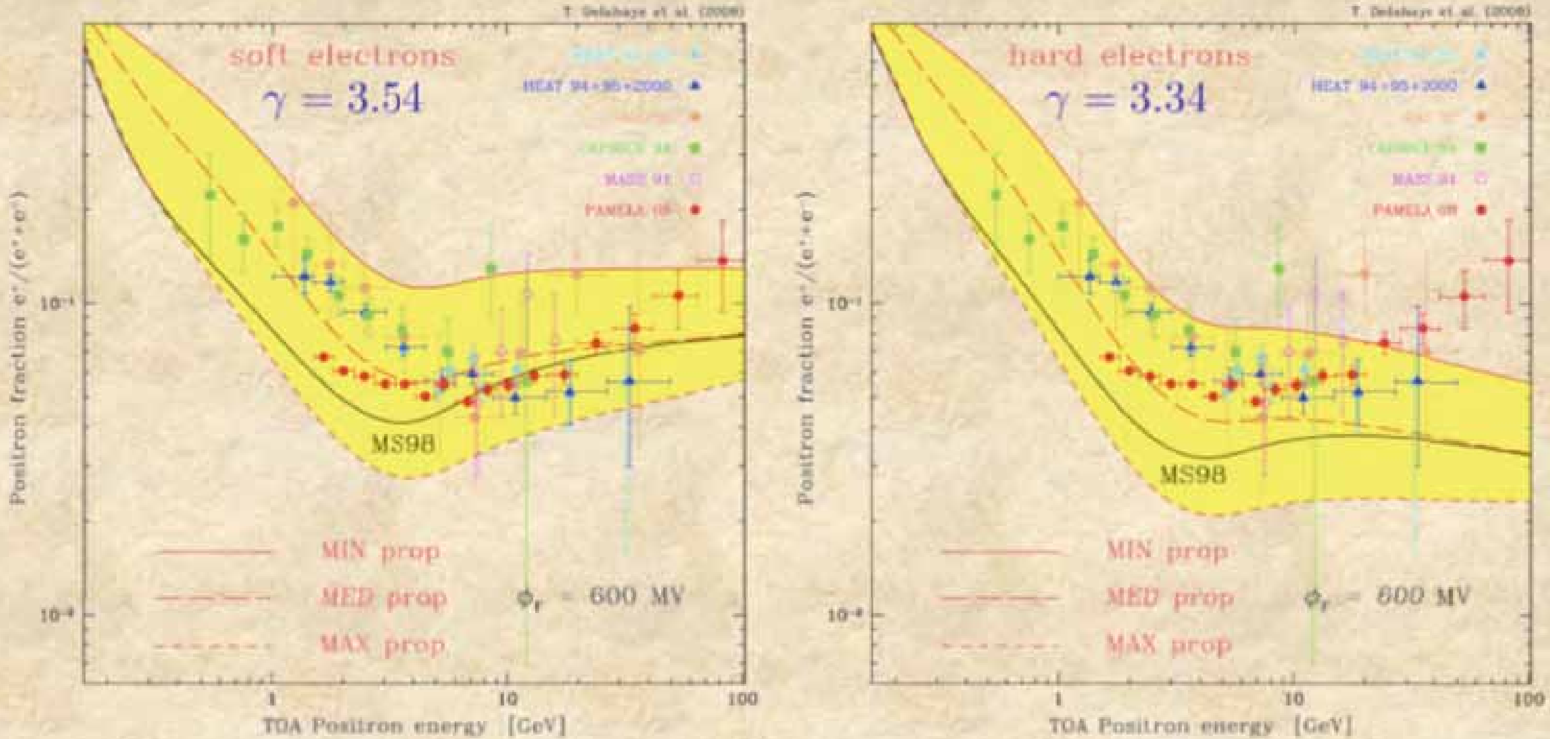




Positron fraction: CR background

Timur Delahaye

The background is an important issue



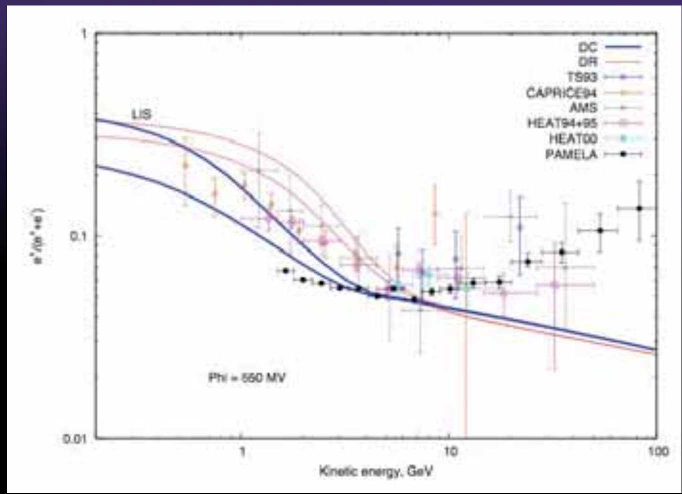
Are we seeing Dark Matter in cosmic rays?

I don't know, I fear it's unlikely

Marco Cirelli

Another possibility for explaining the PAMELA/ATIC positron excess is an astrophysical origin: Tsvi Piran

SNR are the canonical sources of CRs



A new source of electrons & positrons that becomes dominant at ~10 GeV

Consider a Local Source of CR electrons

Tsvi Piran

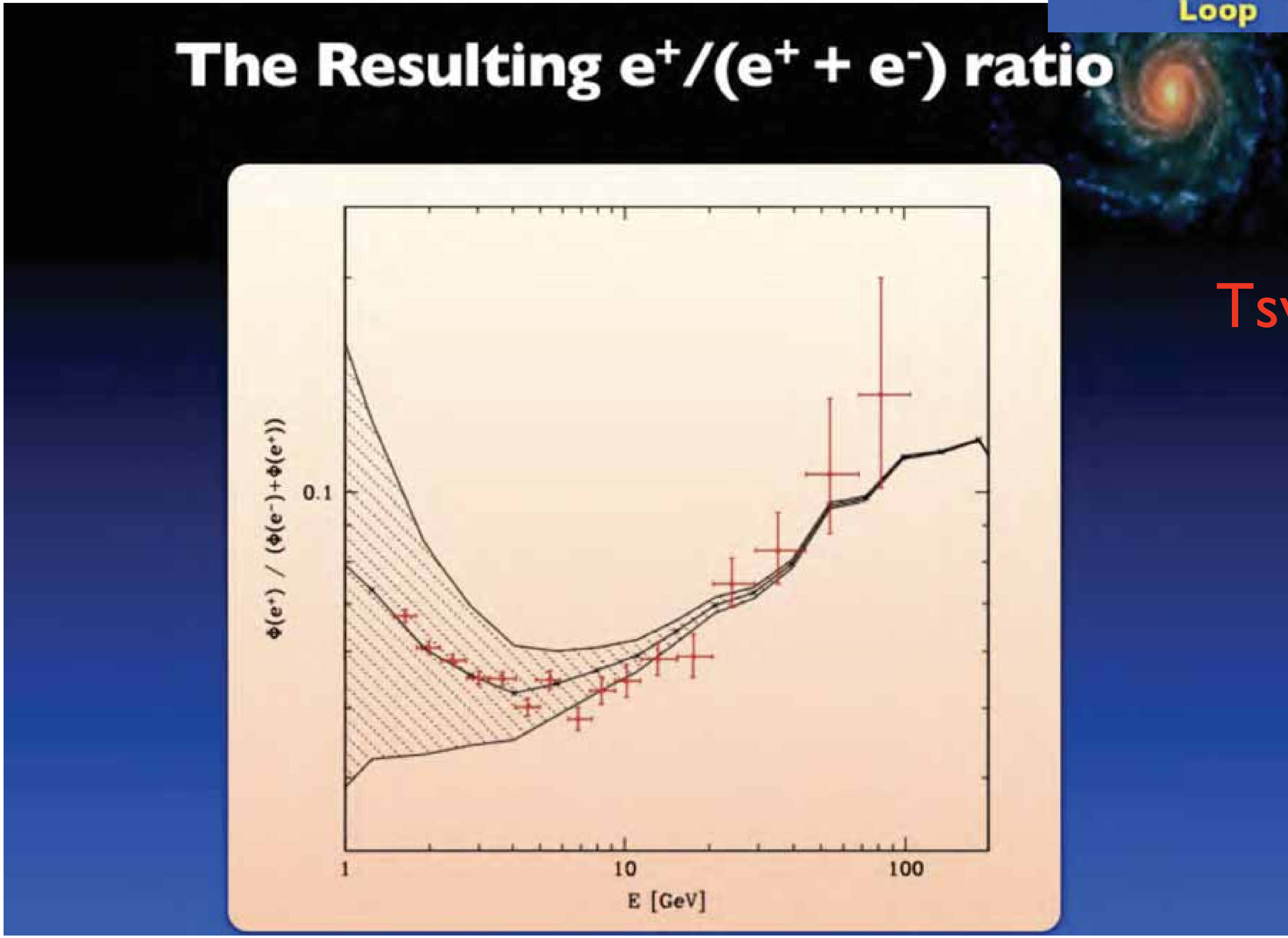
- Above $E_b \sim 20$ GeV, the electrons will start cooling and disappear.
- Positrons however, form continousely along the way from proton-ISM interactions.
- **Therefore the positron/electron ratio will increase**

- Primary electron cool and disappear before reaching earth
- Secondary electron/positron form nearer and can reach earth before cooling

The source can be SNR in spiral arm

In the Milky Way: Almost all SNe are non-Type Ia, and occur where almost all star formation takes place: In the Spiral Arms

Contribution from nearby KNOWN young SNRs: Geminga, Monogem, Gela LoopI and Cygnus Loop



Tsvi Piran

A very general comparison with recent DM experiments

Kathryn Zurek

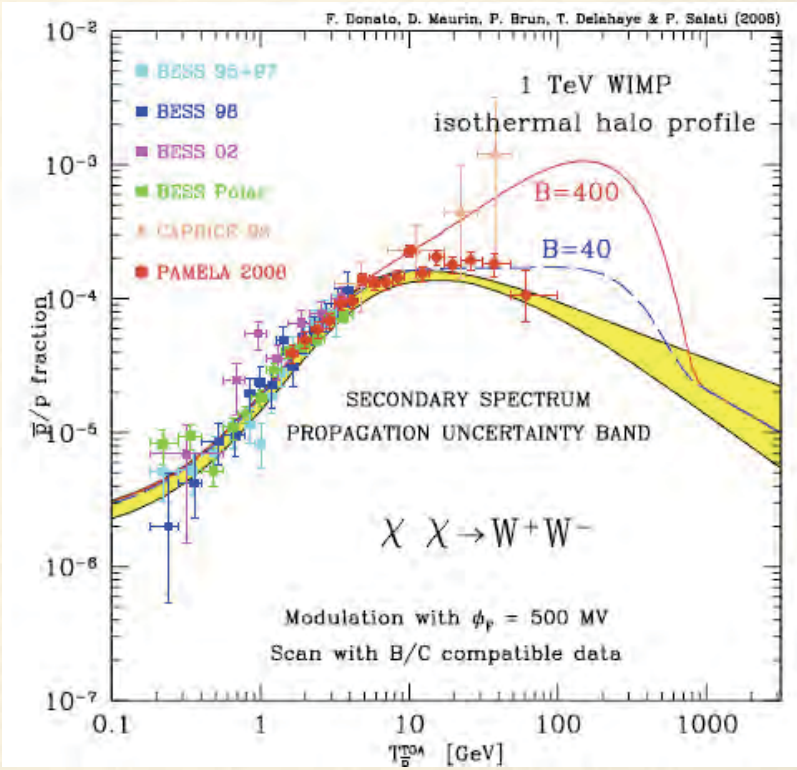
- PAMELA and ATIC electron/positron excesses
  - This morning's talks
- 511 keV line
  - No time
- DAMA
  - Focus of this talk
- None suggest ordinary SUSY WIMP DM
- Suggest that DM dynamics may be more complex

Non-standard requirements of PAMELA/ATIC

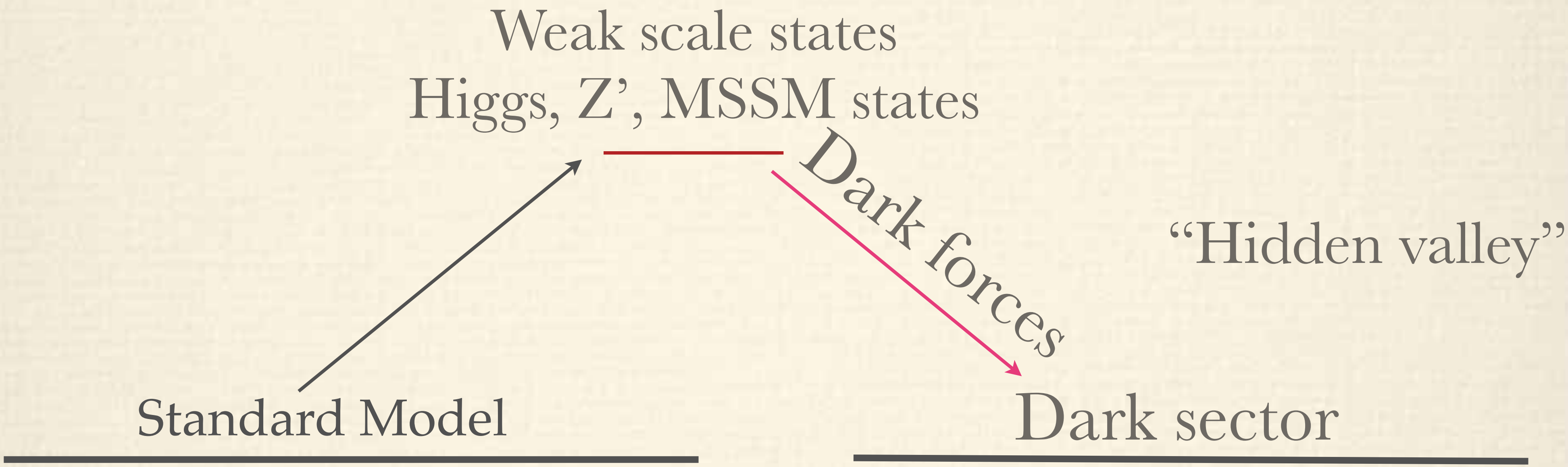
- Not an ordinary WIMP
- Non-standard annihilation modes $\rightarrow W^+W^-, \bar{b}b, \tau^+\tau^-$
- Non-standard annihilation cross-section

$$B\langle\sigma_{ann}v\rangle \simeq 10^{-23}\ \mathrm{cm}^3/\mathrm{s}$$

- Anti-protons--would expect an excess



Complex dark sectors



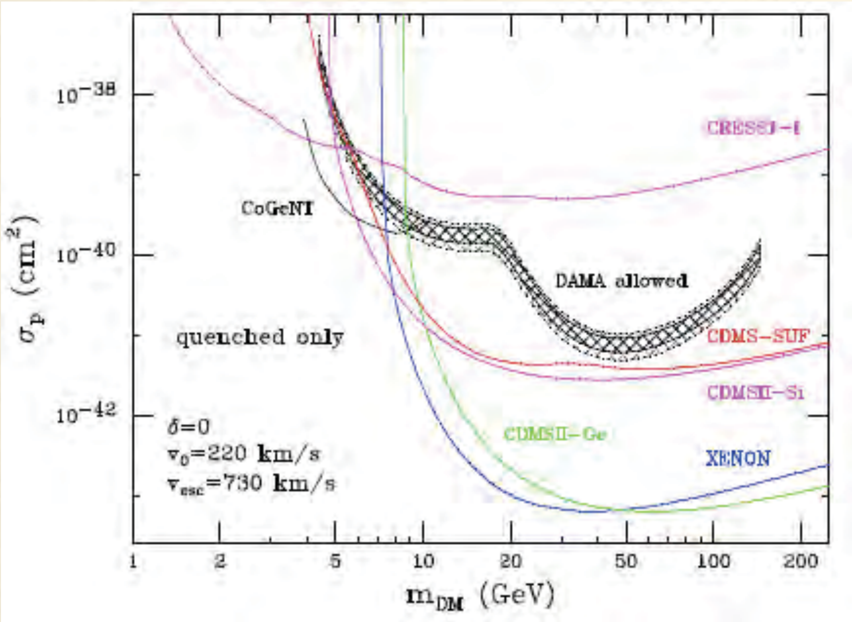
- Multiple stable states?
- New light forces?

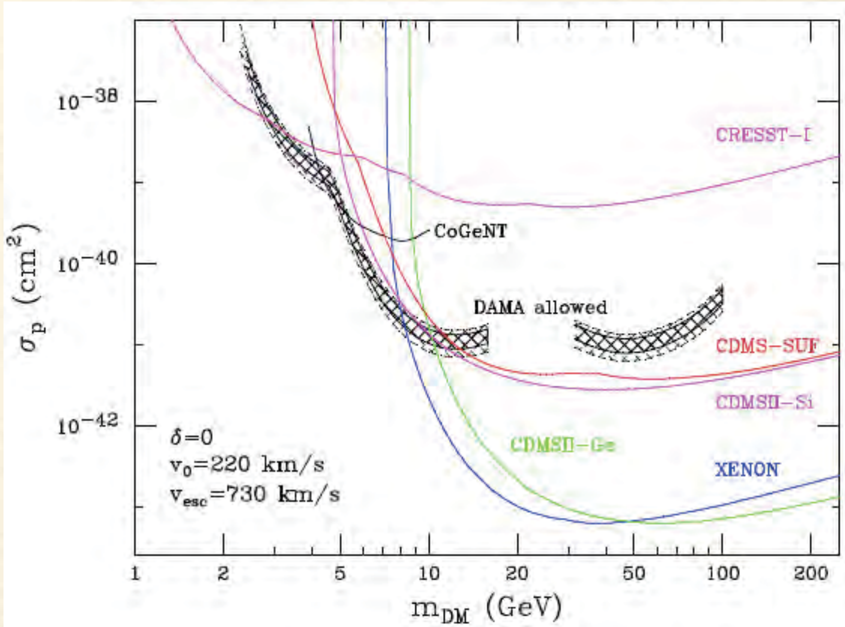
Kathryn Zurek

DAMA and WIMP DM

- New unaccounted for (?) systematic which shifts the threshold: channeling

Petriello, KZ '08





$E_{thresh} = 7$ keV (Na), 22 keV (I) $\qquad E_{thresh} = 2$ keV

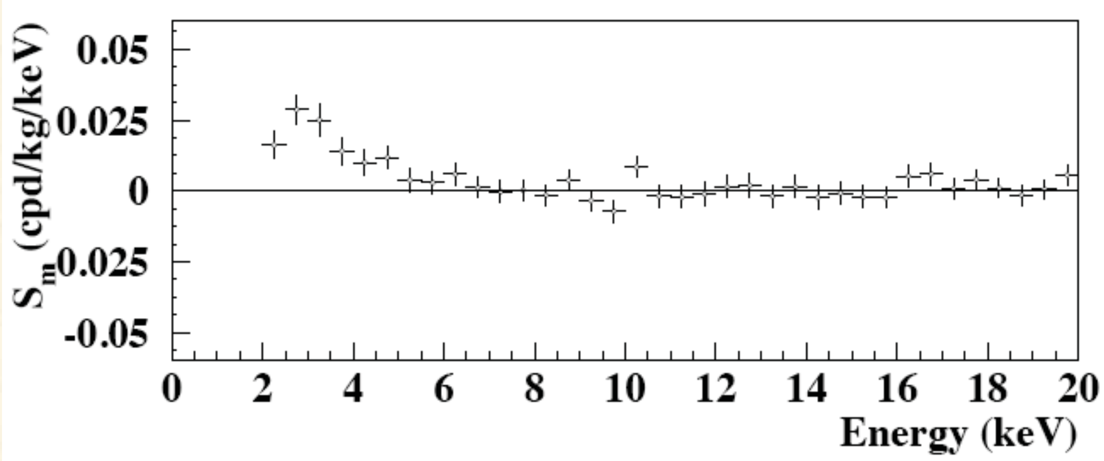
$$v^2 \geq \frac{m_N E_R^{thresh}}{2\mu^2_{DM}}$$

Only a small fraction of the recoil goes into a mode that DAMA measures. The rest goes into phonons/heat

Kathryn Zurek

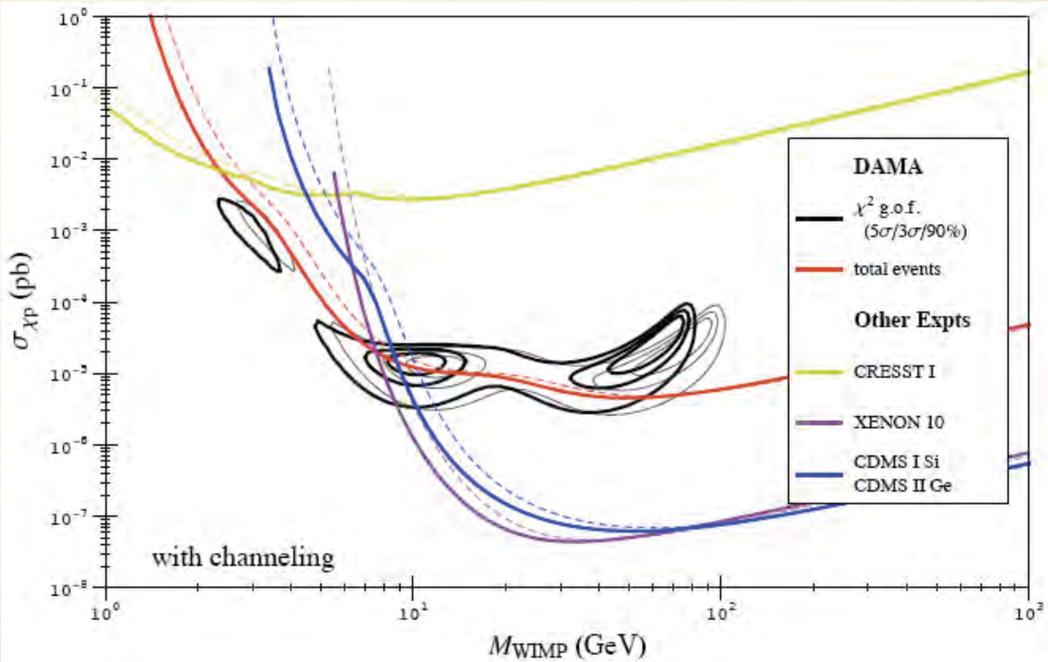
Spectral information

Energy	S_i^1 (cpd/kg/keVee)
$2-4$ keVee	0.0223 ± 0.0027
$2-5$ keVee	0.0178 ± 0.0020
$2-6$ keVee	0.0131 ± 0.0016
$6-14$ keVee	0.0009 ± 0.0011



Window is not ruled out

DAMA results has inspired low threshold analyses in other experiments, e.g. CDMS and XENON



Savage, Freese, Gondolo, Spolyar

Kathryn Zurek

Simple realizations of this solution

Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Find mechanism $n_{DM} \approx n_b$

$m_{DM} \approx 5m_p$

S.M. Barr, D.B. Kaplan

Farrar, Zaharijas
Kitano, Low
Gudnason, Kouvaris, Sannino
Kitano, Murayam, Ratz
Luty, Kaplan, KZ

High scale M

$$W = \frac{X^2 LH}{M}$$

Electroweak scale

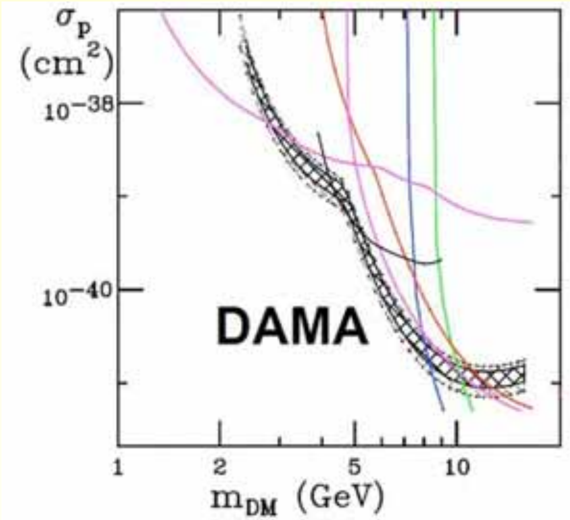
Standard Model

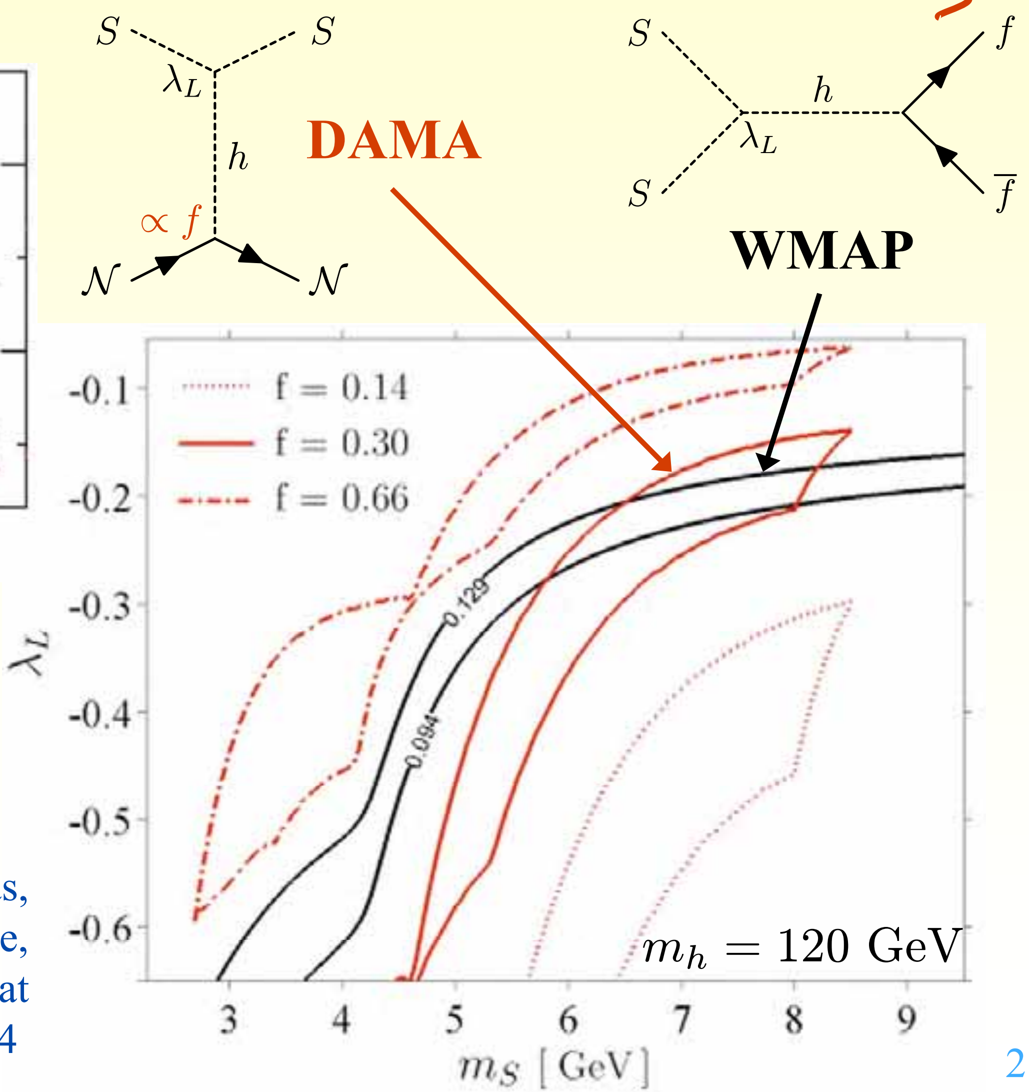
X sector

The issue of explaining DAMA results with scalar DM was also addressed by Sarah Andreas (YSF3)

DAMA and WMAP

F. Petriello, K. M. Zurek (2008)





DAMA and WMAP can be satisfied

S. Andreas,
T. Hambye,
M. H. G. Tytgat
JCAP, **2008**, *0810*, 034

A "theory" of DM is built by Martti Raidal

- Assume that the initial space-time topology is effectively lower dimensional, *e.g.*, $M^3 \times S^1$ with very small compact space dimension.
- Formulate physics theories consistently in 3-dimensions and lift the result to 4 dimensions.
- Take care of CPT and Lorentz invariance violating effects (photon mass, S^1 must be big)
- Use new constraints in 4-dimensional model building

- In 3 dimensions non-Abelian gauge and gravity actions have topological Chern-Simons terms which charges are quantized
- The presence on N_F chiral fermions and N_G gauge bosons induce loop corrections to the actions and the quantization conditions require

$$\frac{1}{16}N_F - \frac{1}{8}N_G = 0$$

- Chiral fermions must come in multiples of 16 and there mus odd number of generations
- Experiment: 15 SM fermions + N fit **16** of SO(10), there are generations
- Number of gauge bosons is $N_G = N_F/2 = 24$
- 24 is an adjoint of SU(5), thus less-dimensions suggest SU(5 GUT and

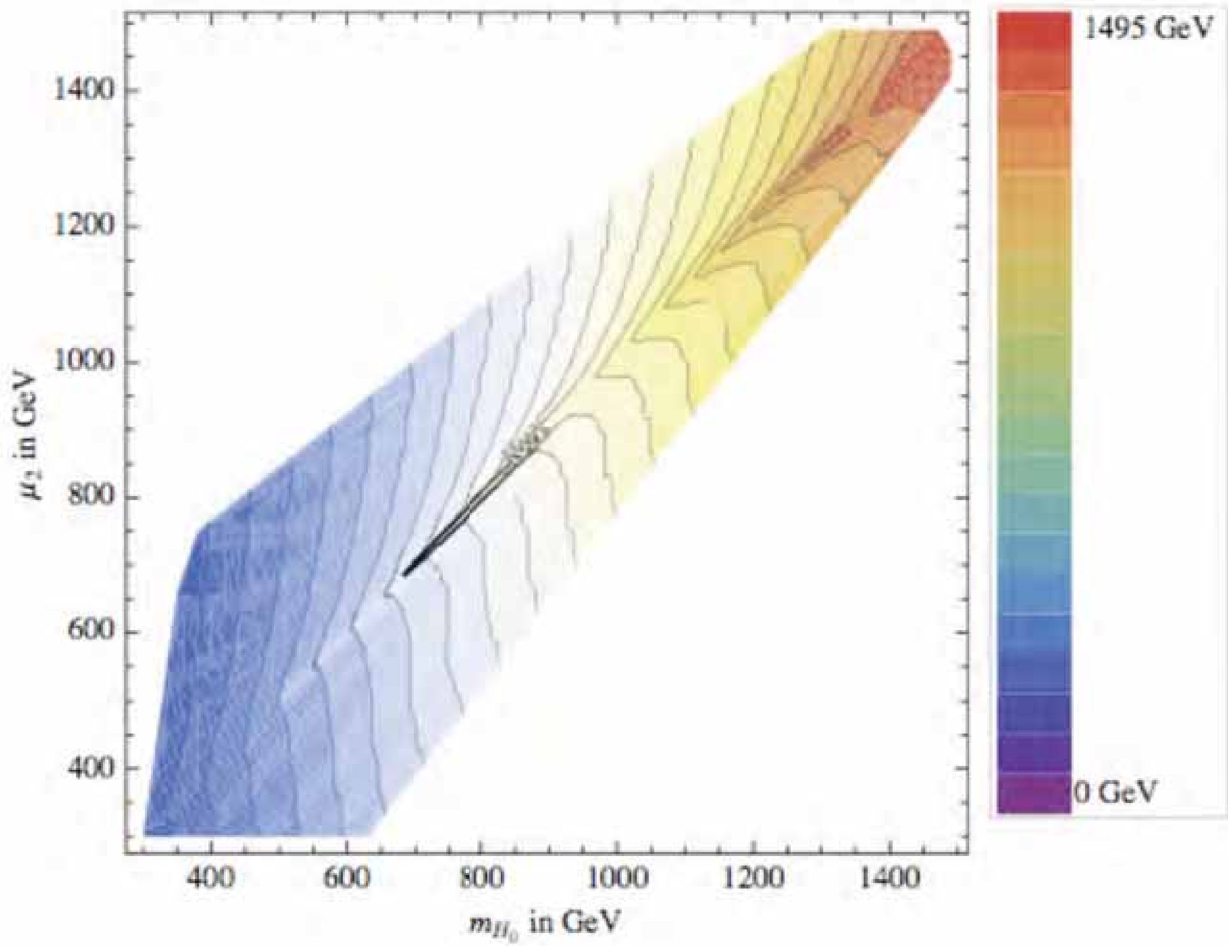
$$SO(10) \to SU(5) \times U(1)_X$$

- If all matter fields come in some representation of SO(10), the U(1) quantum numbers of all of them are well defined
- The $U(1)_X$ is the origin of a discrete Z_n symmetry needed for DM.

$$P_X \equiv P_M = (-1)^{3(B-L)},$$

- Our scenario generalizes matter parity to non-SUSY models
- Matter parity P_M is an intrinsic property of all matter

Martti Raidal



BARYOGENESIS

$$n_B/n_\gamma = 6.12(19) \times 10^{-10}$$

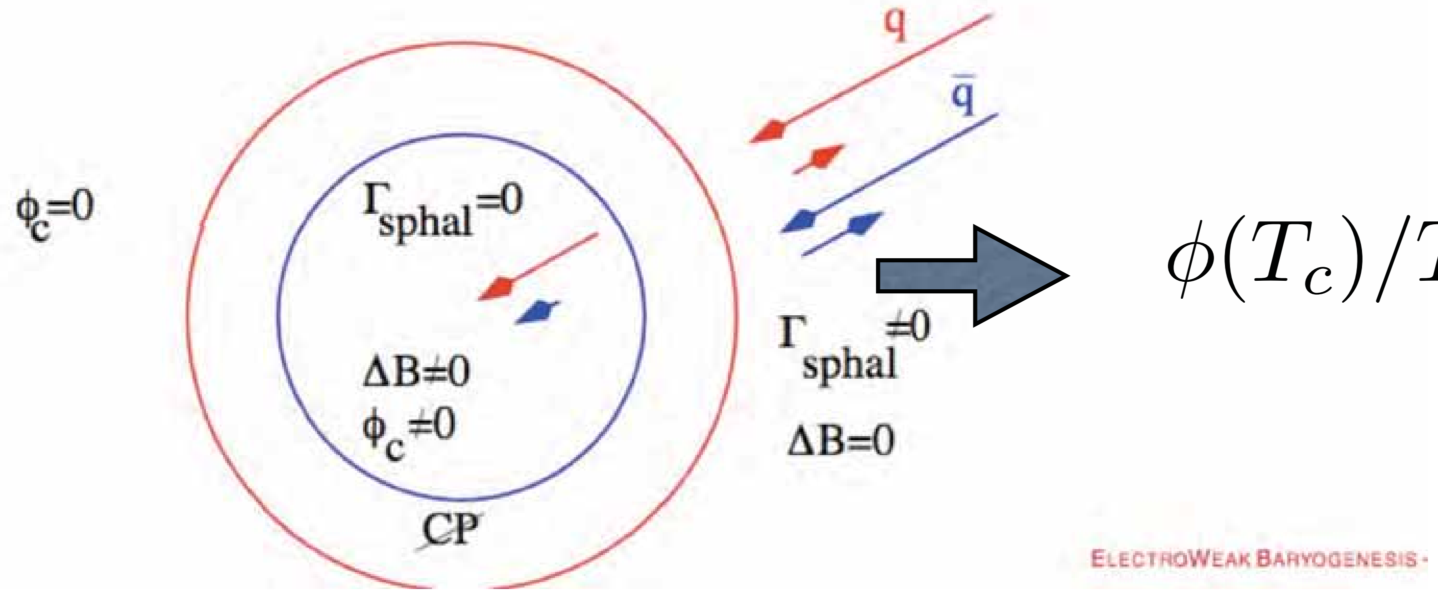
The conditions for baryogenesis were stated by Sakharov in 1967 [A.D. Sakharov, JETPL 91B (1967) 24]

- B violation
- C and CP violation
- Departure from thermal equilibrium

All these conditions are fulfilled in the SM

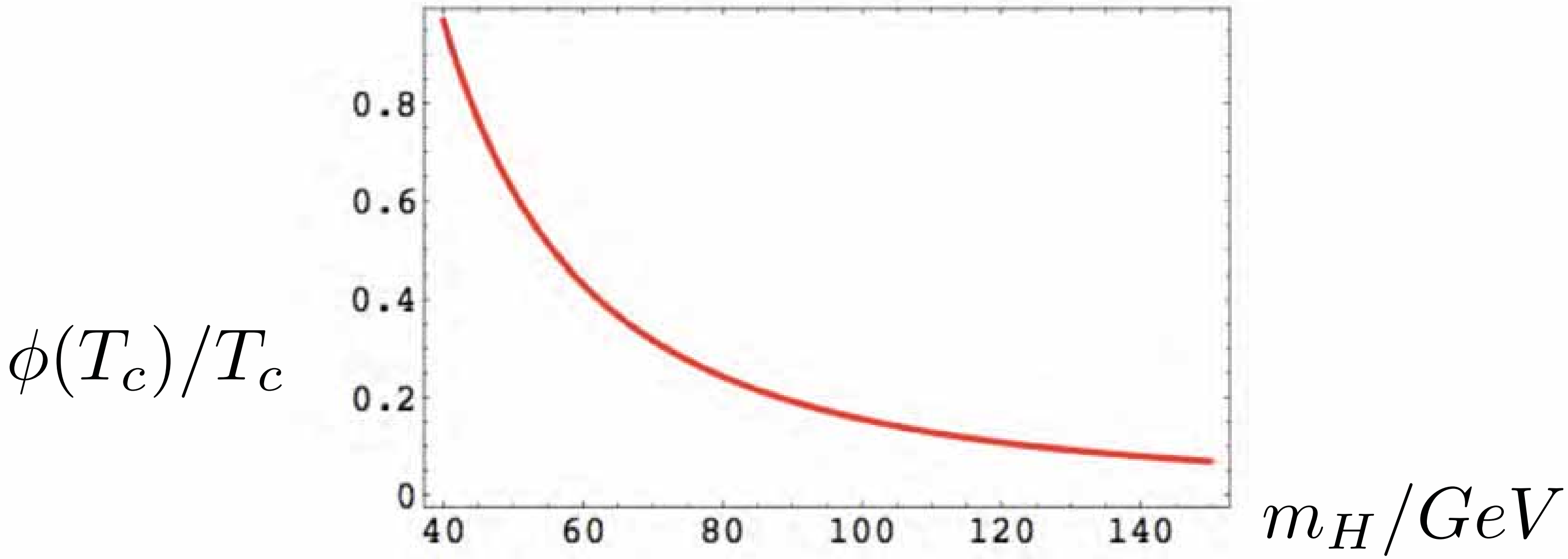
- Baryon number is non-perturbatively violated in the SM: sphalerons at finite temperature
- C and CP violating phases (CKM) are present
- The out-of-equilibrium conditions are present in the bubble walls in a FIRST ORDER PHASE TRANSITION

A mechanism for the generation of the BAU was suggested by Cohen, Kaplan and Nelson in 1993 using CP violating interactions of fermions with the domain wall of a bubble. The reflection and transmission coefficients of fermions and anti-fermions scattering off the CP violating wall are different



$$\phi(T_c)/T_c > 1$$

Although the SM contains all the ingredients for EWBG it fails quantitatively because

- The CP violation provided by the CKM phase is too small to generate the required BAU
- 

$v(T_c)/T_c$ as a function of m_H (in GeV) [one-loop]

The phase transition is too weak

LEPTOGENESIS

- Leptogenesis generates $\Delta L \neq 0$
- Sphalerons $\Delta L = \Delta B \Rightarrow \Delta B \neq 0$
- If right handed neutrinos exist they can do the job

$$\mathcal{L}_N = M_\alpha N_\alpha N_\alpha + \lambda_{\alpha i} N_\alpha L_i \phi$$

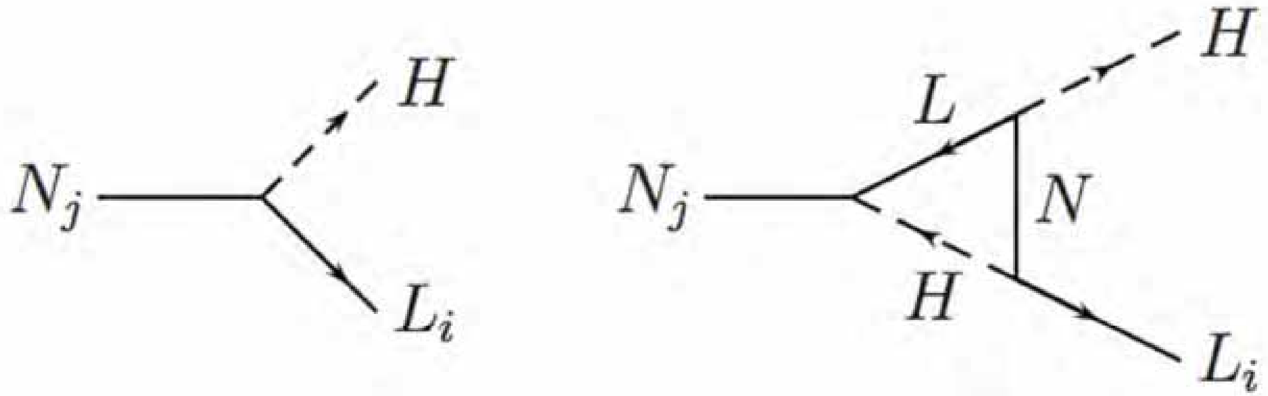
1. It is impossible to assign a lepton number to the N_α's in such a way that $\mathcal{L}_N$ is L-conserving: The M-terms require $L(N) = 0$ while the λ-terms require $L(N) = -1$. Thus, $\mathcal{L}_N$ breaks L and (since it does not break B) $B - L$.

2. We can choose the phases of the N_α fields in a way that makes M real, but then λ will have physical, irremovable phases. Thus $\mathcal{L}_N$ violates CP.

3. The Lagrangian $\mathcal{L}_N$ allows for N decays via $N \to L\phi$. If, however, the Yukawa couplings are small enough, the N-decays occur out of equilibrium.

The Majorana nature of the right-handed neutrino means that any single mass eigenstate can decay both

$L\Phi, \bar{L}\phi$



CP is violated in these decays and CP asymmetry

$$\epsilon_{N_\alpha} = \frac{\Gamma(N_\alpha \to \ell H) - \Gamma(N_\alpha \to \bar{\ell}\bar{H})}{\Gamma(N_\alpha \to \ell H) + \Gamma(N_\alpha \to \bar{\ell}\bar{H})},$$

Leptogenesis In Greater Depth

Boris Kayser

The see-saw model adds to the Standard Model —

Mass of N_k

Yukawa couplings

$$\mathcal{L}_{\text{new}} = -\sum_{k=1}^{3} \frac{M_k}{2} \overline{N_{kR}{}^c} N_{kR} - \sum_{j,\,k=1}^{3} y_{jk} \left[\overline{\nu_{jL}}\, \overline{\varphi^0} - \overline{\ell_{jL}}\, \varphi^- \right] N_{kR} + h.c.$$

$I_W = 0$

SM lepton doublet

SM Higgs doublet

The Yukawa couplings y_{jk} cause —

$$N_k \to \ell_j^{\mp} + \varphi^{\pm} \quad \text{and} \quad N_k \to \overset{(-)}{\nu_j} + \overset{(-)}{\varphi^0} \; .$$

Boris Kayser

Then, summing over the final lepton flavors, the $\not{C}\not{P}$ asymmetry is —

$$\varepsilon \equiv \frac{\Gamma(N_1 \to L\phi) - \Gamma(N_1 \to \bar{L}\bar{\phi})}{\Gamma(N_1 \to L\phi) + \Gamma(N_1 \to \bar{L}\bar{\phi})}$$

$$= \frac{1}{8\pi}\frac{1}{(y^\dagger y)_{11}}\sum_m \Im m\left[\{(y^\dagger y)_{1m}\}^2\right]K\left(\frac{M_m^2}{M_1^2}\right)$$

Kinematical function

$$\varepsilon \sim y^2/10$$

To explain $n_B/n_\gamma \sim 10^{-9}$ requires $\varepsilon \sim 10^{-6}$.

$$M_\nu \sim M_D^2/M_N \sim (yv)^2/M_N \sim 10^{-1}\mathrm{eV}.$$

For leptogenesis, we required that —

Boris Kayser

$$\varepsilon \sim y^2/10 \sim 10^{-6}$$

Together, these requirements imply that —

$$M_N \sim 10^9\ \mathrm{GeV}.$$

Leptogenesis requires very heavy neutrinos, far beyond the range of LHC.

Electromagnetic Leptogenesis

(Nicole Bell, B.K., Sandy Law)

Suppose new physics at a high mass scale $\Lambda > M_N$ leads to the electromagnetic N decay mode —

$$N \rightarrow \nu + \gamma$$ Toy Model

Boris Kayser

or the mode —

$$N \rightarrow \underbrace{L + \varphi}_{\text{Emitted in standard leptogenesis}} + (\gamma \text{ or } Z \text{ or } W)$$

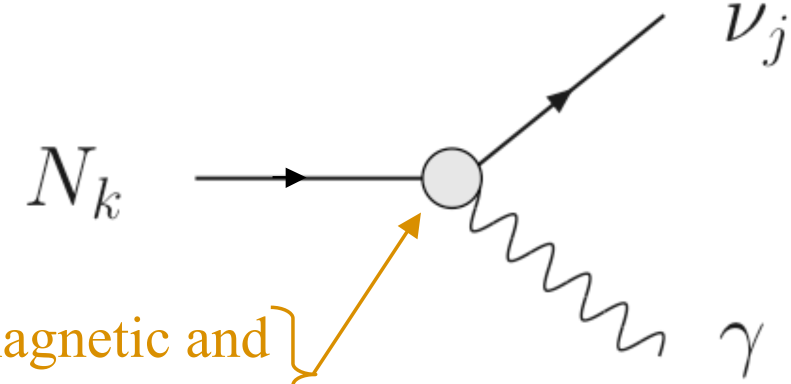
More realistic; respects SM conservation laws

Boris Kayser

Q: Could $\cancel{CP}$ in such decays be a successful alternative to the standard leptogenesis scenario?

Q: If so, could it be successful if $M_N \sim 1$ TeV, within range of the LHC, instead of $\sim 10^9$ GeV?

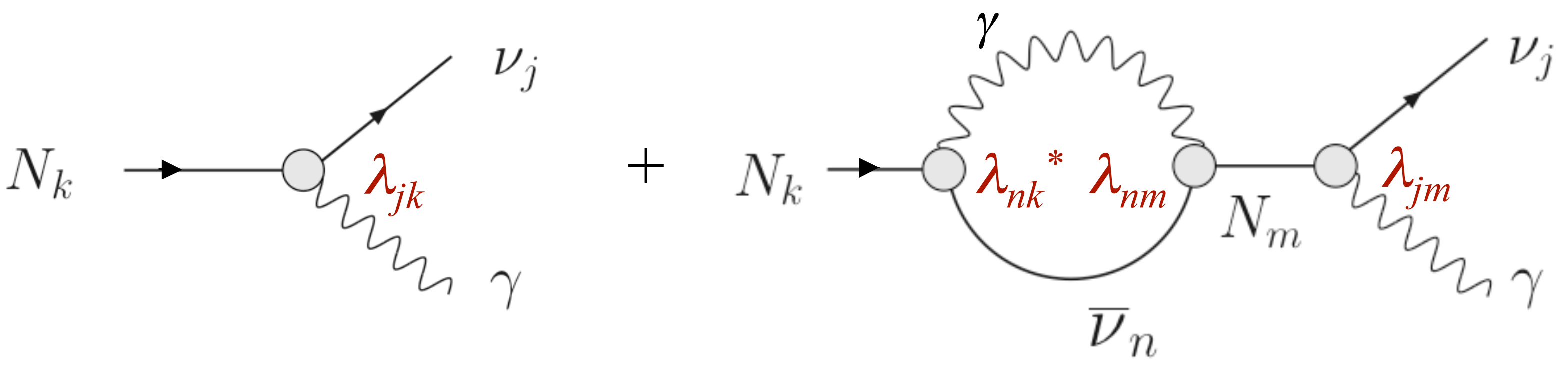
The N → ν + γ Toy Model



Transition magnetic and electric dipole moments

Boris Kayser

An example of tree-loop interference:



$$\Rightarrow \quad \Gamma\left(N_k \to \nu_j + \gamma\right) - \Gamma\left(N_k \to \overline{\nu_j} + \gamma\right) \propto \Im m\left(\lambda_{jk}^* \lambda_{nk}^* \lambda_{nm} \lambda_{jm}\right)$$

This model leads to a ~~CP~~ asymmetry ε rather similar to the one from standard leptogenesis, with $y \Rightarrow \lambda$.

The ~~CP~~ phases are now in λ.

EM leptogenesis can succeed.

Our Two Questions

Q: Could $\cancel{CP}$ in EM decays be a successful alternative to the standard leptogenesis scenario?

A: Yes.

Q: If so, could it be successful if $M_N \sim 1$ TeV, within range of the LHC, instead of $\sim 10^9$ GeV?

A: No. Boris Kayser

The problem "Can LHC disprove Leptogenesis?" has been reconsidered by Gilles Vertongen

TESTING LEPTOGENESIS

Observing N_R ?

1. Hierarchical N_R — Leptogenesis ok if $m(N_R) > 10^8$ GeV [Davidson-Ibarra, 2002] ✘

2. Degenerate N_R — Leptogenesis ok @ low scales [Pilaftsis, 2002] but $m(\nu_\alpha)$ require λ suppressed ✘

If not testable, could leptogenesis at least be *falsified* ?

Leptogenesis in Gauge Framework

Gilles Vertongen

Proposition:

The observation of W_R @ LHC would disprove Leptogenesis

Why a W_R ?

1. Majorana neutrinos are *naturally* present in Grand Unified Theories:

$SO(10) \to \ldots$

$\to SU(3)_C \times SU(2)_R \times SU(2)_L \times U(1)_Y$ Left-Right Sym. Model

$\to SU(3)_C \times SU(2)_L \times U(1)_Y$

New gauge fields : W_R

$$\mathcal{L} \ni \frac{g}{\sqrt{2}} W_R^\mu \left(\bar{u}_R \gamma_\mu d_R + \bar{N} \gamma_\mu l_R\right)$$

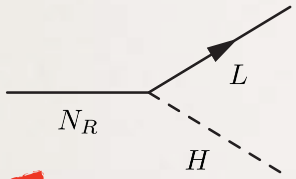
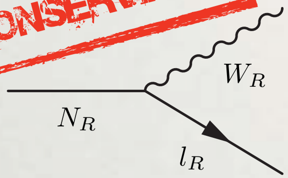
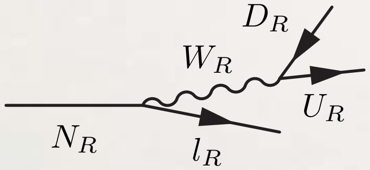
2. LHC arrival !

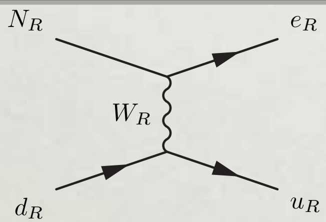
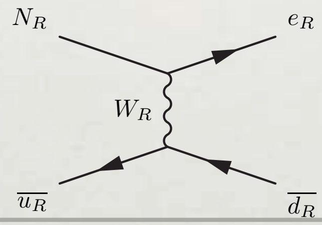
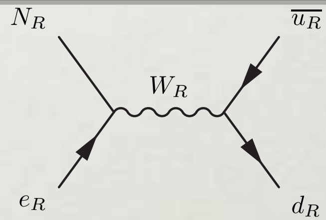
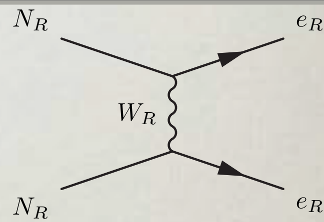
2. Tevatron fixed $m(W_R) > 800$ GeV [CDF Collaboration, note 8747 (2007)]

3. LHC will probe $m(W_R) < 3\text{-}4$ TeV [CERN-LHCC-2006-021]

Gilles Vertongen

Effects of a low Scale W_R

Decays	Diagrams	CP Violation	Efficiency
Yukawa		$\varepsilon^{(0)}_{CP} \equiv \dfrac{\Gamma_{N\to LH} - \overline{\Gamma}_{N\to \bar{L}H^*}}{\Gamma^{(l)}_{\text{tot}}}$ "Average $\triangle$L produced per decay"	$\eta \leq 1$
Gauge	CP CONSERVING !  	$\varepsilon_{CP} = \dfrac{\Gamma - \overline{\Gamma}}{\Gamma^{(l)}_{\text{tot}} + \Gamma^{(W_R)}_{\text{tot}}}$ Dilution ! $= \dfrac{\Gamma - \overline{\Gamma}}{\Gamma^{(l)}_{\text{tot}}} \dfrac{\Gamma^{(l)}_{\text{tot}}}{\Gamma^{(l)}_{\text{tot}} + \Gamma^{(W_R)}_{\text{tot}}}$	$\eta \leq \dfrac{\Gamma^{(l)}_{\text{tot}}}{\Gamma^{(l)}_{\text{tot}} + \Gamma^{(W_R)}_{\text{tot}}}$

Scatterings	Diagrams
Gauge	   

Strong Thermalization

$\Rightarrow$ Easier to produce neutrinos @ Reheating ✓

$\Rightarrow$ Harder decoupling @ Low T° (Washout) ✗

Gilles Vertongen

Inclusion in Boltzmann Equations

Example of Gauge Effects

m(N) = 500 GeV m(W_R) = 3 TeV $\lambda = 10^{-3}$ eV

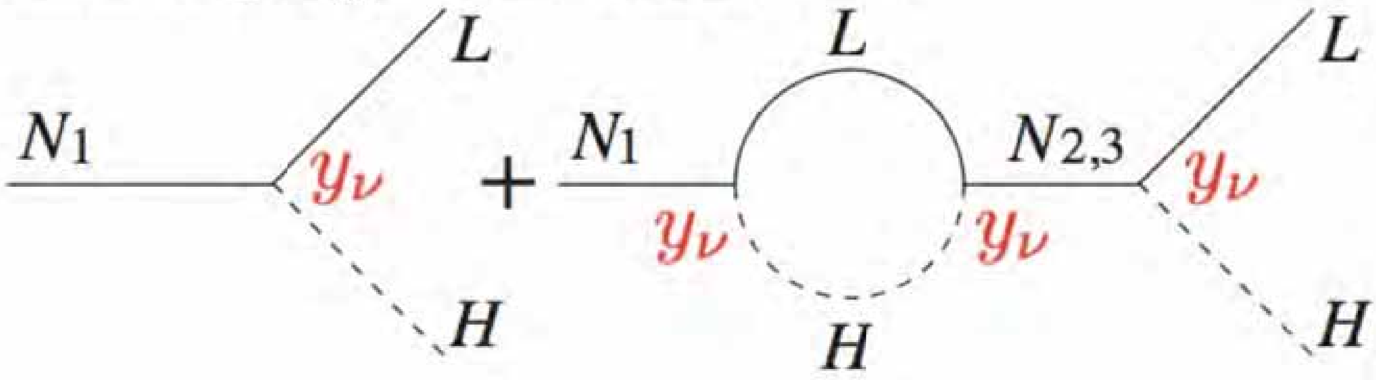
Case	Content	η	Y_B
(a)	Standard Leptogenesis	0,5	6.10^{-4}
(b)	(a)+W_R decays in Y_N	3.10^{-8}	4.10^{-11}
(c)	(b)+W_R scatterings in Y_N	2.10^{-10}	2.10^{-13}
(d)	(c)+W_R scatterings in Y_L	2.10^{-18}	2.10^{-21}
(e)	(d)+W_R decays in Y_L	2.10^{-18}	2.10^{-21}

Type I Leptogenesis

- ➡ could be disproved if W_R observed @ LHC
- ➡ could work if $m(W_R) > 18$ TeV

Another model for TeV Leptogenesis has been considered by Yuji Kajiyama where it is Higgs mediated

•TeV-scale leptogenesis with $y_\nu \sim 10^{-6}$



CP asymmetry: $\epsilon \equiv \dfrac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$

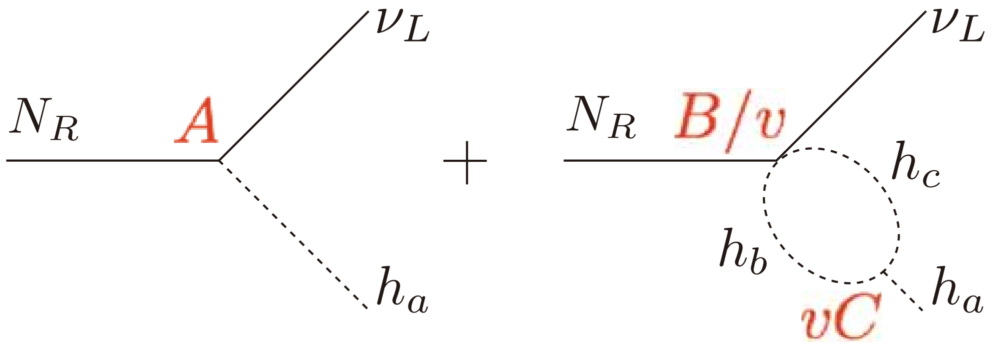
$$\epsilon \sim \frac{1}{8\pi} \frac{\mathrm{Im} y_\nu^4}{y_\nu^2} \frac{M_1 M_2}{M_1^2 - M_2^2} \sim 10^{-13} \frac{M_1 M_2}{M_1^2 - M_2^2} \sim 10^{-6}$$

$\rightarrow \dfrac{M_2 - M_1}{M_1} \sim 10^{-7}$ Resonance condition

Yuji Kajiyama

to avoid resonance condition...

•In this talk, we consider leptogenesis by



$\epsilon \sim \frac{1}{16\pi}\frac{\mathrm{Im}[AB^*]C}{|A|^2}$ can be large $\boxed{\text{if } A \sim B \sim 10^{-6}.}$

We discuss:

(1) leptogenesis below EWSB scale $(T < T_c)$
without resonance condition,

(2) source of CPV is in the Higgs sector.

2. The Model

K.S.Babu and S.Nandi, Phys.Rev.D62,033002(2000)

G.F.Giudice and O.Lebedev, Phys.Lett.B665,79(2008)

Yuji Kajiyama

•Consider a Froggatt-Nielsen type model by Higgs doublets with U(1) charge assignment

$$H_u : 0,\ H_d : 1,\ L_i : -3,\ N_{Ri} : 0$$

U(1) invariant Yukawa terms are given by

$$\mathcal{L}_\nu = y^\nu_{ij} \bar{N}_{Ri} L_{Lj} H_u \left(\frac{H_u H_d}{M^2}\right)^{n^\nu_{ij}} + \frac{1}{2} N_{Ri} M_{Nij} N_{Rj} + c.c.$$

where $(n^\nu_{ij}) = 3$. Mass hierarchy: $\left(\frac{v_u v_d}{M^2}\right)^{n_{ij}} \equiv \epsilon^{n_{ij}} = 10^{-2n_{ij}}$

$\boxed{y^\nu \sim \mathcal{O}(1) \text{ and real,}}$ $M \sim 1\mathrm{TeV}$.

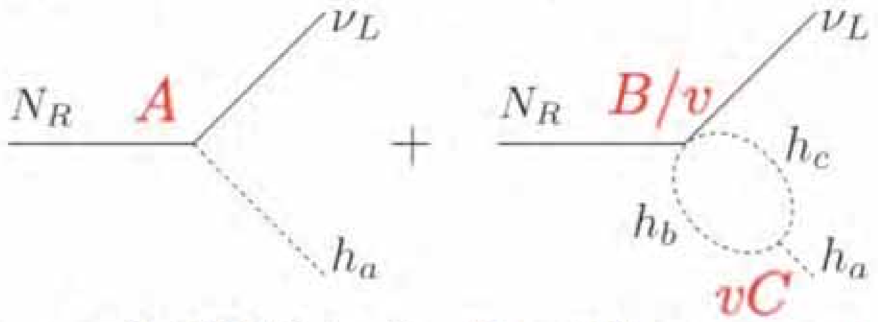
•Higgs potential is given by

$$\begin{aligned} V &= m^2_{H_u} |H_u|^2 + m^2_{H_d} |H_d|^2 + \lambda_1 |H_u|^4 + \lambda_2 |H_d|^4 + \lambda_3 |H_u|^2 |H_d|^2 + \lambda_4 |H_u H_d|^2 \\ &+ \boxed{\left[m^2 H_u H_d + \lambda_5 (H_u H_d)^2 + \lambda_6 |H_u|^2 H_u H_d + \lambda_7 |H_d|^2 H_u H_d + c.c.\right]} \end{aligned}$$

Source of CPV $(m^2, \lambda$ are complex.)

Yuji Kajiyama

(1) leptogenesis occurs below EWSB scale $(T < T_c)$,



(2) source of CPV is in the Higgs sector,

(3) large CP asymmetry ($0 < \epsilon < 10^{-3}$) is generated without resonance condition,

(4) sphaleron converts $\eta_L \to \eta_B$ for $z_c < z < z_d$,

(5) and we can get baryon asymmetry.

Present perspectives

- Using AdS/CFT correspondence some quantities in non-perturbative QCD can be computed: AdS/QCD
- Less-conventional solutions to hierarchy problem
  - Higgs mass protected by global symmetry (pseudo-Goldstone boson): Little Higgs
  - Higgs mass protected by higher dimensional gauge theory: gauge-Higgs unification
  - Composite Higgs: using AdS/CFT correspondence
  - Higgless models (breaking by boundary condition)
  - Higgs in conformal sector (unHiggs): dimension of H*H > 2: quadratic corrections softened
- Unexpected physics: hidden valley models, quirks, unparticles,..., leaving unexpected signatures

Future perspectives

- They should depend on LHC !

PERHAPS AT MORIOND 2010...