KimFest, Seoul National Univ., 30 July 2026

Axions & SUSY: the (long) journey to naturalness with Jihn E. Kim

Antonio Masiero

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Meeting Jihn E at the right place (CERN) at the right moment (early ‘80s)

’70s GUTs → gauge hierarchy →
early ‘80s low-energy SUSY in the particle physics arena

Late 70’s Strong CP → PQ symmetry → Weinberg-Wilczek (too visible) axion → Kim (invisible) axion

Early ‘80’s → SUSY B violation → R parity → byproduct of low-energy SUSY: LSP WIMP DM candidate

Late ‘70s – early 80’s GUTs B violation → Baryogenesis

Early-mid 80’s: CERN = (one of) the place with the highest density of experts working on the above research issues

VOLUME 43, NUMBER 2 PHYSICAL REVIEW LETTERS 9 JULY 1979

Weak-Interaction Singlet and Strong *CP* Invariance

Jihn E. Kim
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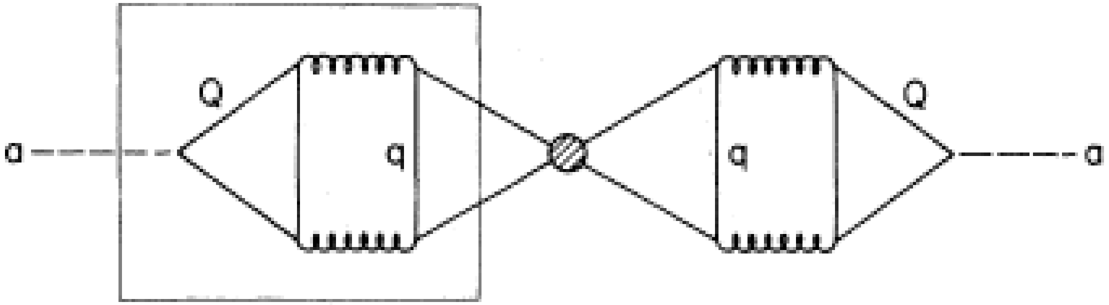
(Received 16 February 1979)

Strong *CP* invariance is *automatically* preserved by a spontaneously broken chiral $U(1)_A$ symmetry. A weak-interaction singlet heavy quark Q, a new scalar meson σ^0, and *a very light axion* are predicted. Phenomenological implications are also included.



Invisible axion couples directly to the new heavy quarks Q carrying the PQ charge

very low mass axion m < 1 eV, PQ symmetry broken at a very high energy scale PQ

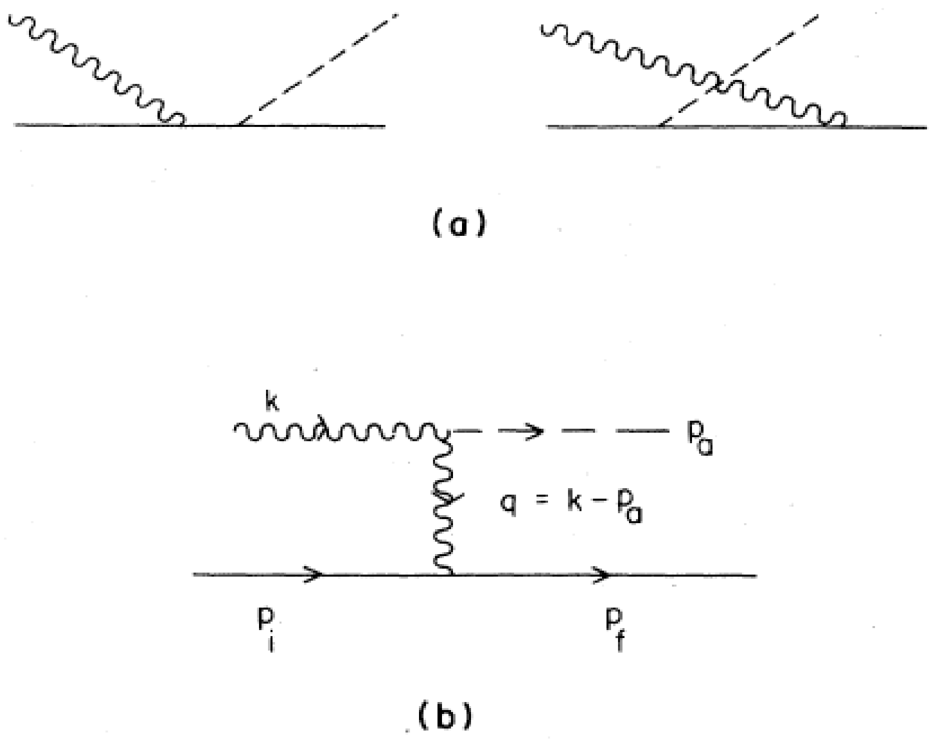
“Stellar evolution may be affected by the existence of a light axion by the Primakoff process”

Astrophysical bounds on axion mass (hence on V_{PQ})

1978 Implications of the Weinberg– Wilczek axion for stellar evolution →such axion removes energy from the stellar thermal bath by the direct processes a) and Primakoff process b). The direct process a) gives the most important contribution. From the existence of the helium-burning red giants the **LOWER bound**

m_{axion} < 0.3 MeV for the Weinberg – Wiczek axion

Dicus, Kolb, Teplitz, Wagoner PRD 1978 ; Vsyotskii, JETP Lett. 1978



1979 Implications of the Kim axion for stellar evolution: stellar energy loss ONLY through the Primakoff process in b).

UPPER bound on m_{axion}

$$m_a \leq 6.3\times10^{-3}\ \text{eV} \quad (e_Q = -\tfrac{1}{3}e),$$
$$m_a \leq 9.0\times10^{-2}\ \text{eV} \quad (e_Q = 0).$$

→ **$V_{PQ} > 10^8$ GeV**

Dicus, Kolb, Teplitz, Wagoner, PRD 1979

For the KSVZ axion 10^8 GeV < V_{PQ} < 10^{12} GeV

Kim --> axion couplings decrease with decreasing axion mass so that stellar evolution is not to be affected by an axion of sufficiently small mass → **upper bound on axion mass → lower bound on V_{PQ}**

$$V_{PQ} > 10^8 \text{ GeV}$$

Dicus, Kolb, Teplitz, Wagoner, PRD 1979

Presently such lower bound on V_{PQ} has moved to **10^{12} GeV**
for a review Kim, Carosi Rev. Mod. Phys. 2010

From the computation of **temperature dependent axion mass** of
Gross, Pisarski, Yaffe Rev. Mod. Phys. 1981

Upper bound on V_{PQ} → $V_{PQ} < 10^{12}$ GeV

Preskill, Wise, Wilczek, PLB 1983;
Abbott, Sikivie PLB 1983; Dine, Fischler PLB 1983

How to kill two birds with one stone

tackling **2 naturalness** issues
at the same time

Gauge hierarchy → **SUSY** ⟷ **Strong CP problem** → **PQ symmetry**

Nilles, Raby NPB 1982
Tamvakis, Wyler PLB 1982;
Frère, Gérard , Lett. Nuovo Cim. 1983

SLAC-PUB-2743
May 1981
(T/E)

SUPERSYMMETRY AND THE STRONG CP PROBLEM*

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ABSTRACT

We show how supersymmetric grand unified theories (SSGUT) provide a natural solution to the strong CP problem. Such theories contain an additional global $U(1)_{PQ}$ chiral (Peccei-Quinn) symmetry which is conserved up to color anomalies. Hence the QCD θ angle is irrelevant. Moreover the PQ symmetry is spontaneously broken at the grand unified scale. As a result the st ... -Wilczek axion has a mass

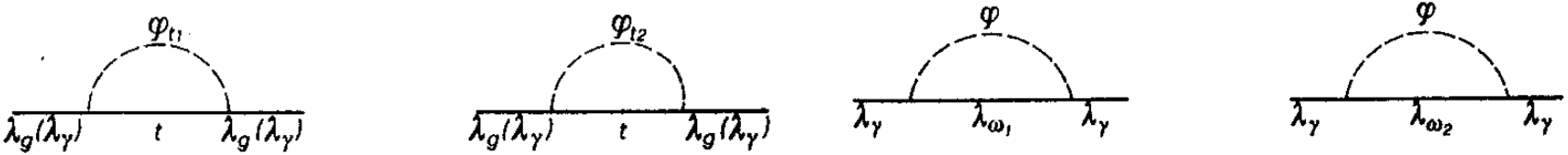
$$m_a \sim \frac{\Lambda_{QCD}^2}{\Lambda_{GUM}} \sim 10^{-10} \text{ eV}$$

which effectively decouples from ordinary matter.

Radiative gluino and photino masses in Spontaneously Broken SUGRA

$$\mathcal{L} = \mathcal{L}\,(\text{supersymmetric}; f) + m^2_{3/2}\, \Sigma_a |y_a|^2 + $$
$$+\, m_{3/2}\,\left(\Sigma_a \frac{\partial f}{\partial y_a}\, y_a + \text{h.c.}\right)$$

Barbieri, Girardello, AM PLB 1983



$M_{gluino} \sim O$ (1Gev), $M_{photino} \sim O$ (1- 100MeV)) $\lesssim$ 1 GeV

If a stable photino is the LSP → to have the photino pair annihilation fast enough →

$M_{photino} > 0.5$ GeV

Goldberg PRL 1983; Ellis, Hagelin, Nanopoulos, Olive, Srednicki NPB 1984

UNSTABLE PHOTINO MASS BOUND FROM COSMOLOGY

Jihn E. Kim*, A. Masiero and D.V. Nanopoulos
CERN, Geneva

$$\tilde{\gamma} + \tilde{a} + \gamma$$

ABSTRACT

If there exis[illegible] invisible axion, it is likely [illegible] its superpartne[illegible] the axino, is lighter than the photino, [illegible] consequently, [illegible] photinos can decay into axinos [illegible]-tons. We derive [illegible] masses for this case of unstable photinos in terms of the Peccei-Quinn symmetry breaking scale.

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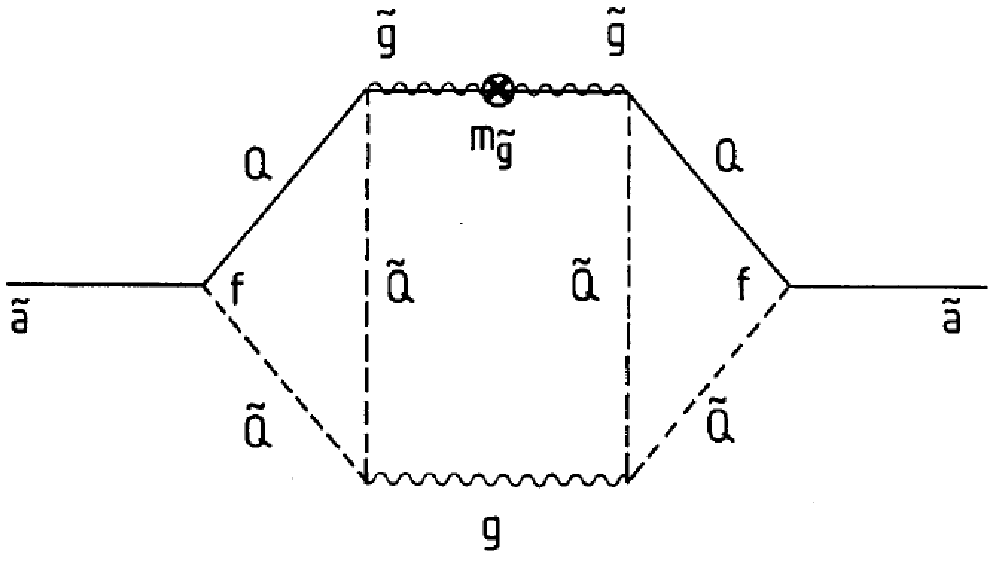
* On leave of absence from Department of Physics, Seoul National University, Seoul 151, Korea.

Ref.TH.3788-CERN
February 1984

Phys. Lett. 139B (1984) 346-350

AXINO possible LSP (lighest susy particle)



$$(f^2 \alpha_c^3 / 32\, \pi^4)\; m_{3/2} \approx (3\ \text{eV},\ 300\ \text{eV})$$

$$f = (10^{-2},\ 10^{-1}) \text{ and } m_{3/2} = 100\ \text{GeV}$$

Generically the axino mass ~ 0 ($m_{3/2}$), but the theoretically allowed mass range encompasses the entire range relevant for hot, warm (keV mass range Rajagopal, Turner, Wilczek NPB 1991) and cold DM
Choi, Kim, Roszkowski J. of the Korean Phys. Soc. 2013

Chun, Kim, Nilles PLB 1992
Chun, Lukas PLB 1995;
Kim, Seo NPB 2012

AXION SUPERMULTIPLET

$$A = \frac{1}{\sqrt{2}}(s + ia) + \sqrt{2}\tilde{a}\vartheta + F_A\vartheta\vartheta$$

SAXION AXION AXINO AUXILIARY FIELD

PQMSSM

$$\mathcal{L}_a^{\text{eff}} = \frac{\alpha_s}{8\pi f_a} a\, G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

SUSY

$$\mathcal{L}^{\text{eff}} = -\frac{\alpha_s}{2\sqrt{2}\pi f_a}\int A\,\mathrm{Tr}\left[W_\alpha W^\alpha\right]$$

Vector supermultiplet with the gluon field

$$\mathcal{L}^{\rm eff}_{\rm int} = c_1 \frac{(\partial_\mu a)}{f_a} \sum_q \bar{q}\gamma^\mu\gamma_5 q - \sum_q (\bar{q}_L m q_R e^{ic_2 a/f_a} + \text{h.c.}) + \frac{c_3}{32\pi^2 f_a} a G\widetilde{G} + \frac{C_{aWW}}{32\pi^2 f_a} a W\widetilde{W} + \frac{C_{aYY}}{32\pi^2 f_a} a Y\tilde{Y} + \mathcal{L}_{\rm leptons},$$

$$\mathcal{L}^{\rm eff}_{\tilde{a}} = i\frac{\alpha_s}{16\pi f_a}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\tilde{G}^b G^b_{\mu\nu} + \frac{\alpha_s}{4\pi f_a}\bar{\tilde{a}}\tilde{g}^a \sum_{\tilde{q}} g_s \tilde{q}^* T$$
$$+ i\frac{\alpha_2 C_{aWW}}{16\pi f_a}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\tilde{W}^b W^b_{\mu\nu}$$
$$+ \frac{\alpha_2}{4\pi f_a}\bar{\tilde{a}}\tilde{W}^a \sum_{\tilde{f}_D} g_2 \tilde{f}^*_D T^a \tilde{f}_D$$
$$+ i\frac{\alpha_Y C_{aYY}}{16\pi f_a}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\tilde{Y} Y_{\mu\nu}$$
$$+ \frac{\alpha_Y}{4\pi f_a}\bar{\tilde{a}}\tilde{Y} \sum_{\tilde{f}} g_Y \tilde{f}^* Q_Y \tilde{f},$$

In the Kim-Shifman-Vainstein – Zakharov (KSVZ) model $c_1 = c_2 = 0$ and $c_3 = 1$

K.-Y. Choi, L. Covi, J. E. Kim, L. Roszkowski, JHEP 2012

Photino (NLSP) decays into the axino + photon

$$\tilde{\gamma} \rightarrow \tilde{a} + \gamma$$

Kim, Nanopoulos, AM
Phys. Lett. 139B (1984) 346-350

New bounds on the photino mass in presence of the photino radiative decay

3 fundamental ingredients for the analysis:

i) The **photino decoupling temperature** T_D;

ii) The **temperature at which the universe gets photino dominated** T^*

iii) The **photino decay temperature** T_{decay}

$$\tilde{\gamma} = \sin\theta_W \tilde{W}^3 + \cos\theta_W \tilde{B}^\circ$$

$$\mathcal{L}_{\tilde{\gamma}\tilde{\gamma}\to f\bar{f}} = \sum_f \bar{\tilde{\gamma}} \gamma^\mu \gamma_5 \tilde{\gamma} \bar{f} \gamma_\mu \left[A_f \left(\frac{1-\gamma_5}{2}\right) + B_f \left(\frac{1+\gamma_5}{2}\right)\right] f$$

A_f and B_f refer only to the s-fermion exchange since the Z^0 mediated photino annihilation amplitude is proportional to the Higgsino contribution to photino. For photino masses , 100MeV only electrons can be produced in the photino-photino annihilation into fermions.

$$T^* = \frac{m_{\tilde{\gamma}}}{(1.68)(2.75)} \exp(-m_{\tilde{\gamma}}/T_D)$$

Photino $T_{decoupling}$ > 1Mev →
photino decouples before nucleosynthesis starts

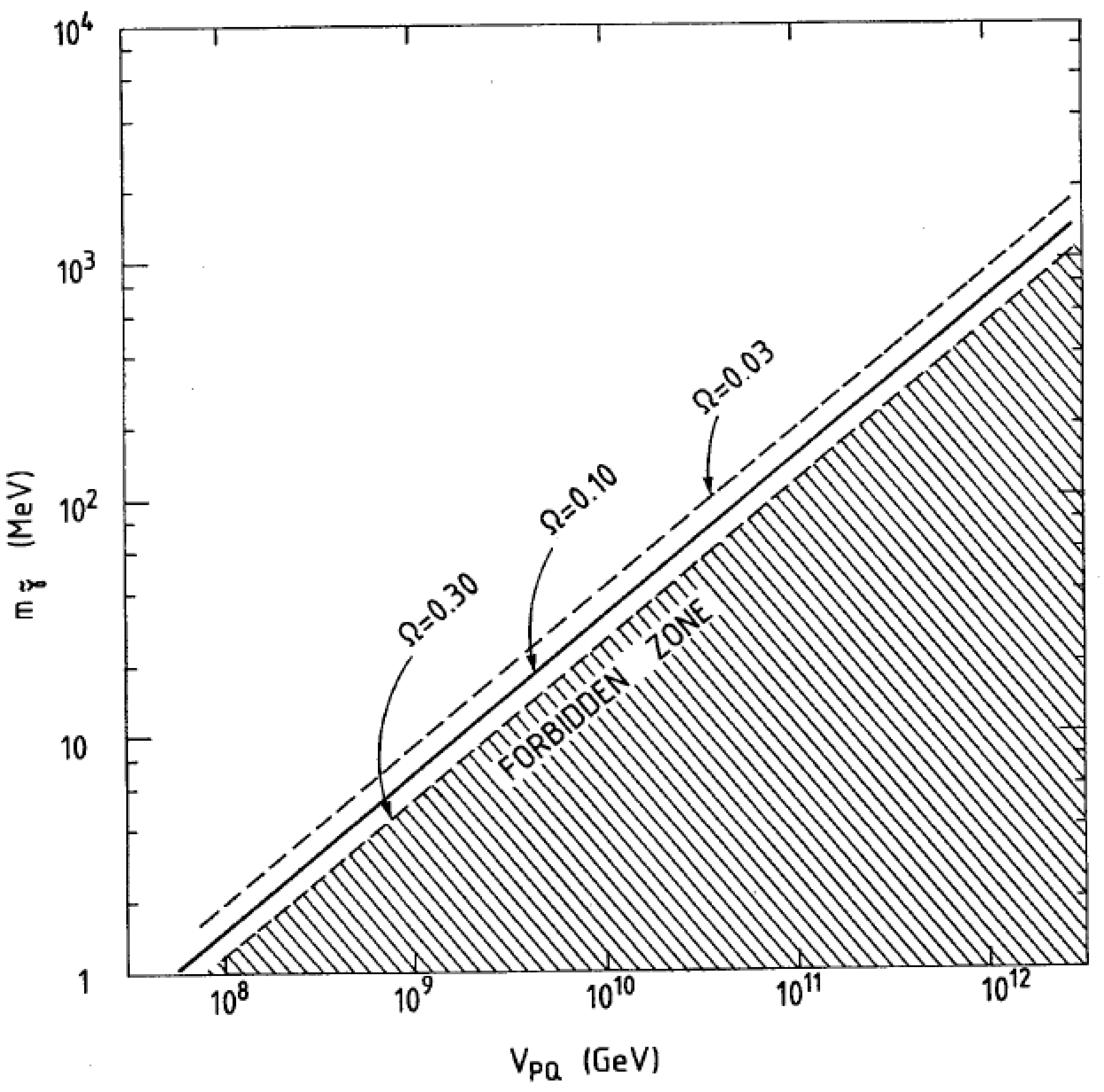
$T^* < T_{BBN}$ → universe dominated by radiation during BBN --> only requirement on photino decay time is that photinos decay sufficiently fast to get a thermalization of the photons in the decay products (Dicus, Kolb, Teplitz Astrophys. J. 1978)

$m_{\tilde{\gamma}}$ \ v	$m_{\tilde{\gamma}}$ \ v_{PQ}	10^8 GeV	10^9 GeV	10^{10} GeV	10^{11} GeV	10^{12} GeV
1000	1000	9.59×10^{-4}	9.59×10^{-2}	9.59	9.59×10^{2}	9.59×10^{4}
800	800	1.87×10^{-3}	1.87×10^{-1}	1.87×10	1.87×10^{3}	1.87×10^{5}
500	500	7.67×10^{-3}	7.67×10^{-1}	7.67×10	7.67×10^{3}	7.67×10^{5}
100	100	0.959	9.59×10	9.59×10^{3}	9.59×10^{5}	9.59×10^{7}
80	80	1.87	1.87×10^{2}	1.87×10^{4}	1.87×10^{6}	1.87×10^{8}
60	60	4.44	4.44×10^{2}	4.44×10^{4}	4.44×10^{6}	4.44×10^{8}
50	50	7.67	7.67×10^{2}	7.67×10^{4}	7.67×10^{6}	7.67×10^{8}
40	40	15.0	1.50×10^{3}	1.50×10^{5}	1.50×10^{7}	1.50×10^{9}
30	30	35.52	3.55×10^{3}	3.55×10^{5}	3.55×10^{7}	3.55×10^{9}
20	20	1.20×10^{2}	1.20×10^{4}	1.20×10^{6}	1.20×10^{8}	1.20×10^{10}
10	10	9.59×10^{2}	9.59×10^{4}	9.59×10^{6}	5.59×10^{8}	9.59×10^{10}

Photino mass (MeV)

Photino lifetimes (sec.)

Efficient thermalization of photons from $\tilde{\gamma} \rightarrow \tilde{a} + \gamma$ ⇒ $\tau_{\tilde{\gamma}} < 3 \times 10^5$ secs.

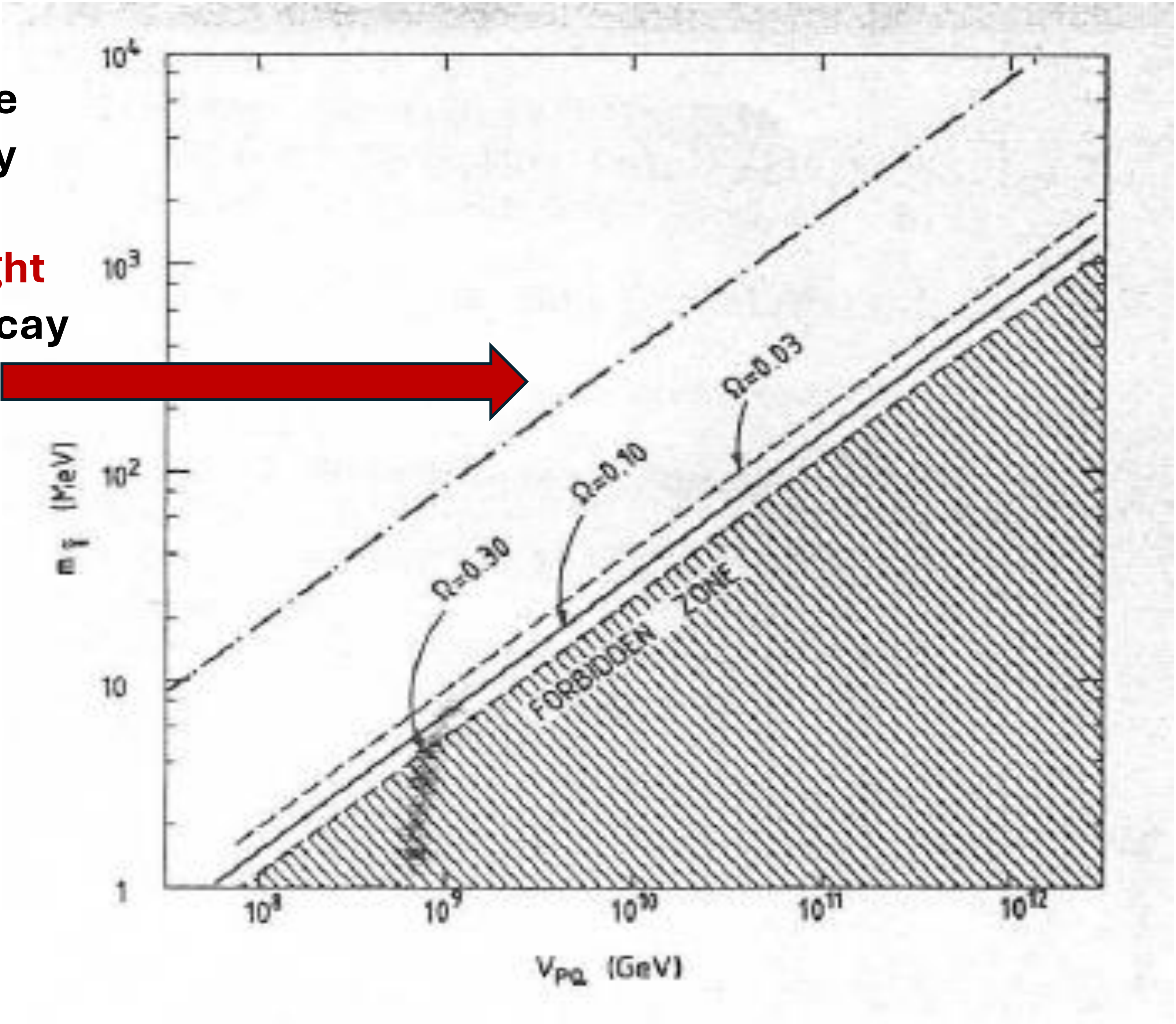


Lower bound on the photino mass > 1.5 MeV for any allowed value of V_{PQ}

for $V_{PQ} = 10^{10}$ GeV $m_{photino} > 40$ MeV

For the maximal value of $V_{PQ} = 10^{12}$ GeV $m_{photino} > 700$ MeV, hence with a decaying photino and $V_{PQ} = 10^{12}$ GeV, even the region 500 MeV < $m_{photino}$ < 700MeV – allowed in the case of a stable photino – becomes now forbidden

More stringent bound on the photino lifetime provided by the constraints due to the possible photofission of light elements (D, ^{4}He) by the decay photons



Lindley, Mon. Not. R.Astr. Soc. 1979;
Sarkar, Cooper Proc. ESO/CERN Symposium 1983

Post-1984 Photino, Axino and DM (continuous) update

Axino THERMAL production (TP): **axino production through scatterings and decays of particles in thermal equilibrium → dependence on the REHEATING temperature after inflation (T_R)**

TP Axinos from neutralino NLSP decays: **CDM** candidates ; for axino masses between O(MeV) to several GeV $T_R < 10^5$ GeV (Covi, Kim, Roszkowski PRL 1999; Covi, H.B. Kim, J.E.Kim, Roszkowski JHEP 2001; Covi, Kim New J. Physics 2009

TP axinos → with masses ~ O(keV) **WDM** (Rajagopal, Turner, Wilczek NPB 1991); with masses << O(keV) **HDM** (Kim, AM, Nanopoulos PLB 1984

Choi, Covi, Kim, Roszkowski JHEP 2012

Axino NON-THERMAL production (NTP): independent of T_R, axinos produced from the decay of the NLSP after its freeze-out.

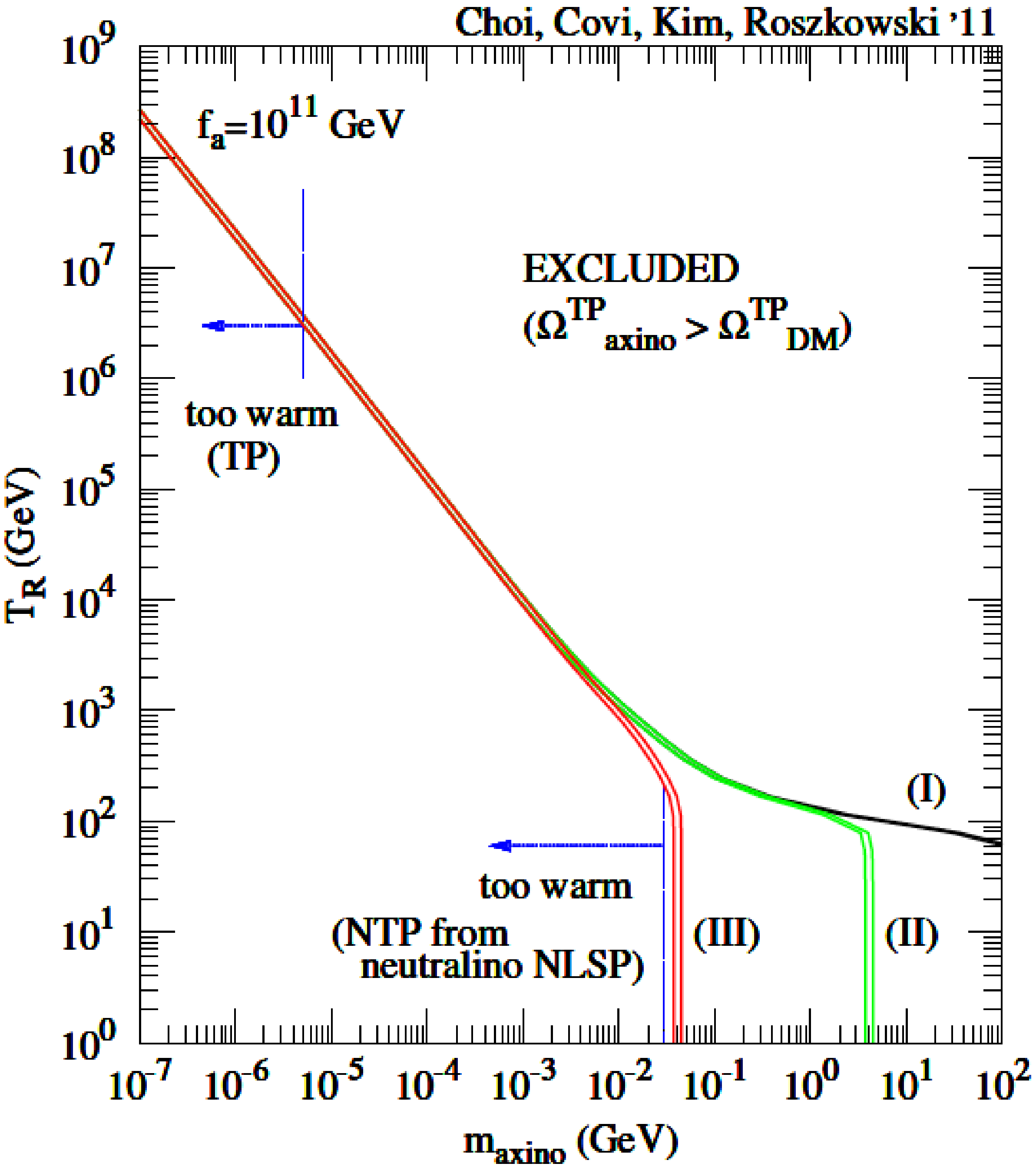
For a bino-dominated lightest neutralino → For neutralino NLSP decays into axino+photon, the NTP production is usually more efficient

$$\Omega_{\tilde{a}}^{\rm NTP} = \frac{m_{\tilde{a}}}{m_{\rm NLSP}} \Omega_{\rm NLSP} \simeq 2.7 \times 10^{10} \left(\frac{m_{\tilde{a}}}{100\ {\rm GeV}} \right) Y_{\rm NLSP}$$

$$Y_\chi \simeq (1 \sim 10) \times 10^{-12} \left(\frac{m_\chi}{100\ {\rm GeV}} \right)$$

Choi, Covi, Kim, Roszkowski JHEP 2012

Baer, Choi, Kim, Roszkowski Phys. Rept. 2015 DM beyond the thermal WIMP paradigm



Kim, Nanopoulos, AM
PLB 145 (1984) 187-191

Ref.TH.3866-CERN

CONFLICTS BETWEEN B VIOLATING PHENOMENA IN SUPERGRAVITY MODELS

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CERN - Geneva

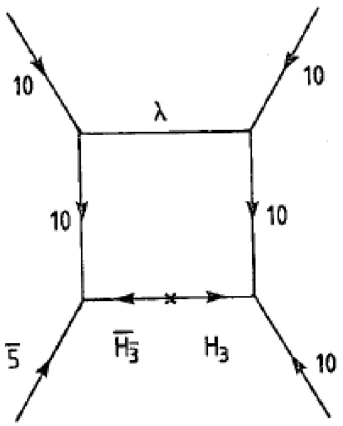
*) Permanent address: Dept. of Physics, Seoul National University, Seoul 151, Korea.

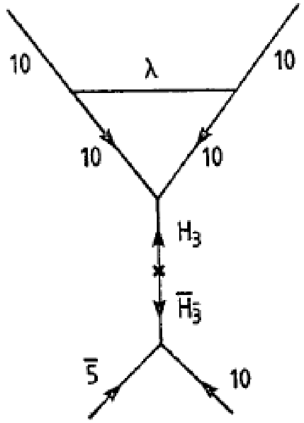
Ref.TH.3866-CERN
April 1984

Baryon-number violation in SUGRA

on the difficulty to create matter (baryogenesis) and then keep it stable (no p-decay)

Threat of too fast p-decay in SUSYGUT from dim.5 operators:





$$m_{\tilde{H}_3} > 10^{16}\ \mathrm{GeV}$$

$m_{3/2} \sim 10^2 - 10^3$ GeV cosmologically forbidden (Pagel, Primack PRL 1982; Weinberg PRL 1982) → need inflationary epoch to inflate way the gravitinos (Ellis, Linde, Nanopoulos PLB 1982; Nanopoulos, Olive, Srednicki PLB 1983)

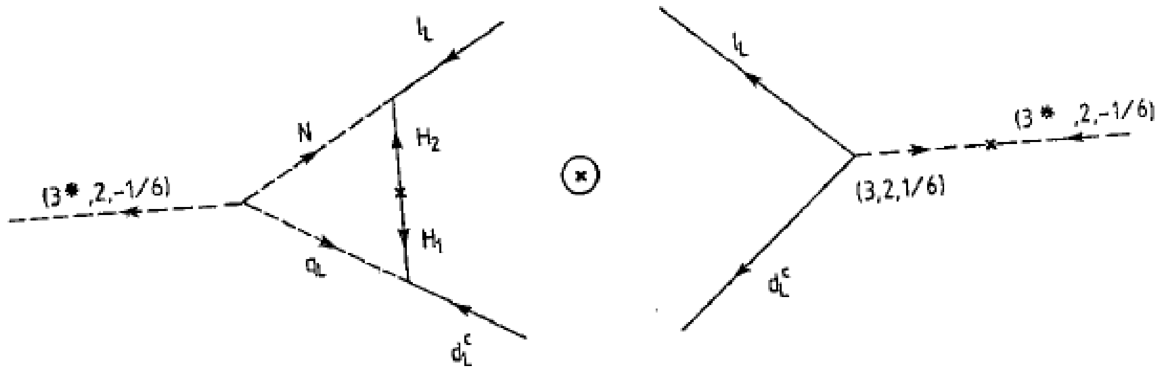
But if $T_{reheating}$ is too big, gravitinos are produced by 2-body reactions a+b → c + gravitino (Ellis, Kim, Nanopoulos PLB1982) → from BBN and CMB constraints need $T_{reheating} < 10^9 - 10^{10}$ **GeV**

Need baryon production AFTER inflation → the coloured Higgs triplet H_3 cannot be used to produce the cosmic baryon asymmetry

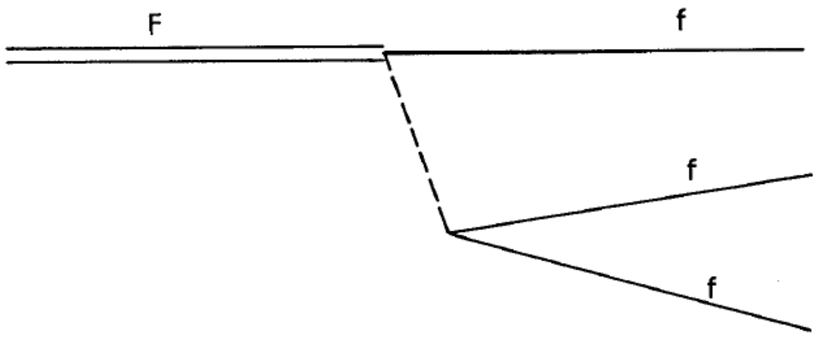
The **same difficulty** as for the Higgs triplets (3*, 1, 1/3) is encountered when considering **other scalars responsible for 4-fermion ΔB = 1 processes** (i.e., (3, 1, -4/3), (3, 3, -1/3) in MSSM

in N = 1 SUGRA SU(5) and in the MSSM with the introduction of ΔB ≠ 0 Yukawa couplings with coloured Higgs fields (3, 1, -1/3), (3, 1, -4/3), etc. with $m_{3/2}$ ~ O (100 – 1000 GeV) it is NOT possible to obtain a sufficient cosmological baryon asymmetry (unless there is large mixing of the 5-plets $H_1 - H_2$ at high T, while such mixing becomes ~ $m_{3/2}$ at zero temperature.

Efficient baryogenesis is NOT achieved even using scalars, such as (3*, 2, -1/6) whose decay can lead to baryon production, while they **cannot mediate p-decay** (Kim PLB 1983)



Introduction of superheavy FERMIONS which can produce baryons through their decays into 3 ordinary fermions



Barbieri, AM, Nanopoulos PLB 1981; Yanagida, Yoshimura PRL 1980;
AM, Mohapatra PLB 1981

Heavy fermion F with m < 10^{10} GeV decaying via the exchange of superheavy scalars with mass > 10^{15} GeV

It does NOT work since the net baryon asymmetry is diluted too much in decay of such heavy fermions F (AM, Nanopoulos Tamvakis, Yanagida Z. Phys. C 1983

Major conclusion of our paper Kim, AM, Nanopoulos PLB 1984

INCOMPATIBILITY between matter stability and cosmological baryon production in N=1 SUGRA →
possible (weird) ways-out: introduction of new heavy scalars (not mediating p-decay) **with μ mixing proportional to T^2** or **superheavy (or superlight) gravitinos** (Ellis, Enqvist, Gelmini, Kounnas, AM, Nanopoulos, Smirnov NPB 1982)

Other way-out: **$m_{3/2}$ ~ 100 – 1000 GeV and high $T_{reheating}$ ~ 10^{12} – 10^{14} GeV are compatible with cosmology if the gravitino decays predominantly into neutrino-sneutrino pairs (the sneutrino could be the LSP)**

Frieman, Giudice PLB 1989

The evergreen photino (today bino) → axino (today ALPino) + photon decay process

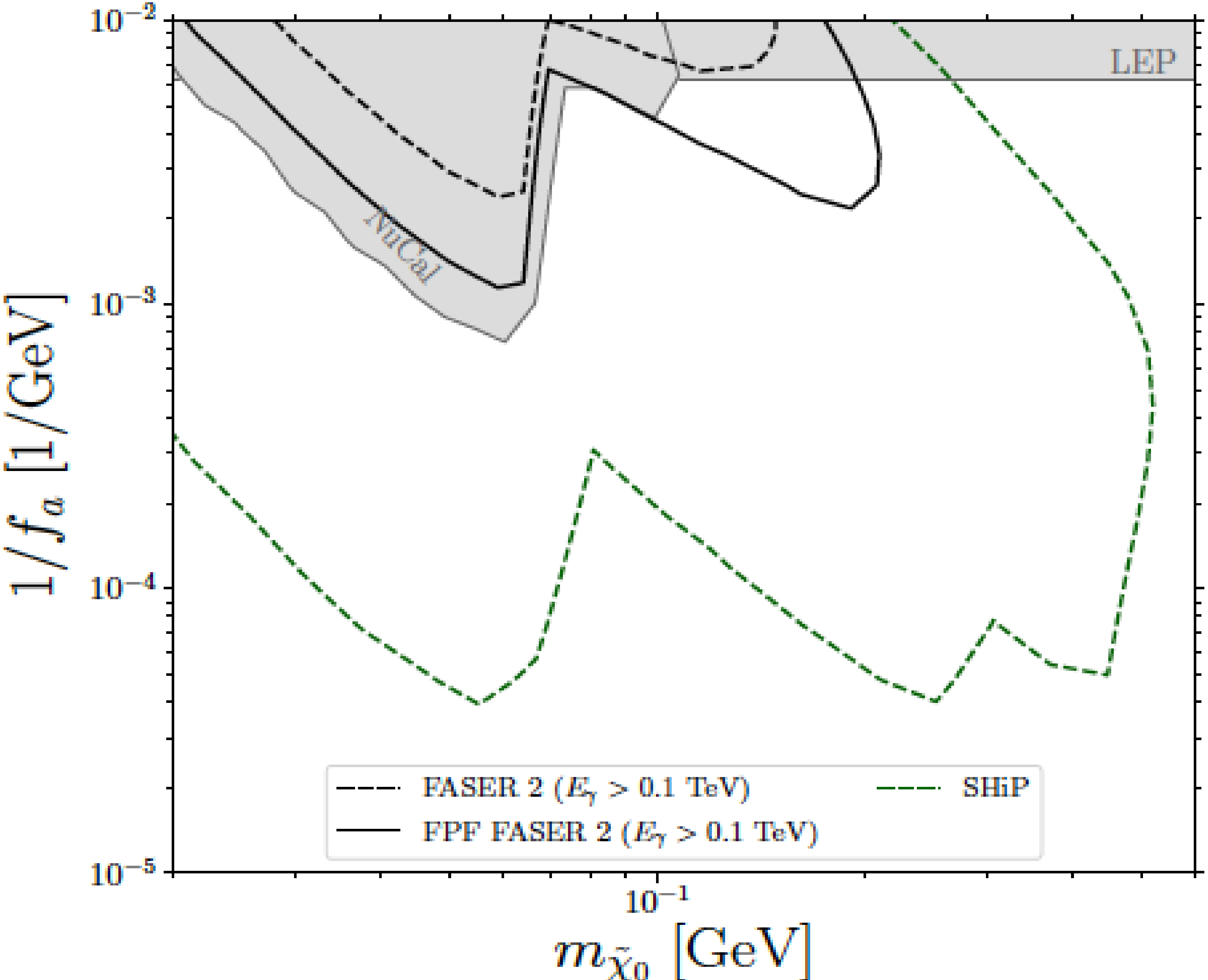
Bino → very poor constraints from collider physics → **sub-GeV Bino** still allowed by HE physics, but possible problems if it is the (predominant) source of DM

Bino decay → SUSY with R-Parity violation

Bino decay → Bino → LSP (gravitino or axino (ALP-ino)) + γ

Search for single-photon LLP (Long-Lived Particle) decays: i) at LHC, in addition to the already existing detectors like FASER, a new dedicated facility to the search of LLP, the Forward Physics Facility (FPF) has been proposed; ii) beam dump experiments CHARM, NuCal, SHiP

Jodlowski 2306.0098; PRD 2023

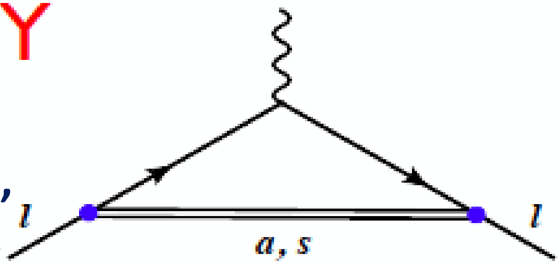


LEP
NuCal
FASER 2 ($E_\gamma > 0.1$ TeV)
FPF FASER 2 ($E_\gamma > 0.1$ TeV)
SHiP
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-1}
$1/f_a$ [1/GeV]
$m_{\tilde{\chi}_0}$ [GeV]

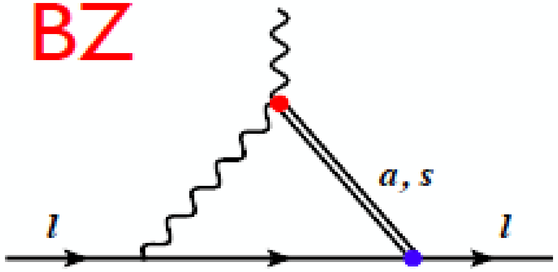
ALPs contributions to the muon g-2?

Marciano, AM, Paradisi, Passera ‘16; Bauer, Neubert, Thamm ‘17; Bauer, Neubert, Renner, Schnubel, Thamm ‘19; Cornella, Paradisi, Sumensari ‘19

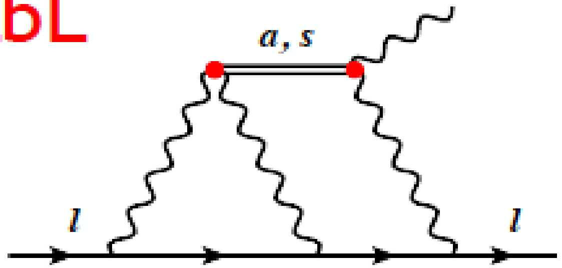
Y



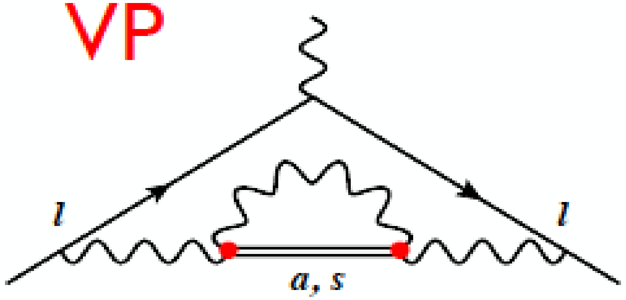
BZ



LbL



VP



- Both scalar and pseudoscalar ALPs can solve Δa_μ for masses ~ [100MeV-1GeV] and couplings allowed by current experimental constraints.
- They can be tested at present low-energy e^+e^- experiments, via dedicated $e^+e^- \to e^+e^-$+ALP & $e^+e^- \to \gamma$+ALP searches.

$$\mathcal{L} = e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{c_{\mu\mu}}{2} \frac{\partial^\nu a}{\Lambda} \bar{\mu}\gamma_\nu\gamma_5\mu$$

$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + i\, y_{a\psi}\, a\, \bar{\psi}\gamma_5\psi$$

$$g_{a\gamma\gamma} \equiv \frac{2\sqrt{2}\,\alpha}{\Lambda} c_{a\gamma\gamma}$$

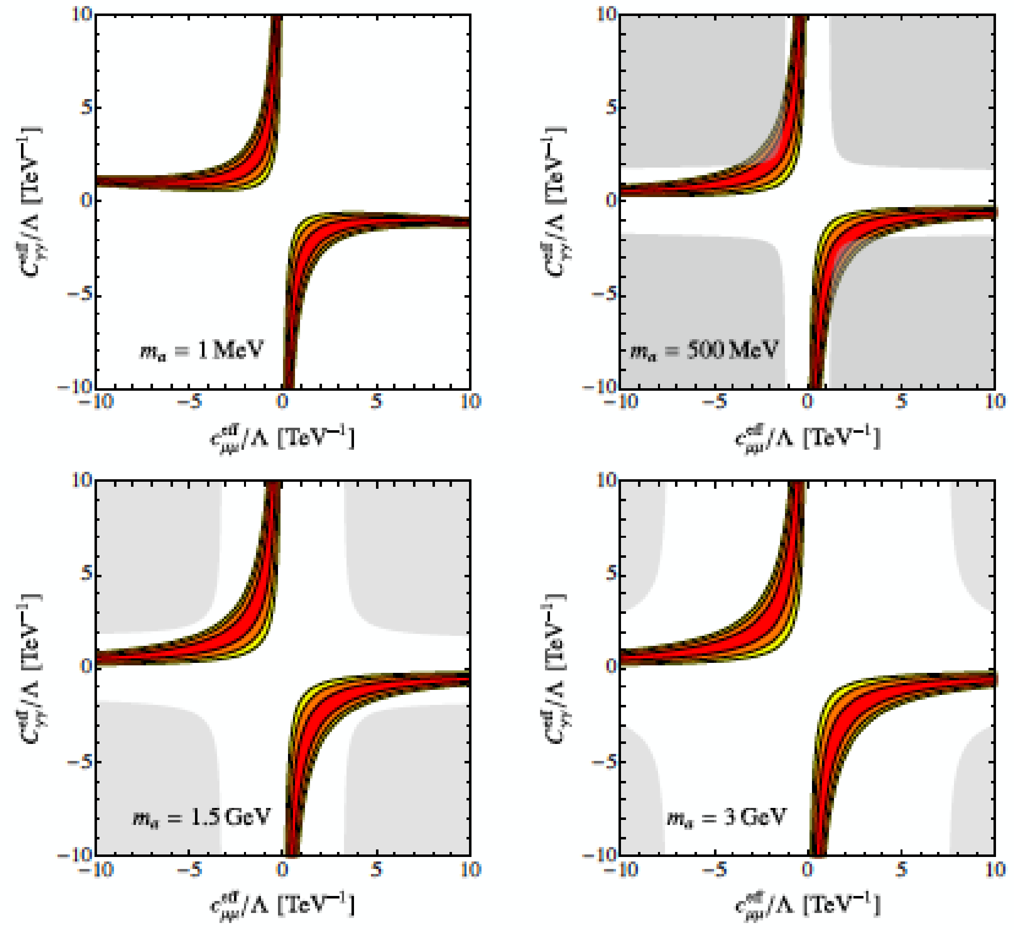
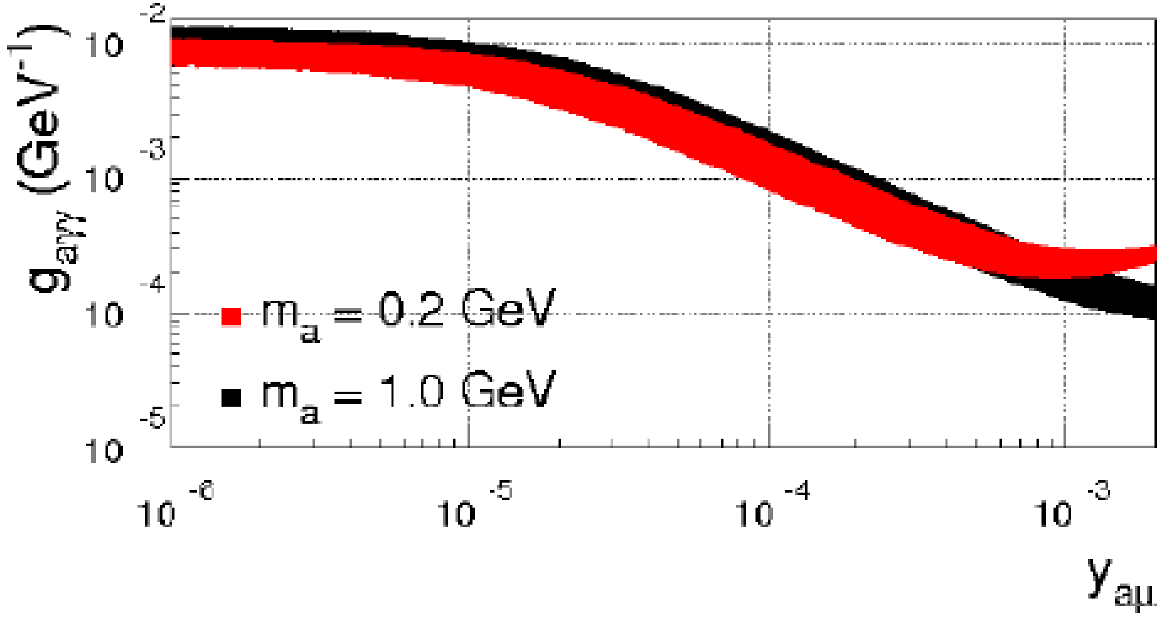
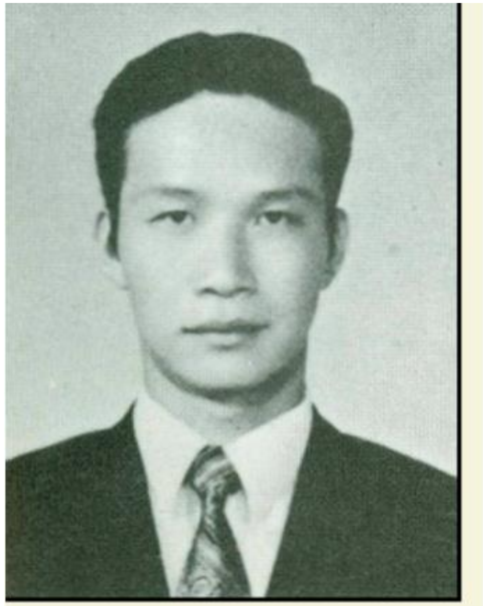


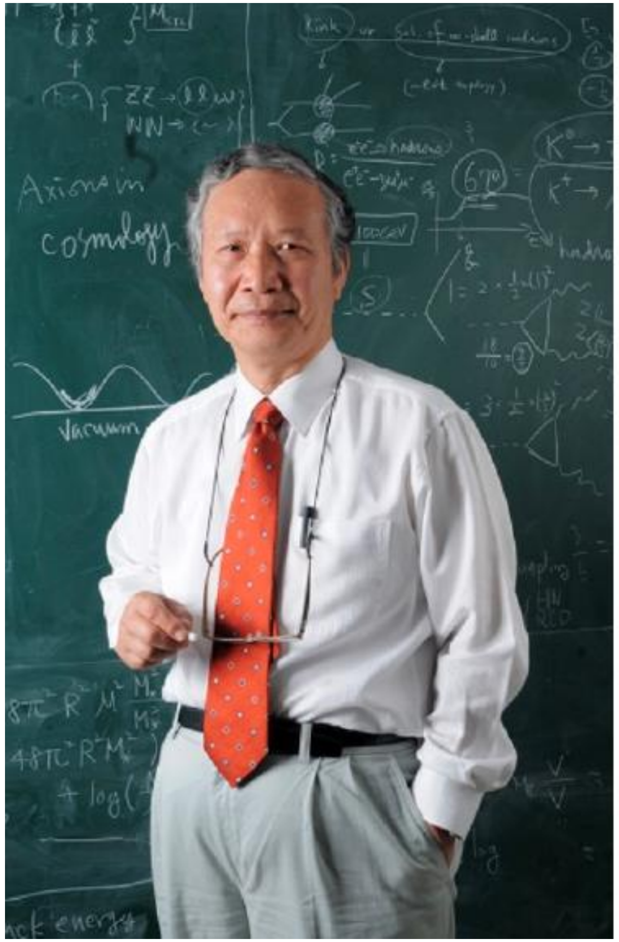
Figure: Δa_μ regions favoured at 68% (red), 95% (orange) and 99% (yellow) CL. Gray regions are excluded by the BaBar search $e^+e^- \to \mu^+\mu^- + \mu^+\mu^-$ [Bauer, Neubert, Thamm, '17]



Pseudoscalar 1σ solution bands to the g-2 muon anomaly taking Λ = 1 TeV

Marciano, A.M., Paradisi, Passera '16





감사합니다

GAMSAHAMNIDA ! **for the great opportunity (and pleasure!) to work with you, benefiting from your calm and thorough wisdom, just at the beginning of my research trip and from time to time along the fascinating and hard journey to (try to) know something more ...**

and... 감사합니다

to the organizers and to the personnel who so efficiently contributed to realize such a successful workshop and this wonderful occasion to be close to Jihn E in this special moment