IBS-SNU Joint Workshop - KIM Fest - Seoul, 04.05.2016

From Axion to Axino DM

Laura Covi

Institute for Theoretical Physics
Georg-August-University Göttingen

OUTLINE

- From Axions to Axinos
- Axino Dark Matter and the maximal reheating temperature
- General FIMP/SuperWIMP scenario at the LHC
- Leptogenesis with broken EW symmetry
- Outlook

From Axions to Axinos

AXION:

STRONG CP problem $\Rightarrow$ PQ symmetry [Peccei & Quinn 1977]

$\theta_{QCD} < 10^{-9}$ axion a

Introduce a global $U(1)_{PG}$ symmetry broken at f_a, then θ becomes the dynamical field a,

a pseudogoldstone boson with interaction:

$$\mathcal{L}_{PQ} = \frac{g^2}{32\pi^2 f_a} a \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

A small axion mass is generated at the QCD phase transition by instanton's effects

$$m_a = 6.2 \times 10^{-5} \text{eV} \left(\frac{10^{11} \text{ GeV}}{f_a} \right)$$

Axion physics constrains

$$5 \times 10^9 \text{ GeV} \leq f_a \leq 10^{12} \text{ GeV}$$

SN cooling $\Omega_a h^2 \leq 1$ [Raffelt '98]

ADD SUSY: $a \Rightarrow \Phi_a \equiv (s + ia, \tilde{a})$ with $W_{PQ} = \frac{g^2}{16\sqrt{2}\pi^2 f_a} \Phi_a W^\alpha W_\alpha$ [Nilles & Raby '82] [Frére & Gerard '83]

AXINO couplings equal mostly to those of the axion

AXINO mass depends on SUSY breaking : free parameter

Possibility of mixed axino/axion DM depending on f_a !

AXION and AXINO MODELS

KSVZ

[Kim '79], [Shifman, Vainstein & Zakharov '80]

$W = h_H \Phi_a \bar{Q} Q$ $\quad \bar{Q}, Q$ heavy quarks

SM fields are not charged under $U(1)_{PQ}$

$$m_Q = h_H f_a$$

$$h_H \simeq \mathcal{O}(1)$$

DFSZ

[Dine, Fischler & Srednicki '81], [Zhitnitskii '80]

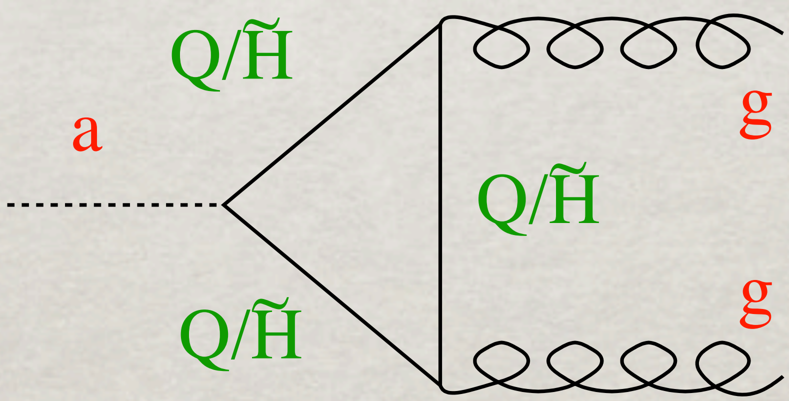
$W = h\, \Phi_a H_u H_d$ $\quad H_u, H_d$ Higgs multiplets

SM fields are charged under $U(1)_{PQ}$

$h f_a = \mu$ $\quad \mu$-term

$\rightarrow h \ll 1$

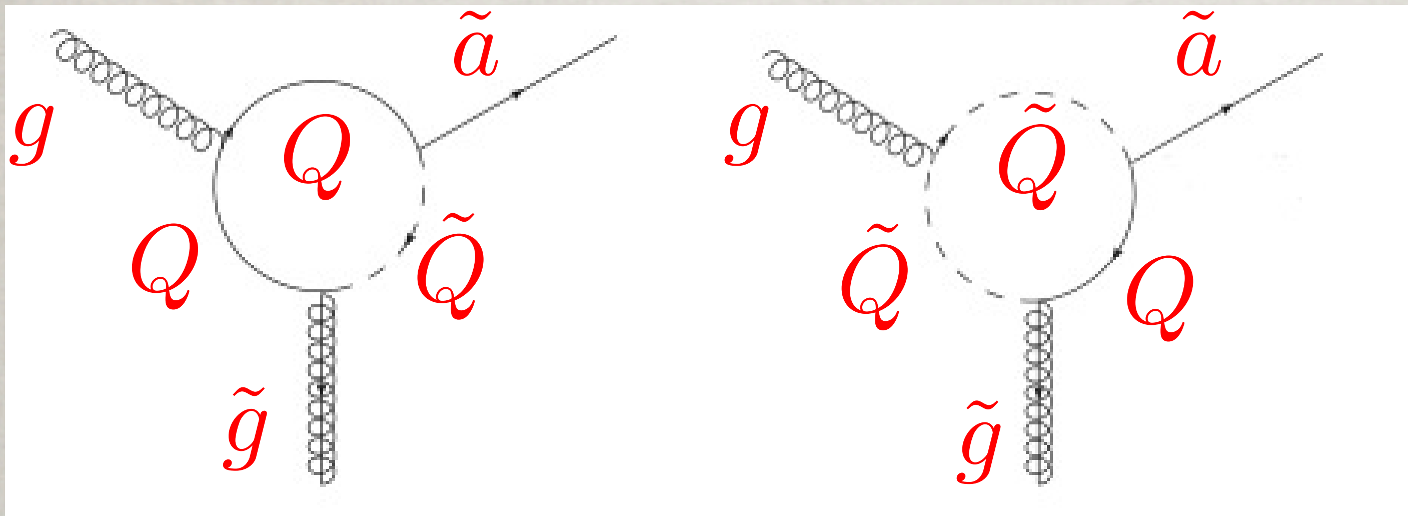
~ NMSSM



While the axion/axino couplings to QCD are model independent, the couplings to matter, quarks and leptons, and also Higgses, are model-dependent.

Axino effective coupling

But full computation of effective vertex: [Bae, Choi & Im 11]



$$\mathcal{A}(p, q, M_Q)$$

$$\mathcal{A}(p, q, M_Q) \propto \begin{cases} \frac{M_Q^2}{p^2} \ln^2\left(\frac{M_Q^2}{p^2}\right) & \text{for } \; p^2 >> M_Q^2 \\ 1 - \frac{p^2}{12 M_Q^2} & \text{for } \; p^2 << M_Q^2 \end{cases}$$

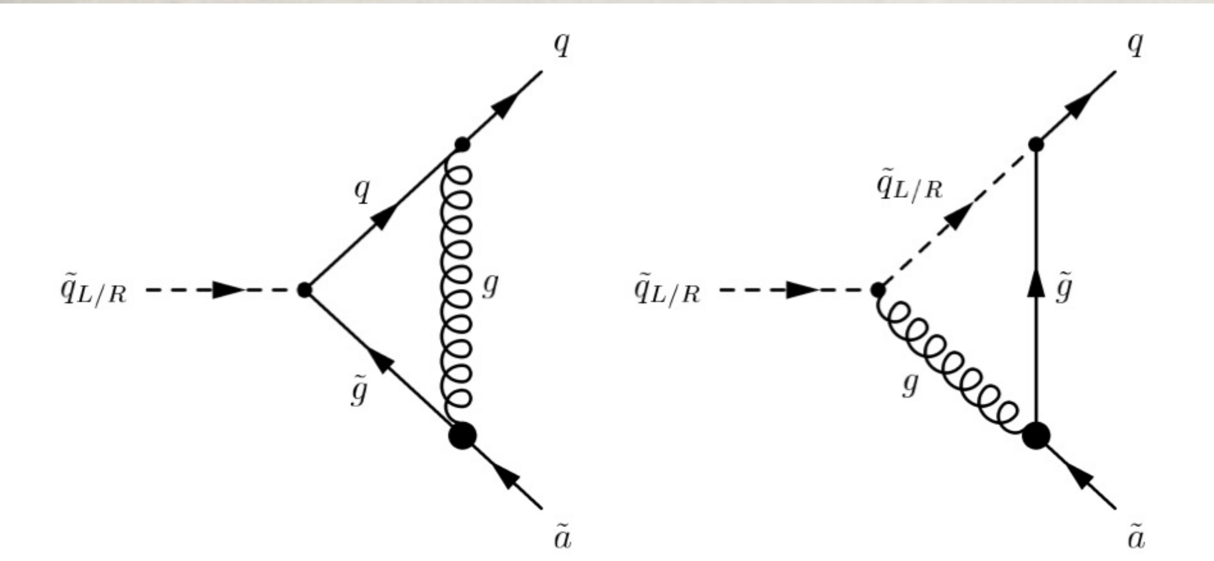
Constant vertex only for heavy quarks/squarks !

OK for KSVZ with $M_Q \sim f_a$. Suppressed for DFSZ.

AXINO EFFECTIVE COUPLINGS

KSVZ axino effective vertex with matter:

[LC, L. Roszkowski M. Small 2002]



Couplings are generated at one loop effective (two loop really...)

$$g_{eff}^{L/R} \simeq \mp \frac{\alpha_s}{\sqrt{2}\pi} \frac{m_{\tilde{g}}}{f_a} \left[\ln\left(\frac{f_a}{m_{\tilde{g}}}\right) + \mathcal{O}(1) \right] + \mathcal{O}\left(\frac{m_q}{f_a}\right)$$

Enhanced for heavy gluino/Wino/Bino !

Terms of order one difficult to estimate in effective theory...

Axino-stau coupling

The full two-loop computation of the axino couplings to sleptons-lepton and quark-squarks in the hadronic axion models has been done by [Freitas, Steffen, Tajuddin & Wyler 09].
this is important for the stau NLSP decay:

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

at leading log, where the e.m. charge and mass of the heavy quarks are $e_Q, y f_a$ respectively. It is suppressed by loop factors and large powers of the coupling.
It gives ~ 20% correction to the previous computation using an effective one loop approximation [LC, L. Roszkowski, M. Small, 02]
This is important for computing the stau NLSP lifetime !

Axino
Dark Matter

Axino CDM connection

J.E. Kim L. Roszkowski LC

Axino CDM connection

Axinos as Cold Dark Matter

Laura Covi[1], Jihn E. Kim[2,3], and Leszek Roszkowski[1]
(1) *Department of Physics, Lancaster University, Lancaster LA1 4YB, England*
(2) *Center for Theoretical Physics, Seoul National University, Seoul 151-742, Korea*
(3) *Korea Institute for Advanced Study, Cheongryangri-dong, Seoul 130-012, Korea*
(February 1, 2008)

THE WIMP PARADIGM

Primordial abundance of stable massive species

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma(X + X \rightarrow \text{anything})v \rangle \left(n_{eq}^2 - n_X^2\right)$$

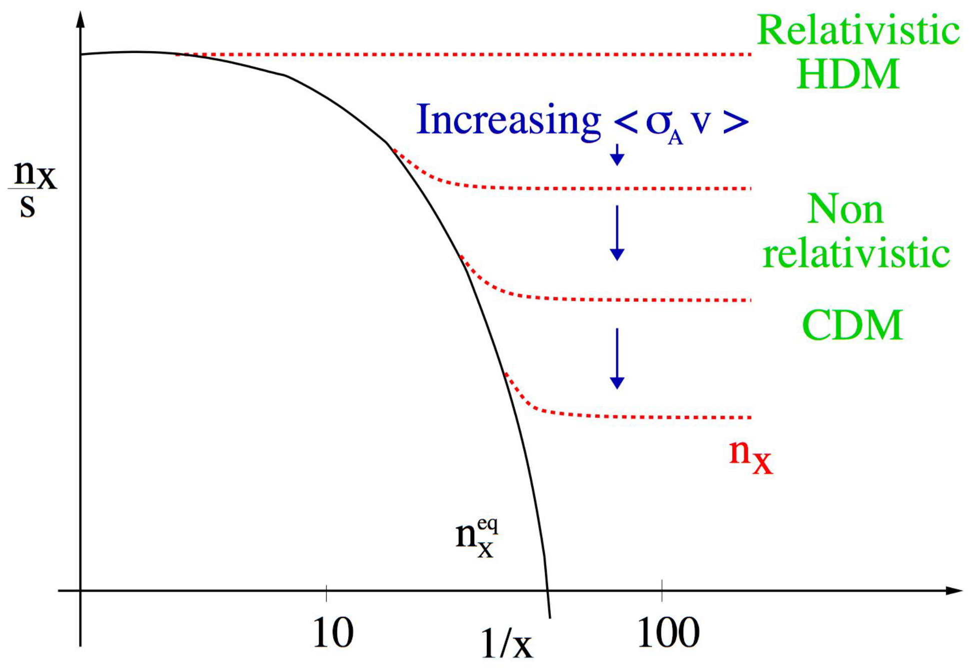
Hubble expansion   Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

defined by $n_{eq} \langle \sigma_A v \rangle_{x_f} = H(x_f)$ and that gives

$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties



For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !

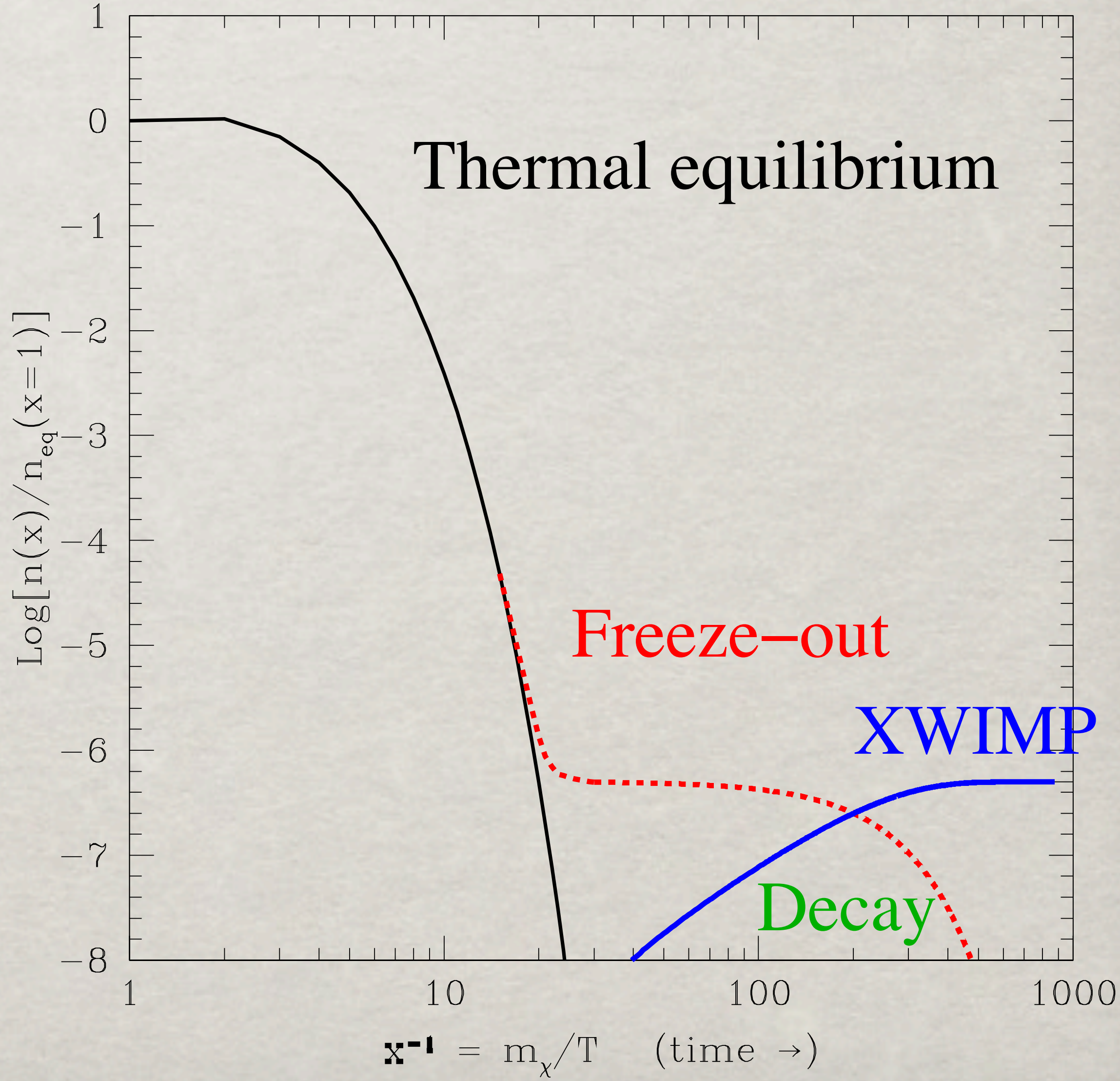
NLSP DECAY

- For long lifetime the NLSP decays after freeze-out and R-parity is conserved

$$\boxed{\Omega_X^{NT} = \frac{m_X}{m_{NLSP}} \Omega_{NLSP}}$$

- The LSP is not thermal
- Other energetic particles are produce in the decay: beware of BBN... But the axino is much safer than the gravitino !

[JE Kim, A Masiero, D Nanopoulos '84]
[LC, JE Kim, L Roszkowski '99],
[J Feng et al '04]



A MATTER OF LIFETIME...

Due to the suppressed couplings, the NLSP decays slowly into an axino/gravitino and a SM particle.
Consider a Bino neutralino NLSP and R-parity conservation.
What is its lifetime for axino or gravitino LSP?

For an axino LSP:

$$\Gamma_{\tilde{B}}^{-1} = 0.25\,\mathrm{s} \left(\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}} \right)^{-3} \left(\frac{f_a}{10^{11}\ \mathrm{GeV}} \right)^{2}$$

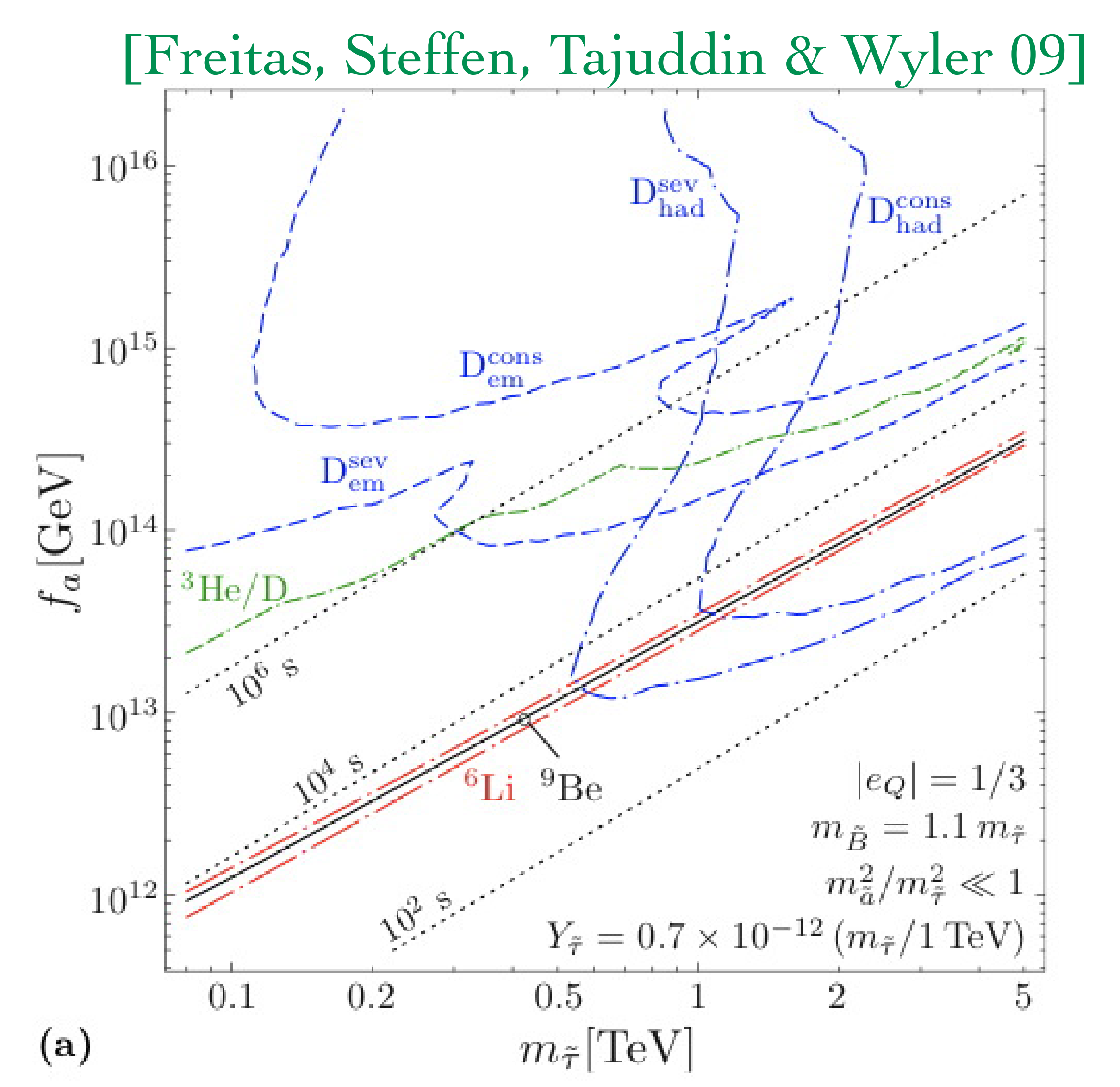
For a gravitino LSP:

$$\Gamma_{\tilde{B}}^{-1} = 5.7 \times 10^{4}\mathrm{s} \left(\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}} \right)^{-5} \left(\frac{m_{\tilde{G}}}{1\ \mathrm{GeV}} \right)^{2}$$

Quite different timescale, apart for large f_a or small gravitino mass... Trouble for a gravitino heavier than 1 GeV !

UPPER BOUND ON f_a

For τ_R NLSP



More stringent bounds than for neutralino NLSP [H. Baer et al]

CAN THE AXINO BE COLD DARK MATTER ?

YES, if the Universe was never hot enough
for axino to be in thermal equilibrium...

Very weakly interacting particles as the axino & gravitino
are produced even in this case, at least by two mechanisms

PLASMA SCATTERINGS

$$\Omega_{DM} h^2 \propto T_R \; \frac{m_{\tilde{a}}}{f_a^2}$$

NLSP DECAY OUT OF EQUILIBRIUM

$$\Omega_{DM} h^2 \propto \frac{m_{DM}}{m_{NLSP}} \Omega_{NLSP} h^2$$

THERMAL PRODUCTION

At high temperatures, the dominant gravitino production is due to 2-to-2 scatterings with the gauge sector, mostly QCD:

$$\Omega_{3/2}h^2 \simeq 0.3 \left(\frac{1\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{T_R}{10^{10}\ \mathrm{GeV}}\right)\sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}}\right)^2$$

[Bolz,Brandenburg & Buchmuller 01], [Pradler & Steffen 06, Rychkov & Strumia 07]

where M_i are the gaugino masses and $c_i \sim 0(1)$

So in general there is always a bound on the reheat temperature and such temperature has to take a specific value in order to match the DM density. Note that the smaller $m_{3/2}$, the smaller the temperature has to be.

Tension with thermal leptogenesis for small gravitino masses !

Axino CDM connection II

Hang Bae Kim Jihn E. Kim L. Roszkowski LC

Axino CDM connection II

Axinos as dark matter

Laura Covi (DESY) , Hang-Bae Kim (Lancaster U.) , Jihn E. Kim (Seoul Natl. U.) ,
Leszek Roszkowski (Lancaster U. & CERN)

Jan 2001 - 30 pages

JHEP 0105 (2001) 033
DOI: 10.1088/1126-6708/2001/05/033
CERN-TH-2000-378, DESY-00-193, SNUTP-00-034
e-Print: hep-ph/0101009 | PDF

THERMAL PRODUCTION

[LC, Hang Bae Kim, Jihn E. Kim, L. Roszkowski]

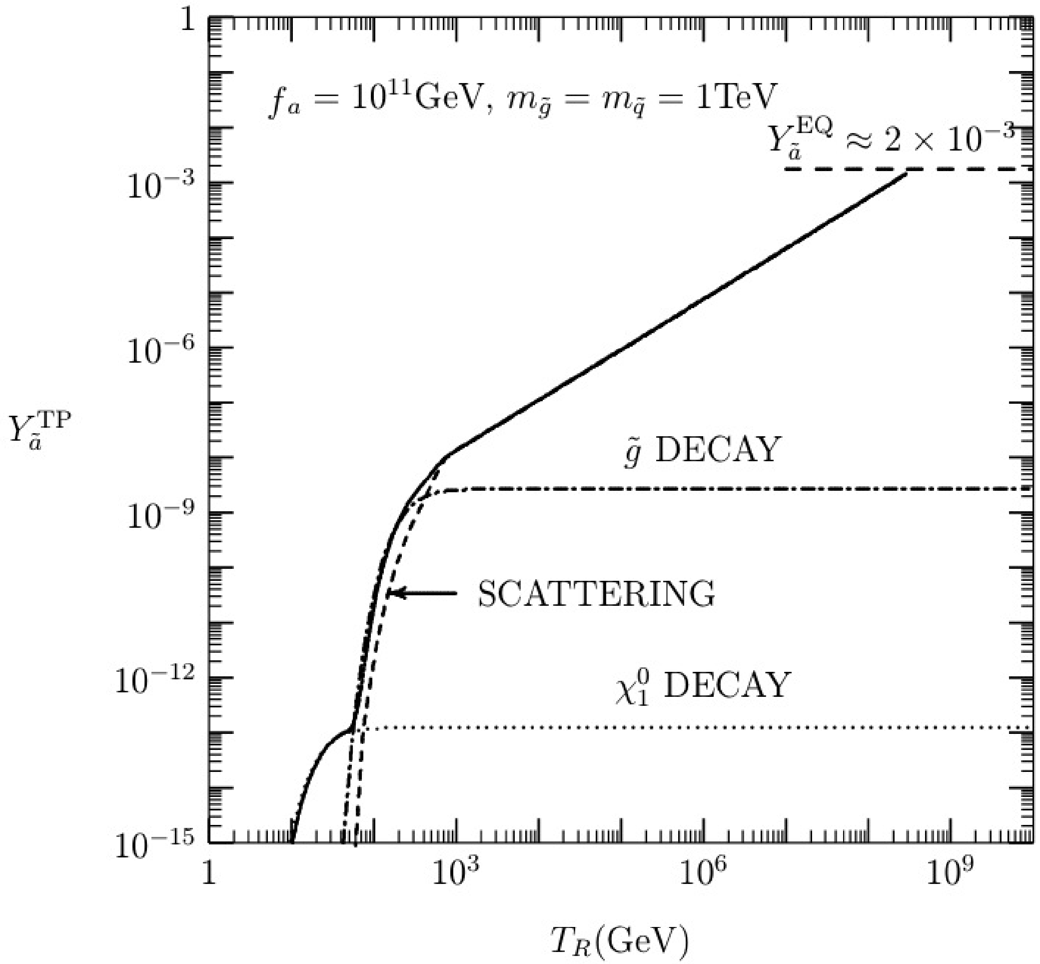
CROSS SECTIONS from QCD "anomalous" vertex

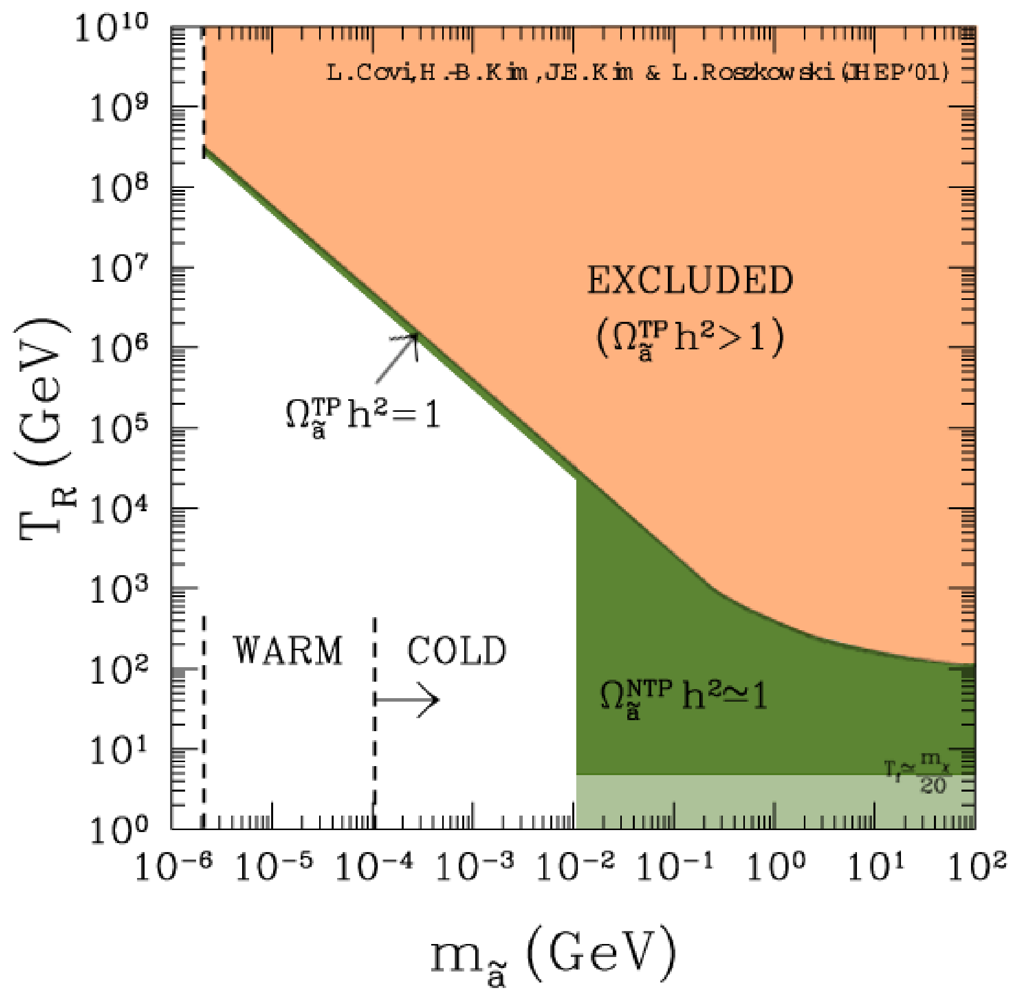
$$\sigma_N = \frac{\alpha_s^3}{4\pi^2 f_a^2}\bar{\sigma}_N$$

N	Process	$\bar{\sigma}_N$	n_S	n_F	$\eta_1\eta_2$
A	$g^a + g^b \to \tilde{a} + \tilde{g}^c$	$\frac{1}{8}\lvert f^{abc}\rvert^2$	4	1	1
B	$g^a + \tilde{g}^b \to \tilde{a} + g^c$	$\frac{5}{16}\lvert f^{abc}\rvert^2\left[\log\left(\frac{s}{\mu_g^2}\right) - \frac{15}{8}\right]$	4	1	$\frac{3}{4}$
C	$g^a + \tilde{q}_k \to \tilde{a} + q_j$	$\frac{1}{8}\lvert T^a_{jk}\rvert^2$	2	$2N_F$	1
D	$g^a + q_k \to \tilde{a} + \tilde{q}_j$	$\frac{1}{32}\lvert T^a_{jk}\rvert^2$	4	$2N_F$	$\frac{3}{4}$
E	$\tilde{q}_j + q_k \to \tilde{a} + g^a$	$\frac{1}{16}\lvert T^a_{jk}\rvert^2$	2	$2N_F$	$\frac{3}{4}$
F	$\tilde{g}^a + \tilde{g}^b \to \tilde{a} + \tilde{g}^c$	$\frac{1}{2}\lvert f^{abc}\rvert^2\left[\log\left(\frac{s}{\mu_g^2}\right) - \frac{29}{12}\right]$	4	1	$\frac{3}{4}\ \frac{3}{4}$
G	$\tilde{g}^a + q_k \to \tilde{a} + q_j$	$\frac{1}{4}\lvert T^a_{jk}\rvert^2\left[\log\left(\frac{s}{\mu_g^2}\right) - 2\right]$	4	N_F	$\frac{3}{4}\ \frac{3}{4}$
H	$\tilde{g}^a + \tilde{q}_k \to \tilde{a} + \tilde{q}_j$	$\frac{1}{4}\lvert T^a_{jk}\rvert^2\left[\log\left(\frac{s}{\mu_g^2}\right) - \frac{15}{8}\right]$	2	$2N_F$	$\frac{3}{4}$
I	$q_k + \bar{q}_j \to \tilde{a} + \tilde{g}^a$	$\frac{1}{24}\lvert T^a_{jk}\rvert^2$	4	N_F	$\frac{3}{4}\ \frac{3}{4}$
J	$\tilde{q}_k + \tilde{q}_j \to \tilde{a} + \tilde{g}^a$	$\frac{1}{24}\lvert T^a_{jk}\rvert^2$	1	$2N_F$	1

THERMAL PRODUCTION

[LC, Hang Bae Kim, Jihn E. Kim, L. Roszkowski]





THERMAL PRODUCTION

Similarly for the axino, but the couplings are not enhanced by a small axino mass. A new computation by Strumia exploiting the similarity between axino & gravitino gives:

$$\Omega h^2 \simeq 2.72 \left(\frac{m_{\tilde{a}}}{0.1\mathrm{GeV}}\right) \left(\frac{T_R}{10^4\mathrm{GeV}}\right) \left(\frac{10^{11}\mathrm{GeV}}{f_a}\right)^2$$

[Strumia 10]

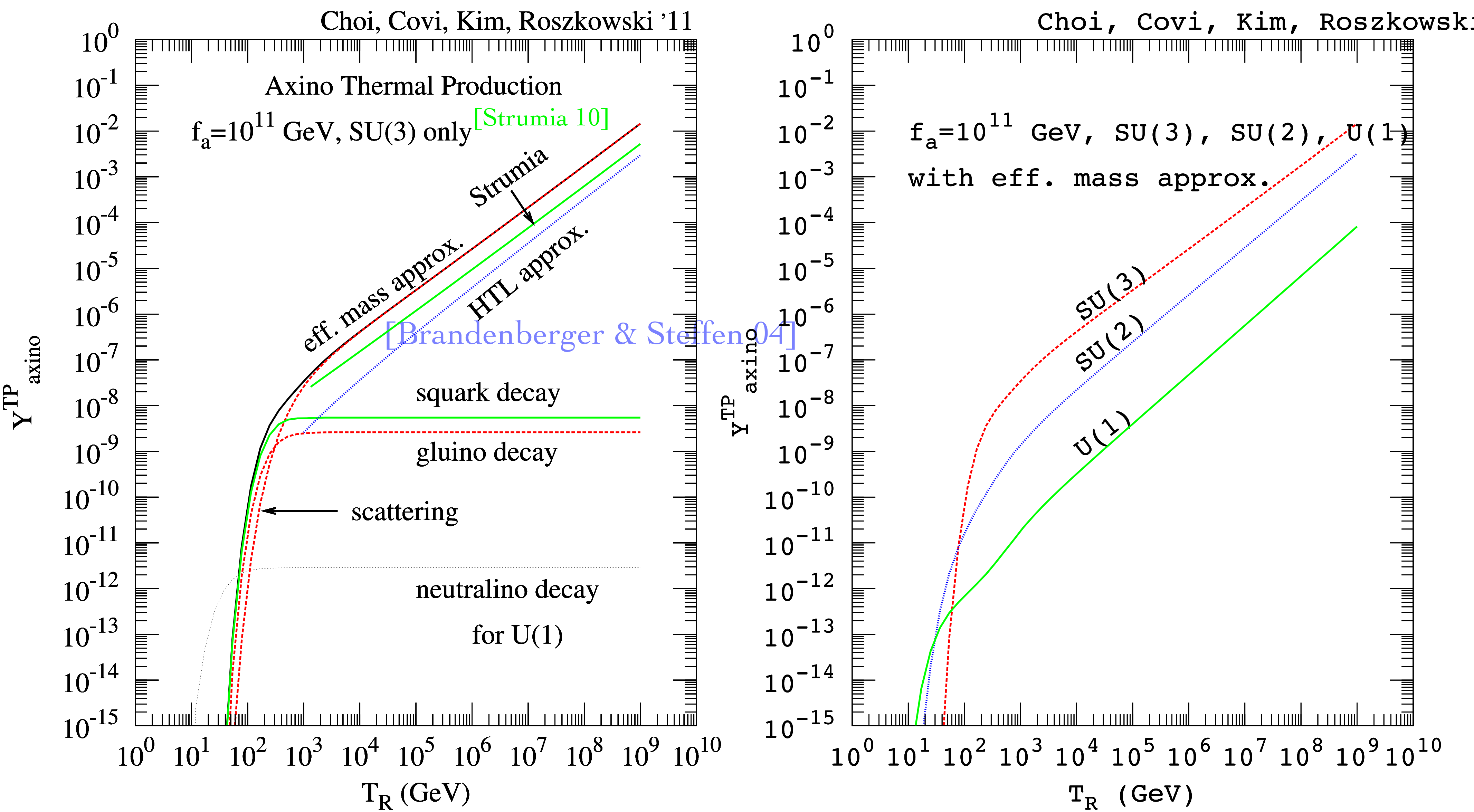
This includes a D-term contribution previously neglected and the effect of (thermally massive) gluon decay.

This is a factor ~ 2-3 larger than [Brandenberger & Steffen 04] and nearly equal to our earlier one with a gluino thermal mass introduced by hand [LC, HB Kim, JE Kim & Roszkowski 01].

Tension with thermal leptogenesis is stronger, even for small axino masses ! Non-thermal leptogenesis ? [Baer et al...]

Revisiting axino production

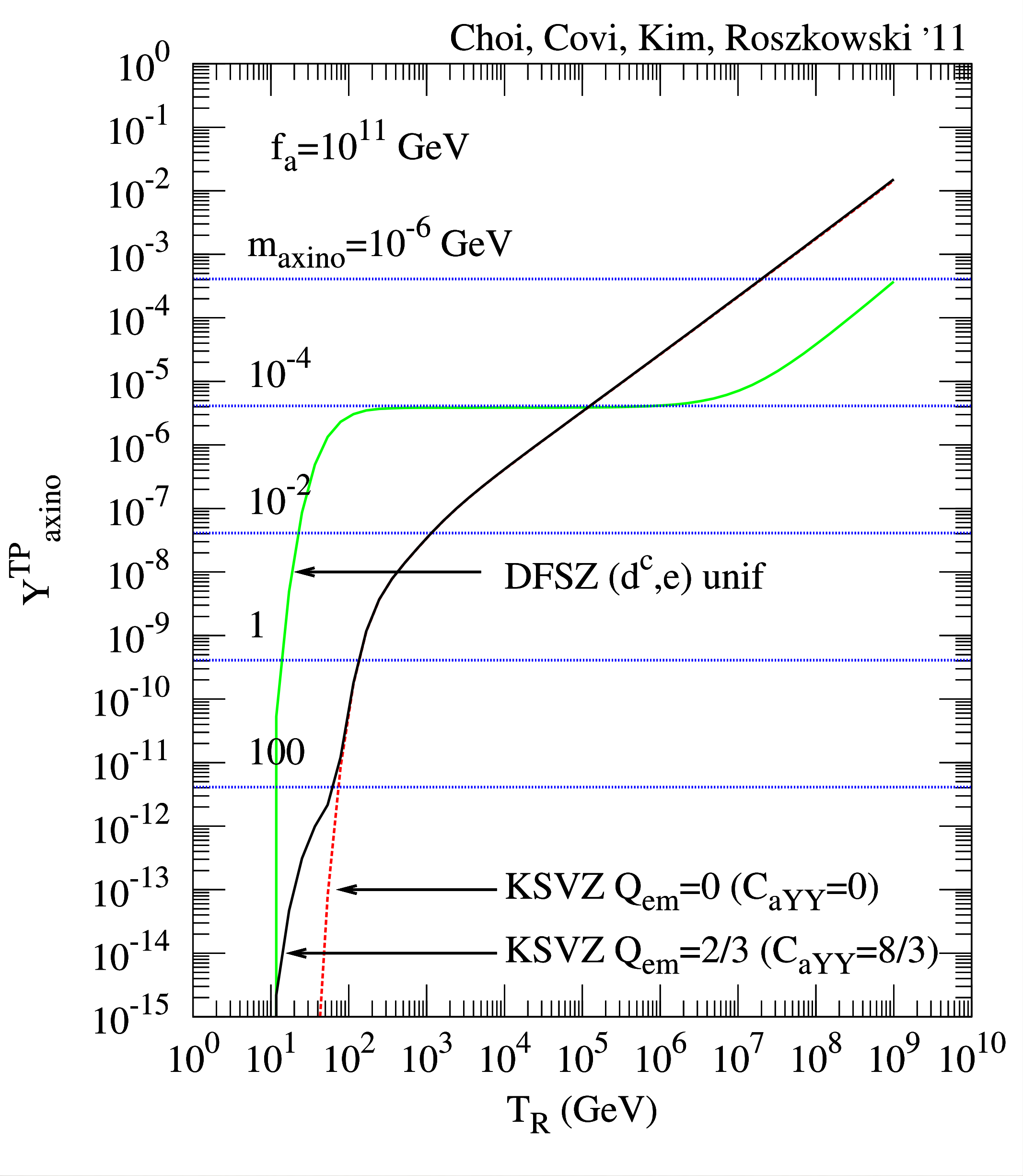
[K.Y. Choi, LC, J.E. Kim, L. Roszkowski 01]



Do not worry: Perturbation series seems converging...

Revisiting axino production

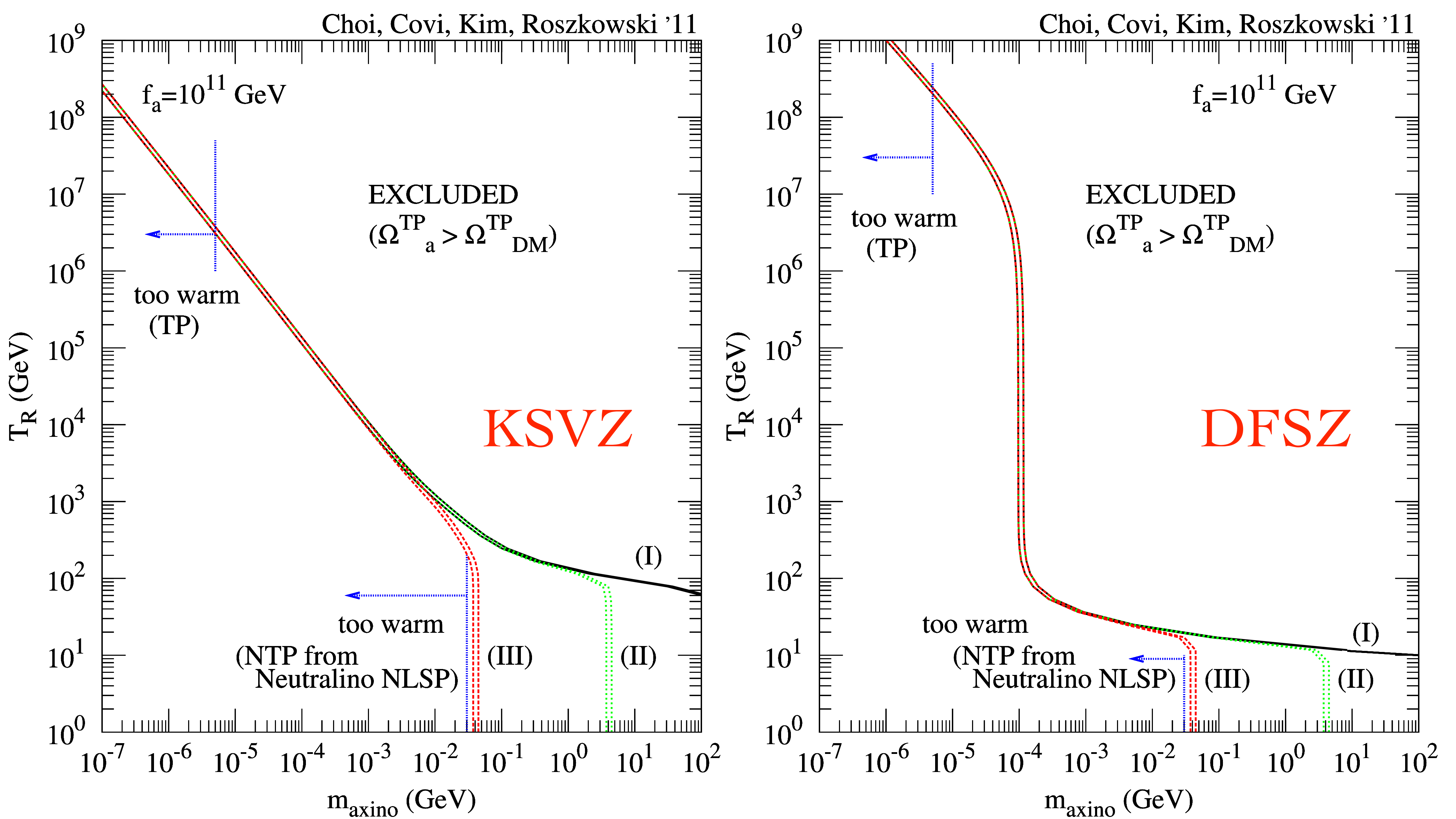
[E.J. Chun 11, Bae, Choi & Im 11]
[K.Y. Choi, LC, J.E. Kim, L. Roszkowski 01]



Actually for the DFSZ case, there is a direct coupling to the Higgses : so the Higgsino decay channel dominates over the other production channels, e.g. SU(2) coupling...

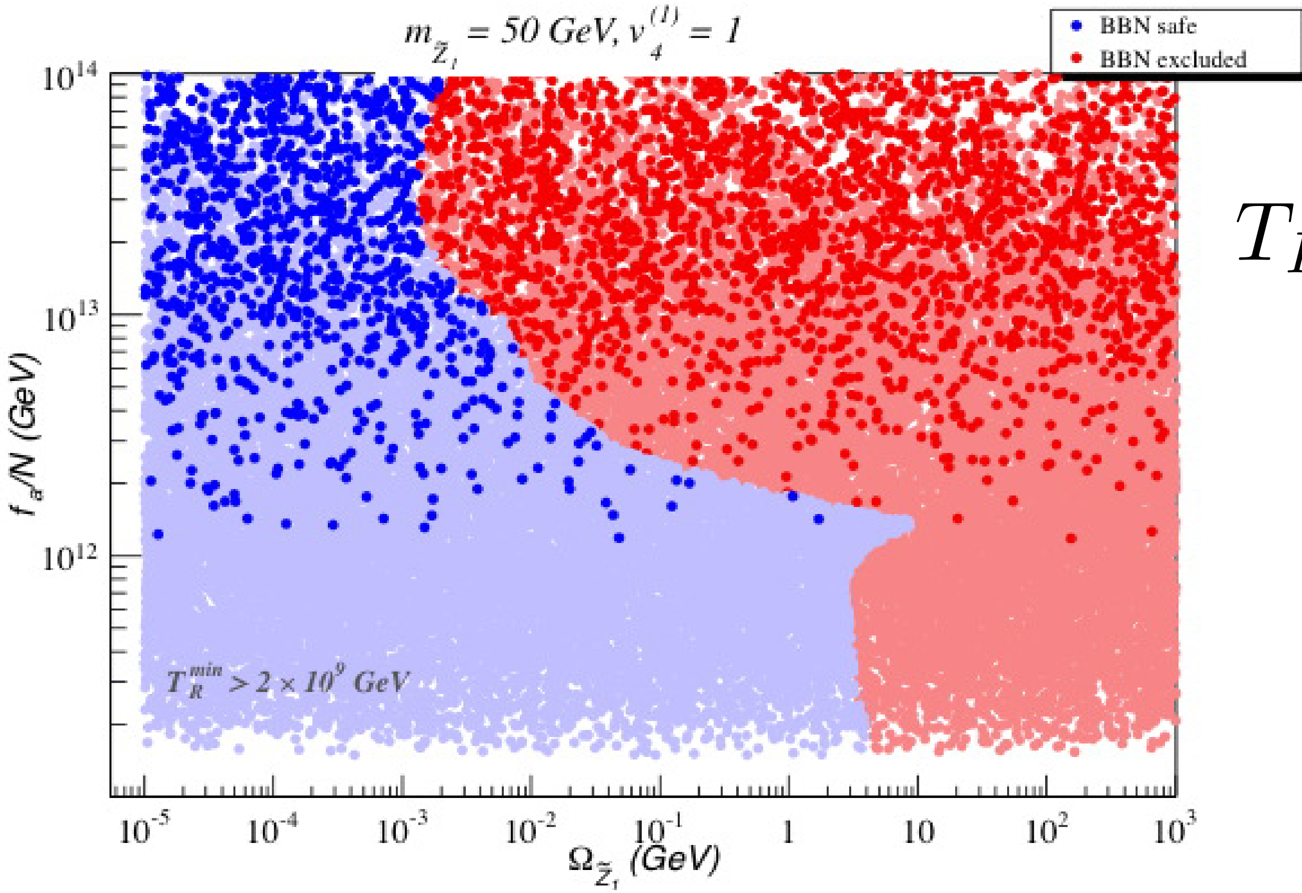
Revisiting axino production

[K.Y. Choi, LC, J.E. Kim, L. Roszkowski 01]



Mixed Axino/axion DM

[Baer et al 10]



$$T_{RH} > 2 \times 10^9 \text{ GeV}$$

needs large

$$f_a/N$$

With mixed axion/axino DM high reheat temperature is possible also in the PQ case for small axino mass.

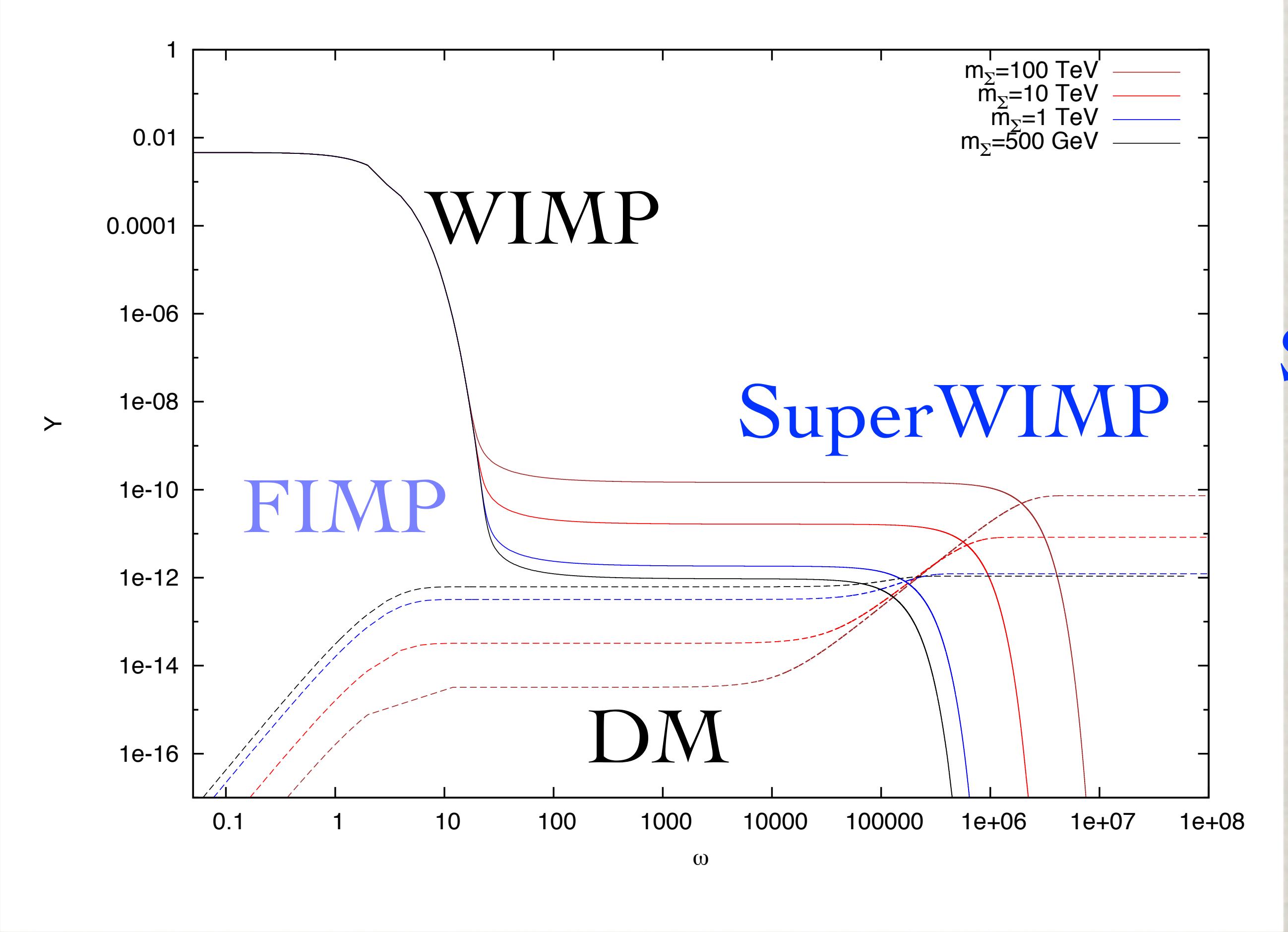
Generic FIMP/SuperWIMP scenario

SuperWIMP/FIMP paradigms

Add to the BE a small decaying rate for the WIMP into a much more weakly interacting (i.e. decaying !) DM particle:

[Hall et al 10]

FIMP DM produced by WIMP decay in equilibrium



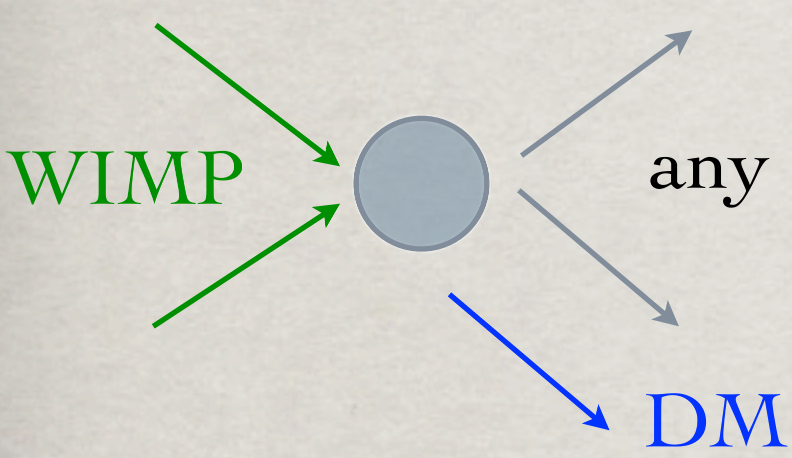
[Feng et al 04]

SuperWIMP DM produced by WIMP decay after freeze-out

Two mechanism naturally giving "right" DM density depending on WIMP/DM mass & DM couplings

F/SWIMP CONNECTION

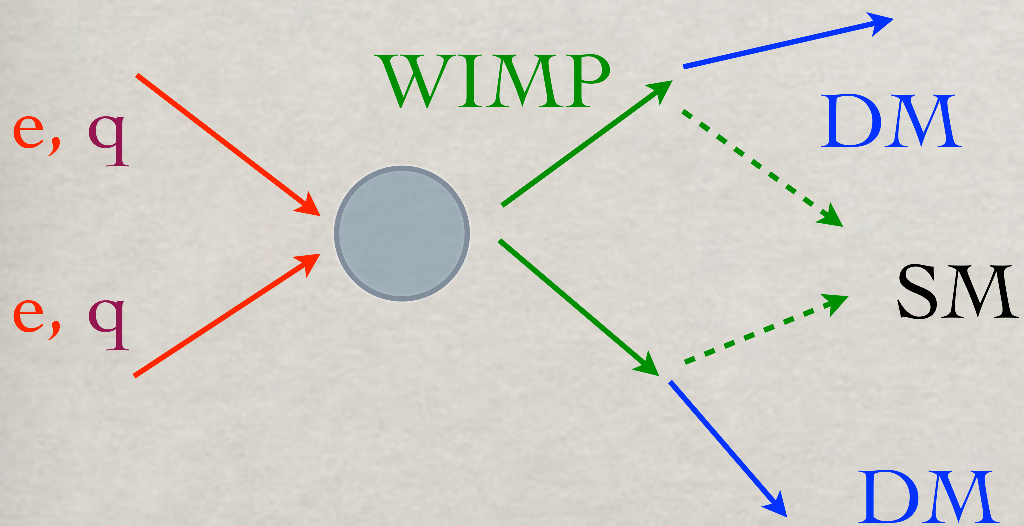
Early Universe: $\Omega_{CDM} h^2$



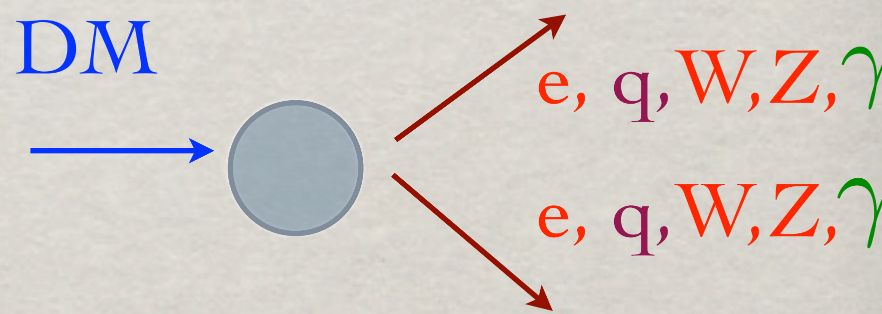
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:



decaying DM !

3 different ways to check this hypothesis !!!

A simple WIMP/SWIMP model

[G. Arcadi & LC 1305.6587]

Consider a simple model where the Dark Matter, a Majorana SM singlet fermion, is coupled to the colored sector via a renormalizable interaction and a new colored scalar Σ :

$$\lambda_\psi \bar{\psi} d_R \Sigma + \lambda_\Sigma \bar{u}_R^c d_R \Sigma^\dagger$$

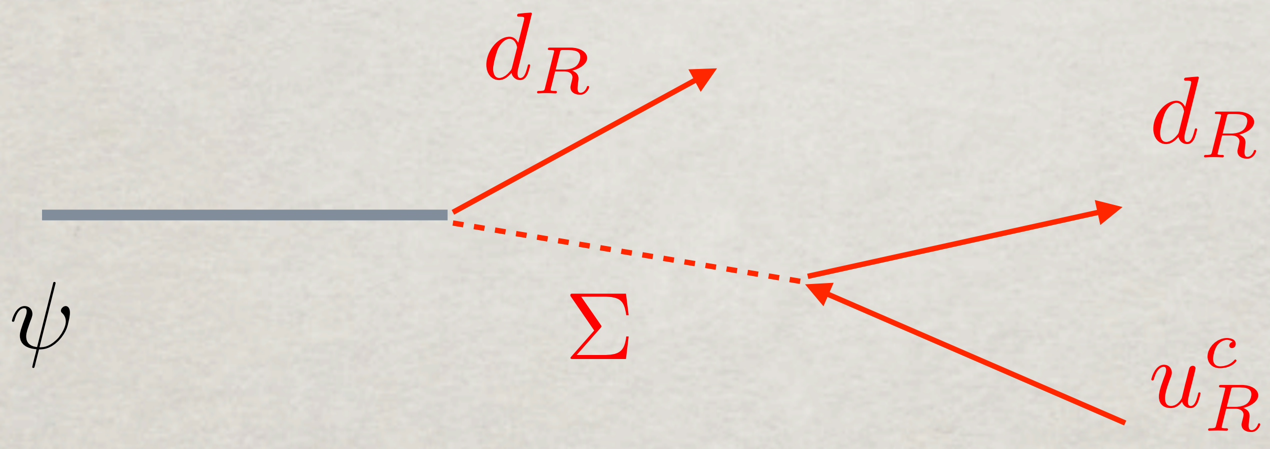
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

$\longrightarrow$ FIMP/SWIMP connection

A simple WIMP/SWIMP model

[G. Arcadi & LC 1305.6587]

No symmetry is imposed to keep DM stable, but the decay is required to be sufficiently suppressed. For $m_\Sigma \gg m_\psi$:

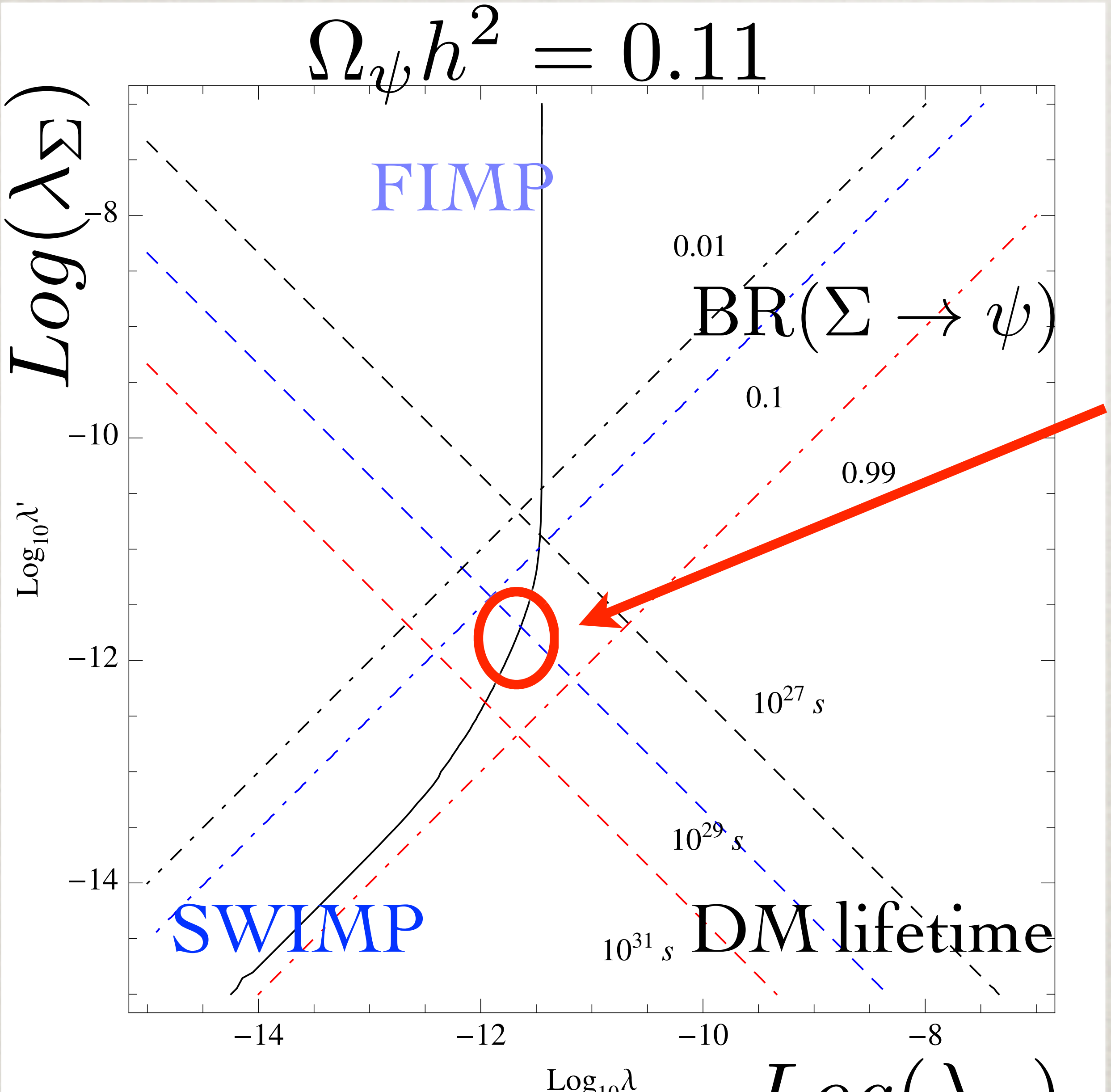


Decay into 3 quarks via both couplings !

To avoid bounds from the antiproton flux require then

$$\tau_\psi \propto \lambda_\psi^{-2} \lambda_\Sigma^{-2} \frac{m_\Sigma^4}{m_\psi^5} \sim 10^{28} s$$

A simple WIMP/SWIMP model



[G. Arcadi & LC 1305.6587]

DM decay observable in indirect detection & right abundance & sizable BR in DM

$\lambda_\psi \sim \lambda_\Sigma$

But unfortunately Σ decays outside the detector @ LHC! Perhaps visible decays with a bit of hierarchy...

FIMP/SWIMP AT LHC

At the LHC we expect to produce the heavy charged scalar Σ, as long as the mass is not too large... In principle the particle has two channels of decay with very long lifetimes.
Fixing the density by FIMP mechanism we have:

$$l_{\Sigma,DM} = 2.1 \times 10^5 \mathrm{m}\, g_\Sigma x \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-1} \left(\frac{\Omega_{CDM} h^2}{0.11}\right)^{-1} \left(\frac{g_*}{100}\right)^{-3/2}$$

Very long apart for small DM mass, i.e. $x = \dfrac{m_{DM}}{m_{\Sigma_f}} \ll 1$

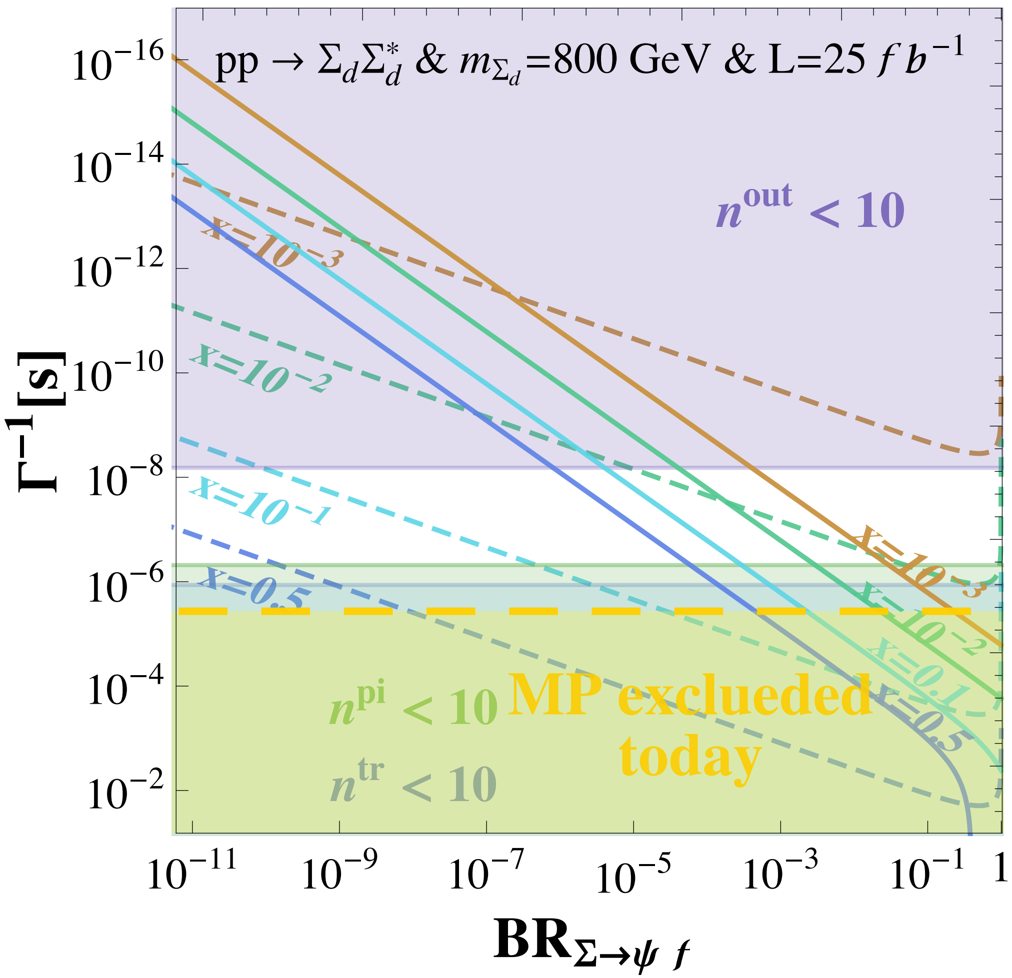
Moreover imposing ID "around the corner" gives

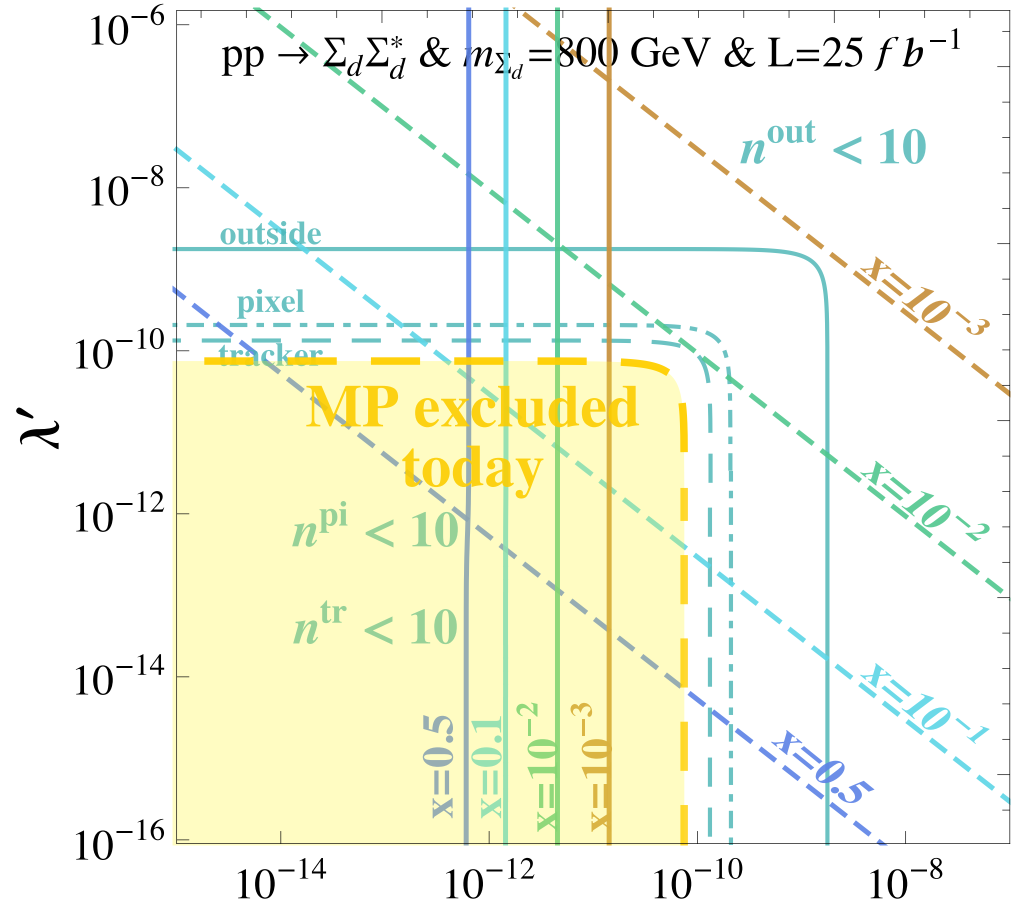
$$l_{\Sigma,SM} \simeq 55\,\mathrm{m}\,\frac{1}{g_\Sigma}\left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-4}\left(\frac{m_\psi}{10\mathrm{GeV}}\right)^{4}\left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right)\left(\frac{\Omega_{CDM} h^2}{0.11}\right)\left(\frac{g_*}{100}\right)^{3/2}$$

At least one decay could be visible !!!

FIMP/SWIMP & COLORED Σ

[G. Arcadi, LC & F. Dradi 1408.1005]



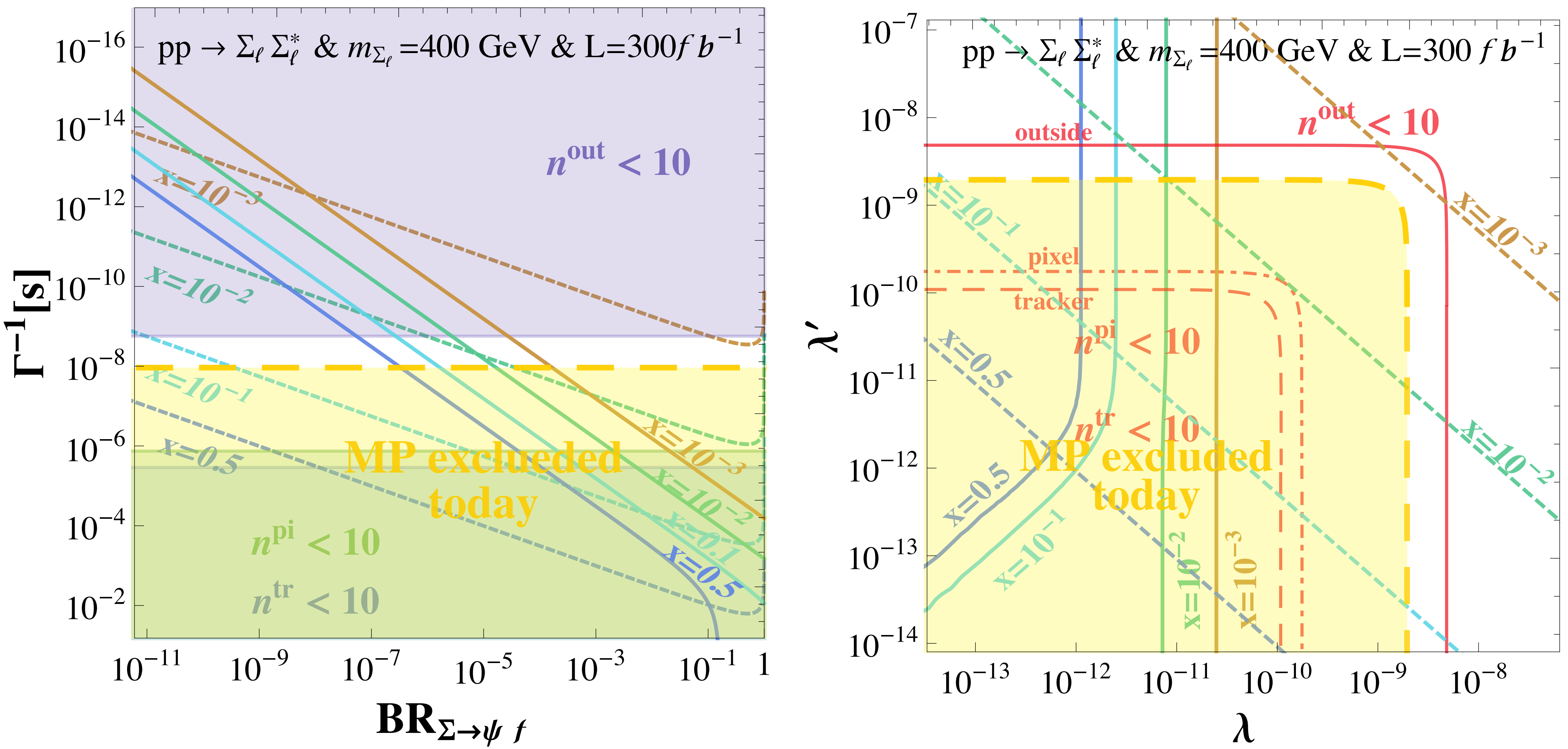


solid DM lines

Practically pure FIMP production: both displaced vertices & "stable" charged particle @ LHC possible...

FIMP/SWIMP & EW Σ

[G. Arcadi, LC & F. Dradi1408.1005]



Production at LHC is much more suppressed !

SWIMP at large x for "stable" charged particle @ LHC

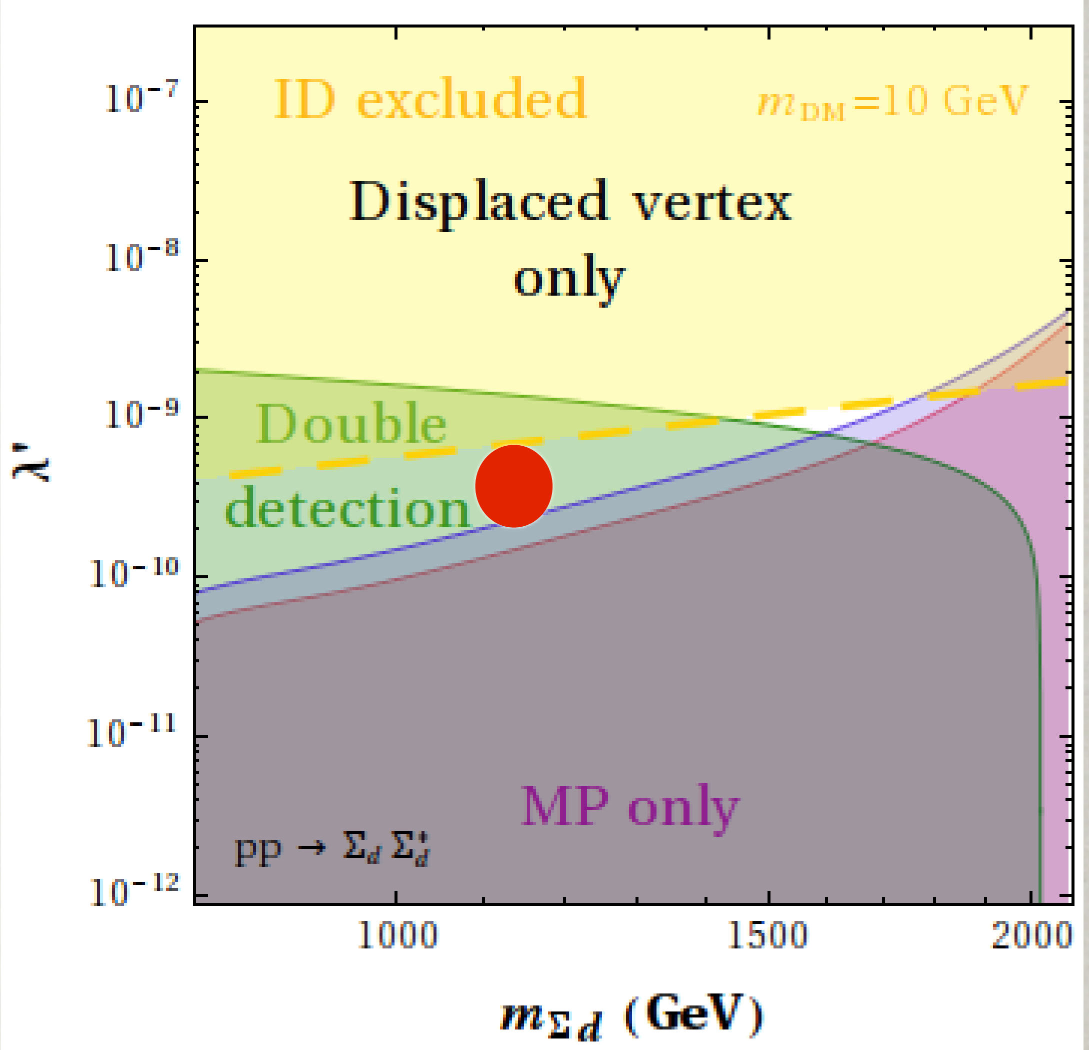
$\sum$ Combined detection

Still possible to have multiple detection of

- DM decay:
  $m_\psi \quad \Gamma_\psi \to \lambda\lambda'$
- displaced vertices
  $m_\Sigma \quad \Gamma_{\Sigma,SM} \to \lambda'$
- metastable tracks
  $m_\Sigma \quad \Gamma_{\Sigma,SM} < X \to \lambda'$

with stopped tracks maybe both $\Gamma_{\Sigma,SM}, \Gamma_{\Sigma,DM}$

[G. Arcadi, LC & F. Dradi 1408.1005]

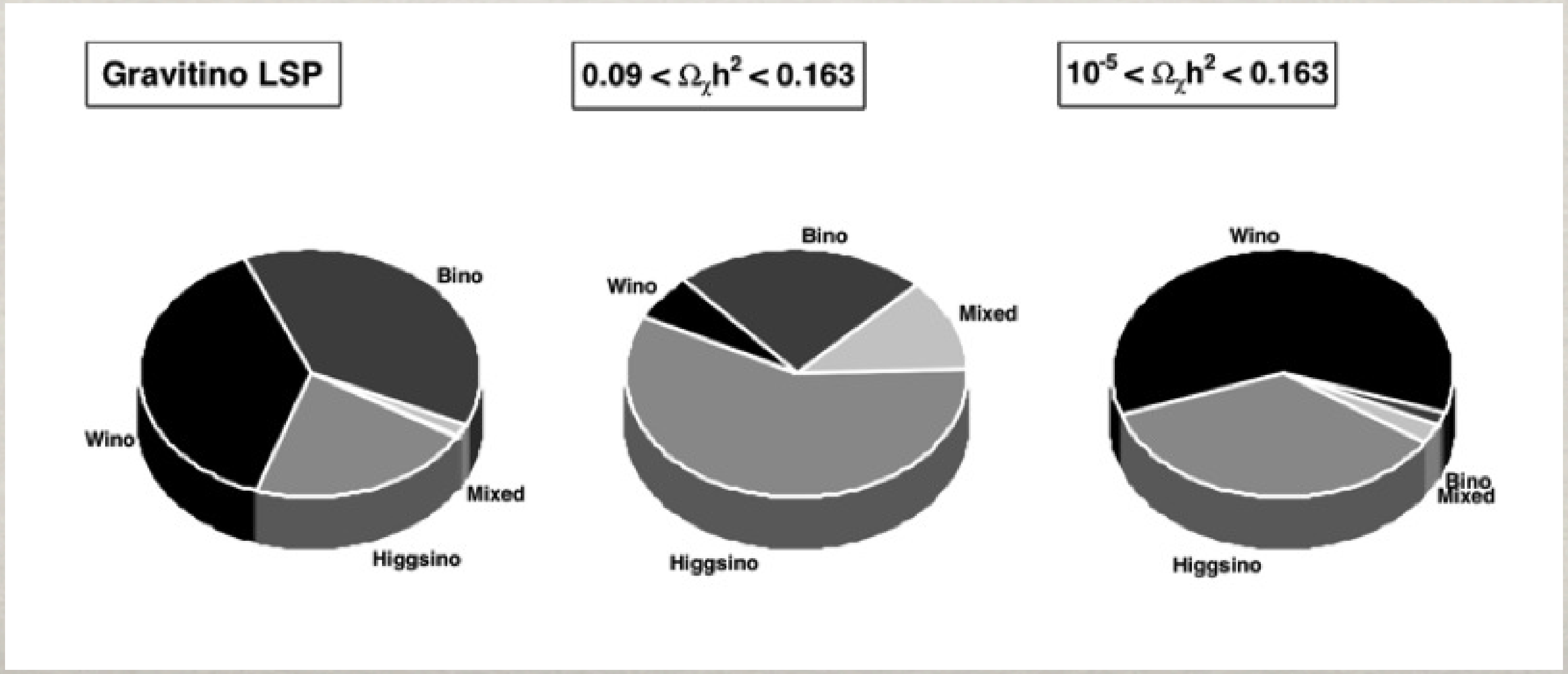


It is possible to over-constraint the model and check the hypothesis of FIMP production !

Gravitino DM in pMSSM

[Arbey et al. 1505.04595]

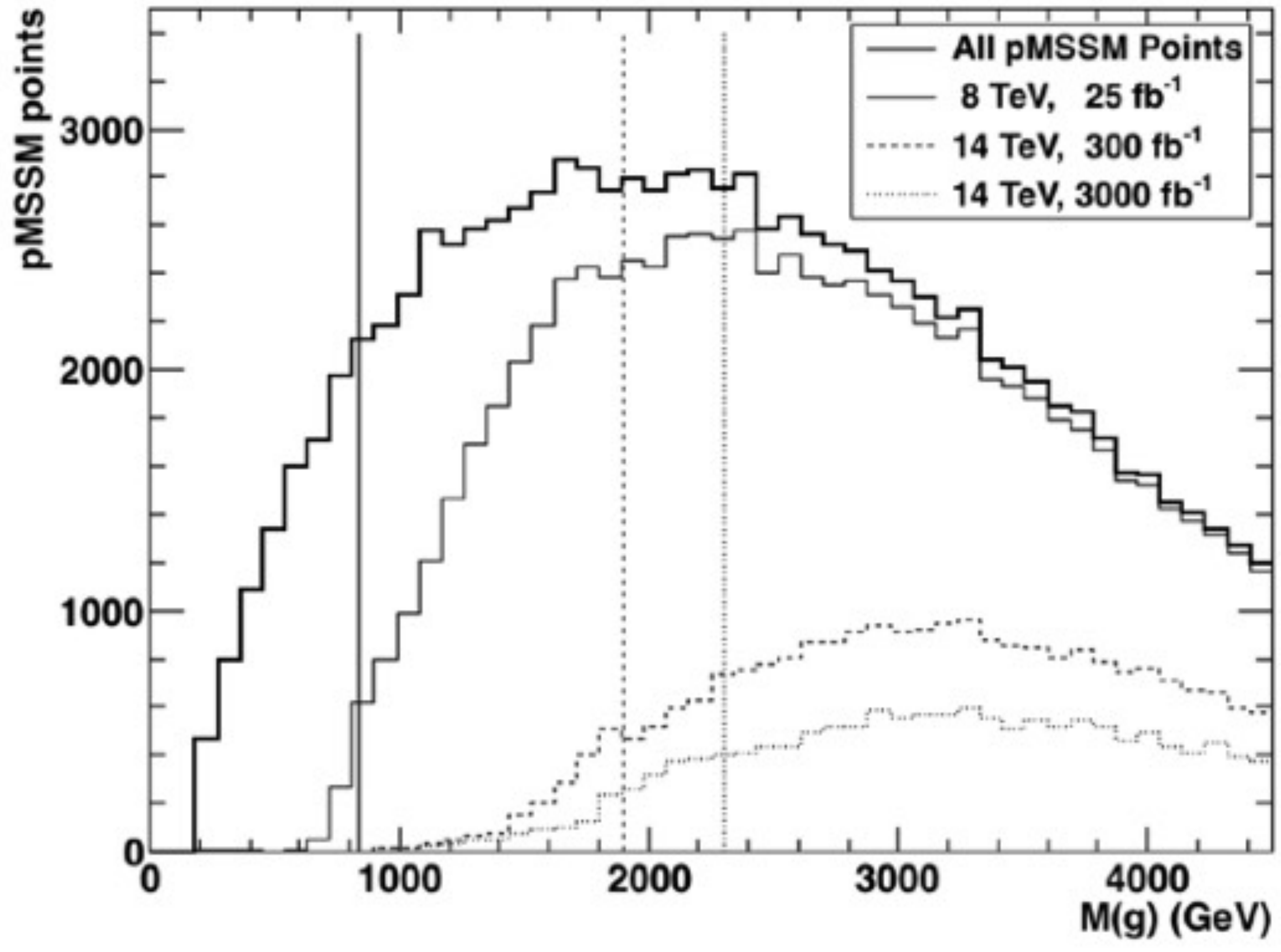
Let us consider gravitino DM with neutralino NLSP within the RPC pMSSM with 19+1 parameters, i.e. no unification assumption, flavour & CP conserving SUSY breaking.
Impose all constraints from low energy, flavour observables, LHC SUSY searches and monojets, as well as DM density and BBN limits on neutralino NLSP...



Gluino mass in pMSSM

In the generic pMSSM limits on the gluino mass are less strong than in constrained models !

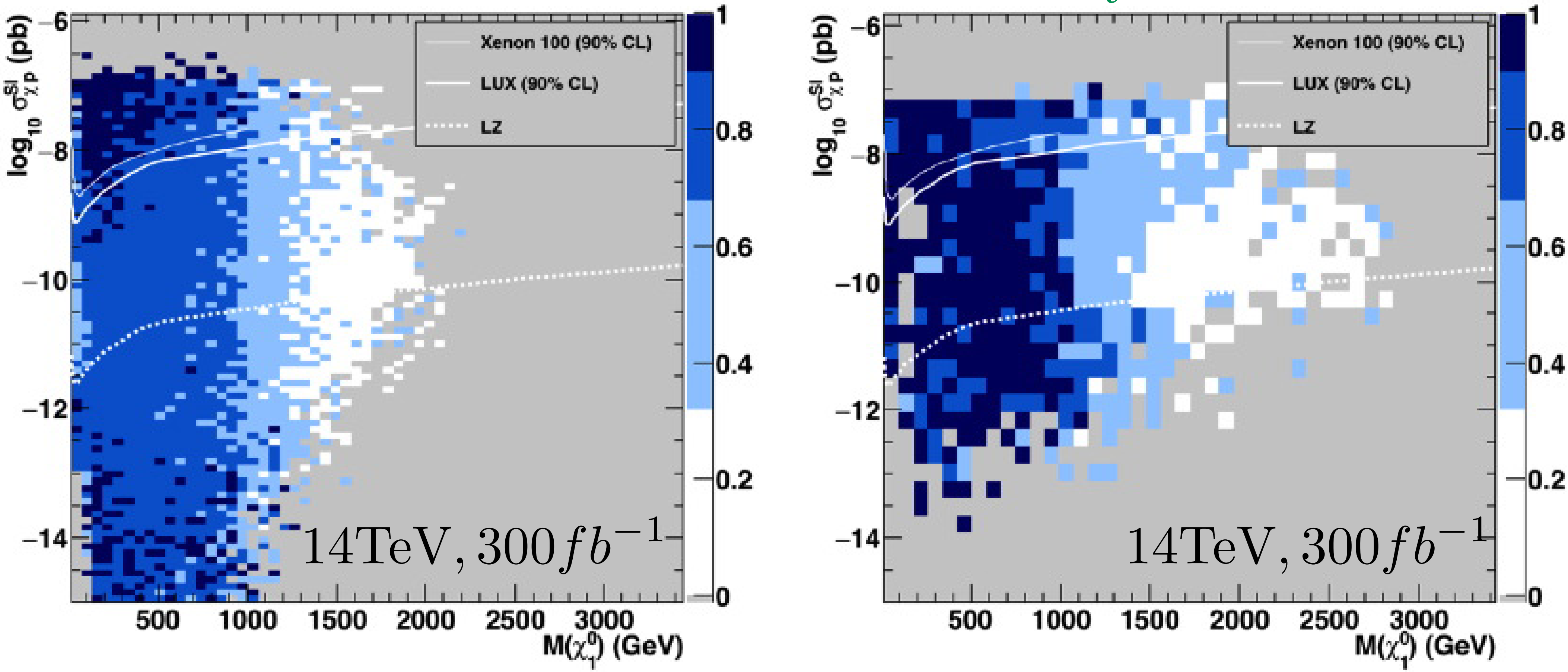
[Arbey et al. 1505.04595]



Gravitino vs neutralino

The neutralino compositions in the two scenarios is very different and so also the LHC reach in the next run: only half the neutralino DM points will be excluded, while 75% of the gravitino DM points...

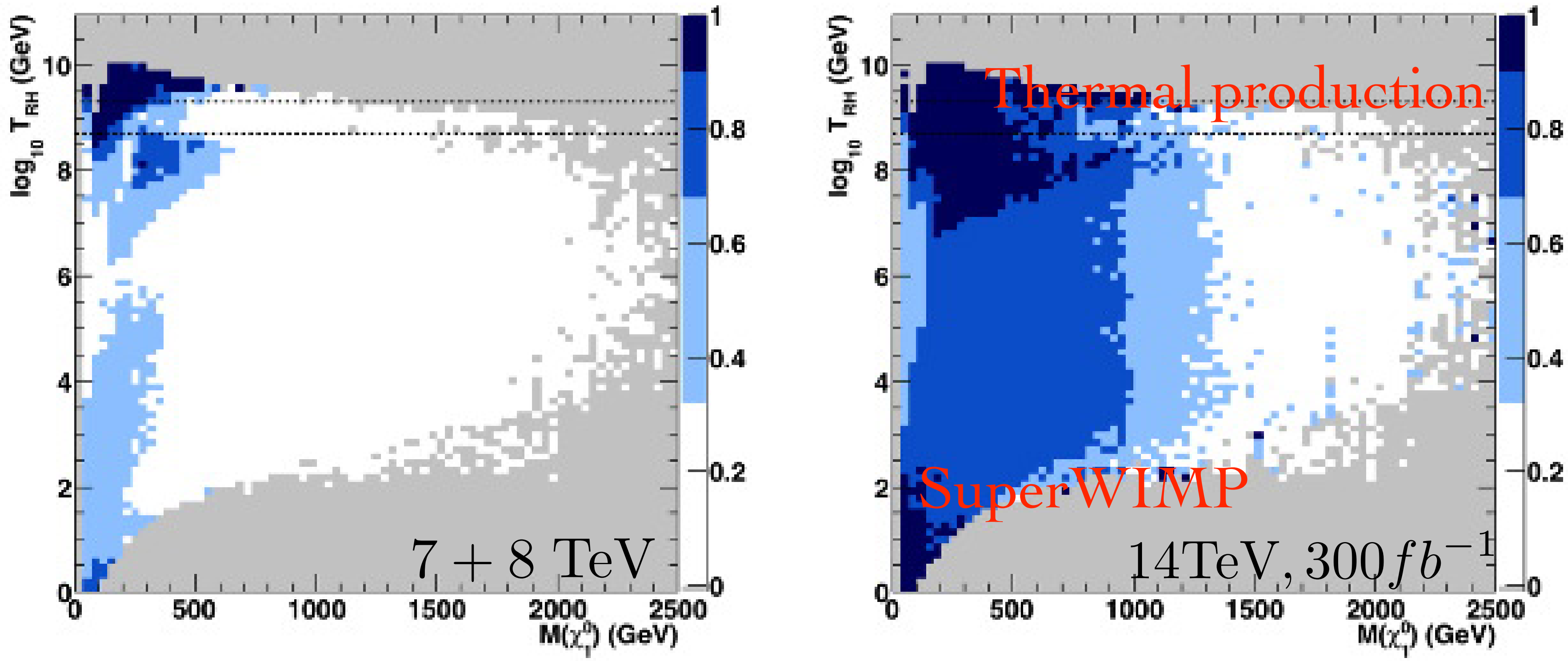
[Arbey et al. 1505.04595]



Gravitino DM in pMSSM

[Arbey et al. 1505.04595]

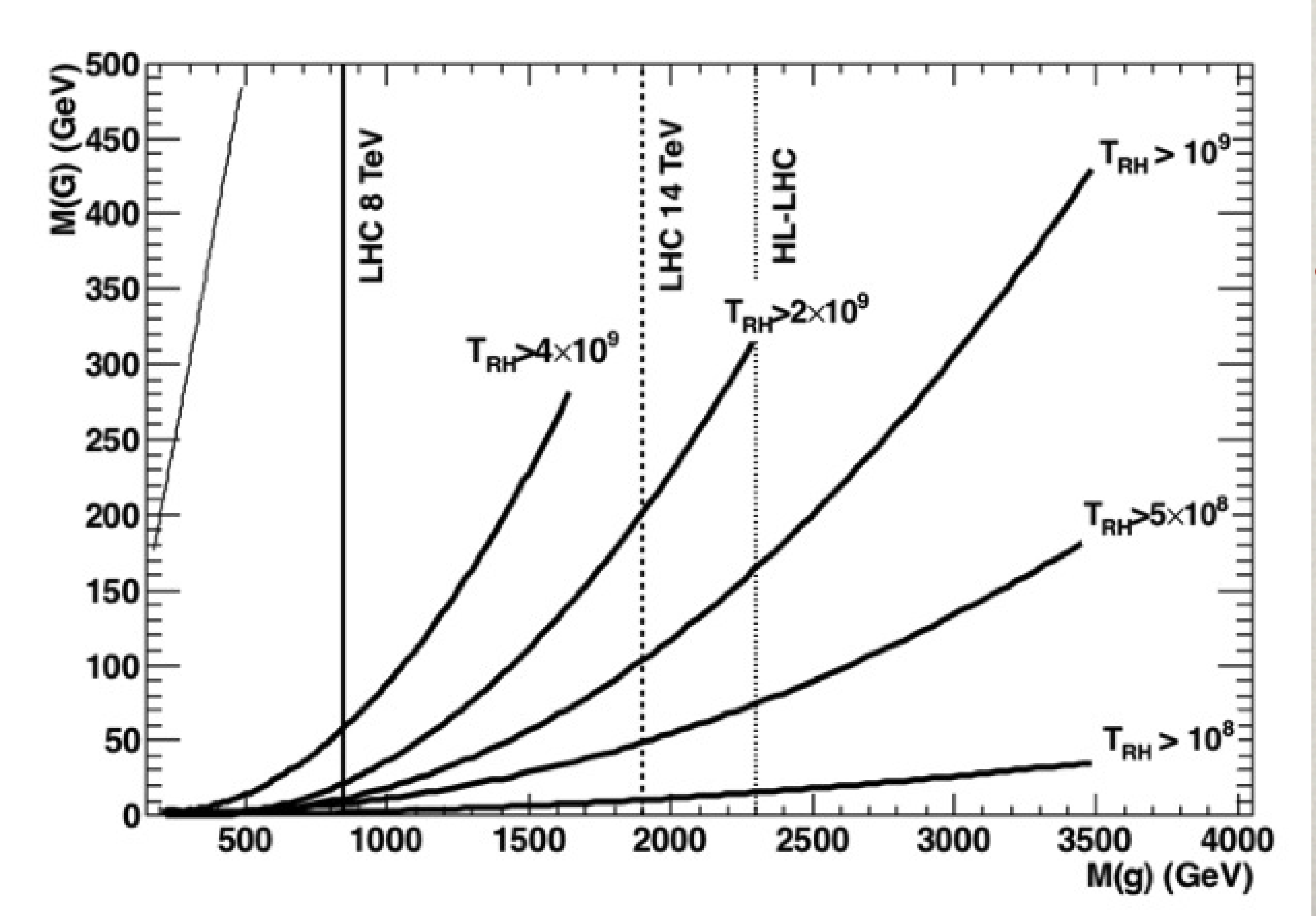
Interplay between gravitino production and gaugino masses very strong: high T_{RH} region corresponds to light gauginos and it is more easily tested as well as SuperWIMP region !



Gravitino DM & gluino

[Arbey et al. 1505.04595]

Gluino mass is an important parameter in gravitino thermal production: the next LHC run will probe the parameter space compatible with classical (no-flavour) thermal leptogenesis.



Minimal gravitino mass such that $\Omega_{\tilde{G}} h^2 < 0.12$ is given by

$$m_{\tilde{G}} \propto m_{\tilde{g}}^2$$

STOP NLSPs AT LHC

[LC & F. Dradi 1403.4923]

We have for the lightest stop always relatively long lifetimes, both for R-parity conservation or violation...

RPC: $\tilde{t}_1 \to t\,\tilde{G} \to b\,W^+\tilde{G} \to b\,\ell^+\nu\tilde{G}$

$$\tau_{\tilde{t}_1} \sim 19\ \mathrm{s} \left(\frac{m_{\tilde{t}_1}}{500\mathrm{GeV}}\right)^{-5} \left(\frac{m_{3/2}}{1\mathrm{GeV}}\right)^{2}$$

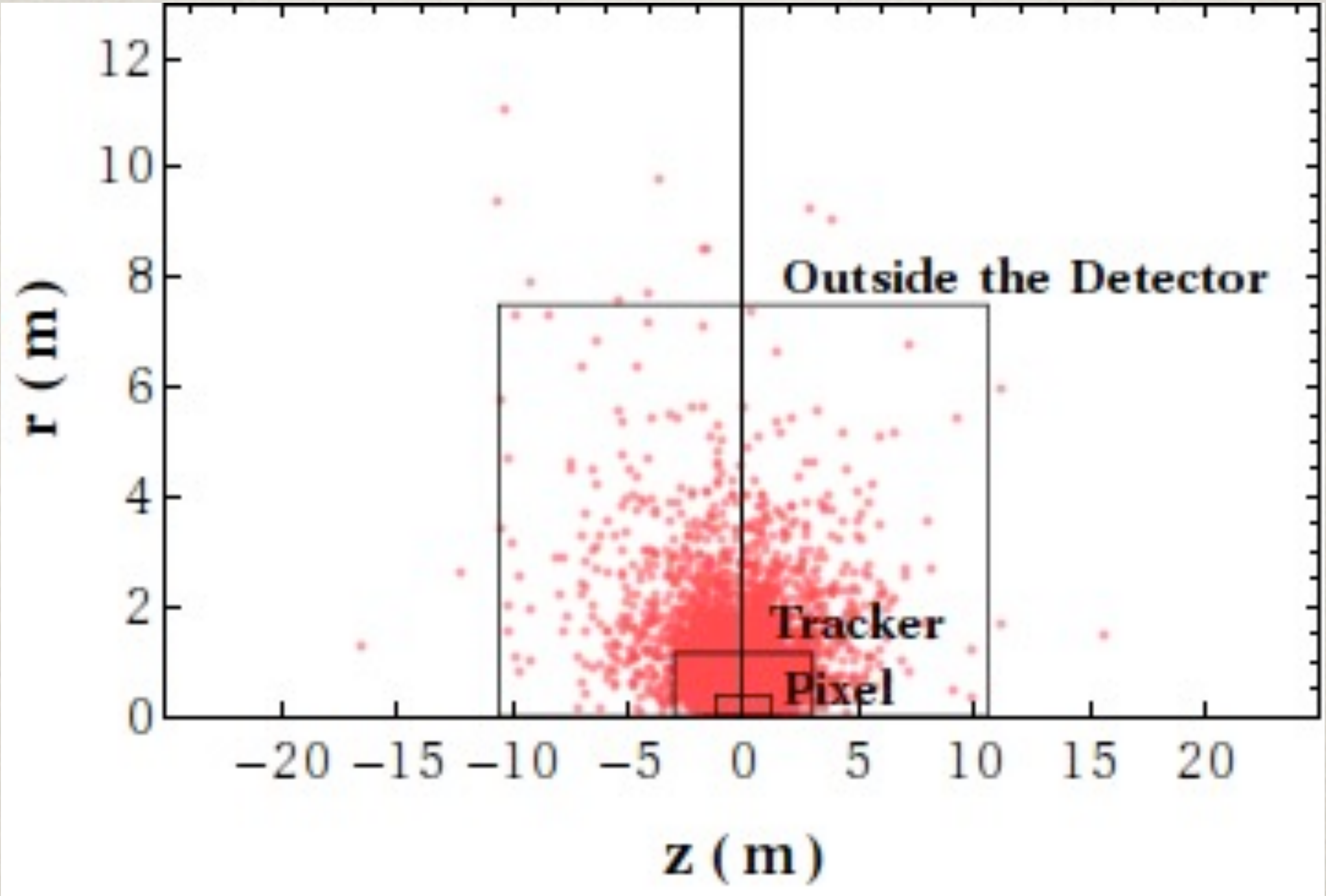
RPV: $\tilde{t}_1 \to b\,\ell^+$

$$\tau_{\tilde{t}_1} \sim 10^{-4}\ \mathrm{s} \left(\frac{m_{\tilde{t}_1}}{500\mathrm{GeV}}\right)^{-1} \left(\frac{\epsilon \sin\theta_{\tilde{t}}}{10^{-9}}\right)^{-2}$$

The usual searches looking for prompt decay do not apply !

LHC: long-lived stop

Generate from the kinematic of production the stop/antistop the distribution of the decay vertices within/without the detector (here CMS) as a function of the stop lifetime.

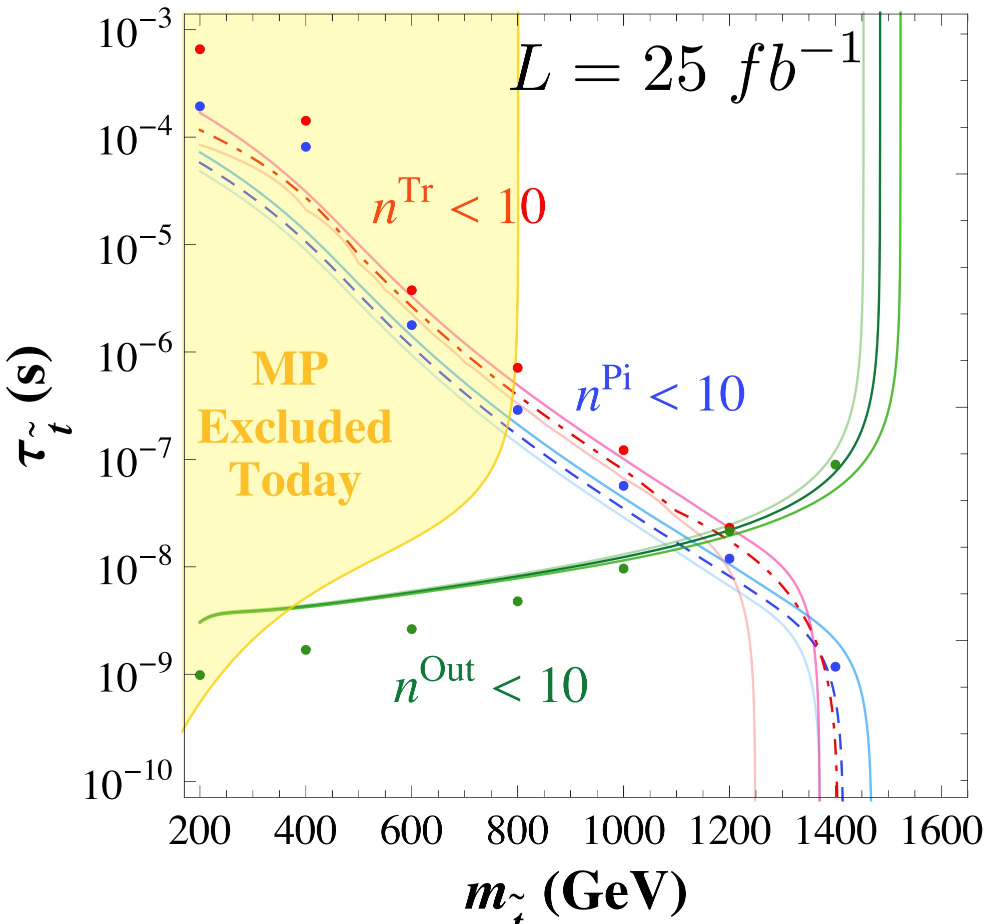


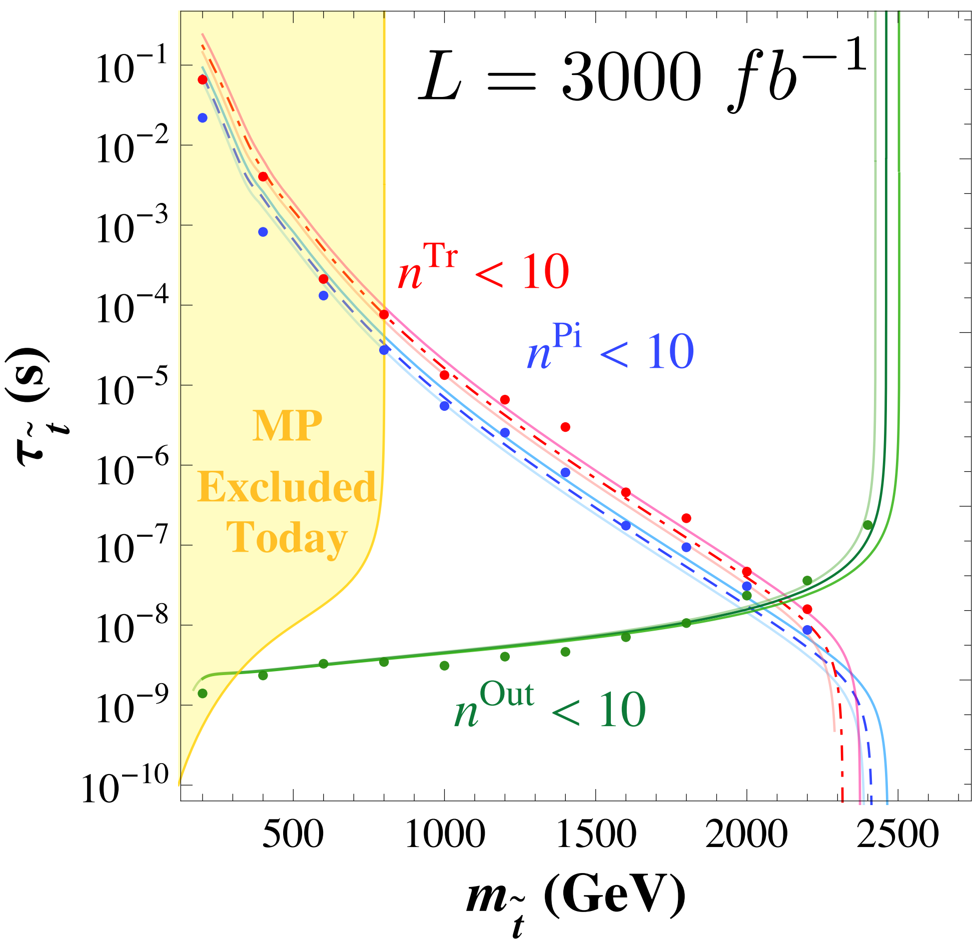
Neglect magnetic fields and intervening matter...

LHC: LONG-LIVED STOP

Best strategy: combine searches for metastable particles (out) and displaced decay vertices in tracker or pixel CMS detector. Draw the lines for 10 events of any type to be conservative:

[LC & F. Dradi 1403.4923]





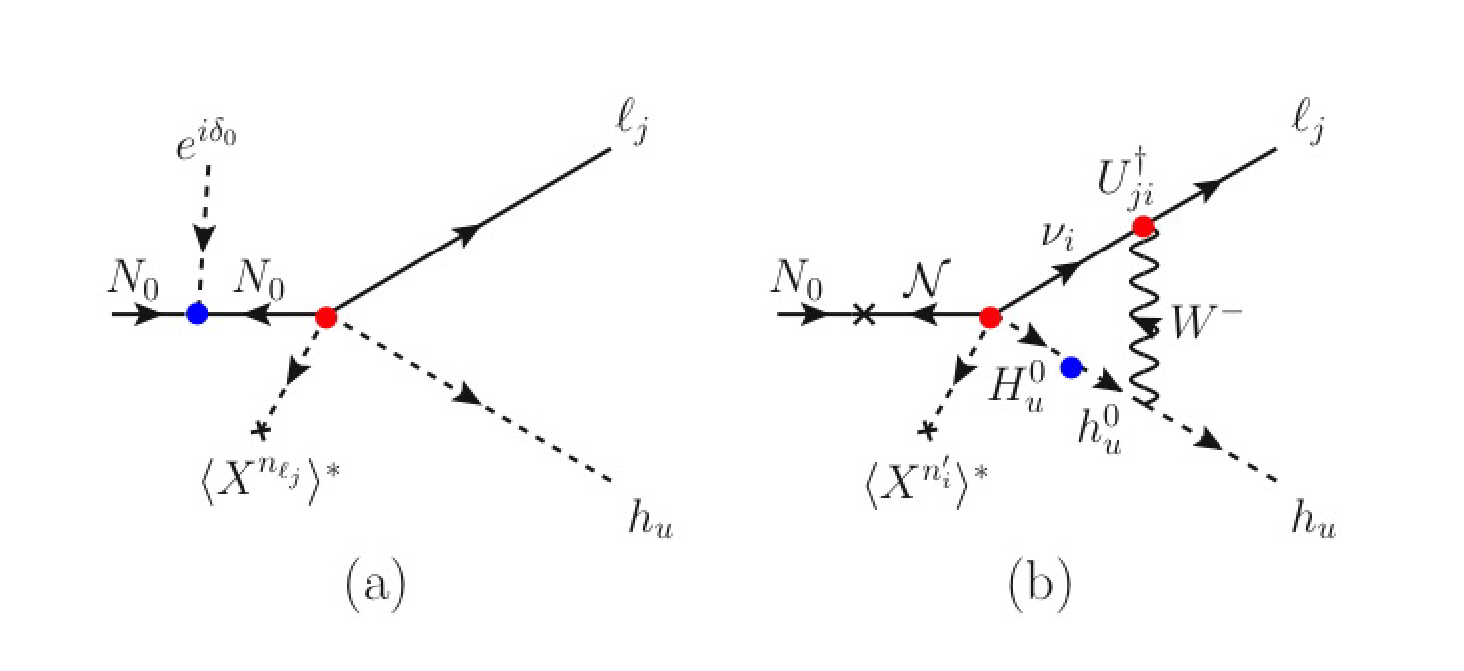
Band is the +/- 1 sigma fluctuation for a Poisson distribution..

Leptogenesis with broken SU(2)

Leptogenesis through PMNS phases

[LC, Jihn E Kim, Bumseok Kyae, Soonkeon Nam '16]

Consider leptogenesis in an extended model where the EW symmetry remains broken at high T and there is a new contribution from a W diagram containing the PMNS matrix...



Contribution to CP asymmetry vanishing for $v_{EW} = 0$

Leptogenesis through PMNS phases

[LC, Jihn E Kim, Bumseok Kyae, Soonkeon Nam '16]

For non-degenerate Higgs masses an imaginary part for the loop remains and gives

$$\epsilon_L^{N_0}(W) = \frac{\alpha_{\rm em}}{2\sqrt{2}\sin^2\theta_W}\frac{\Delta m_h^2}{m_0^2}\frac{1}{\sum_i |f_i^{eff}|^2}\,{\rm Im}\left[\sum_{i,j}\left[f_j^{eff}U_{ji}^\dagger(f_i^{eff})^* - f_j^{eff}U_{ji}(f_i^{eff})^*\right]\right]\times\left[1+\ln\left(\frac{m_W^2}{m_0^2}\right)\right].$$

Enhanced by small W mass compared to RH neutrino mass, not so suppressed by $\Delta m_h \propto v_{EW} \propto T$.

Even for a single real Yukawa, e.g. for the third generation, an imaginary part remains from the PMNS phases as

$$\epsilon_L^{N_0}(W) = -\frac{\alpha_{\rm em}}{\sqrt{2}\sin^2\theta_W}\frac{\Delta m_h^2}{m_0^2}\,{\rm Im}\left[c_2c_3e^{i\delta_c}+c_1s_2s_3e^{i(\delta_{\rm PMNS}+\delta_c)}\right]\times\left[1+\ln\left(\frac{m_W^2}{m_0^2}\right)\right].$$

Direct connection between leptogenesis and low energy !

Conclusion

TO CONCLUDE

- As You probably noticed, the axino connection was quite fruitful and I enjoyed very much the collaboration with Jihn E. Kim, Leszek Roszkowski, Hang-Bae Kim and Ki-Young Choi !
  We contributed to establish an alternative to the WIMP scenario, which can be realised not only in the axino case, but more in general and that is now under study at LHC.
- Jihn E. Kim has been a pioneer in the field of particle cosmology at the time when collider physics was dominating the field. I learned a lot from him, not only about physics, but especially to dare to have new ideas and try new directions !

TO CONCLUDE

- Dear Jihn E. Kim: happy birthday ! Live long and prosper continuing to propose new scenarios in particle physics and cosmology !