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Introduction to Cosmology

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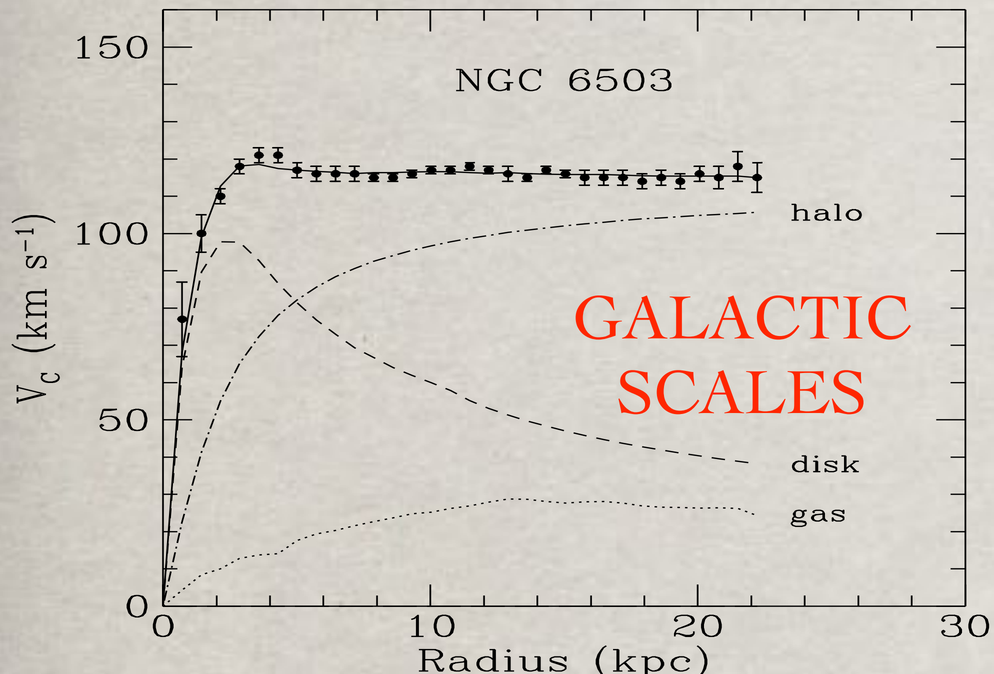
HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

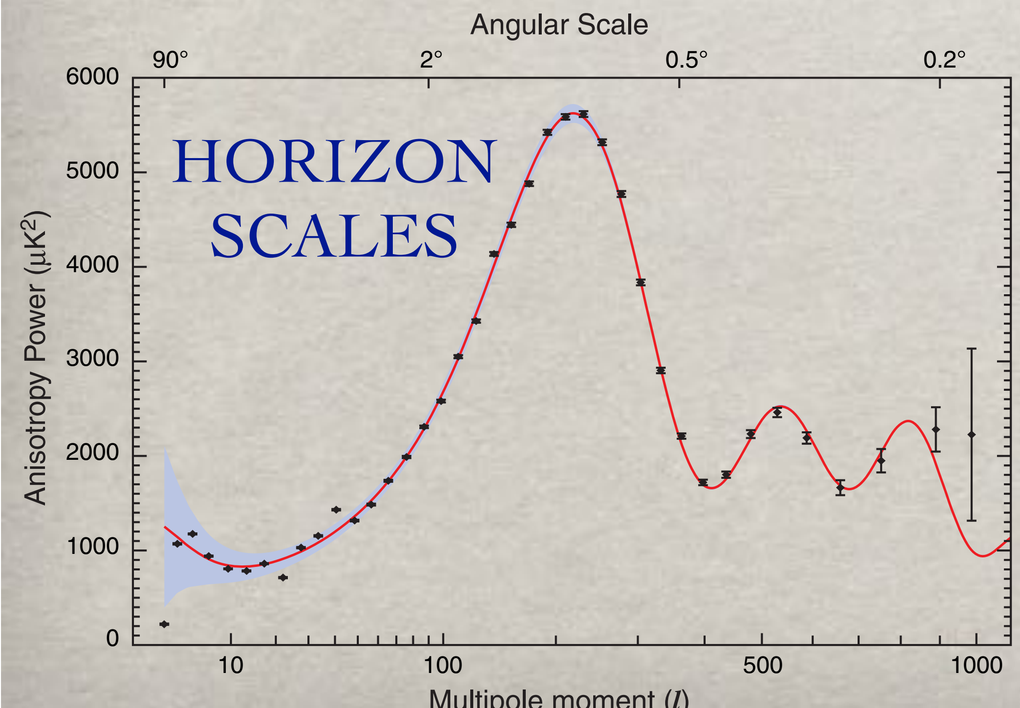
Outline

- Introduction:
  - DM evidence & properties
  - Theoretical guiding principles
- SUSY WIMP Dark Matter
- SUSY FIMP/SuperWIMP/Decaying Dark Matter
- SUSY Co-genesis
- Outlook

Introduction

DARK MATTER EVIDENCE





Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

DARK MATTER EVIDENCE

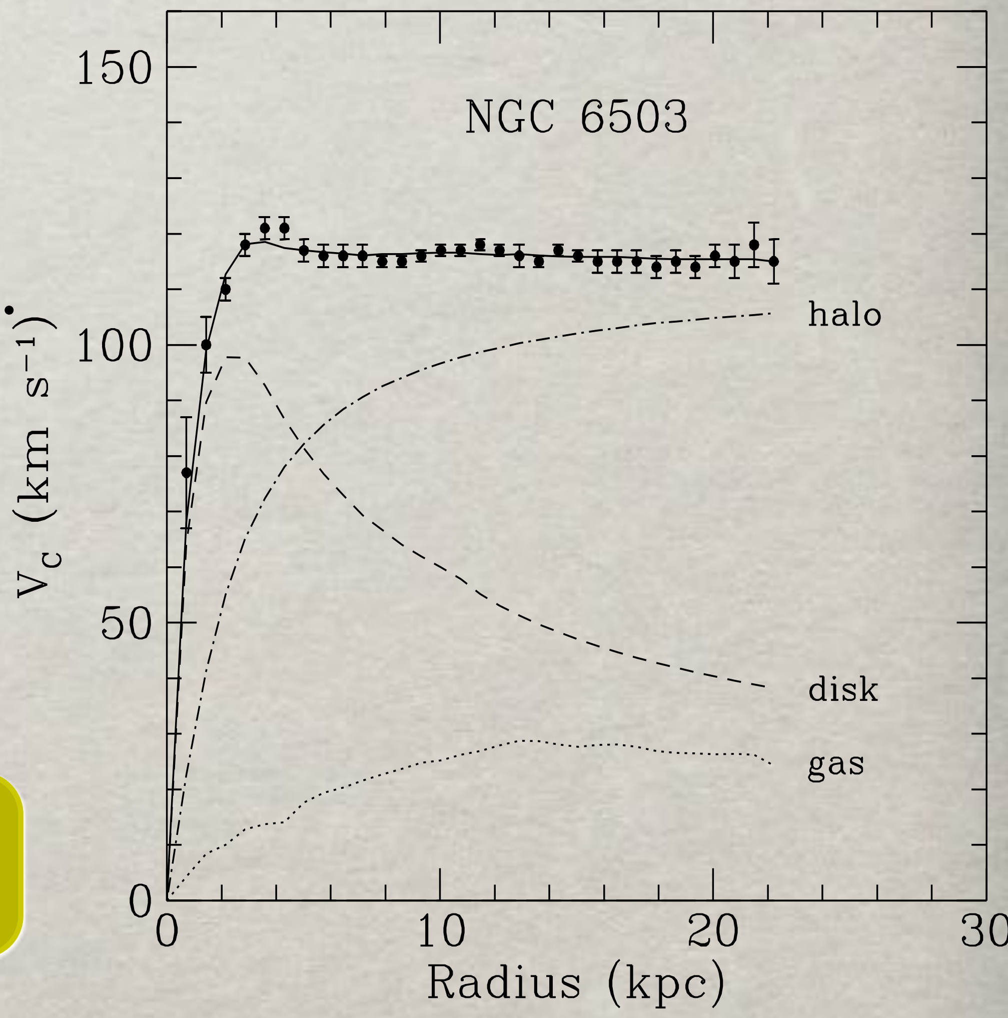
GALACTIC SCALES:

the stars in the outer part of galaxies are faster than expected...

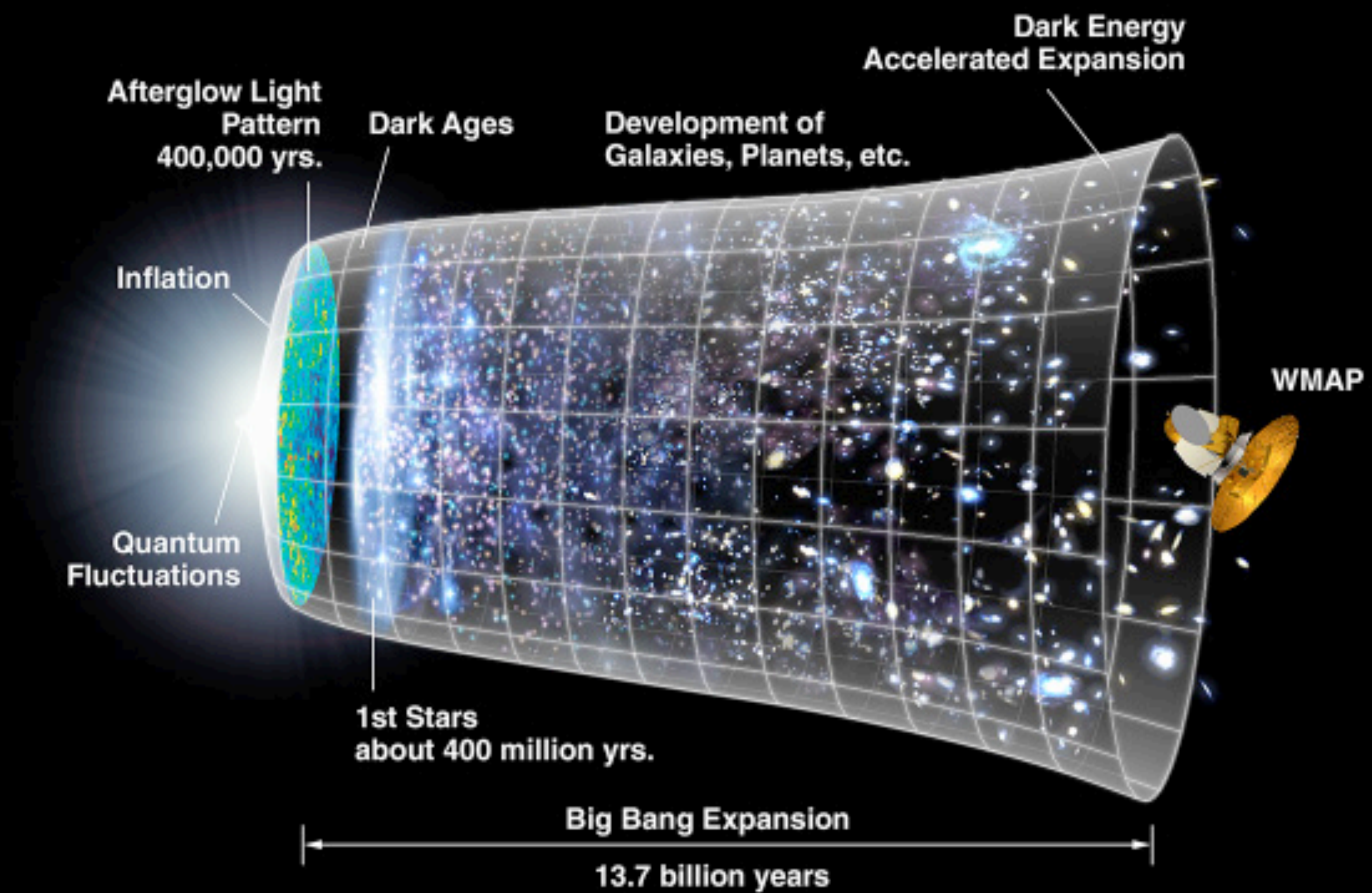
$$v_c^2 \propto G_N \frac{M(r)}{r} \propto \frac{M_{tot}}{r}$$

But instead it is constant ! Need

$$M(r) \propto r, \text{ i.e. } \rho_{DM} \propto r^{-2}$$



Following the fluctuations



We need seeds of small fluctuations, that were amplified by gravity & are the origin of the structure we see today

How do fluctuations grow ?

What happens after such perturbations "re-enter" the horizon ?

In the Newtonian limit we have for the density perturbations of a matter fluid $\delta = \frac{\delta\rho}{\rho}$

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(\frac{{c_s}^2 k^2}{a^2} - 4\pi G\rho \right) \delta_k = 0,$$

where $c_s = \delta p / \delta\rho$ is the sound speed in the plasma. Again a linear equation with a negative "mass" term... The fluctuations with negative mass grow and those have k below k_J ,i.e. a physical wavelength larger than the Jeans length:

$$\lambda_J = \frac{2\pi a}{k} = c_s \sqrt{\frac{\pi}{G\rho}} \simeq \frac{c_s}{H} \quad \text{sound horizon}$$

How strongly do they grow ? The growing solution is

$$\delta_k \sim C_1 H \int \frac{dt}{a^2 H^2} + C_2 H \sim C_1 t^{2/3} + C_2 t^{-1} \quad \text{for matter dominance}$$

NOTE: much weaker than exponential due to the expansion friction term $\propto H$! Also if the expansion is dominated by radiation, the growth is inhibited and at most only logarithmic in time. We need a long time of matter dominance to make initial fluctuations become large...

Non Linear regime

DARK MATTER PROPERTIES

- Interacts very weakly, but surely gravitationally (electrically neutral, non-baryonic and decoupled from the primordial plasma !!!)
- It must have the right density profile to “fill in” the galaxy rotation curves, i.e. non-dissipative.
- No pressure and negligible free-streaming velocity, it must cluster & cause structure formation.

⬇

COLD DARK MATTER

But unfortunately too many realizations !

Which model Beyond the SM ?

weakly coupled ⟷ strongly coupled

Cosmology

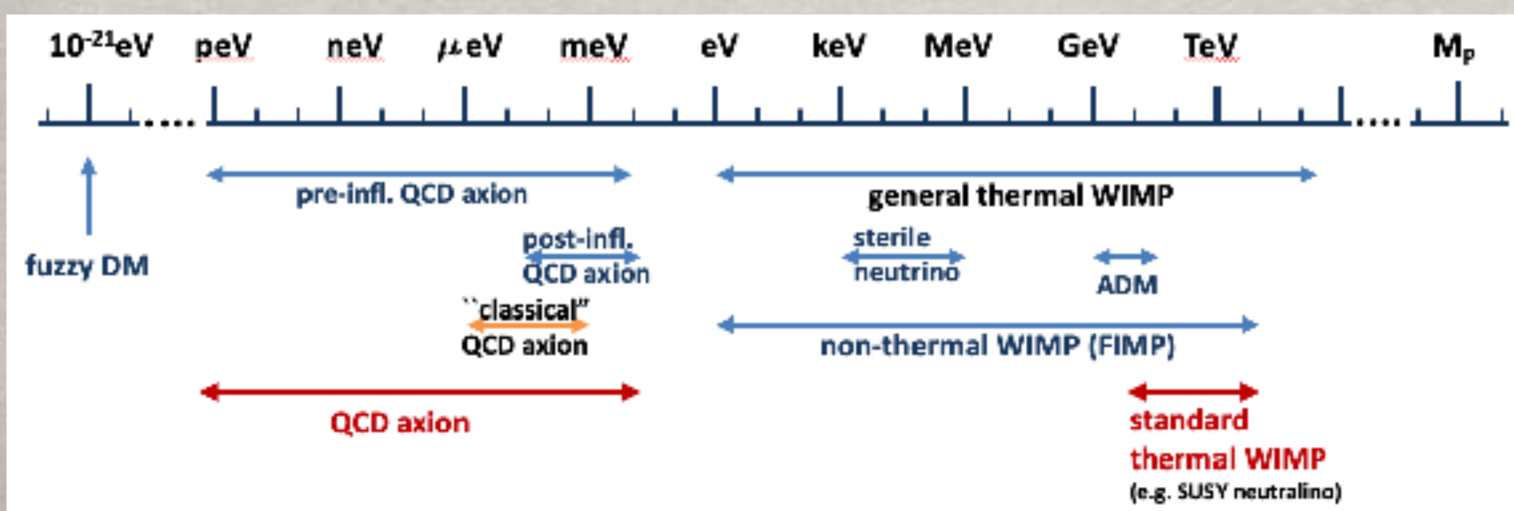
(Collider-based) Particle Physics

To pinpoint the completion of the SM, exploit the complementarity between Cosmology and Particle Physics to explore all the sectors of the theory: the more weakly coupled and the more strongly coupled to the Standard Model fields...

Best results if one has information from both sides, e.g. neutrinos, axions, DM, etc… ???

GUIDING PRINCIPLES 4 DM

- An effective DM production mechanism should be present, possibly independent from initial conditions.
- The DM particle or the DM sector should fit into a BSM model solving more than the DM problem, e.g. hierarchy, neutrino masses, strong CP problem, etc…
- Possibly detectable Dark sector in the near future.



DARK MATTER paradigms

SUPERSYMMETRIC SM

With the introduction of R-parity the lightest SUSY particle is stable and often a good DM candidate:

SUPERSYMMETRY: boson <-> fermion

Standard Model			
Matter			Forces
e	μ	τ	γ
ν_e	ν_μ	ν_τ	$W^\pm, Z$
u	c	t	g
d	s	b	G

SUSY SM			
SMatter			SForces
$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	$\tilde{\gamma}$
$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{W}^\pm, \tilde{Z}$
$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$
$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	$\tilde{G}$

$\tilde{\chi}$

$\psi_{3/2}$

SUSY is broken: MASSIVE !

Lots of massive new particles... any good one for DM ?

SUSY BREAKING

Supersymmetry has to be broken, but NOT spontaneously in the visible (MSSM) sector since then $STr\mathcal{M}^2 = 0$, i.e. in a multiplet it is impossible to push up the scalar masses only...

Way out: break SUSY in a hidden sector (where the STr formula holds...) and then transmit it to the MSSM

The mediation interaction can be of different types: renormalizable gauge interaction, non-renormalizable gravitational interaction, etc...

Different mediations give different SUSY spectra !

Note: In the most general case 105 parameters....

SUSY Breaking Masses

Given $\langle F \rangle \neq 0$ and requiring zero cosmological constant in SUGRA the gravitino mass is universal: $m_{3/2} = \frac{\langle F \rangle}{M_P}$.

Gauge mediation: sparticle masses given by loops of the messenger particles via gauge interaction:

$$m_{1/2} \sim \frac{\alpha}{4\pi} \frac{\langle F \rangle}{M_{mes}} \qquad m_0^2 \sim \frac{\alpha^2}{(4\pi)^2} \frac{\langle F^2 \rangle}{M_{mes}^2}$$

Gravity mediation: sparticle masses given by gravitational contact interaction with SUSY breaking sector:

$$m_{1/2} \sim \partial_Z f(Z) \frac{\langle F \rangle}{M_P} \qquad m_0^2 \sim \frac{\langle F^2 \rangle}{M_P^2}$$

Anomaly mediation: loop effect in supergravity:

$$m_{1/2} \sim \frac{\beta_\alpha}{4\pi} \frac{\langle F \rangle}{M_P} \qquad m_0^2 \sim \frac{\beta_m}{4\pi} \frac{\langle F^2 \rangle}{M_P^2}$$

Who is the LSP ?

Depending on the SUSY breaking mediation mechanism, different SUSY particles can be the LSP:

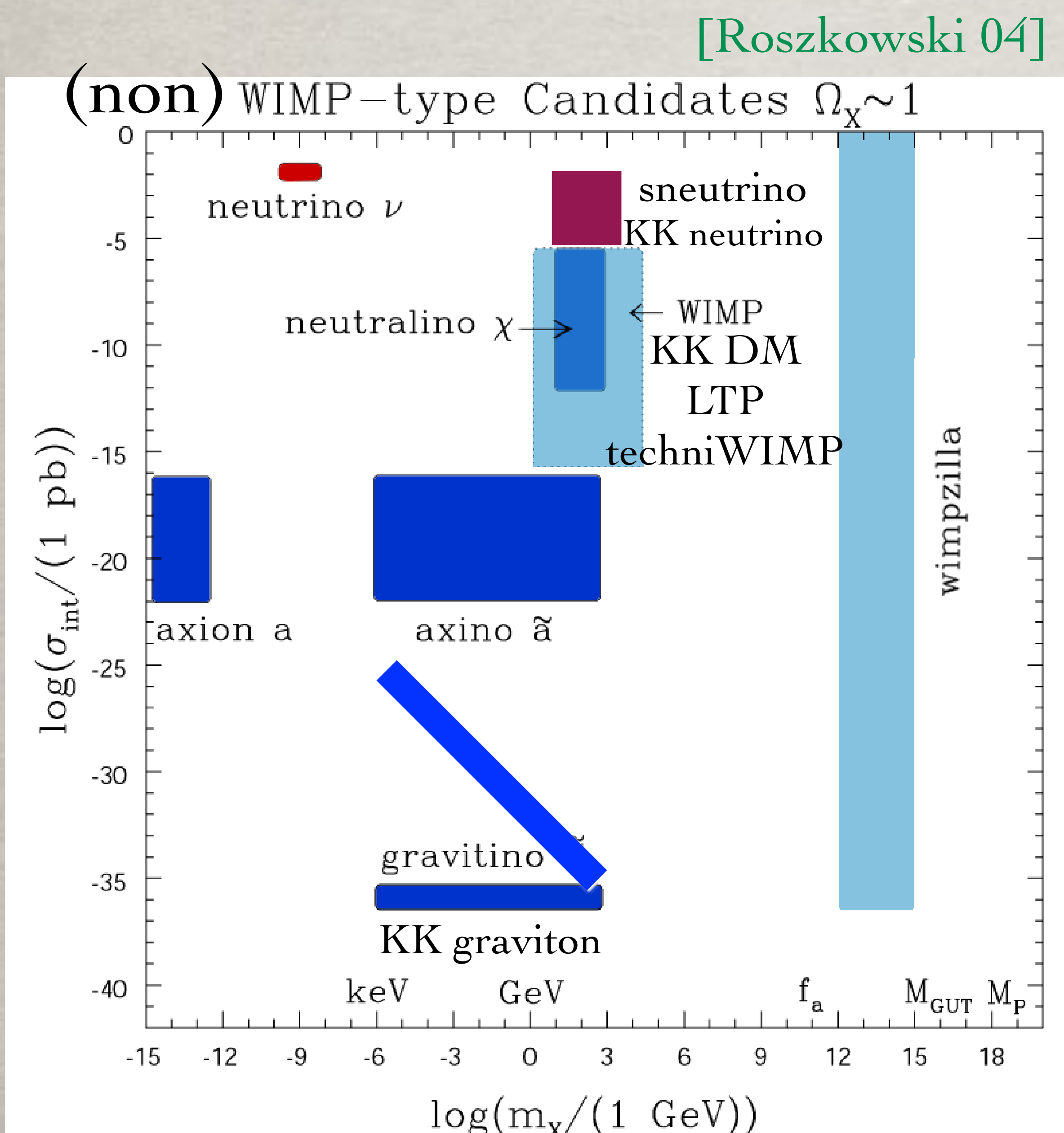
Gauge mediation: gravitino is lighter than the rest as long as the messenger mass is smaller than Planck...

Gravity mediation: for universal boundary conditions on can have either neutralino, RH stau or gravitino as LSP; for non-universal boundary conditions also LH sleptons can be the lightest or Higgsinos

Anomaly mediation: in pure anomaly mediation the leptons are tachyonic, usually a mixed mediation is needed. Then of the neutralinos the Wino is the lightest, while the gravitino is always the heaviest state...

Different LSP and DM in different scenarios !

DARK MATTER CANDIDATES



Multidimensional space !

DM production paradigms:

WIMPs

(e.g. neutralino)

&

"FIMP/SuperWIMPs"

(e.g. gravitino)

&

Misalignment

(e.g. axion/condensate)

GRAVITINO properties: completely fixed by SUGRA !

Gravitino mass: set by the condition of ”vanishing” cosmological constant

$$m_{\tilde G} = \langle W e^{K/2} \rangle = \frac{\langle F_X \rangle}{M_P}$$

~~SUSY~~

It is proportional to the SUSY breaking scale and varies depending on the mediation mechanism, e.g. gauge mediation can accomodate very small $\langle F_X \rangle$ giving $m_{\tilde G} \sim$ keV, while in anomaly mediation we can even have $m_{\tilde G} \sim$ TeV (but then it is not the LSP...).

Gravitino couplings: determined by masses, especially for a light gravitino since the dominant piece becomes the Goldstino spin 1/2 component: $\psi_\mu \simeq i\sqrt{\frac{2}{3}} \frac{\partial_\mu \psi}{m_{\tilde G}}$. Then we have:

$$-\frac{1}{4M_P} \bar\psi_\mu \sigma^{\nu\rho} \gamma^\mu \lambda^a F^a_{\nu\rho} - \frac{1}{\sqrt{2} M_P} \mathcal{D}_\nu \phi^* \bar\psi_\mu \gamma^\nu \gamma^\mu \chi_R - \frac{1}{\sqrt{2} M_P} \mathcal{D}_\nu \phi \bar\chi_L \gamma^\mu \gamma^\nu \psi_\mu + h.c.$$

$$\Rightarrow \quad \frac{-m_\lambda}{4\sqrt{6} M_P m_{\tilde G}} \bar\psi \sigma^{\nu\rho} \boxed{\lambda^a F^a_{\nu\rho}} + \frac{i(m^2_\phi - m^2_\chi)}{\sqrt{3} M_P m_{\tilde G}} \bar\psi \chi_R \phi^* + h.c.$$

Couplings proportional to SUSY breaking masses and inversely proportional to $m_{\tilde G}$!

The gravitino gives us direct information on SUSY breaking

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

ADD SUSY: $a \Rightarrow \Phi_a \equiv (s + ia, \tilde{a})$ with $$W_{PQ} = \frac{g^2}{16\sqrt{2}\pi^2 f_a}\Phi_a W^\alpha W_\alpha$$

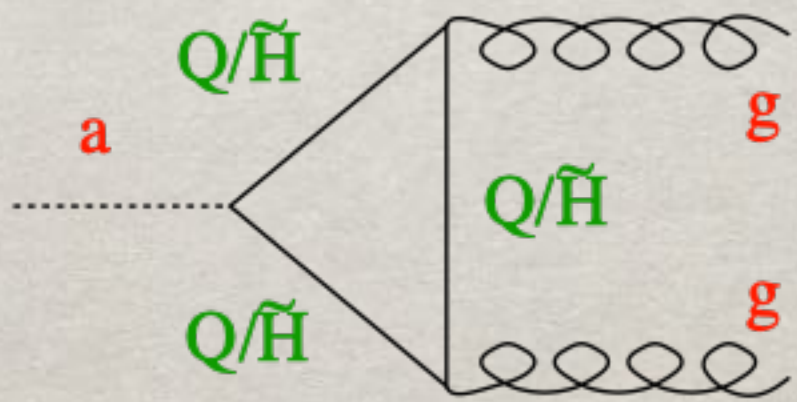
[Nilles & Raby '82]
[Frére & Gerard '83]

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	DFSZ
[Kim '79], [Shifman, Vainstein & Zakharov '80]	[Dine, Fischler & Srednicki '81], [Zhitnitskii '80]
$W = h_H \Phi_a \bar{Q} Q$ $\quad \bar{Q}, Q$ heavy quarks	$W = h\, \Phi_a H_u H_d$ $\quad H_u, H_d$ Higgs multiplets
SM fields are not charged under $U(1)_{PQ}$	SM fields are charged under $U(1)_{PQ}$
$m_Q = h_H f_a$	$h f_a = \mu$ $\quad \mu$-term
$h_H \simeq \mathcal{O}(1)$	$\rightarrow h \ll 1$

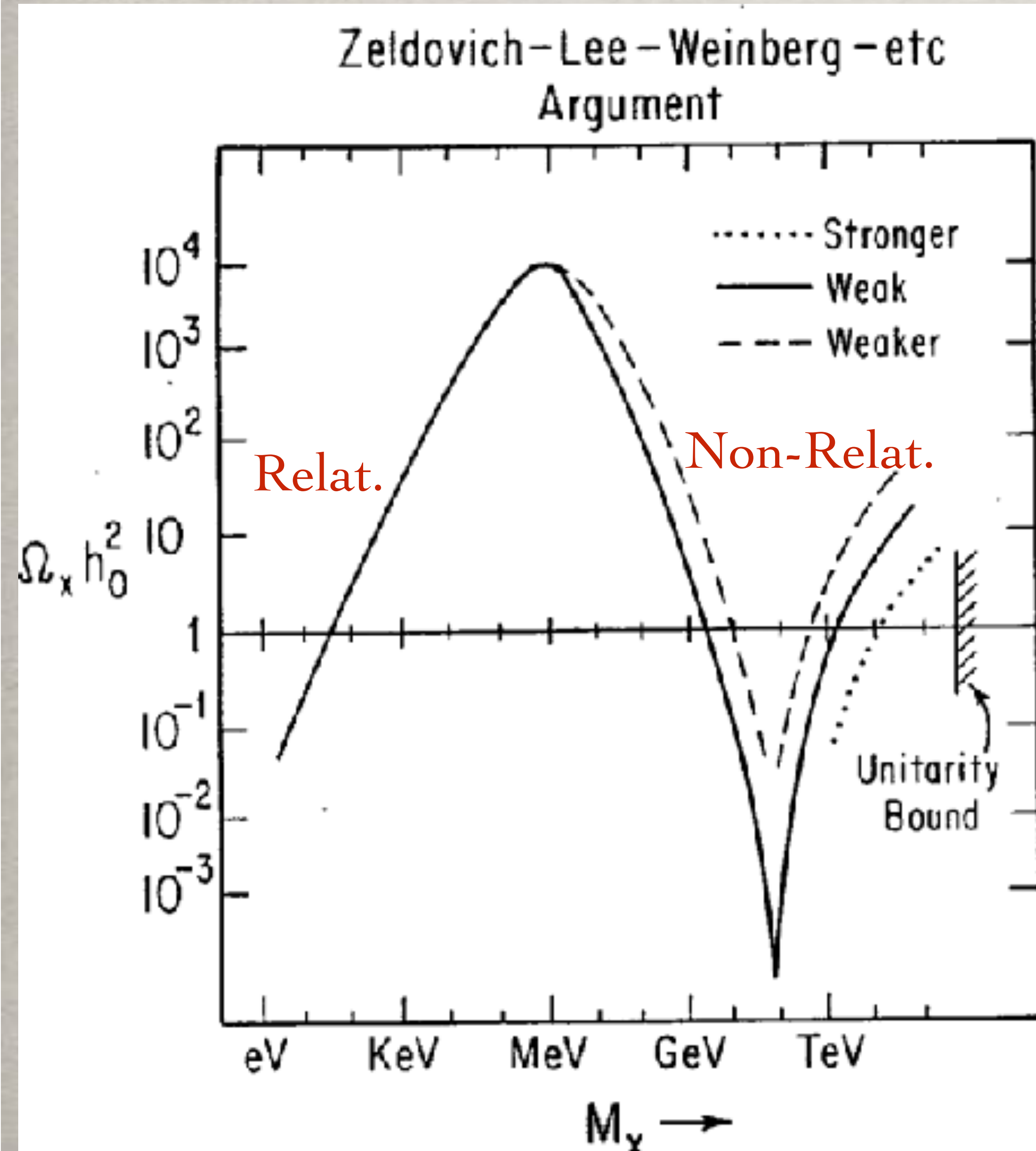
~ NMSSM



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

SUSY WIMP
Dark Matter

Zeldovich-Lee-Weinberg bound



Two possibilities for obtaining the "right" value of $\Omega_\nu h^2$: decoupling as relativistic species or as non-relativistic ! In-between the density is too large !

$$m_\nu > 4(12)\mathrm{GeV}$$

for Dirac (Majorana)

Neutrino as (prototype) DM

- Massive neutrino is one of the first candidates for DM discussed; for thermal SM neutrinos:

$$\Omega_\nu h^2 \sim \frac{\sum_i m_{\nu_i}}{93 \text{ eV}}$$

but $m_\nu \leq 0.8 \text{ eV}$ (Katrin exp.) so $\Omega_\nu \leq 0.026$

- Unfortunately the small mass also means that neutrinos are HOT DM... Their free-streaming is non negligible and the LSS data actually constrain

$$m_\nu \leq 0.27 \sim 1 \text{ eV} \quad \Rightarrow \quad \boxed{\Omega_\nu \ll \Omega_{DM}}$$

NEED to go beyond the Standard Model !

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

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

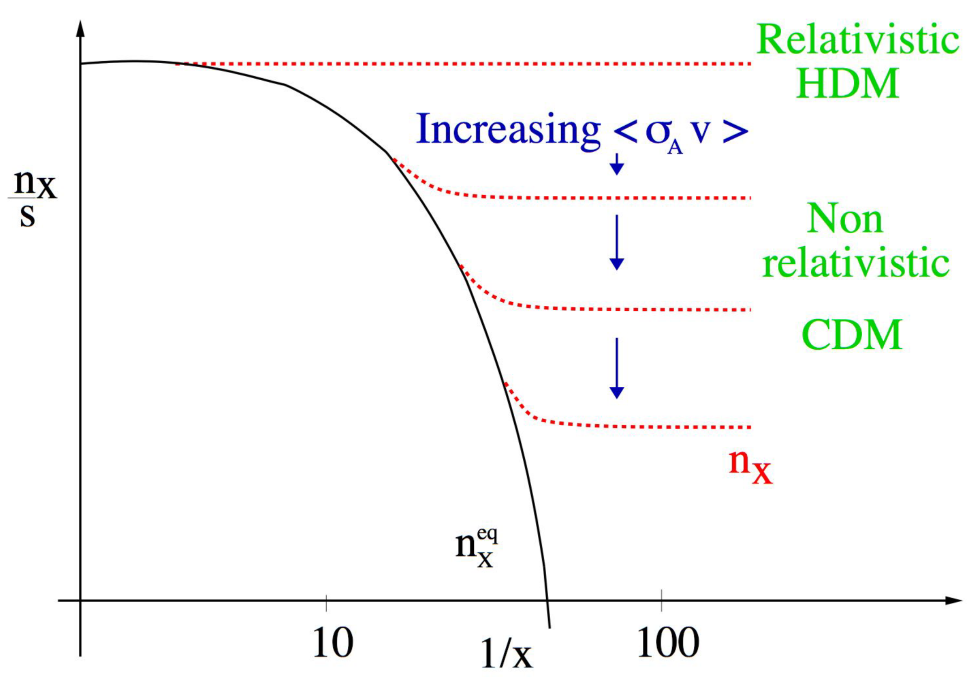
Hubble expansion   Collision integral

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



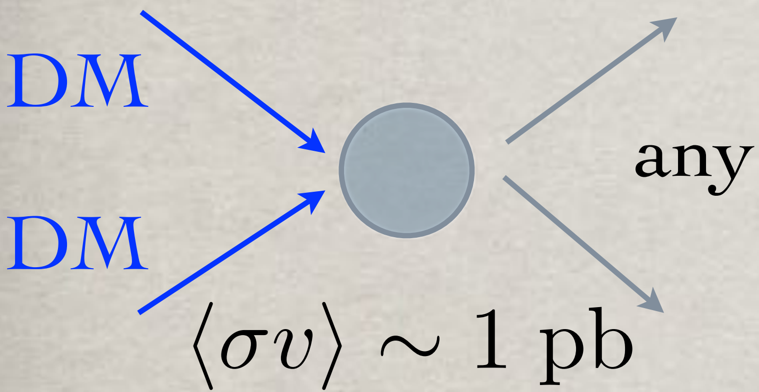
For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

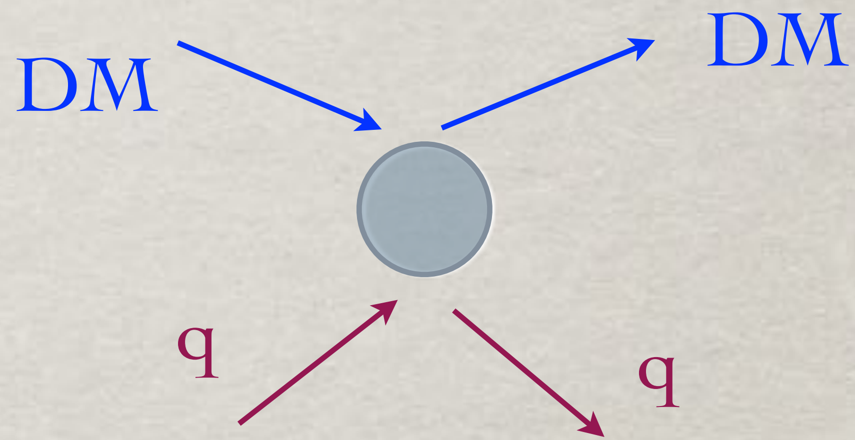
For weaker interactions need lighter masses HOT DM !

THE WIMP CONNECTION

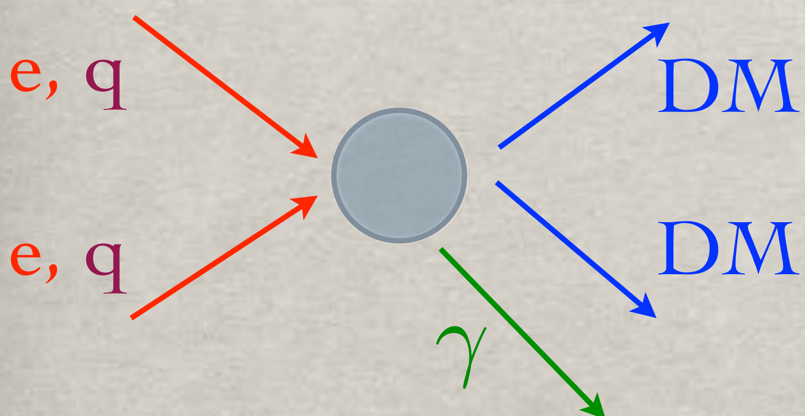
Early Universe: $\Omega_{CDM} h^2$



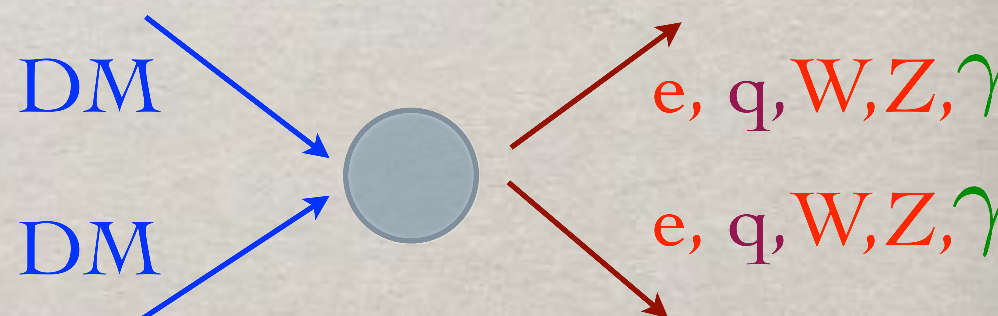
Direct Detection:



Colliders: LHC/ILC

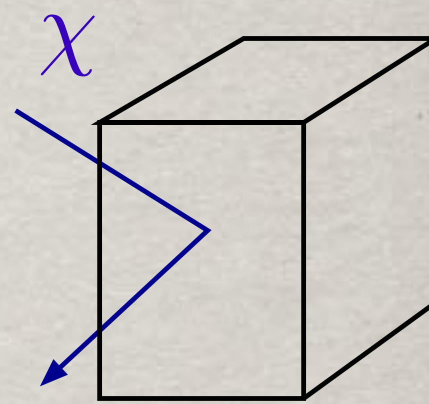


Indirect Detection:



3 different ways to check this hypothesis !!!

Direct WIMP detection



- Elastic scattering of a WIMP on nuclei. The recoil energy is in the keV range:

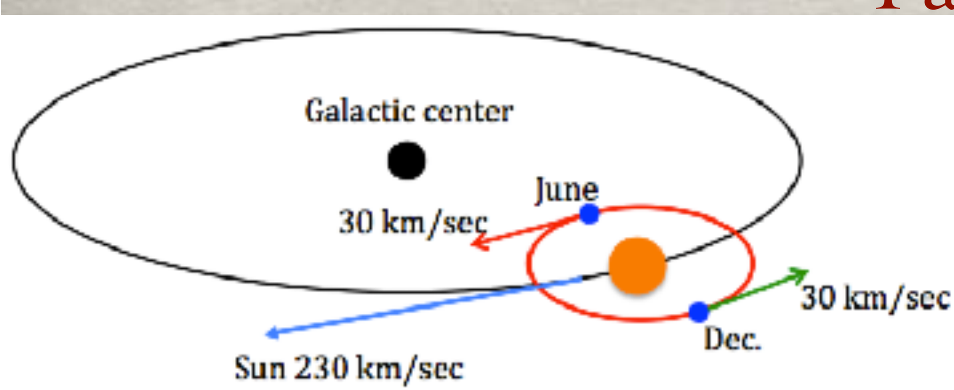
with $$\Delta E = \frac{4 m_{DM} m_N}{(m_{DM} + m_N)^2}\, E_{kin}^{DM}$$

$$E_{kin}^{DM} \sim \frac{1}{2} m_{DM} v^2 \sim 50 \text{ keV} \frac{m_{DM}}{100\text{GeV}}$$

Need very low threshold !

- The rate is $$\frac{dR}{dE_R} \propto \sigma_n F^2(E_R) \; \frac{\rho_{DM}}{m_{DM}} \int_{v_{min}}^{\infty} \frac{dv}{v} f(v)$$

Particle Physics   Halo physics



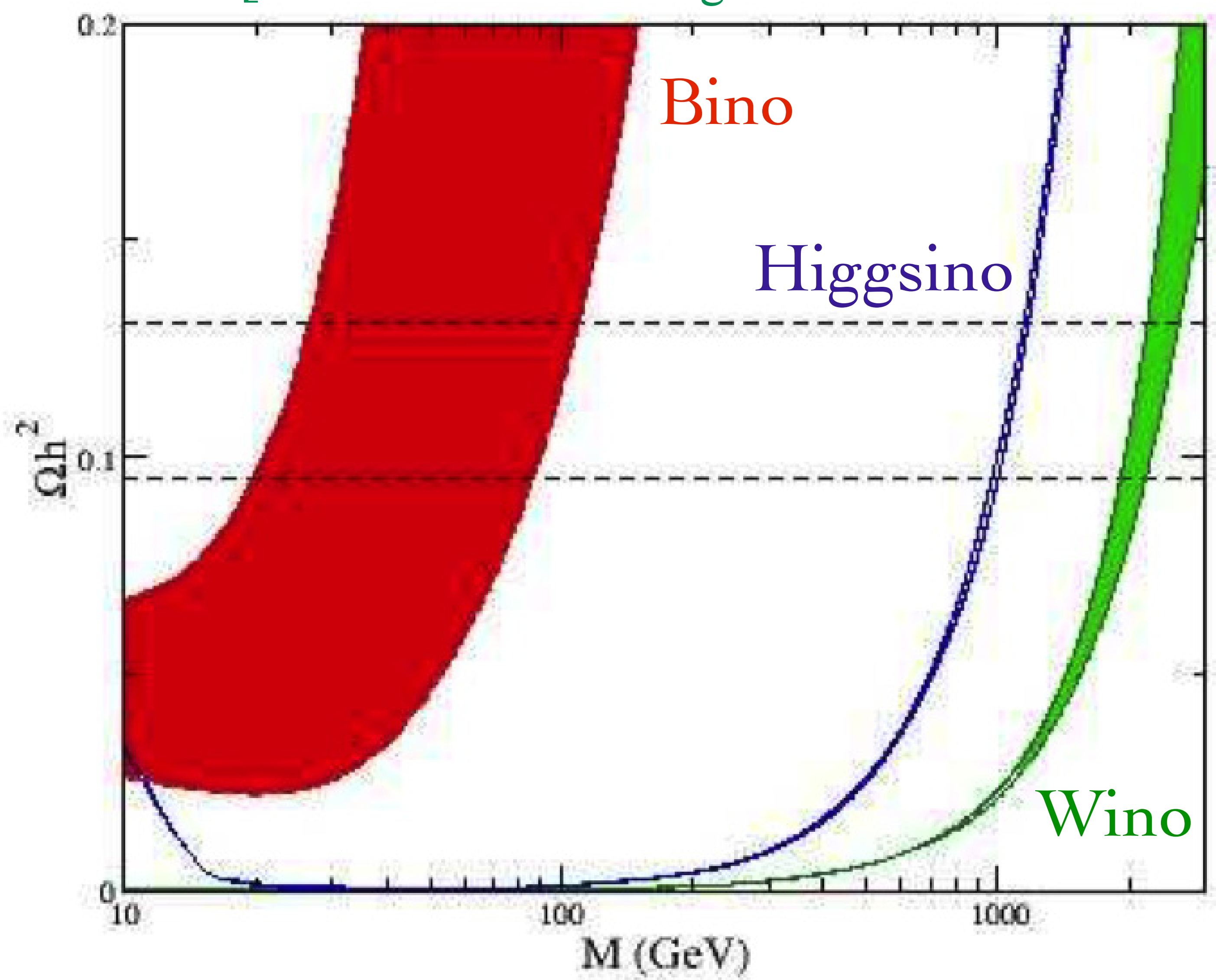
Rate depends on v in lab frame

→ annual modulation !

Well-tempered neutralino

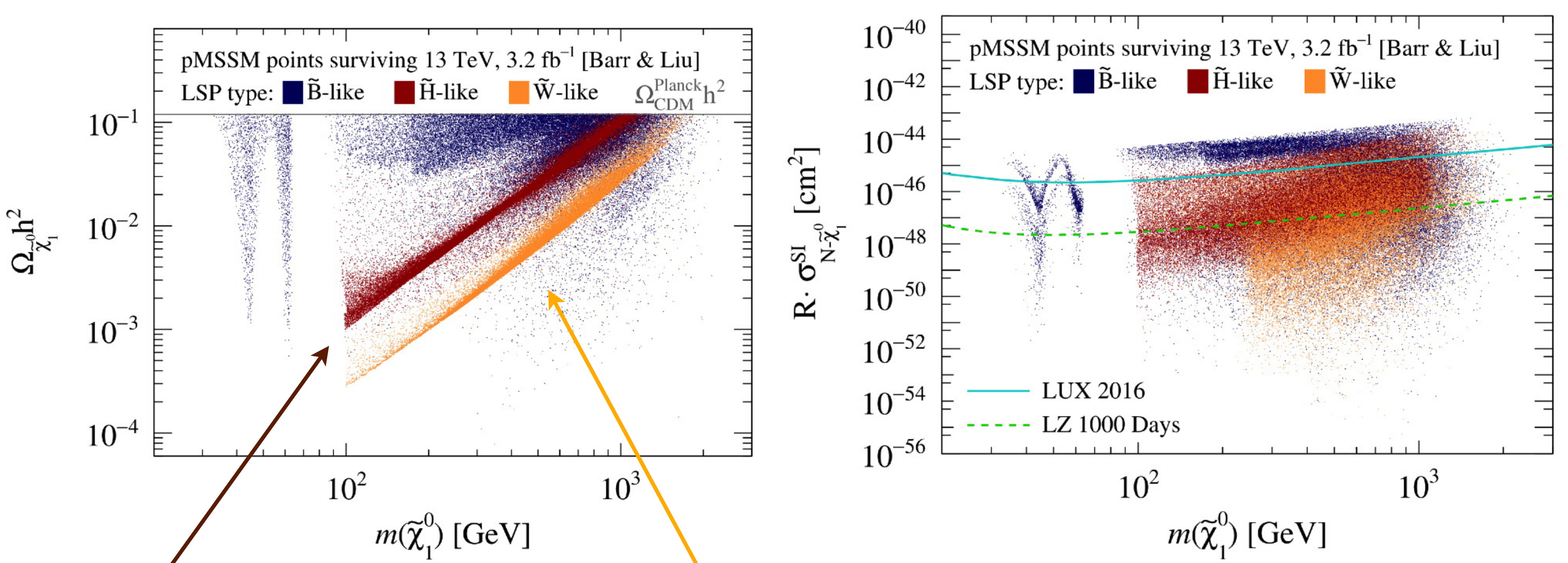
Relic density strongly dependent on neutralino nature !!!

[Arkani-Hamed, Delgado & Giudice 0601041]



SUSY MODELS STILL ALIVE

pMSSM points surviving after LHC-13 data [Barr & Liu 2016]



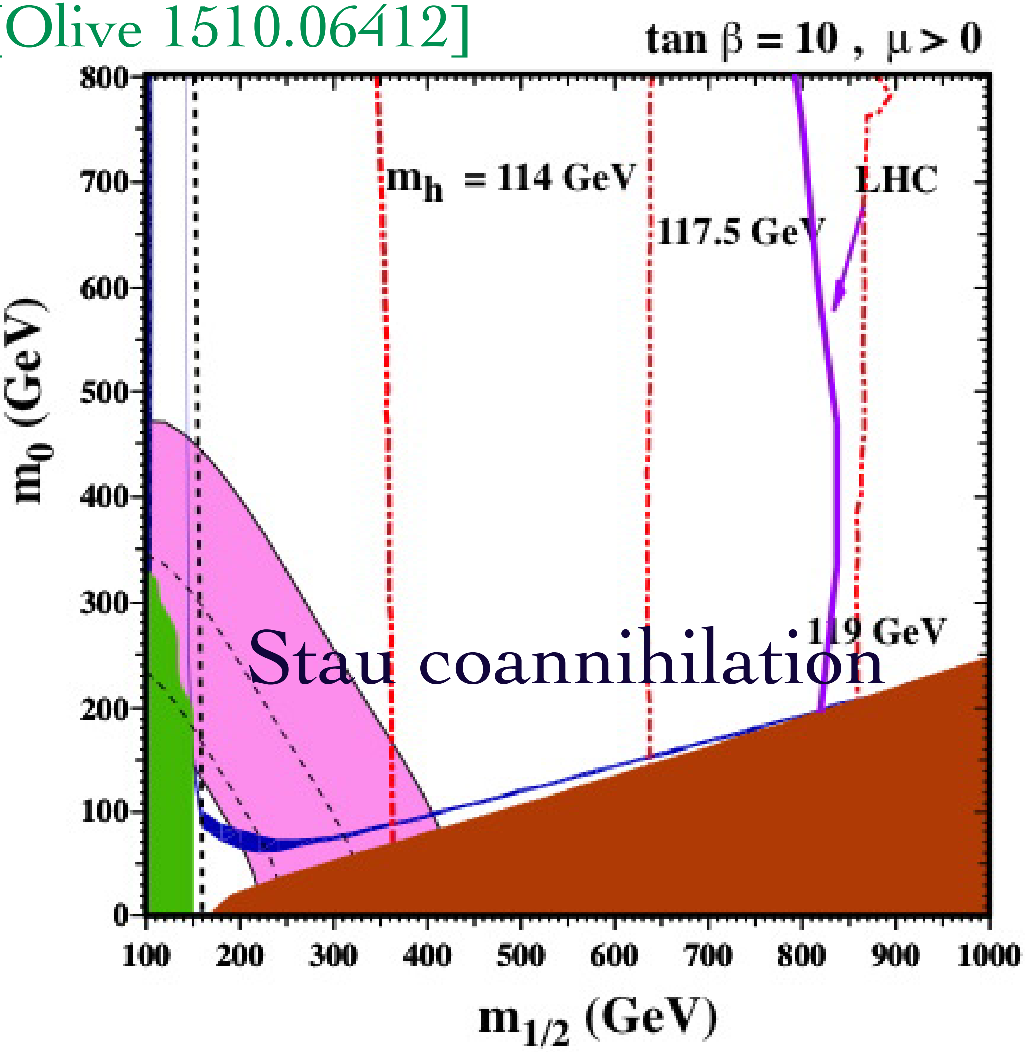
Higgsino band Wino band

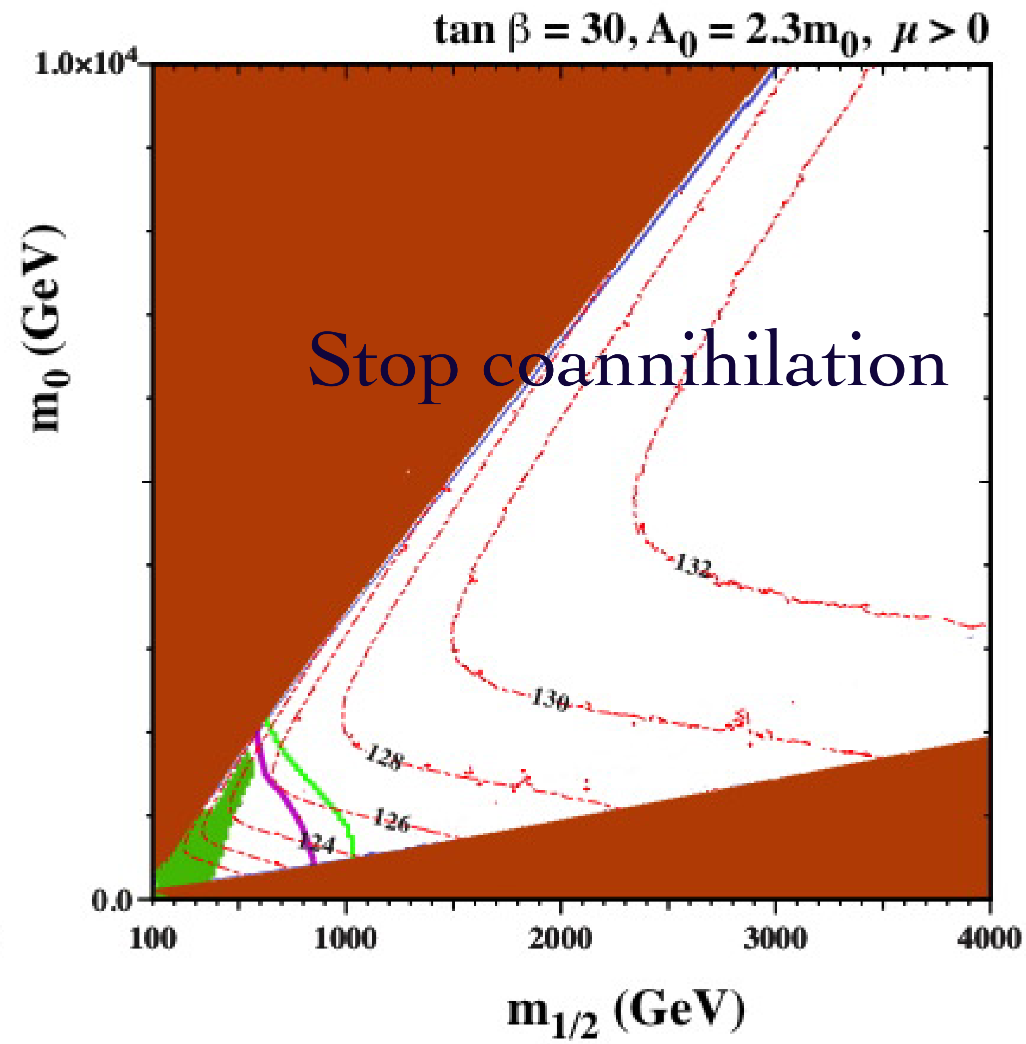
Wino DM challenged by Indirect Detection, but Higgsino parameter space still viable (and also some Bino-like...)

Bino coannihilation

To have the correct relic density for a Bino LSP, need to suppress the density, e.g. by coannihilation… also in CMSSM:

[Olive 1510.06412]

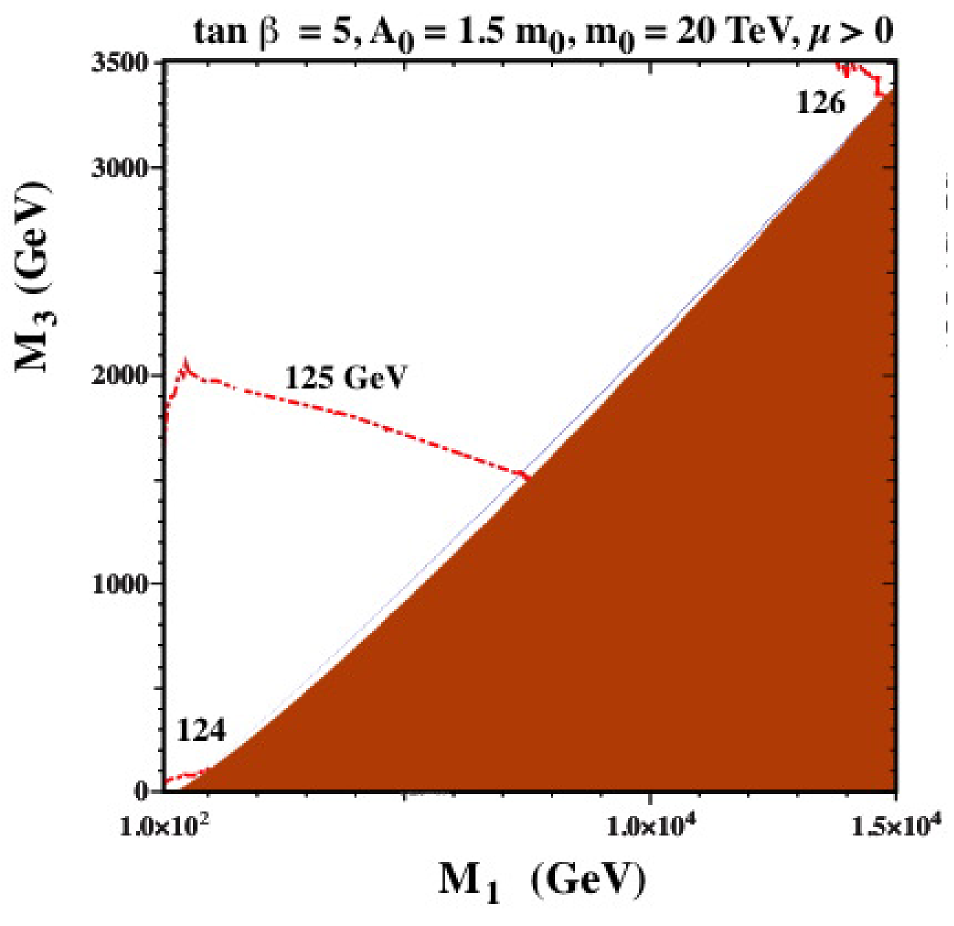




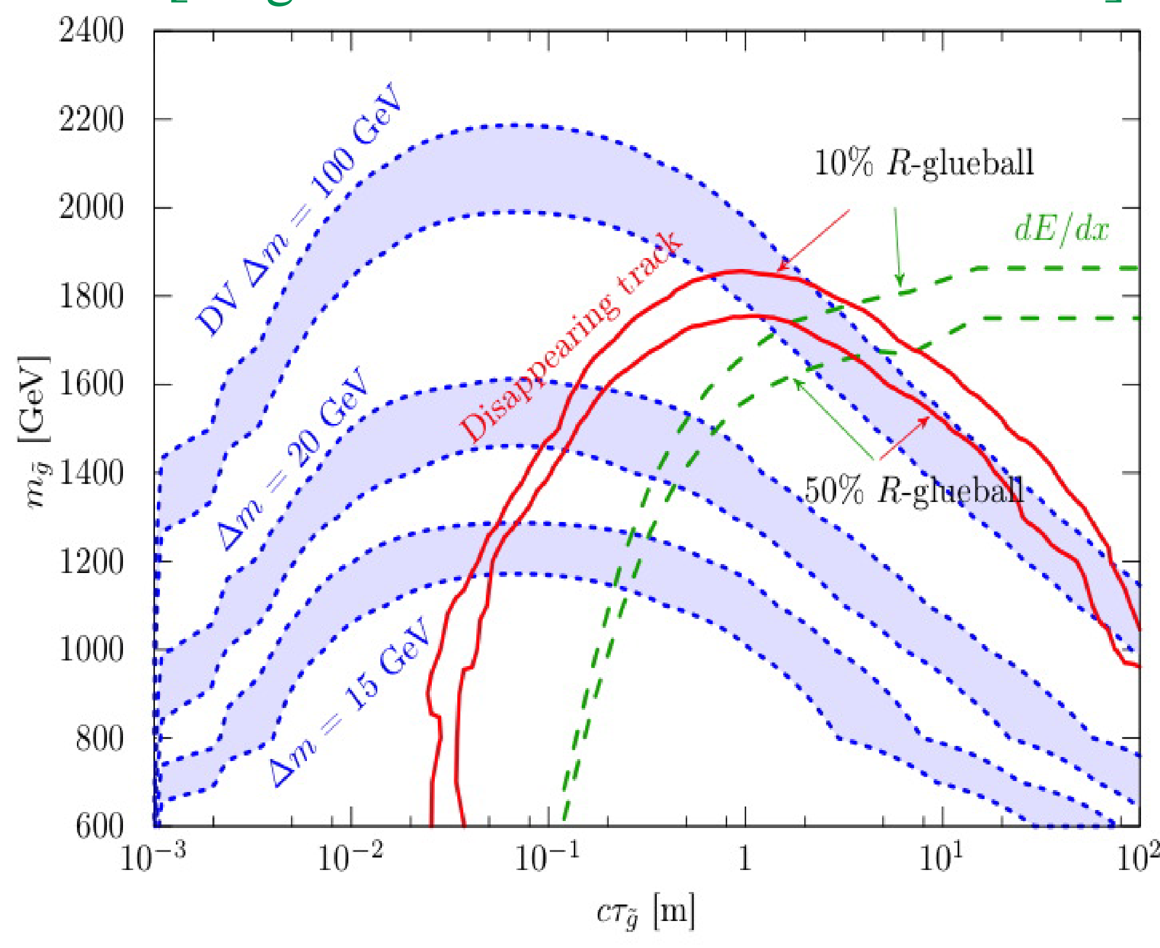
Bino-gluino coannihilation

For non-universal gaugino masses also the gluino plays a role and extends the mass to the multiTeVs !

[Ellis, Evans, Luo & Olive 1510.03498]



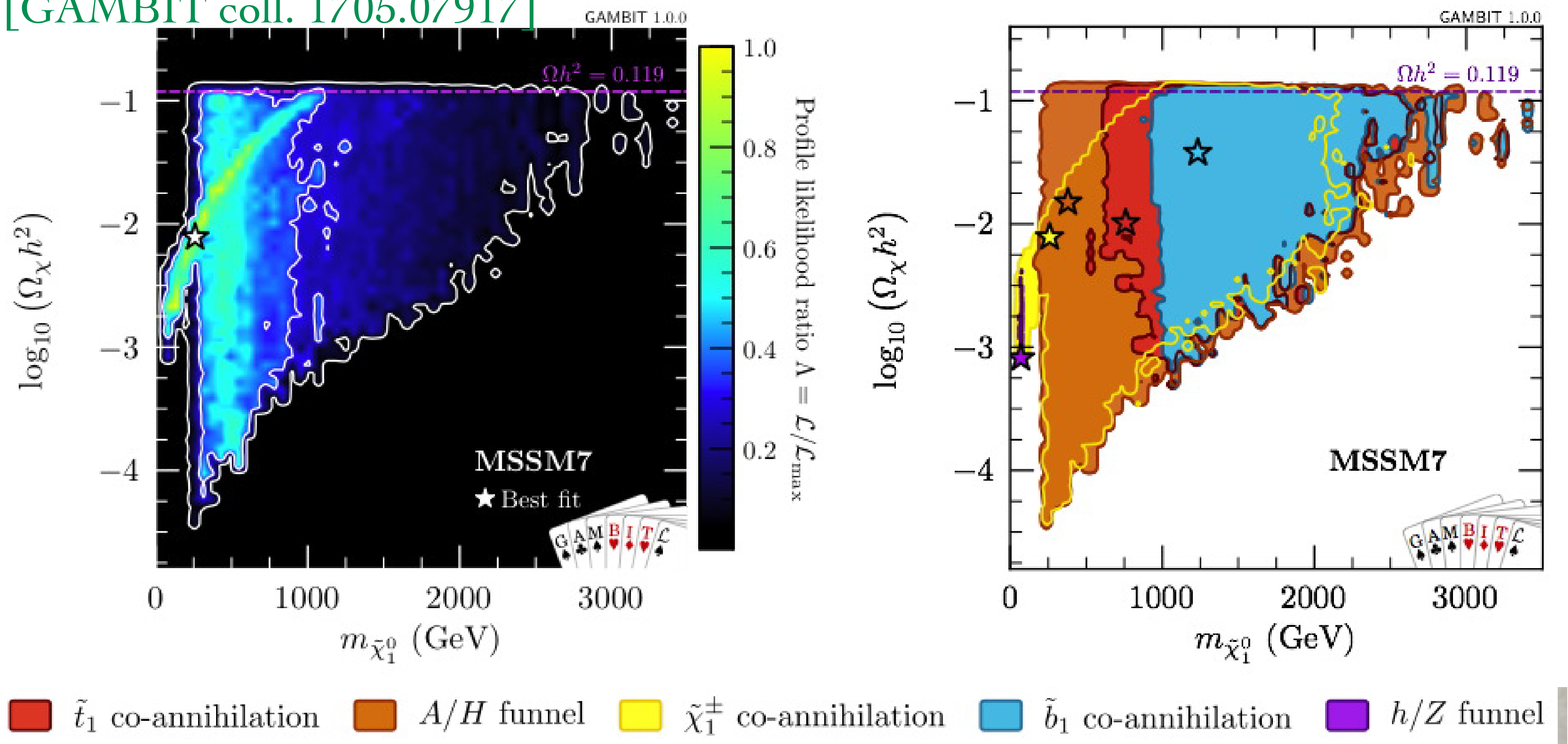
[Nagata, Otono & Shirai 1701.07664]



MSSM-7 Dark Matter

With more parameters, more mechanism are possible, i.e. in the MSSM with 7 parameters: both Bino & Higgsino DM !

[GAMBIT coll. 1705.07917]

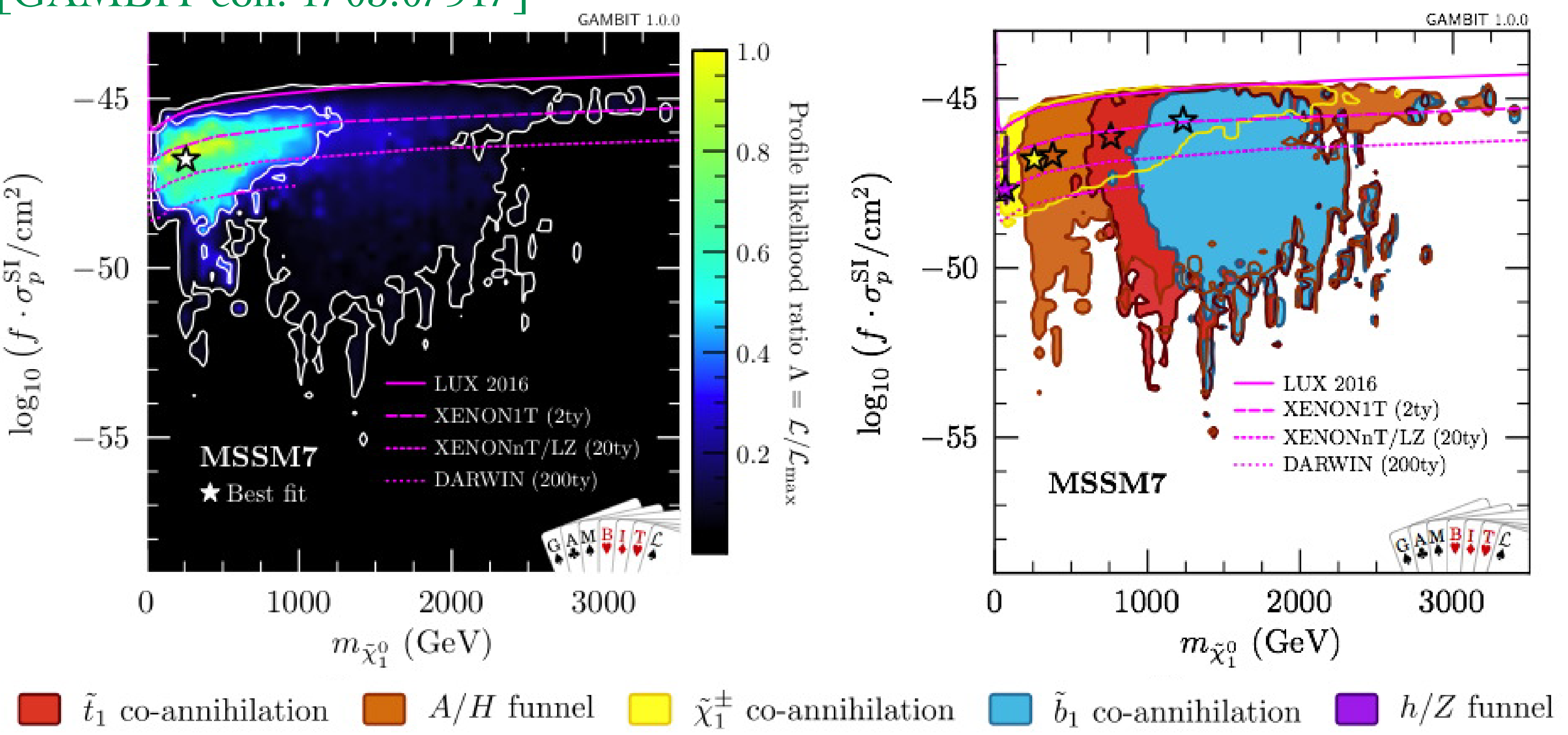


For Higgsino coannihilation with charginos is always present !

Higgsino Dark Matter

The Higgsino DM region mostly covered by Direct Detection:

[GAMBIT coll. 1705.07917]

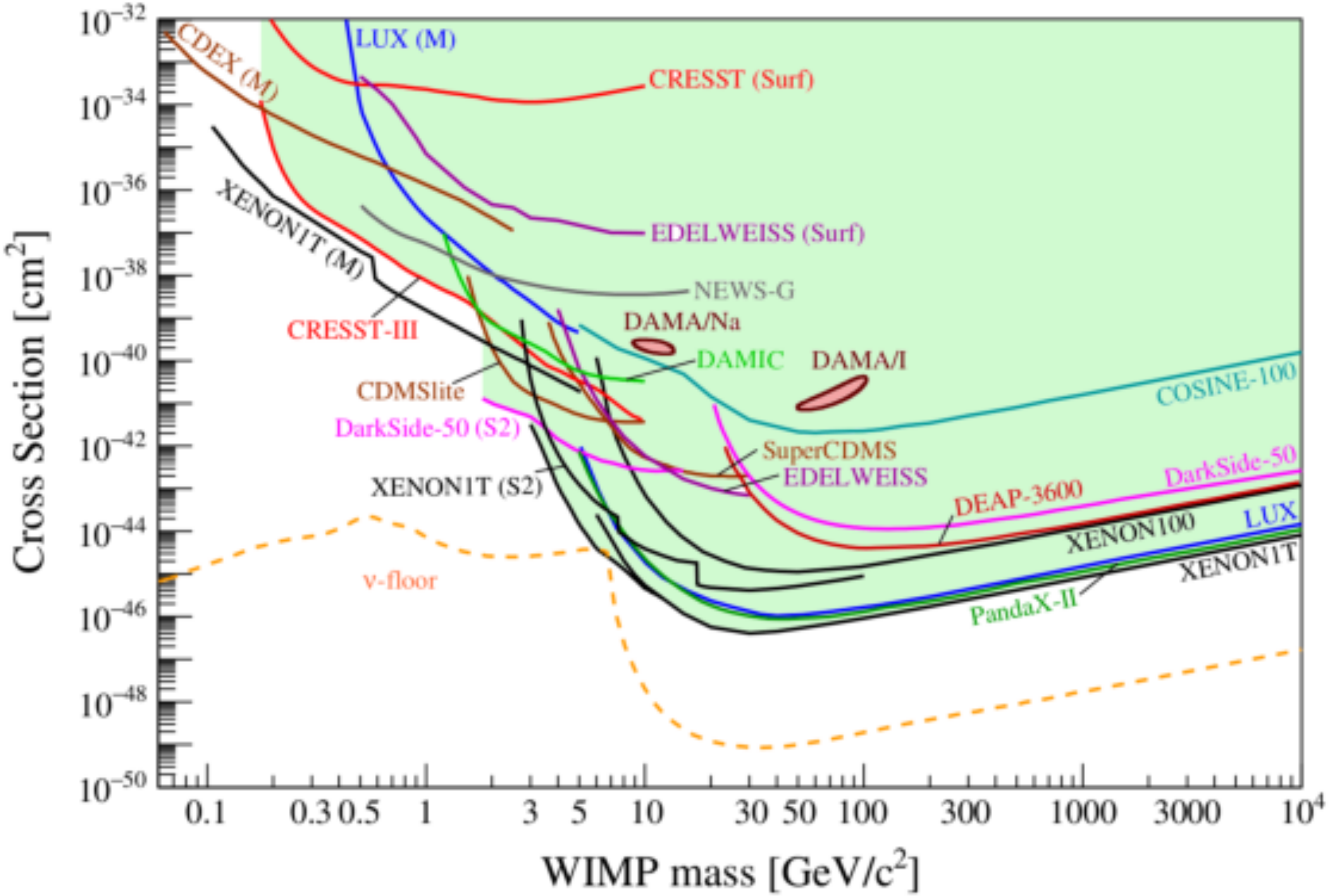


Nevertheless for other compositions low cross-section is possible

Direct detection

The constraints are moving towards the neutrino floor, with new frontiers at low masses:

[Billard et al. 2104.07634]



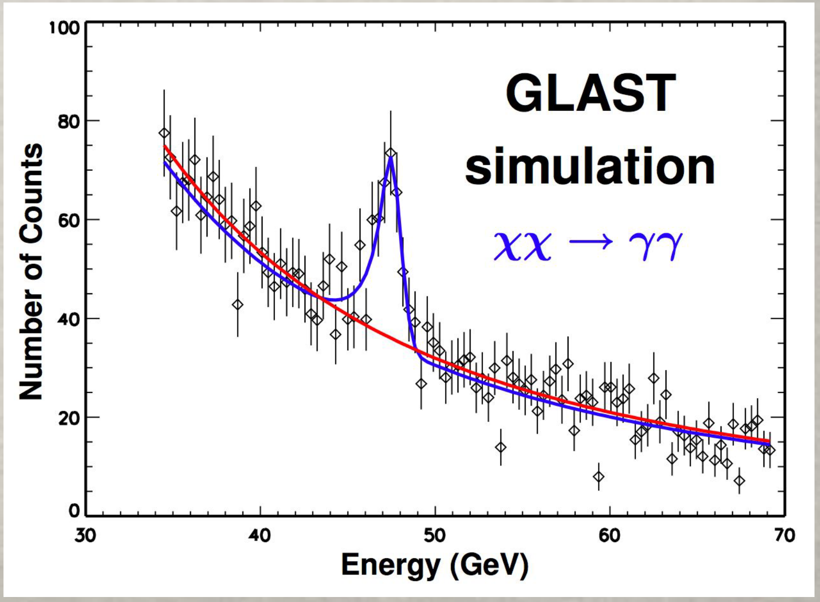
THE HOPE: DETECT DM !

- The flux in a species i is given by

$$\Phi(\theta, E) = \sigma v \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}^2} \int_{l.o.s.} ds\, \rho^2(r(s,\theta))$$

Particle Physics — Halo property J(θ)

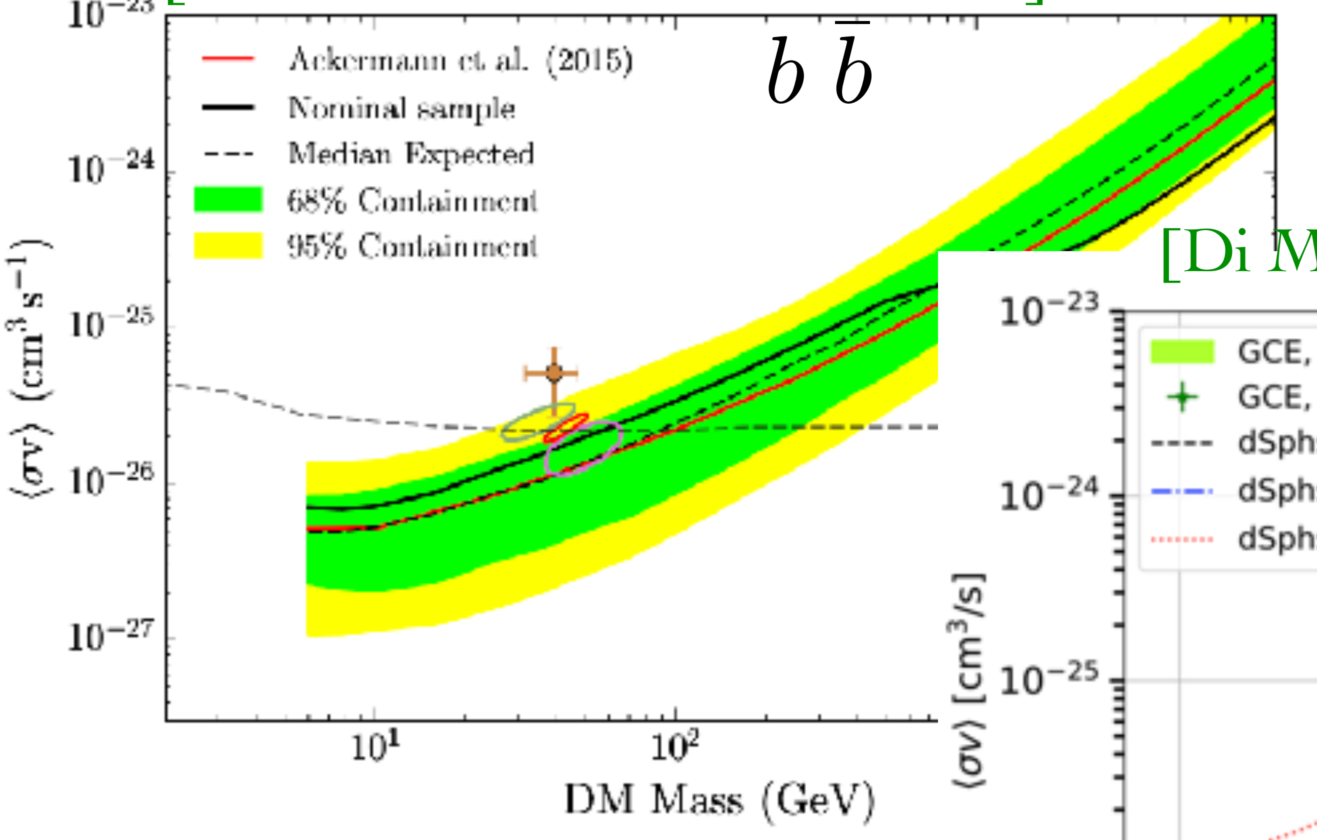
- Strongly dependent on the halo model/density via J and the DM clumping: BOOST factor !
- Spectrum in gamma-rays determined by particle physics ! Smoking gun: gamma line...
- For other species also the propagation plays a role.



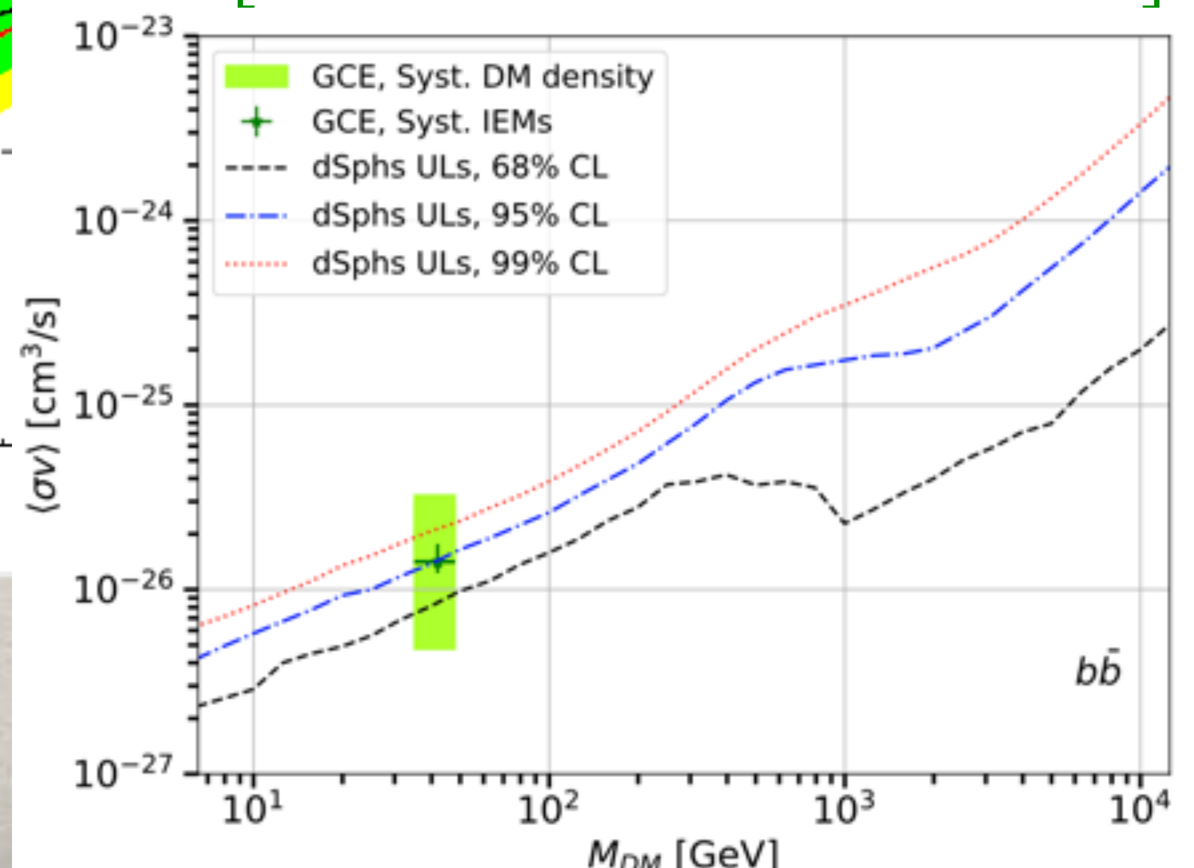
Bounds on WIMP DM

Strong limits are obtained from dwarf satellite galaxies, considering measured J-factors:

[Fermi-LAT & DES 1611.03184]

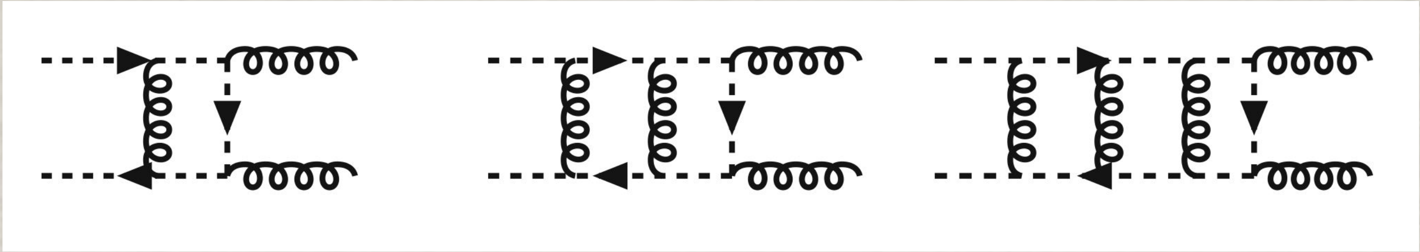


[Di Mauro & Winkler 2101.11027]



Sommerfeld Factor

[Sommerfeld 39, Sakharov 48]



- Consider one particle moving in the Coulomb field produced by the other... In Feynman diagrams it correspond to resumming over all ladder diagrams with soft gluons. The effect arises from the long-range nature of the force !
- The cross-section factorizes for a massless gauge boson:

$$\sigma_S = \sigma_0 \times E_S(\beta) \qquad E_S(\beta) = \frac{z}{1 - e^{-z}} \quad \text{with} \quad z = \frac{C\pi\alpha_N}{\beta}$$

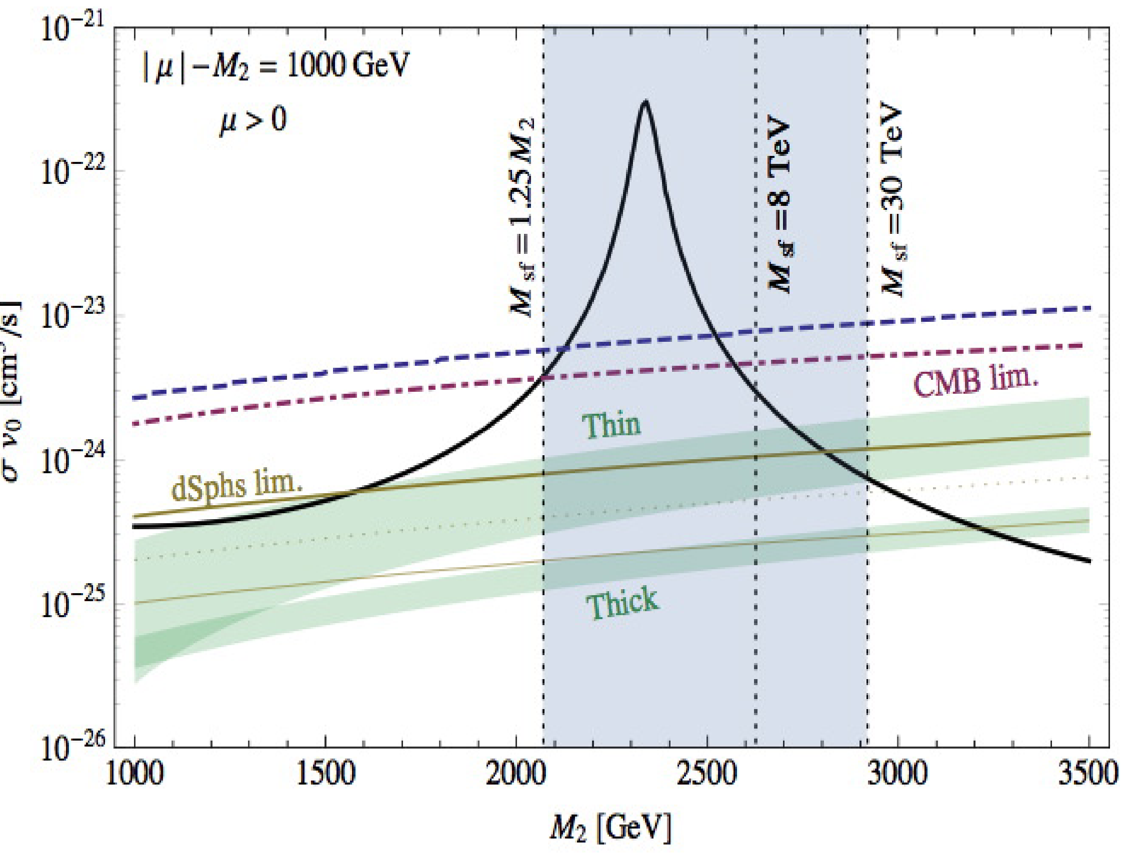
- Dominant correction for small velocity !!!

  RELEVANT AT FREEZE-OUT and TODAY !

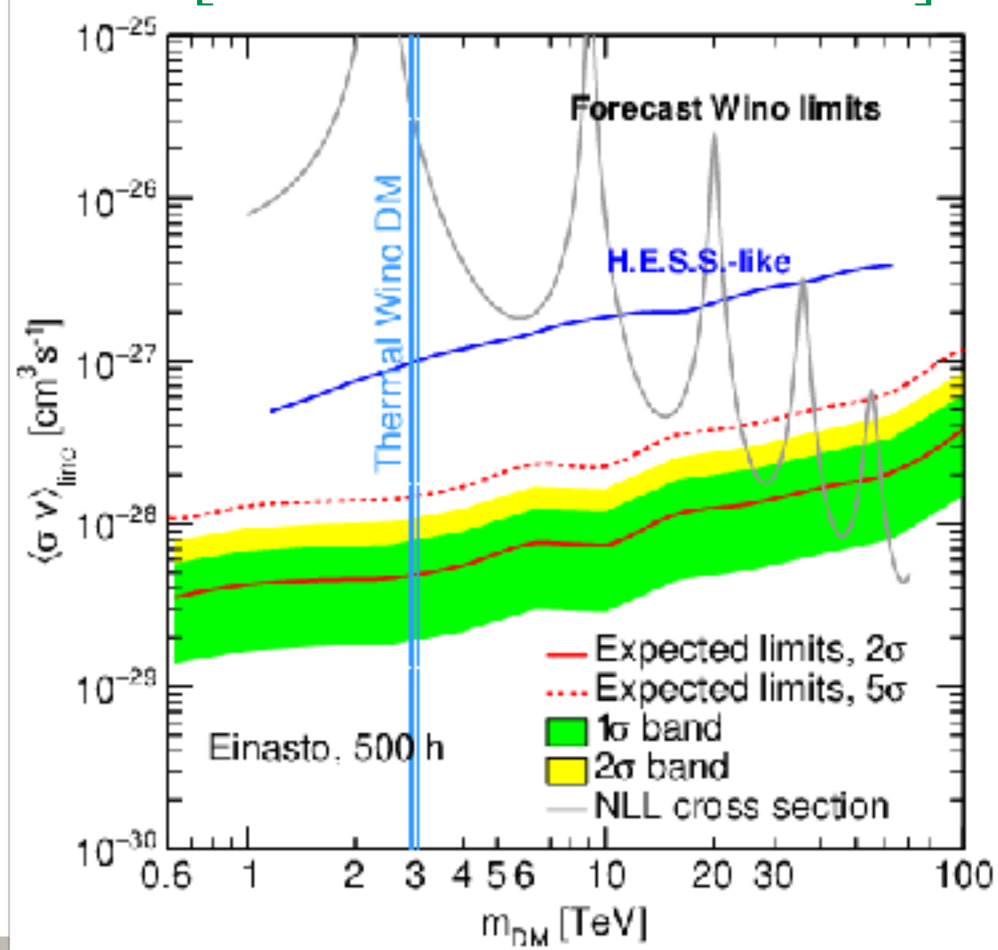
Wino Dark Matter

In the case of the Wino the Sommerfeld enhancement of the cross-section plays an important role !
Indirect detection can exclude pure Wino, also in the high mass region by CTA

[Beneke et al.1611.00804]



[Rinchiuso et al. 2008.00692]

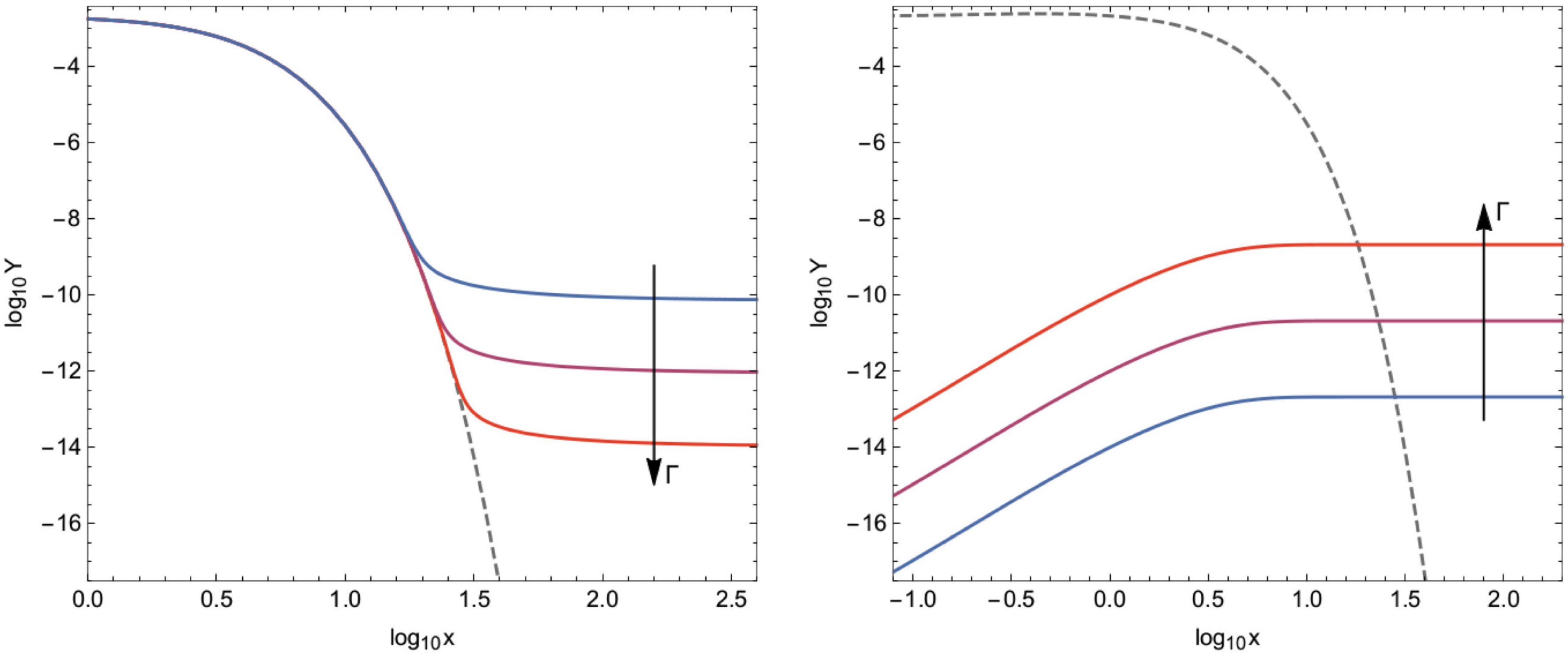


SUSY FIMP/ SuperWIMP/ Decaying Dark Matter

SuperWIMP/FIMP paradigms

WIMP vs FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$



[Figure from N. Bernal's talk at Invisibles18]

Instead of starting from thermal equilibrium, consider the opposite case: a particle so weakly interacting that is not initially in equilibrium, but it is driven towards it by the interaction with particles in the thermal bath.

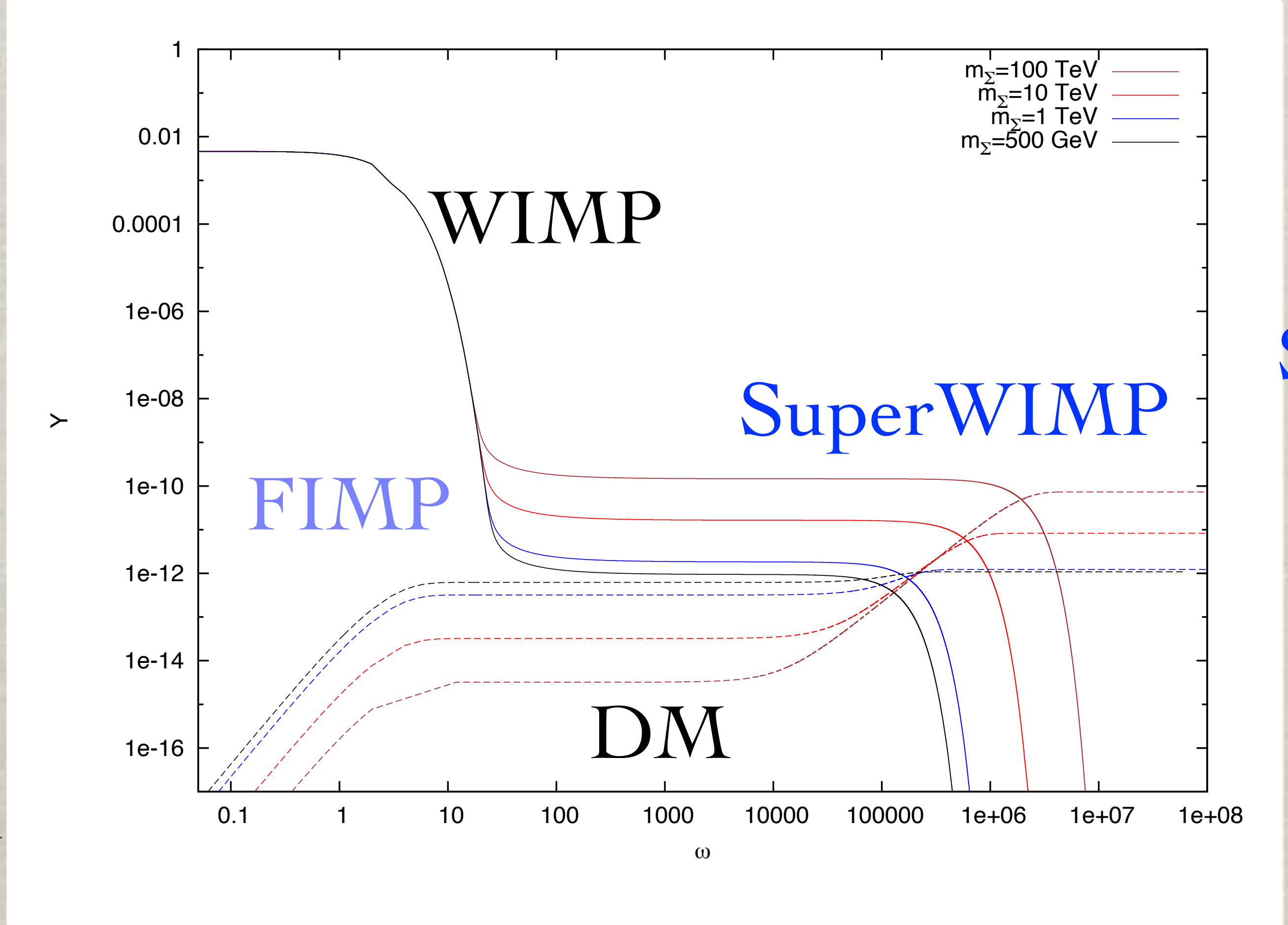
Same Boltzmann equation, but different dynamics !

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



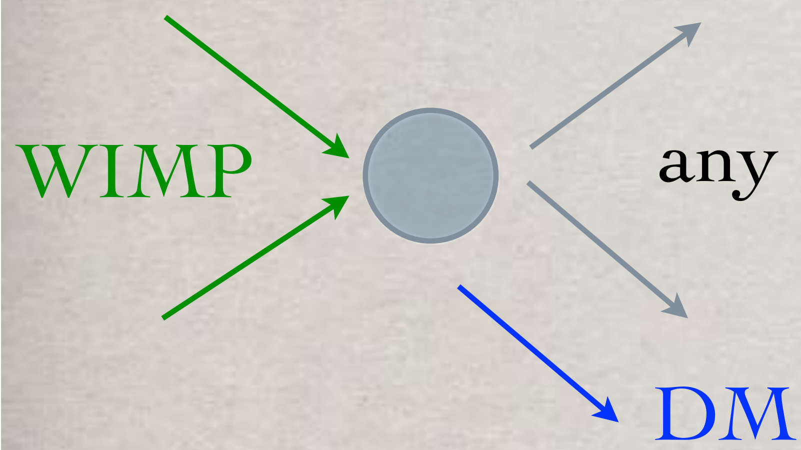
[Feng et al 04]

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

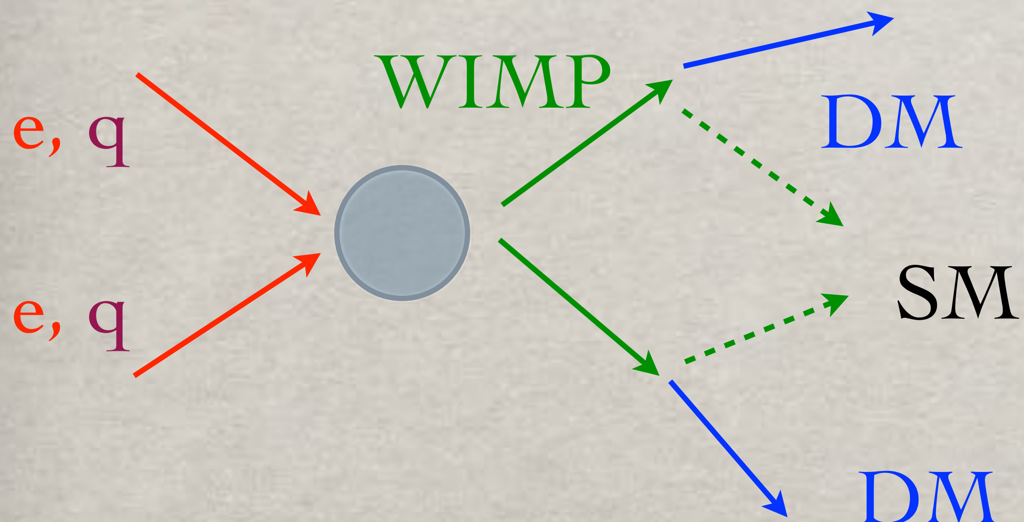
Early Universe: $\Omega_{CDM} h^2$



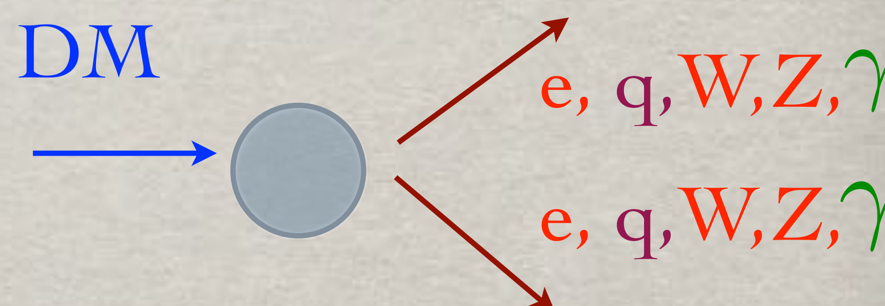
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:



decaying DM !

3 different ways to check this hypothesis !!!

Gravitino & Cosmology

Gravitinos can interact very weakly with other particles and therefore cause trouble in cosmology, either because they decay too late, if they are not LSP, or, if they are the LSP, because the NLSP decays too late...

If gravitinos are in thermal equilibrium in the Early Universe, they decouple when relativistic with number density given by

$$\Omega_{3/2} h^2 \simeq 0.1 \left(\frac{m_{3/2}}{0.1 \mathrm{keV}} \right) \left(\frac{g_*}{106.75} \right)^{-1}$$

Warm DM !

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

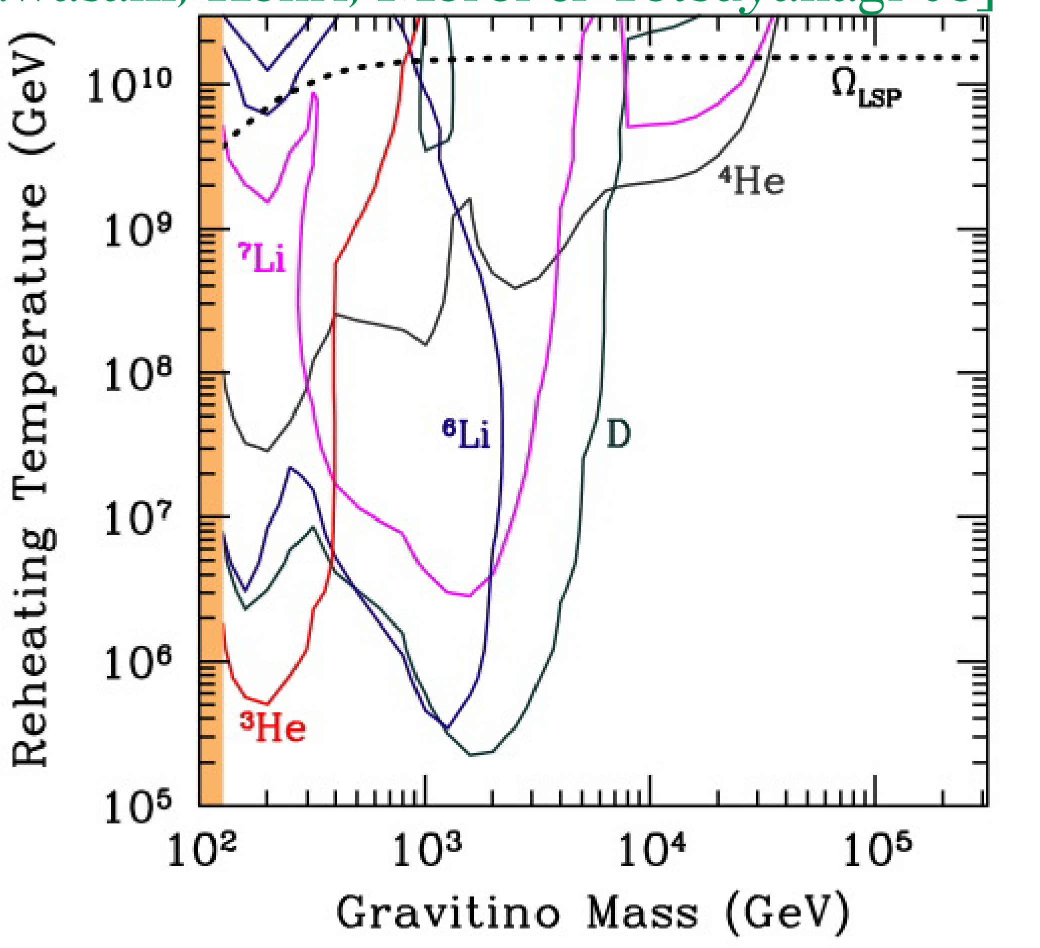
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1 \mathrm{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}} \right)^2$$

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

THE GRAVITINO PROBLEM

The gravitino, the spin 3/2 superpartner of the graviton, interacts only "gravitationally" and therefore decays (or "is decayed into") very late on cosmological scales.

[Kawasaki, Kohri, Moroi & Yotsuyanagi 08]



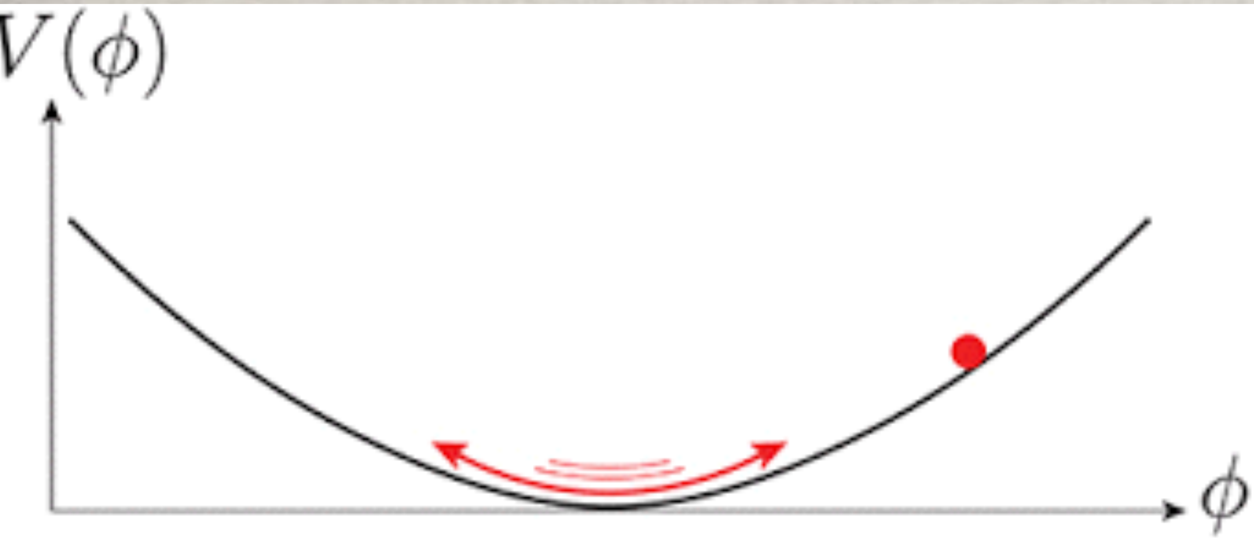
$$\tau_{3/2} = 6 \times 10^7 \mathrm{s} \left(\frac{m_{3/2}}{100 \mathrm{GeV}} \right)^{-3}$$

BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than ~ 1 s, or if the reheating temperature is small! Indeed due to non-renormalizable coupling

$$\Omega_{3/2} \propto T_R \, M_i^2 / m_{3/2}$$

THE MODULI PROBLEM

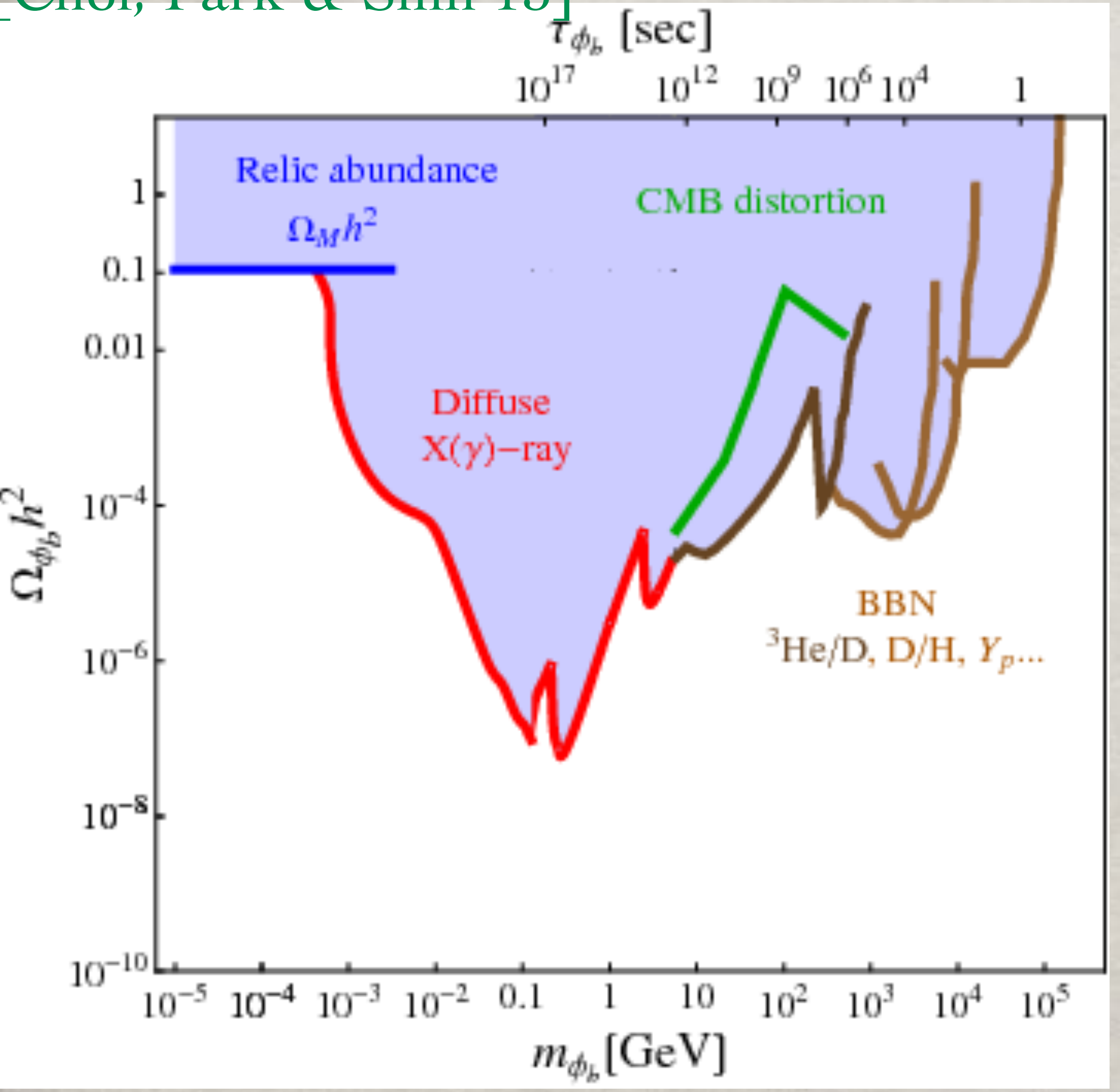
Also moduli fields connected with the shape/size of extra dimensions in string theory are expected to be light with mass of the order of the gravitino mass and generated only by SUSY breaking. Moreover they also only decay gravitationally to the SM sector.
In the case of moduli, they arise in the early Universe also from the misalignment mechanism.



The potential arises only from SUSY breaking, so it is very shallow and the field can be displaced during inflation

THE MODULI PROBLEM

[Choi, Park & Shin 13]



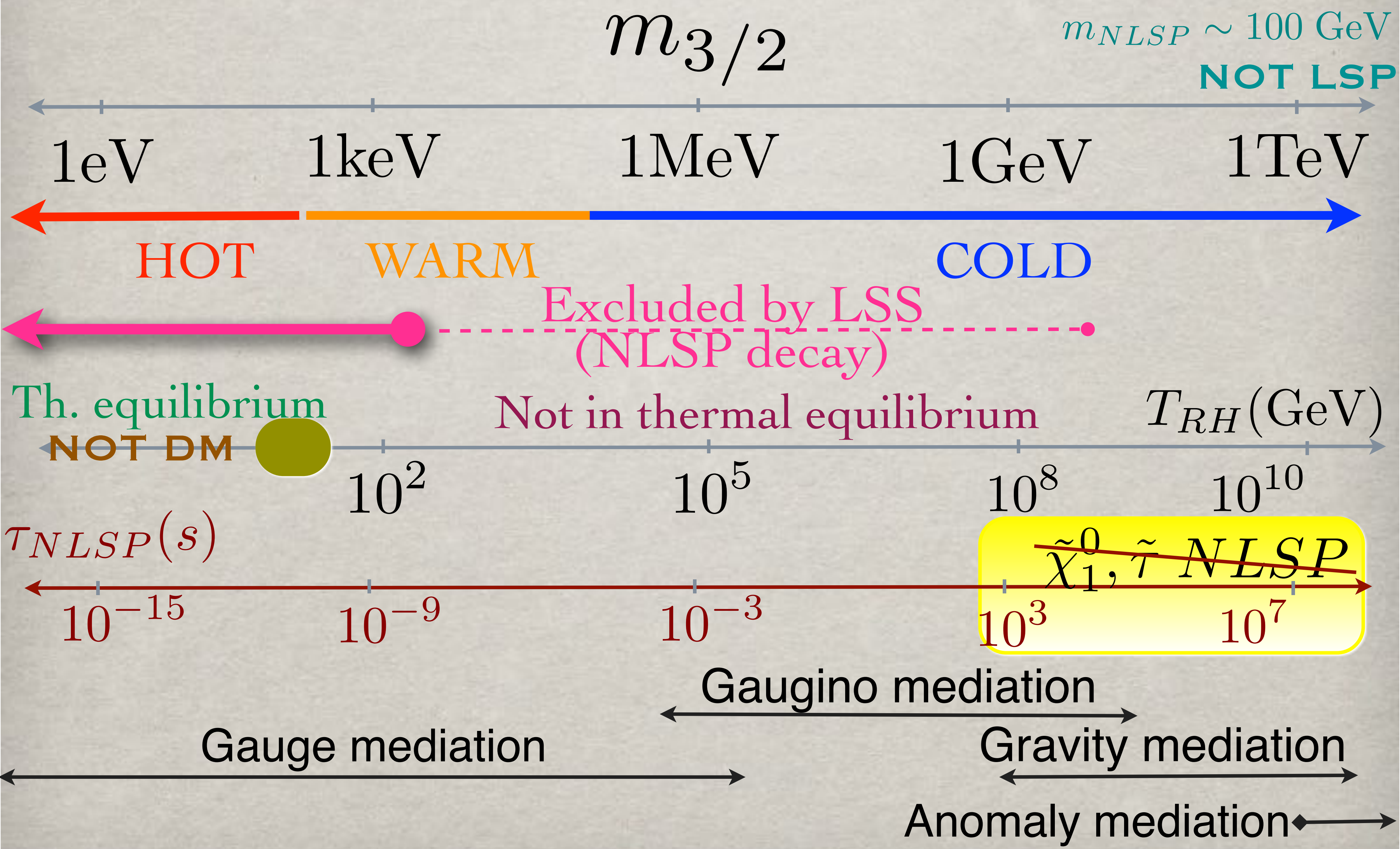
$$\tau_{mod} \sim 0.6 \text{ s} \left(\frac{100 \text{ TeV}}{m_{mod}}\right)^3$$

$$m_{mod} \sim \mathcal{O}(1)\, m_{3/2}$$

Again generic trouble due to too many moduli around after inflation…

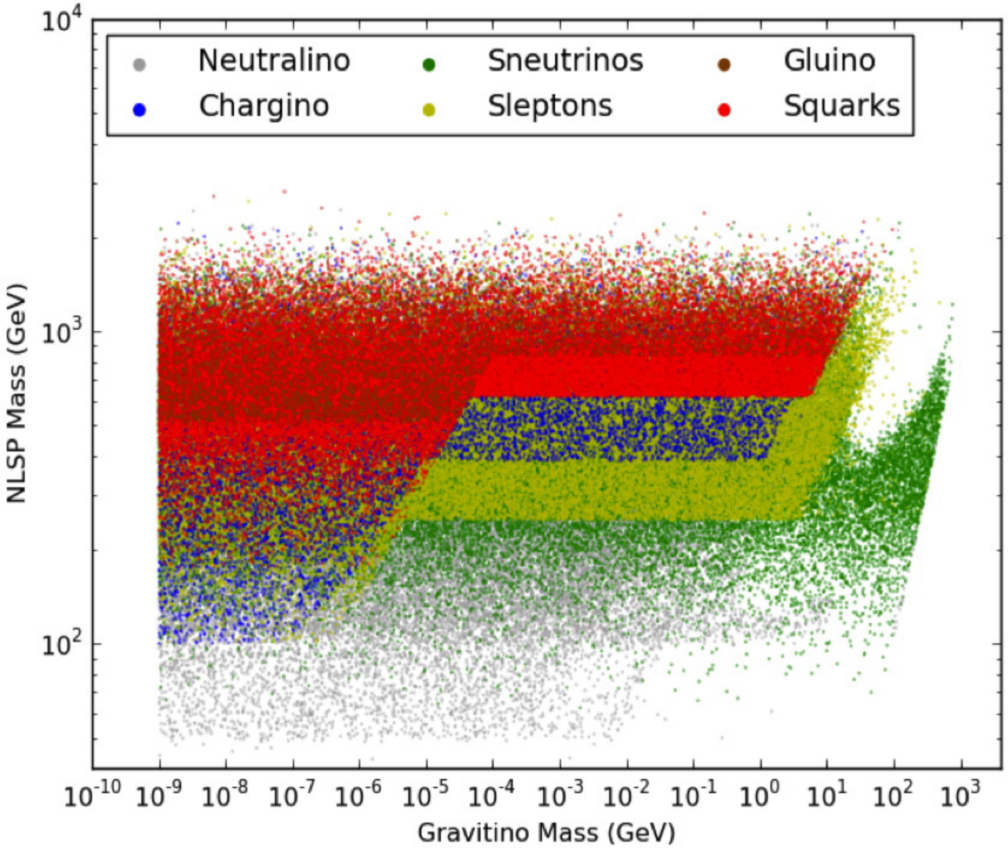
Ways out: heavy moduli or dilution factor, e.g. thermal inflation.

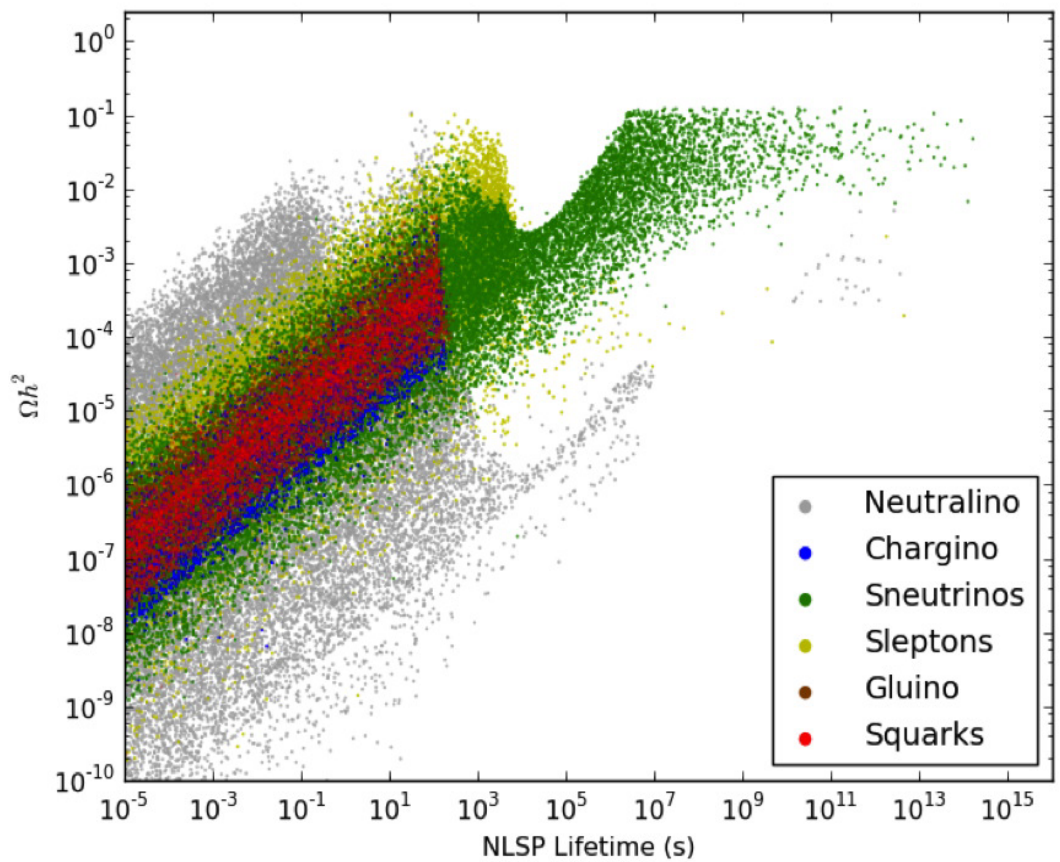
Gravitino DM summary



BBN bounds on pMSSM

[Cahill-Rawley et al 12]





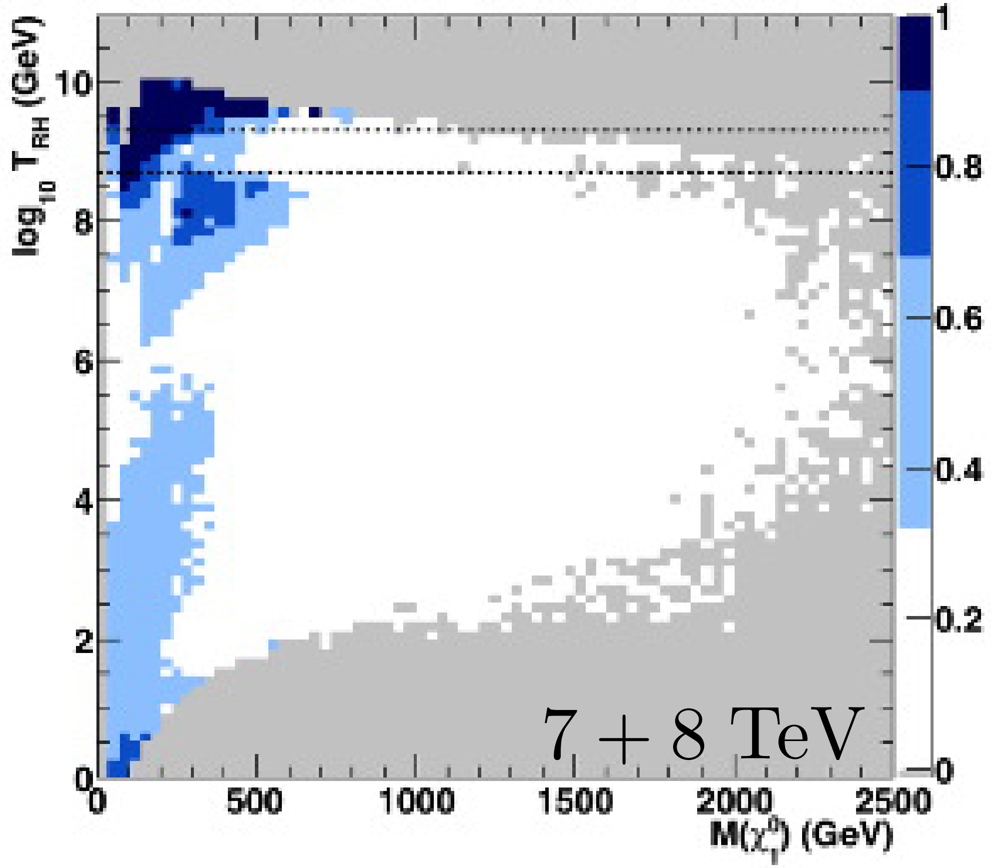
Many points for various NLSPs excluded by BBN: only the sneutrino survives to large gravitino masses.

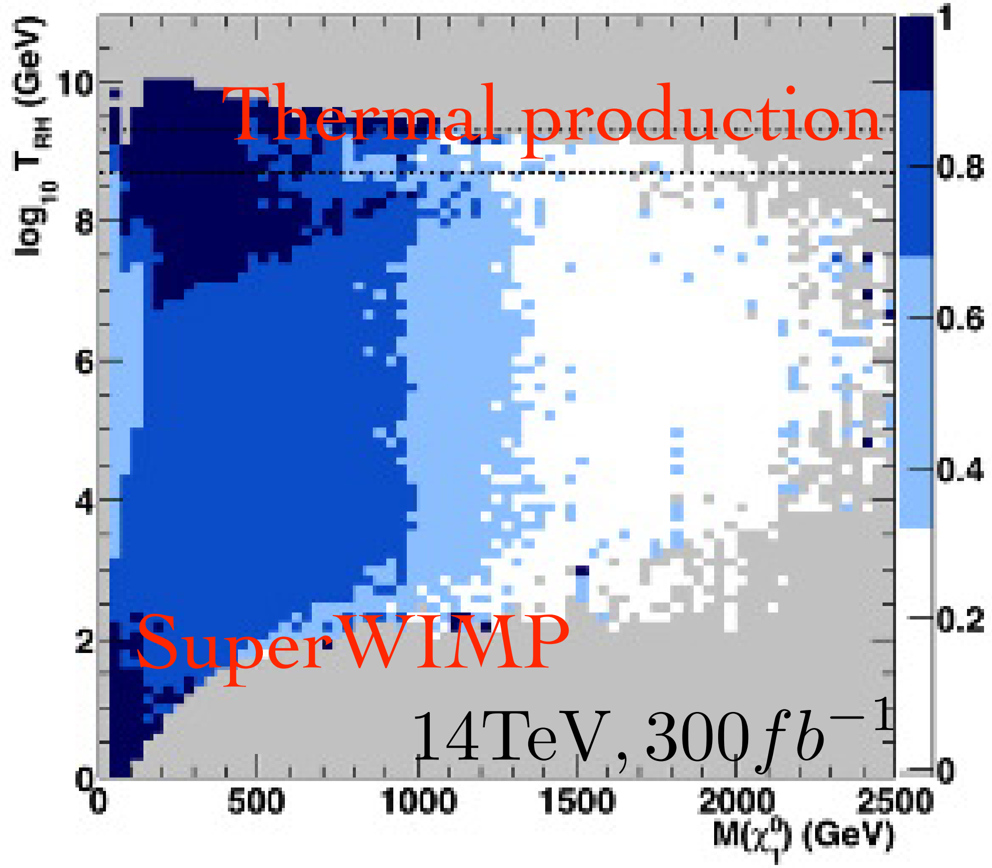
Heavy NLSP is actually preferred !

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 !

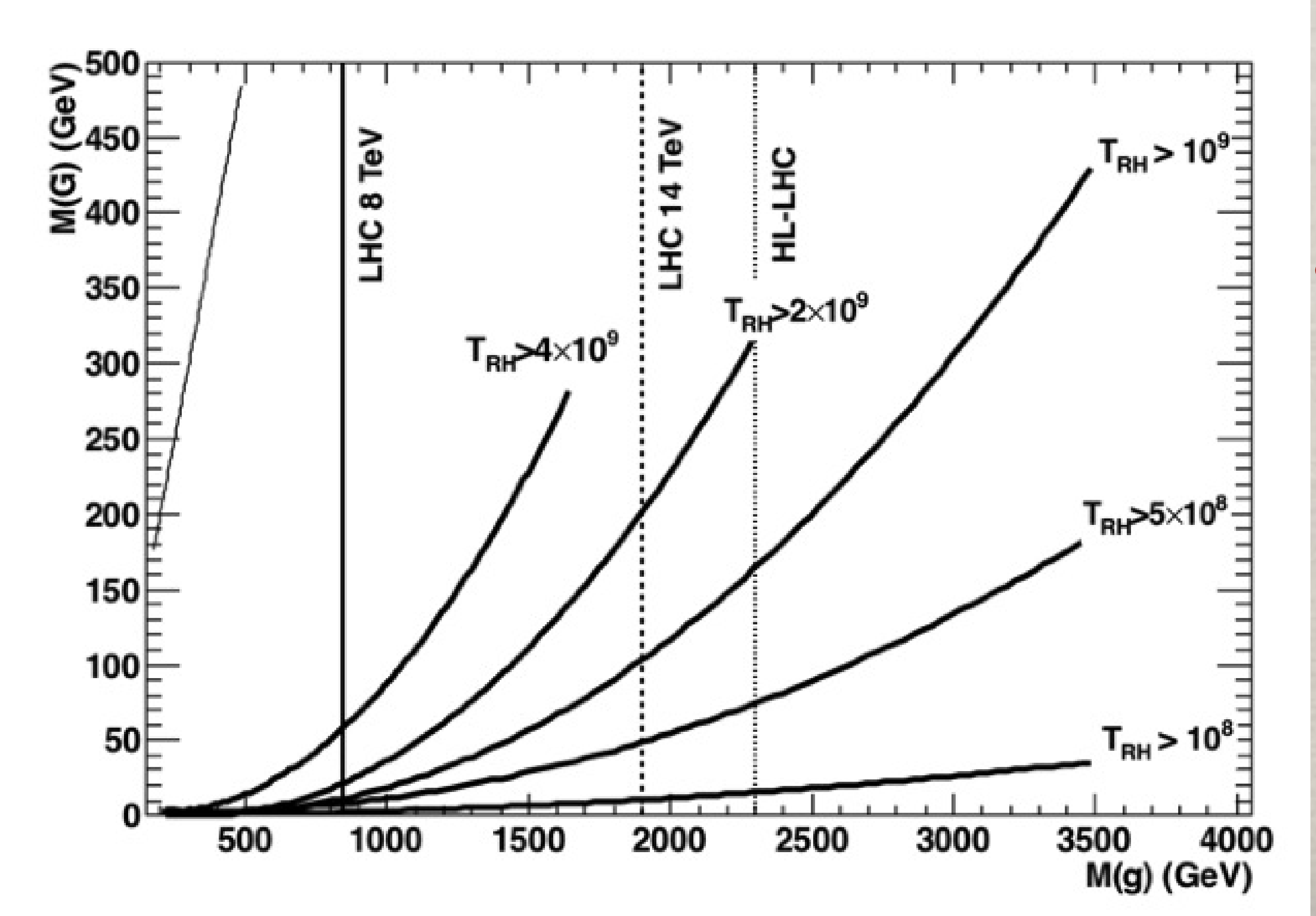




Gravitino DM & gluino

[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

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

R-parity or not R-parity

[Buchmuller, LC, Hamaguchi, Ibarra & Yanagida 07]

Actually there is a simple way to avoid BBN constraints: break R-parity a little... ! Then the NLSP decays quickly to SM particles before BBN and the cosmology returns standard.

$$W_{R\not p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \cancel{\lambda'' U^c D^c D^c}$$

no p decay

Open window:

$$10^{-12-14} < |\frac{\mu_i}{\mu}|, |\lambda|, |\lambda'| < 10^{-6-7}$$

For the NLSP to decay before BBN

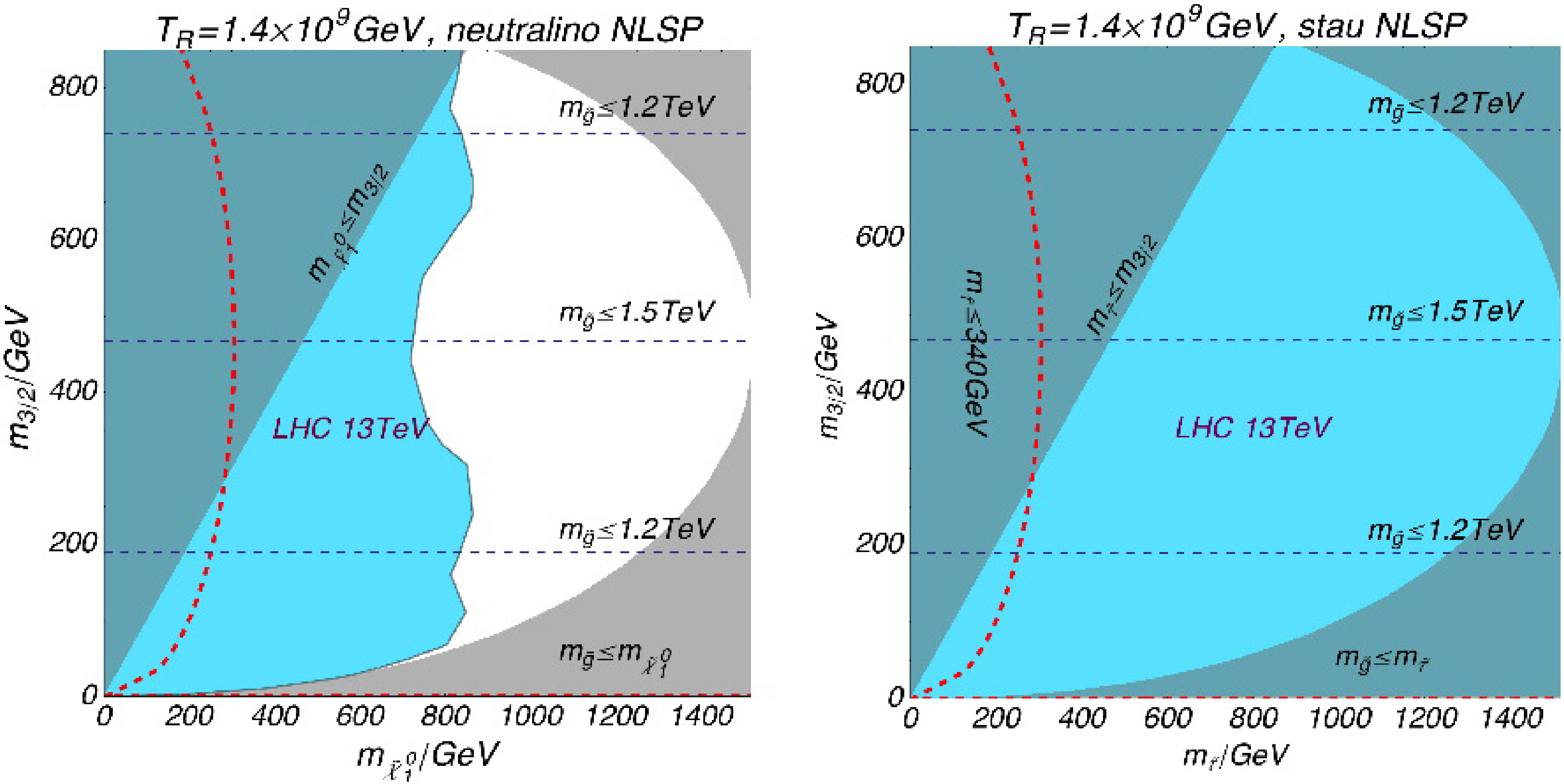
To avoid wash-out of lepton number

Explicit bilinear R-parity breaking model which ties R-parity breaking to B-L breaking and explains the small coupling.

Gravitino DM & T_RH

The LHC run 2 already constrains the heavy T_RH scenario for gravitino DM with bilinear RPV :

[Ibe, Suzuki & Yanagida 1609.06834]



Decaying axino/gravitino?

- If R-parity is broken the NLSP decays fast to SM particles, but axino & gravitino are much longer-lived

$$\tau_{\tilde{G}} \sim 10^{27}\mathrm{s} \left(\frac{\epsilon}{10^{-7}}\right)^{-2} \left(\frac{M_1}{100\mathrm{GeV}}\right)^{2} \left(\frac{m_{\tilde{G}}}{10\mathrm{GeV}}\right)^{-3}$$

$$\tau_{\tilde{a}} \sim 10^{27}\mathrm{s} \left(\frac{\epsilon}{10^{-10}}\right)^{-2} \left(\frac{M_1}{100\mathrm{GeV}}\right)^{2} \left(\frac{m_{\tilde{a}}}{10\mathrm{GeV}}\right)^{-3} \left(\frac{f_a}{10^{11}\mathrm{GeV}}\right)^{2}$$

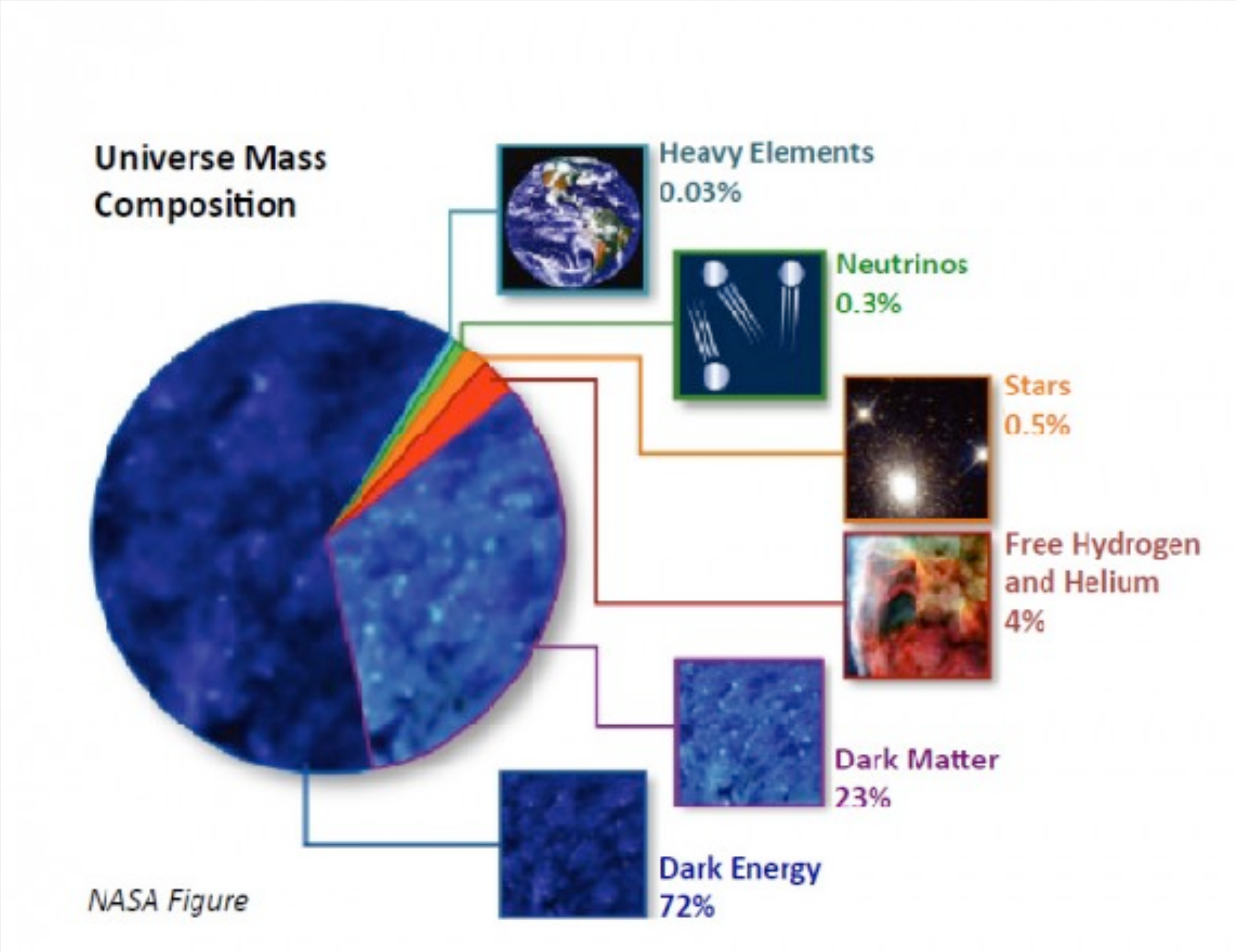
- For bilinear R-parity breaking, they decay similarly to gauge boson/Higgs and neutrino

[Takayama &Yamaguchi 00, Buchmuller et al '07, LC & JE Kim 09]

For trilinear R-parity breaking, the 3-body decays into leptons can dominate and give a leptophilic DM
[Bomark et al 09, LC & JE Kim 09, Bajc et al 10]

High scale SUSY co-genesis

Universe composition



Why $\Omega_{DM}h^2 \sim 5\,\Omega_B h^2$?

Sakharov Conditions

Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- B-L violation: sphalerons reprocess L into B number…
- C and CP violation: otherwise matter and antimatter would still be annihilated/created at the same rate
- Departure from thermal equilibrium: the maximal entropy state is for B = 0, or for conserved CPT, no B generated without time-arrow...

Now exactly the same conditions have to hold also for the generation of a Dark Matter Asymmetry !

Baryogenesis in RPV SUSY

RPV superpotential includes couplings that violate baryon number and can be complex, i.e.

$$W = \lambda''_{ijk} U_i D_j D_k$$

Possible to generate a baryon asymmetry from out-of-equilibrium decay of a superparticle into channels with different baryon number, e.g. for a neutralino

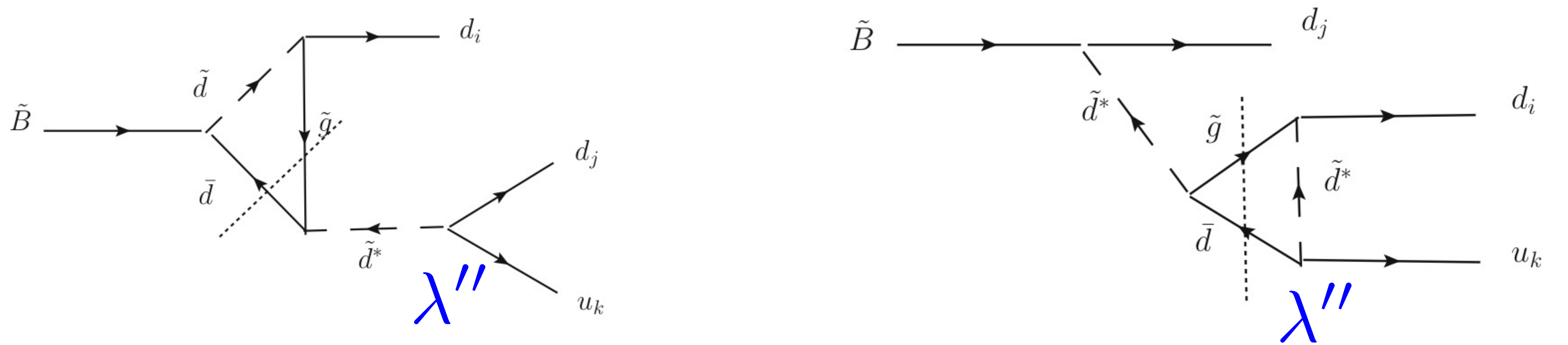
$$\tilde{B} \to udd,\ \bar{u}\bar{d}\bar{d},\ \tilde{g}\bar{q}q$$

Initial density of neutralino can arise from usual WIMP mechanism, since the decay rate is very suppressed !

Baryogenesis in RPV SUSY

[Sundrum & Cui 12, Cui 13, Rompineve 13, ...]

Realization of good old baryogenesis via out-of-equilibrium decay of a superpartner, possibly WIMP-like, e.g. in the model by Cui with Bino decay via RPV B-violating coupling.



CP violation arises from diagrams with on-shell gluino lighter than the Bino. To obtain right baryon number the RPC decay has to be suppressed, i.e. due to heavy squarks, the RPV coupling large and the Bino density very large...

Baryogenesis & SW DM

[Arcadi, LC & Nardecchia 1312.5703]

In such scenario it is also possible to get gravitino DM via the SuperWIMP mechanism and the baryon and DM densities can be naturally of comparable order due to the suppression by the CP violation and Branching Ratio respectively...

$$\Omega_{\Delta B} = \frac{m_p}{m_\chi} \epsilon_{\rm CP}\, BR\left(\chi \to \not{B}\right) \Omega_\chi^{\tau\to\infty}$$

Small numbers

$$\Omega_{\rm DM} = \frac{m_{\rm DM}}{m_\chi} BR\left(\chi \to DM + \text{anything}\right) \Omega_\chi^{\tau\to\infty}$$

$$\frac{\Omega_{\Delta B}}{\Omega_{DM}} = \frac{m_p}{m_{DM}} \; \frac{\epsilon_{CP}\, BR(\chi \to \not{B})}{BR(\chi \to DM + \text{anything})}$$

independent of Bino density

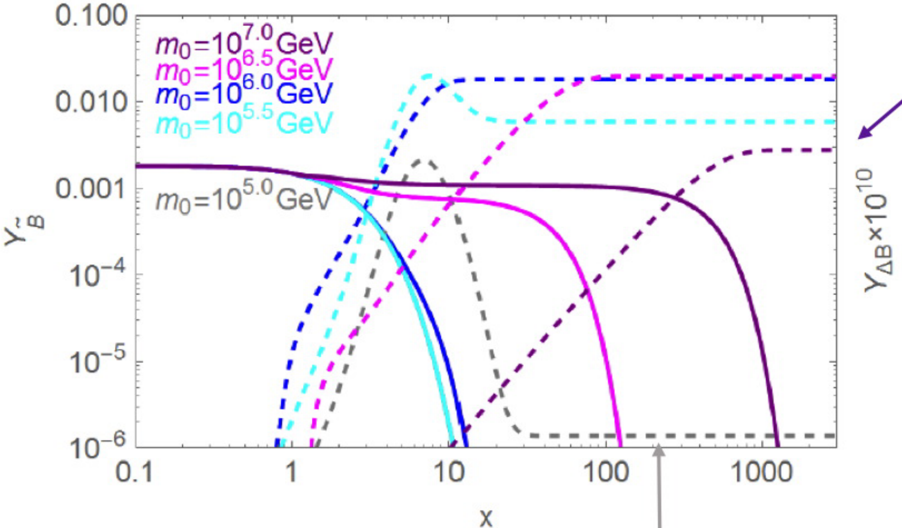
Gravitino DM: BR is naturally small and DM stable enough !

Baryogenesis in RPV SUSY

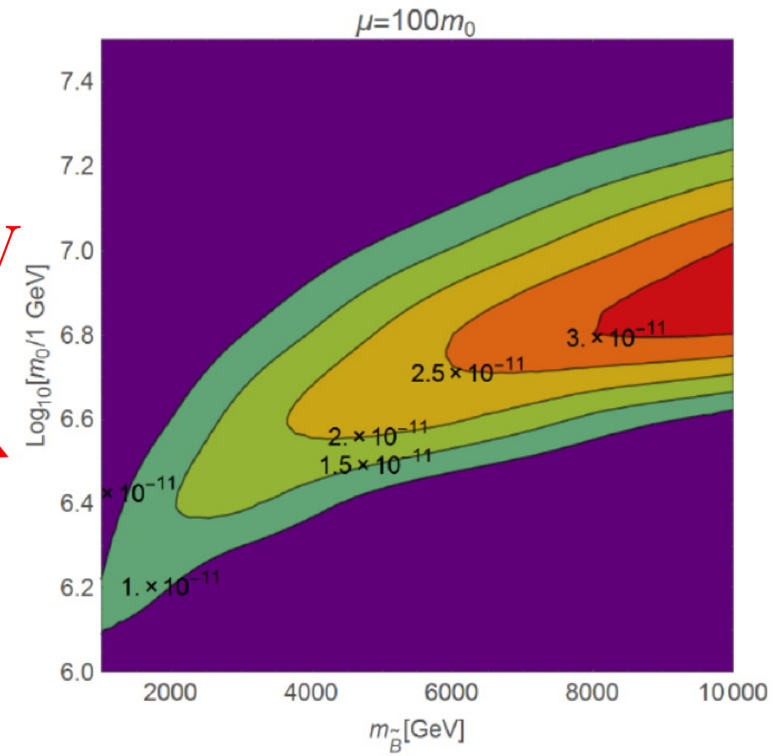
[Arcadi, LC & Nardecchia 1507.05584]

Unfortunately realistic models are more complicated than expected: wash-out effects play a very important role !!!

Asymmetry suppressed by the high scalars



10^7GeV

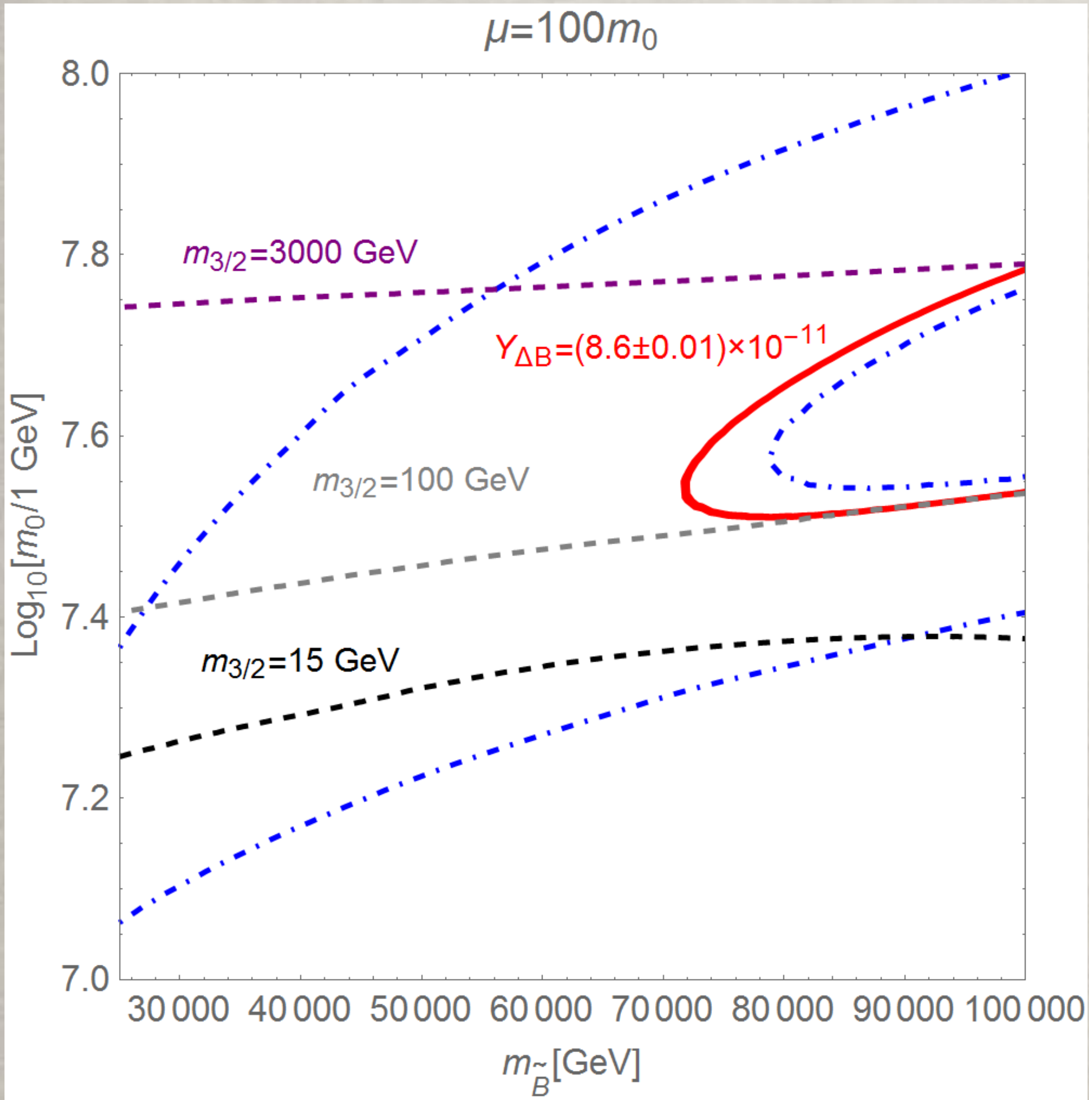


Asymmetry suppressed by wash-out

Rather definite prediction for range of scalar masses Heavy !!!

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]



Moreover the large scalar mass suppresses the branching ratio into gravitinos too much...

$$BR(\tilde{B} \to \psi_{3/2} + \text{any}) << \epsilon_{CP}$$

Need a large gravitino mass to compensate & obtain $\Omega_{DM} \sim 5\, \Omega_B$, not so simple explanation after all..., but still possible with $m_{3/2} < m_{\tilde{g}}$.

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584, Arcadi, LC, Khan to appear]

Thanks to the large gravitino mass, the squark mass suppression is partially compensated and a visible gravitino decay is possible:

$$\Gamma(\psi_{3/2} \to u_k d_i d_j) = \frac{3\lambda^2}{124\pi^3} \frac{m_{3/2}^7}{m_0^4 M_P^2}$$

$$\tau_{3/2} = 0.26 \times 10^{28}\mathrm{s} \left(\frac{\lambda}{0.4}\right)^{-2} \left(\frac{m_{3/2}}{1\mathrm{TeV}}\right)^{-7} \left(\frac{m_0}{10^{7.5}\mathrm{GeV}}\right)^{4}$$

Right ballpark for indirect DM detection, but strongly dependent on the gravitino and squark masses…

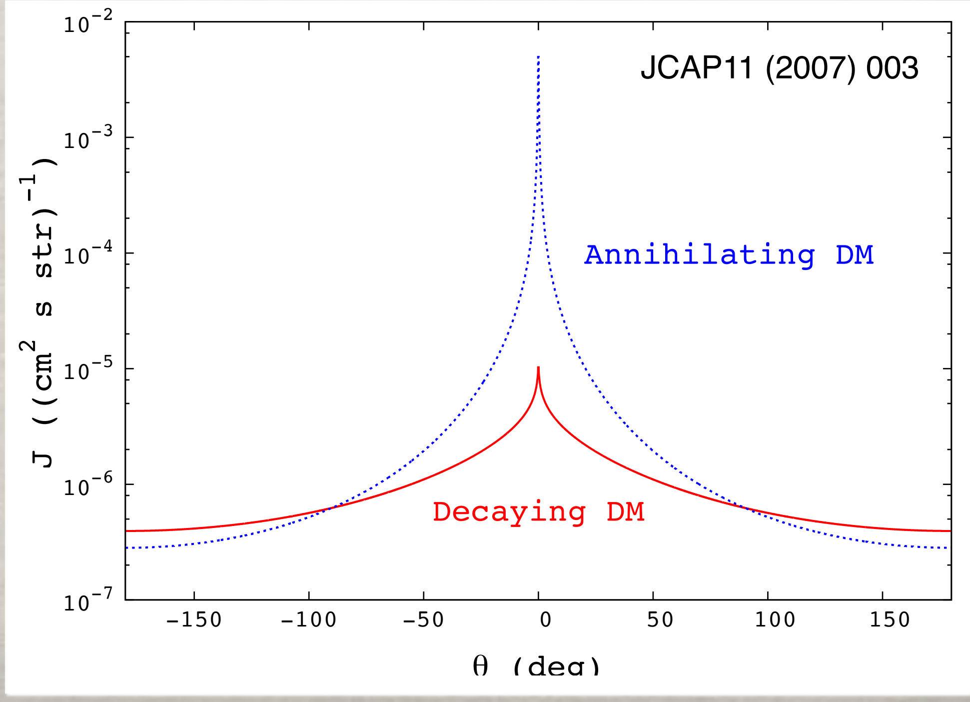
DECAYING DM

- The flux from DM decay in a species i is given by

$$\Phi(\theta, E) = \frac{1}{\tau_{DM}} \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}} \int_{l.o.s.} ds\, \rho(r(s,\theta))$$

Particle Physics   Halo property $J(\theta)$

- Very weak dependence on the Halo profile; what matters is the DM lifetime...
- Galactic & extragalactic signals are comparable...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...



Gluino NLSP in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584, Arcadi, LC, Khan to appear]

The gluino is in this scenario the next-to-lightest SUSY particle and may be produced at colliders; we are still exploring how much lighter than the Bino it can be. For the range

$$m_{\tilde{g}} \sim 0.1 - 0.4\, m_{\tilde{B}} \sim 7 - 28 \text{ TeV}$$

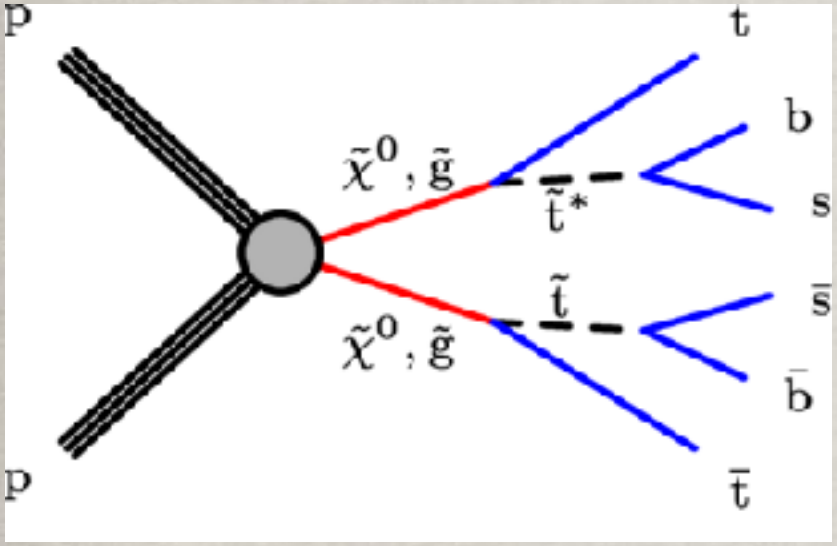
it could be in the reach of a 100 TeV collider.

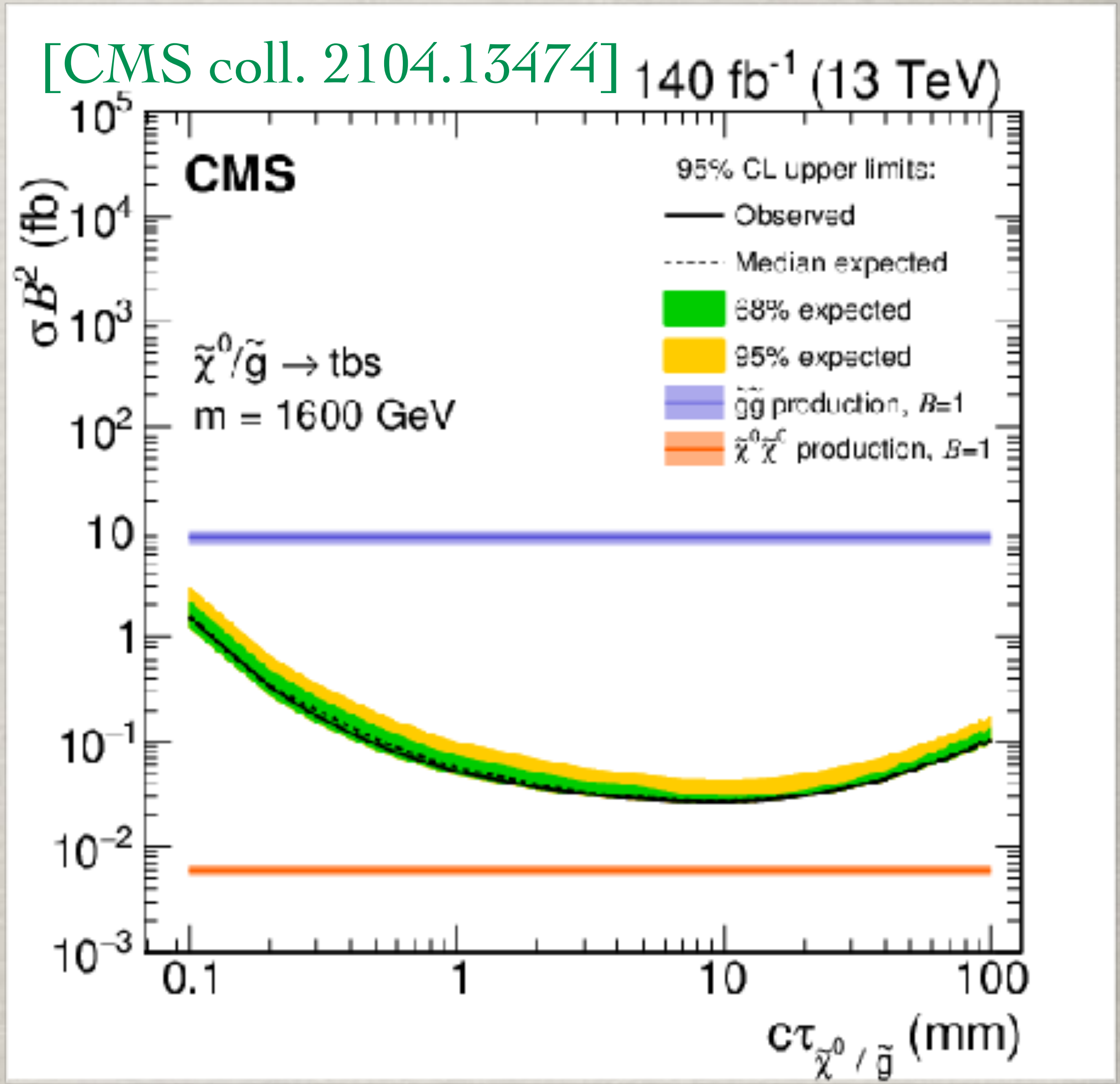
$$c\tau_{\tilde{g}} \sim 1,5 \text{ cm} \left(\frac{\lambda''}{0.4}\right)^{-2} \left(\frac{m_0}{4 \times 10^7 \text{GeV}}\right)^4 \left(\frac{m_{\tilde{g}}}{7 \text{ TeV}}\right)^{-5}$$

The heavy squarks give displaced vertices for the gluino decay via RPV, even for RPV coupling of order 1.

Gluino decay into gravitino DM is much too suppressed to be measured.

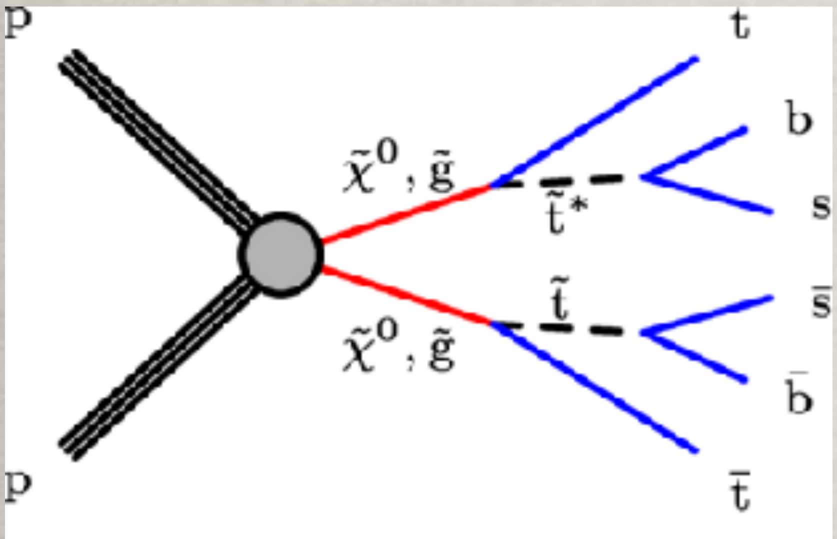
Displaced vertices at LHC

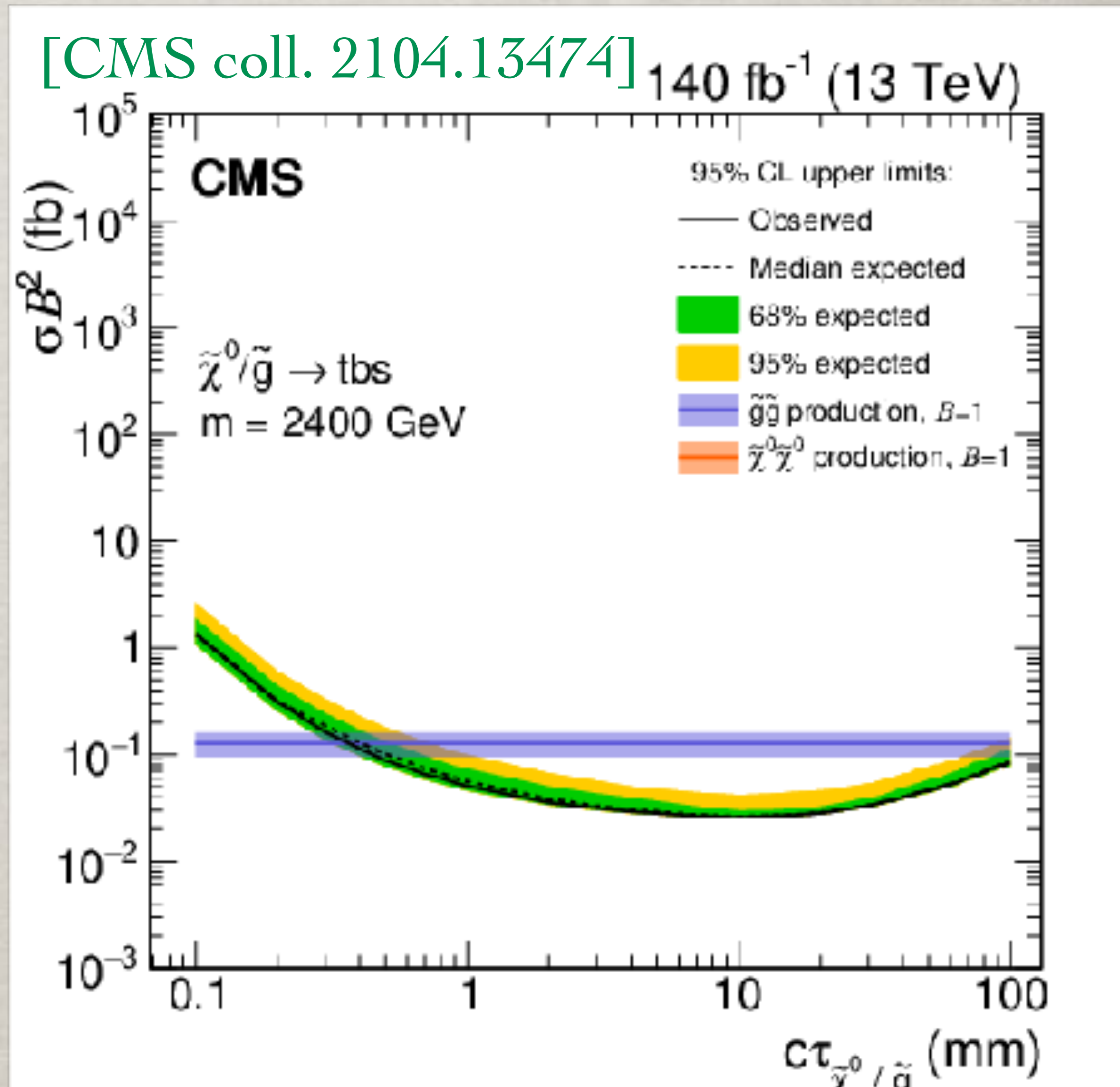




Also limits from ATLAS for gluino decay into neutralino

Displaced vertices at LHC





Also limits from ATLAS for gluino decay into neutralino

Outlook

Outlook

- From the theoretical perspective, we have a few "natural" DM production mechanisms, not only the WIMP, but also the FIMP/SuperWIMP mechanisms or misalignment for axions.
- SUSY WIMPs are still a promising target,
- SUSY FIMP/SuperWIMP like the gravitino/axino are not in thermal equilibrium, but are produced sufficiently to be DM, pointing to heavy metastable particles or displaced vertices at LHC and maybe decaying DM in Indirect detection.
- Finally gravitino DM could be produced together with the baryon asymmetry in the correct abundance if SUSY is heavy.

Stay tuned, SUSY is still alive and kicking...

References

- TASI Lectures on "Dark Matter Models and Direct Detection" by Tongyan Lin, arXiv:1904.07915
- History of Dark Matter G. Bertone & D. Hooper, *Rev.Mod.Phys.* 90 (2018) 4, 045002, arXiv:1605.04909
- Particle Dark Matter: Evidence, candidates and constraints by G. Bertone, D. Hooper, J. Silk, *Phys.Rept.* 405 (2005) 279-390, arXiv:hep-ph/0404175