

GGI Workshop "Collider Physics and the Cosmos"

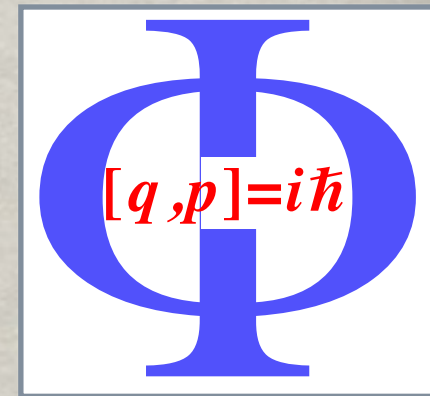
Florence, 11 October 2017

COLLIDER PHYSICS & THE EARLY UNIVERSE



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elusives-invisiblesPlus
neutrinos, dark matter & dark energy physics



OUTLINE

- Introduction:
 - The cosmos-particle connection
 - The cosmological probes
- SUSY @ Colliders and in Cosmology
- Inflation & Colliders
- Electroweak phase transition & baryogenesis
- DM interactions in cosmology
- Outlook

INTRODUCTION

EINSTEIN'S EQUATION: ENERGY IS GEOMETRY

$$\mathcal{R}_{\mu}^{\nu} - \frac{1}{2}\delta_{\mu}^{\nu}\mathcal{R} = 8\pi G_N T_{\mu}^{\nu} + \Lambda\delta_{\mu}^{\nu}$$

Einstein's Tensor:
Geometry of Space-time

Classical so far...

Energy-momentum Tensor:
ALL the Physics content

Quantum

The birth of Cosmology as a science:
the Universe's dynamics and fate is determined
by its Energy (Particle) content,
both the known and the unknown....

THE STANDARD MODEL

Our present understanding of the forces and particles is based on the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$.

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

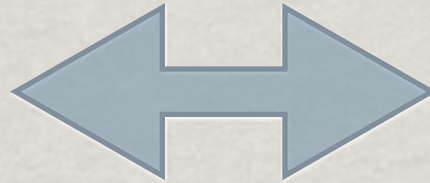
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It describes perfectly the data so far, but it is incomplete:

- theoretically it does not explain flavour and the presence of 3 generations, nor why the Higgs is light...
- it lacks a Dark Matter and inflaton candidate and also a mechanism to generate the baryon asymmetry...

WHICH MODEL BEYOND THE SM ?

weakly
coupled



strongly
coupled

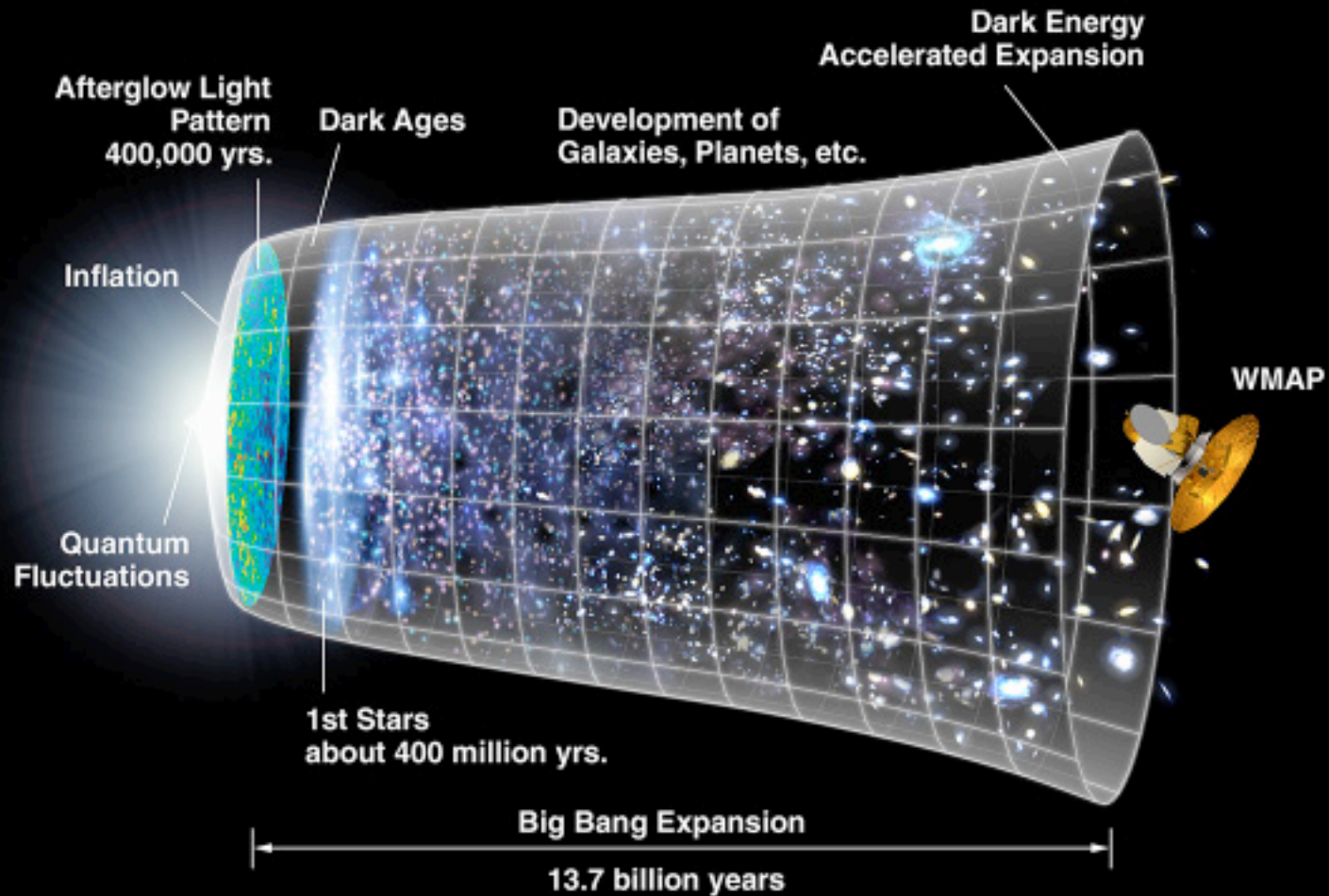
Cosmology

(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...

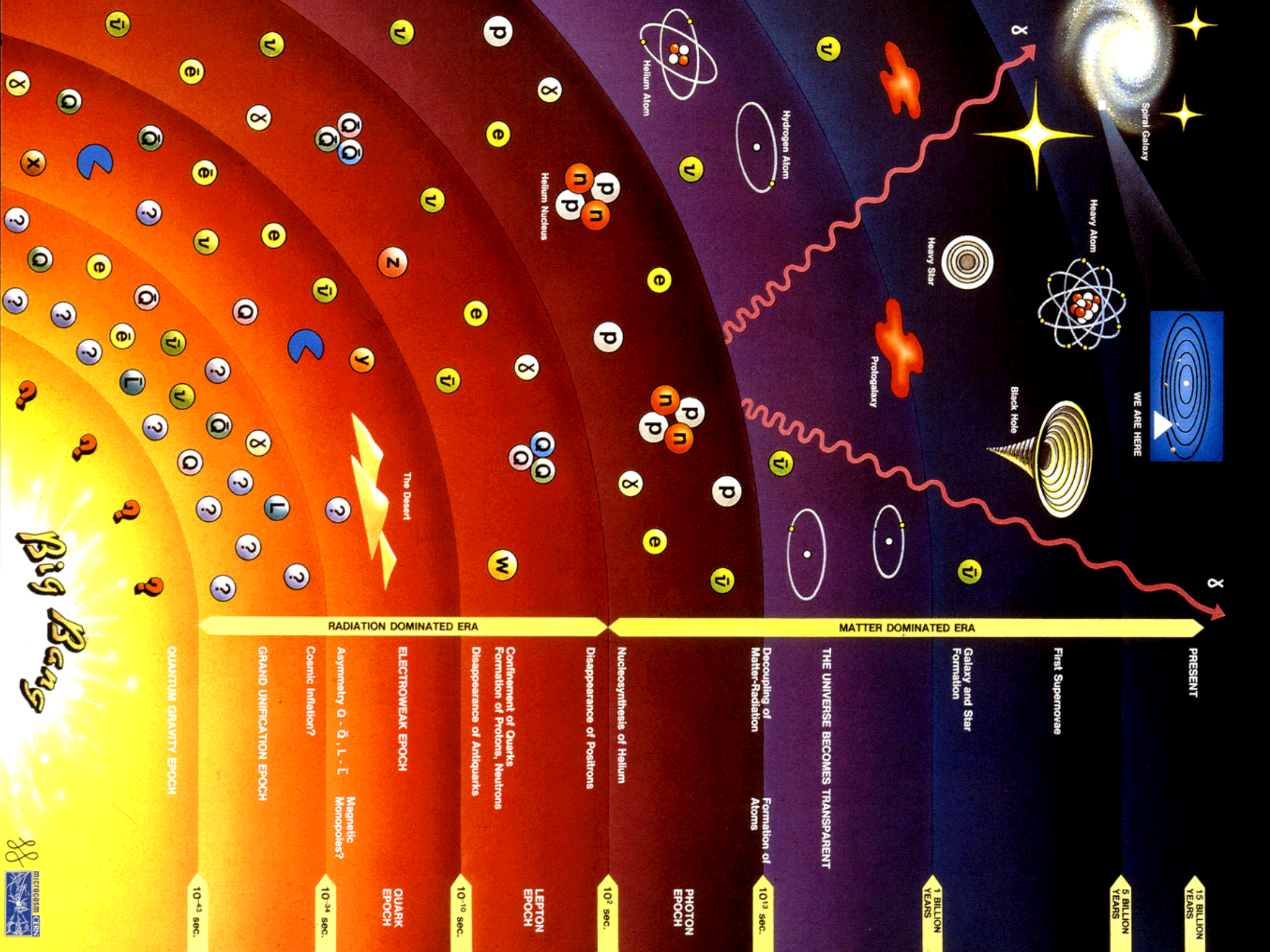
Best results if one has information from both sides,
e.g. neutrinos, axions, DM, etc... ???

FOLLOWING THE FLUCTUATIONS



These small fluctuations are amplified by gravity & are the origin of the structure we see today

Big Bang

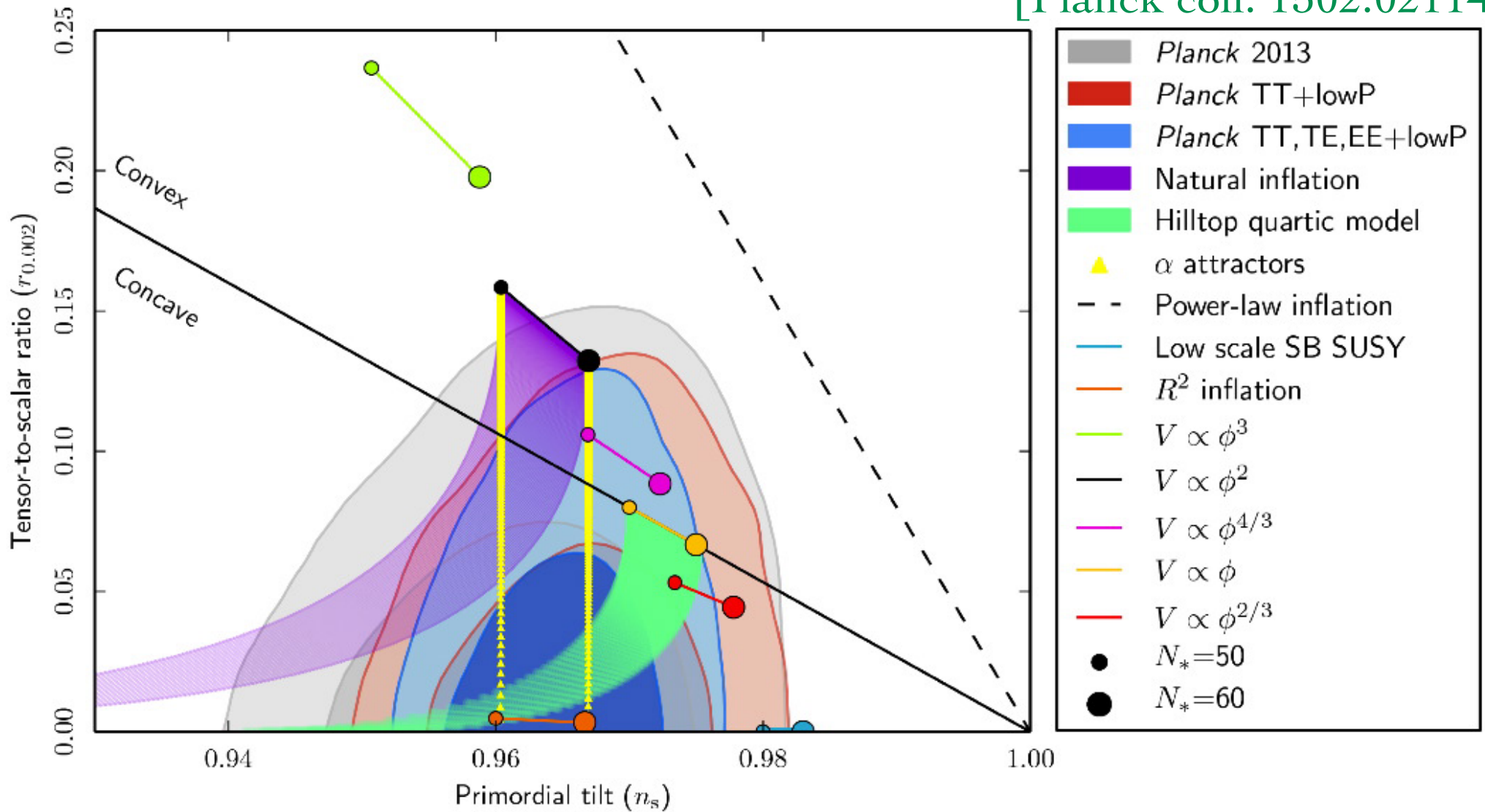


IMPORTANT EPOCHS

- Today: $T = 2.7K \sim 10^{-4} \text{ eV}$ $z = 0$
- First stars: $T \sim 10^{-3}$ $z \sim 15 - 20$
- Photon decoupling: CMB $T = 0.4 \text{ eV}$ $z = 1100$
- Matter and Radiation equality: $T = 1 \text{ eV}$ $z \sim 1300$
- Nucleosynthesis: $T = 0.1 \text{ MeV}$
- Neutrino decoupling: $C\nu B$ $T \sim 1 \text{ MeV}$
- QCD phase transition $T \sim 0.3 \text{ GeV}$
- EW phase transition $T \sim 100 \text{ GeV}$
- ?????

PLANCK: INFLATION

[Planck coll. 1502.02114]

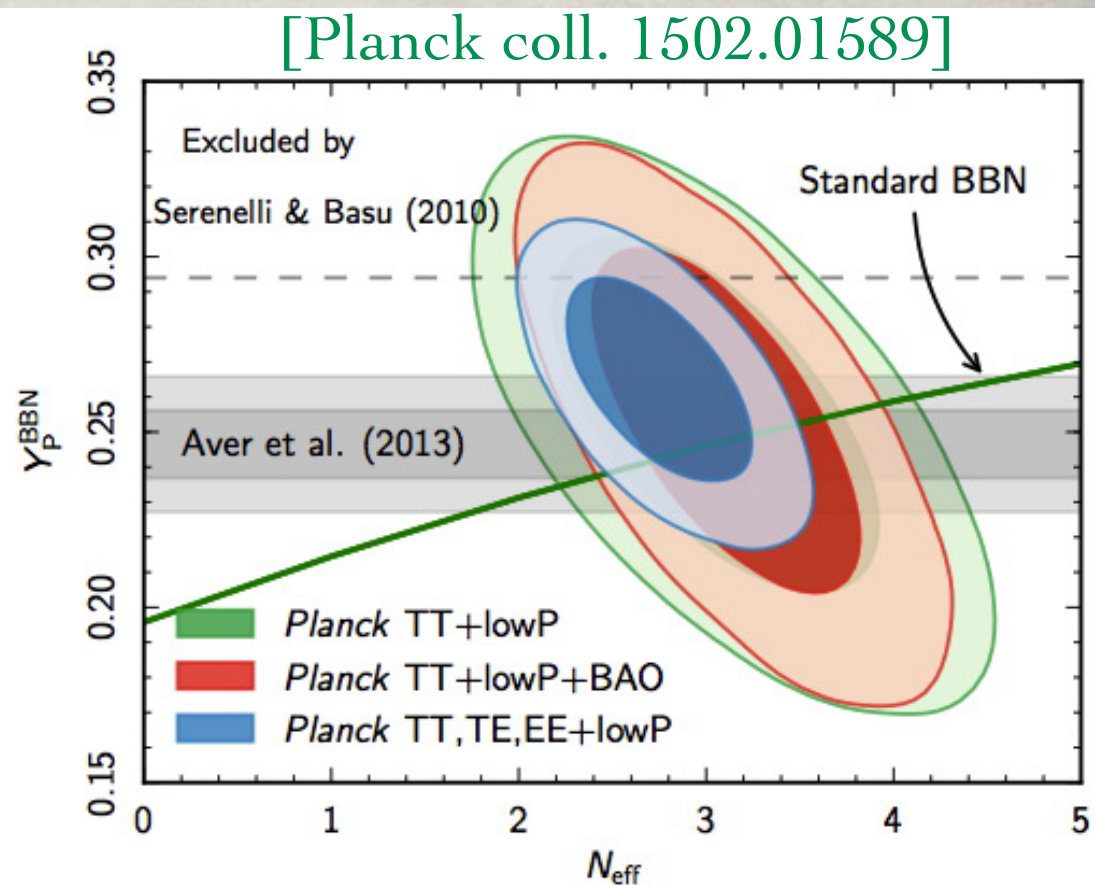
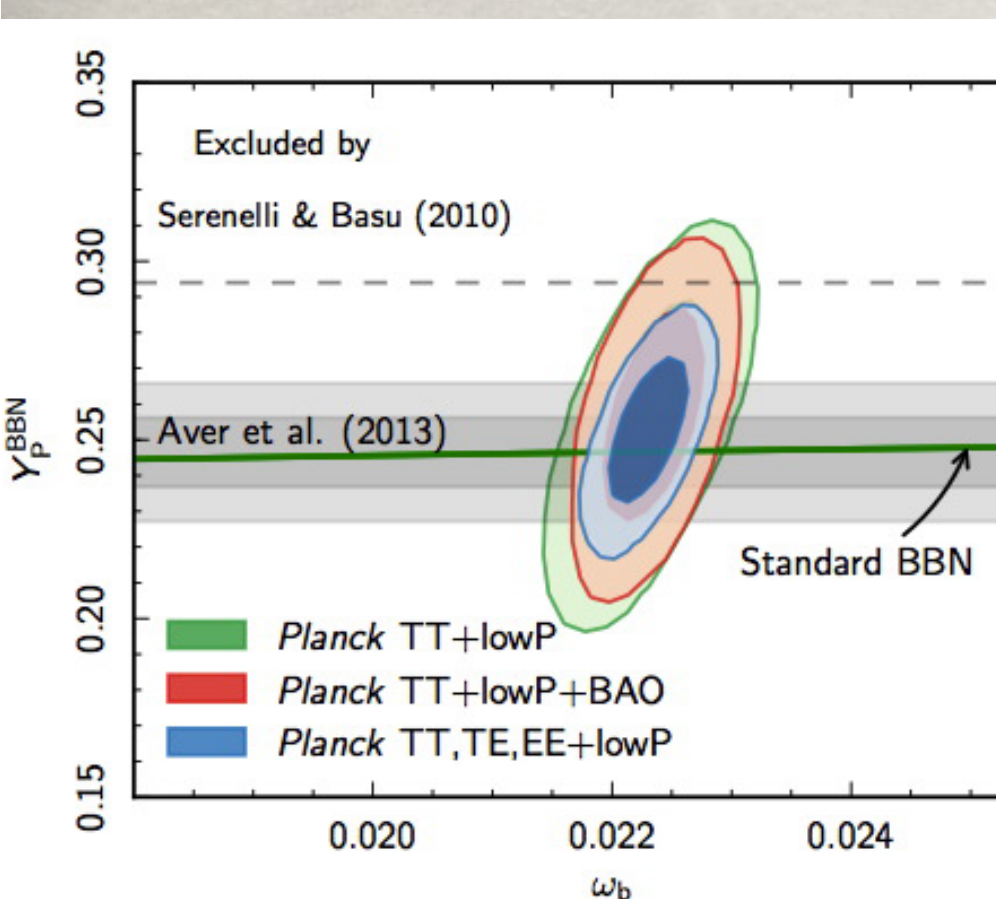


$$n_s = 0.968 \pm 0.006$$

$$r_{0.02} < 0.11 (95\% CL)$$

No evidence for running of n_s : $\frac{dn}{d \log(k)} < -0.003 \pm 0.007$

PLANCK:NUCLEOSYNTHESIS



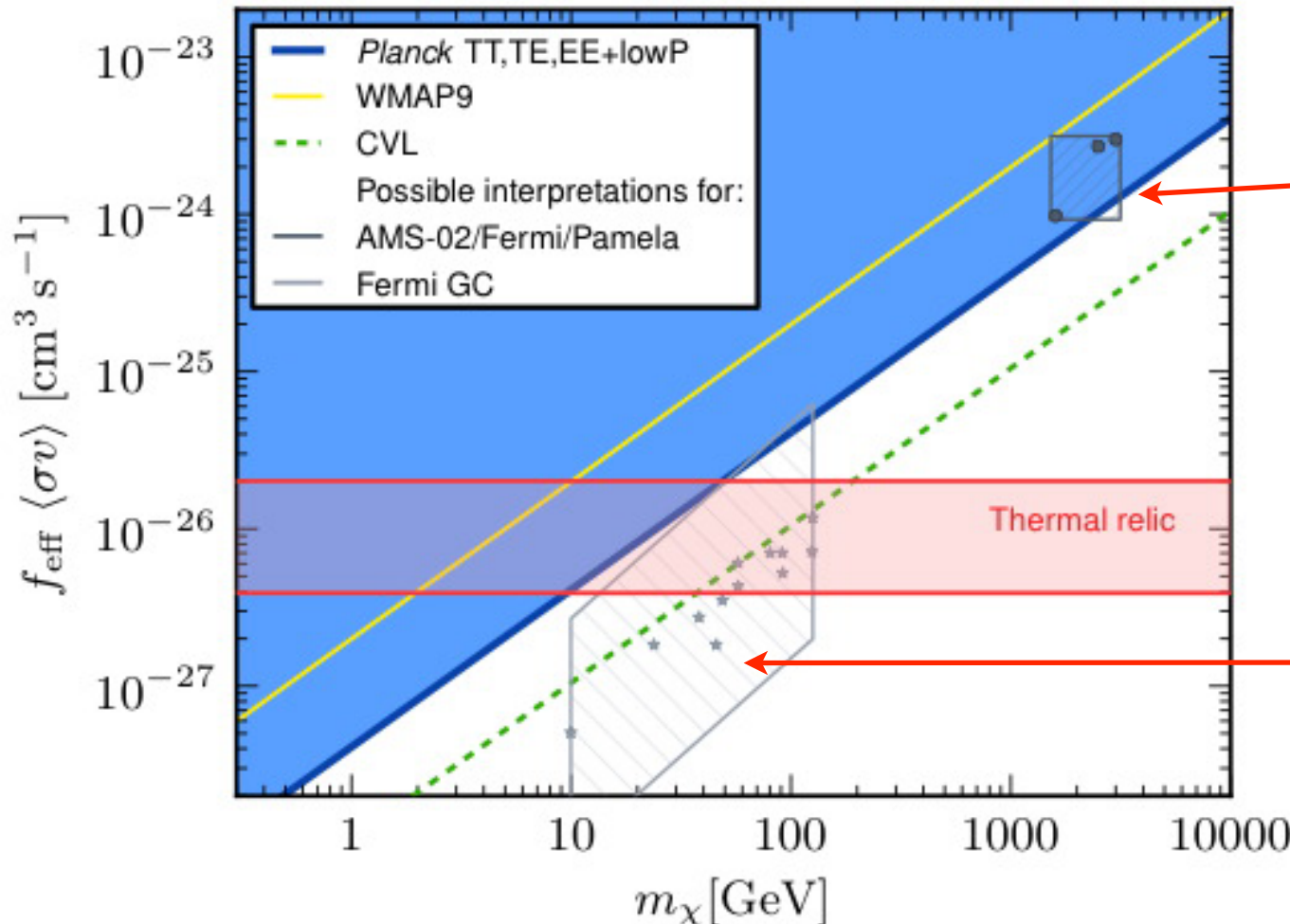
CMB consistent with BBN even fitting both N_{eff} & Y_p .

Note the degeneracy between these two parameters,
but orthogonal compared to BBN !

PLANCK: DM ANNIHILATION

WIMP annihilation also modifies the epoch of recombination due to the release of energy in the primordial plasma and leaves imprints into the CMB ! Planck can now exclude cross-sections as those needed by PAMELA and AMS-02:

[Planck 1502.01589]



Pamela-inspired
DM models

Galactic centre
excess

SUSY @ COLLIDERS AND IN COSMOLOGY

SUSY AT LHC RUN 2

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2017

ATLAS Preliminary

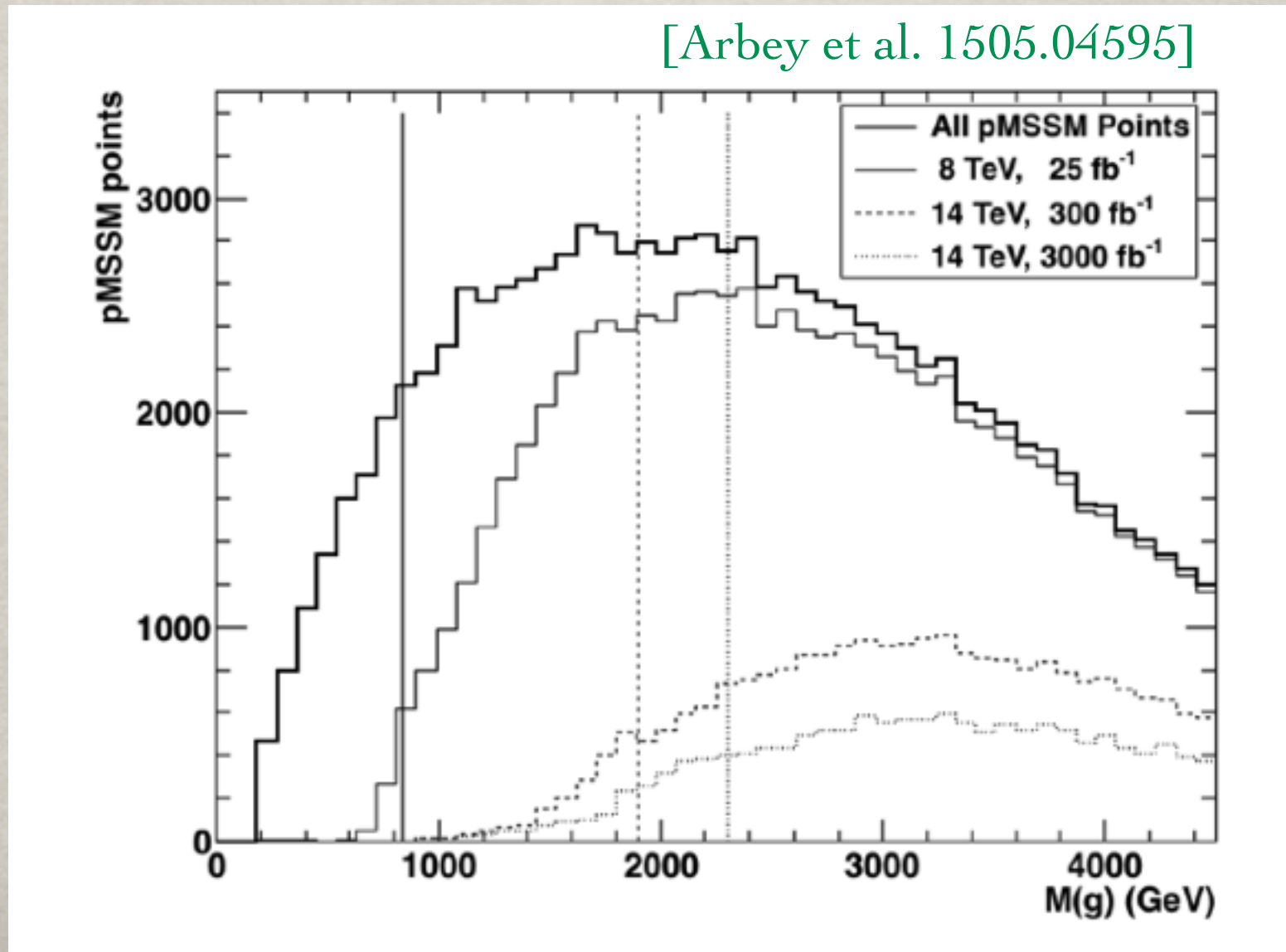
$\sqrt{s} = 7, 8, 13$ TeV

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} d\Omega (\text{fb}^{-1})$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference
Inclusive Searches	MSUGRA/CMSSM	$0-3 e, \mu / 1-2 \tau$	2-10 jets/3 b	Yes	20.3	1.85 TeV	$m(\tilde{g})=m(\tilde{q})$	1507.05525
	$\tilde{q}\tilde{q} \rightarrow \tilde{q}\tilde{q}^0$	0	2-6 jets	Yes	36.1	1.57 TeV	$m(\tilde{t}_1) < 200$ GeV, $m(\tilde{t}_2) \text{ gas. } \tilde{q} \rightarrow m(\tilde{G}^{\text{eff}} \text{ gas. } \tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q} \rightarrow \tilde{q}\tilde{q}^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	508 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2) < 5$ GeV	1604.07773
	$\tilde{g}\tilde{g} \rightarrow \tilde{q}\tilde{q}^0$	0	2-6 jets	Yes	36.1	2.02 TeV	$m(\tilde{t}_1) < 200$ GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g} \rightarrow \tilde{q}\tilde{q}^0 + \tilde{q}\tilde{q}^0$	0	2-6 jets	Yes	36.1	2.01 TeV	$m(\tilde{t}_1) < 200$ GeV, $m(\tilde{t}_2) > 0.5 m(\tilde{t}_1) + m(\tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g} \rightarrow \tilde{q}\tilde{q}^0 / \tau\tau / \tilde{t}\tilde{t}^0$	$3 e, \mu$	4 jets	-	13.2	1.7 TeV	$m(\tilde{t}_1) < 400$ GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g} \rightarrow \tilde{q}\tilde{q}^0 W Z / \tau\tau / \tilde{t}\tilde{t}^0$	$2 e, \mu$ (SS)	0-3 jets	Yes	13.2	1.6 TeV	$m(\tilde{t}_1) < 500$ GeV	ATLAS-CONF-2016-037
	GMSB (\tilde{g} NLSP)	$1-2 \tau + 0-1 \ell$	0-2 jets	Yes	3.2	2.0 TeV		1607.05979
	GGM (bino NLSP)	2γ	-	Yes	3.2	1.65 TeV	$c\tau(\text{NLSP}) < 0.1$ mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	1.37 TeV	$m(\tilde{t}_1) < 950$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu = 0$	1607.05493
GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.2	1.8 TeV	$m(\tilde{t}_1) < 680$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu = 0$	ATLAS-CONF-2016-066	
GGM (higgsino NLSP)	$2 e, \mu$ (Z)	2 jets	Yes	20.3	900 GeV	$m(\text{NLSP}) > 430$ GeV	1503.03290	
Gravitino LSP	0	mono-jet	Yes	20.3	865 GeV	$m(\tilde{g}) > 1.8 \times 10^{-1}$ eV, $m(\tilde{g}) = m(\tilde{q}) = 1.5$ TeV	1502.01518	
3 rd gen. \tilde{g} prod.	$\tilde{g}\tilde{g} \rightarrow b\bar{b}\tilde{q}^0$	0	3 b	Yes	36.1	1.92 TeV	$m(\tilde{t}_1) < 600$ GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g} \rightarrow t\bar{t}\tilde{q}^0$	$0-1 e, \mu$	3 b	Yes	36.1	1.97 TeV	$m(\tilde{t}_1) < 200$ GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g} \rightarrow b\bar{b}\tilde{t}^0$	$0-1 e, \mu$	3 b	Yes	20.1	1.37 TeV	$m(\tilde{t}_1) < 300$ GeV	1407.0600
3 rd gen. squarks direct production	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow b\bar{b}\tilde{q}^0$	0	2 b	Yes	3.2	840 GeV	$m(\tilde{t}_1) < 100$ GeV	1606.08772
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\bar{t}\tilde{q}^0$	$2 e, \mu$ (SS)	1 b	Yes	13.2	325-685 GeV	$m(\tilde{t}_1) < 150$ GeV, $m(\tilde{t}_2) > m(\tilde{t}_1) + 100$ GeV	ATLAS-CONF-2016-037
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow b\bar{b}\tilde{t}^0$	$0-2 e, \mu$	1-2 b	Yes	4.7/13.3	117-170 GeV	$m(\tilde{t}_1) = 2m(\tilde{t}_2), m(\tilde{t}_2) < 55$ GeV	1209.2162, ATLAS-CONF-2016-077
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow W\tilde{q}^0$ or $\tilde{t}\tilde{q}^0$	$0-2 e, \mu$	0-2 jets/1-2 b	Yes	20.3	90-198 GeV	$m(\tilde{t}_1) < 1$ GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow \tilde{q}\tilde{q}^0$	0	mono-jet	Yes	3.2	90-323 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2) < 5$ GeV	1604.07773
	$\tilde{d}_1\tilde{d}_1$ (natural GMSB)	$2 e, \mu$ (Z)	1 b	Yes	20.3	150-600 GeV	$m(\tilde{t}_1) < 150$ GeV	1403.5232
3 rd gen. squarks direct production	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\bar{t} + Z$	$3 e, \mu$ (Z)	1 b	Yes	36.1	290-793 GeV	$m(\tilde{t}_1) < 0$ GeV	ATLAS-CONF-2017-019
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow t\bar{t} + b$	$1-2 e, \mu$	4 b	Yes	36.1	320-880 GeV	$m(\tilde{t}_1) < 0$ GeV	ATLAS-CONF-2017-019
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow \tilde{q}\tilde{q}^0$	$2 e, \mu$	0	Yes	20.3	90-335 GeV	$m(\tilde{t}_1) < 0$ GeV	1403.5294
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow \tilde{t}\tilde{t}^0$	$2 e, \mu$	0	Yes	13.2	540 GeV	$m(\tilde{t}_1) < 0$ GeV, $m(\tilde{t}_2) > 0.5(m(\tilde{t}_1) + m(\tilde{t}_2))$	ATLAS-CONF-2016-096
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow \tilde{t}\tilde{t}^0$	2τ	0	Yes	14.8	580 GeV	$m(\tilde{t}_1) < 0$ GeV, $m(\tilde{t}_2) > 0.5(m(\tilde{t}_1) + m(\tilde{t}_2))$	ATLAS-CONF-2016-093
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow \tilde{t}\tilde{t}^0$	$3 e, \mu$	0	Yes	13.2	1.0 TeV	$m(\tilde{t}_1) = m(\tilde{t}_2), m(\tilde{t}_2) < 0, \tilde{t} \text{ decoupled}$	ATLAS-CONF-2016-096
EW direct	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow W\tilde{q}^0$	$2-3 e, \mu$	0-2 jets	Yes	20.3	425 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2), m(\tilde{t}_2) < 0, \tilde{t} \text{ decoupled}$	1403.5294, 1402.7029
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow W\tilde{t}^0$	e, μ, τ	0-2 b	Yes	20.3	270 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2), m(\tilde{t}_2) < 0, \tilde{t} \text{ decoupled}$	1501.07110
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow \tilde{t}\tilde{t}^0$	$4 e, \mu$	0	Yes	20.3	635 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2), m(\tilde{t}_2) < 0, \tilde{t} \text{ decoupled}$	1405.5086
	GGM (bino NLSP) weak prod.	$1 e, \mu + \gamma$	-	Yes	20.3	115-370 GeV	$c\tau < 1$ mm	1507.05493
	GGM (bino NLSP) weak prod.	2γ	-	Yes	20.3	590 GeV	$c\tau < 1$ mm	1507.05493
	Direct $\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1$ prod., long-lived $\tilde{d}_1^0, \tilde{b}_1^0$	Disapp. trk	1 jet	Yes	36.1	430 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2) < 160$ MeV, $\tau(\tilde{d}_1^0) > 0.2$ ns	ATLAS-CONF-2017-017
	Direct $\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1$ prod., long-lived $\tilde{d}_1^0, \tilde{b}_1^0$	dE/dx trk	-	Yes	18.4	495 GeV	$m(\tilde{t}_1) = m(\tilde{t}_2) < 160$ MeV, $\tau(\tilde{d}_1^0) < 15$ ns	1506.05332
	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	850 GeV	$m(\tilde{t}_1) < 100$ GeV, $10 \mu\text{s} < c\tau(\tilde{g}) < 1000$ s	1310.6584
	Stable \tilde{g} R-hadron	trk	-	-	3.2	1.58 TeV		1606.05129
	Metastable \tilde{g} R-hadron	dE/dx trk	-	-	3.2	1.57 TeV		1604.04520
Long-lived particles	GMSB, stable $\tilde{t}_1, \tilde{d}_1^0 \rightarrow \tilde{t}(\tilde{d}_1^0) + \tau(e, \mu)$	$1-2 \mu$	-	-	19.1	537 GeV	$m(\tilde{t}_1) < 100$ GeV, $\tau > 10$ ns	1411.6795
	GMSB, $\tilde{d}_1^0 \rightarrow \gamma G$, long-lived \tilde{d}_1^0	2γ	-	Yes	20.3	440 GeV	$1 < \tau(\tilde{d}_1^0) < 3$ ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{d}_1^0 \rightarrow \tau\tau / \mu\mu / \mu\tau$	displ. or $e\mu / \mu\mu$	-	-	20.3	1.0 TeV	$7 < c\tau(\tilde{d}_1^0) < 740$ mm, $m(\tilde{d}_1^0) > 1.3$ TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{d}_1^0 \rightarrow ZG$	displ. vtx + jets	-	-	20.3	1.0 TeV	$6 < c\tau(\tilde{d}_1^0) < 480$ mm, $m(\tilde{d}_1^0) > 1.1$ TeV	1504.05162
	LFV $pp \rightarrow \tilde{q}_i + X, \tilde{q}_i \rightarrow e\mu / \tau\mu$	$e\mu / \tau\mu$	-	-	3.2	1.8 TeV	$A_{\tilde{q}_i} < 0.11, A_{\tilde{q}_i, \tilde{q}_i, \tilde{q}_i} < 0.07$	1607.08079
	Bi-linear RPV CMSSM	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	1.45 TeV	$m(\tilde{g}) = m(\tilde{q}), c\tau_{\tilde{q}_i} > 1$ mm	1404.2500
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow W\tilde{q}^0, \tilde{d}_1^0 \rightarrow \tau\tau, \mu\mu, \mu\tau$	$4 e, \mu$	-	Yes	13.2	1.14 TeV	$m(\tilde{t}_1) < 400$ GeV, $A_{\tilde{d}_1, \tilde{d}_1} < 0$ ($k = 1, 2$)	ATLAS-CONF-2016-075
	$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow W\tilde{t}^0, \tilde{d}_1^0 \rightarrow \tau\tau, \mu\tau, \tau\tau$	$3 e, \mu + \tau$	-	Yes	20.3	450 GeV	$m(\tilde{t}_1) > 0.2 m(\tilde{t}_2), A_{\tilde{d}_1, \tilde{d}_1} < 0$	1405.5086
	$\tilde{g}\tilde{g} \rightarrow \tilde{q}\tilde{q}^0$	0	4-5 large-R jets	-	14.8	1.08 TeV	$BR(\tilde{g}) \rightarrow BR(\tilde{q}) \rightarrow BR(\tilde{q}) > 0\%$	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{d}_1^0 \rightarrow \tilde{q}\tilde{q}^0$	0	4-5 large-R jets	-	14.8	1.55 TeV	$m(\tilde{t}_1) < 850$ GeV	ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}, \tilde{d}_1^0 \rightarrow \tilde{t}\tilde{t}^0, \tilde{d}_1^0 \rightarrow \tilde{q}\tilde{q}^0$	$1 e, \mu$	8-10 jets/0-4 b	-	36.1	2.1 TeV	$m(\tilde{t}_1) < 1$ TeV, $A_{\tilde{d}_1, \tilde{d}_1} < 0$	ATLAS-CONF-2017-013	
$\tilde{g}\tilde{g}, \tilde{d}_1^0 \rightarrow \tilde{t}\tilde{t}^0, \tilde{d}_1^0 \rightarrow \tilde{q}\tilde{q}^0$	$1 e, \mu$	8-10 jets/0-4 b	-	36.1	1.65 TeV	$m(\tilde{t}_1) < 1$ TeV, $A_{\tilde{d}_1, \tilde{d}_1} < 0$	ATLAS-CONF-2017-013	
$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow b\bar{b}$	0	2 jets + 2 b	-	15.4	410 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-064	
$\tilde{d}_1\tilde{d}_1, \tilde{b}_1\tilde{b}_1 \rightarrow b\bar{t}$	$2 e, \mu$	2 b	-	20.3	850-910 GeV	$BR(\tilde{d}_1) \rightarrow BR(\mu) > 20\%$	ATLAS-CONF-2015-015	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{q}^0$	0	2 c	Yes	20.3	510 GeV	$m(\tilde{t}_1) < 200$ GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on

GLUINO MASS IN PMSSM

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



SUSY AT LHC RUN 2

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2017

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$ TeV

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} d\mathcal{R} [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference
Inclusive Searches	MSUGRA/CMSSM	$0-3 e, \mu / 1-2 \tau$	2-10 jets/3 b	Yes	20.3	1.85 TeV	$m(\tilde{g})=m(\tilde{U})$	1507.05525
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0	2-6 jets	Yes	36.1	1.65 TeV	$m(\tilde{U}) < 200 \text{ GeV}, m(\tilde{1}^{\pm}) \text{ gas. } \tilde{q} \rightarrow m(\tilde{G}^{\pm}) \text{ gas. } \tilde{q}$	ATLAS-CONF-2017-022
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ (compressed)	mono-jet	1-3 jets	Yes	3.2	608 GeV	$m(\tilde{g})=m(\tilde{U}) < 5 \text{ GeV}$	1604.07773
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0	2-6 jets	Yes	36.1	2.02 TeV	$m(\tilde{U}) < 200 \text{ GeV}$	ATLAS-CONF-2017-022
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^{\dagger} + \tilde{q}\tilde{q}^{\dagger}$	0	2-6 jets	Yes	36.1	2.01 TeV	$m(\tilde{U}) < 200 \text{ GeV}, m(\tilde{1}^{\pm}) > 0.5 m(\tilde{U}^{\pm}) + m(\tilde{G})$	ATLAS-CONF-2017-022
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^{\dagger} + \tilde{q}\tilde{q}^{\dagger}$	$3 e, \mu$	4 jets	-	13.2	1.7 TeV	$m(\tilde{U}) < 400 \text{ GeV}$	ATLAS-CONF-2016-037
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^{\dagger} + \tilde{q}\tilde{q}^{\dagger}$	$2 e, \mu$ (SS)	0-3 jets	Yes	13.2	1.6 TeV	$m(\tilde{U}) < 500 \text{ GeV}$	ATLAS-CONF-2016-037
	GMSB (\tilde{g} NLSP)	$1-2 \tau + 0-1 \ell$	0-2 jets	Yes	3.2	2.0 TeV		1607.05979
	GGM (bino NLSP)	2γ	-	Yes	3.2	1.65 TeV	$c\tau(\text{NLSP}) < 0.1 \text{ mm}$	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	1.37 TeV	$m(\tilde{U}) < 950 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu = 0$	1607.05493
GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	1.8 TeV	$m(\tilde{U}) < 680 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu = 0$	ATLAS-CONF-2016-066	
GGM (higgsino NLSP)	$2 e, \mu$ (Z)	2 jets	Yes	20.3	900 GeV	$m(\text{NLSP}) > 430 \text{ GeV}$	1503.03290	
Gravitino LSP	0	mono-jet	Yes	20.3	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-1} \text{ eV}, m(\tilde{g})=m(\tilde{U})=1.5 \text{ TeV}$	1502.01518	
3 rd gen. \tilde{g} prod.	$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}$	0	3 b	Yes	36.1	1.92 TeV	$m(\tilde{U}) < 600 \text{ GeV}$	ATLAS-CONF-2017-021
	$\tilde{g}, \tilde{g} \rightarrow t\tilde{t}$	$0-1 e, \mu$	3 b	Yes	36.1	1.97 TeV	$m(\tilde{U}) < 200 \text{ GeV}$	ATLAS-CONF-2017-021
	$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}$	$0-1 e, \mu$	3 b	Yes	20.1	1.37 TeV	$m(\tilde{U}) < 300 \text{ GeV}$	1407.0600
3 rd gen. squarks direct production	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	0	2 b	Yes	3.2	840 GeV	$m(\tilde{U}) < 100 \text{ GeV}$	1606.08772
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	$2 e, \mu$ (SS)	1 b	Yes	13.2	325-685 GeV	$m(\tilde{U}) < 150 \text{ GeV}, m(\tilde{U}^{\pm}) > m(\tilde{U}) + 100 \text{ GeV}$	ATLAS-CONF-2016-037
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	$0-2 e, \mu$	1-2 b	Yes	4.7/13.3	117-170 GeV	$m(\tilde{U}) = 2m(\tilde{U}^{\pm}), m(\tilde{U}^{\pm}) < 50 \text{ GeV}$	1209.2162, ATLAS-CONF-2016-077
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow W\tilde{b} + \tilde{d}\tilde{b}$ or $\tilde{d}\tilde{b}$	$0-2 e, \mu$	0-2 jets/1-2 b	Yes	20.3	90-198 GeV	$m(\tilde{U}) > 1 \text{ GeV}$	1506.08616, ATLAS-CONF-2017-020
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	0	mono-jet	Yes	3.2	90-323 GeV	$m(\tilde{U}) = m(\tilde{U}^{\pm}) < 5 \text{ GeV}$	1604.07773
	\tilde{d}_1, \tilde{d}_1 (natural GMSB)	$2 e, \mu$ (Z)	1 b	Yes	20.3	150-600 GeV	$m(\tilde{U}) > 150 \text{ GeV}$	1403.5232
3 rd gen. squarks direct production	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	$3 e, \mu$ (Z)	1 b	Yes	36.1	290-793 GeV	$m(\tilde{U}) > 0 \text{ GeV}$	ATLAS-CONF-2017-019
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	$1-2 e, \mu$	4 b	Yes	36.1	320-880 GeV	$m(\tilde{U}) > 0 \text{ GeV}$	ATLAS-CONF-2017-019
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	$2 e, \mu$	0	Yes	20.3	90-335 GeV	$m(\tilde{U}) > 0 \text{ GeV}$	1403.5294
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	$2 e, \mu$	0	Yes	13.3	640 GeV	$m(\tilde{U}) < 0 \text{ GeV}, m(\tilde{U}^{\pm}) > 0.5(m(\tilde{U}^{\pm}) + m(\tilde{U}^{\pm}))$	ATLAS-CONF-2016-096
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	2τ	0	Yes	14.8	580 GeV	$m(\tilde{U}) < 0 \text{ GeV}, m(\tilde{U}^{\pm}) > 0.5(m(\tilde{U}^{\pm}) + m(\tilde{U}^{\pm}))$	ATLAS-CONF-2016-093
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow d\tilde{d}$	$3 e, \mu$	0	Yes	13.3	1.0 TeV	$m(\tilde{U}) = m(\tilde{U}^{\pm}), m(\tilde{U}^{\pm}) < 0, m(\tilde{U}^{\pm}) > 0.5(m(\tilde{U}^{\pm}) + m(\tilde{U}^{\pm}))$	ATLAS-CONF-2016-096
EW direct	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow W\tilde{b} + \tilde{d}\tilde{b}$ or $\tilde{d}\tilde{b}$	$2-3 e, \mu$	0-2 jets	Yes	20.3	425 GeV	$m(\tilde{U}) = m(\tilde{U}^{\pm}), m(\tilde{U}^{\pm}) < 0, \tilde{f}$ decoupled	1403.5294, 1402.7029
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow W\tilde{b} + \tilde{d}\tilde{b}$ or $\tilde{d}\tilde{b}$	e, μ, τ	0-2 b	Yes	20.3	270 GeV	$m(\tilde{U}) = m(\tilde{U}^{\pm}), m(\tilde{U}^{\pm}) < 0, \tilde{f}$ decoupled	1501.07110
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow W\tilde{b} + \tilde{d}\tilde{b}$ or $\tilde{d}\tilde{b}$	$4 e, \mu$	0	Yes	20.3	635 GeV	$m(\tilde{U}) = m(\tilde{U}^{\pm}), m(\tilde{U}^{\pm}) < 0, m(\tilde{U}^{\pm}) > 0.5(m(\tilde{U}^{\pm}) + m(\tilde{U}^{\pm}))$	1405.5086
	GGM (bino NLSP) weak prod.	$1 e, \mu + \gamma$	-	Yes	20.3	115-370 GeV	$c\tau < 1 \text{ mm}$	1507.05493
	GGM (bino NLSP) weak prod.	2γ	-	Yes	20.3	590 GeV	$c\tau < 1 \text{ mm}$	1507.05493
	Direct \tilde{d}_1, \tilde{d}_1 prod., long-lived \tilde{d}_1	Disapp. trk	1 jet	Yes	36.1	430 GeV	$m(\tilde{U}) = m(\tilde{U}^{\pm}) < 160 \text{ MeV}, \nu(\tilde{d}_1) > 0.2 \text{ ns}$	ATLAS-CONF-2017-017
	Direct \tilde{d}_1, \tilde{d}_1 prod., long-lived \tilde{d}_1	dE/dx trk	-	Yes	18.4	495 GeV	$m(\tilde{U}) = m(\tilde{U}^{\pm}) < 160 \text{ MeV}, \nu(\tilde{d}_1) < 15 \text{ ns}$	1506.05332
	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	850 GeV	$m(\tilde{U}) > 100 \text{ GeV}, 10 \mu\text{s} < c\tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
	Stable \tilde{g} R-hadron	trk	-	-	3.2	1.58 TeV		1606.05129
	Metastable \tilde{g} R-hadron	dE/dx trk	-	-	3.2	1.57 TeV		1604.04520
Long-lived particles	GMSB, stable $\tilde{t}, \tilde{d}_1 \rightarrow \tilde{t}(\tilde{d}_1) + \nu(\tilde{e}, \mu)$	$1-2 \mu$	-	Yes	19.1	537 GeV	$m(\tilde{U}) > 100 \text{ GeV}, \tau > 10 \text{ ns}$	1411.6795
	GMSB, $\tilde{d}_1 \rightarrow \tilde{d}_1 + \gamma$, long-lived \tilde{d}_1	2γ	-	Yes	20.3	440 GeV	$1 < c\tau(\tilde{d}_1) < 3 \text{ ns}, \text{SPS8 model}$	1409.5542
	$\tilde{g}, \tilde{g} \rightarrow \nu\nu + \tilde{g}\tilde{g}$	displ. or $\tilde{g}\tilde{g}$	-	-	20.3	1.0 TeV	$7 < c\tau(\tilde{g}) < 740 \text{ mm}, m(\tilde{g}) > 1.3 \text{ TeV}$	1504.05162
	GGM $\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}$	displ. vtx + jets	-	-	20.3	1.0 TeV	$6 < c\tau(\tilde{g}) < 480 \text{ mm}, m(\tilde{g}) > 1.1 \text{ TeV}$	1504.05162
	LFV $\tilde{g}\tilde{g} \rightarrow \tilde{g}, X, \tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}$	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}$	-	-	3.2	1.8 TeV	$A_{\tilde{g}\tilde{g}} < 0.11, A_{\tilde{g}\tilde{g}\tilde{g}} < 0.07$	1607.08079
	Bi-linear RPV CMSSM	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	1.45 TeV	$m(\tilde{U}) = m(\tilde{U}^{\pm}), c\tau_{\tilde{U}^{\pm}} < 1 \text{ mm}$	1404.2500
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow W\tilde{b} + \tilde{d}\tilde{b}$ or $\tilde{d}\tilde{b}$	$4 e, \mu$	-	Yes	13.3	1.14 TeV	$m(\tilde{U}) < 400 \text{ GeV}, A_{\tilde{d}_1\tilde{d}_1} = 0 (\tilde{d}_1 = 1, 2)$	ATLAS-CONF-2016-075
	$\tilde{d}_1, \tilde{d}_1, \tilde{d}_1 \rightarrow W\tilde{b} + \tilde{d}\tilde{b}$ or $\tilde{d}\tilde{b}$	$3 e, \mu + \tau$	-	Yes	20.3	450 GeV	$m(\tilde{U}) > 0.2 m(\tilde{U}^{\pm}), A_{\tilde{d}_1\tilde{d}_1} = 0$	1405.5086
	$\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	4-5 large-R jets	-	14.8	1.08 TeV	$\text{BR}(\tilde{g}) \rightarrow \text{BR}(\tilde{g}) \rightarrow \text{BR}(\tilde{g}) > 0\%$	ATLAS-CONF-2016-057
	$\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}, \tilde{d}_1 \rightarrow \tilde{d}_1$	0	4-5 large-R jets	-	14.8	1.55 TeV	$m(\tilde{U}) < 850 \text{ GeV}$	ATLAS-CONF-2016-057
$\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}, \tilde{d}_1 \rightarrow \tilde{d}_1$	$1 e, \mu$	8-10 jets/0-4 b	-	36.1	2.1 TeV	$m(\tilde{U}) < 850 \text{ GeV}$	ATLAS-CONF-2017-013	
$\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}, \tilde{d}_1 \rightarrow \tilde{d}_1$	$1 e, \mu$	8-10 jets/0-4 b	-	36.1	1.65 TeV	$m(\tilde{U}) < 1 \text{ TeV}, A_{\tilde{d}_1\tilde{d}_1} = 0$	ATLAS-CONF-2017-013	
$\tilde{d}_1, \tilde{d}_1 \rightarrow b\tilde{b}$	0	2 jets + 2 b	-	15.4	410 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-064	
$\tilde{d}_1, \tilde{d}_1 \rightarrow b\tilde{b}$	$2 e, \mu$	2 b	-	20.3	850-910 GeV	$\text{BR}(\tilde{d}_1) \rightarrow \text{BR}(\mu) > 20\%$	ATLAS-CONF-2015-015	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{c}$	0	2 c	Yes	20.3	510 GeV	$m(\tilde{U}) < 200 \text{ GeV}$	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on

HEAVY SUSY ???

Maybe the arguments requiring SUSY at the EW scale like naturalness are just red-herrings and instead SUSY is somewhat heavier...

Indeed there are some counterargument in favour of heavy SUSY from successful cosmology and not only:
e.g.

Gravitino and moduli problems

as well as **the flavour problem**, i.e. heavy squarks and sleptons fit better than light ones with the SM-like nature of the CP violation in the quark sector and generically with flavour observables.

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

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

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

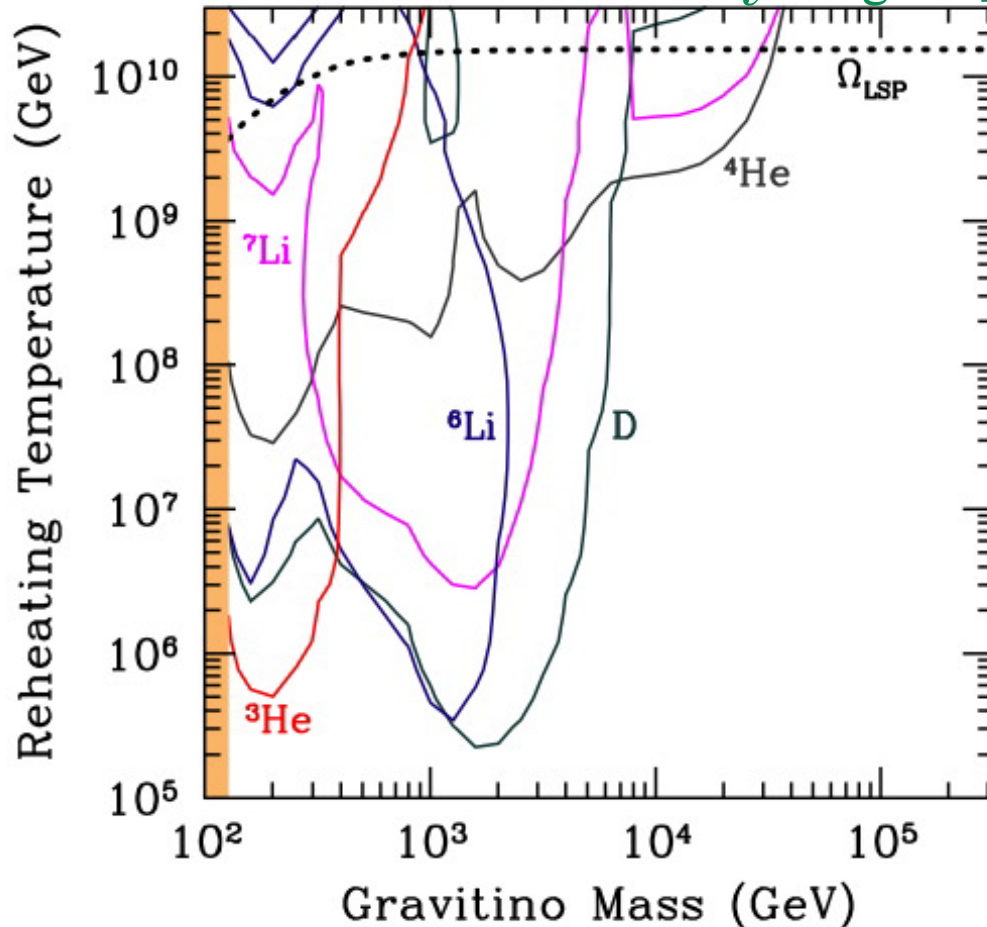
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1 \text{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10} \text{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100 \text{GeV}} \right)^2$$

[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]



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

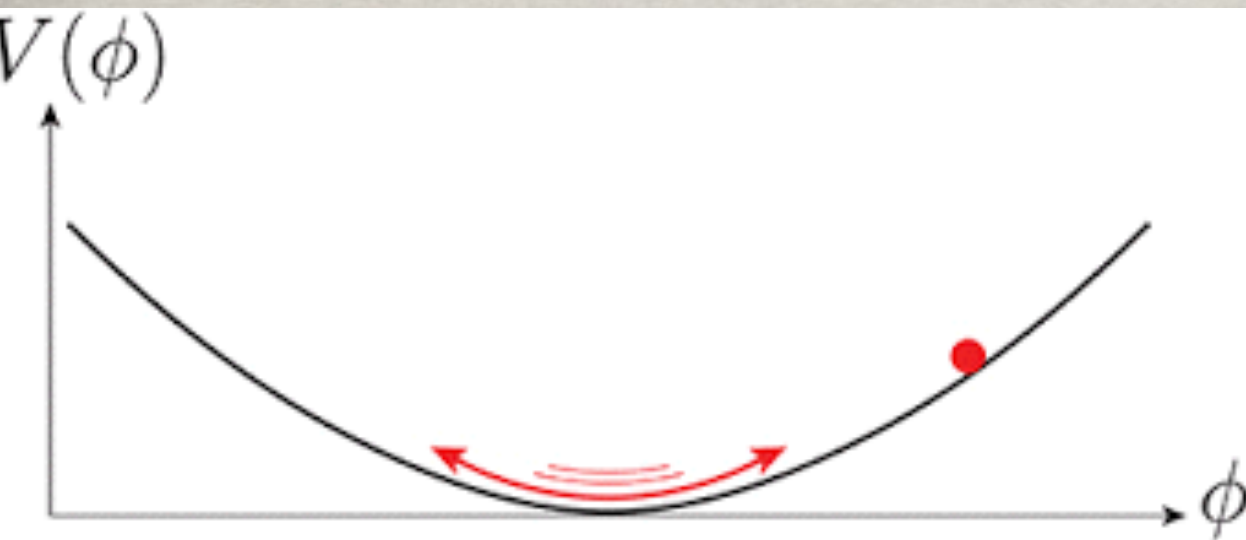
BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than ~ 1 s, or if the reheating temperature **is small!** Indeed due to non-renormalizable coupling

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

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.

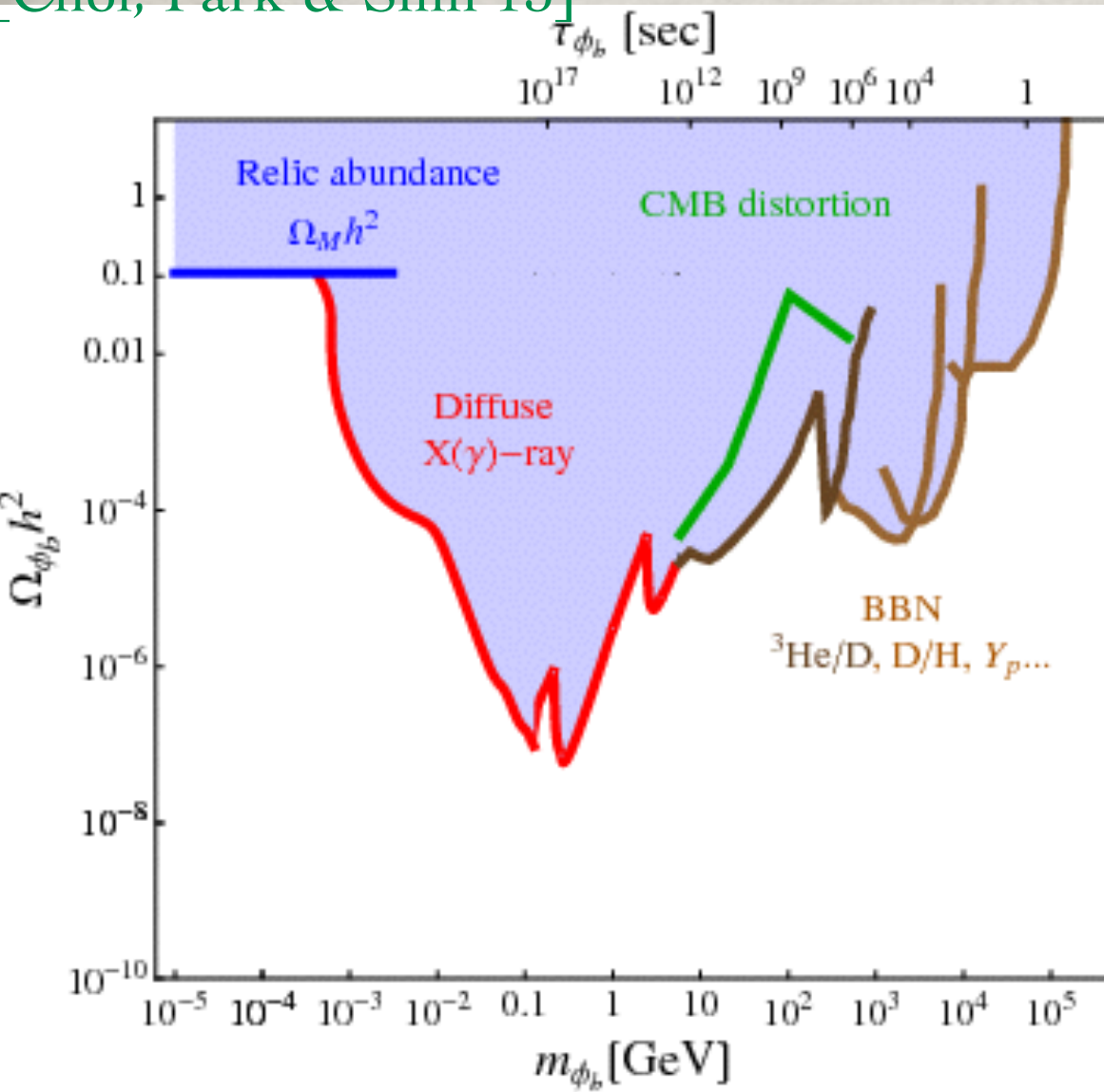
In the case of moduli, they arise in the early Universe also from the misalignment mechanism:



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...

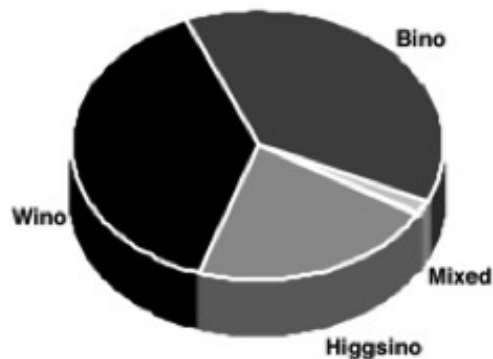
Ways out: heavy moduli or dilution factor, e.g. thermal inflation.

DM IN PMSSM

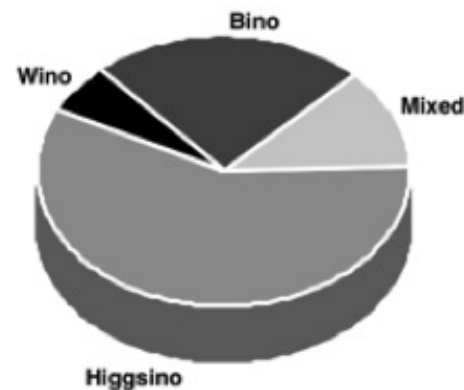
[Arbey et al. 1505.04595]

Take neutralino DM or 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...

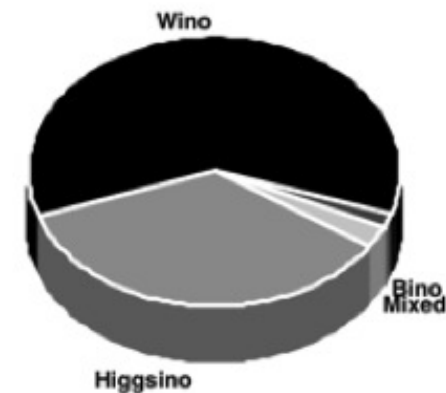
Gravitino LSP



$0.09 < \Omega_\chi h^2 < 0.163$



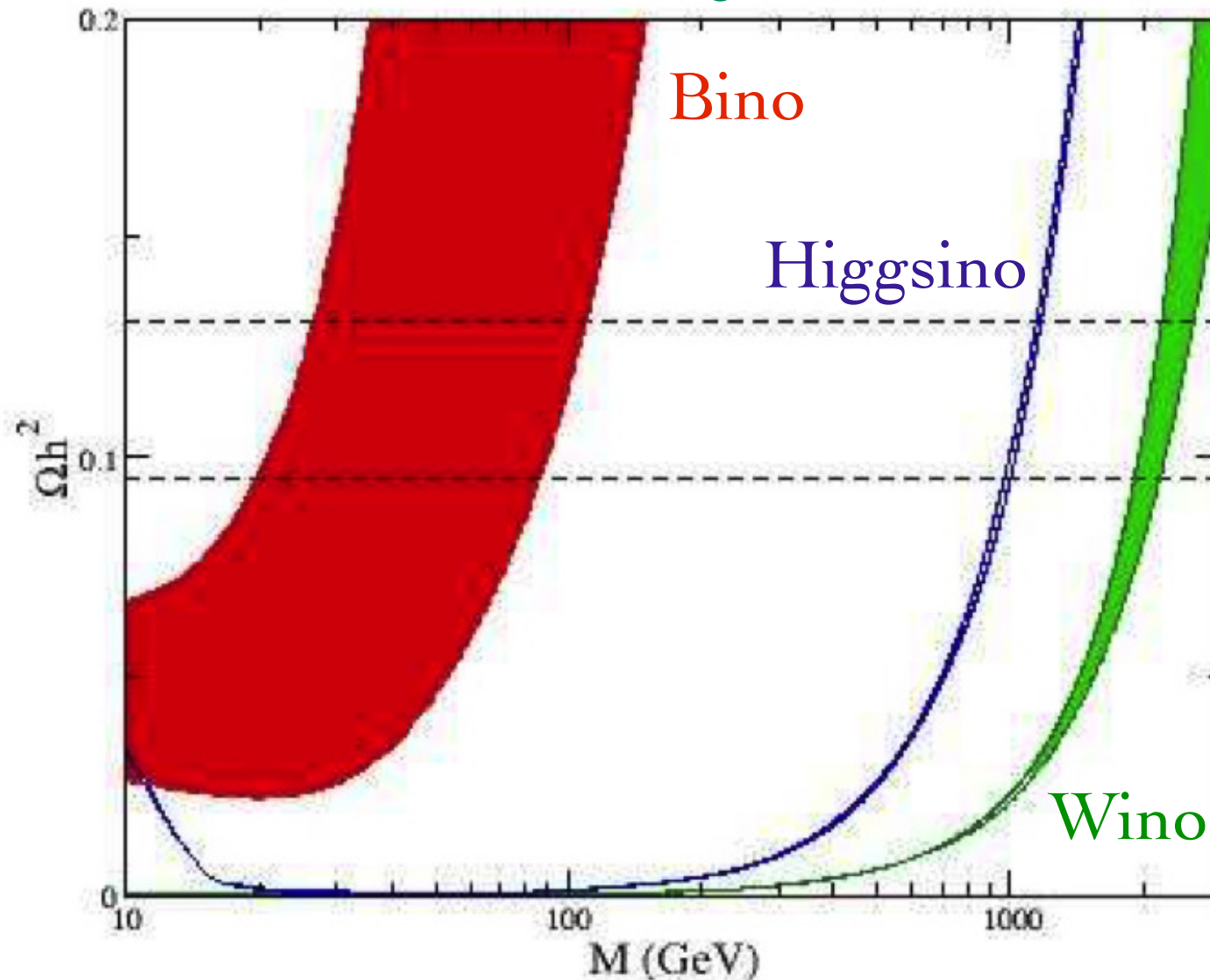
$10^{-5} < \Omega_\chi h^2 < 0.163$



WELL-TEMPERED NEUTRALINO

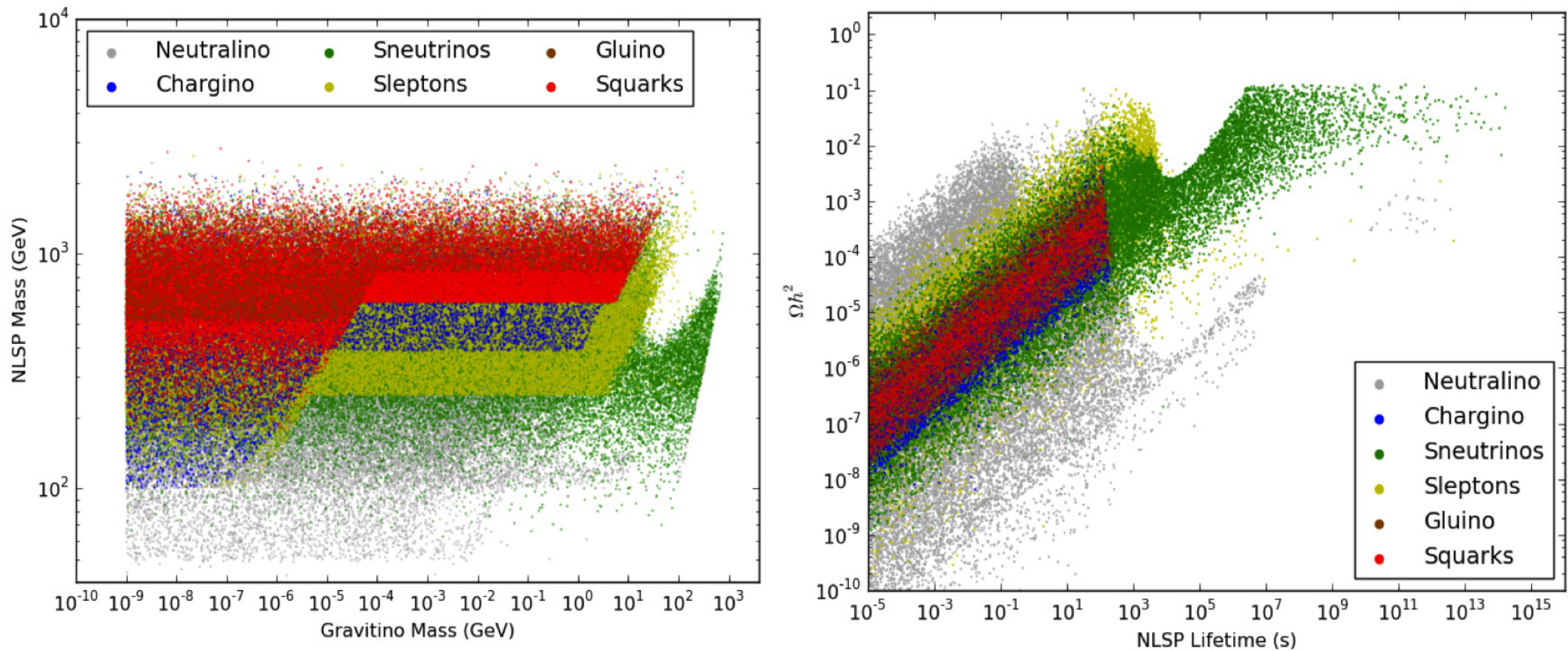
Relic density strongly dependent on neutralino nature !!!

[Arkani-Hamed, Delgado & Giudice 0601041]



BBN BOUNDS ON PMSSM

[Cahill-Rawley et al 12]

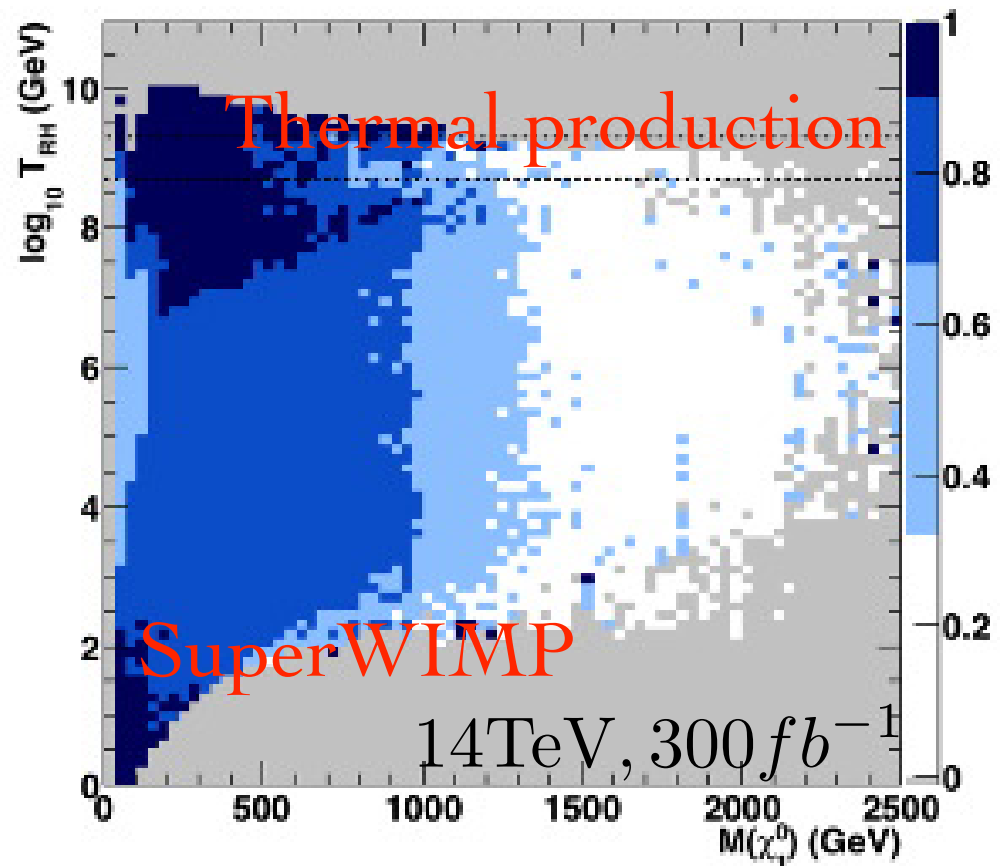
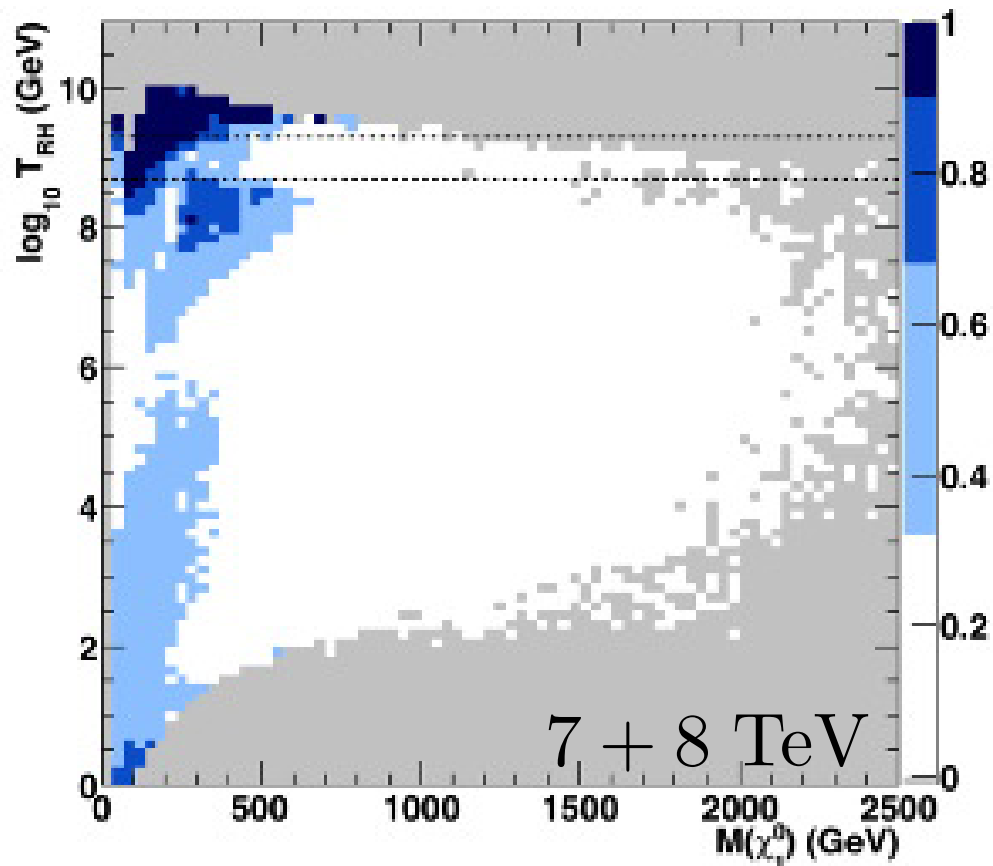


Many points for various NLSPs excluded by BBN: only the sneutrino survives to large gravitino masses.
Heavy NLSP is actually preferred !

GRAVITINO DM IN PMSSM

[Arbey et al. 1505.04595]

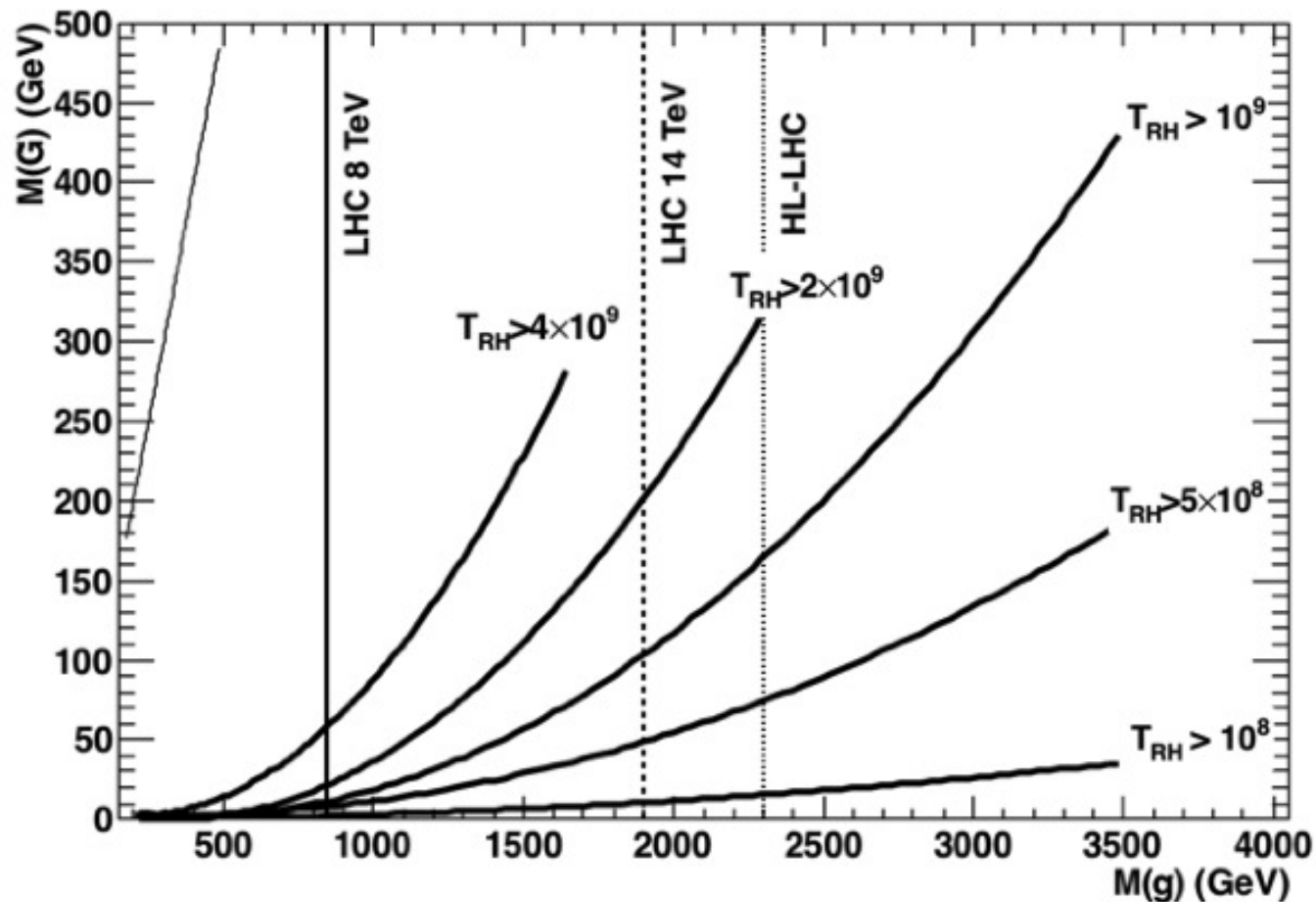
Interplay between gravitino production and gaugino masses very strong: high T_{RH} region corresponds to light gauginos and it is more easily tested as well as SuperWIMP region !



GRAVITINO DM & GLUINO

[Arbey et al. 1505.04595]

Glino 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.

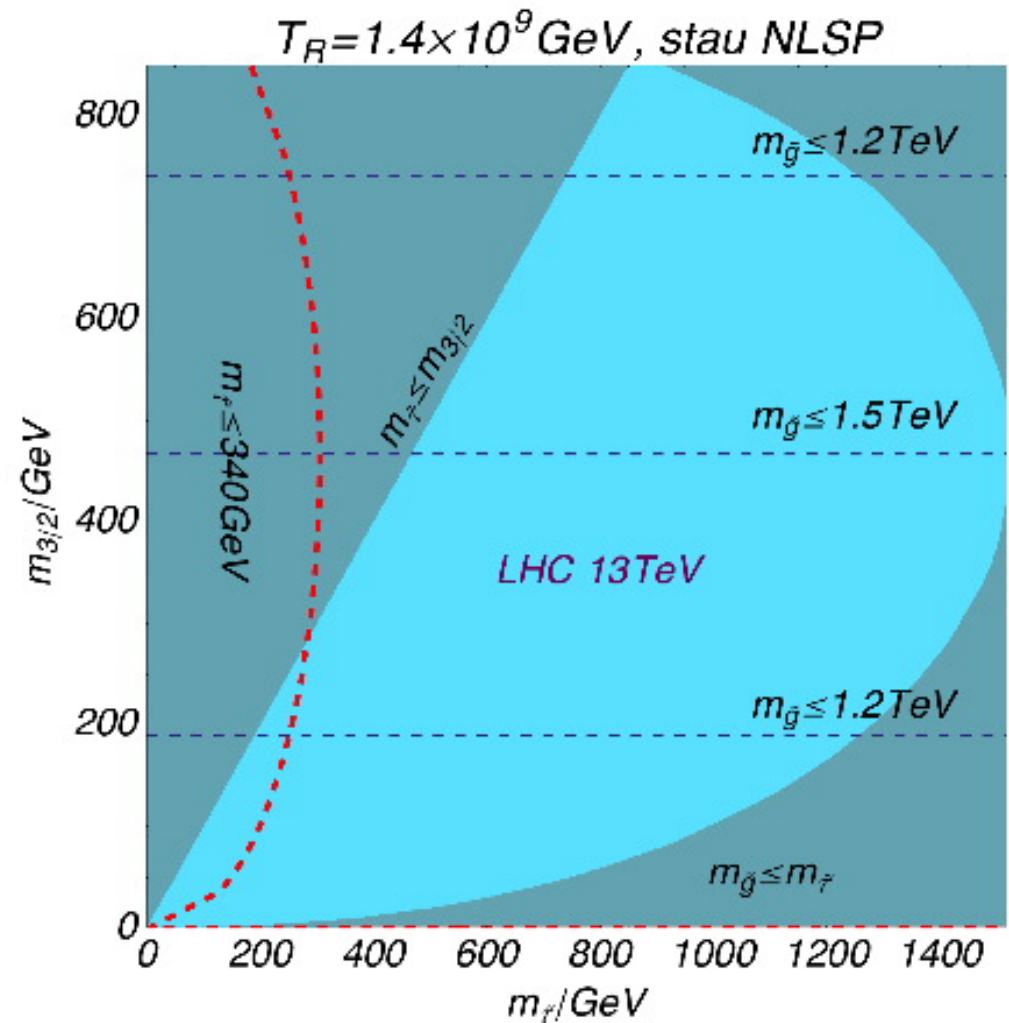
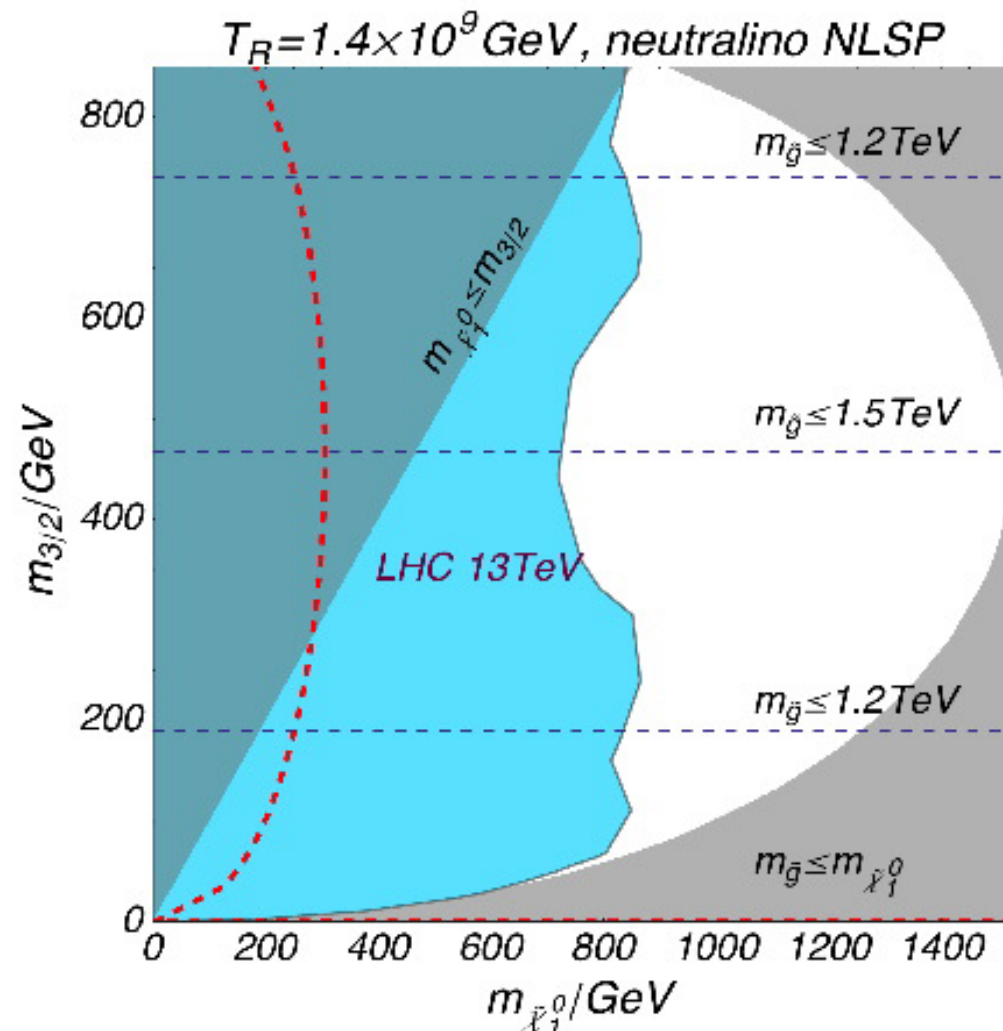


Minimal
gravitino mass
such that
 $\Omega_{\tilde{G}} h^2 < 0.12$
is given by
 $m_{\tilde{G}} \propto m_{\tilde{g}}^2$

GRAVITINO DM & T_RH

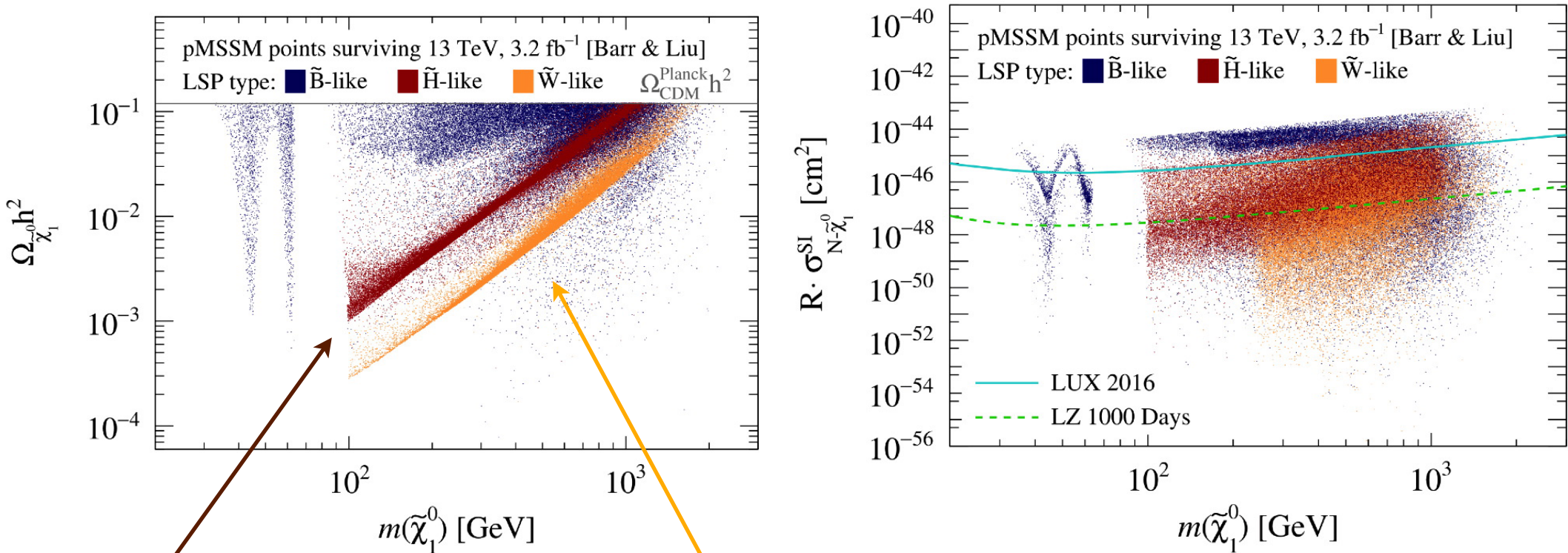
The LHC run 2 already constrains the heavy T_RH scenario for gravitino DM with bilinear RPV :

[Ibe, Suzuki & Yanagida 1609.06834]



NEUTRALINO DM 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...)

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

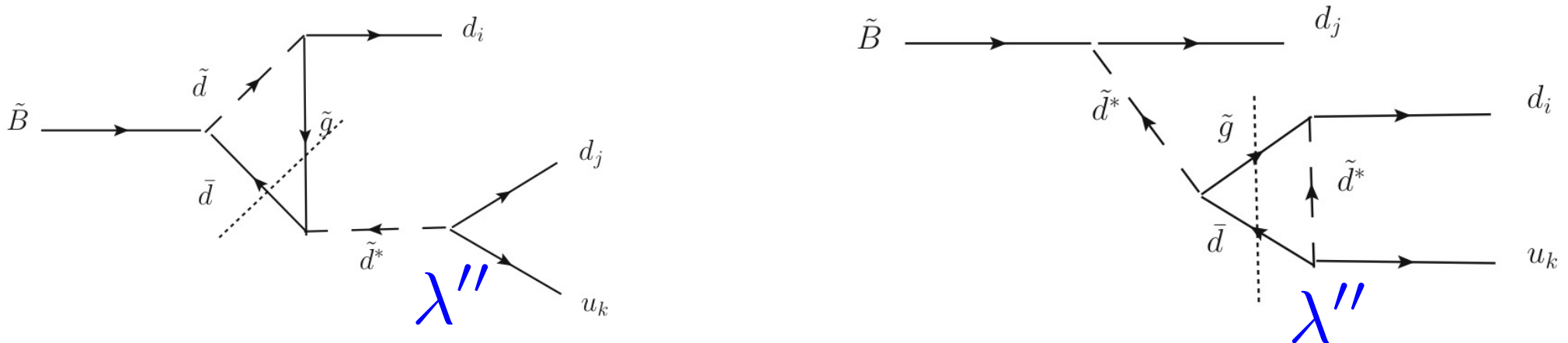
$$\tilde{B} \rightarrow udd, \bar{u}\bar{d}\bar{d}, \tilde{g}\bar{q}q$$

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...

$$\Omega_{\Delta B} = \frac{m_p}{m_\chi} \epsilon_{CP} BR(\chi \rightarrow \cancel{B}) \Omega_\chi^{\tau \rightarrow \infty}$$

Small numbers

$$\Omega_{DM} = \frac{m_{DM}}{m_\chi} BR(\chi \rightarrow DM + \text{anything}) \Omega_\chi^{\tau \rightarrow \infty}$$

→
$$\frac{\Omega_{\Delta B}}{\Omega_{DM}} = \frac{m_p}{m_{DM}} \frac{\epsilon_{CP} BR(\chi \rightarrow \cancel{B})}{BR(\chi \rightarrow DM + \text{anything})}$$
 independent of Bino density

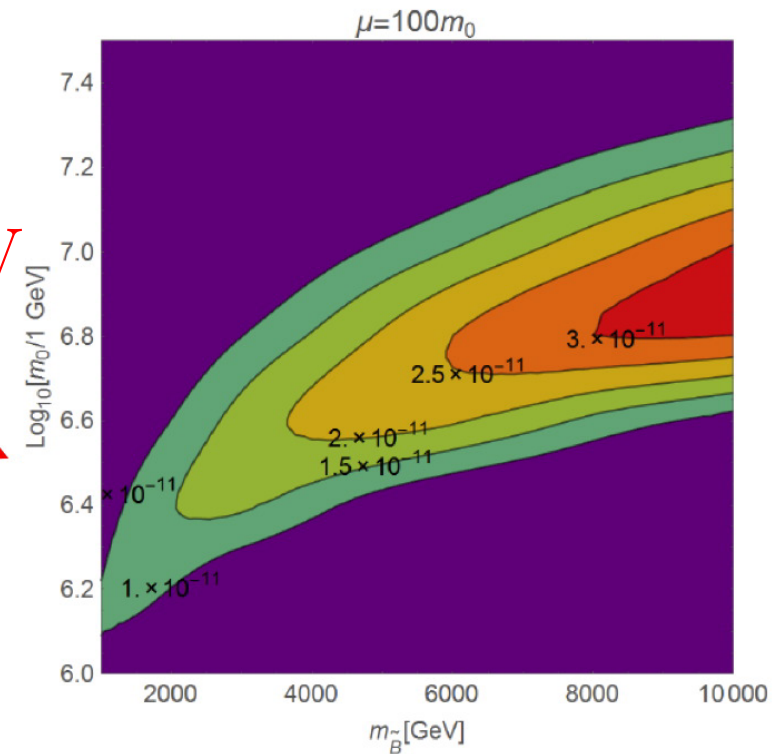
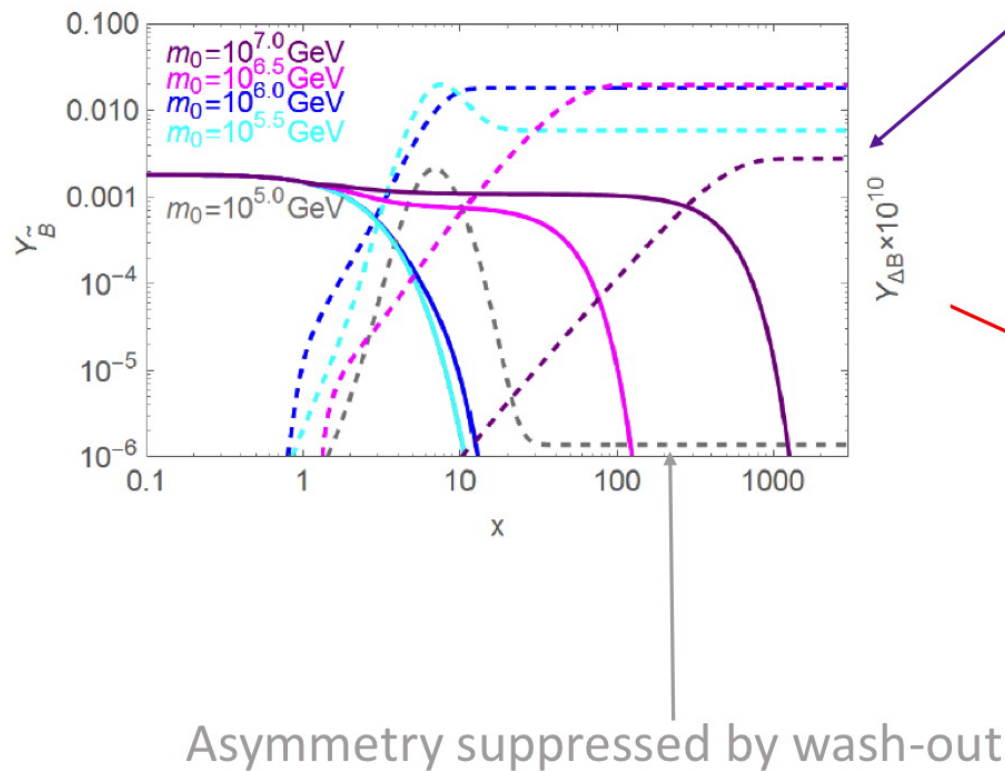
Gravitino DM: BR is naturally small and DM stable enough !

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 !!!

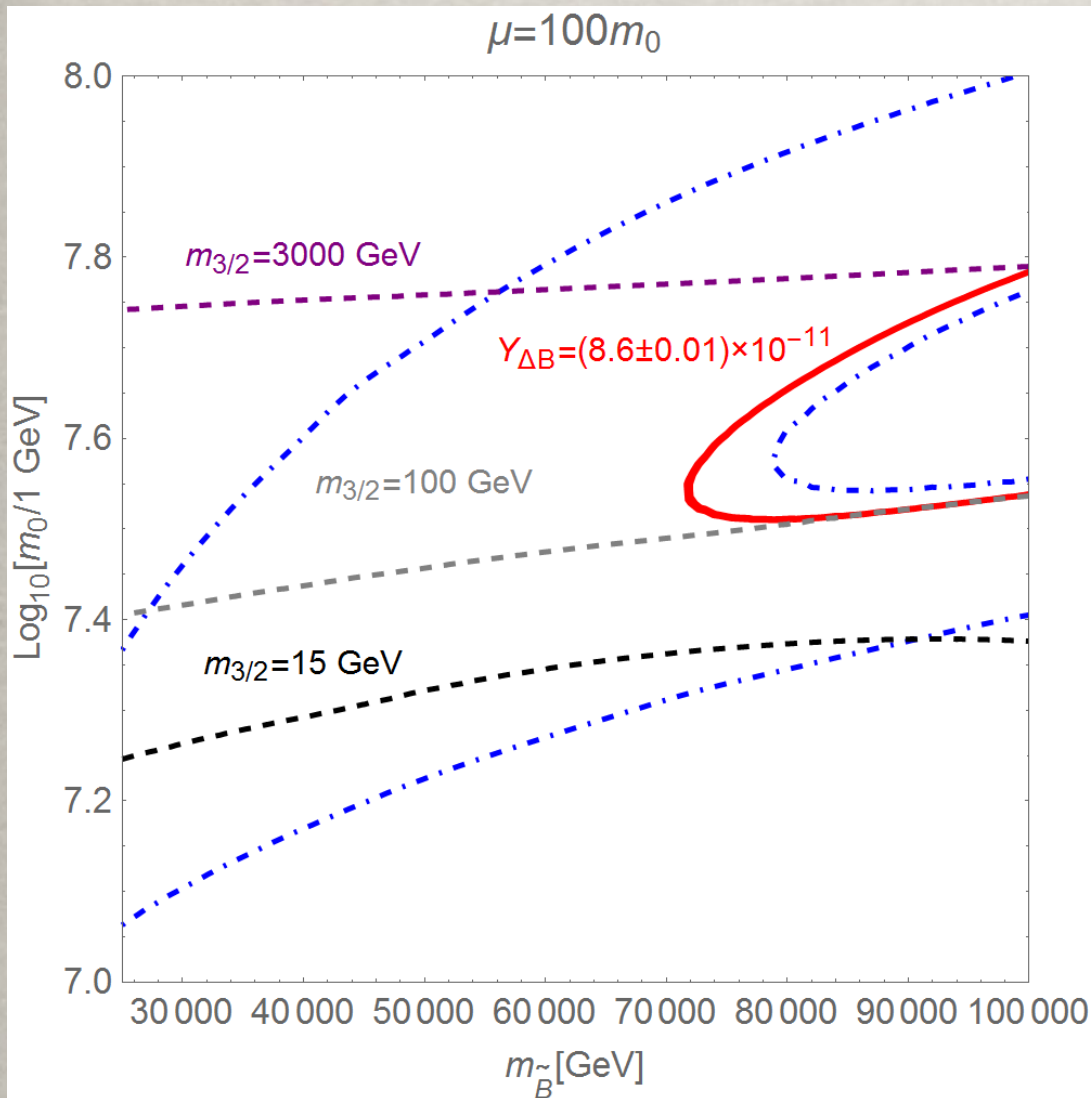
Asymmetry suppressed by the high scalars



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...

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

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]

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

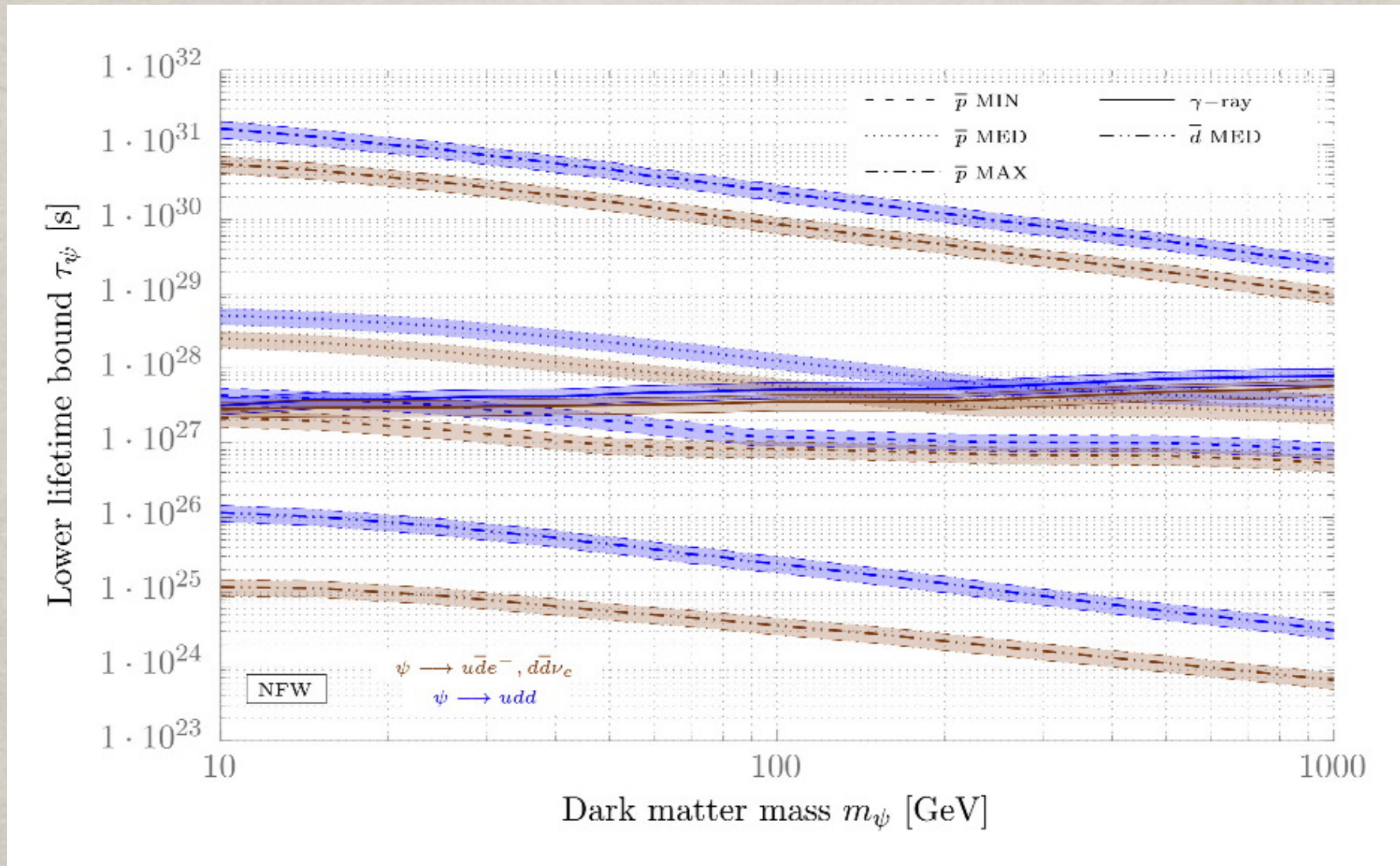
$$\Gamma(\psi_{3/2} \rightarrow u_k d_i d_j) = \frac{3\lambda^2}{124\pi^3} \frac{m_{3/2}^7}{m_0^4 M_P^2}$$

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

Right ballpark for indirect DM detection, but strongly dependent on the gravitino mass...

ID OF FIMP/SWIMP DM

[LC, Eckner & Gustafsson, work in progress]



Dominant decay into antiprotons, possibly observable !!!

GLUINO NLSP IN RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

The gluino is in this scenario the lightest SUSY particle and may be produced at colliders; but it should be not too much lighter than the Bino, i.e. $m_{\tilde{g}} \sim 0.1 - 0.4 m_{\tilde{B}} \sim 7 - 28 \text{ TeV}$, possibly 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.

INFLATION & COLLIDERS

HIGGS INFLATION

[Bezukov & Shaposhnikov 09]

Couple the Higgs field non-minimally to gravity:

$$\mathcal{L}_\xi = -\frac{\xi}{2}\phi^2 R$$

The term combines with the usual Einstein-Hilbert term and changes the strength of gravity at large field:

$$(M_P^{eff})^2 = M_P^2 + \xi \phi^2$$

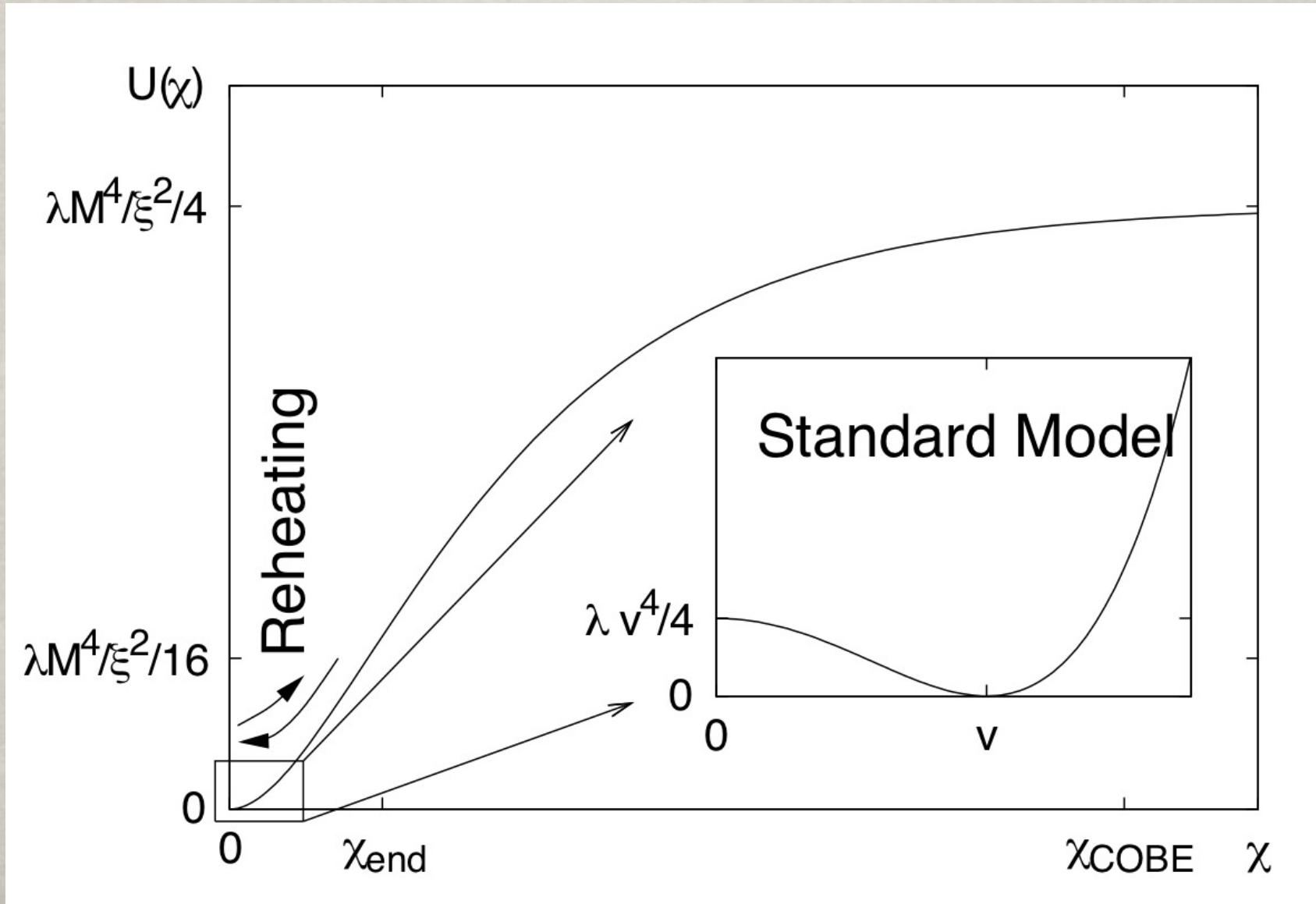
At large field values all the mass scales are proportional to the field and this can be “rescaled” away \gg flat direction !
Indeed in the Jordan frame (via conformal transformation)

$$\tilde{g}_{\mu\nu} = \left(1 + \frac{\xi\phi^2}{M_P^2}\right) g_{\mu\nu} \quad \frac{d\chi}{d\phi} = \frac{1}{\Omega} \sqrt{1 + \frac{6\xi^2\phi^2}{\Omega^2 M_P^2}}$$

HIGGS INFLATION

[Bezukov & Shaposhnikov 09]

In the redefined canonically normalized field the potential is:



HIGGS INFLATION

[Bezukov & Shaposhnikov 09]

Inflation is possible, BUT

- the normalization of the CMB power spectrum requires $\xi \sim 5 \times 10^4 \sqrt{\lambda} \gg 1$

Very large non-minimal coupling to gravity !

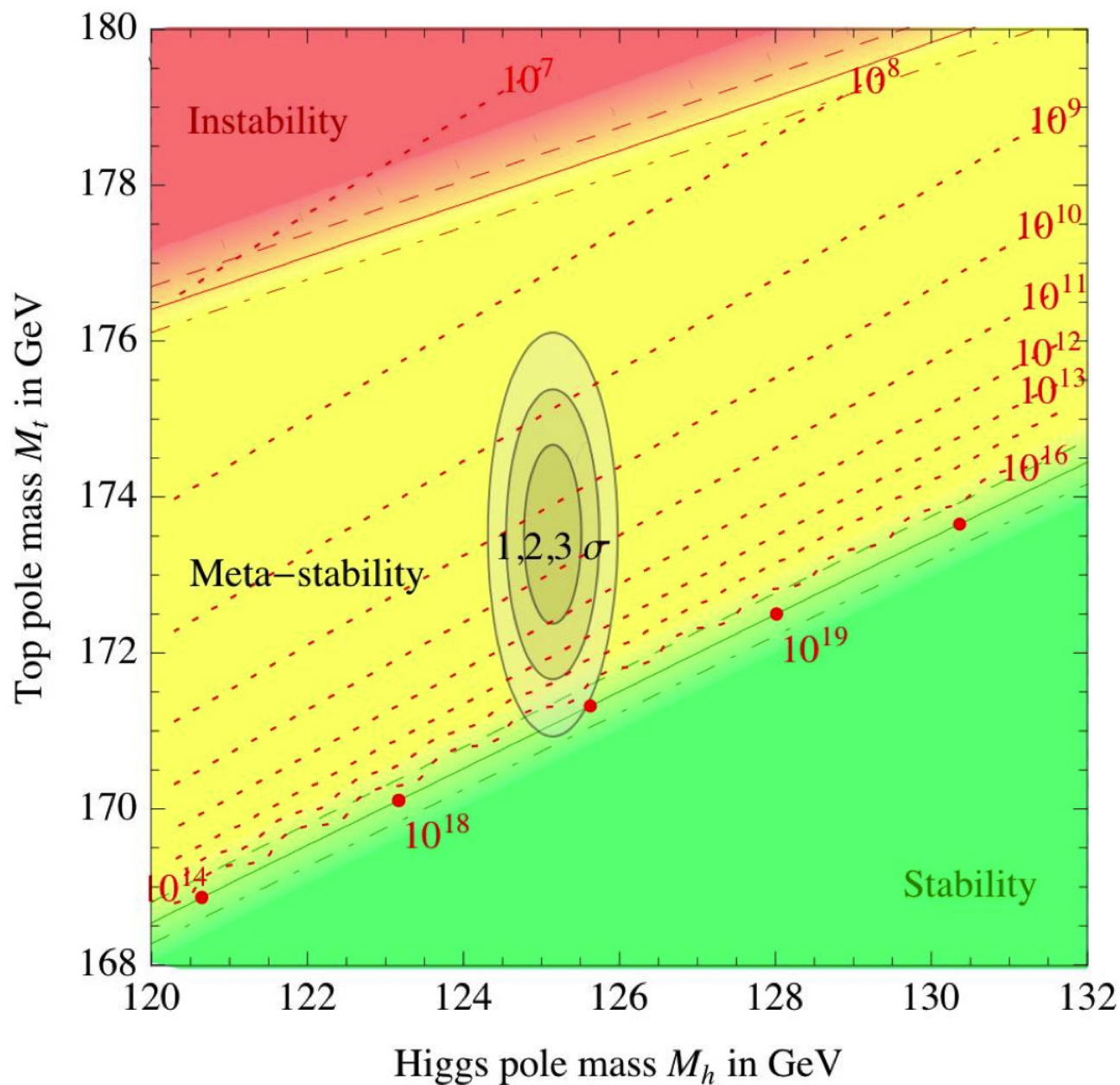
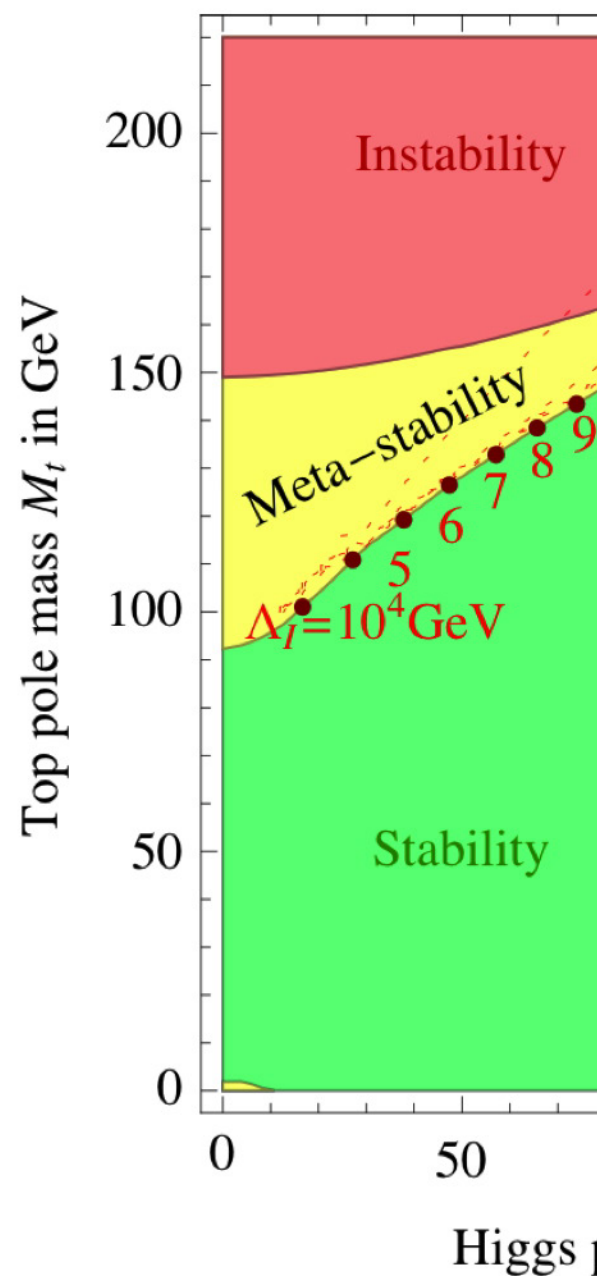
- connection to the Higgs coupling and therefore the Higgs mass as well by requiring consistency to the inflationary scale: $130 \text{ GeV} \leq m_H \leq 194 \text{ GeV}$
... now a bit on the boundary due to Higgs mass !
- Possible trouble: unitarity bound saturated at a scale

$$M_P / \sqrt{\xi} < M_P$$

HIGGS POTENTIAL AT M_{PL} ?

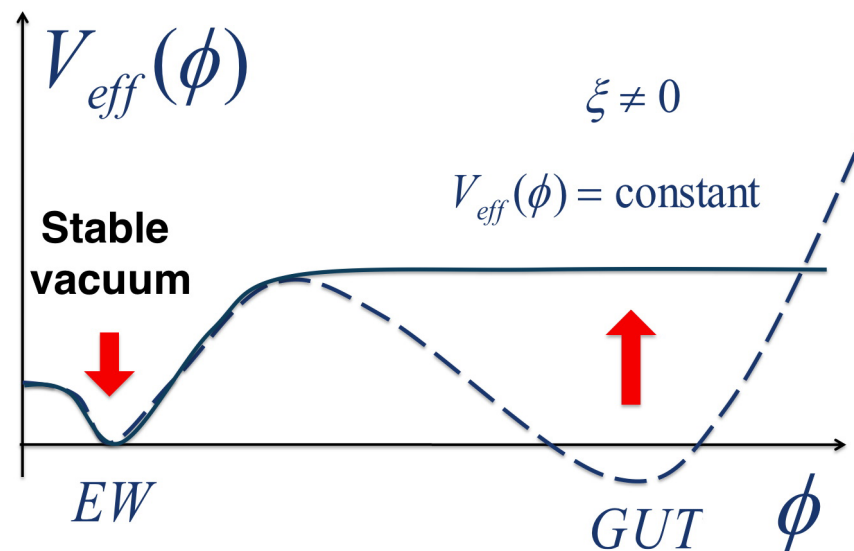
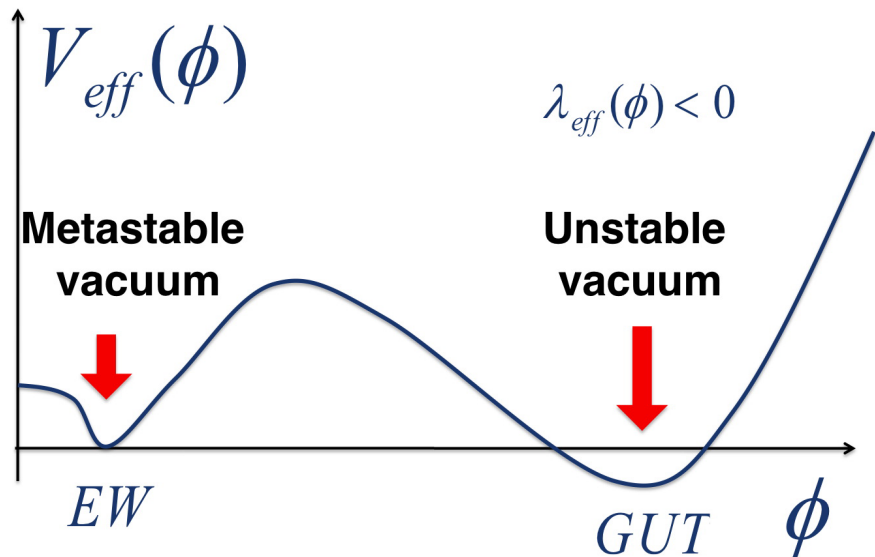
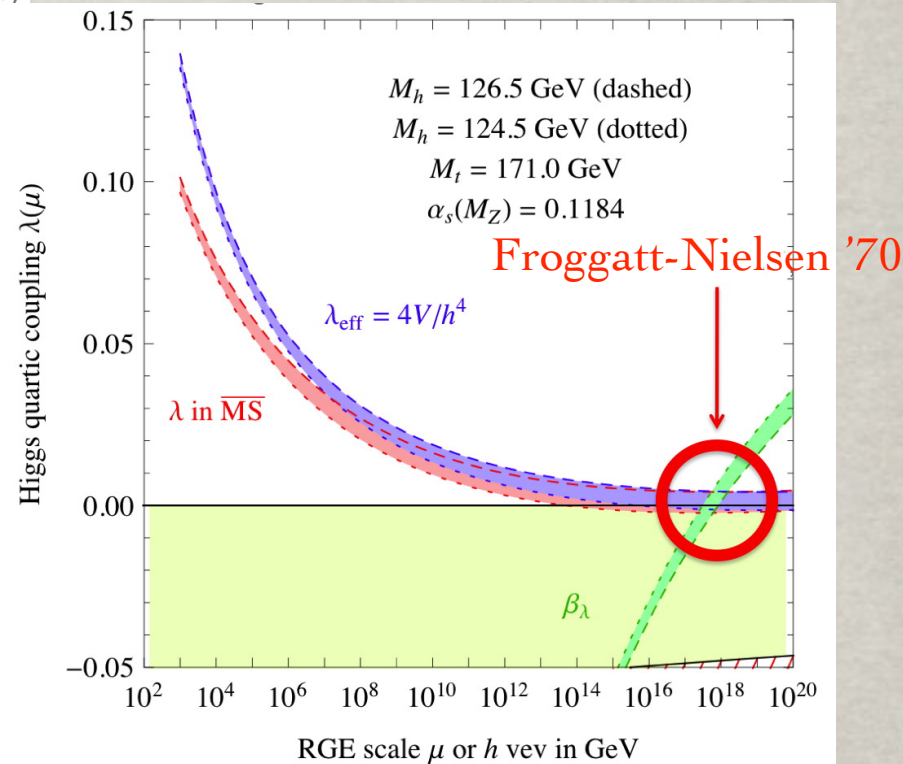
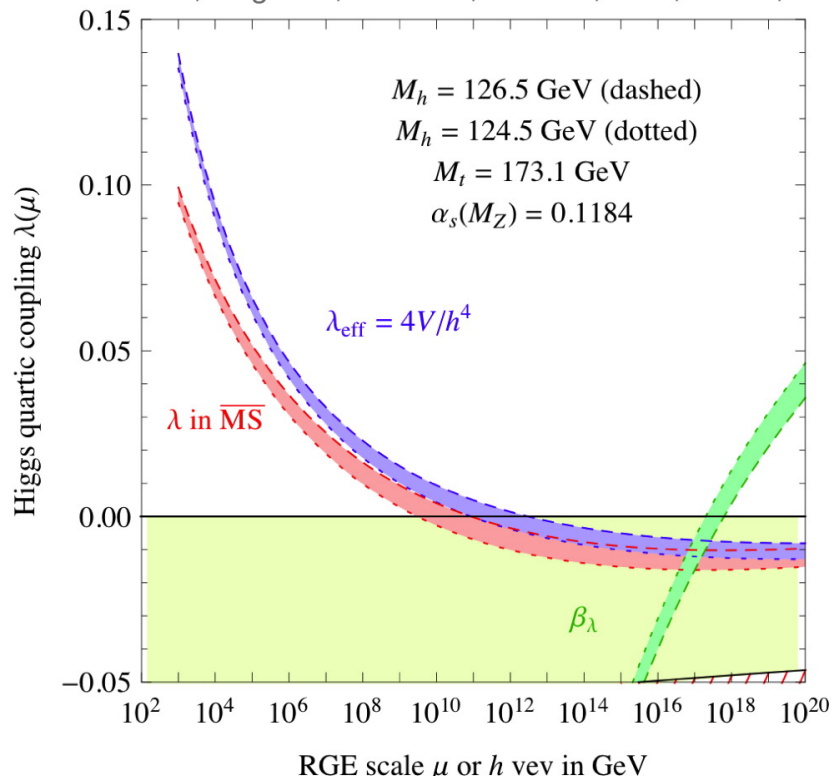
[Buttazzo & al. 14]

Buttazzo, Degrandi, Giardino, Giudice, Sala, Salvio, Strumia (2014)



HIGGS POTENTIAL AT M_{PL} ?

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2014)

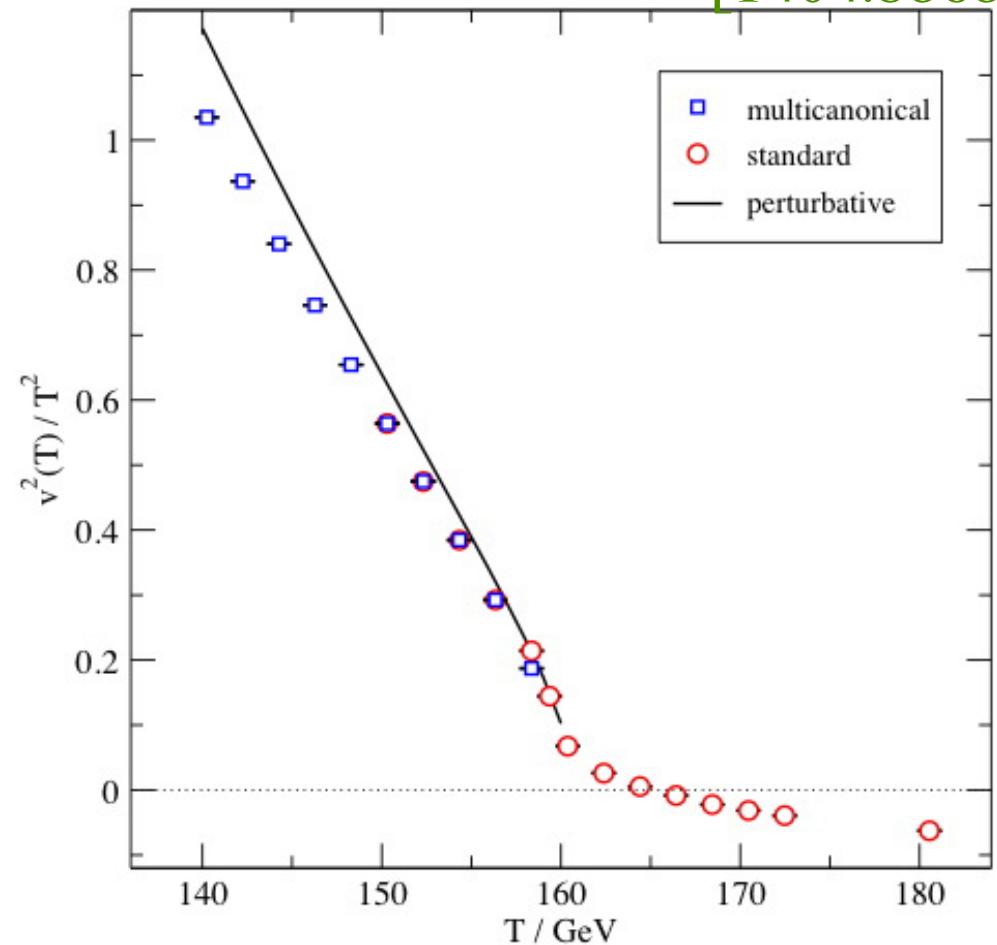
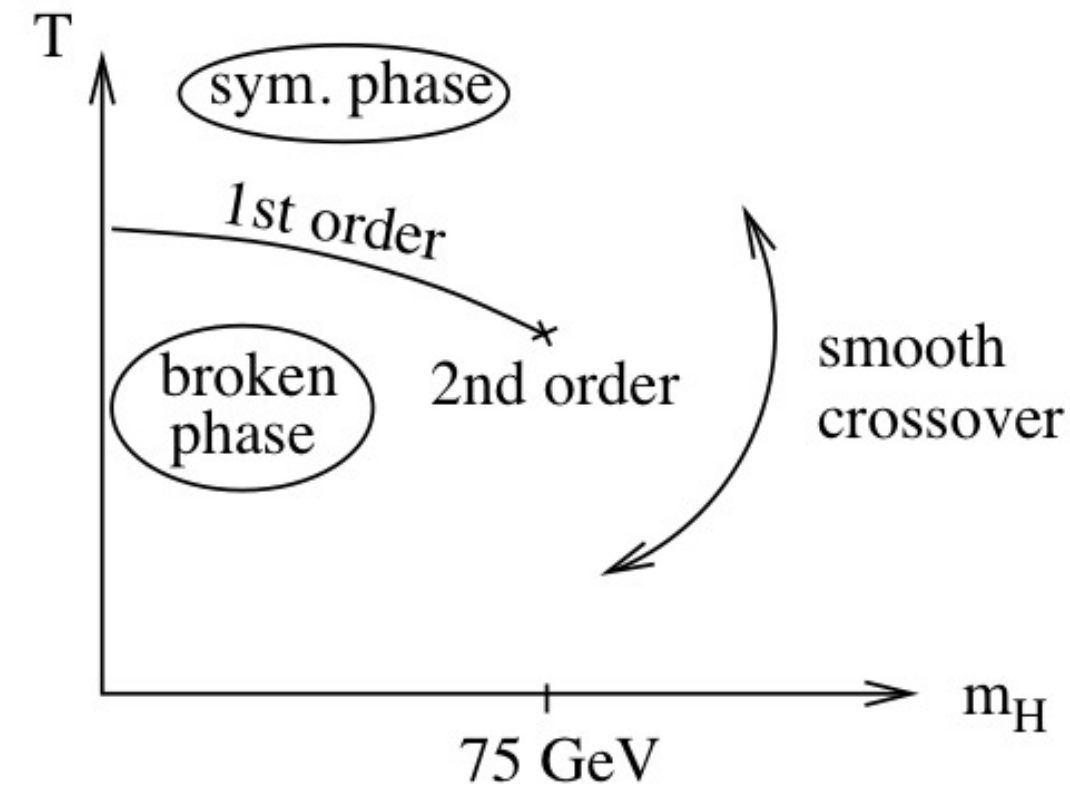


ELECTROWEAK PHASE TRANSITION

EW PHASE TRANSITION IN SM

Compute the phase diagram for the EW phase transition:
for the physical Higgs mass it is a smooth cross-over !

[1404.3565]



NO EW baryogenesis in the SM !

EW BARYOGENESIS IN SUSY

In SUSY extensions of the SM EW baryogenesis is possible if

- The phase transition is stronger: e.g. by enhancing the cubic term in the Higgs potential thanks to (light) scalars, e.g. in SUSY stops or singlets !
- There are additional CP violating phases to increase the amount of CP violation.
- Still the Higgs has to be light... in MSSM EW baryogenesis ~ 120 GeV with one stop state below the top... Is it possible with a 125 GeV Higgs ?

EW PHASE TRANSITION BSM

Again compute the effective potential at finite temperature:

$$V(H, T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$

The cubic term determines mostly the presence of a barrier

Bosonic Loops contribute to $E(T)$, increasing the strength of the phase transition, so in order to make it first order increase the number of bosons in the model !

Many different possibilities, the simplest ones are:

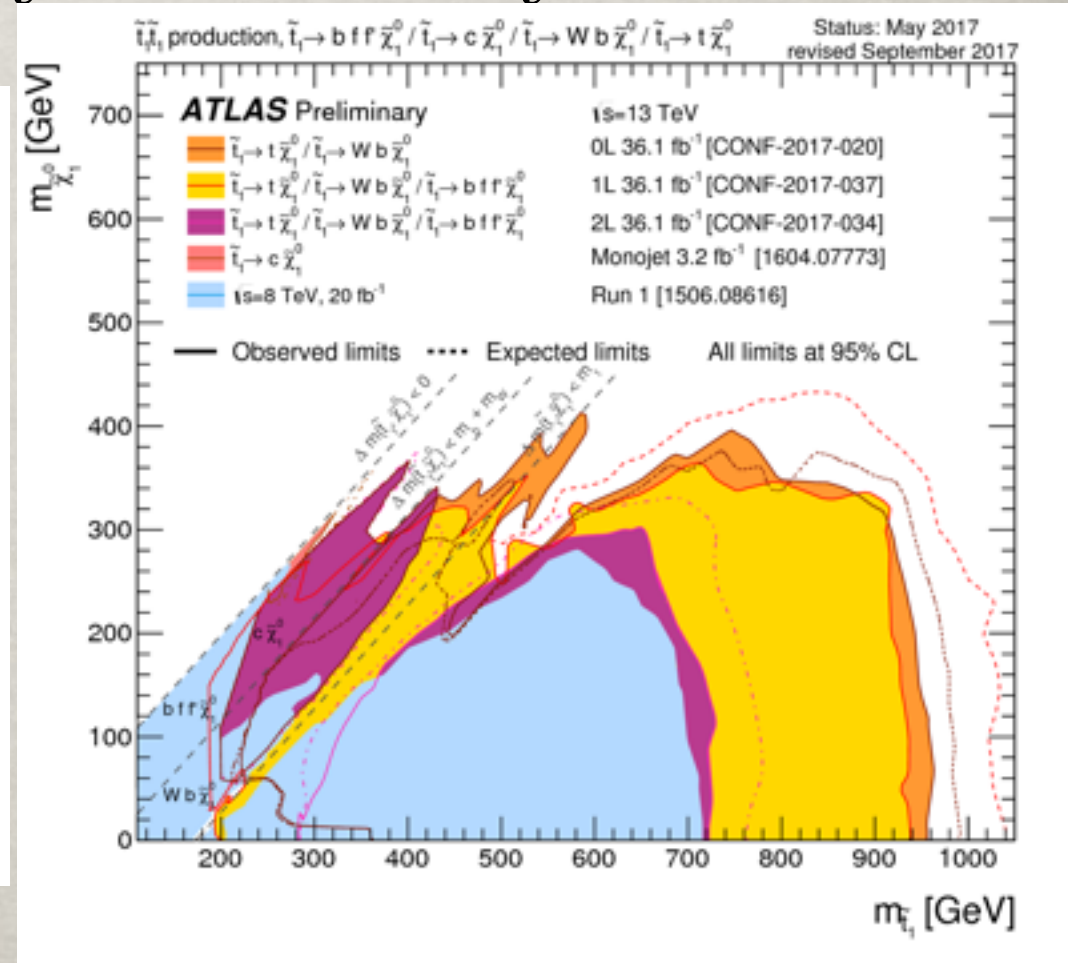
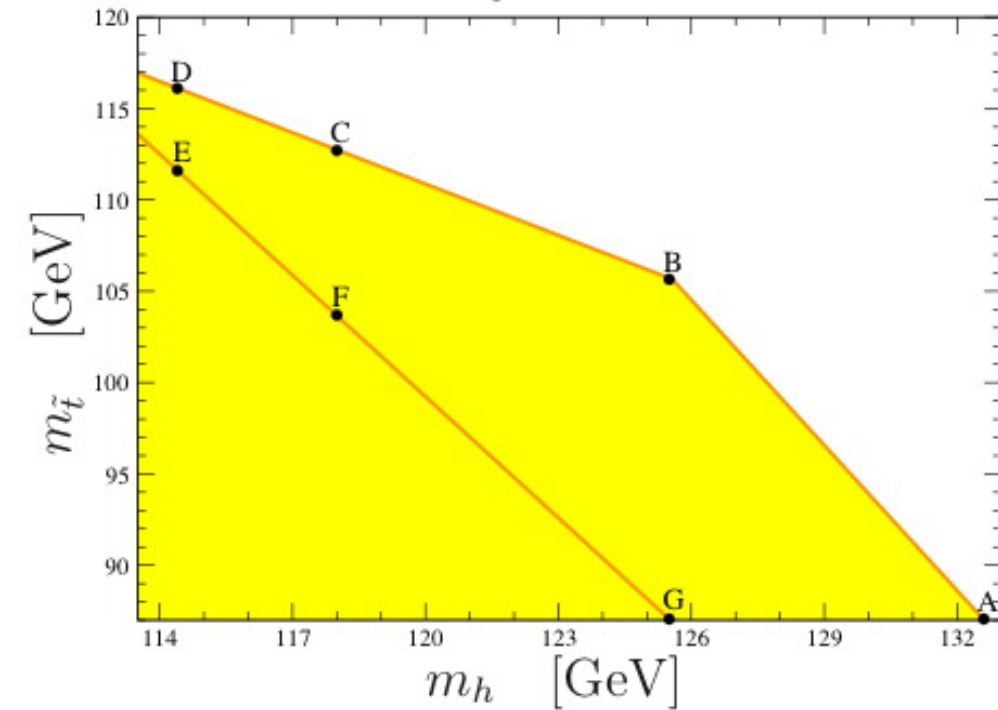
- extend the scalar/Higgs sector of the SM;
- add supersymmetry;
- add higher dimensional operators.

EW BARYOGENESIS IN SUSY

In the MSSM a 125 GeV Higgs is still OK for heavy squarks.
 Still the light stop should be lighter than the top, such mass range is already strongly constrained by LHC...

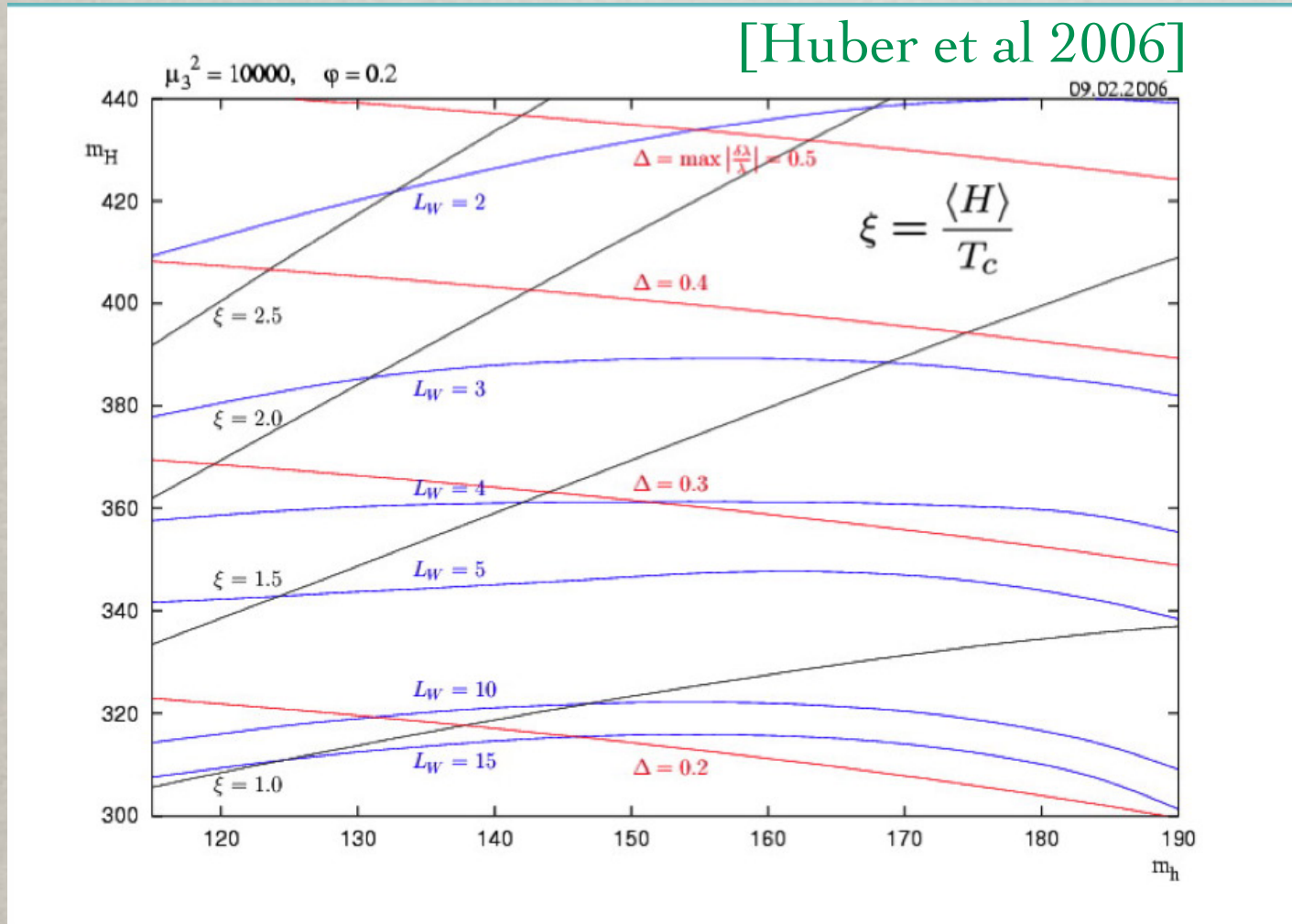
[Carena et al 1207.6330]

$$m_Q \leq 10^6 \text{ TeV}$$



Need possibly to go beyond the simple MSSM !

EW BARYOGENESIS IN 2HDM



More room for generic 2HDM, there a first order phase transition can happen up to heavy higgs mass above 300 GeV.

Need probably large phases that could show up in future EDMs experiments

LOOKING FOR DARK INTERACTIONS

10+BILLION\$ QUESTION: HOW DOES DARK MATTER INTERACT APART GR ?

We detected DM so far only through its gravitational effects, which are universal and do not tell us what DM is !
BUT probably we some other interaction is needed to produce DM since gravity is not very effective.

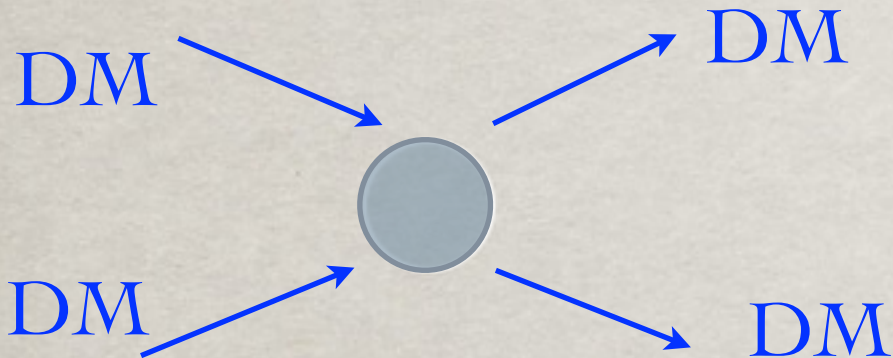
Moreover the standard CDM simulations do not fare so well on the small scales...: **the missing satellites, core vs cusp in dwarves galaxies, too big to fail problems may be a hint that we need to go beyond the CDM/WIMP paradigms !**

[Klypin et al 1999, Moore et al 1999], [Moore 1994, Flores & Primack 1994],
[Bolyan-Kolchin, Bullock & Kaplinghat 2011+2011]

Of course there is also a chance that baryons solve it all...

DM-DM INTERACTION

Self-interaction:



Bullett cluster bound on self-interaction:

$$\sigma \leq 1.7 \times 10^{-24} \text{ cm}^2 \sim 10^9 \text{ pb} \quad (m = 1 \text{ GeV})$$

[Markevitch et al 03]

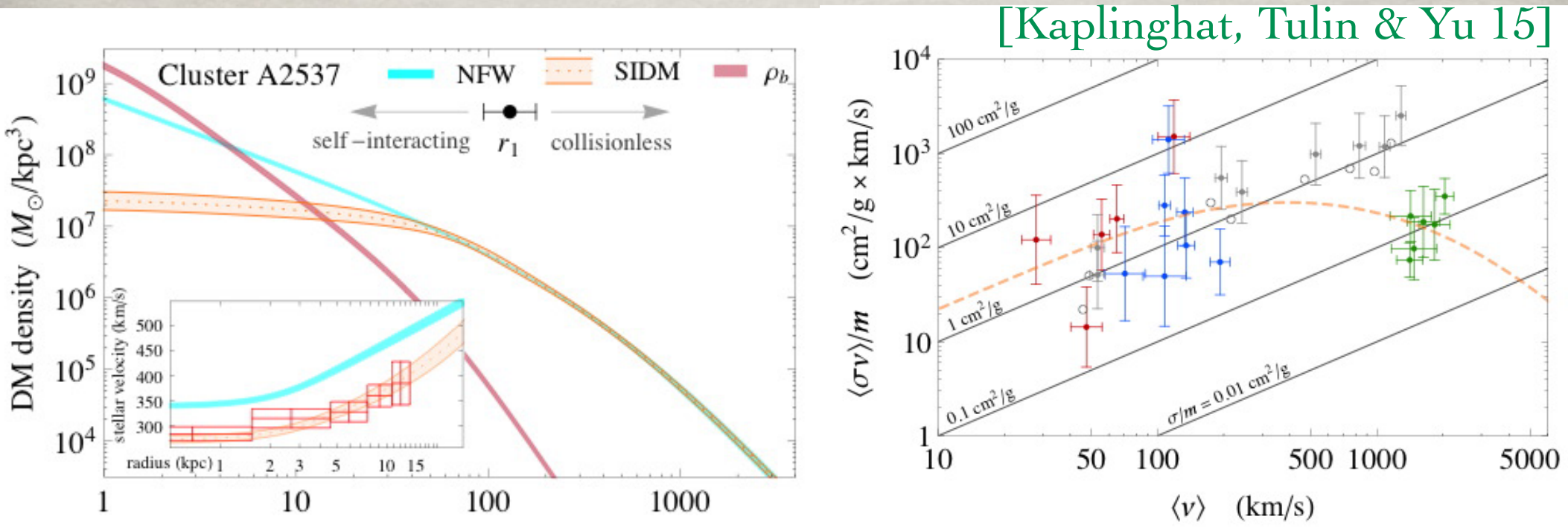
Slightly stronger constraint by requiring a sufficiently large core & from sphericity of halos... [Yoshida, Springer & White 00]

But at the boundary maybe some effect on small scales:

Strongly Interacting Massive Particle [Spergel & Steinhardt 99]

DM-DM INTERACTION

SIMP Dark Matter can relax some of the tensions at small scales and flatten the density in the centre:

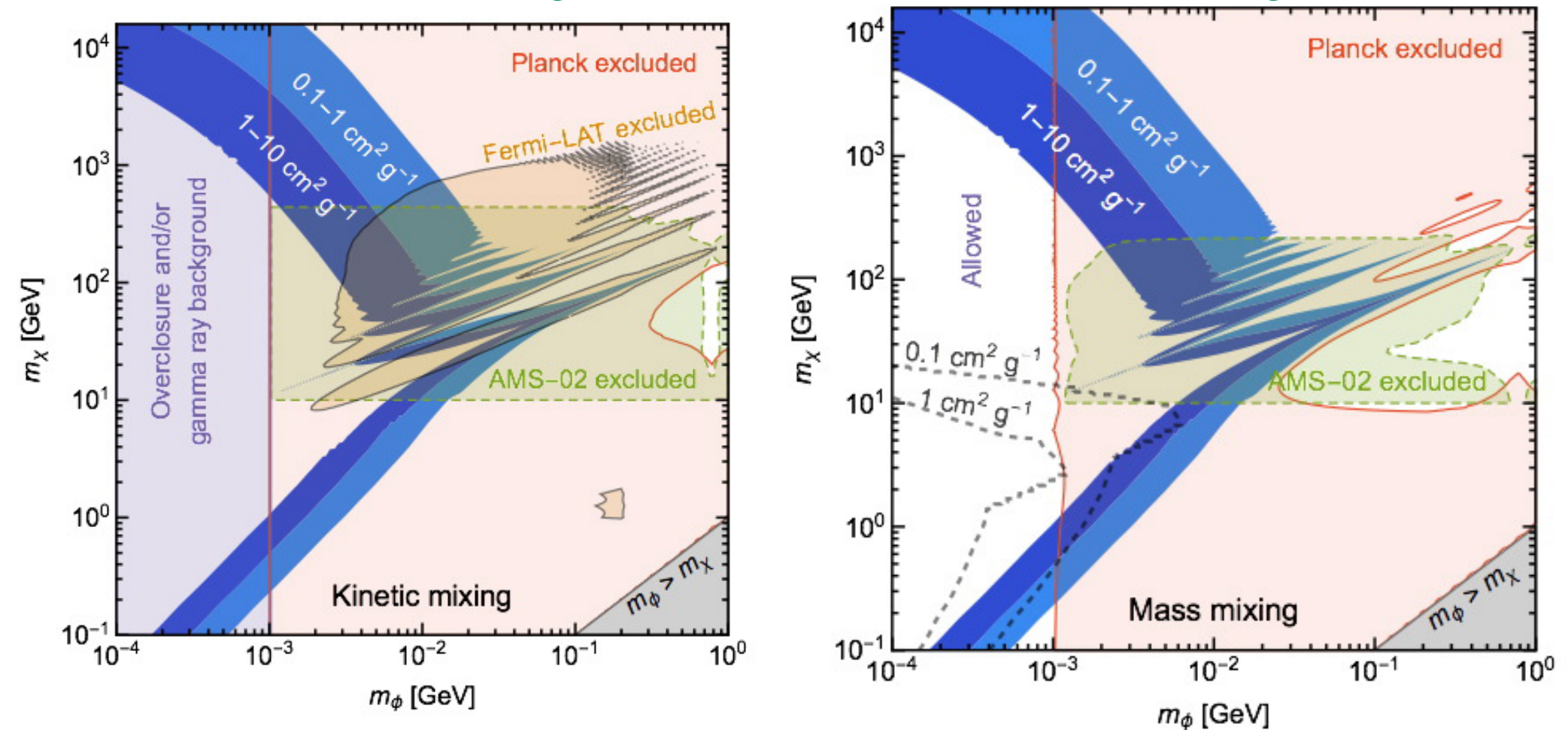


On the other hand it looks that larger cross-sections are needed at **dwarves galaxies/low surface brightness galaxies** compared to **cluster scales...**

DM-DM INTERACTION

New constraints for light mediator from ID and CMB:

[Bringmann, Kahlhoefer, Schmidt-Hoberg and Walia 16]

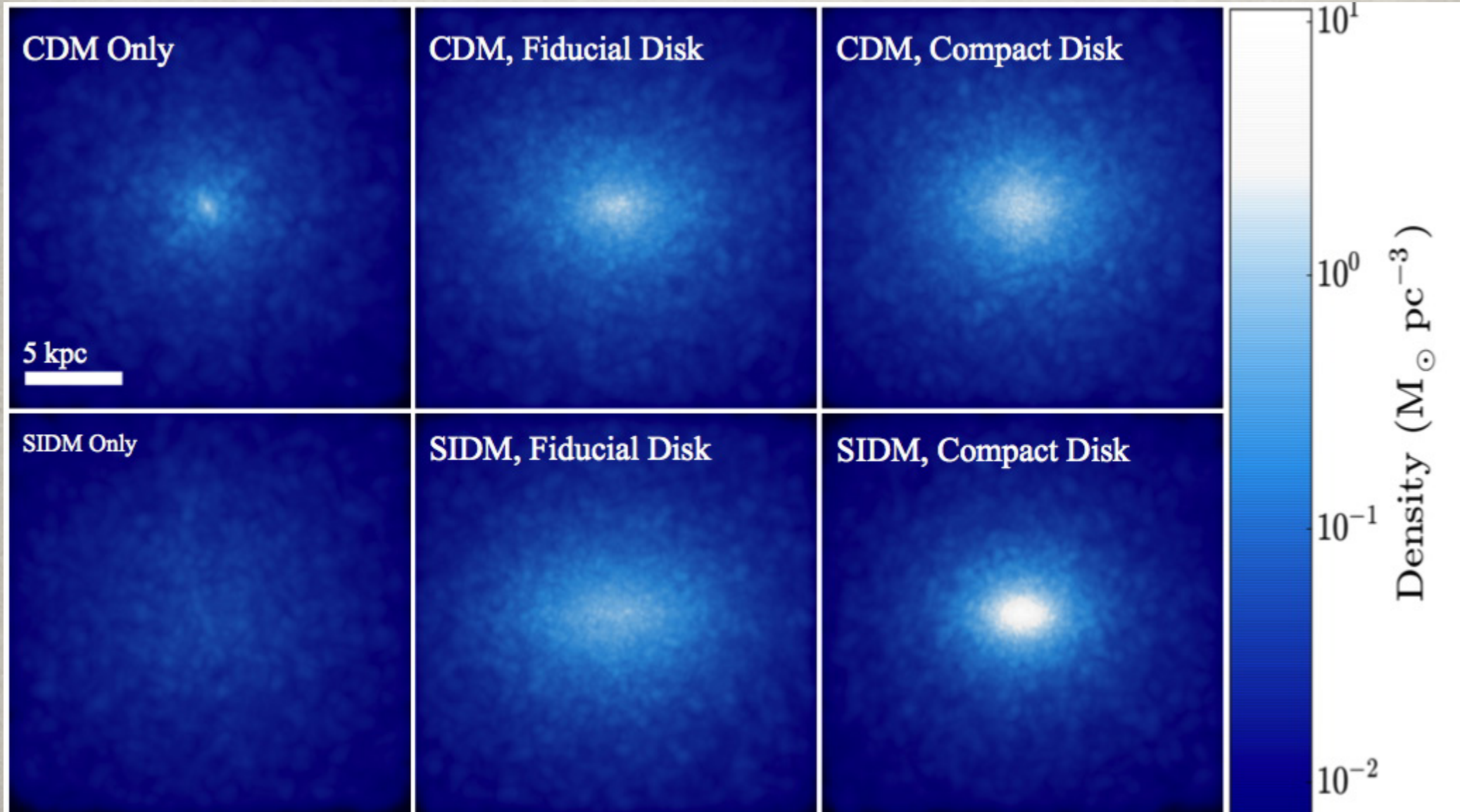


S-wave annihilation into Vector with Sommerfeld effect,
weaker bounds on p-wave annihilation

DM-DM INTERACTION

First simulations with SIMP and baryons:

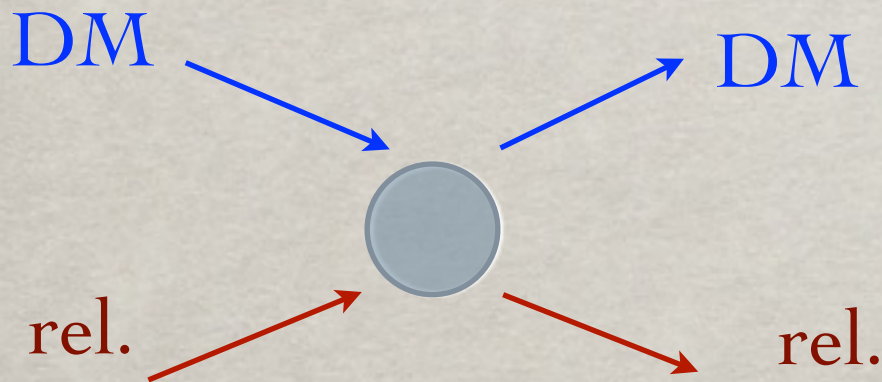
[Elbert et al.16]



INTERACTING DARK MATTER

Apart for chemical decoupling of DM, also the kinetic decoupling is important as it sets the cut-off in the power spectrum at small scales. ANY interaction of the DM, even with a hidden (relativistic) Dark Sector can influence the DM kinetic decoupling and structure formation at small scales.

[Hofmann, Schwarz & Stecker 2001, Green, Hofmann & Schwarz 2005, Bringmann & Hofmann 2007, ...]



Probes ANY interaction with a relativistic species !

A lot of activity for different interactions/mediators !
Not clear if it can always resolve the small scale crises,
though

INTERACTING DARK MATTER

[J.Kasahara PhD Thesis 2009, Binder et al. 1602.07624]

In the non-relativistic limit for DM, one can expand these expression for small (but not vanishing !) momentum transfer:

$$C[f_1] = m_1 \frac{\partial}{\partial \mathbf{p}_{1i}} \left[\gamma \left(m_1 T \frac{\partial f_1}{\partial \mathbf{p}_{1i}} + (\mathbf{p}_{1i} - m_1 \mathbf{u}_i) f_1 \right) \right]$$

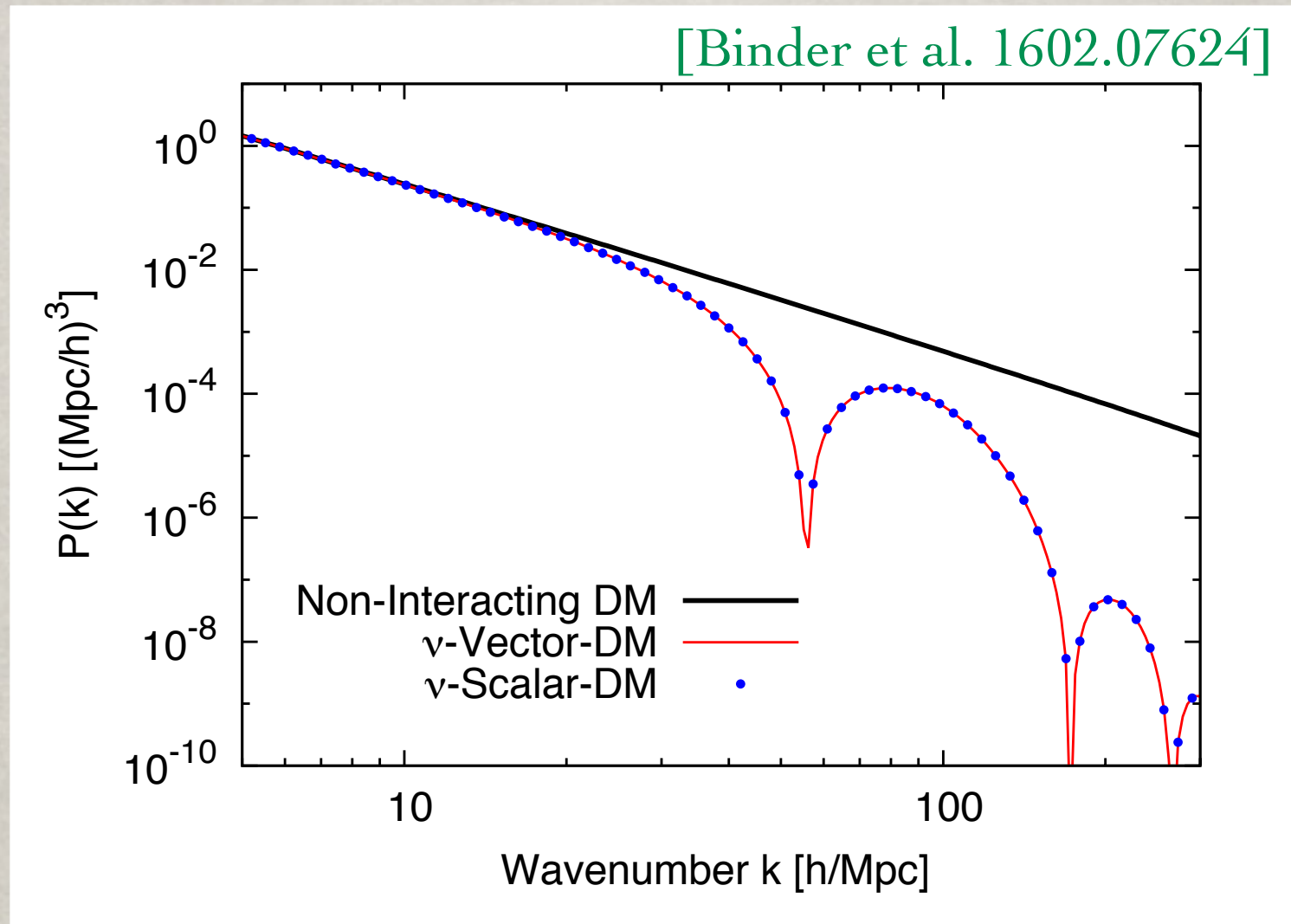
where we defined

$$\gamma = \frac{1}{6m_1 T} \sum_{s_2} \int \frac{d^3 \mathbf{p}_2}{(2\pi)^3} f_2^{\text{eq}} (1 \mp f_2^{\text{eq}}) \int_{-4\mathbf{p}_2^2}^0 dt (-t) \frac{d\sigma}{dt} v$$

t-averaged cross-section

Fokker-Planck equation for the DM momentum distribution function, which can be recast into the Boltzmann hierarchy for density, bulk velocity, pressure and anisotropic stress,...

INTERACTING DARK MATTER



$$M^{\text{cut}} = 10^9 M_{\odot} \left(\frac{N_{\nu} \alpha_{\nu} \alpha_{\chi}}{2 \times 10^{-4}} \right) \left(\frac{m_{\chi}}{1 \text{ TeV}} \right)^{-3/4} \left(\frac{m_{\phi}}{1 \text{ MeV}} \right)^{-3}$$

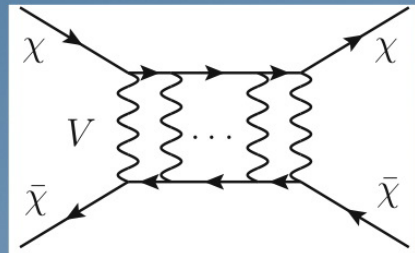
Similar results from ETHOS group

[Bringmann et al. 1603.04884]

ETHOS PROJECT

[Bringmann et al., 1512.05344, 1512.05349, 1603.04884]

From theory to observations



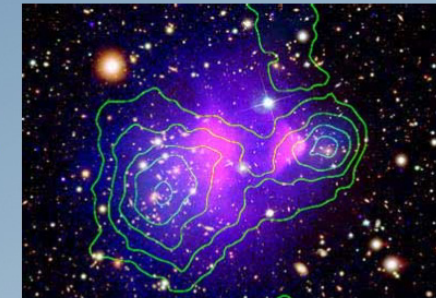
particle model

input:
masses, spins,
coupling constants



cosmological
simulations

input:
consistent initial
conditions, non-
gravitational forces
between “particles”



astrophysical
observables

input
(for interpretation of data):
**output from
simulations**

- The first step can be **demanding**, the second in addition computationally very expensive
- But expect large degeneracies, so **very inefficient**...
- **Idea of ETHOS**: introduce **effective parameters** and provide **maps** for each of those steps (\rightsquigarrow no need to re-compute each model!)



OUTLOOK

OUTLOOK

- Collider particle physics and cosmology are strongly complementary and provide informations about different sectors of the BSM model.
- Heavy SUSY has some cosmological advantages and maybe this is a reason for NOT seeing it at LHC...
- Still in some cases the solutions to cosmological problems, e.g. inflationary or DM/baryogenesis model do give very distinct signature also at colliders.
- Cosmological and colliders bound are very important to pin down models with very weakly interacting particles in hidden sectors.