"Tell me that you have found no sign of
New Physics again, I dare you.
I double dare you. Tell me
one more goddamn time!"

Where to find SUSY?!

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Madrid, 06/2017

1. Introduction & Models
2. Results in GUT based models
3. Results in low-energy models
4. Conclusions

1. Introduction & Models

Some "recent" measurements:

- top quark mass
- Higgs boson mass
- Higgs boson "couplings"
- Dark Matter (properties)

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Simple SUSY models predicted correctly:

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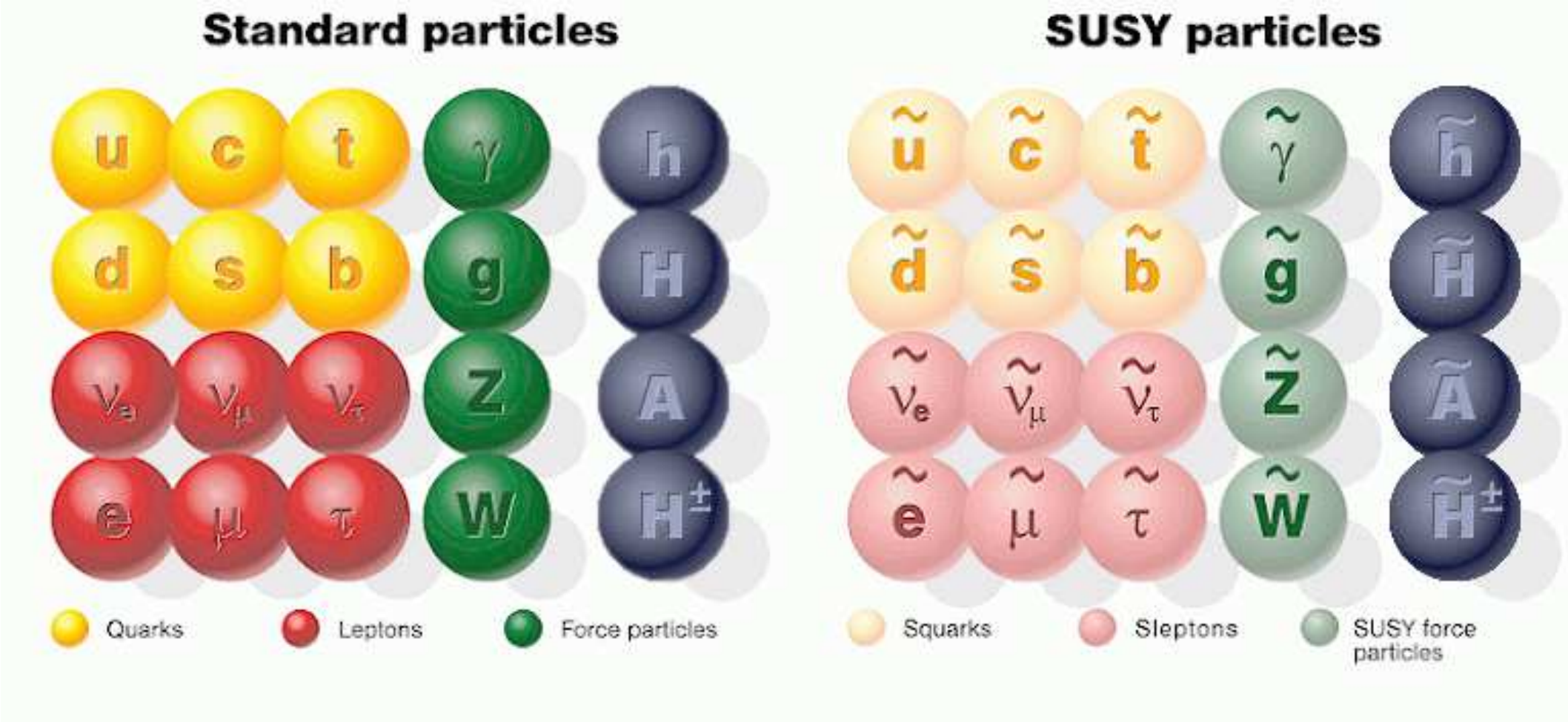
$\Rightarrow$ good motivation to look at SUSY!

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved

no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

most general case:

$\Rightarrow$ 105 new parameters: masses, mixing angles, phases

$\Rightarrow$ no model missed (within the MSSM)

$\Rightarrow \mathcal{O}(100)$ parameters difficult to handle

B. Constrained models:

CMSSM, NUHM1, NUHM2, SU(5), mAMSB, . . . :

assumption on the scenario that achieves spontaneous SUSY breaking

$\Rightarrow$ prediction for soft SUSY-breaking terms
in terms of small set of parameters

$\Rightarrow$ easy to handle

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

} at the GUT scale

$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

$\Rightarrow$ particle spectra from renormalization group running to weak scale

$\Rightarrow$ Lightest SUSY particle (LSP) is the lightest neutralino $\Rightarrow$ DM!

GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A as free parameters at the EW scale

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu \text{ and } M_A$$

GUT based models: 3.) NUHM2: (Non-universal Higgs mass model 2)

Assumption: no unification of scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A and μ as free parameters at the EW scale

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu \text{ and } M_A$$

GUT based models: 4.) SU(5) GUT:

Assumption I:

no unification of scalar Higgs parameter at the GUT scale

($\Rightarrow$ effectively M_A and μ as free parameters at the EW scale)

Assumption II:

$$(q_L, u_L^c, e_L^c)_i \in \mathbf{10}_i, \quad (\ell_L, d_L^c)_i \in \bar{\mathbf{5}}_i$$

$\Rightarrow$ Scenario characterized by

$$m_5,\ m_{10},\ m_{1/2},\ A_0,\ \tan\beta,\ m_{H_u},\ m_{H_d}$$

GUT based models: 5.) mAMSB:

mAMSB scenario characterized by

$$m_{3/2}, m_0, \tan\beta, \text{sign}(\mu)$$

$m_{3/2} = \langle F \rangle / M_{\text{Planck}}$: overall scale of SUSY particle masses

m_0: phenomenological parameter: universal scalar mass term introduced in order to keep squares of slepton masses positive

typical feature: very small neutralino–chargino mass difference
$\Rightarrow \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 + \pi^{\pm}$ with very soft pions

Problem: We cannot be sure about the SUSY-breaking mechanism

$\Rightarrow$ it is possible that with the CMSSM, NUHM1, NUHM2, SU(5), mAMSB we missed the "correct" mechanism

$\Rightarrow$ hint: strong connection between colored and uncolored sector
tension between low-energy EW effects and (colored) LHC searches

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tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the "general MSSM"

$\Rightarrow$ 10 parameters are manageable $\Rightarrow$ pMSSM10

- squark mass parameters: $m_{\tilde{q}_{1,2}} =: m_{\tilde{q}}$, $m_{\tilde{q}_3}$
- slepton mass parameter: $m_{\tilde{l}}$
- gaugino masses: M_1, M_2, M_3
- trilinear coupling: A
- Higgs sector parameters: M_A, $\tan\beta$
- Higgs mixing paramter: μ

Our tool: **Mastercode**

⇒ collaborative effort of theorists and experimentalists

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[*Bagnaschi, Borsato, Buchmüller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Liu, Lucio, Martinez Santos, Olive, Richards, Sakurai, Weiglein*]

Über-code for the combination of different tools:

– Über-code original in Fortran, now re-written in C++

– tools are included as subroutines

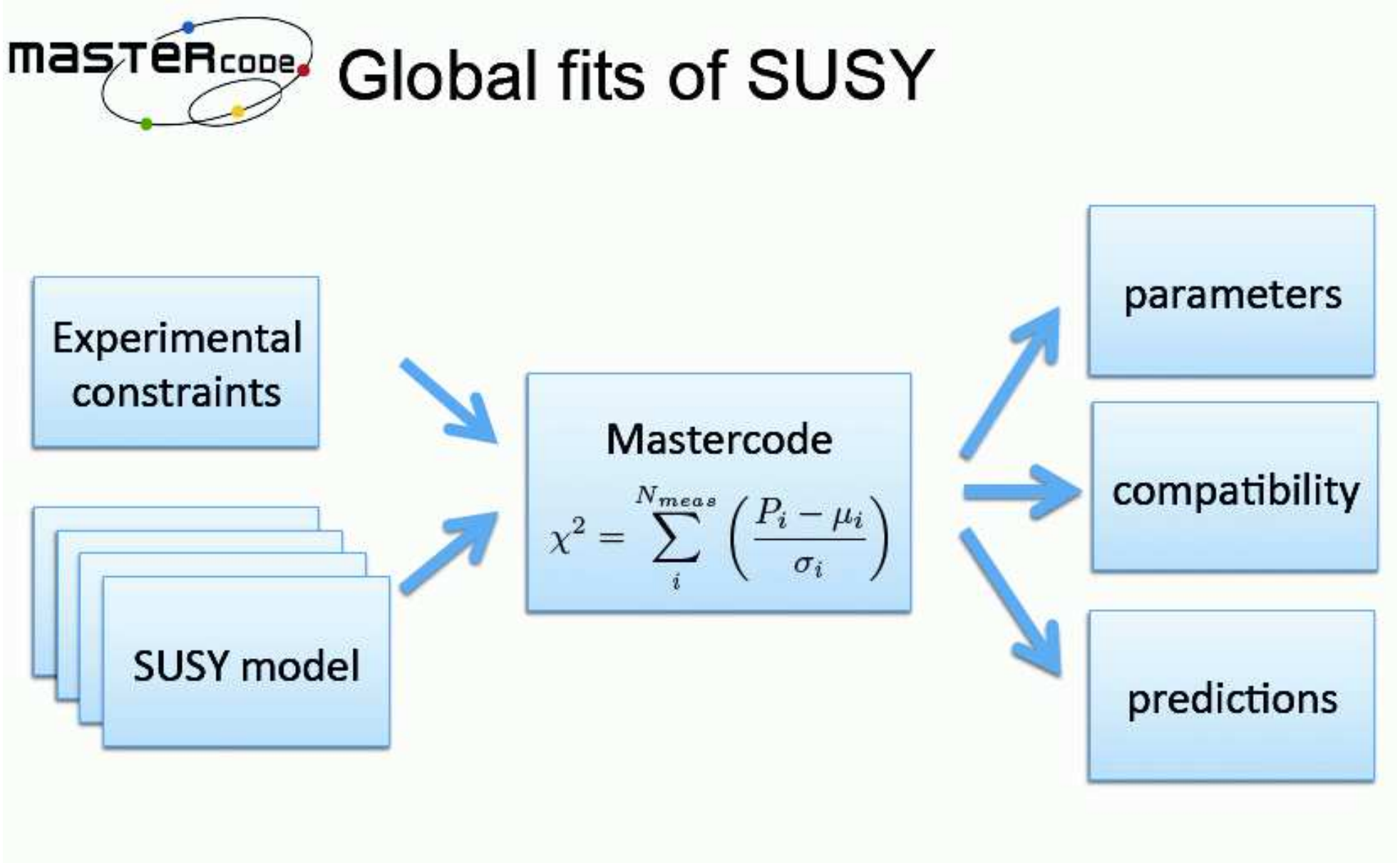
– compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)

– sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

The χ^2 evaluation:



Data we have:

– Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs

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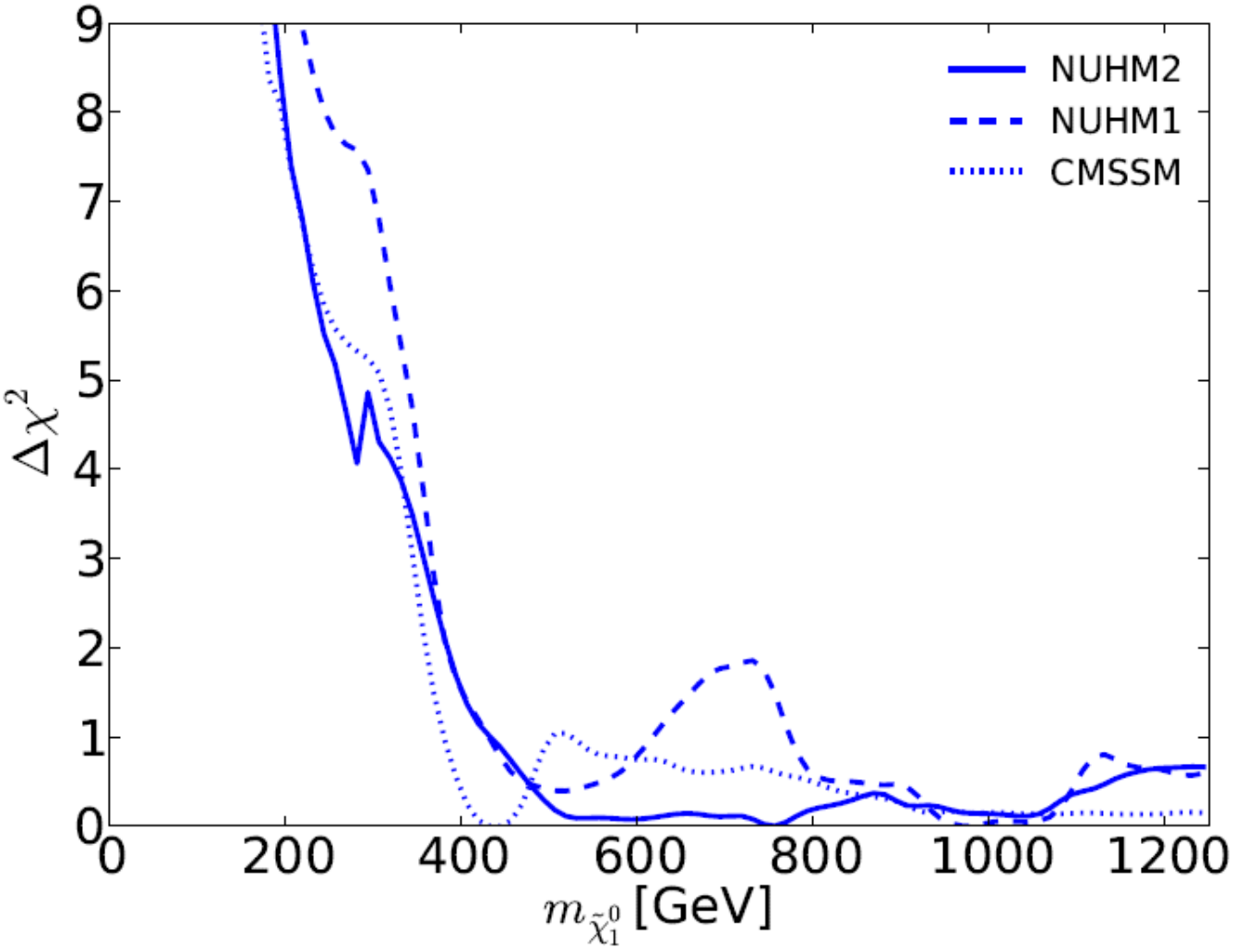
- electroweak precision data $\Rightarrow$ FeynWZ, FeynHiggs
- flavor data $\Rightarrow$ SuperIso, SuFla
- astrophysical data (DM properties) $\Rightarrow$ MicrOMEGAs, SSARD

2. Results GUT based models

[2014]

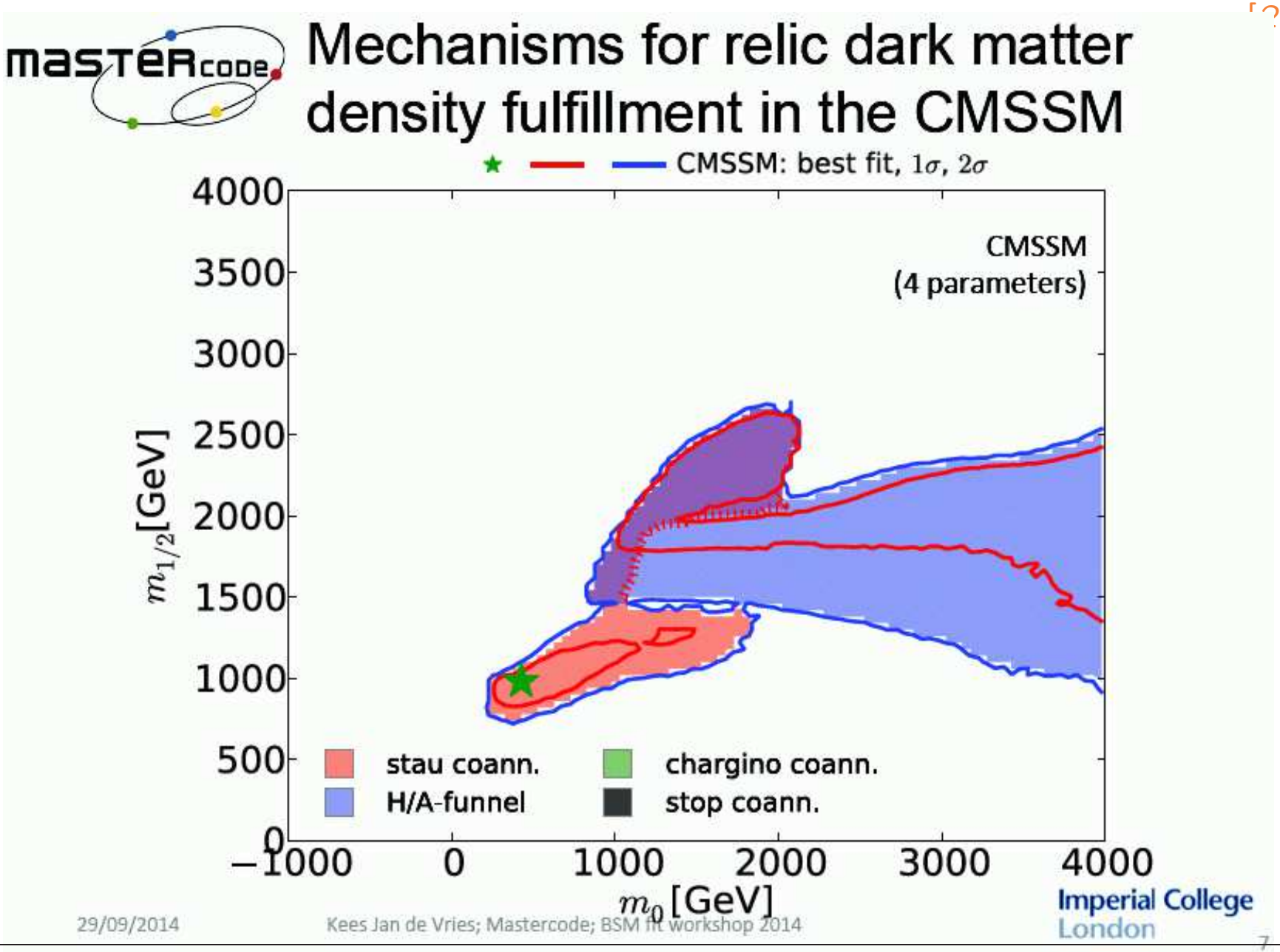
Results in the CMSSM, NUHM1, NUHM2



⇒ only very large values are favored

CMSSM DM prediction

[?2014]



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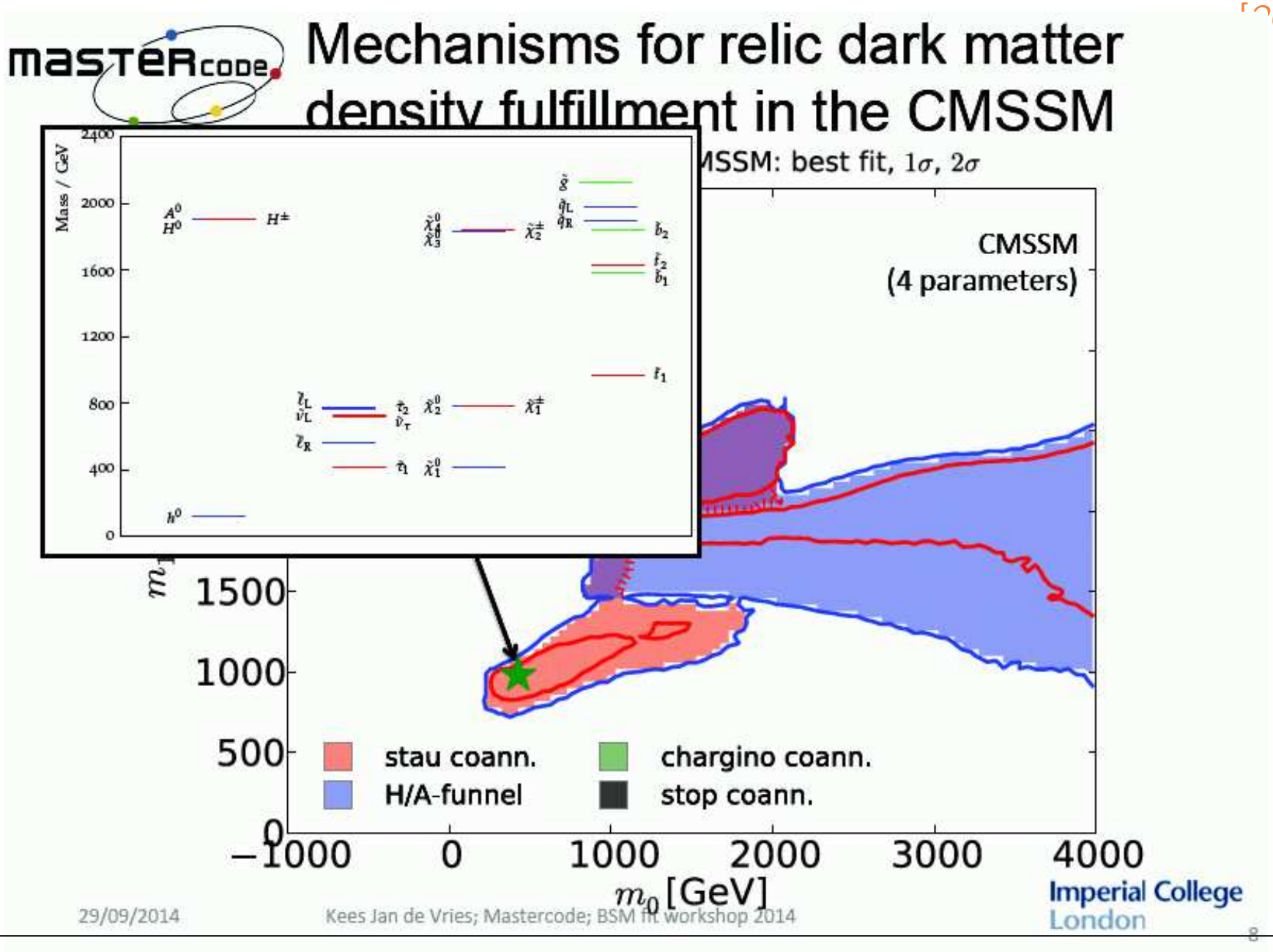
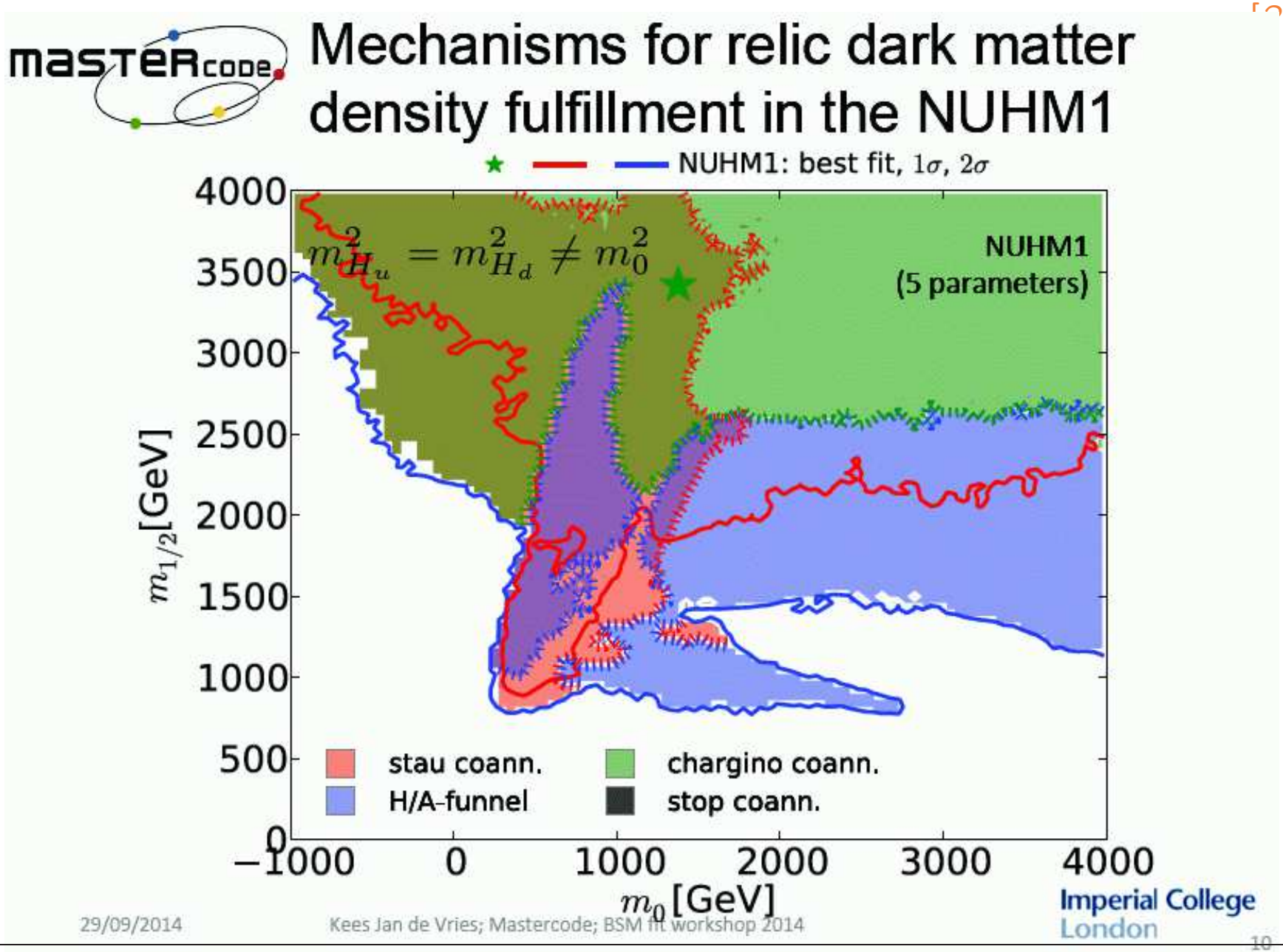


NUHM1 DM prediction

[2014]



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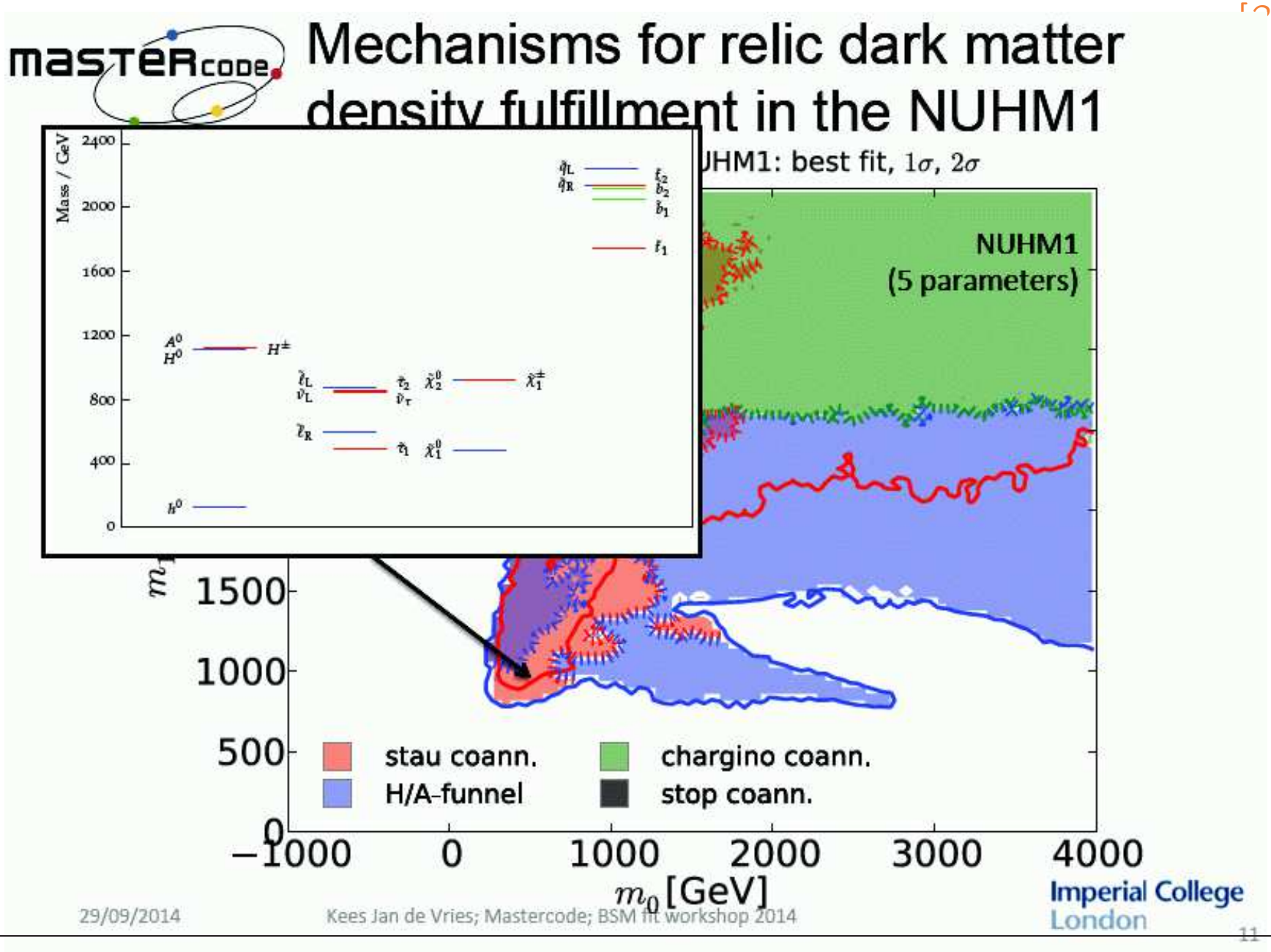
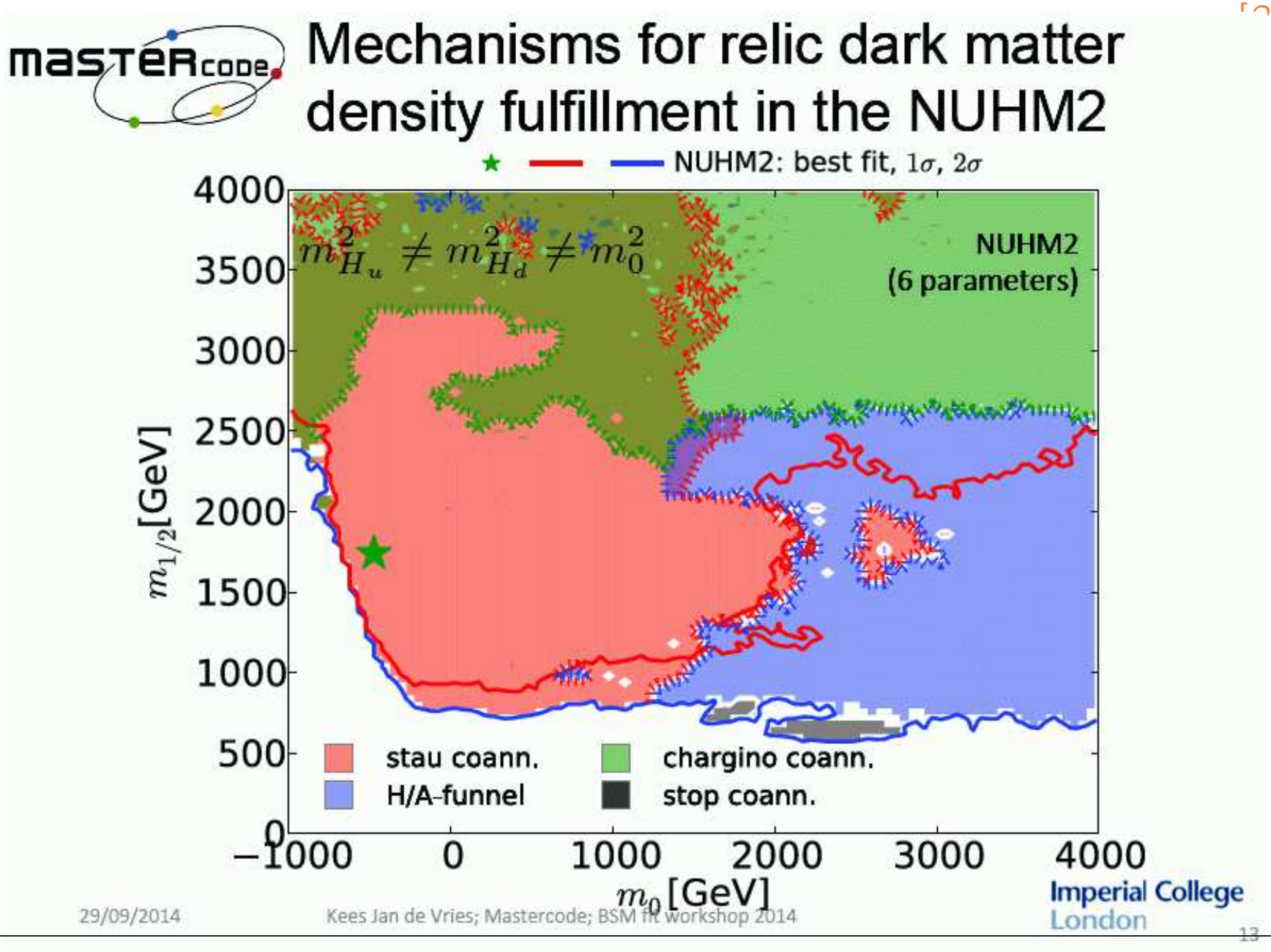


NUHM2 DM prediction

[2014]



NUHM2 DM prediction

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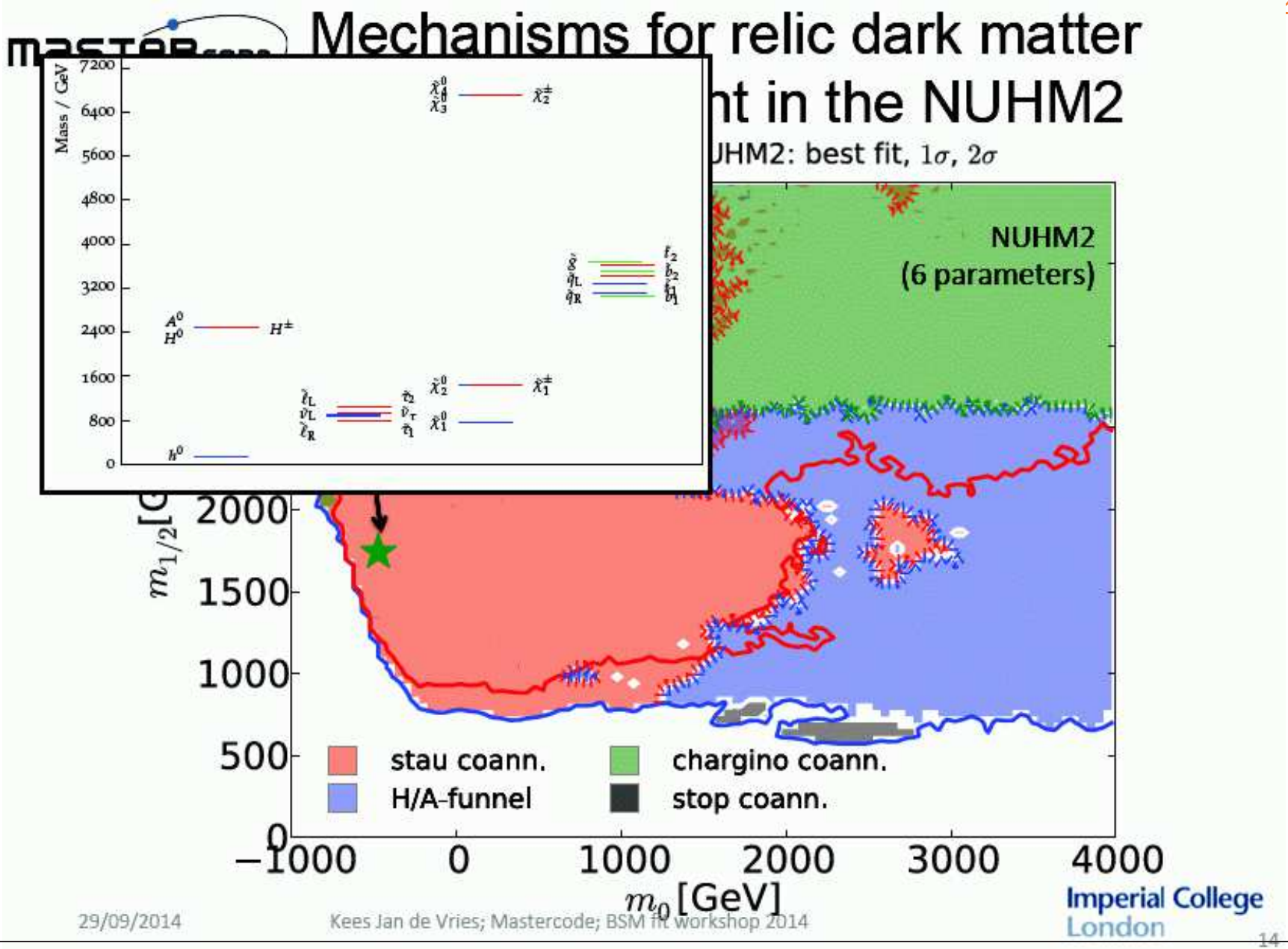
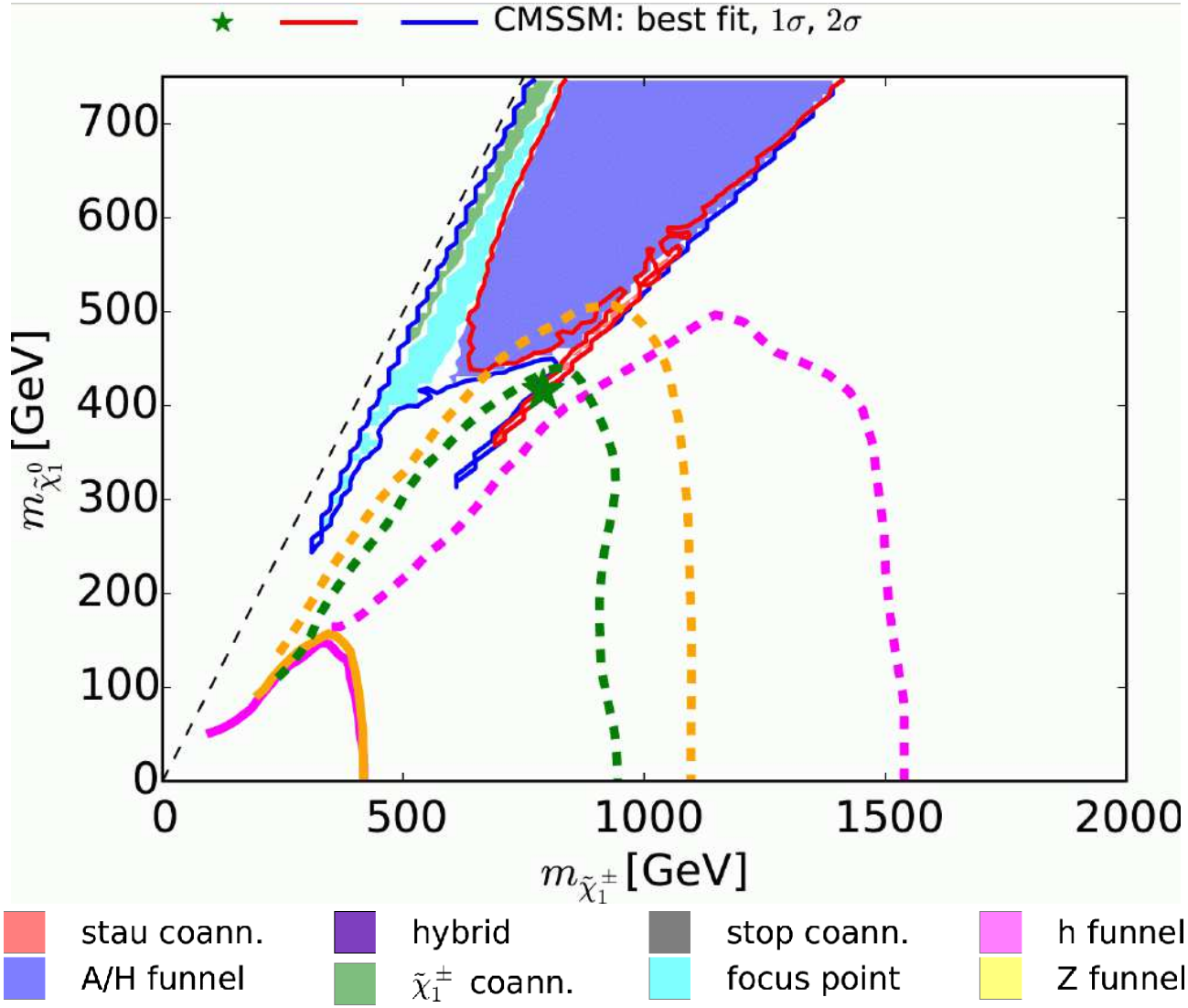


LHC prospects for CMSSM:

[2015]



solid: current LHC limits, dashed: HL-LHC prospects

$\Rightarrow$ best-fit regions can be covered! (in EW searches)

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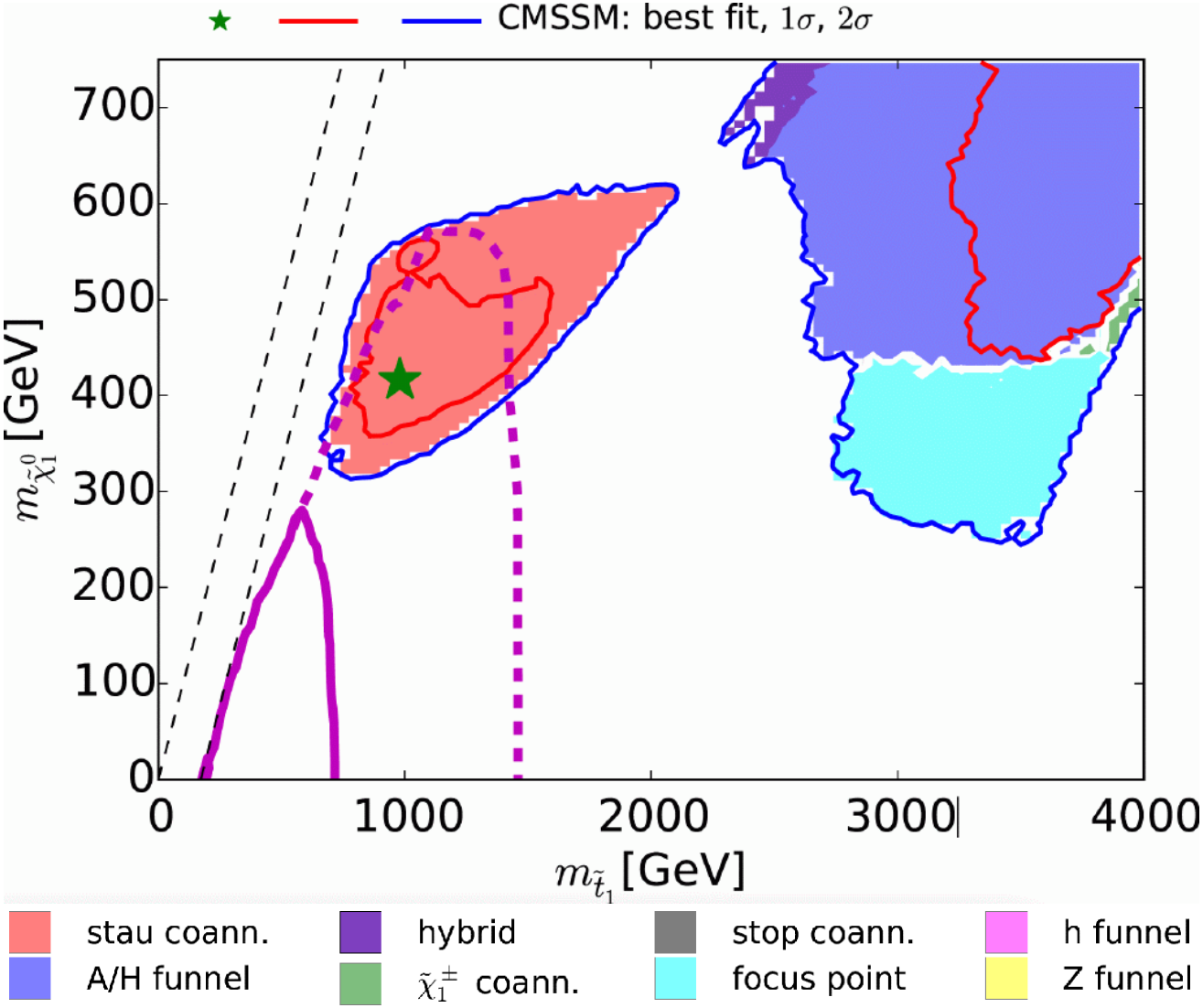
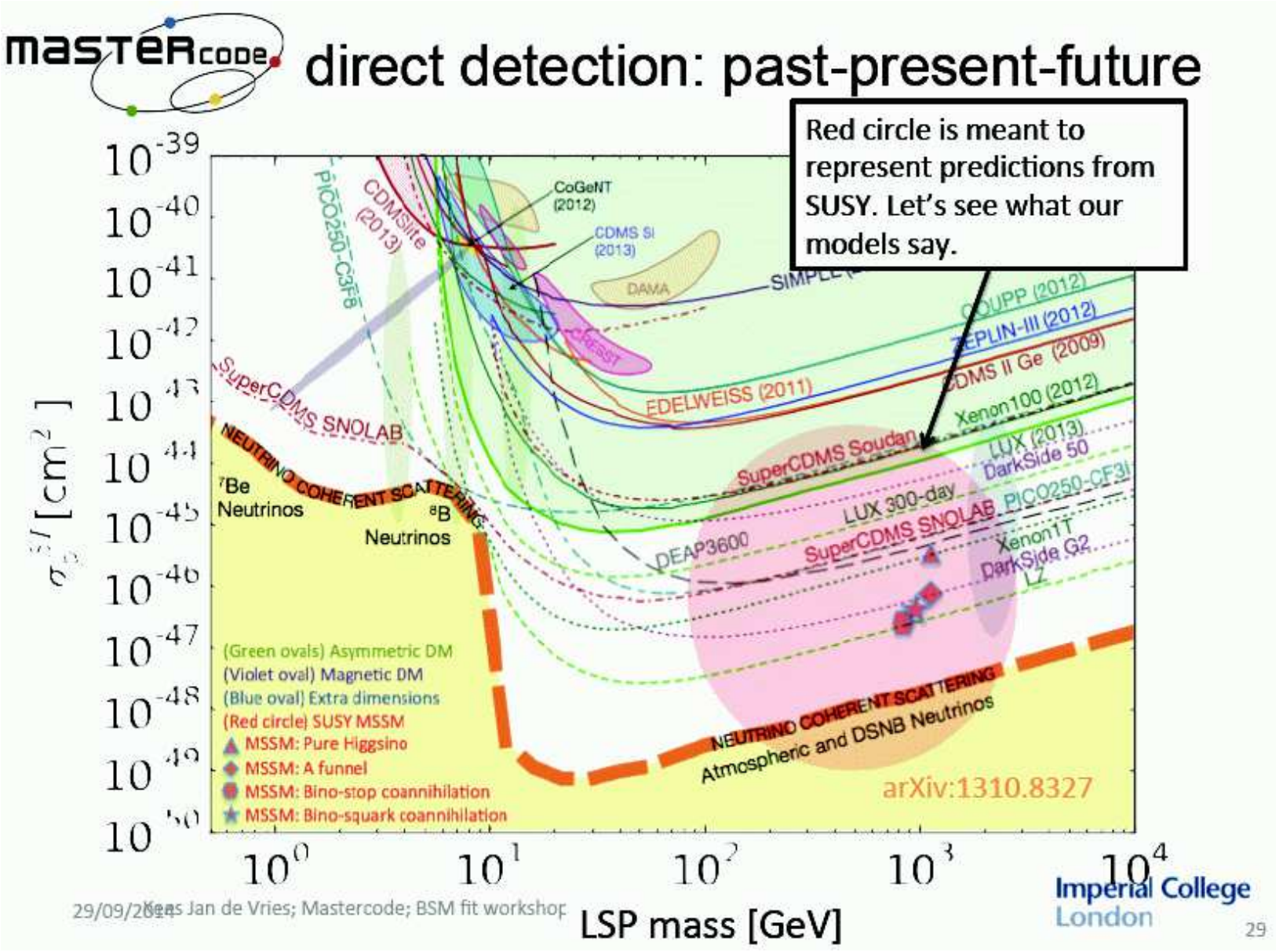


solid: current LHC limits, dashed: HL-LHC prospects

$\Rightarrow$ best-fit regions can partially be covered! (in colored searches)

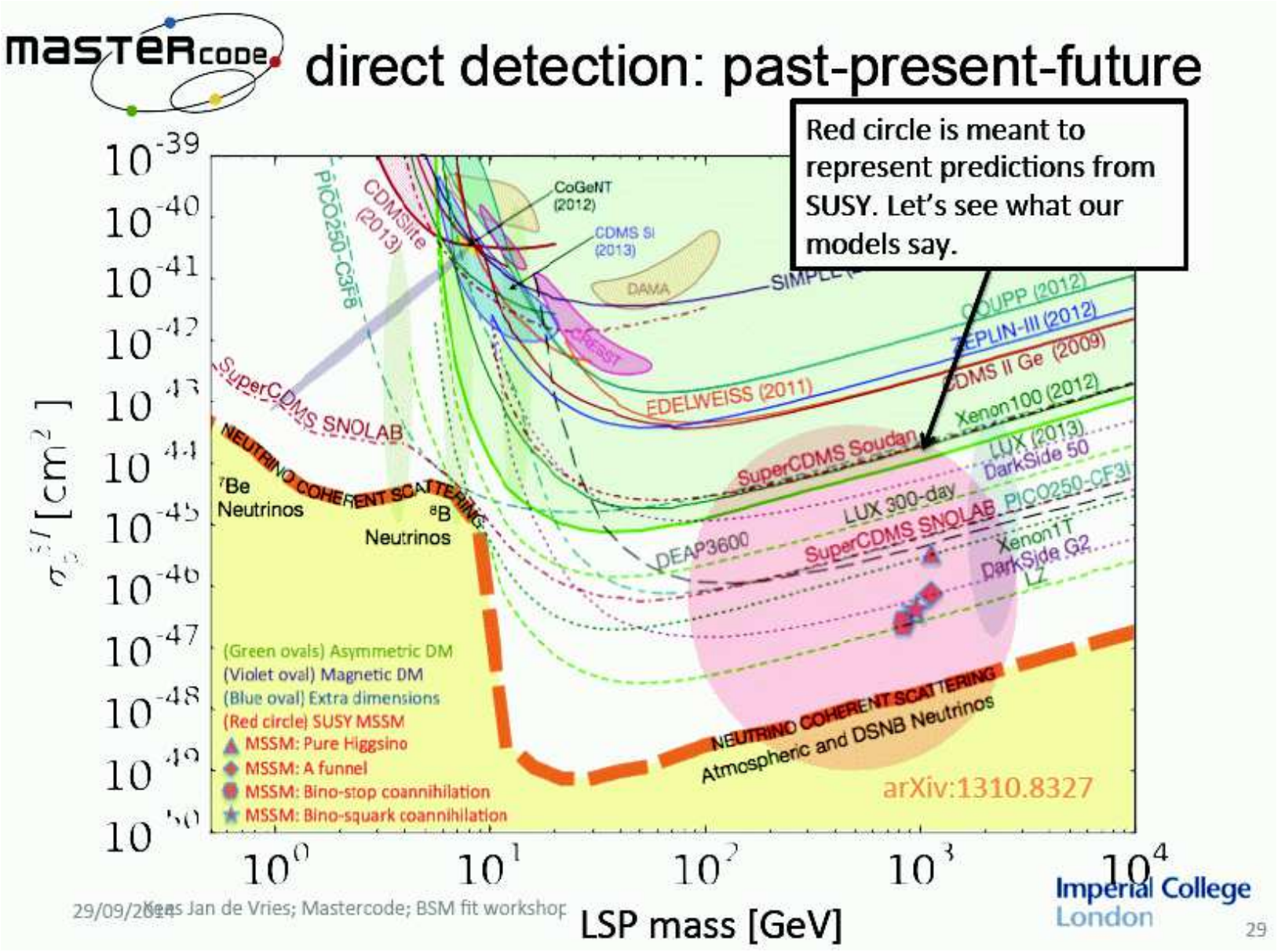
MSSM DM prediction

[2014-2016]



MSSM DM prediction ⇒ no time ⇒ back-up

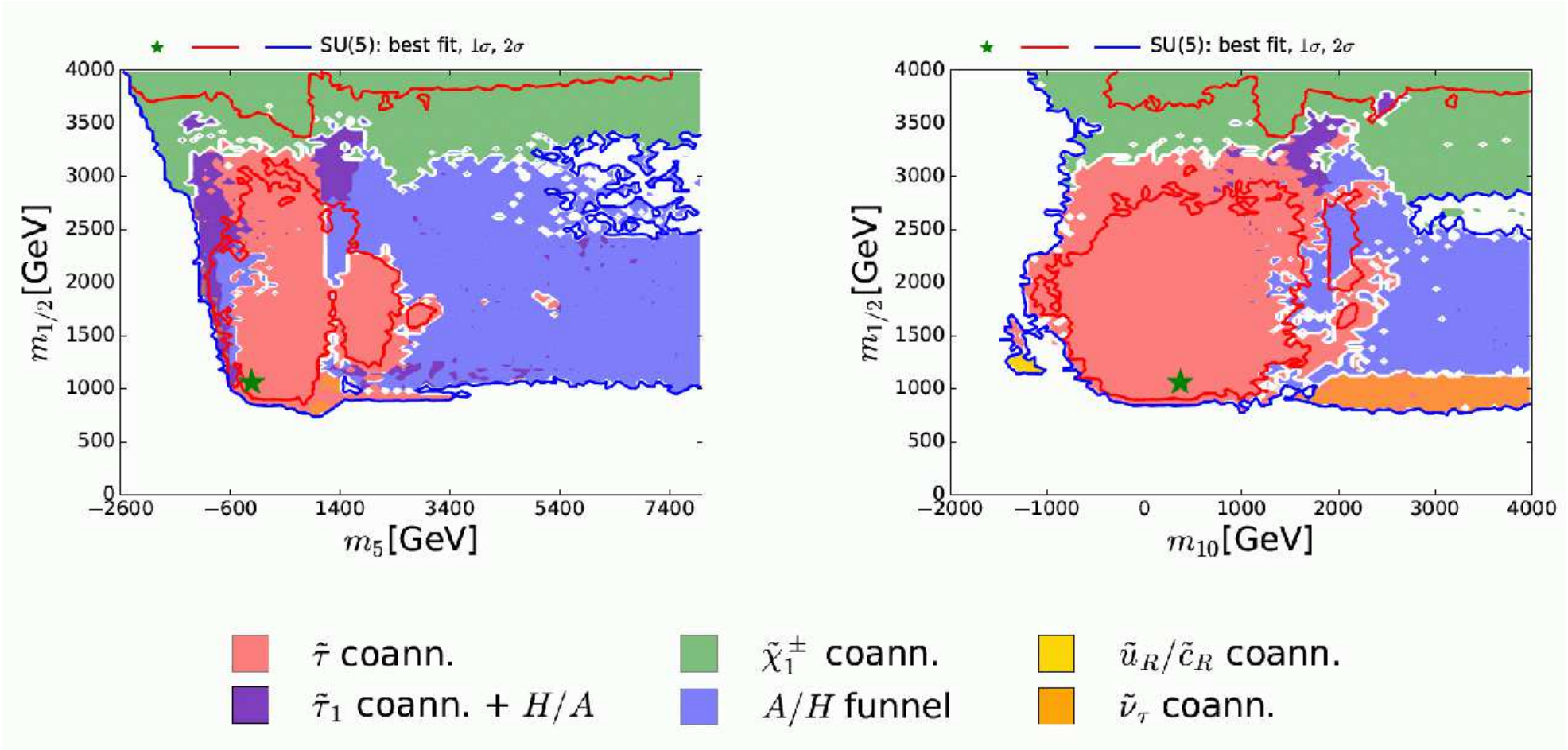
[2014-2016]



Results in the SU(5)

Dark Matter annihilation mechanism:

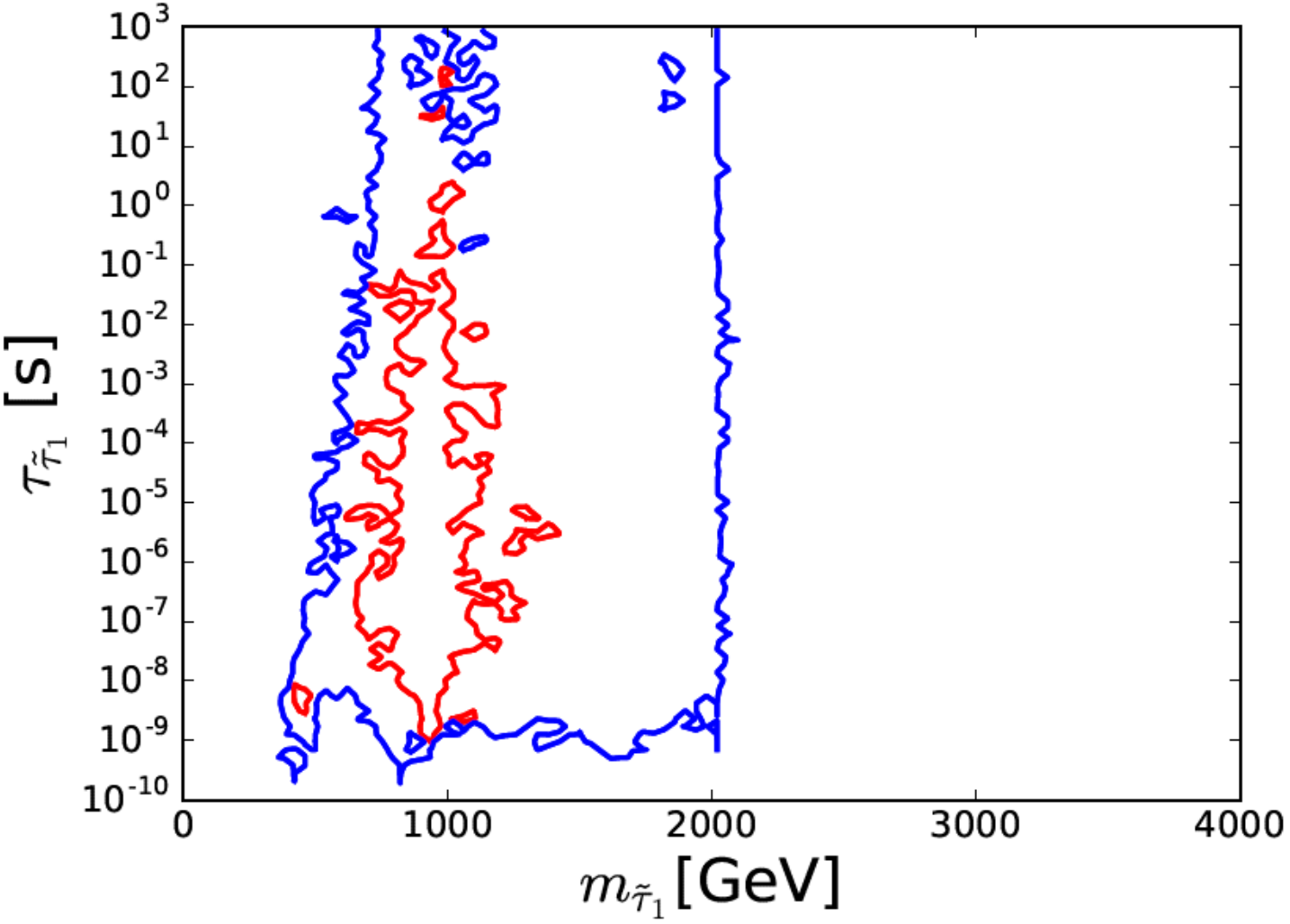
[2016]



$\Rightarrow \tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$ co-ann. possible $\Rightarrow$ but $\tilde{\tau}_1$ co-ann. dominant!

NLSP stau searches at the LHC:

[2016]

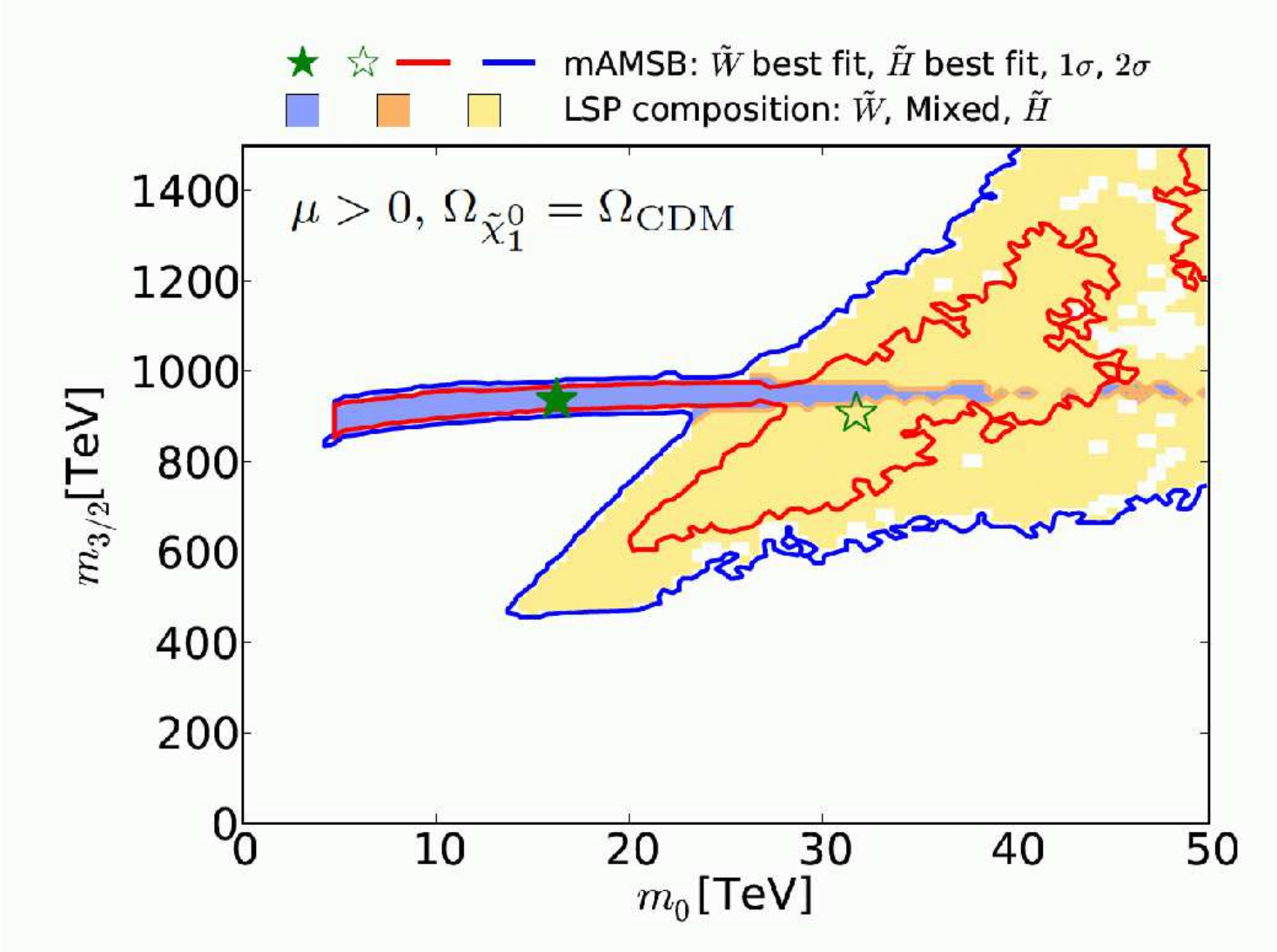


⇒ search for long-lived staus!

Results in the mAMSB

Dark Matter composition:

[2016]

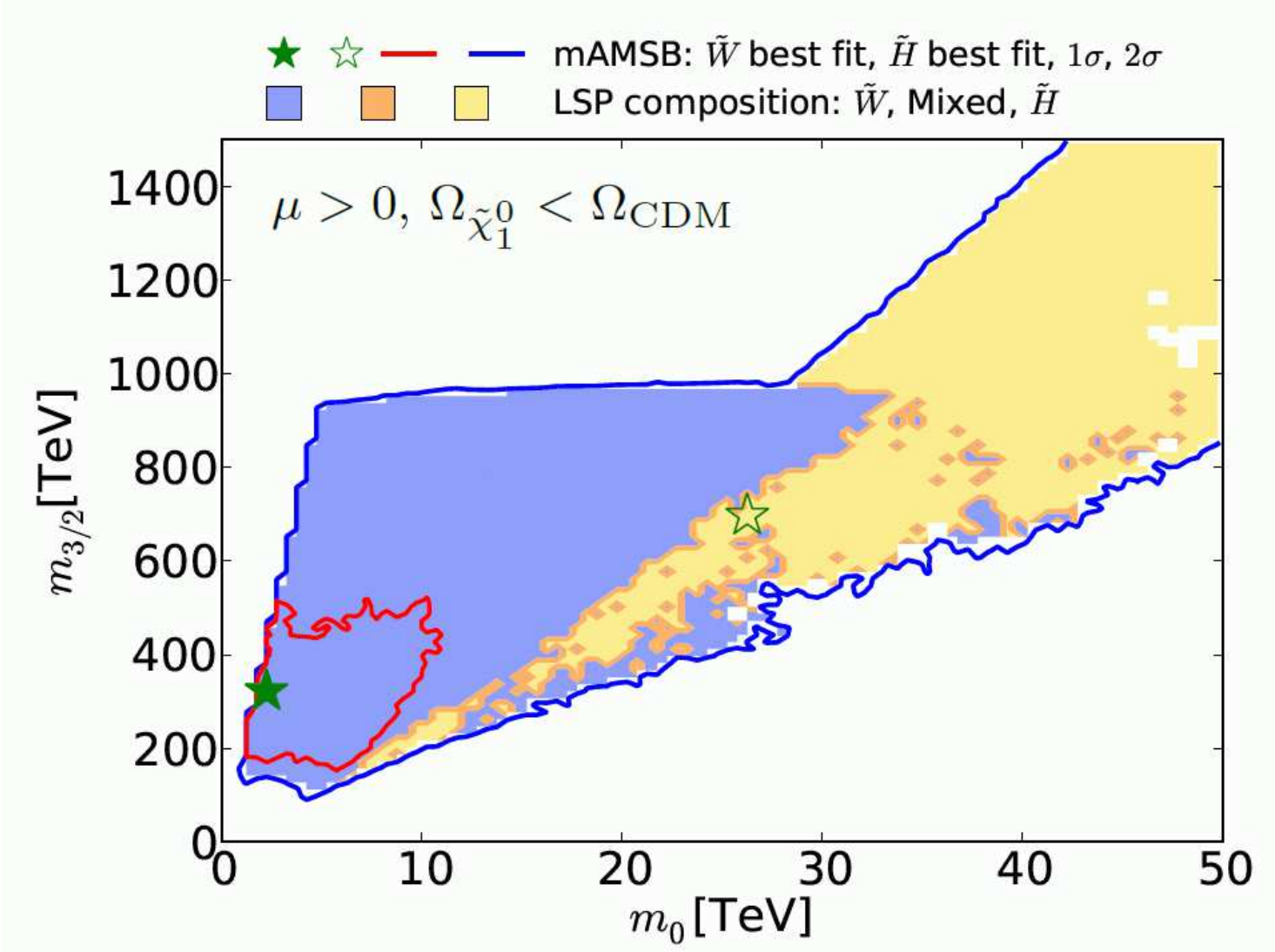


$\Rightarrow m_{\tilde{\chi}_1^0} \sim 2.9 \pm 0.1$ TeV (wino), $\sim 1.1 \pm 0.02$ TeV (higgsino)

Results in the mAMSB

Dark Matter composition:

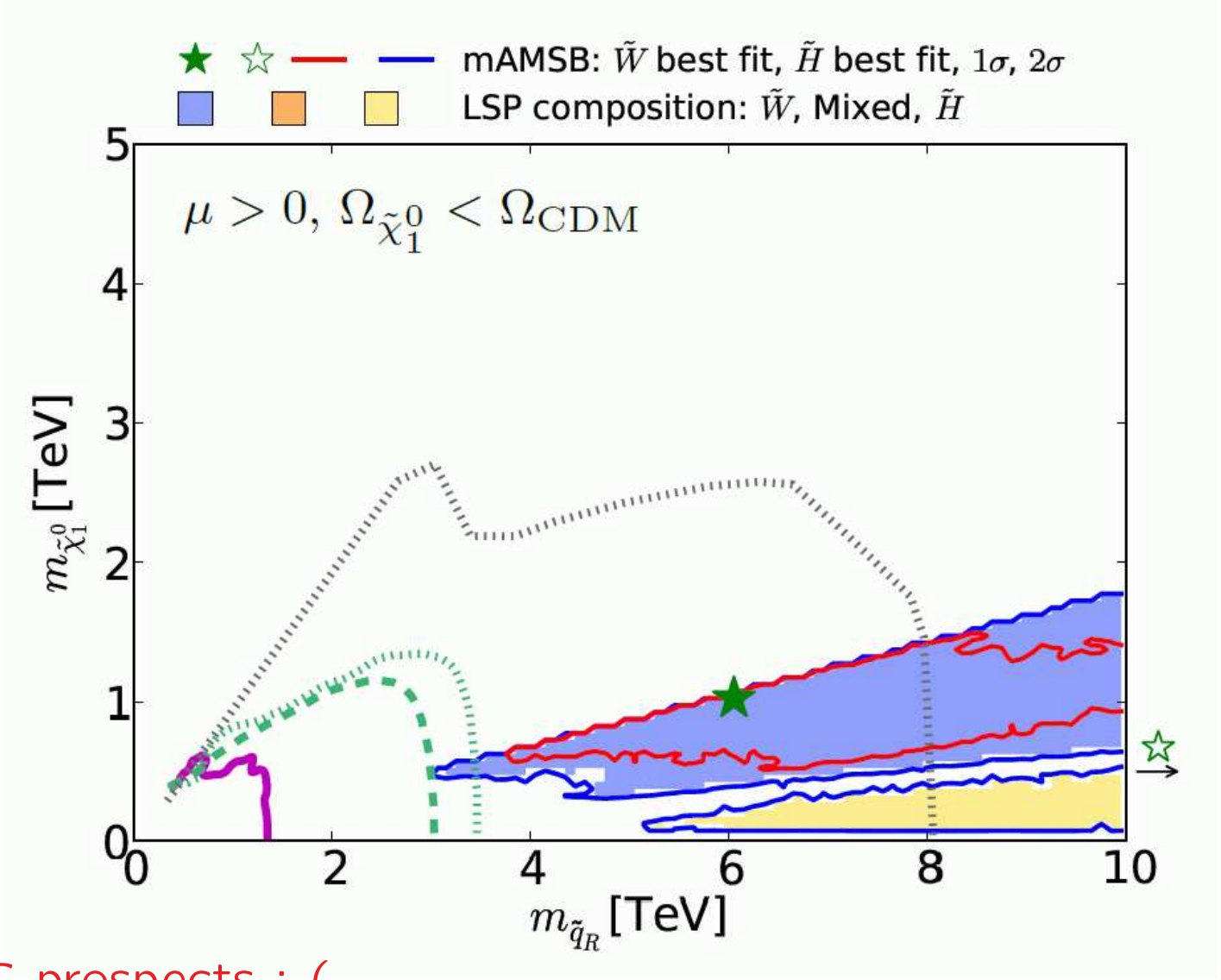
[2016]



$\Rightarrow$ very relaxed limits $\Rightarrow$ lower masses

Squark mass vs. DM mass:

[2016]

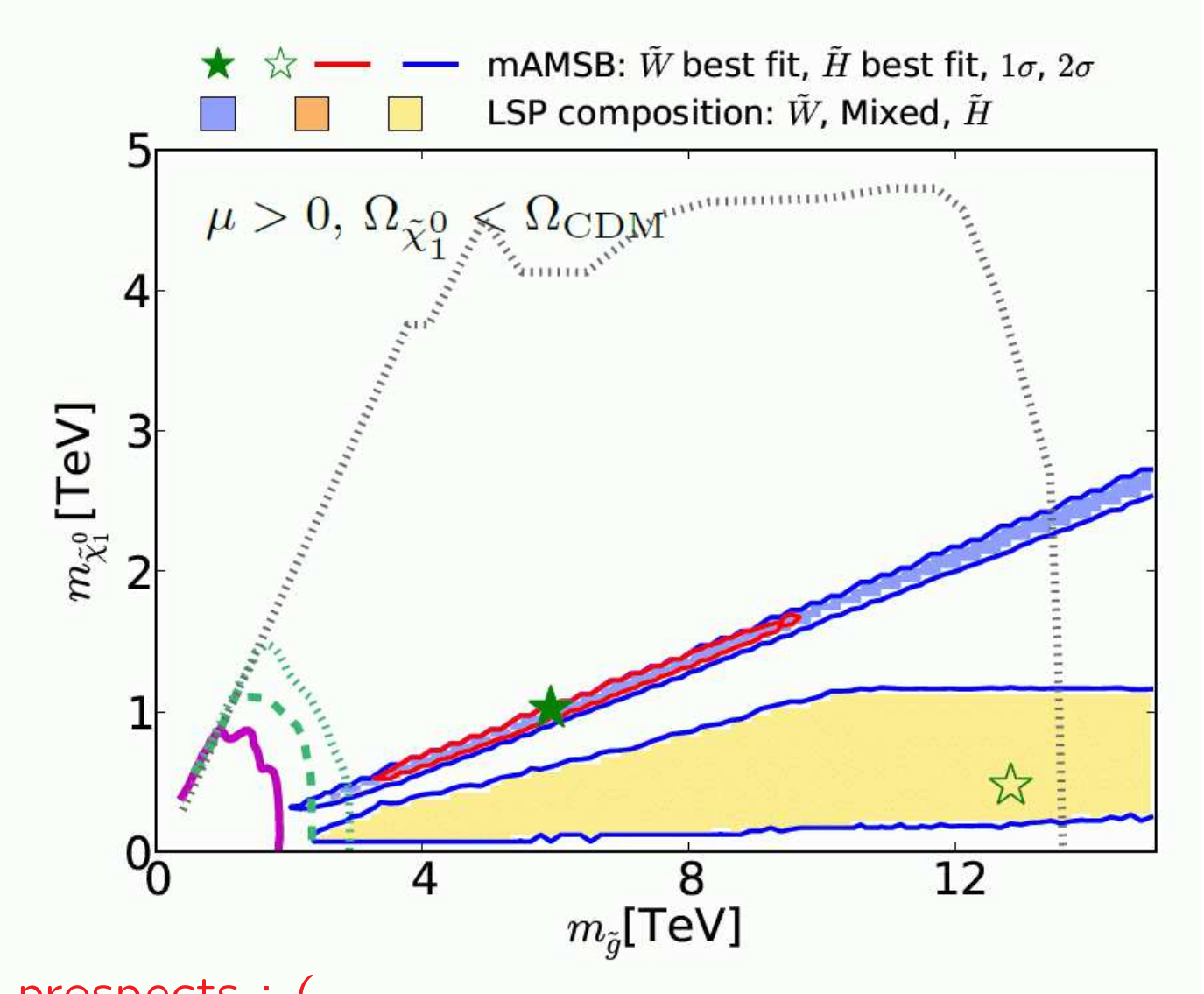


⇒ bad LHC prospects :-(

⇒ better FCC-hh prospects :-)

Gluino mass vs. DM mass:

[2016]



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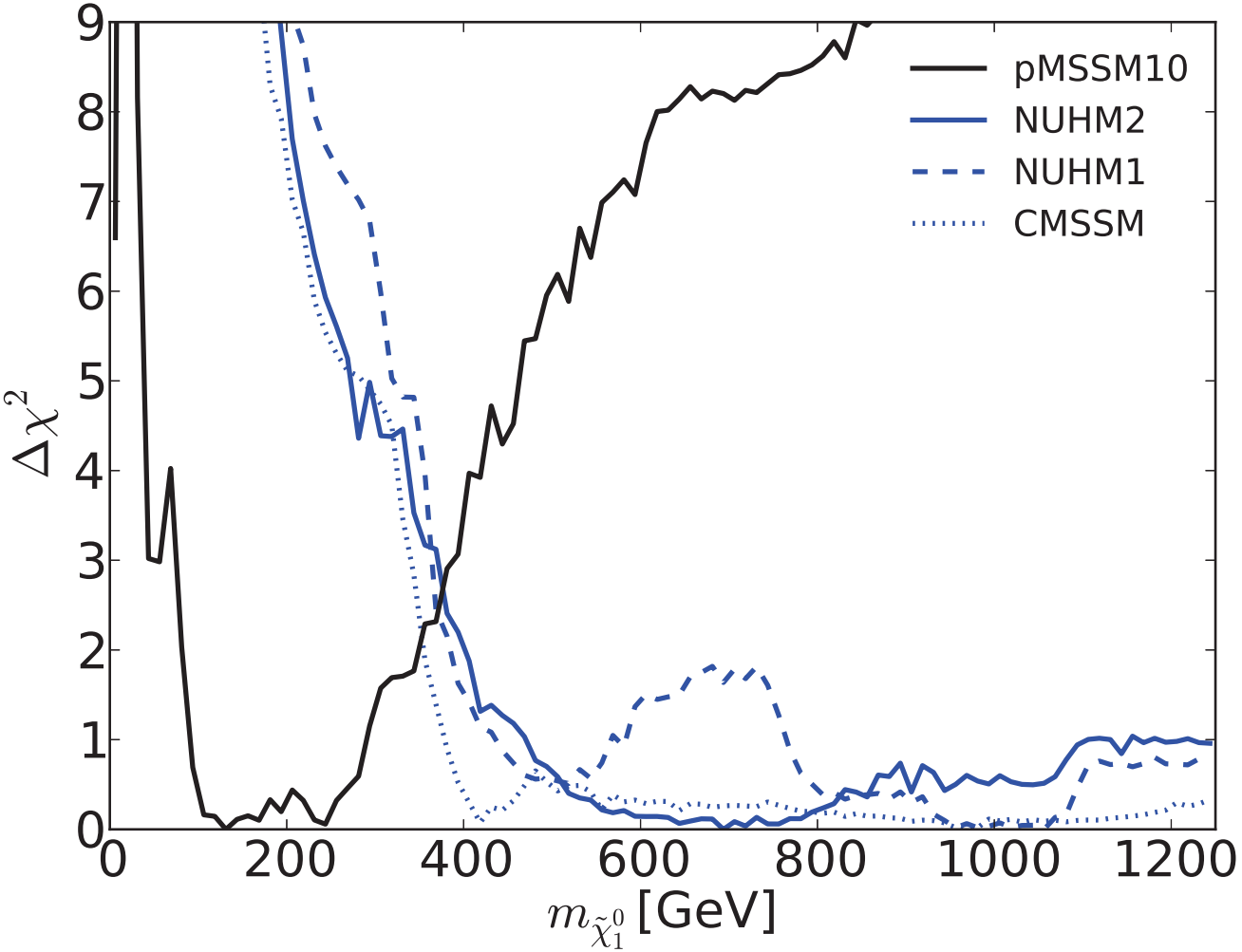
⇒ better FCC-hh prospects :-)

3. Results in low-energy models ⇒ pMSSM10

DM mass: pMSSM10 vs. GUT based models prediction:

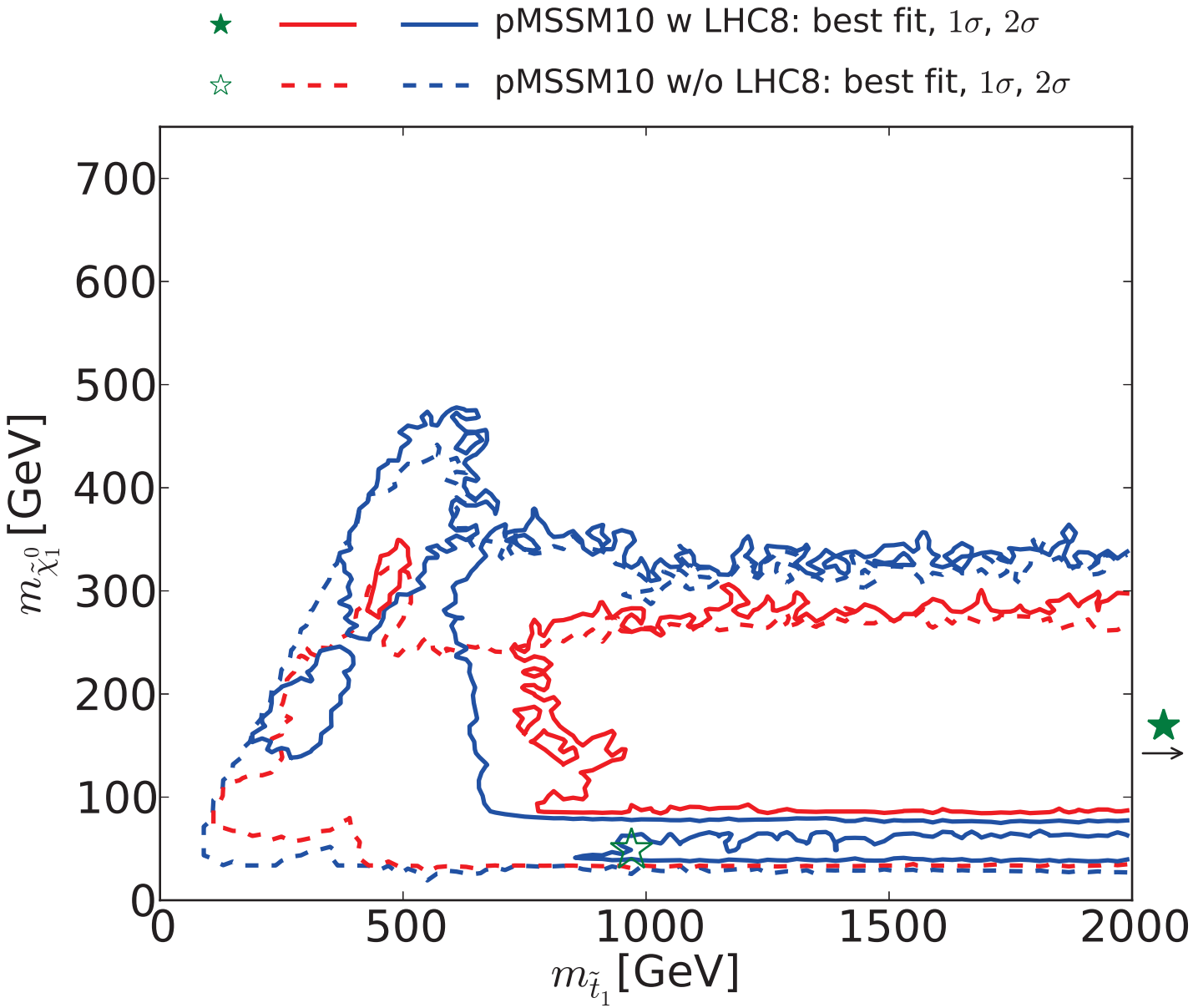
[2015]



⇒ pMSSM10 predicts much lower DM mass than GUT-based models

pMSSM10 prediction: DM mass vs. light stop mass:

[2015]



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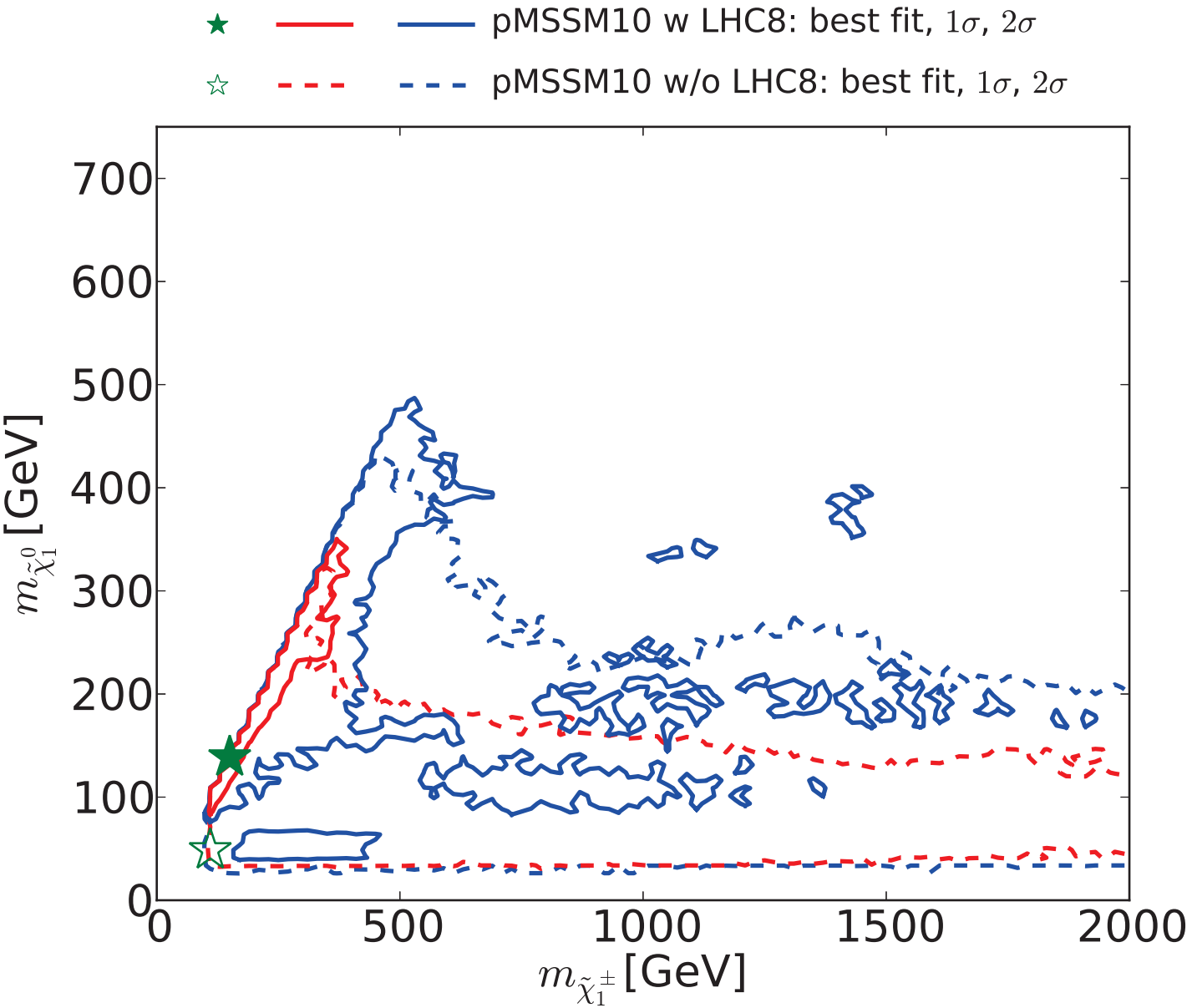

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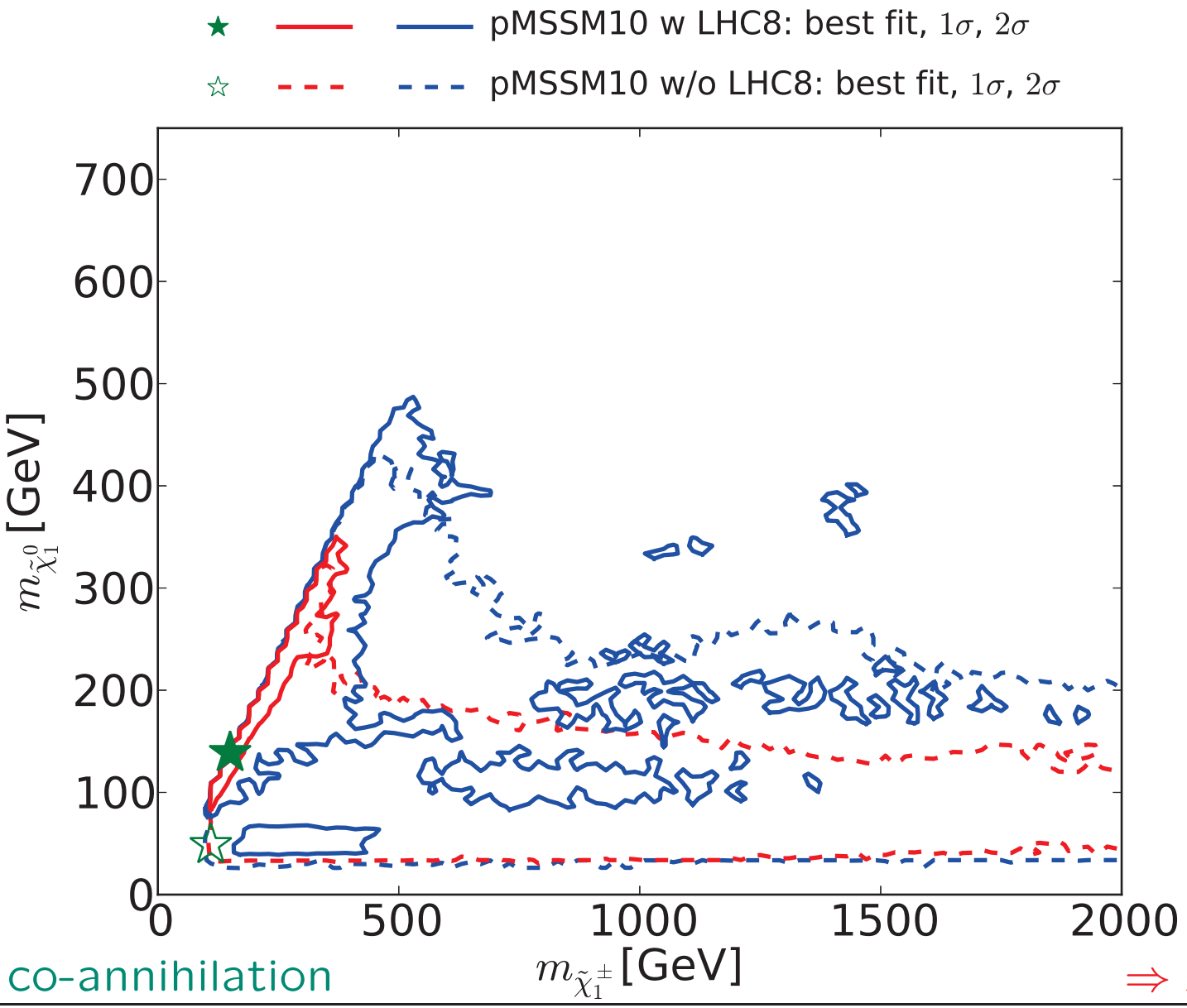
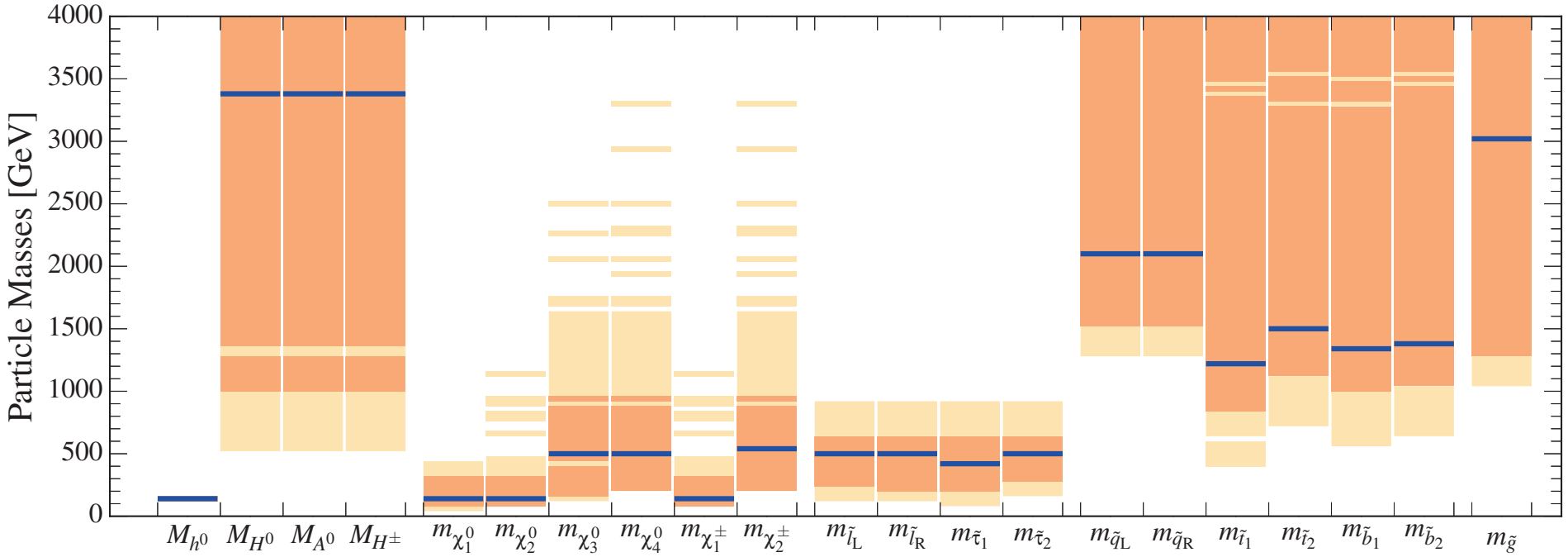


⇒ chargino co-annihilation

⇒ $M_1 \approx M_2$

pMSSM10 prediction: best-fit masses

[2015]



$\Rightarrow$ high colored masses

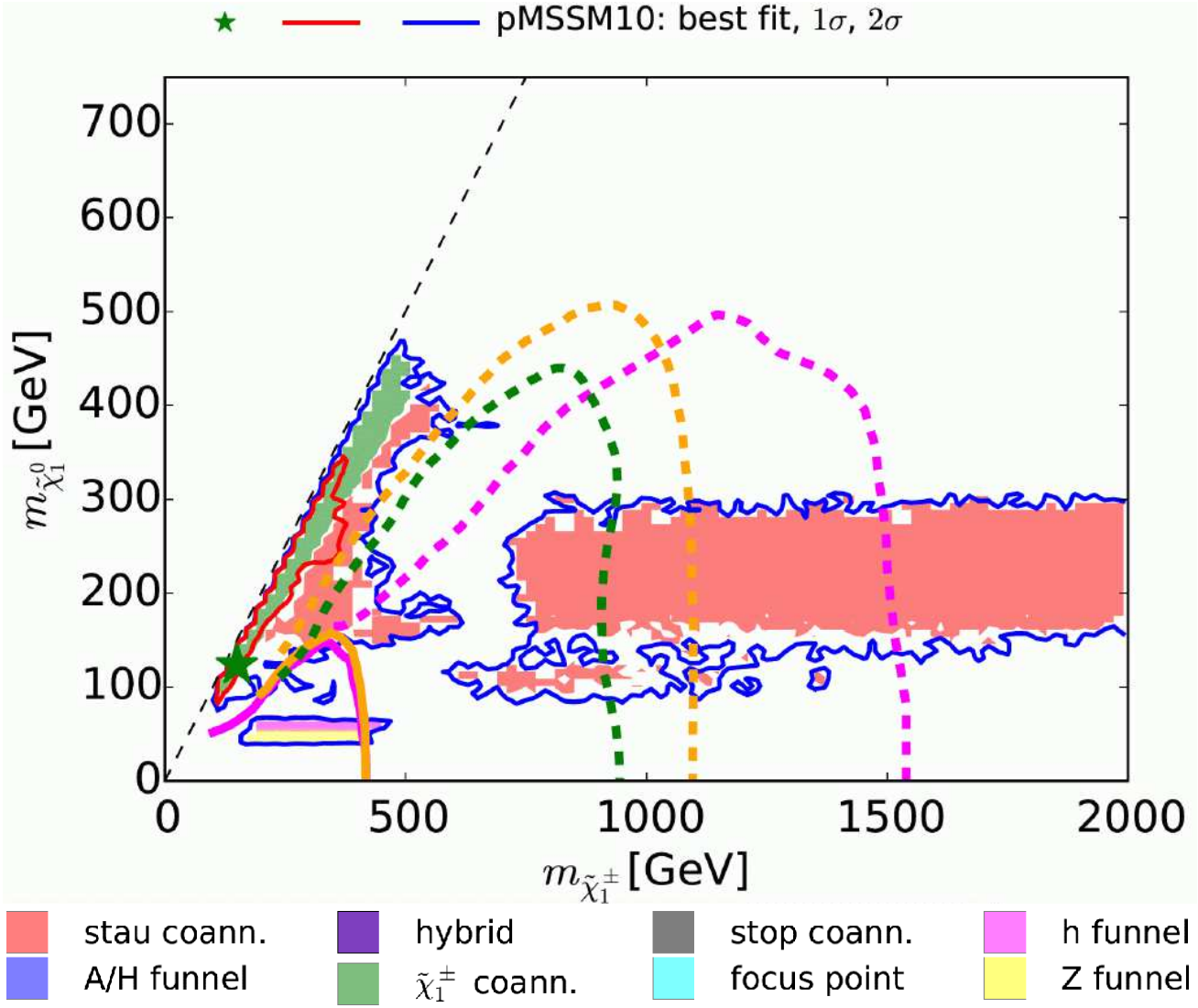
$\Rightarrow$ relatively low electroweak masses

partially with not too large ranges

$\Rightarrow$ clear prediction for $m_{\tilde{\chi}_1^0}$

LHC prospects for pMSSM10:

[2015]



solid: current LHC limits, dashed: HL-LHC prospects

$\Rightarrow$ best-fit regions not covered! (in EW searches)

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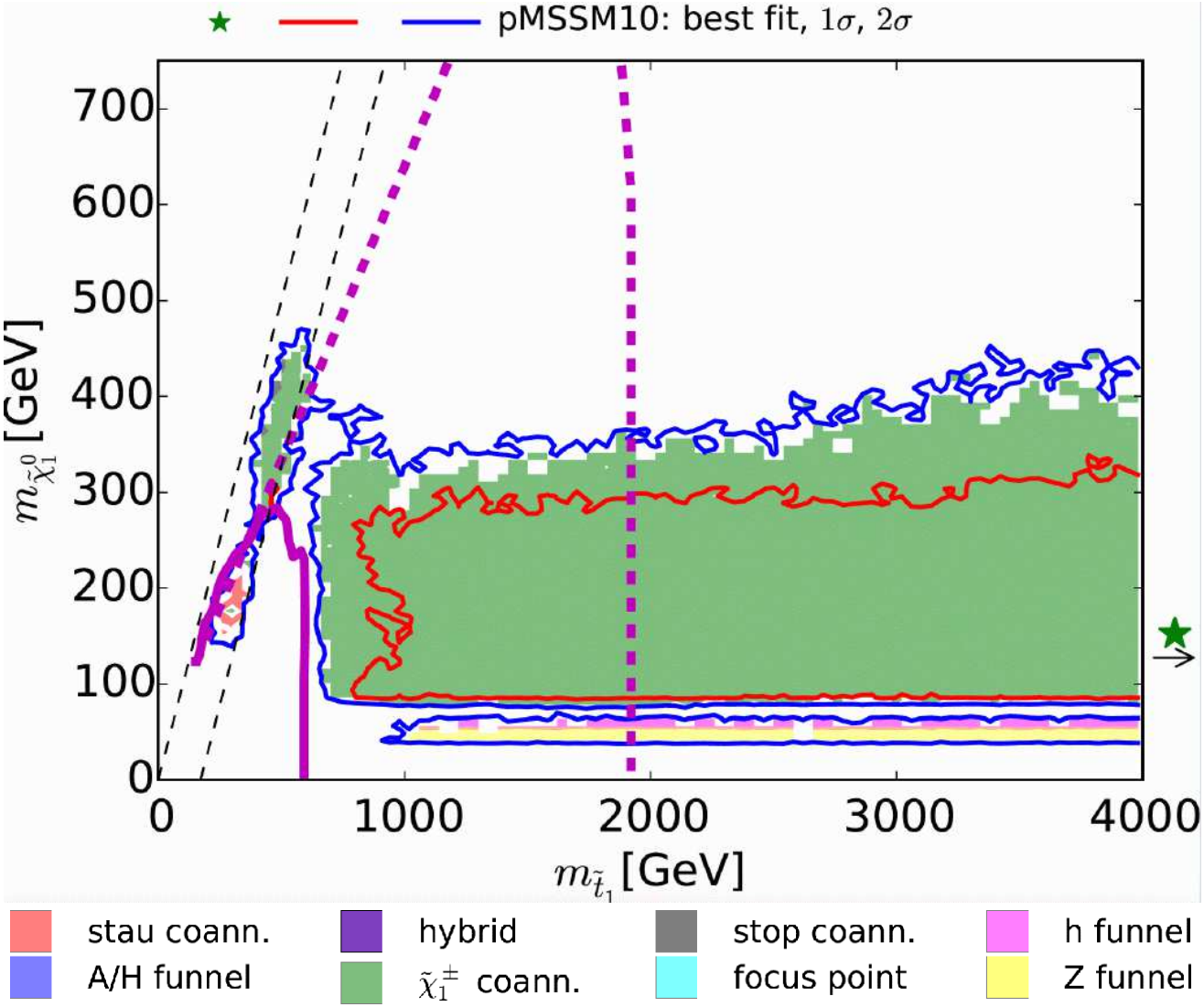

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⇒ best-fit regions can partially be covered! (in colored searches)

4. Conclusinos

- SUSY is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM1, NUHM2, SU(5), mAMSB
  - general models: pMSSM10, ...
- Our tool: MasterCode: combination of LHC searches, Higgs measurements, EWPO, BPO, CDM $\Rightarrow \chi^2$ evaluation
- CMSSM, NUHM1, NUHM2: – some accessible spectra
  – many unaccessible spectra
  – CMSSM best-fit points $\rightarrow$ HL-LHC
- SU(5): – some accessible spectra, many unaccessible spectra
  – long-lived staus ?!
- mAMSB: – $\Omega_{\tilde{\chi}_1^0} = \Omega_{\rm CDM} \Rightarrow$ mostly unaccessible spectra
  – $\Omega_{\tilde{\chi}_1^0} < \Omega_{\rm CDM} \Rightarrow$ lower masses allowd
  – still bad HL-LHC prospects, but good FCC-hh prospects
- pMSSM10: – $m_{\tilde{\chi}_1^0} \lesssim 400$ GeV; important: chargino co-annihilation
  – colored searches cover parts of 68% CL region
  – EW searches miss 68% CL region (compr. spectrum!)

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  - general models: pMSSM10, ...
- Our tool: MasterCode: combination of LHC searches, Higgs measurements, EWPO, BPO, CDM $\Rightarrow \chi^2$ evaluation
- CMSSM, NUHM1, NUHM2: – $m_{\tilde{\chi}_1^0} \gtrsim 400$ GeV neutrino floor
  – best-fit regions (mostly) above/at/below
- SU(5): – stau co-ann., but also $\tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$ co-ann. possible
  – $m_{\tilde{\chi}_1^0}$ as in CMSSM, NUHM1, NUHM2
  – best-fit region at neutrino floor
- mAMSB: – $m_{\tilde{\chi}_1^0} \sim 2.9 \pm 0.1$ TeV (wino), $\sim 1.1 \pm 0.02$ TeV (higgsino)
  – DD: wino at neutrino floor, higgsino tested by next round
- pMSSM10: – $m_{\tilde{\chi}_1^0} \lesssim 400$ GeV; important: chargino co-annihilation
  – at the 68% CL accessible at the next generation of DD
  – at the 95% CL even below neutrino floor

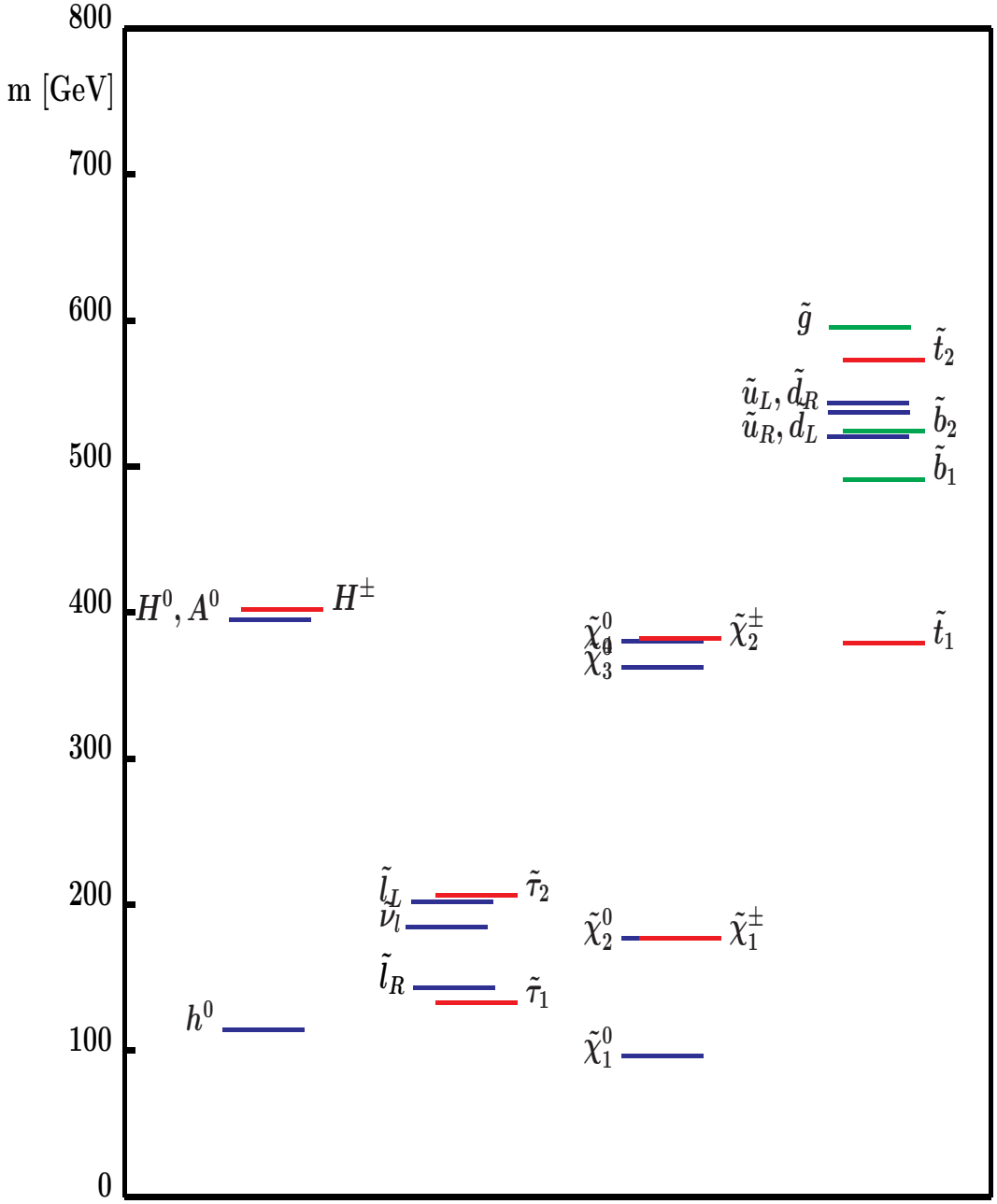

Further Questions?

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

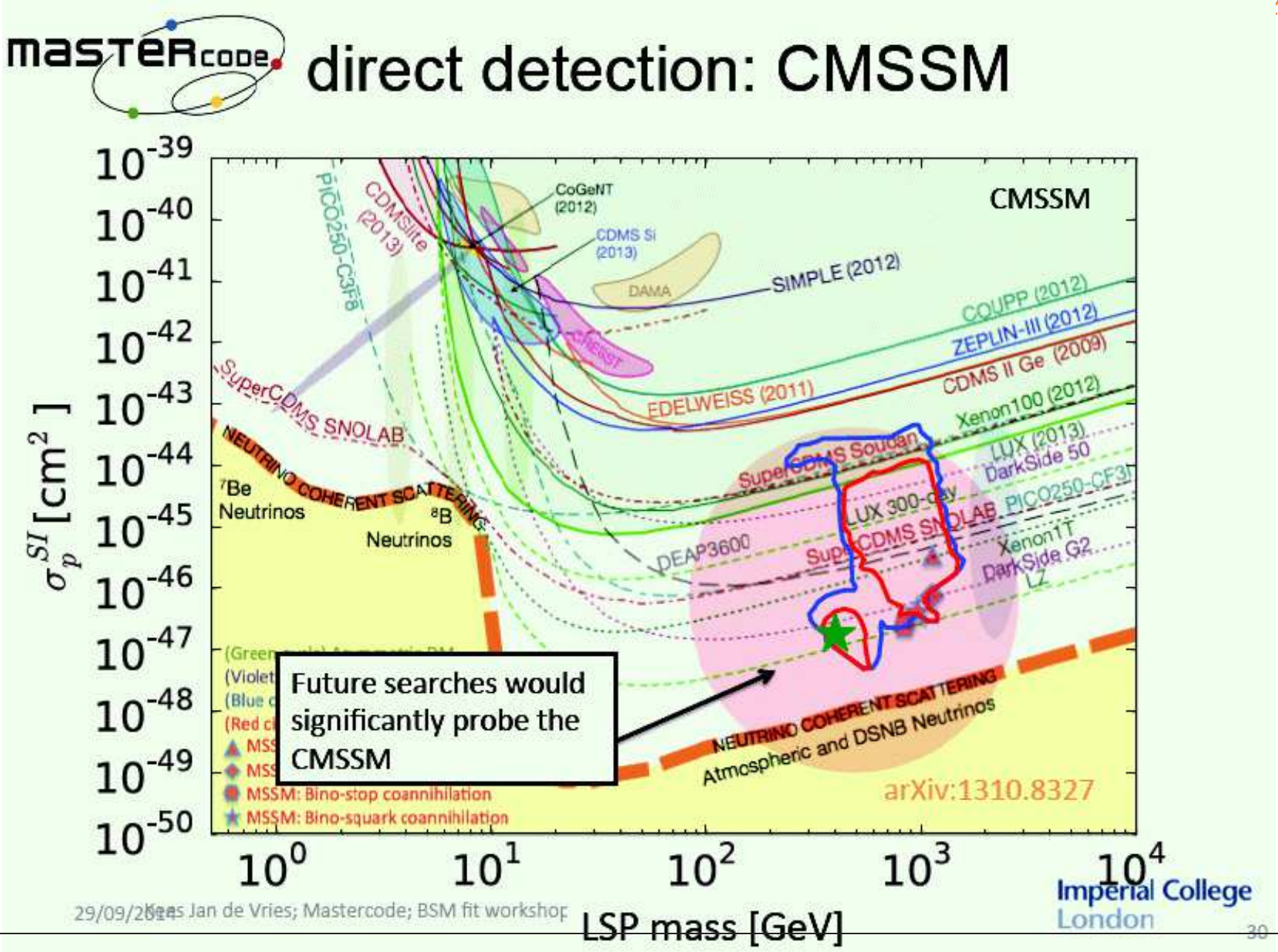
Strong connection between

all the sectors



MSSM DM prediction

[2014]



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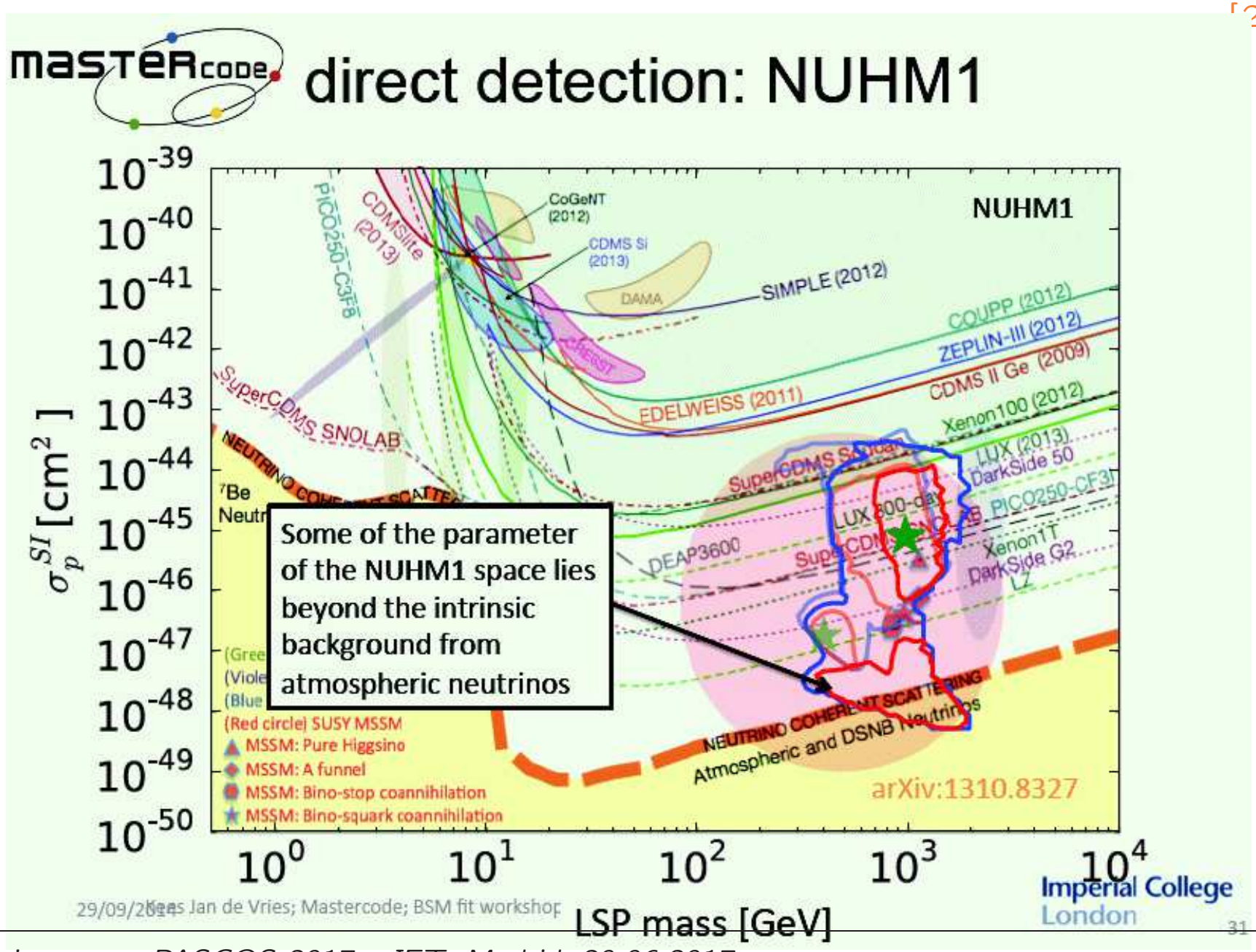

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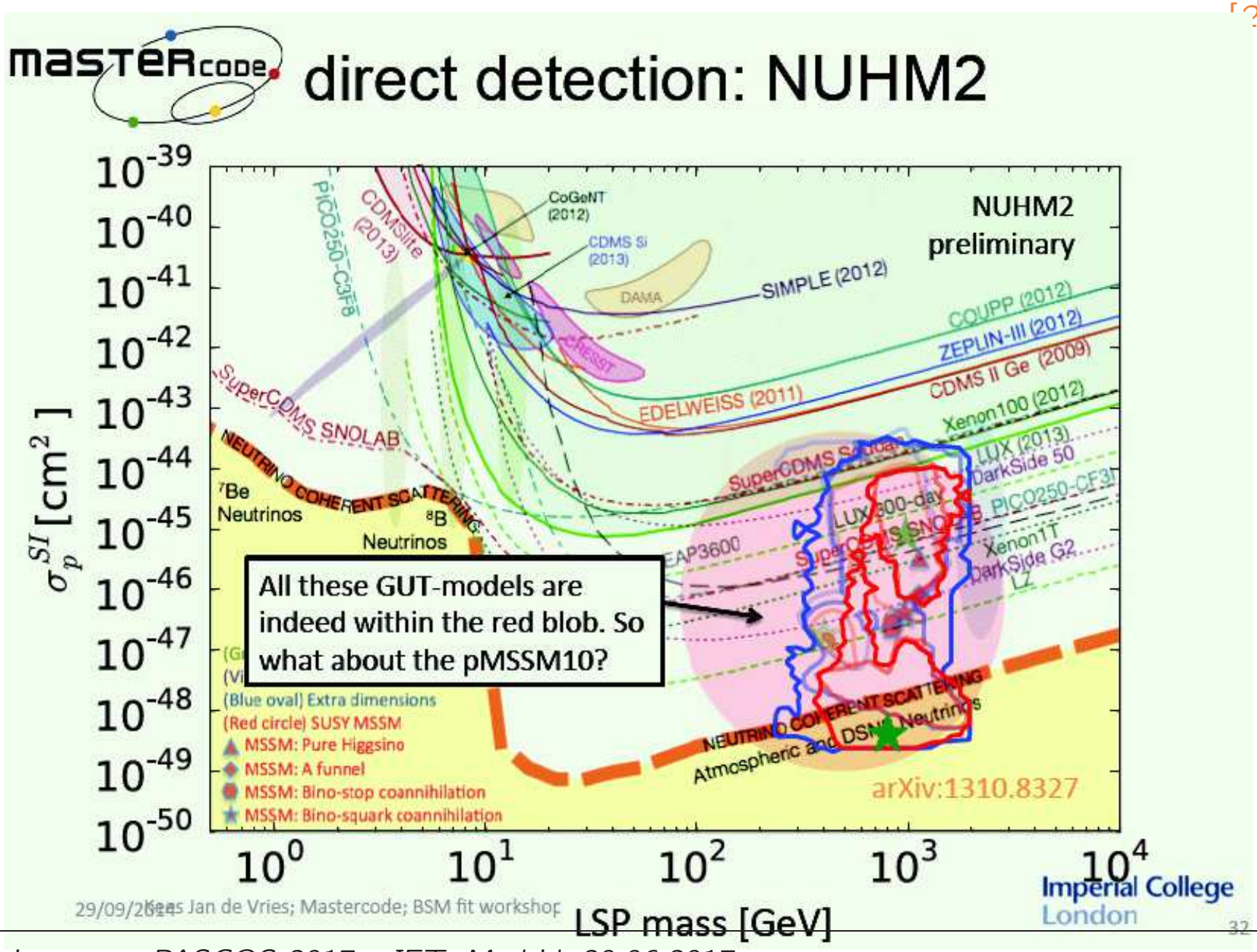
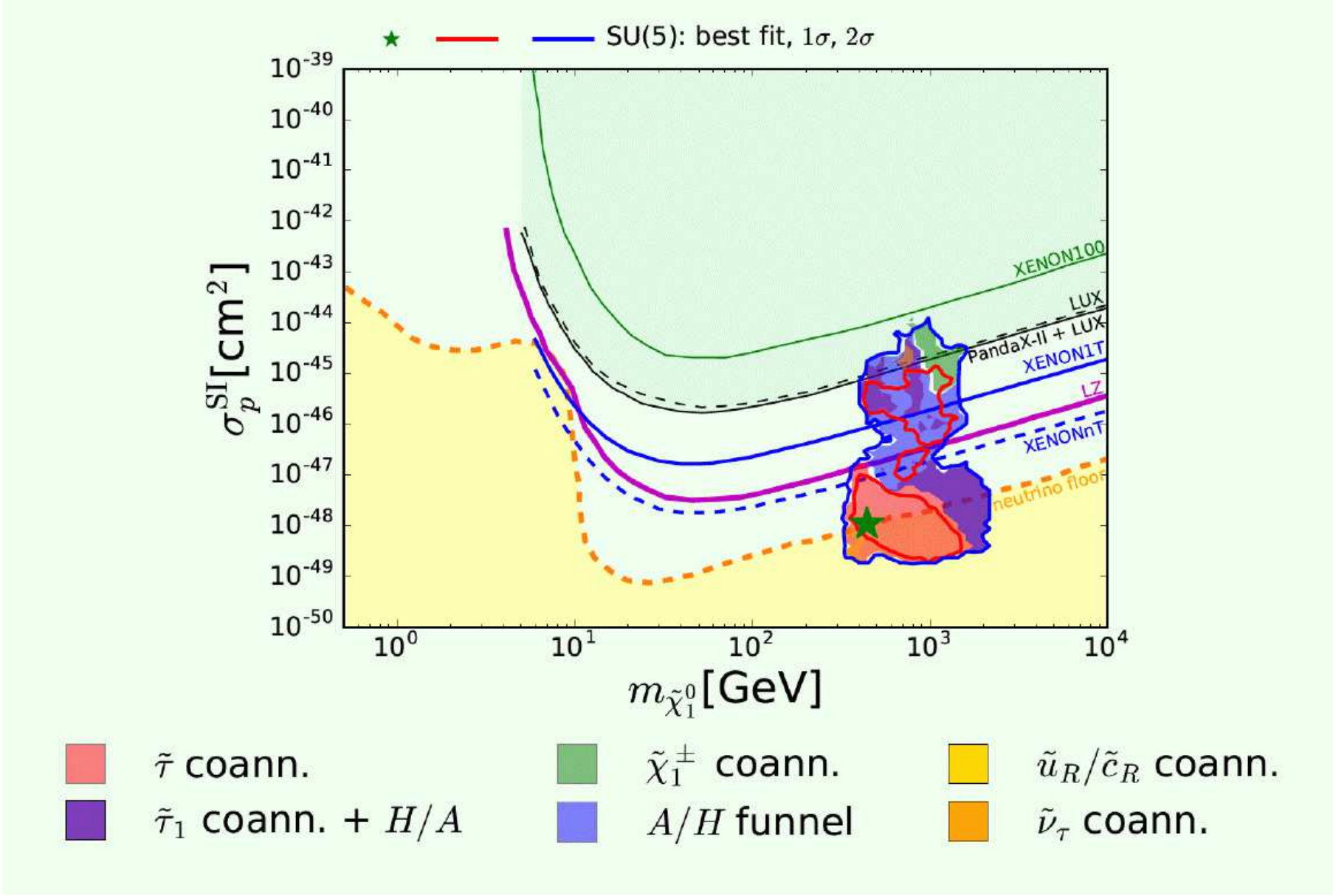


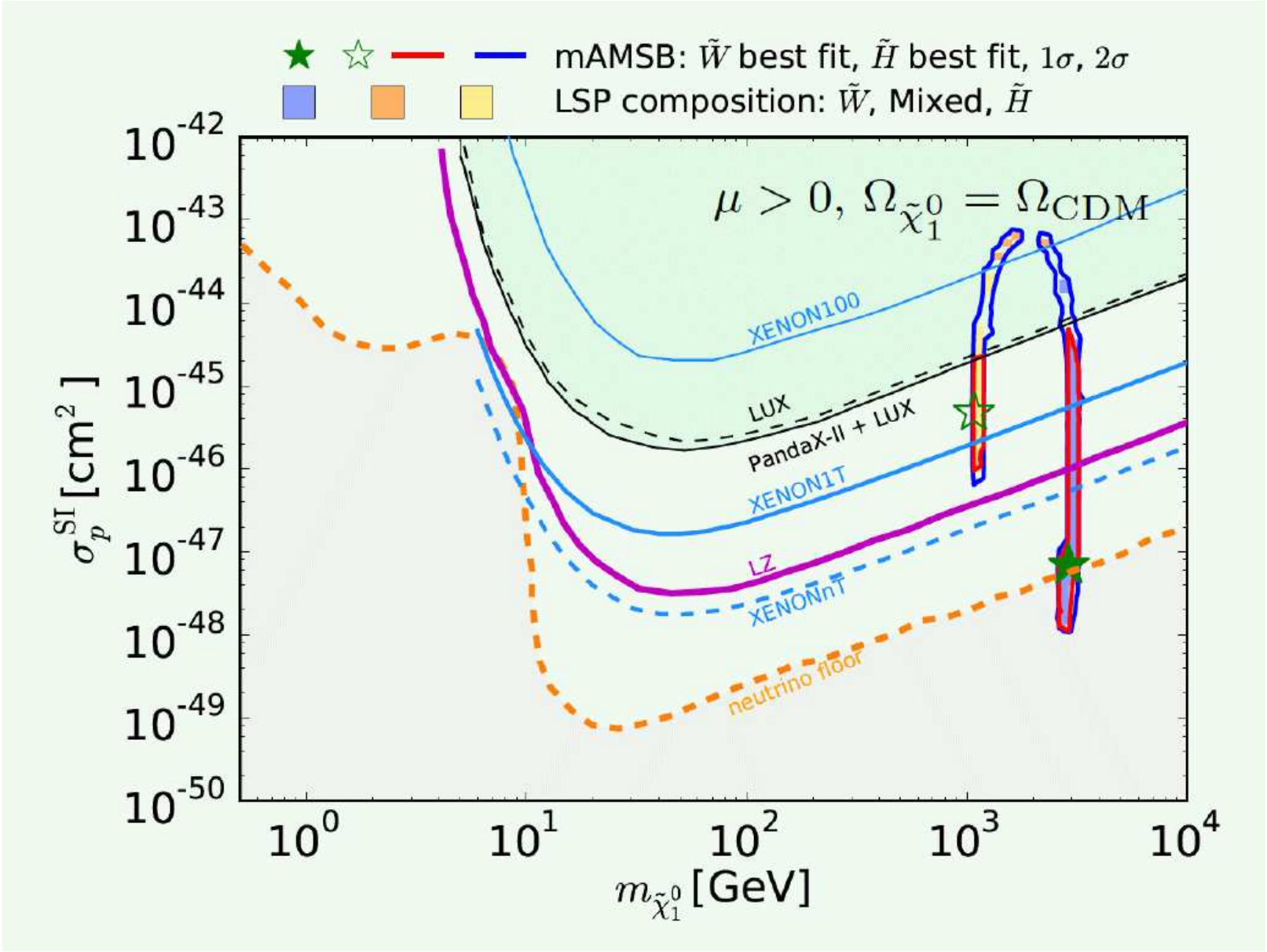
Dark Matter Diret Detection prospects in SU(5):

[2016]



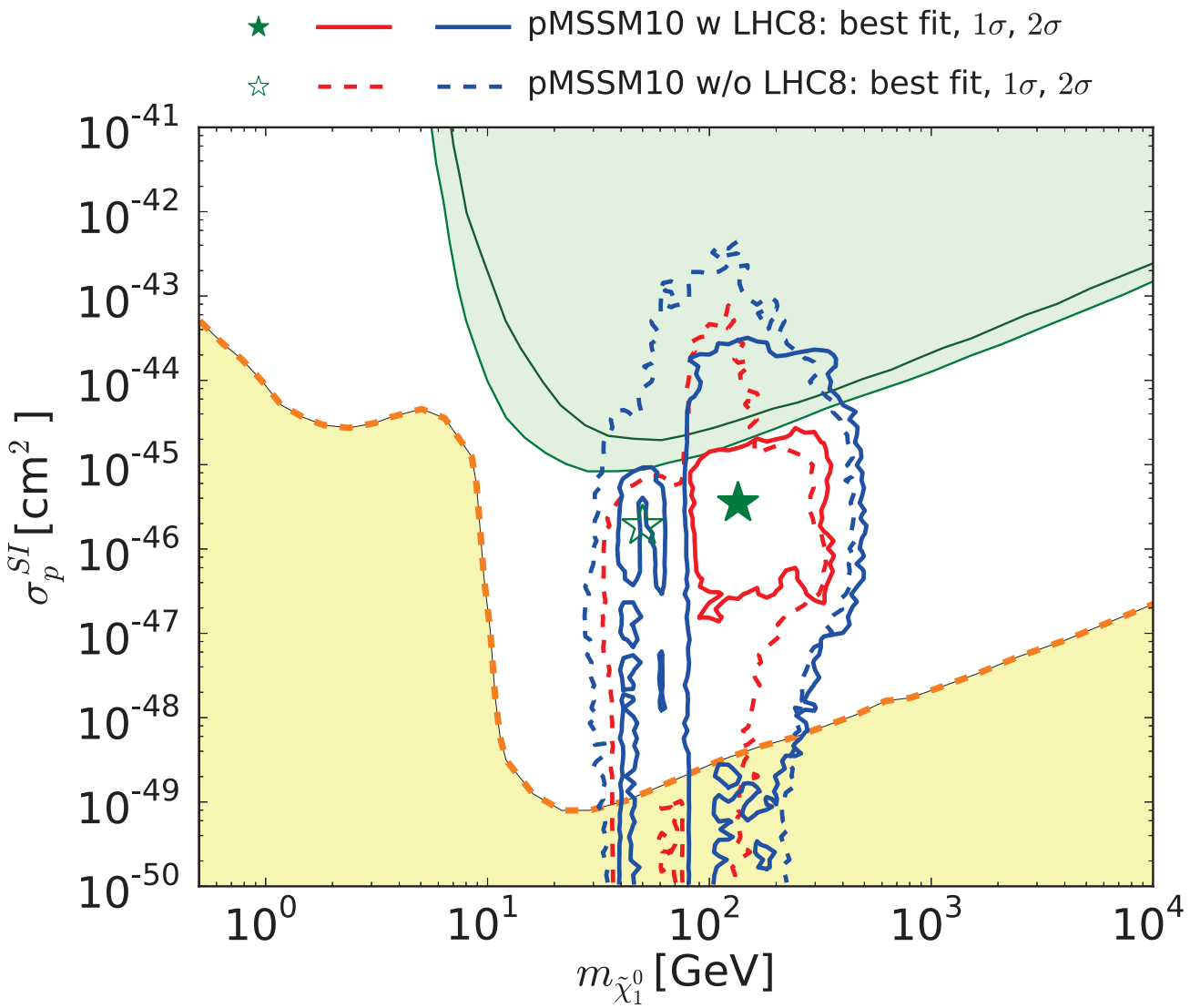
Dark Matter Diret Detection prospects in mAMSB:

[2016]



pMSSM10 prediction: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{\rm SI}$:

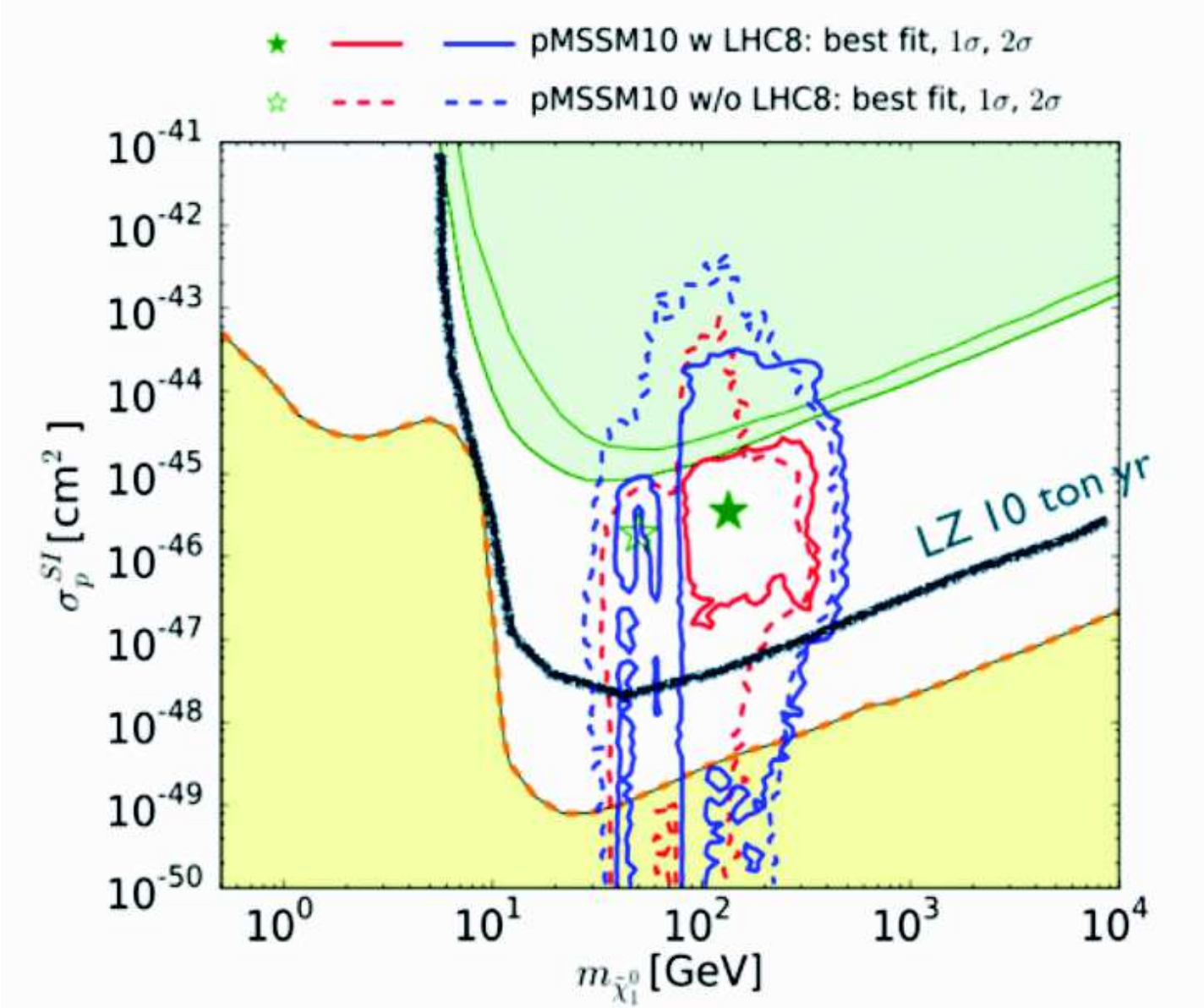
[2015]



$\Rightarrow$ LHC bounds try to "rescue" DD experiments!

pMSSM10 prediction: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{\rm SI}$: future expectations

[2015]



$\Rightarrow$ 68% CL areas covered by next round of DD experiments

pMSSM10 analysis: DD experiments: p- vs. n-scattering

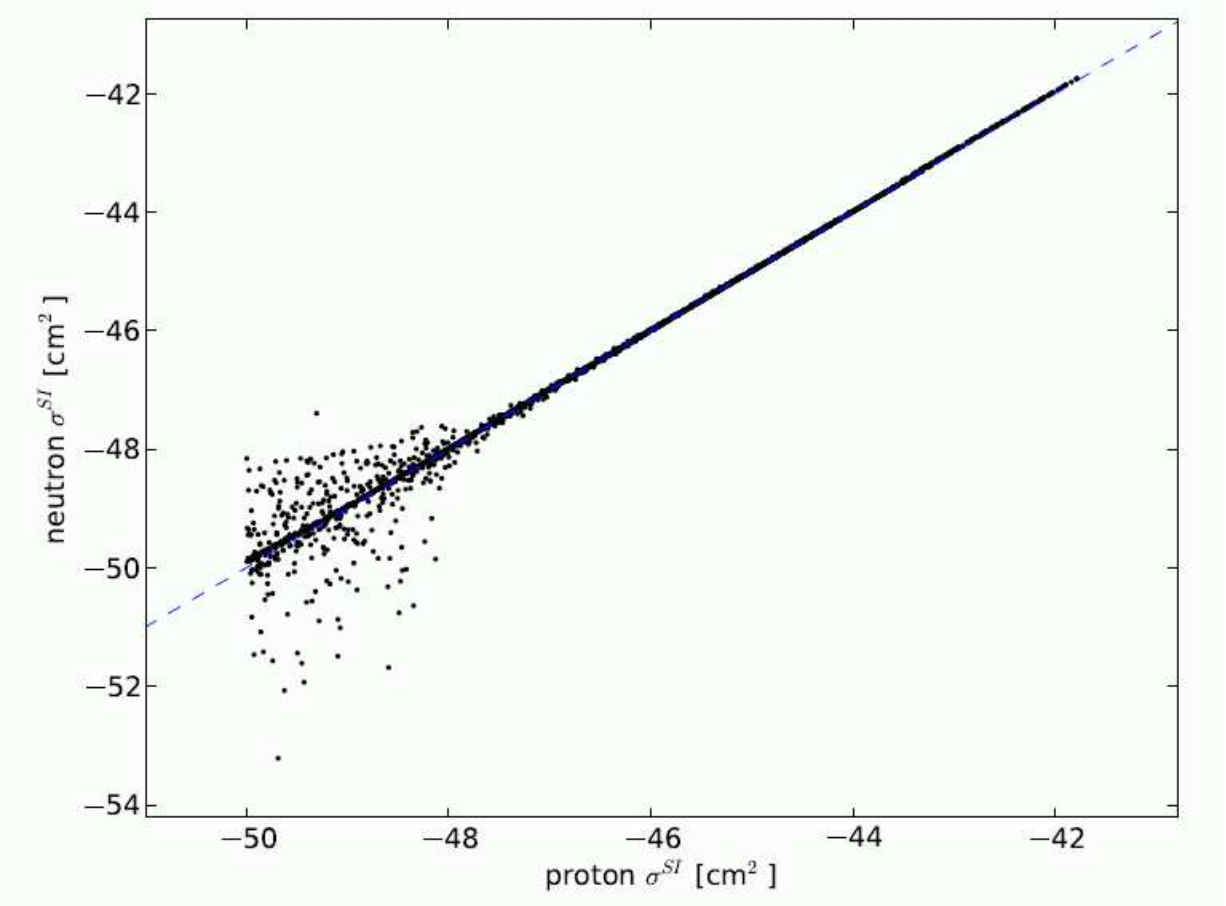
[2015]

$\sigma_p^{\rm SI}$ is evaluated for p-scattering

Can n-scattering come to rescue?

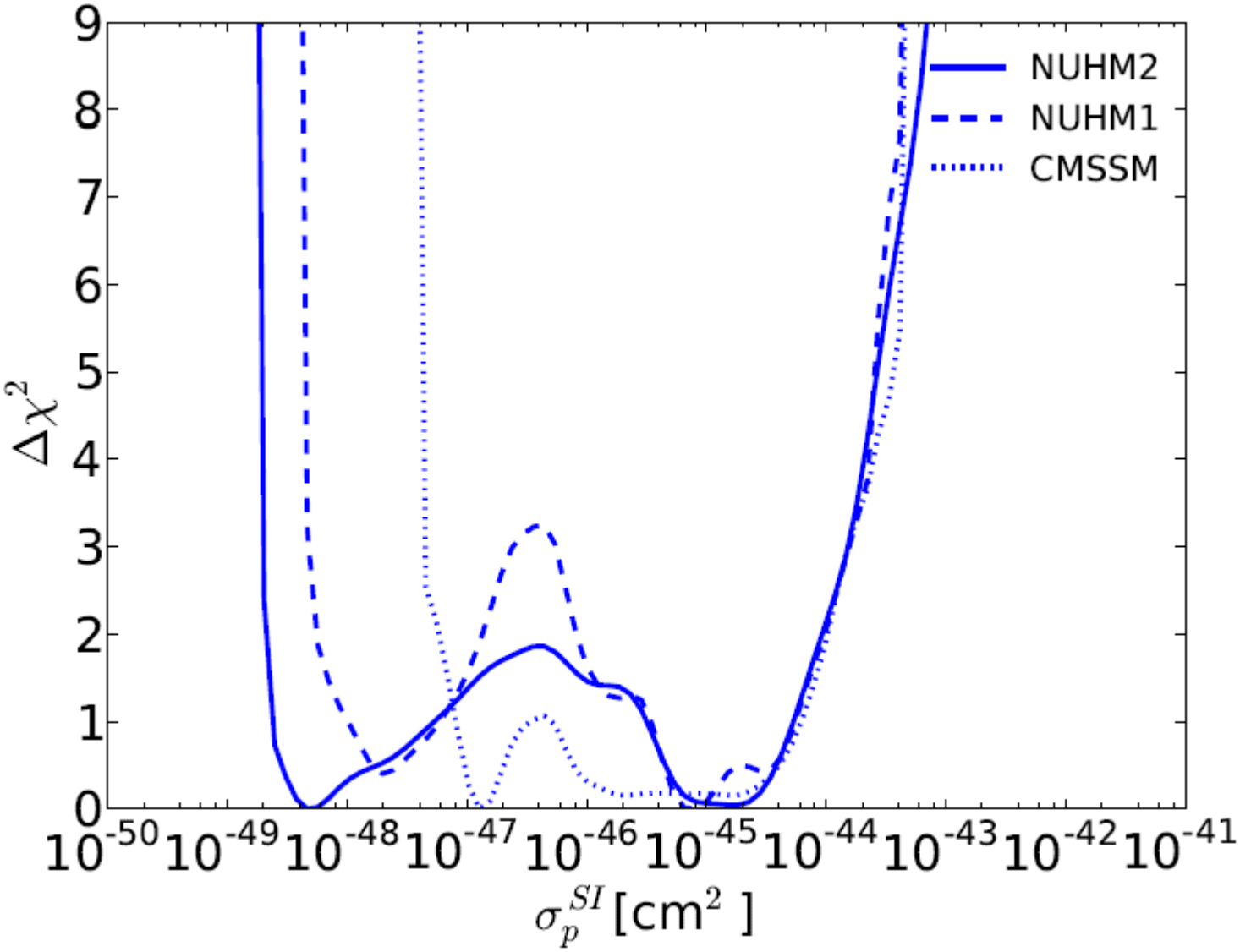
Some points with low $\sigma_p^{\rm SI}$ have even lower $\sigma_n^{\rm SI}$

$\Rightarrow$ no "no-lose theorem" for DD experiments!



$\sigma_p^{\rm SI}$ incl. 20/fb of LHC data in CMSSM

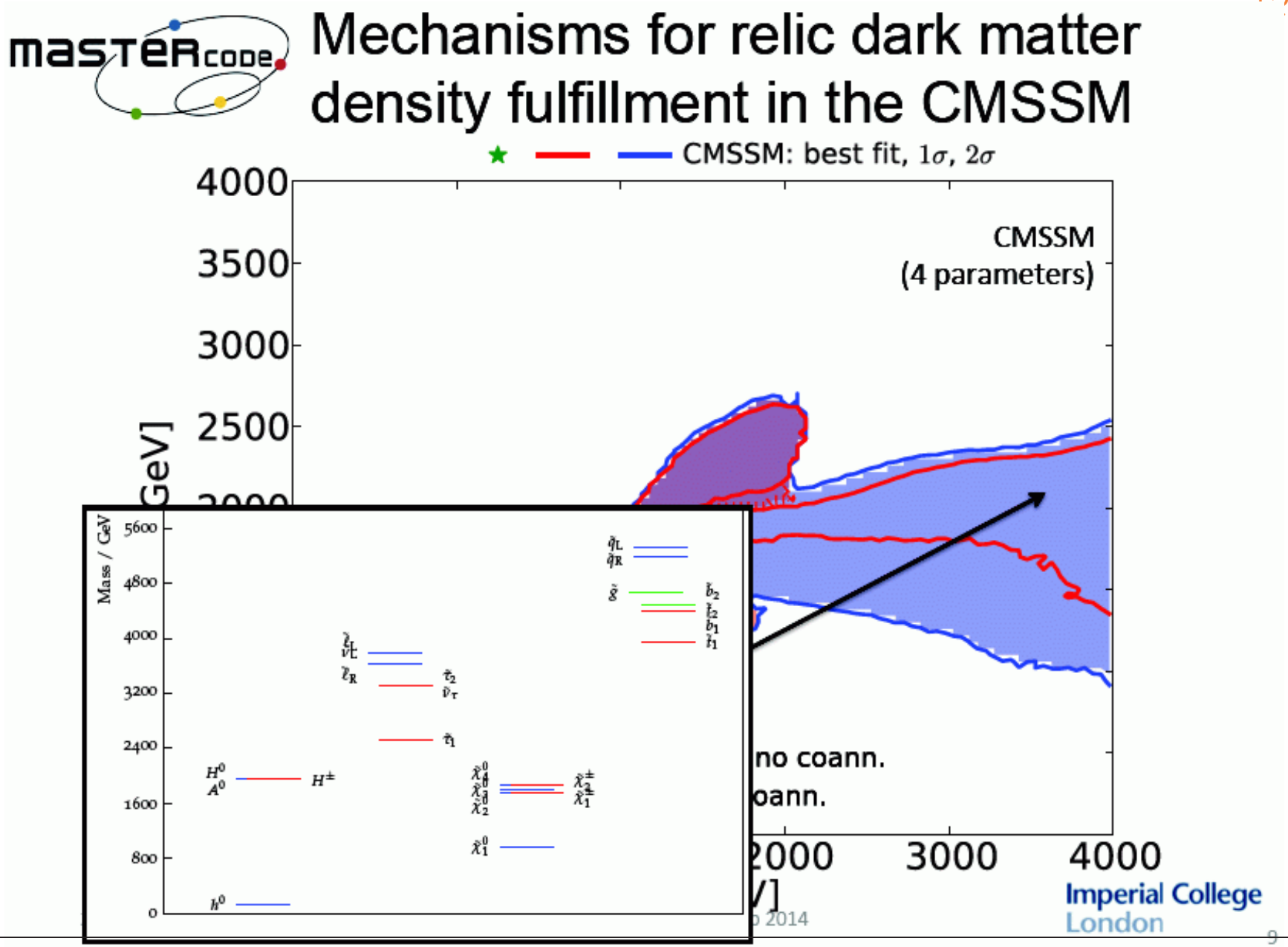
[2014]



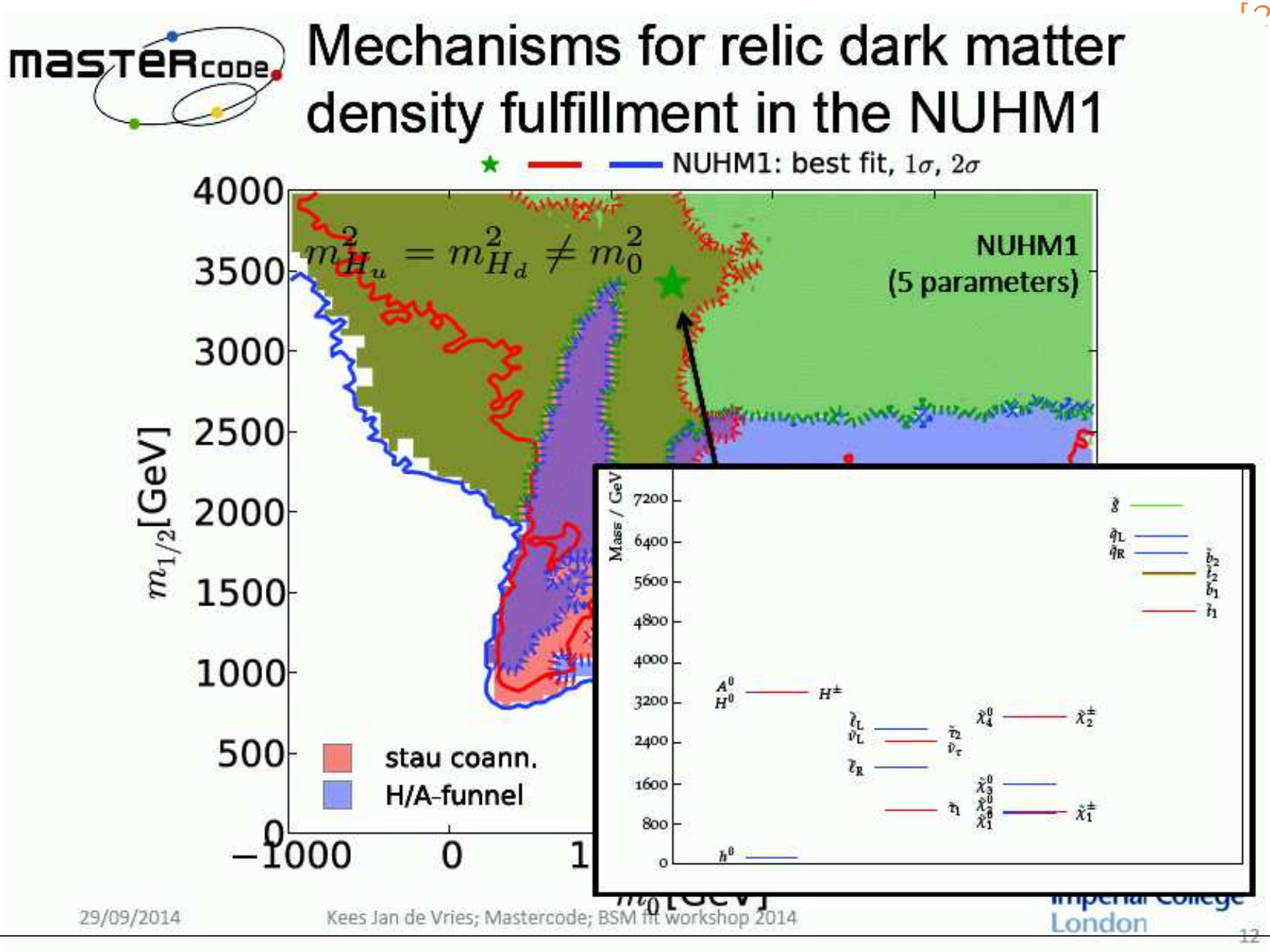
$\Rightarrow$ only very small values are favored

CMSSM DM prediction

[2014]

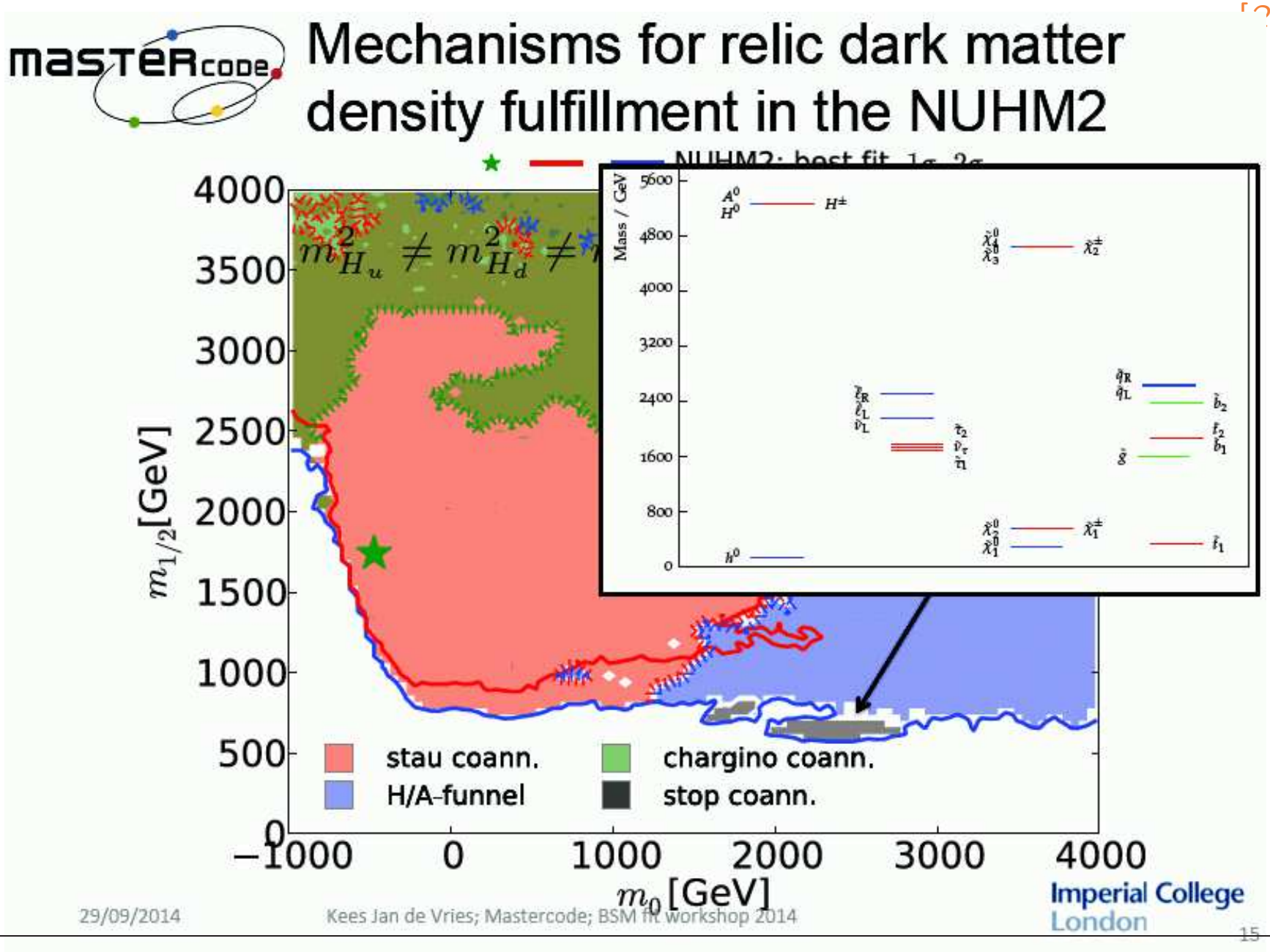


[2014]


Mechanisms for relic dark matter density fulfillment in the NUHM1
NUHM1: best fit, 1σ, 2σ
$m^2_{H_u} = m^2_{H_d} \neq m^2_0$
NUHM1
(5 parameters)
$m_{1/2}$[GeV]
4000
3500
3000
2500
2000
1500
1000
500
0
−1000
0
stau coann.
H/A-funnel
Mass / GeV
7200
6400
5600
4800
4000
3200
2400
1600
800
0
A^0 H^0
$H^\pm$
h^0
$\tilde{g}$
$\tilde{q}_L$ $\tilde{q}_R$
$\tilde{b}_2$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{t}_1$
$\tilde{\ell}_L$ $\tilde{\nu}_L$
$\tilde{\tau}_2$ $\tilde{\nu}_\tau$
$\tilde{\ell}_R$
$\tilde{\tau}_1$
$\tilde{\chi}^0_4$ $\tilde{\chi}^\pm_2$
$\tilde{\chi}^0_3$ $\tilde{\chi}^0_2$ $\tilde{\chi}^0_1$ $\tilde{\chi}^\pm_1$
29/09/2014
Kees Jan de Vries; Mastercode; BSM fit workshop 2014
London
12

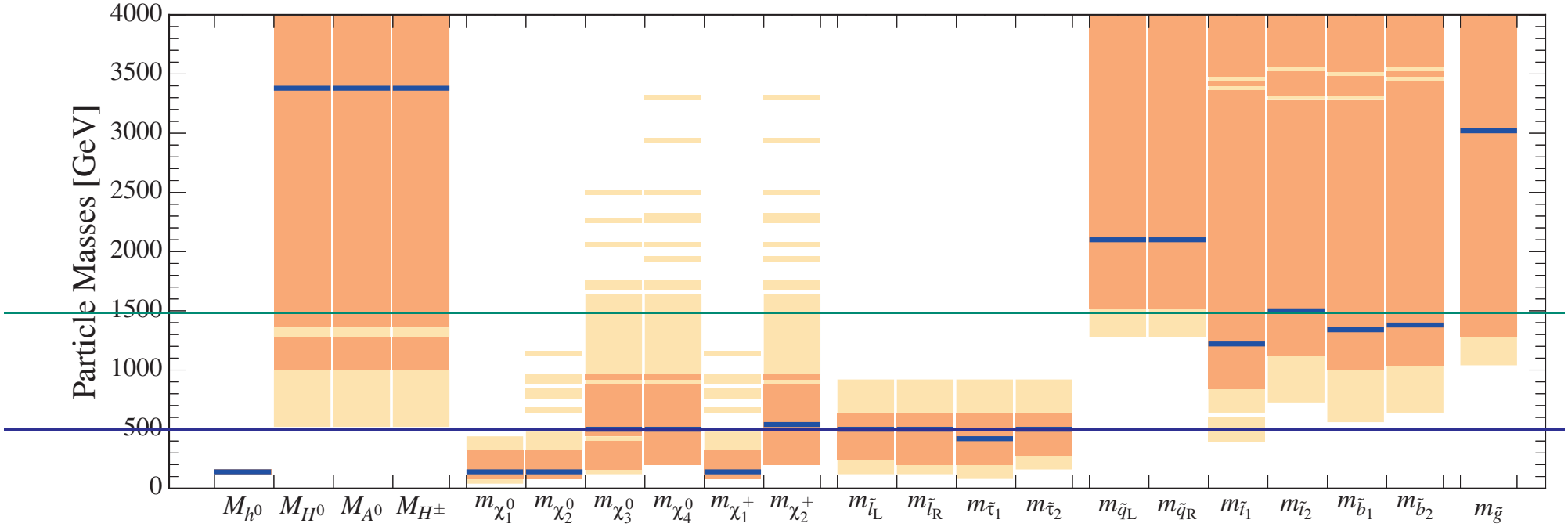
NUHM2 DM prediction

[2014]



e^+e^- prospects for pMSSM10:

[2015]

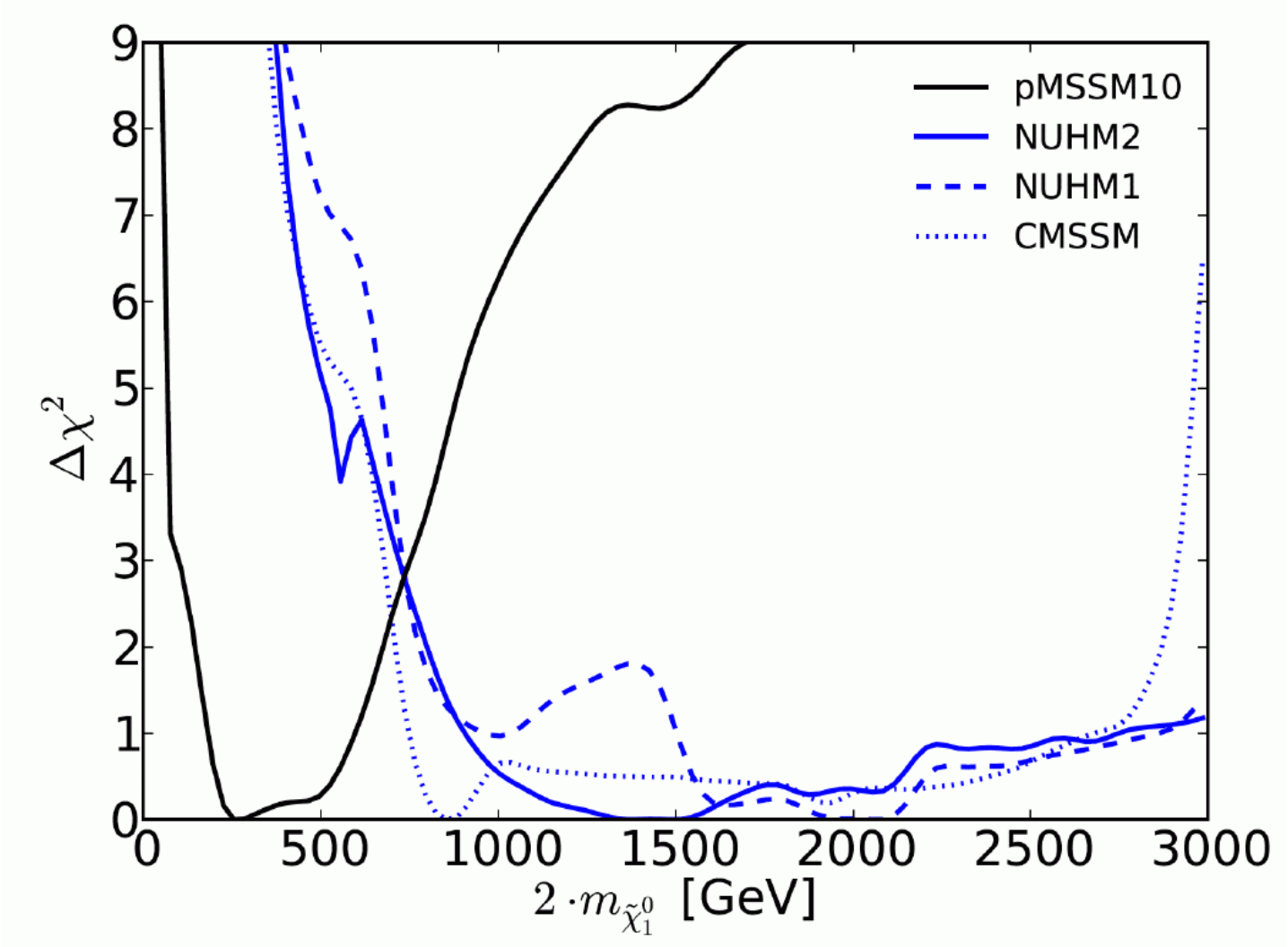


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ precision analysis of DM particle easy!

CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ precision analysis of DM particles easy!

DM production cross sections: $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0(+\gamma)$

[2014]

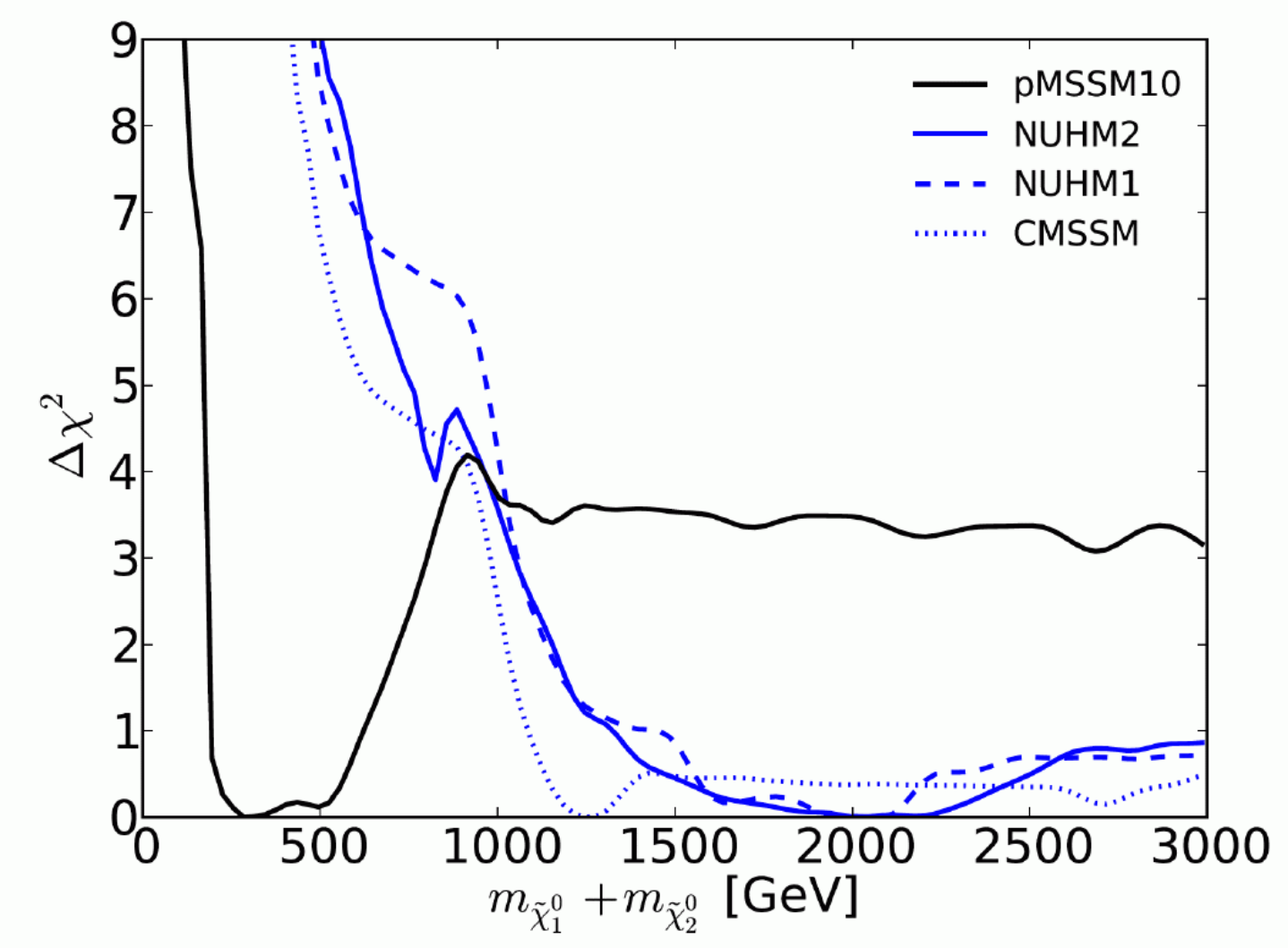


$\Rightarrow$ GUT based models: ILC :-(, CLIC possible

$\Rightarrow$ pMSSM10: easy at the ILC

DM production cross sections: $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$

[2014]



⇒ GUT based models: ILC :-(, CLIC possible

⇒ pMSSM10: easy at the ILC - but no real upper limit