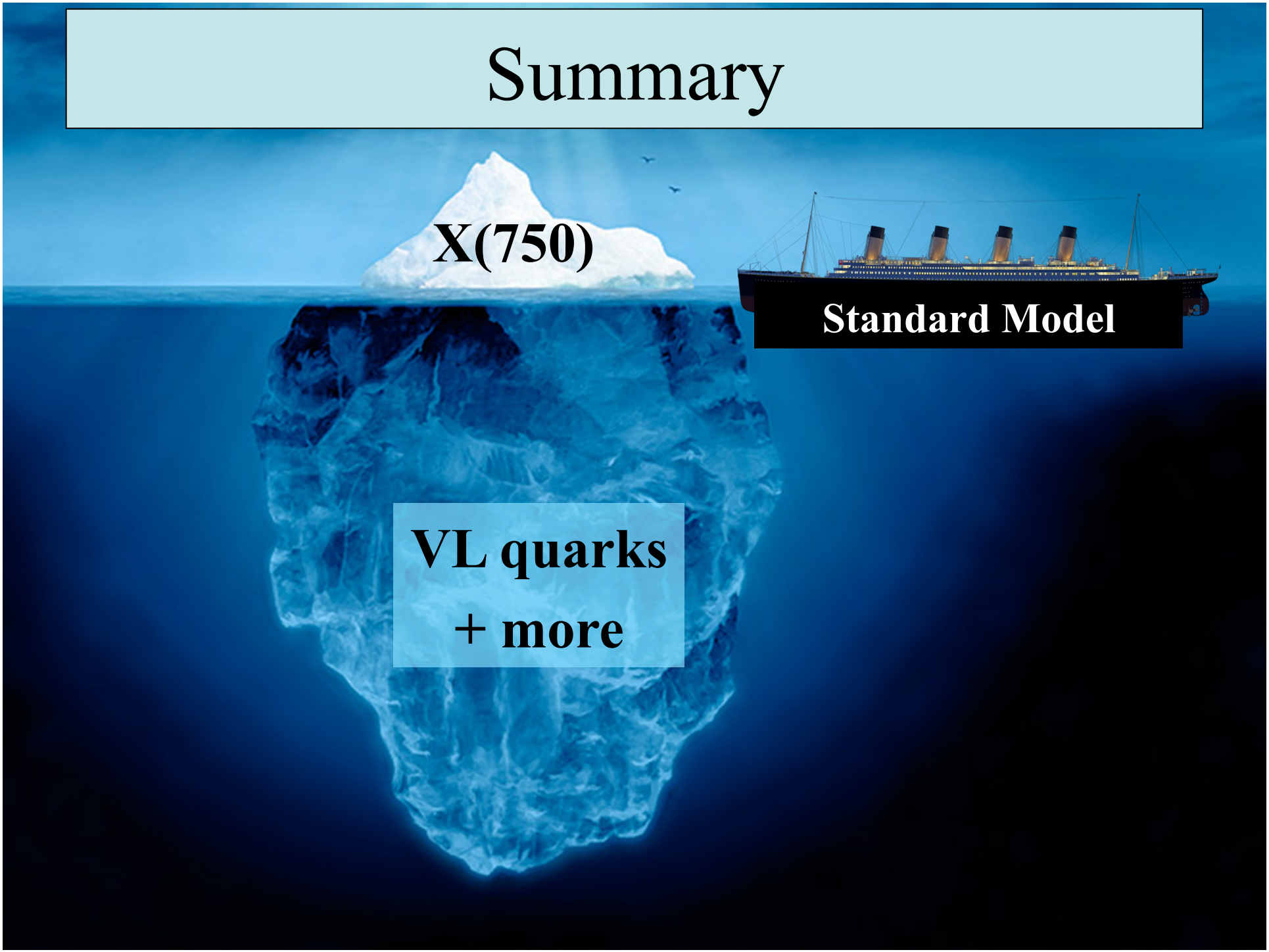
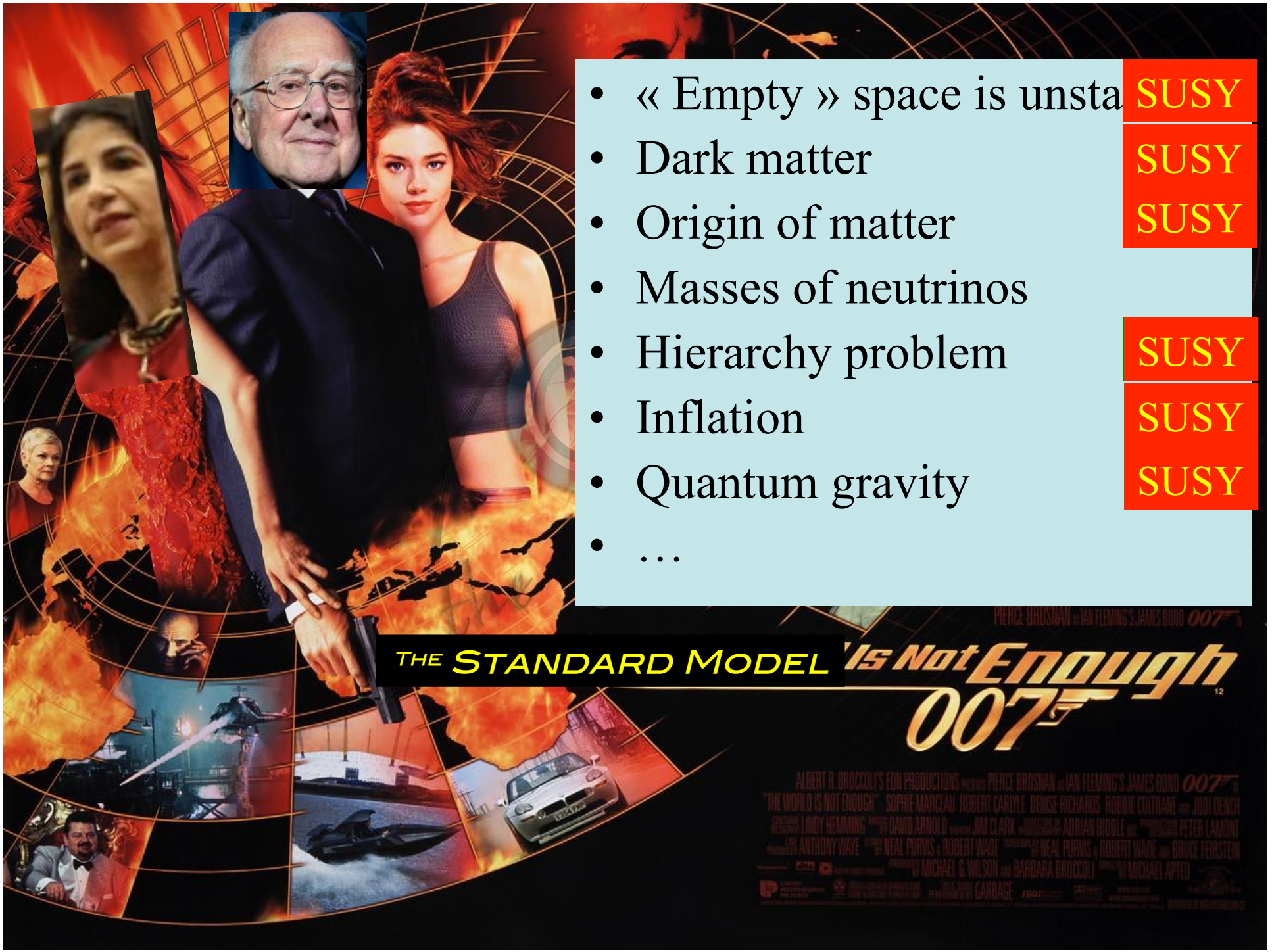
Keep the (S)Faith!

John Ellis

KING'S College LONDON

Summary



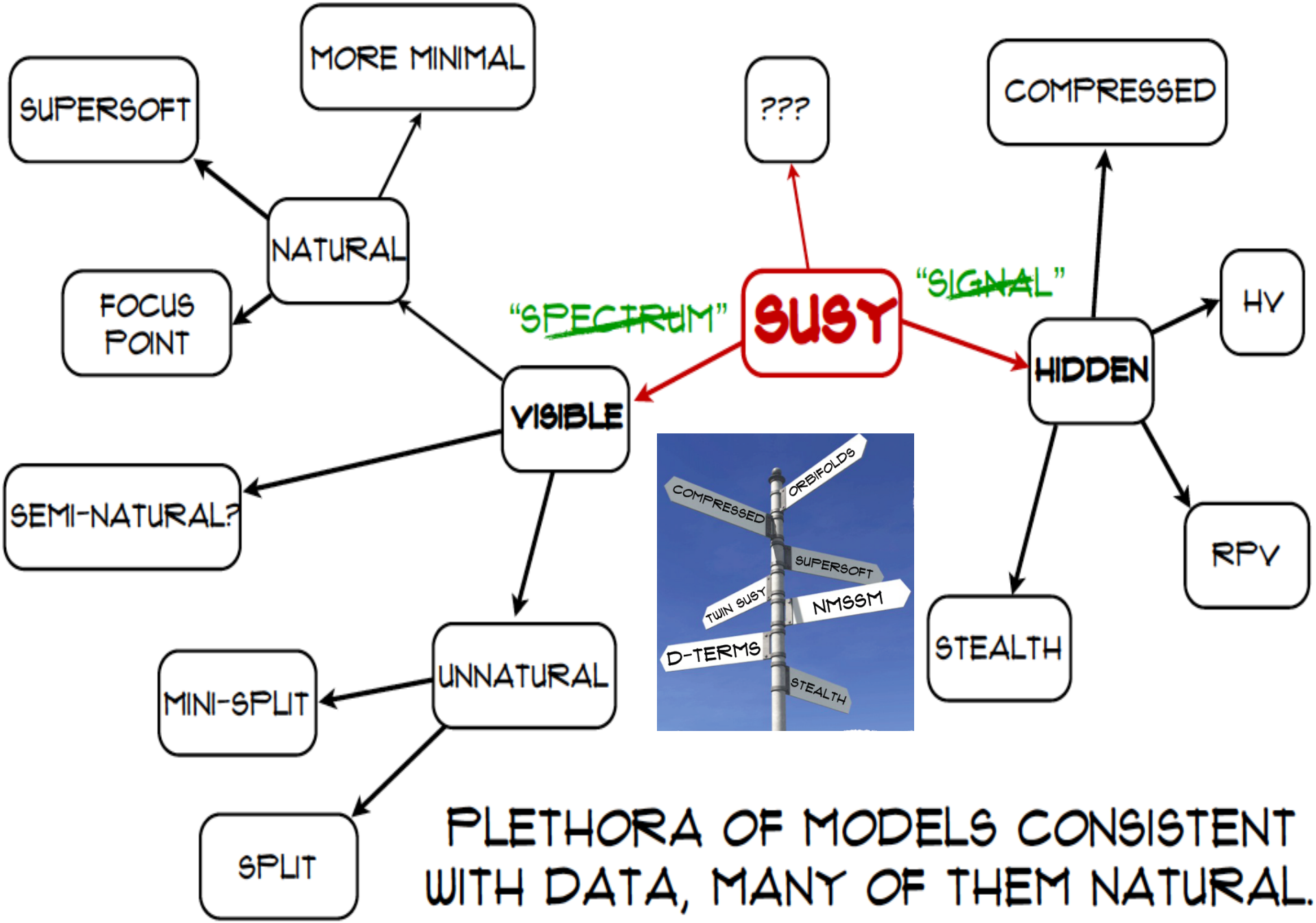

• « Empty » space is unsta SUSY
• Dark matter SUSY
• Origin of matter SUSY
• Masses of neutrinos
• Hierarchy problem SUSY
• Inflation SUSY
• Quantum gravity SUSY
• …
THE STANDARD MODEL
Is Not Enough
007

What lies beyond the Standard Model?

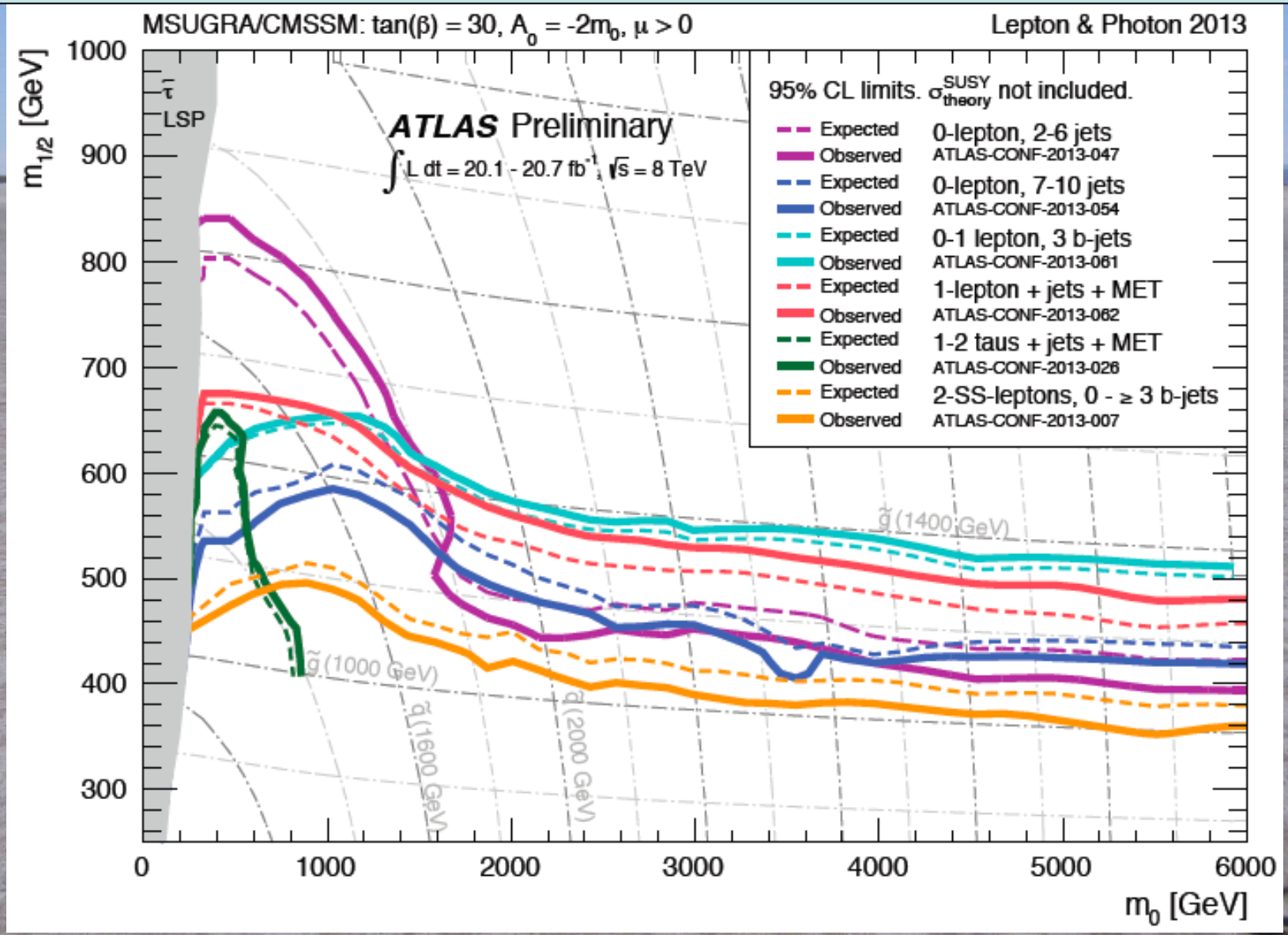
Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

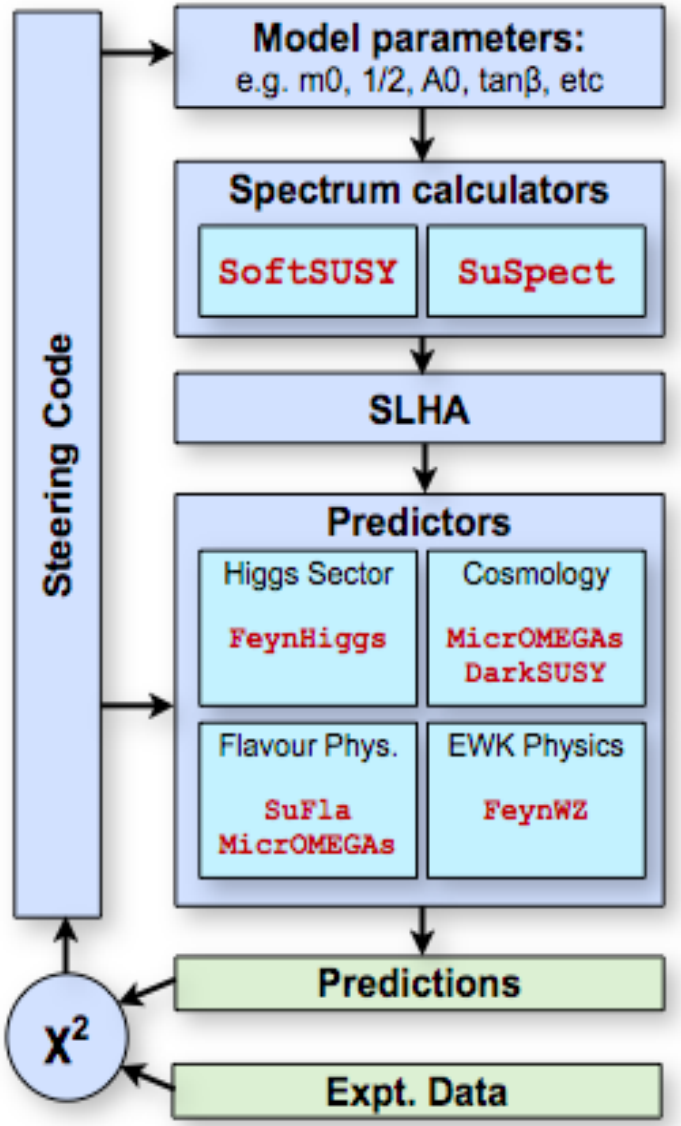

MORE MINIMAL
SUPERSOFT
???
COMPRESSED
NATURAL
FOCUS POINT
"SPECTRUM"
SUSY
"SIGNAL"
HV
HIDDEN
VISIBLE
SEMI-NATURAL?
ORBIFOLDS
COMPRESSED
SUPERSOFT
TWIN SUSY
NMSSM
D-TERMS
STEALTH
RPV
STEALTH
UNNATURAL
MINI-SPLIT
SPLIT
PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL.
WHERE DOES THE DATA POINT US?
Craig@LHCP

Searches with ~ 20/fb @ 8 TeV



MasterCode

- **Combines diverse set of tools**
  - different codes : all state-of-the-art
    - Electroweak Precision (`FeynWZ`)
    - Flavour (`SuFla`, `micrOMEGAs`)
    - Cold Dark Matter (`DarkSUSY`, `micrOMEGAs`)
    - Other low energy (`FeynHiggs`)
    - Higgs (`FeynHiggs`)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- **Compatibility is crucial! Ensured by**
  - close collaboration of tools authors
  - standard interfaces

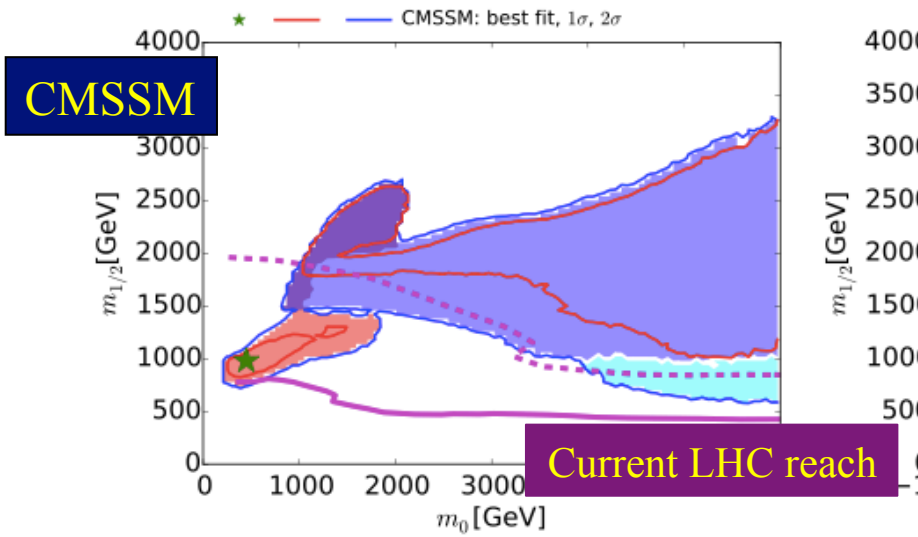


E. Bagnaschi, M. Borsato, O. Buchmueller, R. Cavanaugh, V. Chobanova, M. Citron, J. Costa, A. De Roeck, M.J. Dolan, J.E., H. Flacher, S. Heinemeyer, G. Isidori, M. Lucio, D. Martinez Santos, K.A. Olive, A. Richards, K. Sakurai, G. Weiglein

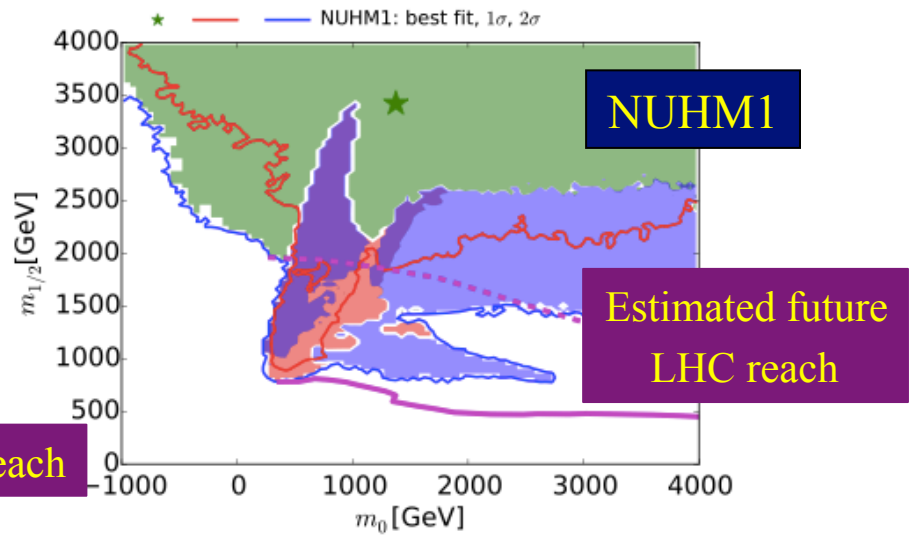
Sample Supersymmetric Models

- Universal soft supersymmetry breaking at input GUT scale?
  - For gauginos and all scalars: CMSSM
  - Non-universal Higgs masses: NUHM1,2
- **Strong pressure from LHC ($p \sim 0.1$)**
- Treat soft supersymmetry-breaking masses as phenomenological inputs at EW scale
  - pMSSMn (n parameters)
  - With universality motivated by upper limits on flavour-changing neutral interactions: pMSSM10
- **Less strongly constrained by LHC ($p \sim 0.3$)**

Dark Matter in CMSSM, NUHM1/2, pMSSM10



CMSSM

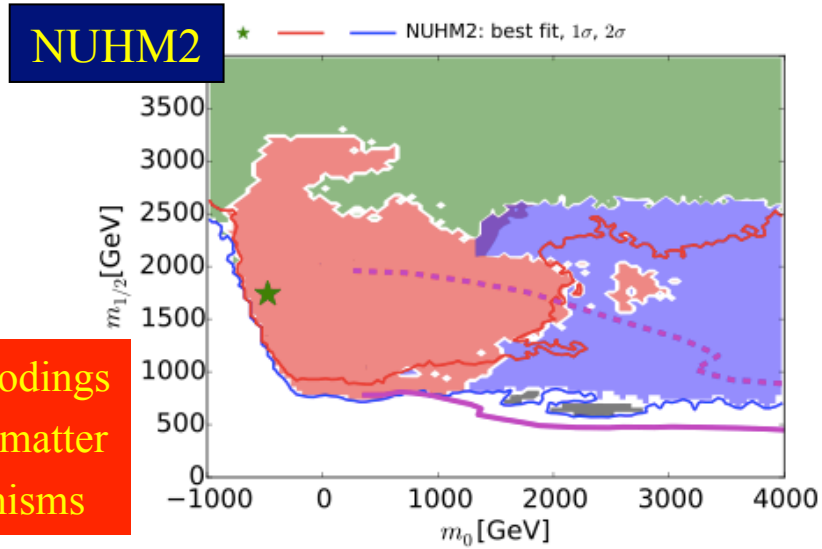


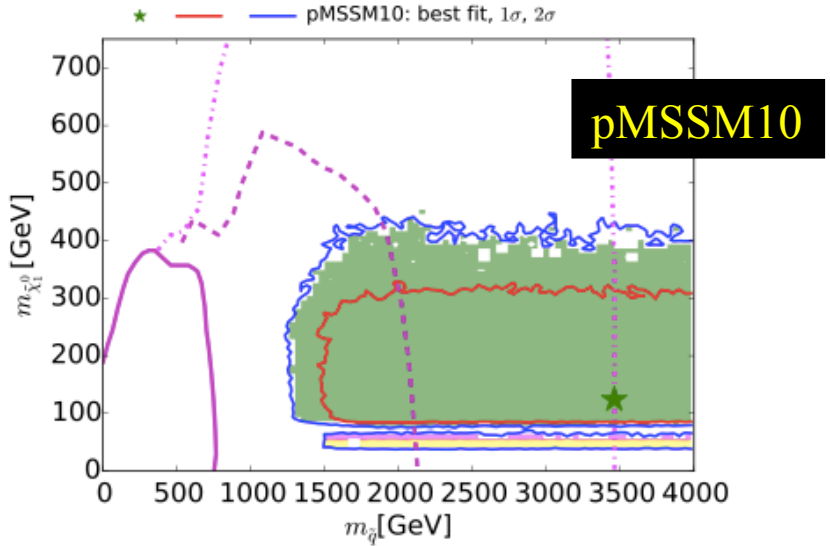
NUHM1

Current LHC reach

Estimated future LHC reach

NUHM2





pMSSM10

Colour codings for dark matter mechanisms

stau coann.

A/H funnel

hybrid

$\tilde{\chi}_1^{\pm}$ coann.

stop coann.

focus point

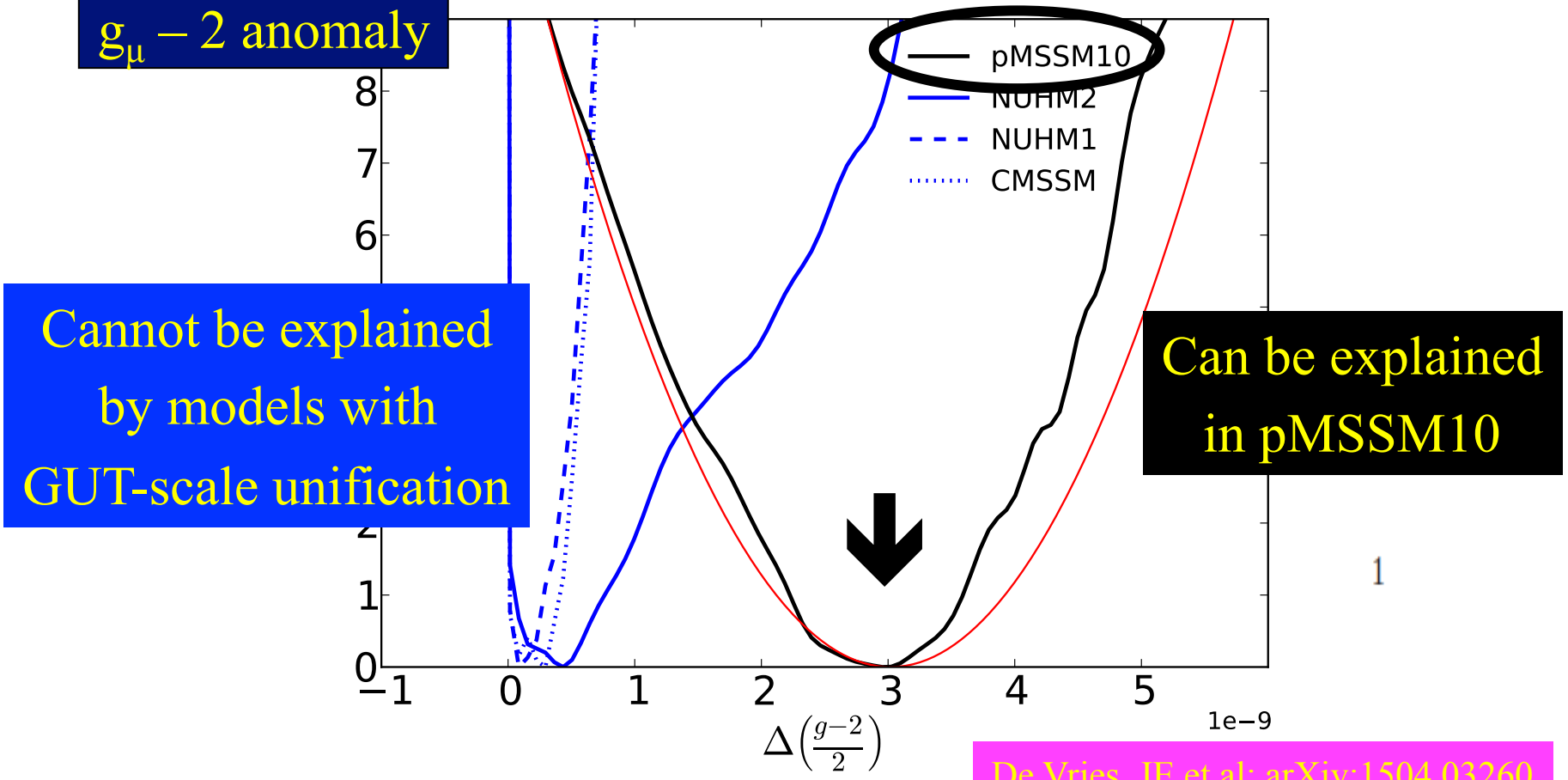
$\tilde{\tau}_1$ coannihilation (pink) :	$\frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} - 1$	$<$	0.15 ,
A/H funnel (blue) :	$\lvert\frac{M_A}{2m_{\tilde{\chi}_1^0}} - 1\rvert$	$<$	0.2 ,
$\tilde{\chi}_1^{\pm}$ coannihilation (green) :	$\frac{m_{\tilde{\chi}_1^{\pm}}}{m_{\tilde{\chi}_1^0}} - 1$	$<$	0.1 ,
$\tilde{t}_1$ coannihilation (grey) :	$\frac{m_{\tilde{t}_1}}{m_{\tilde{\chi}_1^0}} - 1$	$<$	0.2 .

Bagnaschi, JE et al: arXiv:1508.01173

Anomalous Magnetic Moment of Muon

2012 ATLAS + CMS with 20/fb of LHC Data

$g_\mu - 2$ anomaly



Cannot be explained by models with GUT-scale unification

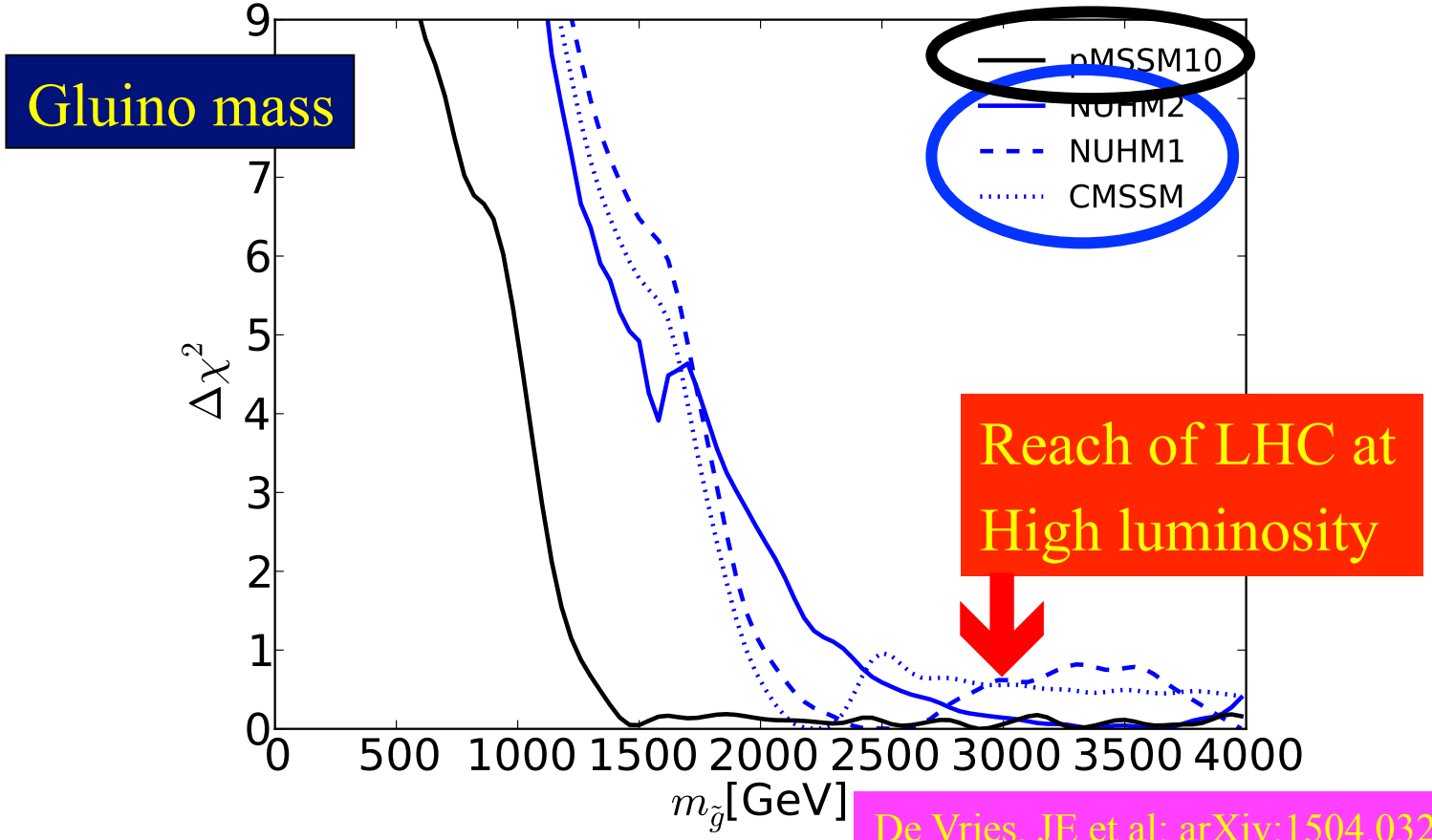
Can be explained in pMSSM10

De Vries, JE et al: arXiv:1504.03260

pMSSM10 can explain experimental measurements of g_μ - 2

Fits to Supersymmetric Models

2012 ATLAS + CMS with 20/fb of LHC Data

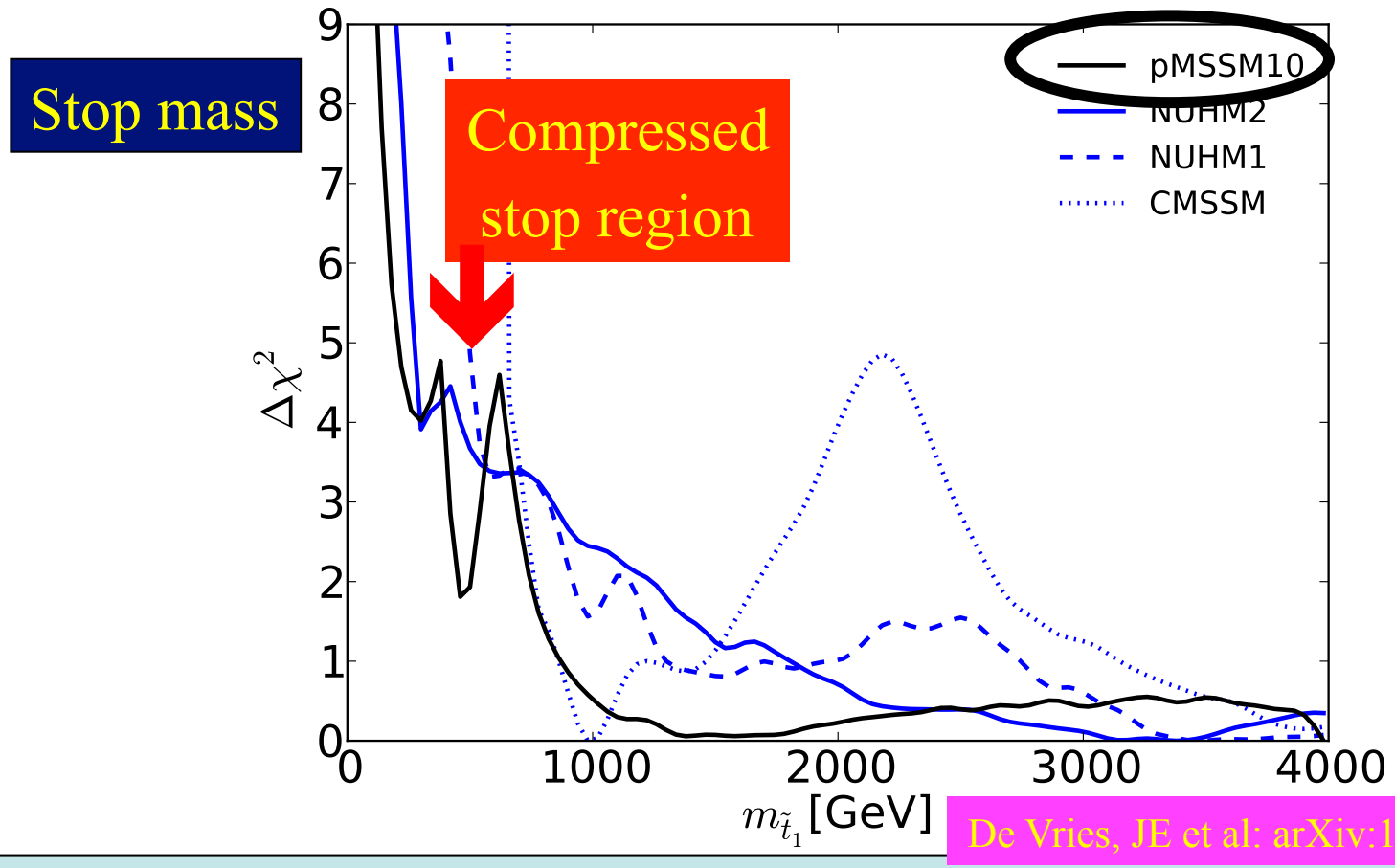


De Vries, JE et al: arXiv:1504.03260

Favoured values of gluino mass also significantly above pre-LHC, > 1.2 TeV

Fits to Supersymmetric Models

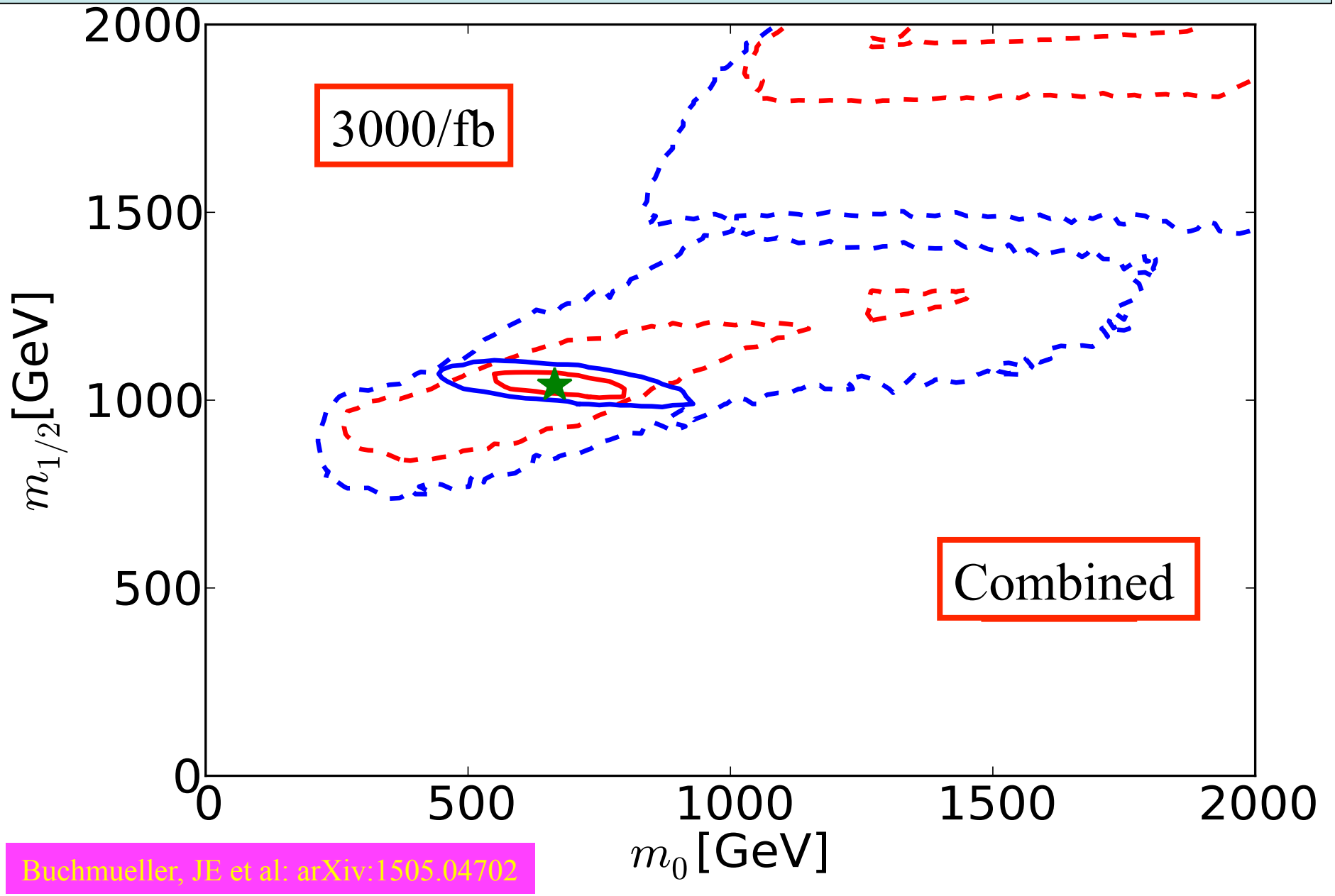
2012 ATLAS + CMS with 20/fb of LHC Data



De Vries, JE et al: arXiv:1504.03260

Remaining possibility of a light "natural" stop weighing ~ 400 GeV

Measuring the CMSSM with the LHC



Buchmueller, JE et al: arXiv:1505.04702

Long-Lived Stau in CMSSM, NUHM?

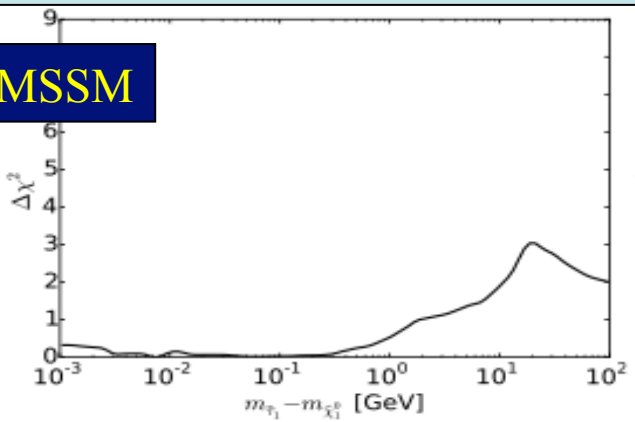
Possible if $m_{stau} - m_{LSP} < m_\tau$

Generic possibility in CMSSM, NUHM1, NUHM2

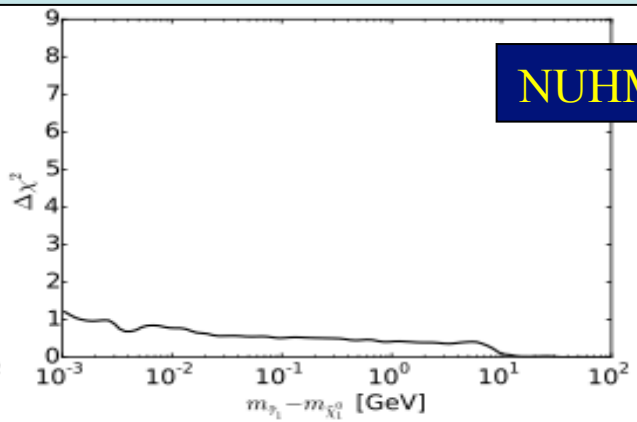
(stau coannihilation region)

Bagnaschi, JE et al: arXiv:1508. 01173

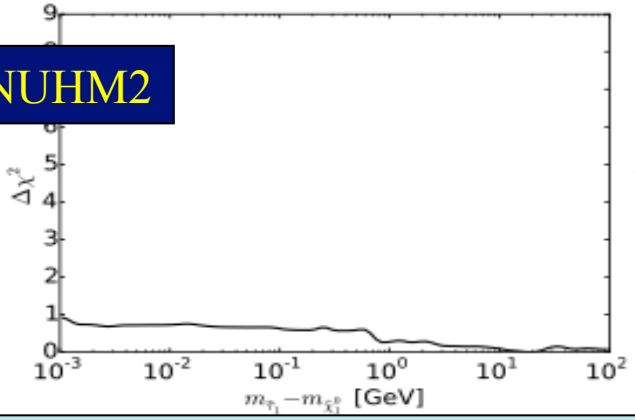
CMSSM



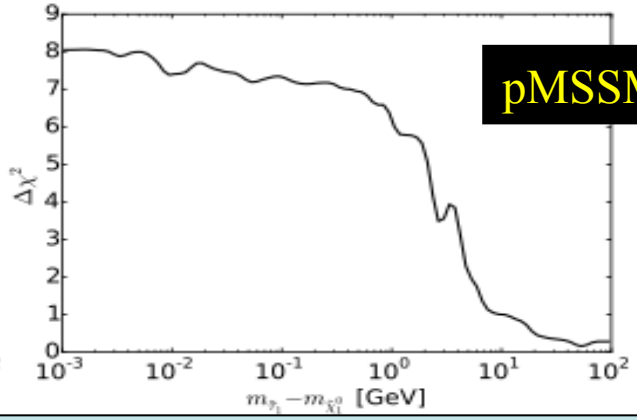
NUHM1



NUHM2



pMSSM10



$\tau_{stau} > 10^3$ s gives problems with nucleosynthesis

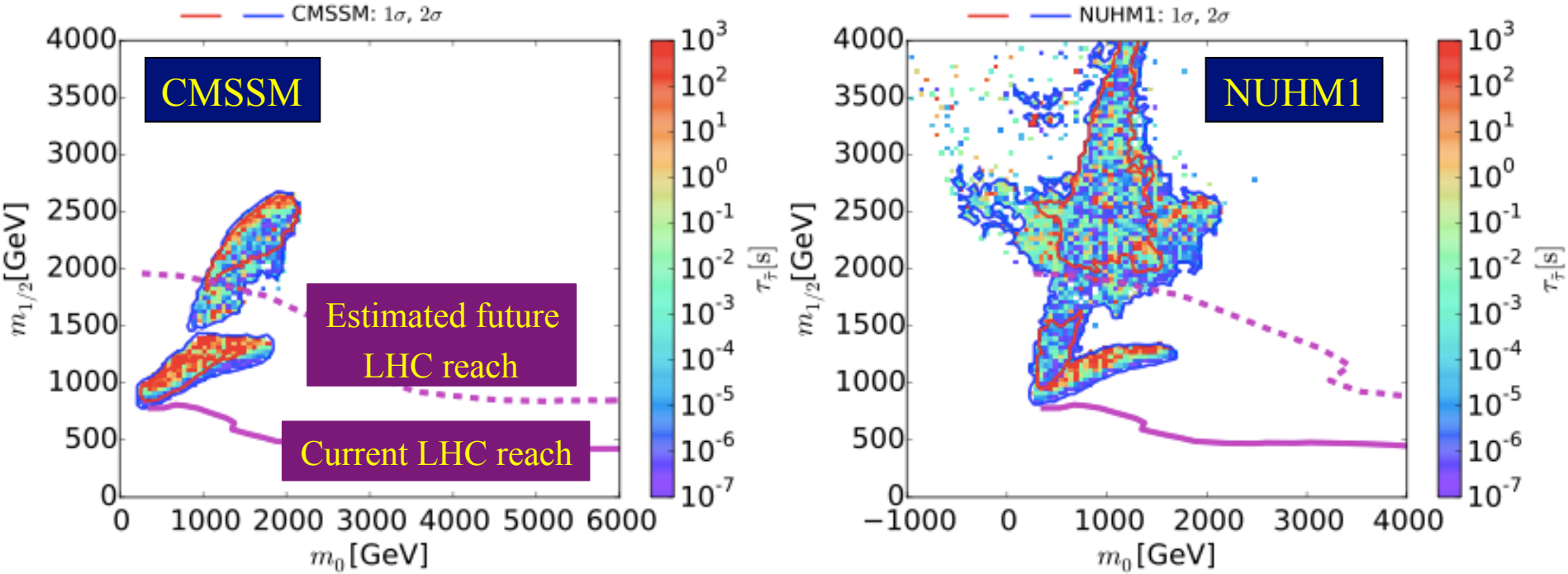
$\tau_{stau} > 10^{-7}$ s gives separated vertex signature

Long-Lived Stau in CMSSM, NUHM?

Possible if $m_{stau} - m_{LSP} < m_{\tau}$

Generic possibility in CMSSM, NUHM

(stau coannihilation region)



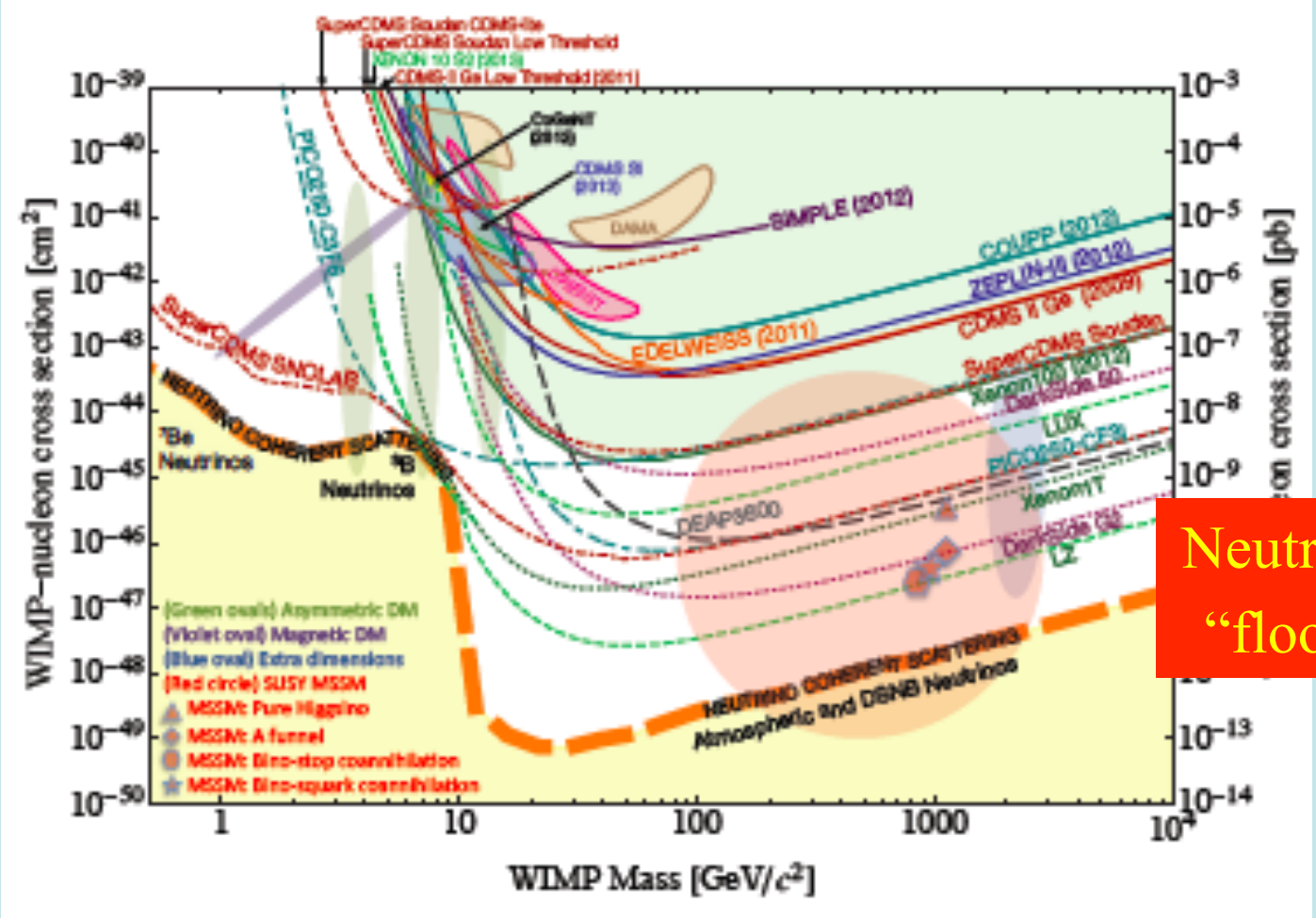
$\tau_{stau} > 10^{3}$ s gives problems with nucleosynthesis

$\tau_{stau} > 10^{-7}$ s gives separated vertex signature **for τ-like decays**

Bagnaschi, JE et al: arXiv:1508. 01173

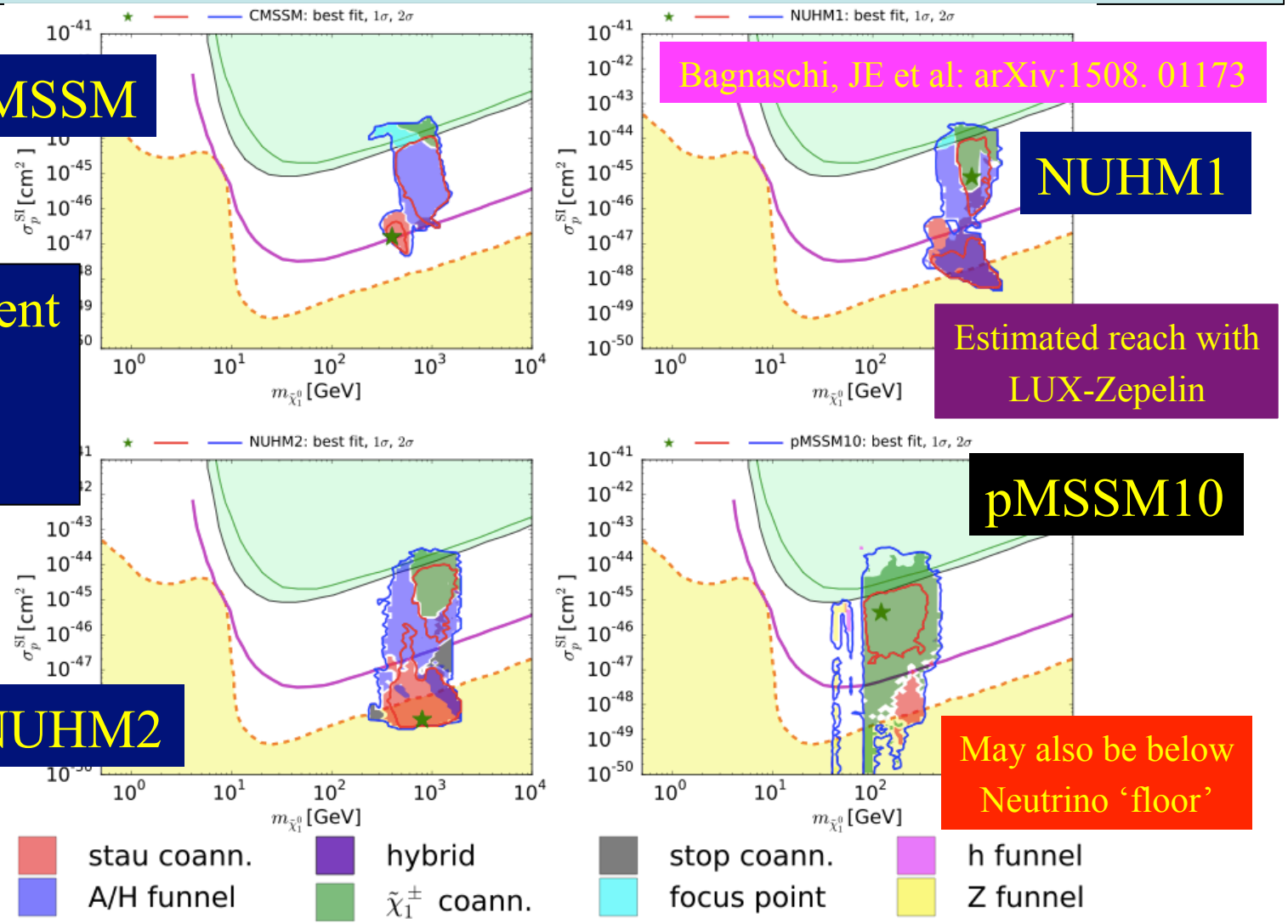
Direct Dark Matter Searches

- Compilation of present and future sensitivities



Neutrino "floor"

Direct Dark Matter Search



CMSSM

NUHM1

Bagnaschi, JE et al: arXiv:1508. 01173

Spin-independent dark matter scattering

Estimated reach with LUX-Zepelin

pMSSM10

NUHM2

May also be below Neutrino 'floor'

Direct scattering cross-section may be very close to LUX upper limit, accessible to LZ experiment

Prospects for SUSY Searches

- Different models, various dark matter mechanisms

DM mechanism	Exp't	Models			
		CMSSM	NUHM1	NUHM2	pMSSM10
$\tilde{\tau}_1$	LHC	✓ $\not{E}_T$, ✓ LL	(✓ $\not{E}_T$, ✓ LL)	(✓ $\not{E}_T$, ✓ LL)	(✓ $\not{E}_T$), × LL
coann.	DM	(✓)	(✓)	×	×
$\tilde{\chi}_1^{\pm}$	LHC	–	×	×	(✓ $\not{E}_T$)
coann.	DM	–	✓	✓	(✓)
$\tilde{t}_1$	LHC	–	–	✓ $\not{E}_T$	–
coann.	DM	–	–	×	–
A/H	LHC	✓ A/H	(✓ A/H)	(✓ A/H)	–
funnel	DM	✓	✓	(✓)	–
Focus	LHC	(✓ $\not{E}_T$)	–	–	–
point	DM	✓	–	–	–
h, Z	LHC	–	–	–	(✓ $\not{E}_T$)
funnels	DM	–	–	–	(✓)

- No guarantees, but good prospects

Bagnaschi, JE et al: arXiv:1508. 01173

Constraints from ICHEP 2016

2016 ATLAS with 13/fb LHC Data

Supersymmetric SU(5) model:
5 SUSY X parameters

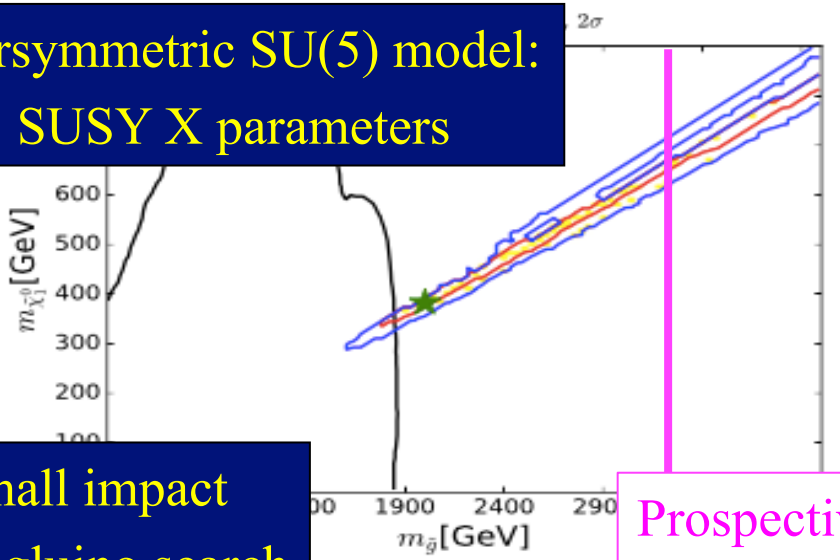
Small impact
from gluino search

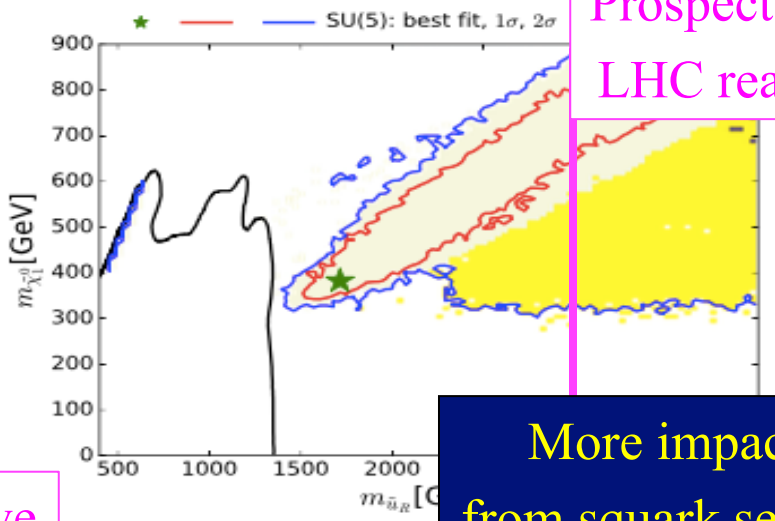
Prospective
LHC reach

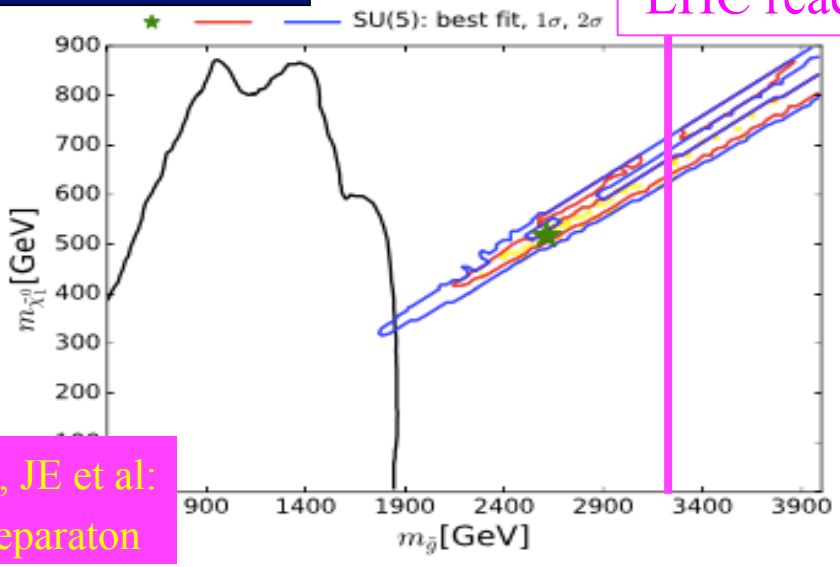
Prospective
LHC reach

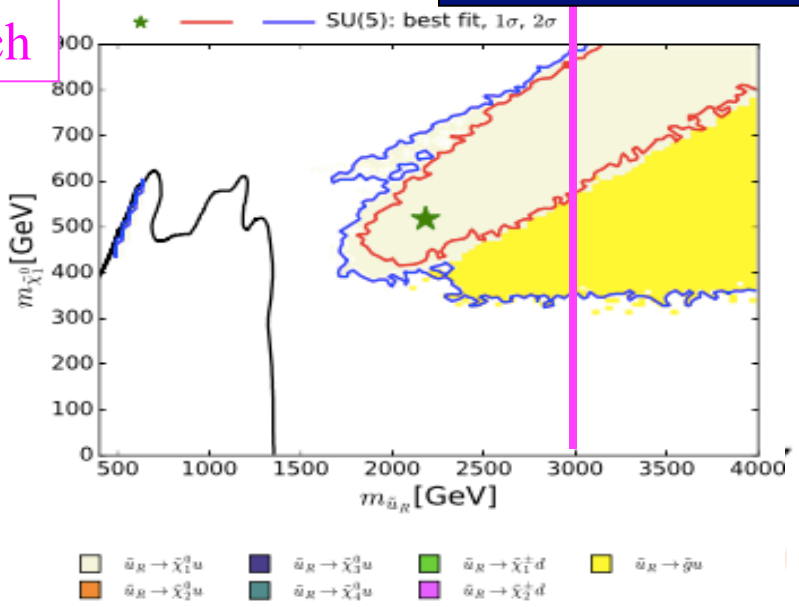
More impact
from squark search

Costa, JE et al:
in preparaton





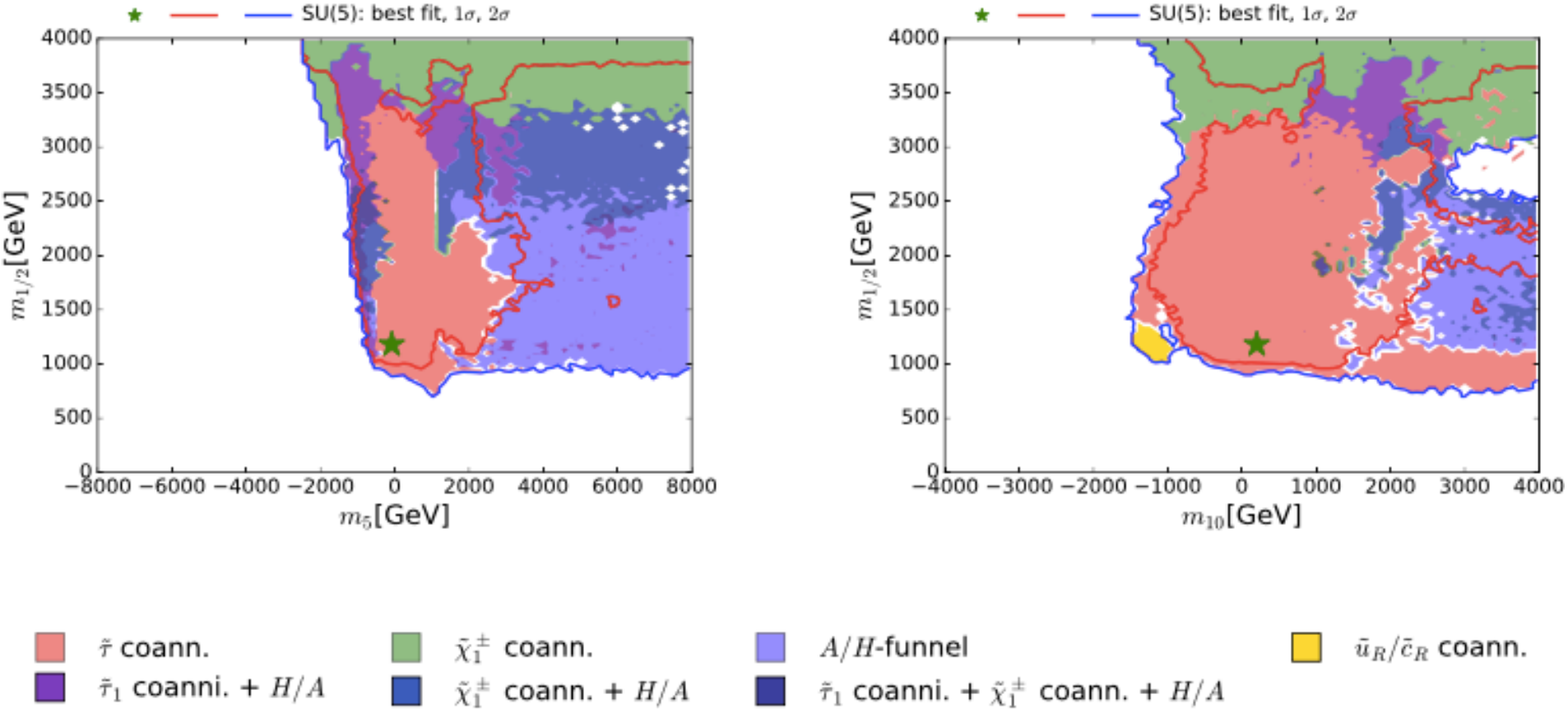




Constraints from ICHEP 2016

2016 ATLAS with 13/fb LHC Data

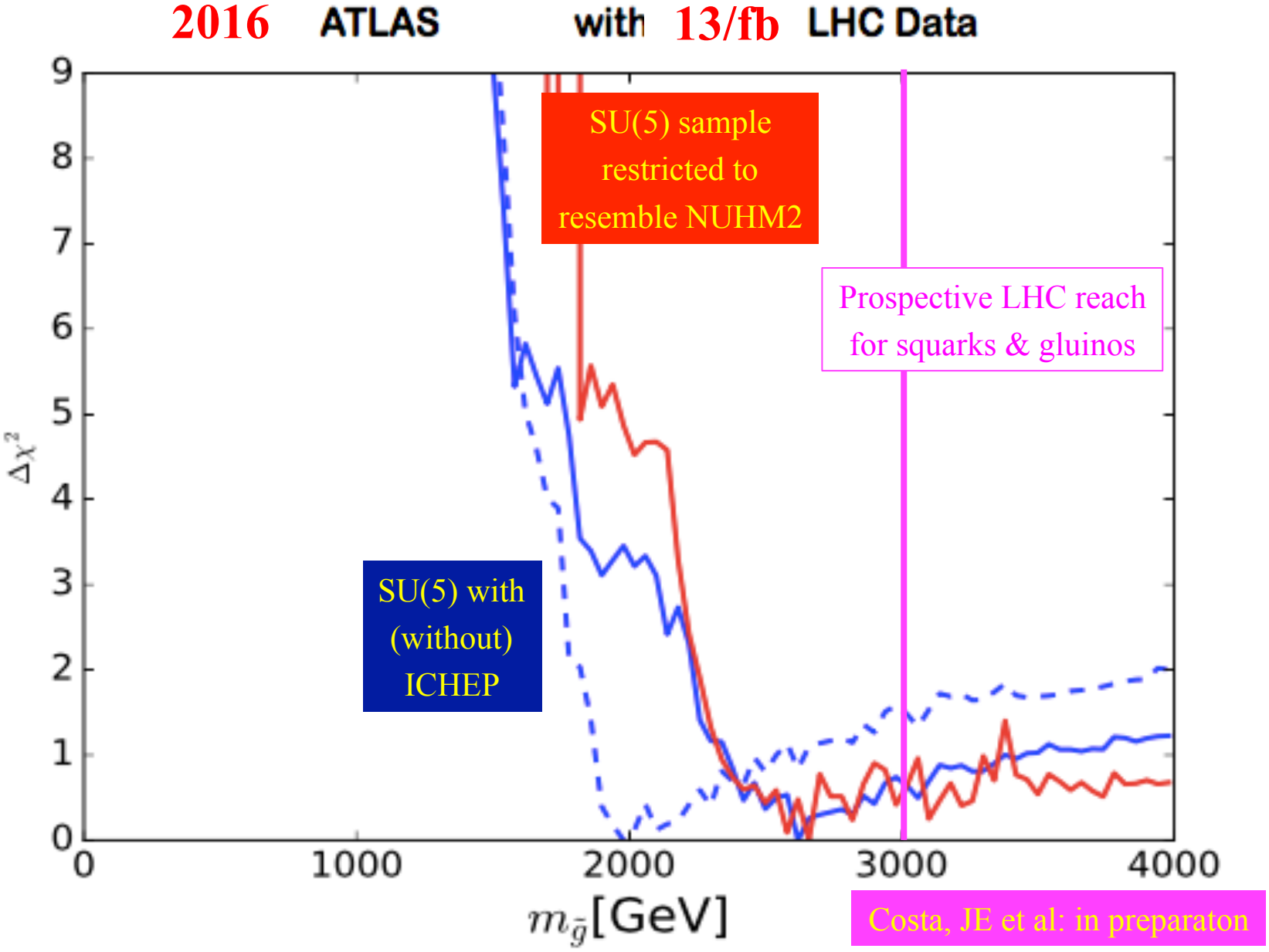
Parameter planes in supersymmetric SU(5) model



Colour-coded according to dominant mechanisms for fixing dark matter density

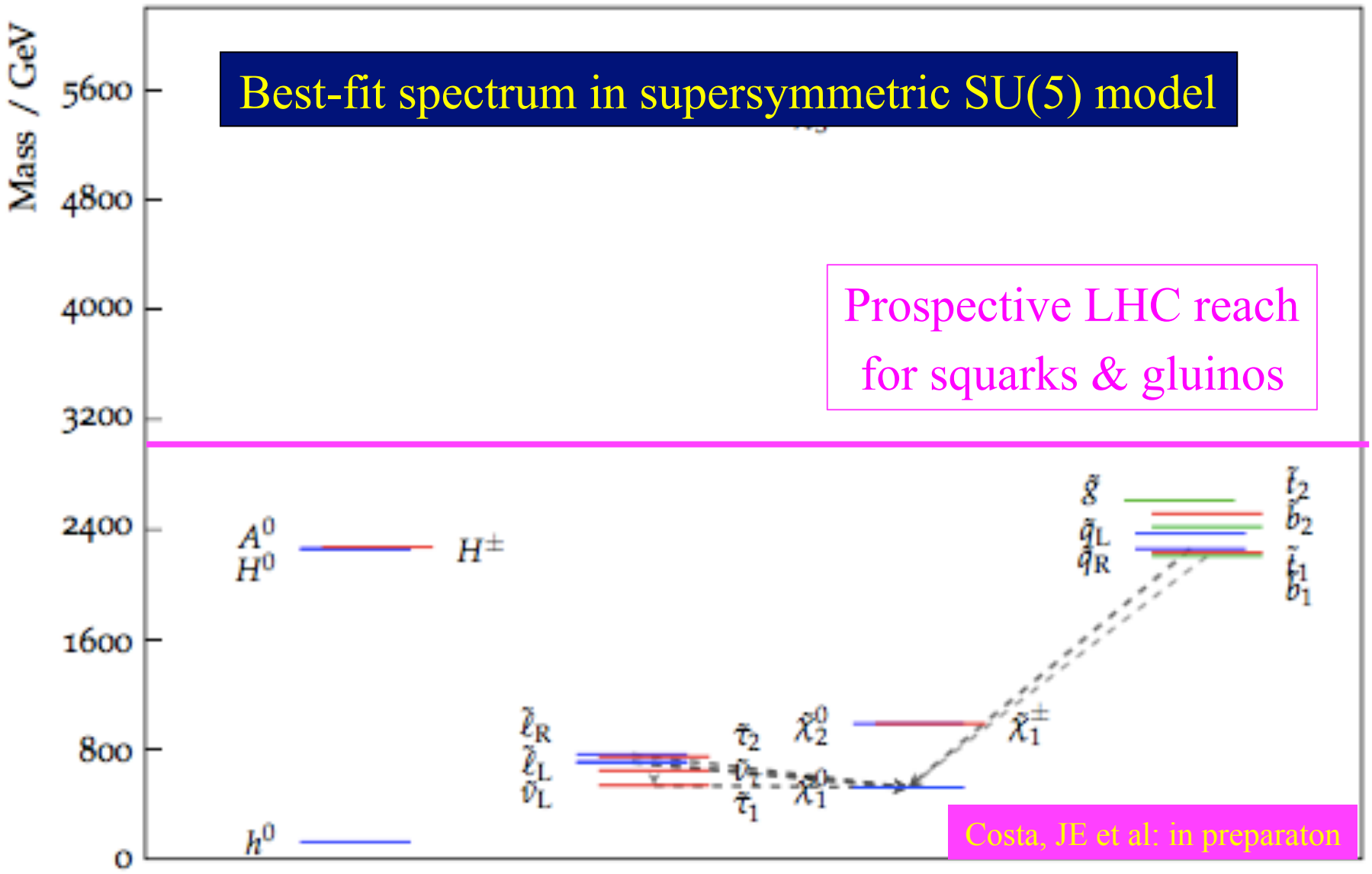
Costa, JE et al: in preparaton

Constraints from ICHEP 2016



Constraints from ICHEP 2016

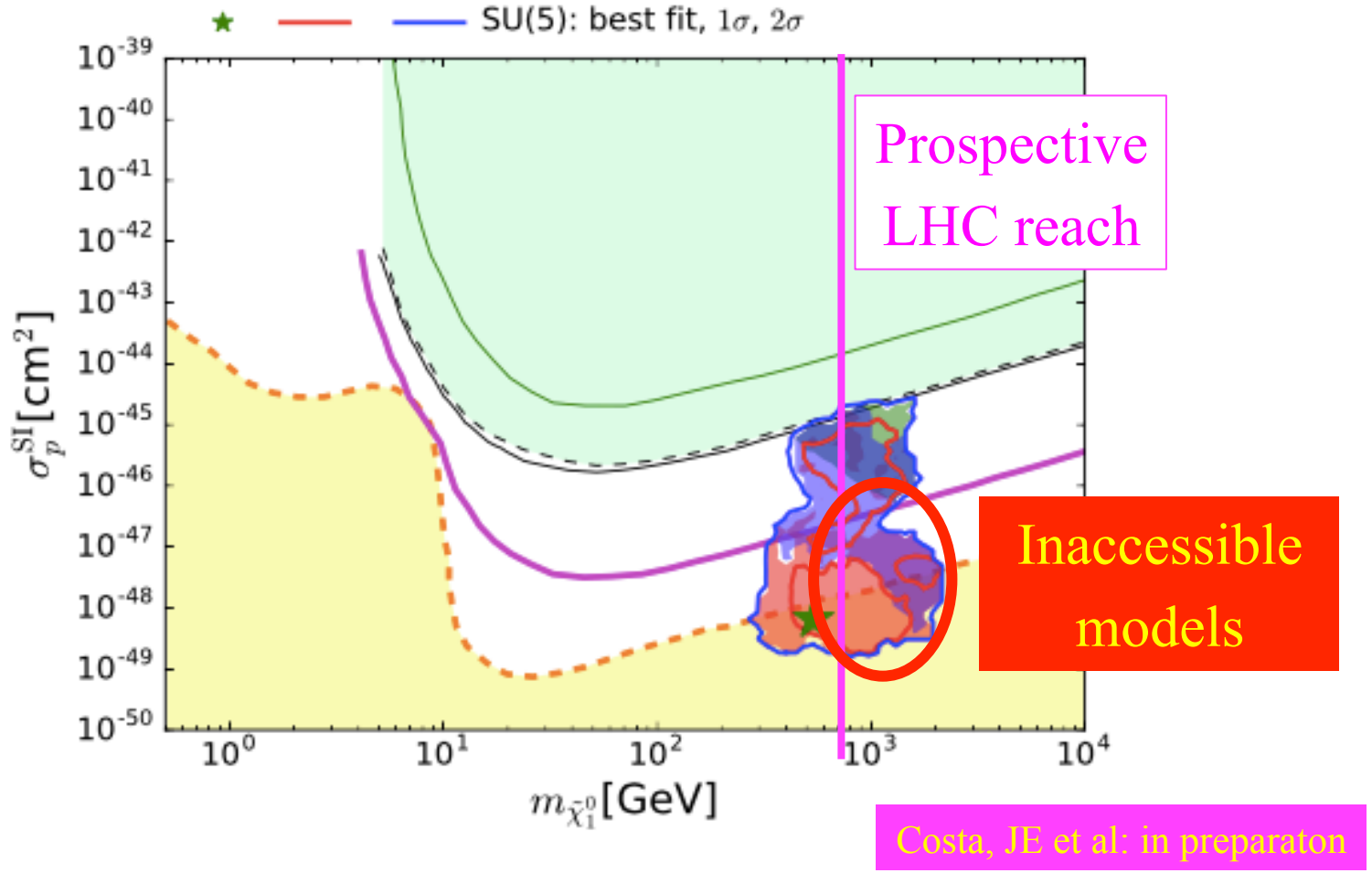
2016 ATLAS with 13/fb LHC Data



Constraints from ICHEP 2016

2016 ATLAS with 13/fb LHC Data

Direct Dark Matter scattering in supersymmetric SU(5) model



More Supersymmetry, not less?

JE, Quevillon & Sanz: arXiv:1607.05541

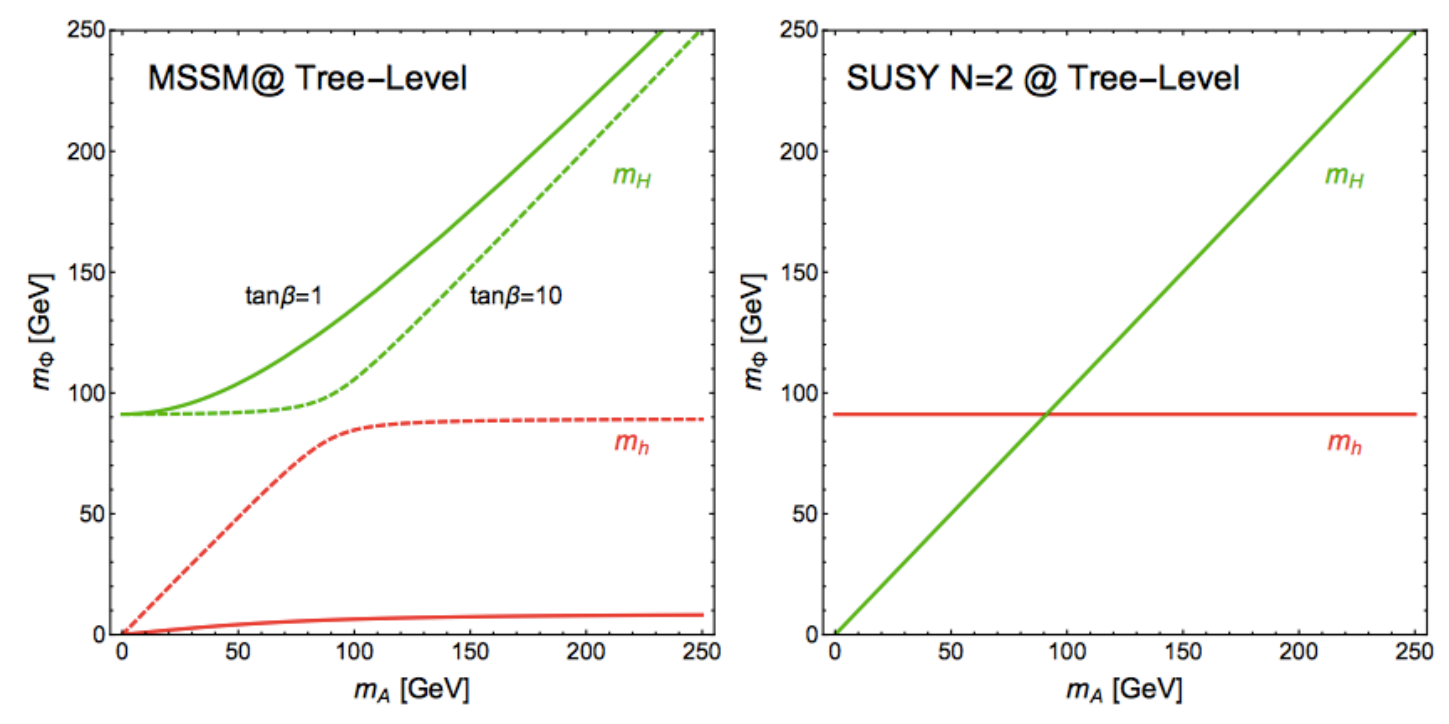
- 750 GeV ☹ ➔re-examined vector-like fermions
- Appear in many extensions of the Standard Model
  - Five-dimensional models
  - String compactifications
  - GUTs
- Could accommodate N=2 supersymmetry
- **Double up on supersymmetry?**
- N=2 gauge sector?
- **Higgs sector also vector-like, could be N=2**

Doubling up on Supersymmetry

JE, Quevillon & Sanz: arXiv:1607.05541

- Higgs sector as portal to N=2 world at TeV scale?
- Tree-level neutral Higgses:

$$\mathcal{M}^{2,N2}_{\rm tree} = \begin{pmatrix} m_Z^2\cos^2\beta + m_A^2\sin^2\beta & -(m_A^2 - m_Z^2)\cos\beta\sin\beta \\ -(m_A^2 - m_Z^2)\cos\beta\sin\beta & m_Z^2\sin^2\beta + m_A^2\cos^2\beta \end{pmatrix} \qquad m_h^{N2} = m_Z; \quad m_H^{N2} = m_A$$

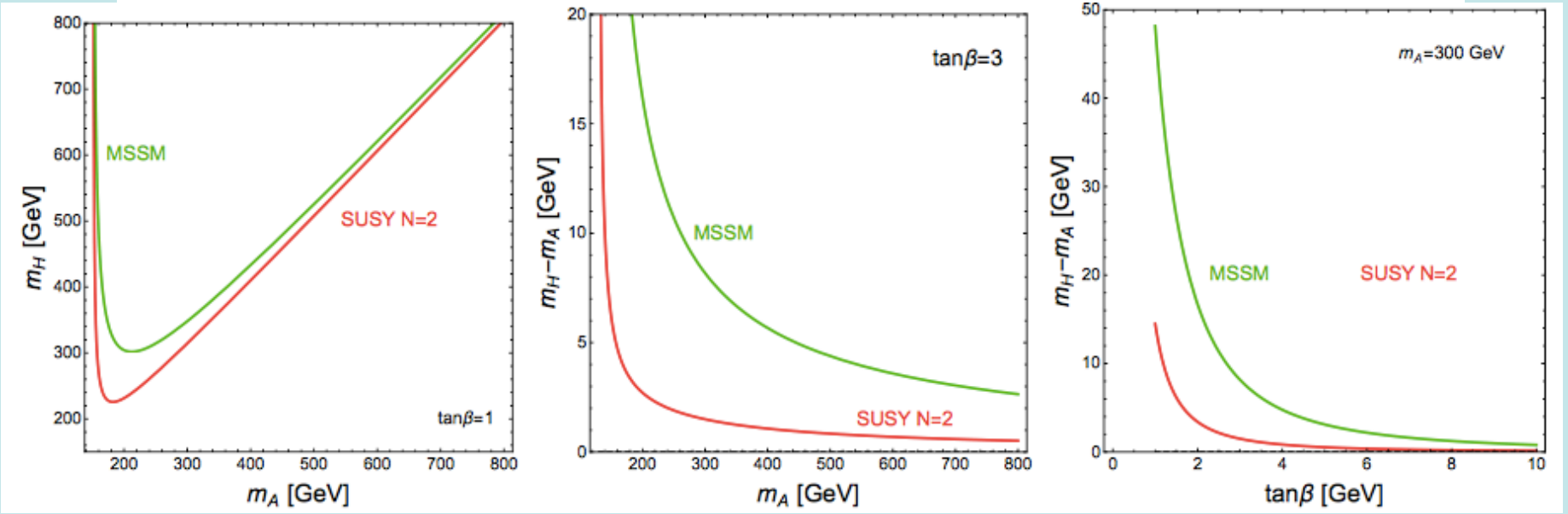


Doubling up on Supersymmetry

JE, Quevillon & Sanz: arXiv:1607.05541

- Include 1-loop radiative corrections from stops
- Require lighter scalar neutral Higgs @ 125 GeV

$$\epsilon_{N2} = \Delta\mathcal{M}^{2,N2}_{22} = \frac{2(m_A^2 - m_h^2)(m_h^2 - m_Z^2)}{\cos 2\beta\,(m_Z^2 - m_A^2) + m_A^2 - 2m_h^2 + m_Z^2}$$

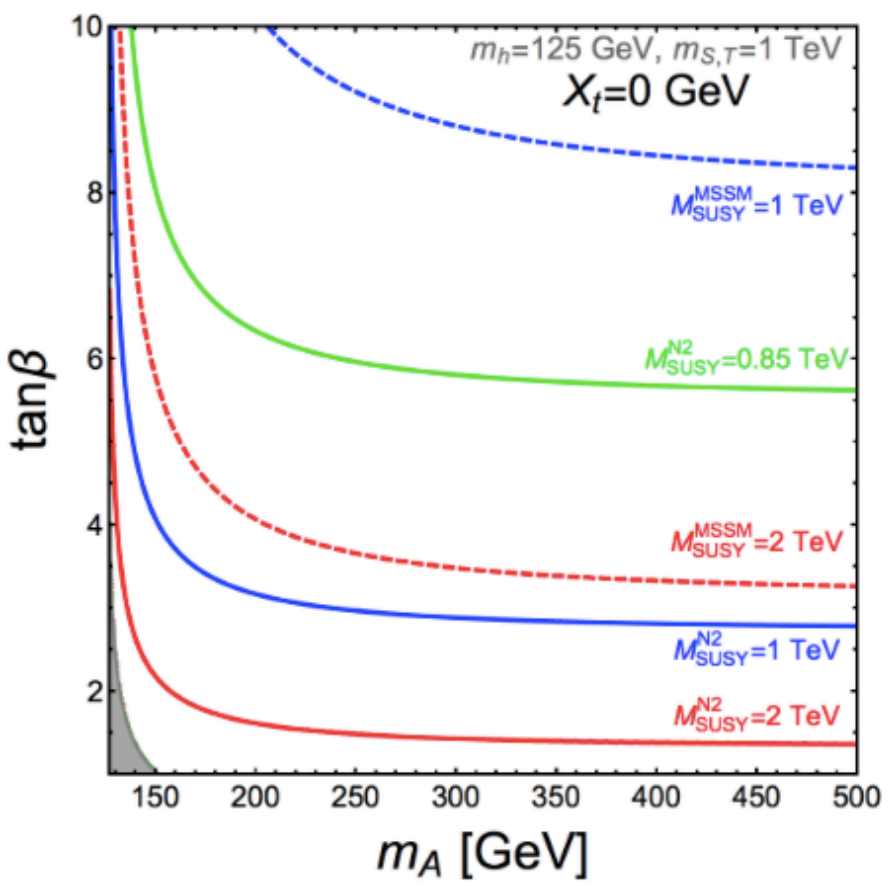


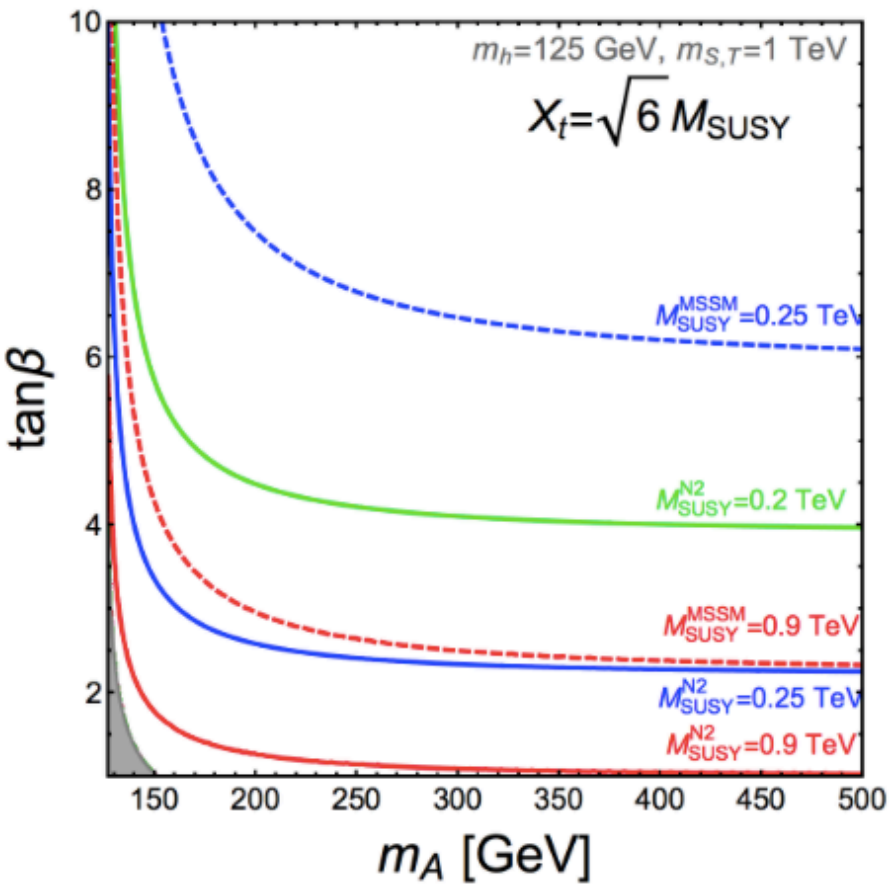
- H can be lighter than in MSSM, $m_H - m_A$ smaller

Doubling up on Supersymmetry

JE, Quevillon & Sanz: arXiv:1607.05541

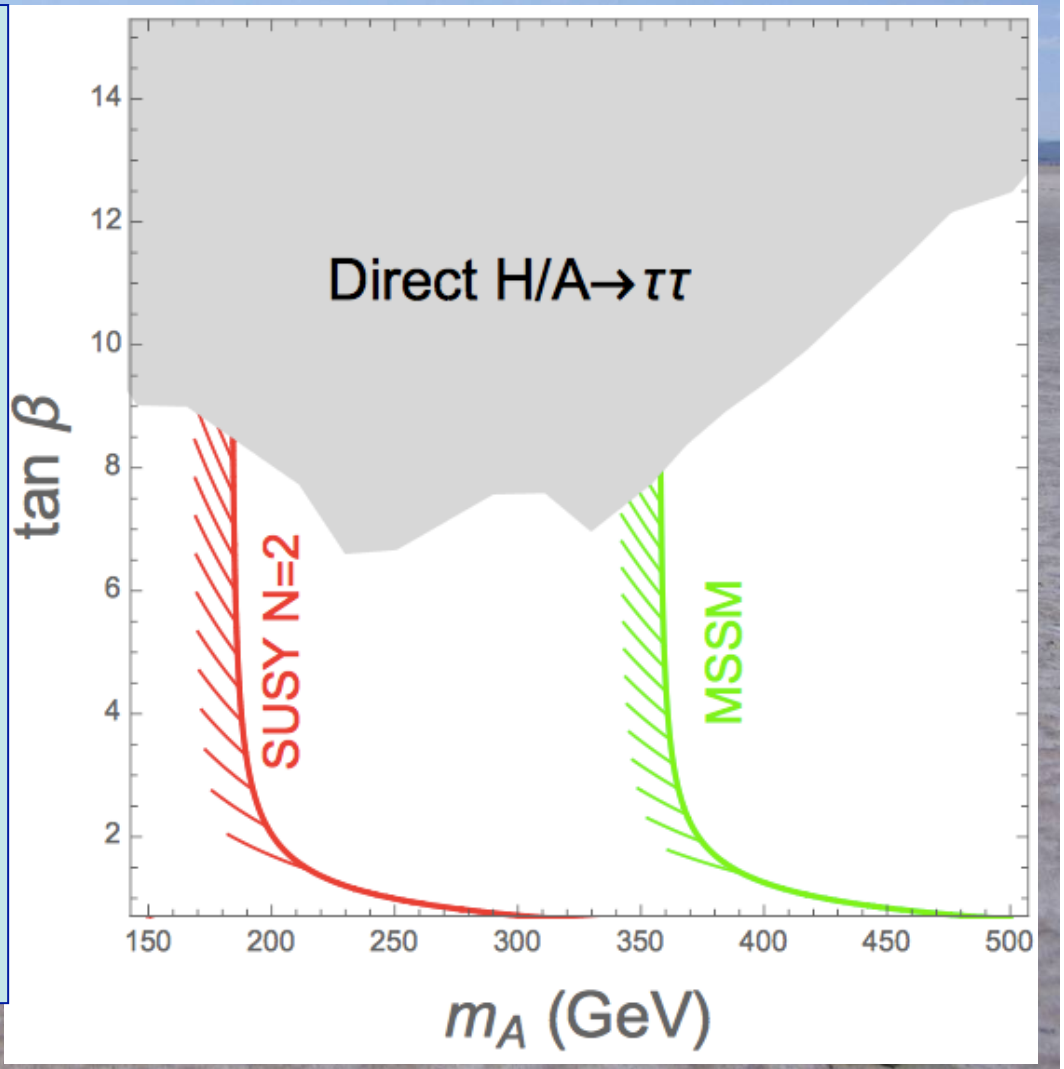
- **M_{SUSY} smaller than MSSM for same $m_{h,A}$, tan β**





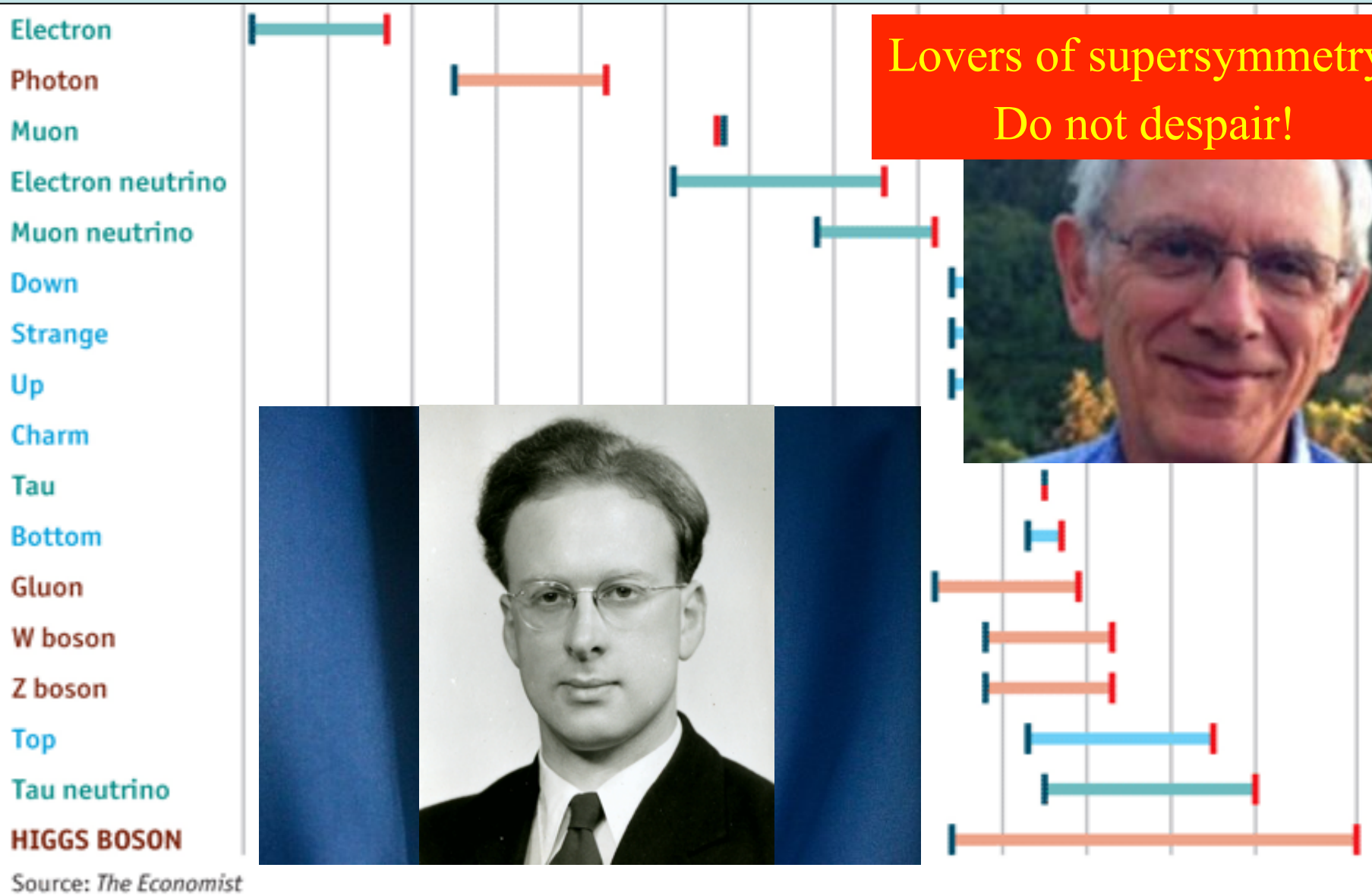
Doubling up on Supersymmetry

- Including LHC constraints
- m_A can be smaller than in MSSM for all tan β
- Supersymmetry and SUSY Higgses may be closer than suggested by MSSM



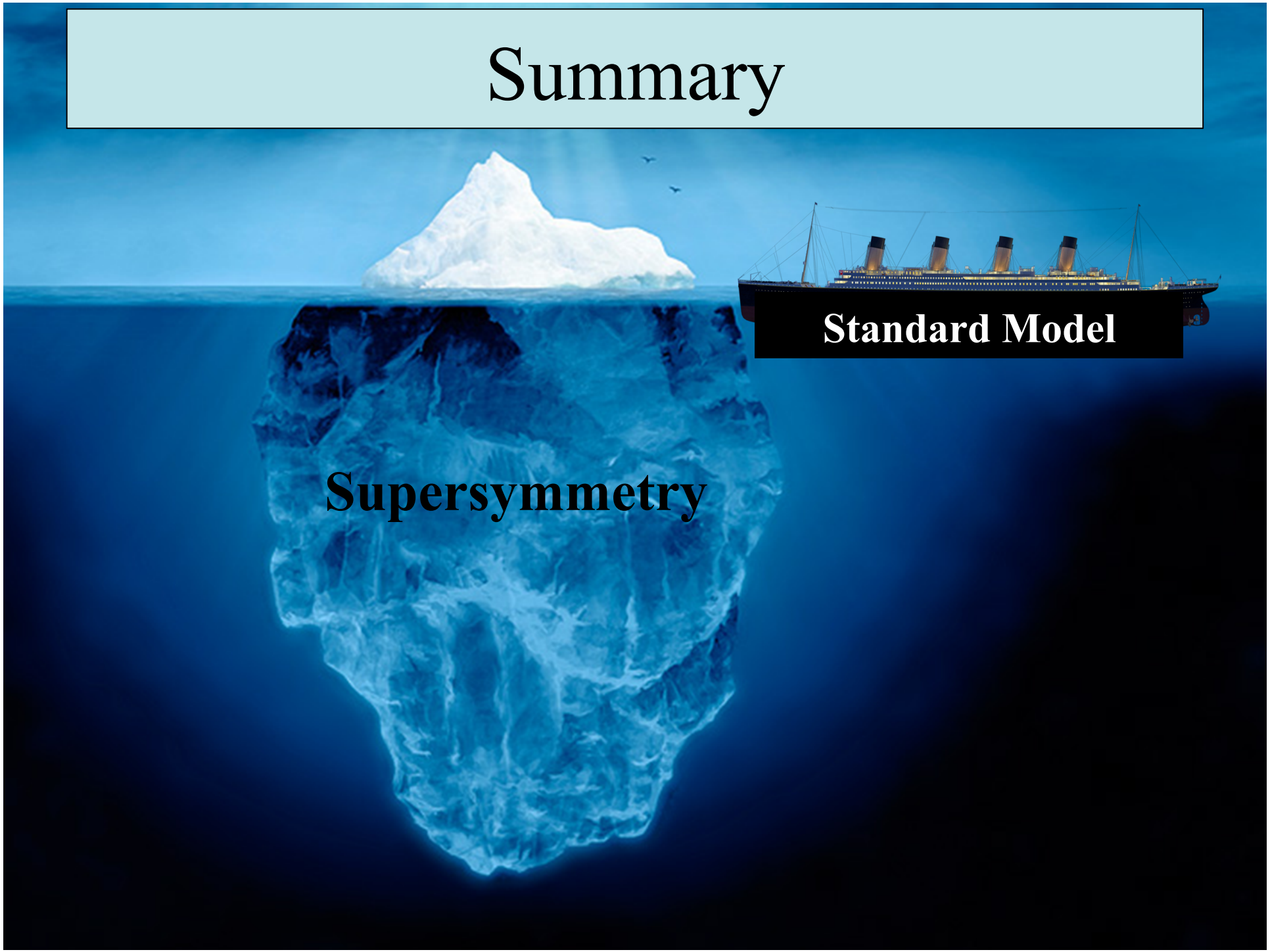
JE, Quevillon & Sanz: arXiv:1607.05541

Standard Model Particles:
Years from Proposal to Discovery



Still **Optimistically** Seeking SUSY

Summary



CERN's Next Major Discovery?

Cern 'greatest discovery yet'

Scientists at the Cern laboratory in Switzerland believe the Hadron Collider has detected traces of a coherent plan for UK Brexit.

"If this is true, it surely is the discovery of the century, one that puts finding the Higgs boson totally in the shade. This is massive," said one leading scientist.

"People have long theorised that a coherent plan for the UK exiting Europe could theoretically exist, but to have found proof of its existence now is something no one expected."

Other scientists were quick to urge caution, saying the supposed trace of a Brexit plan detected was so minuscule it would be ten years before they knew for sure what it was. Their official statement read: "It is too soon to say that we have discovered Particle 50."