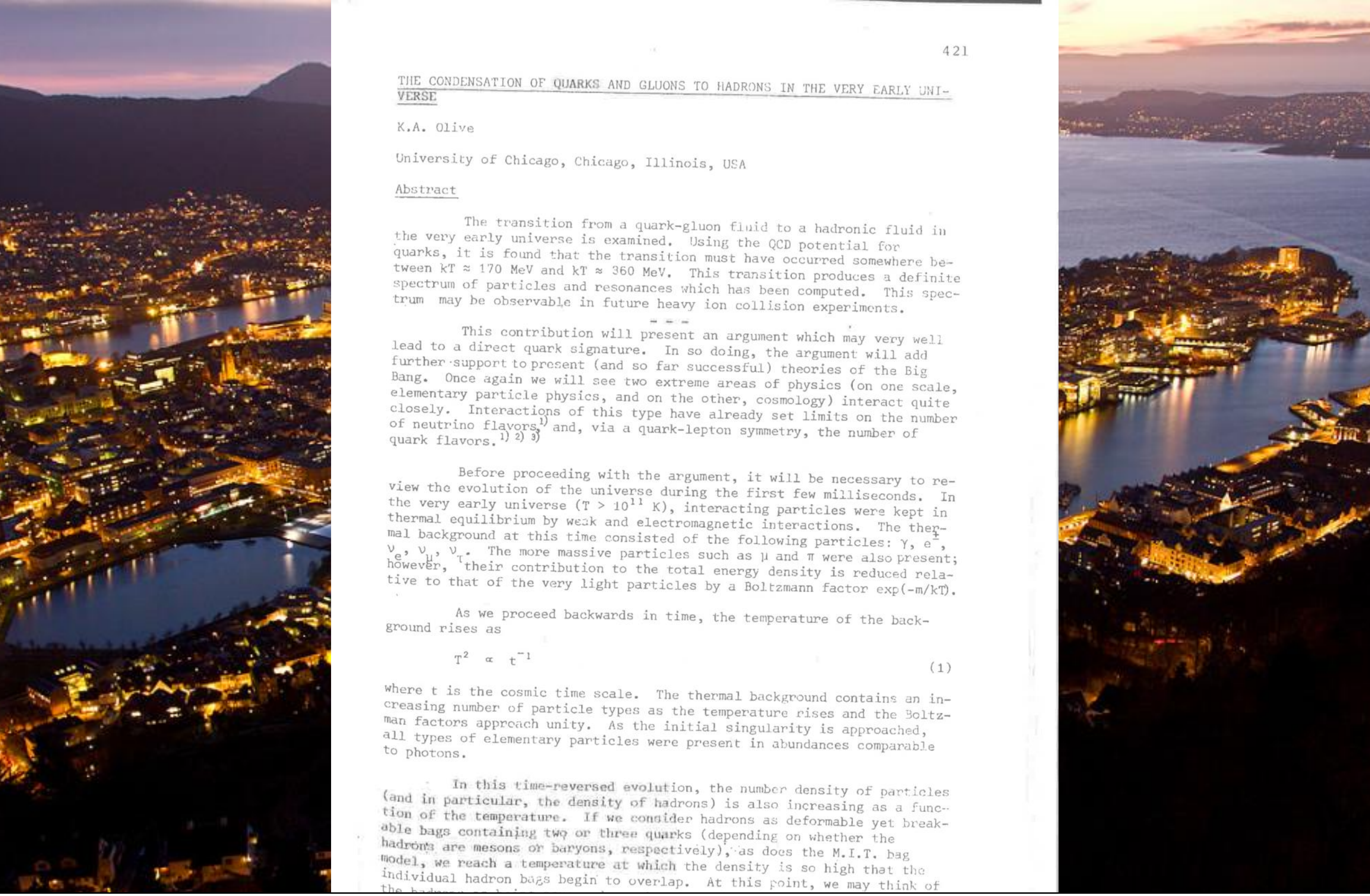
Keith’s Dark Side

(& some others)



THE CONDENSATION OF QUARKS AND GLUONS TO HADRONS IN THE VERY EARLY UNIVERSE

K.A. Olive

University of Chicago, Chicago, Illinois, USA

Abstract

The transition from a quark-gluon fluid to a hadronic fluid in the very early universe is examined. Using the QCD potential for quarks, it is found that the transition must have occurred somewhere between $kT \approx 170$ MeV and $kT \approx 360$ MeV. This transition produces a definite spectrum of particles and resonances which has been computed. This spectrum may be observable in future heavy ion collision experiments.

- - -

This contribution will present an argument which may very well lead to a direct quark signature. In so doing, the argument will add further support to present (and so far successful) theories of the Big Bang. Once again we will see two extreme areas of physics (on one scale, elementary particle physics, and on the other, cosmology) interact quite closely. Interactions of this type have already set limits on the number of neutrino flavors,[1] and, via a quark-lepton symmetry, the number of quark flavors.[1) 2) 3)]

Before proceeding with the argument, it will be necessary to review the evolution of the universe during the first few milliseconds. In the very early universe ($T > 10^{11}$ K), interacting particles were kept in thermal equilibrium by weak and electromagnetic interactions. The thermal background at this time consisted of the following particles: γ, $e^{\pm}$, ν_e, ν_μ, ν_τ. The more massive particles such as μ and π were also present; however, their contribution to the total energy density is reduced relative to that of the very light particles by a Boltzmann factor $\exp(-m/kT)$.

As we proceed backwards in time, the temperature of the background rises as

$$T^2 \propto t^{-1} \qquad (1)$$

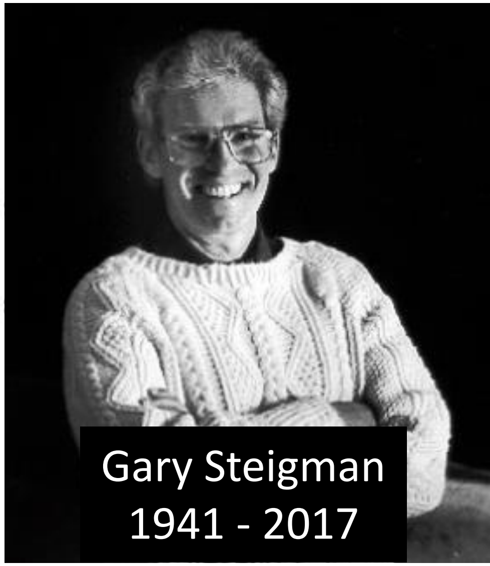
where t is the cosmic time scale. The thermal background contains an increasing number of particle types as the temperature rises and the Boltzman factors approach unity. As the initial singularity is approached, all types of elementary particles were present in abundances comparable to photons.

In this time-reversed evolution, the number density of particles (and in particular, the density of hadrons) is also increasing as a function of the temperature. If we consider hadrons as deformable yet breakable bags containing two or three quarks (depending on whether the hadrons are mesons or baryons, respectively), as does the M.I.T. bag model, we reach a temperature at which the density is so high that the individual hadron bags begin to overlap. At this point, we may think of

First meeting @ 1979 Bergen Neutrino Conference

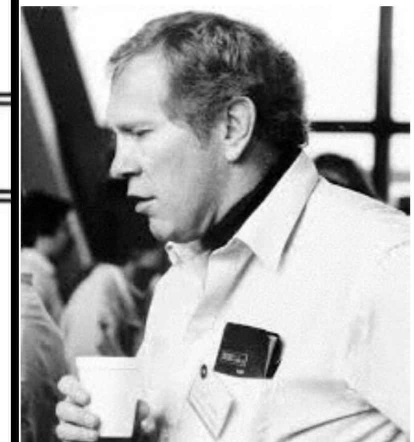
PHYSICAL REVIEW LETTERS

23 JULY 1979



Keith already on his way

David Schramm
1945-1997



Cosmological Constraints on Superweak Particles

G. Steigman

Bartol Research Foundation of the Franklin Institute, University of Delaware, Newwark, Delaware 19711,[(a)] *and Institute for Plasma Research, Stanford University, Stanford, California 94305*[(b)]

and

K. A. Olive and D. N. Schramm

Department of Physics and The Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637[(c)]

(Received 29 May 1979)

Previous work has used the primordial abundance of ^{4}He to infer limits on the number of neutrinos with full-strength neutral-current weak interactions. By accounting for the quark-gluon constituents of hadrons, we extend the analysis to earlier times and higher temperatures and densities and, therefore, to considerably weaker interactions. The maximum number of new, superweakly interacting, light ($\lesssim$ MeV) particles is between ~1 and ~20.

Together with Keith since 1982

- 162 papers(*)
- 15973 citations
  - 1580: *"Supersymmetric Relics from the Big Bang"*
  - 850: PDG 2016
  - > 250: 11 other papers
  - <citations> = 98, h index = 66
- **What to talk about?**
- (*) 60 without other speakers at this meeting
- **Focus later on some of these**

Mostly Seeking SUSY

Sometimes in Proximity

Often at Long Distance

Nuclear Physics B238 (1984) 453–476

Our First Big Hit

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

John ELLIS and J. S. HAGELIN

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

D. V. NANOPOULOS, K. OLIVE†, and M. SREDNICKI‡

CERN, CH-1211 Geneva 23, Switzerland

Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above $\frac{1}{2}$ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than O(100) eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above 10^{14} GeV, and probably not above 3×10^{12} GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.

Inflation cries out for Supersymmetry

Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

COSMOLOGICAL INFLATION CRIES OUT FOR SUPERSYMMETRY

John ELLIS, D.V. NANOPOULOS, Keith A. OLIVE and K. TAMVAKIS
CERN, Geneva, Switzerland

Received 4 August 1982

We re-examine the inflationary scenario in the standard SU(5) model with Coleman–Weinberg symmetry breaking and point out difficulties which may be resolved in a broken supersymmetric model. Because of a partial cancellation at the one-loop level, the effective potential in a broken supersymmetric theory may be much flatter than in standard SU(5), thus permitting a greater amount of inflation.

One of our best-ever paper titles!

No-Scale Inflation

SU(N, 1) INFLATION

John ELLIS, K. ENQVIST, D.V. NANOPOULOS
CERN, Geneva, Switzerland

K.A. OLIVE
Astrophysics Theory Group, Fermilab, Batavia, IL 60510, USA

and

M. SREDNICKI
Department of Physics, University of California, Santa Barbara, CA 93106, USA

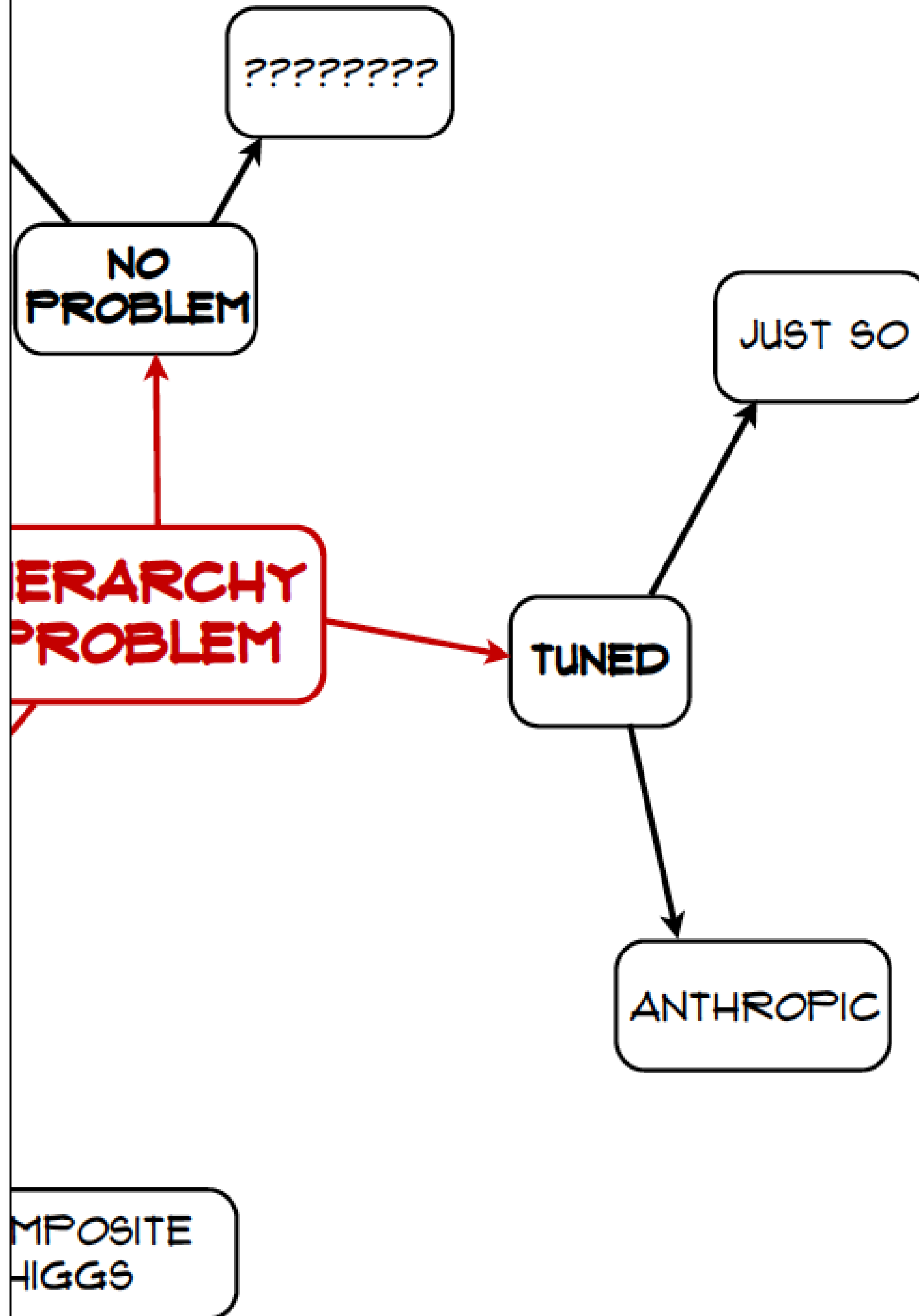
Received 7 December 1984

We present a simple model for primordial inflation in the context of SU(N, 1) no-scale $n = 1$ supergravity. Because the model at zero temperature very closely resembles global supersymmetry, minima with negative cosmological constants do not exist, and it is easy to have a long inflationary epoch while keeping density perturbations of the right magnitude and satisfying other cosmological constraints. We pay specific attention to satisfying the thermal constraint for inflation, i.e. the existence of a high temperature minimum at the origin.

A love to which we returned recently

No-Scale Reunion

If you know of a better hole, go to it

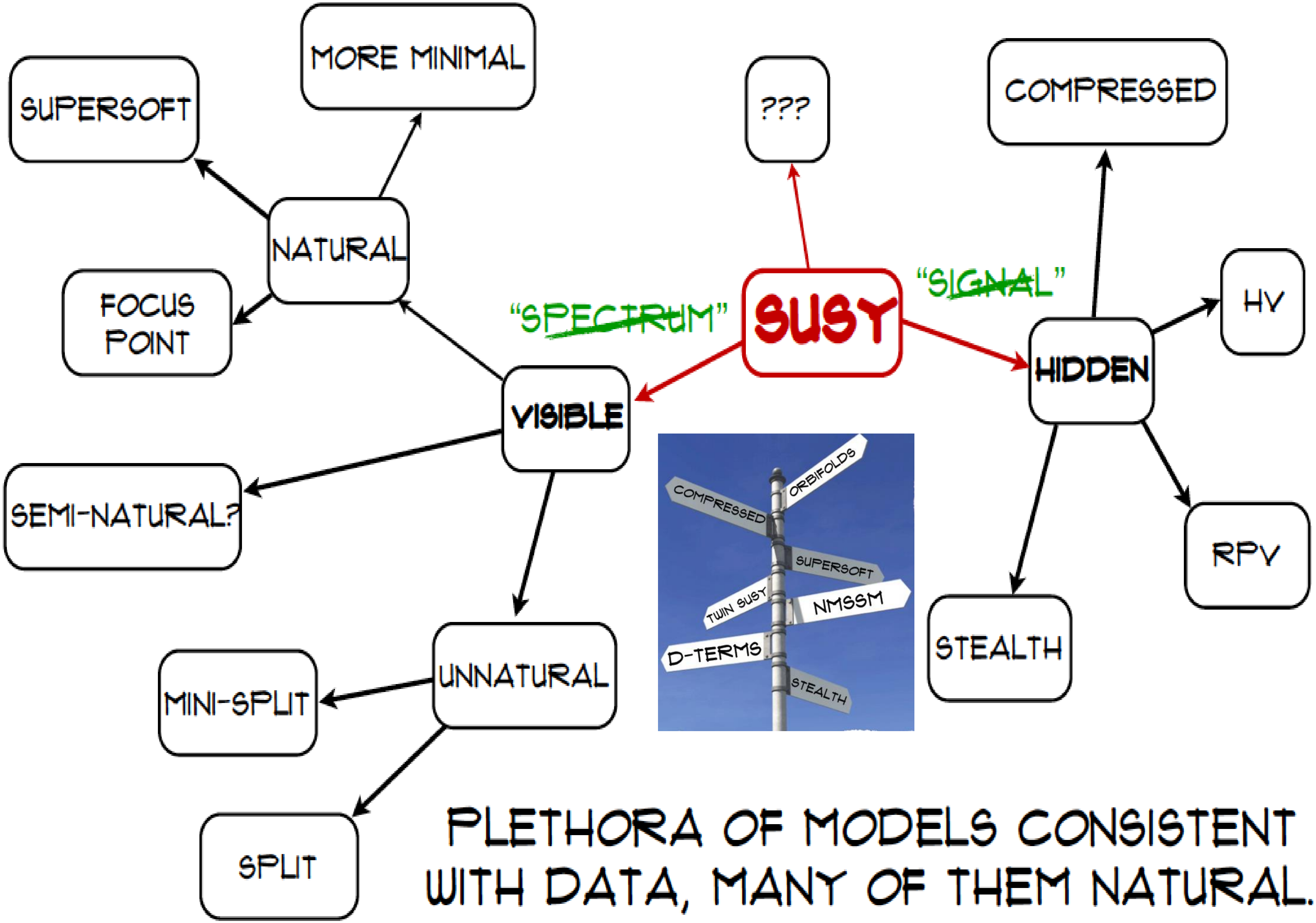


What lies beyond the Standard Model?

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



PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL. WHERE DOES THE DATA POINT US?

Craig@LHCP

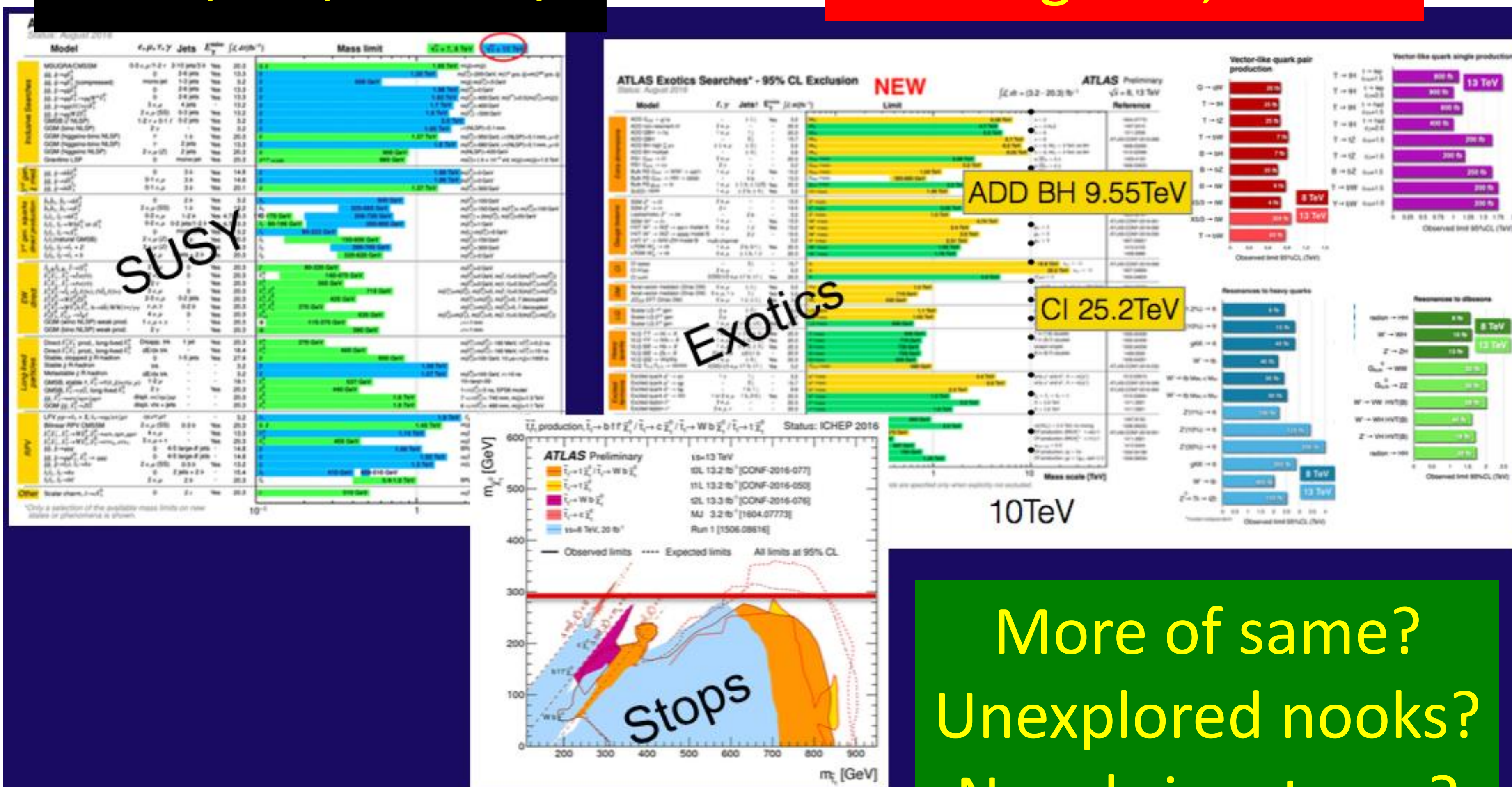
Paraphrasing George Harrison

If you don’t know where you’re going,
Any road may ake you there

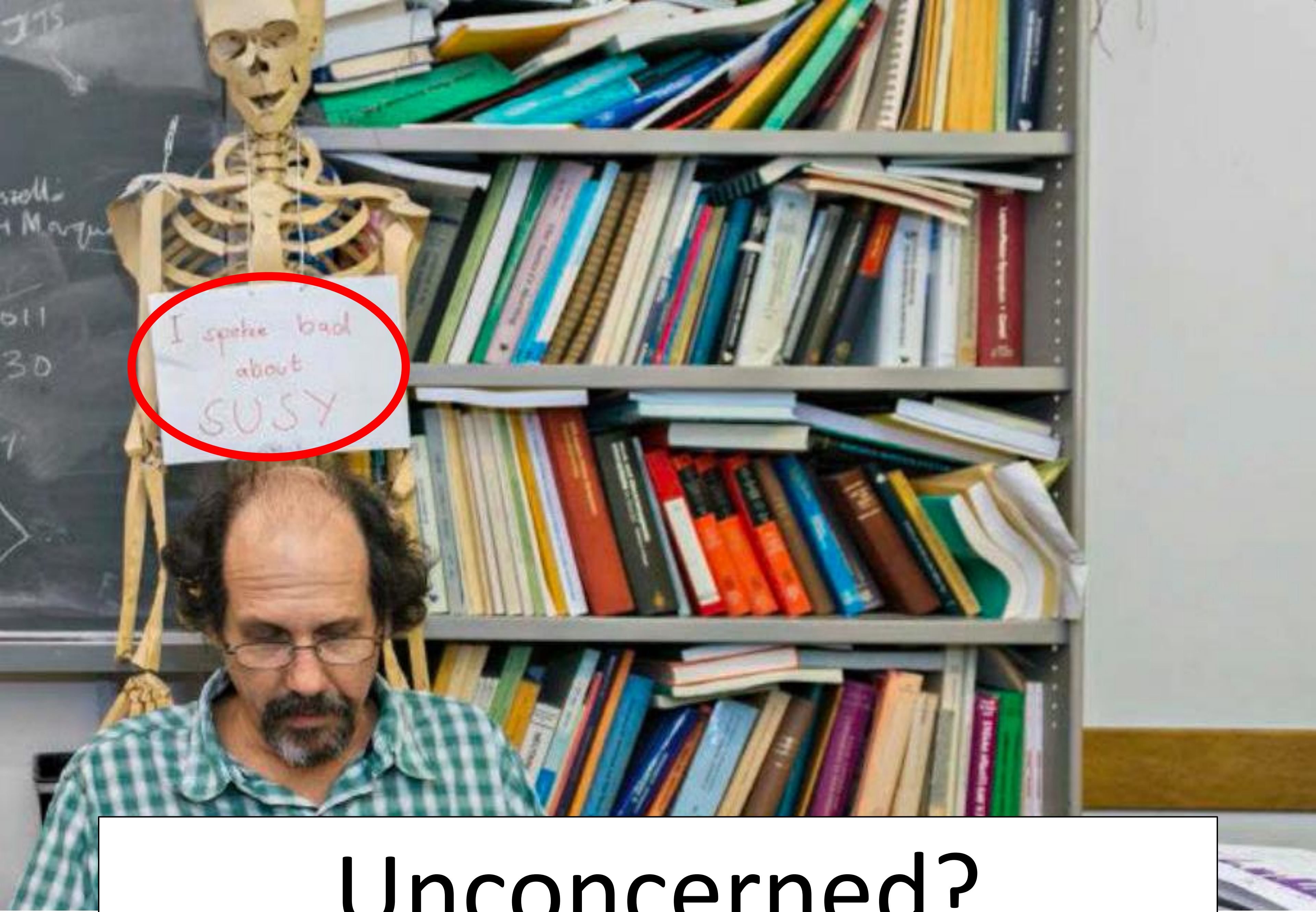
Nothing (yet) at the LHC

No supersymmetry

Nothing else, either

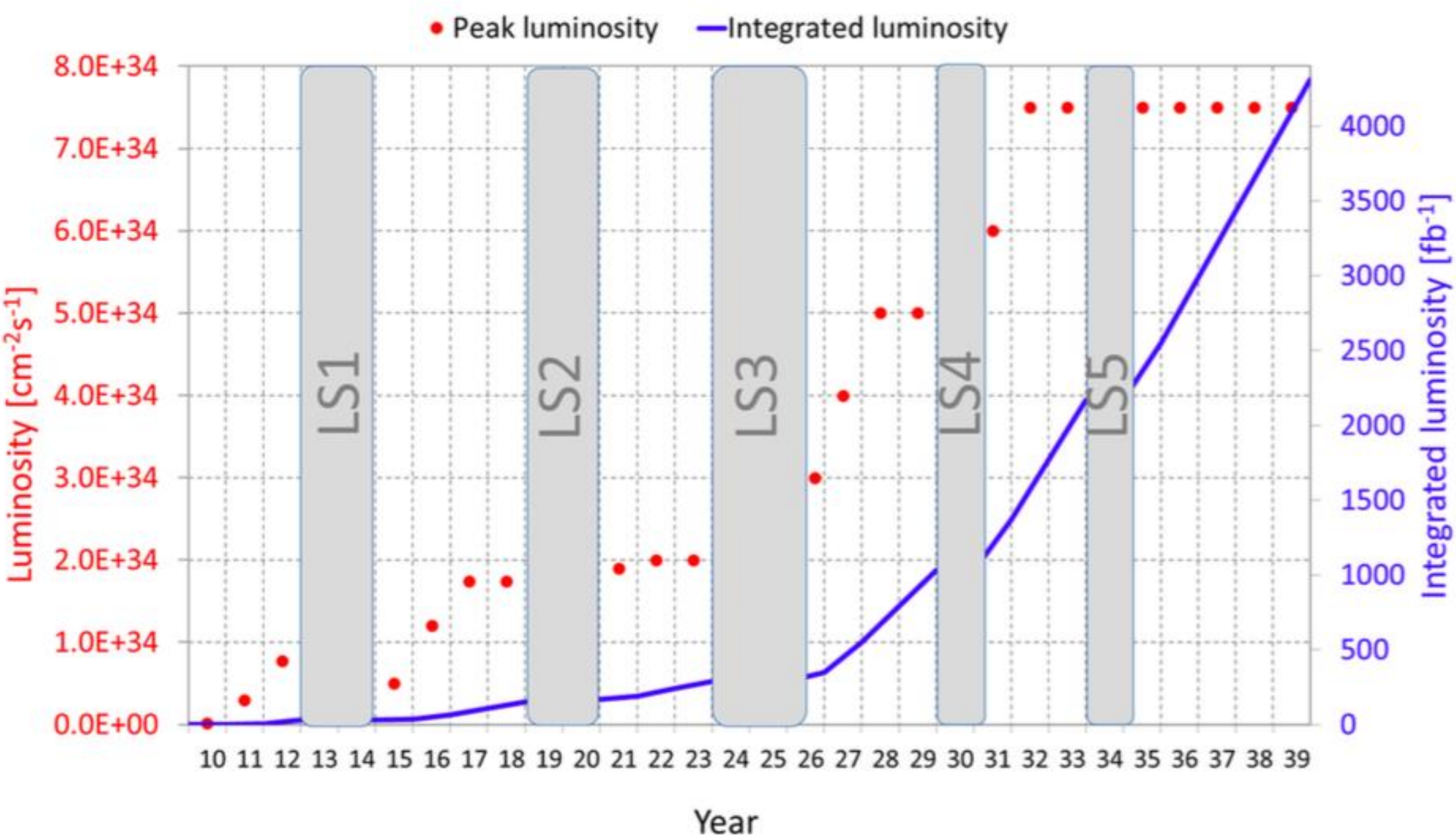


More of same?
Unexplored nooks?
Novel signatures?

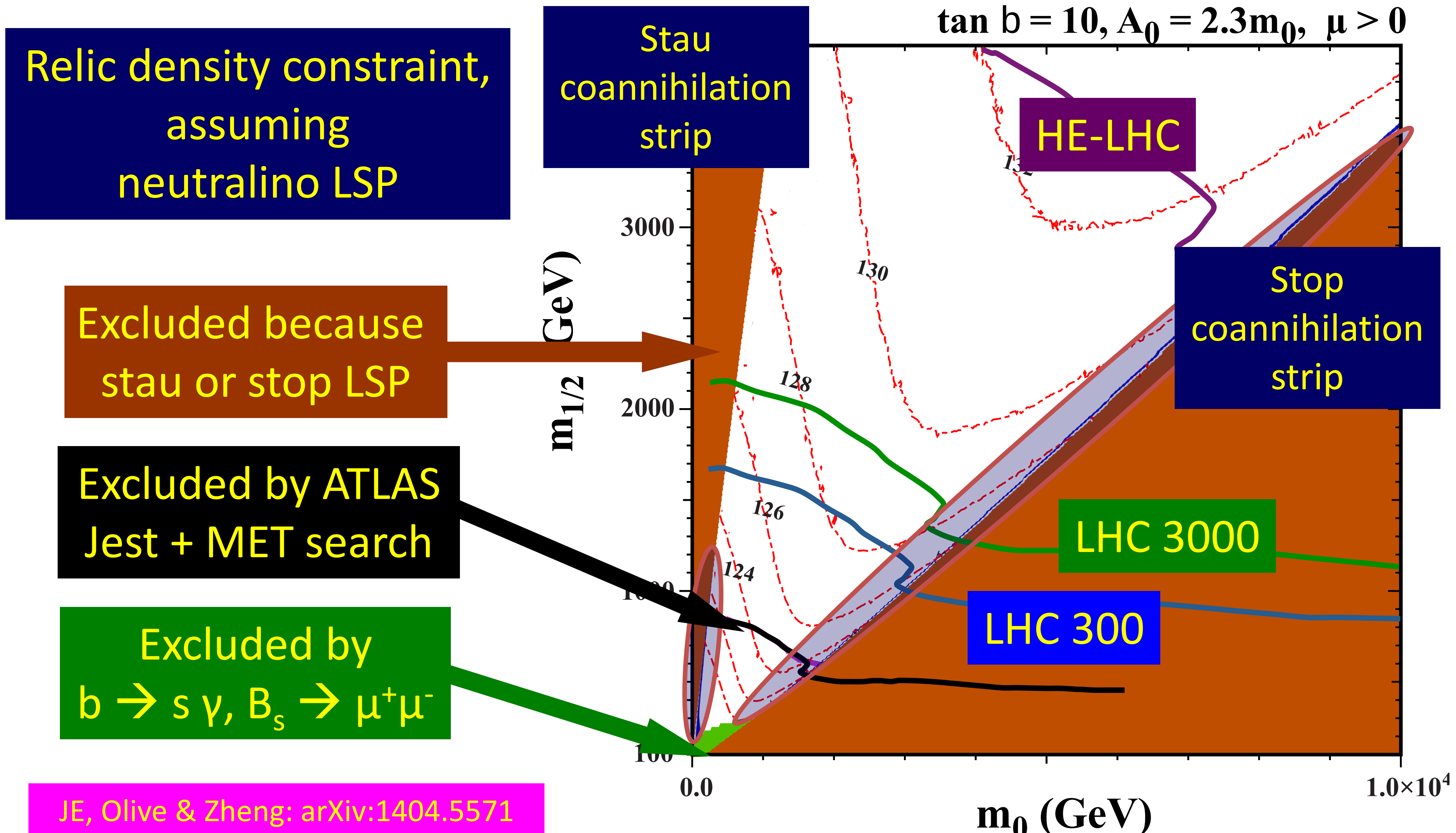


Unconcerned?

The LHC in Future Years



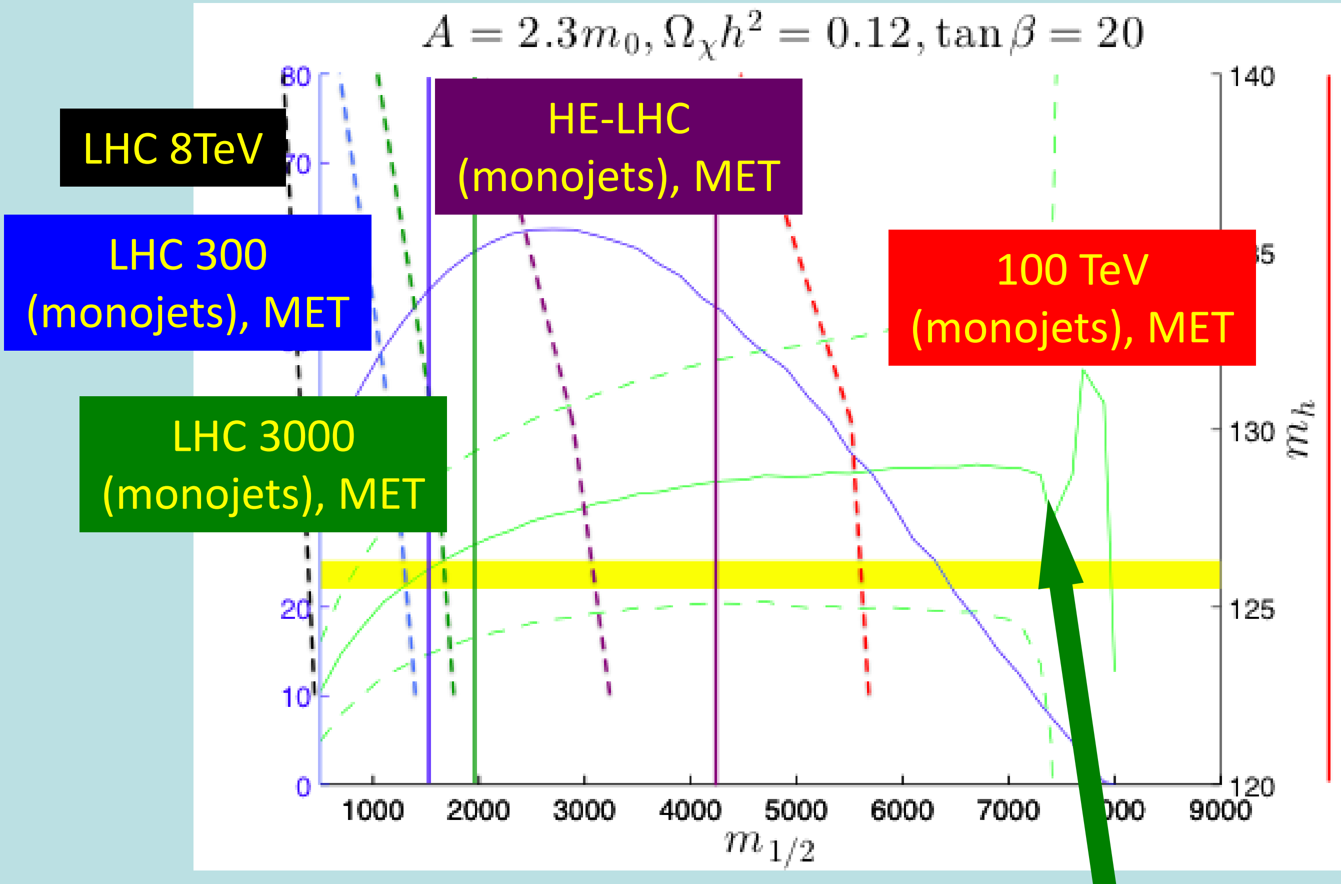
Where May CMSSM be Hiding?



JE, Olive & Zheng: arXiv:1404.5571

Buchmueller, Citron JE, Guha, Marrouche, Olive, de Vries & Zheng, arXiv:1505.0472

Exploring the Stop Coannihilation Strip



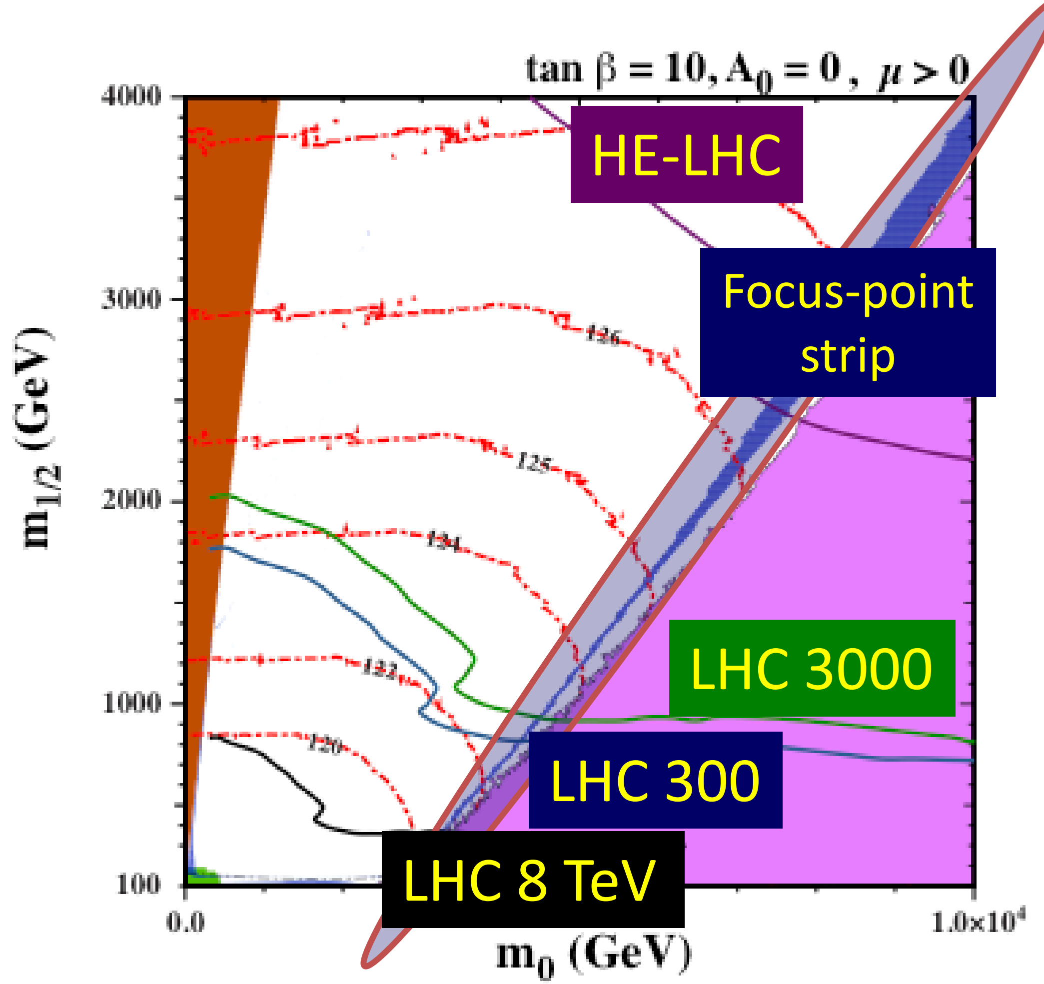
- Compatible with LHC measurement of m_h
- May extend to $m_\chi = m_{stop} \sim 6500$ GeV

JE, Olive & Zheng: arXiv:1404.5571

Buchmueller, Citron JE, Guha, Marrouche, Olive, de Vries & Zheng, arXiv:1505.0472

Where May CMSSM be Hiding?

- Imposing dark matter density constraint
- **Focus-point strip:**
  - $A_0 \sim 0$, large $m_0/m_{1/2}$
- Extends to $m_{1/2} \sim 4$ TeV
- Neutralino has Higgsino mixture
- Truncated by m_h

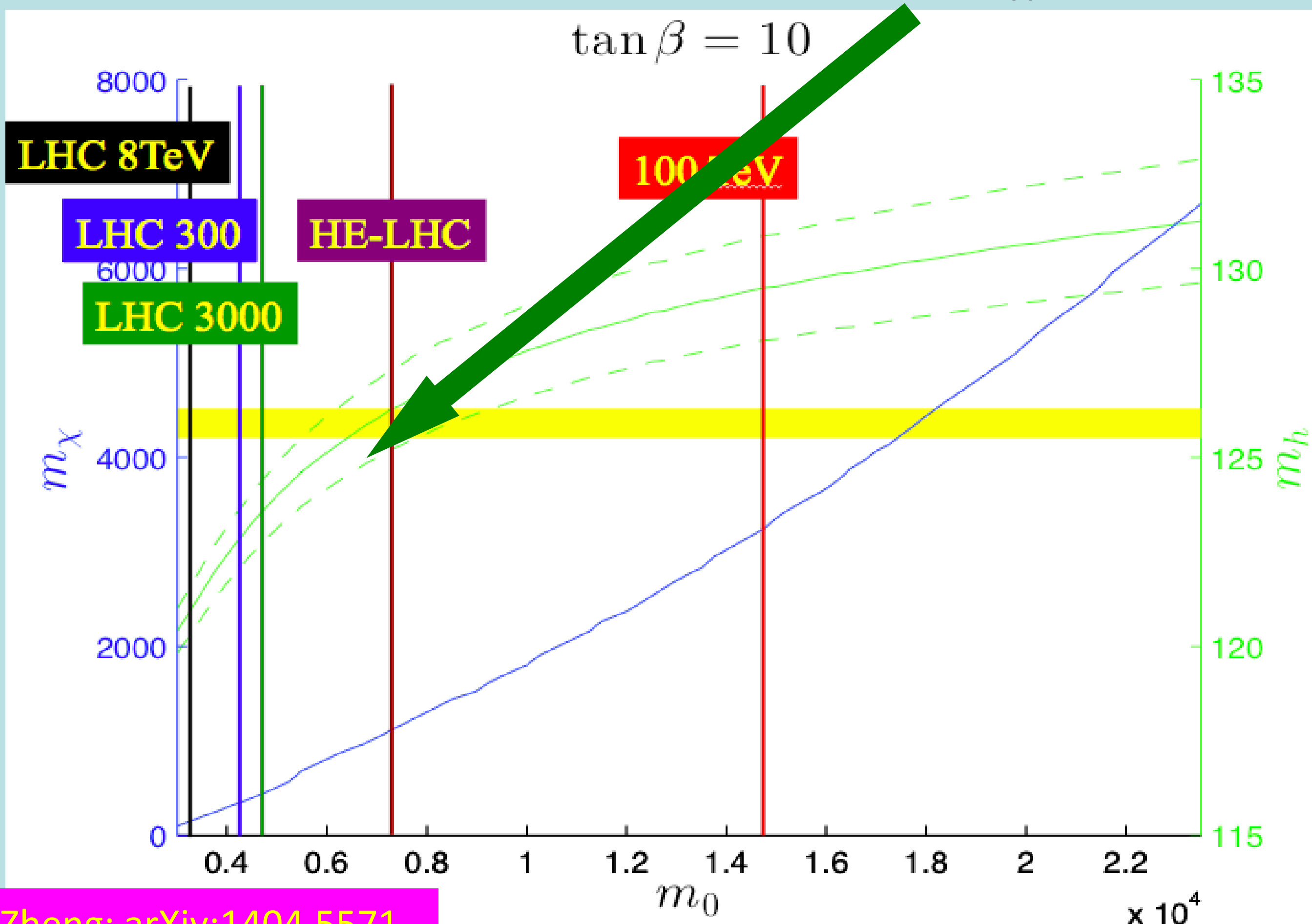


JE, Olive & Zheng: arXiv:1404.5571

Buchmueller, Citron JE, Guha, Marrouche, Olive, de Vries & Zheng, arXiv:1505.0472

Exploring the CMSSM **Focus-Point Strip**

- Limited range compatible with m_h

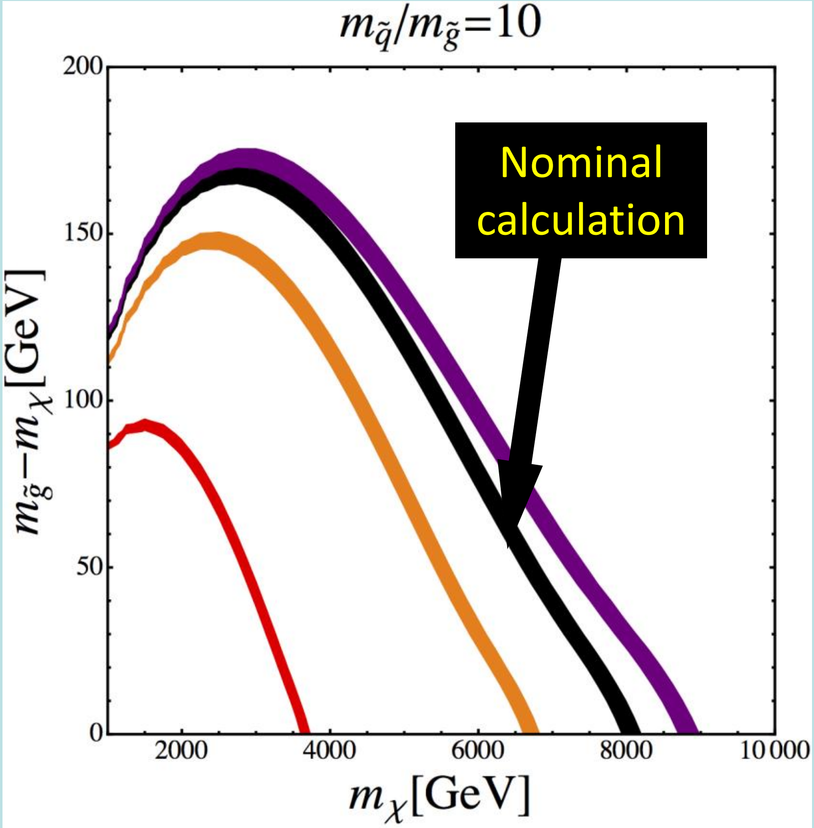


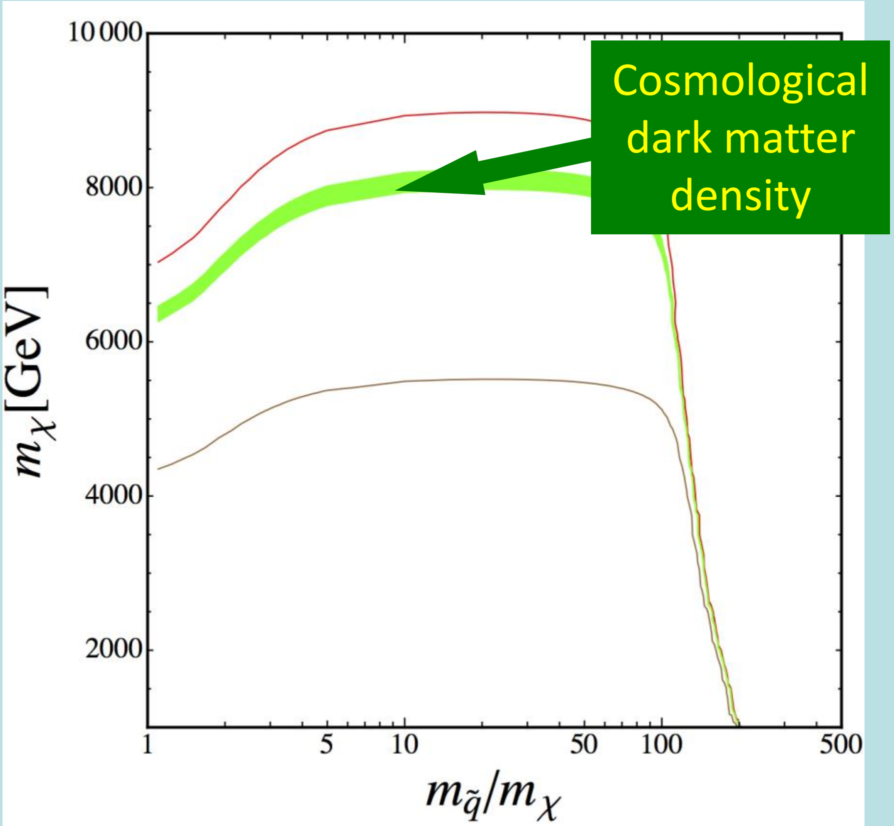
JE, Olive & Zheng: arXiv:1404.5571

Buchmueller, Citron JE, Guha, Marrouche, Olive, de Vries & Zheng, arXiv:1505.0472

How Heavy could Dark Matter be in pMSSM?

- Largest possible mass in pMSSM is along gluino coannihilation strip: $m_{gluino} \sim m_{neutralino}$





- **Extends to $m_{\chi} = m_{gluino} \sim 8$ TeV**

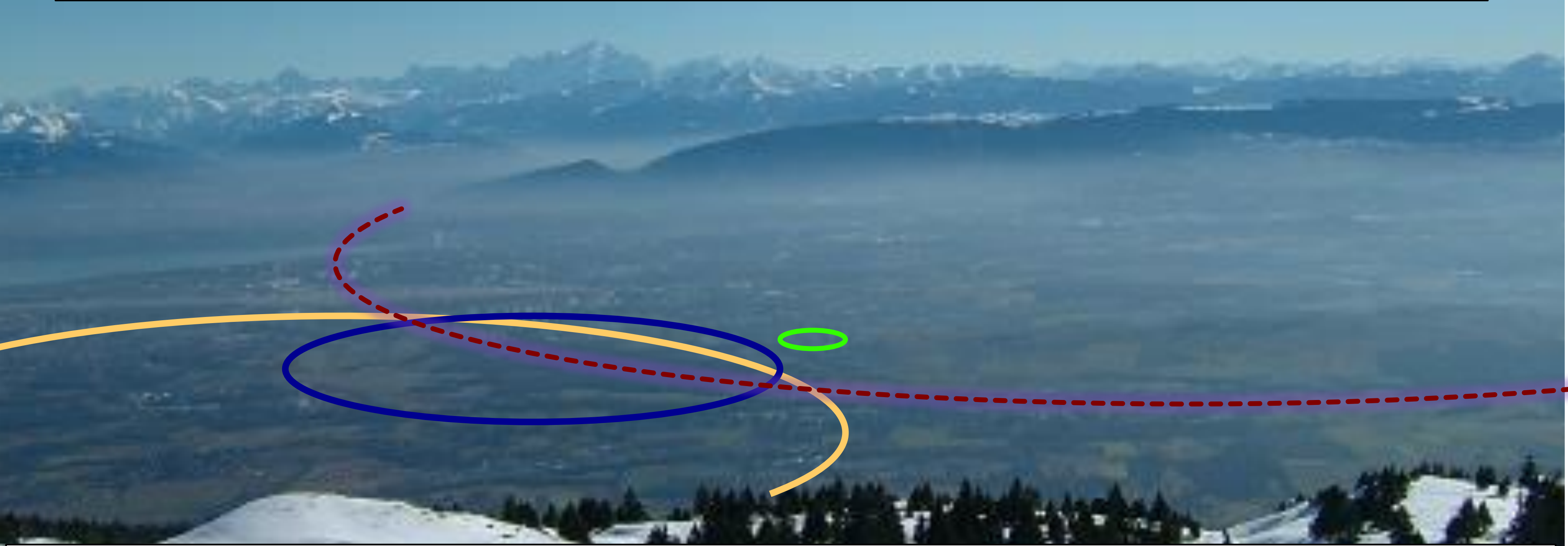
JE, Luo & Olive: arXiv: 1503.07142

FCC hh ee he

CEPC-SPPC

Preliminary Conceptual Design Report

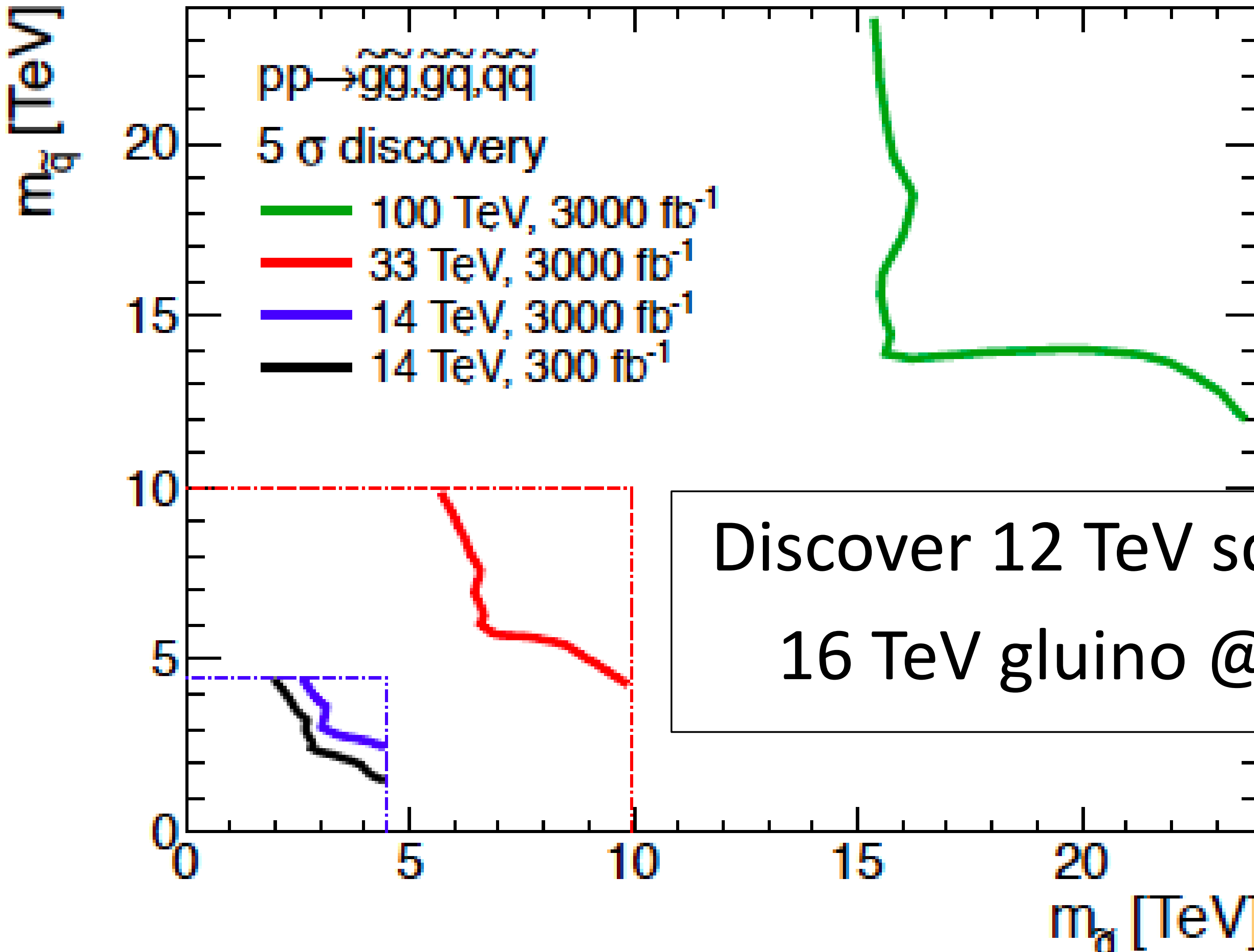
Future Circular Colliders



The vision:

explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

Squark-Gluino Plane

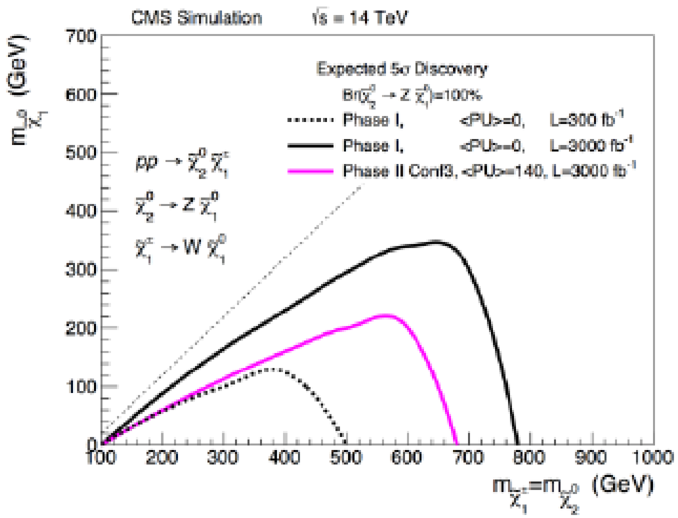


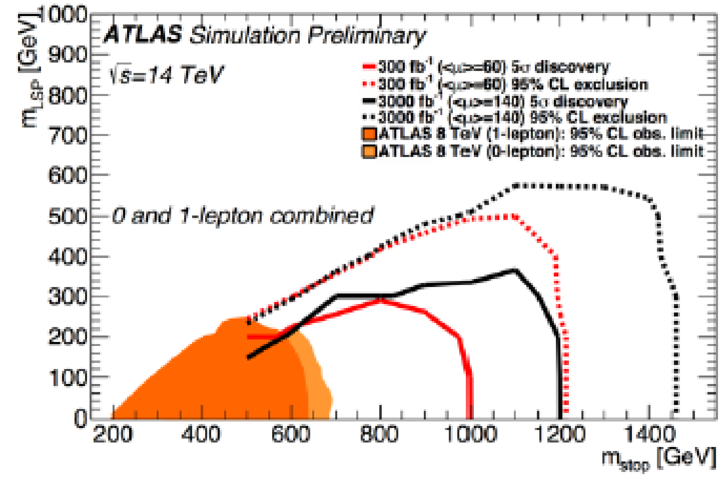
Discover 12 TeV squark,

16 TeV gluino @ 5σ

Reaches for Sparticles

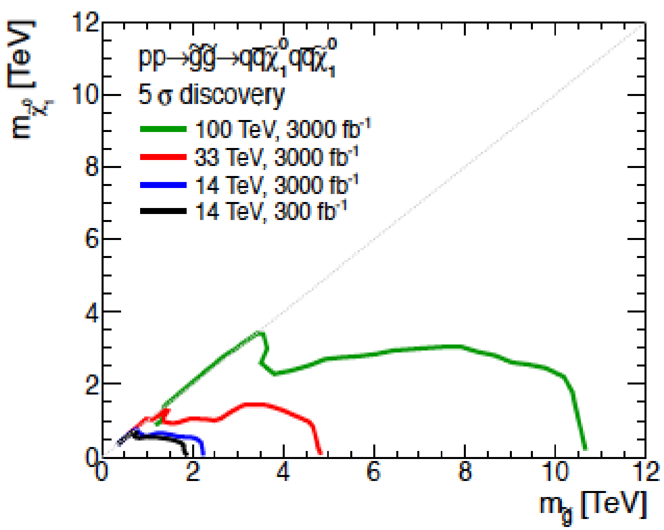
LHC:

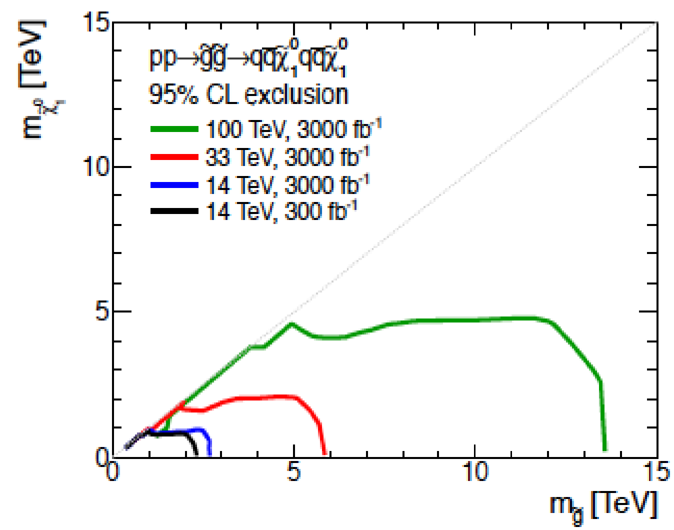




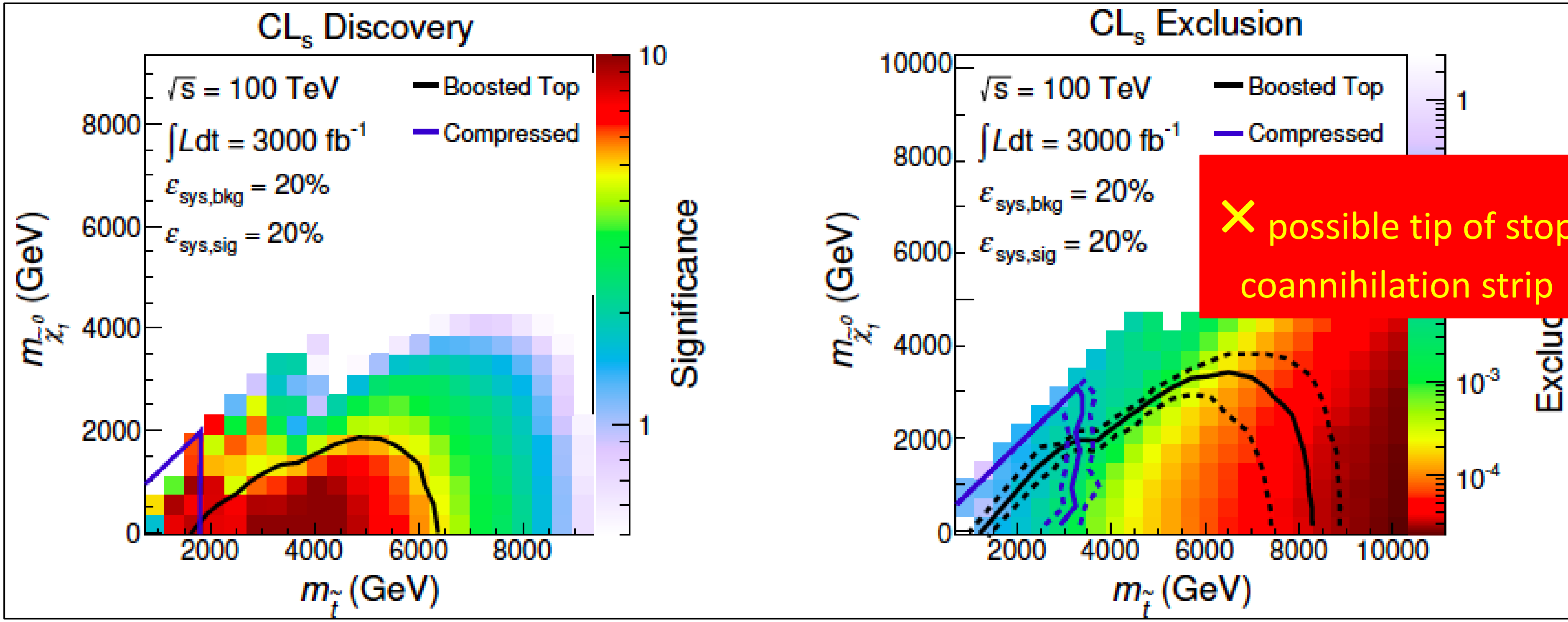
HE-LHC,

FCC-hh





Reach for the Stop



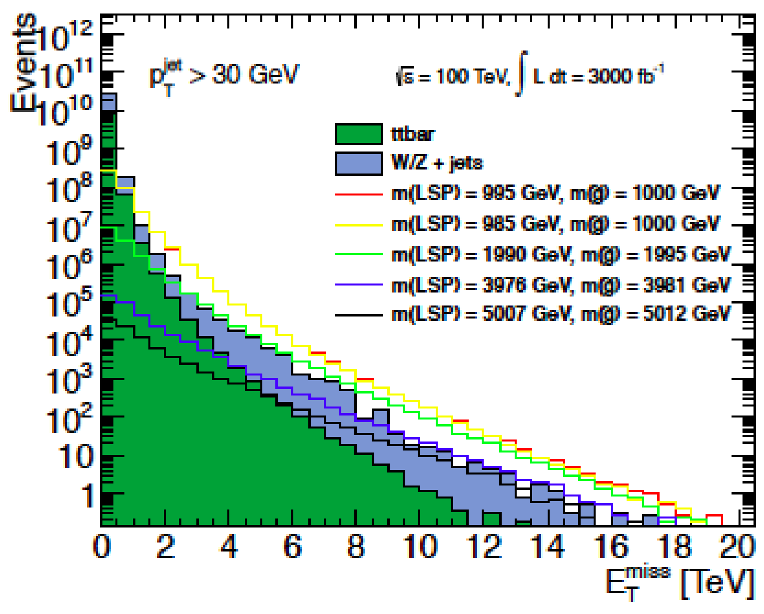
✕ possible tip of stop coannihilation strip

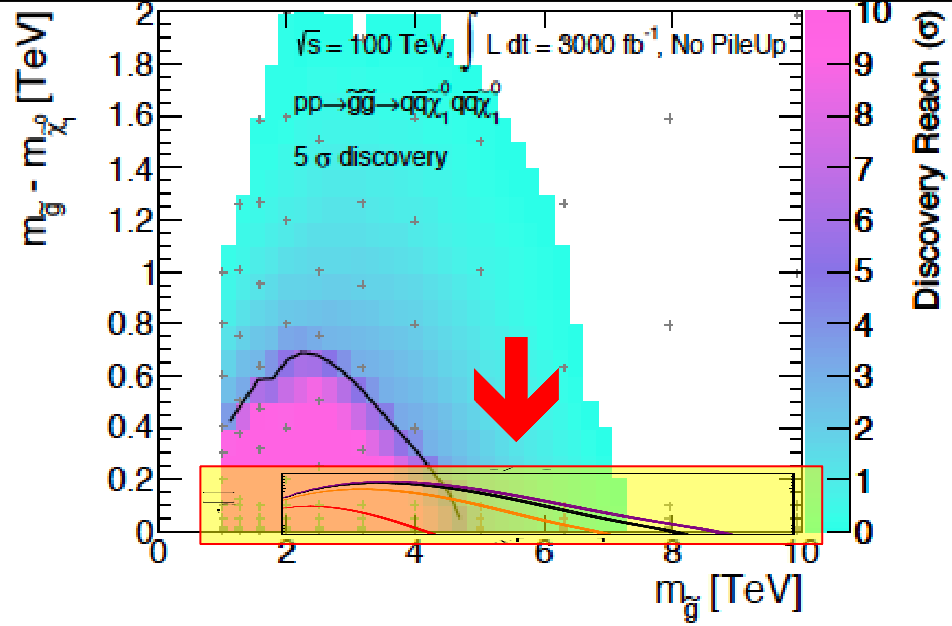
Discover 6.5 TeV stop @ 5σ, exclude 8 TeV @ 95%

Stop mass up to 6.5 TeV possible along coannihilation strip

Reaches for Sparticles

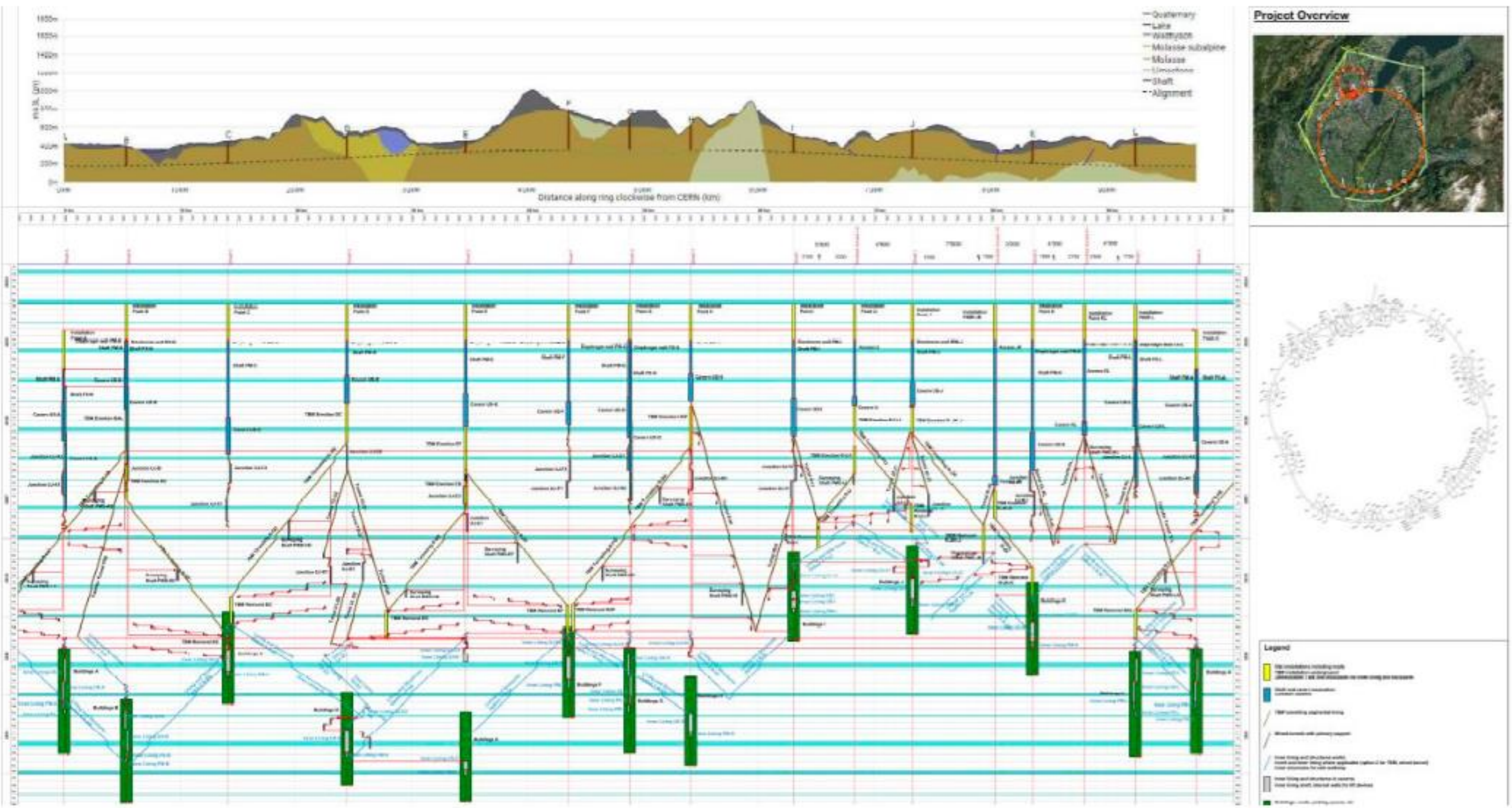
Model with compressed spectrum: small gluino-neutralino mass difference





Large mass possible in gluino coannihilation scenario for dark matter

Tentative FCC-ee Planning

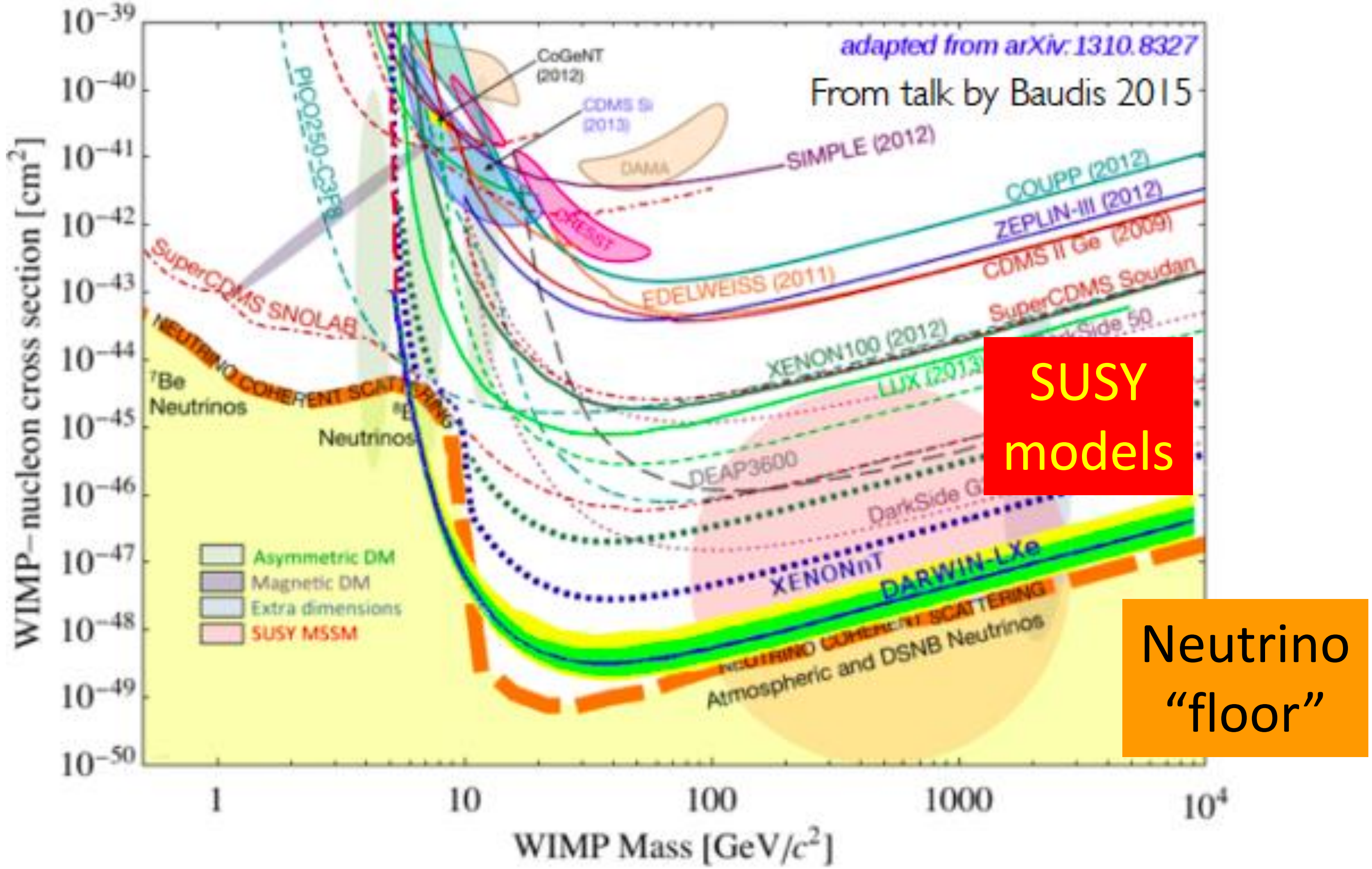


Tentative FCC-ee Schedule

- **Start of magnet installation begin 2036 (driven by CE & 16 T)**
- First 2 short sectors installation & sector test ***3 years***, end 2038.
  - **250 & 250 dipole units to be installed in 2 short sectors in 500 days**
- Remaining sectors, install. & test over 4.5 years, begin 2038 to **mid 2042.**
  - **4000 units to be installed within 1000 days, rate: 4/day or 1000/year.**
- **Earliest beam commissioning from 2043 (15 years project)**

Direct Dark Matter Searches

- Compilation of present and future sensitivities

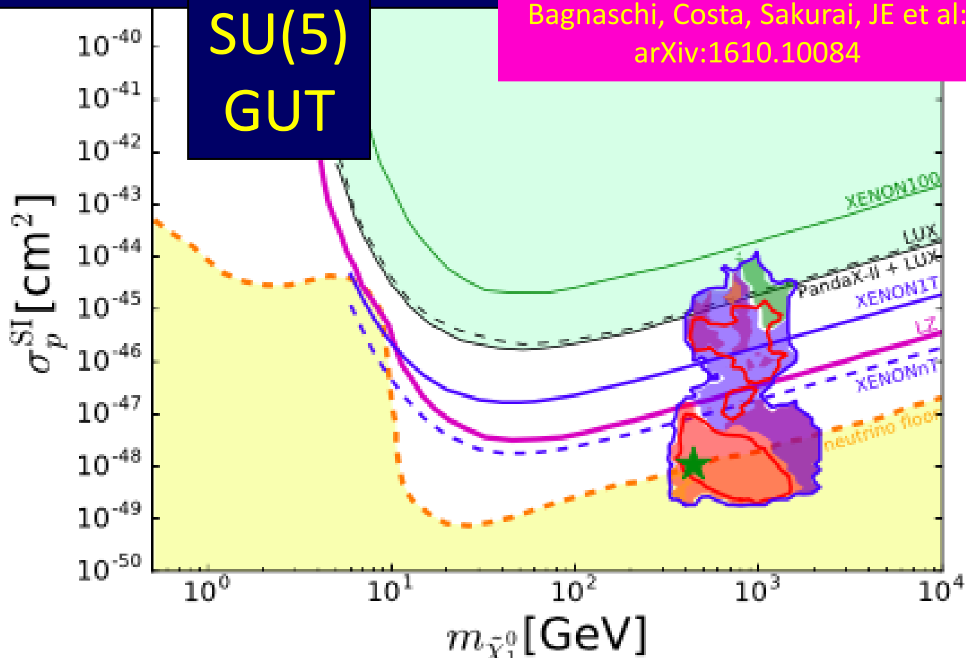


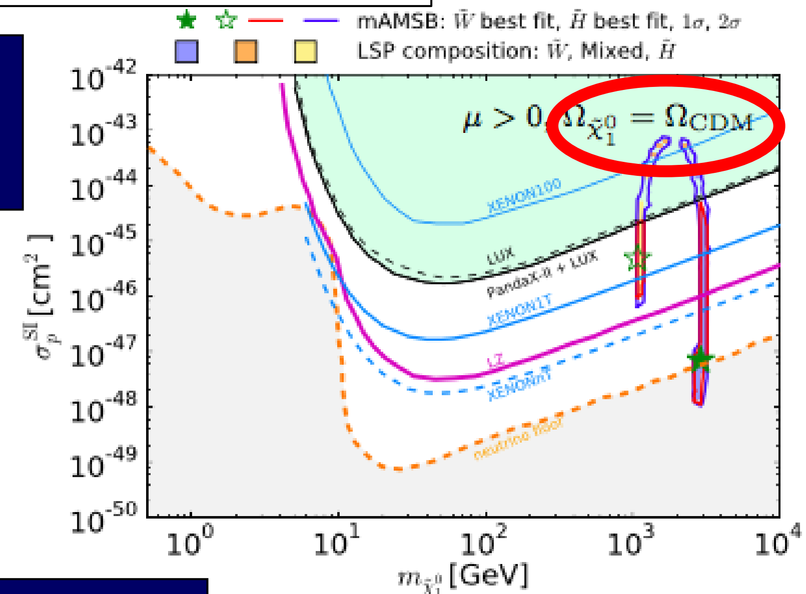
Direct Dark Matter Searches

Spin-independent dark matter scattering

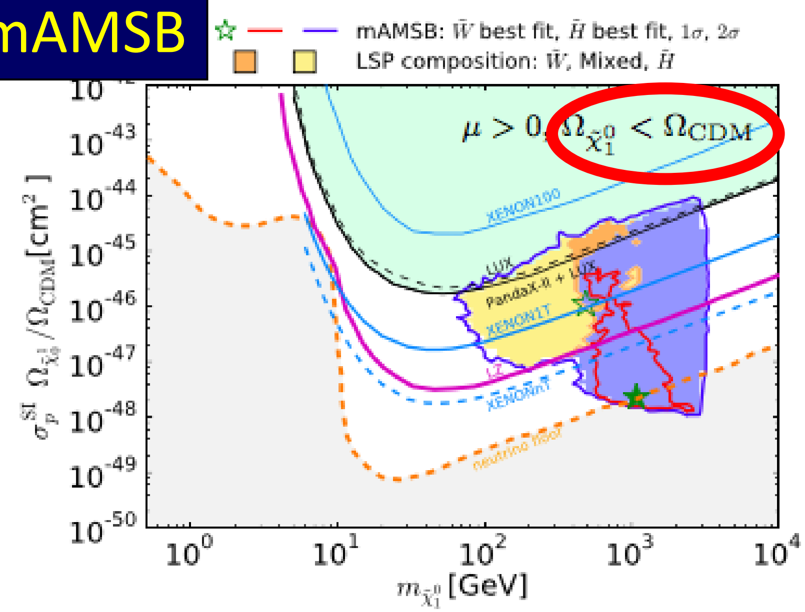
SU(5) GUT

Bagnaschi, Costa, Sakurai, JE et al: arXiv:1610.10084





mAMSB



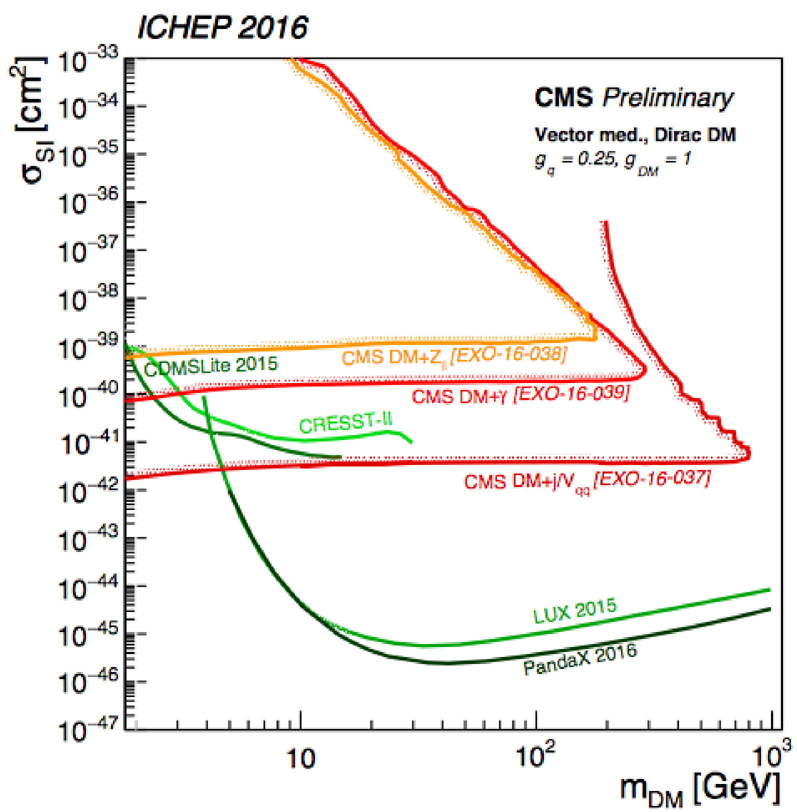
Direct scattering cross-section
may be very close
to LUX upper limit,
accessible to LZ experiment,
Could also be < neutrino "floor"

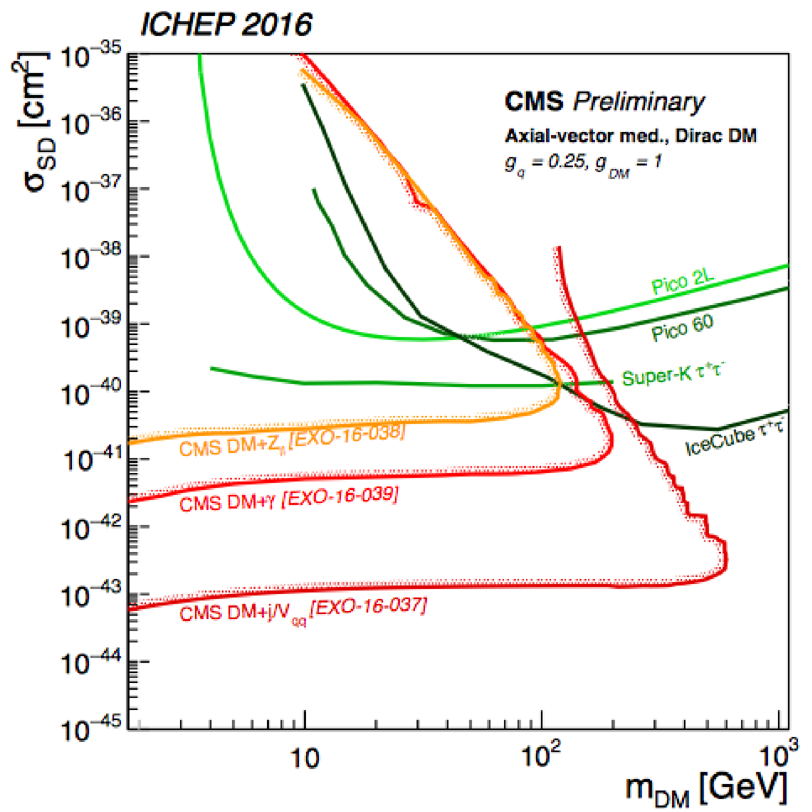
Bagnaschi, Borsato, Sakurai, JE et al: arXiv:1612.05210

Greetings from MASTERcode in Bristol

LHC vs Dark Matter Searches

- Compilation of present “mono-jet” sensitivities

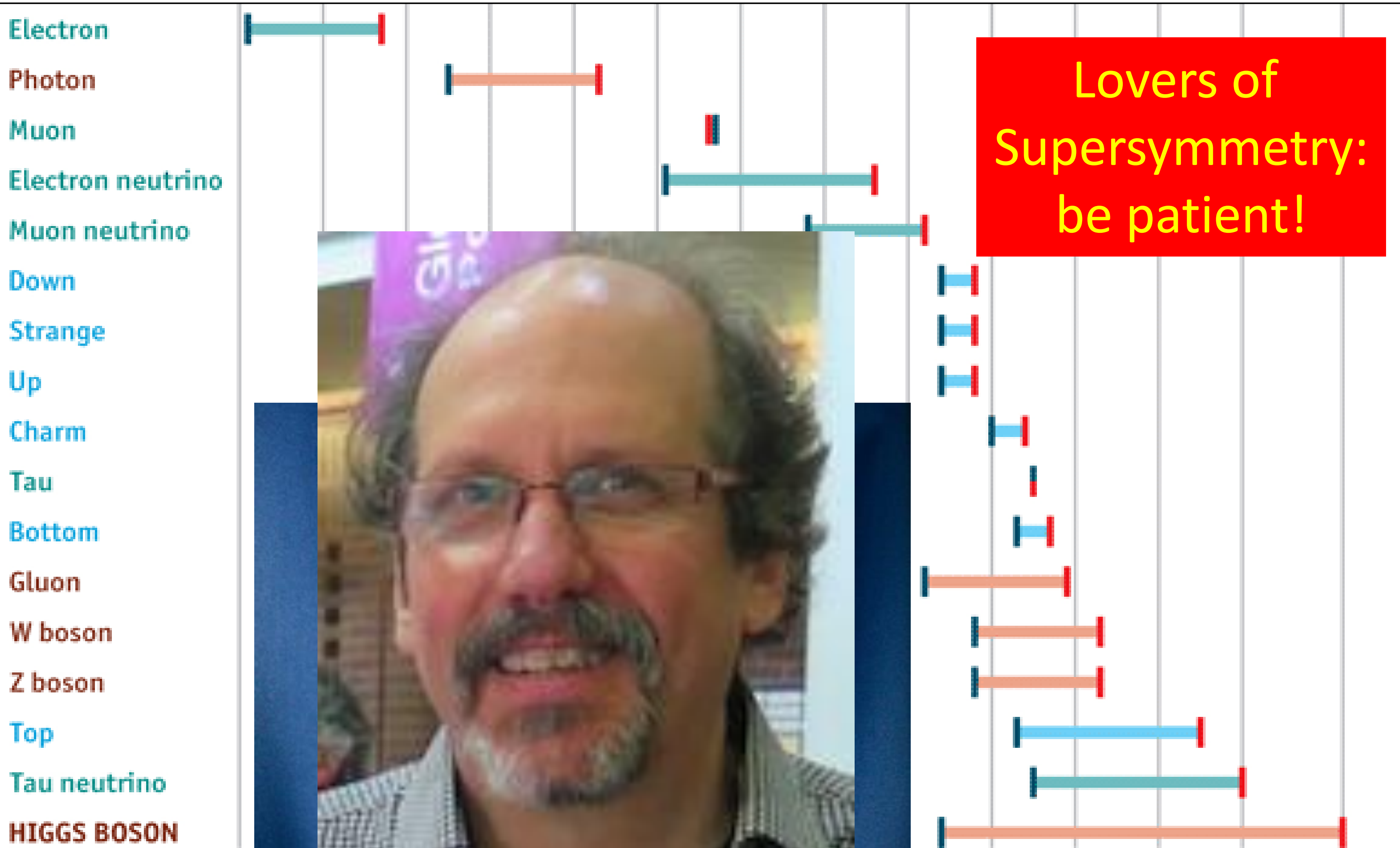




- LHC **loses** for vector, except small m_{DM}
- LHC **wins** for axial, except large m_{DM}

Model dependence

Standard Model Particles:
Years from Proposal to Discovery



Lovers of Supersymmetry: be patient!

Source: *The Economist*