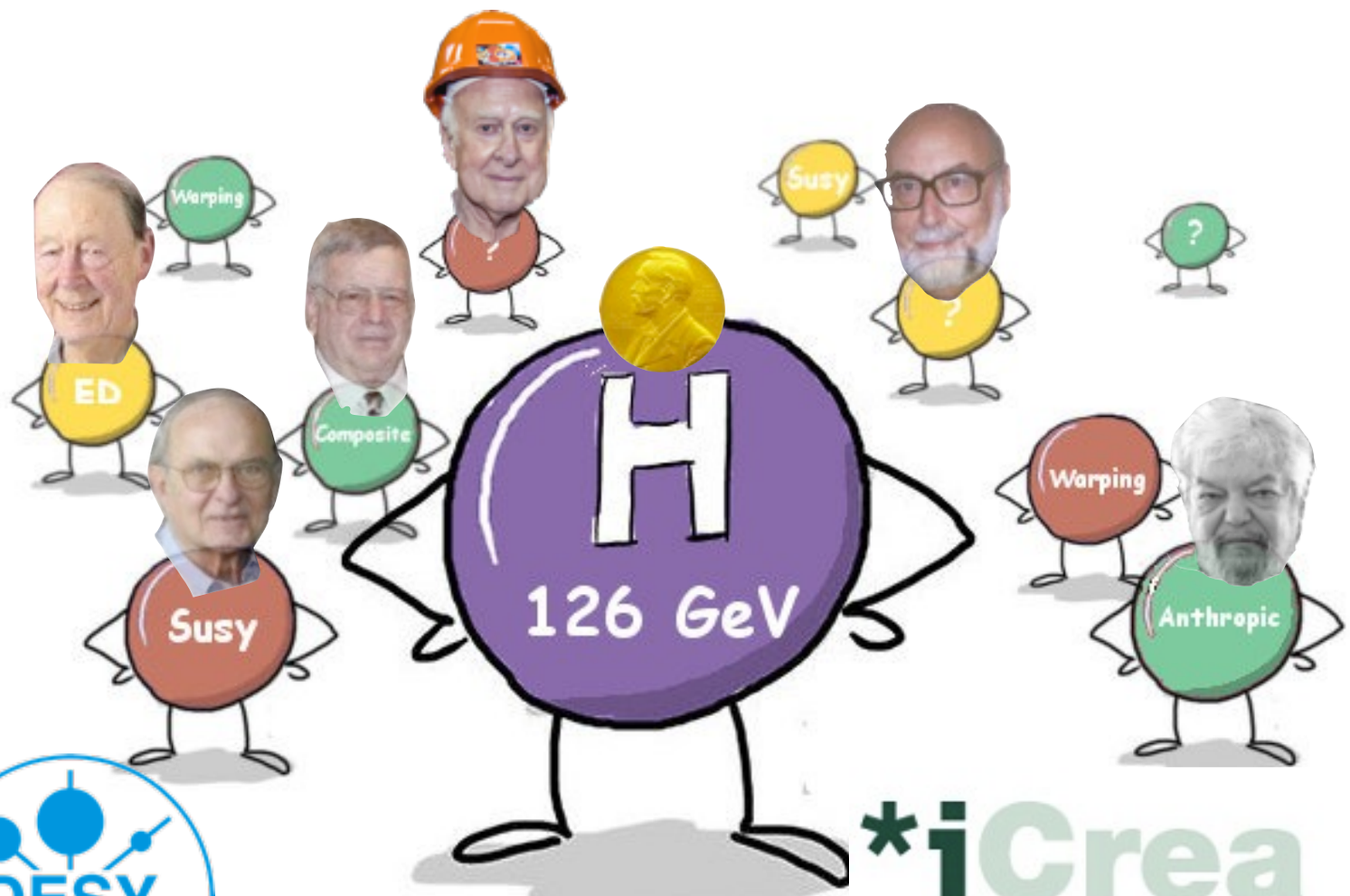
Physics Landscape

SHiP open symposium
CERN, July 2, 2015



P. Cámara/C. Grojean

Christophe Grojean

DESY (Hamburg)
ICREA@IFAE (Barcelona)
(christophe.grojean@cern.ch)

A unique moment in the history of physics

The Higgs discovery is the triumph of XXth century physics
combination of Quantum Mechanism + Special Relativity

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Physics > Popular Physics

Physics in 100 Years

Frank Wilczek

(Submitted on 26 Mar 2015)

The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don't understand, we do understand the Matter we're made from, and that we encounter in normal life - even if we're chemists, engineers, or astrophysicists (sic: DM!)

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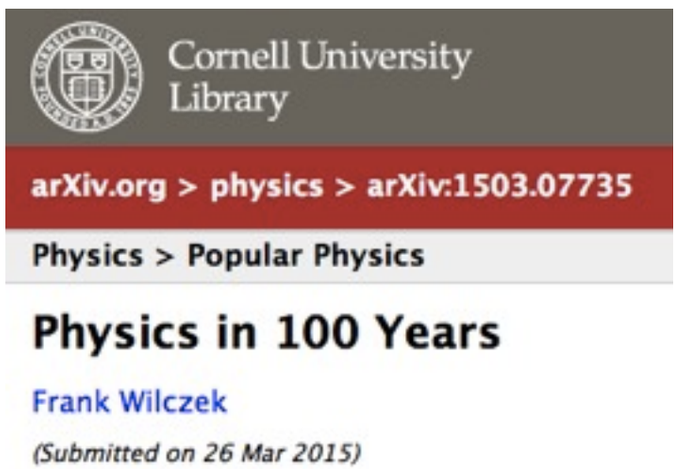
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The SM is not free of inadequacies:

1) Only a description of EW symmetry breaking, not an explanation
   furthermore Higgs field requires a delicate cancelation of large radiative corrections
2) No place for the particle(s) that make up the cosmic DM
3) Does not explain the asymmetry matter-antimatter

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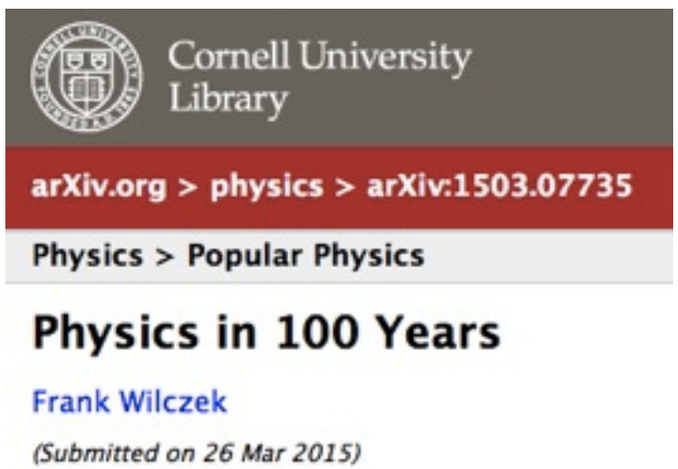
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Where and how does the SM break down?

Which machine(s) will reveal this breakdown?

The SM is not free of inadequacies:

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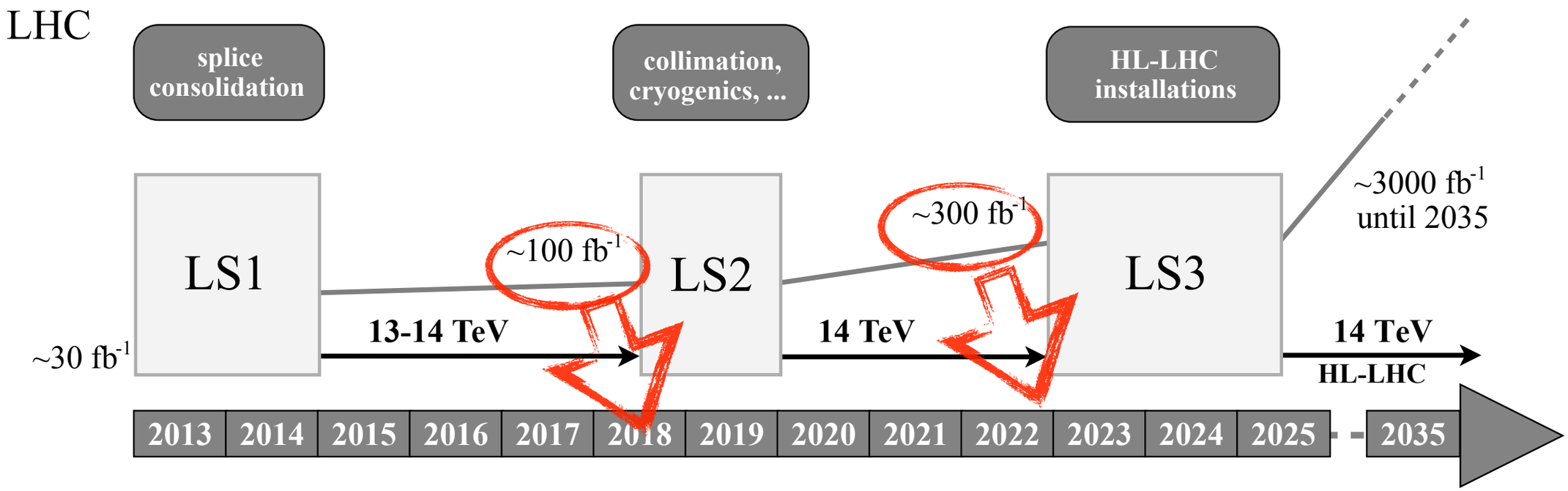
The world according to LHC



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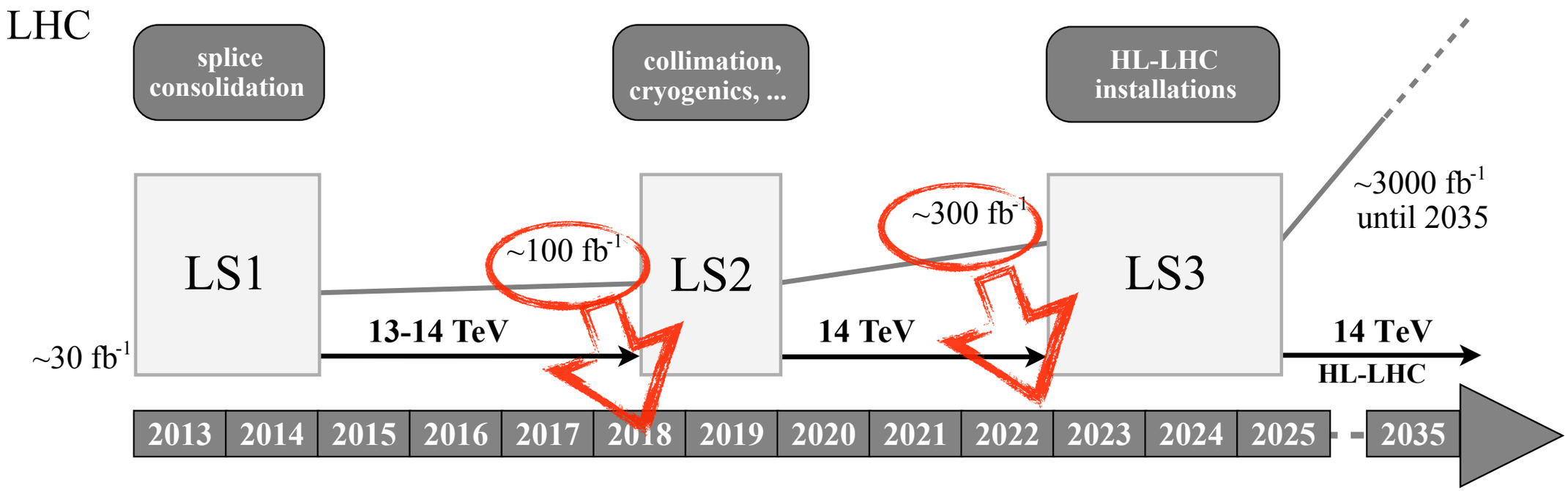
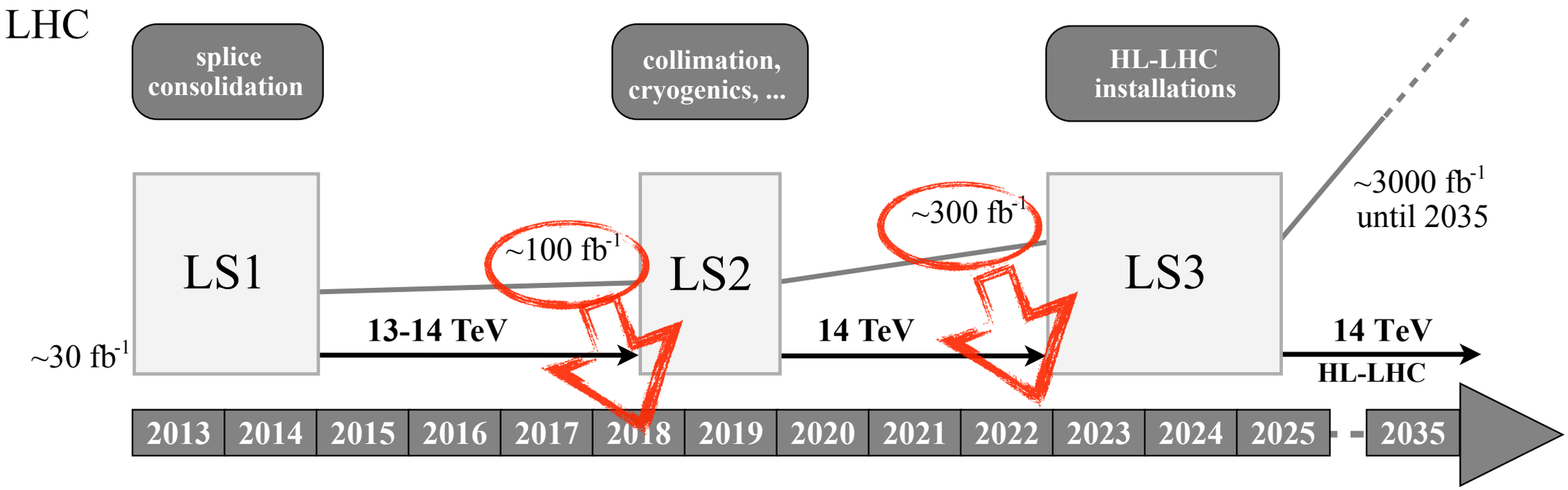


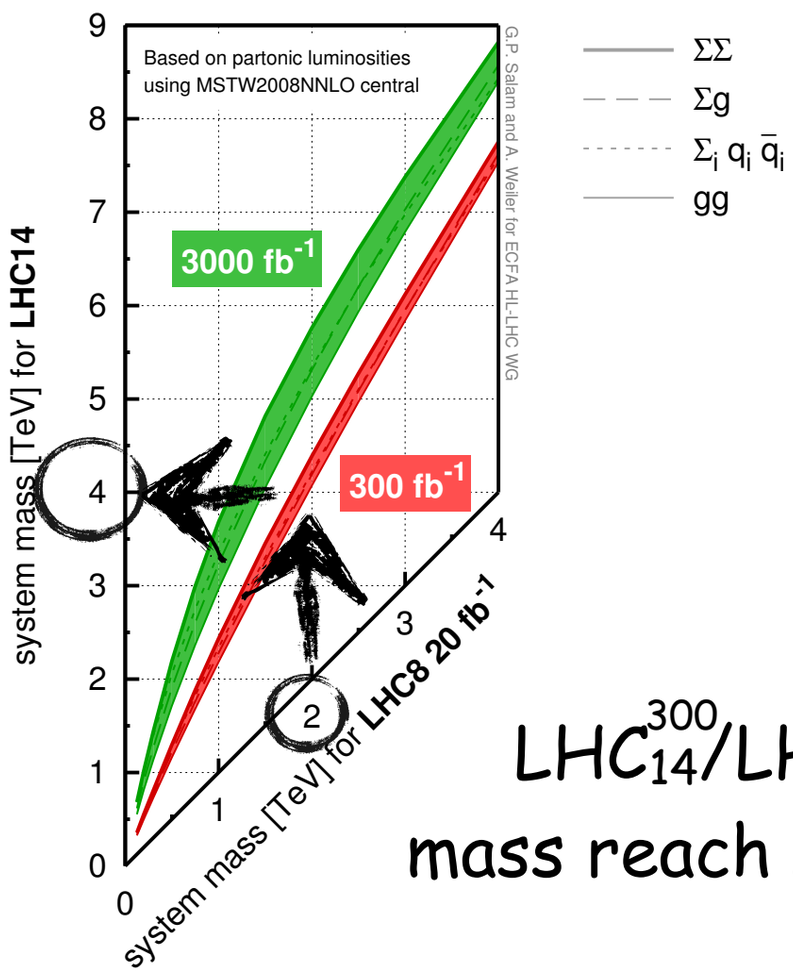
Direct exploration of an uncharted territory

A significative energy step
(maybe the last one before a long time)

The world according to LHC



Salam & Weiler "cern.ch/collider-reach" '14



$LHC_{14}^{300}/LHC_{8}^{20}$

mass reach x O(2)

Direct exploration of an uncharted territory

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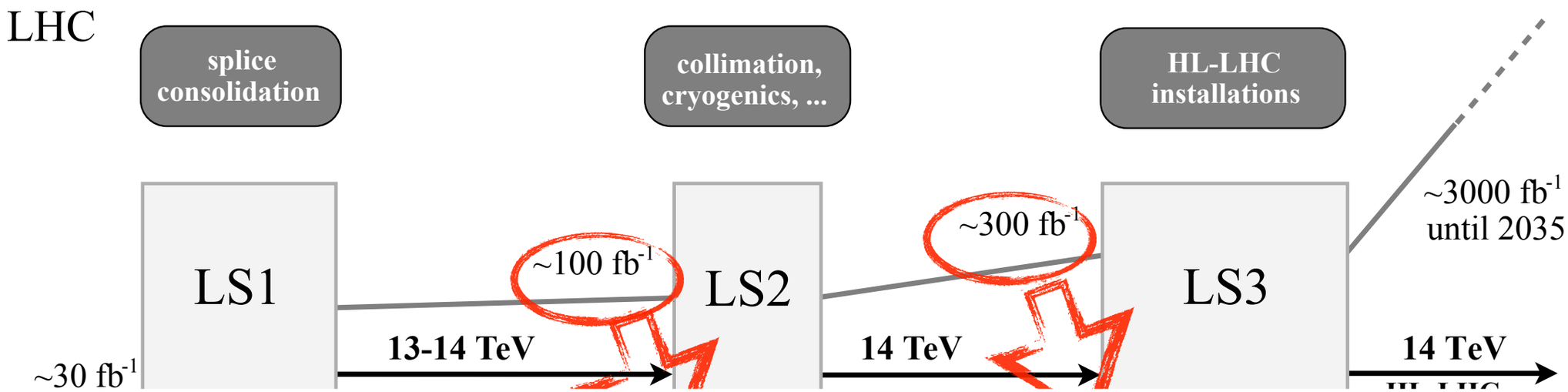
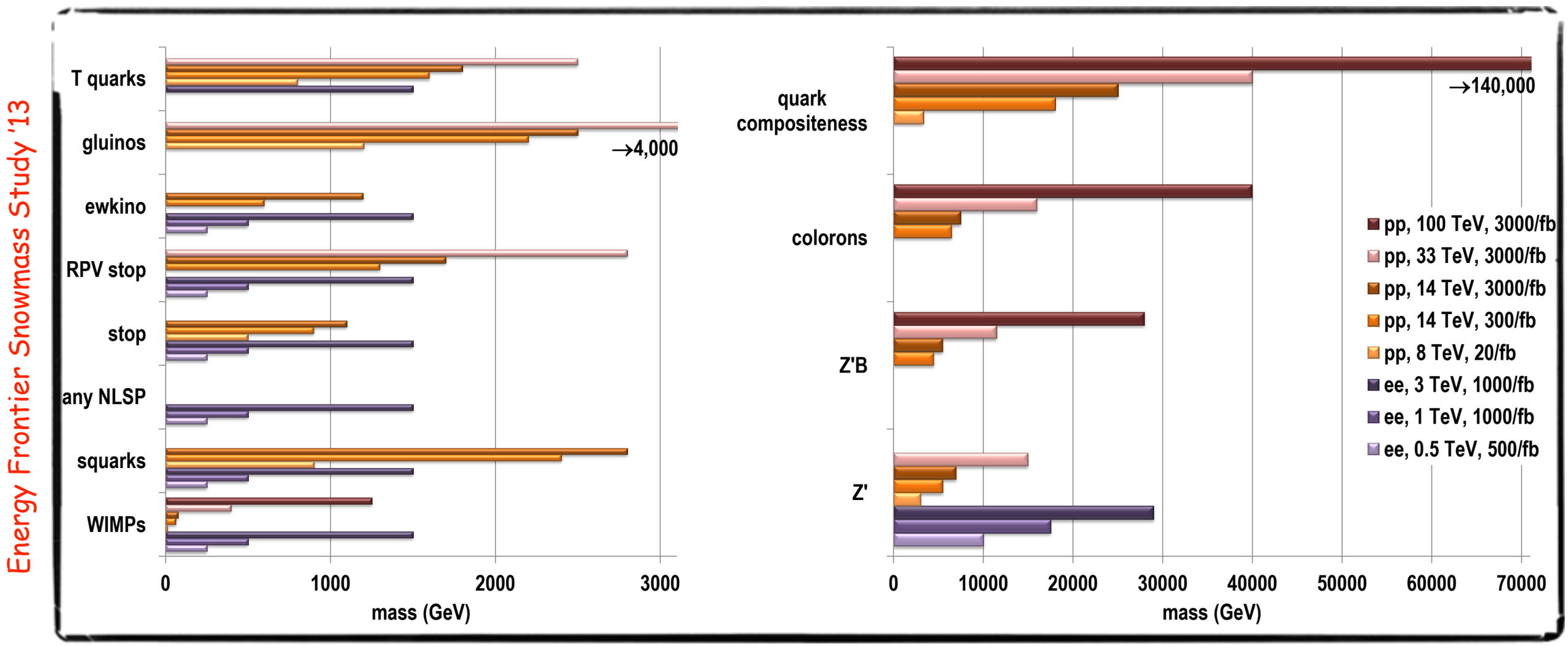
What can be discovered @ 100/fb-14TeV knowing what is excluded @ 20/fb-8TeV?

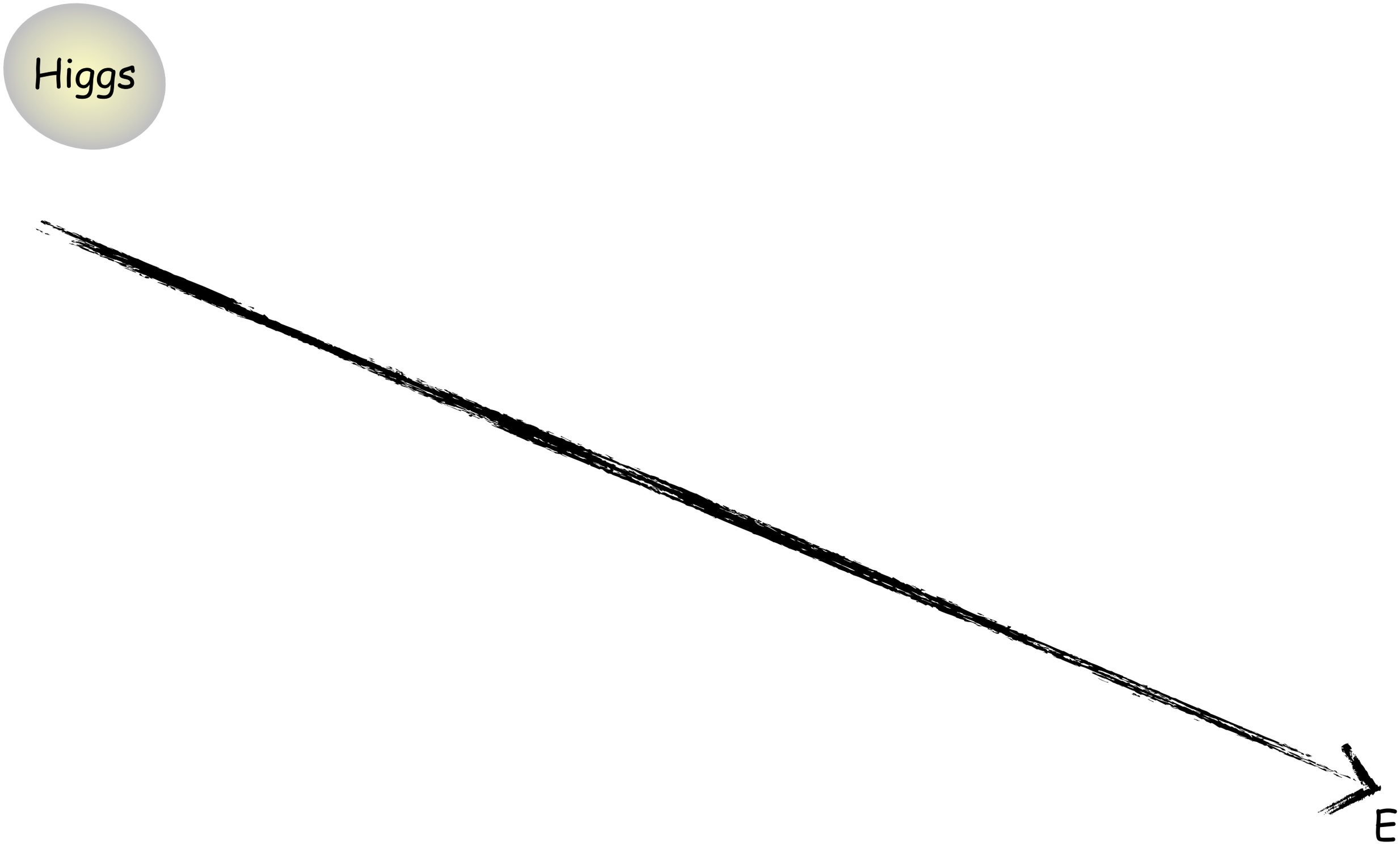
The world according to LHC





We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model



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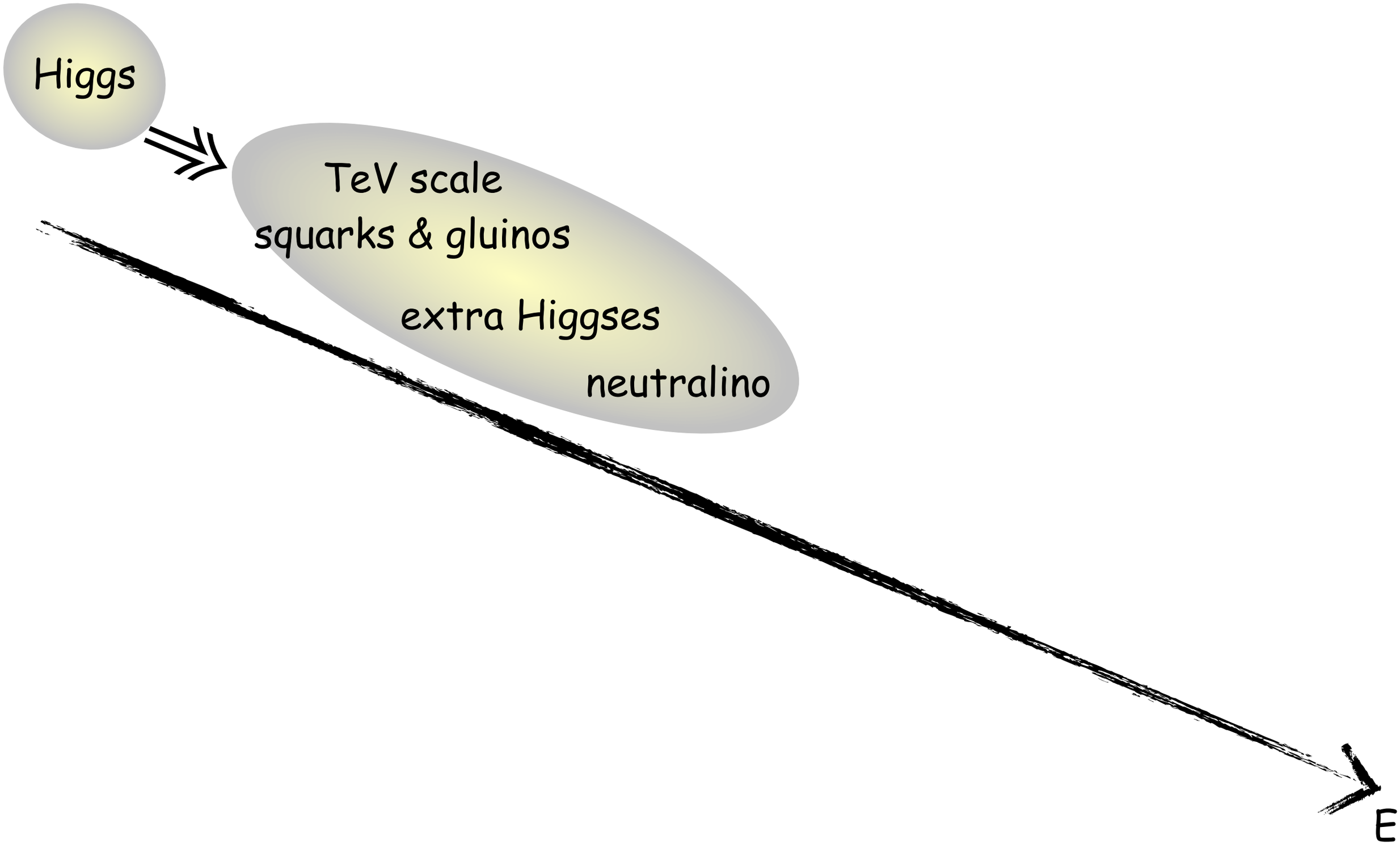

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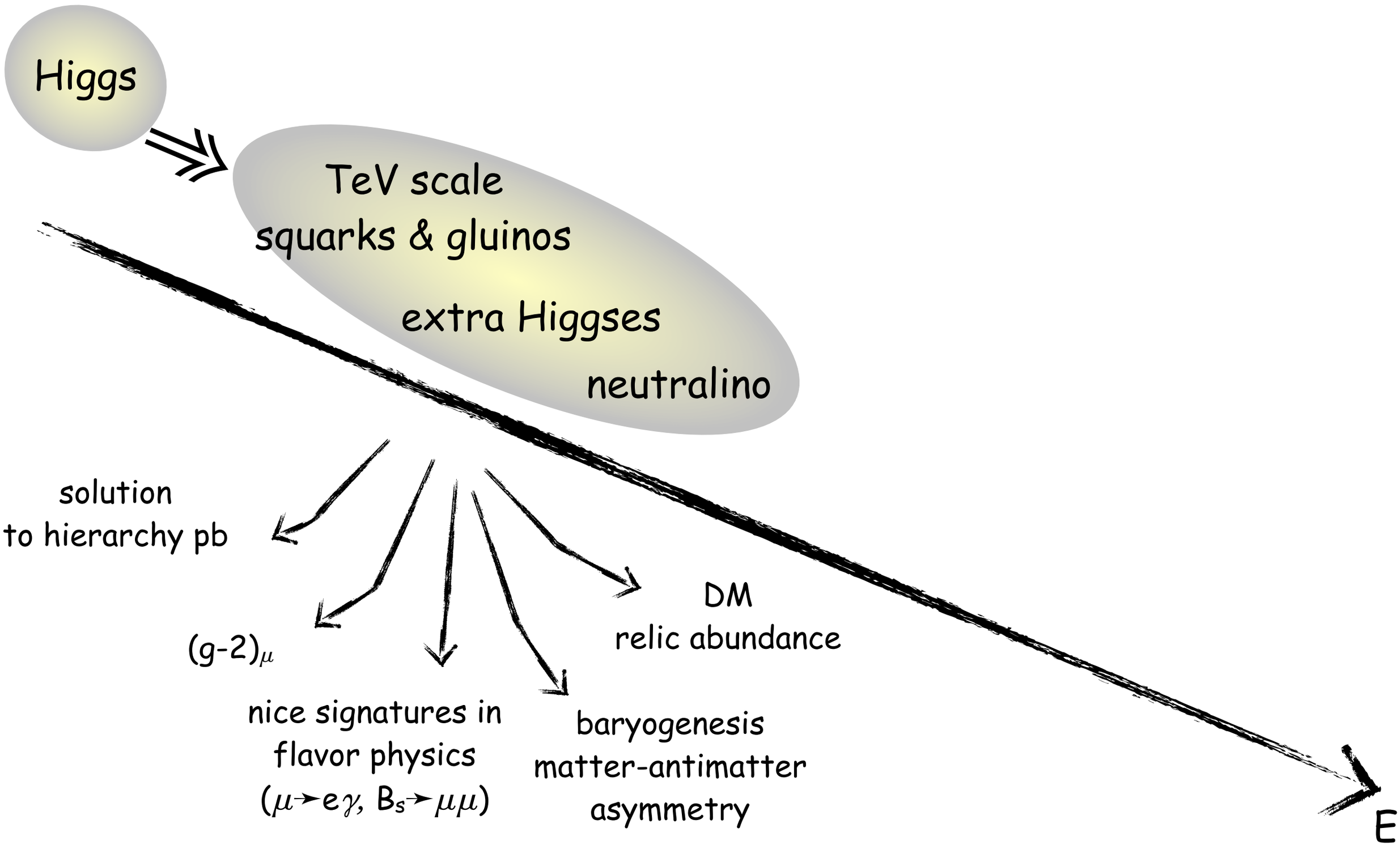

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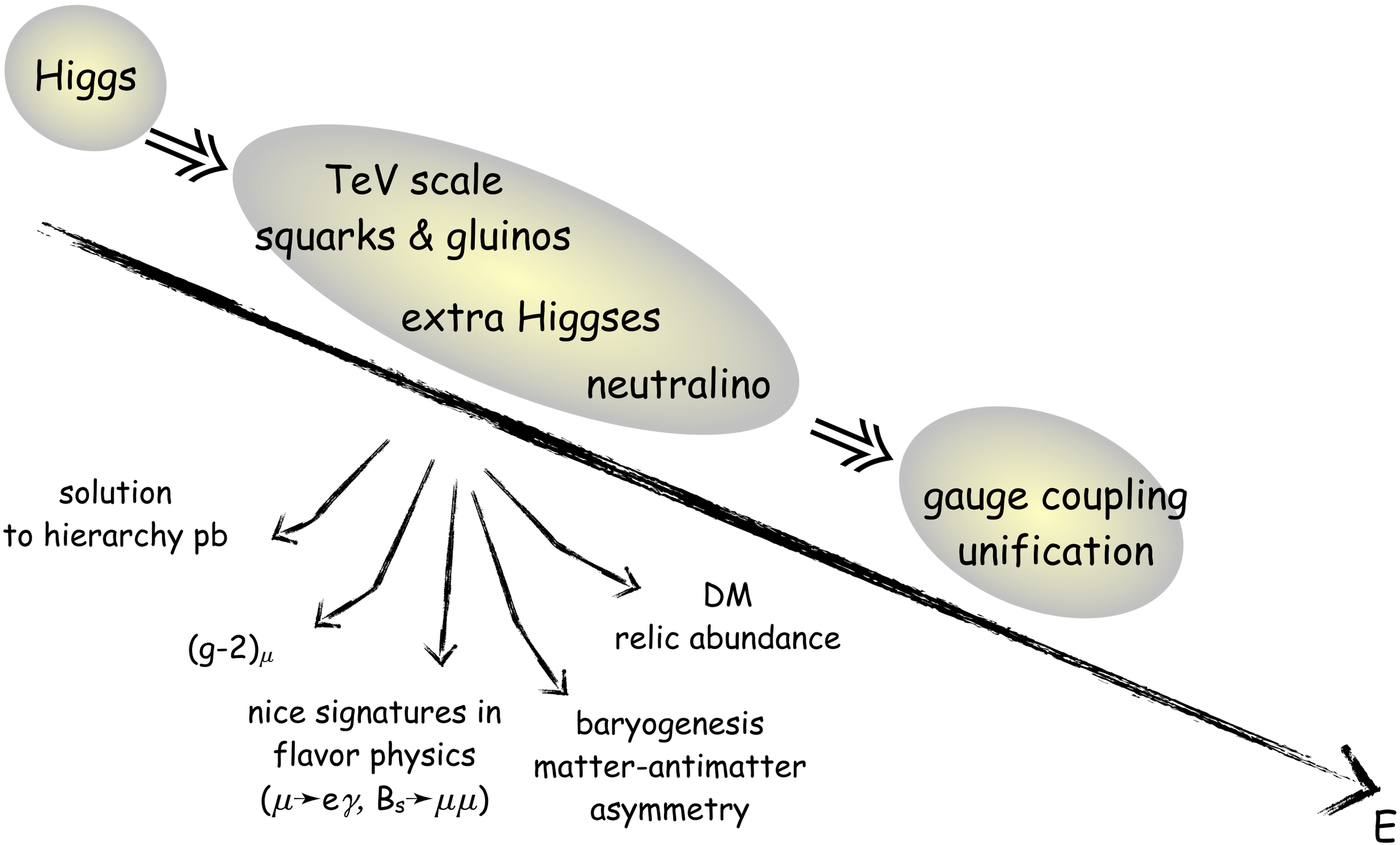

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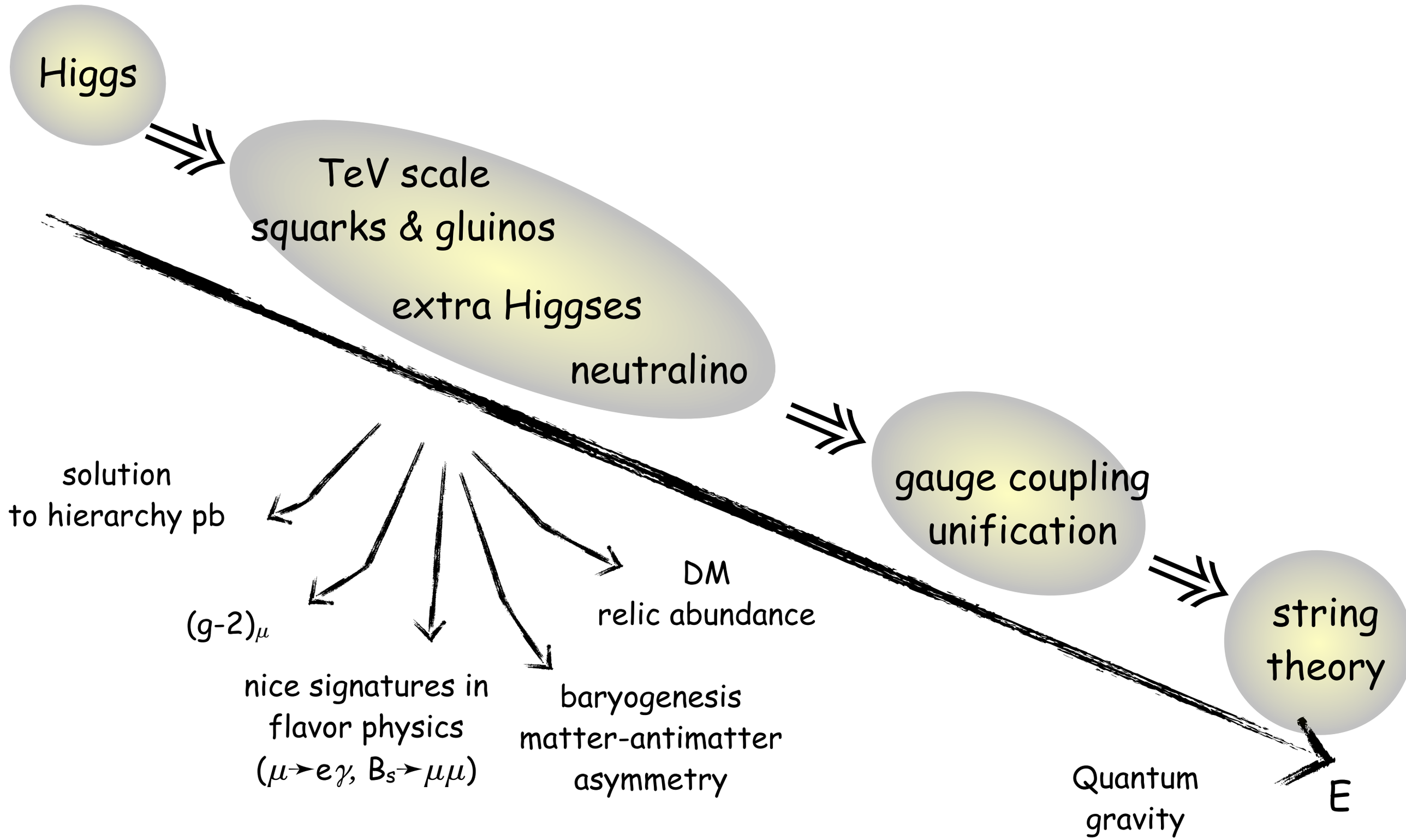

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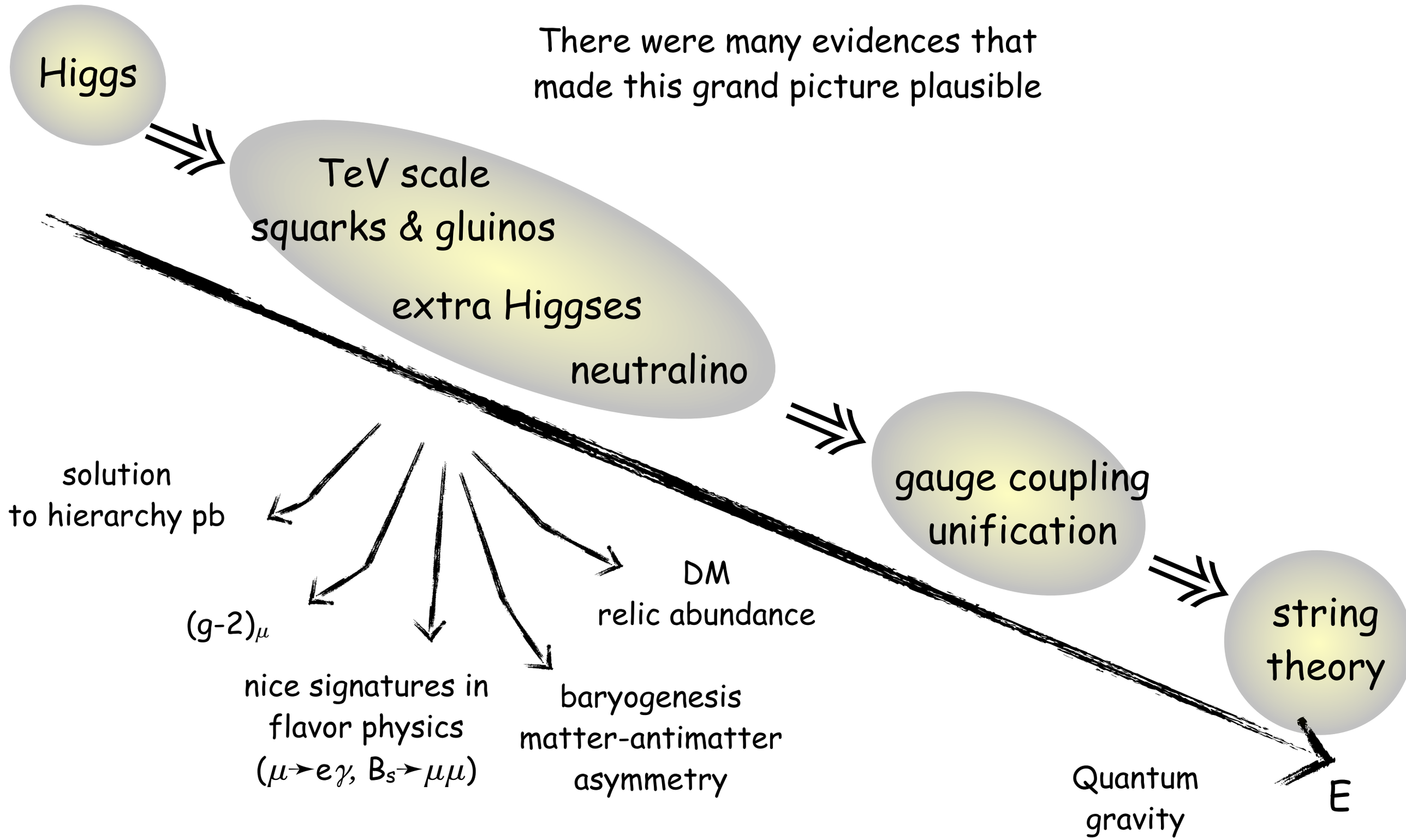

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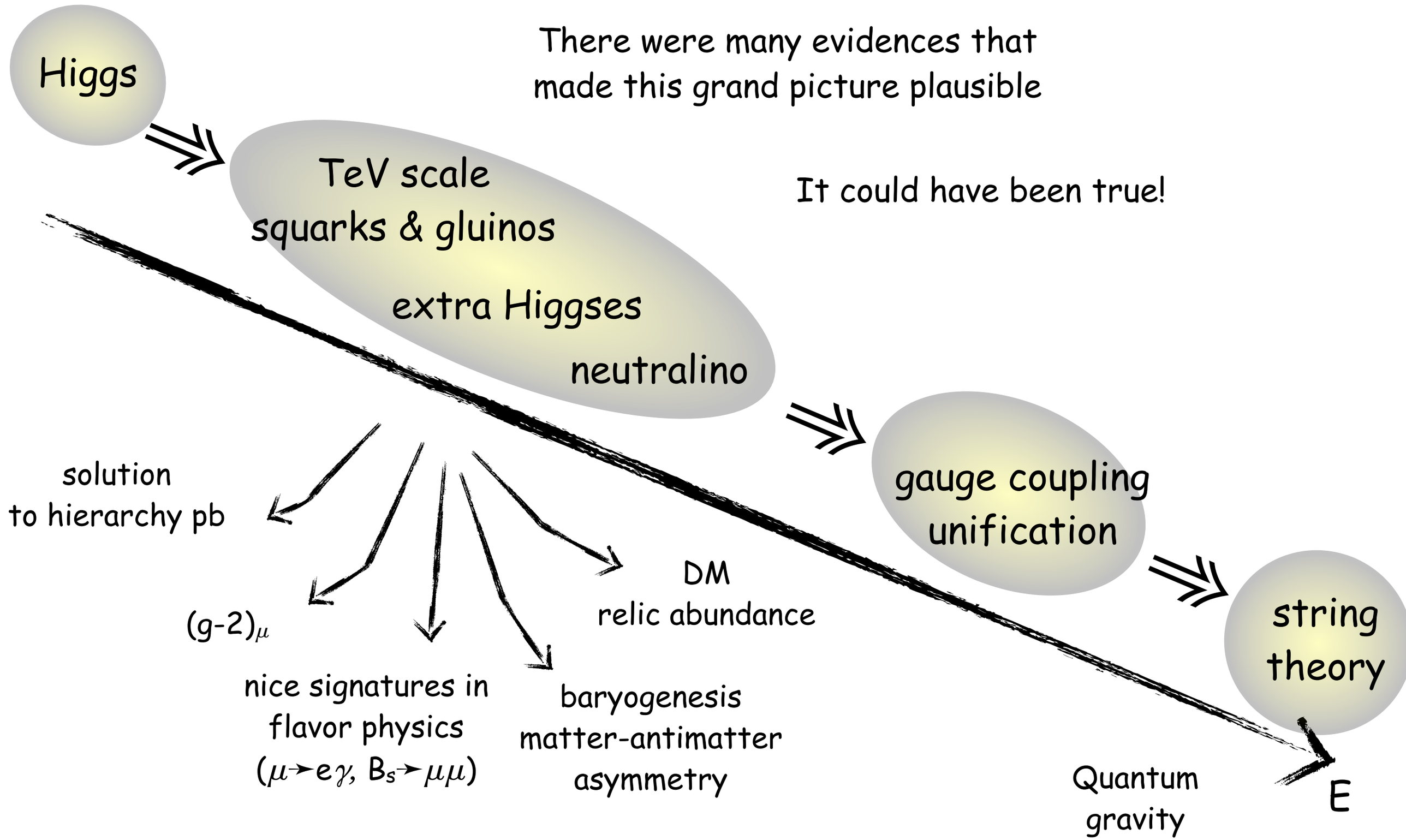

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Higgs

There were many evidences that made this grand picture plausible

TeV scale squarks &

It could have been true!

SUSY anywhere is better than SUSY nowhere

It can still be true (modulo little tunings)

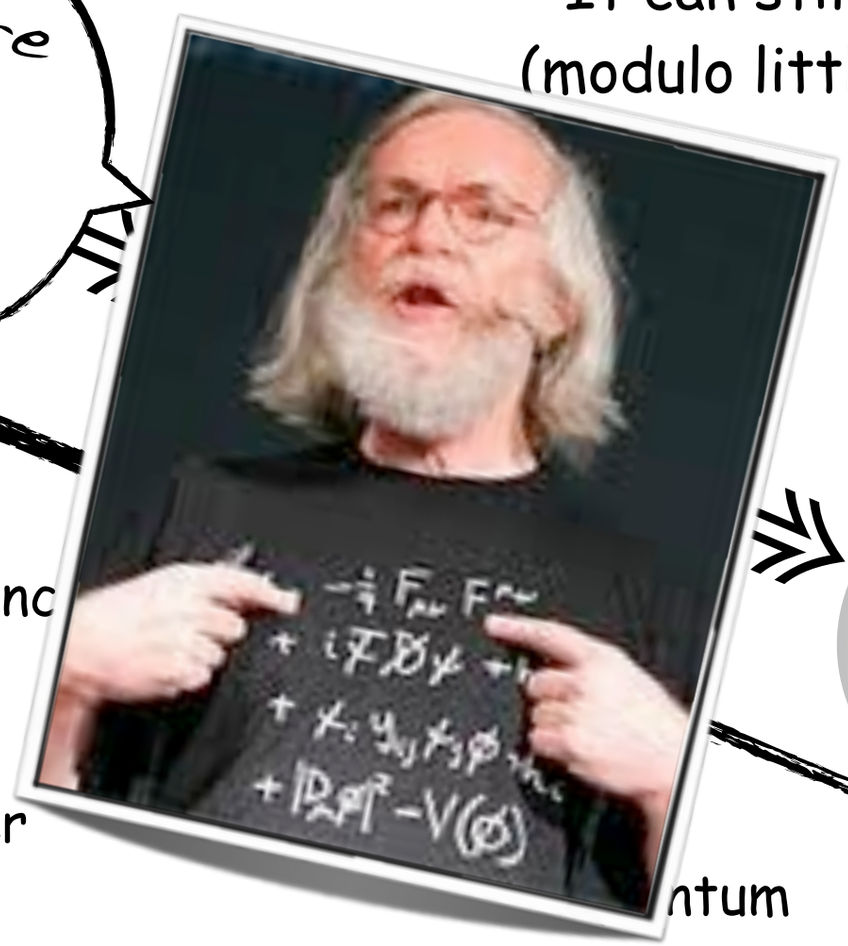
solution to hierarchy pb

$(g\text{-}2)_\mu$

nice signatures in flavor physics ($\mu \to e\gamma$, $B_s \to \mu\mu$)

baryogenesis matter-antimatter asymmetry

DM relic abundanc



ntum gravity

string theory

E

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yesterday

E

We had a dream...

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yesterday

E

today dreaming about tomorrow

HEP with a Higgs boson

" If you don't have the ball, you cannot score "

HEP with a Higgs boson

" If you don't have the ball, you cannot score "

Now with the Higgs boson in their feet,
particle physicists can... play as well as Germans against Brazilians

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Profound change in paradigm:
missing SM particle ➪ tool to explore SM and venture into physics landscape beyond

HEP with a Higgs boson

The successes have been breathtaking

- in O(2) years, the Higgs mass has been measured to 0.2% (vs 0.5% for the 20-year old top)
- some of its couplings, e.g. κ_γ, have been measured with LEP accuracy (10^{-3})

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The meaning of the Higgs

Particle physics is not so much about particles but more about fundamental principles

- About 10^{-10}s after the Big Bang, the Universe filled with the Higgs substance because it saved energy by doing so: the vacuum is not empty!

- The masses are emergent quantities due to a non-trivial vacuum structure

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Higgs agenda for the LHC-II, HL-LHC, ILC/CLIC, FCC, CepC, CppC, SHiP

multiple independent, synergetic and complementary approaches to achieve **precision** (couplings), **sensitivity** (rare and forbidden decays) and **perspective** (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, inflation, naturalness, etc)

M.L. Mangano, Washington '15

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M.L. Mangano, Washington '15

- rare Higgs decays: $h\to\mu\mu$, $h\to\gamma Z$
- Higgs flavor violating couplings: $h\to\mu\tau$ and $t\to hc$
- Higgs CP violating couplings
- exclusive Higgs decays (e.g. $h\to J/\Psi+\gamma$) and measurement of couplings to light quarks
- exotic Higgs decay channels:

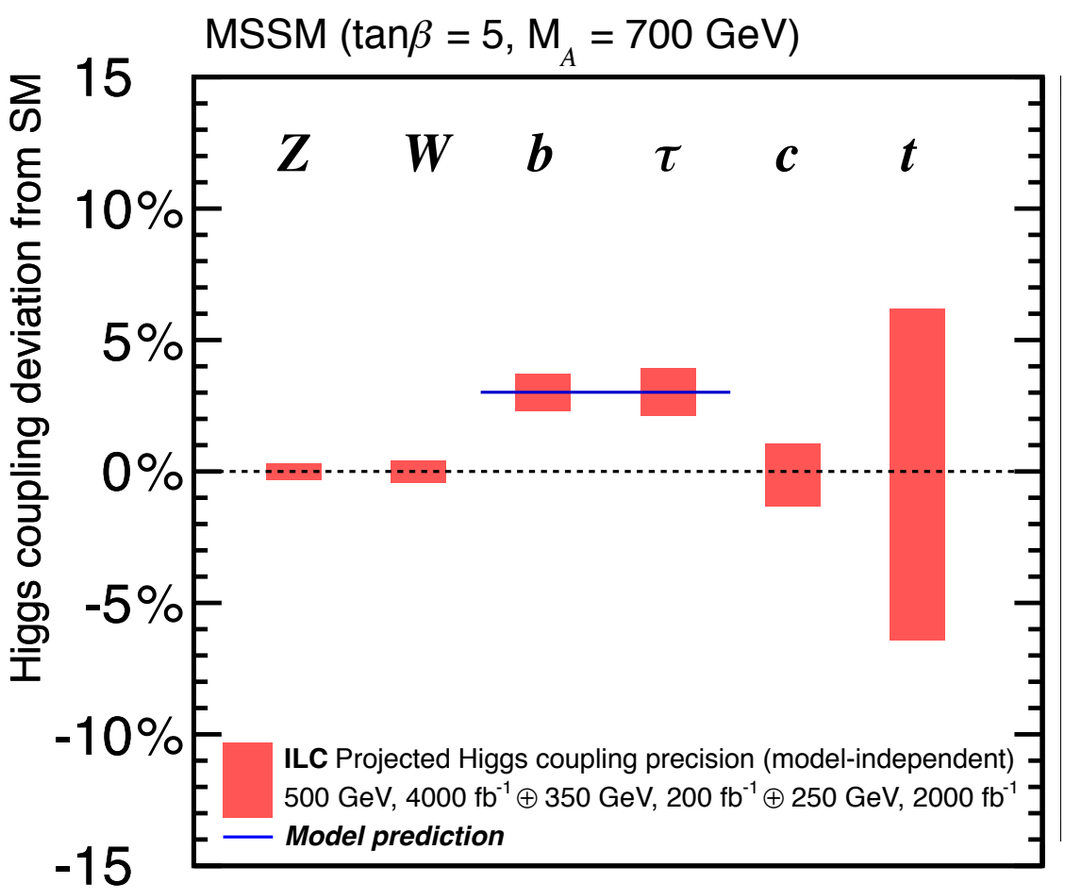
  $h\to \not{E}_T$, $h\to 4b$, $h\to 2b2\mu$, $h\to 4\tau, 2\tau 2\mu$, $h\to 4j$, $h\to 2\gamma 2j$, $h\to 4\gamma$, $h\to\gamma/2\gamma+\not{E}_T$,

  $h\to$isolated leptons$+\not{E}_T$, $h\to 2l+\not{E}_T$, $h\to$one/two lepton-jet(s)+X, $h\to bb+\not{E}_T$, $h\to\tau\tau+\not{E}_T$ ...
- searches for extended Higgs sectors (H, A, $H^\pm$,$H^{\pm\pm}$...)
- Higgs self-coupling(s)
- Higgs width
- Higgs/axion coupling?
- ...

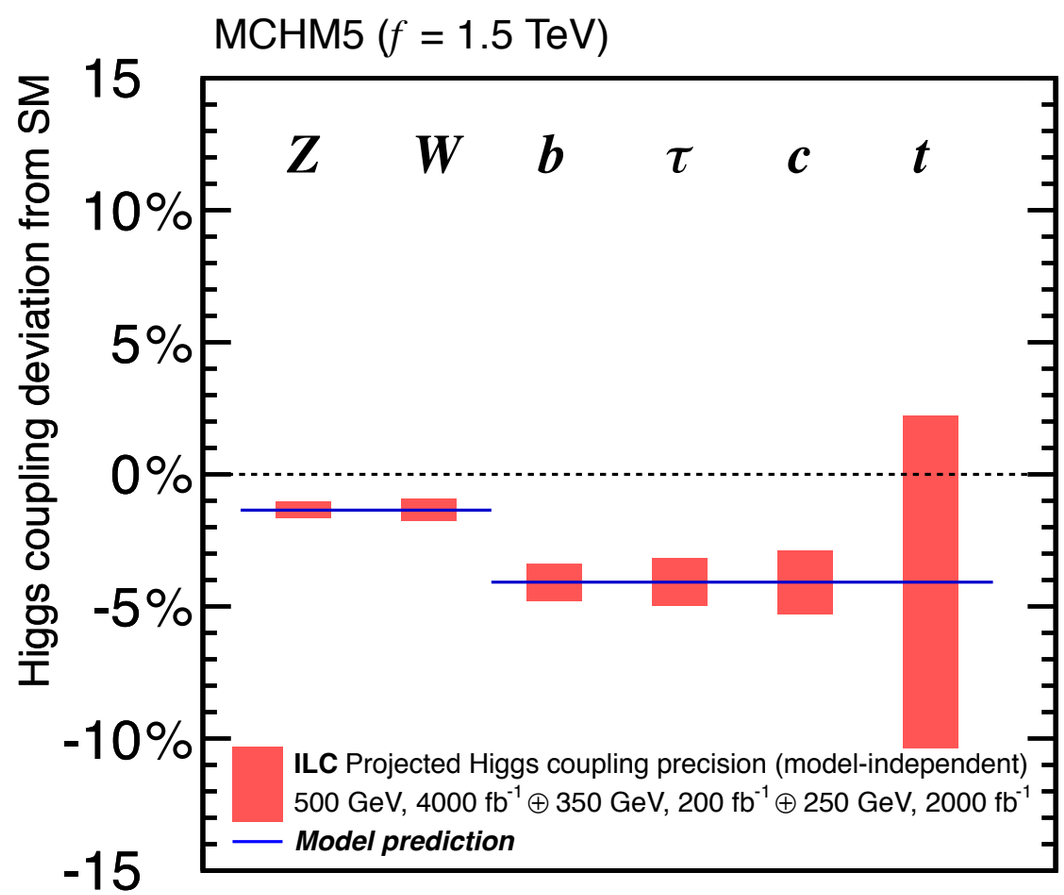
Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



ILC Physics WG, '15

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~~ expected largest relative deviations ~~

	hff	hVV	hγγ	hγZ	hGG	h^3
MSSM	√		√	√	√	
NMSSM	√	√	√	√	√	
PGB Composite	√	√		√		√
SUSY Composite	√	√	√	√	√	√
SUSY partly-composite			√	√	√	√
"Bosonic TC"						√
Higgs as a dilaton			√	√	√	√

A. Pomarol, Naturalness '15

The Higgs boson and the gauge principle

Particle physics is not so much about particles but more about fundamental principles

The Higgs boson and the gauge principle

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Are gauge theories the right principle
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$$\mathcal{L}_{\rm Higgs} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar{\psi}_{Li}\psi_{Rj}H + h.c.\right)$$

vacuum energy
cosmological constant
$V_0 \approx (2\times 10^{-3}\ {\rm eV})^4 \ll M_{\rm PL}^4$

hierarchy problem
$m_H \approx 100\ {\rm GeV} \ll M_{\rm Pl}$

triviality/stability
of EW vacuum

mass and mixing
hierarchy

flavour & CP

Higgs interactions: many different couplings not set by any gauge symmetry

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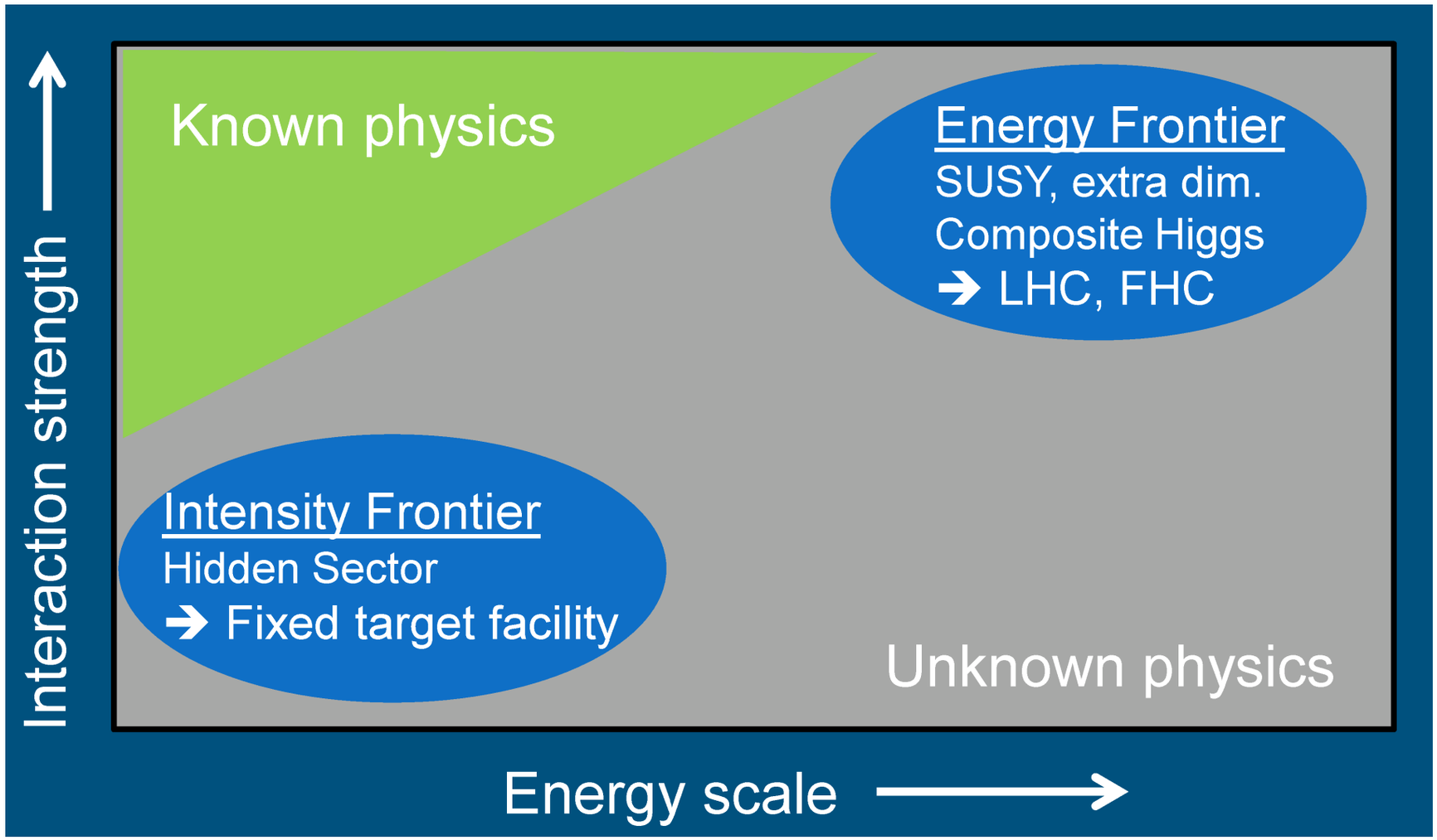
- vacuum energy / cosmological constant — $V_0 \approx (2\times 10^{-3}\ \mathrm{eV})^4 \ll M_{\rm PL}^4$
- hierarchy problem — $m_H \approx 100\ \mathrm{GeV} \ll M_{\rm Pl}$
- triviality/stability of EW vacuum
- mass and mixing hierarchy
- flavour & CP

Higgs interactions: many different couplings not set by any gauge symmetry

What are the interactions of the non-SM matter?

The interactions of the non-SM matter

the jury is still out



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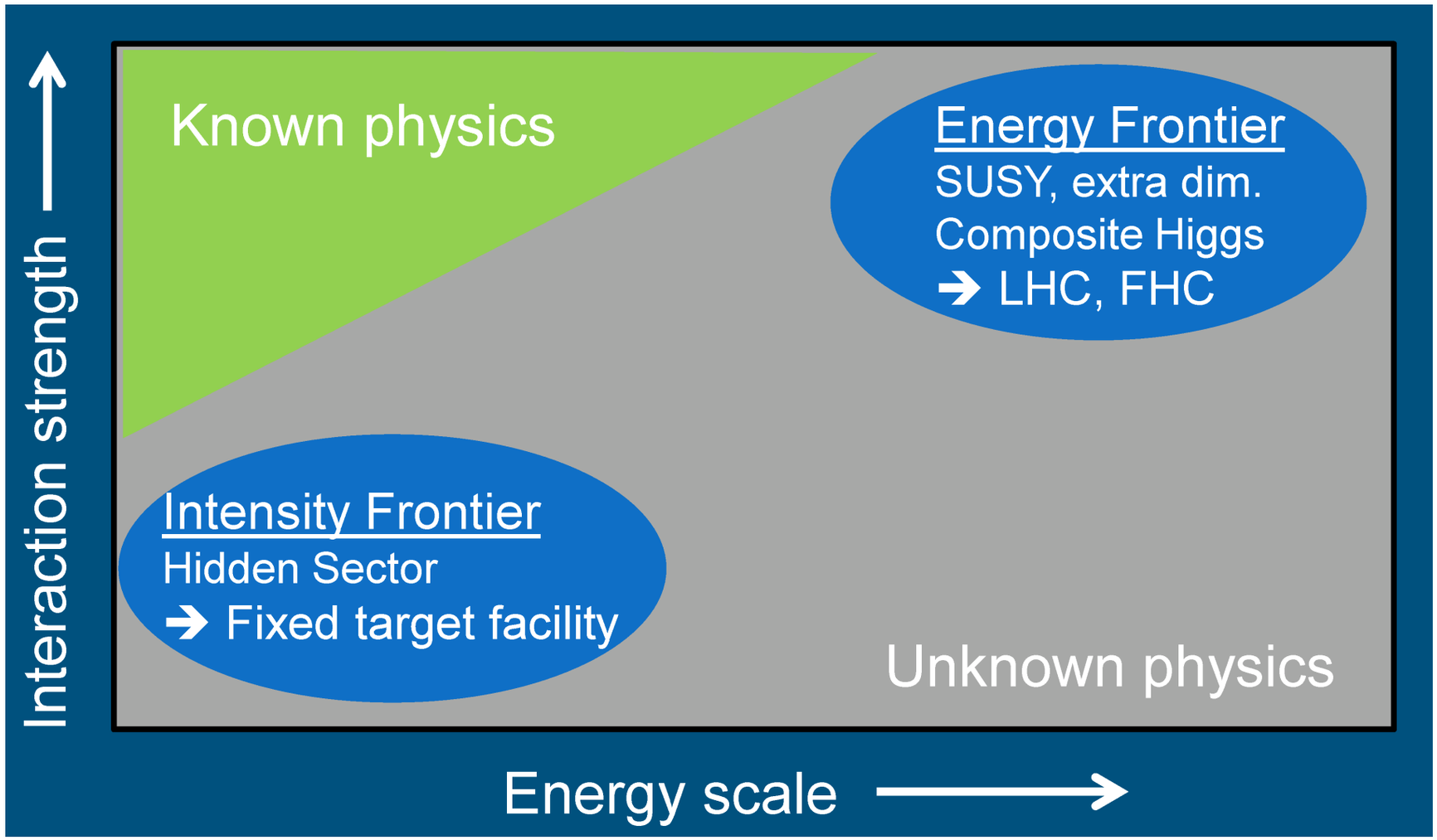

We expected TeV scale new physics with sizable couplings to solve the hierarchy problem, and, since it is easy to obtain DM out of it, there was no need for light/hidden sector

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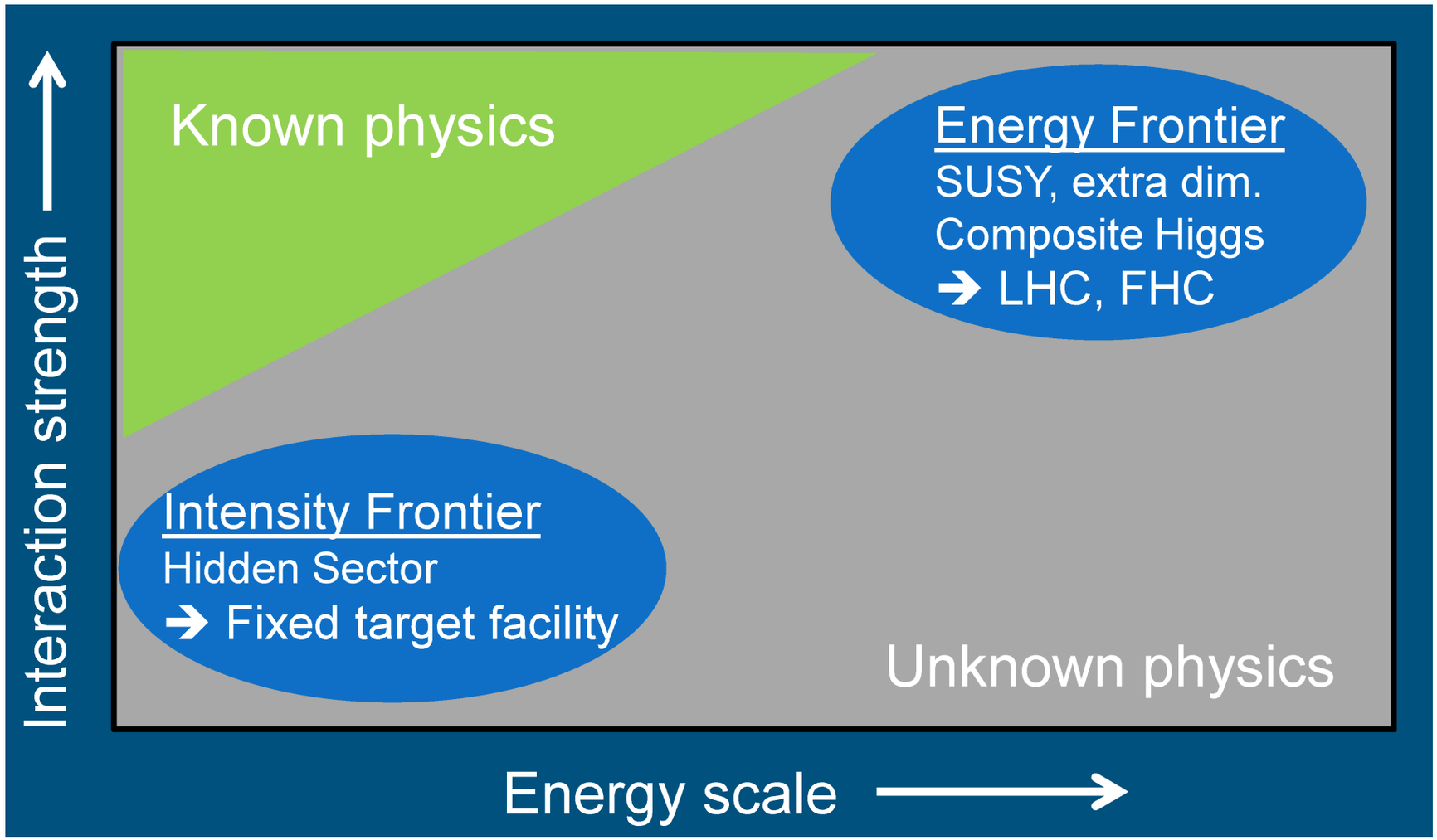

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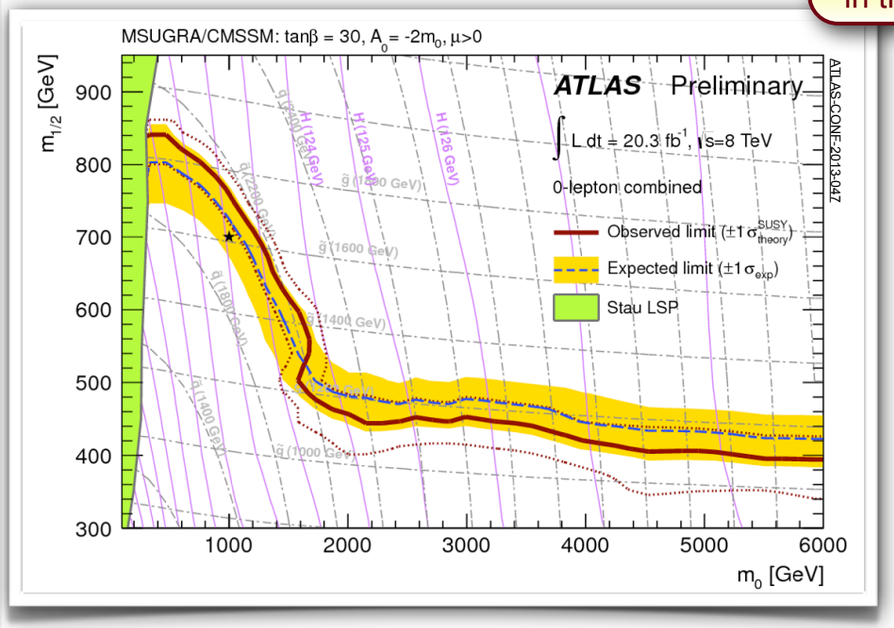
Except for the QCD axion,
light weakly coupled new sector was not part of the theory Grand Picture

Where is everybody: Should we worry?

G. Disserotri, ECFA '13

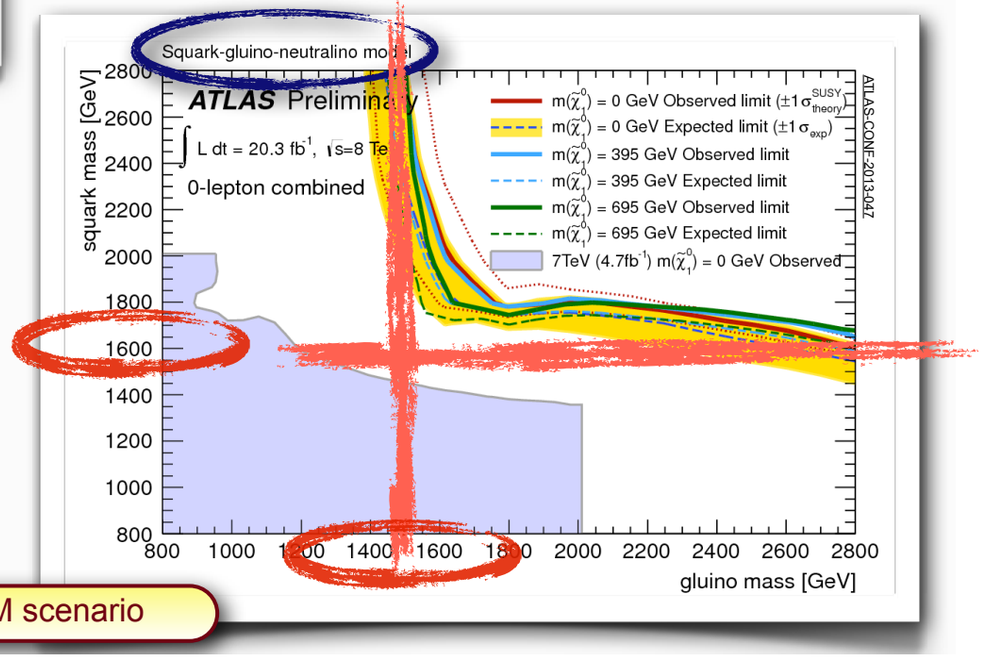
in the context of a concrete model, here MSUGRA/cMSSM

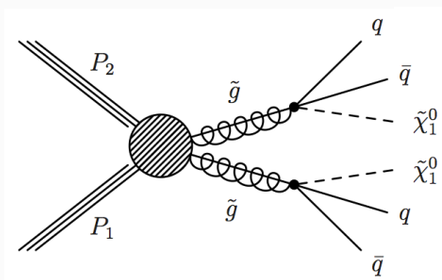


here: example of scenario compatible with a low-mass Higgs as recently discovered

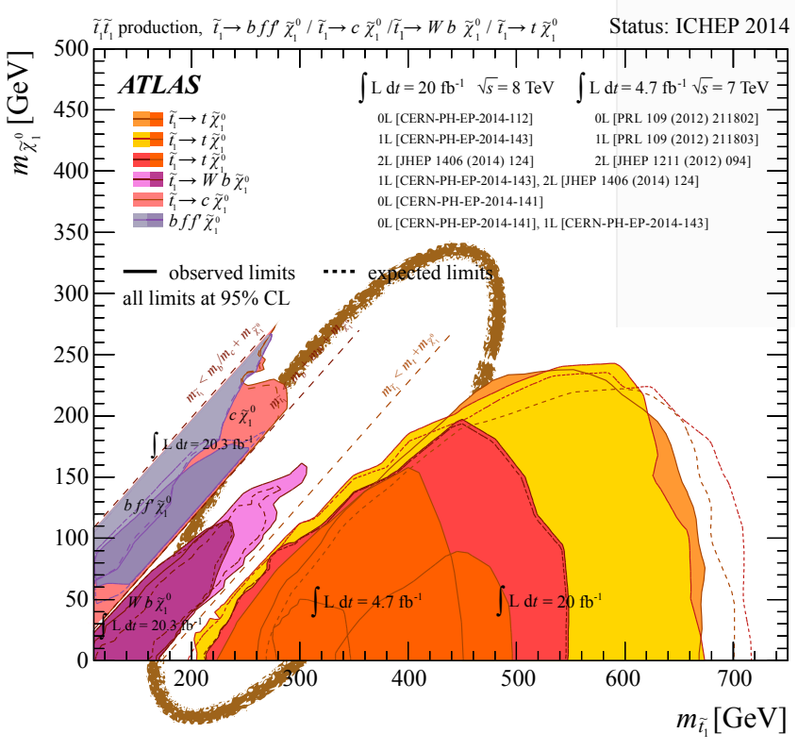
- **eg. for m(squark) = m(gluino), exclude below ~1800 GeV**
- these searches typically target large M_{eff} and large difference m(SUSY) - m(LSP)
- the very inclusive searches keep sensitivity even for m(LSP) up to several hundreds of GeV (at some stage trigger-constrained)

- recently also targeting more compressed spectra and higher jet multiplicities





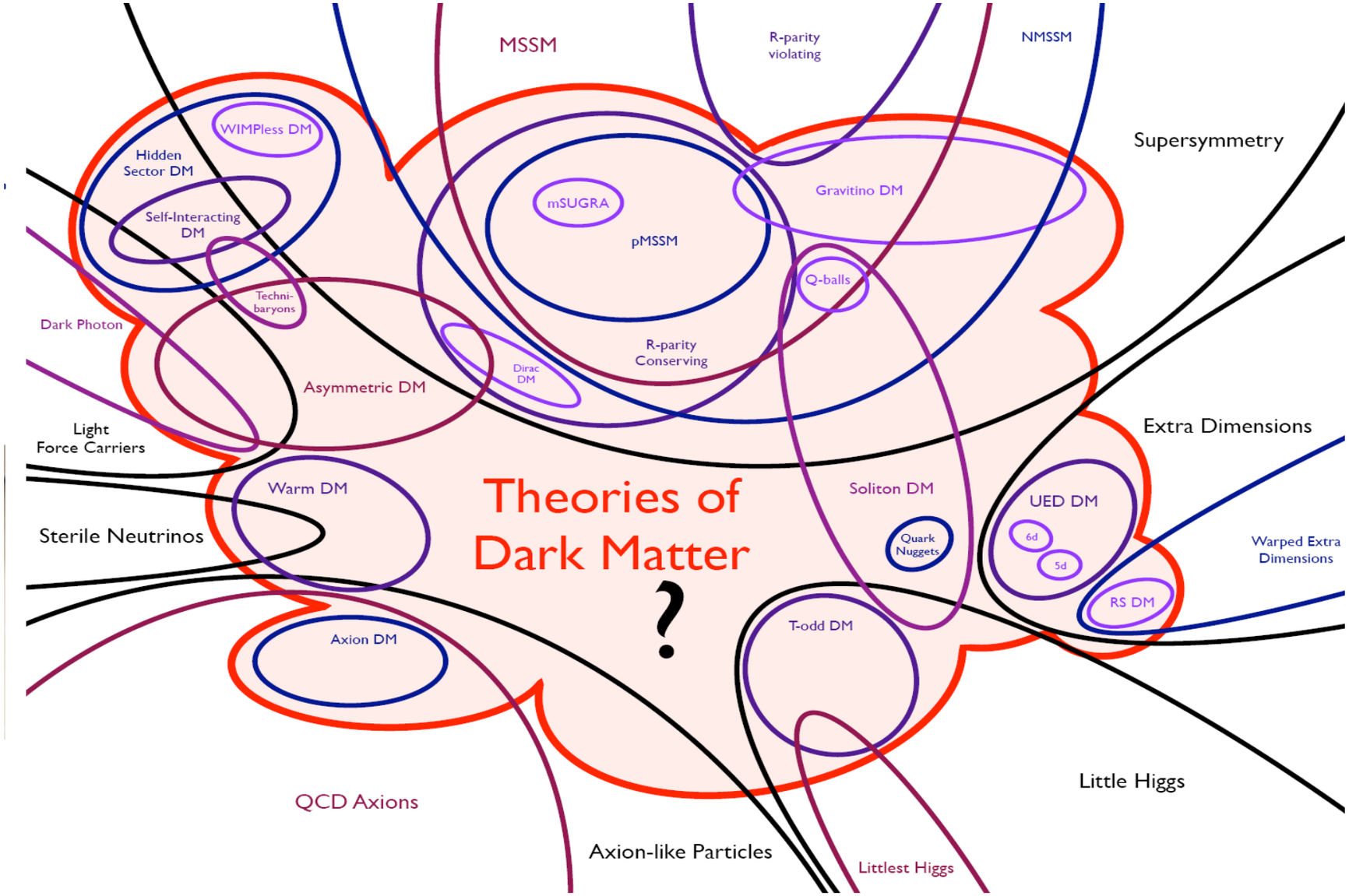
in the context of a simplified MSSM scenario



cMSSM ➛ Natural SUSY/RPV SUSY

There are still holes and the LHC will look at them

The energy scale(s) of new physics



T. Tait, DM@LHC '14

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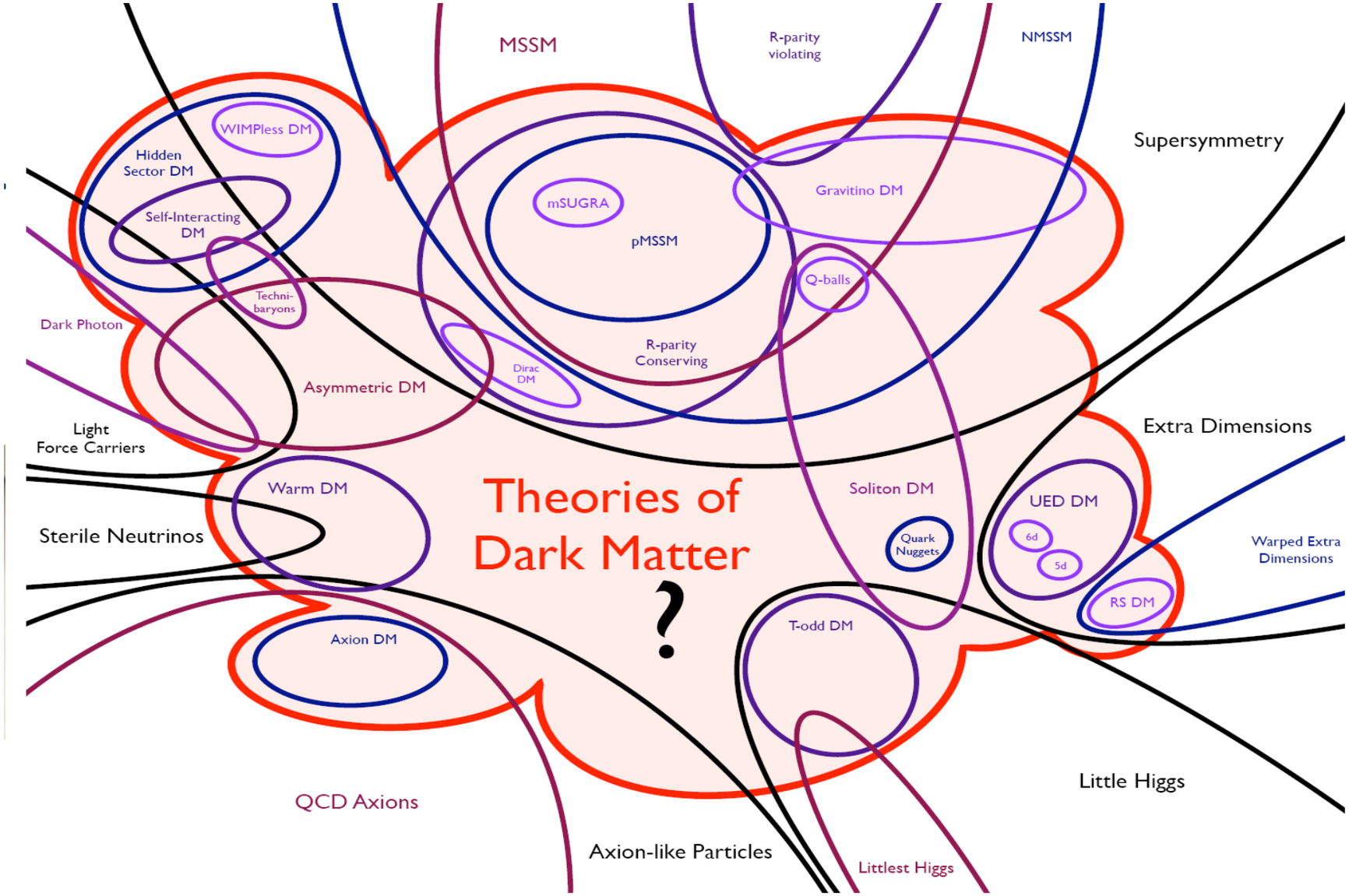


T. Tait, DM@LHC '14

The prediction about the mass scale of DM comes with large error bars:

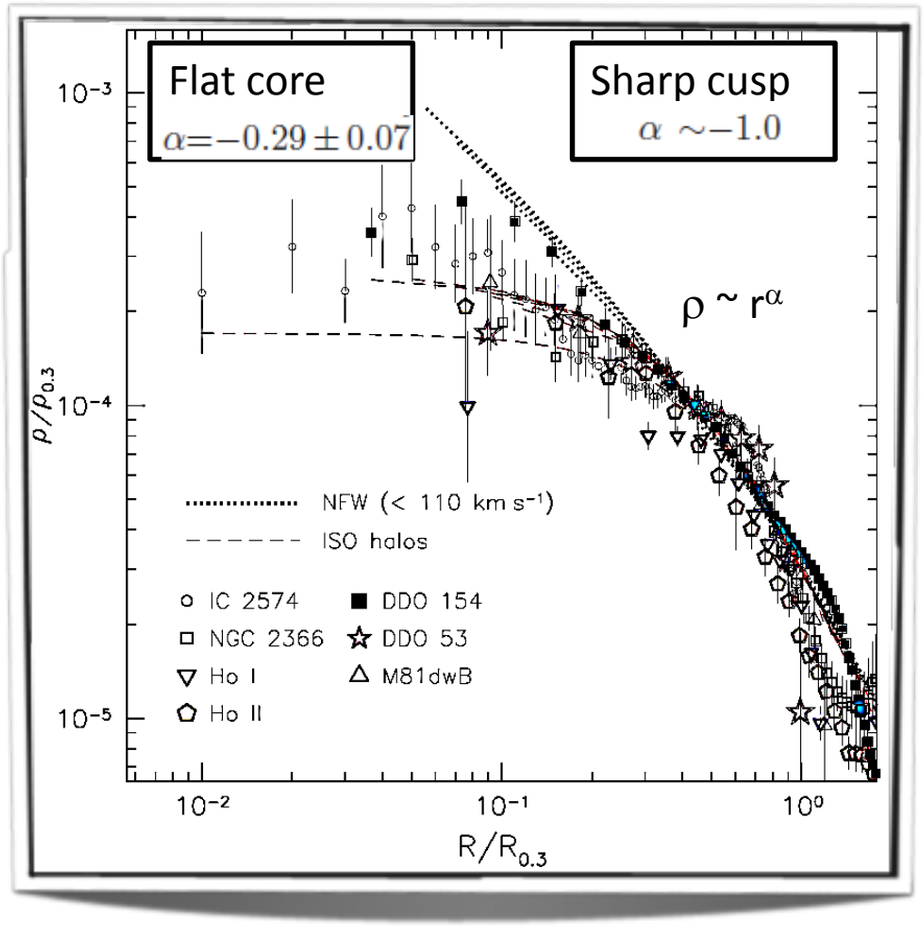
$$10^{-22}\,\mathrm{eV} < m_{DM} < 10^{20}\,\mathrm{GeV}$$

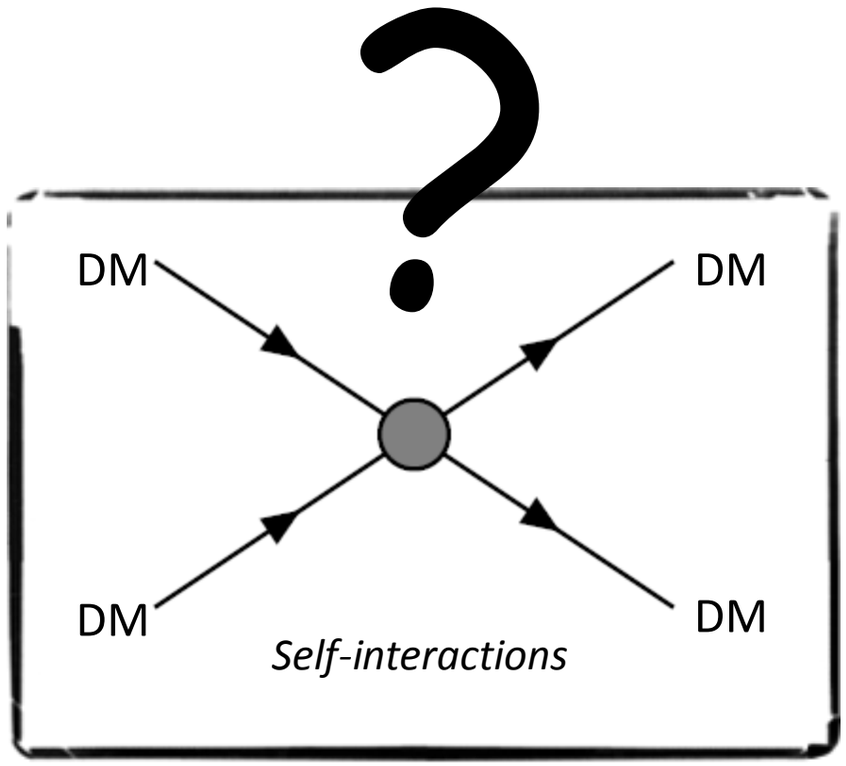
(ALPs) (Wimpzillas, Q-balls)

An interesting experimental clue (?)

Distributions of DM are flatter than what ΛCDM predicts

S.H. Oh et al. '15





$$\sigma/m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g} \approx 2\ \mathrm{barns/GeV}$$

S. Tullin, IFAE '15

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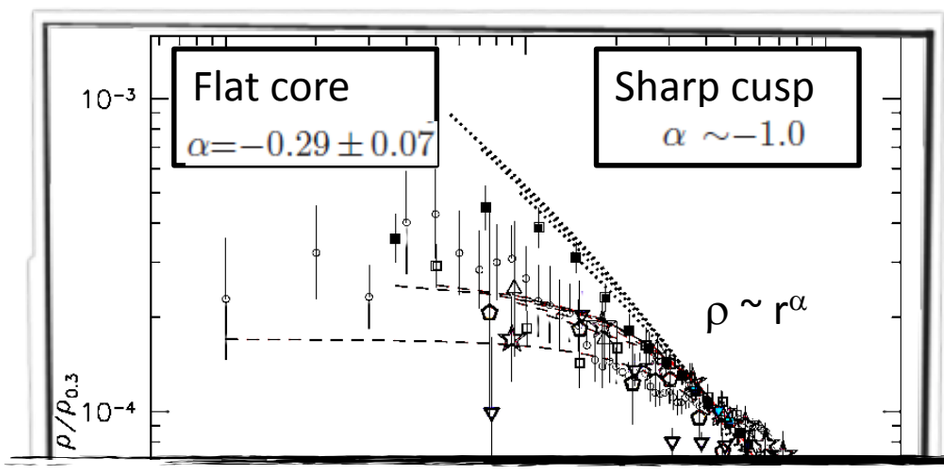
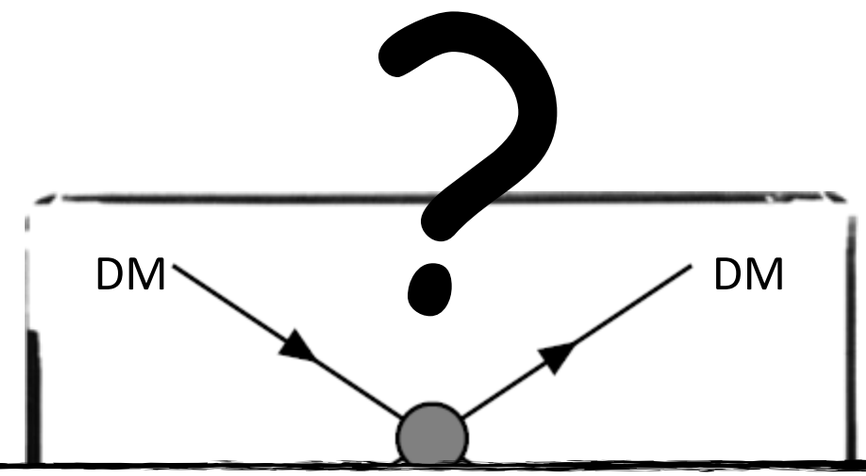
Distributions of DM are flatter than what ΛCDM predicts

S.H. Oh et al. '15





Cores in different systems are probing self-interactions at different energies

Low energies (v/c ~ 10^{-4})

Medium energies (v/c ~ 10^{-3})

High energies (v/c ~ 10^{-2})

Like probing DM at different colliders w/. different beam energies

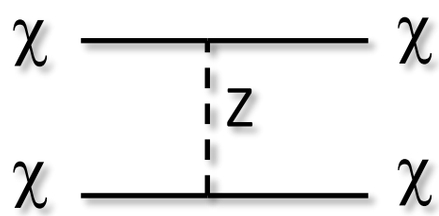
All consistent with the self-interacting DM picture

S. Tullin, IFAE '15

Self-Interacting DM

S. Tullin, IFAE '15

~WIMP DM~



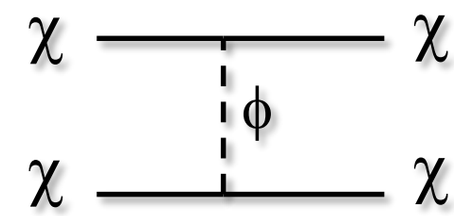
self-interaction

$$\sigma \sim \frac{g^4\, m_\chi^2}{m_Z^4} \sim 10^{-36}\,\mathrm{cm}^2$$

$$m_\chi \sim 100\,\mathrm{GeV}$$

$$\sigma/m_\chi \sim 10^{-14}\,\mathrm{cm}^2/\mathrm{g}$$

~ Light mediator DM~



self-interaction

$$\sigma \sim \frac{g^4\, m_\chi^2}{m_\phi^4}$$

$$\sigma/m_\chi \sim 1\,\mathrm{cm}^2/\mathrm{g}$$

$$m_\phi \sim 1 - 100\,\mathrm{MeV}$$

Dark photon? Dark Higgs?

Are DM self-interactions controlled by gauge symmetry? which one?

Naturalness & TeV scale new physics

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections
(others are not necessarily theoretically inconsistent
but they require some conspiracy at different scales)

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Field	Symmetry as $m \to 0$	Implication
Spin-1/2 $m\Psi\bar{\Psi}$	$\Psi \to e^{i\theta}\Psi$ $\bar{\Psi} \to e^{-i\theta}\bar{\Psi}$ (chiral symmetry)	$\delta m \propto m$ **Natural!**
Spin-1 $m^2 A_\mu A^\mu$	$A_\mu \to A_\mu + \partial_\mu \alpha$ (gauge invariance)	$\delta m \propto m$ **Natural!**

courtesy to N. Craig @ Blois '15

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The Higgs mass in the SM doesn't break any (quantum*) symmetry

* it does break classical scale invariance, as the running of the gauge couplings does too!

Naturalness principle @ work

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see for instance Giudice '13 (and refs. therein) for a recent account

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- the need of the positron to screen the electron self-energy
- the rho meson to cutoff the EM contribution to the charged pion mass
- the kaon mass difference regulated by the charm quark
- the light Higgs boson to screen the EW corrections to gauge bosons self-energies
- ...
- New physics at the TeV scale to cancel the UV sensitivity of the Higgs mass?

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by the time evolution/the age of the Universe

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Graham, Kaplan, Rajendran '15

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Self-organized criticality

when the Higgs mass becomes negative, it
back-reacts and generates a potential barrier
that stops the evolution of the scanning field

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

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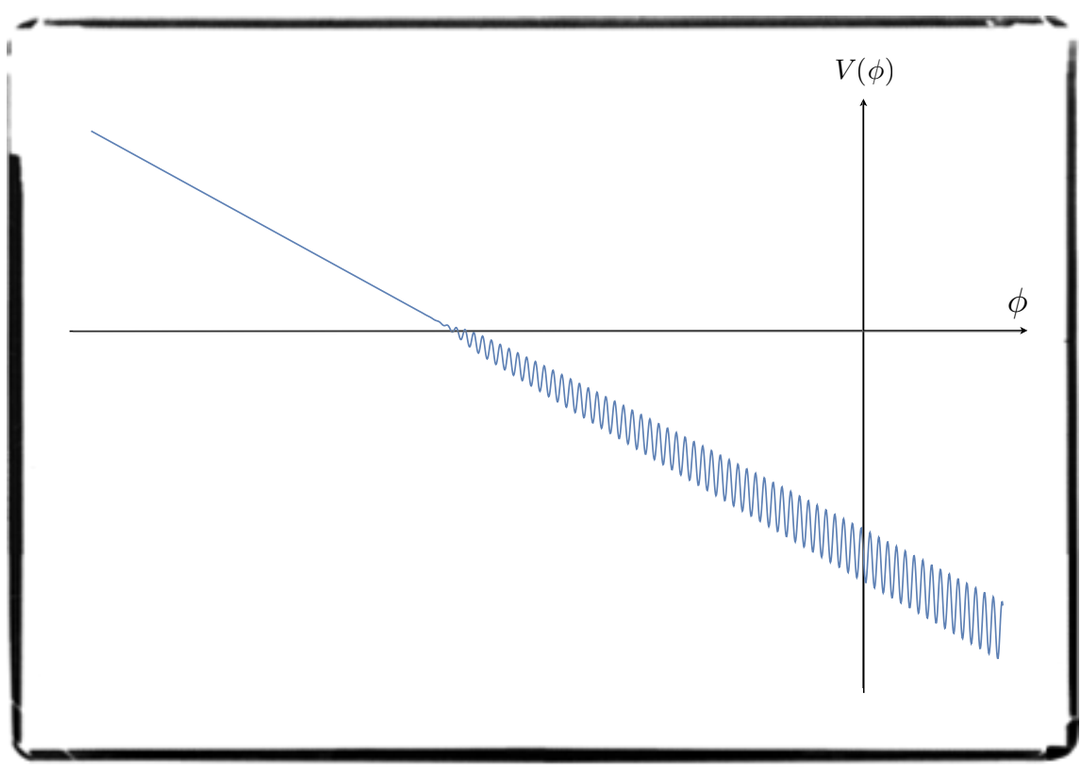

If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

$$v\sim\frac{g\,f\,\Lambda^3}{\Lambda^3_{\rm QCD}}$$

see also Espinosa, Grojean, Pomarol, Pujolas, Servant '15

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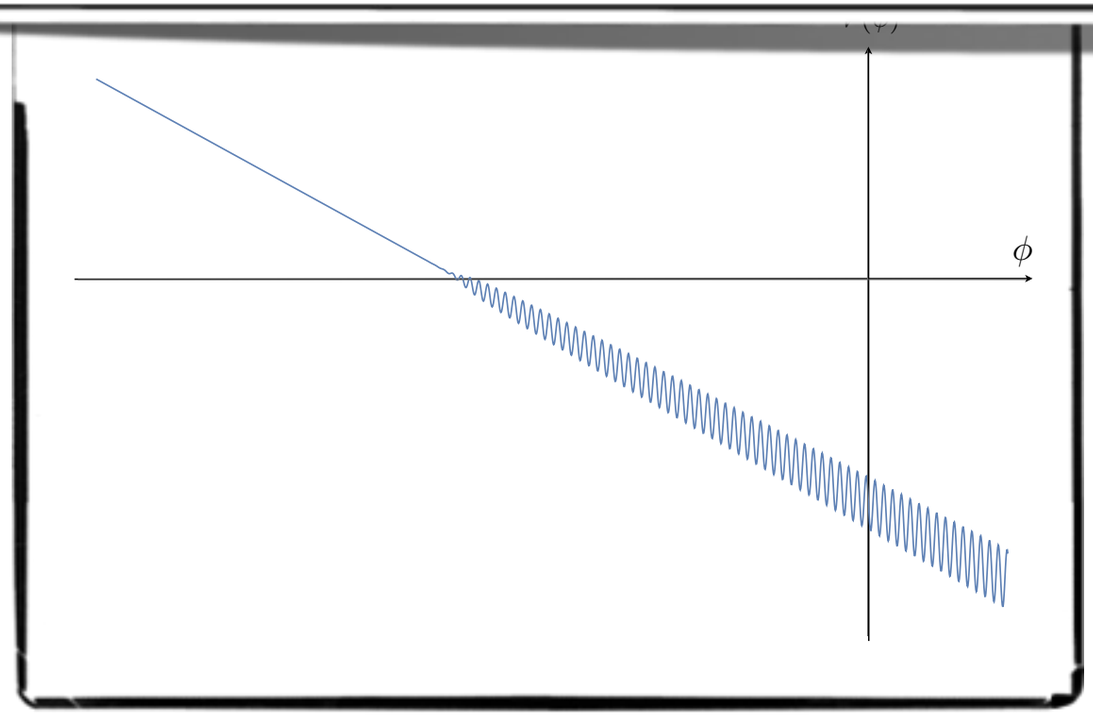
Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics



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~interesting cosmology signatures~

- BBN constraints
- decaying DM signs in γ-rays background
- ALPs
- superradiance

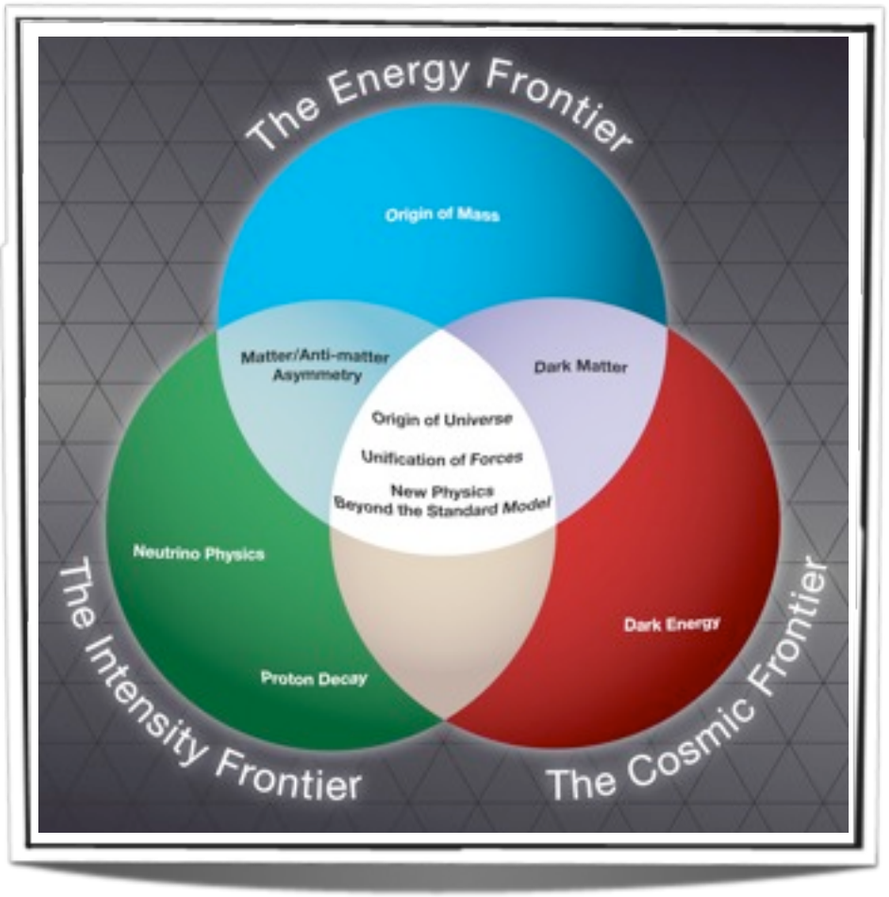
~interesting signatures @ SHiP~

- production of light scalars by B and K decays

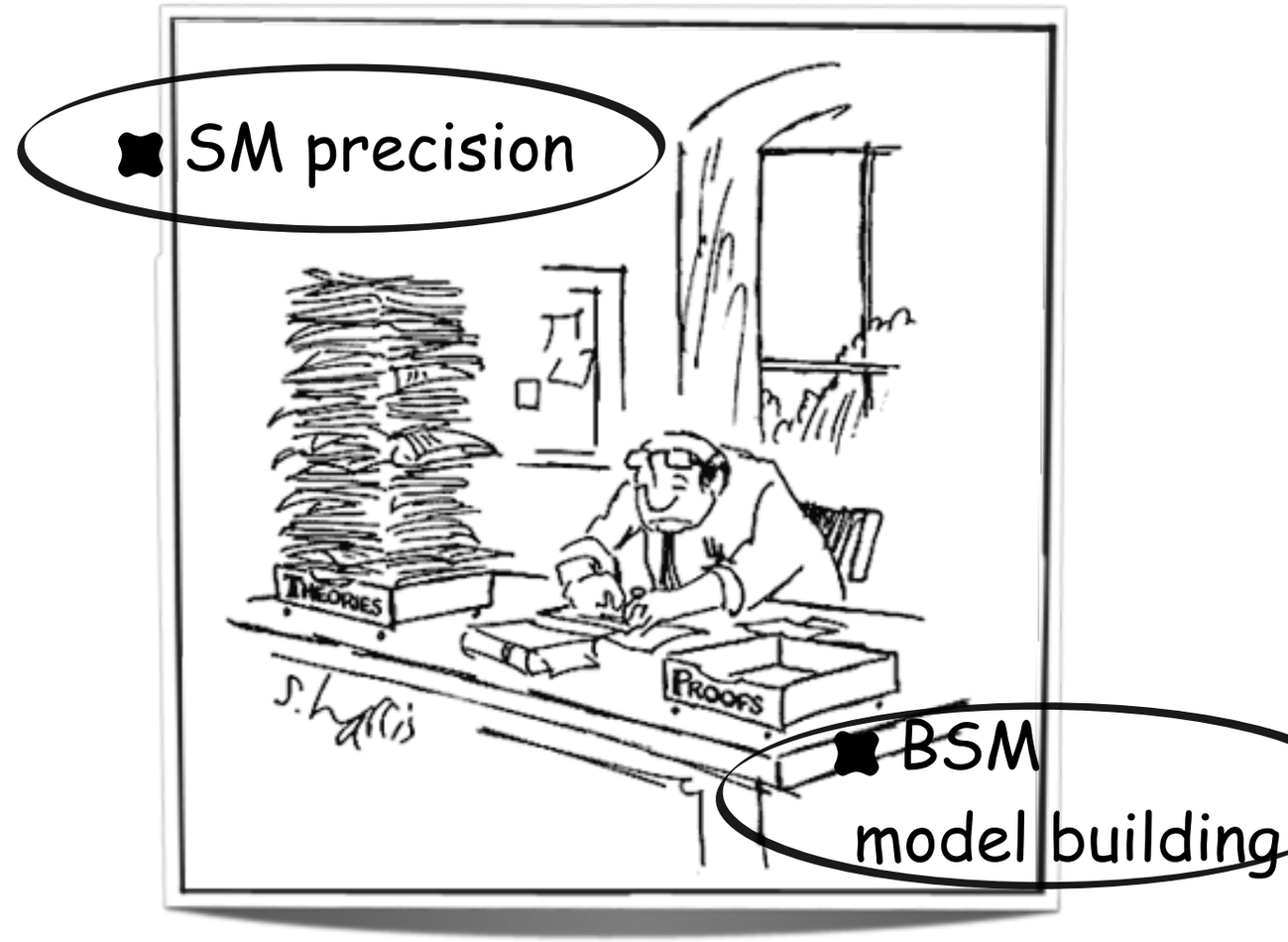
see also Espinosa, Grojean, Pomarol, Pujolas, Servant '15

The HEP frontiers

EXP Frontiers



TH Frontiers



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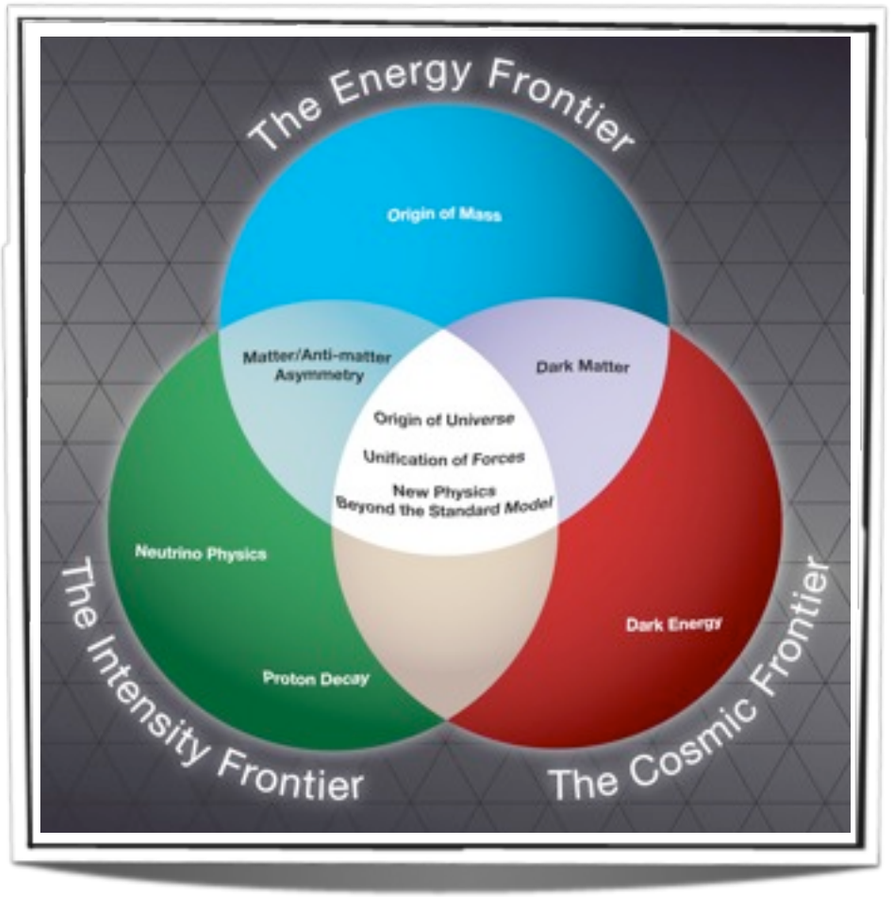

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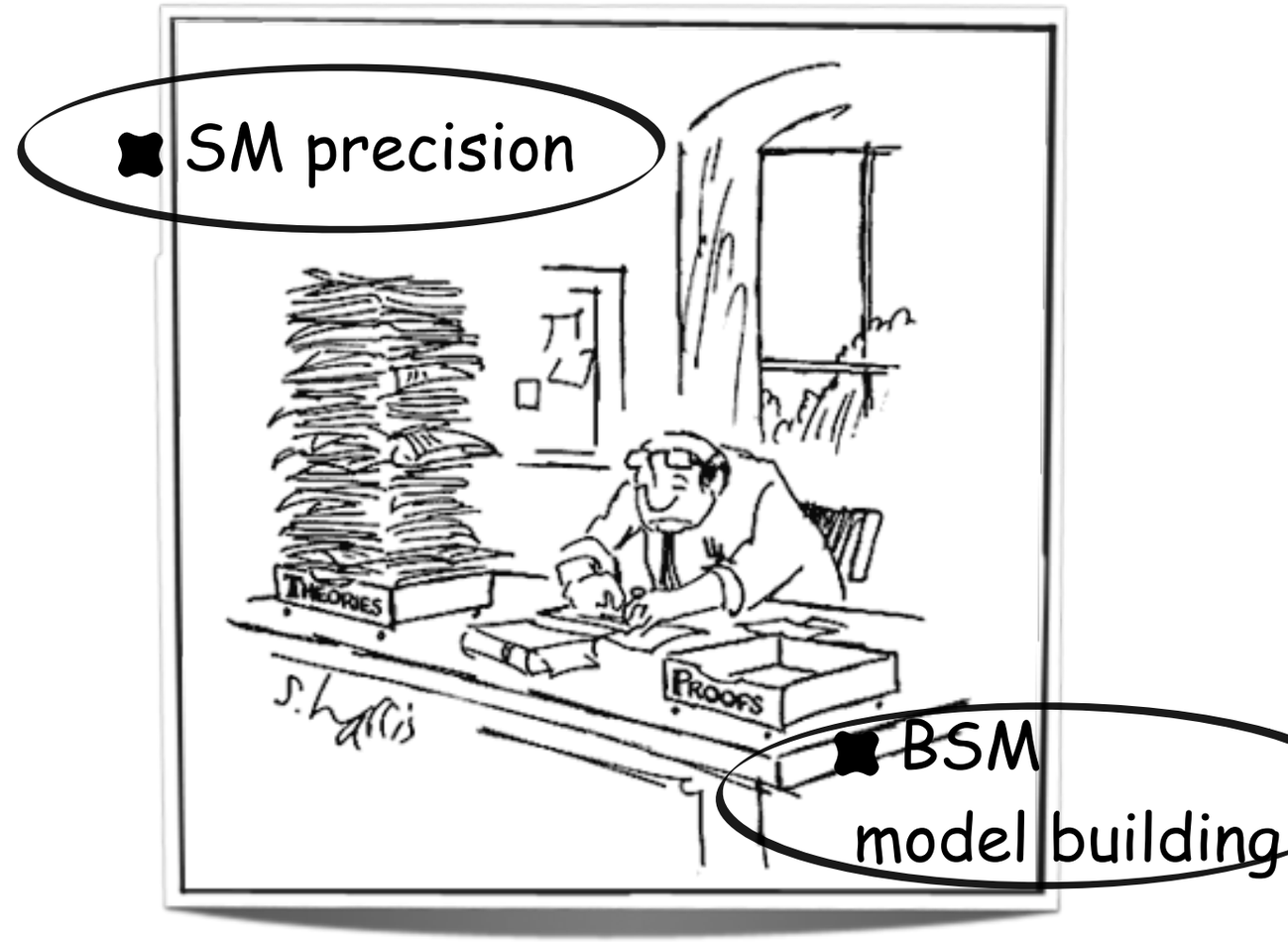

synergy fuels progress

⇓ ⇓ ⇓

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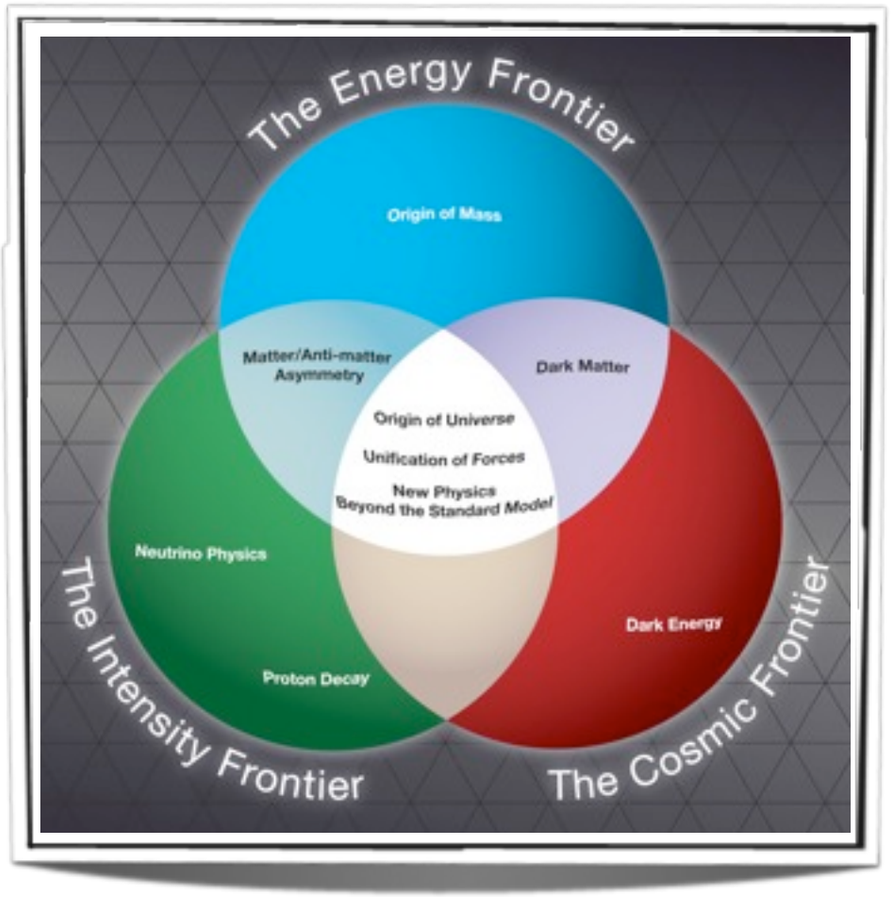

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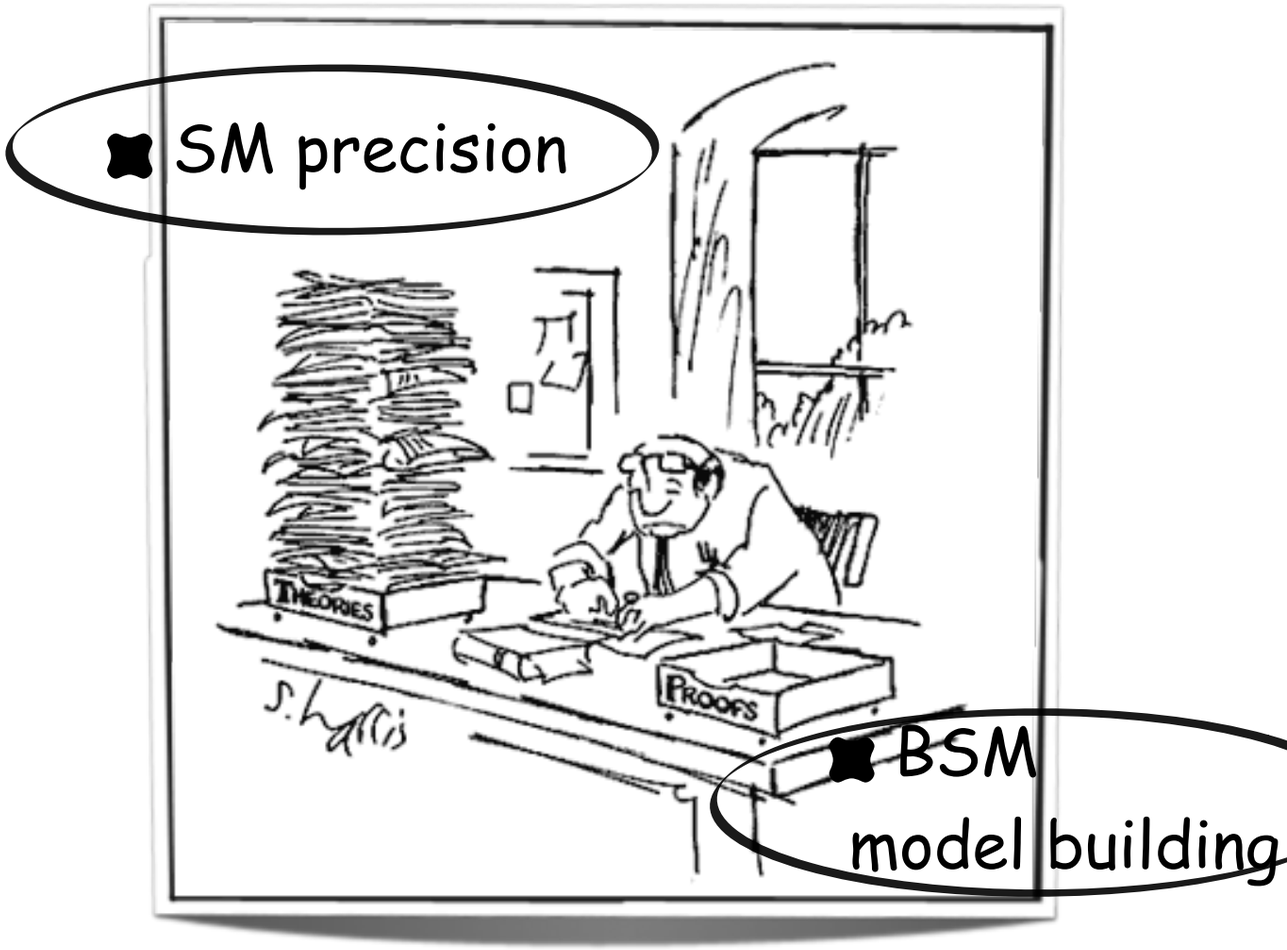

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no BSM major discovery without a thorough understanding of SM background

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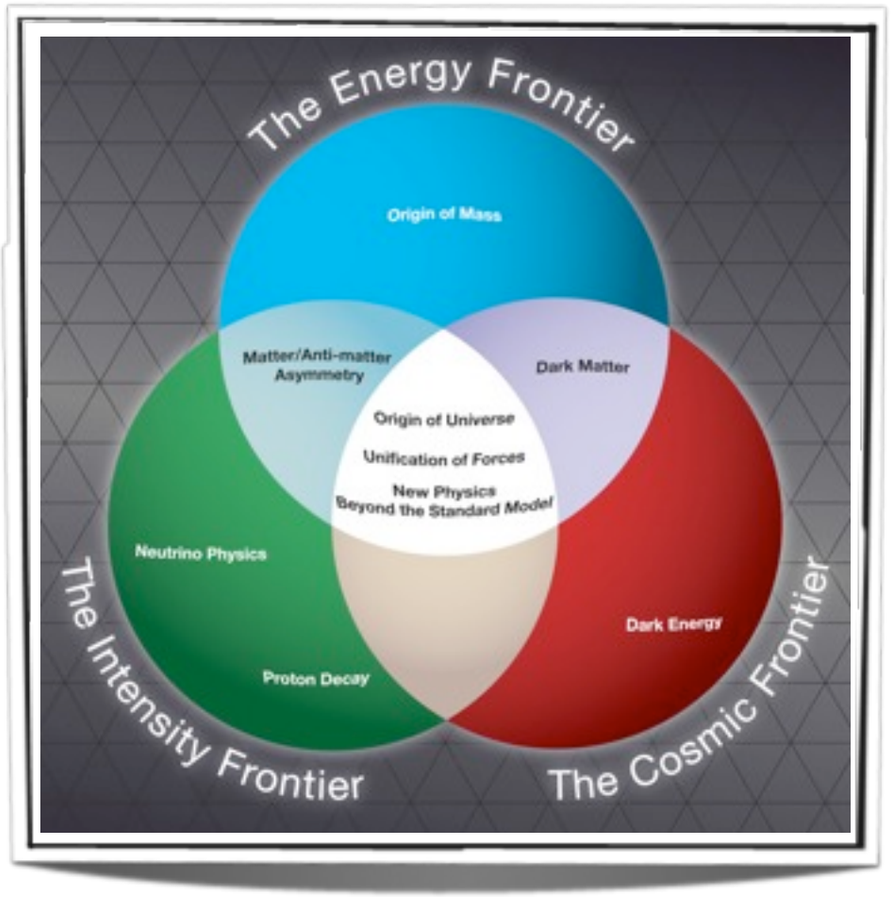
EXP Frontiers



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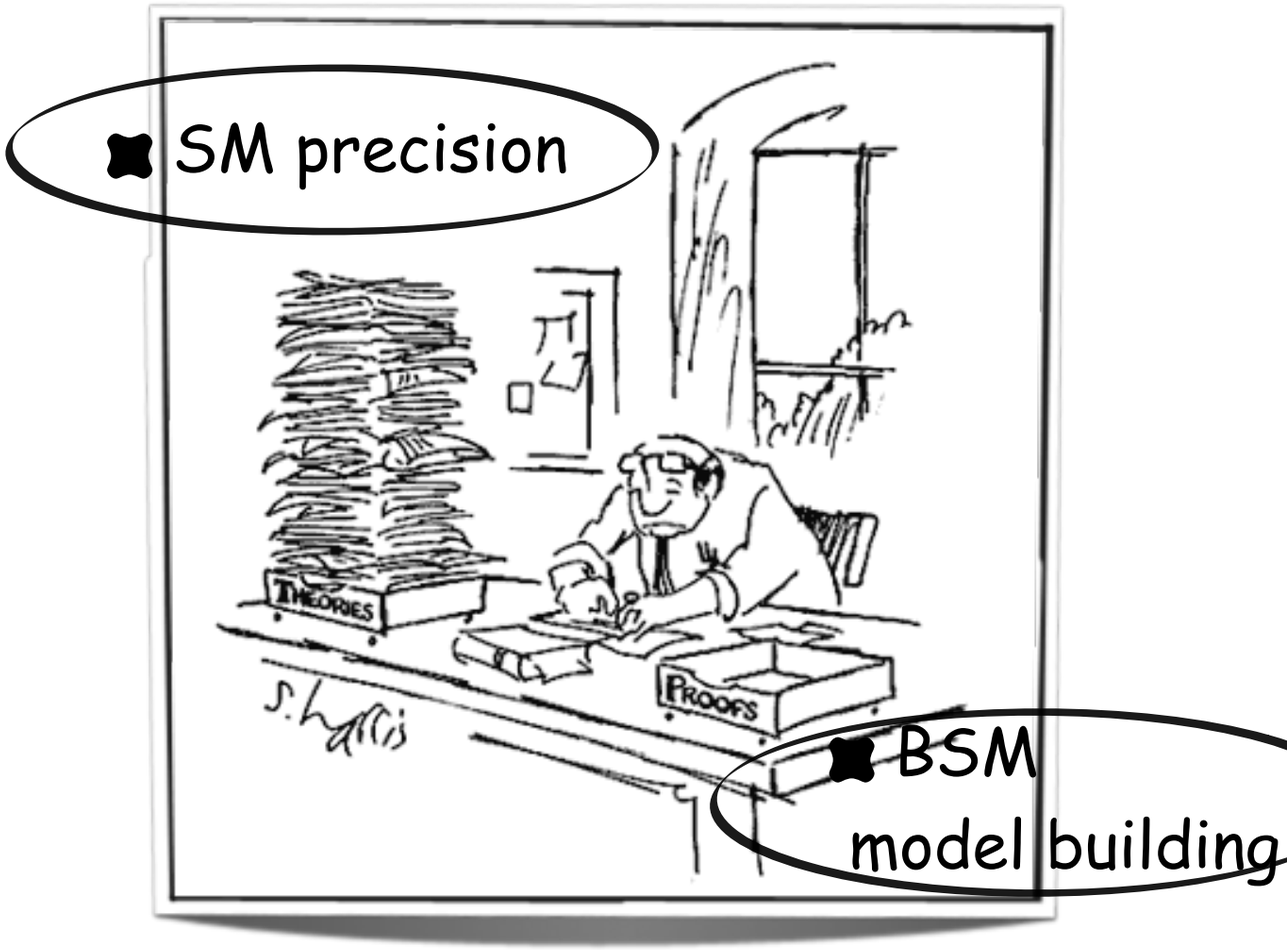


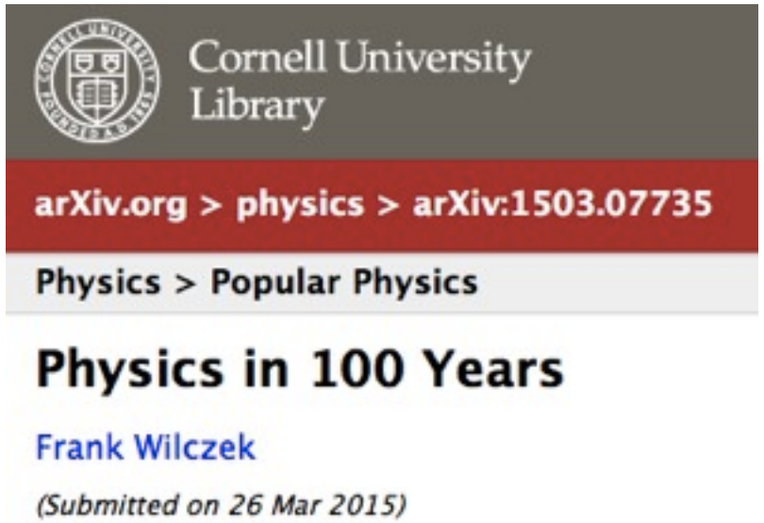
synergy fuels progress

⇓ ⇓ ⇓

the 3 frontiers might be more intertwined than originally thought

no BSM major discovery without a thorough understanding of SM background

Conclusions



- What are the weak points in our current understanding and practices?
- What are the growth areas in technique and capability?
- Where are the sweet spots where those two meet?

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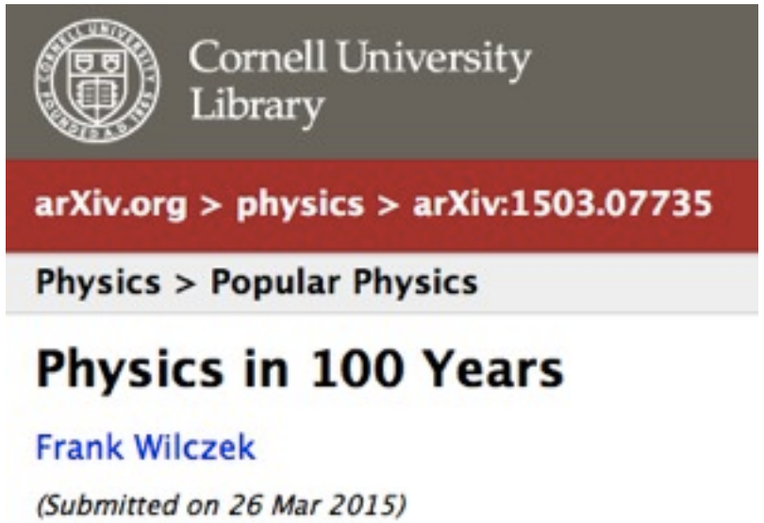

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Let us explore the unknown and be surprised!