Thanks to the Organizers for a great conference!

Lars Bergstrom

Ulf Danielsson

Ariel Goobar

Anupam Mazumdar

Joakim Edsjo

Jakob Nordin
Yashar Akrami
Linda Ostman
Anne Jifalt

Where is SUSY?

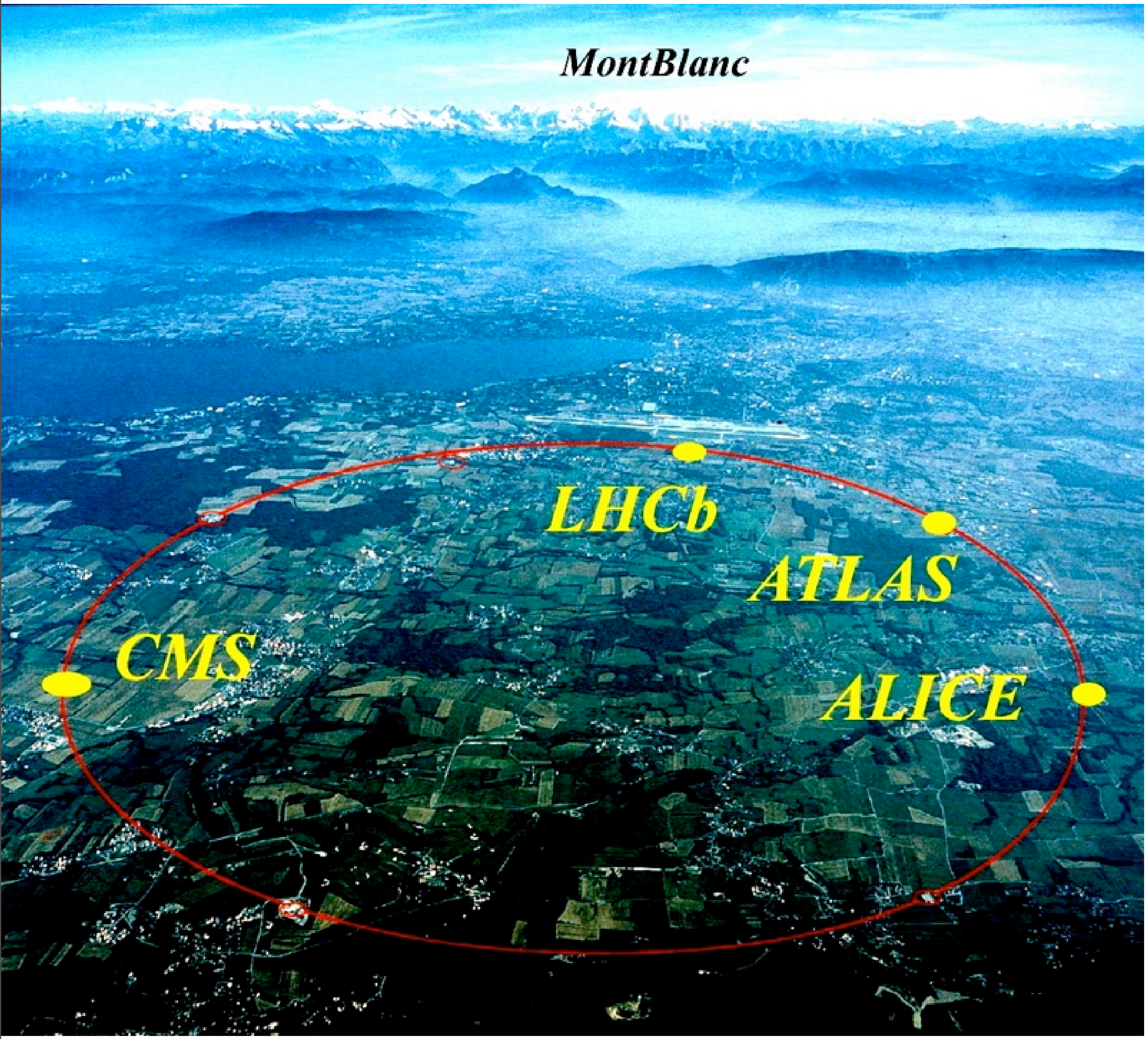
Savas Dimopoulos

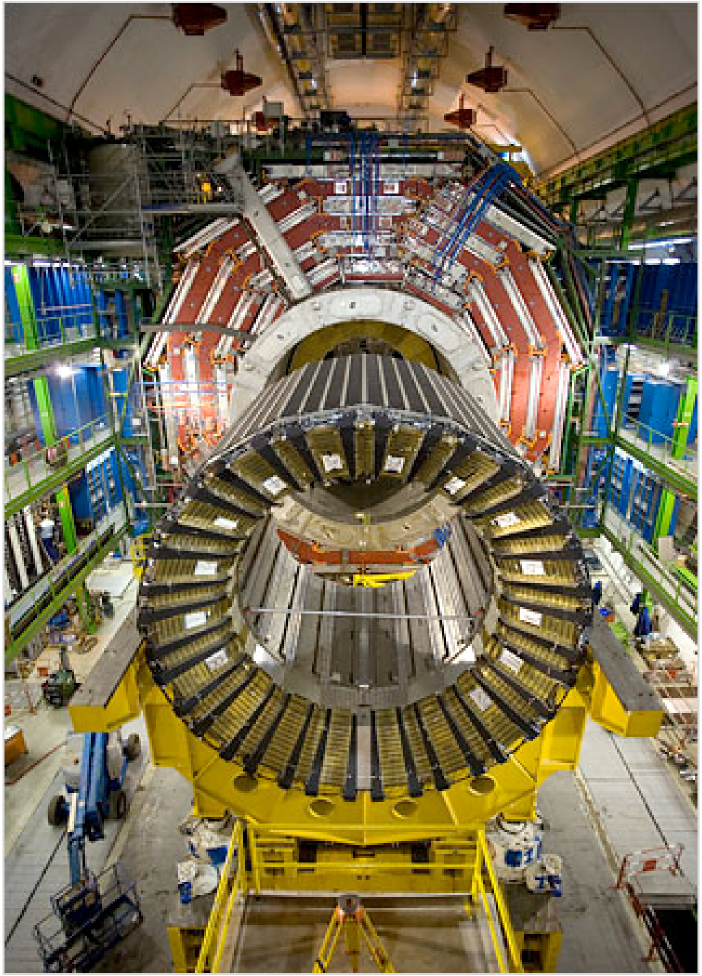
Stanford University

Stockholm, June 20, 2007

Large Hadron Collider

Coming Soon in 2008





ATLAS detector
under construction

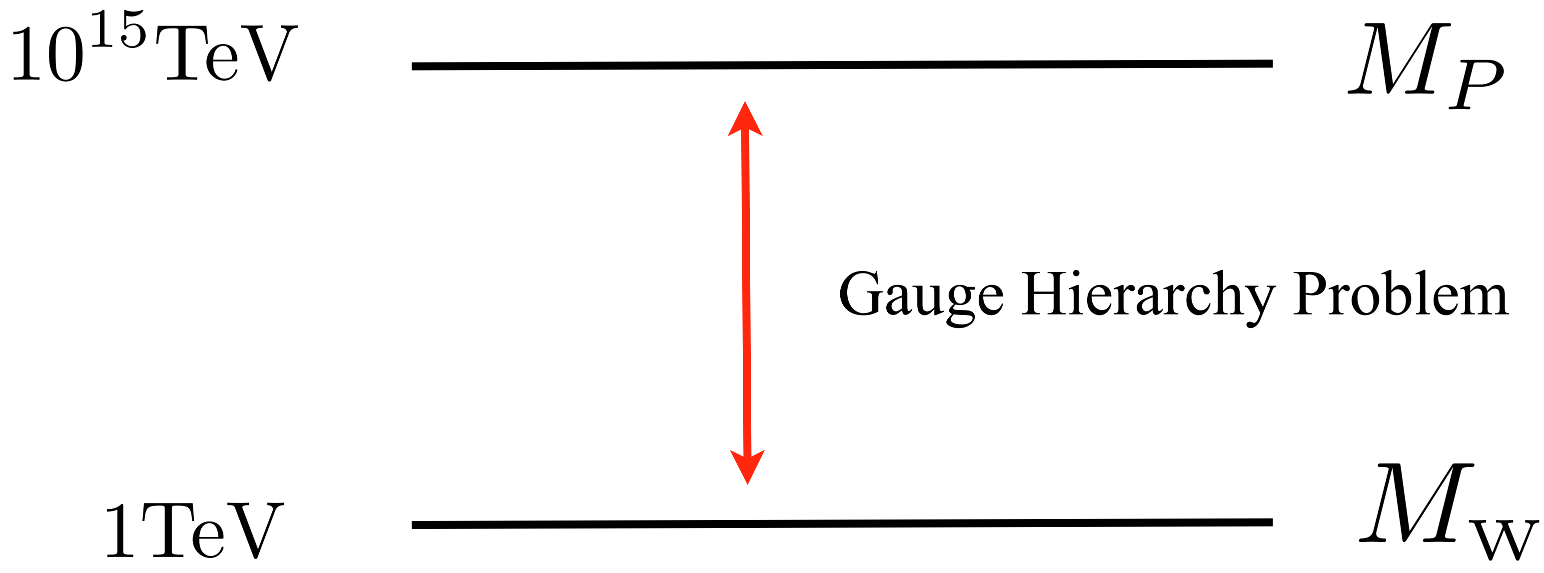
Large Hadron Collider

Energy Frontier $\quad$ 2 TeV $\longrightarrow$ 14 TeV

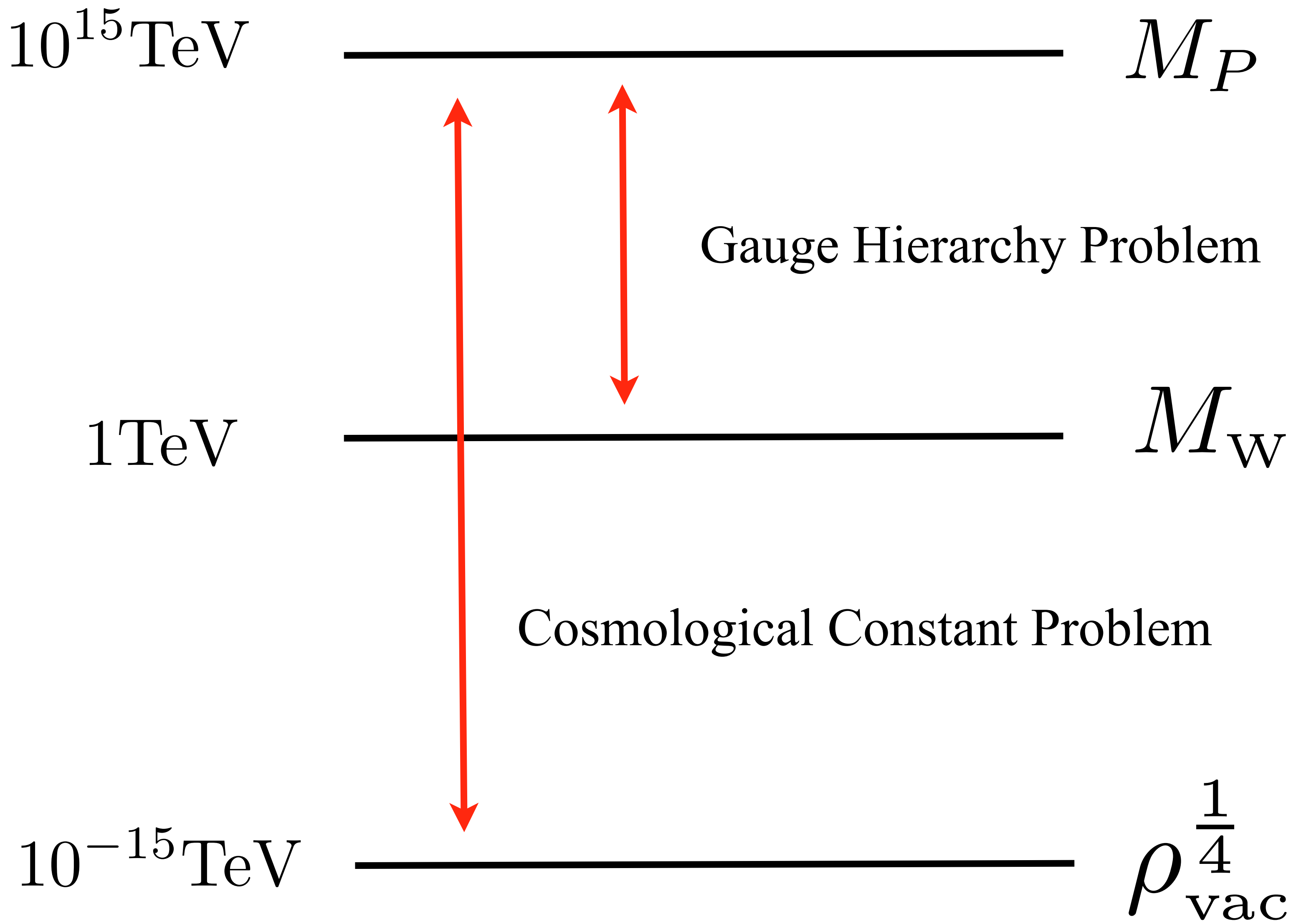
Luminosity Frontier $\quad$ 2 fb^{-1}/yr $\longrightarrow$ 30 fb^{-1}/yr

Will find the Higgs

Will explore the solutions to the hierarchy problem


10^{15}TeV
M_P
Gauge Hierarchy Problem
1TeV
M_{W}

Mystery of Equidistant Scales



Natural Theories:
Theories that explain these hierarchies without ‘fine-tuning’

Approaches to the Gauge Hierarchy Problem

Stages:

- Philosophy (1974) [Wilson]
- Technicolor (1978) [Susskind, Weinberg]
- Supersymmetric Standard Model (1981) [S.D., Georgi]
- Low Scale Gravity (1998) [Antoniadis, Arkani-Hamed, S.D., Dvali]
- Warped Gravity (1999) [Randall, Sundrum]
- Little Higgs (2001) [Arkani-Hamed, Cohen, Georgi]

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Four decades of SUSY

70's Mathematical Formalism

No physical models - charge, color broken

80's Supersymmetric Standard Model

Unification Prediction

Four decades of SUSY

90's

LEP Rollercoster

LEP I: Unification prediction confirmed

Four decades of SUSY

90's LEP Rollercoster

LEP I: Unification prediction confirmed

LEP II: No sparticles found

00's Challenging Naturalness

Cosmological Constant, Landscape,
Split SUSY

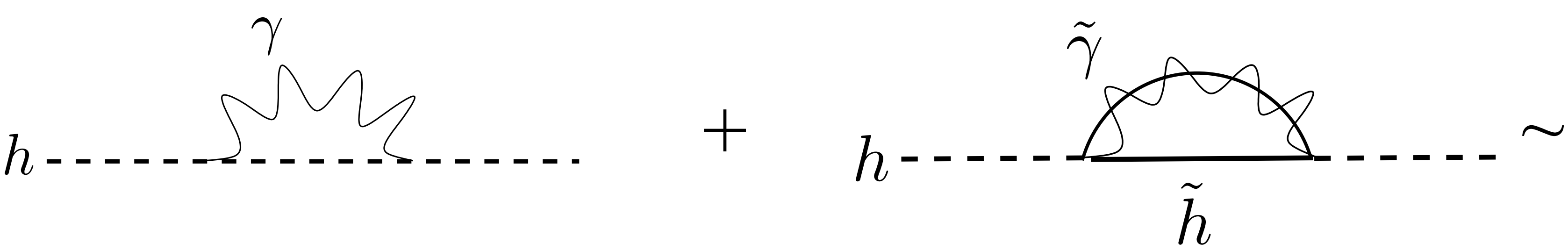
Supersymmetric Standard Model '81

Doubles the number of particles

quark $\longrightarrow$ squark
lepton $\longrightarrow$ slepton

gauge boson $\longrightarrow$ gaugino
2 Higgs $\longrightarrow$ Higgsinos

To keep the Higgs mass at the weak scale



$$\boxed{\alpha M^2_{\mathrm{susy}}}$$

Susy particles @ 0.1 TeV scale $\longrightarrow$

Accessible at colliders

Soft SUSY Breaking

Parametrize SUSY breaking
just as quark masses parametrize chiral breaking

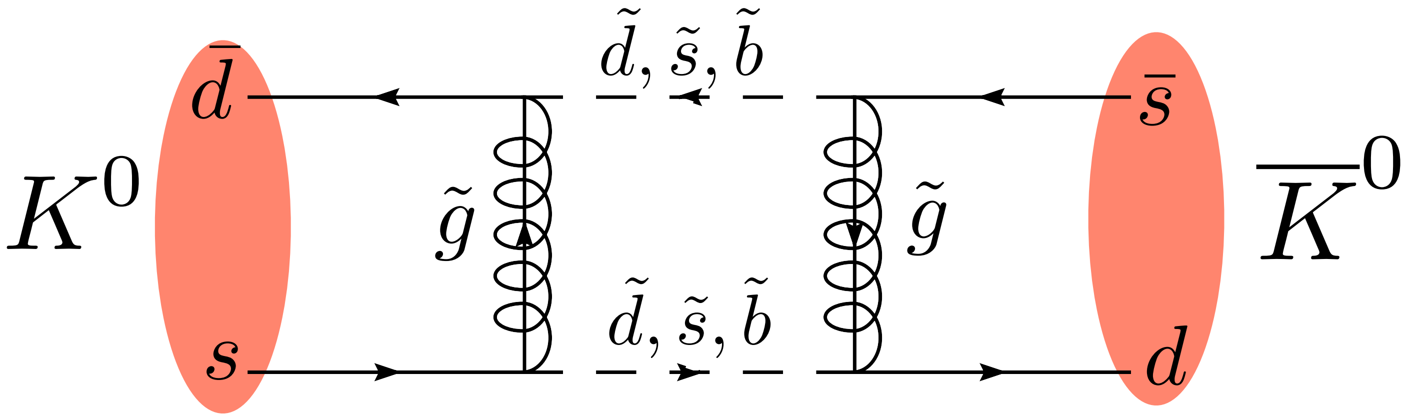
Do accessible physics without knowing inaccessible short-distance details

Soft SUSY Breaking

Parametrize SUSY breaking
just as quark masses parametrize chiral breaking

Universality of soft terms

Super-GIM mechanism

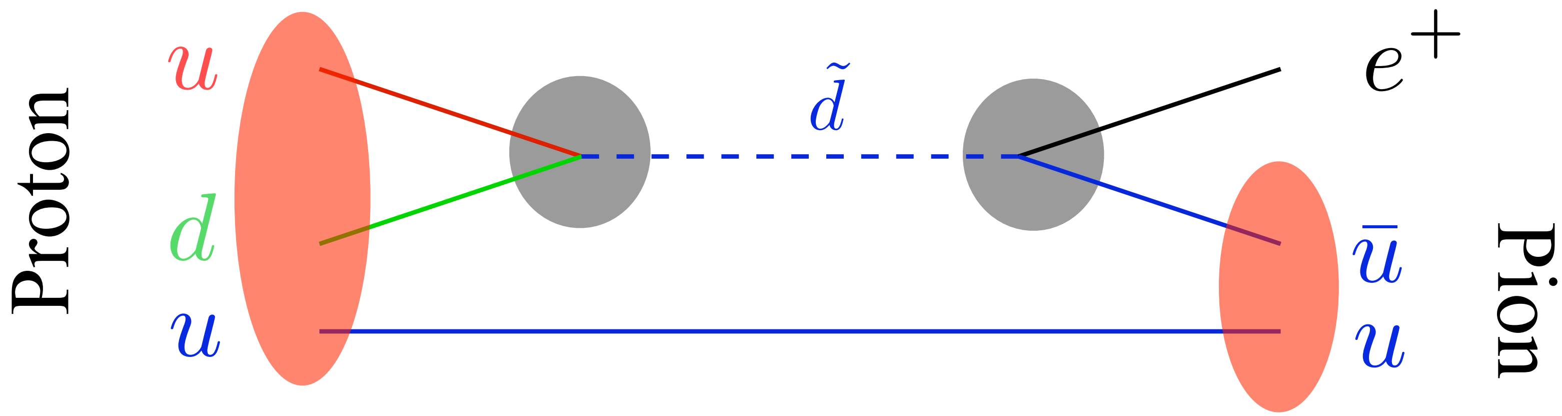


Approximate degeneracy of scalars

LHC: Lots of particles accessible!

Proton Stability ⇒ DM Stability

New particles ⇒ new ways to mediate proton decay



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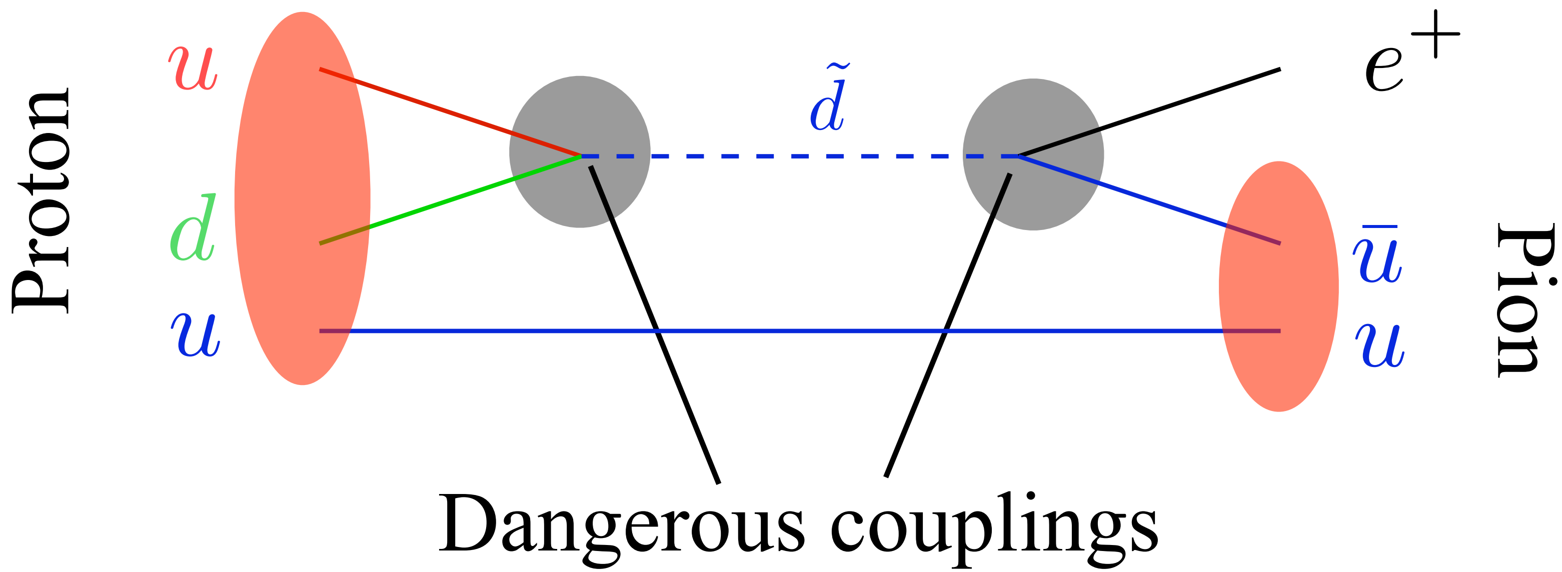

Proton Stability ⇒ DM Stability

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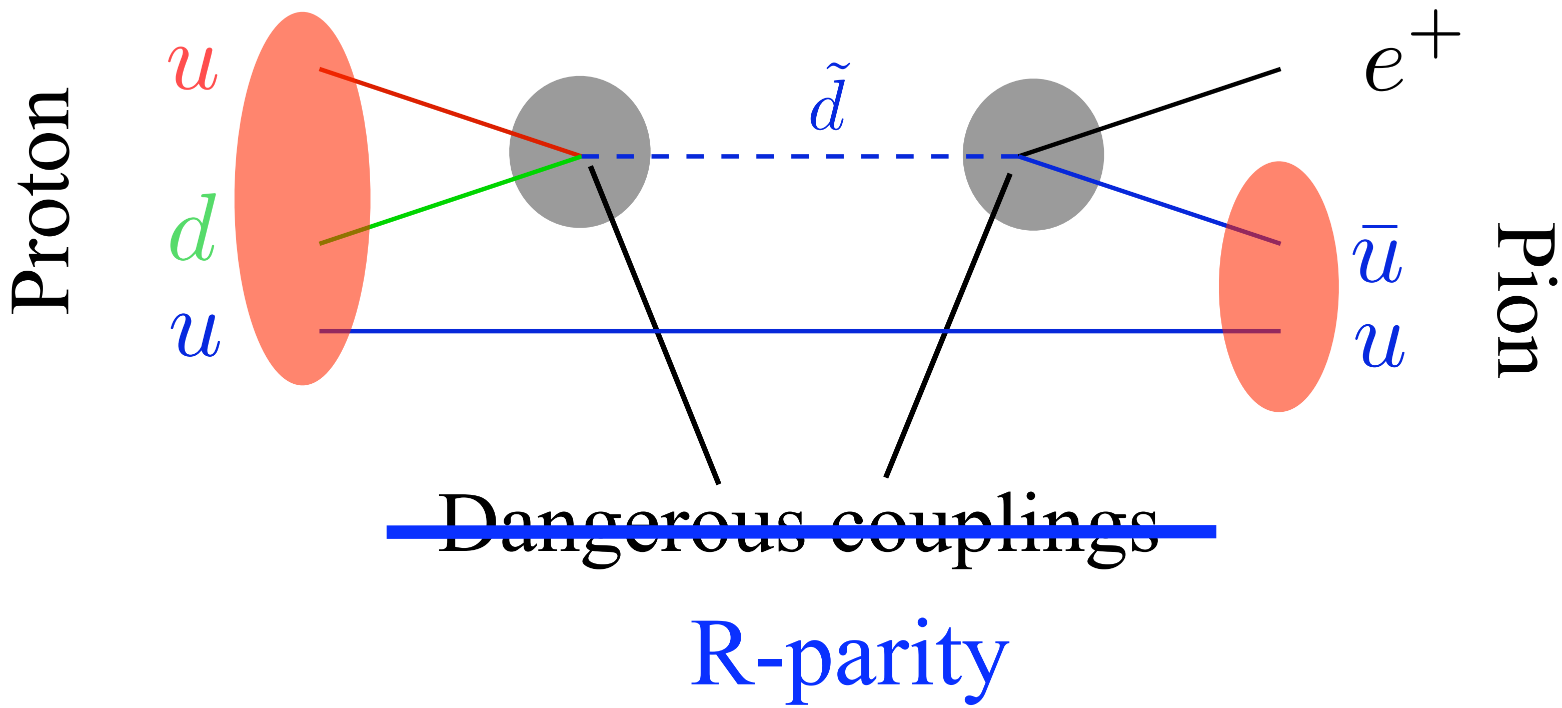
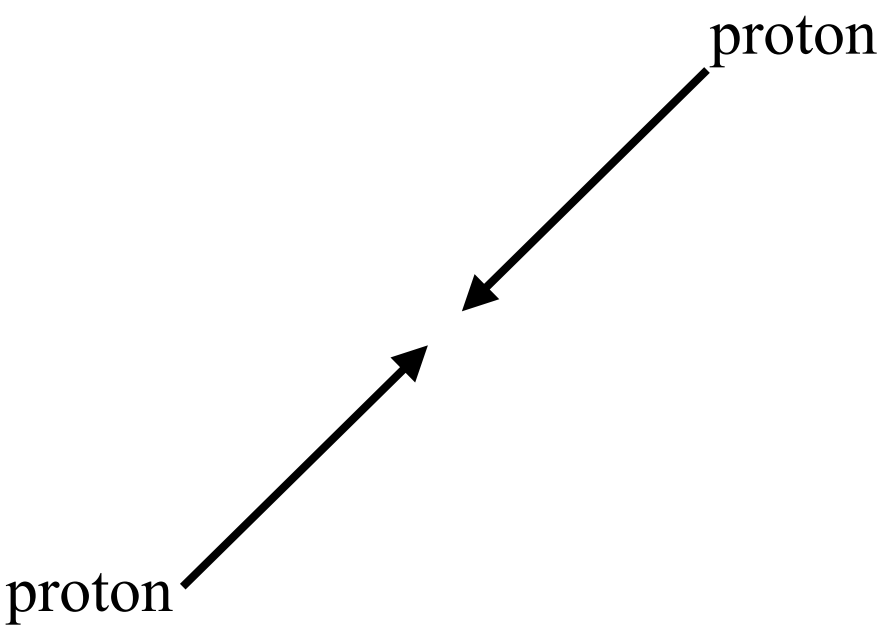


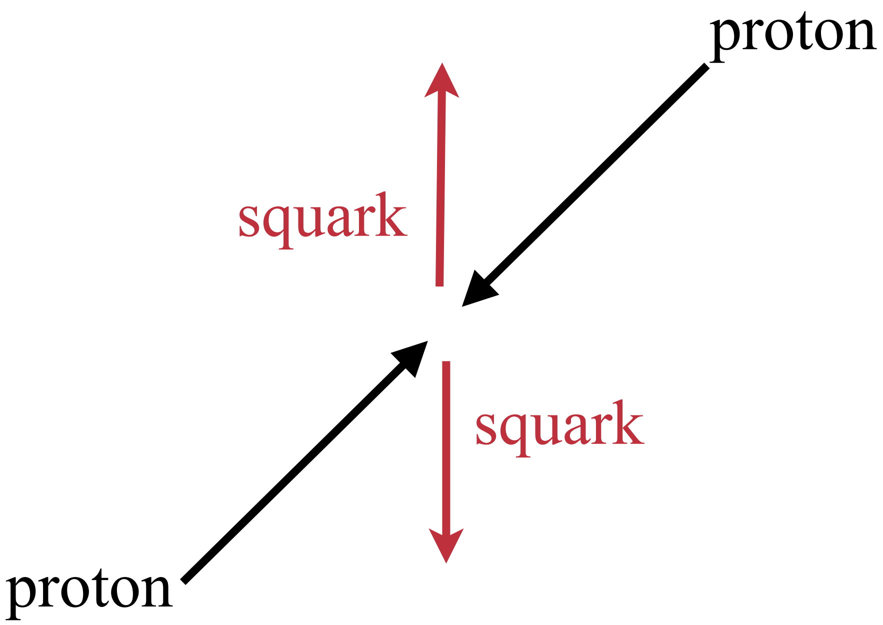
Lightest Supersymmetric Particle (LSP) is stable

If neutral and colorless -- Dark Matter

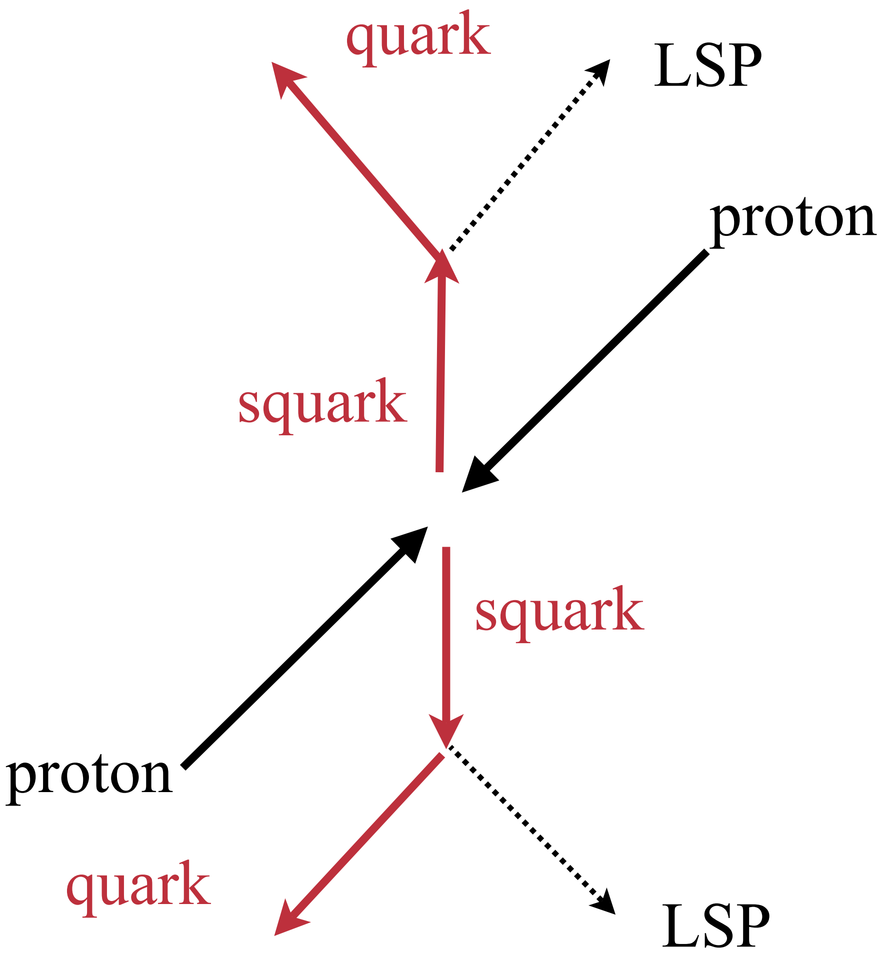
Dark Matter at colliders



Dark Matter at colliders



Dark Matter at colliders



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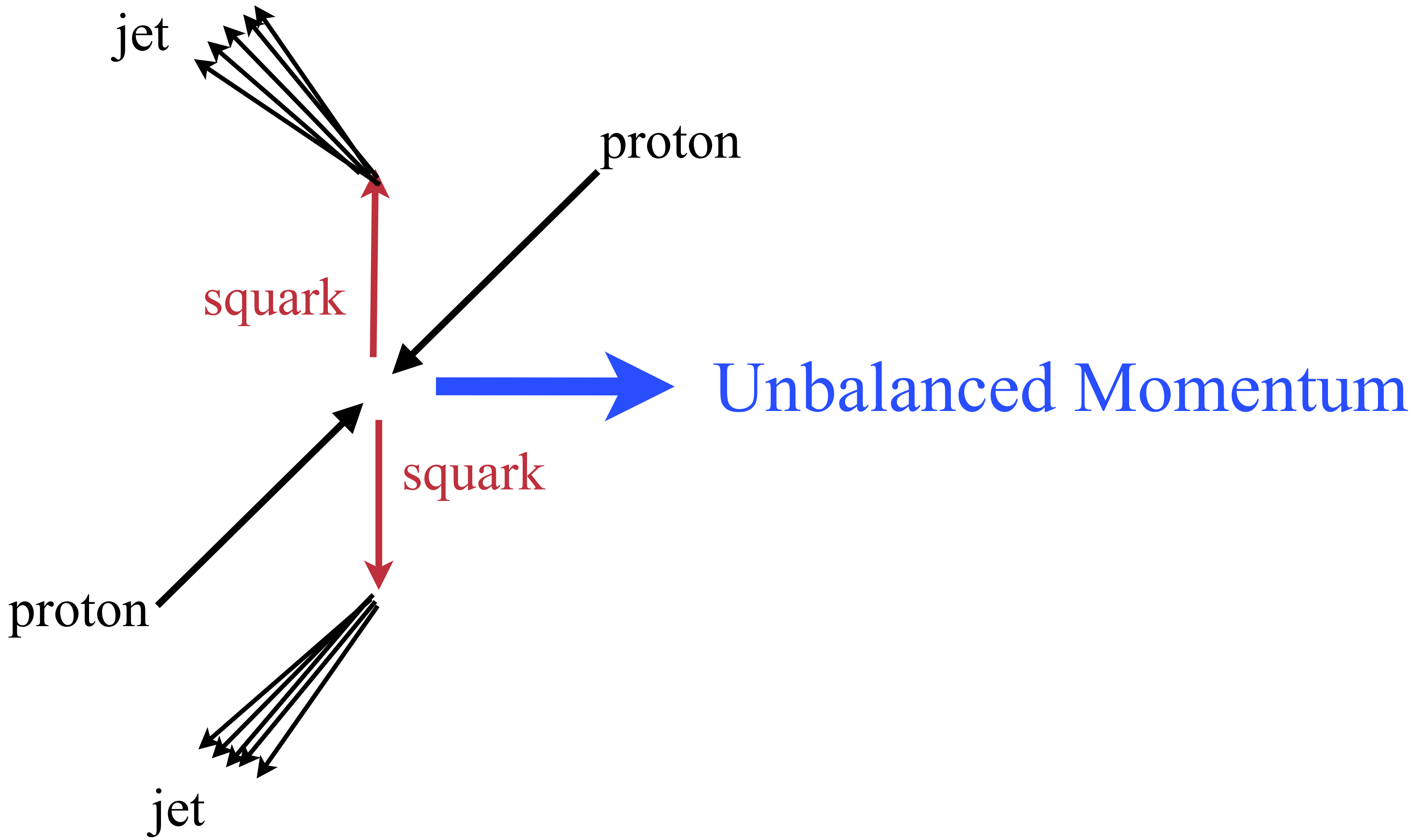
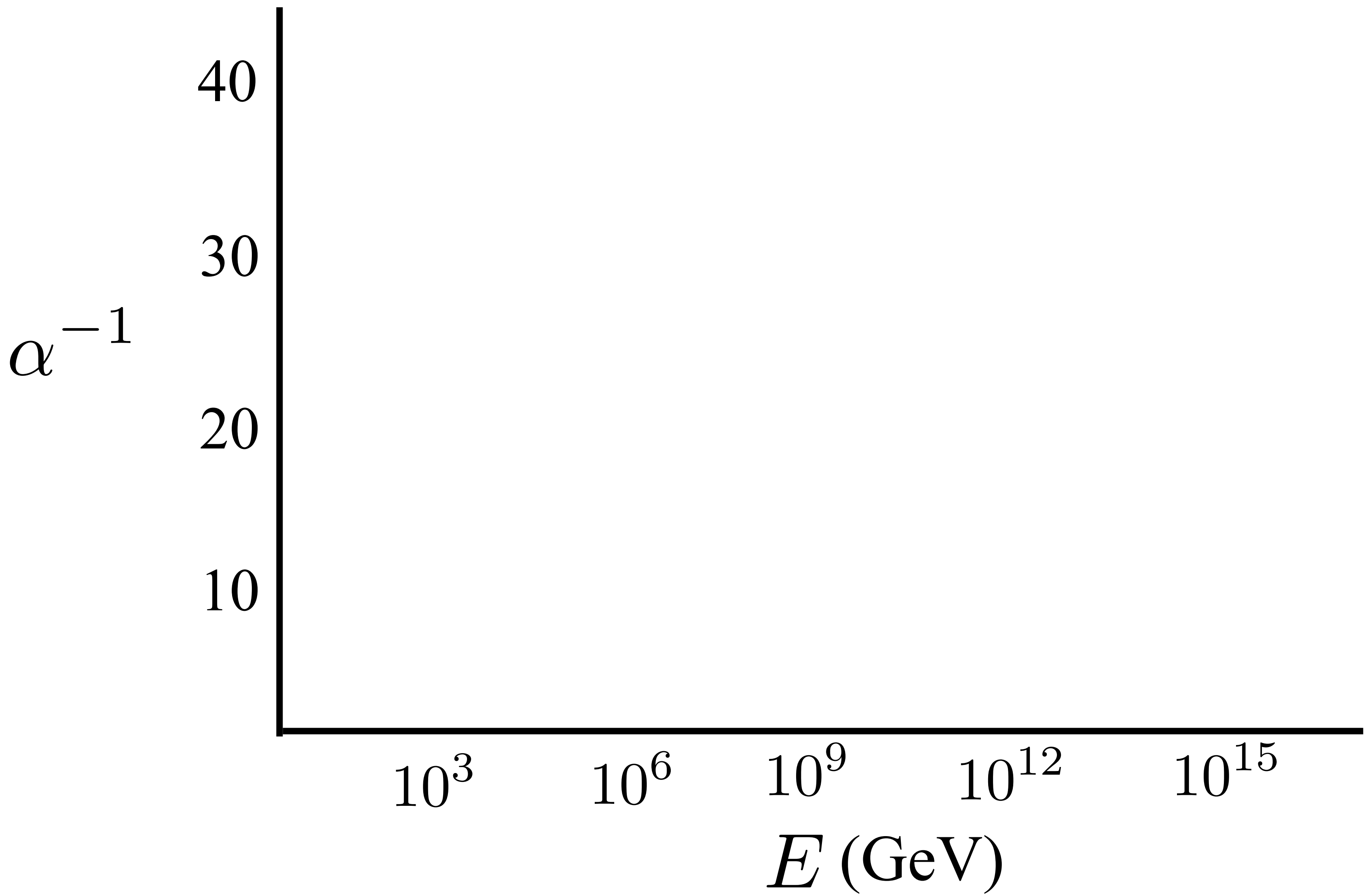


Smoking gun: “Missing Energy” signatures

Follow from proton stability!

Gauge Coupling Unification



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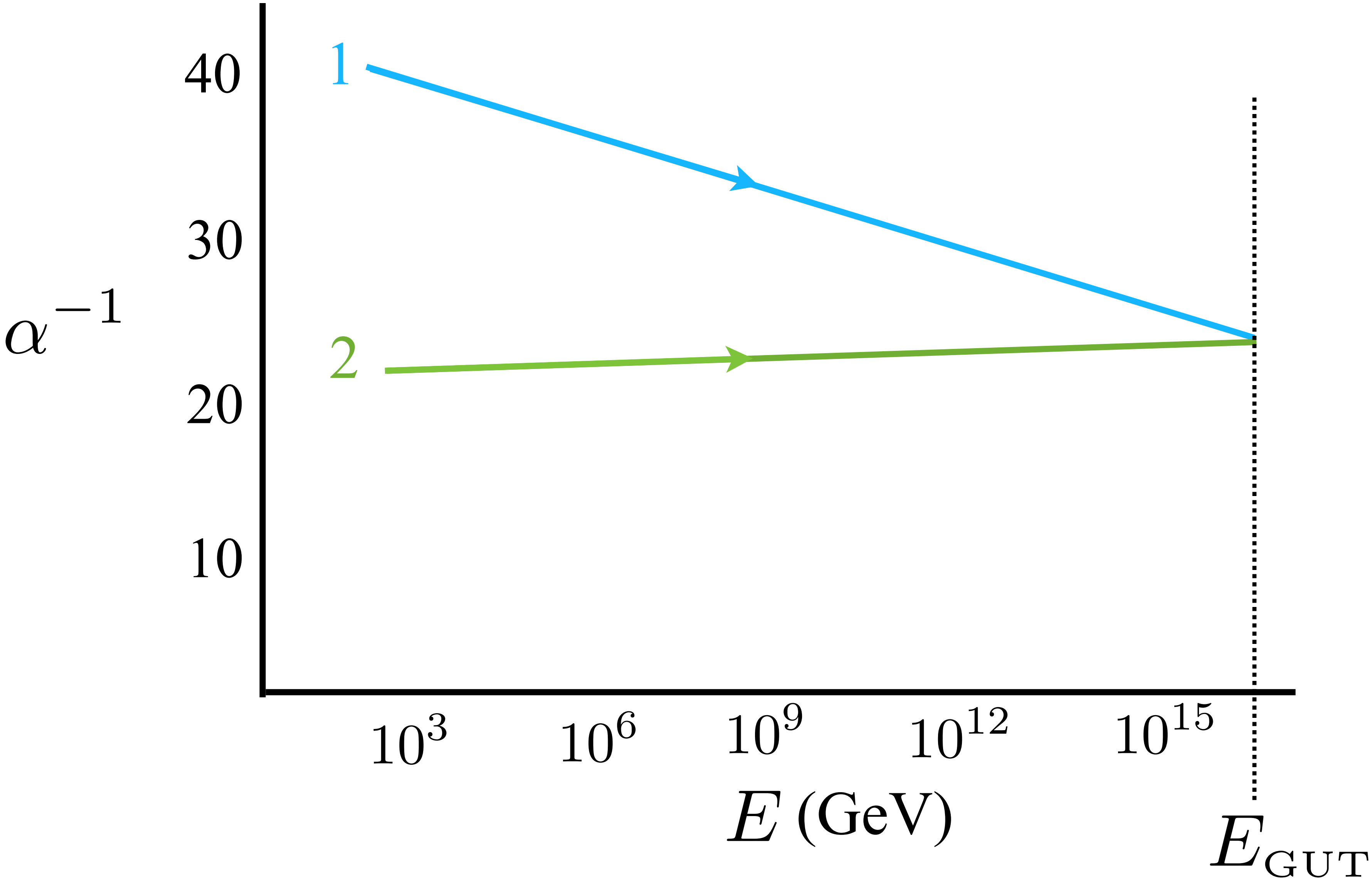

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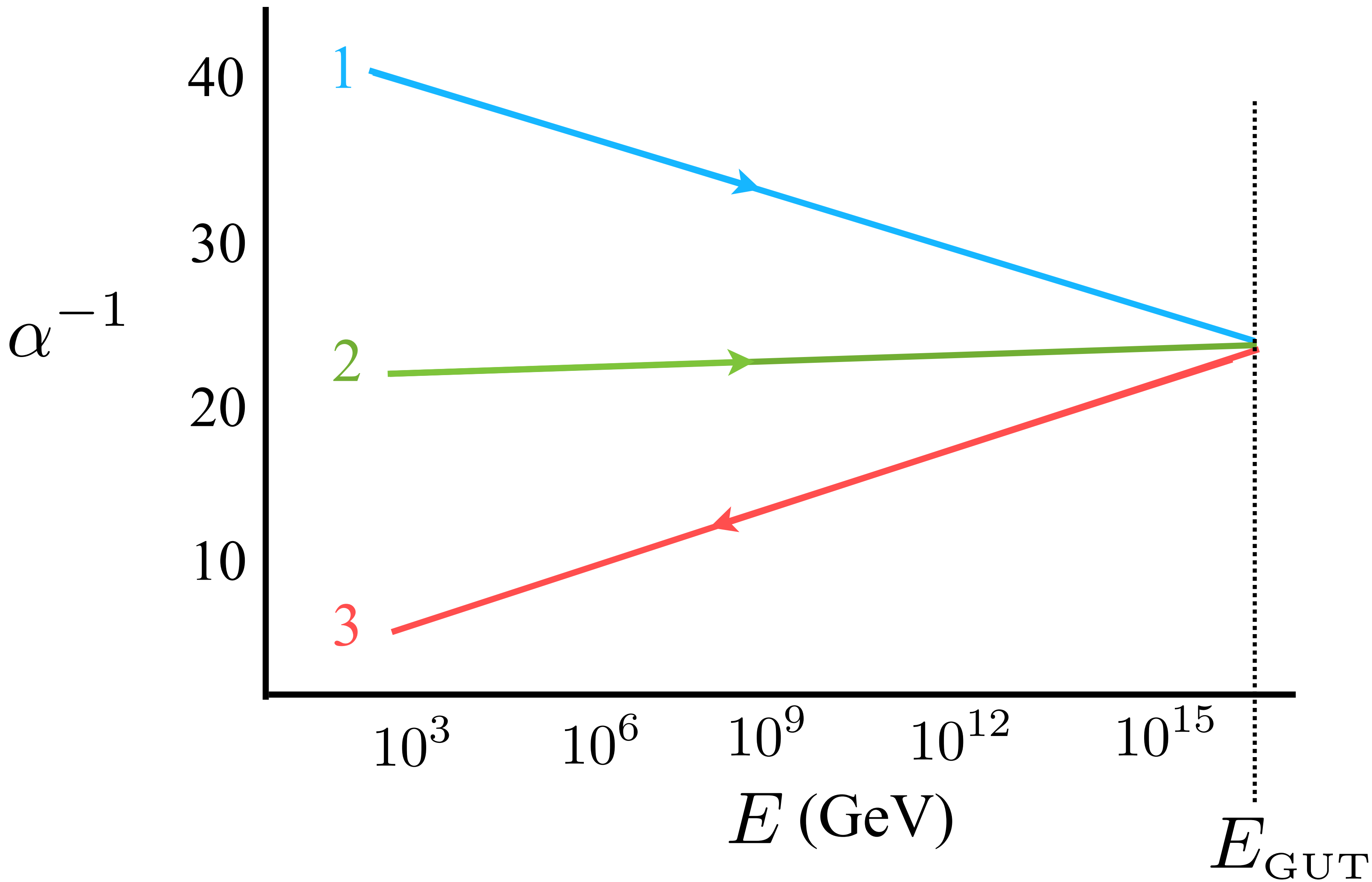

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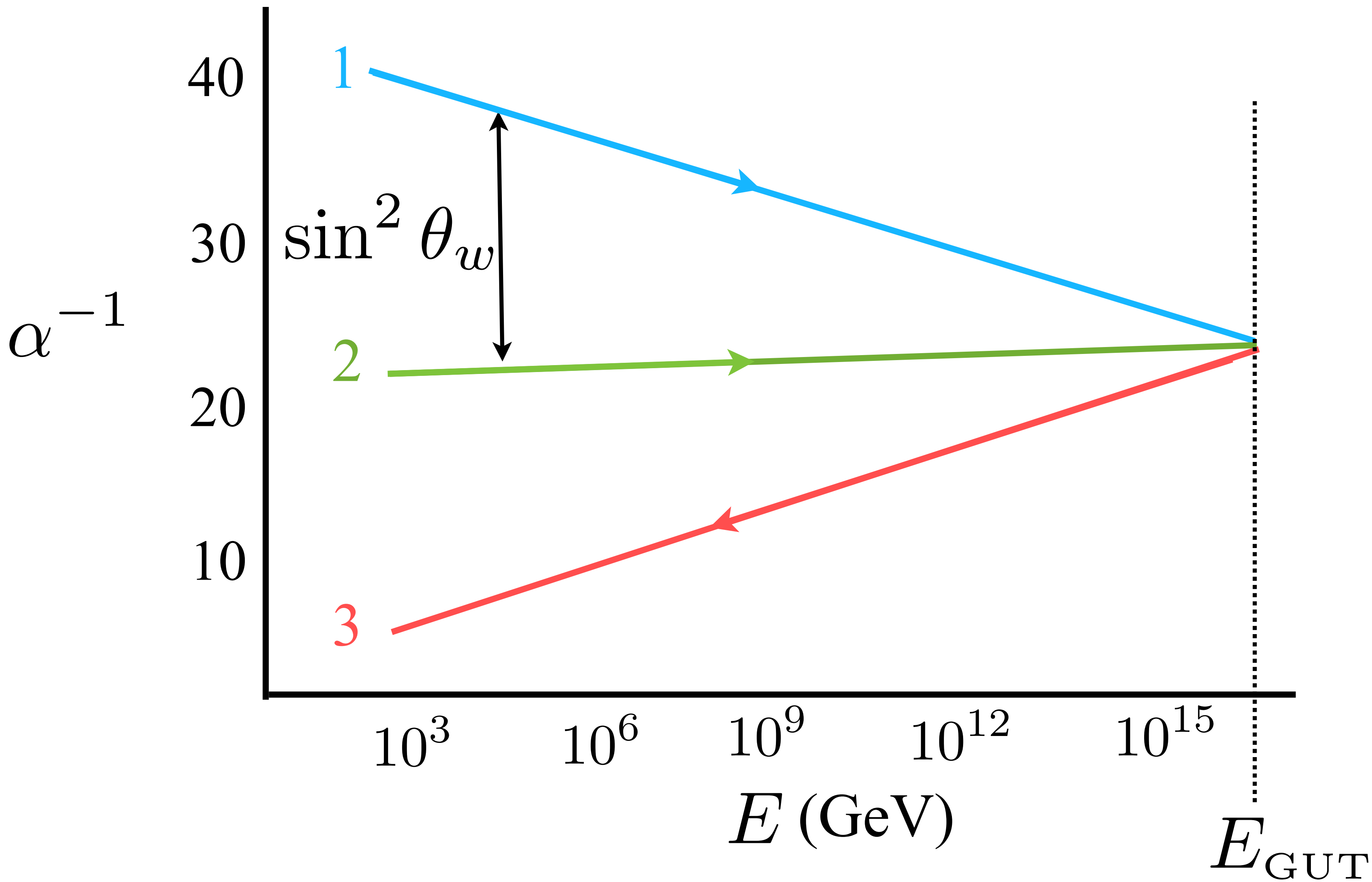
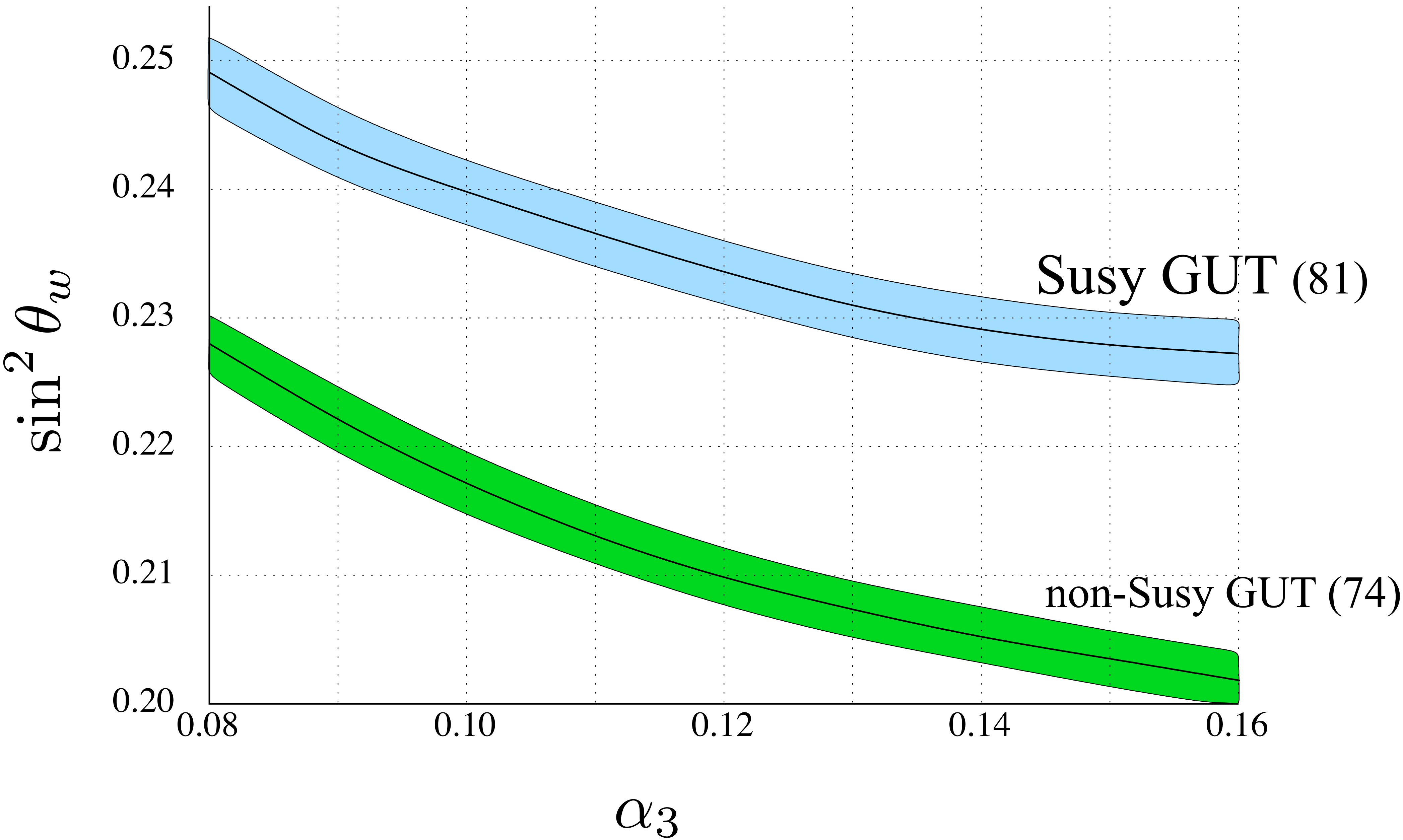
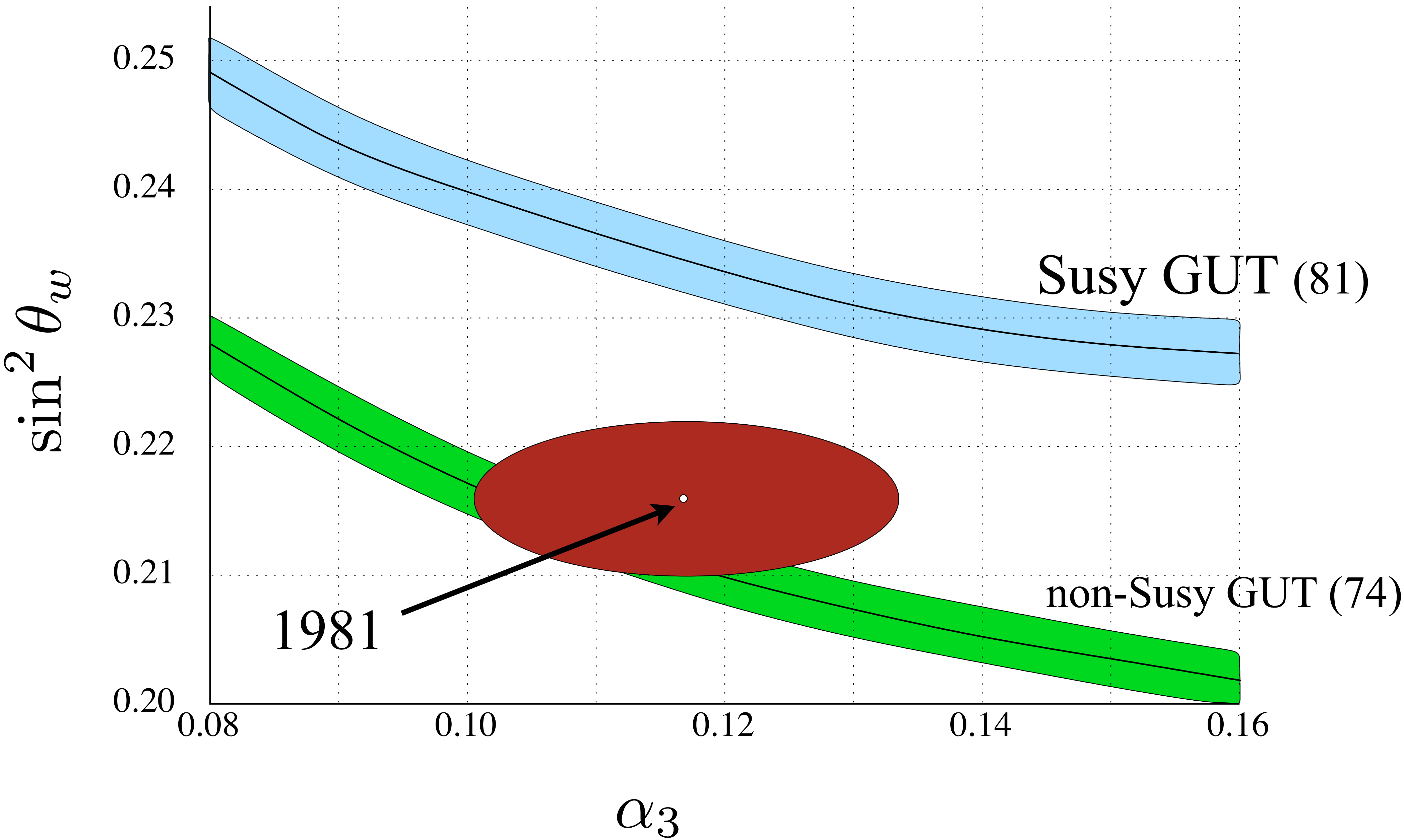


Unification



Unification



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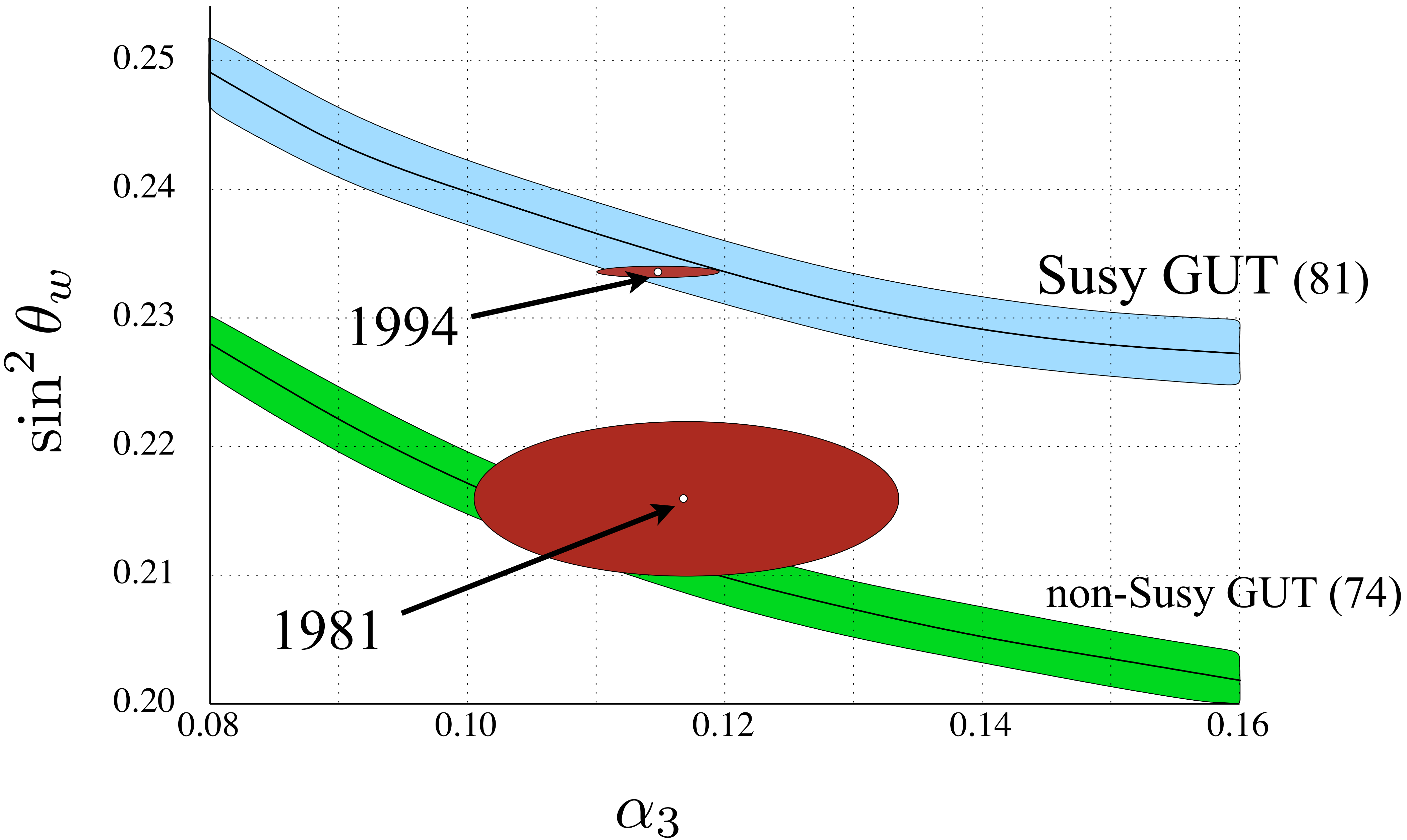
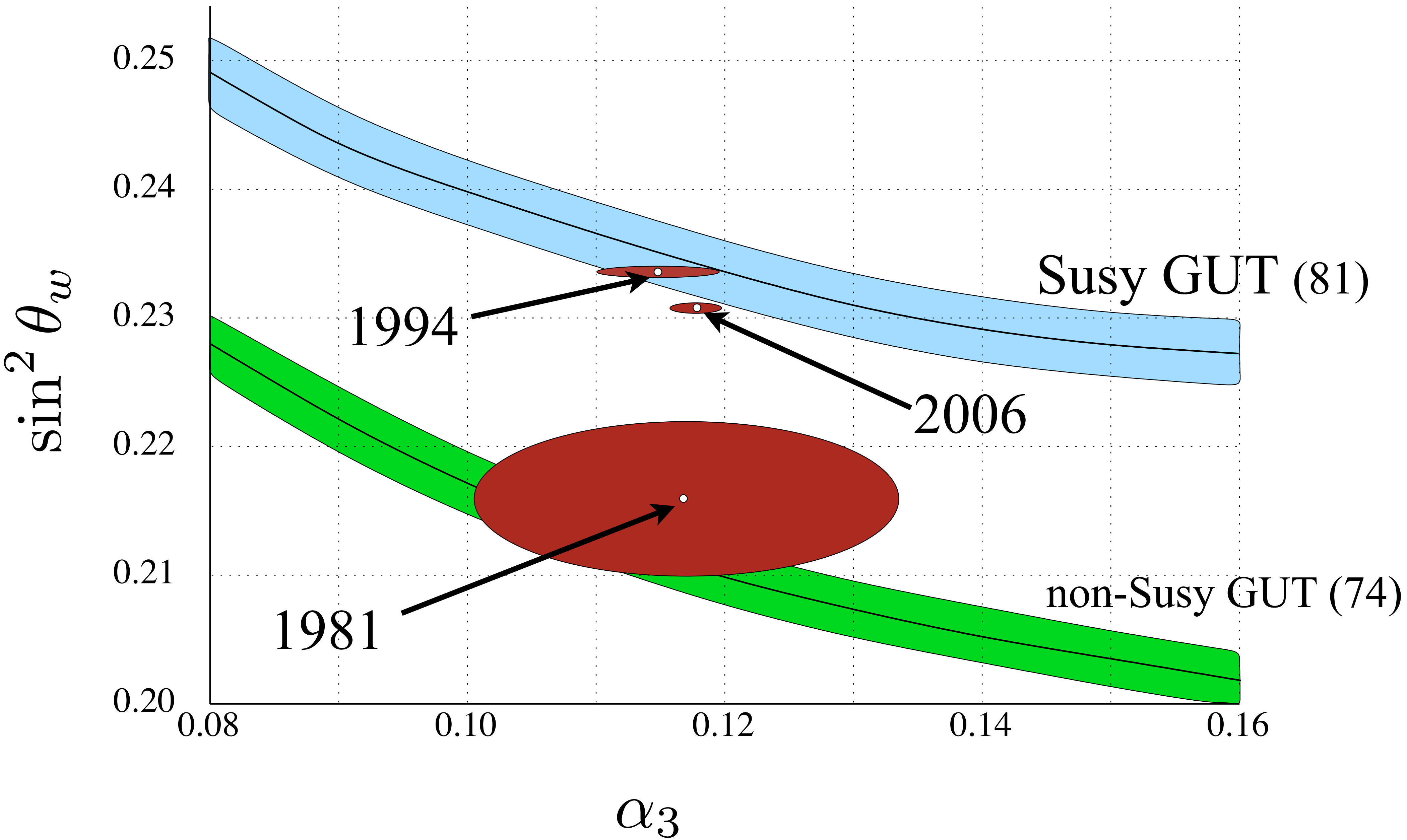


Unification



MSSM 1981 Predictions

S. D., Georgi

Degenerate Soft Terms

Many sparticles to be discovered at once

Stable ~100 GeV LSP

Missing Energy at Colliders

Dark Matter

Unification

New proton decay channels

$\sin^2\theta_w$ vs $\alpha_3 \rightarrow$ already confirmed at LEP!

Late 90's

Everybody expected LEP2/Tevatron
to be discovery machines

Nothing discovered!

No sparticles or Higgs...

Supersymmetric Standard Model

Grade Report: Circa 2000

Successes	Shortcomings
Unification	Higgs?
	Sparticles?
Dark Matter	FCNC, CP ~110 parameters
	Proton Decay
	Gravitino & Moduli Problems

Supersymmetric Standard Model

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Fermions	Scalars
Hierarchy Problem	Cosmological Constant

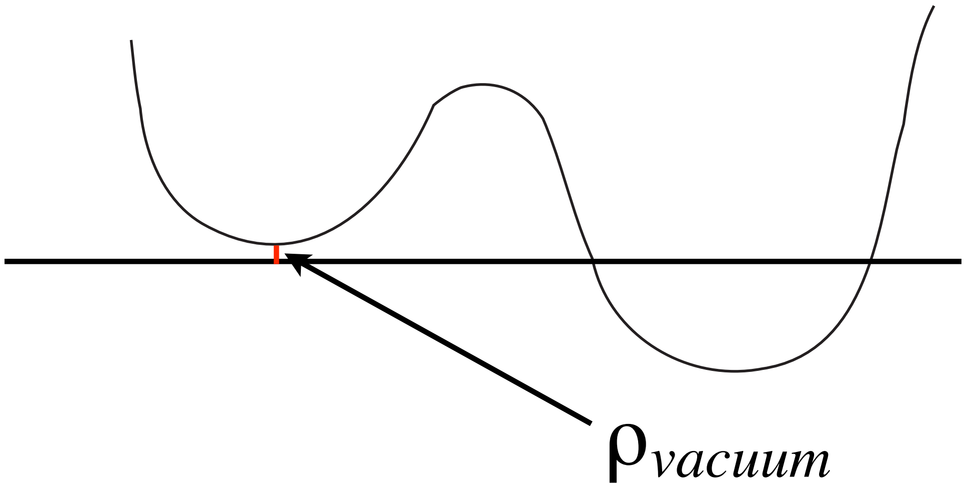
Strategy for the last 30 years

m_{weak} $\qquad\qquad$ ρ_{vacuum}

↑ Focus on this $\qquad$ ↑ Ignore this

This could be flawed

In theories with few vacua

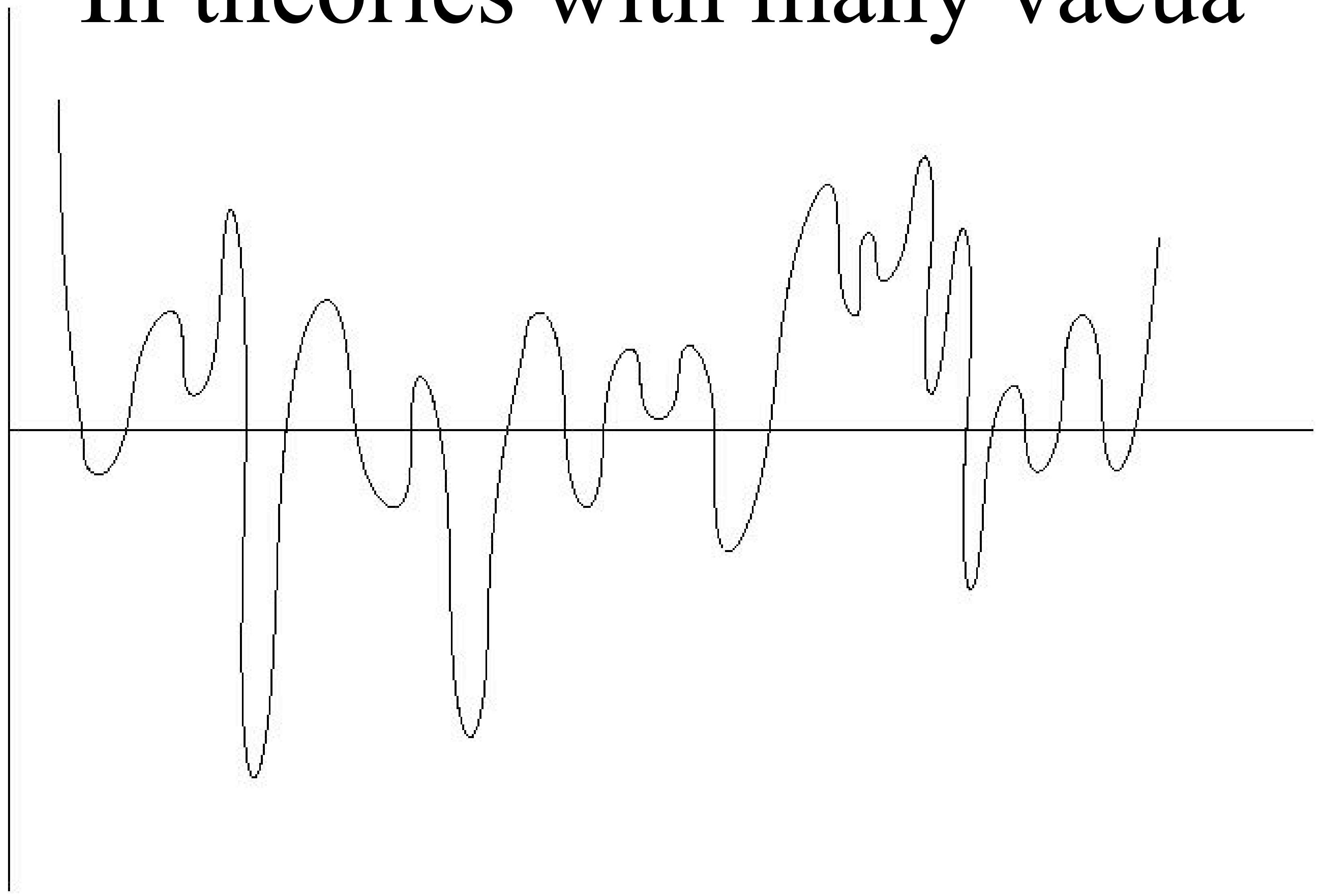


Getting $\rho_{vacuum} \sim (10^{-15} M_W)^4$

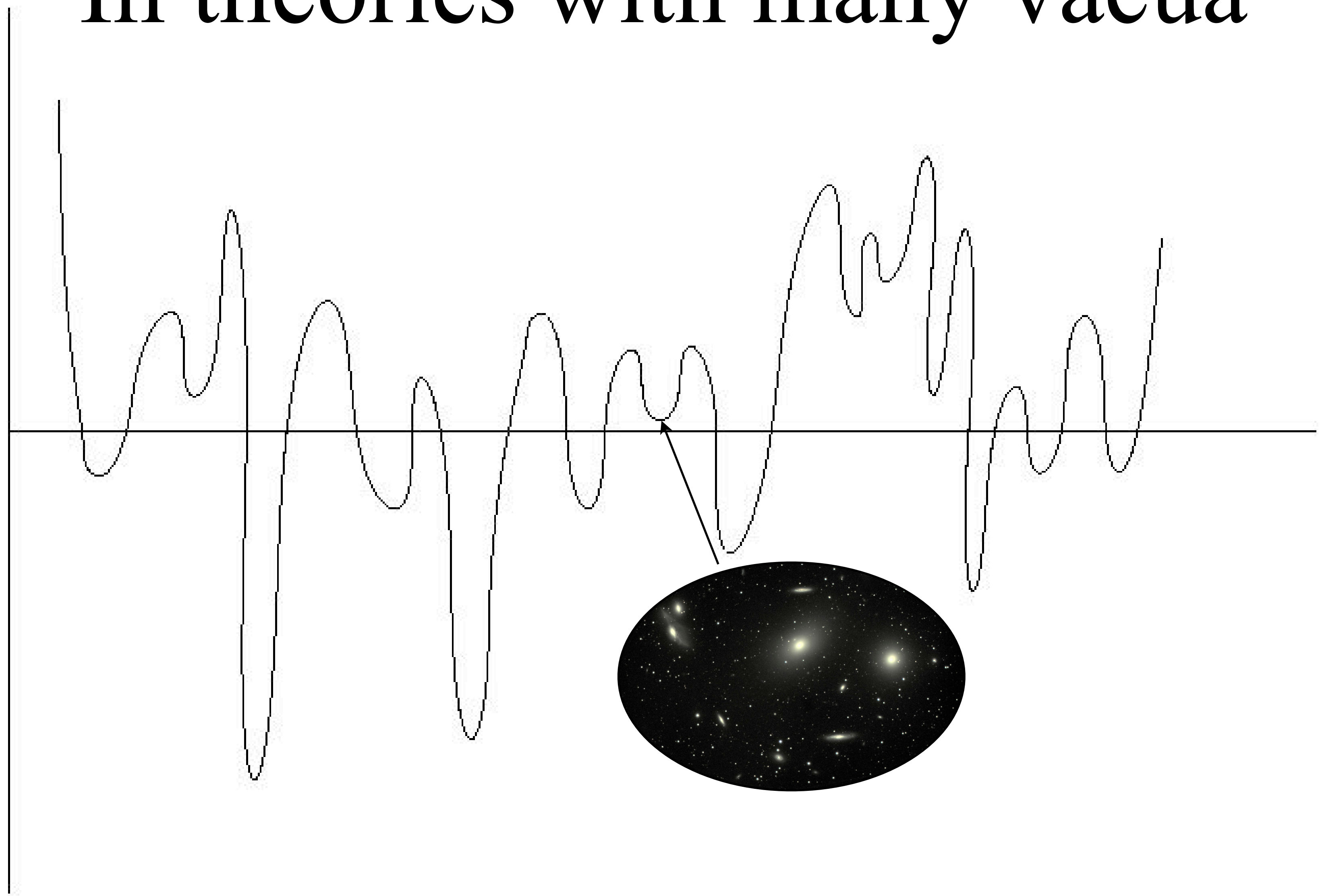
Looks like divine intervention!
Since any bigger value would rip apart galaxies

However... (Weinberg 1987)

In theories with many vacua



In theories with many vacua



Therefore, if there are enough vacua with different ρ_{vacuum}, the "galactic" principle can explain why we live in a universe with small, but nonzero, ρ_{vacuum}

This reasoning correctly predicted a small ρ_{vacuum}

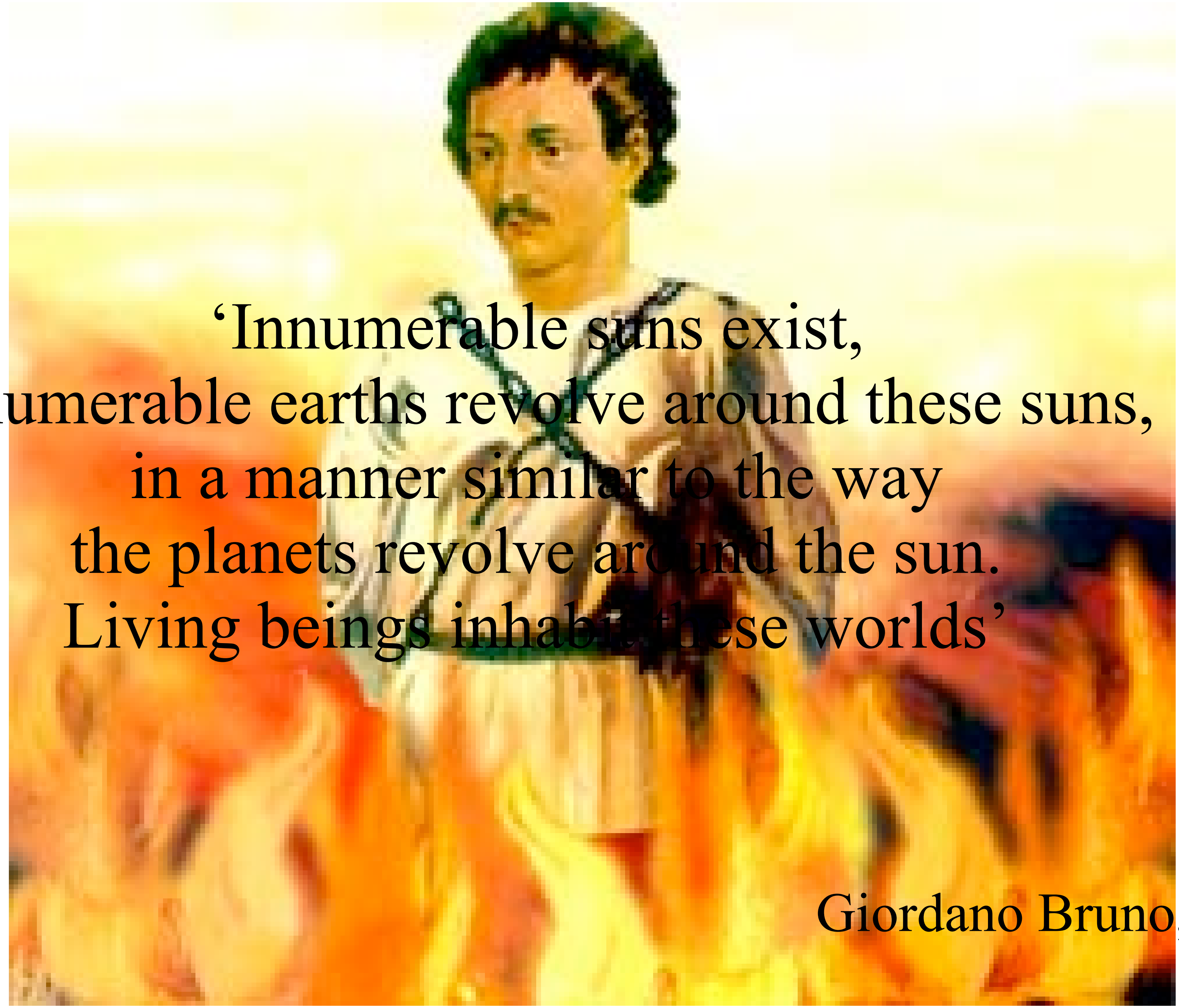
and has recently gained momentum because string theory may well have a vast “landscape” of metastable vacua

$$10^{100s}$$

Bousso, Polchinski; Kachru, Kallosh, Linde, Trivedi; Susskind ; Douglas, Denef et.al.

‘Innumerable suns exist,
innumerable earths revolve around these suns,
in a manner similar to the way
the planets revolve around the sun.
Living beings inhabit these worlds’

Giordano Bruno, 1584



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The presence of so many vacua can drastically affect what we consider natural or likely, through:

1) Statistical reasoning

2) Environmental reasoning

Statistical reasoning

changes notion of Naturalness in the Landscape:

Standard Fine-Tuning $\sim \dfrac{m_H^2}{{m_{susy}}^2}$ few-vac measure

Tuning in the Landscape $\sim \left(\dfrac{m_H^2}{m_{susy}^2}\right)\left(m_{susy}^2\right)^N$ multi-vac measure

favors high-scale SUSY

Environmental reasoning

Cosmological Constant Problem $\longleftarrow$ "Galactic" Principle

Gauge Hierachy Problem $\longleftarrow$ "Atomic" Principle

$$0 < \; m_n - m_p - m_e \; < \; \underset{(\approx 8 \; MeV)}{E_{nucleon}}$$

Environmental reasoning

Cosmological Constant Problem $\longleftarrow$ "Galactic" Principle

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$$0 < \; m_n - m_p - m_e \; < \; E_{nucleon}$$

$(\approx 8\; MeV)$

$\uparrow$

M_W decreases:
unstable Hydrogen

Environmental reasoning

Cosmological Constant Problem $\longleftarrow$ "Galactic" Principle

Gauge Hierachy Problem $\longleftarrow$ "Atomic" Principle

$$0 < \; m_n - m_p - m_e \; < \; E_{nucleon}$$

$$(\approx 8 \; MeV)$$

$\uparrow$ $\uparrow$

M_W decreases:
unstable Hydrogen

M_W increases:
only stable Hydrogen

sets the weak scale

Challenge:

Preserve the successes of SSM: Unification + DM

Just keep the fermions of the SSM!

MSSM

$M_{\mathrm{Pl.}}$ 10^{16} TeV

M_{susy}
M_{weak} 1 TeV

Split Susy

Arkani-Hamed & S.D. (2004)
Giudice & Romanino
Wells

$M_{\mathrm{Pl.}}$ 10^{16} TeV

Scalars
(Squarks, sleptons, ...)

M_{susy} $? \left\{ \begin{array}{l} 10^{15}\ \mathrm{TeV} \\ 10\ \mathrm{TeV} \end{array} \right.$

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Chiral symmetry

Fine tuned

Fermions
(Higgsinos, gauginos)

M_{weak} 1 TeV

SM Higgs

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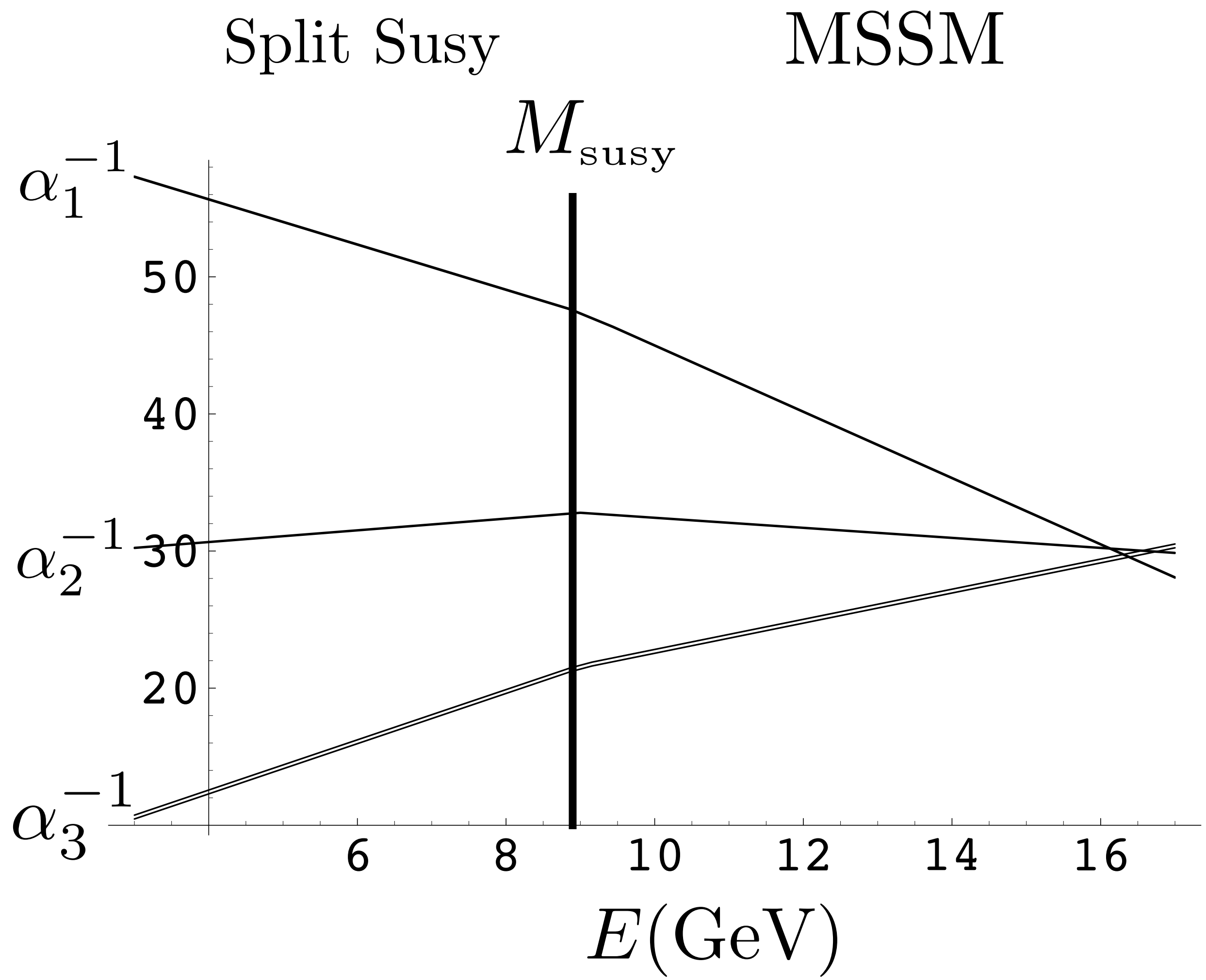
SM Higgs

Unification + Dark Matter

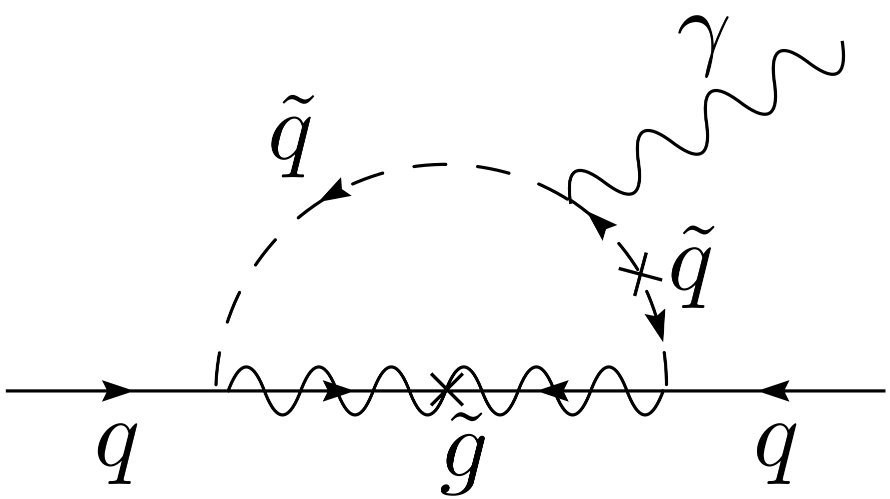
Gauge Coupling Unification

Squarks and Sleptons don't alter unification



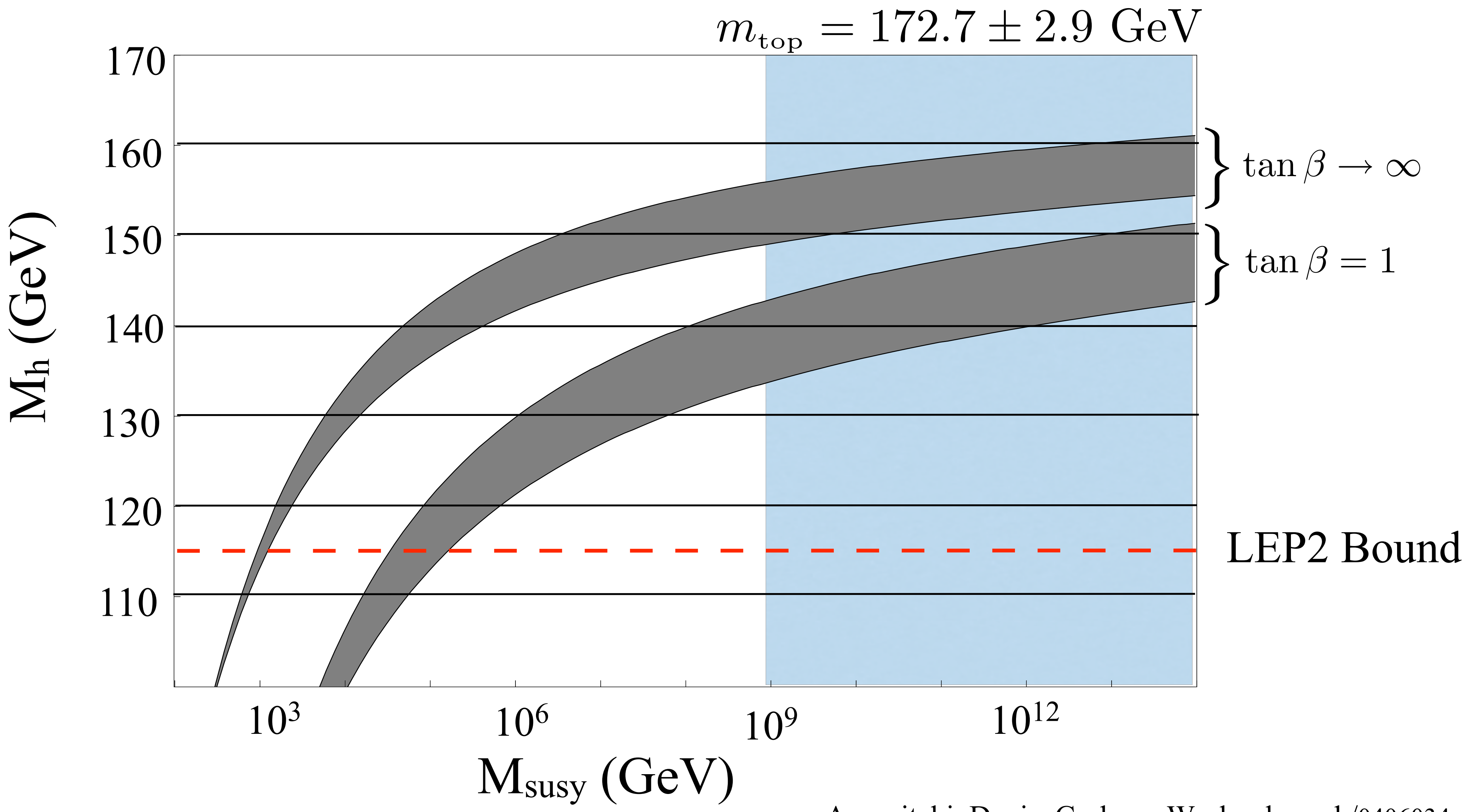
Problems solved in one stroke

- Sparticles
- Proton decay
- FCNC; CP



- The number of new parameters is reduced from 110 to 7
- Gravitino and Moduli problems also solved

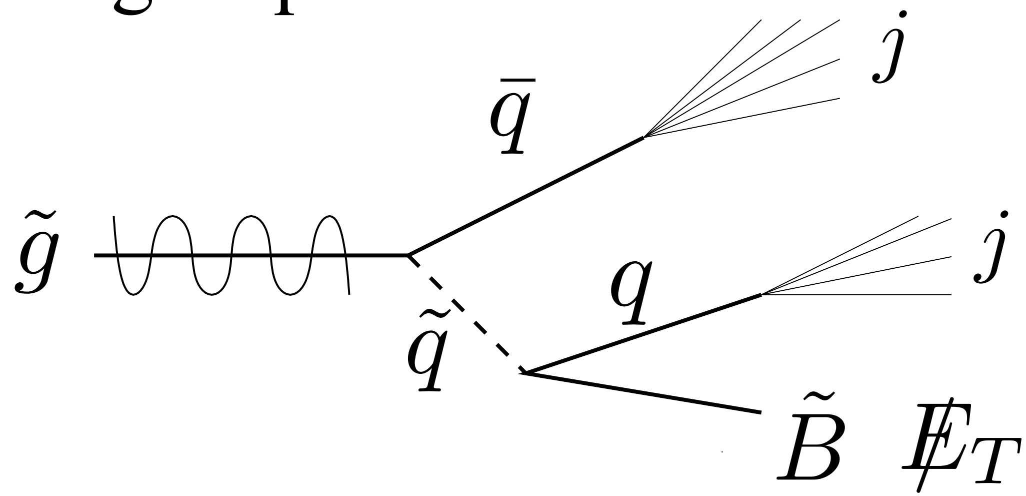
The Higgs Mass



Arvanitaki, Davis, Graham, Wacker hep-ph/0406034

Long-Lived Light Gluinos

Must decay through squarks



$$\tau_{\tilde{g}} \simeq 2 \text{ sec.} \left(\frac{350 \text{ GeV}}{m_{\tilde{g}}} \right)^5 \left(\frac{M_{\text{Susy}}}{10^6 \text{ TeV}} \right)^4$$

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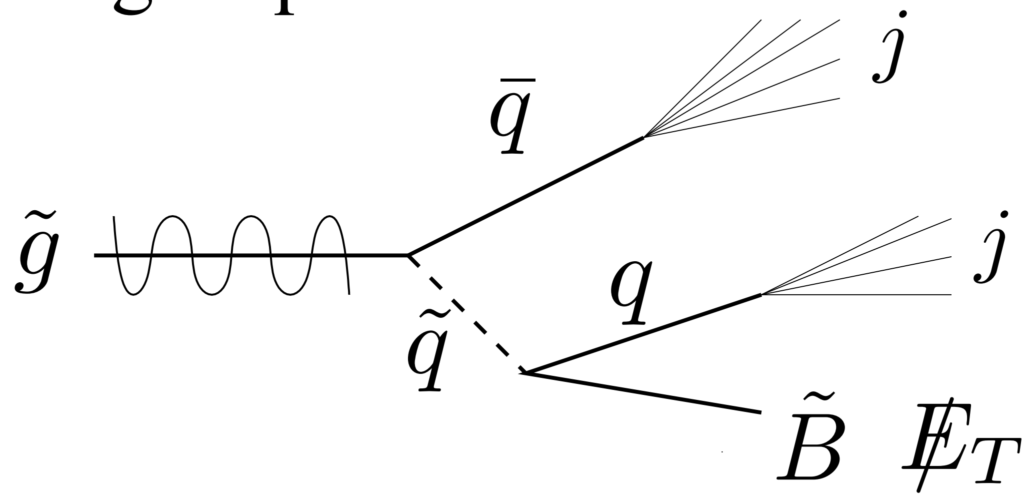

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LHC: 1 gluino/sec for m_{gluino}=350 GeV

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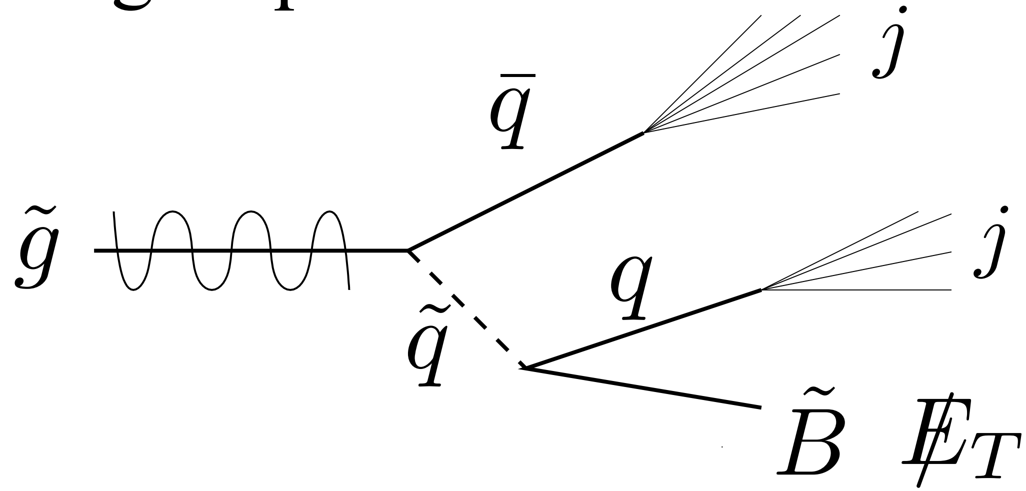

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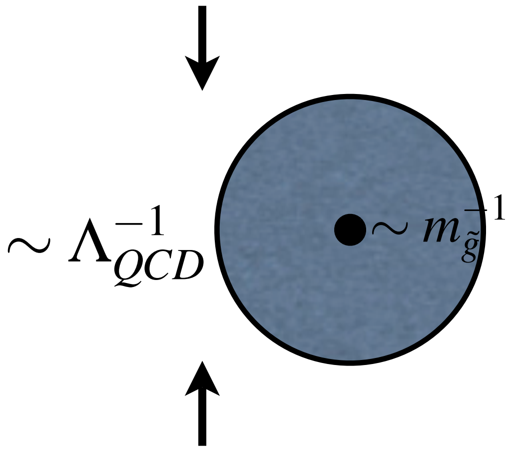
R - hadrons



R-mesons $\left\{ \begin{array}{c} \tilde{g}q\bar{q} \\ \tilde{g}g \end{array} \right.$

R-baryons $\tilde{g}qqq$

Neutral R-hadrons do not stop

Slow charged R-hadrons stop

Bethe-Bloch

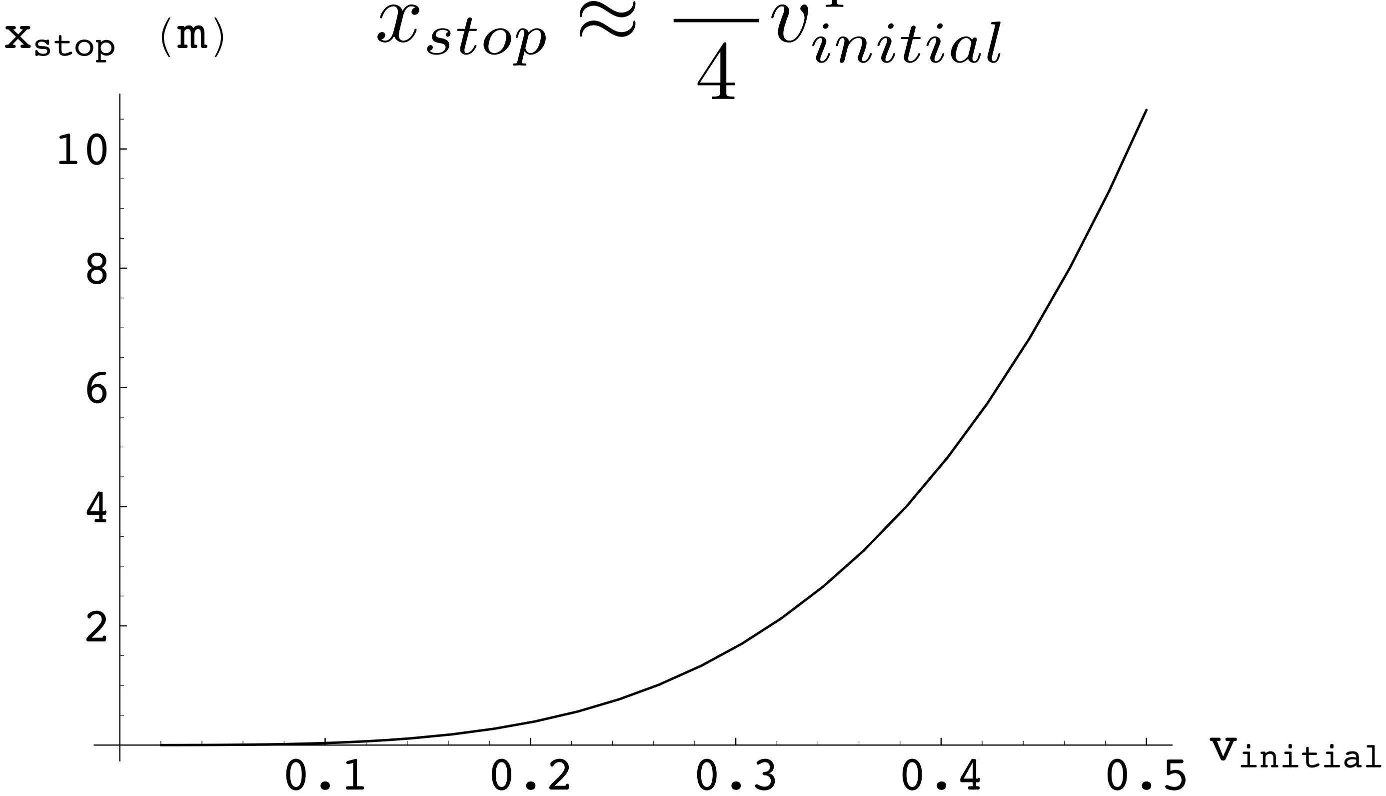
Gluino is a reservoir of kinetic energy:

Hard to stop unless R-hadron is charged

$$\frac{dv}{dx} \approx -\frac{1}{x_o v^3}$$

$x_o \approx 500\ m$ for Cu, Fe and Pb

$$x_{stop} \approx \frac{x_o}{4} v^4_{initial}$$



Matter conversion

The interaction:

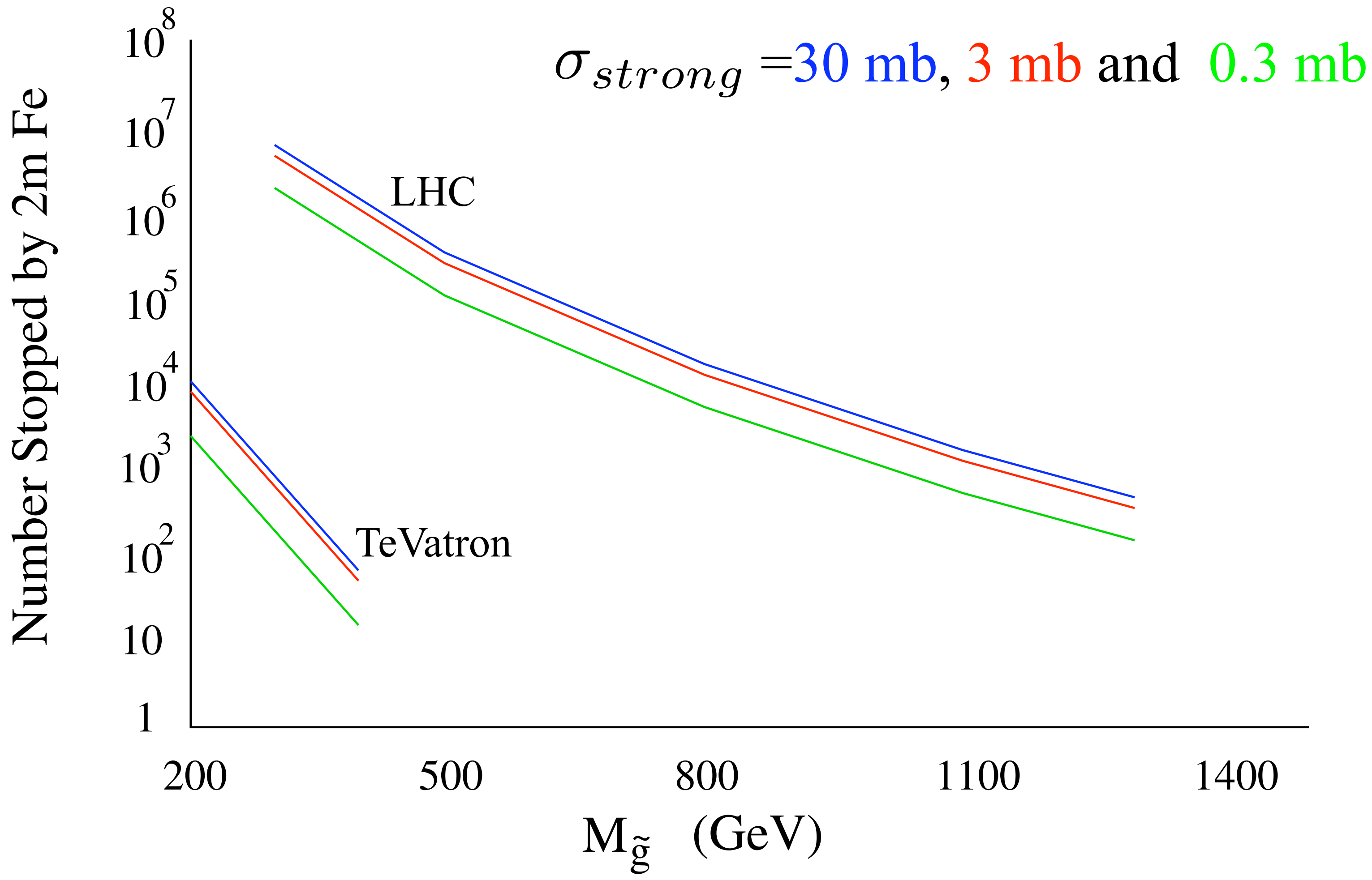
$$R_{meson} + Nucleon \rightarrow R_{Baryon} + \pi$$

is exothermic (Q = 400 MeV)

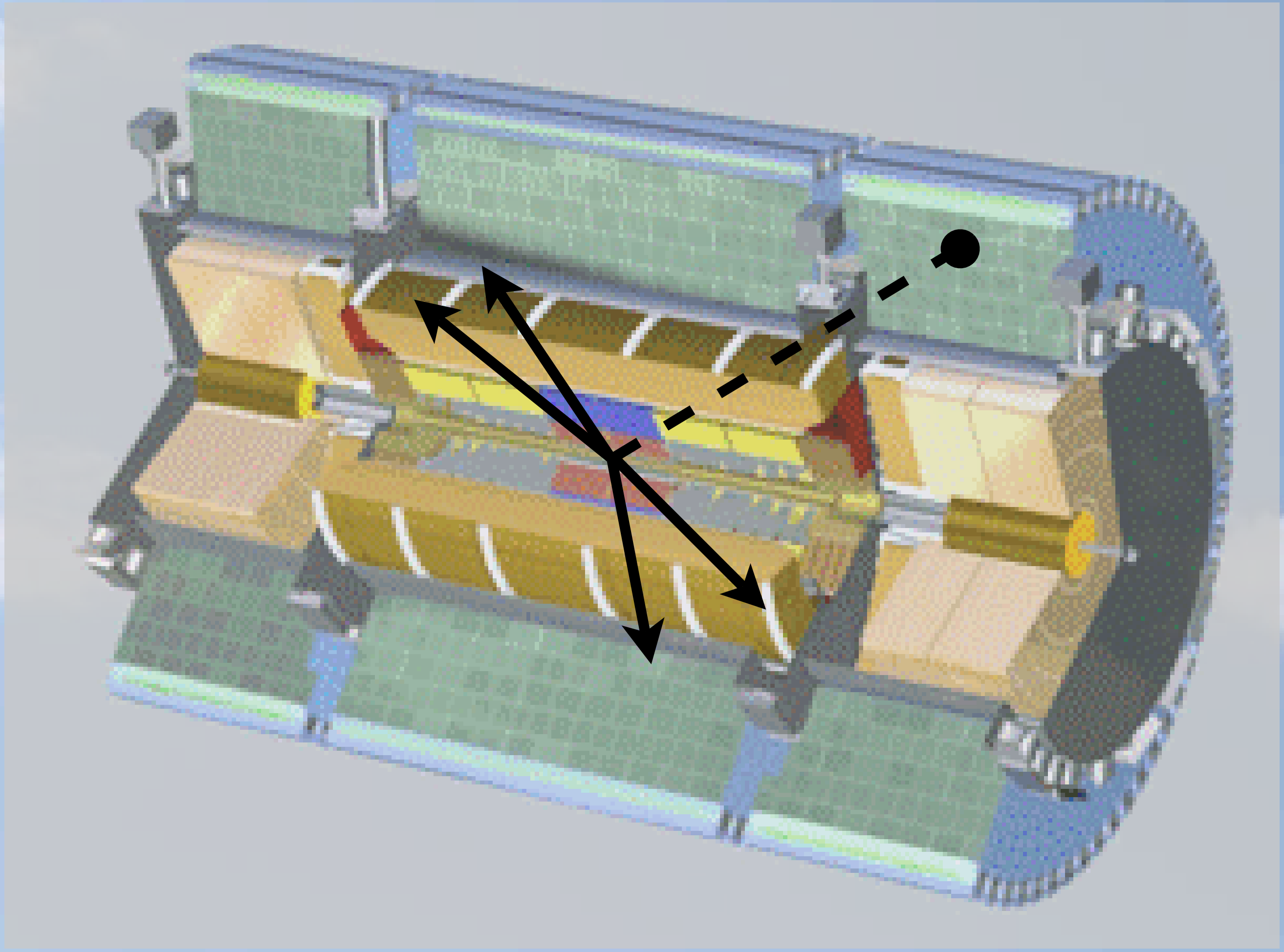
$$\sigma \sim \sigma_{strong} \frac{v_{final}}{v_{initial}}$$

Half the time the R-Baryon is charged

How many stop?



Stopped, late-decaying Gluinos!



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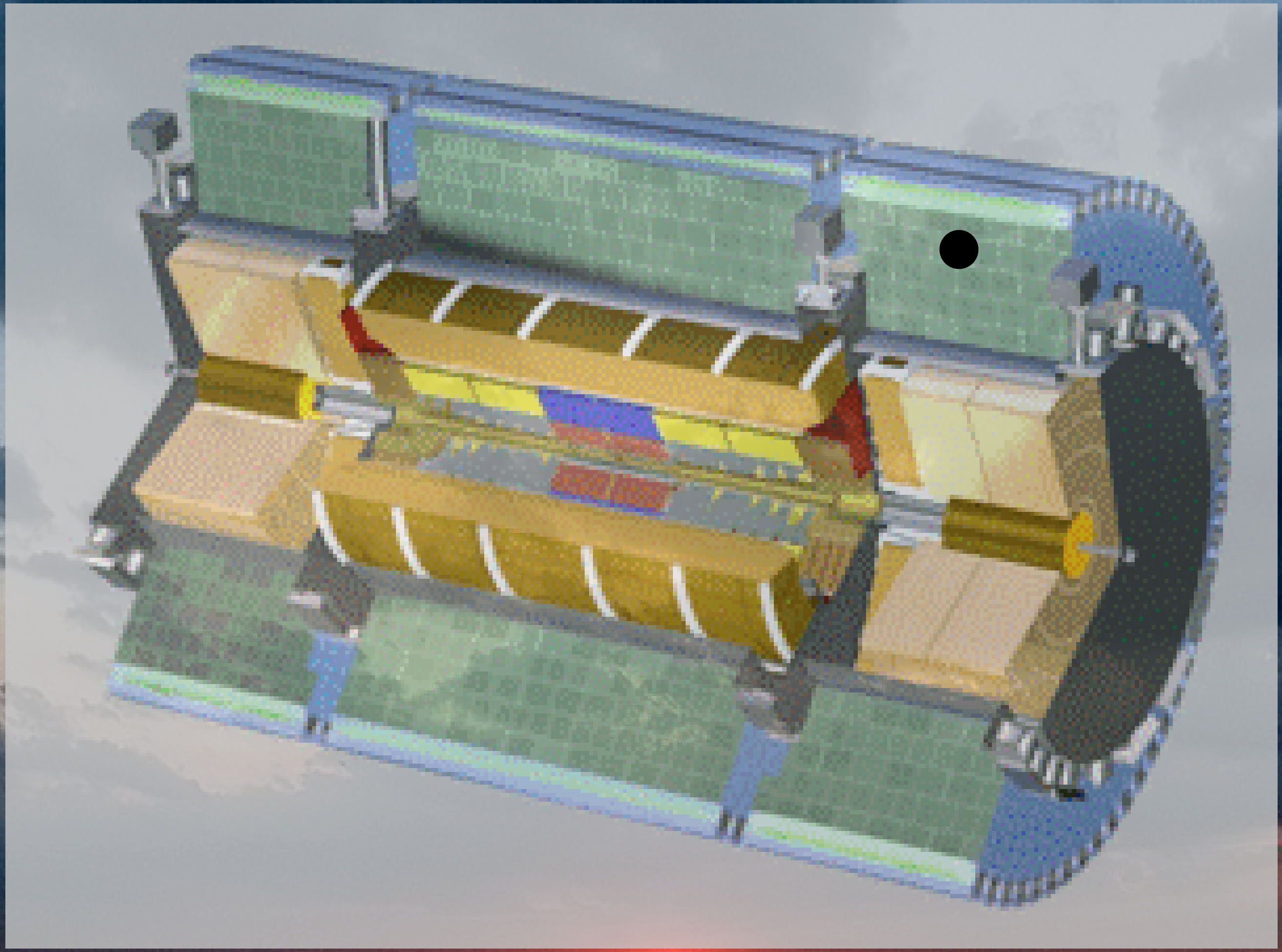

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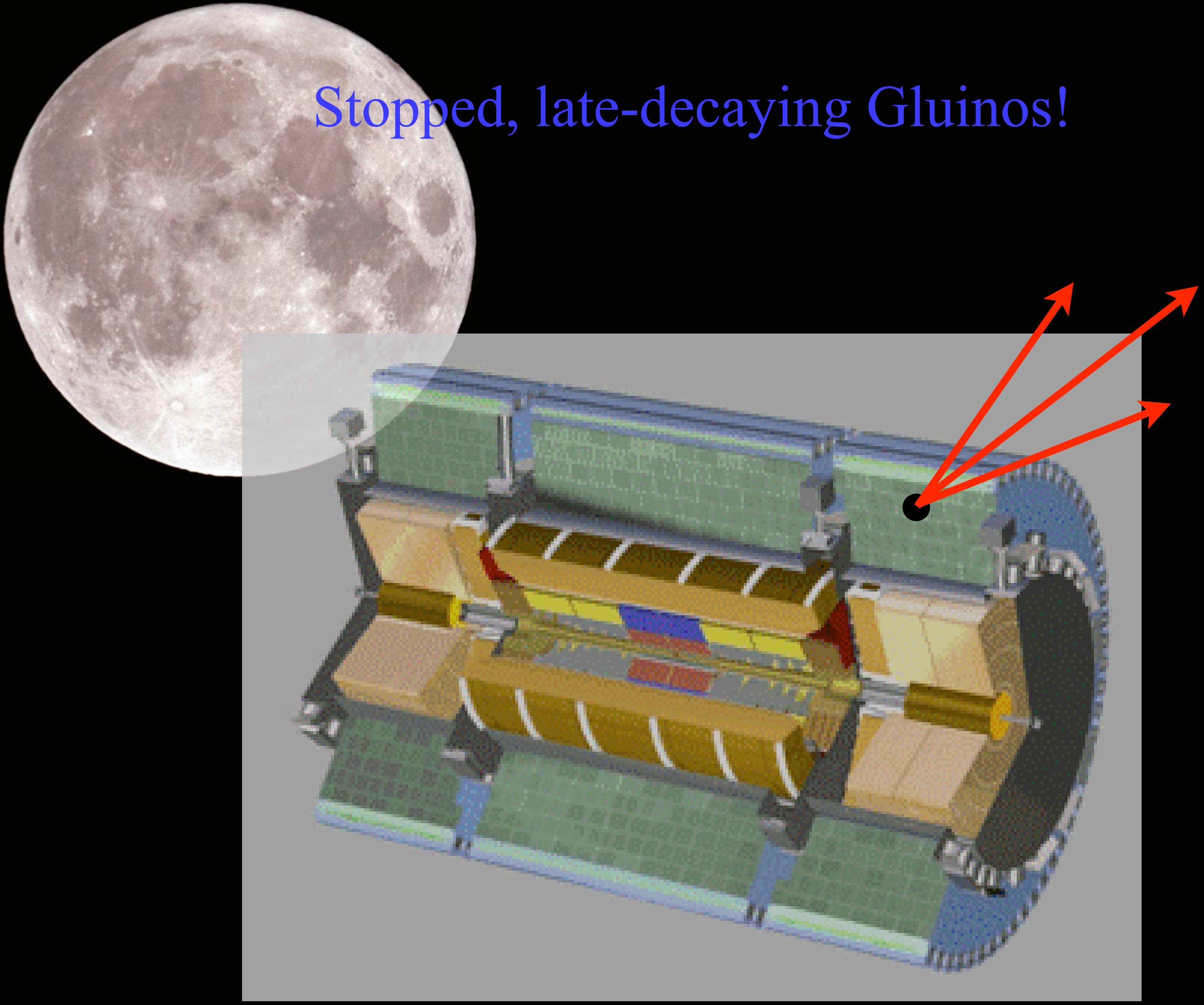
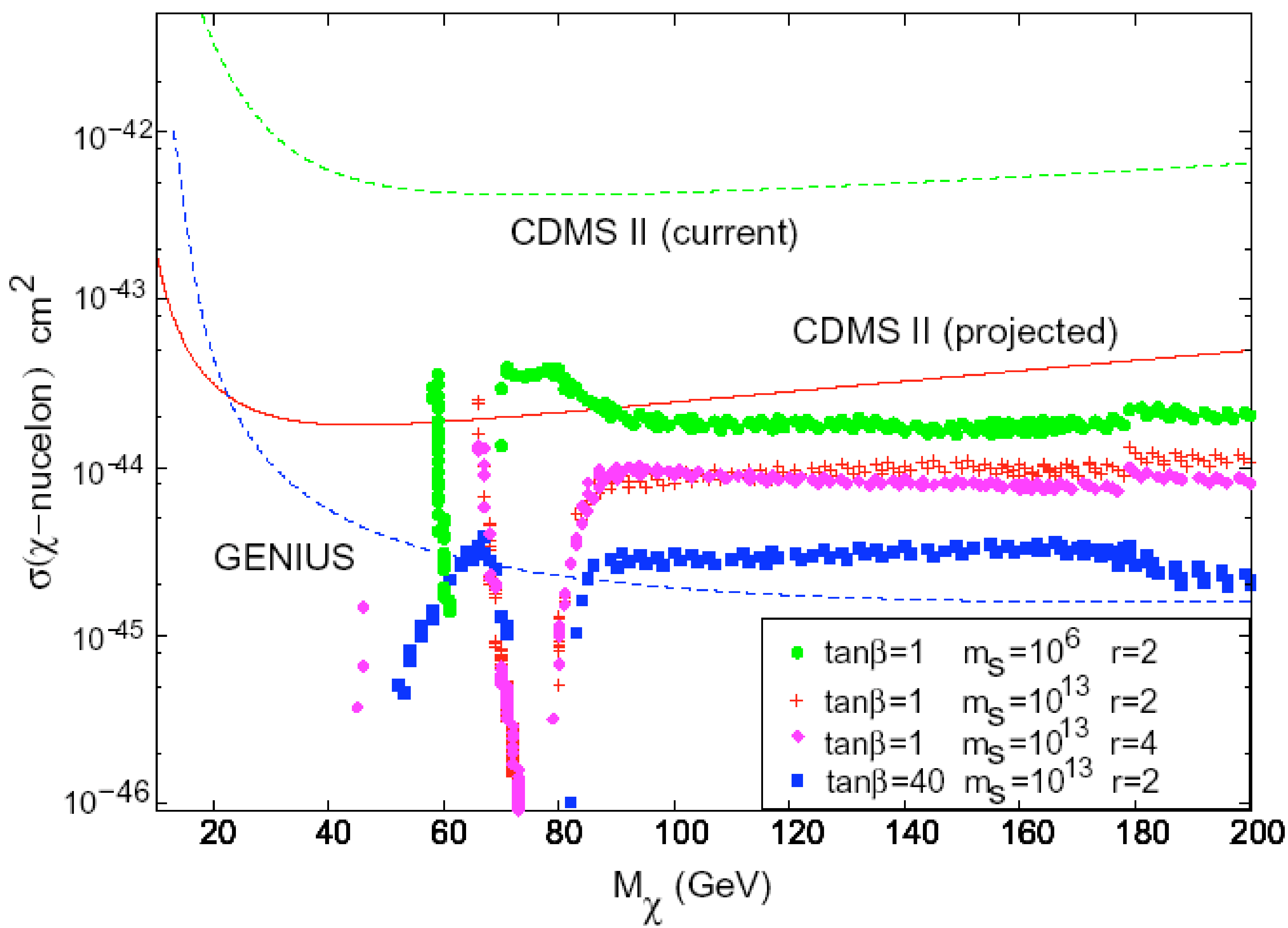


Dark Matter Detection



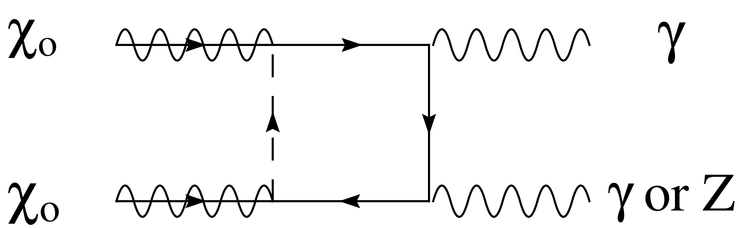
G.F.Giudice, and A. Romanino, hep-ph/0406088, A. Pierce, hep-ph/0406144

Annihilating DM detection

- Signals:

Excess in the continuous cosmic ray spectrum

γ – lines from neutralino annihilation to 2 photons or a photon and a Z boson



Signal depends on the DM distribution

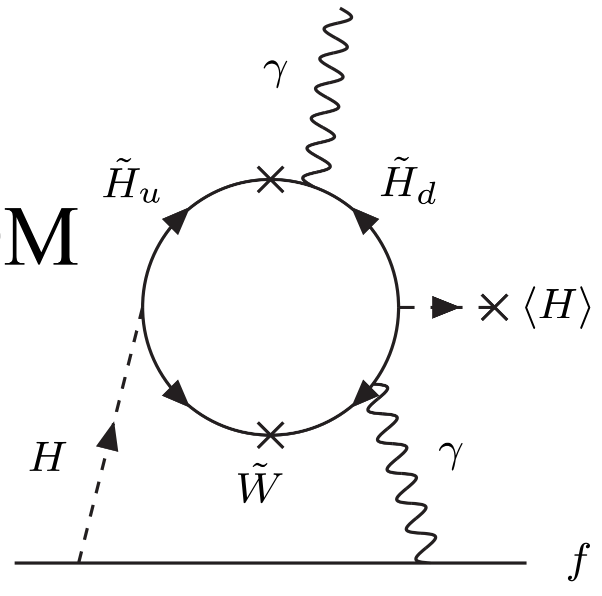
- Experiments:

GLAST

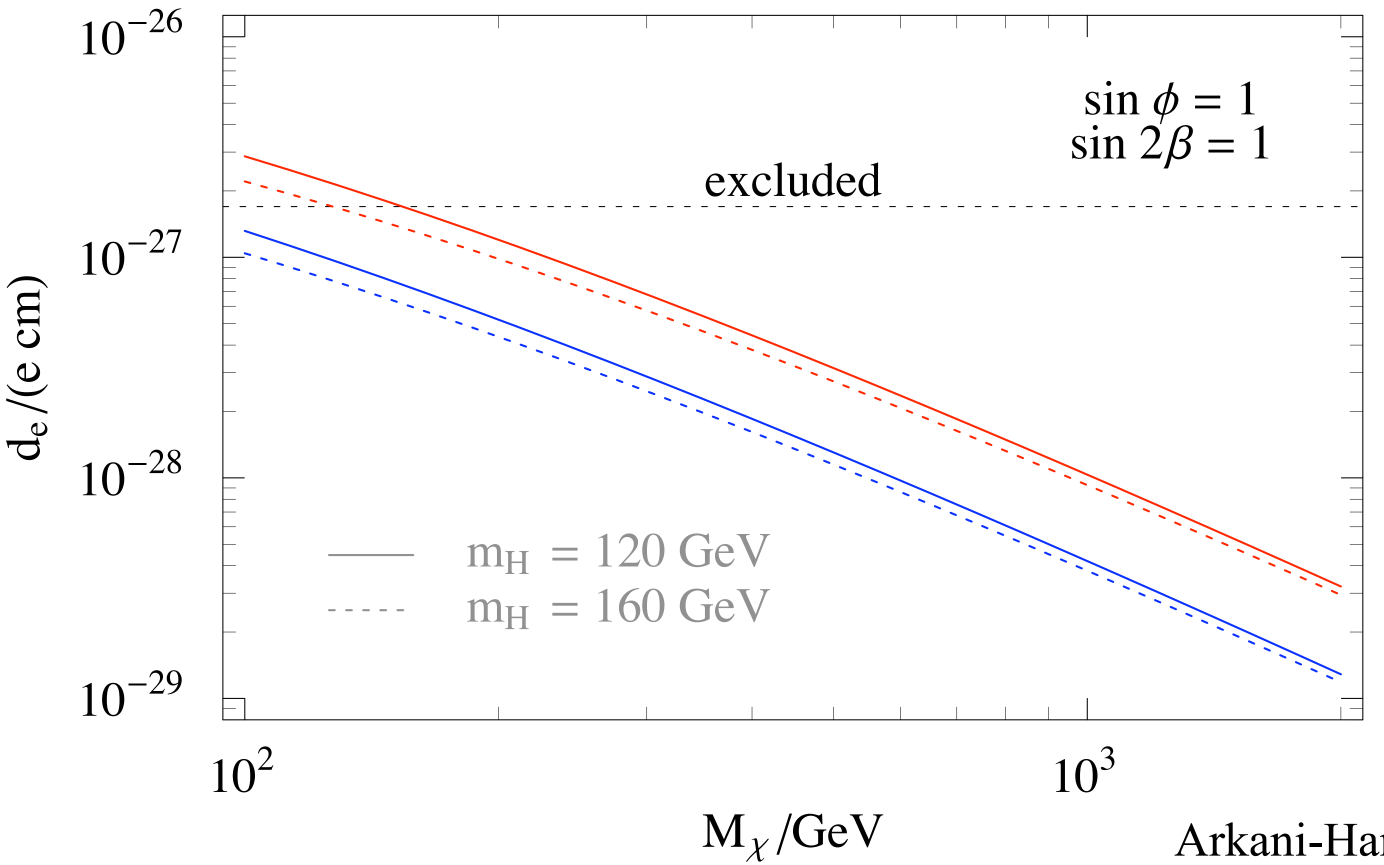
HESS

Electric Dipole Moments

Three phases in split SUSY



Feeds in at 2 loops to electron EDM



Arkani-Hamed, et al hep-ph/0409232

Electric Dipole Moments

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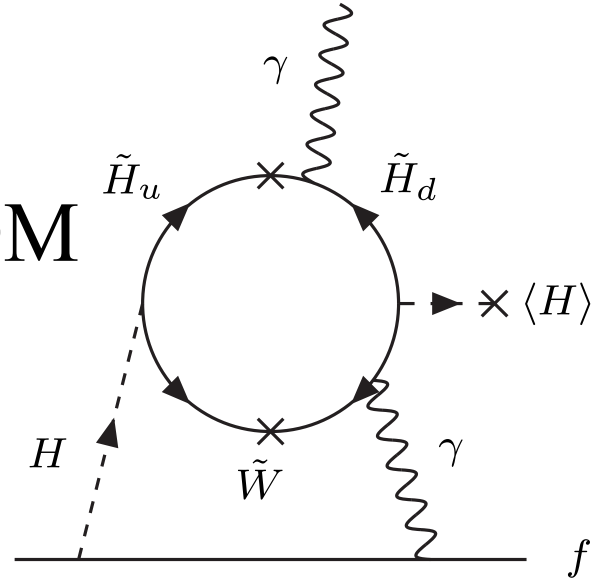
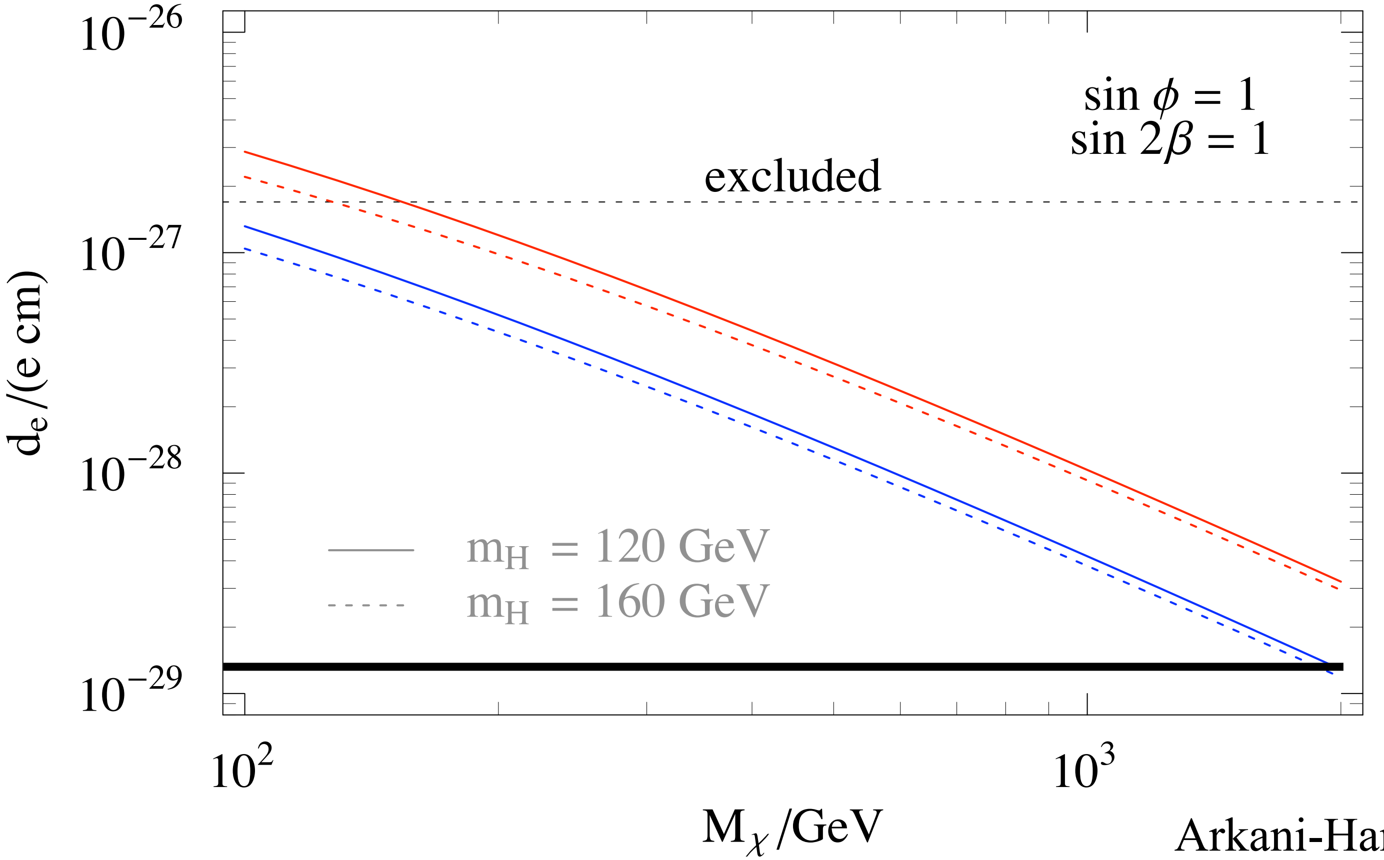




Atomic Experiments

Arkani-Hamed, et al hep-ph/0409232

Other Split SUSY Couplings

Higgs Quartic

$$\lambda|H|^4 - m^2|H|^2$$

Gaugino Yukawas

$$\kappa_u H \widetilde{H_u} \widetilde{W} + \kappa_d H^\dagger \widetilde{H_d} \widetilde{W}$$

$$\kappa'_u H \widetilde{H_u} \widetilde{B} + \kappa'_d H^\dagger \widetilde{H_d} \widetilde{B}$$

$$\lambda(M_s) = \frac{1}{8}\left(g^2 + g'^2\right)\cos^2 2\beta$$

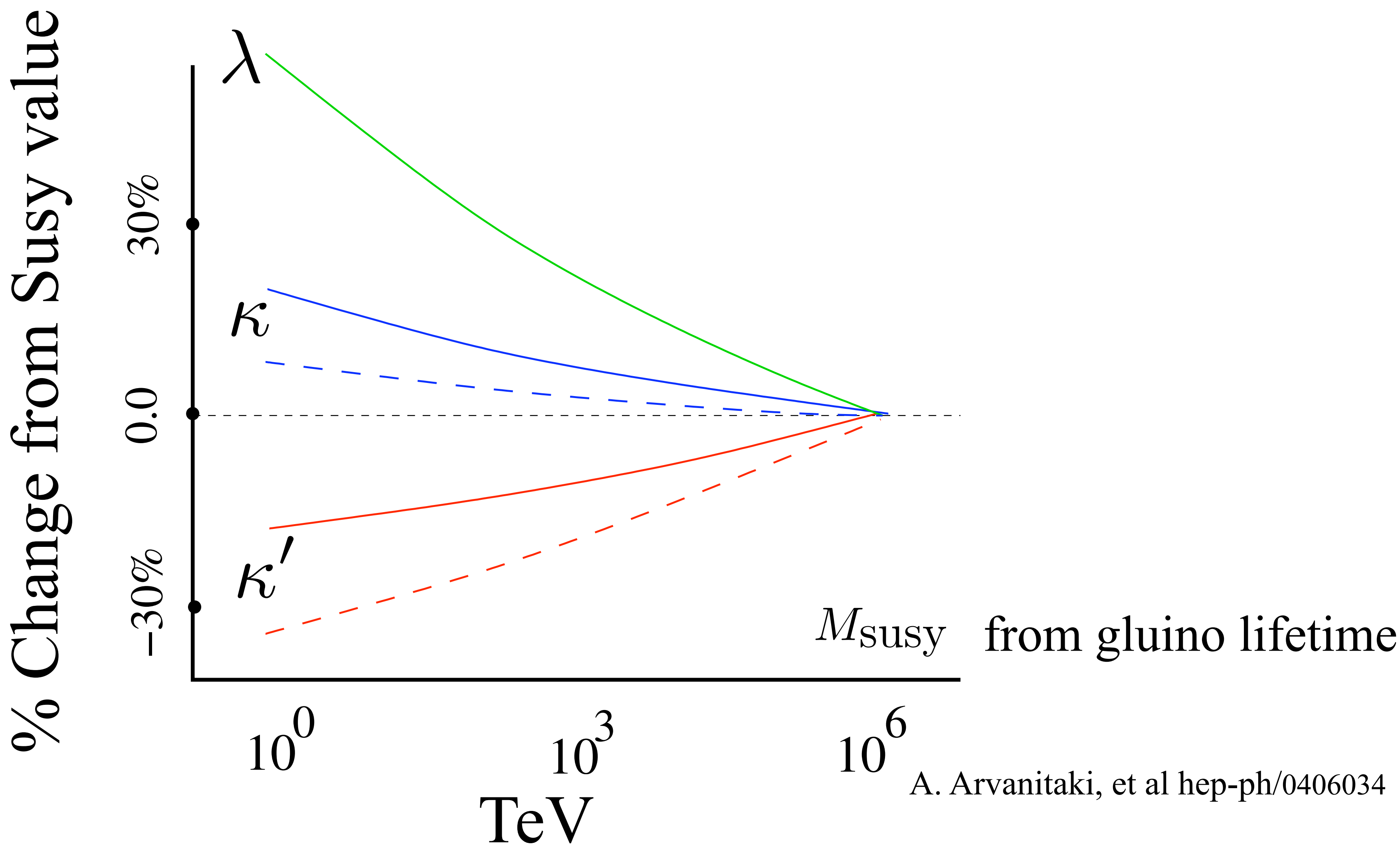
$$\kappa_u(M_s) = g\sin\beta$$

$$\kappa_d(M_s) = g\cos\beta$$

Run from the weak scale to M_{susy}

Yukawa Couplings' Unification

$$\tan\beta \longrightarrow \lambda \;\; \kappa_u \;\; \kappa_d \;\; \kappa'_u \, \kappa'_d$$



A. Arvanitaki, et al hep-ph/0406034

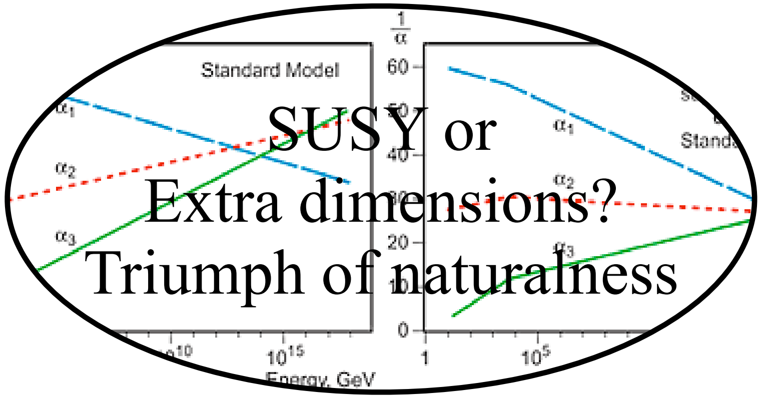
Four predictions, four independent tests of high-scale SUSY !

Split SUSY signatures

- Higgs Mass 120 - 160 GeV
- Gauginos and Higgsinos
- Dark Matter
- EDMs
- Gluino lifetime reveals m_{susy}
- κ's and λ in terms of $\tan\beta$ and m_{susy}

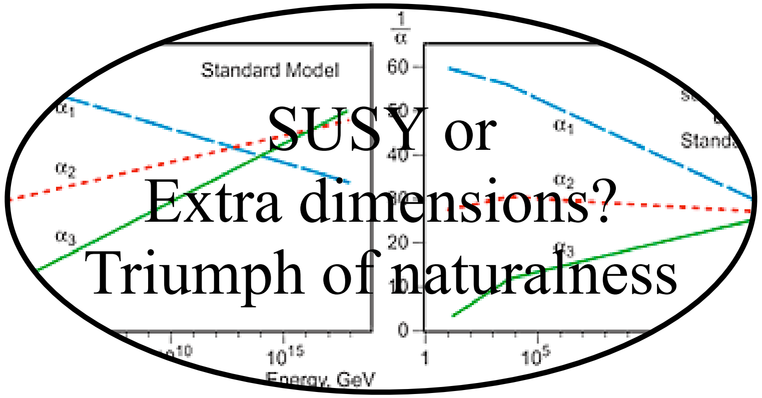
Strong evidence for a fine tuning mechanism, in the EW sector. No subtleties of gravity.

Late 00’s

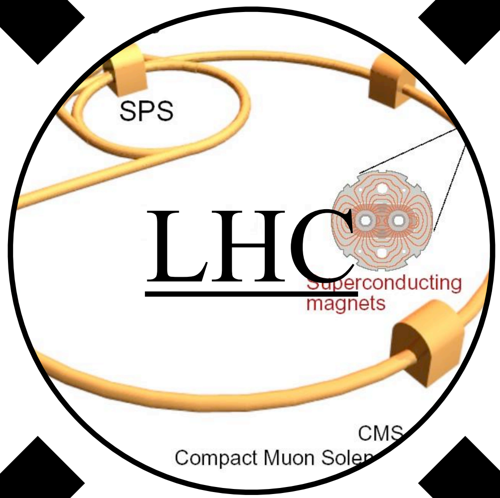


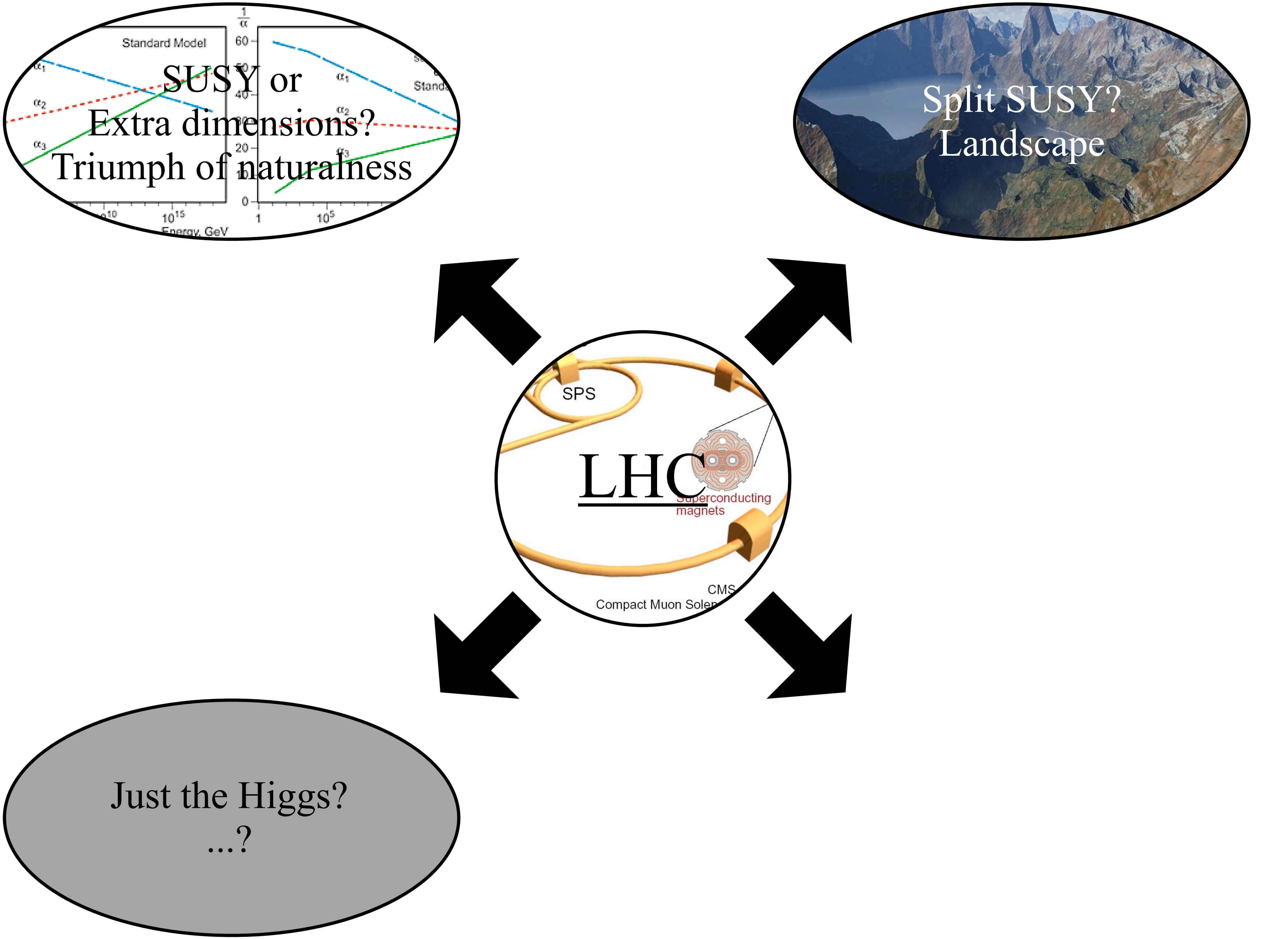
SUSY or
Extra dimensions?
Triumph of naturalness

LHC


Standard Model
SUSY or
Extra dimensions?
Triumph of naturalness
60
20
0
1
10^{15}
10^5
Energy, GeV


Split SUSY?
Landscape


SPS
LHC
Superconducting
magnets
CMS


SUSY or
Extra dimensions?
Triumph of naturalness
Standard Model
Energy, GeV
Split SUSY?
Landscape
LHC
SPS
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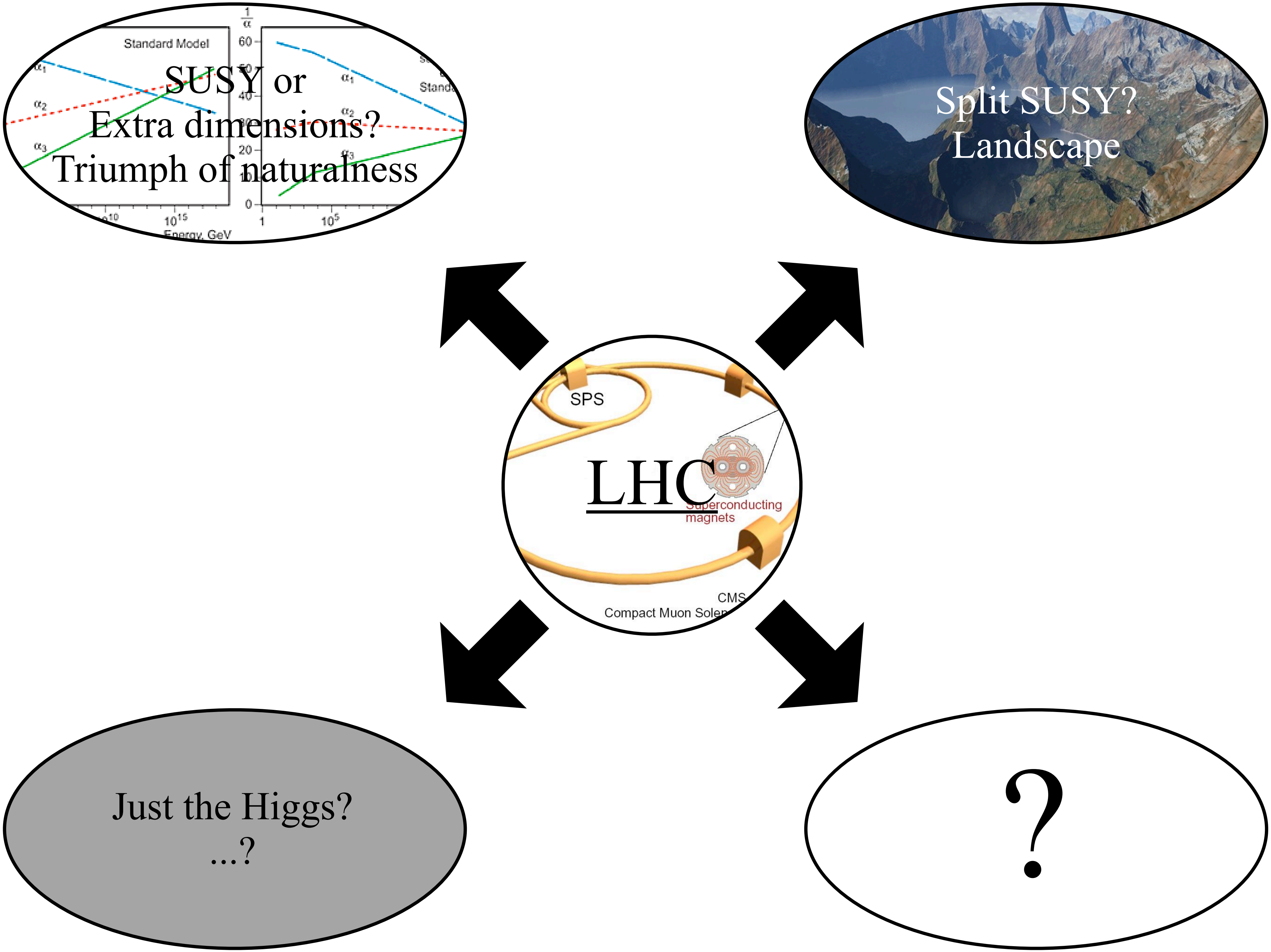
magnets
CMS
Just the Higgs?
...?


SUSY or
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LHC
SPS
Superconducting
magnets
CMS
Just the Higgs?
...?
?

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Jakob Nordin
Yashar Akrami
Linda Ostman