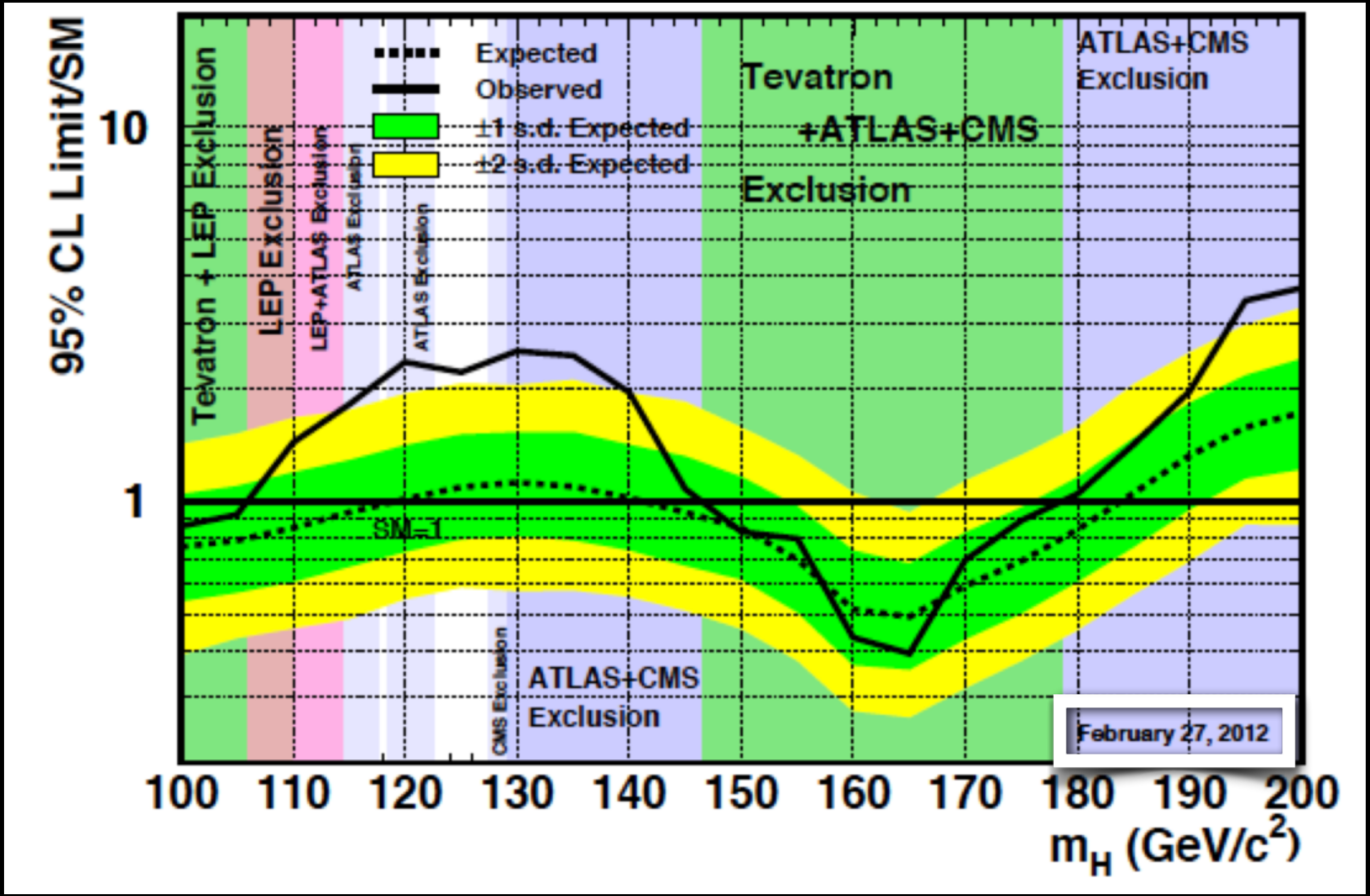
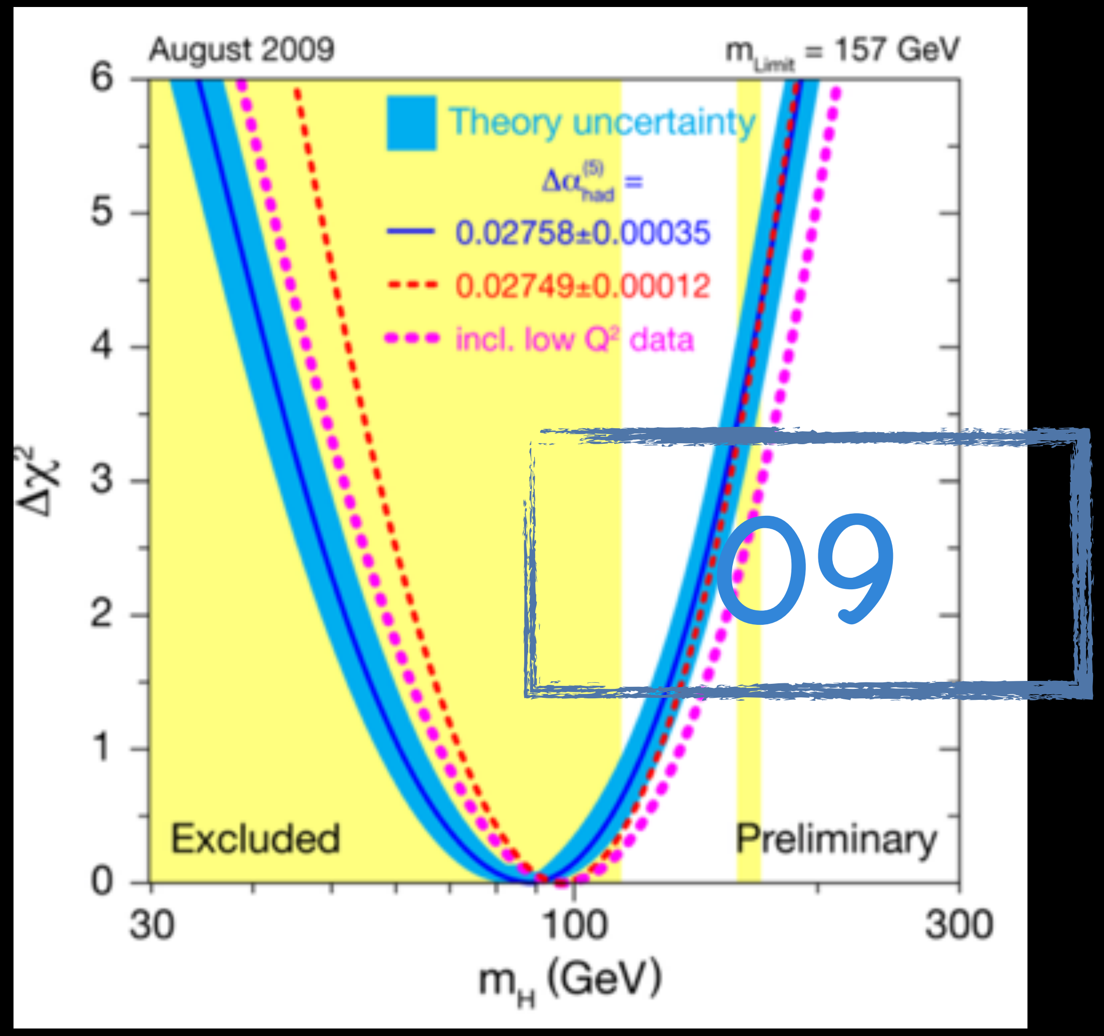
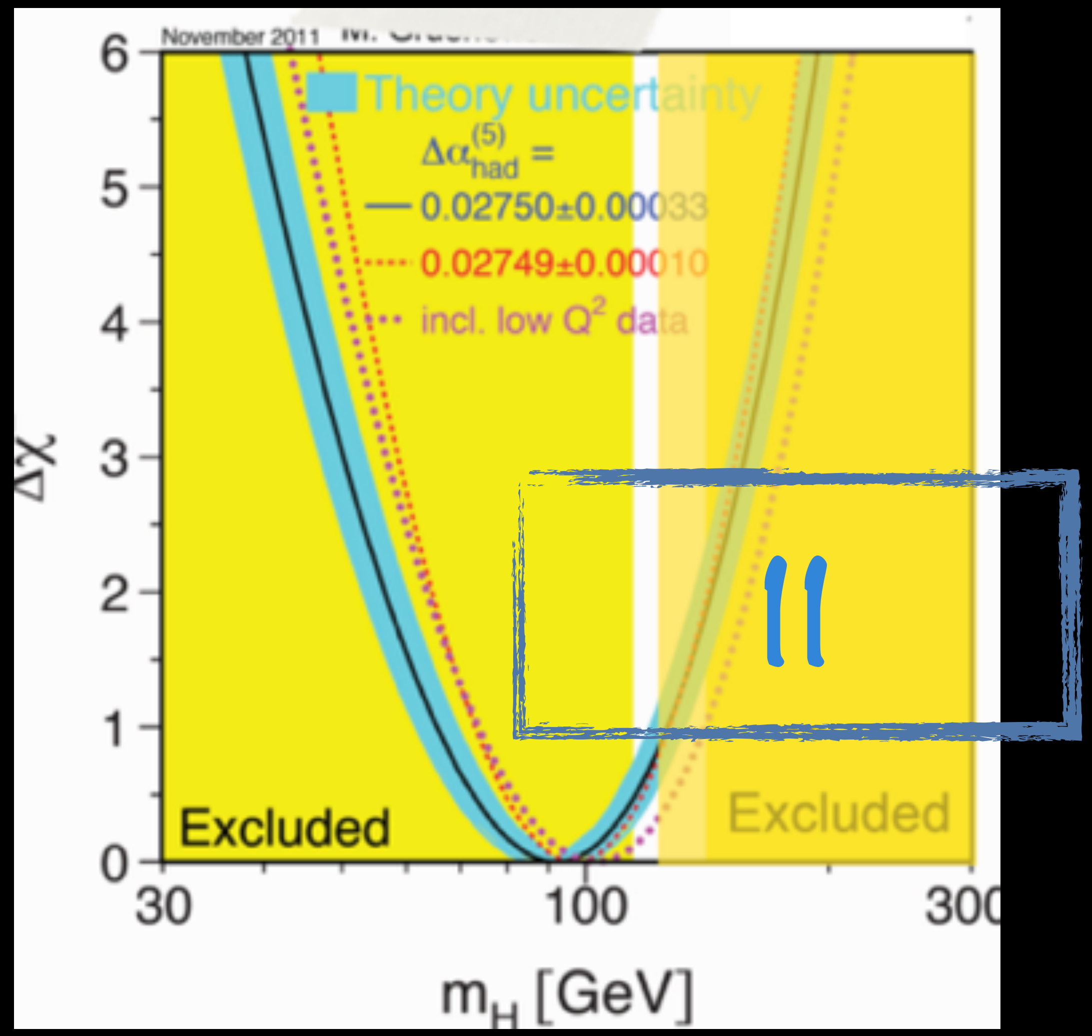
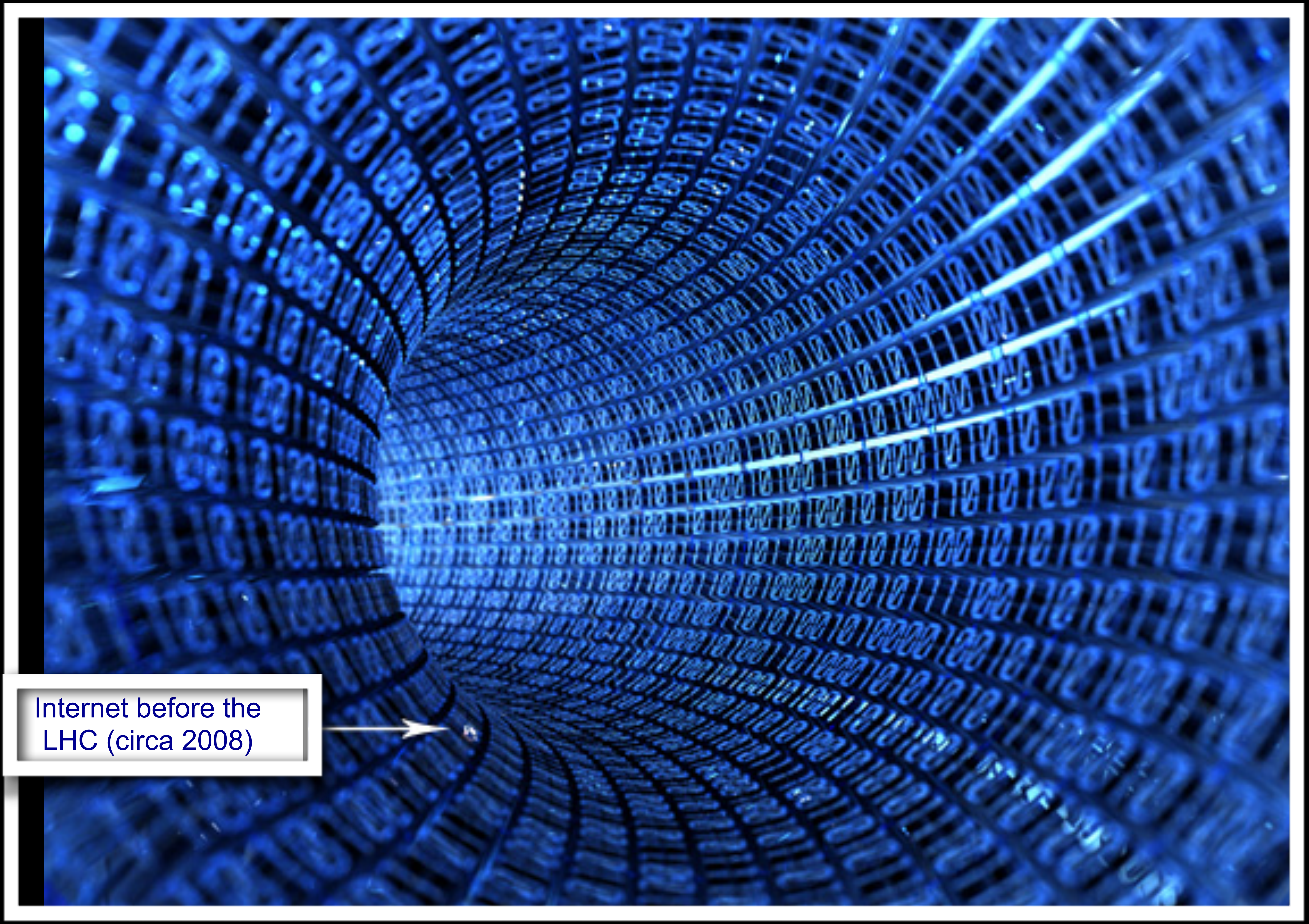
DECADES OF EXPERIMENTAL HUNTING

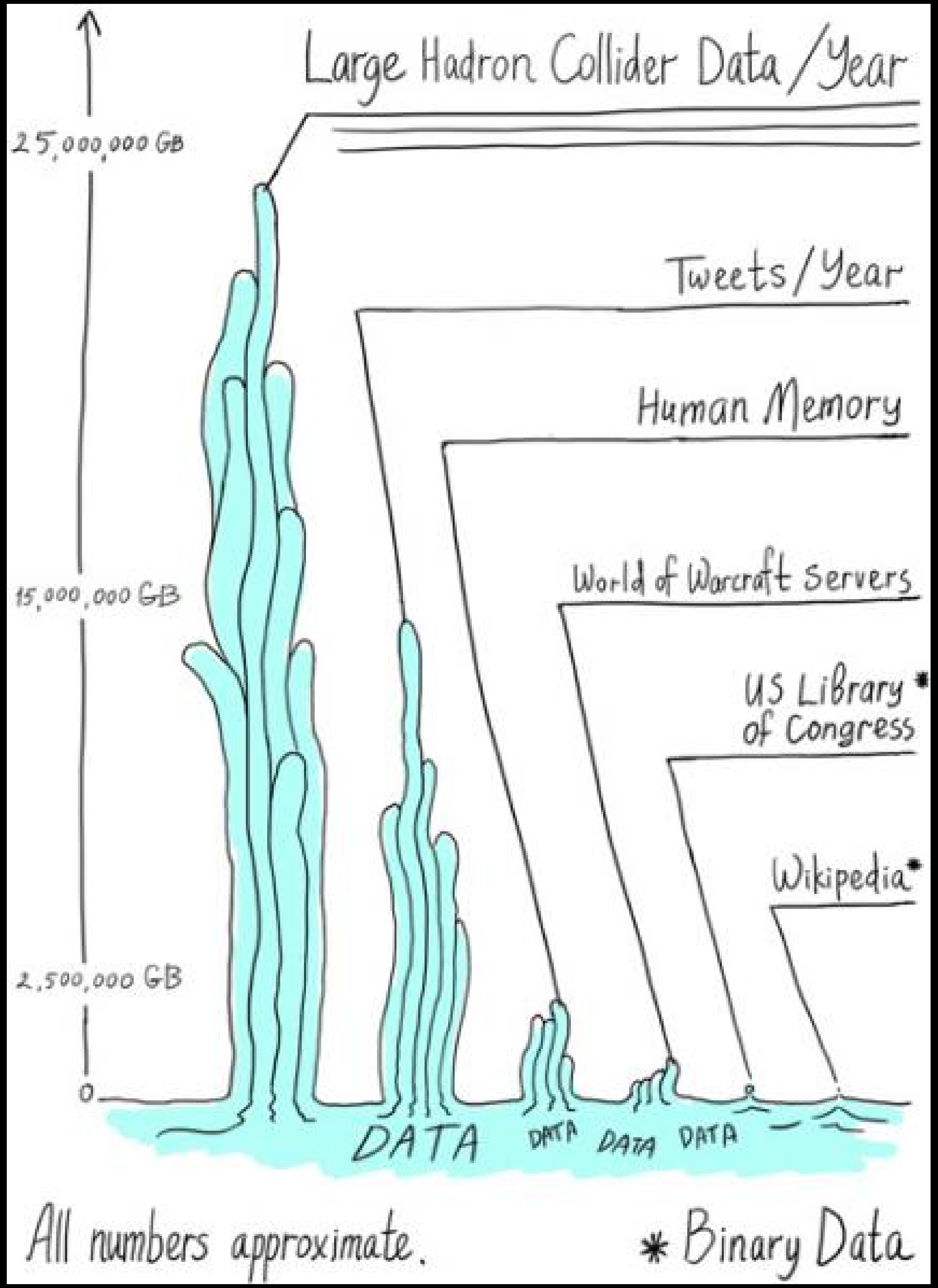




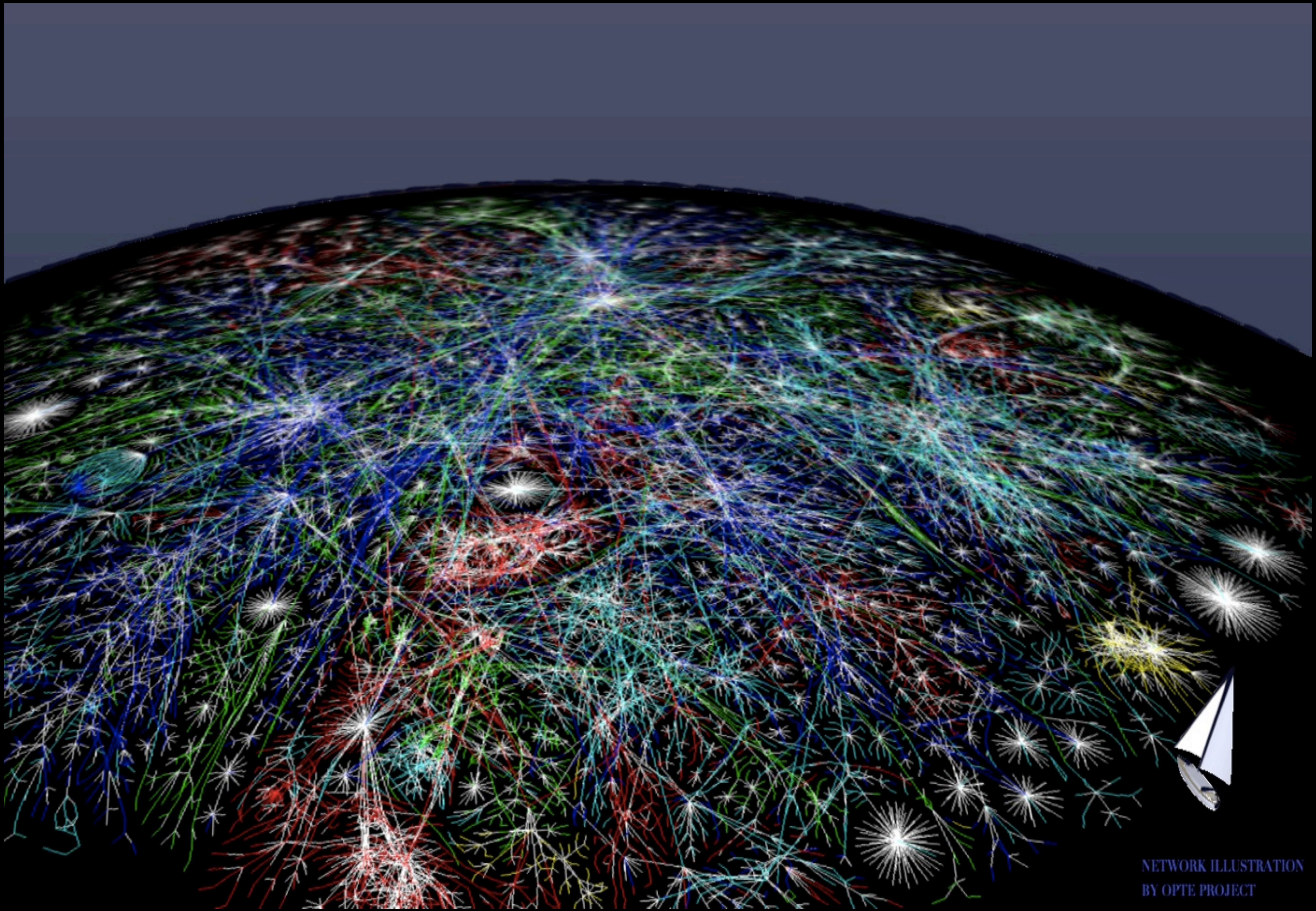


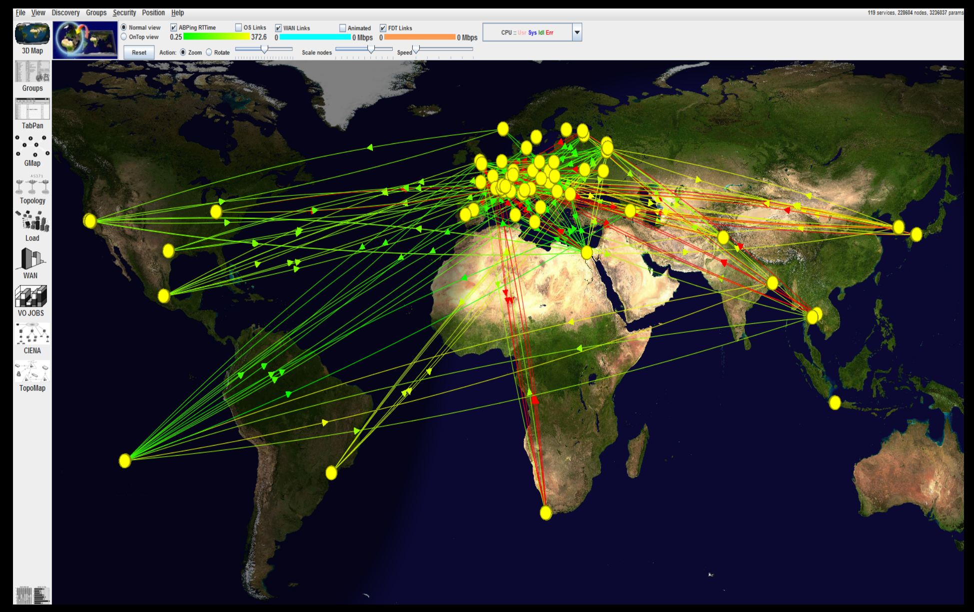
DATA

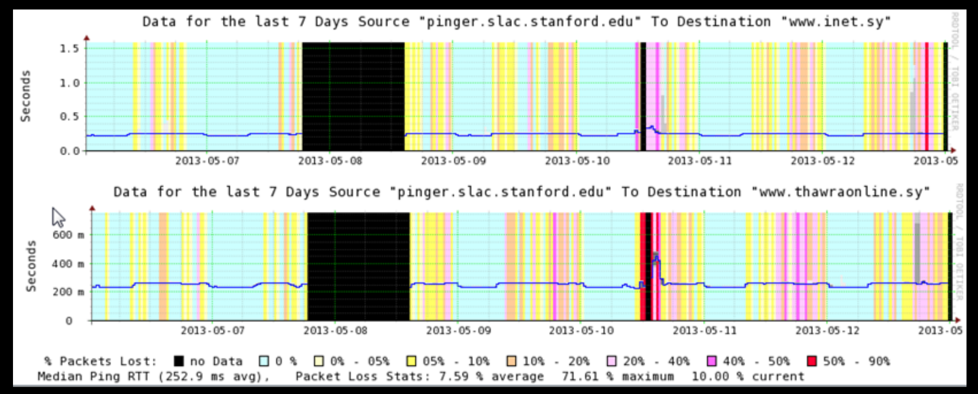

Internet before the
LHC (circa 2008)


Large Hadron Collider Data / Year
Tweets / Year
Human Memory
World of Warcraft Servers
US Library of Congress *
Wikipedia *
25,000,000 GB
15,000,000 GB
2,500,000 GB
0
DATA
DATA
DATA
DATA
All numbers approximate.
* Binary Data

THE WW NETWORK ORGANISM







INTELLIGENCE

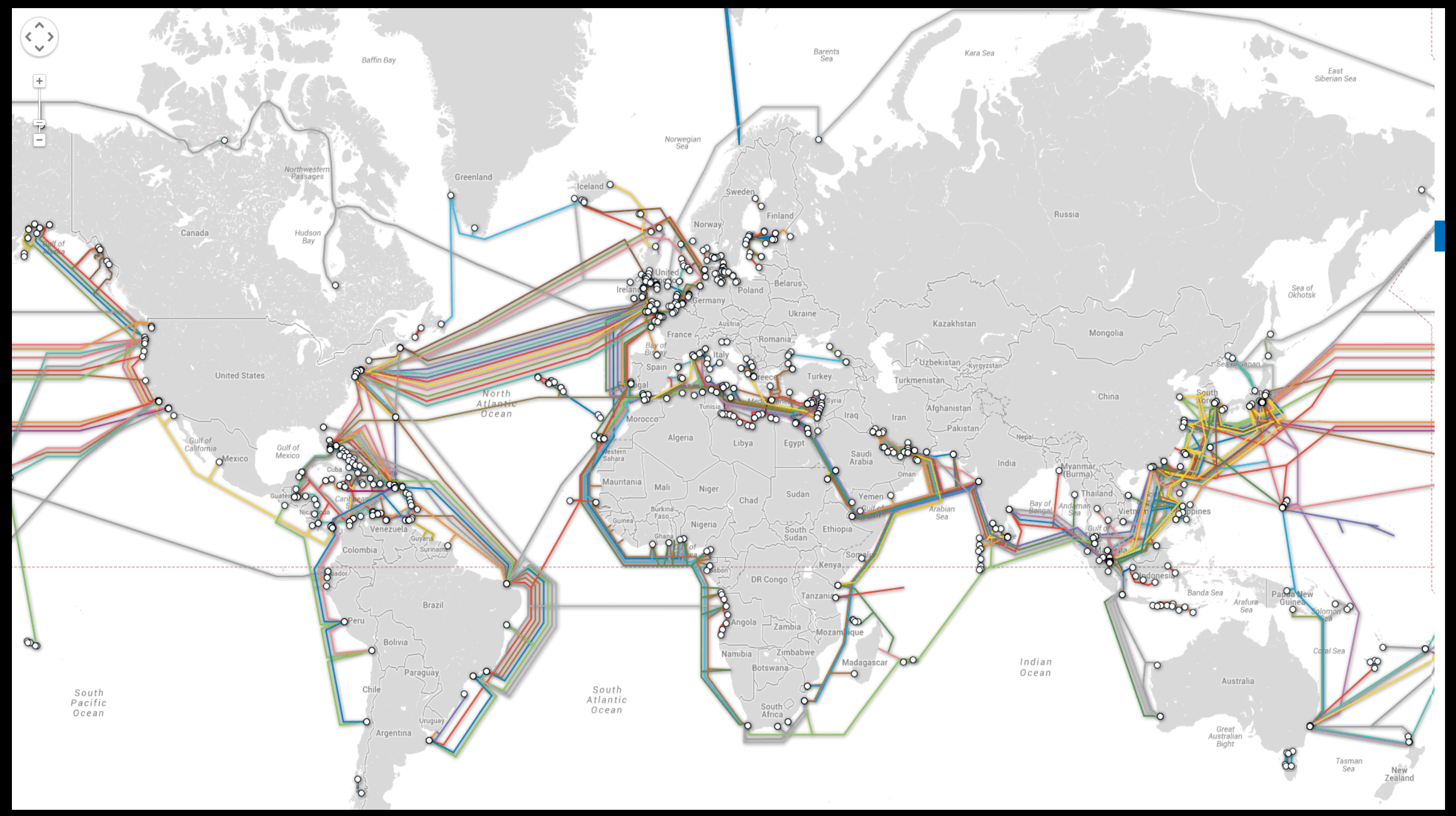
Future Data Hyperloops*

I. **AA (alive/adapting*) Networks** integrating communication, computing, storage resources… -- involving domain-specific science gateways and portals, cloud-based workflows, high-performance and high-throughput computing models, and new data service capabilities.

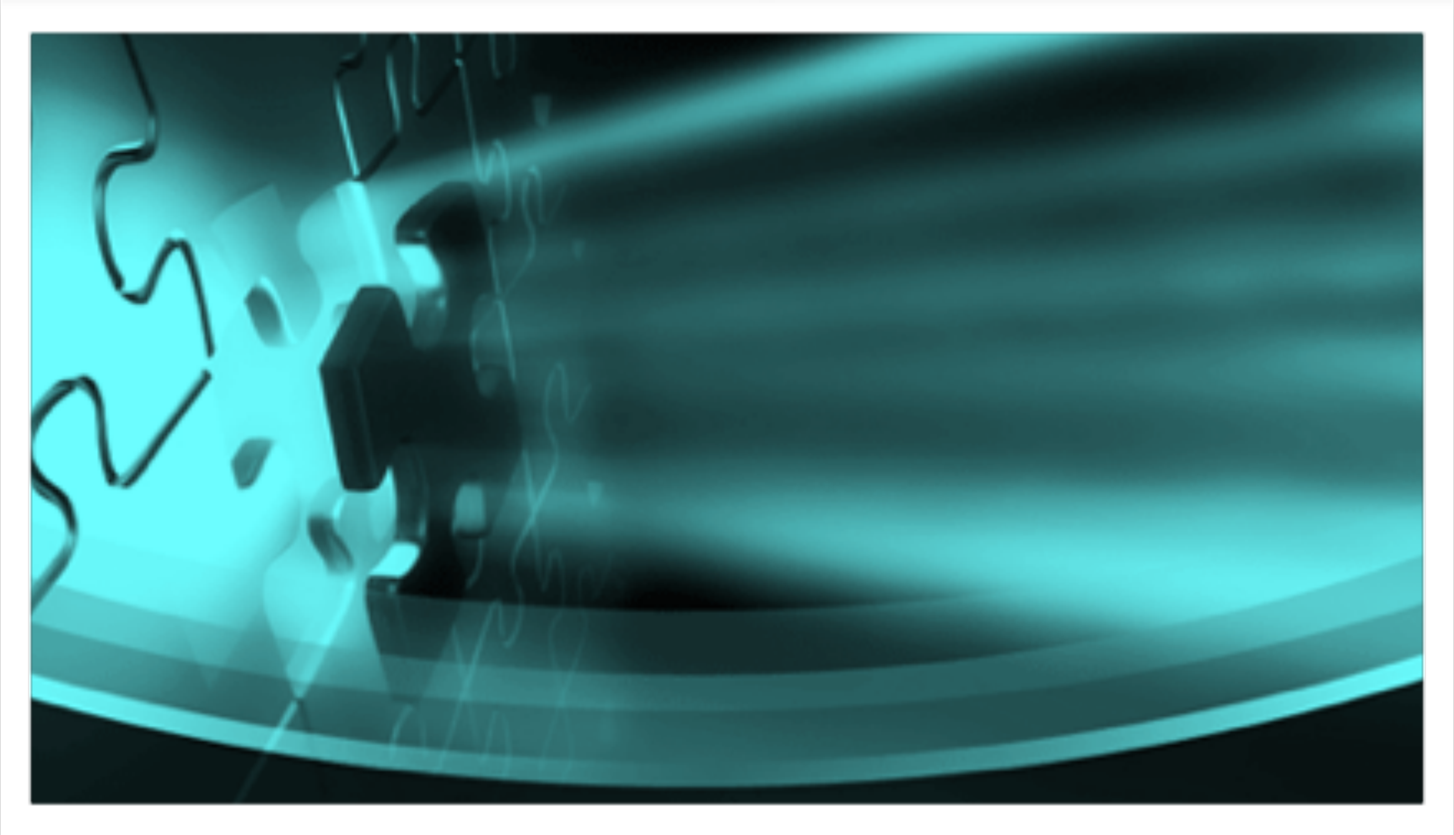
II. **Target for LHC**: Real-Time AAN's intelligent and self-organizing targeted to deal with EBs of data by 2020 (and ZBs, YBs as needed).

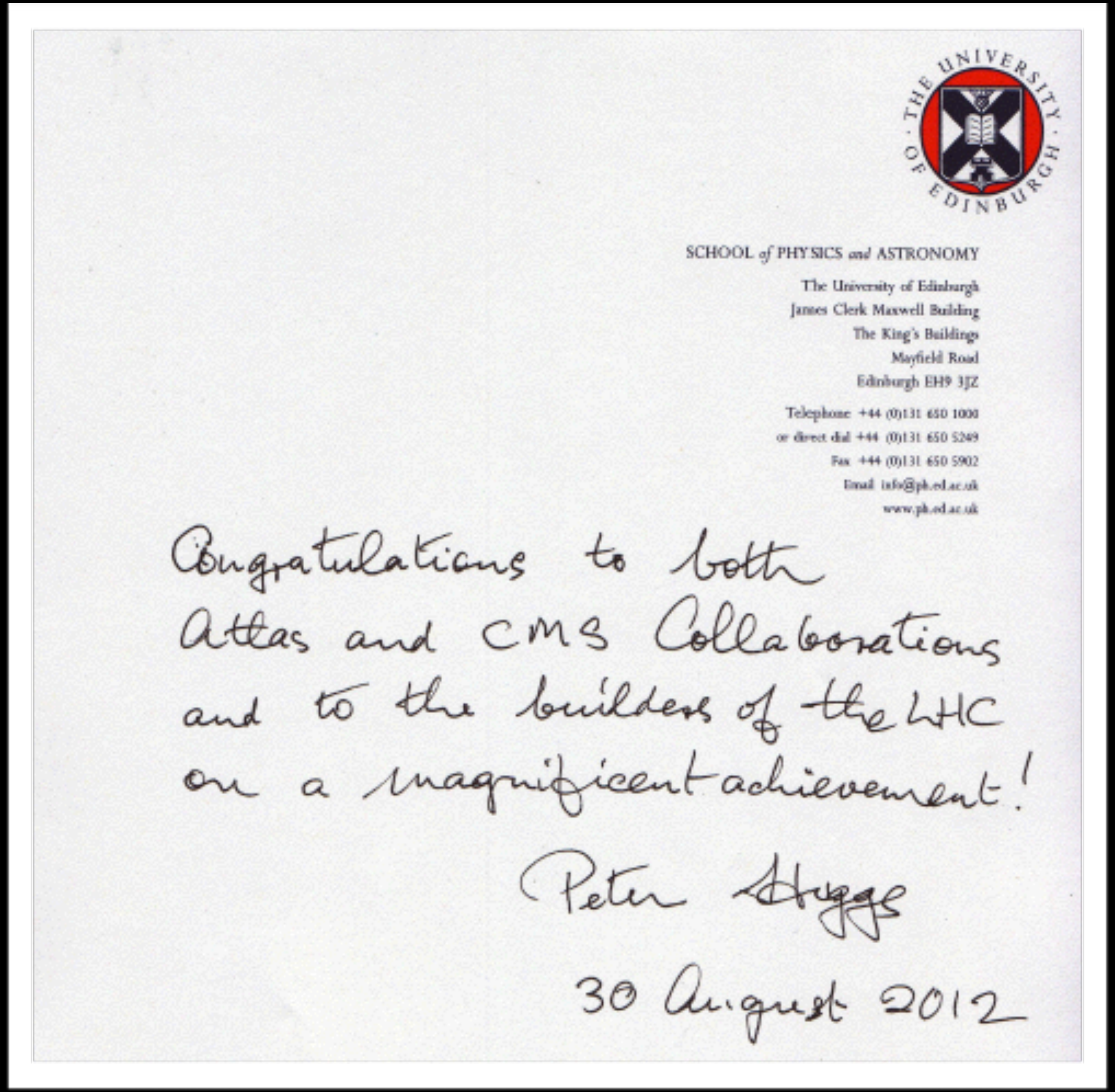
III. (big) **smart** data, **smart** networks

* MS nomenclature/semantics



EUREKA




SCHOOL *of* PHYSICS *and* ASTRONOMY

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Telephone +44 (0)131 650 1000
or direct dial +44 (0)131 650 5249
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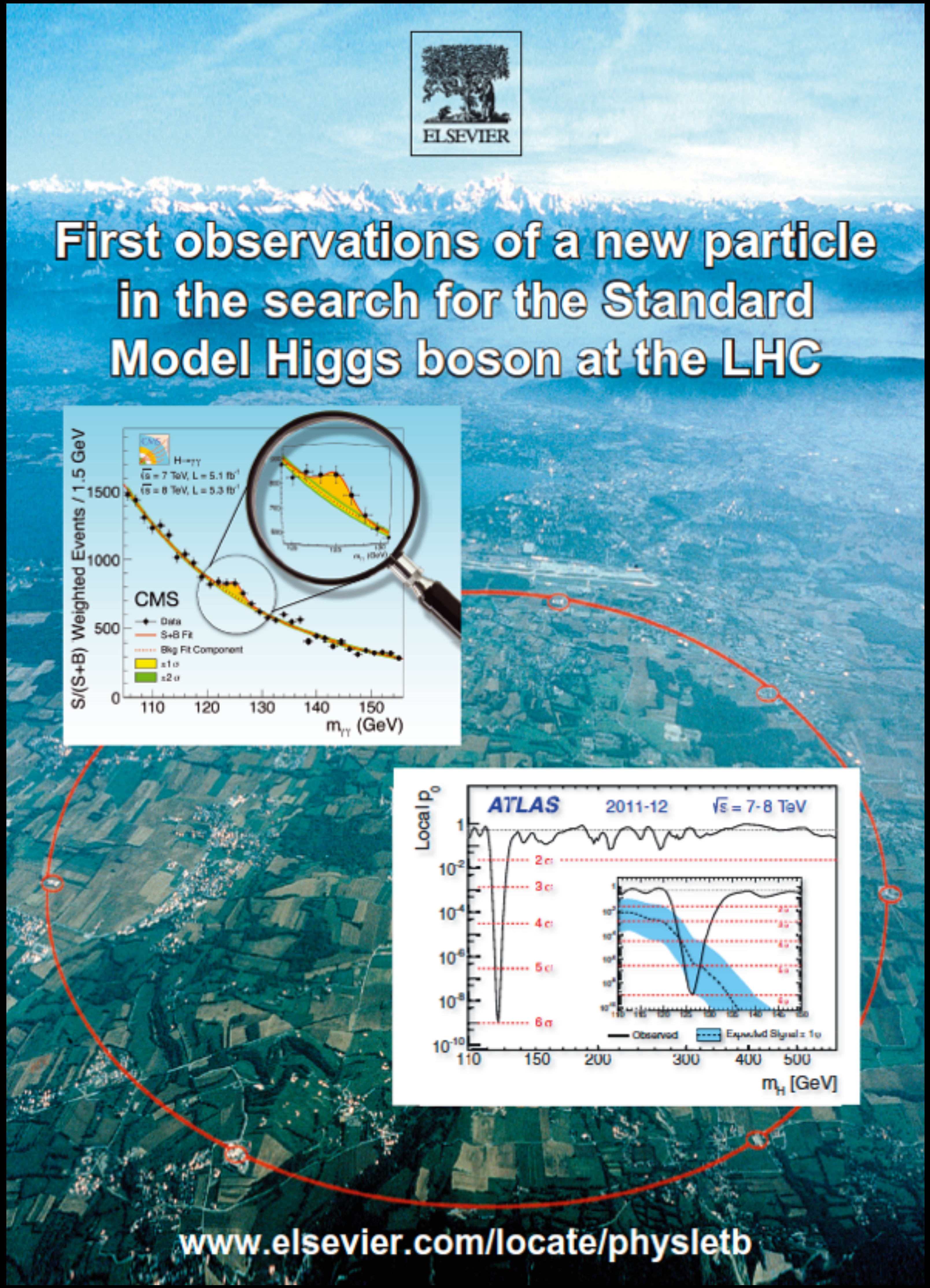
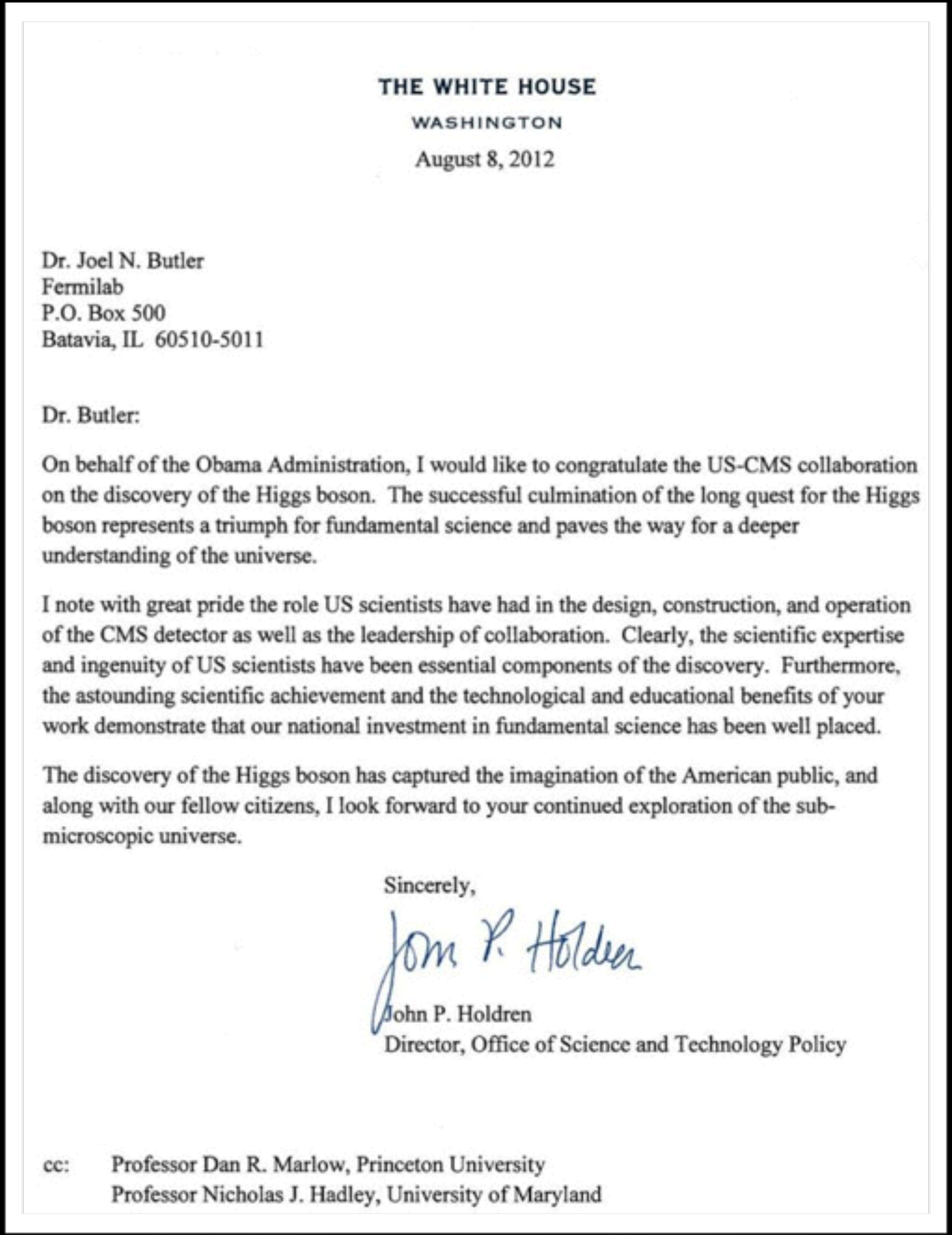
Email info@ph.ed.ac.uk
www.ph.ed.ac.uk

Congratulations to both
Atlas and CMS Collaborations
and to the builders of the LHC
on a magnificent achievement!

Peter Higgs

30 August 2012




THE WHITE HOUSE

WASHINGTON

August 8, 2012

Dr. Joel N. Butler
Fermilab
P.O. Box 500
Batavia, IL 60510-5011

Dr. Butler:

On behalf of the Obama Administration, I would like to congratulate the US-CMS collaboration on the discovery of the Higgs boson. The successful culmination of the long quest for the Higgs boson represents a triumph for fundamental science and paves the way for a deeper understanding of the universe.

I note with great pride the role US scientists have had in the design, construction, and operation of the CMS detector as well as the leadership of collaboration. Clearly, the scientific expertise and ingenuity of US scientists have been essential components of the discovery. Furthermore, the astounding scientific achievement and the technological and educational benefits of your work demonstrate that our national investment in fundamental science has been well placed.

The discovery of the Higgs boson has captured the imagination of the American public, and along with our fellow citizens, I look forward to your continued exploration of the sub-microscopic universe.

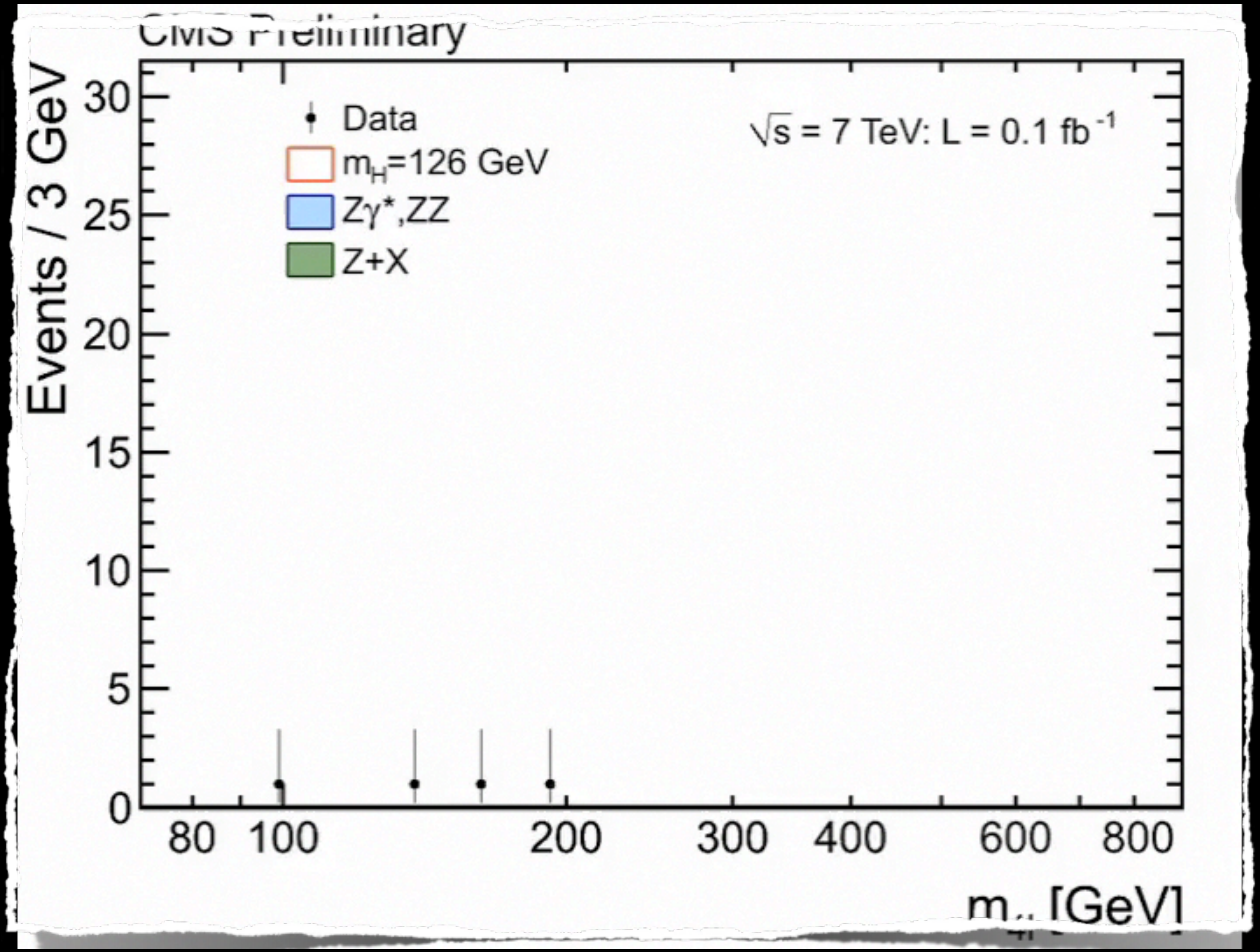
Sincerely,

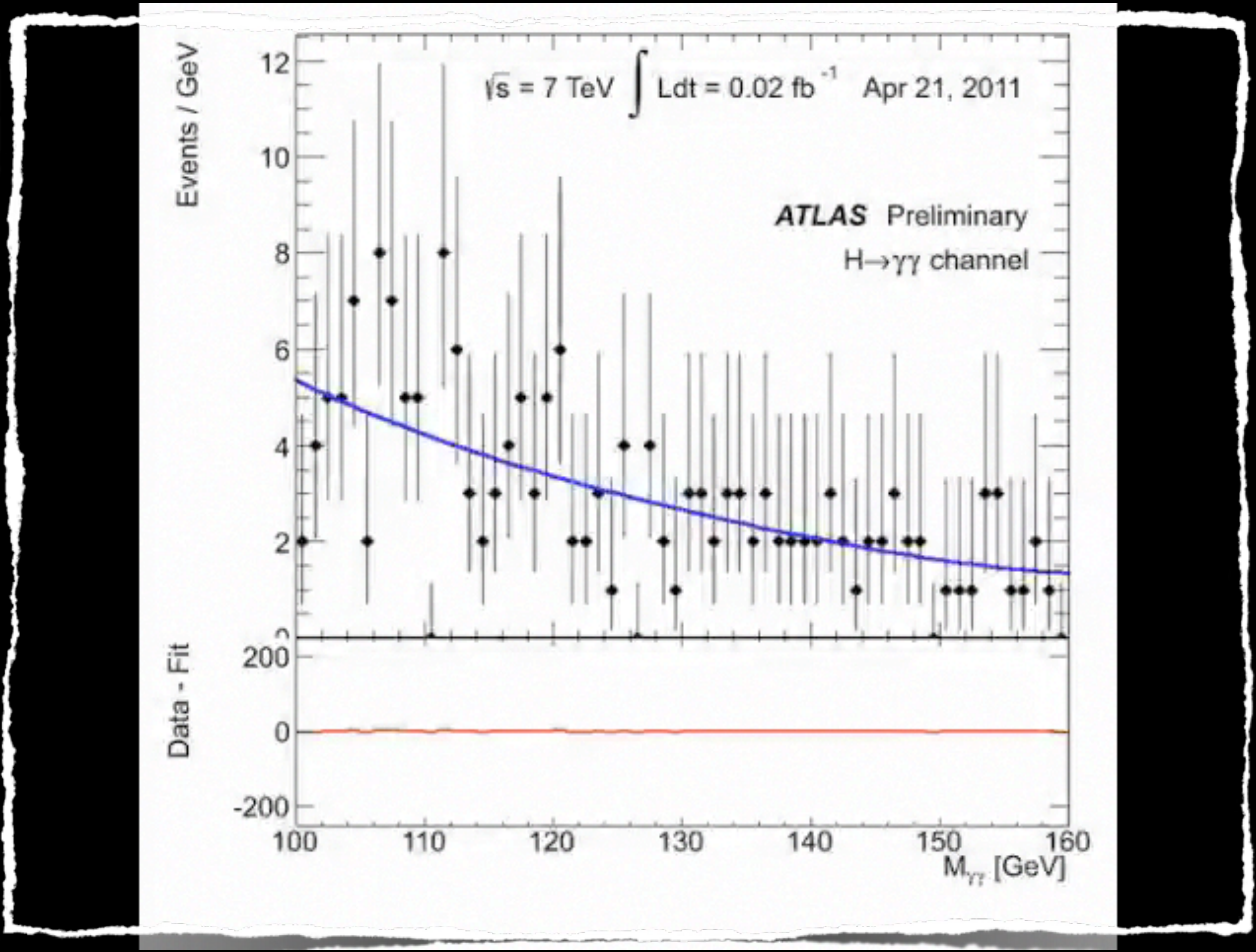
John P. Holdren

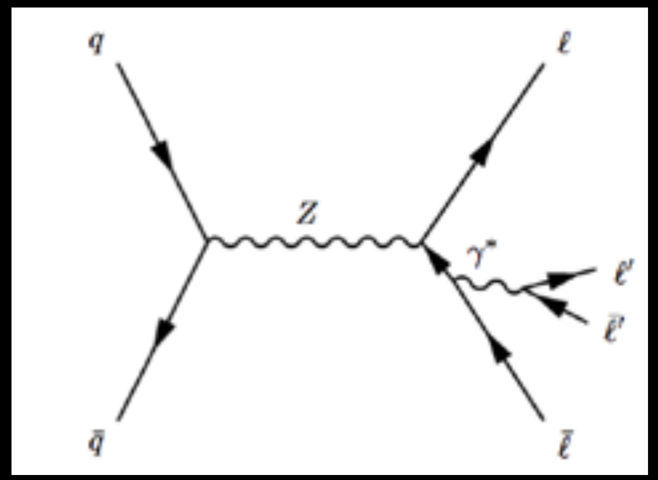
John P. Holdren
Director, Office of Science and Technology Policy

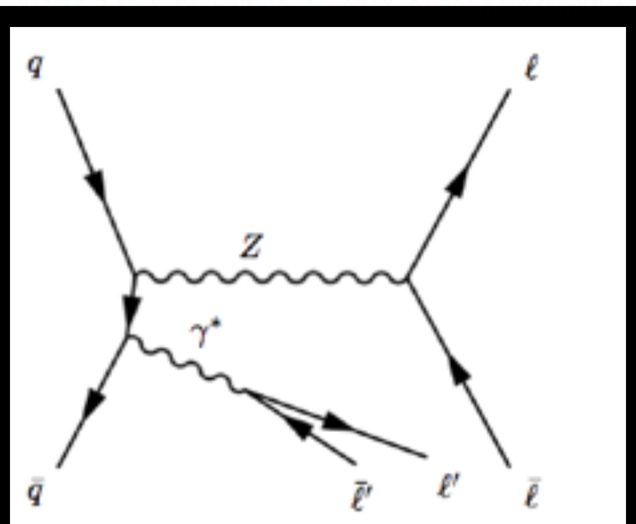
cc: Professor Dan R. Marlow, Princeton University
Professor Nicholas J. Hadley, University of Maryland

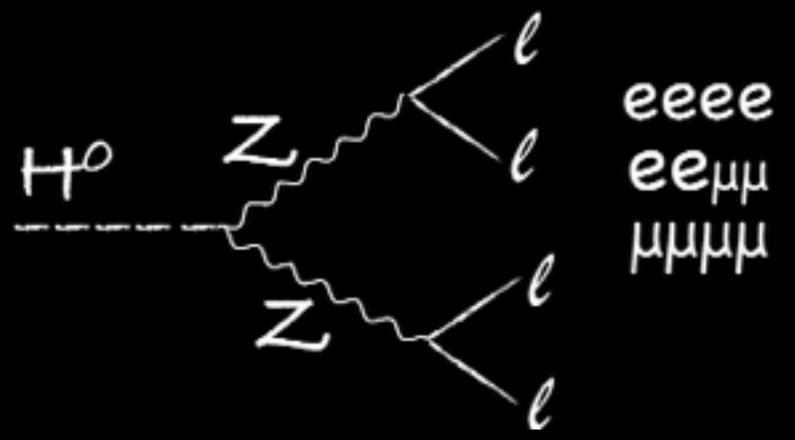
GOLDEN : 4-LEPTONS FROM HIGSS

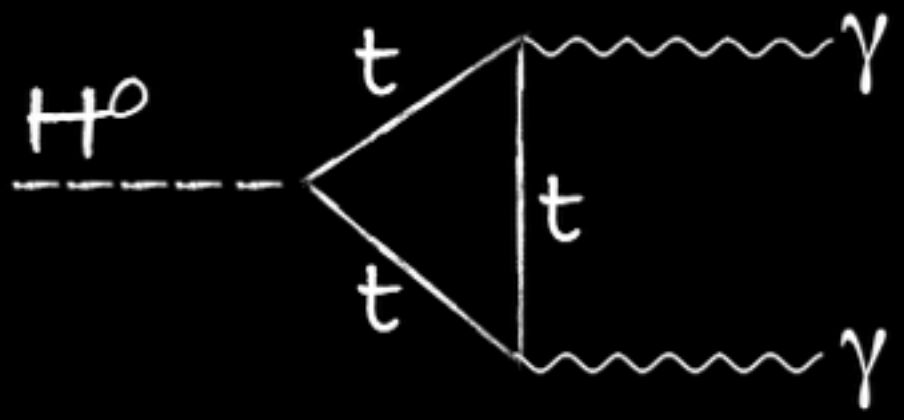












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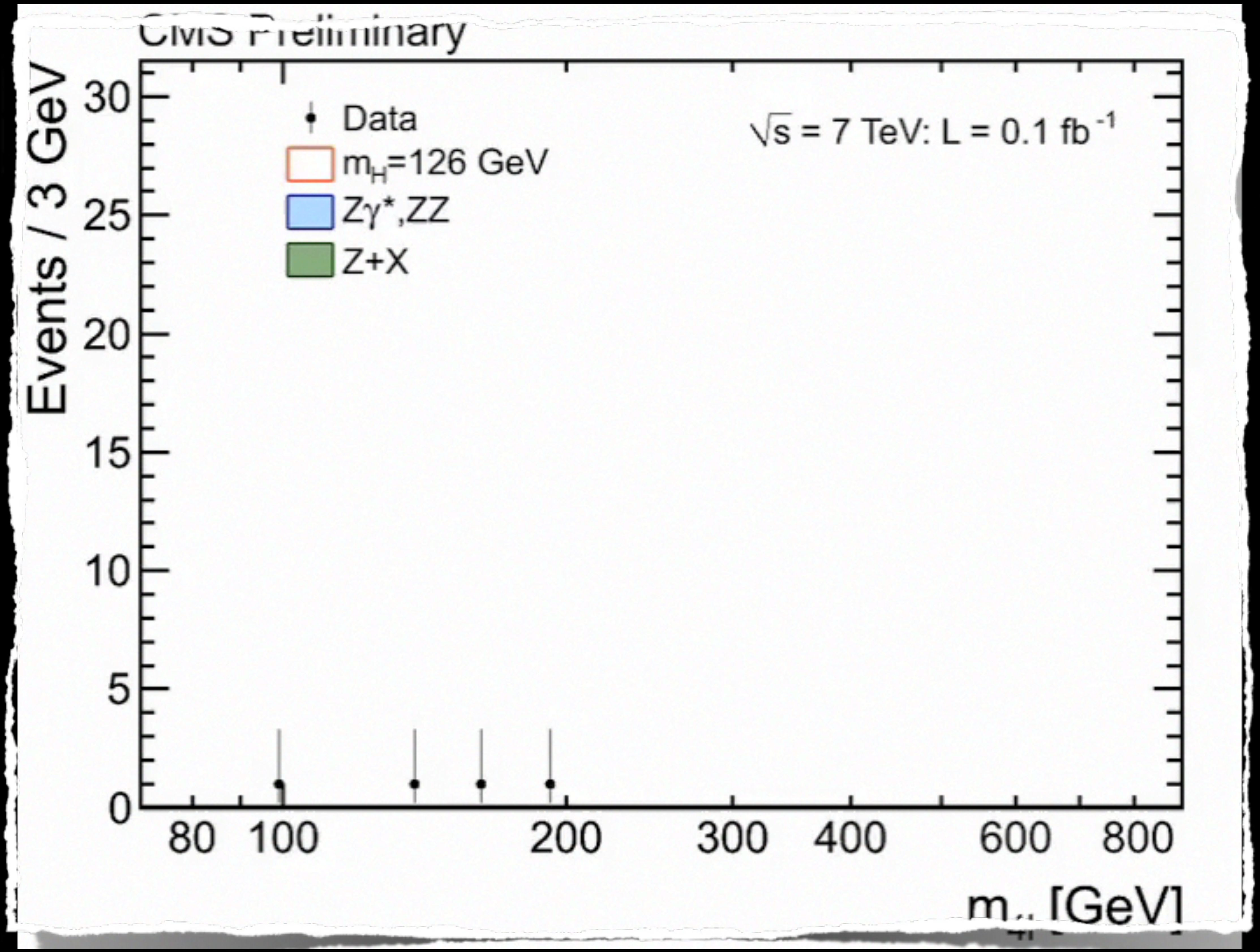

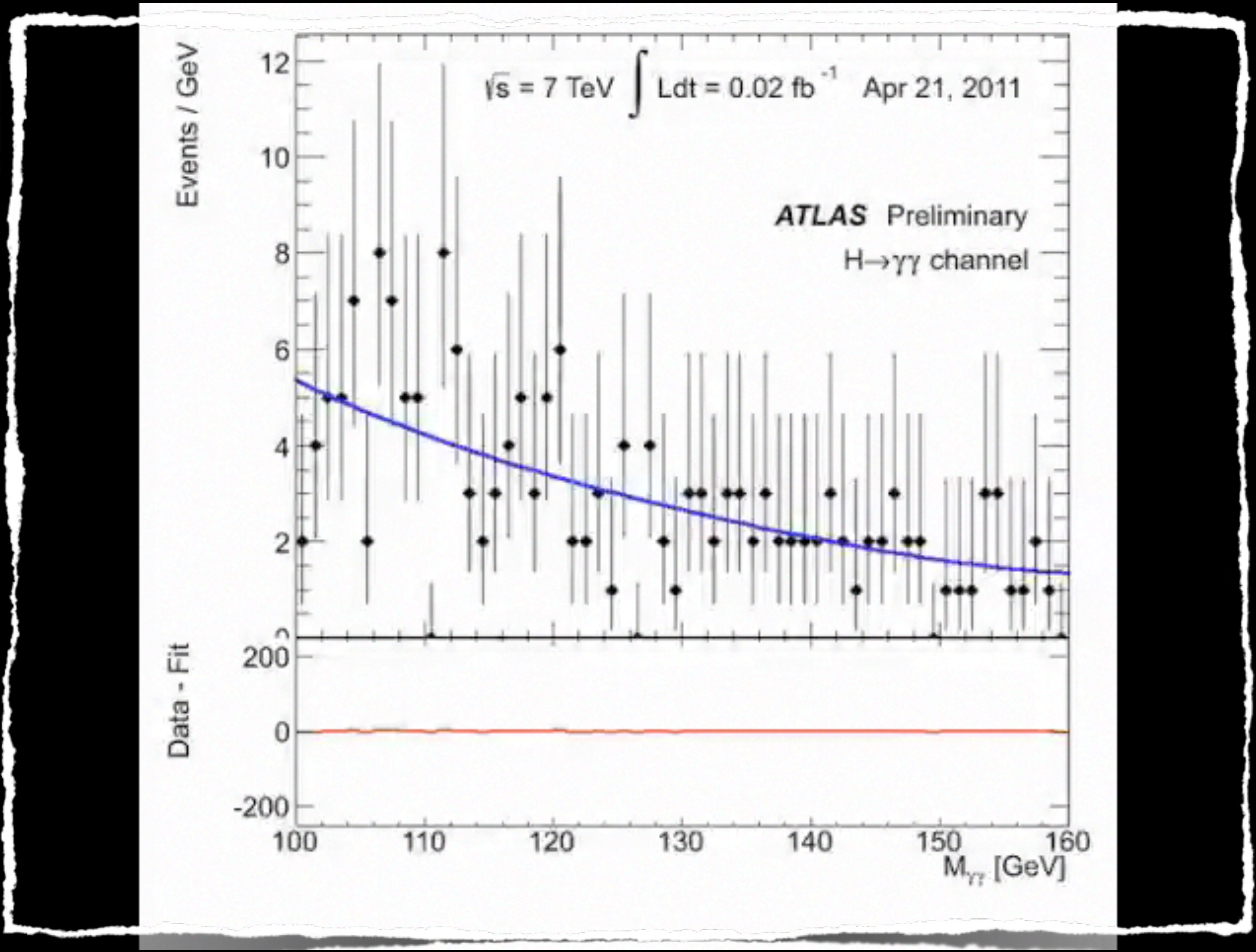

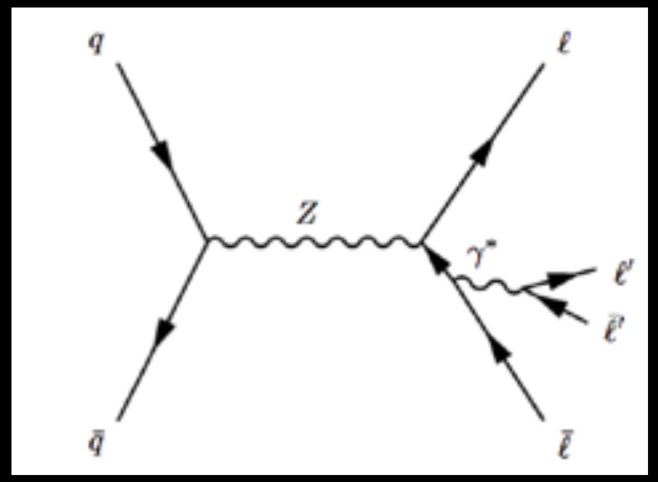

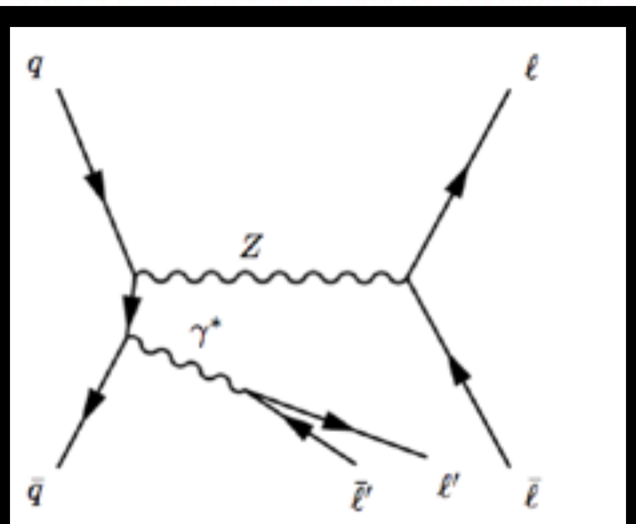

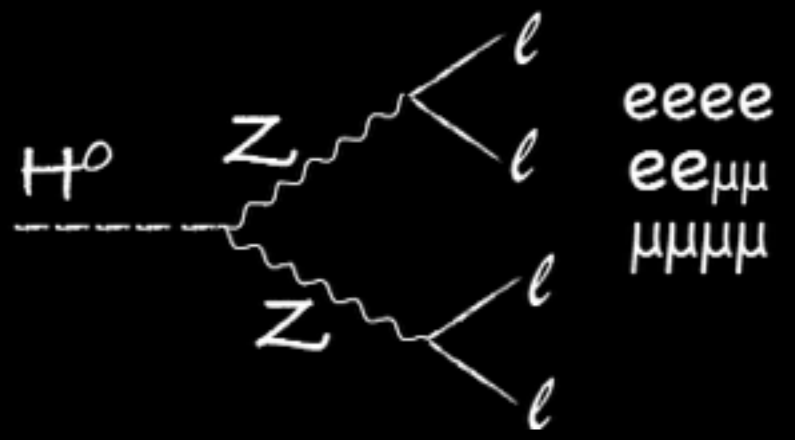

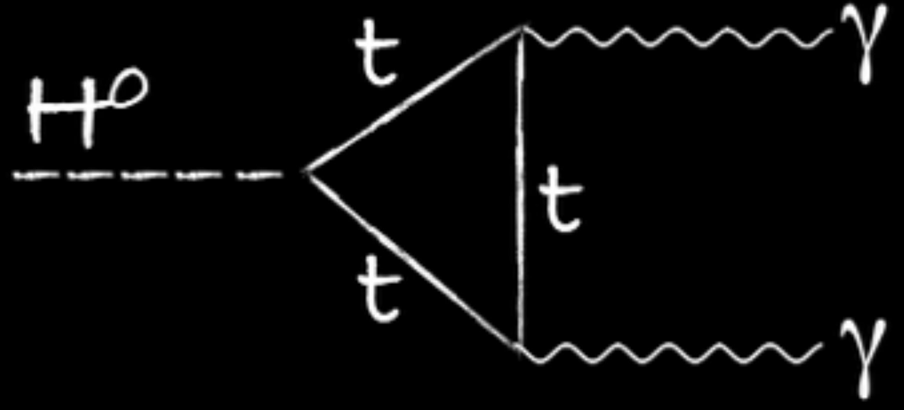

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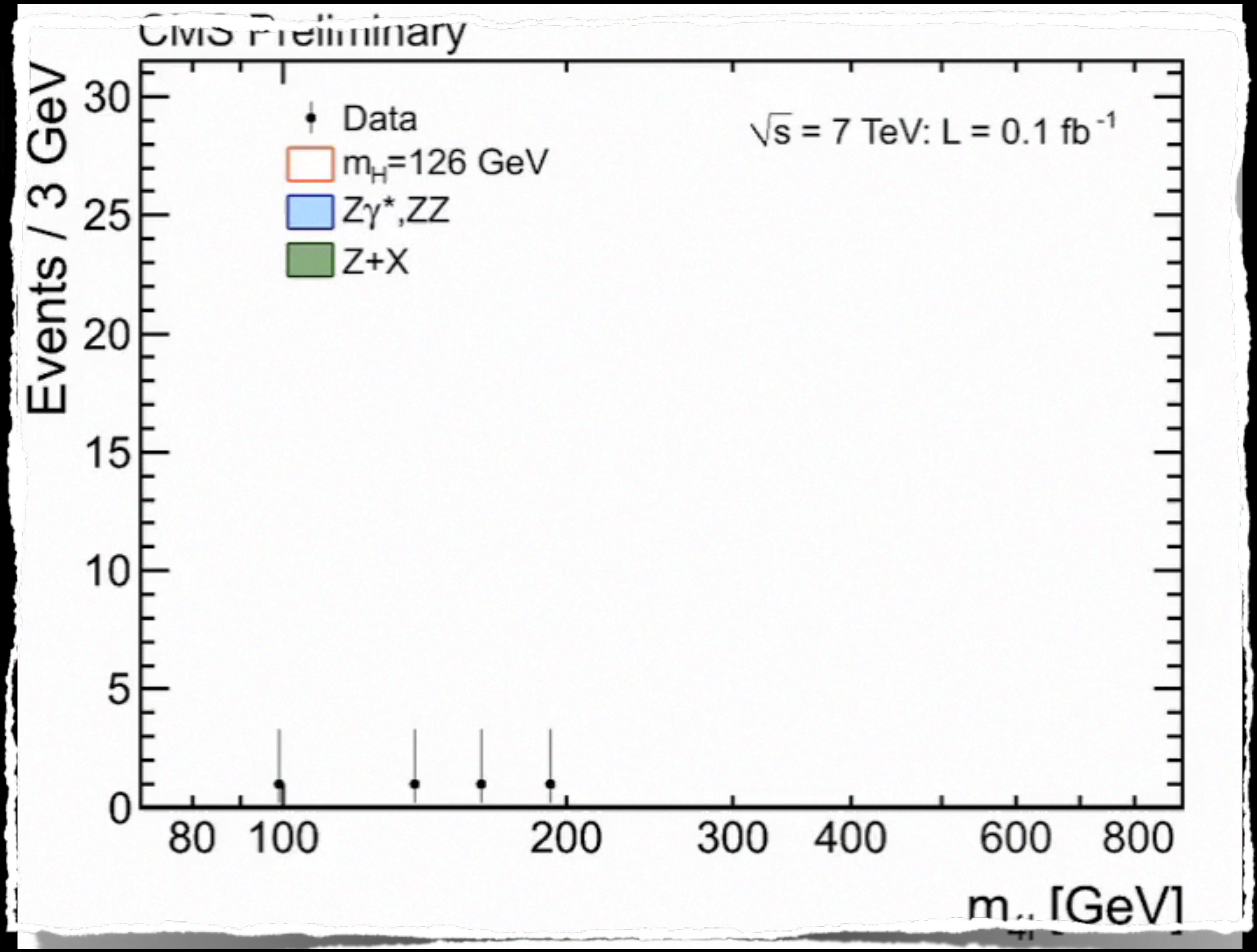
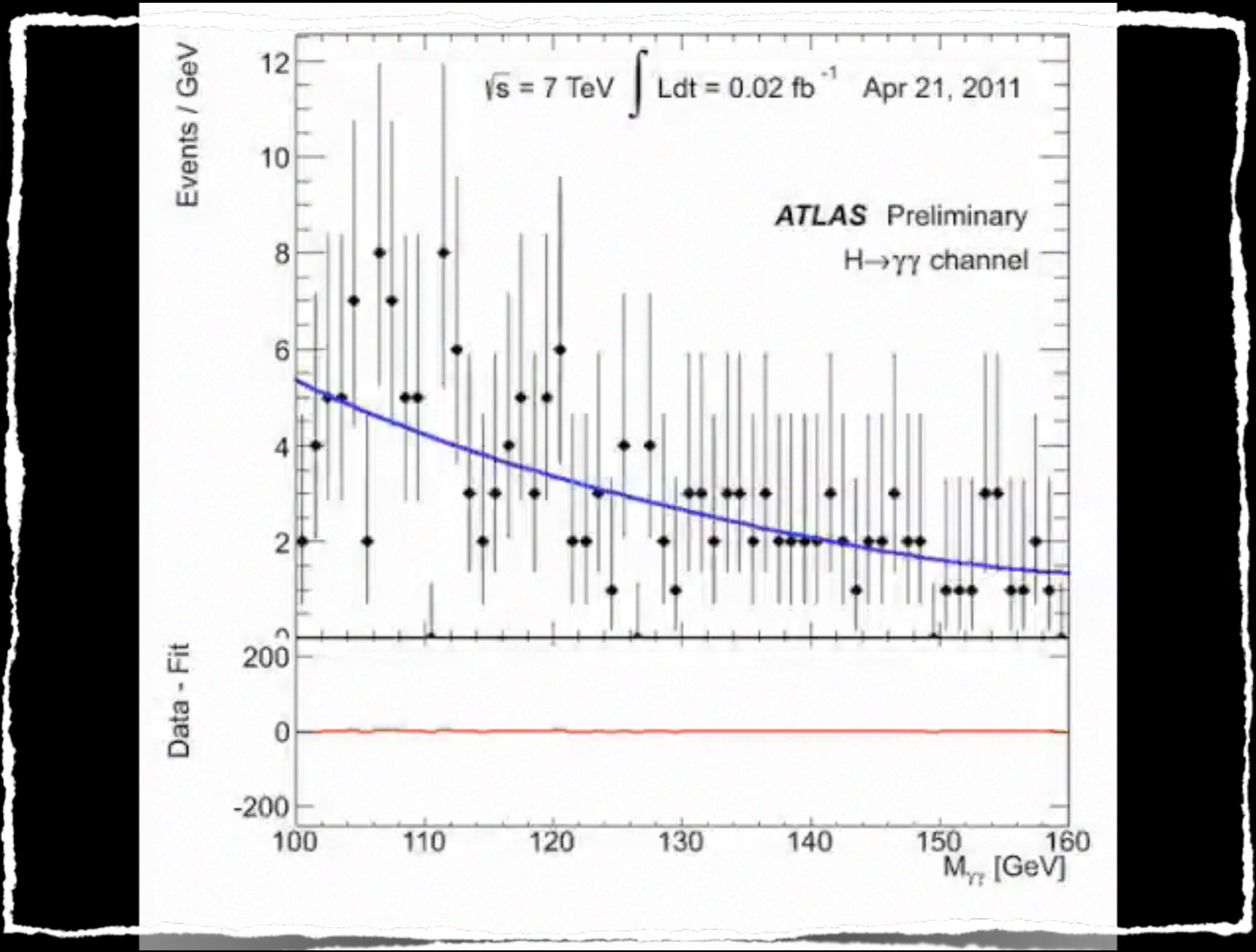
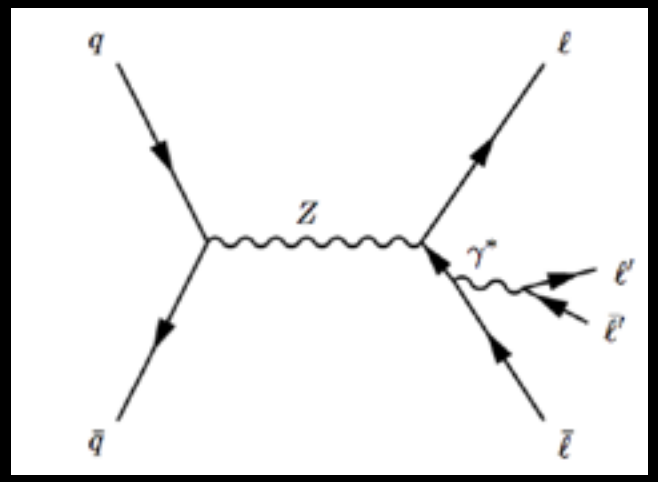
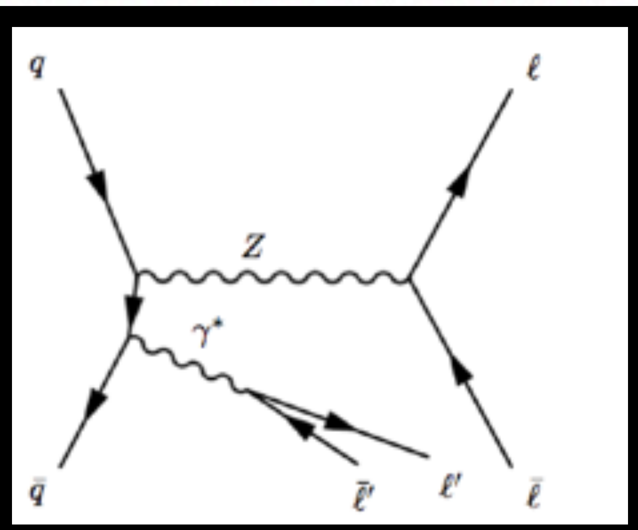
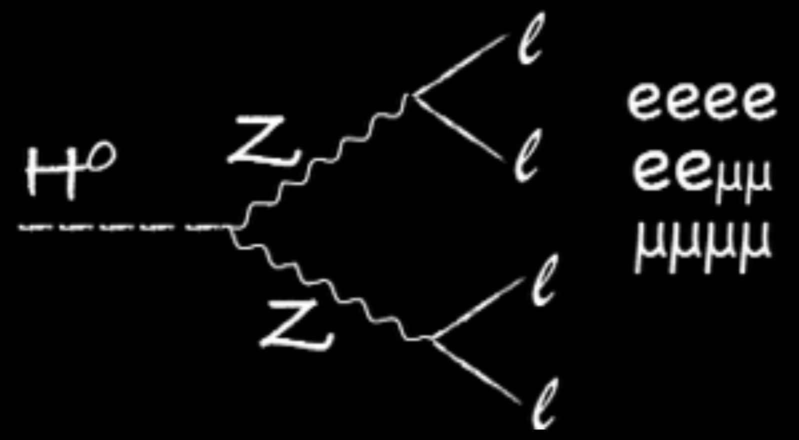
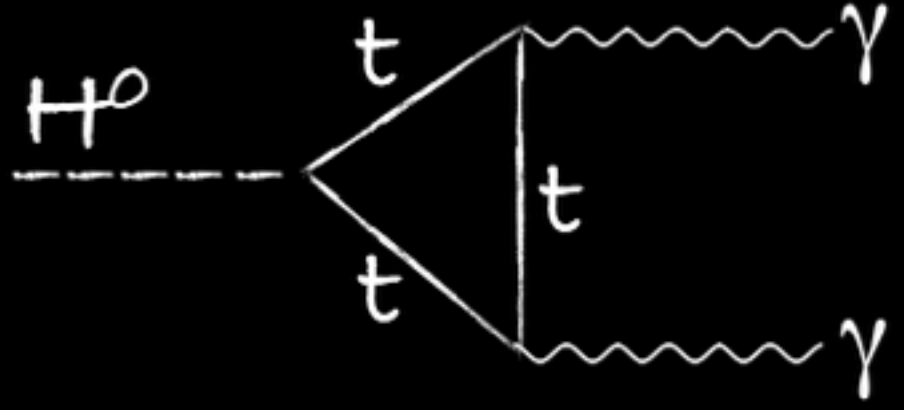


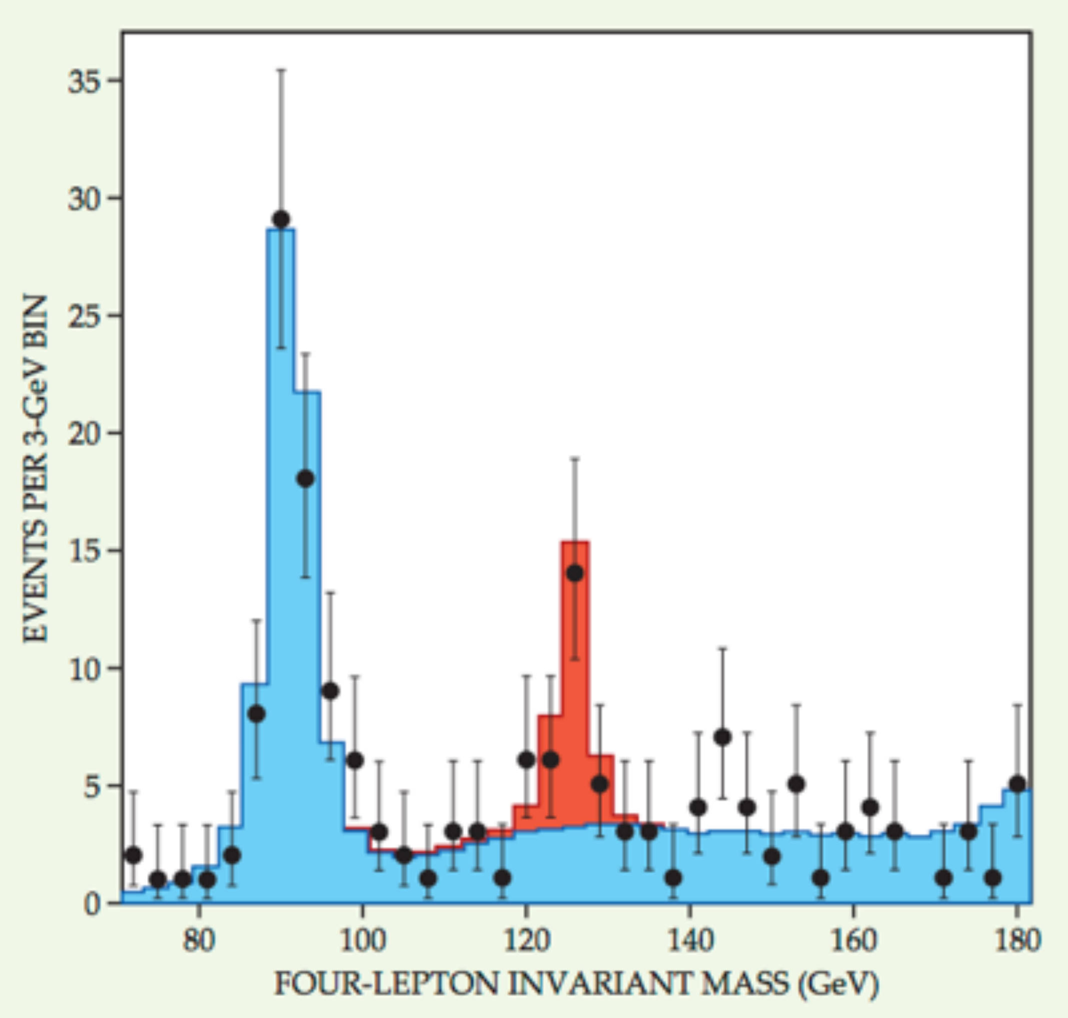


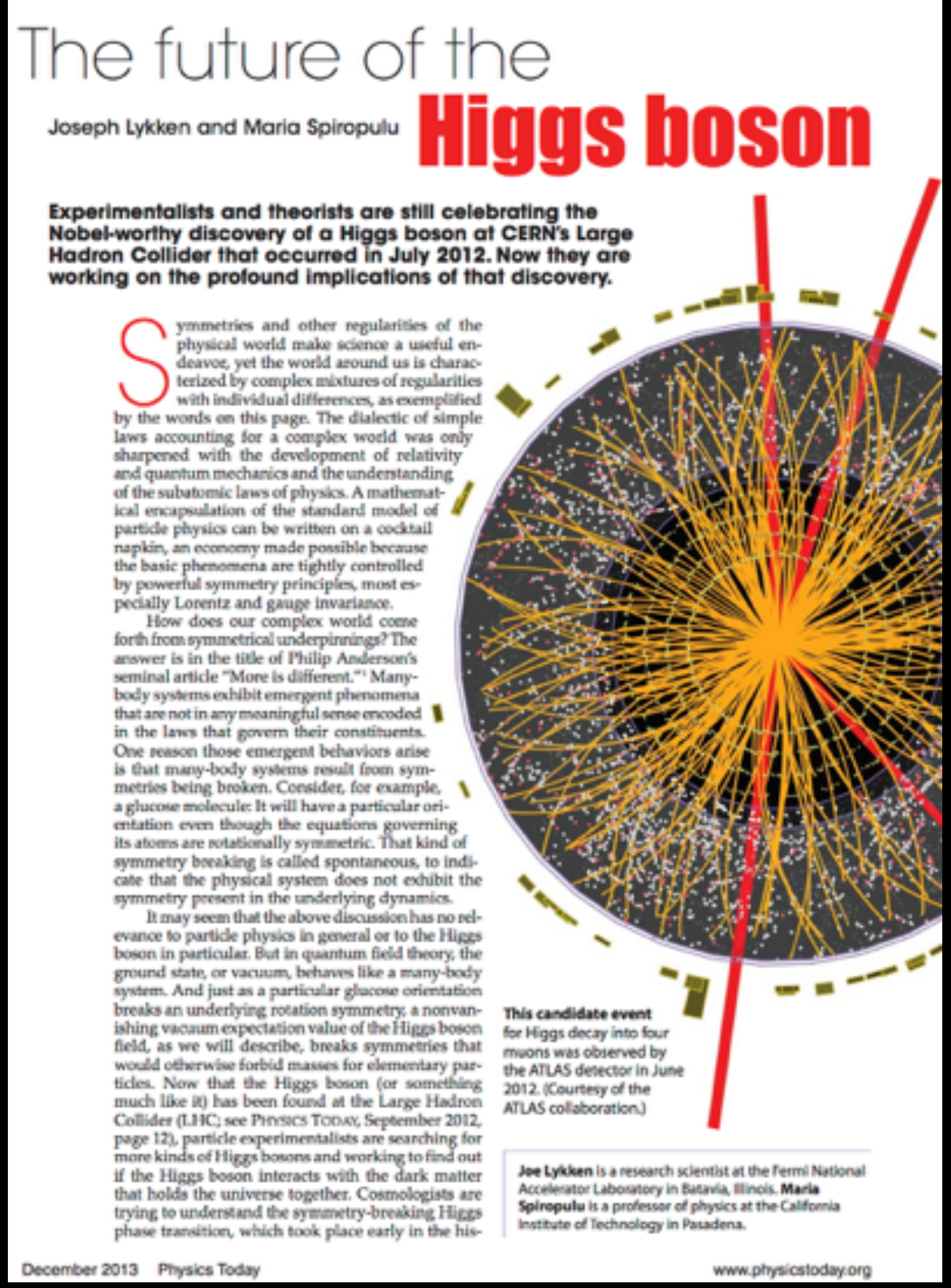












The future of the Higgs boson

Joseph Lykken and Maria Spiropulu

Experimentalists and theorists are still celebrating the Nobel-worthy discovery of a Higgs boson at CERN's Large Hadron Collider that occurred in July 2012. Now they are working on the profound implications of that discovery.

Symmetries and other regularities of the physical world make science a useful endeavor, yet the world around us is characterized by complex mixtures of regularities with individual differences, as exemplified by the words on this page. The dialectic of simple laws accounting for a complex world was only sharpened with the development of relativity and quantum mechanics and the understanding of the subatomic laws of physics. A mathematical encapsulation of the standard model of particle physics can be written on a cocktail napkin, an economy made possible because the basic phenomena are tightly controlled by powerful symmetry principles, most especially Lorentz and gauge invariance.

How does our complex world come forth from symmetrical underpinnings? The answer is in the title of Philip Anderson's seminal article "More is different."[1] Many-body systems exhibit emergent phenomena that are not in any meaningful sense encoded in the laws that govern their constituents. One reason those emergent behaviors arise is that many-body systems result from symmetries being broken. Consider, for example, a glucose molecule: It will have a particular orientation even though the equations governing its atoms are rotationally symmetric. That kind of symmetry breaking is called spontaneous, to indicate that the physical system does not exhibit the symmetry present in the underlying dynamics.

It may seem that the above discussion has no relevance to particle physics in general or to the Higgs boson in particular. But in quantum field theory, the ground state, or vacuum, behaves like a many-body system. And just as a particular glucose orientation breaks an underlying rotation symmetry, a nonvanishing vacuum expectation value of the Higgs boson field, as we will describe, breaks symmetries that would otherwise forbid masses for elementary particles. Now that the Higgs boson (or something much like it) has been found at the Large Hadron Collider (LHC; see PHYSICS TODAY, September 2012, page 12), particle experimentalists are searching for more kinds of Higgs bosons and working to find out if the Higgs boson interacts with the dark matter that holds the universe together. Cosmologists are trying to understand the symmetry-breaking Higgs phase transition, which took place early in the his-

This candidate event for Higgs decay into four muons was observed by the ATLAS detector in June 2012. (Courtesy of the ATLAS collaboration.)

Joe Lykken is a research scientist at the Fermi National Accelerator Laboratory in Batavia, Illinois. **Maria Spiropulu** is a professor of physics at the California Institute of Technology in Pasadena.

December 2013 Physics Today www.physicstoday.org

HIGGS

ORIGINS

&

CONNECTIONS

SYMMETRY BREAKING AND COMPLEXITY

Nambu (1960)

The importance of Spontaneous Symmetry Breaking

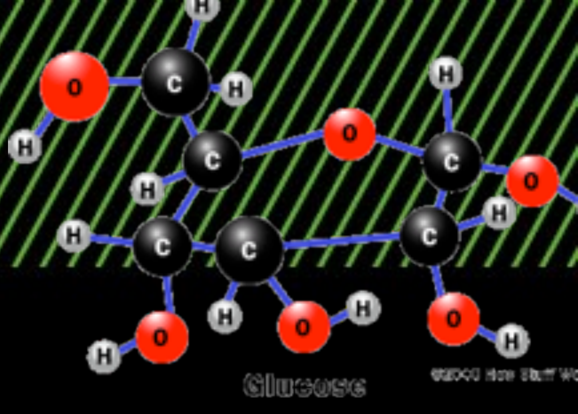
Nobel Lecture: Spontaneous symmetry breaking in particle physics: A case of cross fertilization*

Yoichiro Nambu

Physical system	Broken symmetry
Ferromagnets	Rotational invariance (with respect to spin)
Crystals	Translational and rotational invariance (modulo discrete values)
Superconductors	Local gauge invariance (particle number)

- Apply condensed matter ideas to **particle physics**
- **Now the quantum vacuum is the "medium"**

SYMMETRY BREAKING AND COMPLEXITY



Nambu (1960)
The importance of Spontaneous Symmetry Breaking

Nobel Lecture: Spontaneous symmetry breaking in particle physics: A case of cross fertilization*

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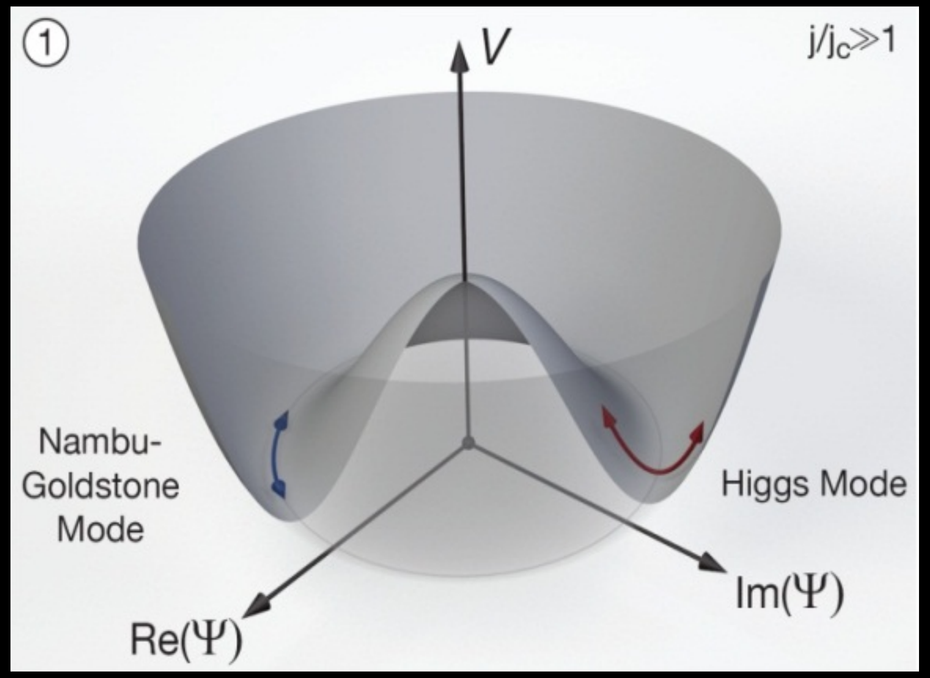
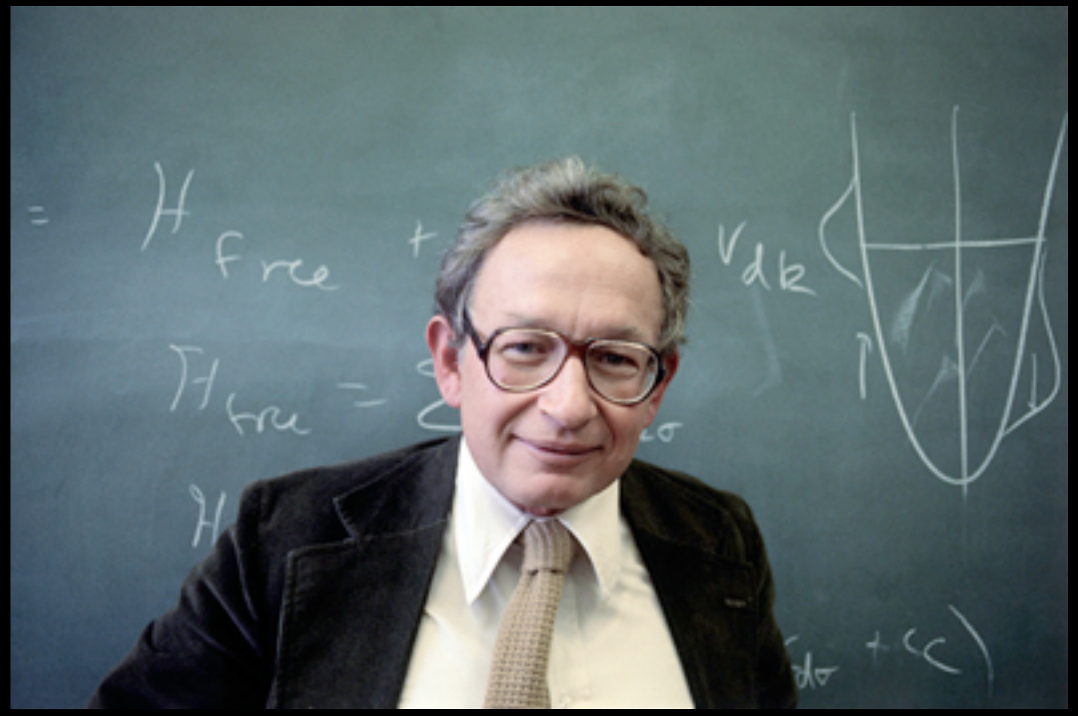
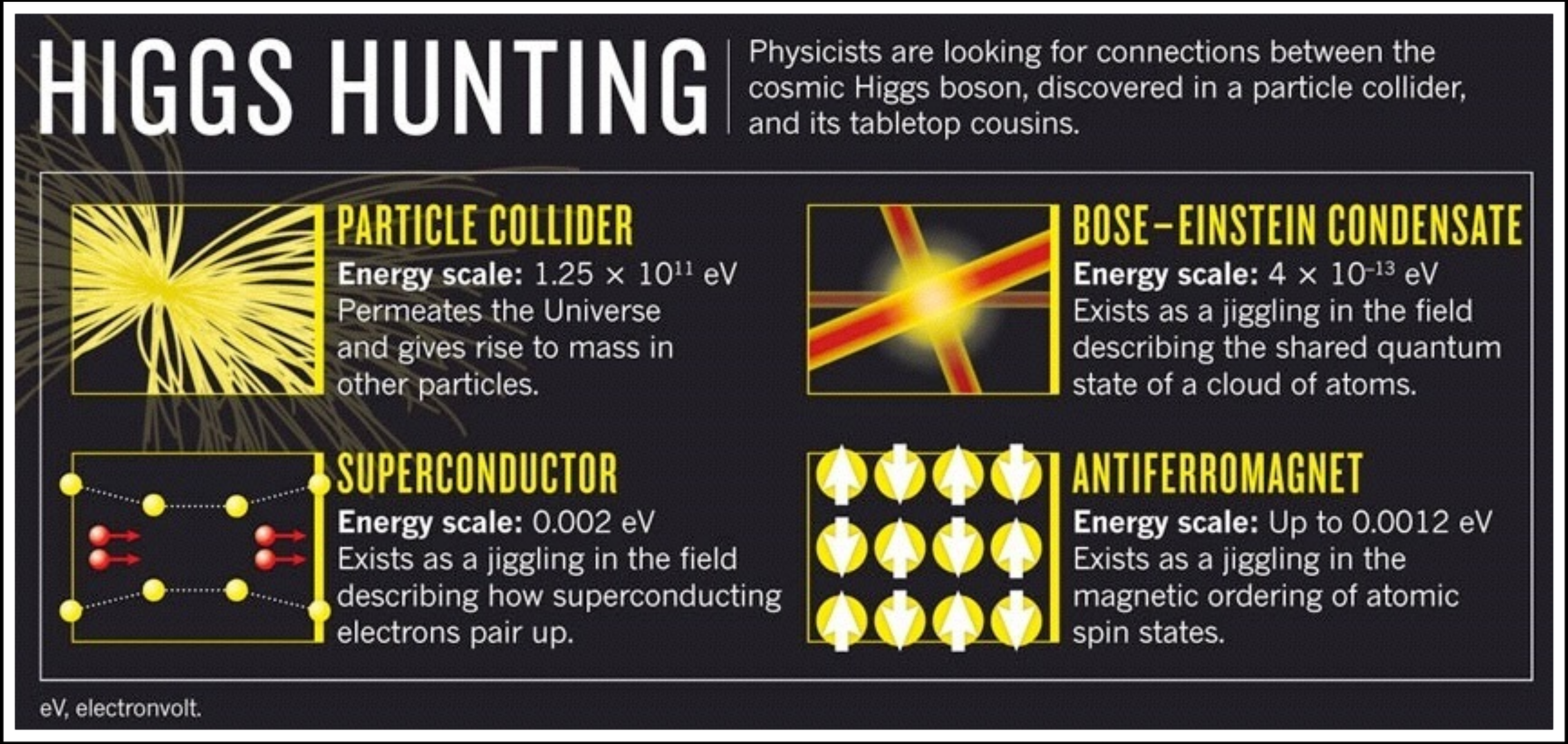




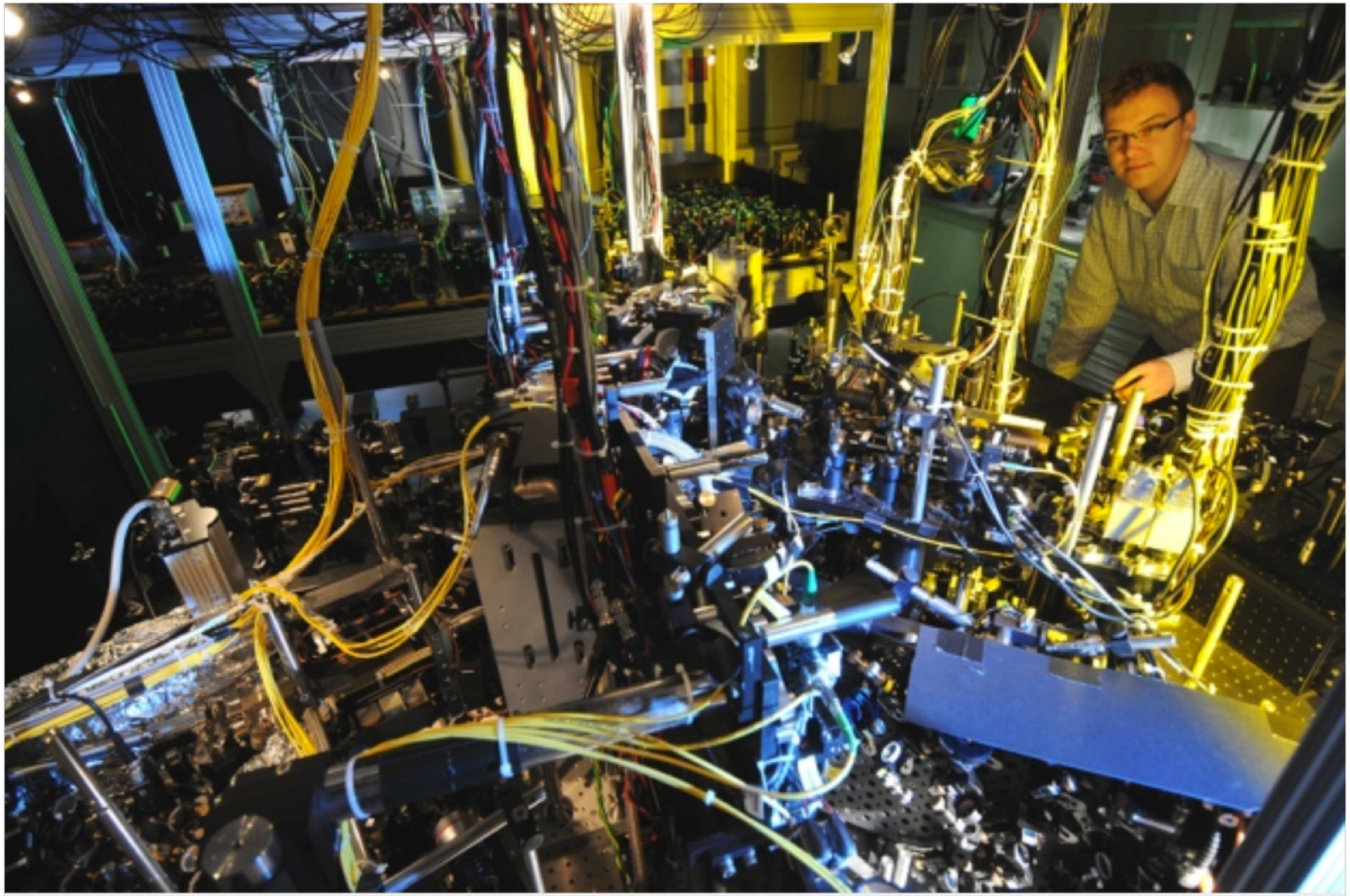
- The key difference is that in quantum field theory it is much more difficult to transition from one one degenerate ground state to another
- ***The quantum vacuum*** is like a many-body system in this sense
- As Phillip Anderson emphasized in his 1972 article "More is Different", spontaneous symmetry breaking is a property of "large" systems

SYMMETRY BREAKING DYNAMICS



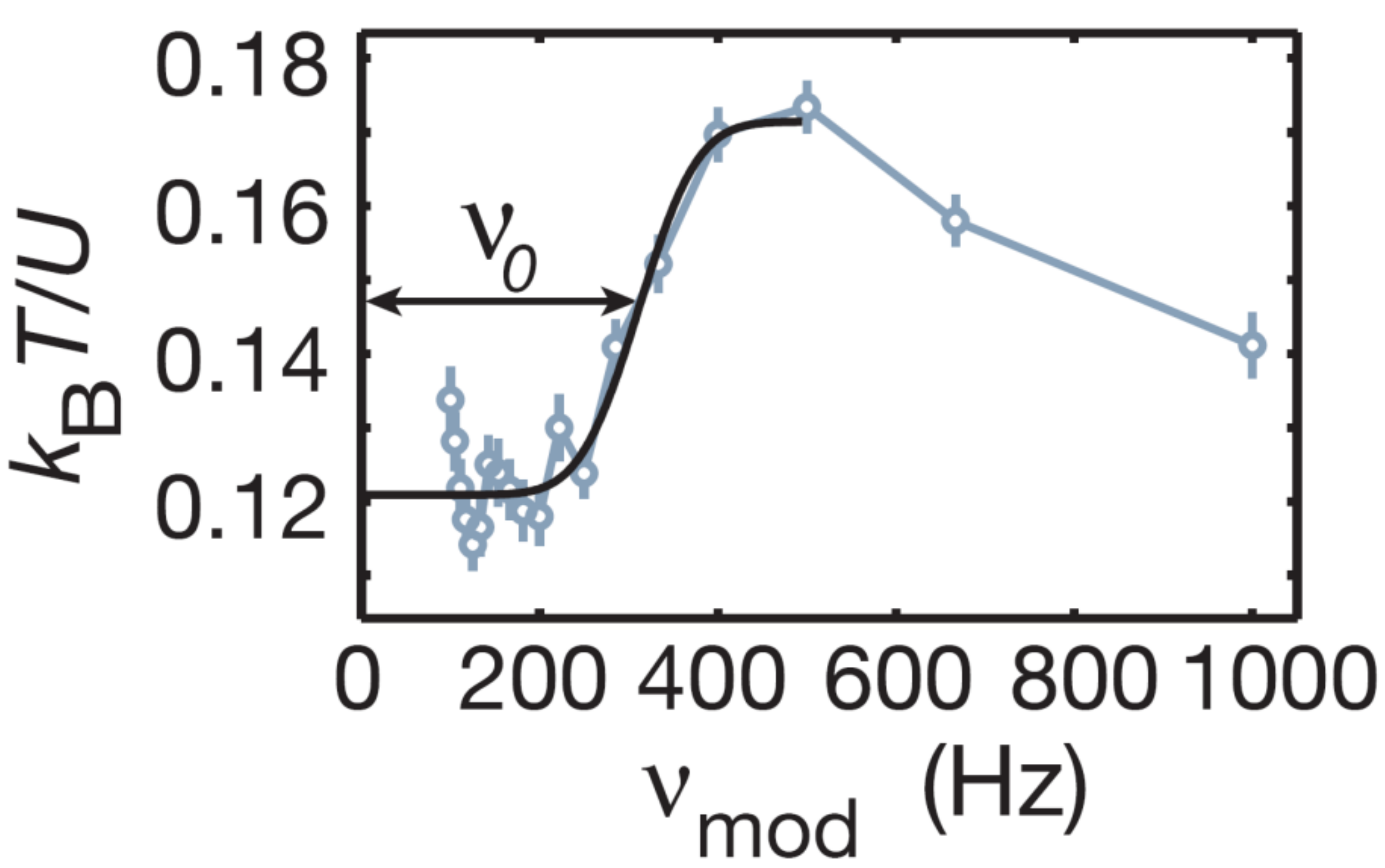
Peter Littlewood and Chandra Varma discovered “light” Higgs bosons in niobium-selenide superconductors, 1981

HIGGS MODES AT PHASE TRANSITIONS



Physicists have found Higgs-like particles in a superfluid at the Max Planck Institute in Munich, Germany.

THORSTEN NAESER/MPQ



SUSY-PARTNERS = THE OTHER SPIN PARTNER

(Electron in superspace) = superelectron (spin 0) + electron (spin1/2)

- **Supersymmetry (with the additional assumption of soft breaking at the TeV scale) has been the dominant BSM framework for the past 27 years.**
- **One reason is simply that SUSY is a comprehensive framework that is both calculable and predictive, making it possible to write > 20,000 papers.**
- **Another reason is that SUSY has many attractive theoretical properties, most especially that it suppresses quantum corrections, and is a space-time symmetry rather than an ad-hoc postulation of extra degrees of freedom and "internal" symmetries.**

SUSY–PARTNERS = THE OTHER SPIN PARTNER

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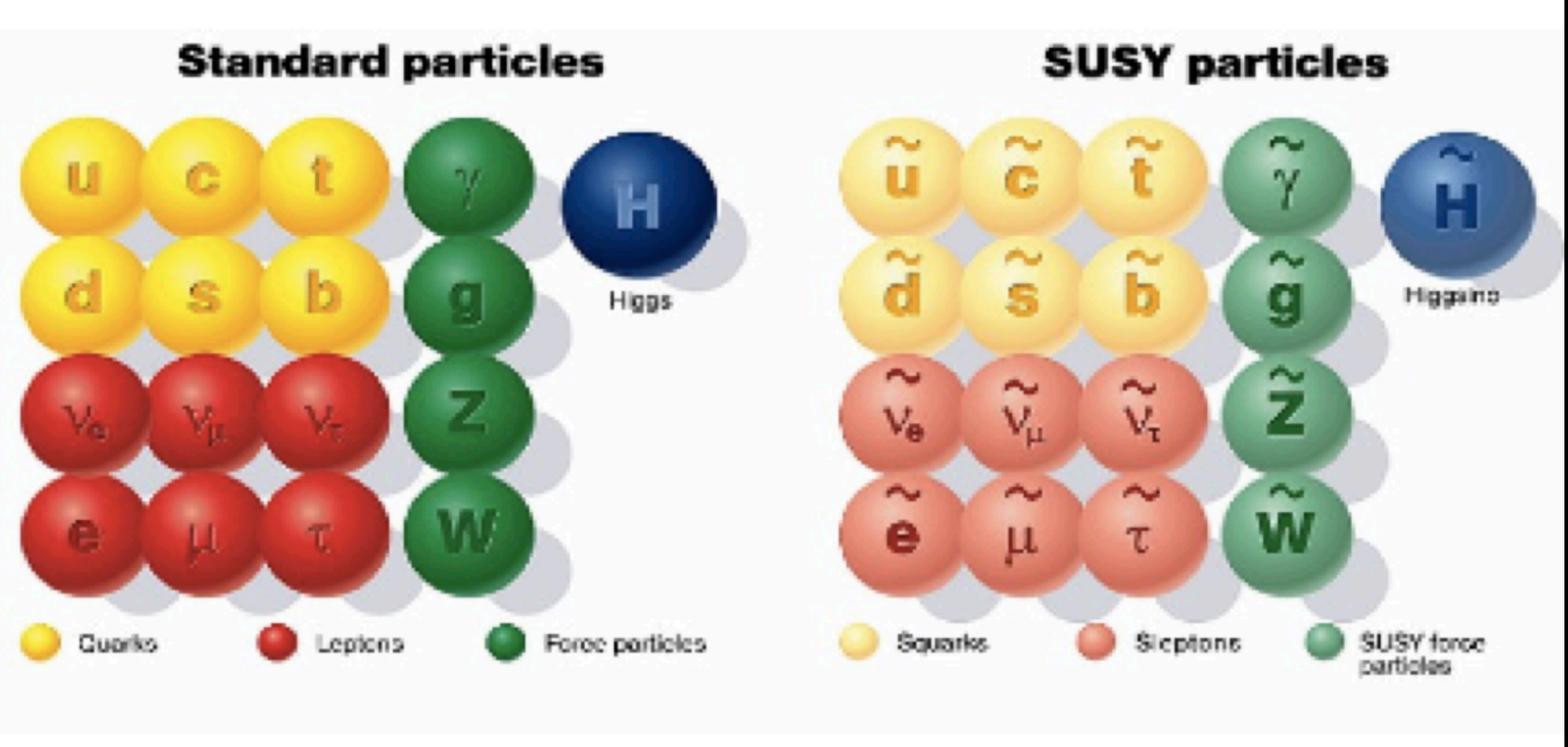


SUSY-PARTNERS = THE OTHER SPIN PARTNER

(Electron in superspace) = superelectron (spin 0) + electron (spin1/2)

Particles and Superpartners

Particle	Spin	*Name*	*Feels These Forces*[a]	*Mediates These Forces*[b]	*Superpartner*	Spin	*SUGRA Mass Range [Atlas Lower Limit](Gev)*
e, μ, τ	1/2	charged leptons (electron, muon, tau)	EM, W	—	sleptons $\tilde{e}, \tilde{\mu}, \tilde{\tau}$ (selectron, smuon, stau)	0	157 - 491 , [$\tilde{\tau}$ > 136]
ν_e, ν_μ, ν_τ	1/2	neutrinos	W	—	sneutrinos $\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	0	230 - 486 , [$\tilde{\nu}_\tau$ > 1320]
u, c, t	1/2	up, charm, top quarks	EM, W, S	—	squarks $\tilde{u}, \tilde{c}, \tilde{t}$	0	312 - 960 , [$\tilde{t}$ > 310] [$\tilde{q}$ > 1400]
d, s, b	1/2	down, strange, bottom quarks	EM, W, S	—	squarks $\tilde{d}, \tilde{s}, \tilde{b}$	0	281 - 964 , [$\tilde{b}$ > 390] [$\tilde{q}$ > 1400]
G	2	graviton	GR	GR	gravitino $\tilde{G}$	3/2	
$W^\pm$	1	weak boson	EM, W	W	Wino[d] $\tilde{W}^\pm$	1/2	97 - 741 , [$\tilde{\chi}_1^\pm$ > 250]
Z	1	weak boson	W	W	Zino[d] $\tilde{Z}$	1/2	45 - 744 , [$\tilde{\chi}_1^0$ > 300]
γ	1	photon	[c]	EM	photino[d] $\tilde{\gamma}$	1/2	45 - 744 , [$\tilde{\chi}_1^0$ > 300]
g	1	gluon	S	S	gluino $\tilde{g}$	1/2	300 - 1009 , [$\tilde{g}$ > 1770]
h	0	Higgs boson[e]	W	generates mass	higgsino[e] $\tilde{h}$	1/2	68 - 1024

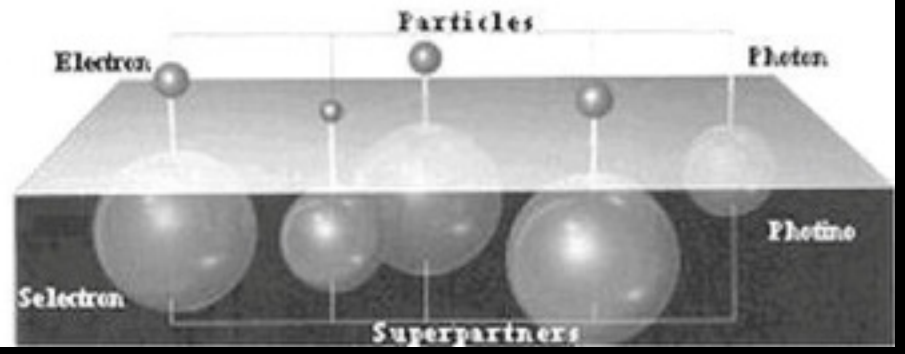
[a] All particles feel the gravitational force.

[b] EM = electromagnetic force, W = weak force, S = strong force, GR = gravitational force.

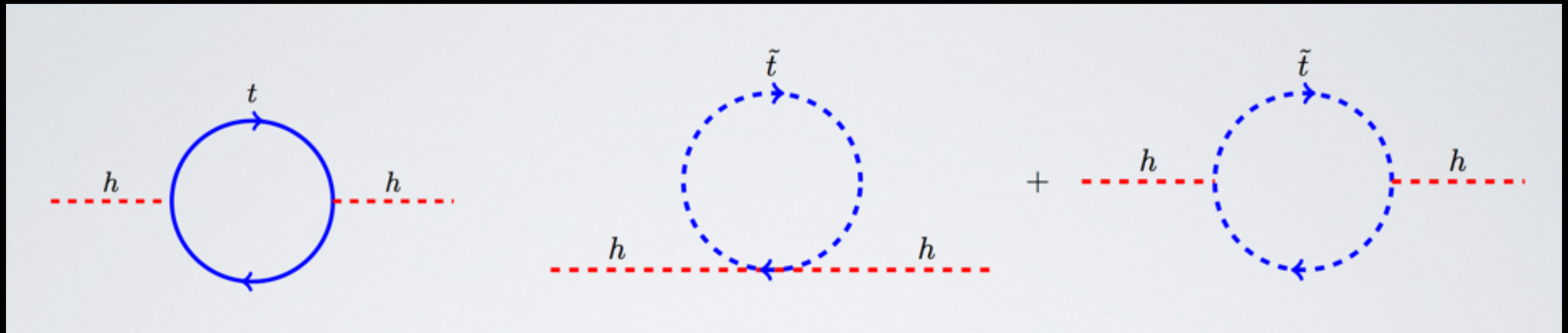
[c] Photons feel only the gravitational force, but they interact with all electrically charged particles.

[d] Mixtures of these particles form charginos $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$, and neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$.

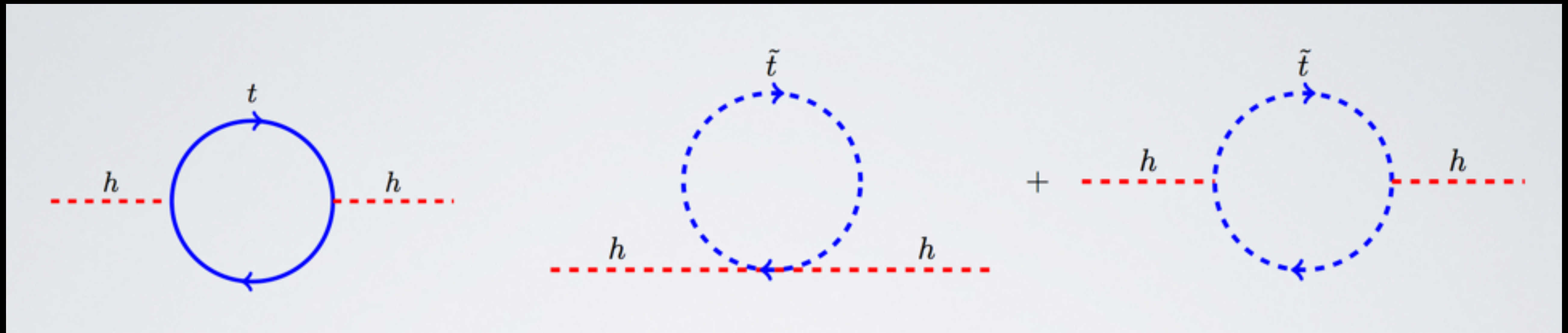
[e] The additional Higgs bosons predicted by supersymmetry are not shown.



SUSY CURES TO HIGGS QUANTUM-PATHOLOGIES



SUSY CURES TO HIGGS QUANTUM-PATHOLOGIES



SUSY models have many other nice features:

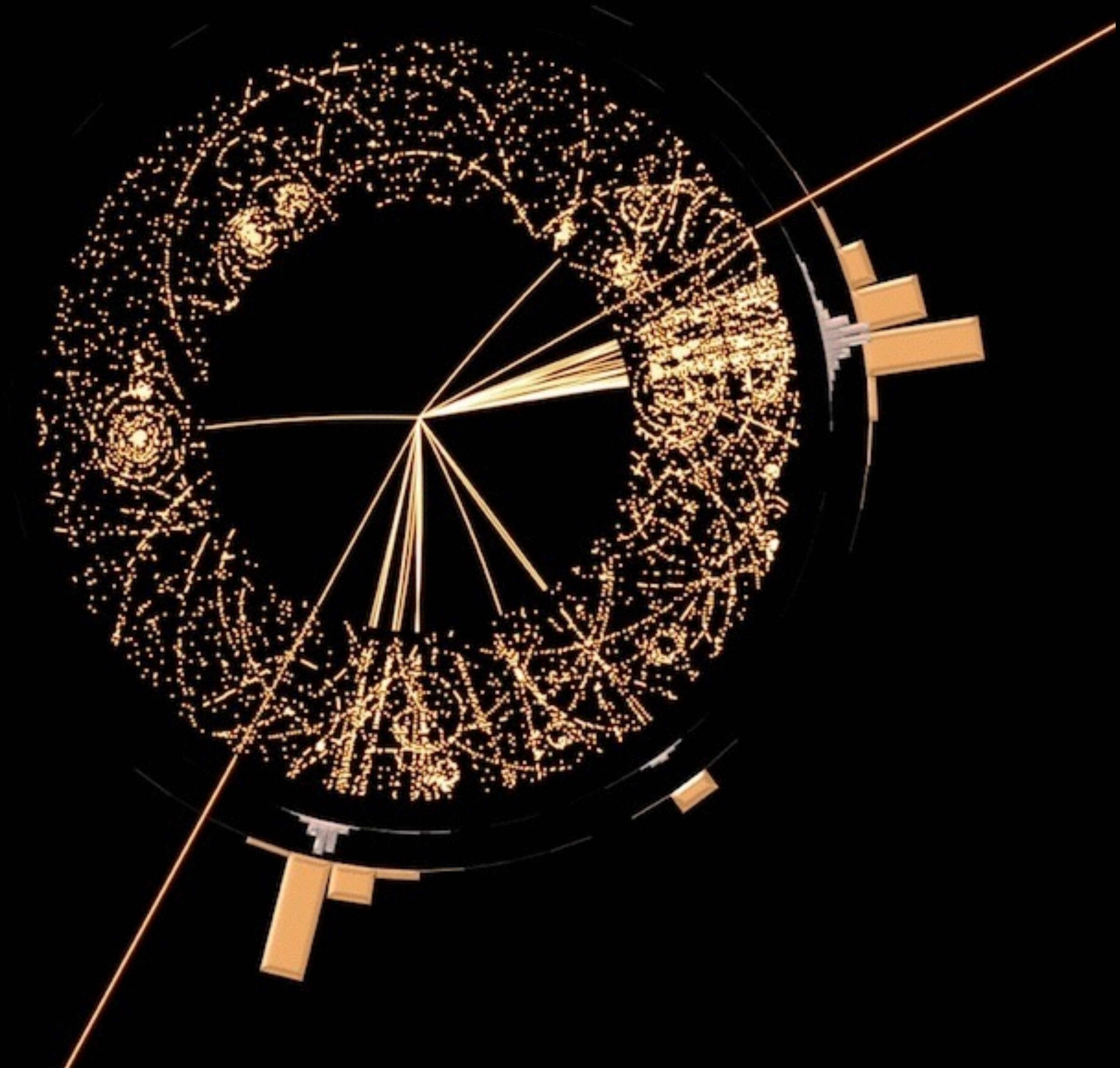
The electroweak scale is derived from the SUSY-breaking scale, and **the Higgs mass-squared parameter is automatically tachyonic due to quantum effects**

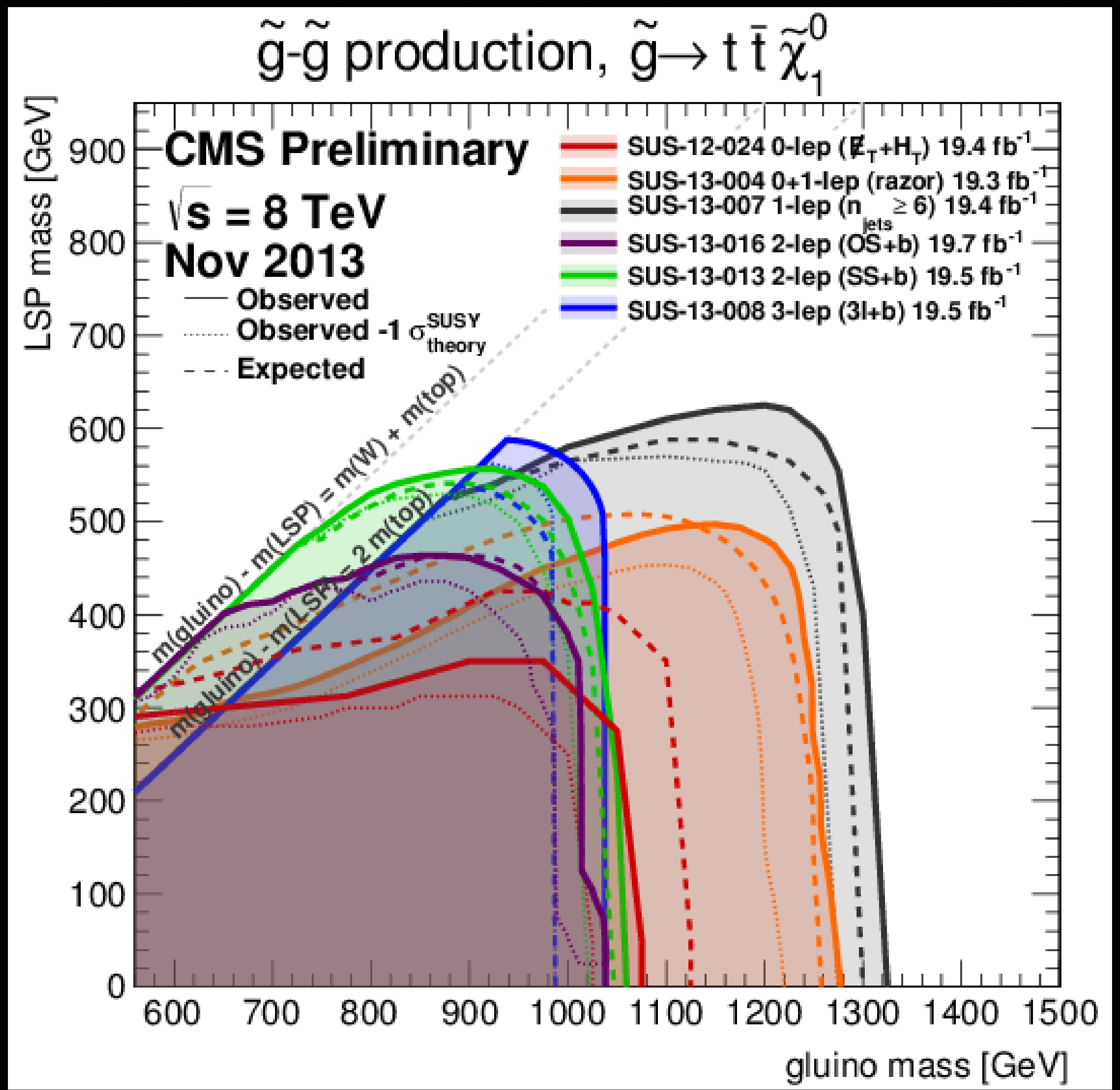
Once you have superpartners at the electroweak scale, **SUSY models make sense up to around the Planck scale ~ 10^{19} GeV, where quantum gravity presumably becomes important**

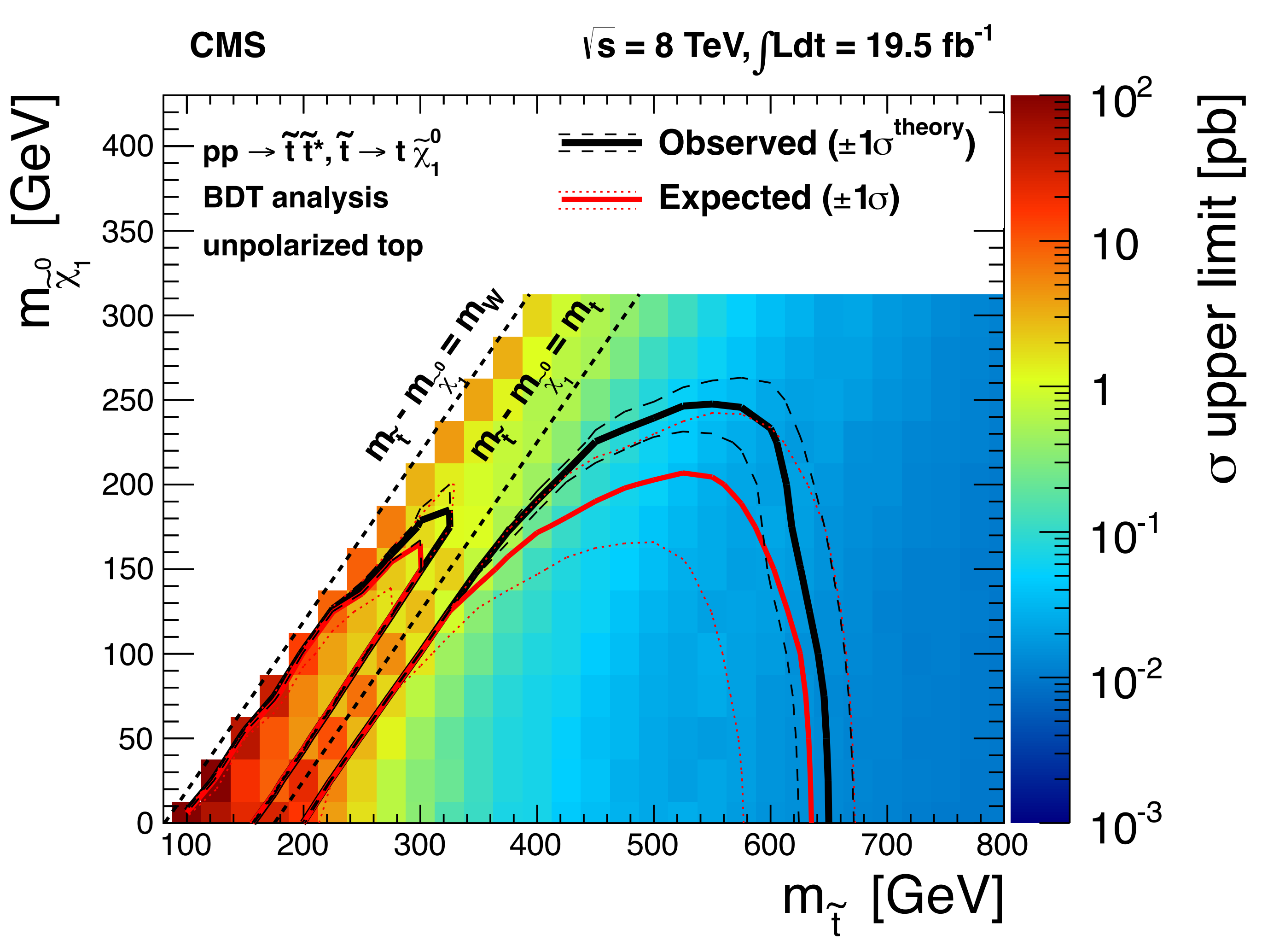
SUSY models are the expected lower energy outcome of **string theory, which may be the correct description of quantum gravity**

And of course you **predict the imminent discovery of all the superpartner particles**, since they are connected to the electroweak scale.

SUSY E–P BALANCE RUPTURE







UPCOMING DISCOVERY (2016)

- if SUSY is the naturalness fix then we just missed it in the 7, 8 TeV runs and it will show up in the 13 TeV run.
- both LEP and Tevatron missed the Higgs which was “just around the corner”

BEYOND THE HIGGS

H boson : is it the Standard Model?

Does it behave as predicted?

Is there more than one?

how many more?

Finding heavy Higgs bosons with non-standard interactions is a major long-term challenge for the LHC

BEYOND THE HIGGS

H boson : is it the Standard Model?

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Supersymmetry predicts at least five kinds of Higgs bosons, differing in their mass and other properties

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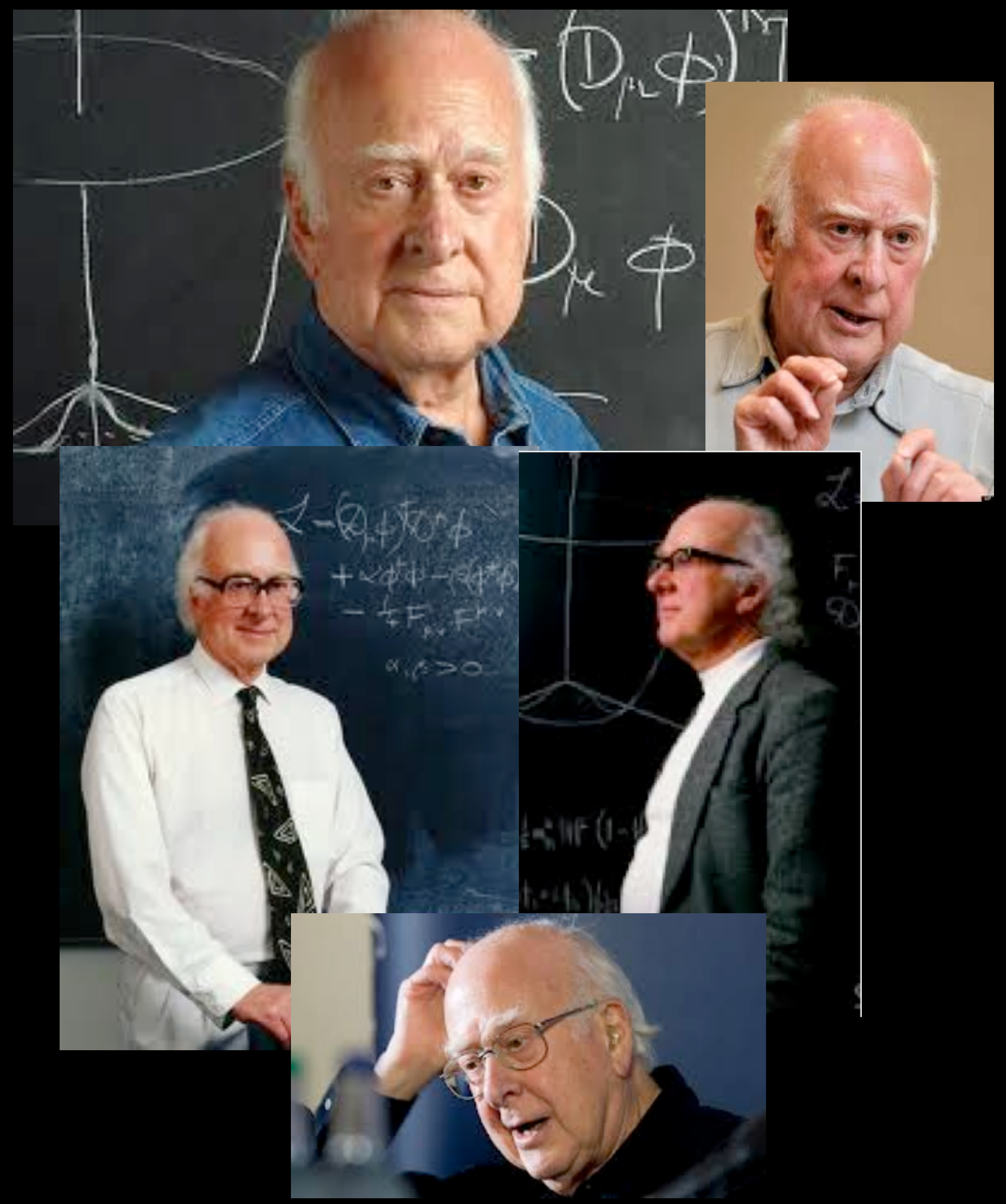
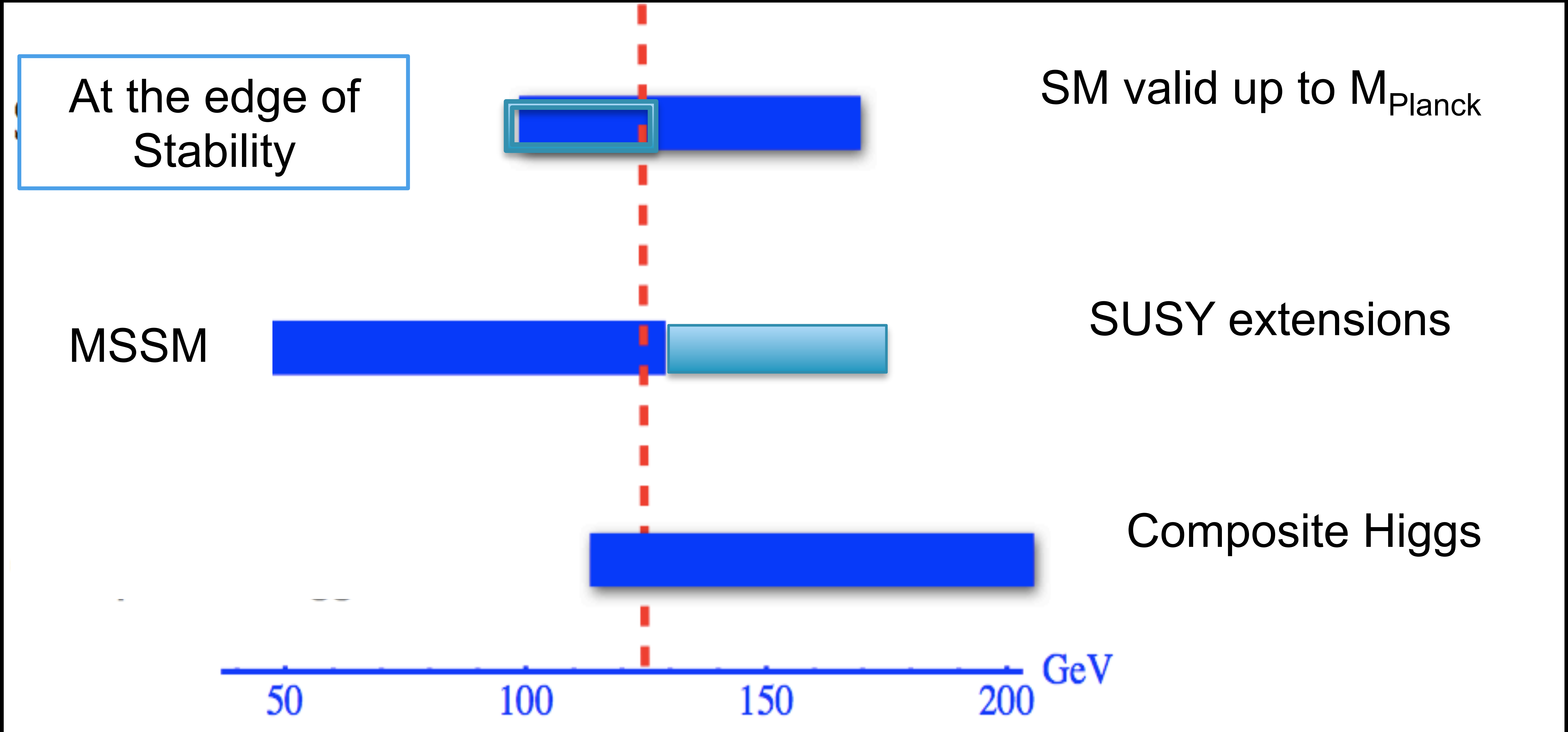


126 BORDERLINE DISORDER



126 GeV is suspiciously light for a composite Higgs boson
and it is suspiciously heavy for minimal SUSY
or you need to work SUSY extensions with **enlarged Higgs sectors**

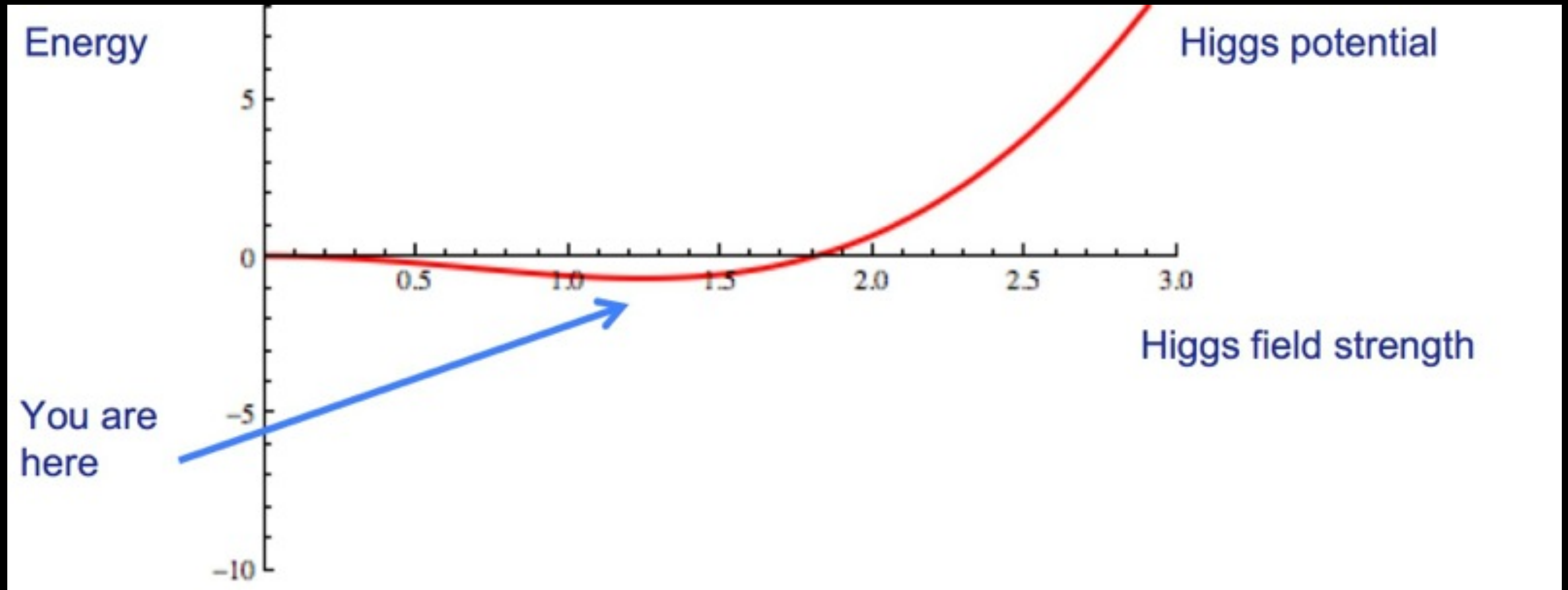
CONNECTIONS

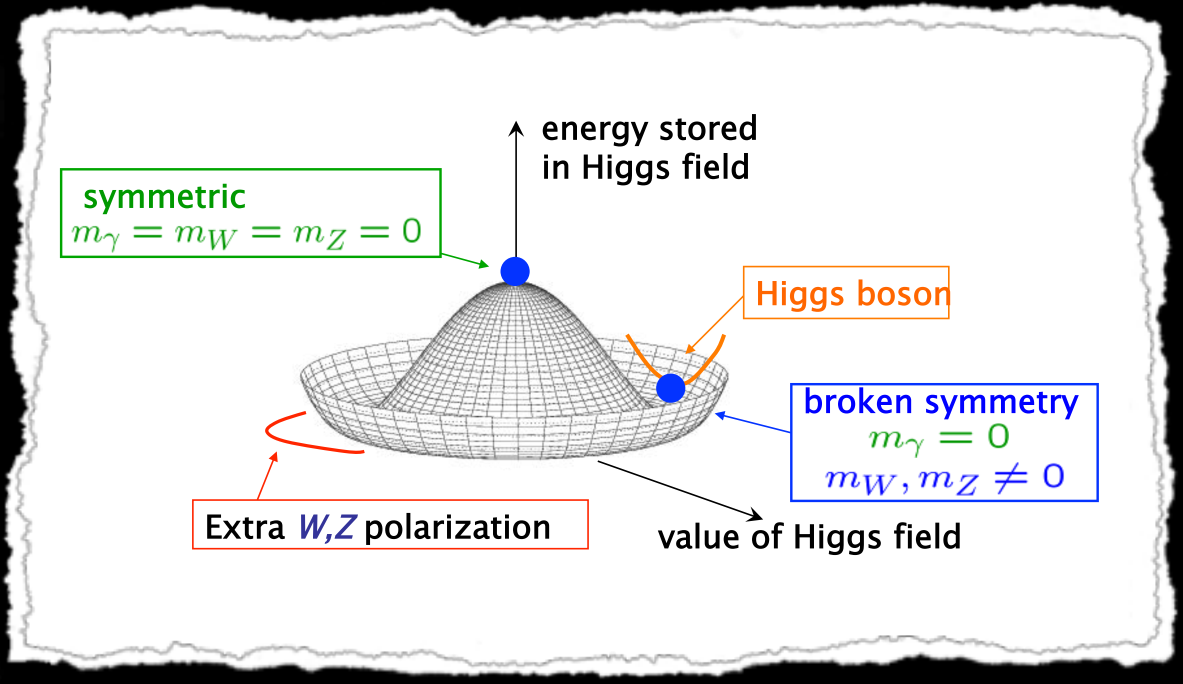
- Does the Higgs destabilize the vacuum
- How does the electroweak scale emerge
- Is there a Higgs portal to dark matter
- Is the Higgs sector responsible for the genesis of matter in the early universe
- How does the Higgs talk to neutrinos
- Is the Higgs related to inflation or dark energy

- motivates: precision program, discovery program (w/ energy push), observation program

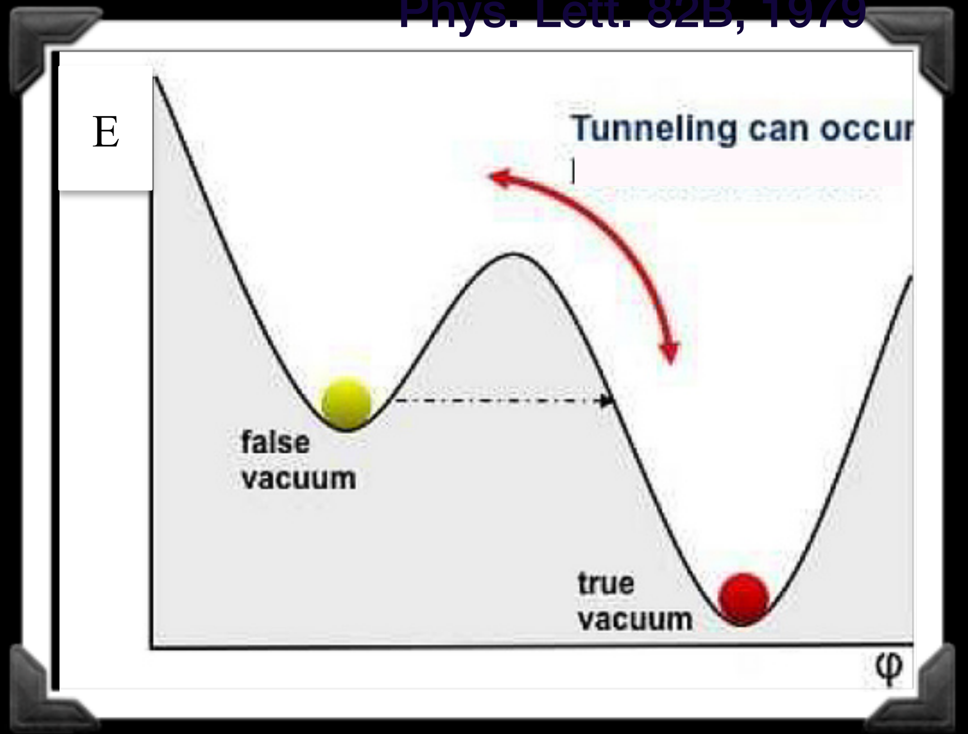
HIGGS AND VACUUM STABILITY

- The Higgs field is self-sourcing with a quartic self-interaction λ
- The strength of this interaction has distance-dependent quantum corrections from the Higgs coupling to other particles, esp. the top quark
- The Higgs effective potential depends on the Higgs mass and the Higgs self coupling
- The quantum corrections depend on the top mass and an energy scale that is bigger the bigger is the strength of the Higgs field.





D. Politzer, S. Wolfram, Phys. Lett. 82B, 1979



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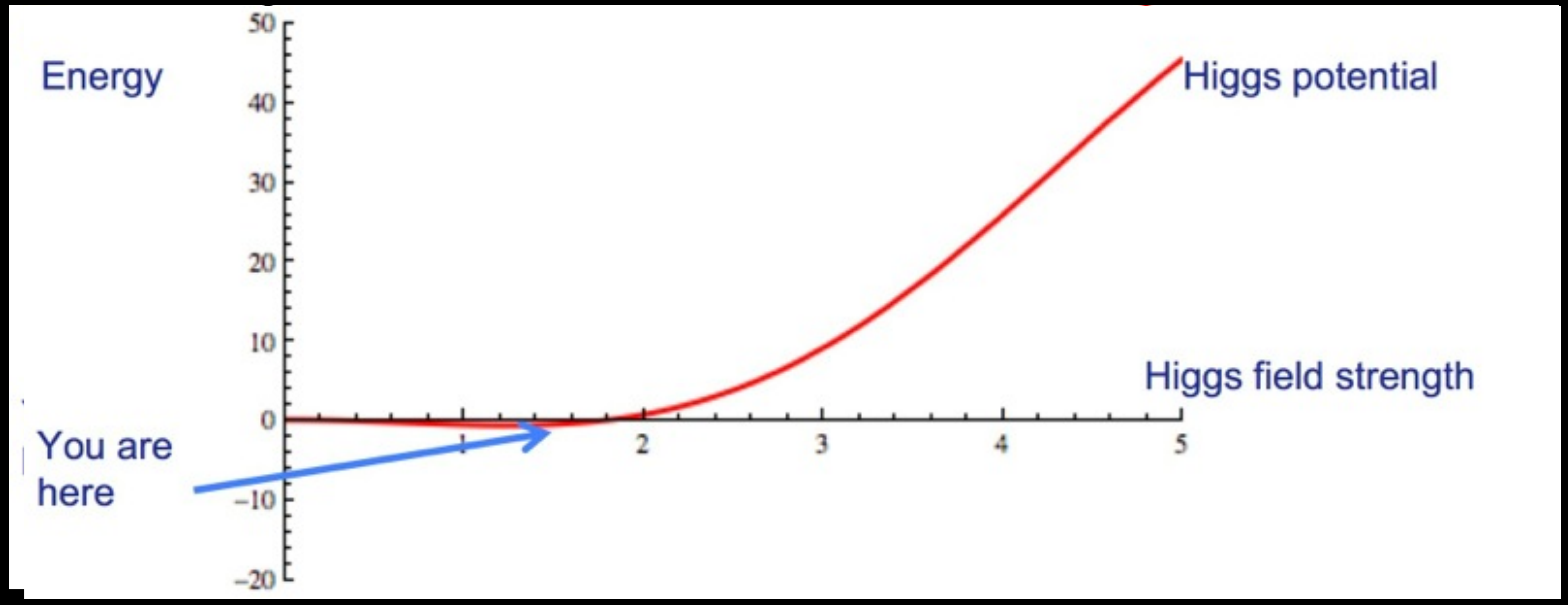

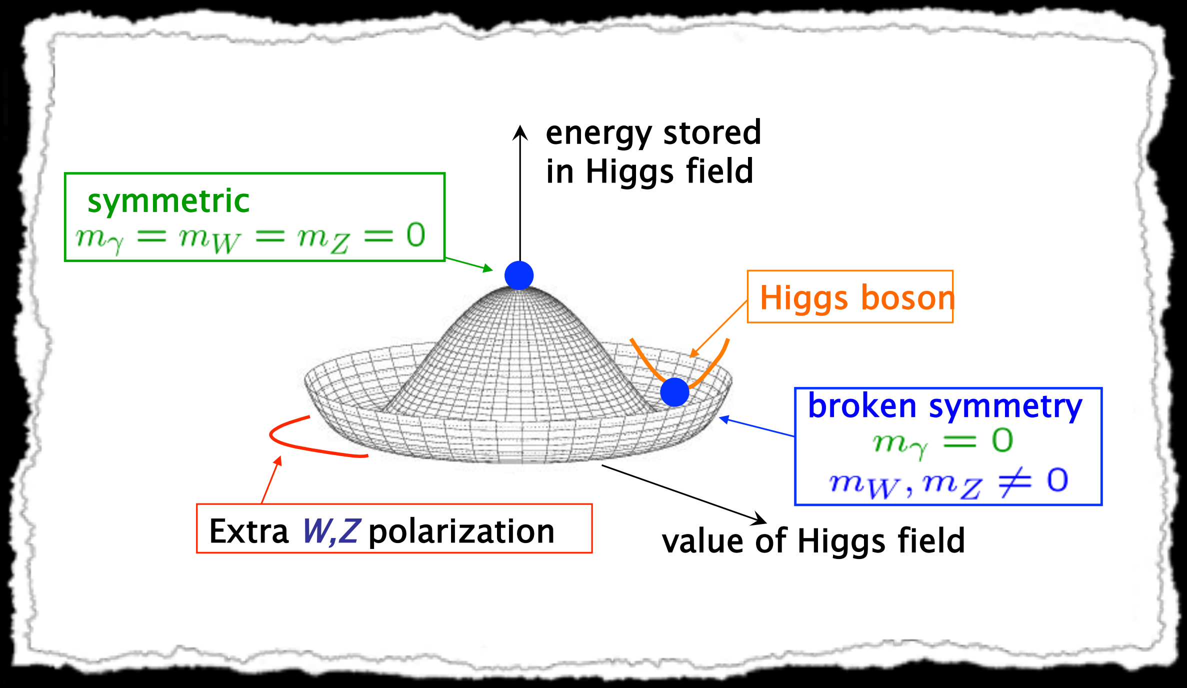

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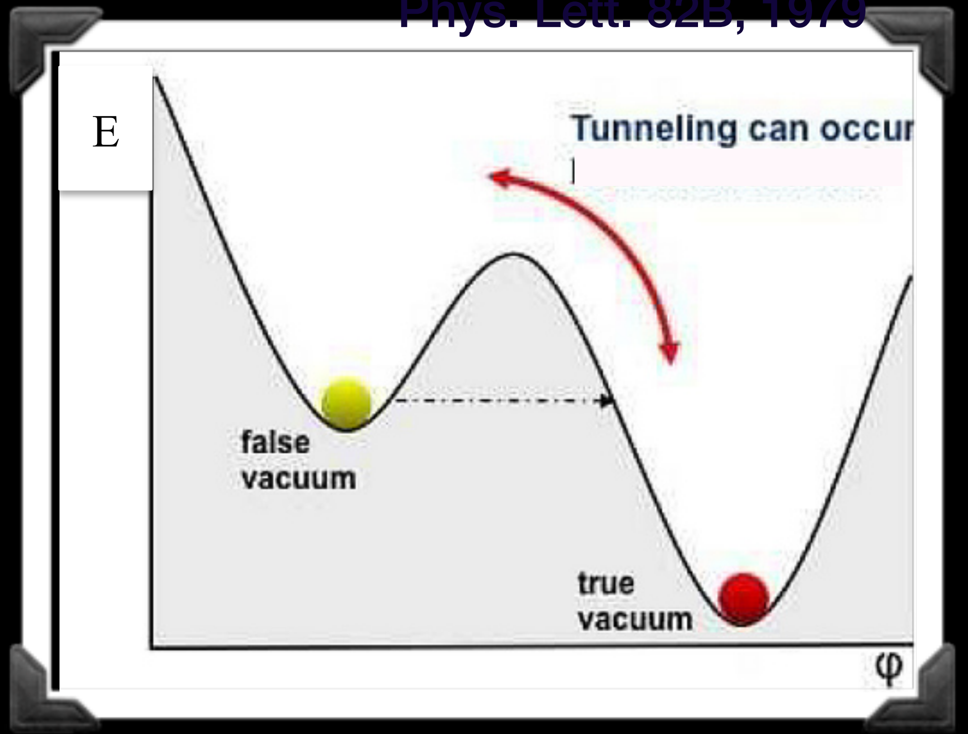

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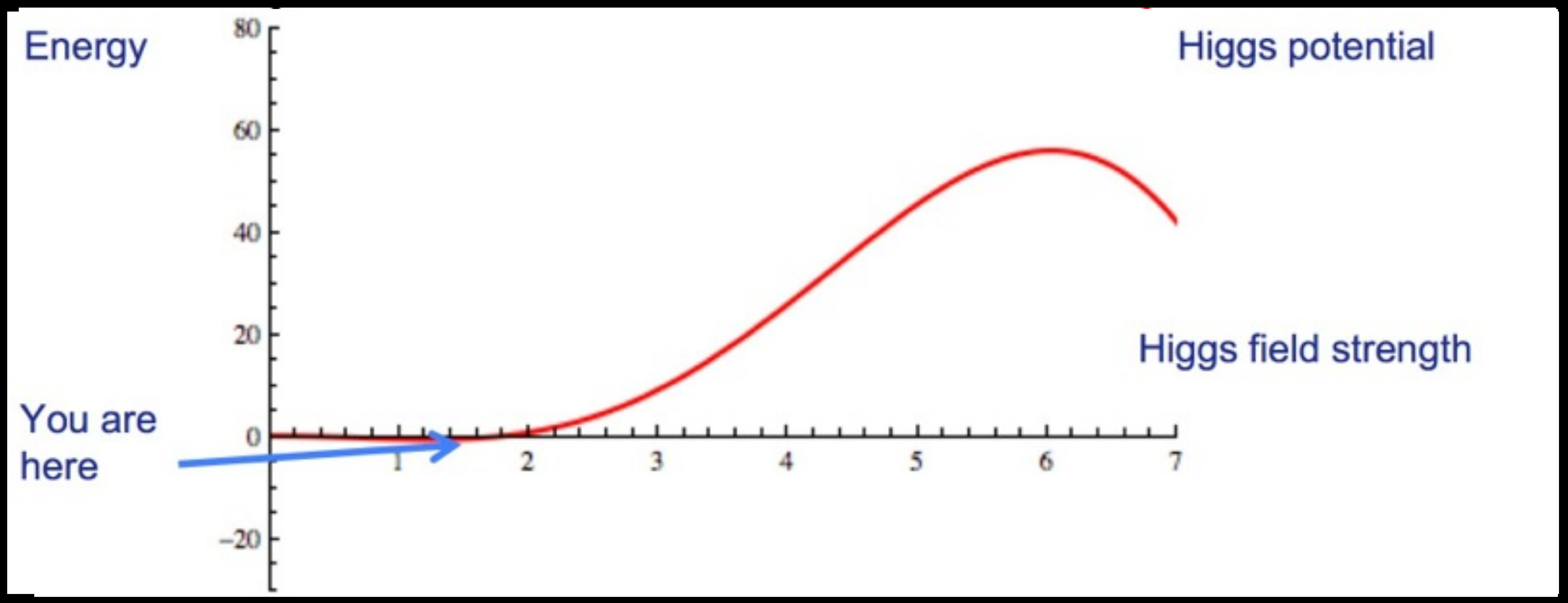

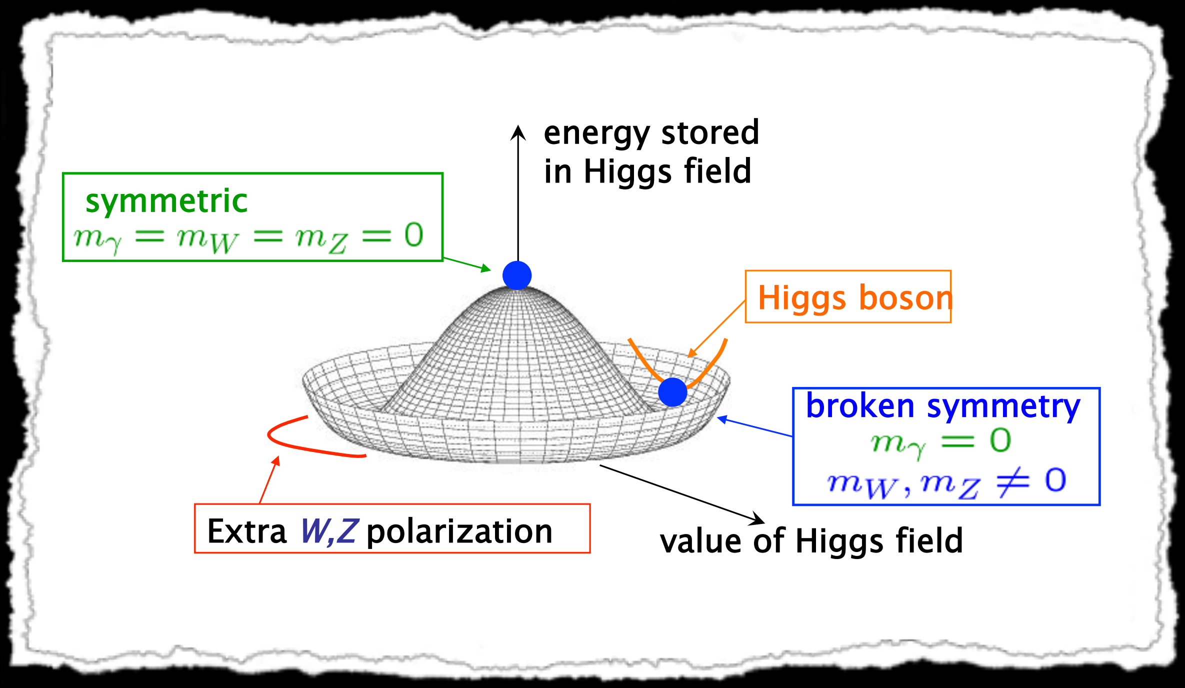

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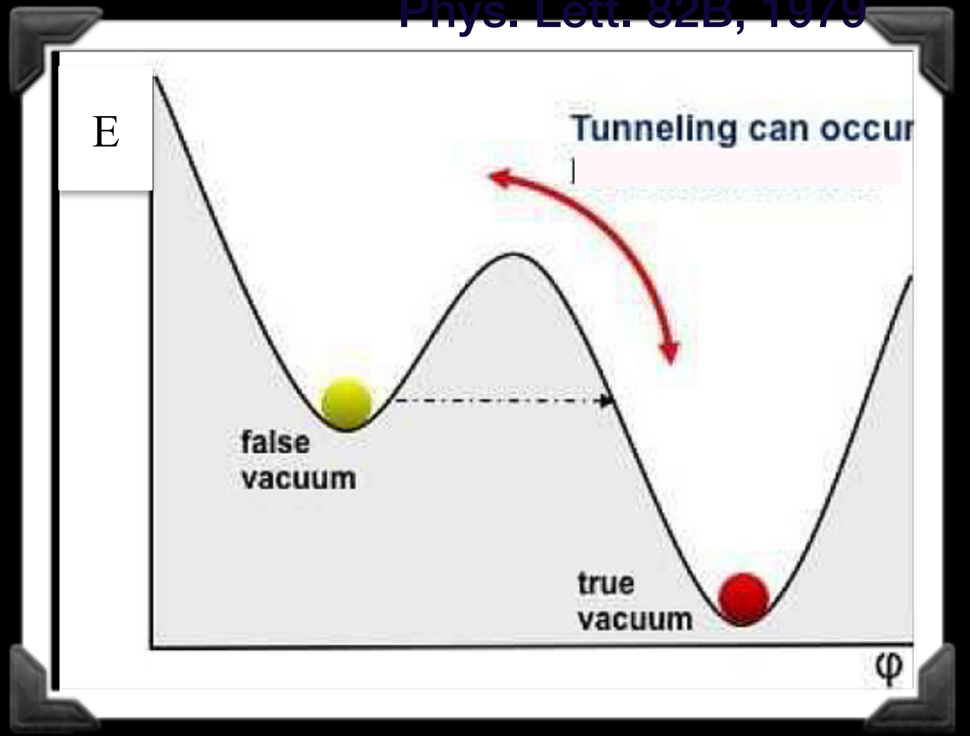

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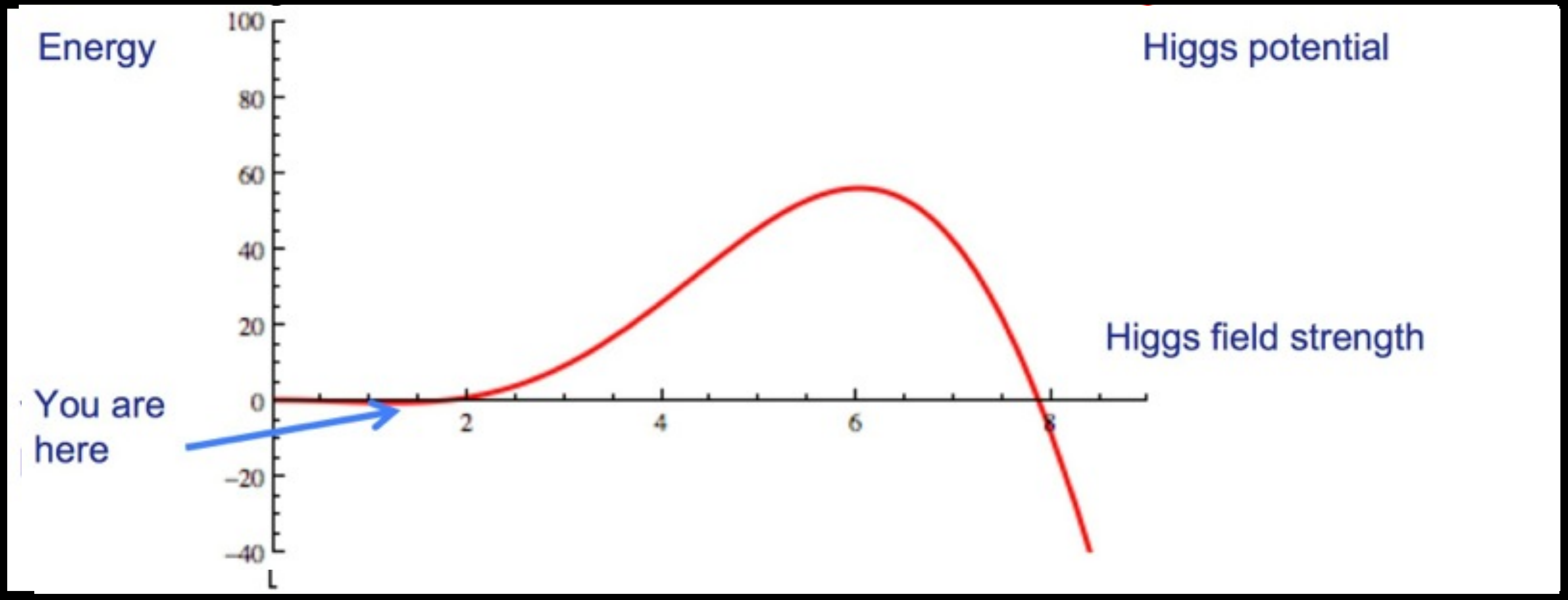

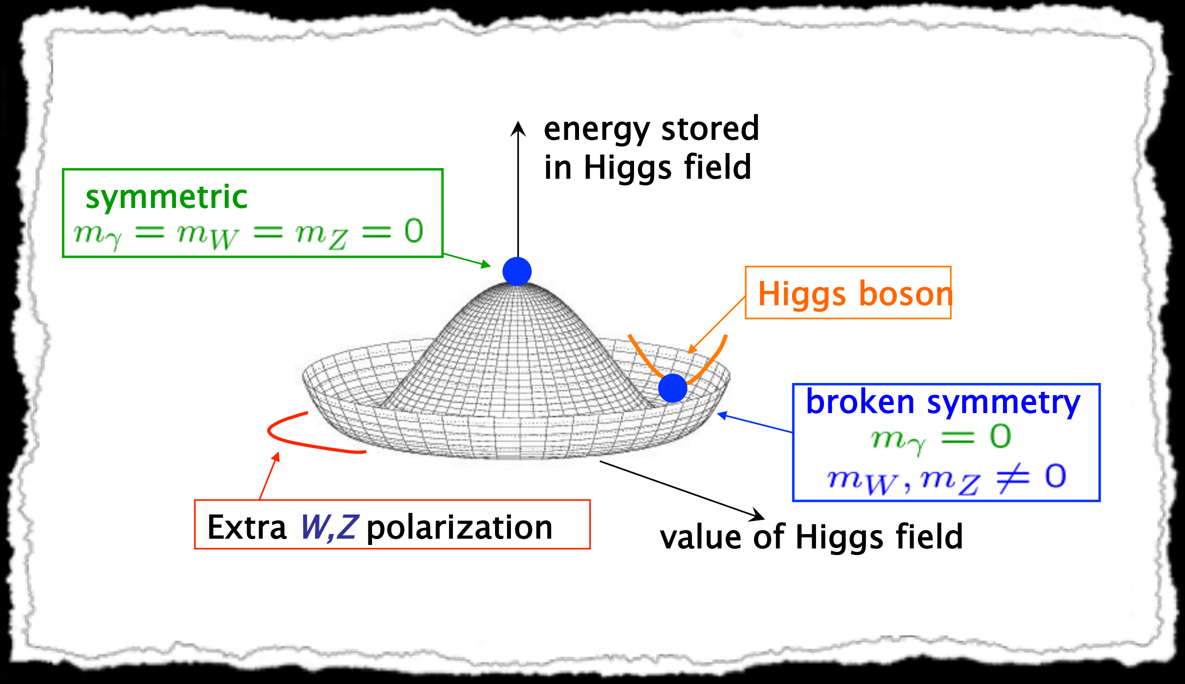

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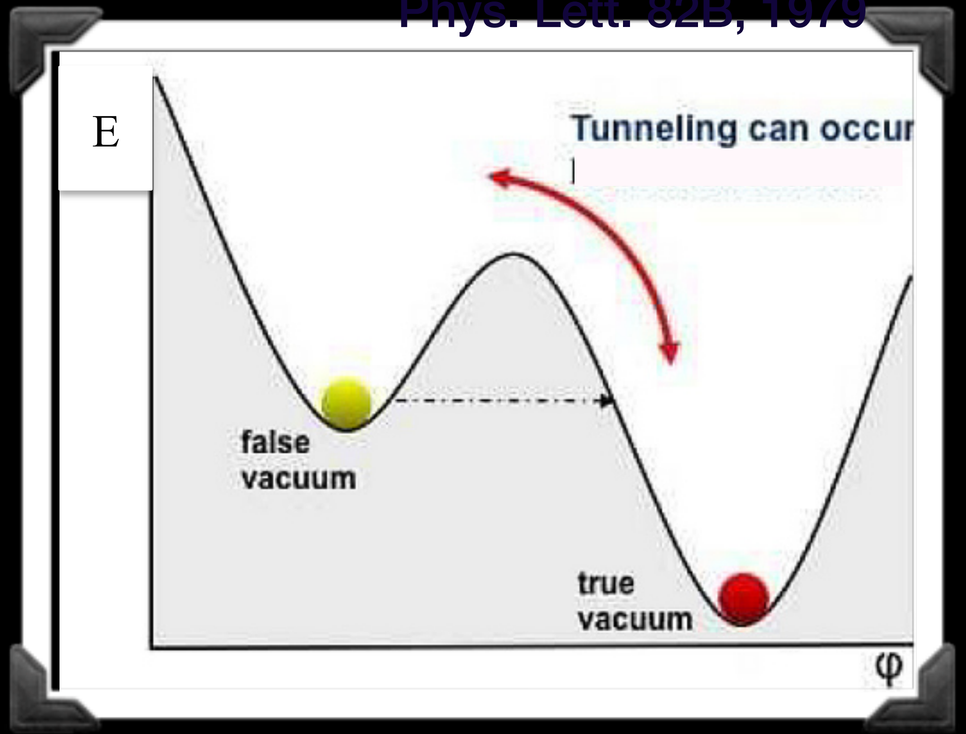
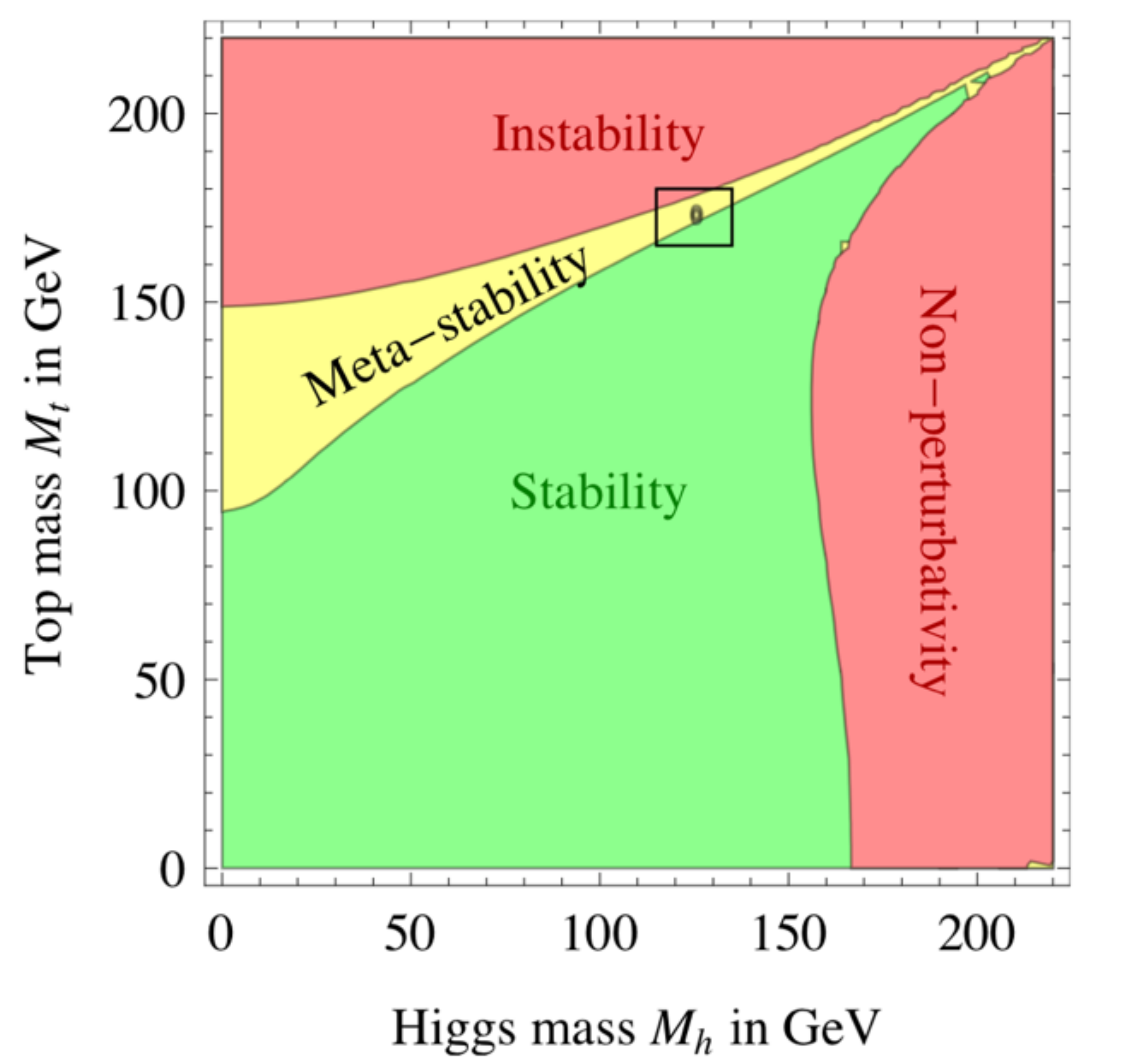
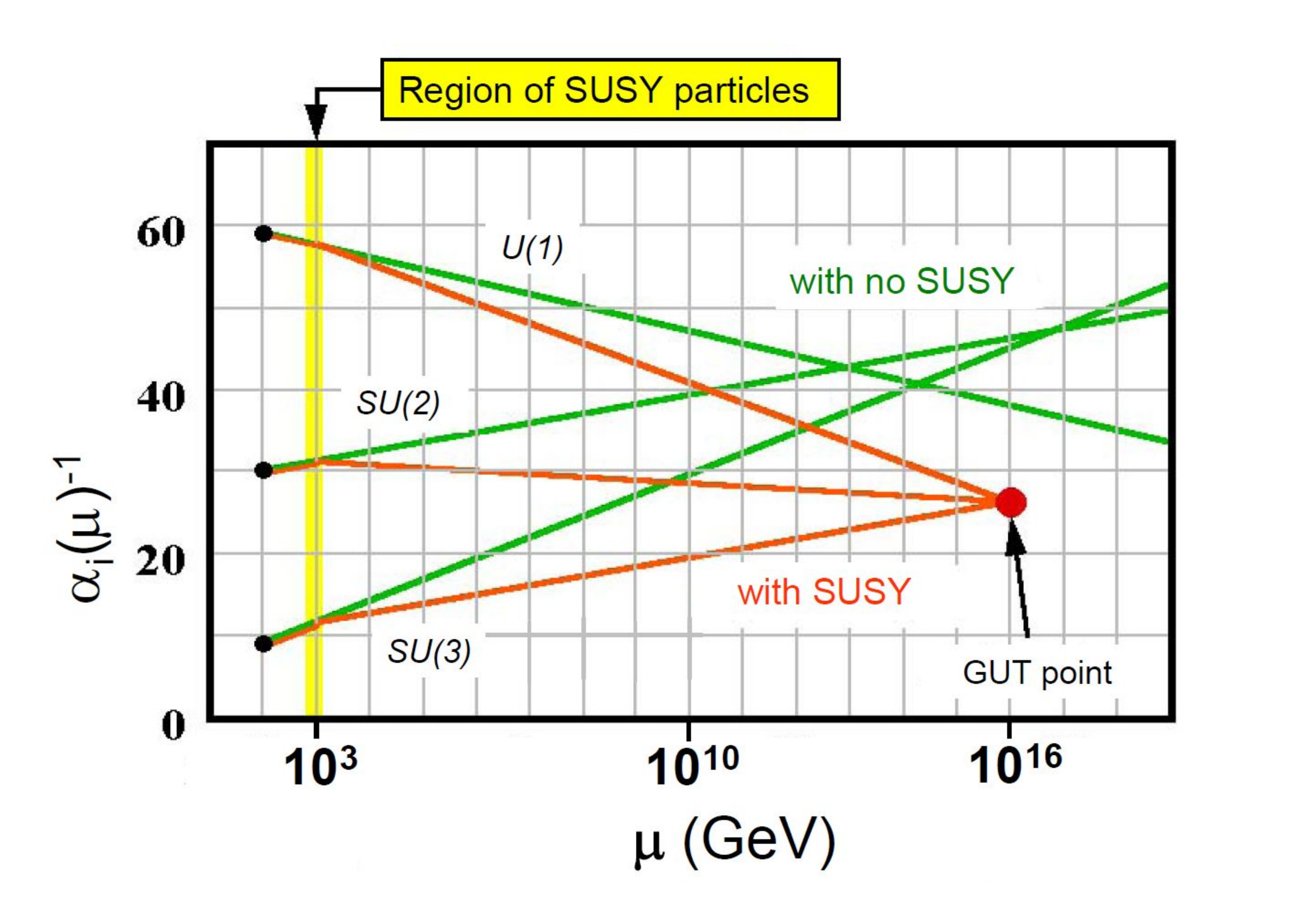


VACUUM META-STABILITY





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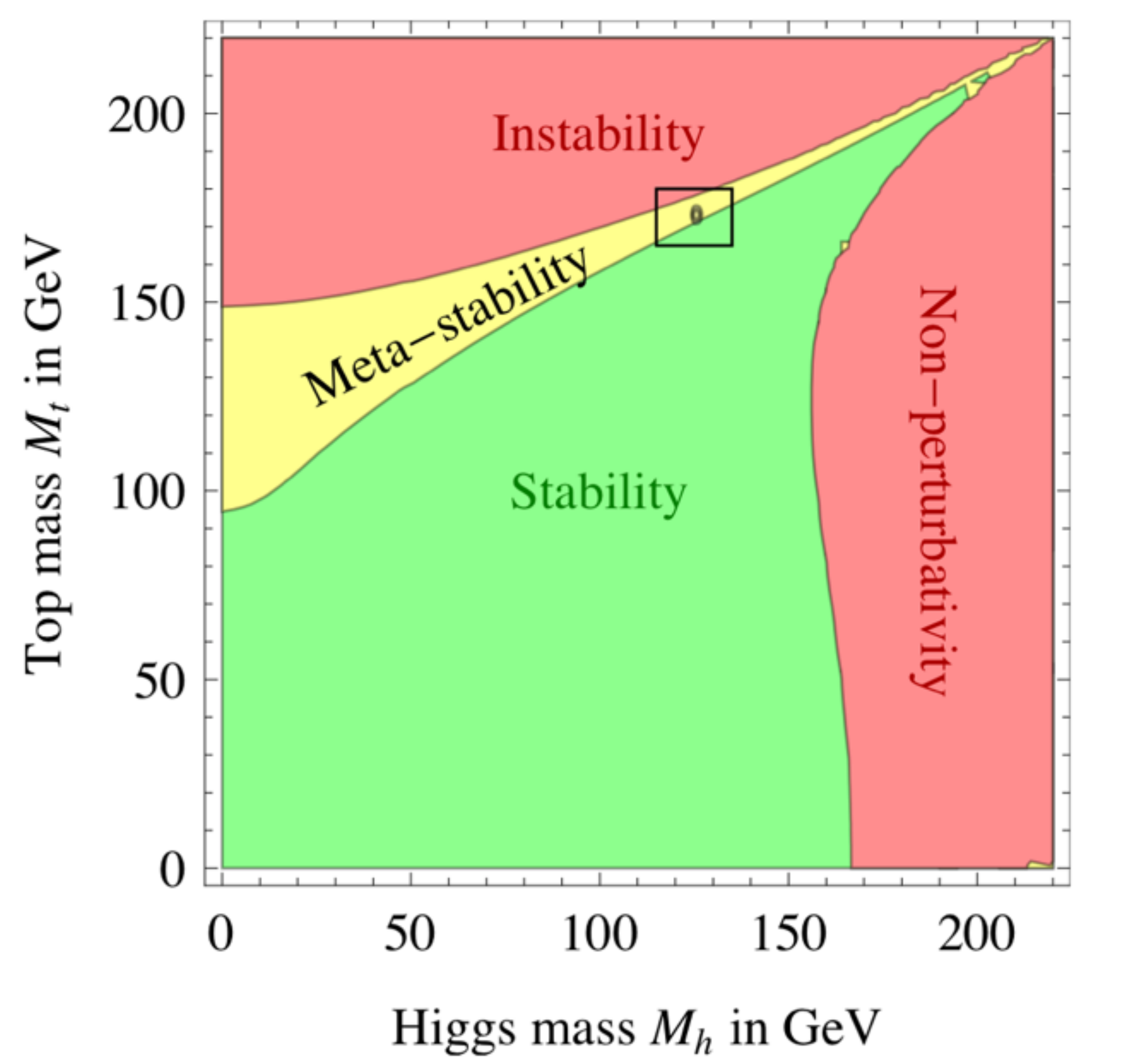
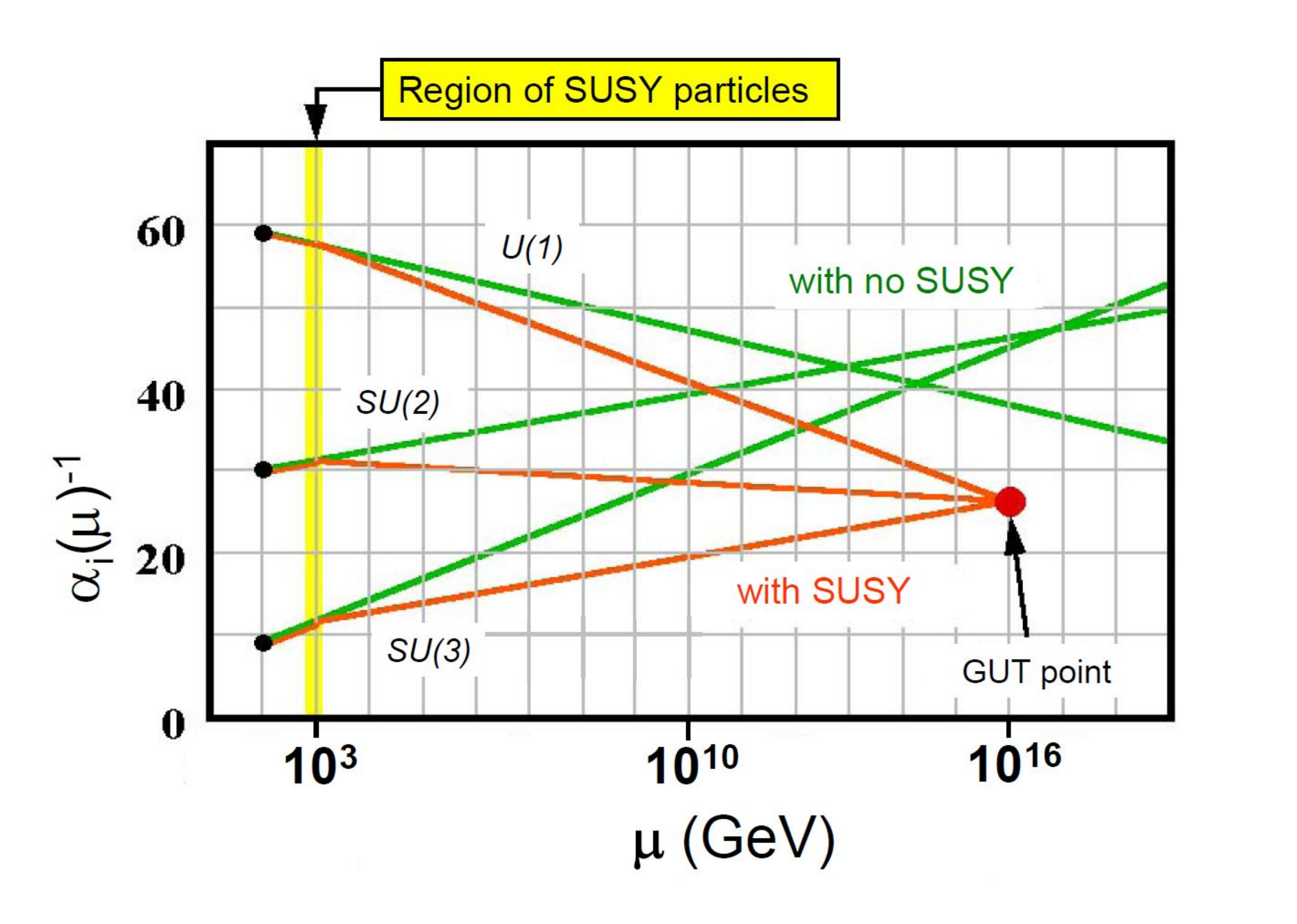




metastability can be averted with insertion of new physics — SUSY in particular works well

DARK MATTERS

DARK MATTER

LUMINOUS

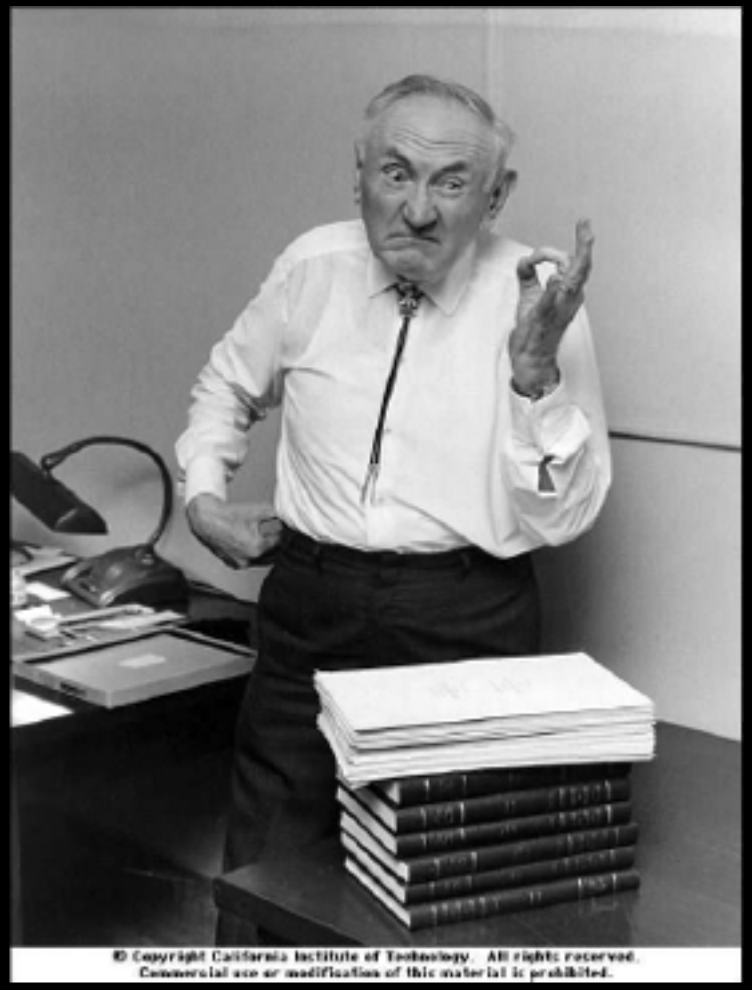
DARK MATTER

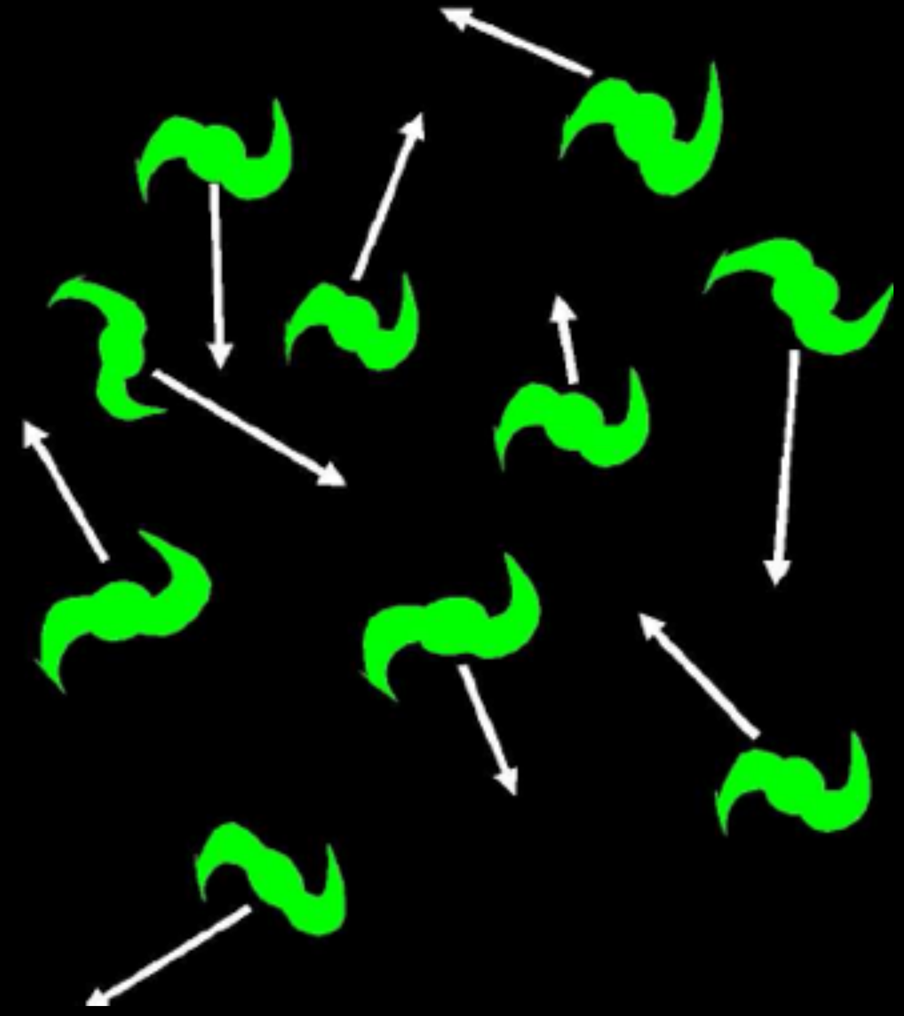
LUMINOUS

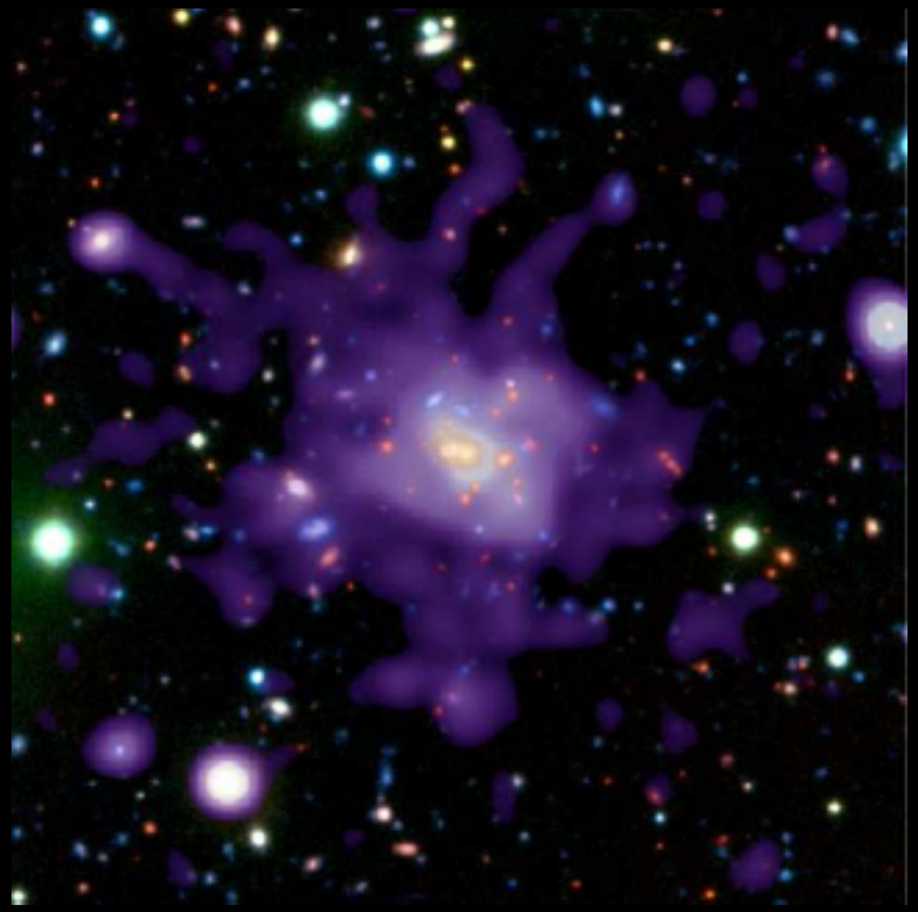
DARK

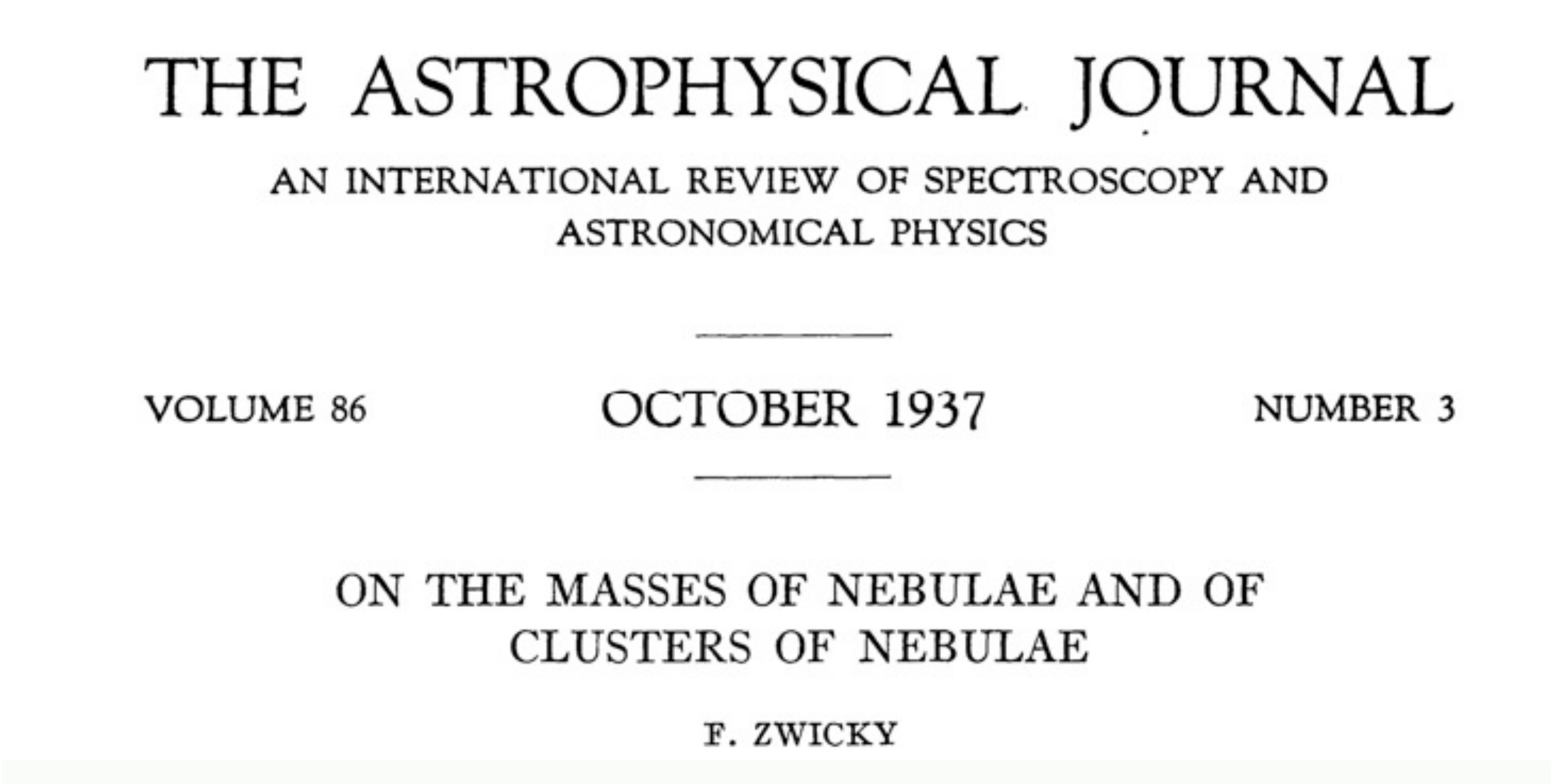
DARK MATTER

DYNAMICS OF GALAXY CLUSTERS









THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

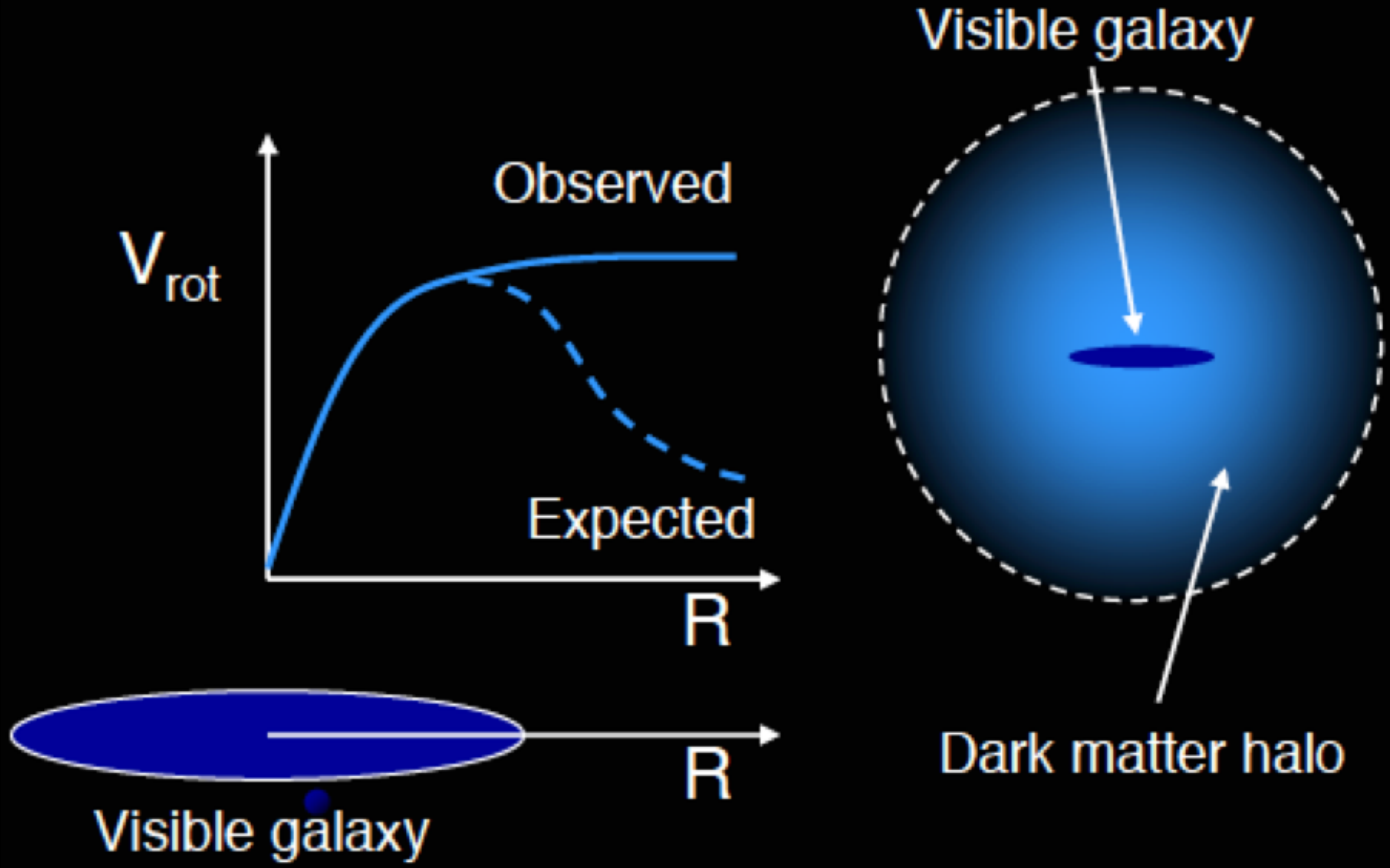
$$KE_{avg} = -\frac{1}{2}\ GPE_{avg}$$

High mass required in order for the gas not to leave the cluster

$$M_{virial} = \frac{<v^2>R}{G}$$

DARK MATTER

DYNAMICS OF GALAXIES



$$\text{Galaxy} \sim \text{stars} + \text{gas} + \text{dust} + \text{black hole} + \text{DM}$$

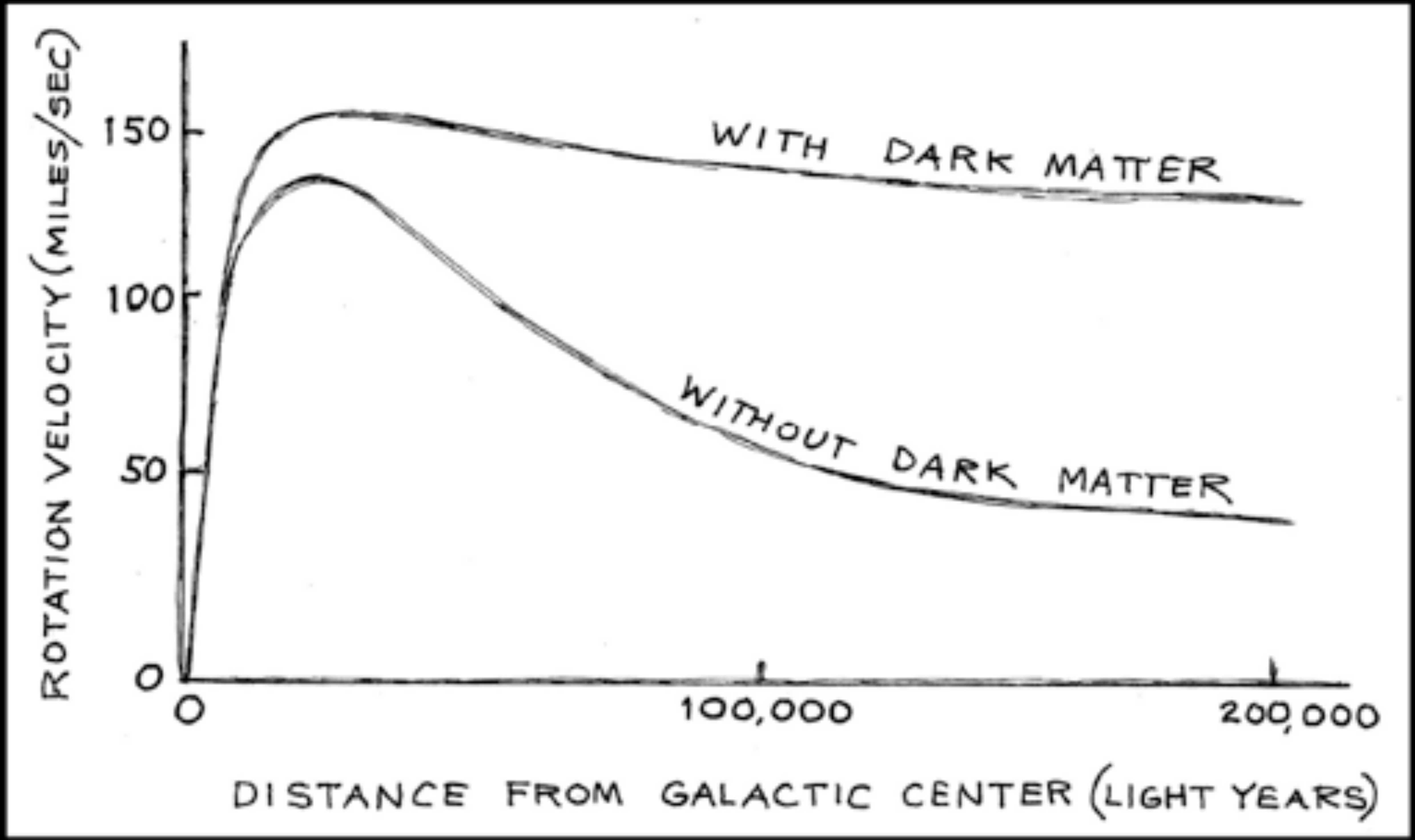
DARK MATTER

DYNAMICS OF GALAXIES

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†

Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡



$$\frac{v^2}{R} = \frac{G\,M_{GALAXY}}{R^2}$$

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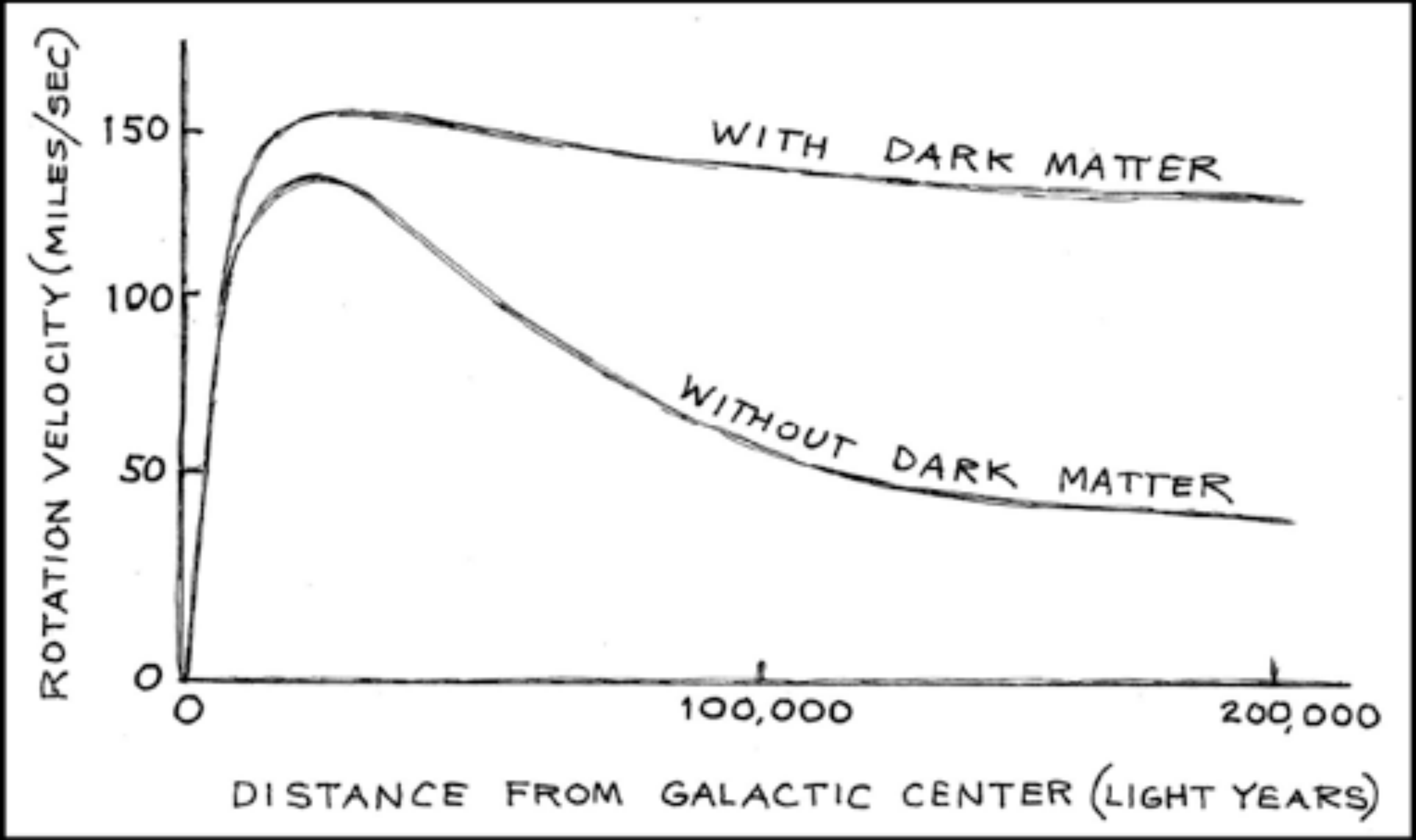

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DARK MATTER

LENSING

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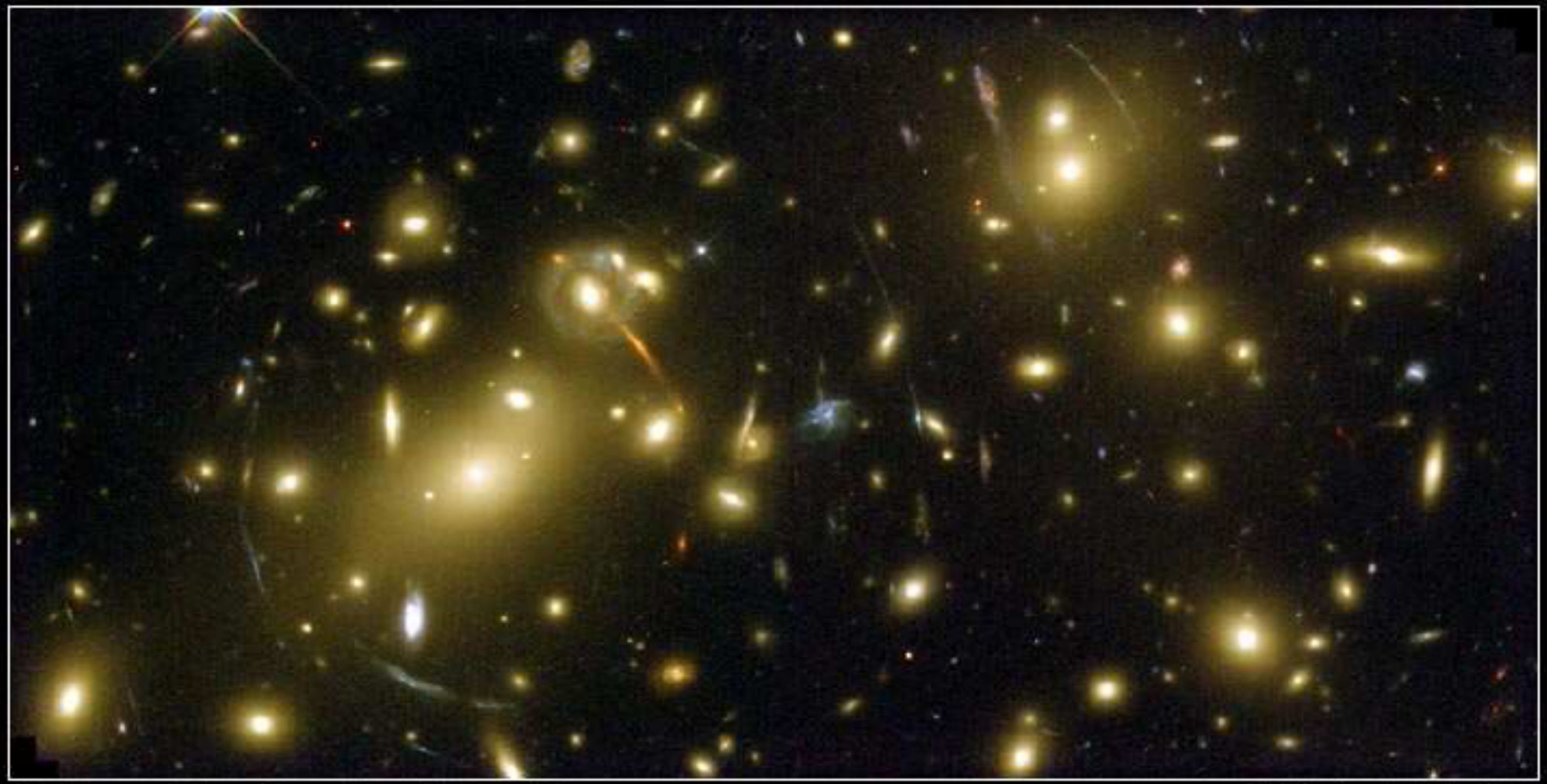
LENSING

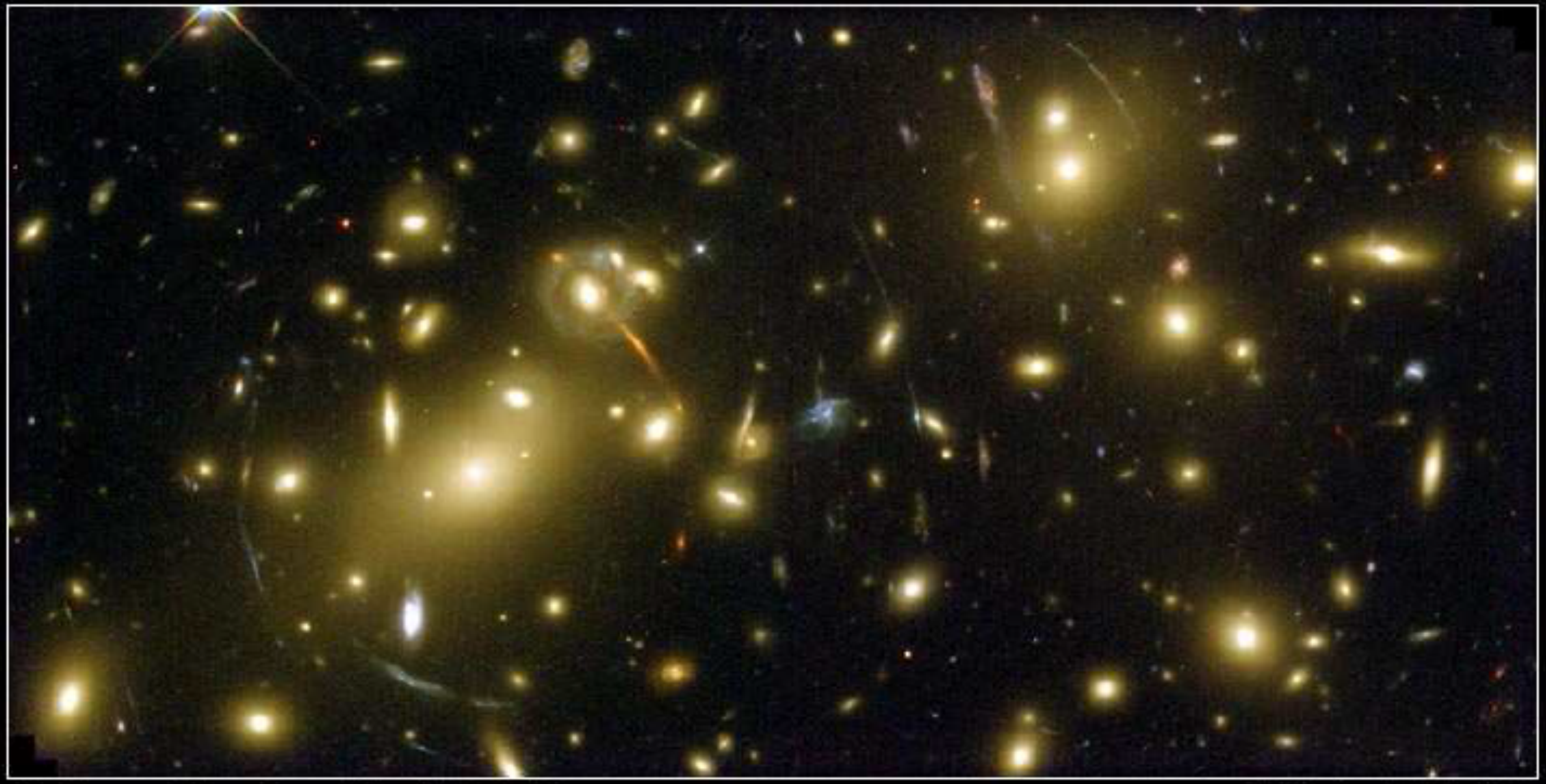


Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

gravitational lensing by dark matter distorts galaxy images

DARK MATTER

LENSING



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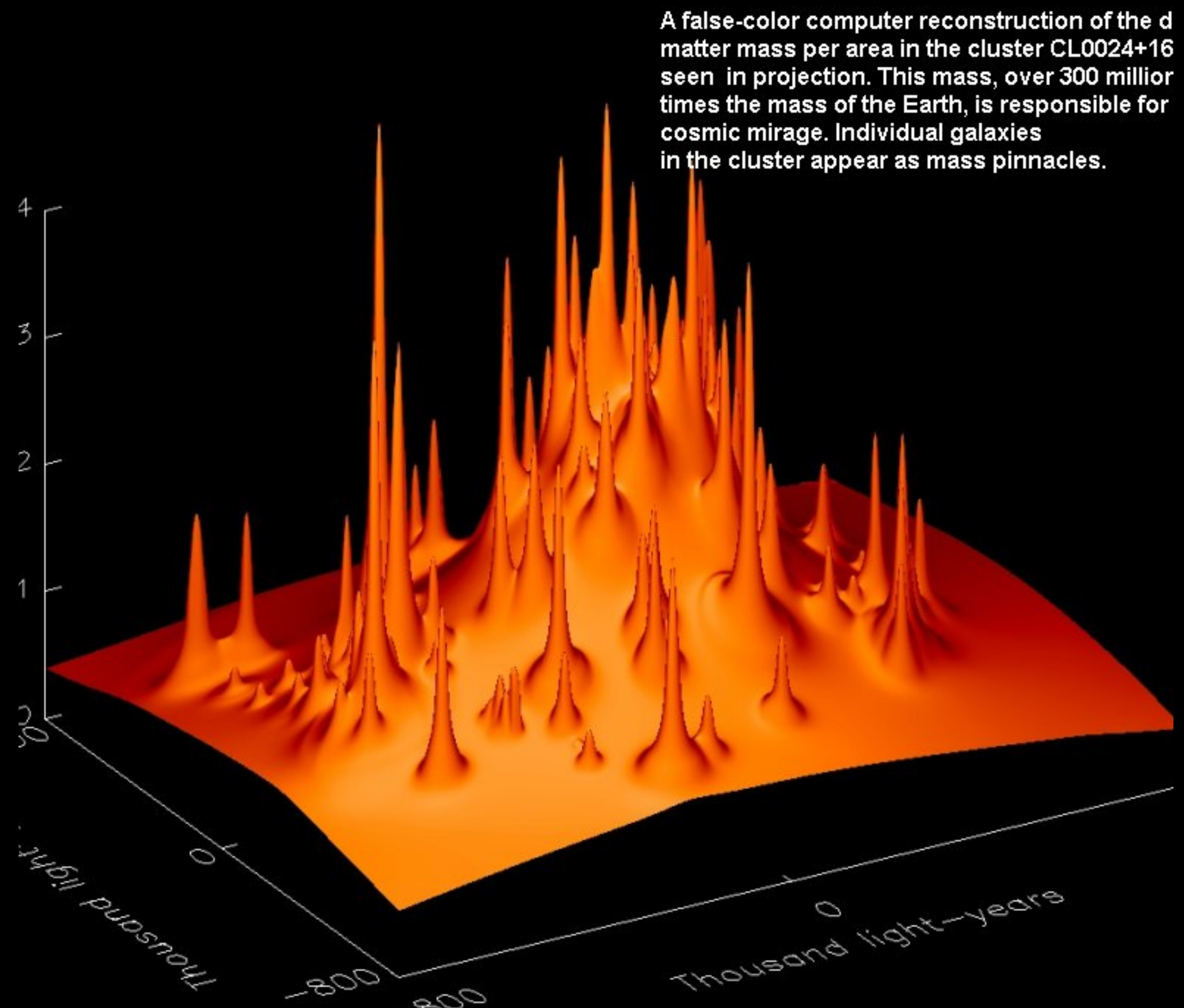
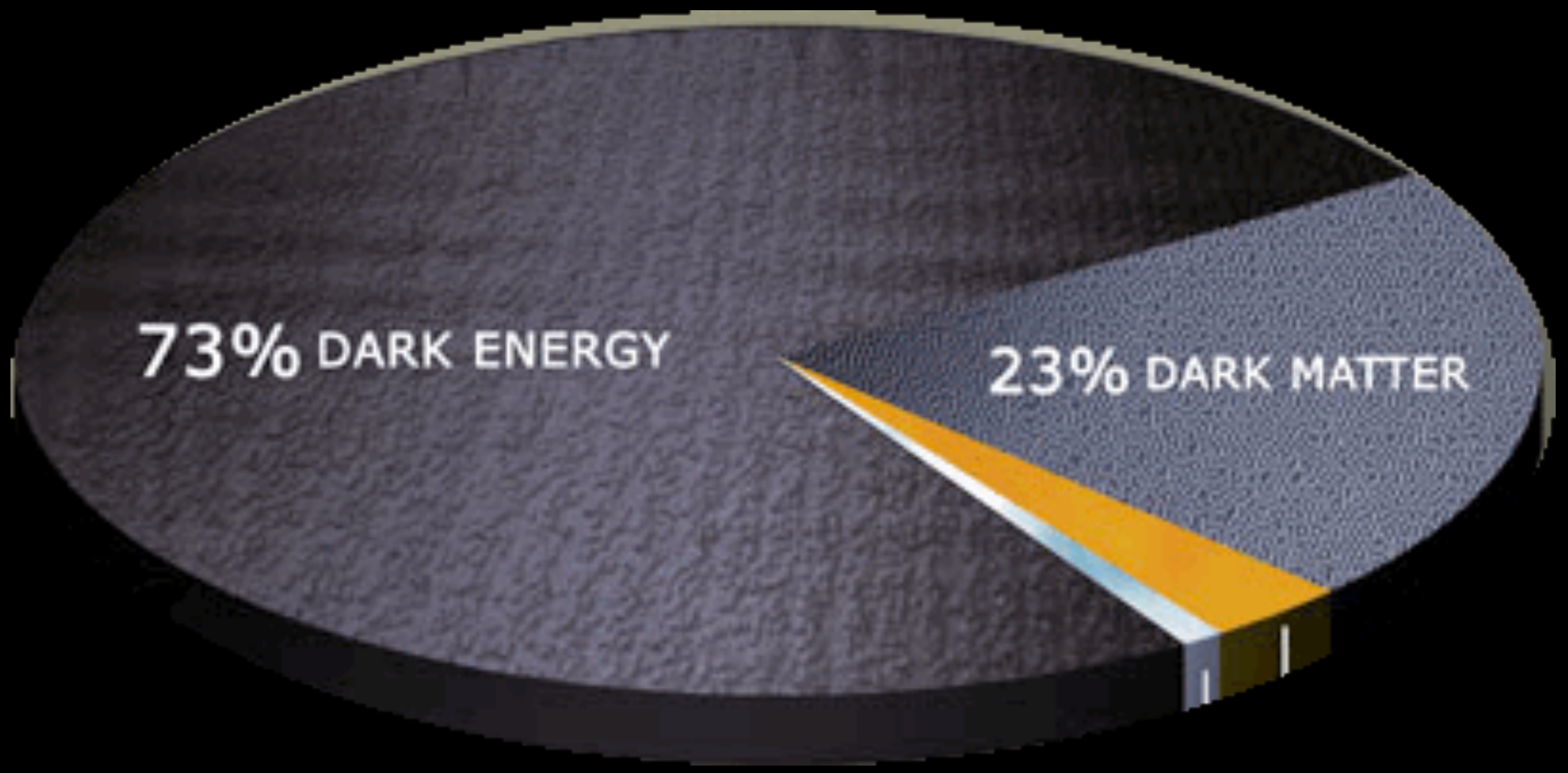


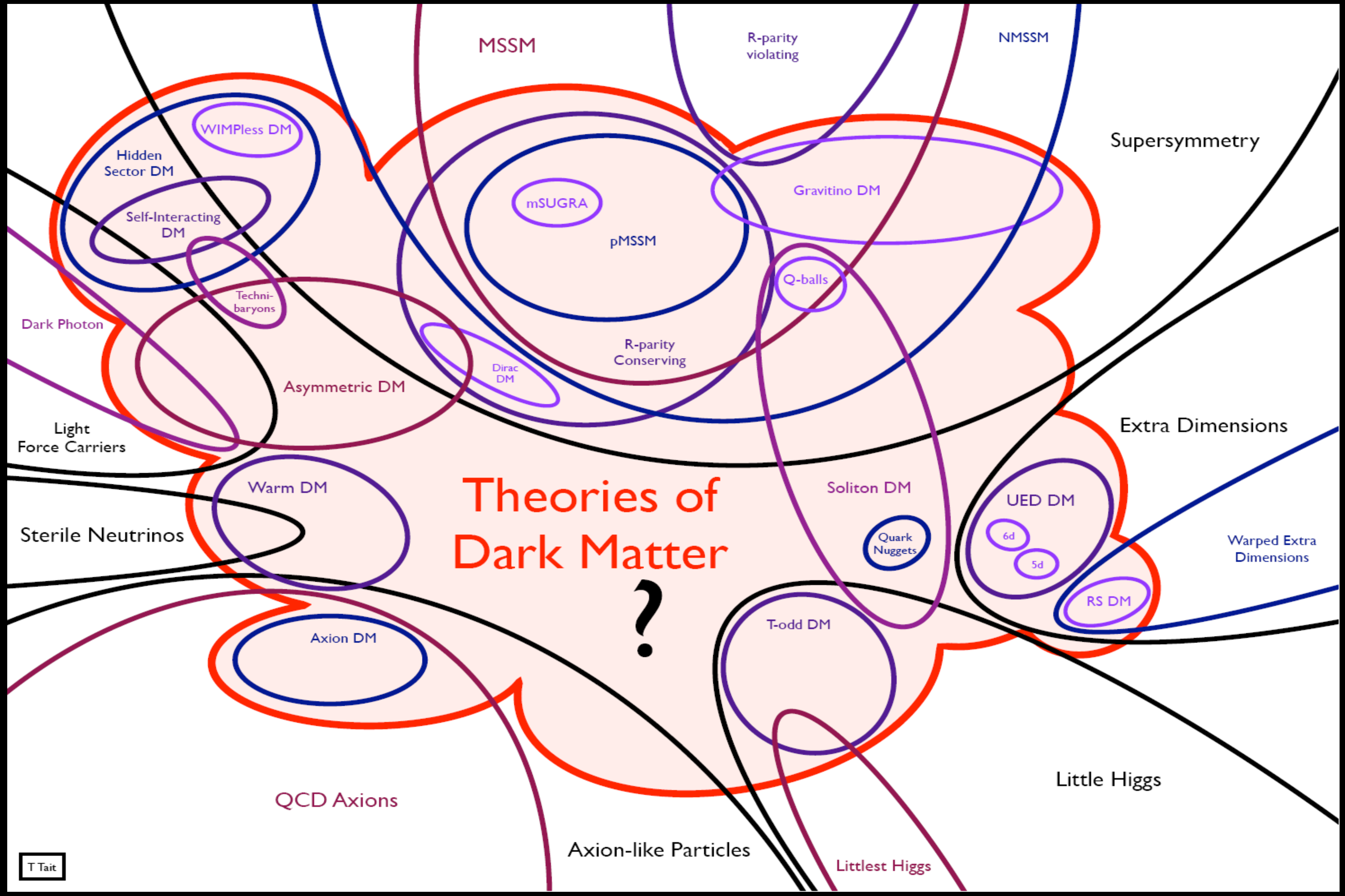
gravitational lensing by dark matter distorts galaxy images

distribution of DM needed to explain lensing

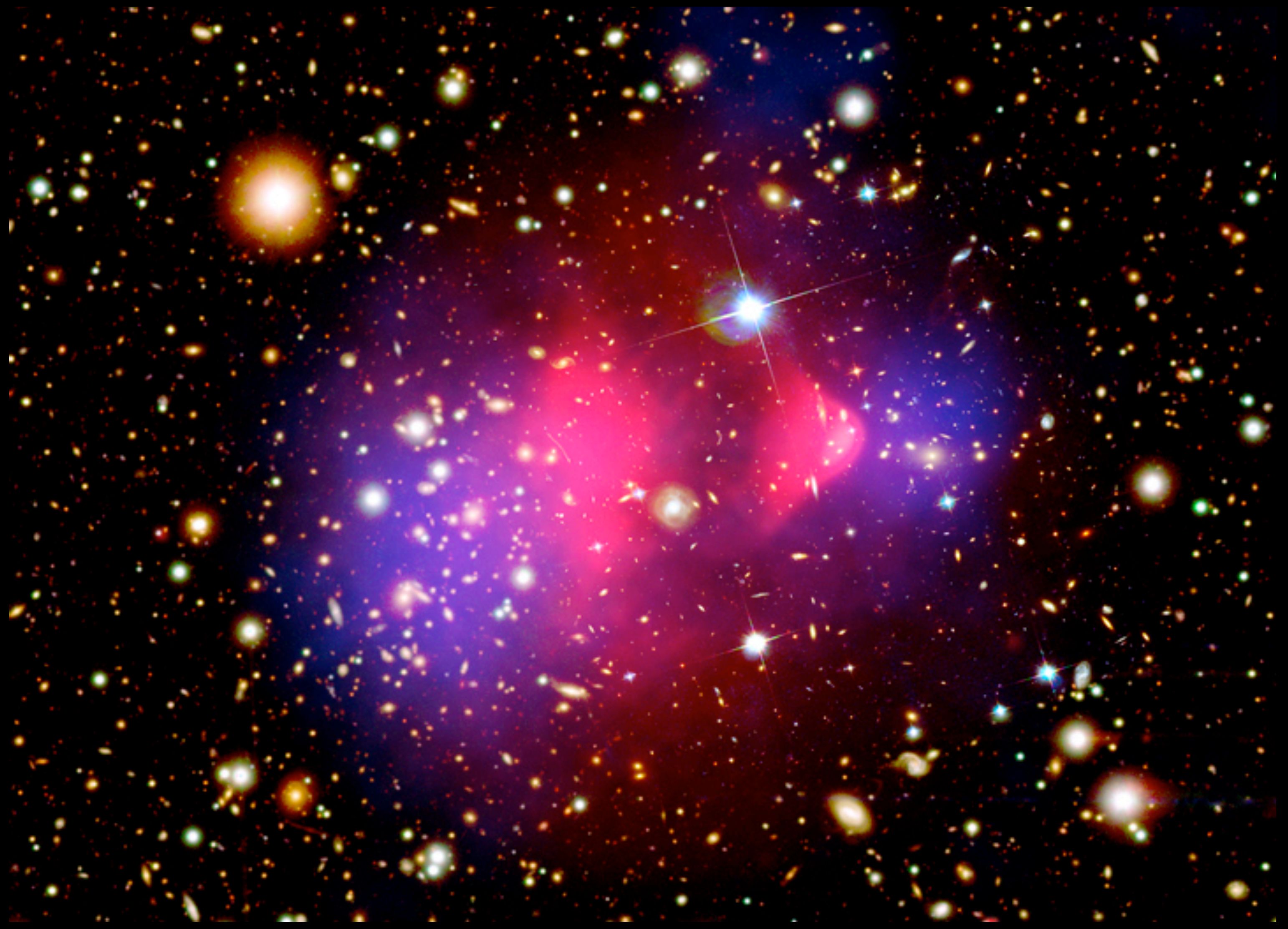
DARK MATTER

Early cosmology, BBN, CMB concordance that the picture of the mass-energy balance in the Universe today looks like





DARK MATTER INTERACTION WITH MATTER



via gravity

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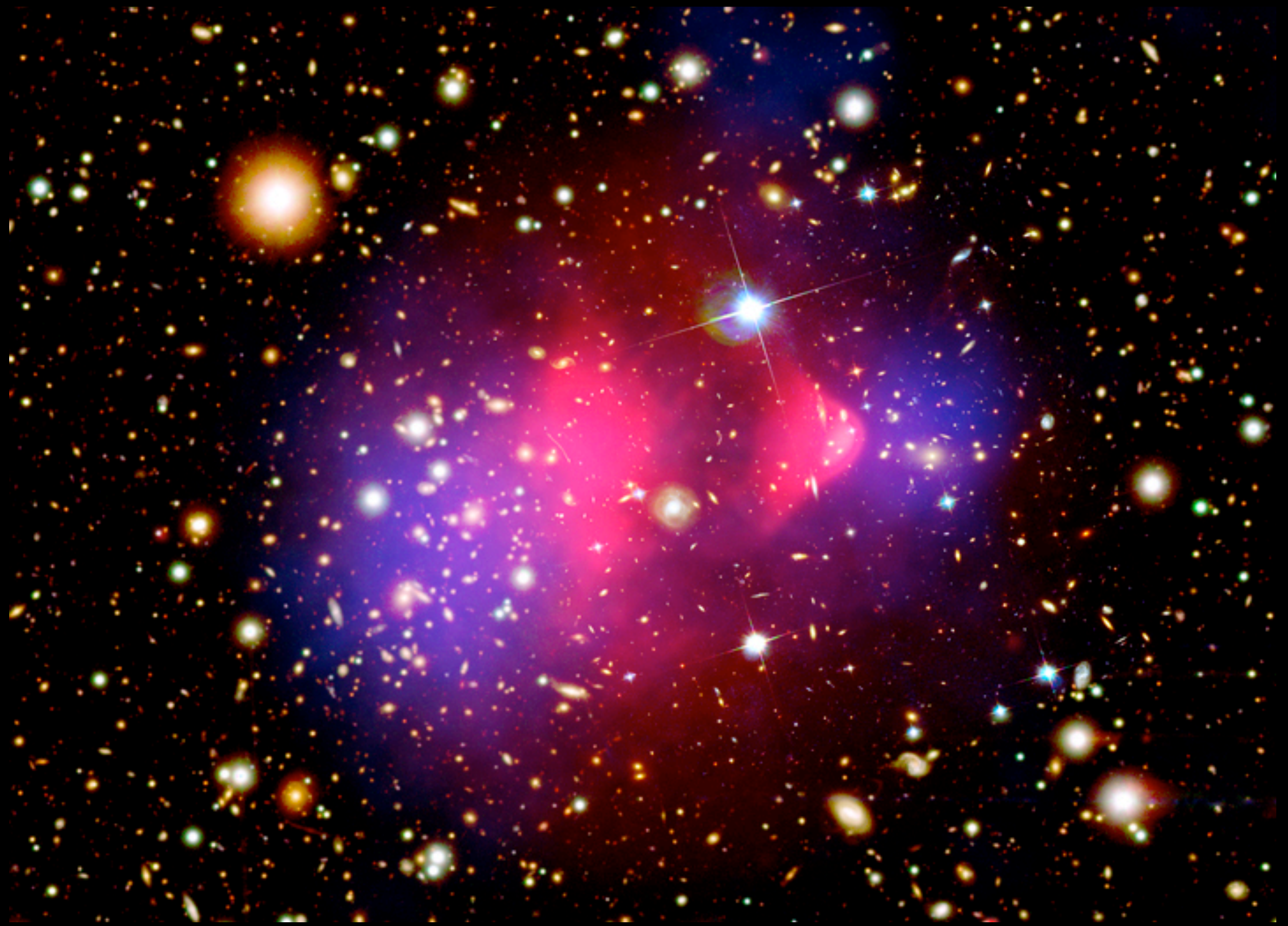

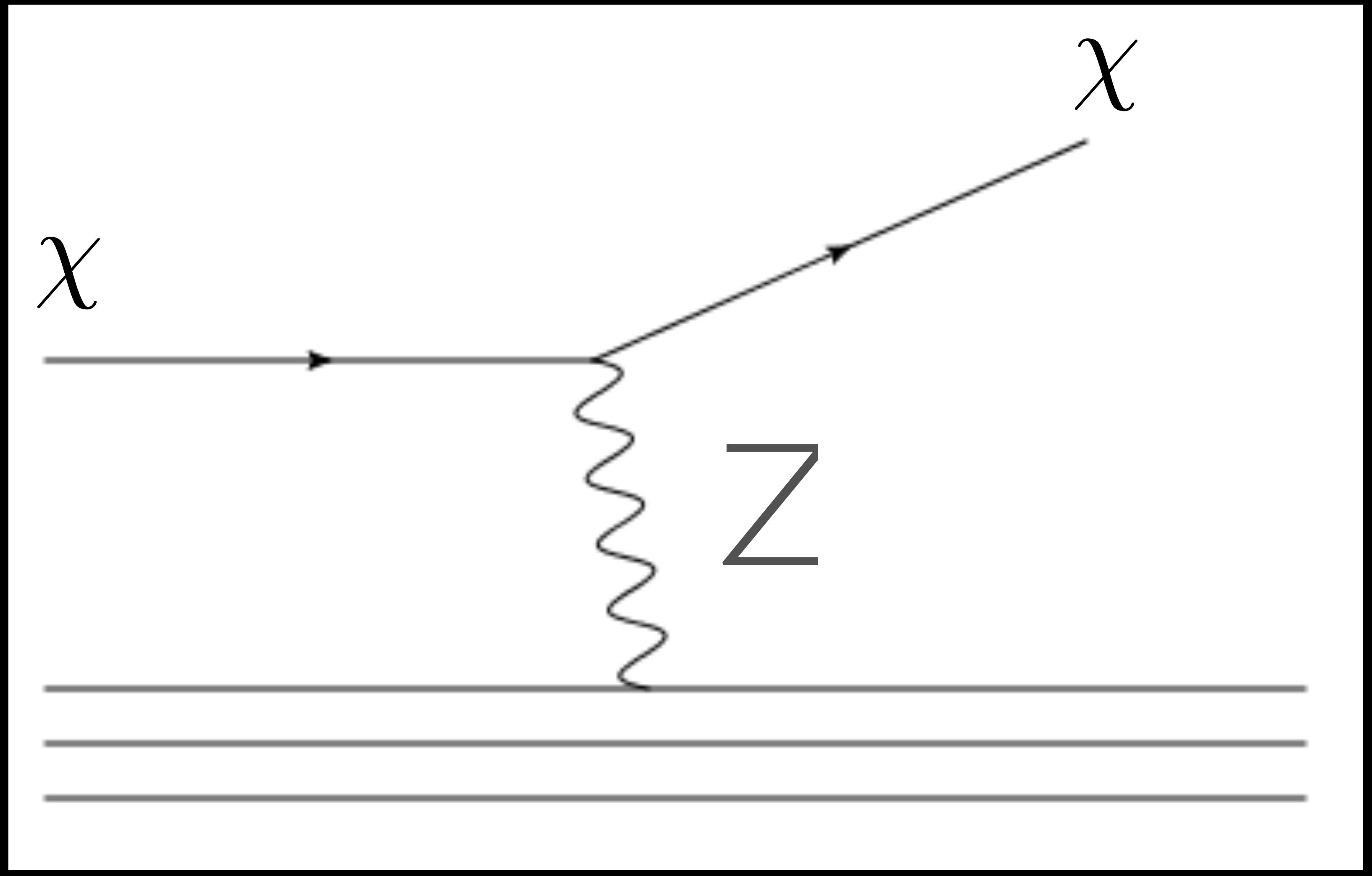

via gravity

via weak interactions
like neutrinos

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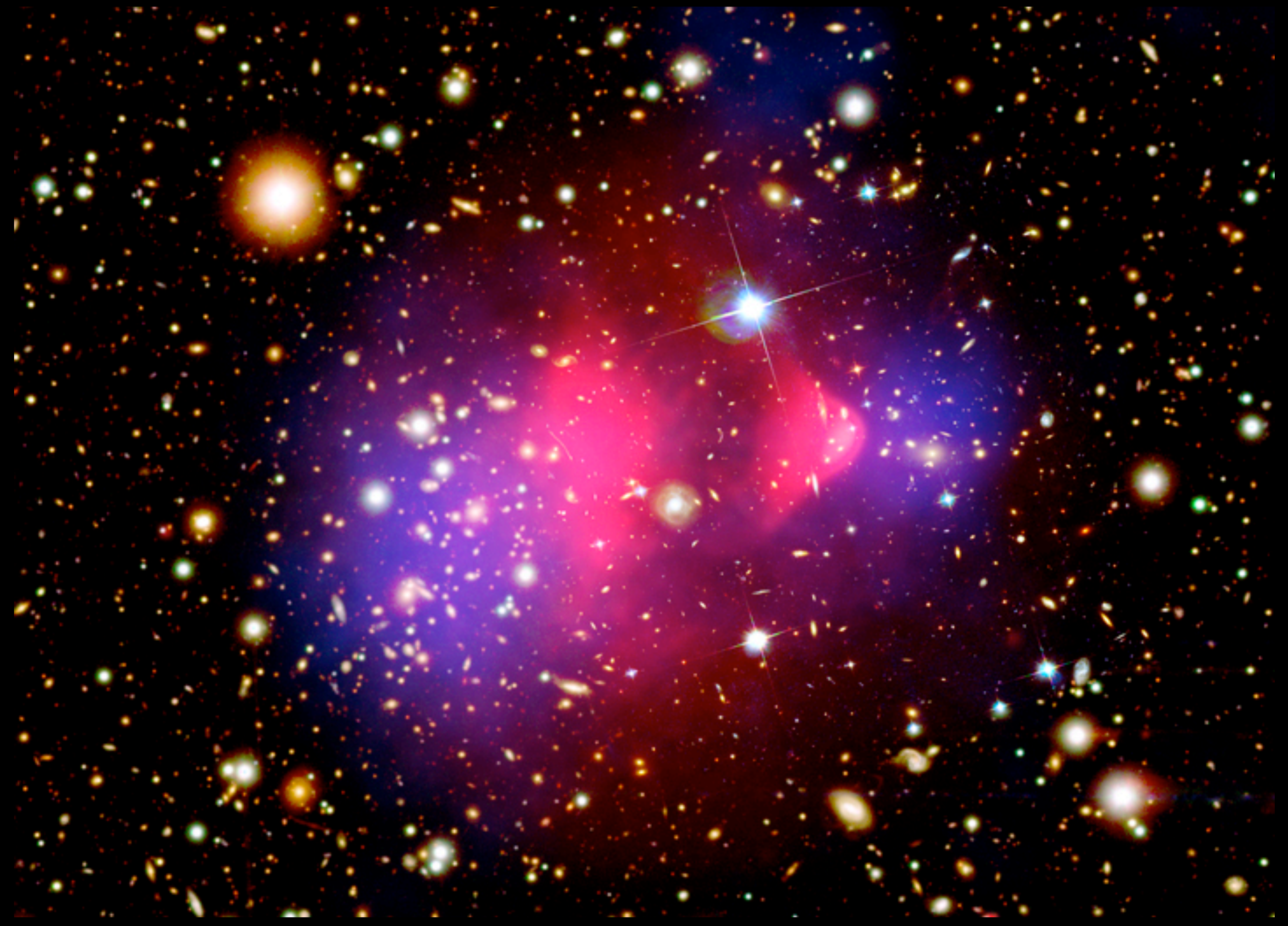

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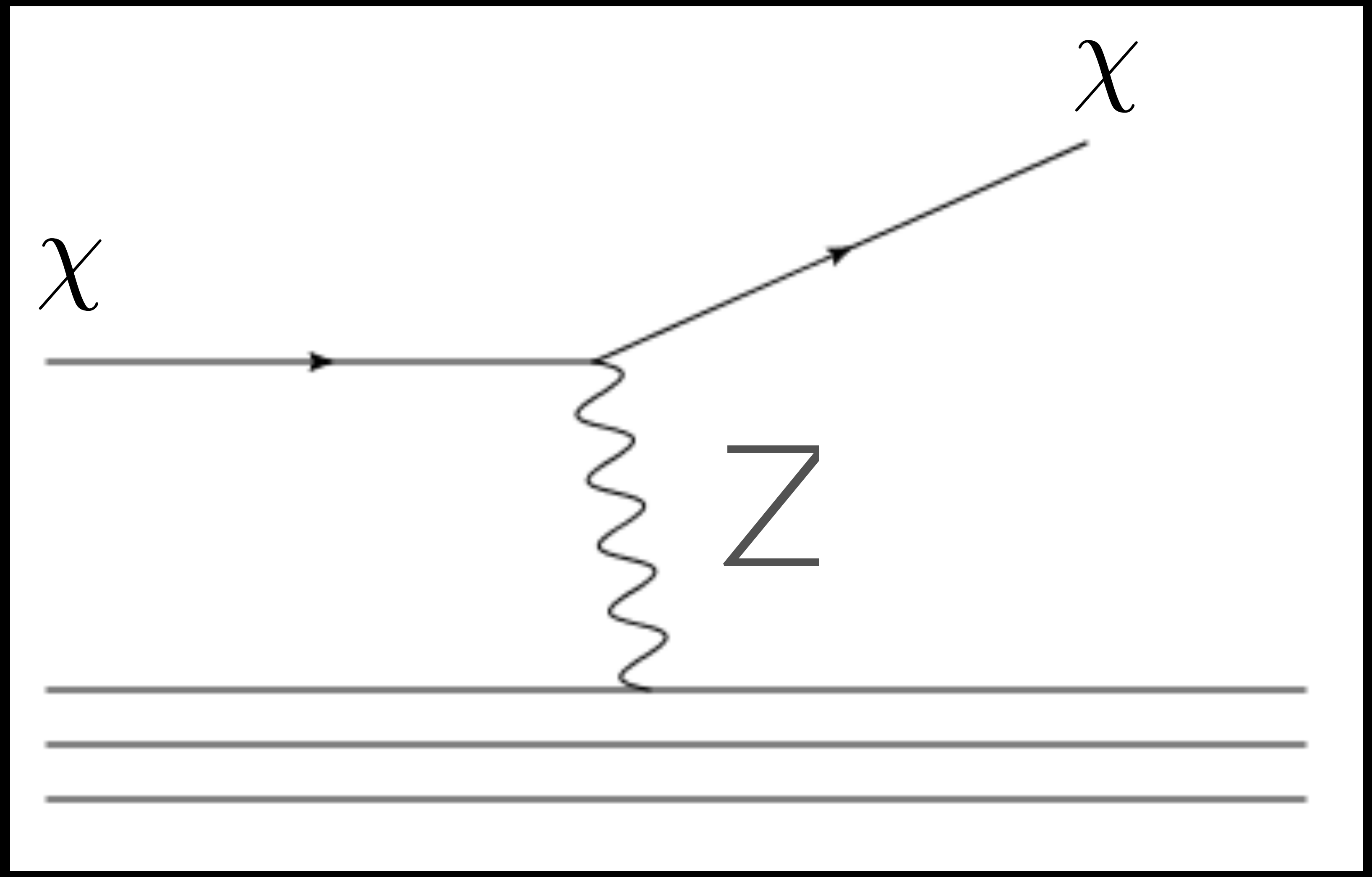

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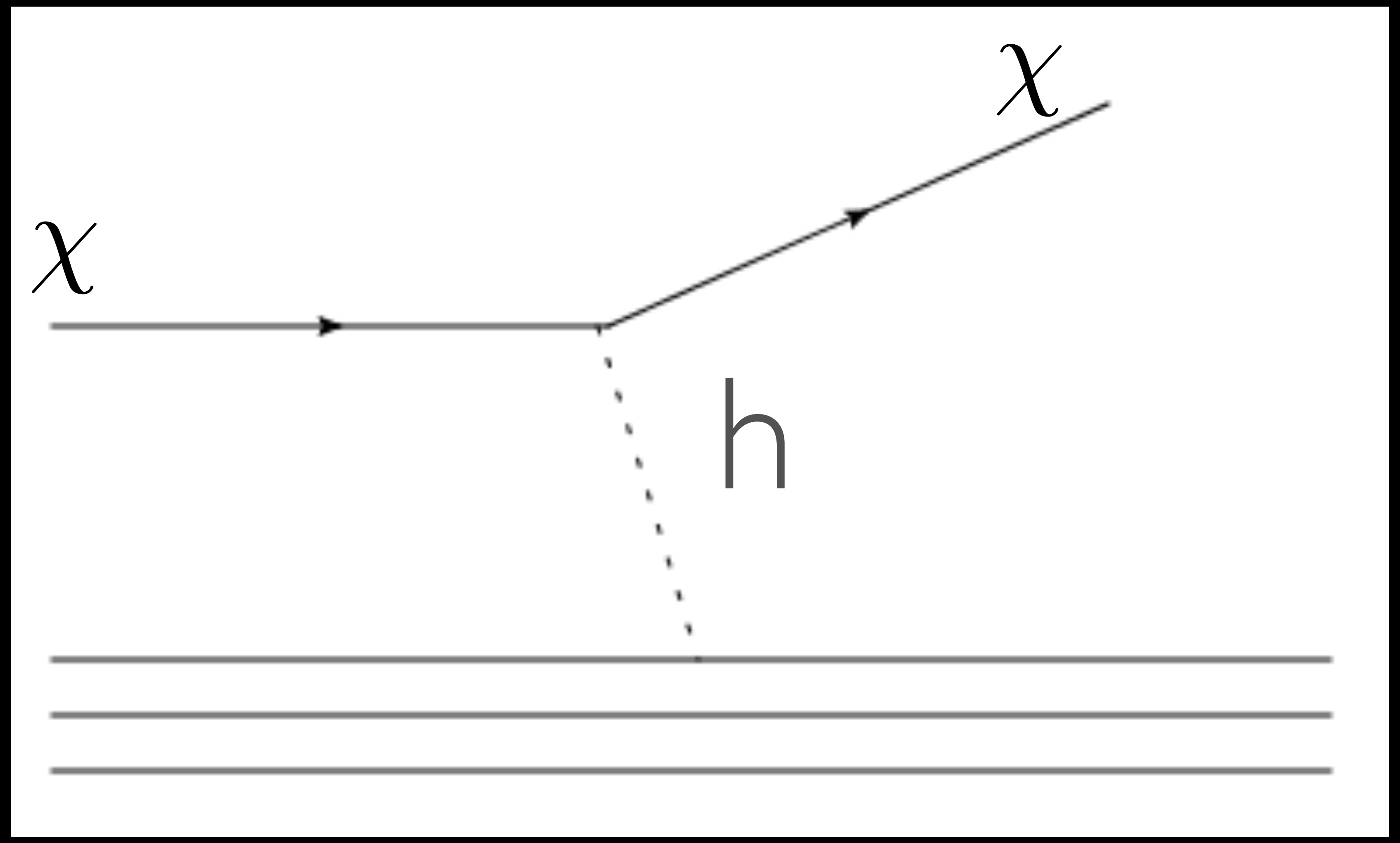

via the newly discovered Higgs Boson

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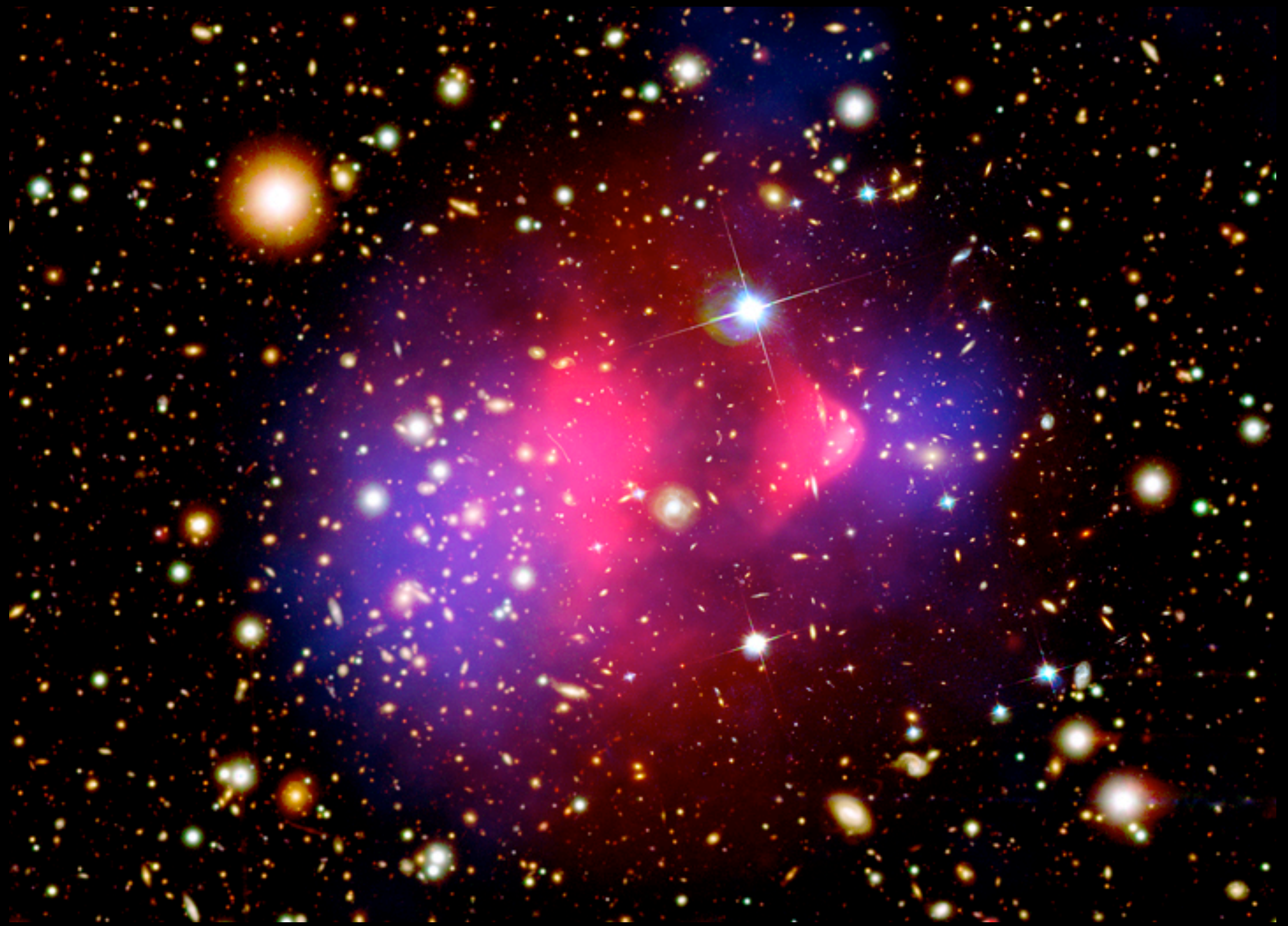
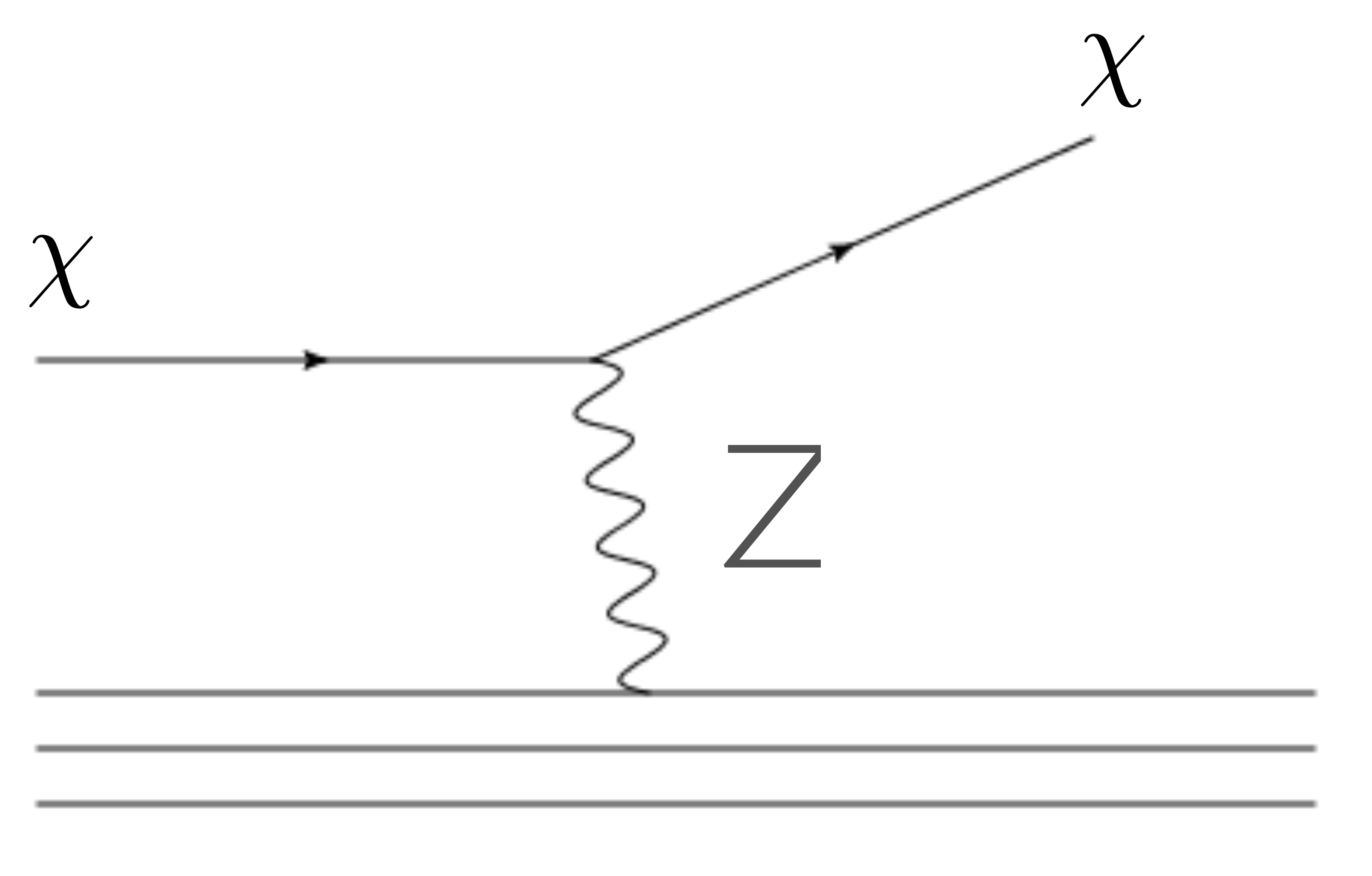
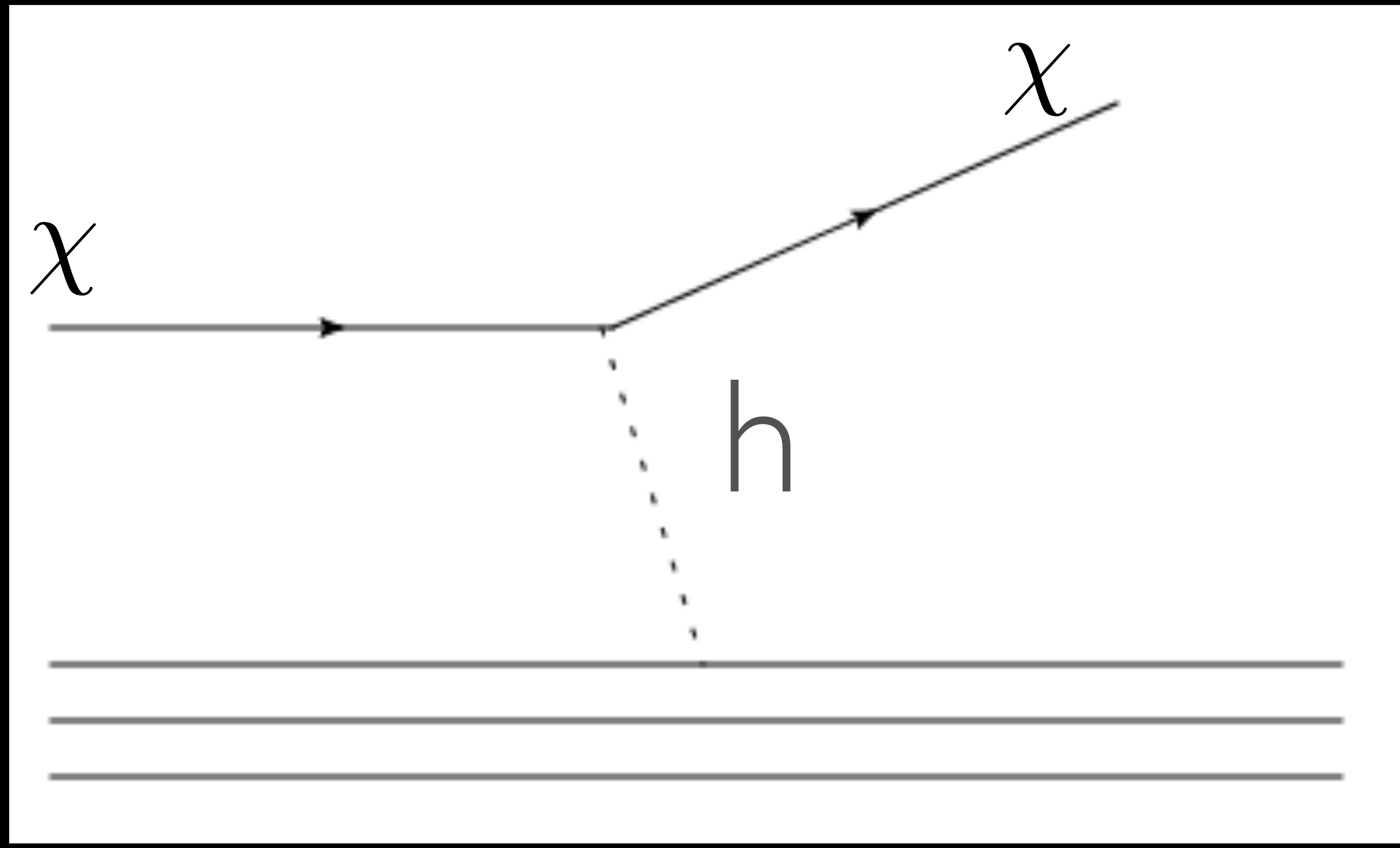






via gravity

via weak interactions like neutrinos

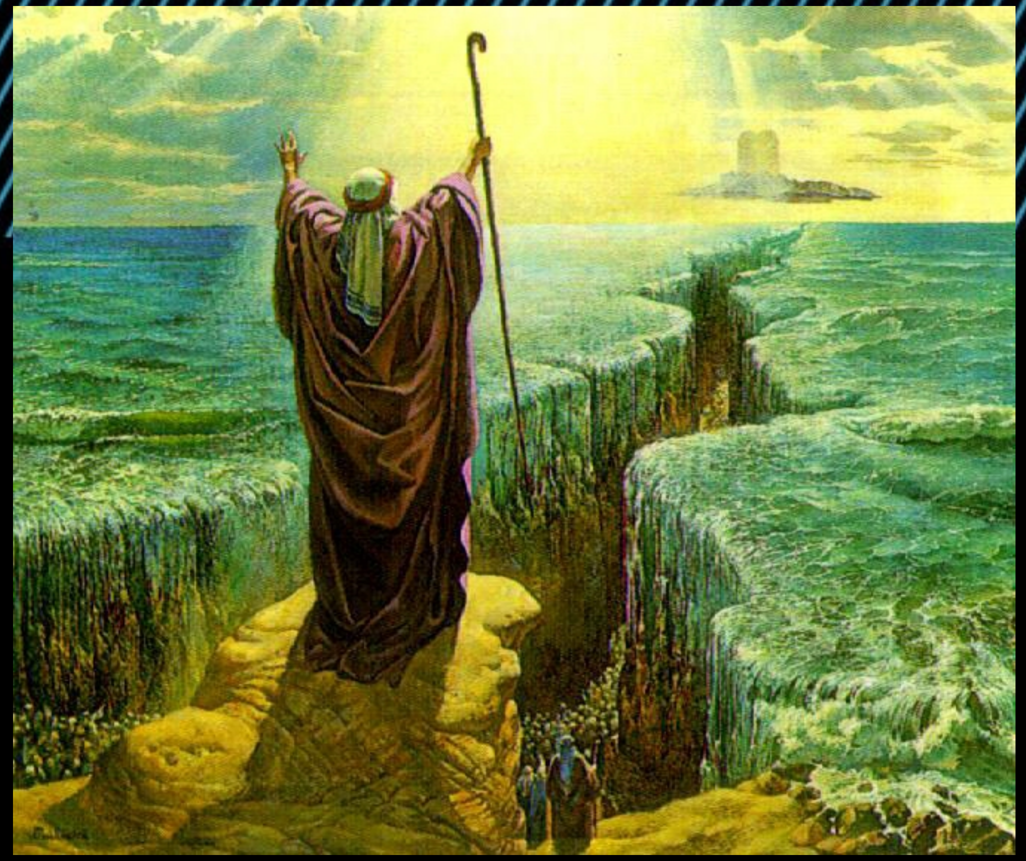
via the newly discovered Higgs Boson

via some exotic dark force?

WIMP DARK MATTER

- Weakly Interacting Massive Particles
- **Cold** i.e. nonrelativistic speeds
- Could have been in thermal equilibrium with ordinary matter early on in the Big Bang
- The rate at which the dark matter can annihilate into ordinary matter would determine how much is around today, the ”thermal relic density”

WIMP DARK MATTER



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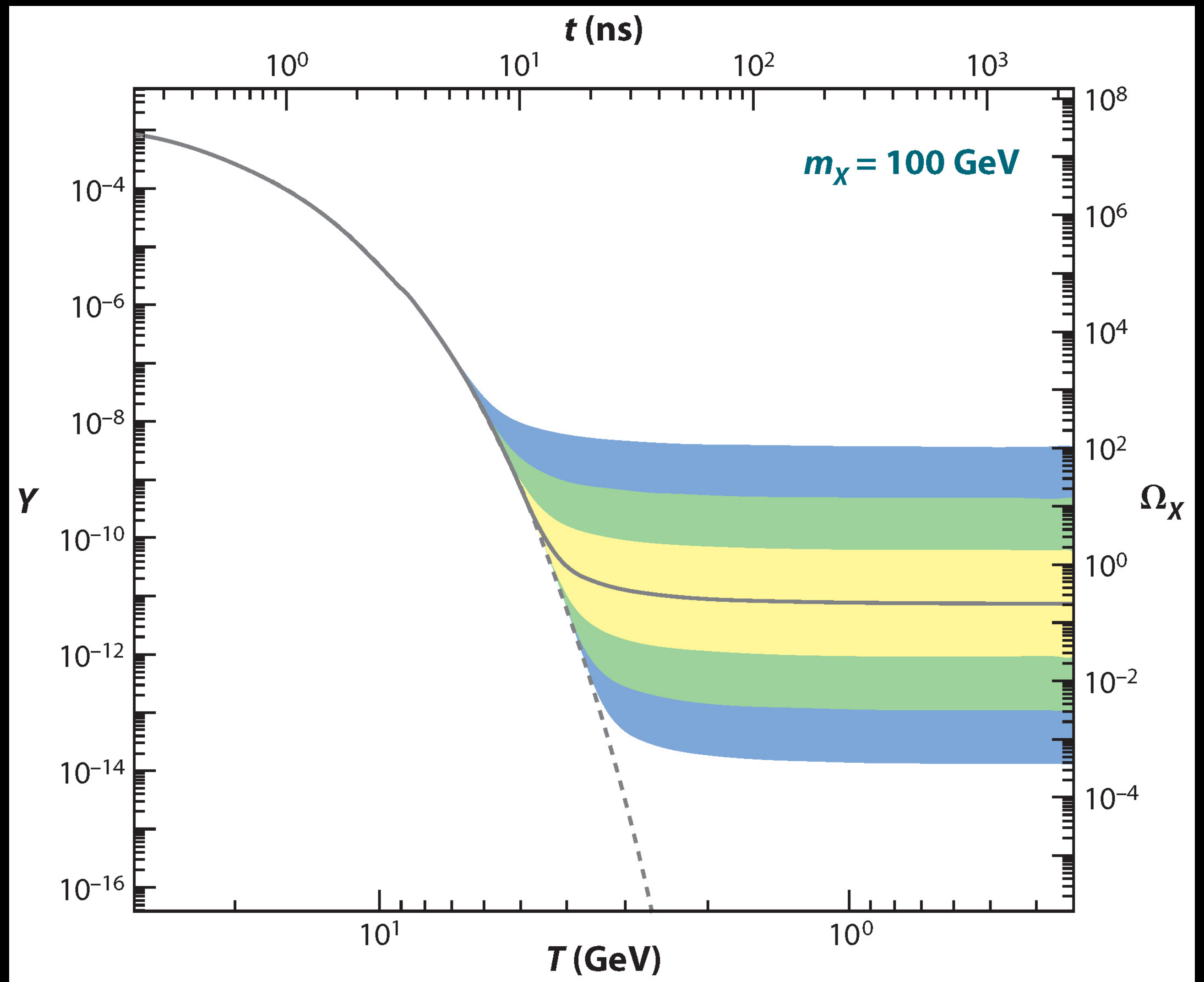

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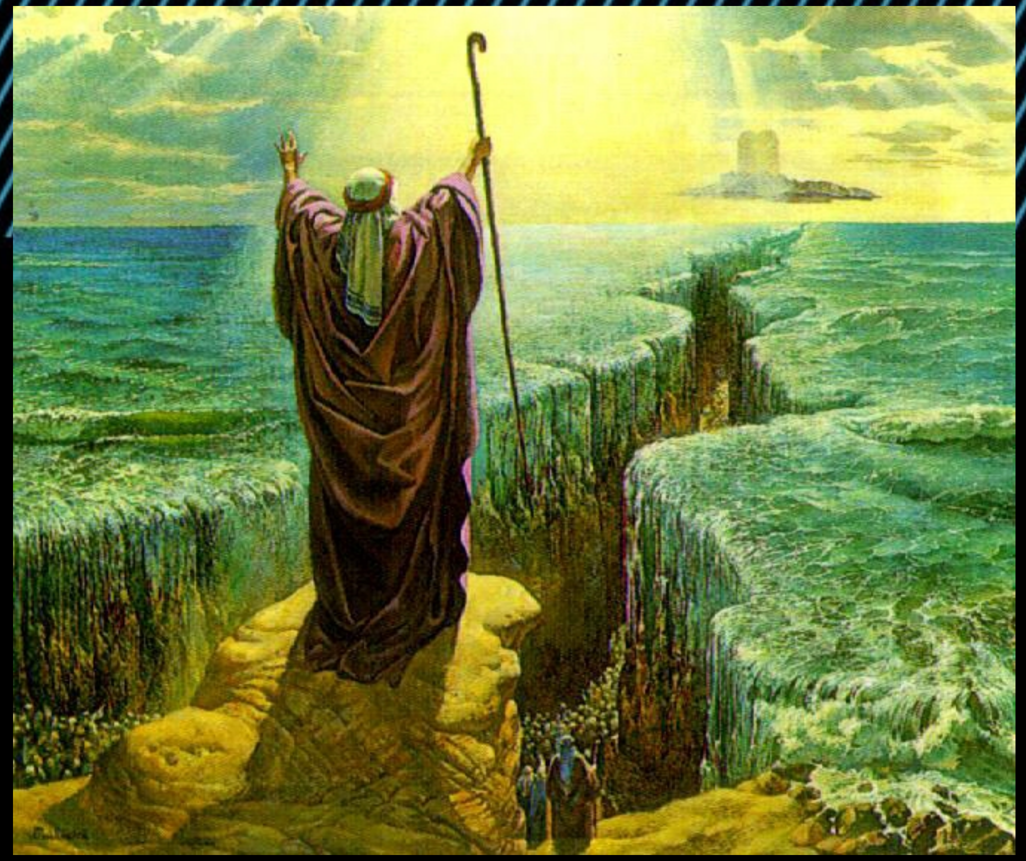

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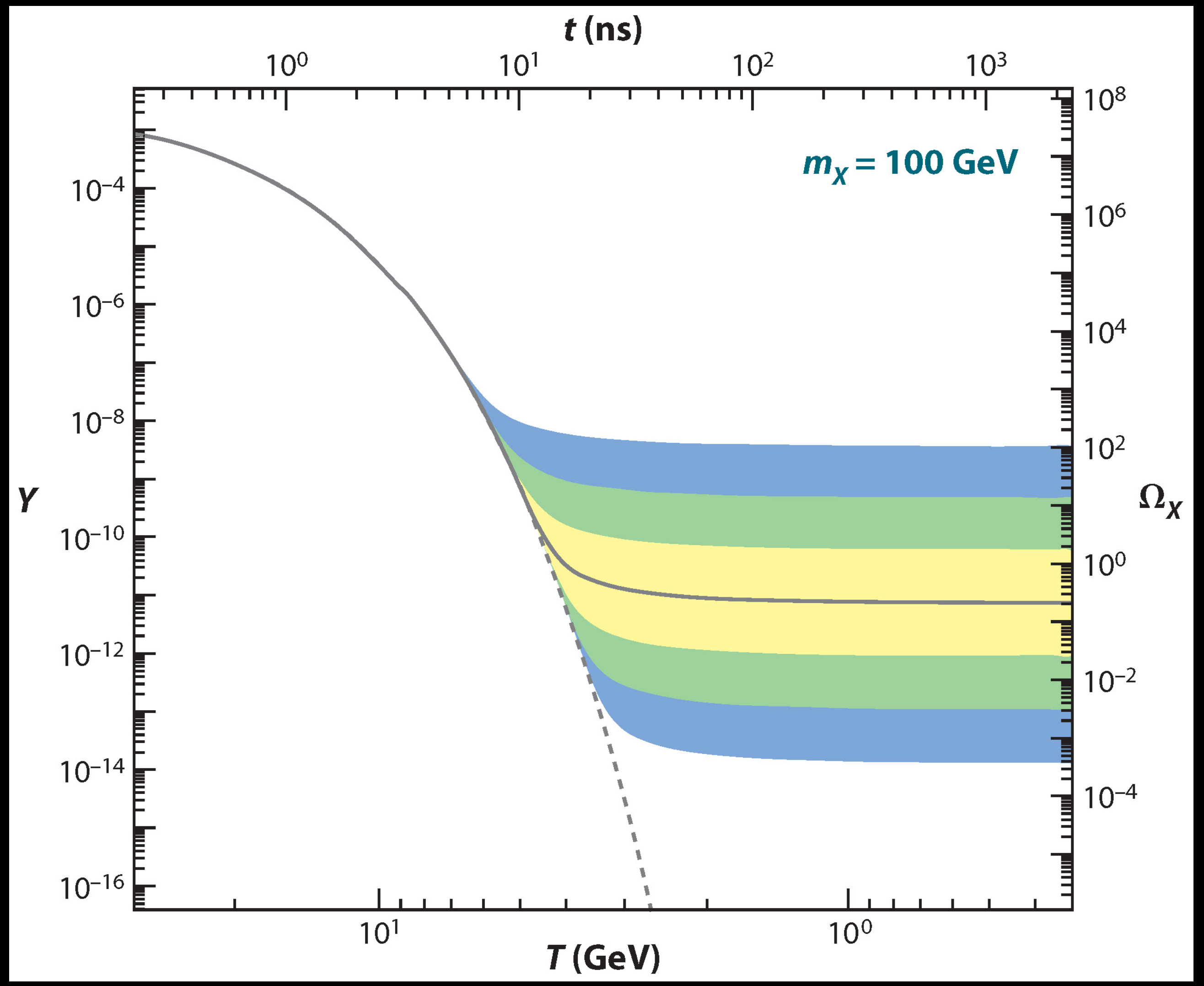


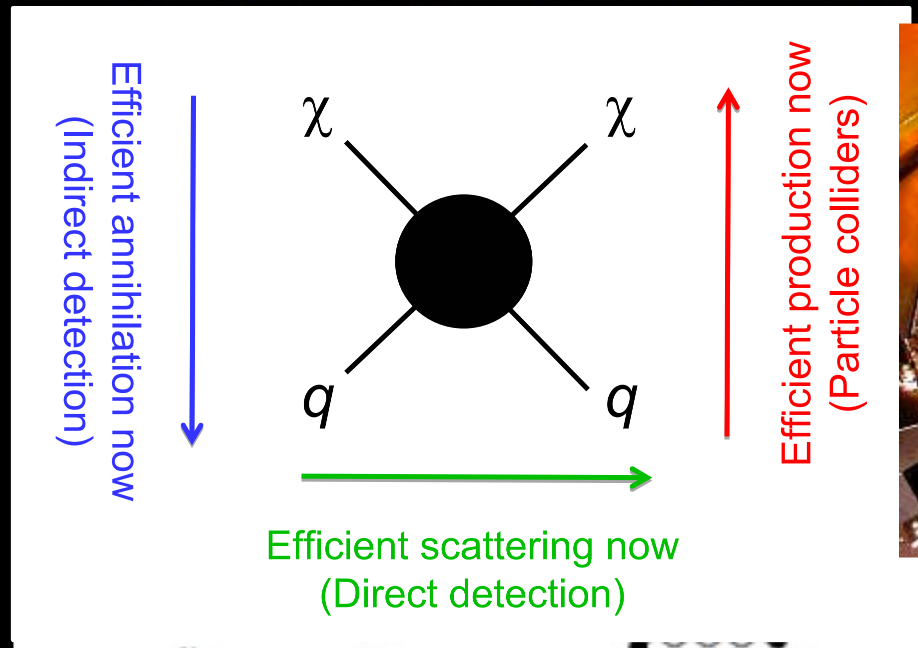
$$\mathbf{\Omega_x h^2 = \frac{3 \cdot 10^{-27}\ cm^3/sec}{\langle \sigma_A v \rangle}}$$

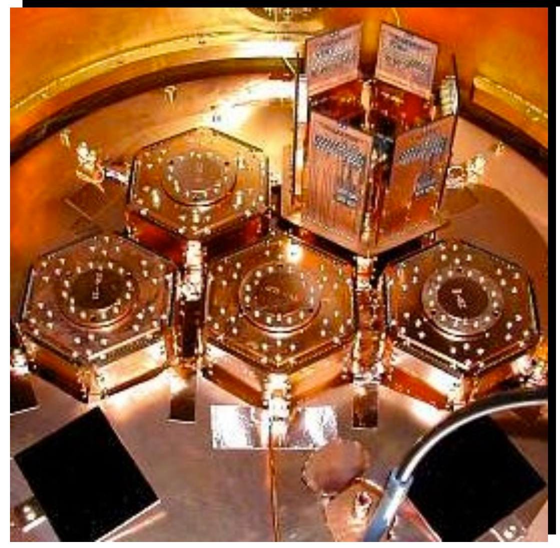
$$\sigma_\mathbf{A} \sim \frac{\alpha^2}{\mathbf{m}_\chi^2}$$

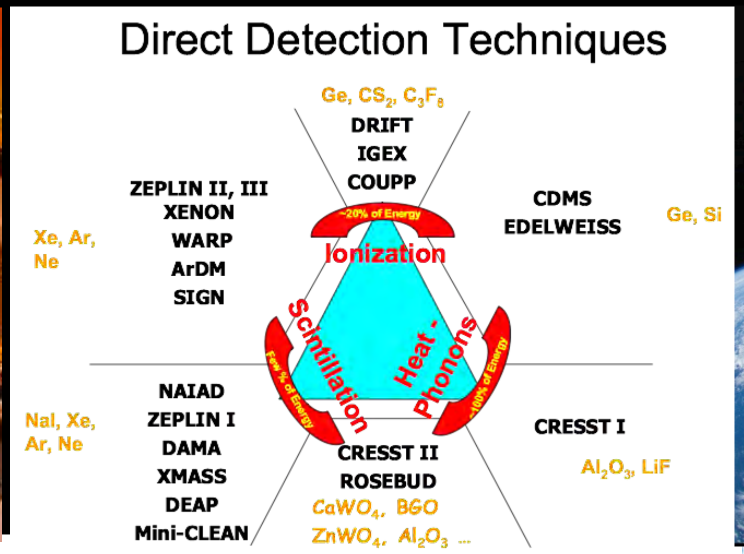
$$\mathbf{m}_\chi \simeq \mathbf{100\ GeV}$$

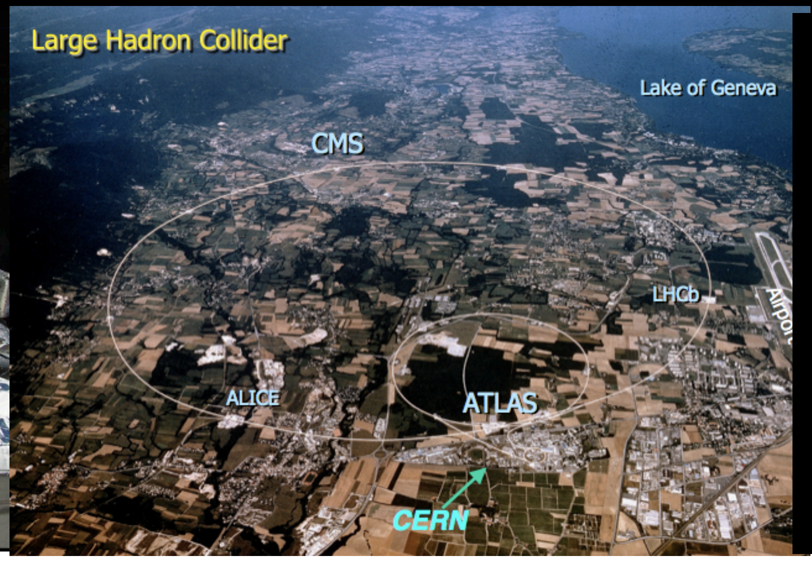
WIMP density “freezes out” when annihilation rate ~ expansion rate

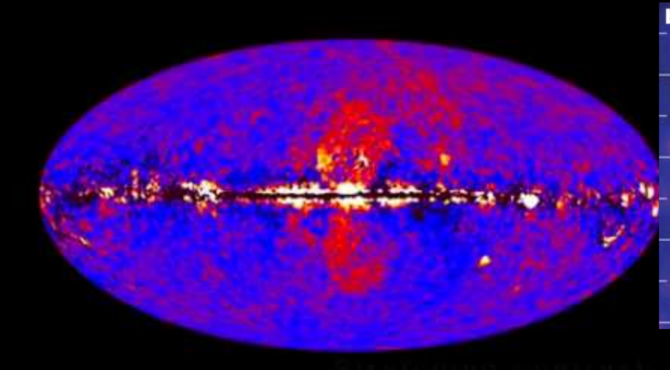
WIMP DARK MATTER & TERRA INCOGNITA

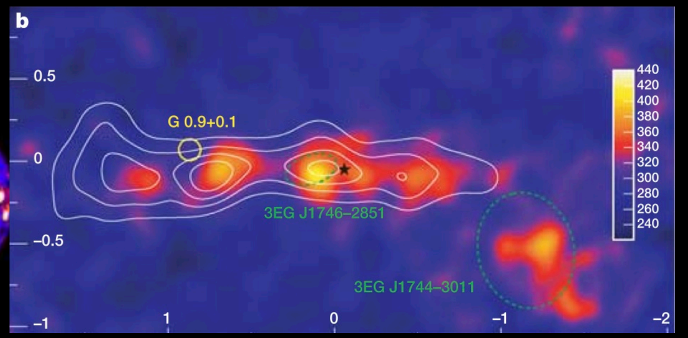


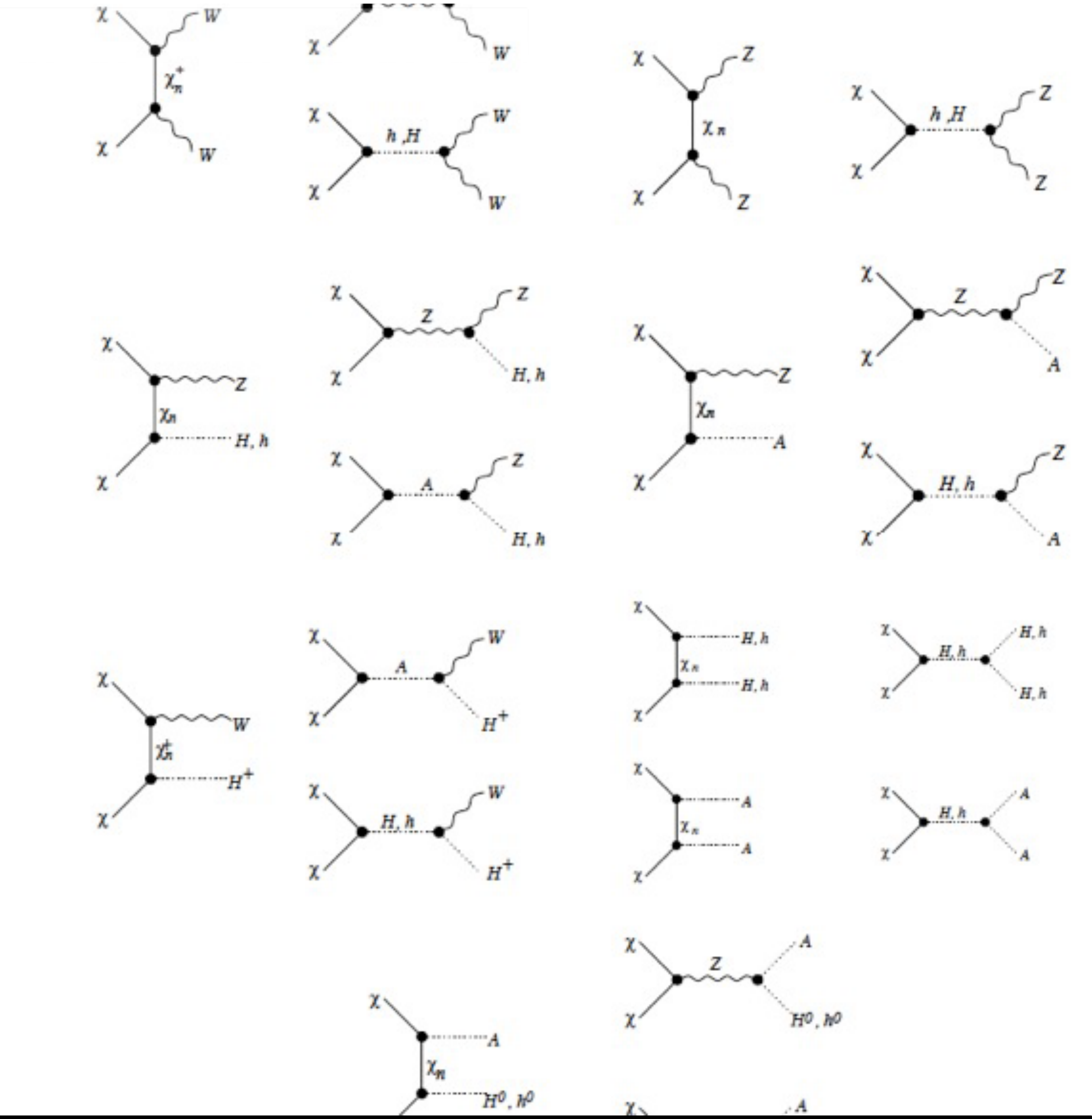


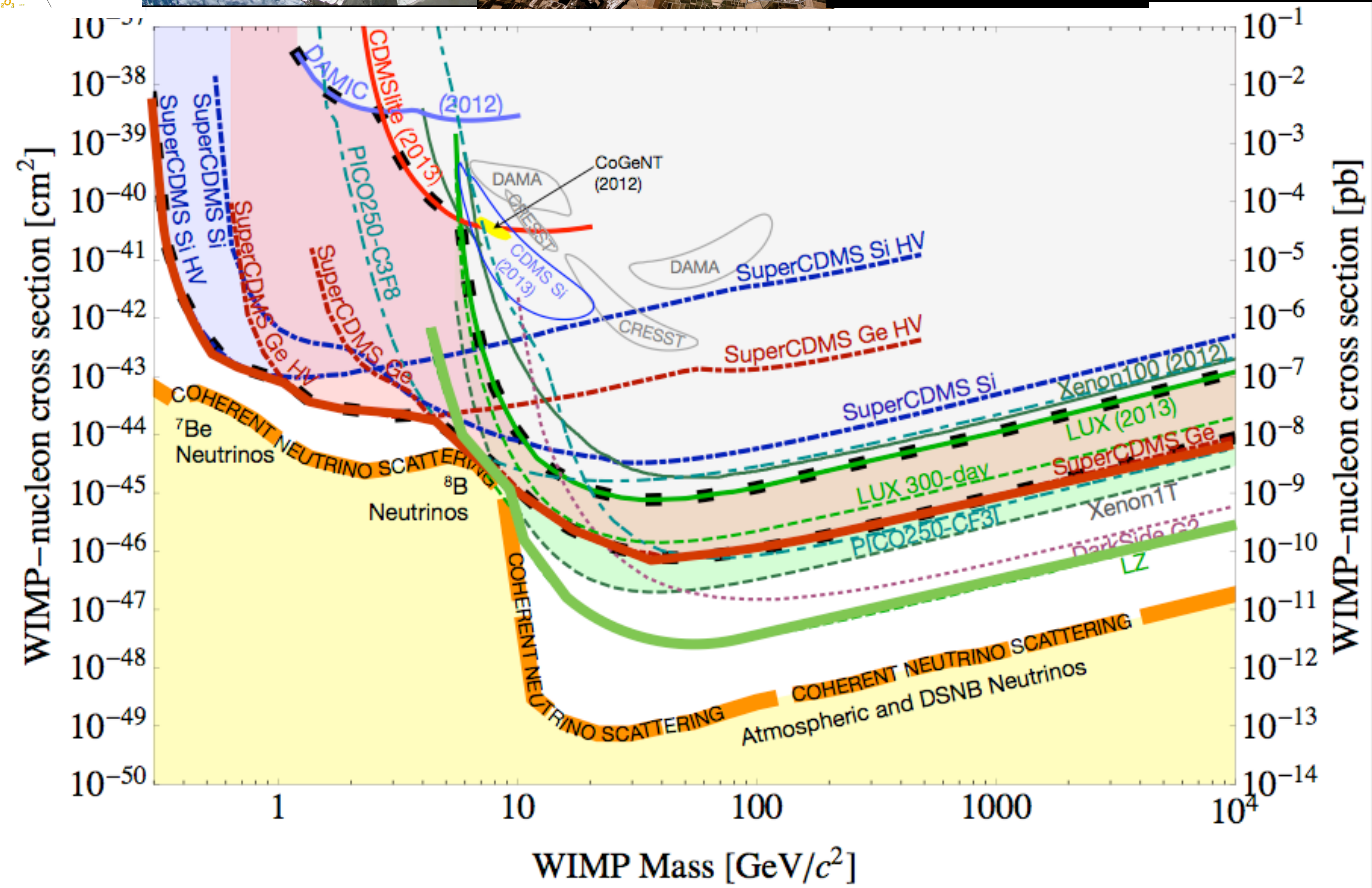




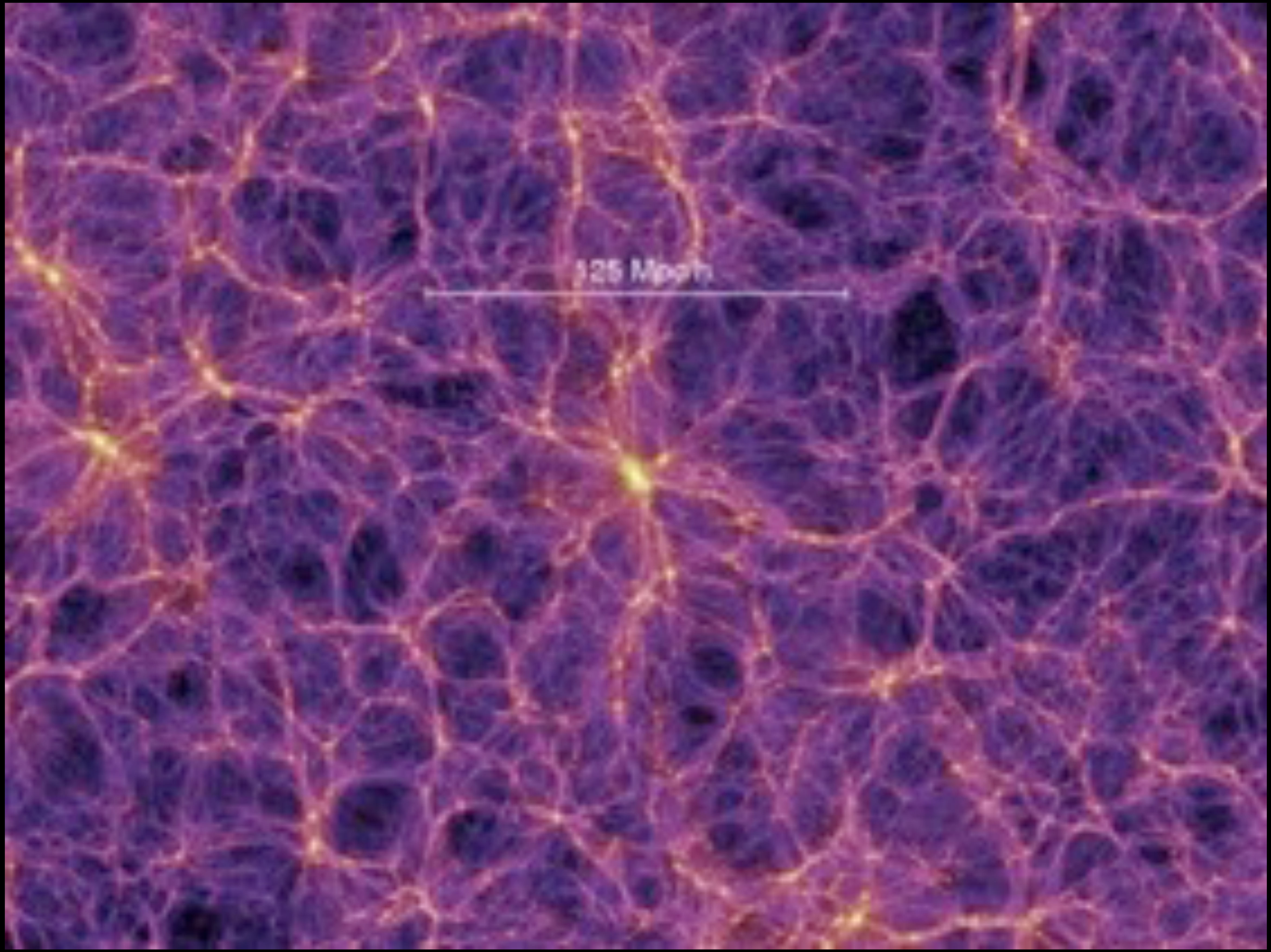








DARK MATTER & NEW PHYSICS



The biggest problem in physics today

HIGGS CONNECTIONS TO "THE BEYOND"

- Is there a Higgs portal to dark matter
- Electroweak baryogenesis
- What principle creates and stabilizes the electroweak scale
- How does the Higgs talk to neutrinos
- What are the dynamical origins of fermion masses, mixings and CP violation
- Extra credit: is the Higgs related to inflation or dark energy

Needs a multi-decade global experimental effort on many fronts, with new ideas and new technologies

THE COMING DISCOVERIES

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