中国科学院高能物理研究所
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New Physics beyond the Standard Model

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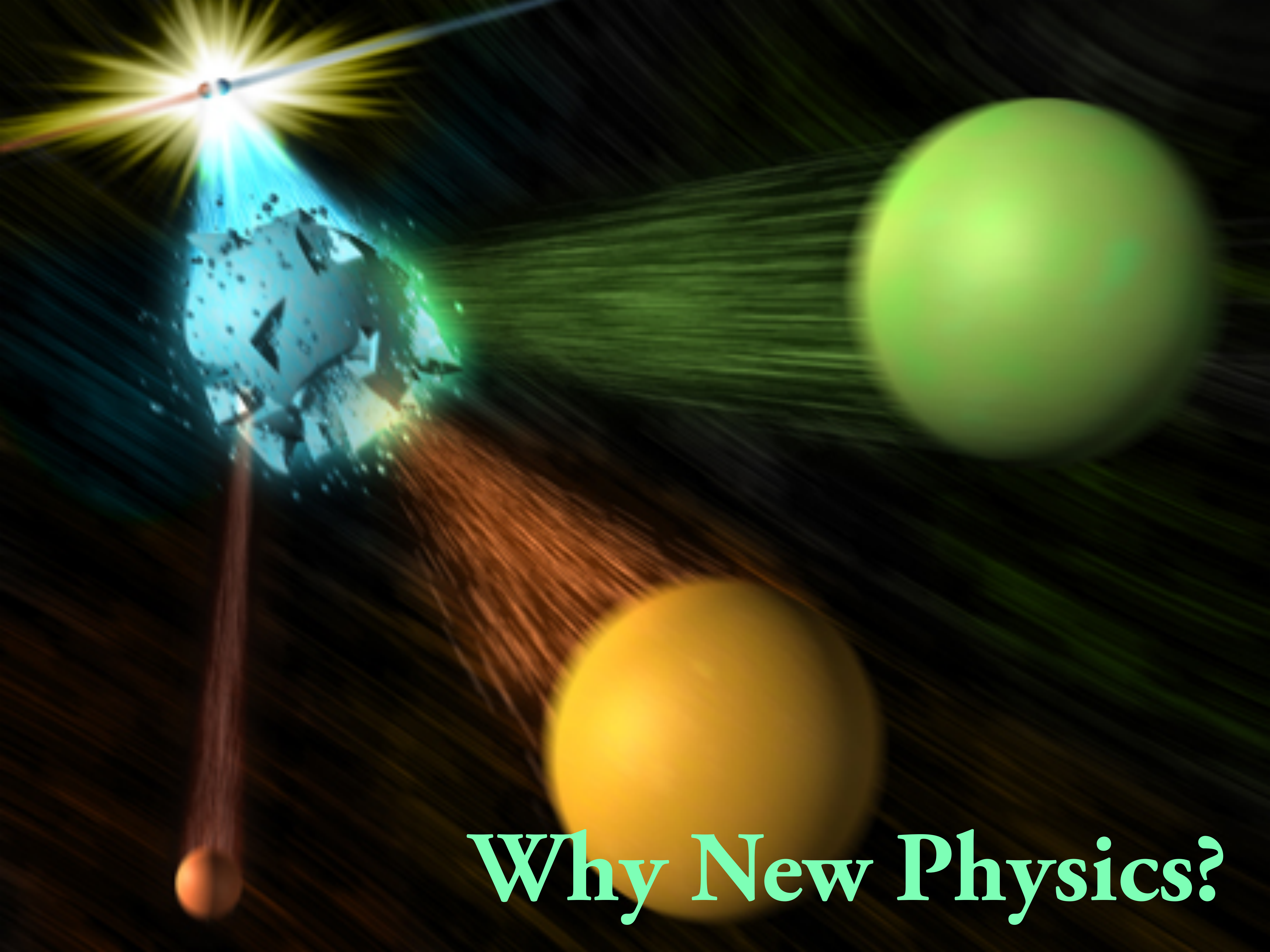
Outlook

- Why new physics?
- Some popular new physics models.
- New physics beyond new physics models.



Why New Physics?

THE STANDARD MODEL OF
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

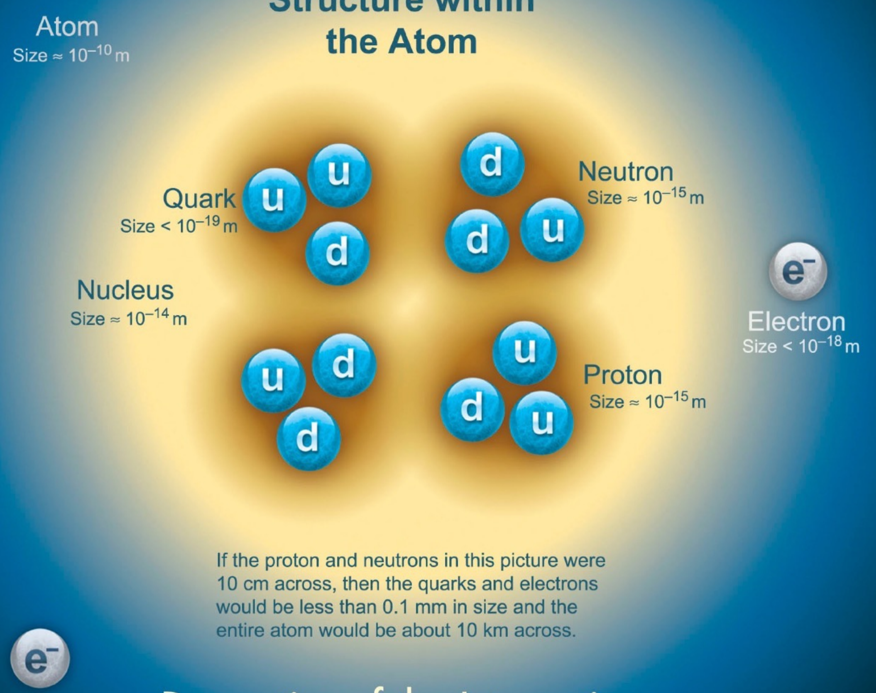
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at **ParticleAdventure.org**

Properties of the Interactions

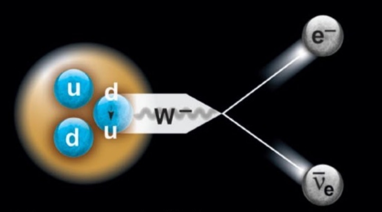
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

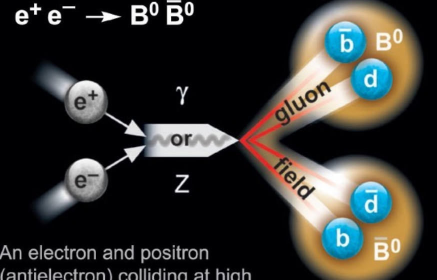
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

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U.S. Department of Energy, U.S. National Science Foundation, & Lawrence Berkeley National Laboratory.

THE HISTORY AND FATE OF THE UNIVERSE

The Big Bang, Inflation & the Expanding Universe

The universe has been expanding since an initial moment called the Big Bang that occurred 13.8 billion (13.8×10^9) years ago. The earliest expansion – called "inflation" – was extraordinarily rapid and smoothed out any wrinkles or imperfections, just as we can stretch out a wrinkled fabric. After inflation ended in a tiny fraction of a second, the universe continued to expand, becoming cooler and less dense. The expansion causes the distance between distant galaxies to increase, and thus the distance from us to them.

A Relic from the Early Universe

For the first 380,000 years the universe was so hot that hydrogen atoms had not yet formed, but were separate electrons and protons. Photons, the particles of light, bounced back and forth from collisions with the electrons. With further cooling, the electrons and protons stuck together in neutral atoms, nearly invisible to the photons, which then escaped. We can see these very same photons today. After traveling for 13.8 billion years they arrive, but with their wavelength stretched by a factor of 1100, since the universe itself has stretched by this factor during that time.

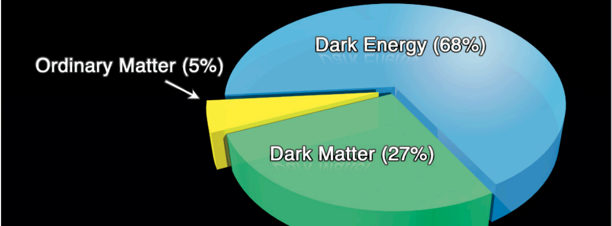
This Cosmic Microwave Background (labeled in the central figure) is nearly the same viewed in every direction. The very small variations – a part in 100,000 – are evidence of the small variations, which grew through gravitational attraction, to make the much larger variations we see today, things such as galaxies and solar systems.

Dark Matter

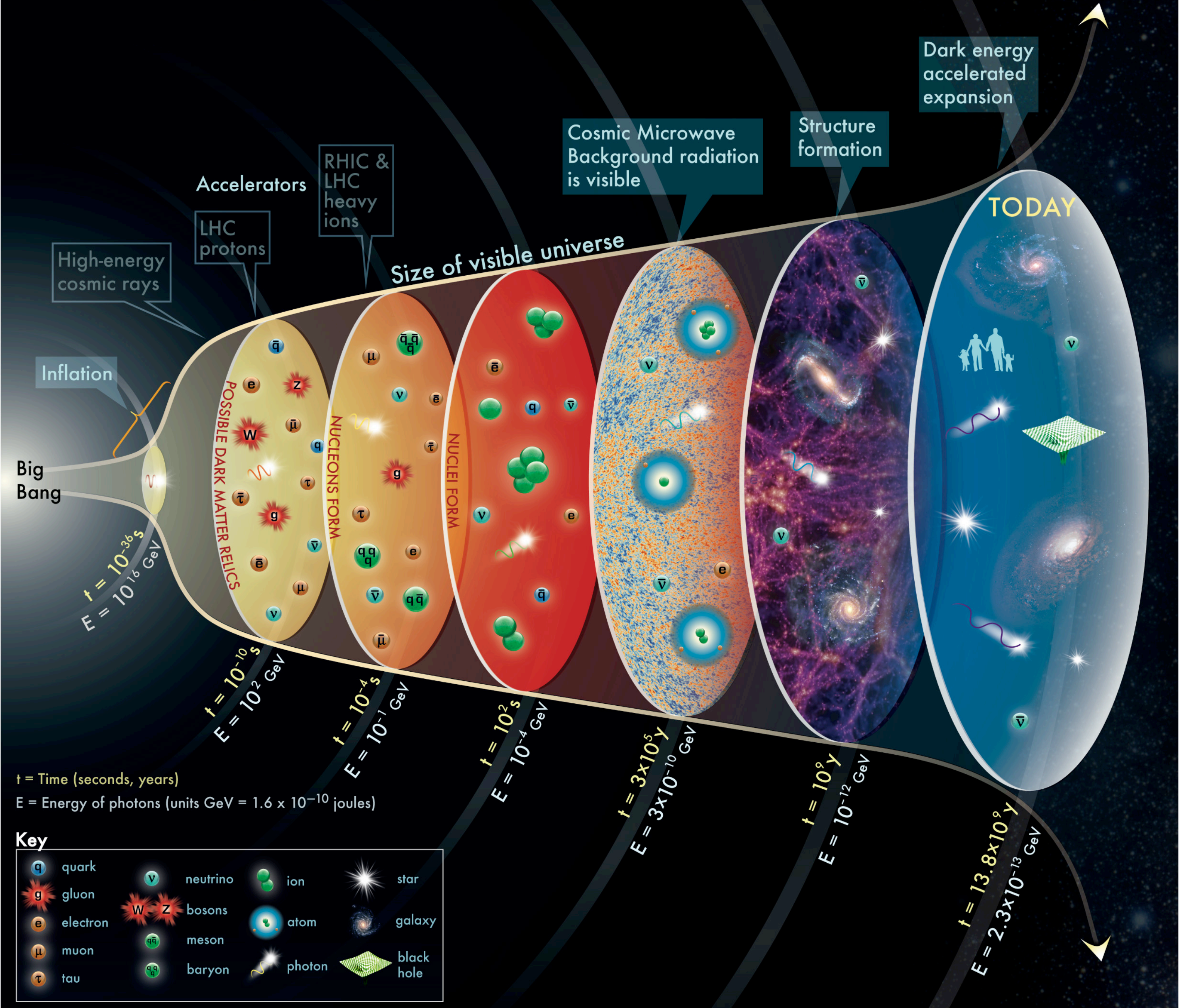
Astronomers discovered that stars far out in a rotating galaxy move just as fast as those nearer the center. This is completely unlike our solar system where the innermost planets move the fastest. This couldn't happen if the matter in the galaxy is concentrated where we see stars; there must be much more unseen matter in the galaxy. This matter doesn't emit light or reflect it, so we call it dark matter. Since dark matter doesn't clump together with ordinary matter, we believe it interacts only feebly with the matter that makes up stars, planets, and people.

We have observed the results of a collision of two clusters of galaxies where the dark matter from the two clusters seems to have passed right through the other cluster, leaving behind the debris from the collision of the ordinary gas in the two clusters. Detailed measurements show that there is about six times more dark matter than ordinary matter in our universe.

Composition of the Universe



Ancient light from sources billions of light-years away, such as galaxies and the cosmic background radiation, show us events occurring billions of years ago. These events map out the history of the universe and even predict its fate. The scales in this figure are often greater by many orders of magnitude than can be shown here (especially for inflation).



The concept for the above figure originated in a 1986 paper by Michael Turner.

Our Cosmic Address

Our sun is one of 400 billion stars in the Milky Way galaxy, which is one of more than 100 billion galaxies in the visible universe.

Invisible Skeleton of our Universe

Dark matter played a crucial role in the early universe creating all the structures we see today. Gravity caused the dark matter to coalesce into strands forming an invisible skeleton, as shown in the central figure (indicated by "Structure formation"). The gravity from the dark matter pulled ordinary matter to it. Then galaxies grew at the intersections of these filaments.

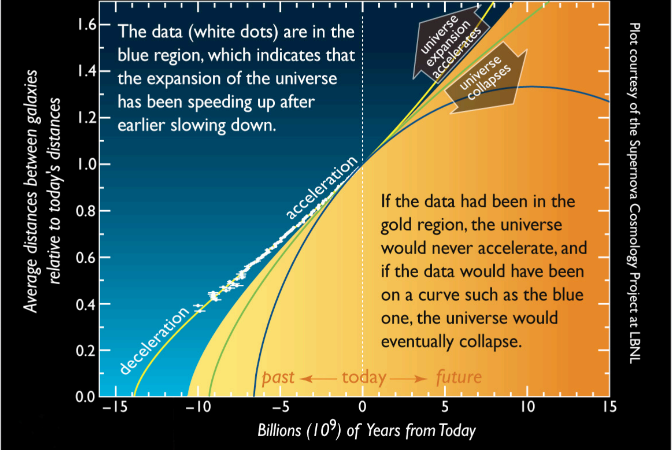
Dark Energy and the Accelerating Universe

By making detailed observations of distant supernovae, which are stars that exploded long ago, scientists discovered that the expansion of the universe is getting faster and faster instead of slowing down as would be expected from the effect of gravity pulling everything back together.

The plot shows data (white dots) from distant supernovae. From the brightness of a supernova we can infer how far away it is. By measuring the wavelengths of light from the supernova, we can determine how much the universe has expanded since the supernova explosion. Combining these gives the expansion history of the universe.

The yellow curve, with the best fit to the supernovae data, shows that about 6 billion years ago the expansion of the universe began to accelerate (the data curve upward slightly). This can only be explained by hypothesizing a new form of energy called "dark energy," which must be unlike any previously known source of energy.

Accelerating Expansion from Dark Energy



Plot courtesy of the Supernova Cosmology Project at LBNL

The Fate of the Universe

Whether the expansion of the universe will speed up, slow down, or even reverse into collapse depends on the types and amounts of matter and energy in it. Current observations imply that the universe will keep expanding forever, with galaxies becoming ever more distant from one another.

We have an excellent understanding of ordinary matter and all the particles discovered at accelerators, but these account for less than 5% of the energy and matter in the universe. The natures of dark energy (68% of the universe) and of dark matter (27%) are two of the greatest challenges scientists face today.

Learn more at
UniverseAdventure.org
and at CPEPphysics.org

CPEP is a non-profit organization of teachers, physicists, and educators. For information on charts, websites, text materials, hands-on classroom activities and workshops, see: CPEPphysics.org.

This chart has been made possible by the generous support of: **U.S. Department of Energy and Lawrence Berkeley National Laboratory.** Photos courtesy of **NASA.**

Why New Physics?

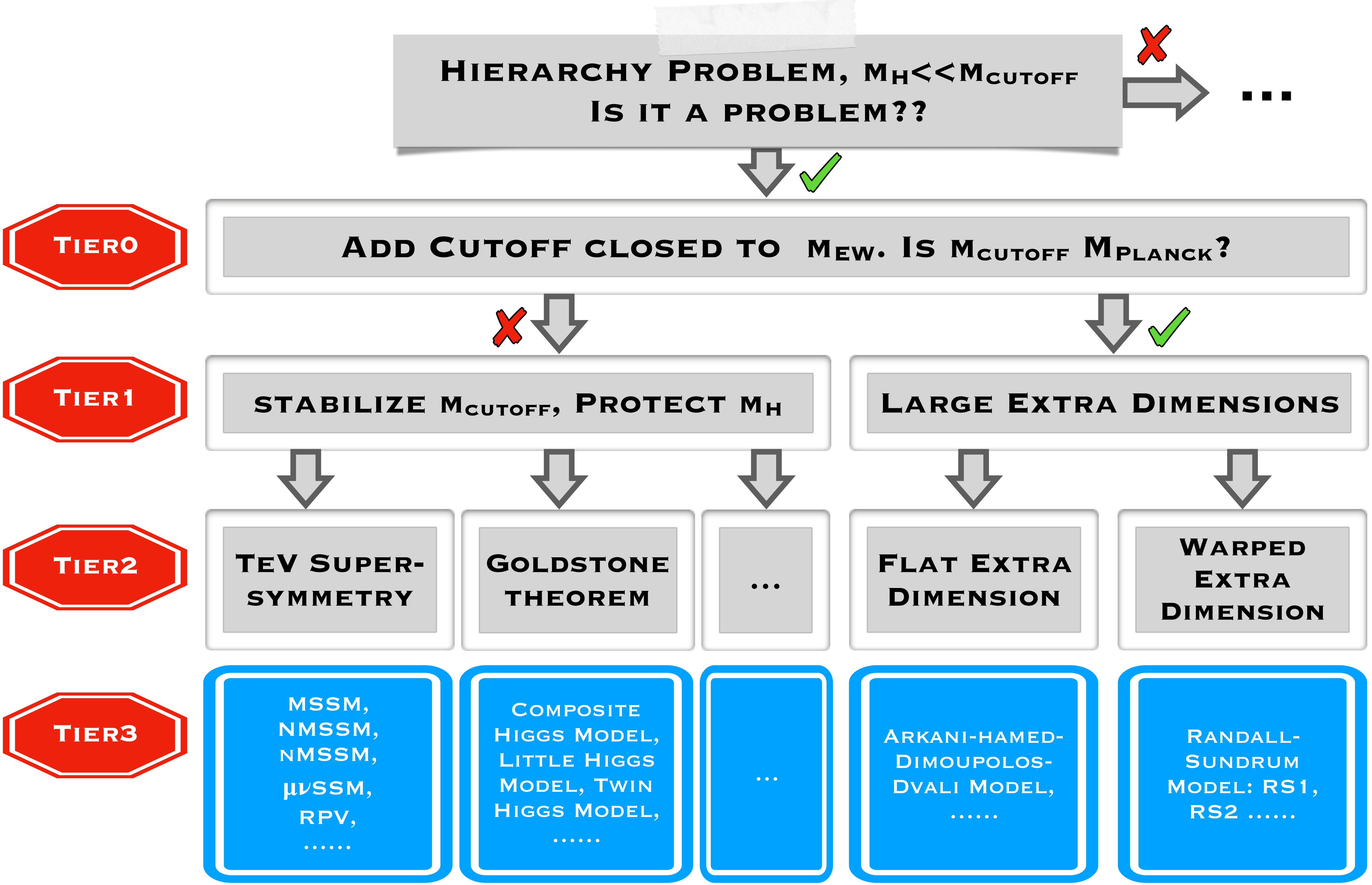
- Quantum gravity
- Cosmological constant hierarchy problems
- Unification of forces
- Higgs mass hierarchy problems
- Vacuum stability
- Origin of electroweak symmetry breaking
- Origin of parity violation
- CP-violation
- QCD vacuum
- Fermion mass hierarchy
- FCNC
- Matter-antimatter asymmetry, baryogenesis
- Dark energy
- Dark matter
- Neutrino mass and oscillation
- Muon g-2 anomaly
- More and more data…

Popular New Physics Models

Popular New Physics Models

- Superstring
- Grand Unification Theory
  - SU(5), SO(10), …
- SUSY Models
  - MSSM, NMSSM, nMSSM, …
- Extra Dimensions
  - UED, ADD, RS, …
- Composite Higgs Model
- Little Higgs Model
- Left-right Symmetry Model
- Twin Higgs Model
- …
- Seesaw Models
  - Type-I,II,III
  - Tree level, one-loop, two-loop, …
- Multi-Higgs Models
  - Singlet: real, complex
  - Doublet: 2HDM, Type-I,II,III,VI
  - …
- Dark Force
- Flavor Symmetry Models
- Axion
- …

Popular New Physics Models



Hierarchy Problem, $M_H << M_{cutoff}$
Is it a problem??

✗ → ...

✓

Tier0

Add cutoff closed to M_{EW}. Is M_{cutoff} M_{Planck}?

✗ ✓

Tier1

Stabilize M_{cutoff}, Protect M_H

Large Extra Dimensions

Tier2

TeV Super-symmetry

Goldstone theorem

...

Flat Extra Dimension

Warped Extra Dimension

Tier3

MSSM,
NMSSM,
NMSSM,
$\mu\nu$SSM,
RPV,
……

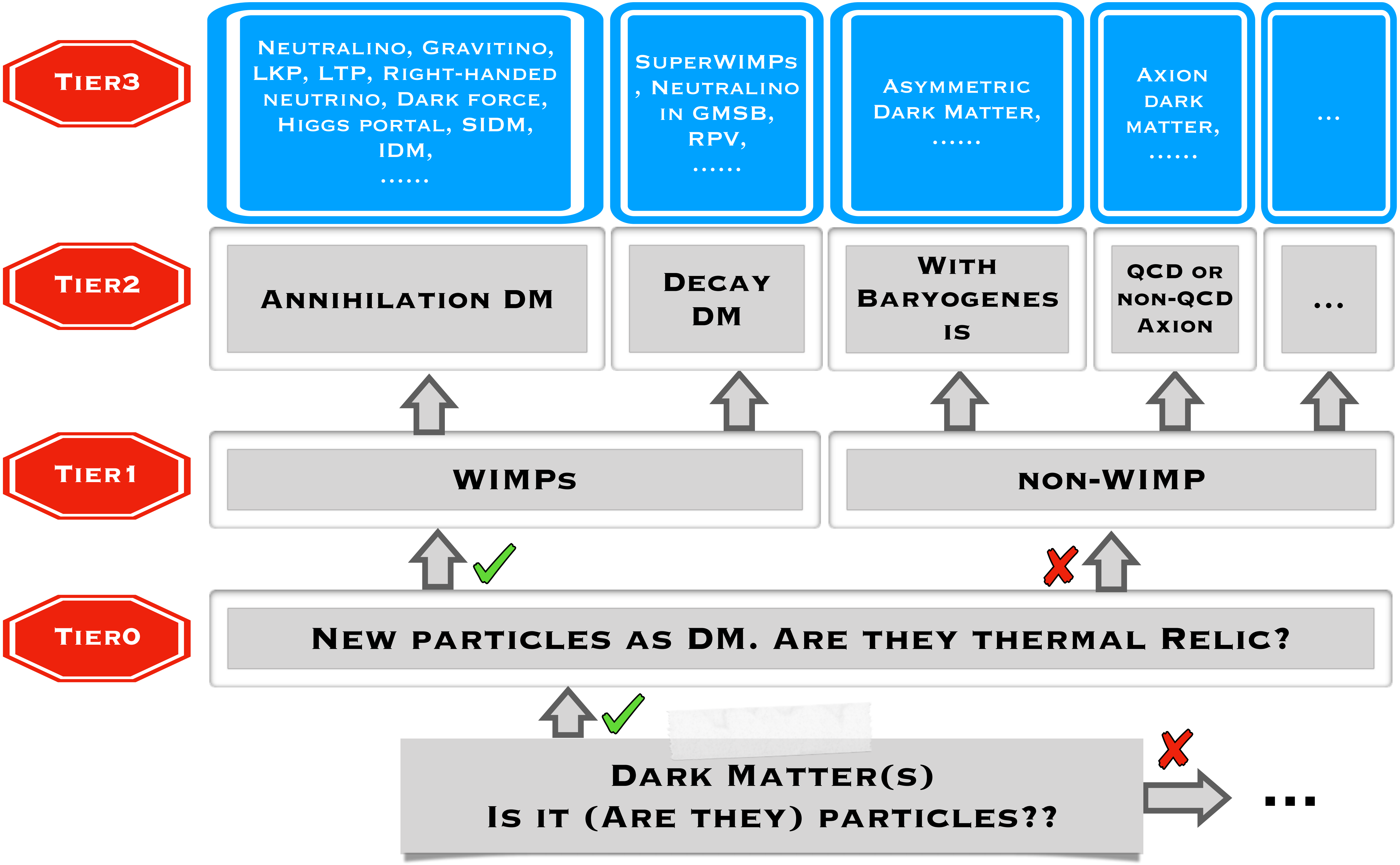
Composite Higgs Model,
Little Higgs Model, Twin Higgs Model,
……

...

Arkani-Hamed-Dimoupolos-Dvali Model,
……

Randall-Sundrum Model: RS1, RS2 ……

Popular New Physics Models



Tier3

Neutralino, Gravitino, LKP, LTP, Right-handed neutrino, Dark force, Higgs portal, SIDM, IDM, ……

SuperWIMPs, Neutralino in GMSB, RPV, ……

Asymmetric Dark Matter, ……

Axion dark matter, ……

…

Tier2

Annihilation DM

Decay DM

With Baryogenesis

QCD or non-QCD Axion

…

Tier1

WIMPs ✓

non-WIMP ✗

Tier0

New particles as DM. Are they thermal Relic? ✓

Dark Matter(s)
Is it (Are they) particles??

✗ …

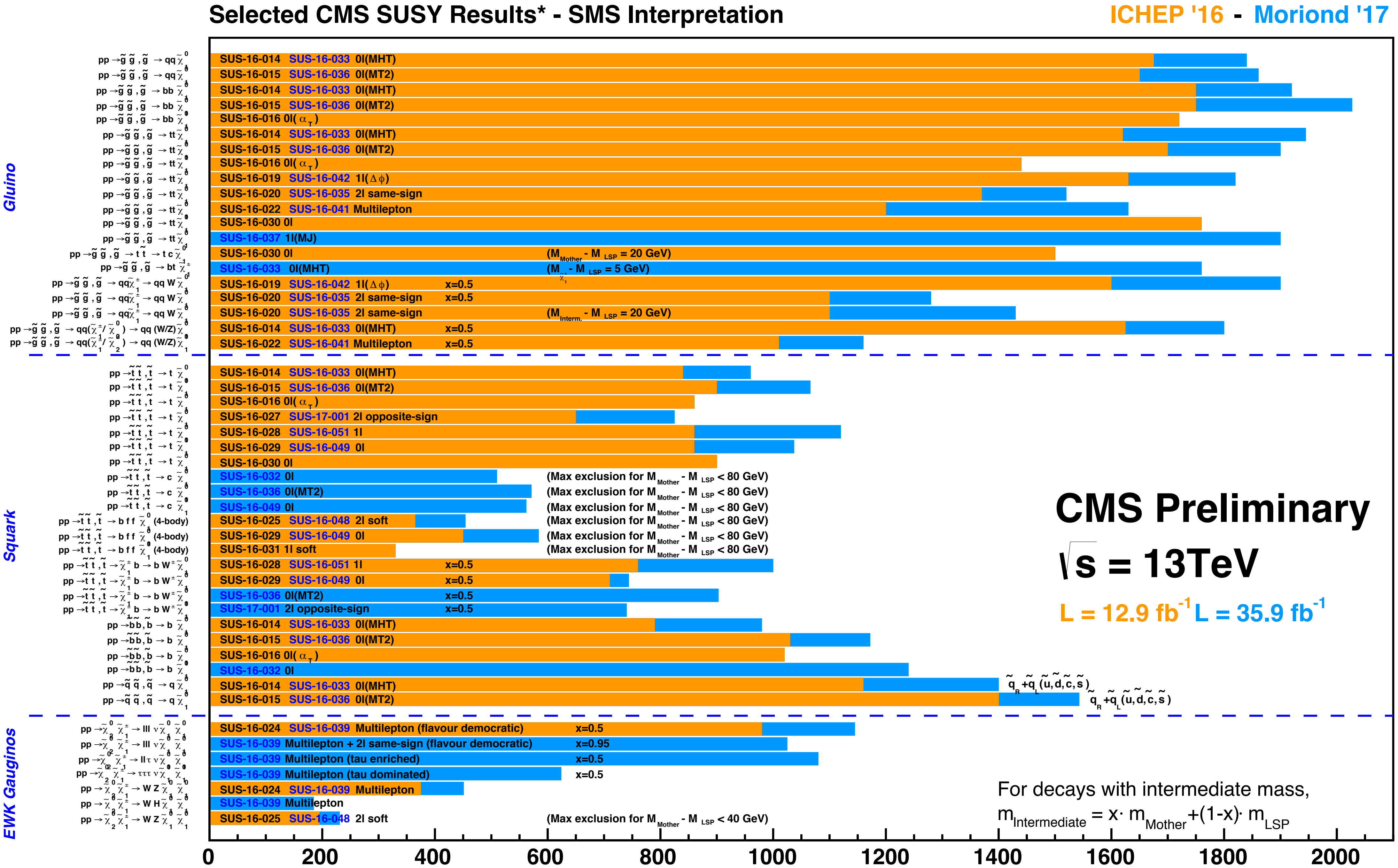
Supersymmetry Models

- An ancient family of new physics models.
- Advantage:
  - Quadratic divergences are cancelled;
  - Stable M_{EW};
  - Radiative triggered EWSB;
  - Dark matter candidate if you want a R-partity.
- Disadvantage:
  - (Too) many new particles and free parameters;
  - Complicated breaking and mediation mechanism;
  - No superpartner has been discovered at colliders (only for TeV SUSY models).

C. S. Li, R. J. Oakes, J. M. Yang, Phys. Rev. D 49 (1994) 293-298; C.-S. Huang, W. Liao, Q.-S. Yan, S.-H. Zhu, Phys. Rev. D 63 (2001) 114021; J. Kang, P. Langacker, T.-j. Li, T. Liu, Phys. Rev. Lett. 94 (2005) 061801; A. Belyeav, Q.-H. Cao, D. Nomura, K. Tobe, C.-P. Yuan, Phys. Rev. Lett. 100 (2008) 061801; Y. Zhang, H. An, X. Ji, R. N. Mohapatra, Nucl. Phys. B802(2008)247-279; J.-J. Cao, Z.-X. Heng, J. M. Yang, Y.-M. Zhang, J.-Y. Zhu, JHEP03(2012)086; J. Ellis, H.-J. He, Z.-Z. Xianyu, Phys. Rev. D 91(2015)021302; W. Huang, Z. Kang, J. Shu, P. Wu, J.-M. Yang, Phys. Rev. D91 (2015) 025006; F. Wang, J. M. Yang, Y. Zhang, JHEP04(2016)177; H. An, J. Gu, L.-T. Wang, JHEP04(2017)084 …

Supersymmetry Models

- Recent progress.



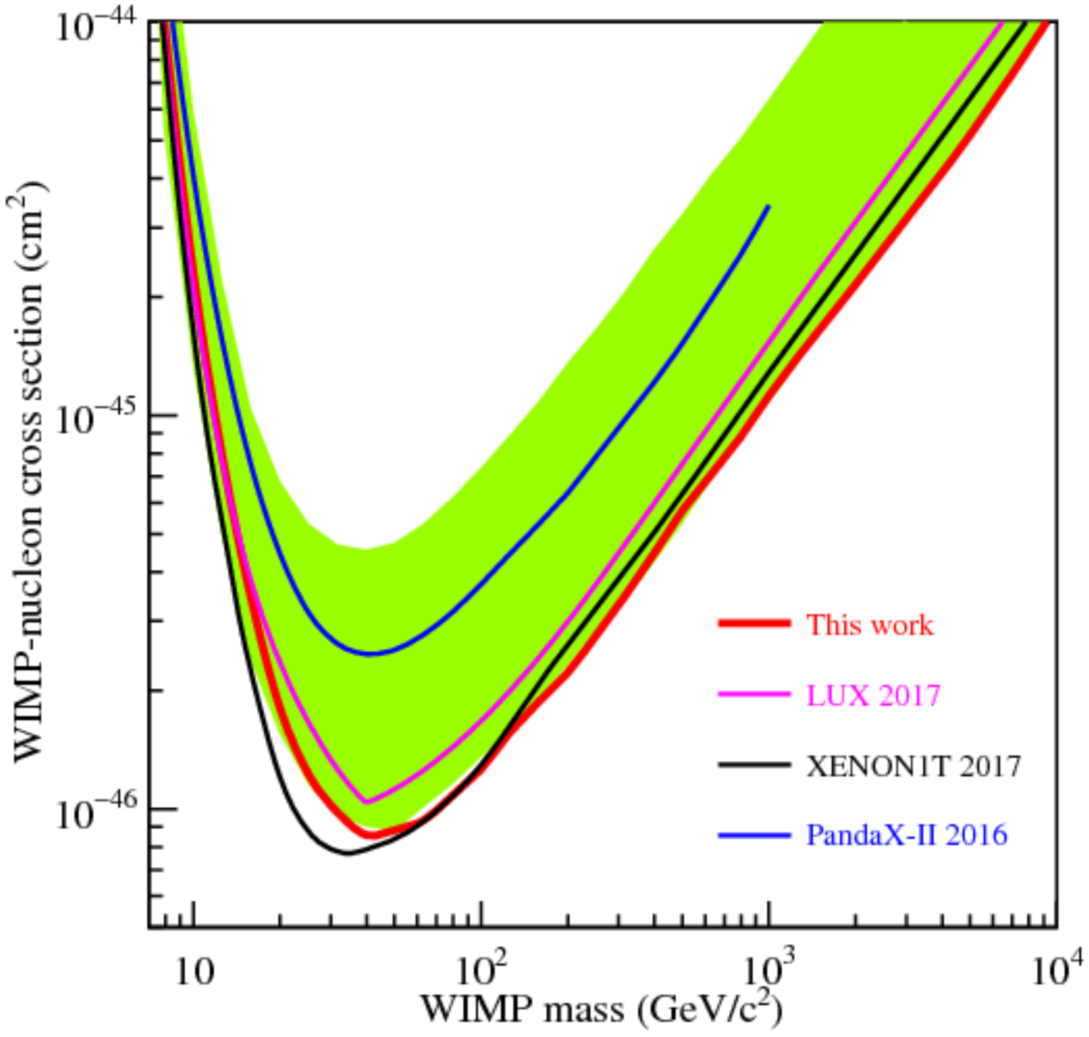
*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise

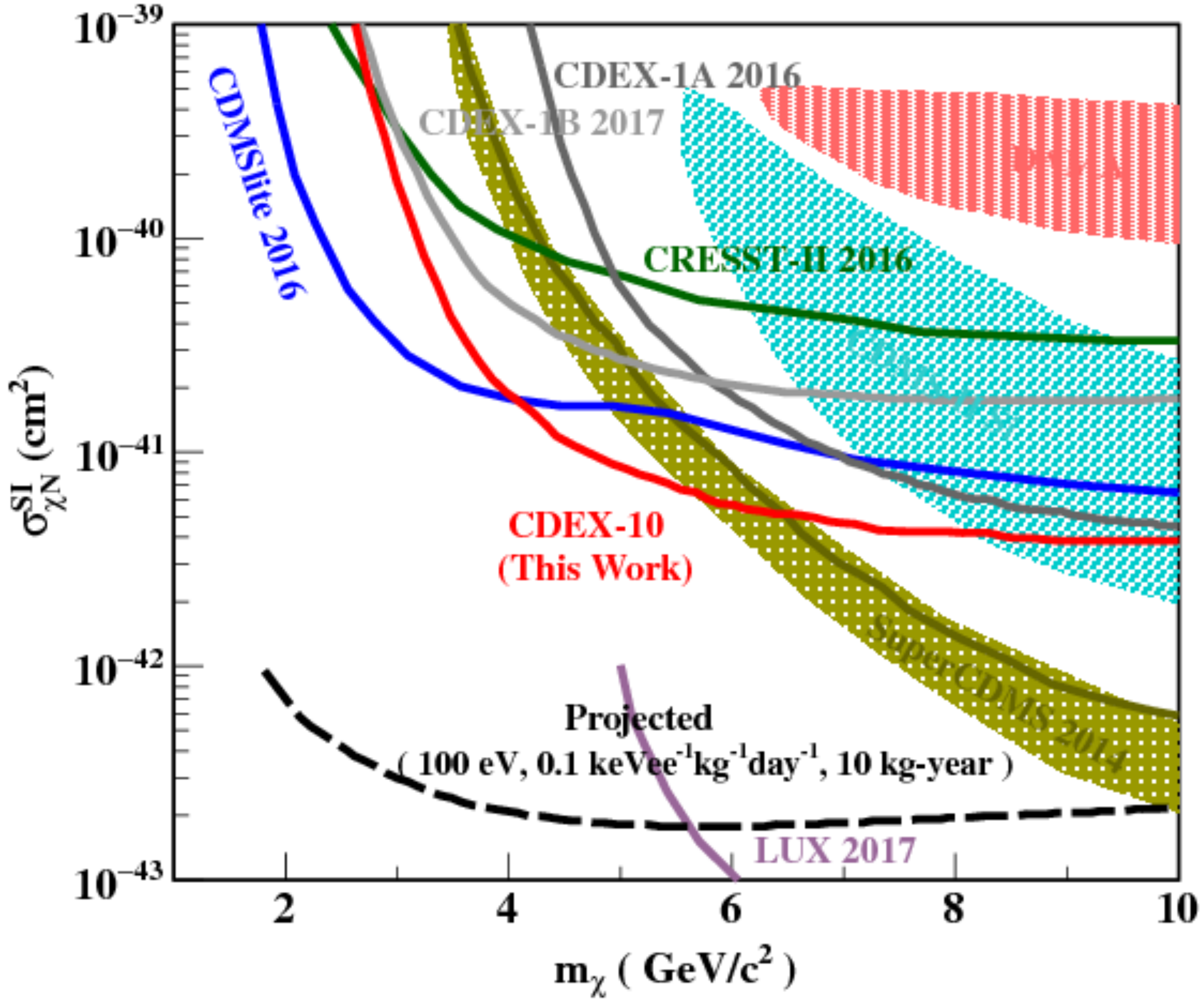
Similar figure from ATLAS collaboration, see backup slides.

Supersymmetry Models

- Challenges from the dark matter direct detection experiments.
- Strong constraint to the LSP dark matter candidate.



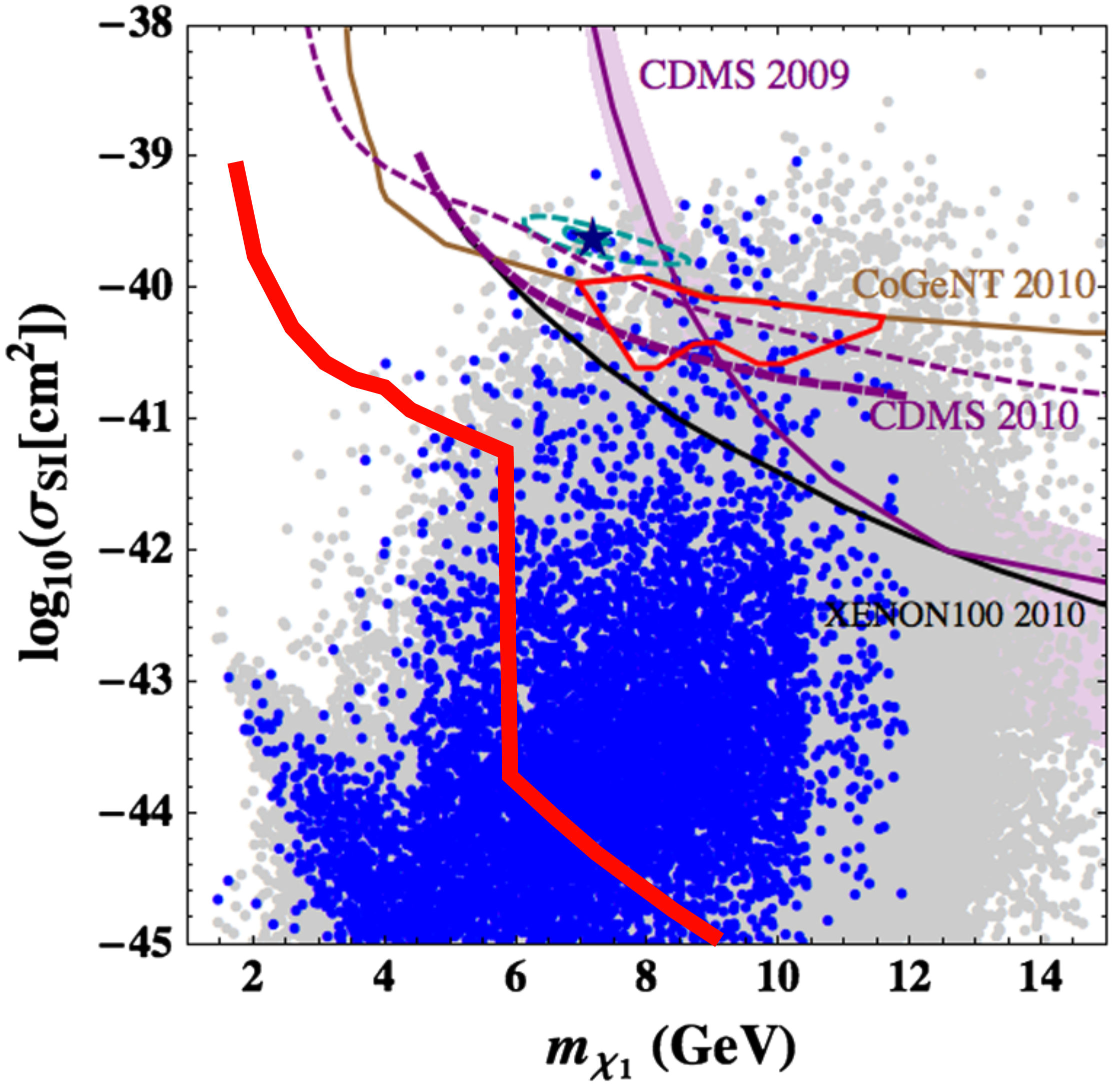
PandaX-II Collaboration,
Phys. Rev. Lett. 119 (2017) 181302.



CDEX Collaboration,
Phys. Rev. Lett. 120 (2018) 241301.

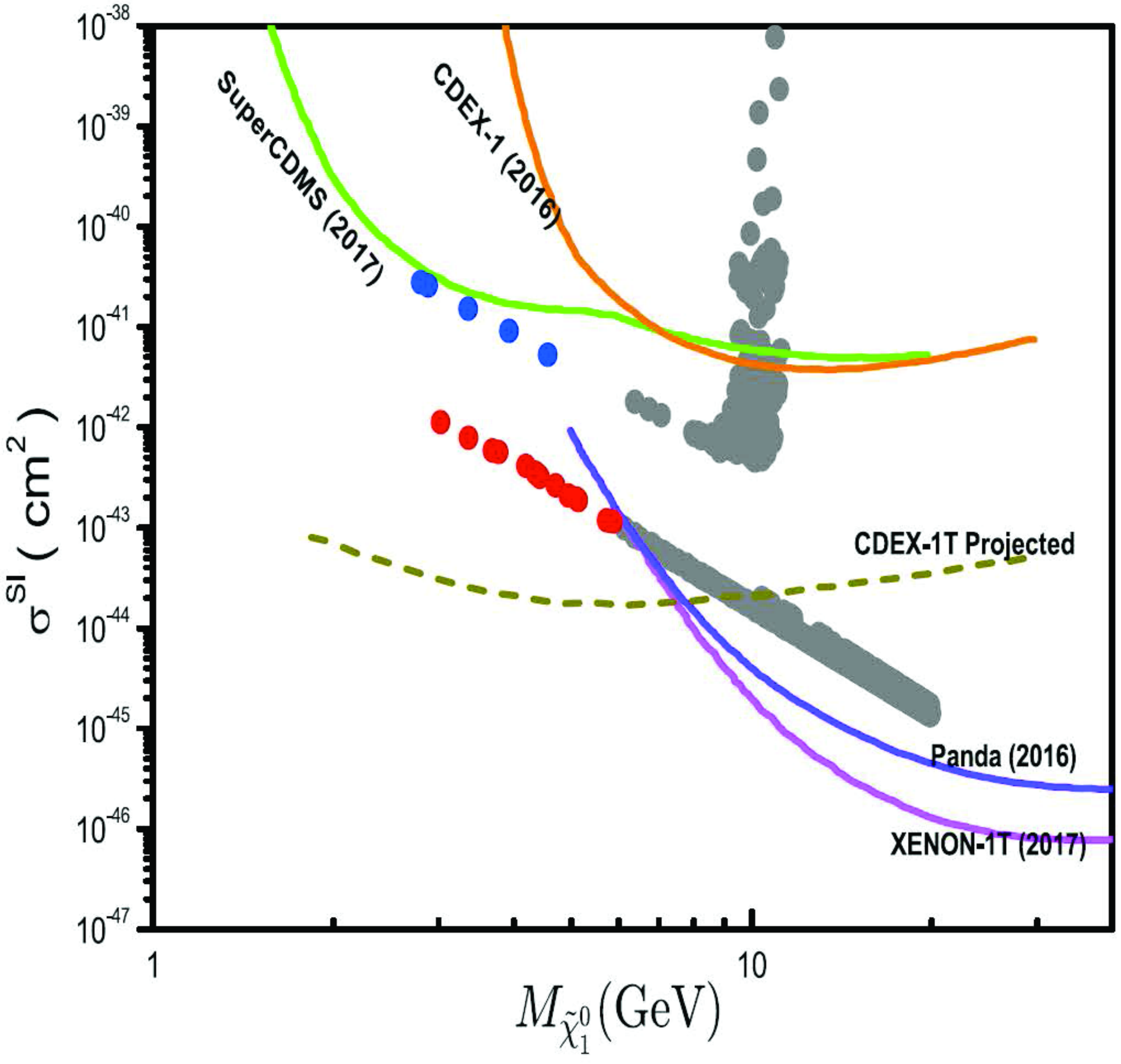
Supersymmetry Models

- Challenges from the dark matter direct detection experiments.
- Stronger constraint to the LSP dark matter candidate.



NMSSM

P. Draper, T. Liu, C. E.M. Wagner, L.-T. Wang, *HZ*, Phys. Rev. Lett. 106 (2011) 121805.

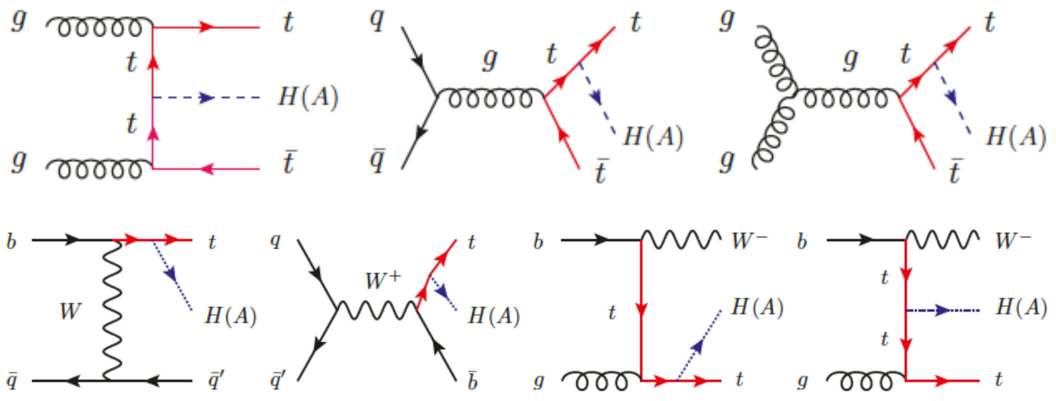


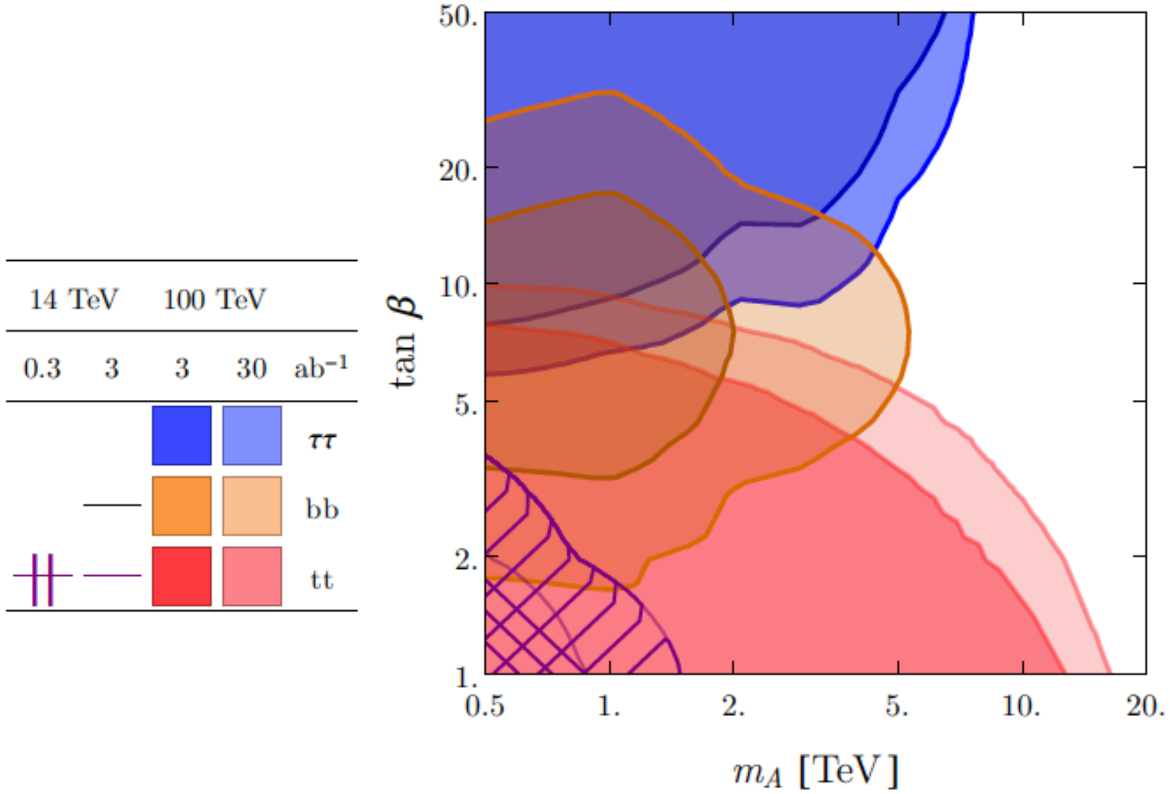
MSSM

G. H. Duan, W. Wang, L. Wu, J. M. Yang, J. Zhao, Phys. Lett. B778 (2018) 296-302.

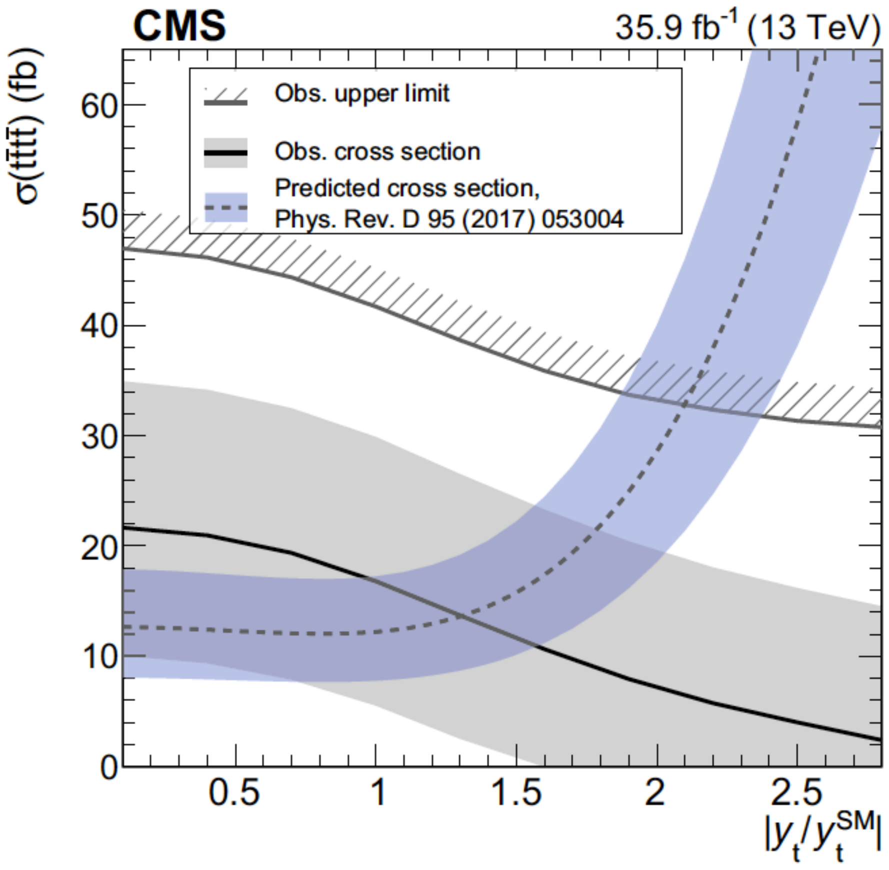
Supersymmetry Models

- Exotic Higgs boson signals and exotic Higgs bosons.
- Example: multi-top signal.





N. Craig, J. Hajer, Y.-Y Li, T. Liu, *HZ*, JHEP01(2017)018.



CMS Collaboration, Eur. Phys. J. C78 (2018) 140;
Q.-H. Cao, S.-L. Chen, Y. Liu, Phys. Rev. D95 (2017) 053004.

Popular New Physics Models

- Other popular models.
- Extra-dimension model:
  - Hierarchy problem: ~TeV Planck scale;
- Composite Higgs model, Little Higgs model:
  - Hierarchy problem: Higgs boson as a Nambu-Goldstone boson;
- Twin-Higgs model:
  - Hierarchy problem: Z_2, or exotic SU(6);
- …

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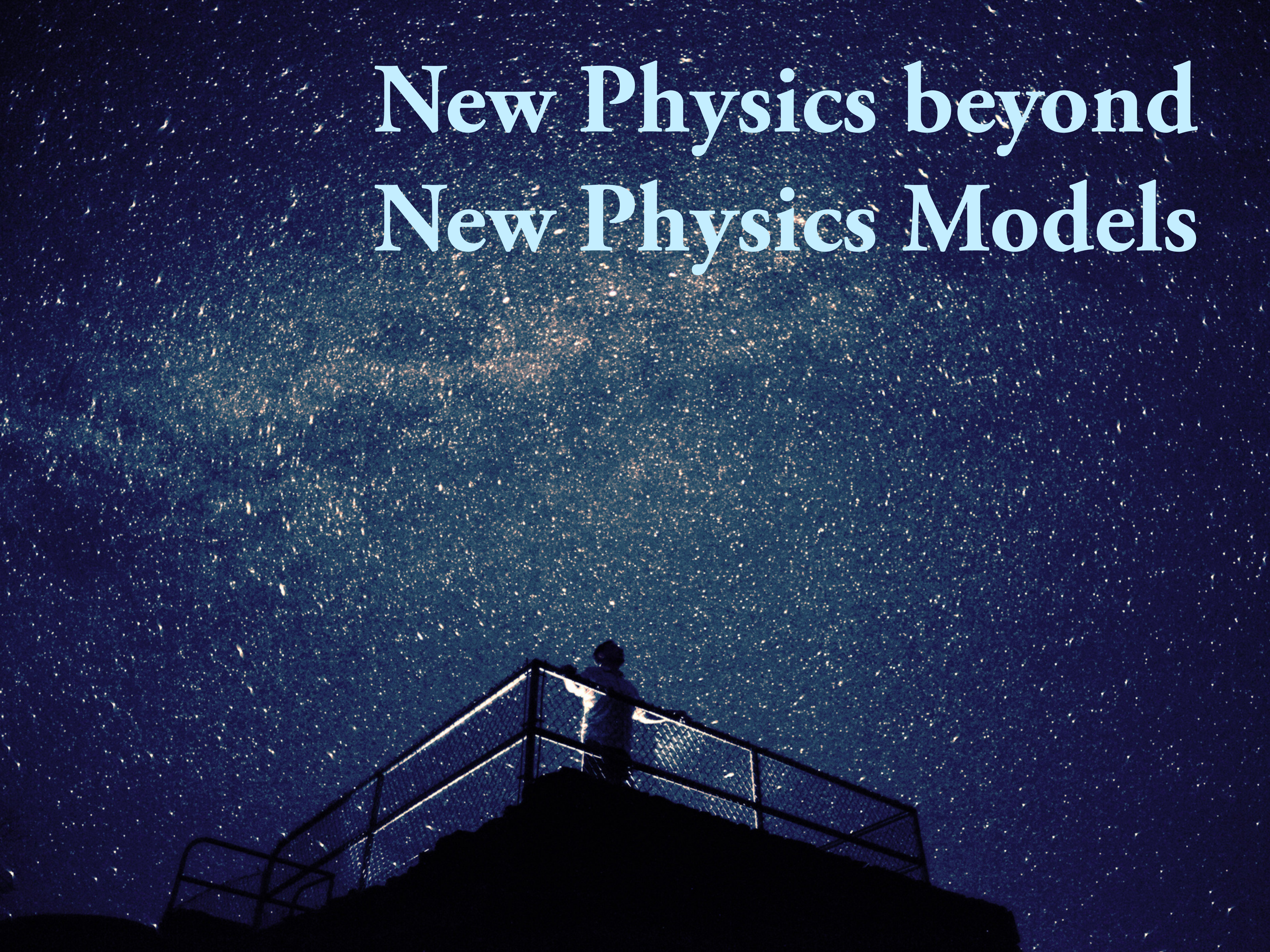
New Physics beyond New Physics Models



Effective Field Theory

- The Standard Model is an effective field theory.
- It contains ***relevant***, ***marginal*** and ***irrelevant*** operators.
- The irrelevant operators are hint of new physics and new physical scale.

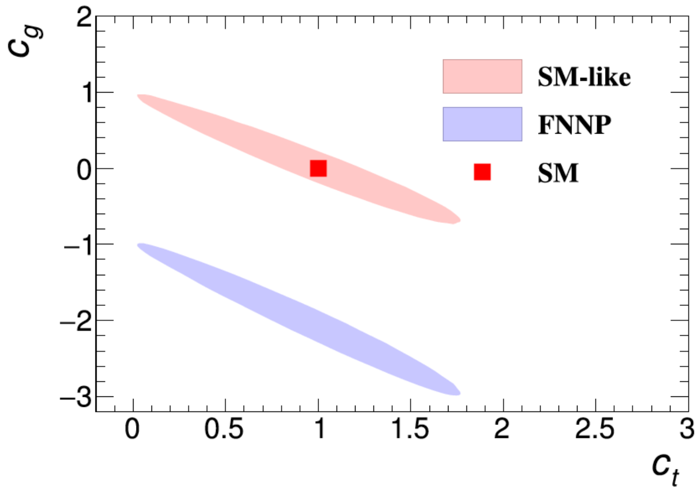
$$\mathcal{L}_{\rm irr} = \sum_{n=1} \sum_{i} \frac{C_i^{(n)}(\mu)}{\Lambda_{\rm cutoff}^n} \mathcal{O}_i^{(n)}$$

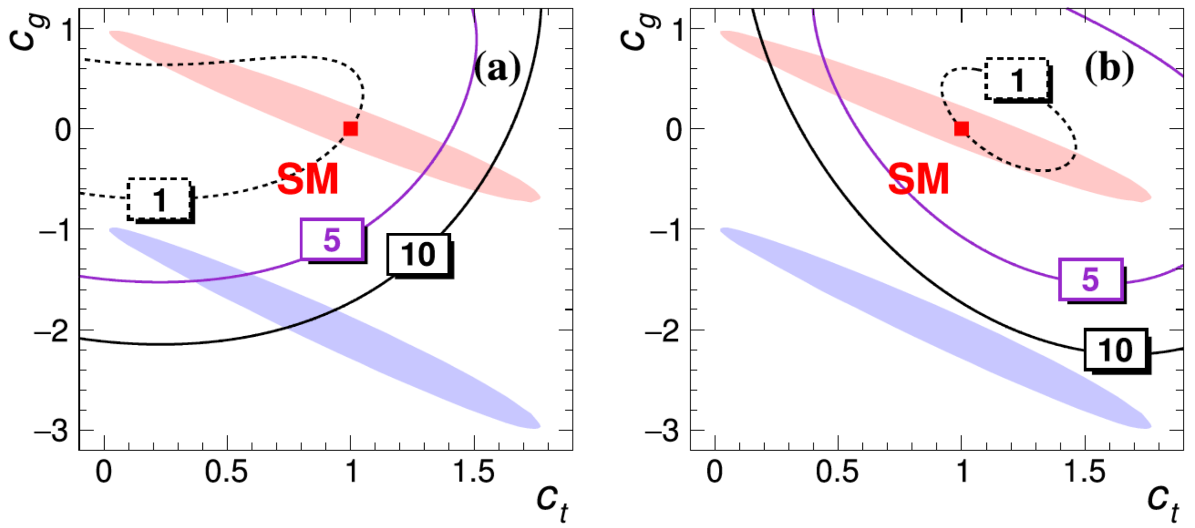
- Example in history: four-fermion theory to standard model.
- Advantage: model-independent.
- Question: effective interaction or the resonance, which should be detected first?

SM EFT

- No exotic fields in the irrelevant operators.
- Example: Higgs-pair signal at hadron colliders.

$$\begin{aligned}\mathcal{L}_{\rm eff} = & -\frac{m_t}{v}\bar{t}(c_t + i\tilde{c}_t\gamma_5)th - \frac{m_t}{2v^2}\bar{t}(c_{2t} + i\tilde{c}_{2t}\gamma_5)th^2 \\ & + \frac{\alpha_s h}{12\pi v}(c_g G^A_{\mu\nu}G^{A,\mu\nu} + \tilde{c}_g G^A_{\mu\nu}\tilde{G}^{A,\mu\nu}) \\ & + \frac{\alpha_s h^2}{24\pi v^2}(c_{2g} G^A_{\mu\nu}G^{A,\mu\nu} + \tilde{c}_{2g} G^A_{\mu\nu}\tilde{G}^{A,\mu\nu}) - c_{3h}\frac{m_h^2}{2v}h^3\end{aligned}$$





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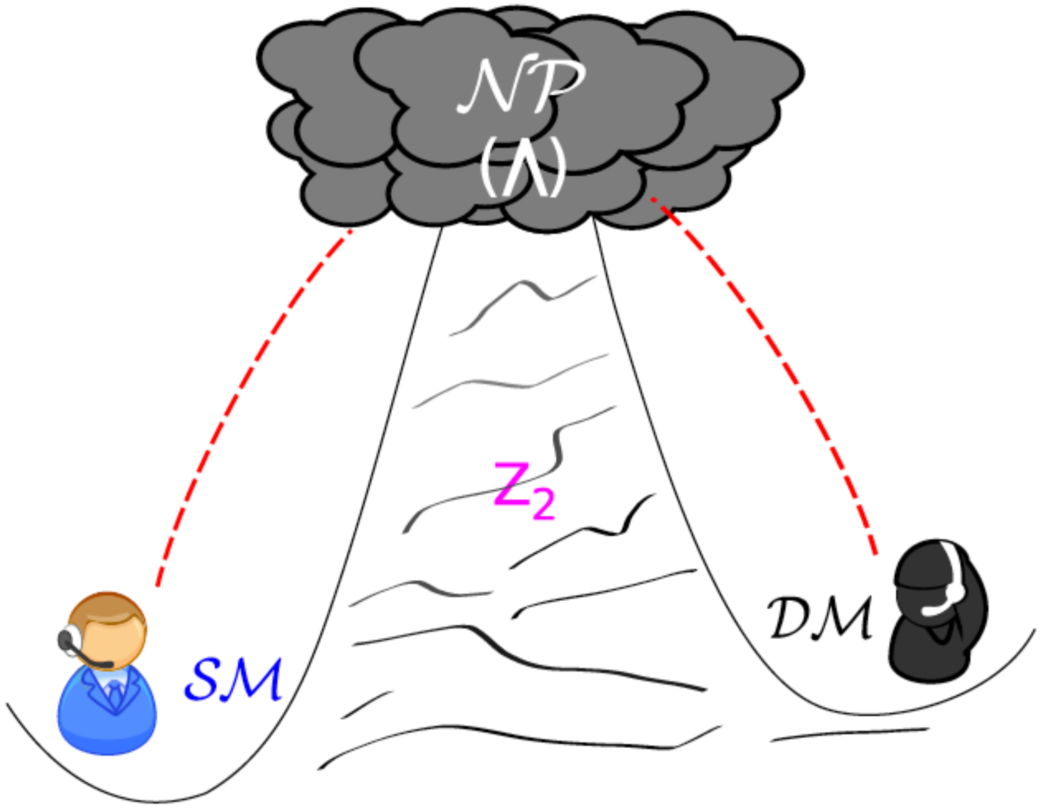
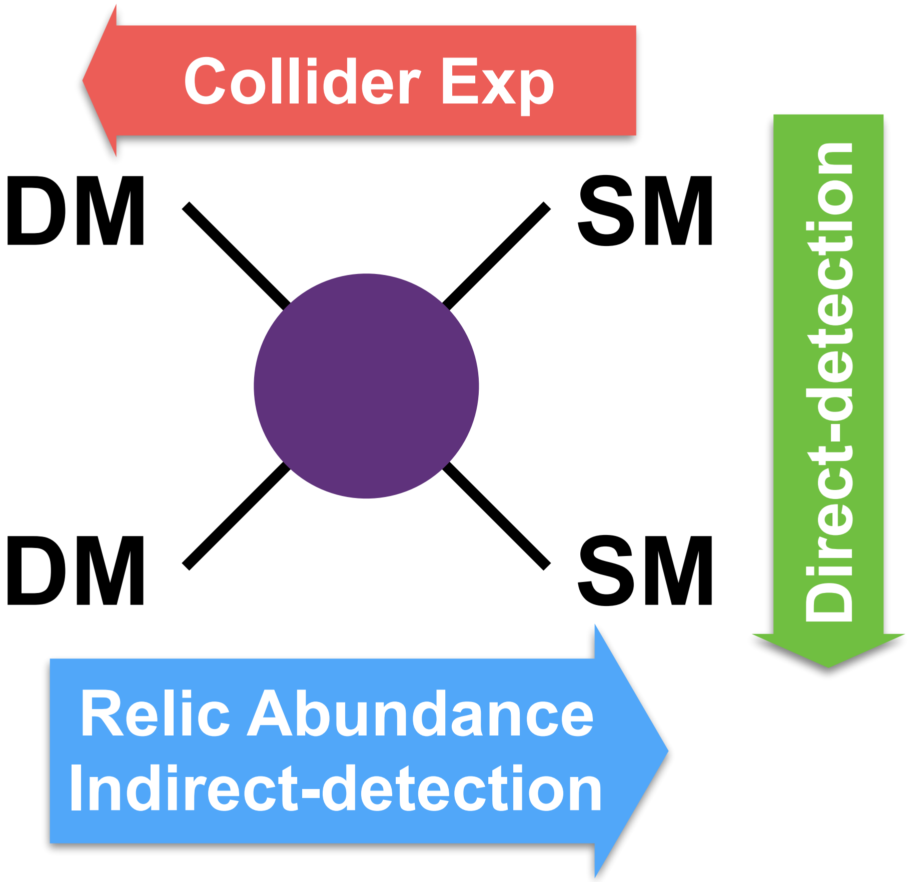
Q.-H. Cao, G. Li, B. Yan, D.-M. Zhang, *HZ*, Phys. Rev. D96 (2017) 095031.

X.-m. Zhang, Phys. Rev. D47(1993)3065-3067, J. J. Zhang, C. S. Li, J. Gao, *HZ*, Z. Li, C.-P. Yuan, T.-C. Yuan, Phys. Rev. Lett. 102 (2009) 072001; H.-J. He, J. Ren, W. Yao, Phys. Rev. D93(2016)015003; C. Zhang, Phys. Rev. Lett. 116 (2016) 162002; I. Brivio, Y. Jiang, M. Trott, JHEP12(2017)070; Y. Jiang, M. Trott, Phys. Lett. B770 (2017) 108-116; T. Corbett, A. Joglekar, H.-L. Li, J.-H. Yu, JHEP05(2018)061; H. Han, R. Huo, M. Jiang, J. Shu, Phys. Rev. D 97 (2018) 095003 …

Dark Matter Effective Field Theory

- Dark matter field(s) appears in the effective operators.





Collider Exp

DM SM

DM SM

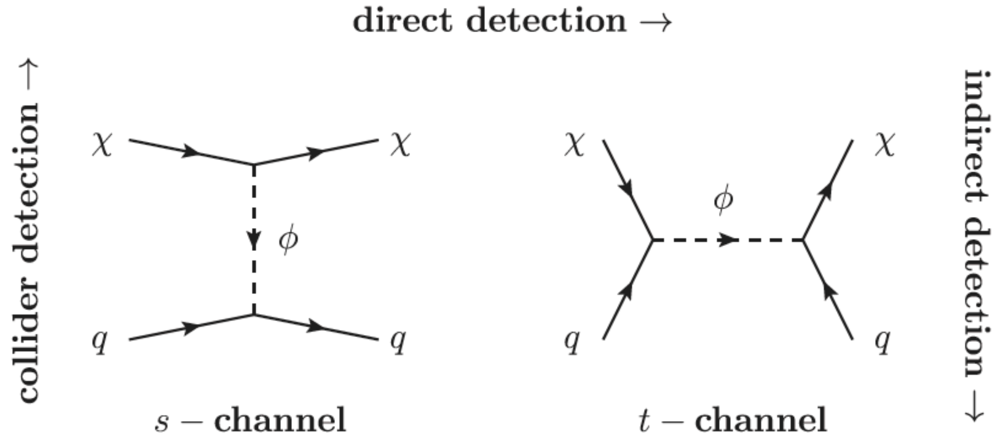
Direct-detection

Relic Abundance
Indirect-detection

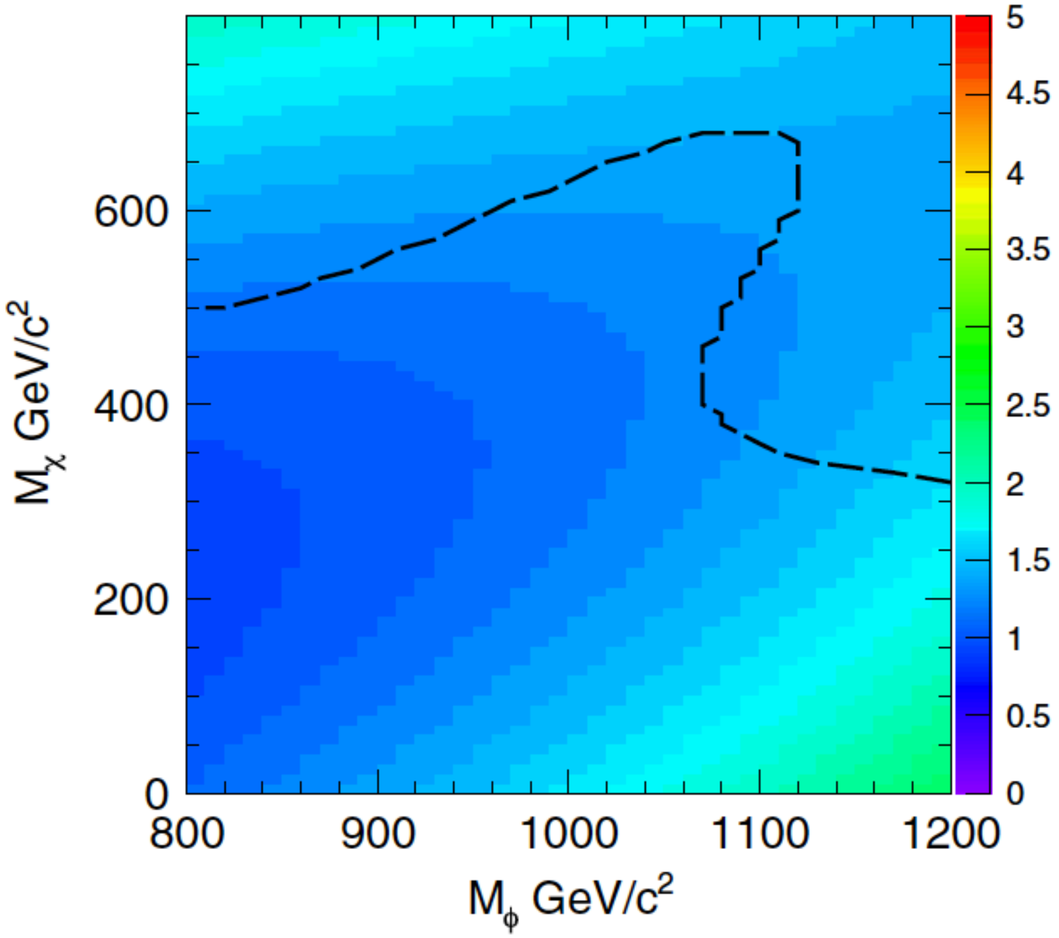
P.-f. Yin, Q. Yuan, J. Liu, J. Zhang, X.-j. Bi, S.-h. Zhu, Phys. Rev. D79(2009)023512; HZ, Q.-H. Cao, C.-R. Chen, C. S. Li, JHEP08(2011)018; J.-M. Zheng, Z.-H. Yu, J.-W. Shao, X.-J. Bi, Z. Li, H.-H. Zhang, Nucl. Phys. B854(2012)350-374; Q.-F. Xiang, X.-J. Bi, P.-F. Yin, Z.-H. Yu, Phys. Rev. D 91(2015)095020; Z.-L. Liang, Y.-L. Wu, Z.-Q. Yang, Y.-F. Zhou, JCAP09(2016)018; …

Beyond Effective Field Theory

- We probably need to go (at least one step) beyond the EFT.
  - The heavy resonance has a chance to be produced at colliders.
  -



$$\mathcal{L}_\chi = \lambda_Q \bar{\chi} \mathbb{P}_L Q \phi_Q^* + \lambda_u \bar{\chi} \mathbb{P}_R u \phi_u^* + \lambda_d \bar{\chi} \mathbb{P}_R d \phi_d^* + \frac{\lambda_{Qu}^{(1)} \bar{\chi} H \phi_Q^* Y_u \mathbb{P}_R u}{\Lambda} + \frac{\lambda_{Qd}^{(1)} \bar{\chi} \tilde{H} \phi_Q^* Y_d \mathbb{P}_R d}{\Lambda} + \frac{\lambda_{Qu}^{(2)} \bar{Q} H Y_u \phi_u \mathbb{P}_R \chi}{\Lambda} + \frac{\lambda_{Qd}^{(2)} \bar{Q} \tilde{H} Y_d \phi_d \mathbb{P}_R \chi}{\Lambda} + \text{H.c.},$$

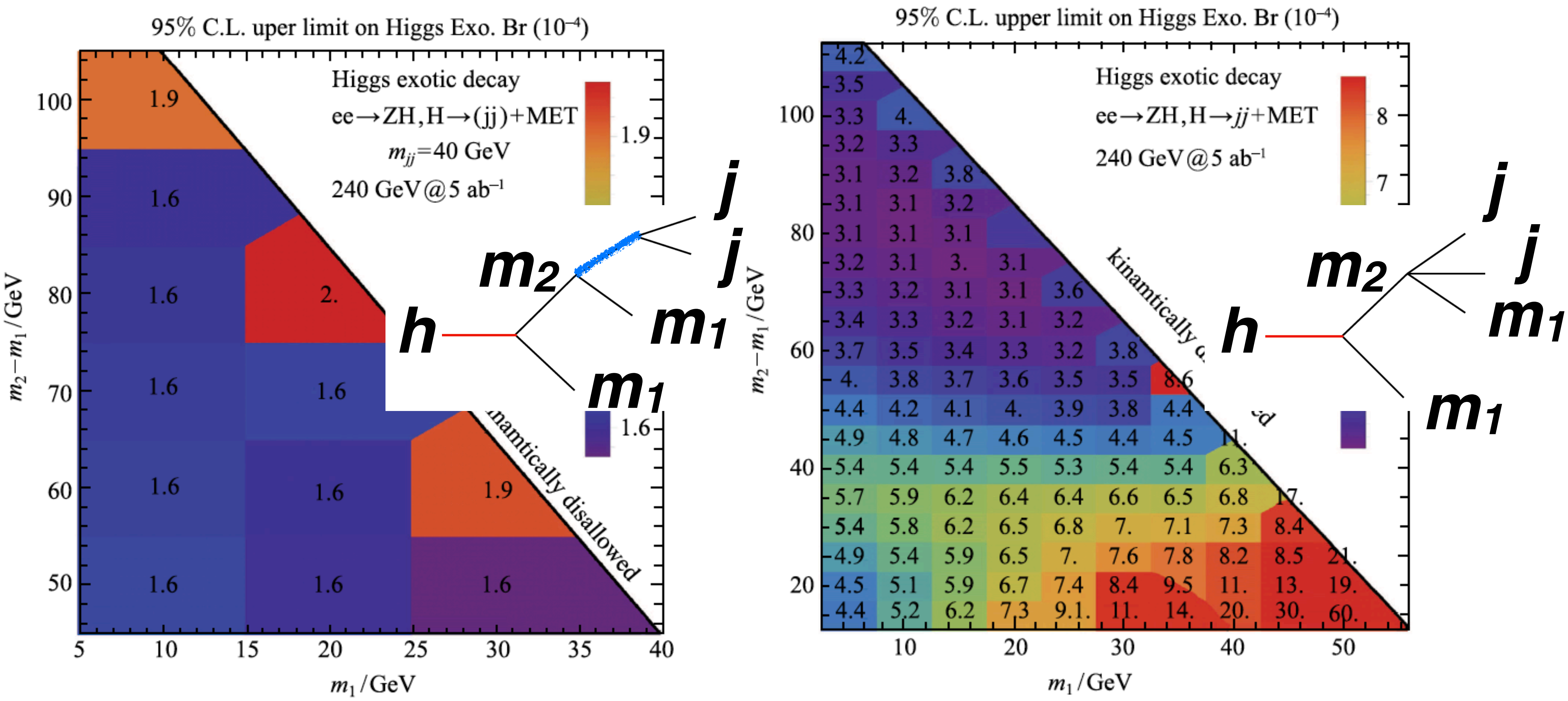


H. An, L.-T. Wang, *HZ*, Phys. Rev. D89 (2014) 115014.

W. Chao, S. Luo, Z.-z. Xing, S. Zhou, Phys. Rev. D77(2008)016001; P. H. Frampton, J. Shu, K. Wang, Phys. Lett. B683 (2010) 294-297; H. An, X. J, L.-T. Wang, JHEP07(2012)182…

Beyond Effective Field Theory

- We probably need to go (at least one step) beyond the EFT.
  - The heavy resonance has a chance to be produced at colliders.
  - There are light resonances.



Z. Liu, L.-T. Wang, *HZ*, Chin. Phys. C41 (2017) 063102.

New …

- New Physics ≠ New Physics Models;
- New Physics ≠ New Particles;
- Category of New Physics:
  - New particle;
  - New physics model;
  - New phenomenon;
  - New mechanism;
  - New frame of theory;
  - New …
- Today, there are so many exciting experiments, from the LHC to satellites. We should contribute more and more interesting and crazy ideas with these experiments.

Example

- We are measuring the properties of the Higgs boson with higher and higher accuracy.
- Most of the Higgs boson lived in the early universe.
- How about their life? How to study it?

Example

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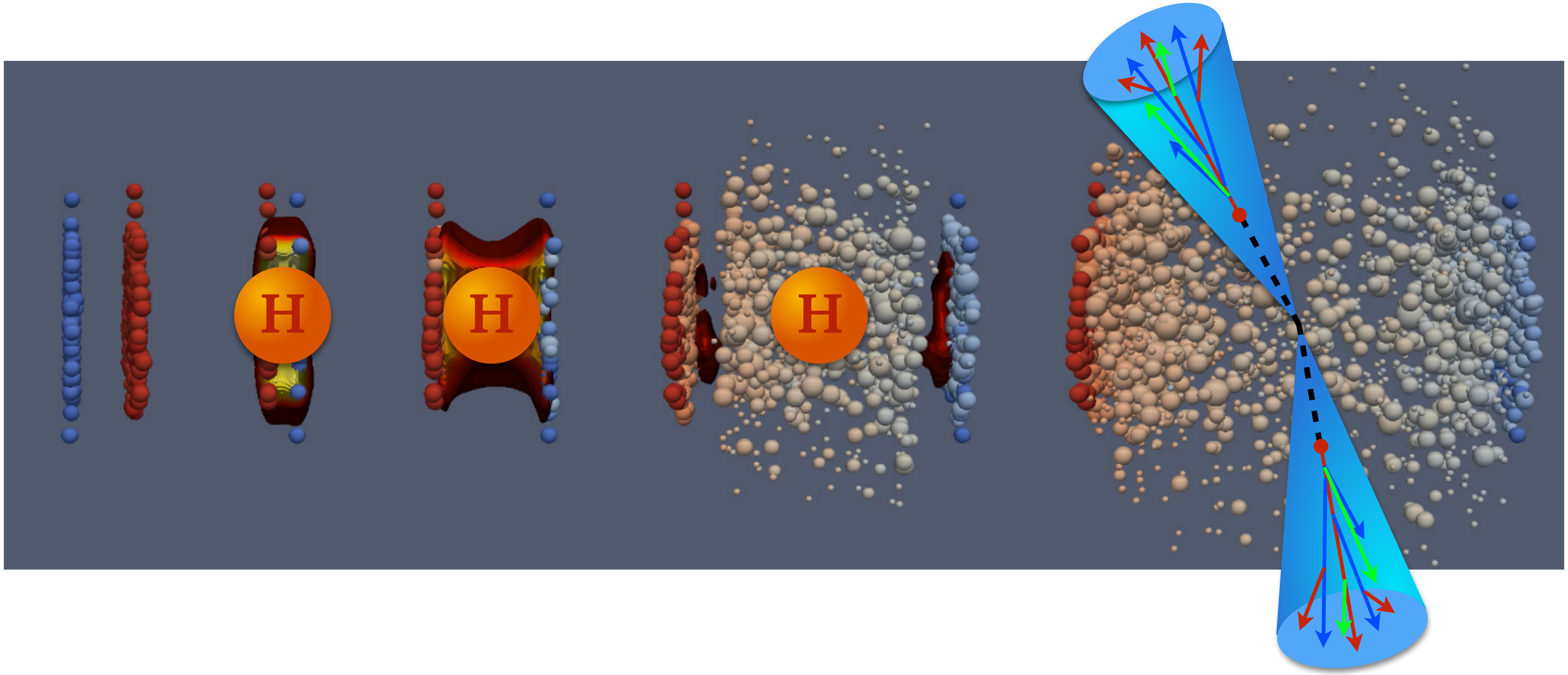
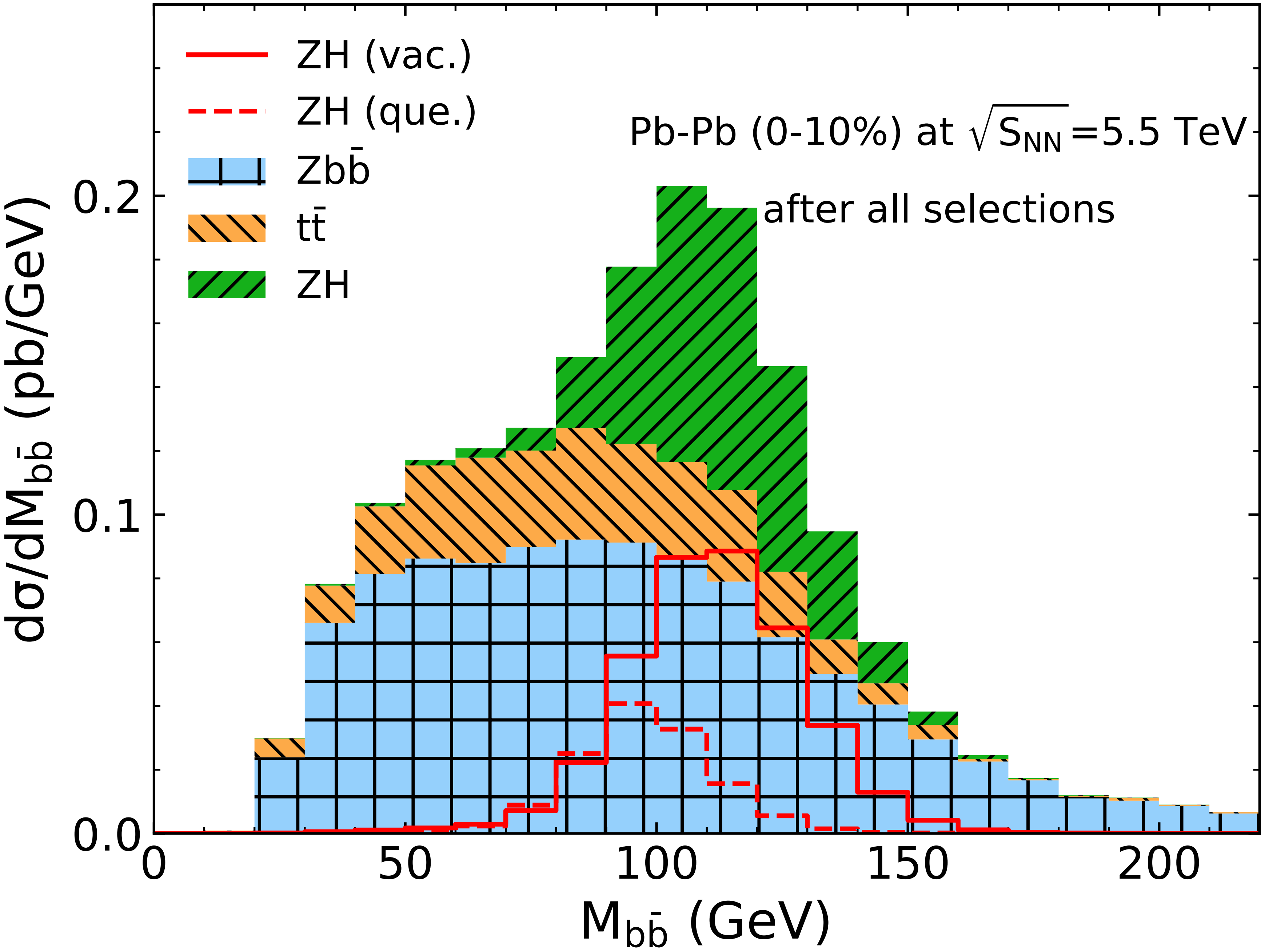


Example

- Higgs boson in heavy-ion collision.



E. L. Berger, J. Gao, A. Jueid, *HZ*, arXiv:1804.06858[hep-ph].

Summary

- We have strong motivation for new physics beyond the SM.
- A lot of new physics models have been developed.
- Both experimentalists and theorists work hard to explore the edge of our knowledge about the universe.
- The law of nature at the next scale is still a secret for us.
- High energy physicists face to great challenges and great chances.

Thank you!

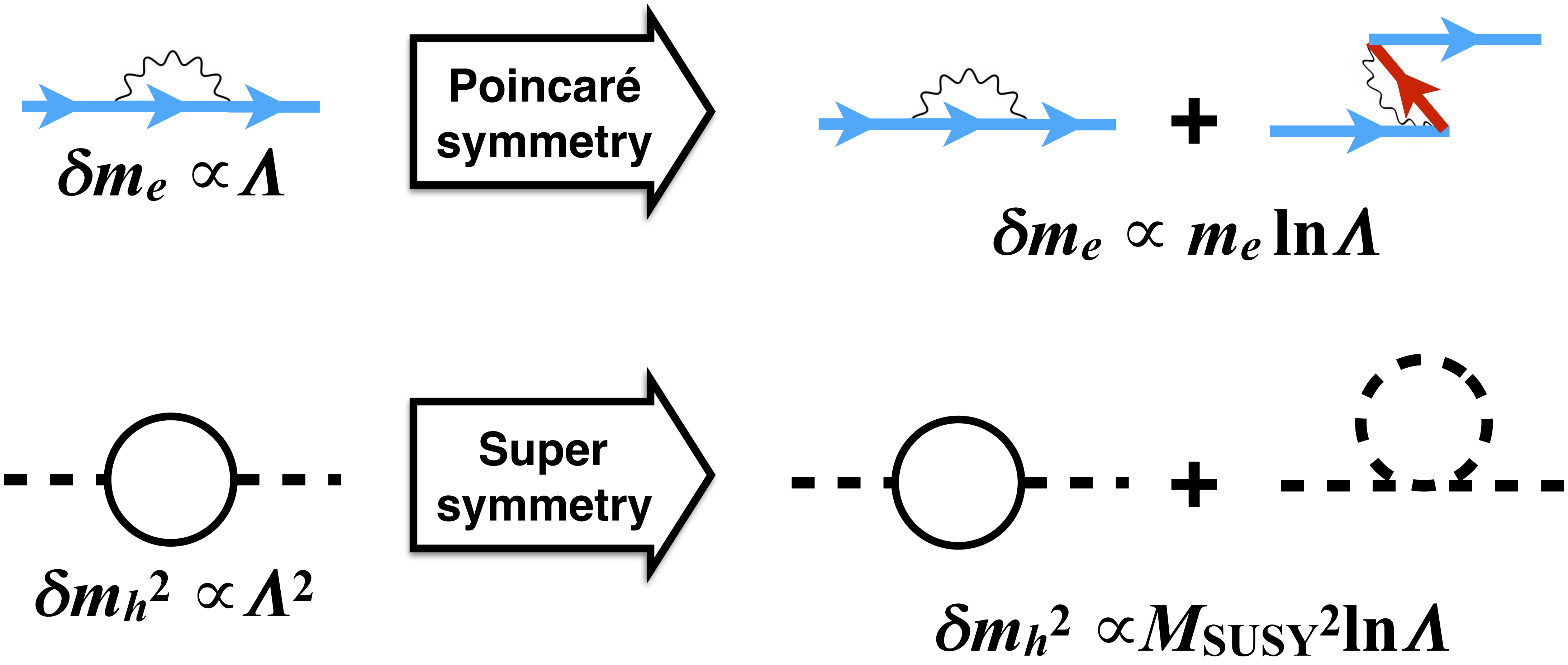
Backup slides

Supersymmetry Models

- An ancient family of new physics models.

  MSSM, NMSSM, nMSSM, $\mu\nu$MSSM, split-SUSY, RPV, …

- Cancel quadratic divergence using symmetry (not the first example)



$\delta m_e \propto \Lambda$

Poincaré symmetry

$\delta m_e \propto m_e \ln\Lambda$

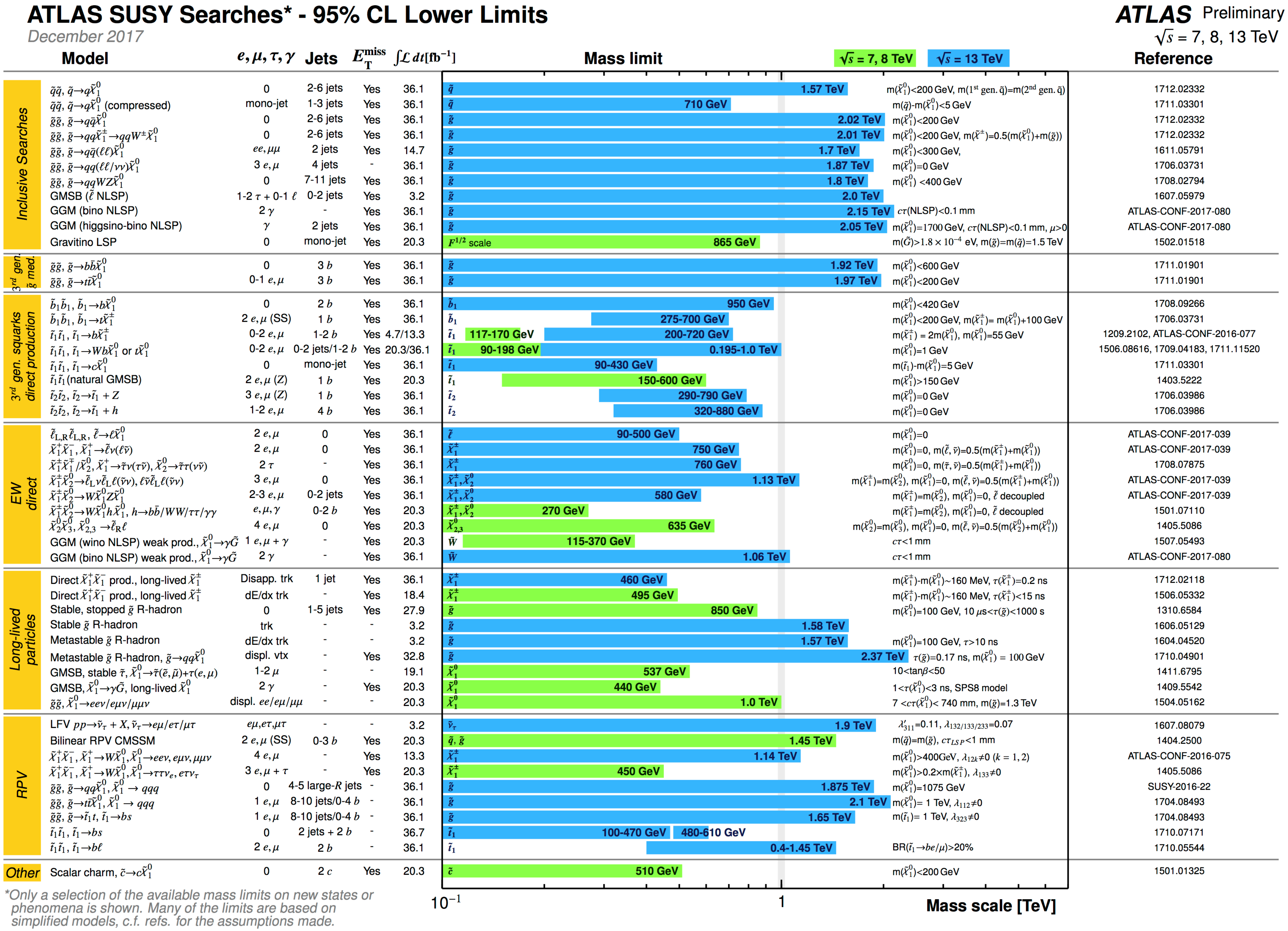
$\delta m_h^2 \propto \Lambda^2$

Super symmetry

$\delta m_h^2 \propto M_{\mathrm{SUSY}}^2 \ln\Lambda$

Supersymmetry Models

- Recent progress.



ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

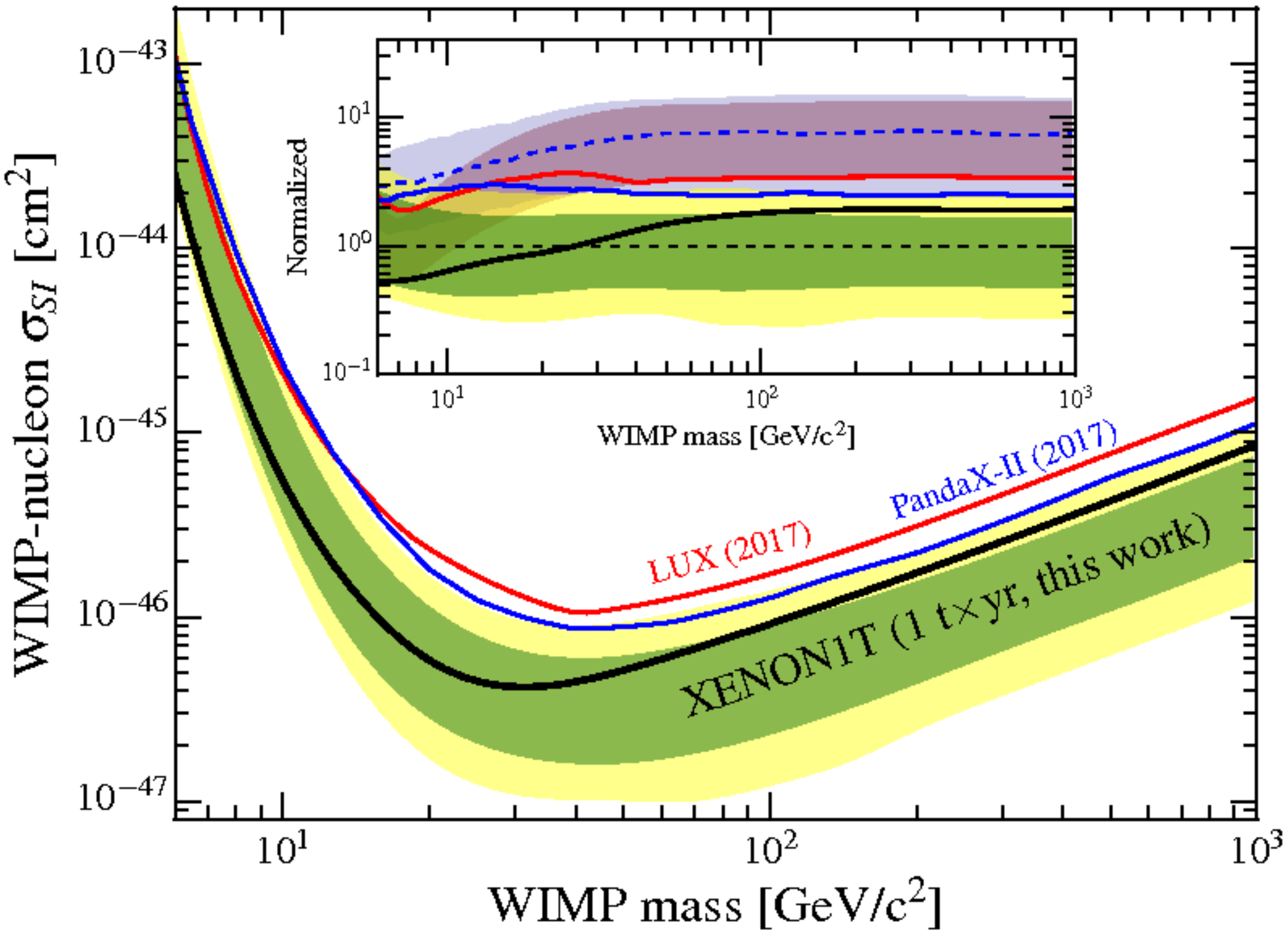
🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	🟦 $\tilde{q}$ 1.57 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1712.02332
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	🟦 $\tilde{q}$ 710 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.02 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^{\pm}\rightarrow qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.01 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	🟦 $\tilde{g}$ 1.7 TeV	m($\tilde{\chi}_1^0$)<300 GeV,	1611.05791
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	🟦 $\tilde{g}$ 1.87 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	🟦 $\tilde{g}$ 1.8 TeV	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	🟦 $\tilde{g}$ 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	🟦 $\tilde{g}$ 2.05 TeV	m($\tilde{\chi}_1^0$)=1700 GeV, $c\tau$(NLSP)<0.1 mm, $\mu>0$	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.92 TeV	m($\tilde{\chi}_1^0$)<600 GeV	1711.01901
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.97 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	🟦 $\tilde{b}_1$ 950 GeV	m($\tilde{\chi}_1^0$)<420 GeV	1708.09266
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	1 b	Yes	36.1	🟦 $\tilde{b}_1$ 275-700 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)= m($\tilde{\chi}_1^0$)+100 GeV	1706.03731
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 0.195-1.0 TeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	🟦 $\tilde{t}_1$ 90-430 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	🟦 $\tilde{t}_2$ 290-790 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	🟦 $\tilde{t}_2$ 320-880 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	🟦 $\tilde{\ell}$ 90-500 GeV	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}$ 750 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\rightarrow\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}$ 760 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 1.13 TeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 580 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 270 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\rightarrow\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	🟩 $\tilde{\chi}_{2,3}^0$ 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$	1 e, μ + γ	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$	2 γ	-	Yes	36.1	🟦 $\tilde{W}$ 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}$ 460 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1712.02118
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}_1^{\pm}$ 495 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.57 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8	🟦 $\tilde{g}$ 2.37 TeV	τ($\tilde{g}$)=0.17 ns, m($\tilde{\chi}_1^0$) = 100 GeV	1710.04901
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}_1^0$ 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q}, \tilde{g}$ 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	🟦 $\tilde{\chi}_1^{\pm}$ 1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq 0$ ($k = 1, 2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau\tau\nu_e, e\tau\nu_\tau$	3 e, μ + τ	-	Yes	20.3	🟩 $\tilde{\chi}_1^{\pm}$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq 0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow qqq$	0	4-5 large-R jets	-	36.1	🟦 $\tilde{g}$ 1.875 TeV	m($\tilde{\chi}_1^0$)=1075 GeV	SUSY-2016-22
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 2.1 TeV	m($\tilde{\chi}_1^0$)= 1 TeV, $\lambda_{112}\neq 0$	1704.08493
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow\tilde{t}_1 t$, $\tilde{t}_1\rightarrow bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq 0$	1704.08493
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow bs$	0	2 jets + 2 b	-	36.7	🟦 $\tilde{t}_1$ 100-470 GeV 480-610 GeV		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\ell$	2 e, μ	2 b	-	36.1	🟦 $\tilde{t}_1$ 0.4-1.45 TeV	BR($\tilde{t}_1\rightarrow be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde{c}\rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Supersymmetry Models

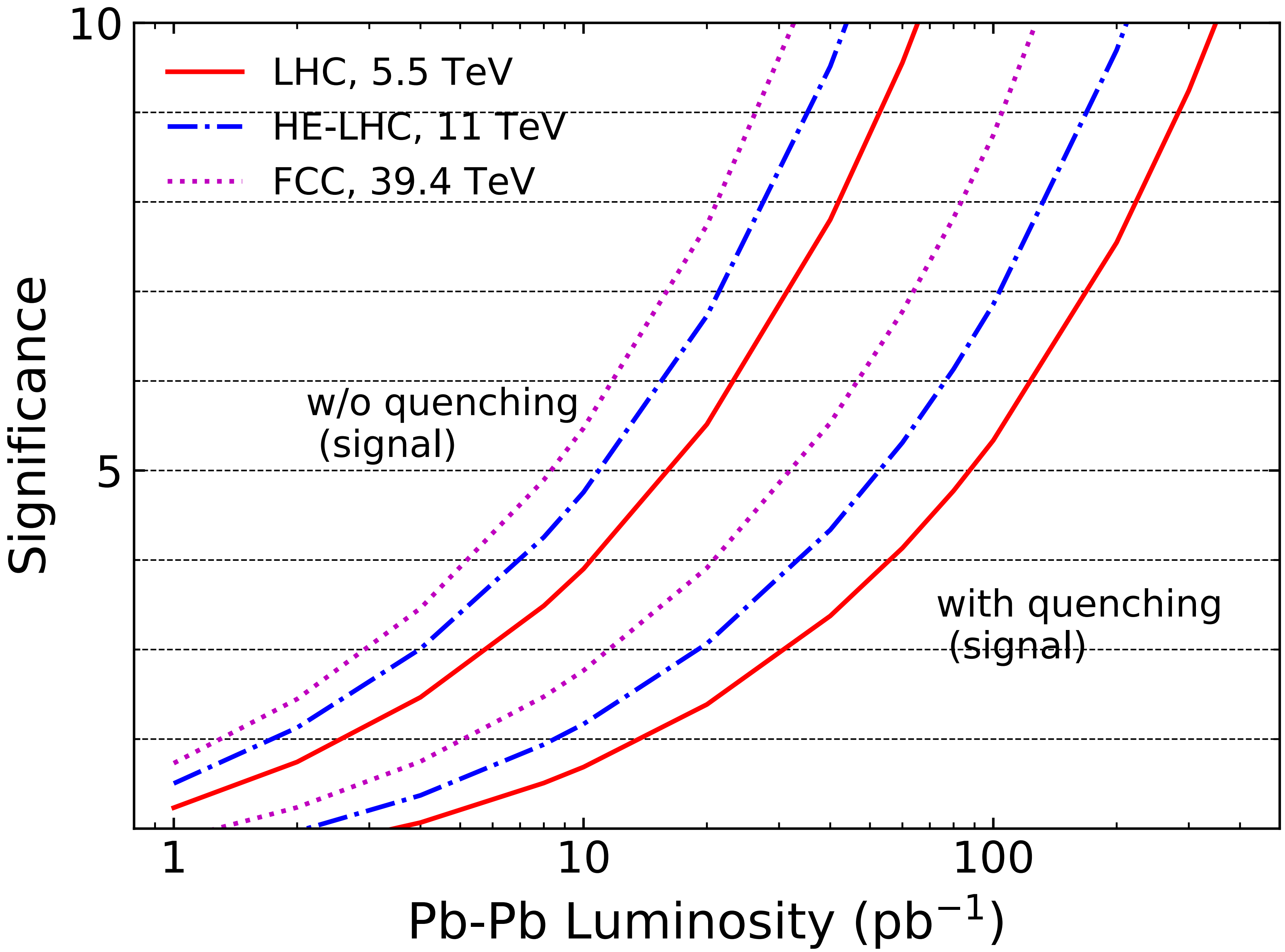
- Challenges from the dark matter direct detection experiments.



Xenon1T collaboration, arXiv:1805.12562[astro-ph.CO].

Example

- Higgs boson in heavy-ion collision.



E. L. Berger, J. Gao, A. Jueid, *HZ*, arXiv:1804.06858[hep-ph].