

A theory perspective on

Future Colliders: is it worth it or not?

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SEP. 30 2024, LNF FRASCATI



Uniquely positioned

- **Laboratory tests of fundamental interactions are the only way to figure out the microscopic laws of Nature.**
- **There is only so much that you can learn if you cannot control the initial state of the experiment**
- **“Dialogue with Nature”**: you have to make experiments aimed at revealing the aspect of Nature you want to study (Descartes, Galilei, ...)

The Higgs boson is nothing like anything else before

- All fundamental bosons we know are gauge bosons. Up to very important technicalities they are the same as the photon.
- The Higgs boson does not follow the same rules, its interactions have nothing to do with those of the photons.
- Higgs-like particles that appear in other types of experiments (e.g. excitations of condensed matter systems) are not a narrow and isolated particle.

Classical Electrodynamics

J. Iliopoulos 2024

- ▶ Around the years 1840 F.E. Neumann and, independently, W.E. Weber, studied the interaction between two closed electric circuits carrying currents I and I' .

$$dW_N = \frac{II'}{c^2} \frac{\mathbf{n} \cdot \mathbf{n}'}{r} ds ds' \quad dW_W = \frac{II'}{c^2} \frac{(\mathbf{n} \cdot \hat{\mathbf{r}})(\mathbf{n}' \cdot \hat{\mathbf{r}})}{r} ds ds'$$

$$d\mathbf{s} = \mathbf{n} ds \text{ and } d\mathbf{s}' = \mathbf{n}' ds'$$

- ▶ 1870 : H.L.F. von Helmholtz noticed that the two differ by a multiple of the perfect differential

$$ds ds' \frac{\partial^2 r}{\partial s \partial s'} = ds ds' \frac{(\mathbf{n} \cdot \hat{\mathbf{r}})(\mathbf{n}' \cdot \hat{\mathbf{r}}) - (\mathbf{n} \cdot \mathbf{n}')}{r}$$

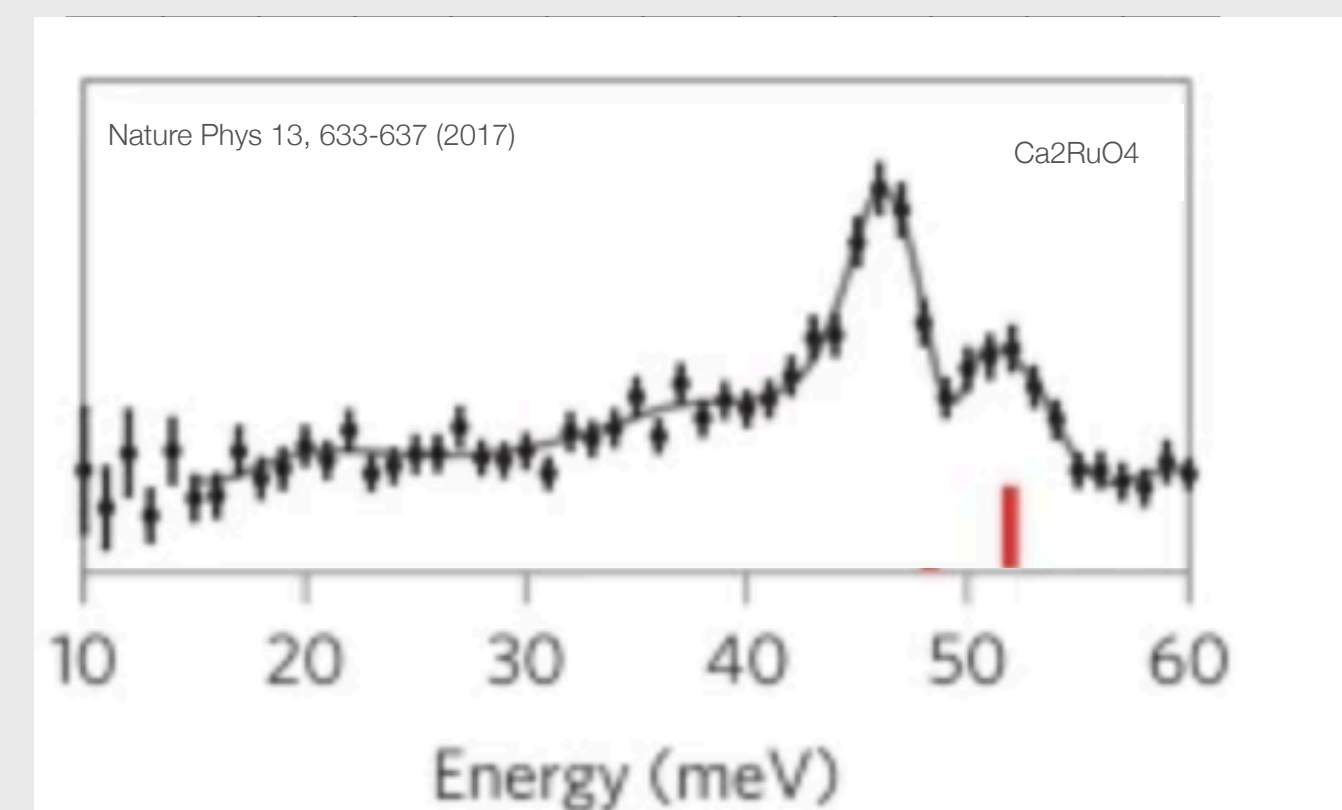
and wrote the first family of gauges

$$dW_\alpha = \frac{II'}{2c^2 r} [(1 + \alpha)(\mathbf{n} \cdot \mathbf{n}') + (1 - \alpha)(\mathbf{n} \cdot \hat{\mathbf{r}})(\mathbf{n}' \cdot \hat{\mathbf{r}})] ds ds'$$

- ▶ In terms of the vector potential

$$\mathbf{A}_\alpha = \mathbf{A}_N + \frac{1-\alpha}{2} \nabla \Psi \quad \Psi = -\frac{1}{c} \int \hat{\mathbf{r}} \cdot \mathbf{J}(\mathbf{x}', t) d^3 x'$$

Navigation icons



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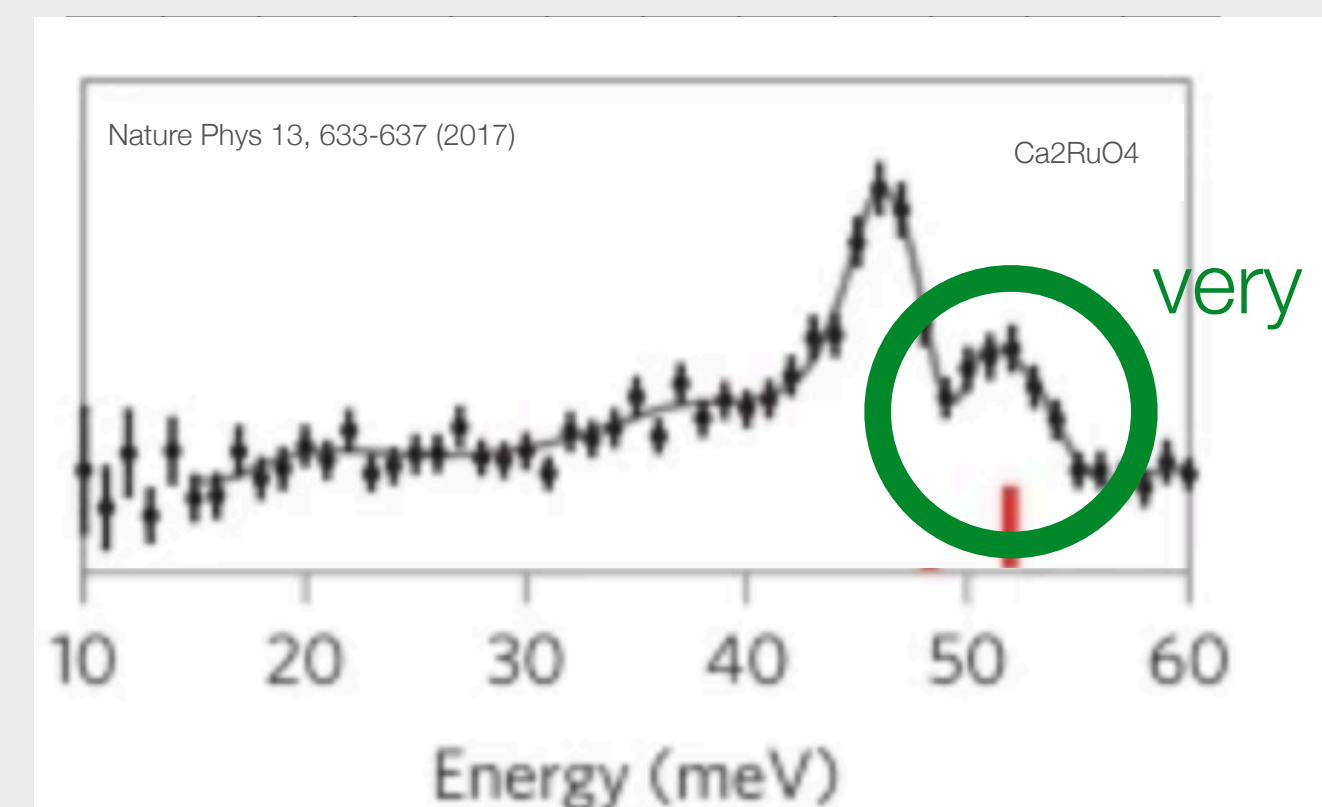
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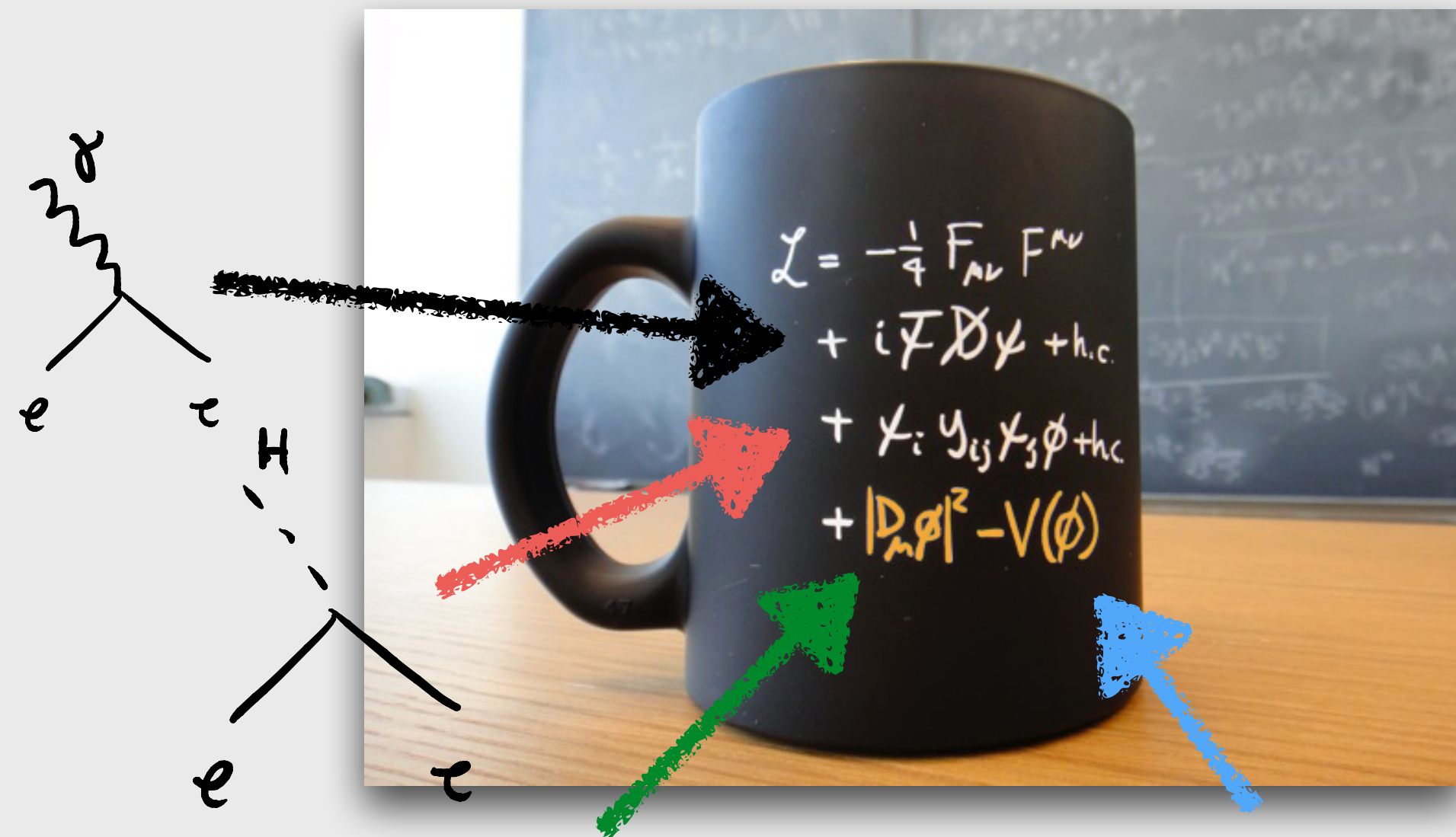
very broad Higgs particle

The Higgs boson is nothing like anything else before

SYMMETRY

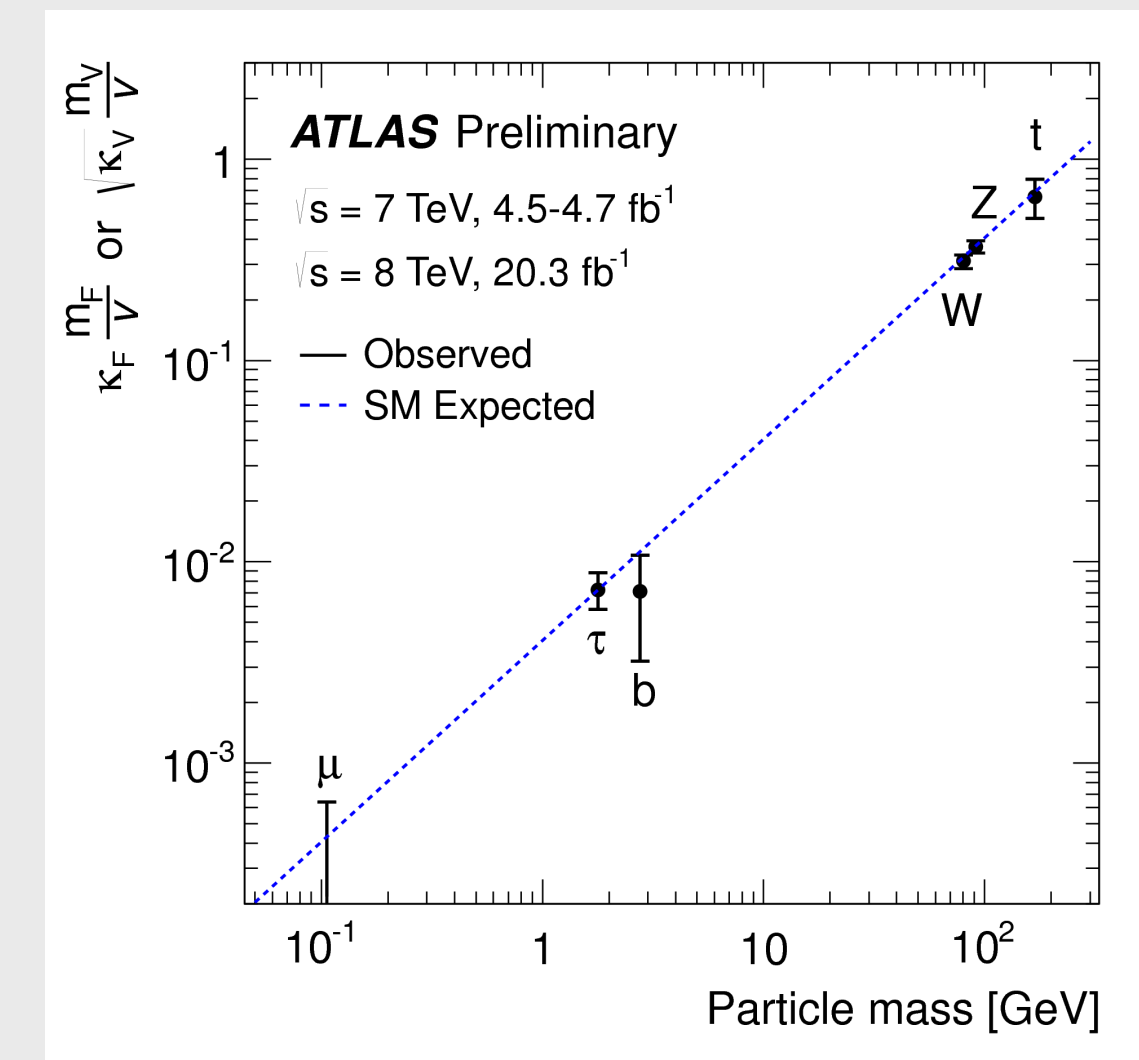
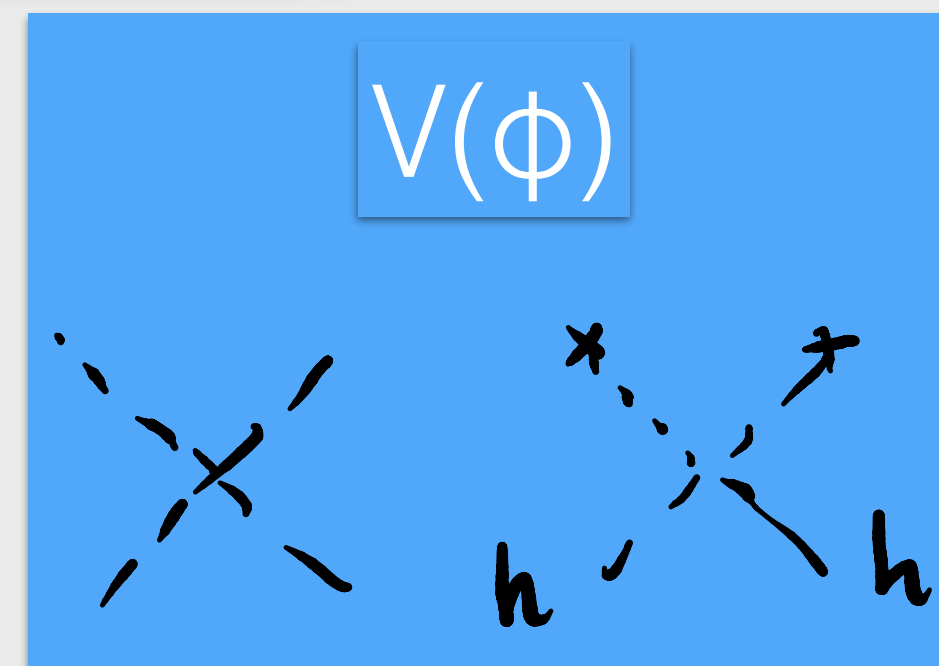
AS A FUNDAMENTAL CHARACTER OF NATURE

?????



electro-weak interactions

strong interactions



The Higgs boson is nothing like anything else before

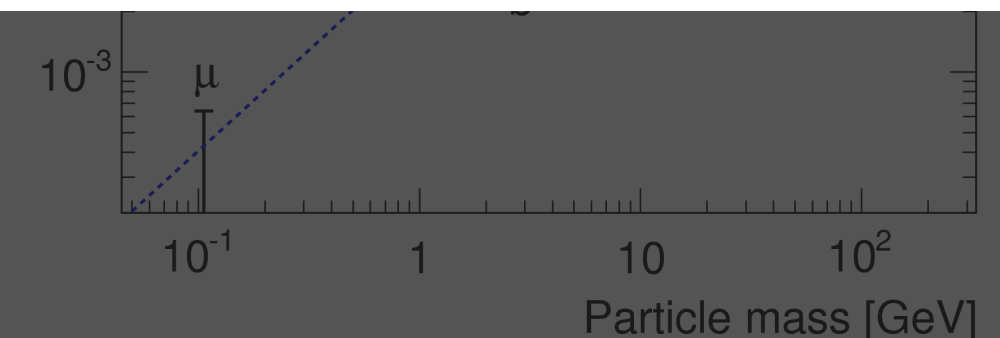
SYMMETRY

AS A FUNDAMENTAL CHARACTER OF NATURE

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electro-weak interactions

- We established the principles behind electroweak and strong interaction very well
- We measured the Higgs boson only very “broad brush”
- The Higgs boson may be a whole new thing compared to strong and electroweak interactions



The Higgs boson is nothing like anything else before

SYMMETRY

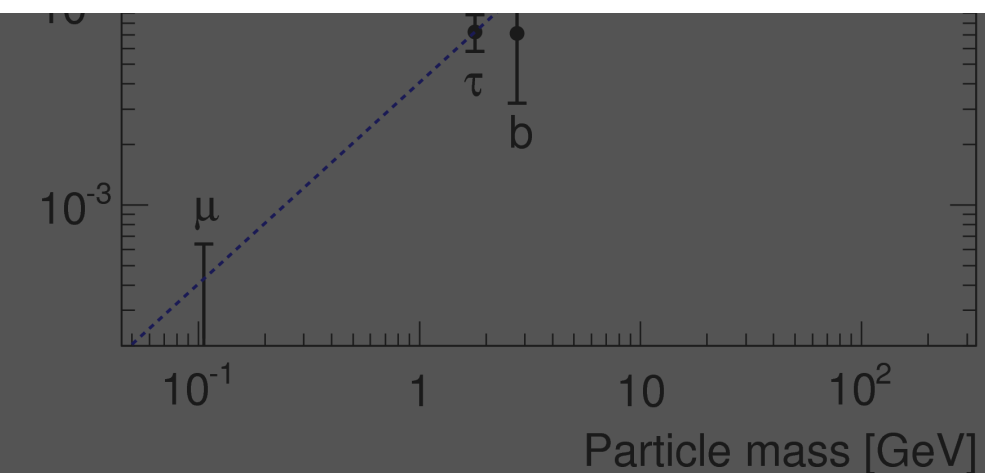
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electro-weak interactions

- Is the Higgs boson a point-like particle? (Can we use the SM at as short distance as we like?)
- Is the Higgs boson related to the origin of matter? (Why the SM treat matter and anti-matter equally, but there is no antimatter around? Are the Higgs interactions somehow getting rid of anti-matter in the Early Universe?)
- Is the Higgs boson keeping the Universe stable?



Is it worth it?

There is a special pleasure that comes from identifying symmetries in nature, from understanding that the ubiquitous and tangible electron is an immediate relative of the elusive neutrino. But the challenge of particle physics today is to understand symmetry breaking, for that is what makes the world what it is. The neutrino and the electron are really as different as they can be. **How** does that happen? **Why** do we have two very light quarks and one very light charged lepton? **Why** did electroweak symmetry breaking leave one symmetry unbroken, bequeathing us the photon? **Why** is there light, and why does matter take the form it does? **These are the goals of particle physics: not to describe the collisions of highly relativistic protons, but to learn why our world has the shape and form it does.** **But to answer questions about the everyday world we need to observe phenomena that occur only at very high energies.**

flashing concrete results for

The size of the Higgs boson

Effects of the size of the Higgs boson

$h \sim \pi$

STRONGLY INTERACTING LIGHT HIGGS

$$\begin{aligned}
 \mathcal{L}_{universal}^{d=6} = & c_H \frac{g_*^2}{m_*^2} \mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2} \mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2} \mathcal{O}_6 + \frac{1}{m_*^2} [c_W \mathcal{O}_W + c_B \mathcal{O}_B] \\
 & + \frac{g_*^2}{(4\pi)^2 m_*^2} [c_{HW} \mathcal{O}_{HW} + c_{HB} \mathcal{O}_{HB}] + \frac{y_t^2}{(4\pi)^2 m_*^2} [c_{BB} \mathcal{O}_{BB} + c_{GG} \mathcal{O}_{GG}] \\
 & + \frac{1}{g_*^2 m_*^2} [c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}] + c_{3W} \frac{3! g^2}{(4\pi)^2 m_*^2} \mathcal{O}_{3W} \\
 & + c_{y_t} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_t} + c_{y_b} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_b}
 \end{aligned}$$

$$1/f \sim g_*/m_*$$

$$1/(g_* f) \sim 1/m_*$$

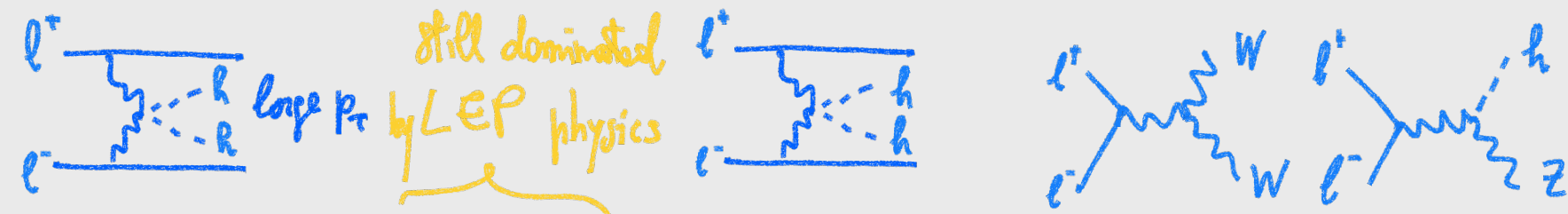
$$g_{SM}/(g_* f) \sim g_{SM}/m_*$$

$$\ell_{Higgs} \sim 1/m_*$$



Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS

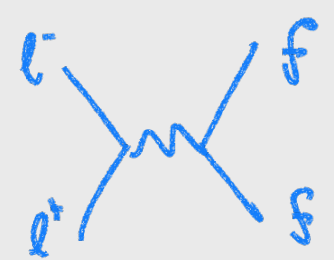


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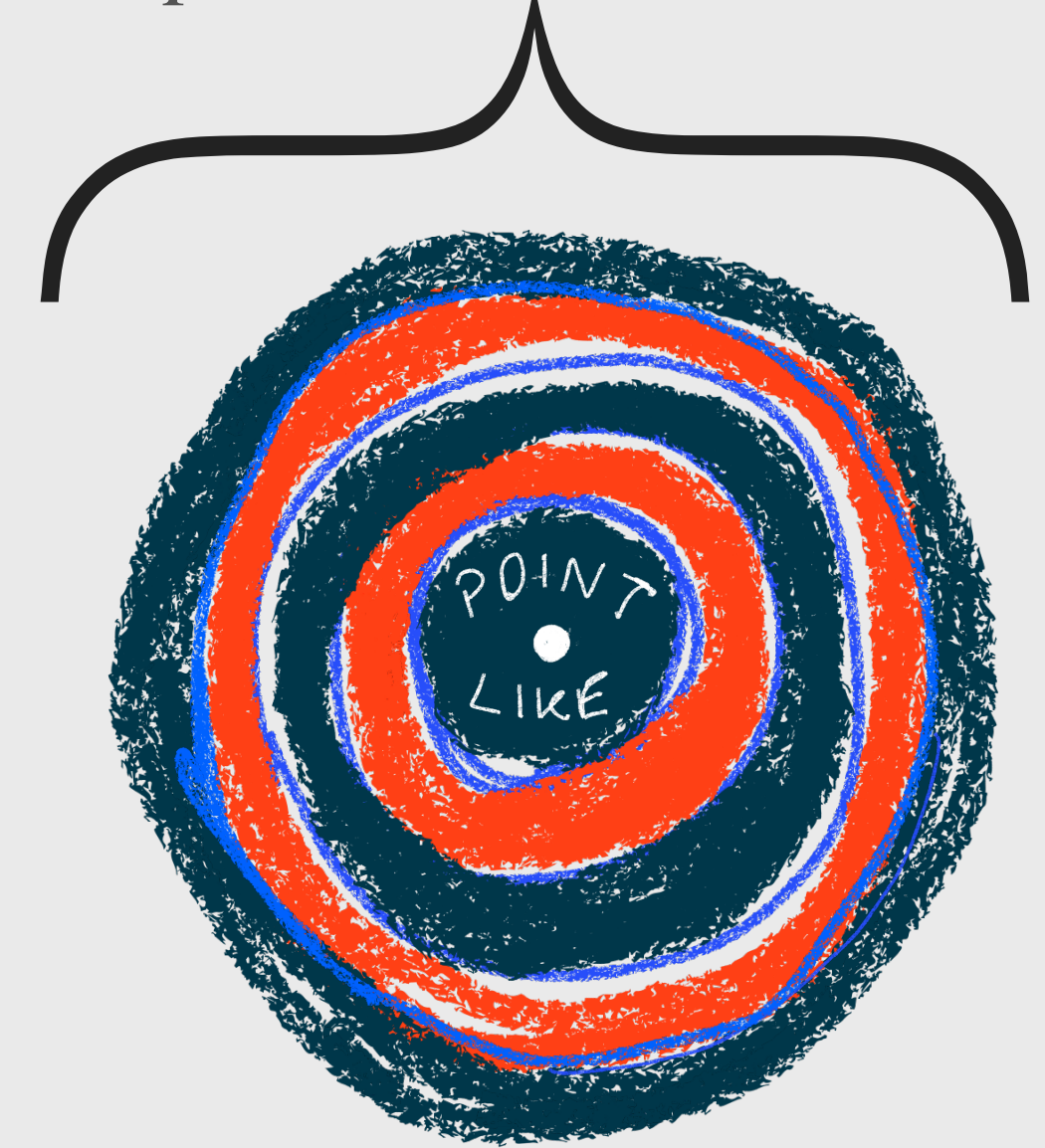


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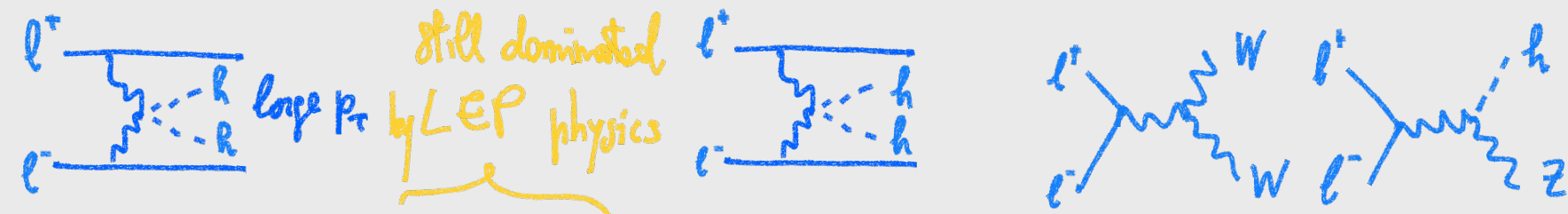
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$$\ell_{top} \sim 1/m_* \sim \ell_{Higgs}$$



Effects of the size of the Higgs boson

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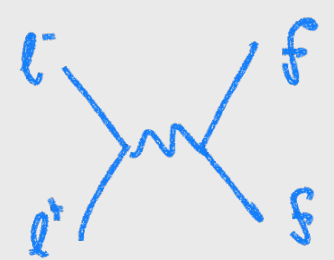


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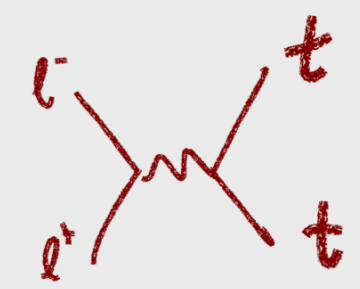
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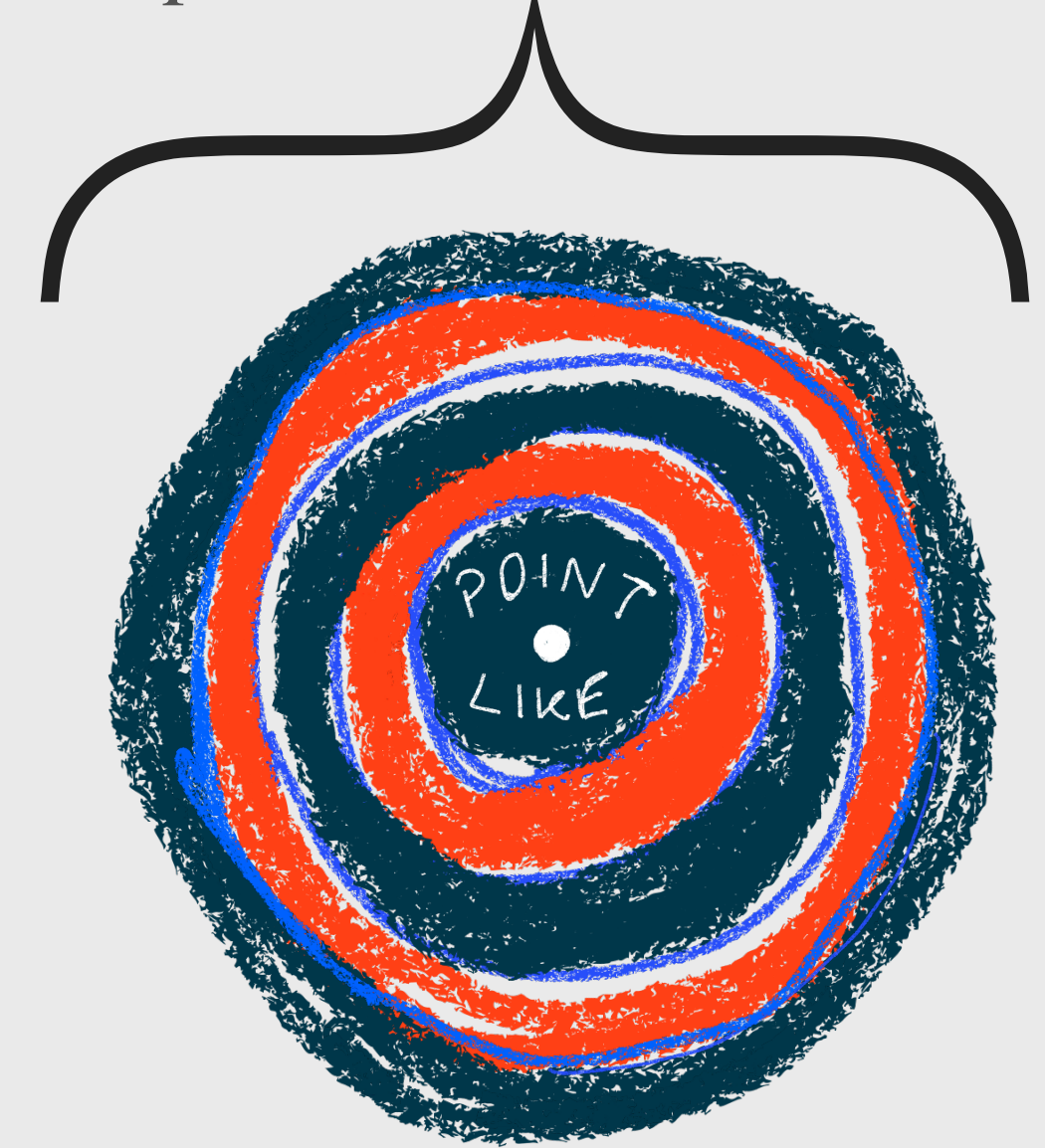
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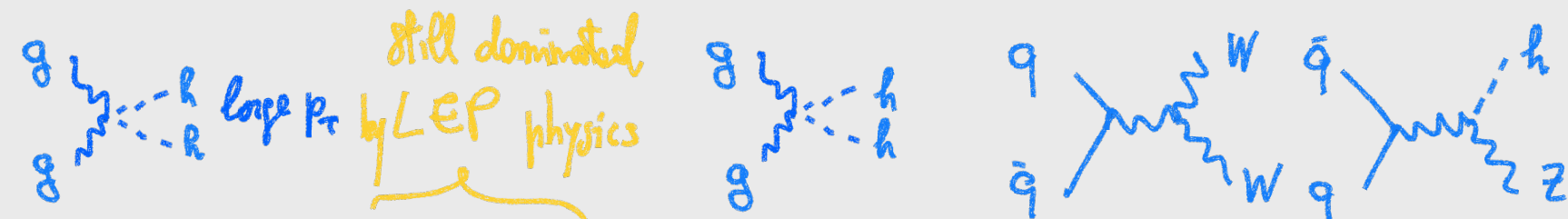
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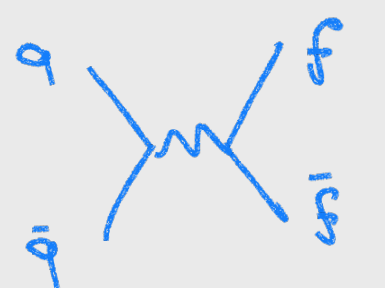


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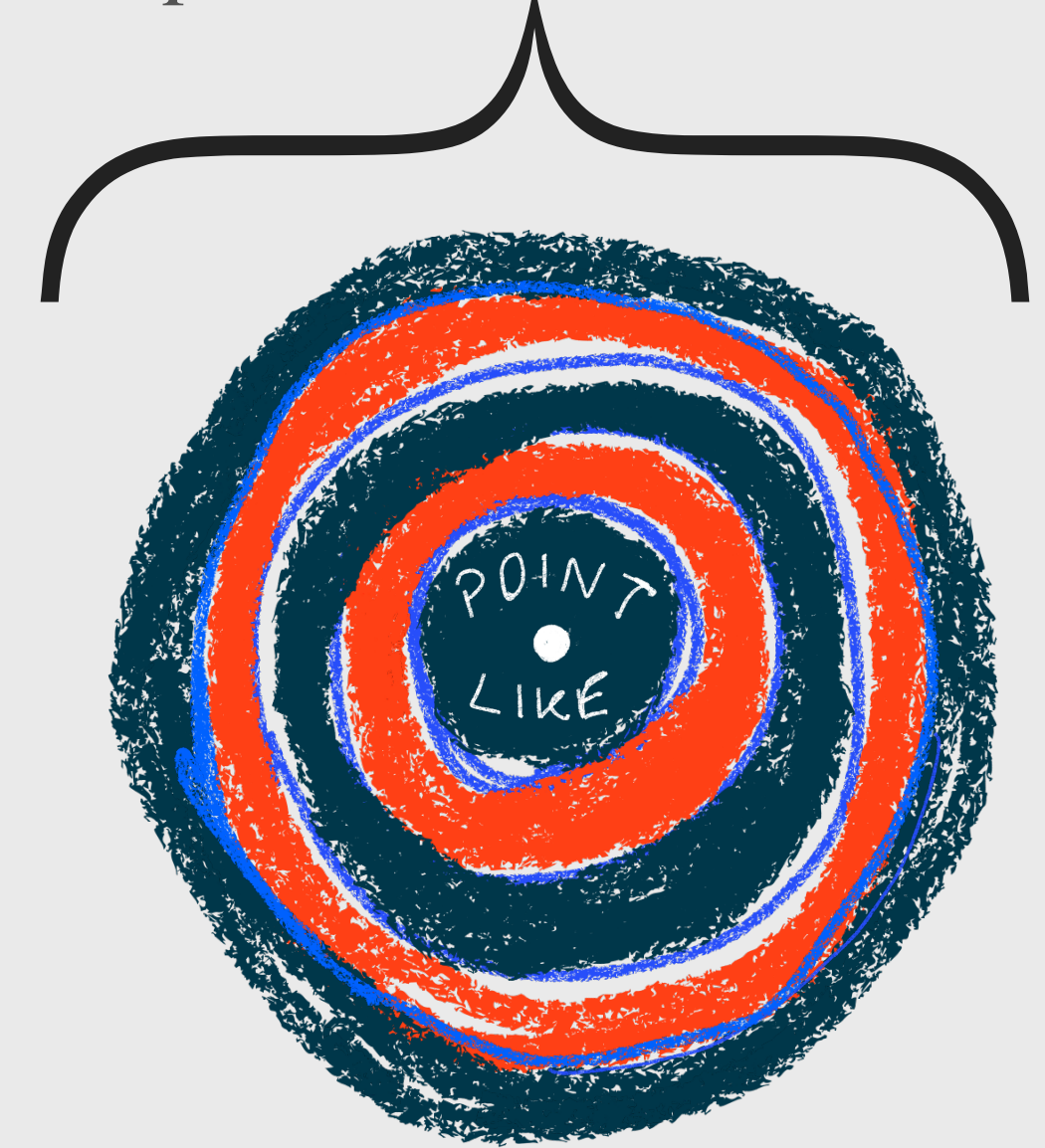


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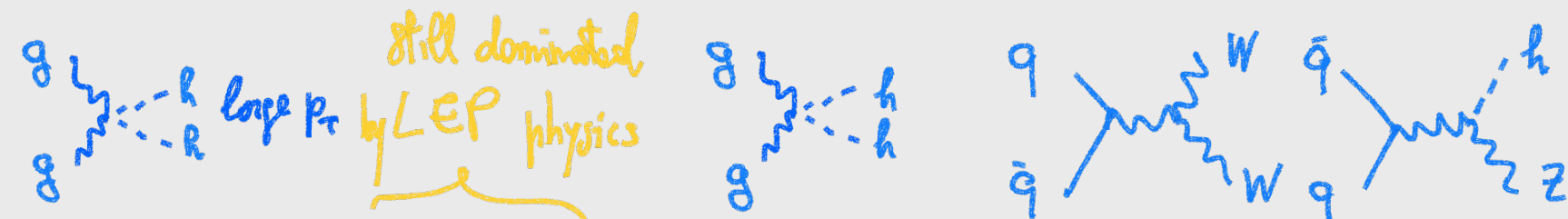
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Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



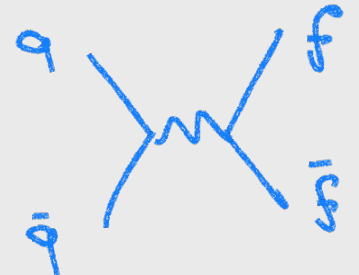
still dominated by LEP physics

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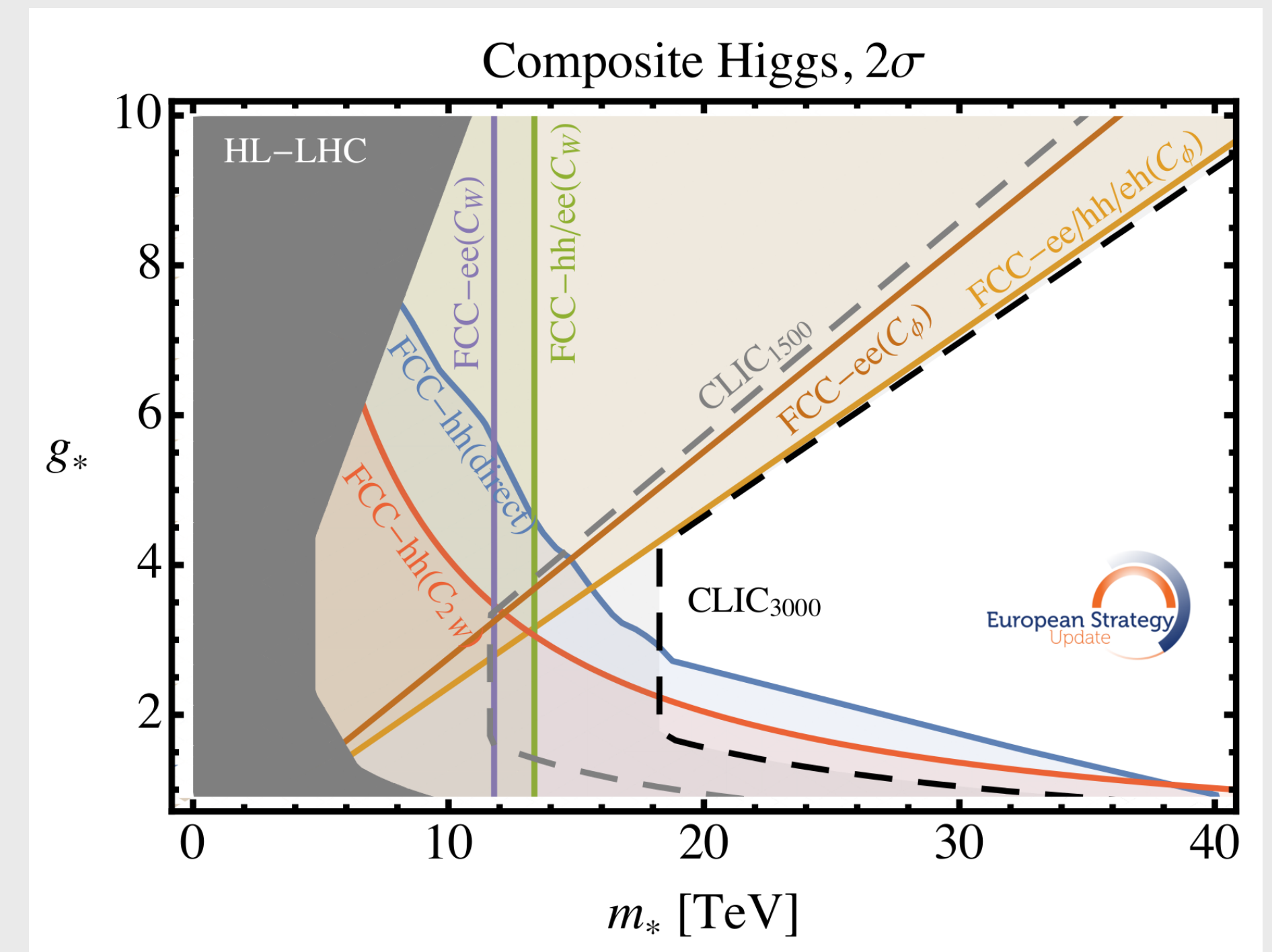
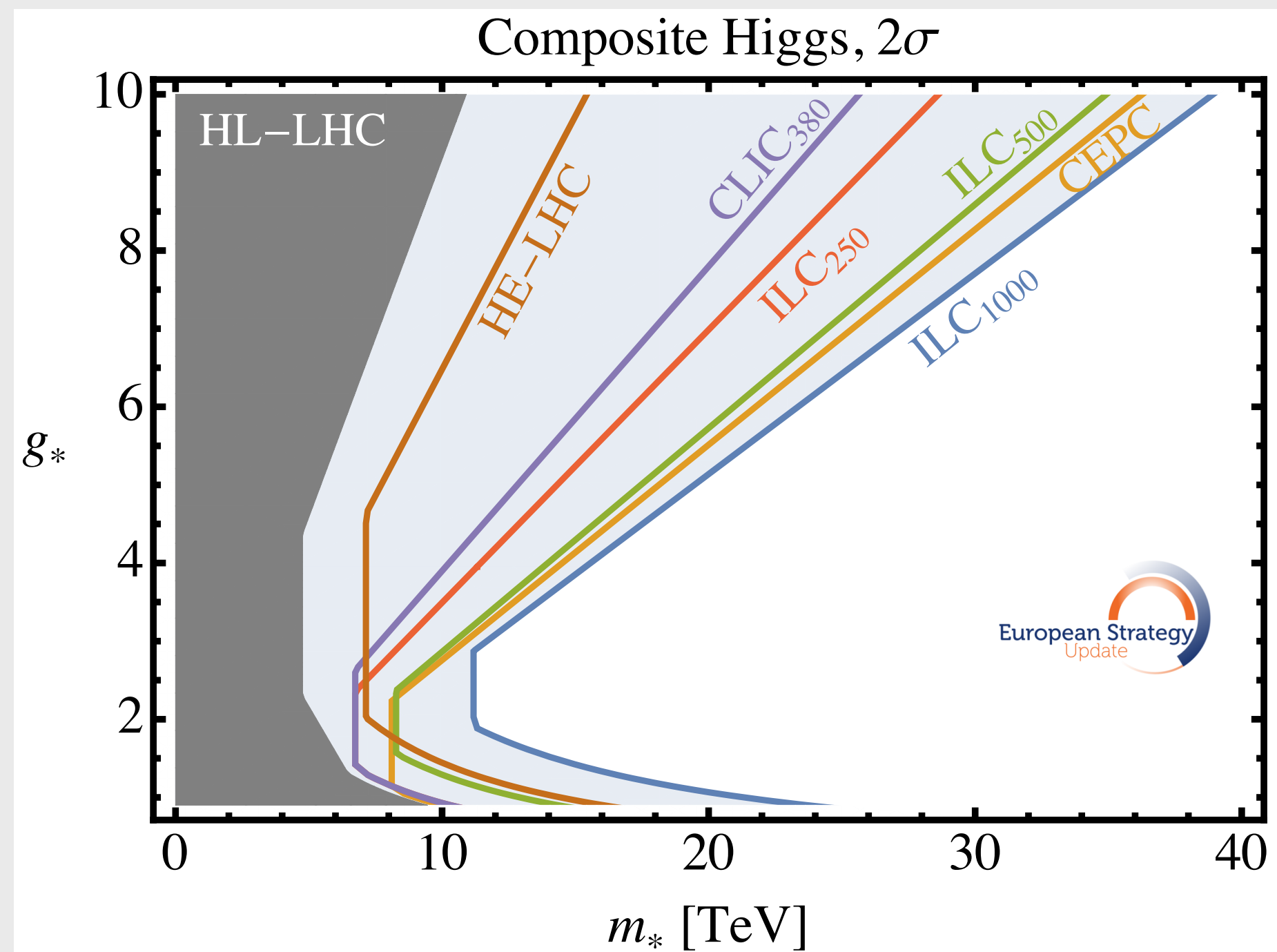


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Higgs compositeness



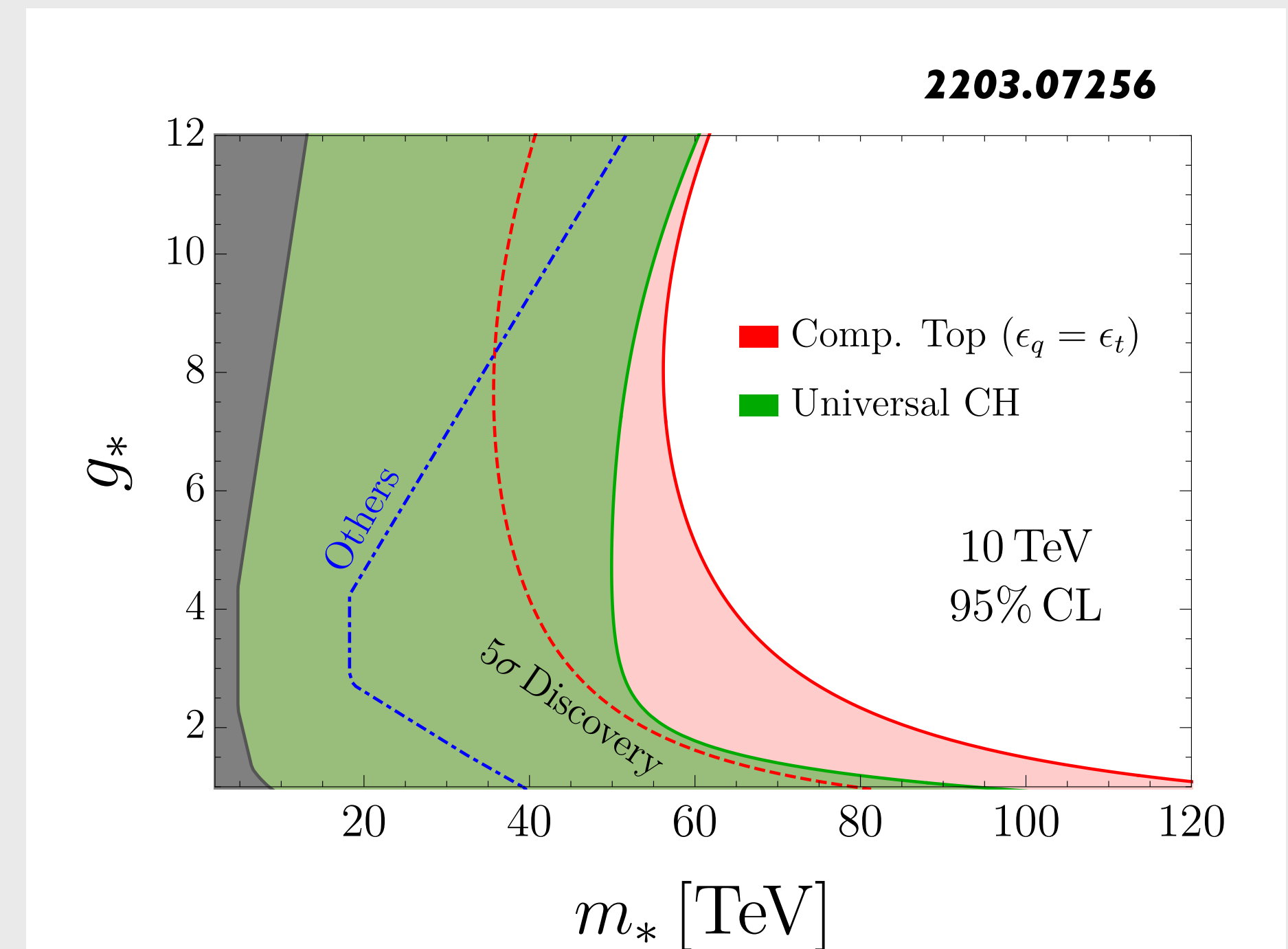
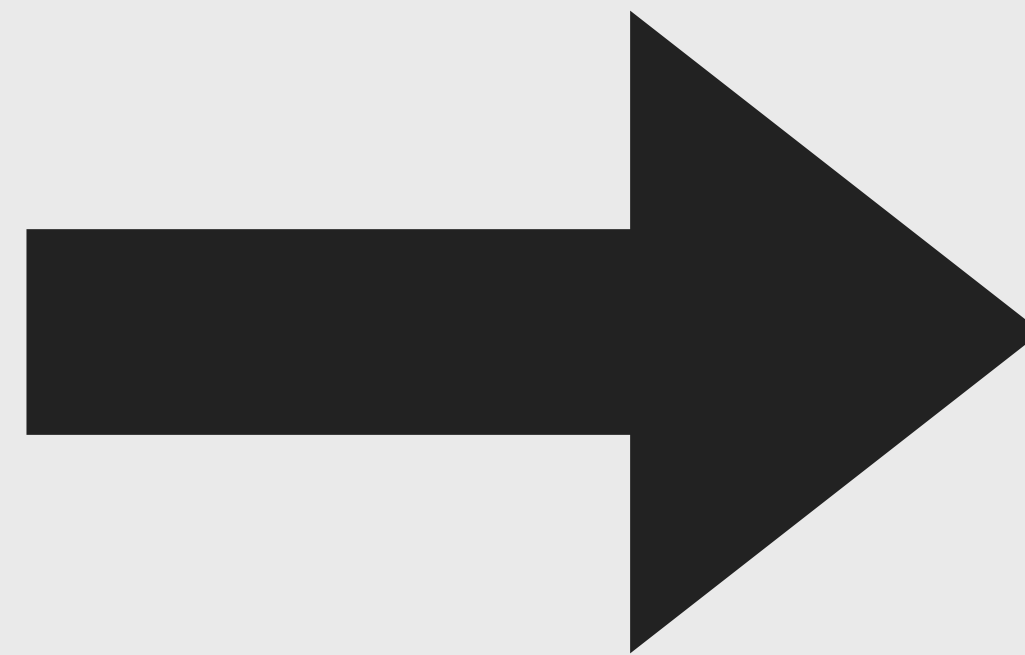
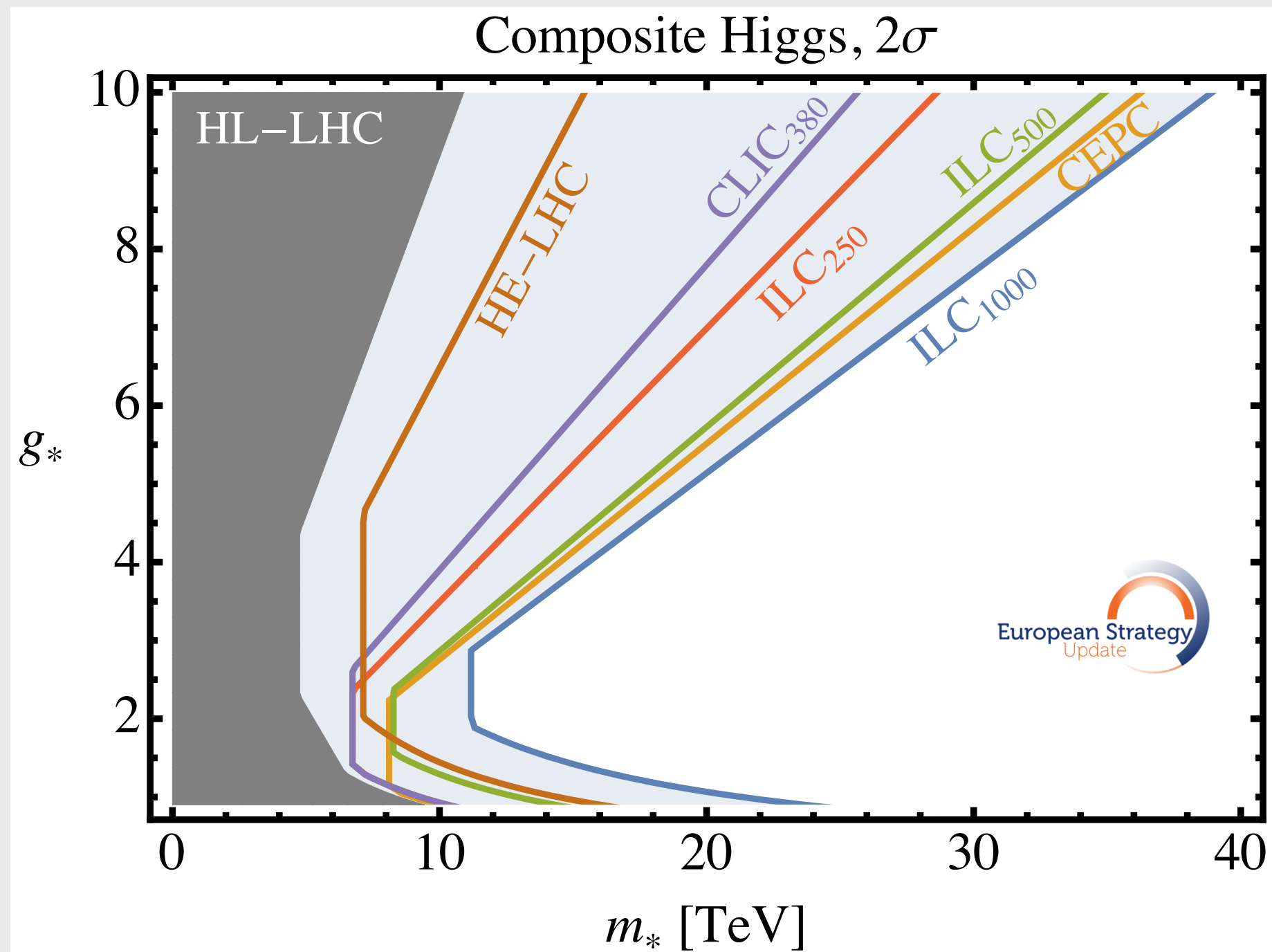
**compositeness at
few TeV @ HL-LHC**

Higgs as composite as QCD pion

**compositeness at
few 10 TeV**

Higgs compositeness

UNIQUE AVENUE TO EXPLORE WEAK INTERACTIONS
FAR OFFSHORE FROM THE WEAK SCALE



**compositeness at
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Higgs as composite as QCD pion

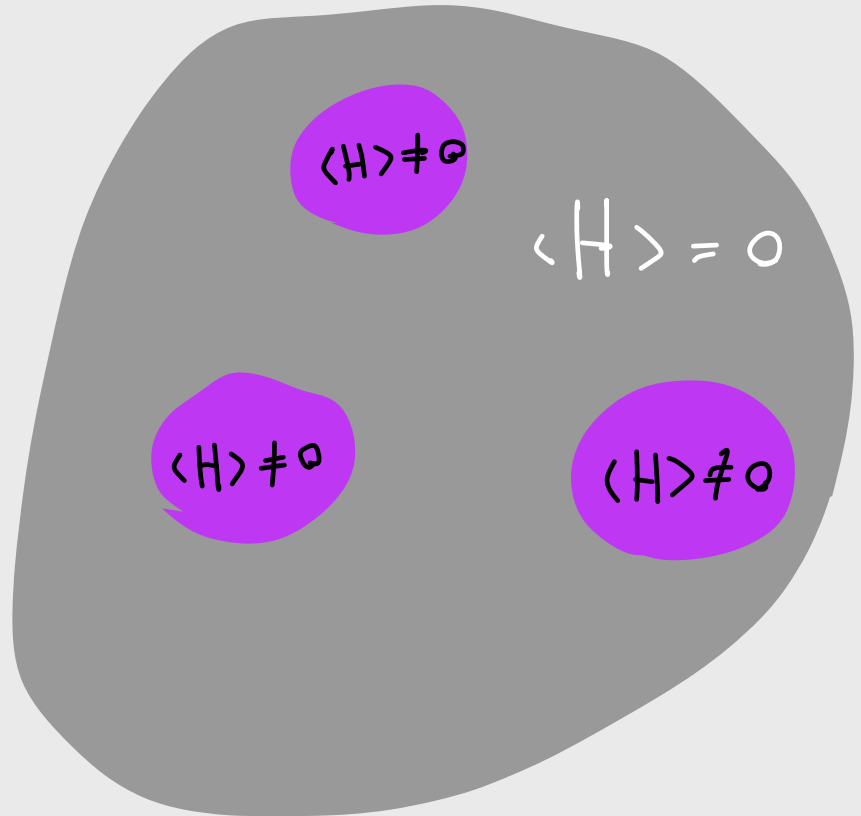
**compositeness at
few 100 TeV**

Higgs 100x more point-like than QCD pion

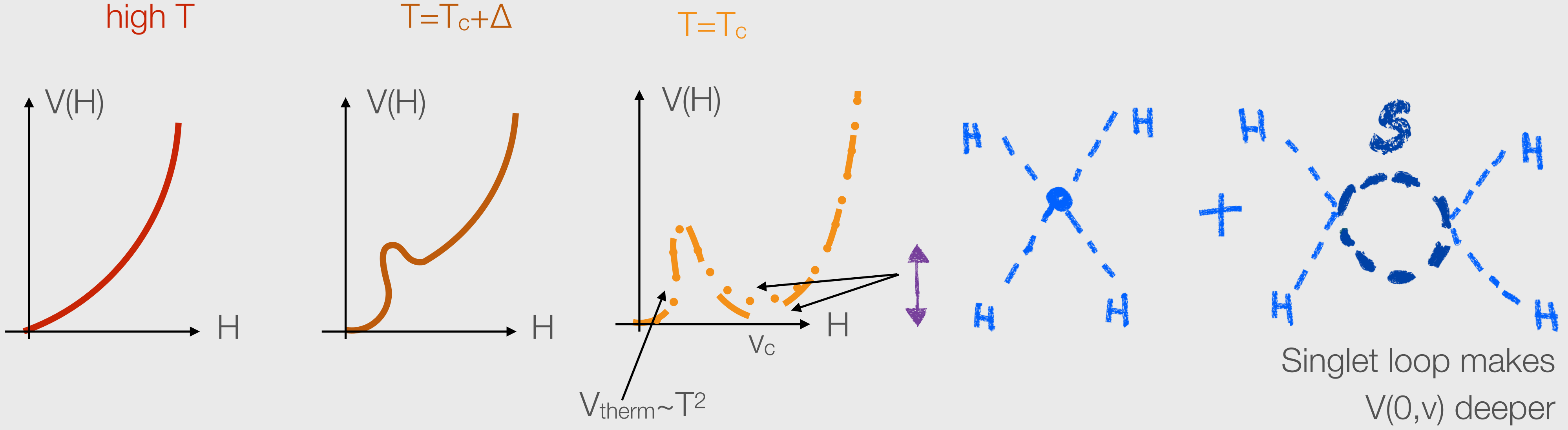
flashing concrete results for

EW phase transition

Electroweak phase transition



- Modifications of the Higgs potential \Rightarrow Out of Equilibrium transition from one vacuum to a new energetically favorable one



Electroweak phase transition

- We need to study all possible new states that induce a change in the Higgs boson potential.
- For these new state to have sizable effects in the early Universe they must be light, around 1 TeV at most.
- All searches for new Higgs bosons (or general electroweak particles) probe such fundamental issue of the origin of matter in the early Universe!

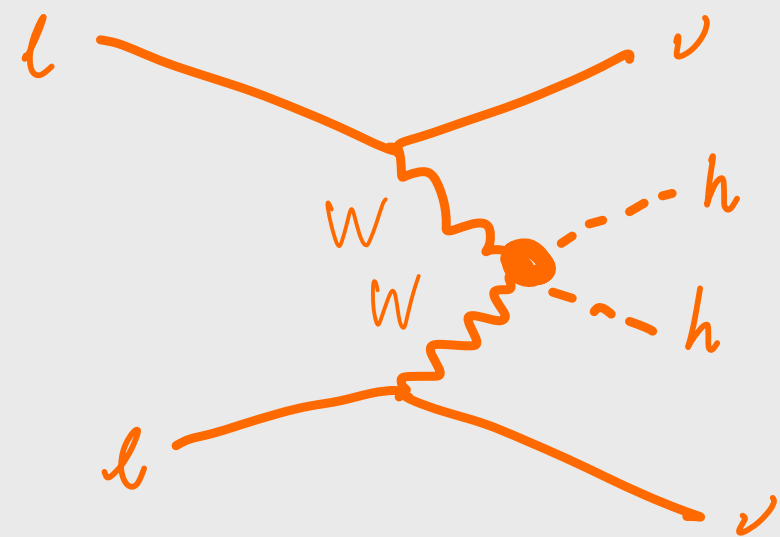
$$V_{\text{therm}} \sim T^2$$

$V(0,v)$ deeper

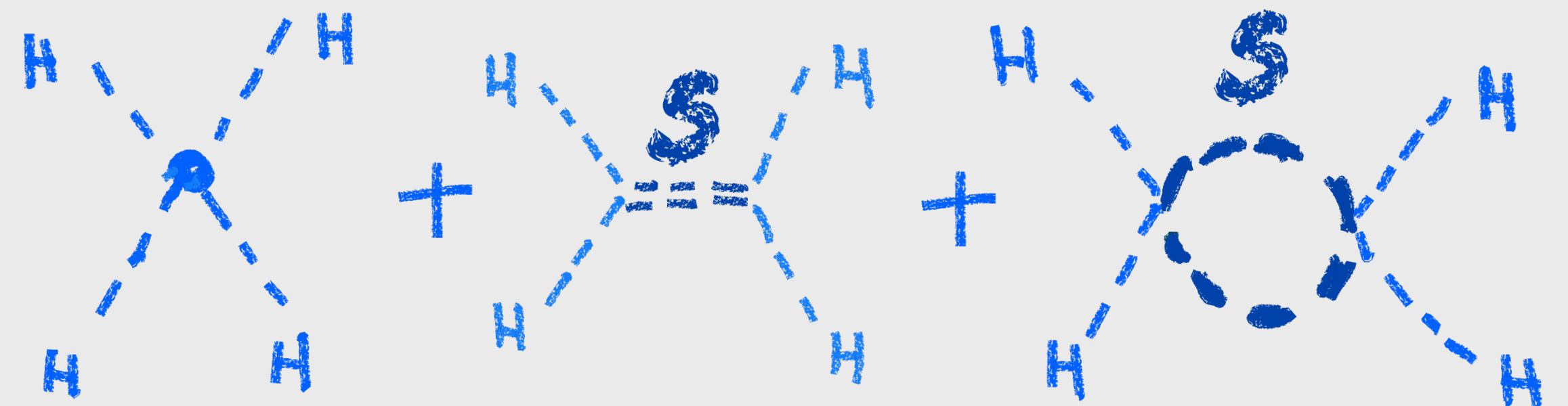
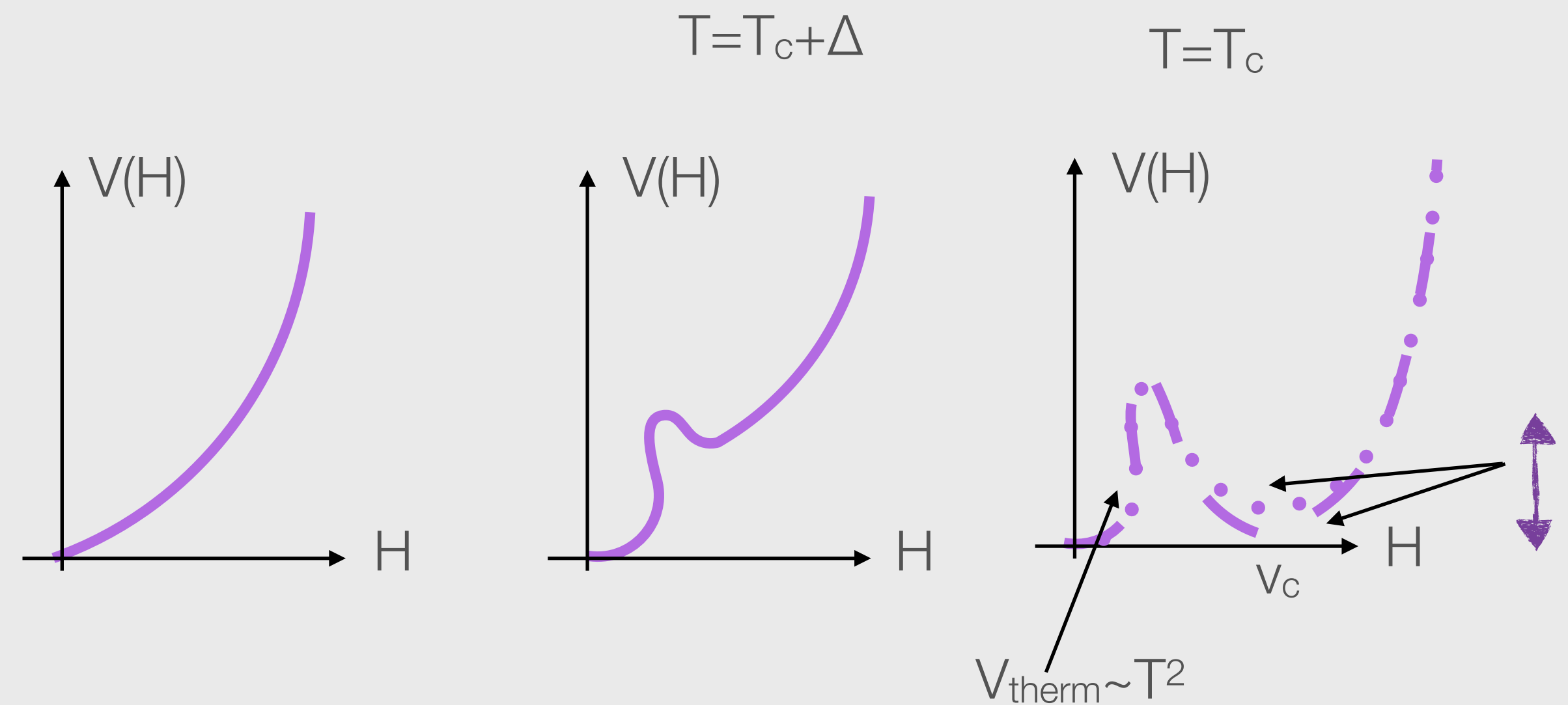
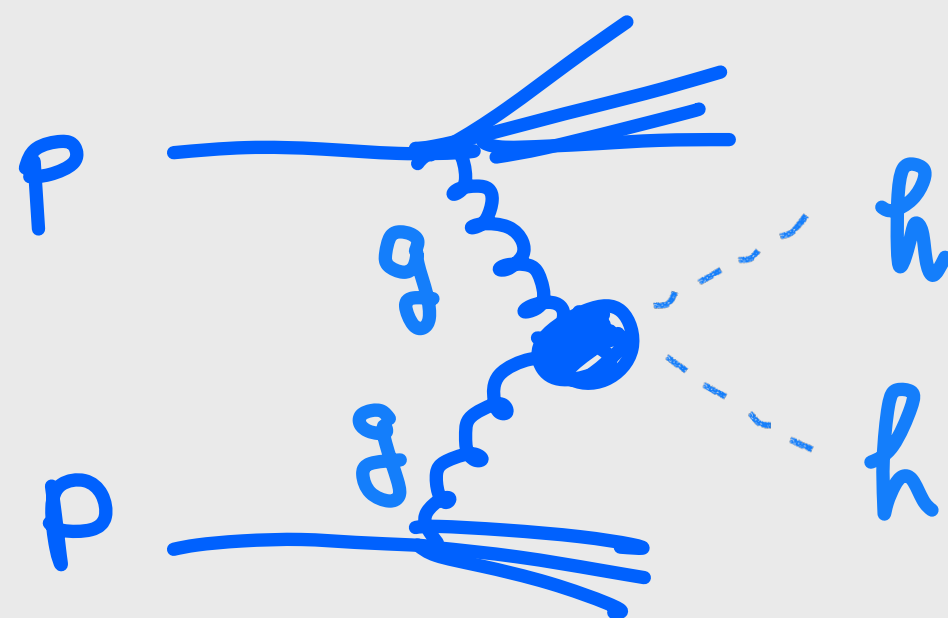
$$pp \text{ or } \ell^+ \ell^- \rightarrow hh$$

Electroweak phase transition

- High-Energy lepton collider has large flux of “partonic” W bosons



- gg collisions (as usual)



Singlet tree and loop makes $V(0, v)$ deeper

EW phase transition

DIRECT & INDIRECT

INTERPLAY

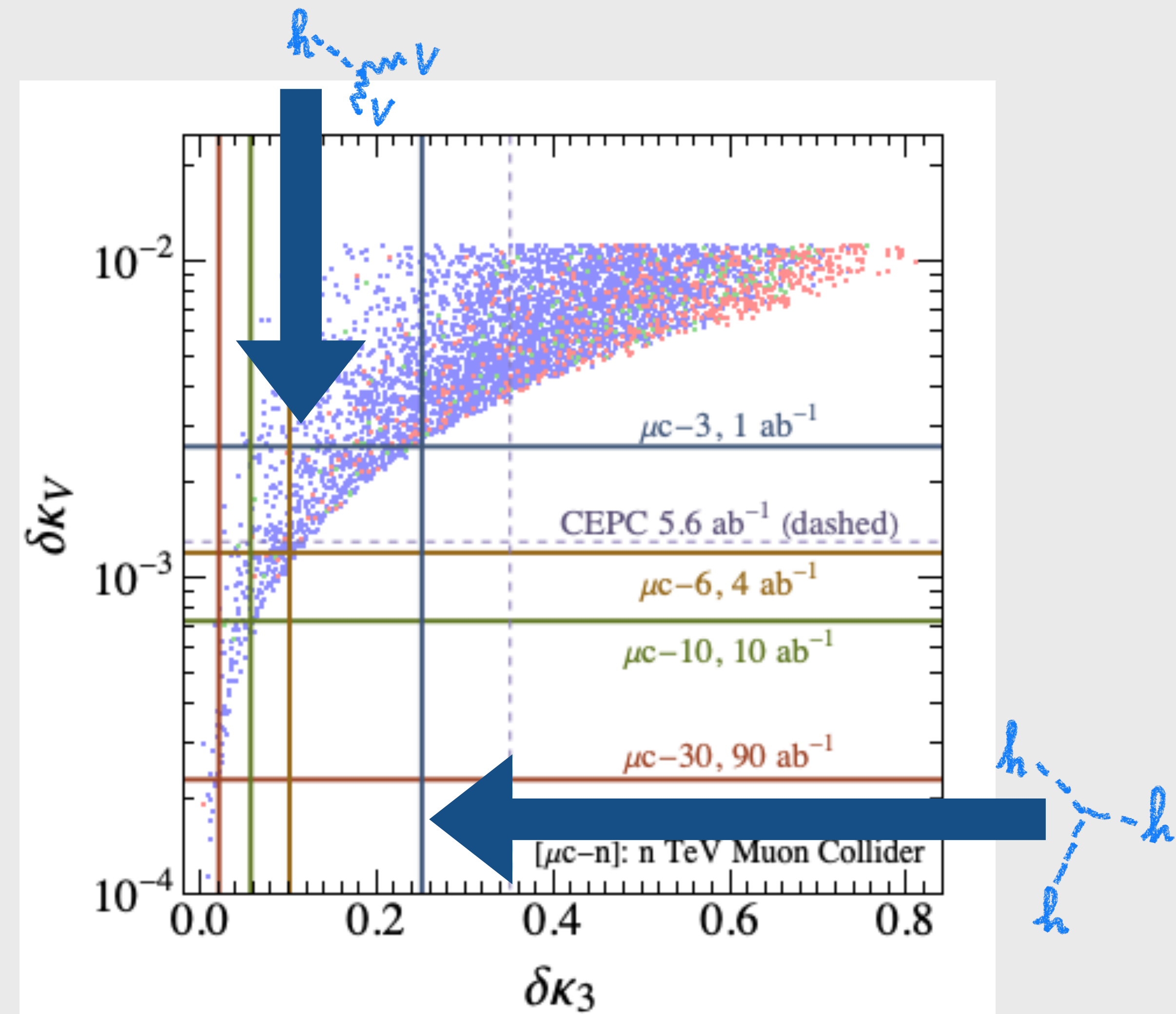
$$V(\Phi, S) = -\mu^2 (\Phi^\dagger \Phi) + \lambda (\Phi^\dagger \Phi)^2 + \frac{a_1}{2} (\Phi^\dagger \Phi) S + \frac{a_2}{2} (\Phi^\dagger \Phi) S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

independent parameters

$$\{M_{h_2}, \theta, v_s, b_3, b_4\}$$

strong First Order EW phase transition on all points

× ● ● → Gravity Wave SNR



EW phase transition

DIRECT & INDIRECT

INTERPLAY

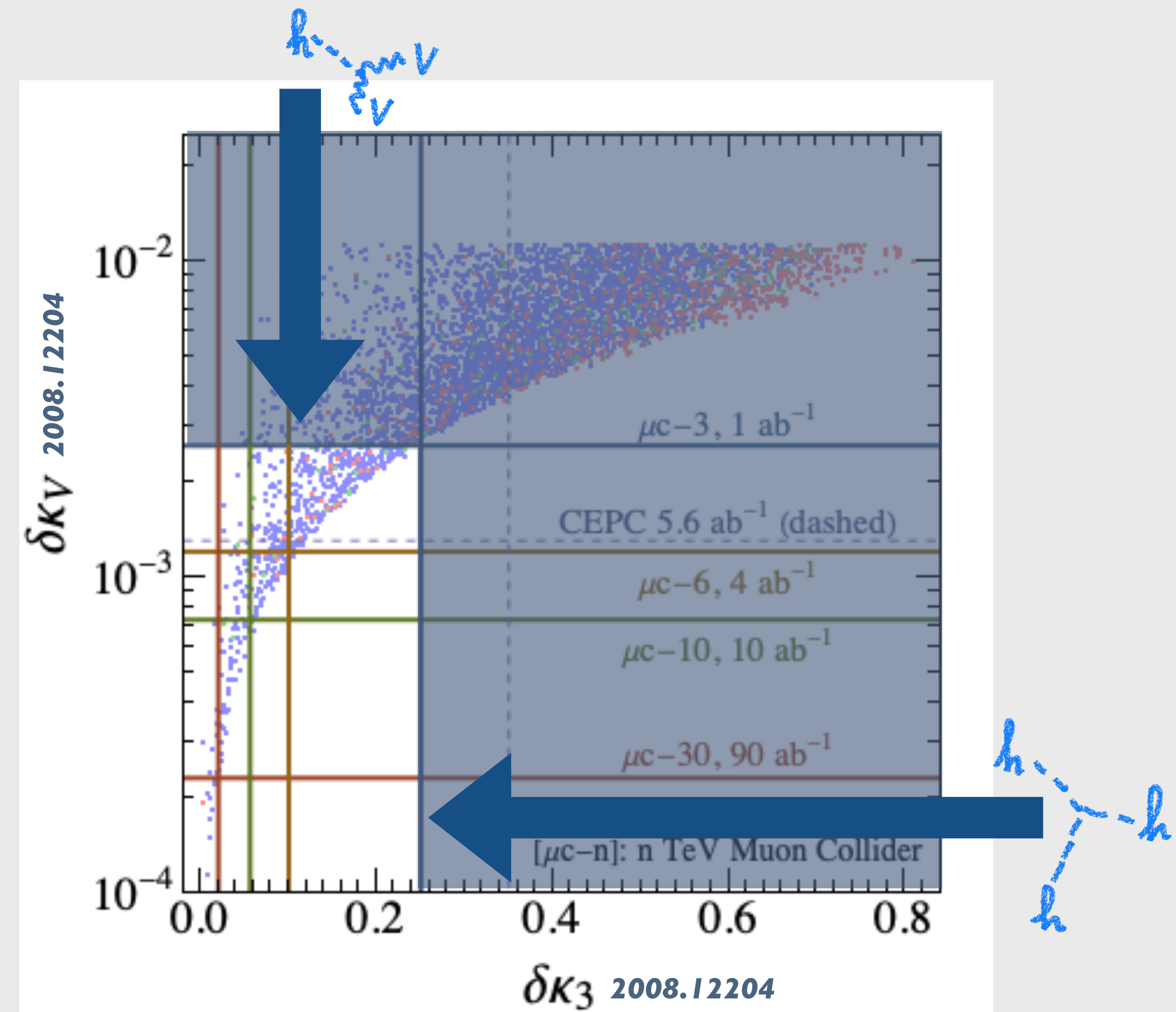
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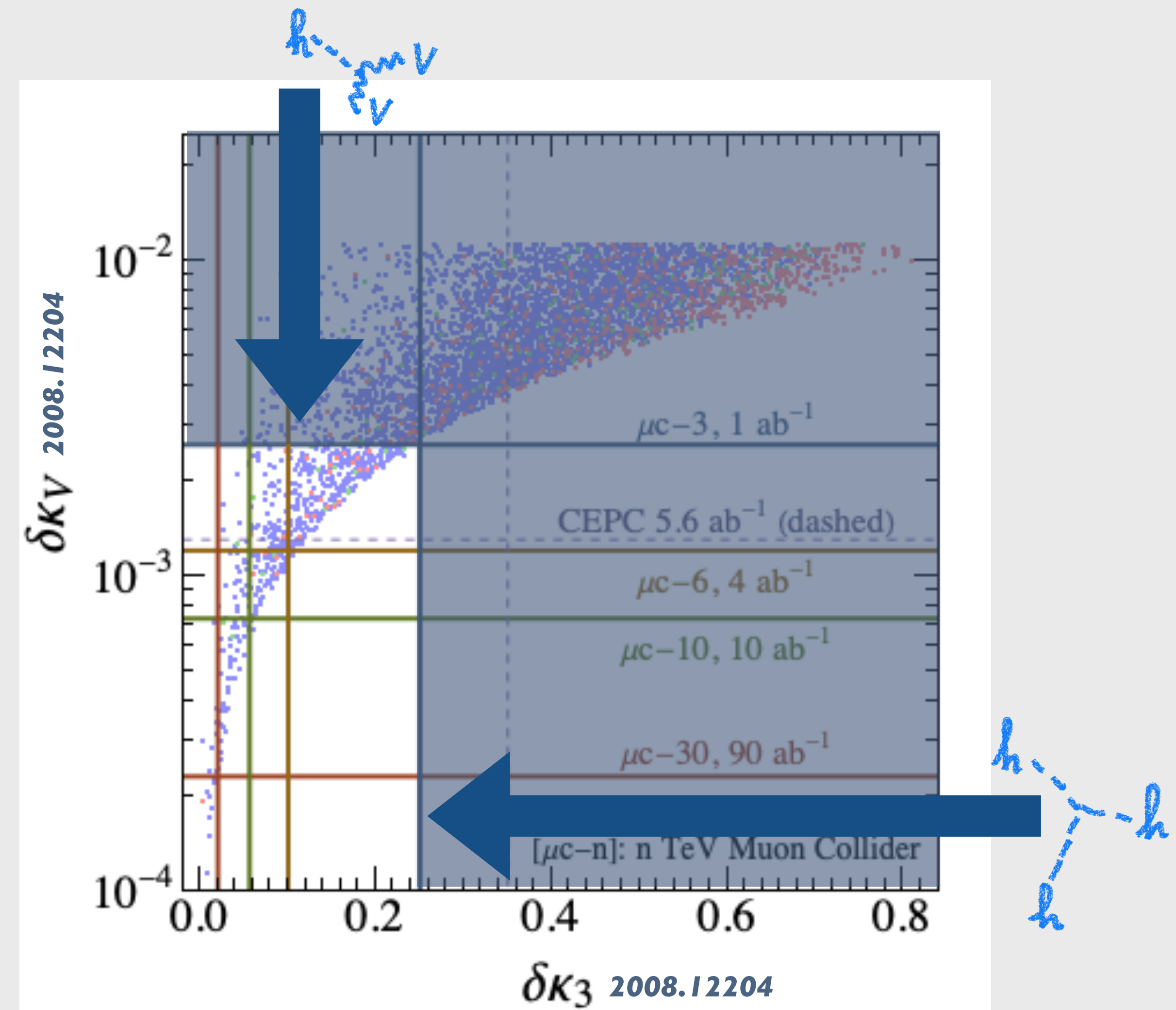
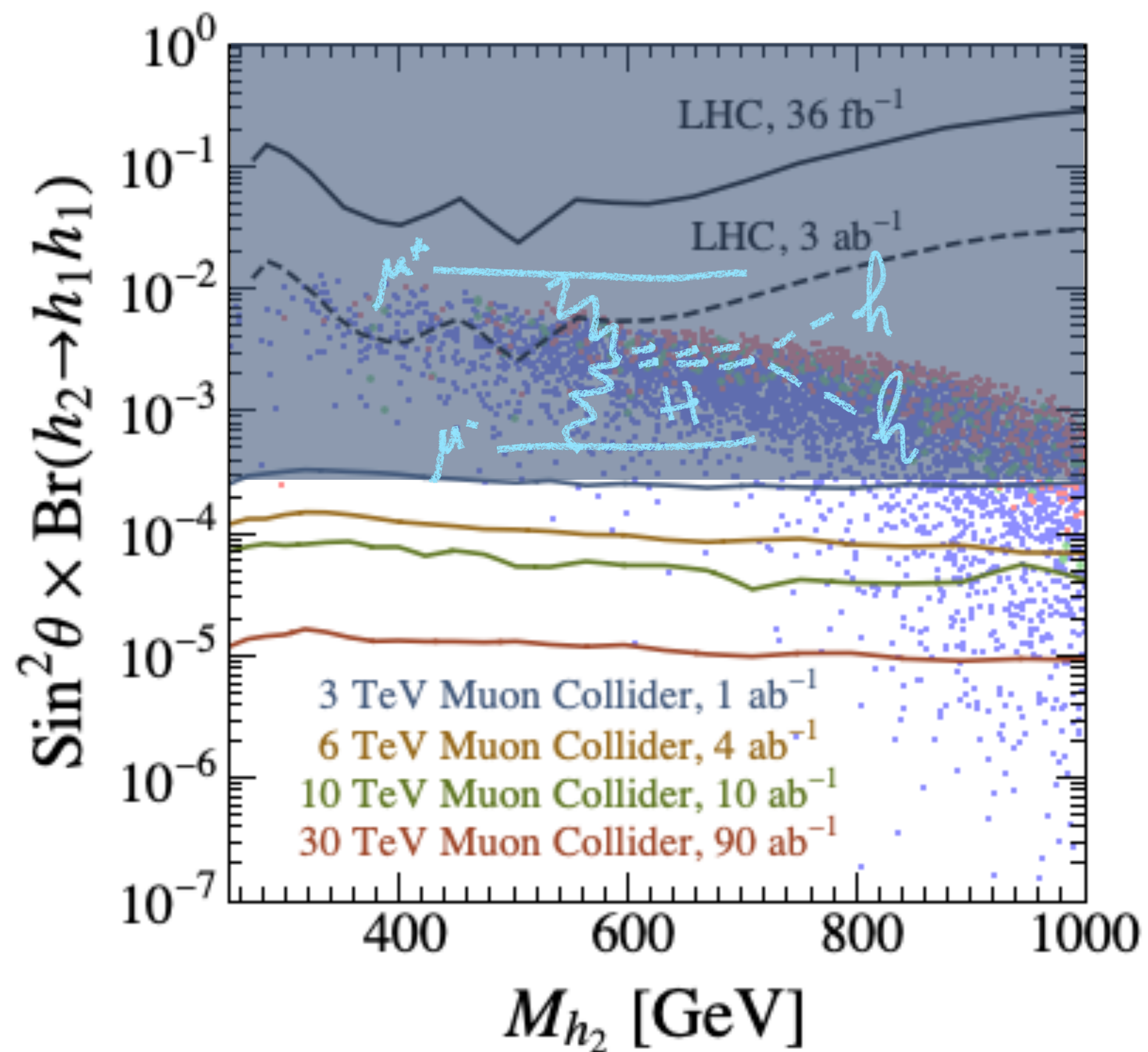
EW phase transition

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DIRECT & INDIRECT

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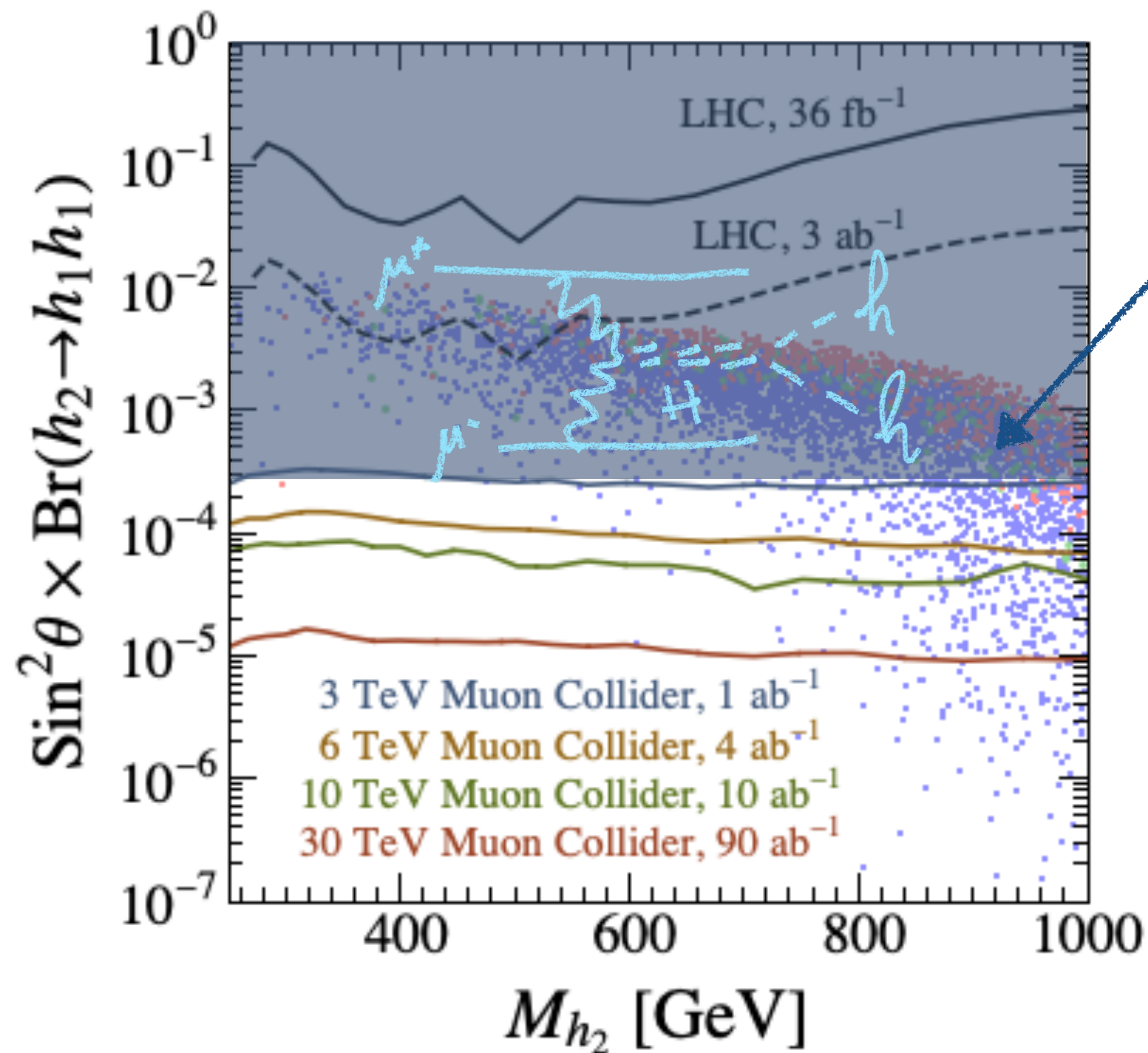
EW phase transition

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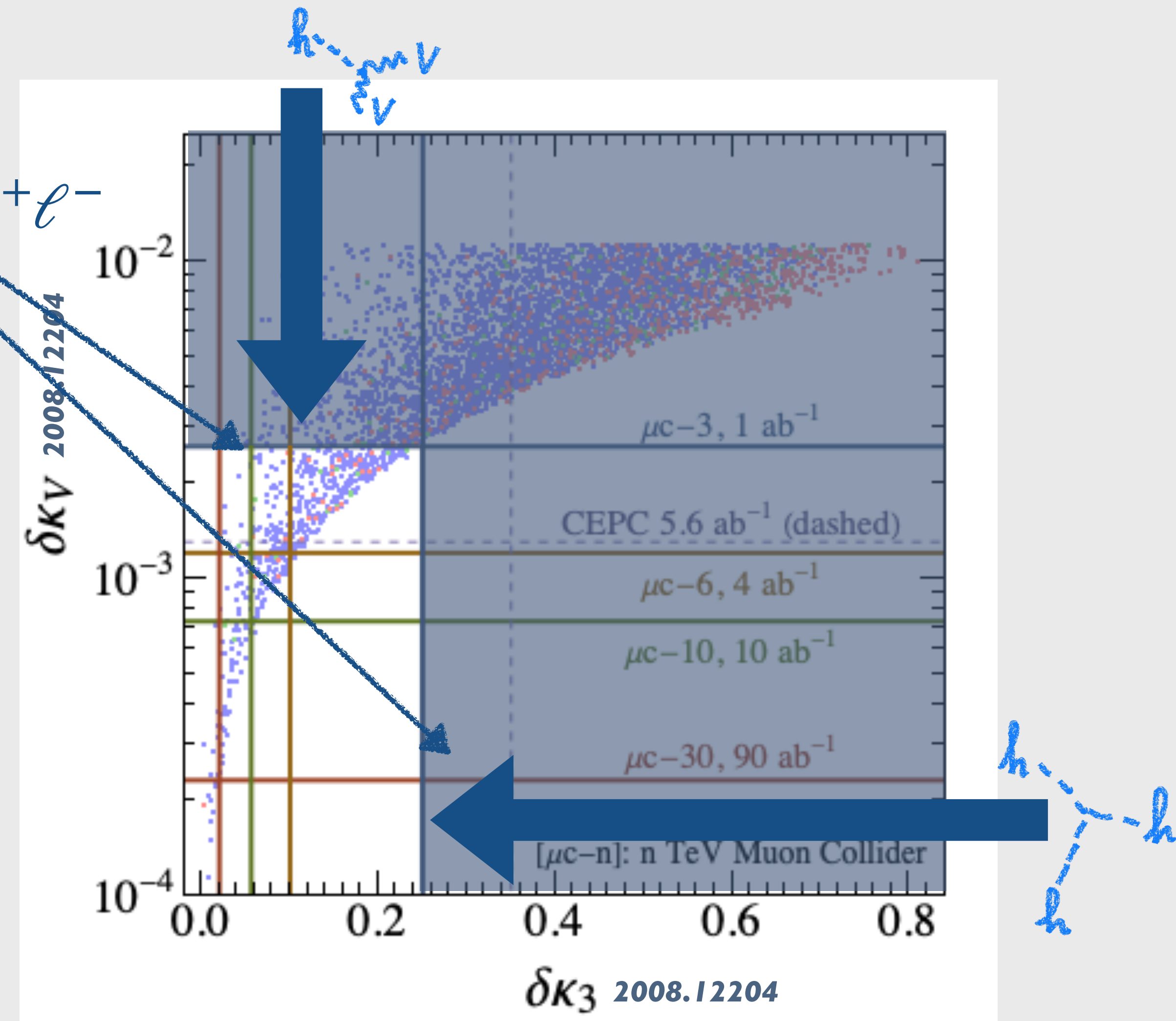
⊗ ⊙ ⊛ → Gravity Wave SNR

DIRECT & INDIRECT

INTERPLAY



3 TeV $\ell^+\ell^-$



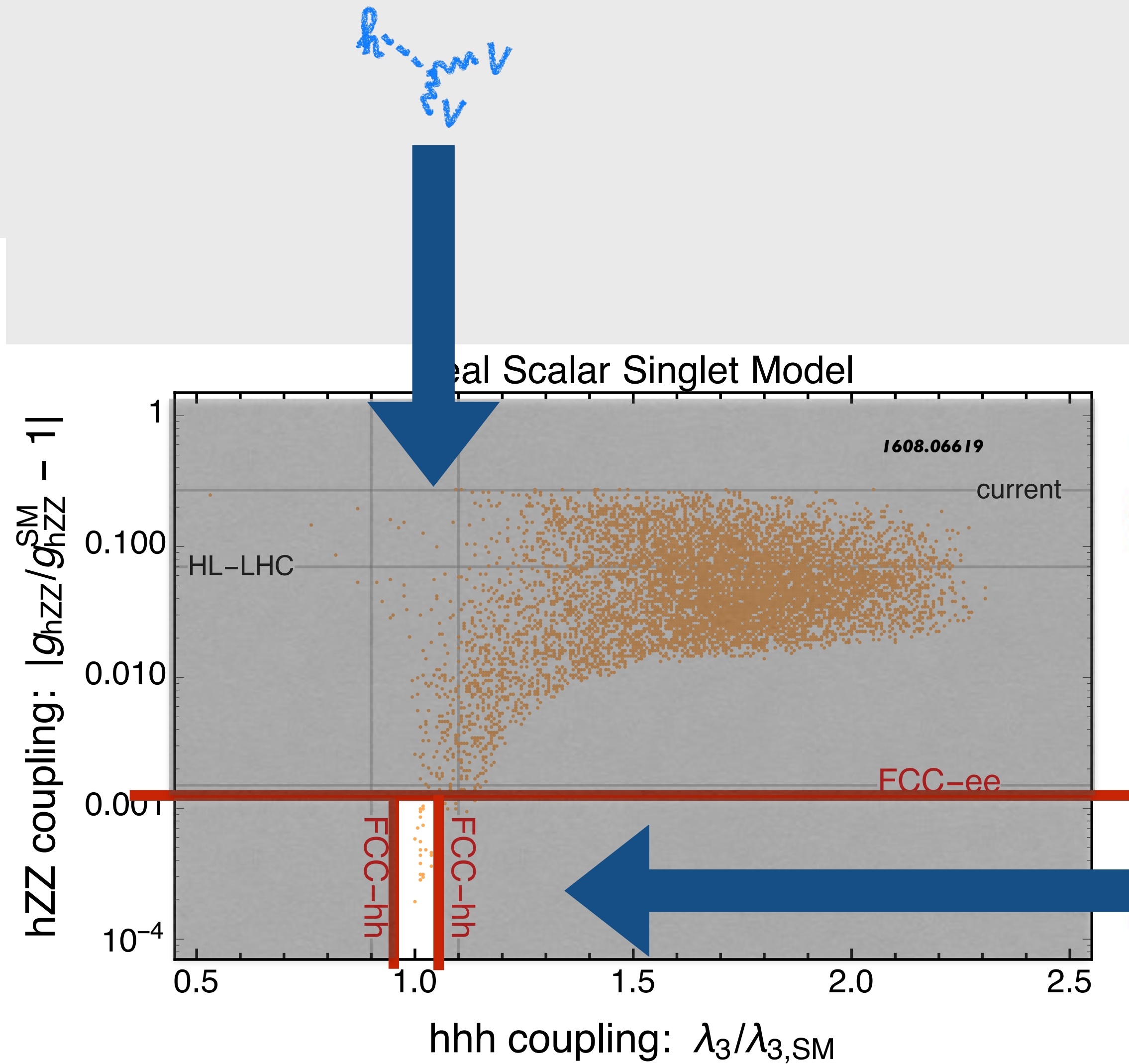
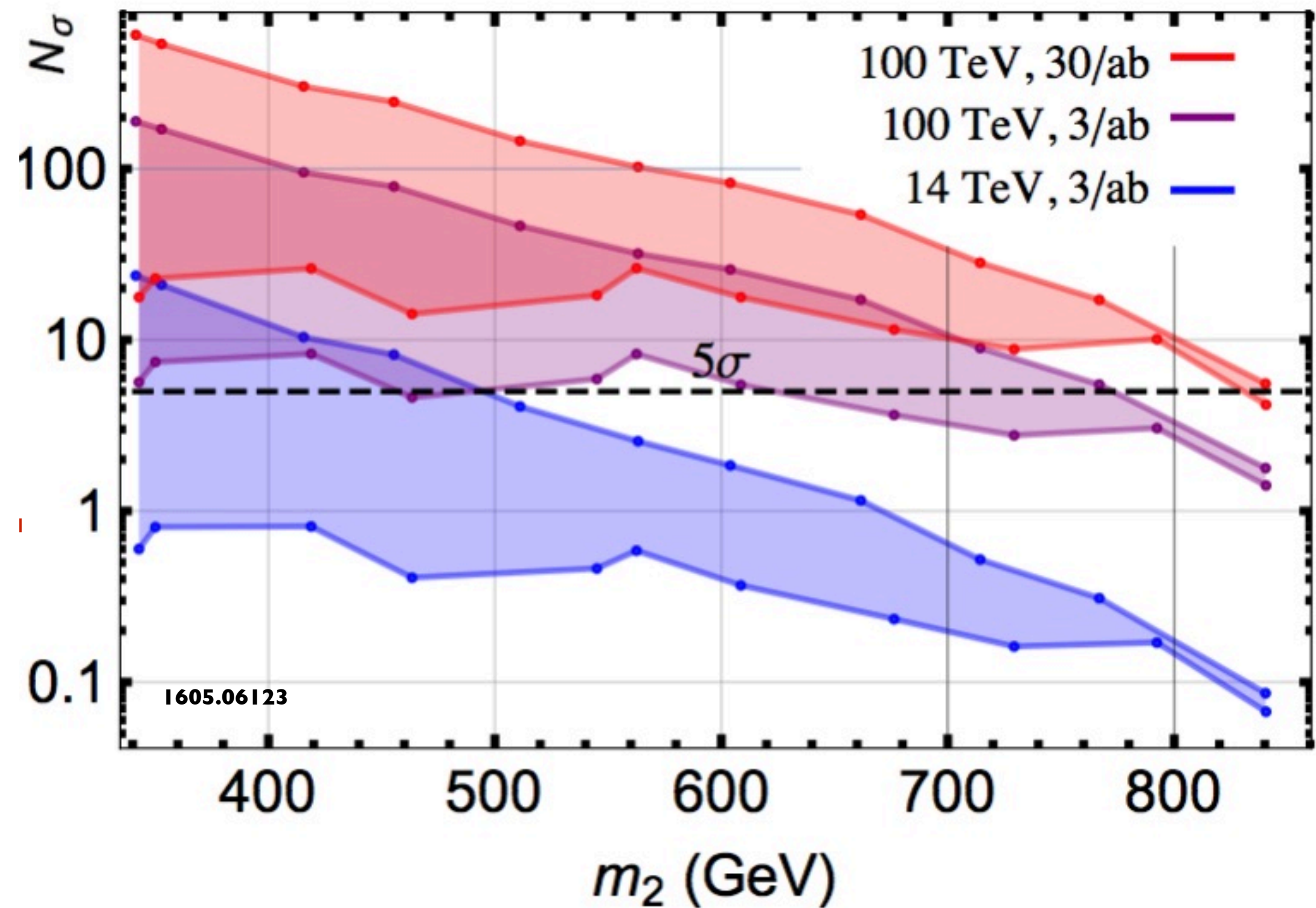
parameters space of 1st order phase transition accessible by **several measurements available at the 3 TeV $\ell^+\ell^-$ collider**

EW phase transition

DIRECT & INDIRECT

INTERPLAY

$$pp \rightarrow h_2 \rightarrow h^{(125)} h^{(125)}$$

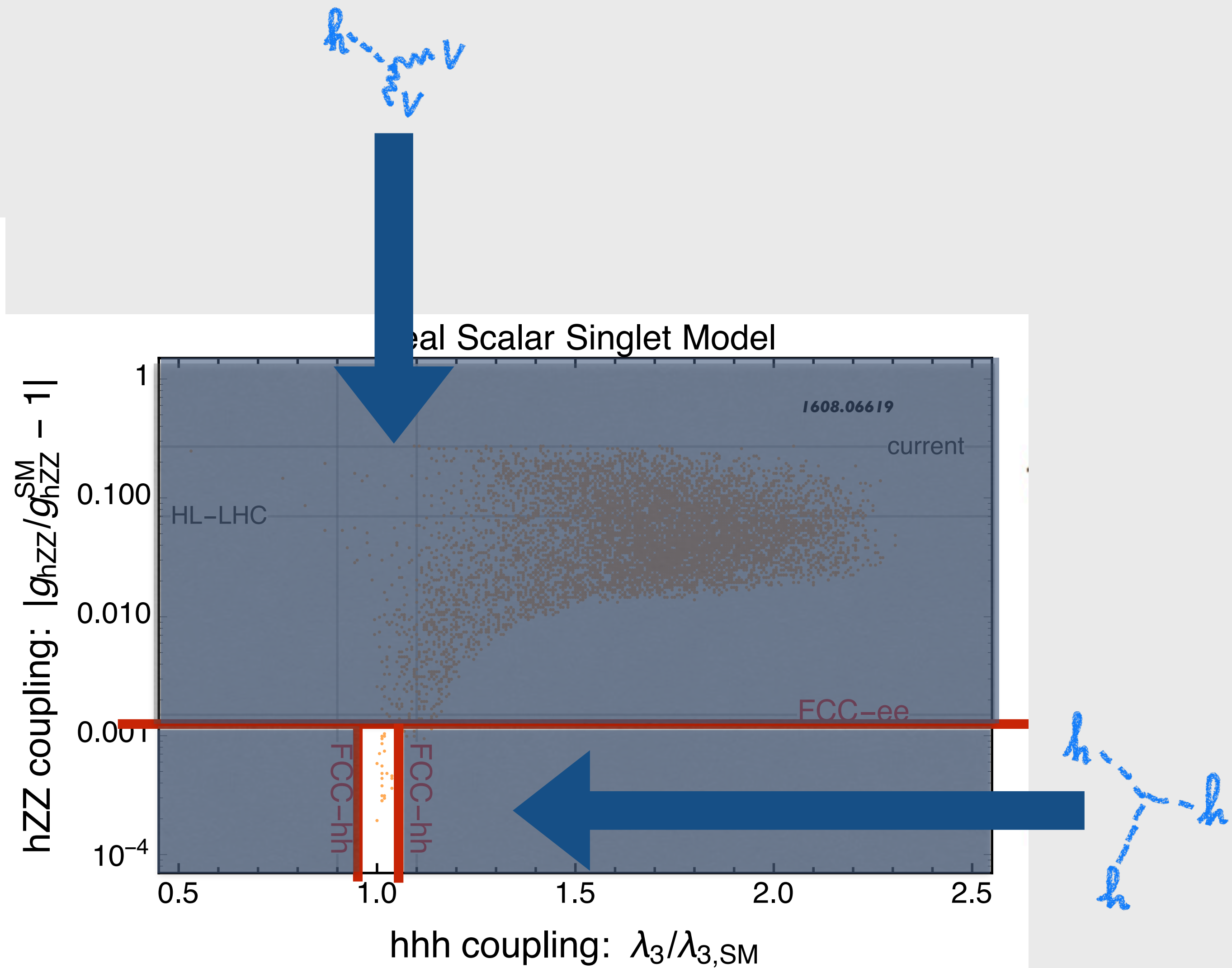
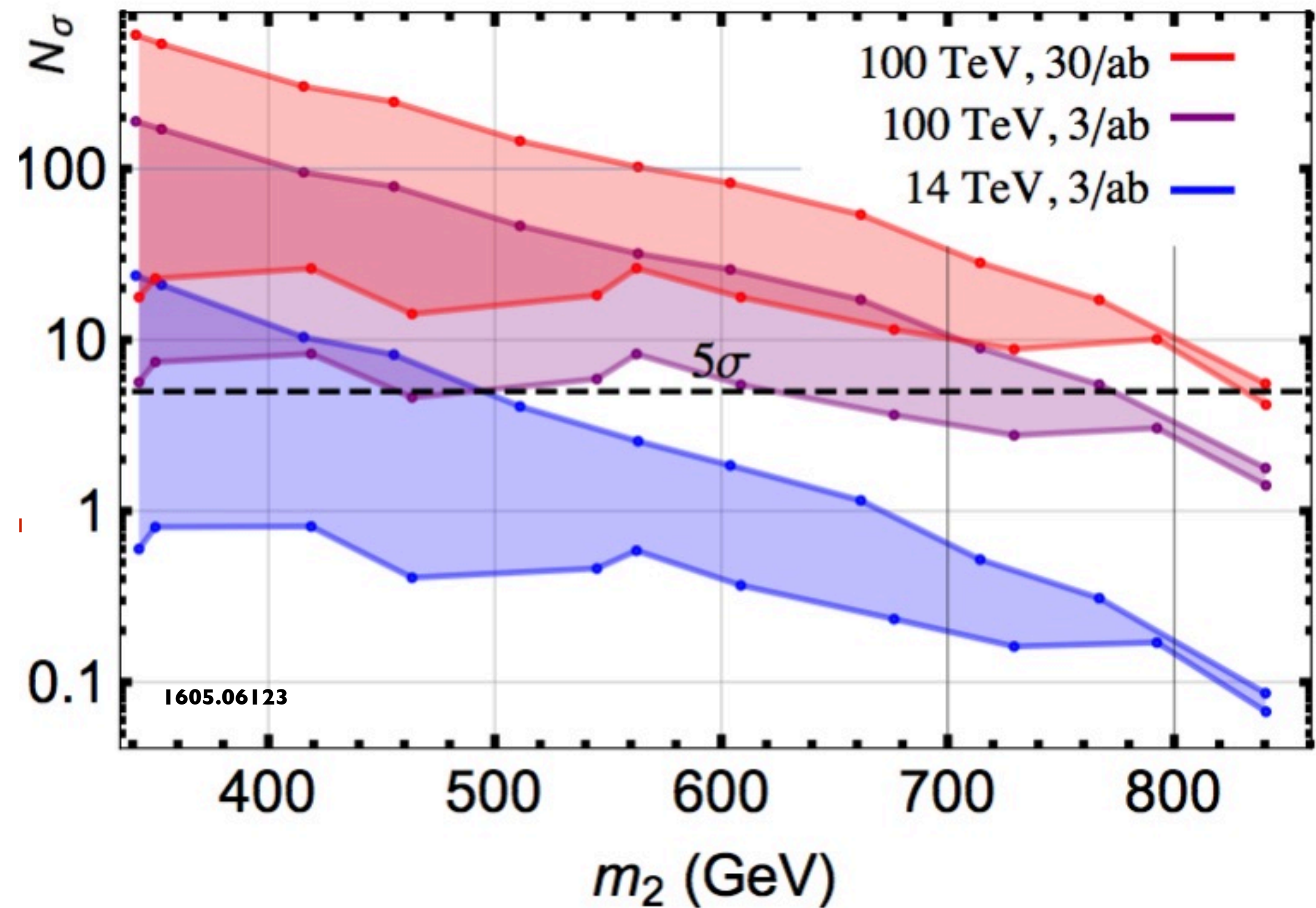


EW phase transition

DIRECT & INDIRECT

INTERPLAY

$$pp \rightarrow h_2 \rightarrow h^{(125)} h^{(125)}$$

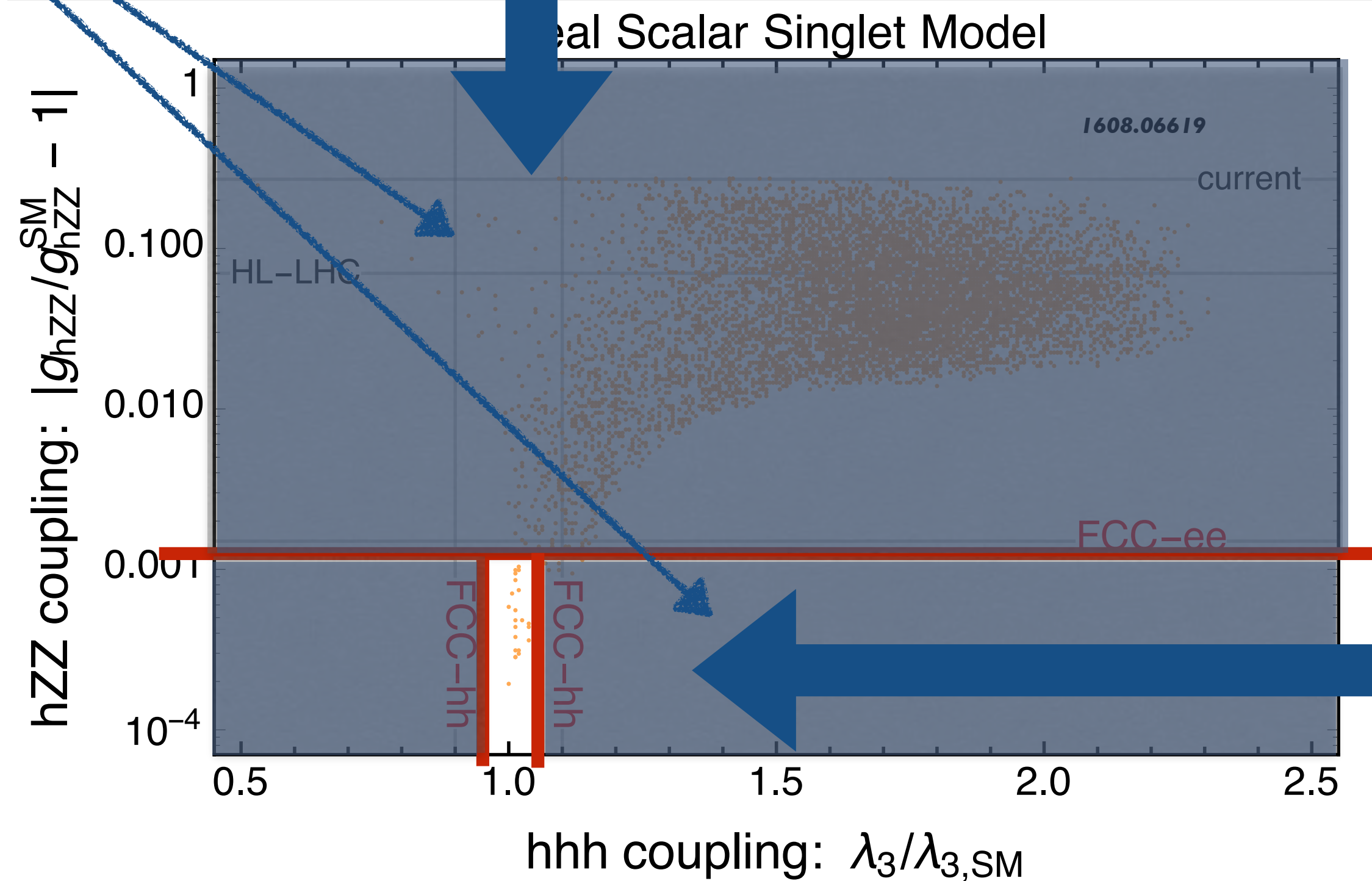
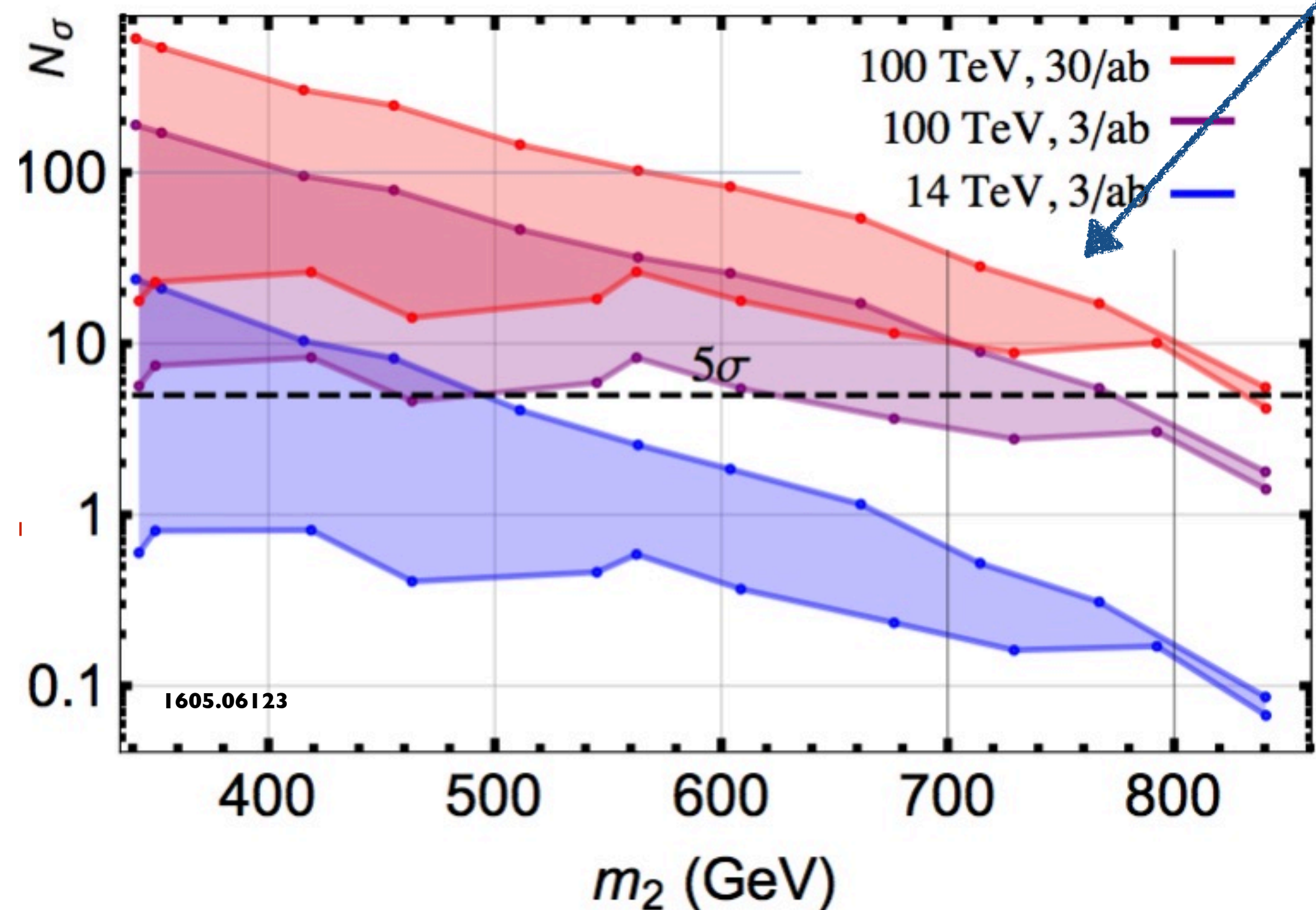


EW phase transition

DIRECT & INDIRECT

INTERPLAY

$$pp \rightarrow h_2 \rightarrow h^{(125)} h^{(125)} \quad 100 \text{ TeV } pp$$



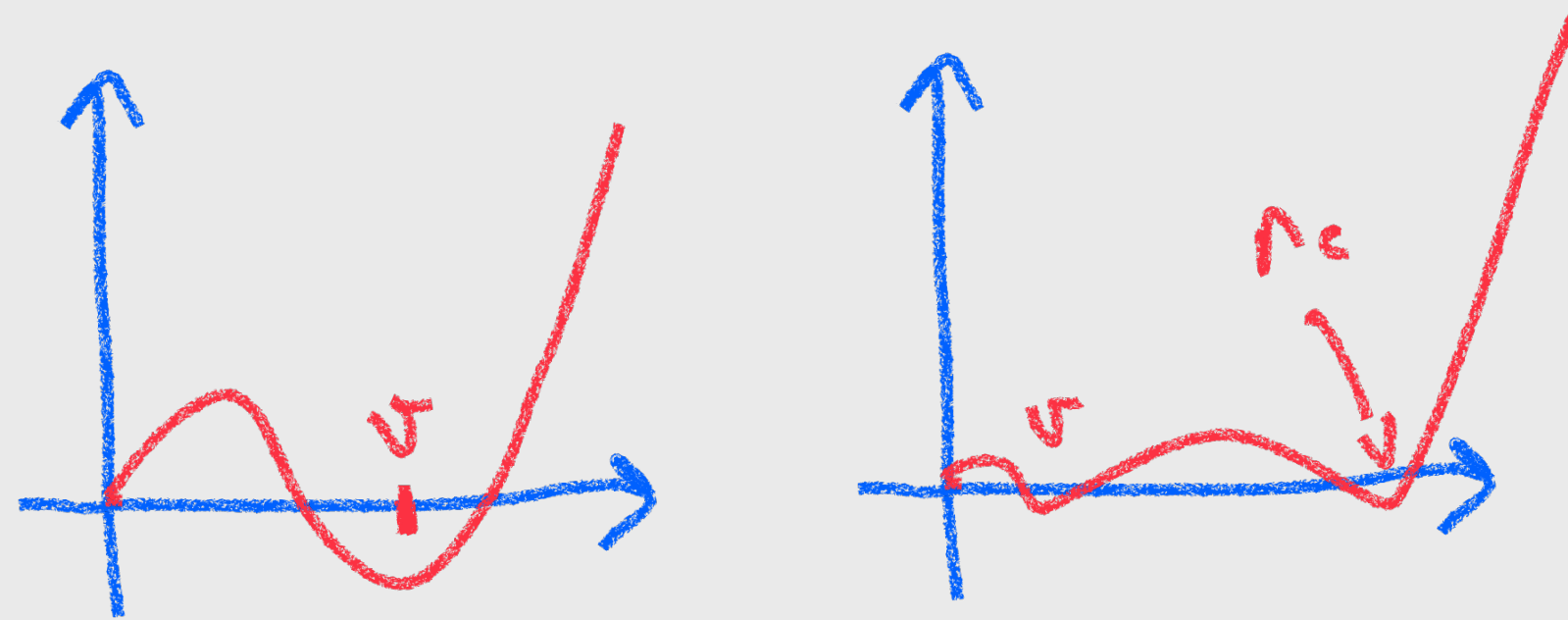
parameters space of 1st order phase transition accessible by **several measurements available at the 100 TeV pp collider**

flashing concrete results for

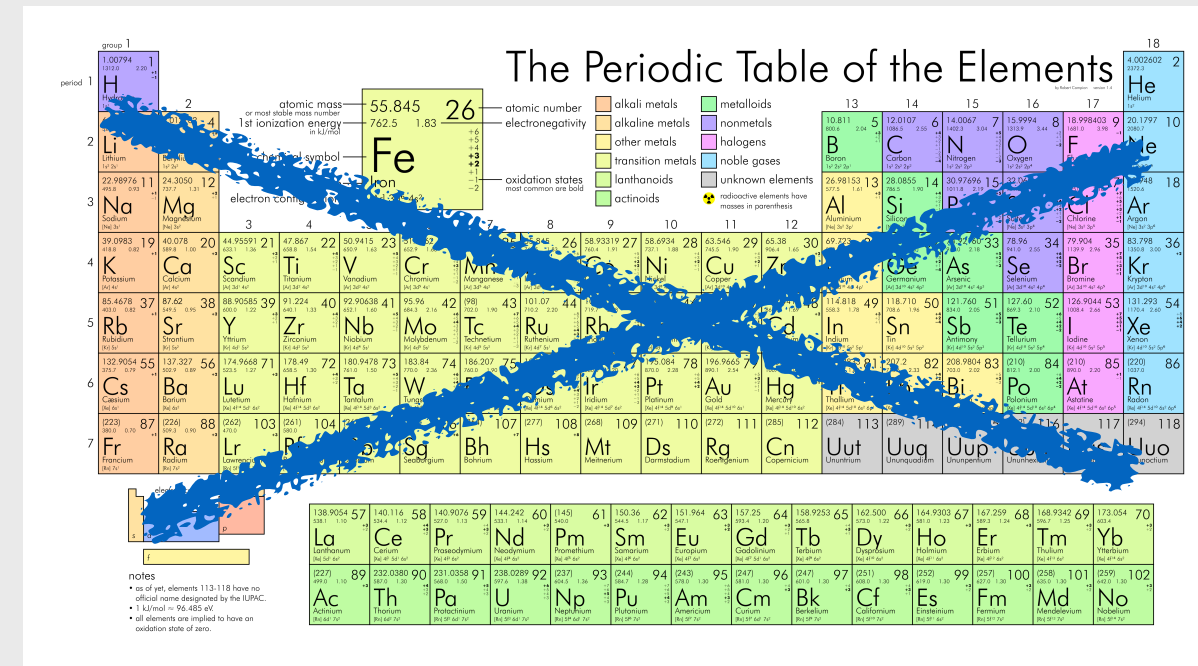
Stability of the Universe

Dialing m_t, m_h, α_3

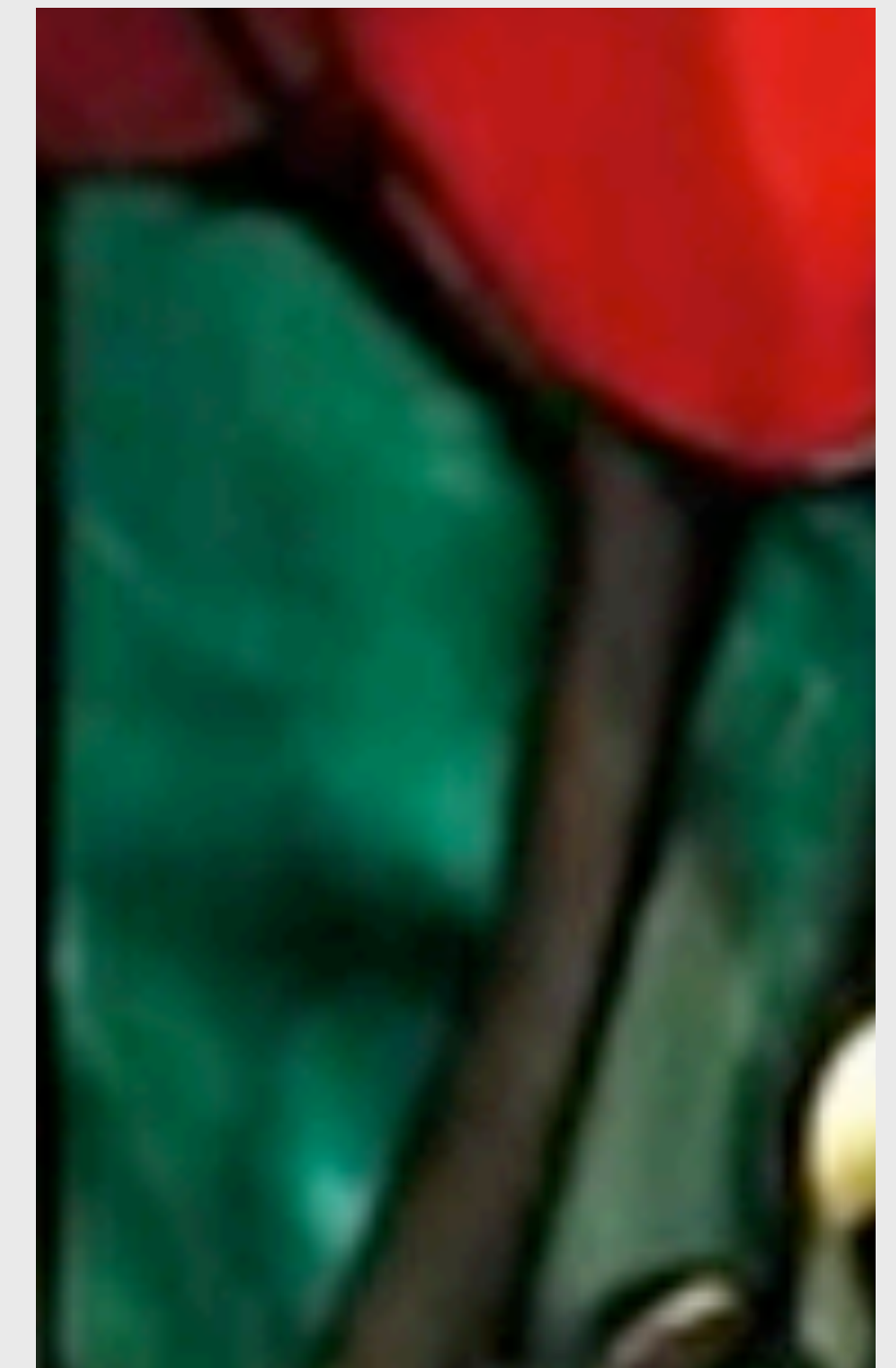
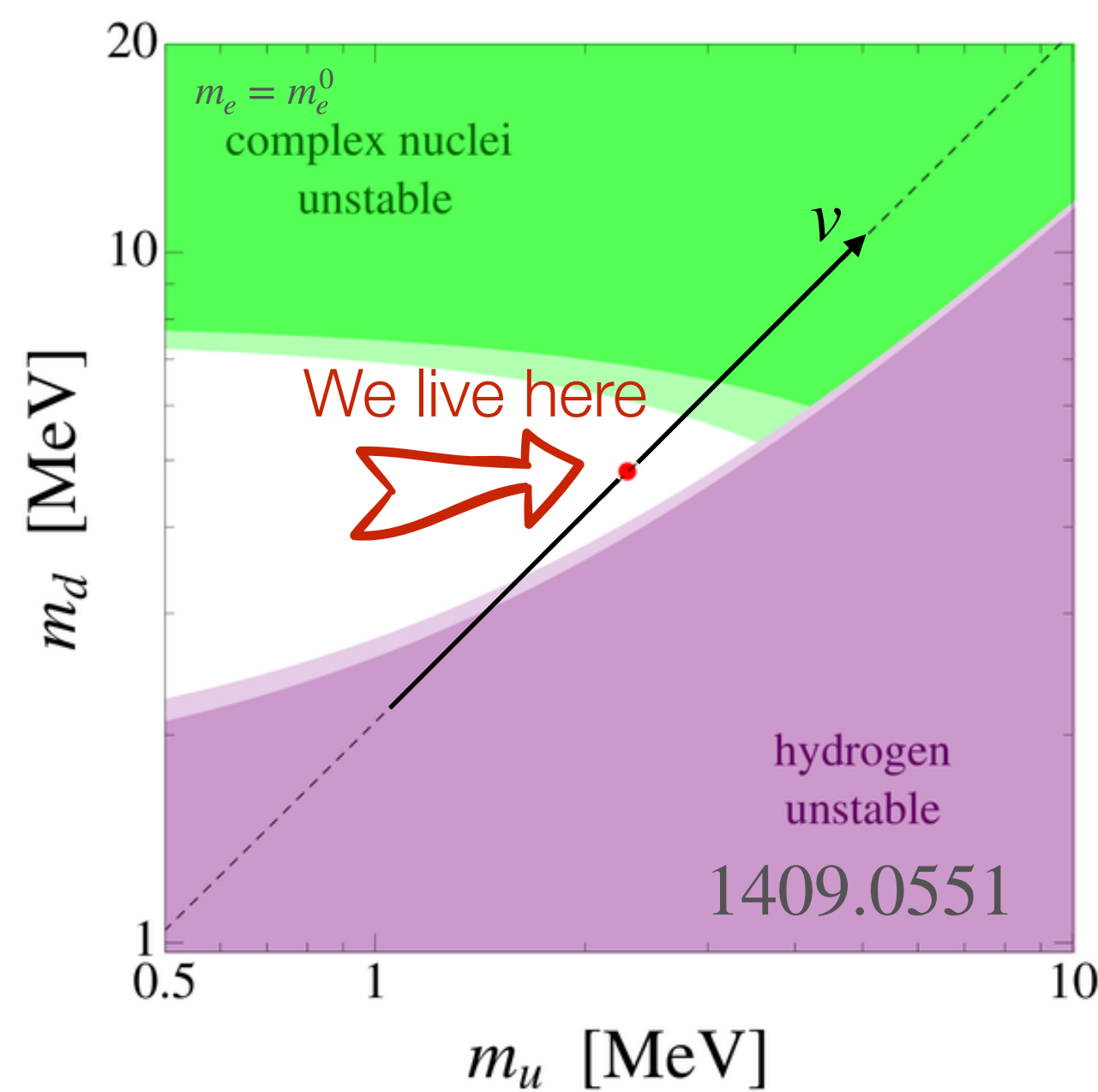
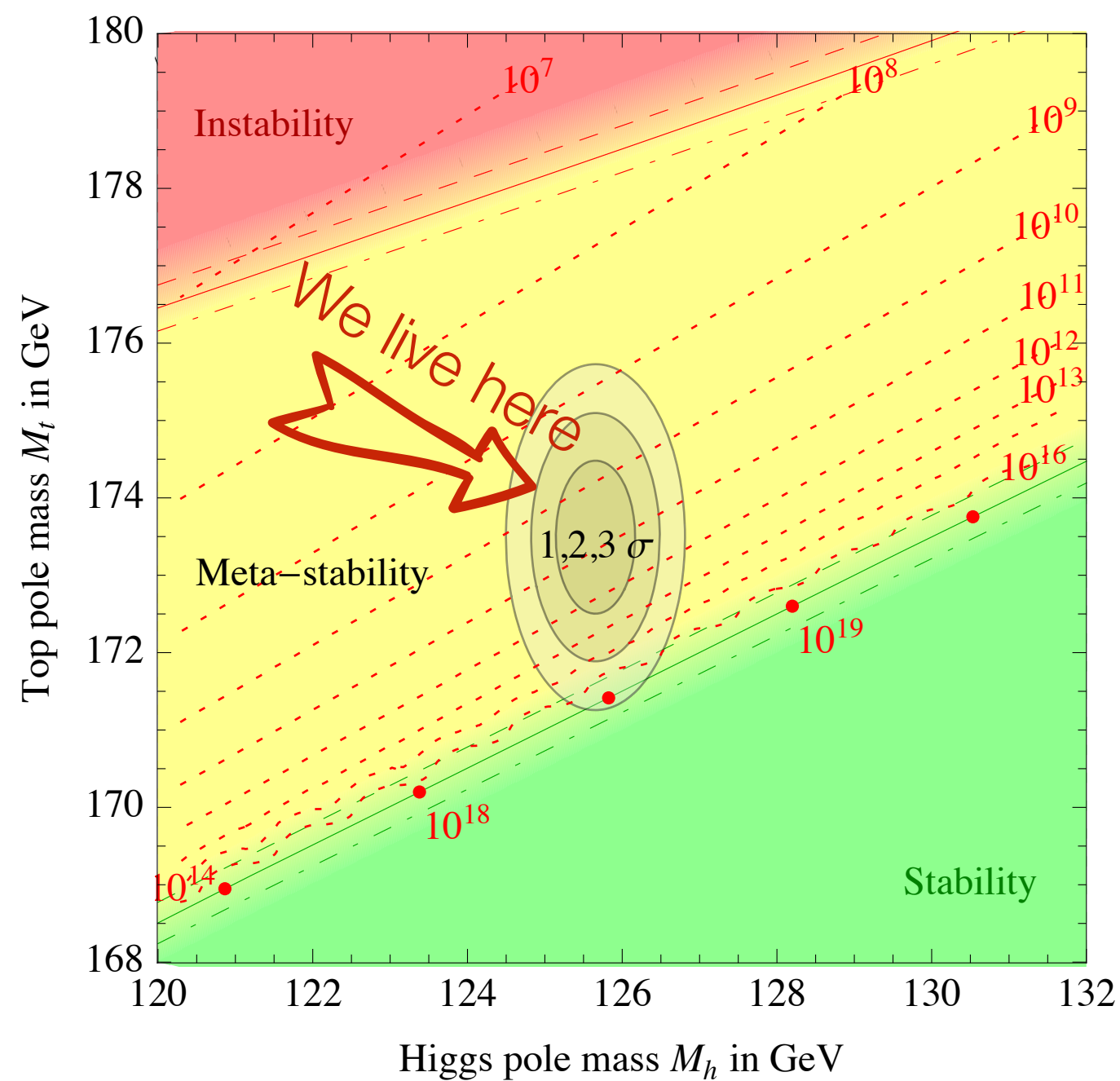
m_e, m_d, m_u, ν



- if another vacuum exist we can tunnel into it

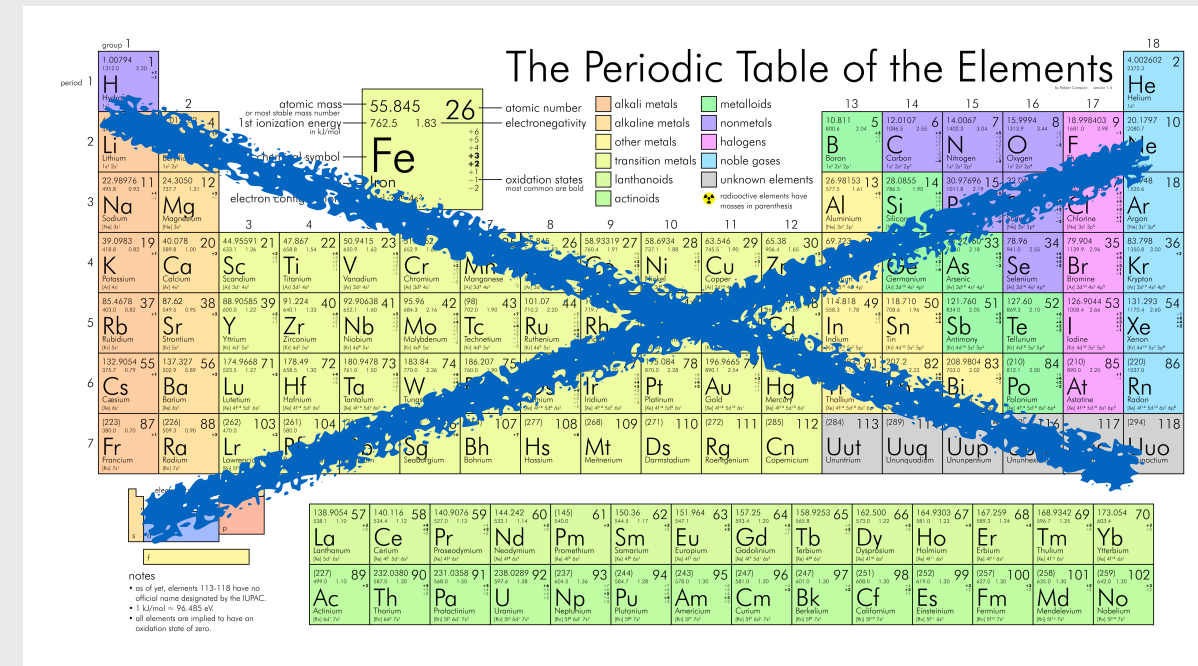
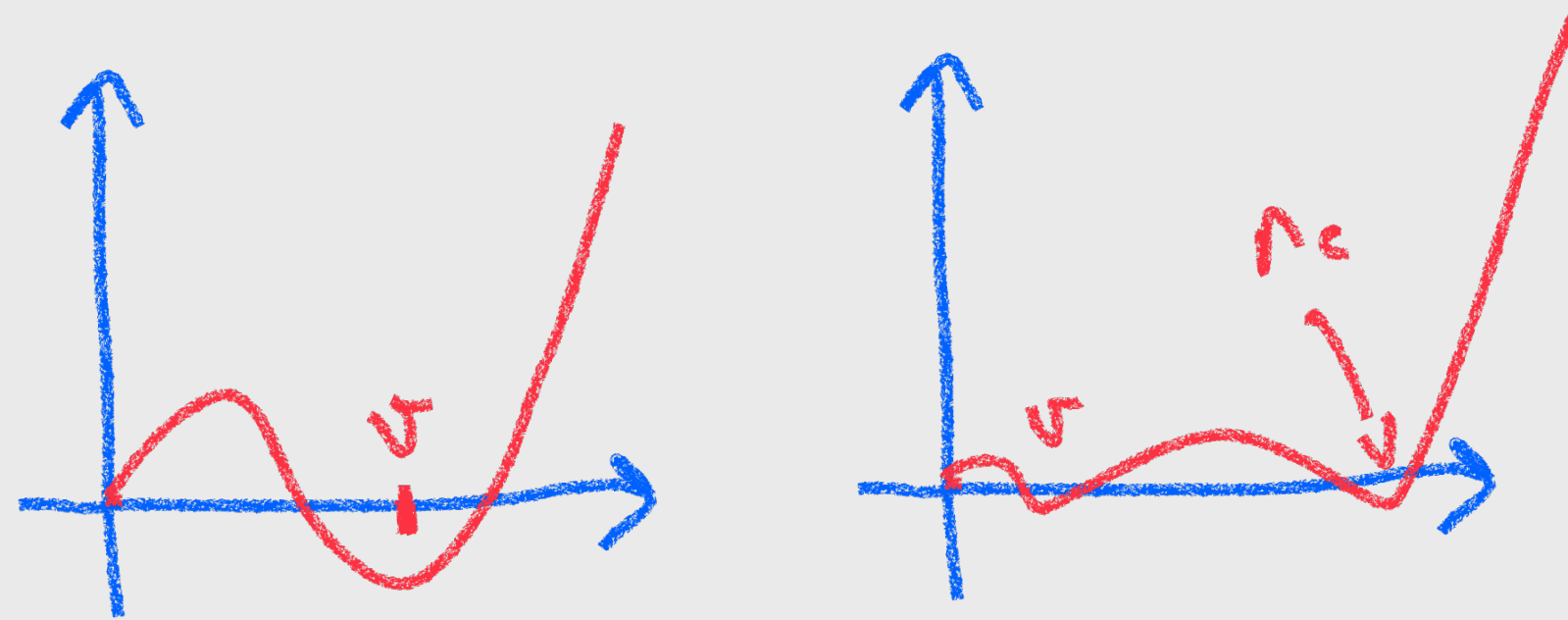


- all stars are neutron stars
- no nuclei beyond deuterium



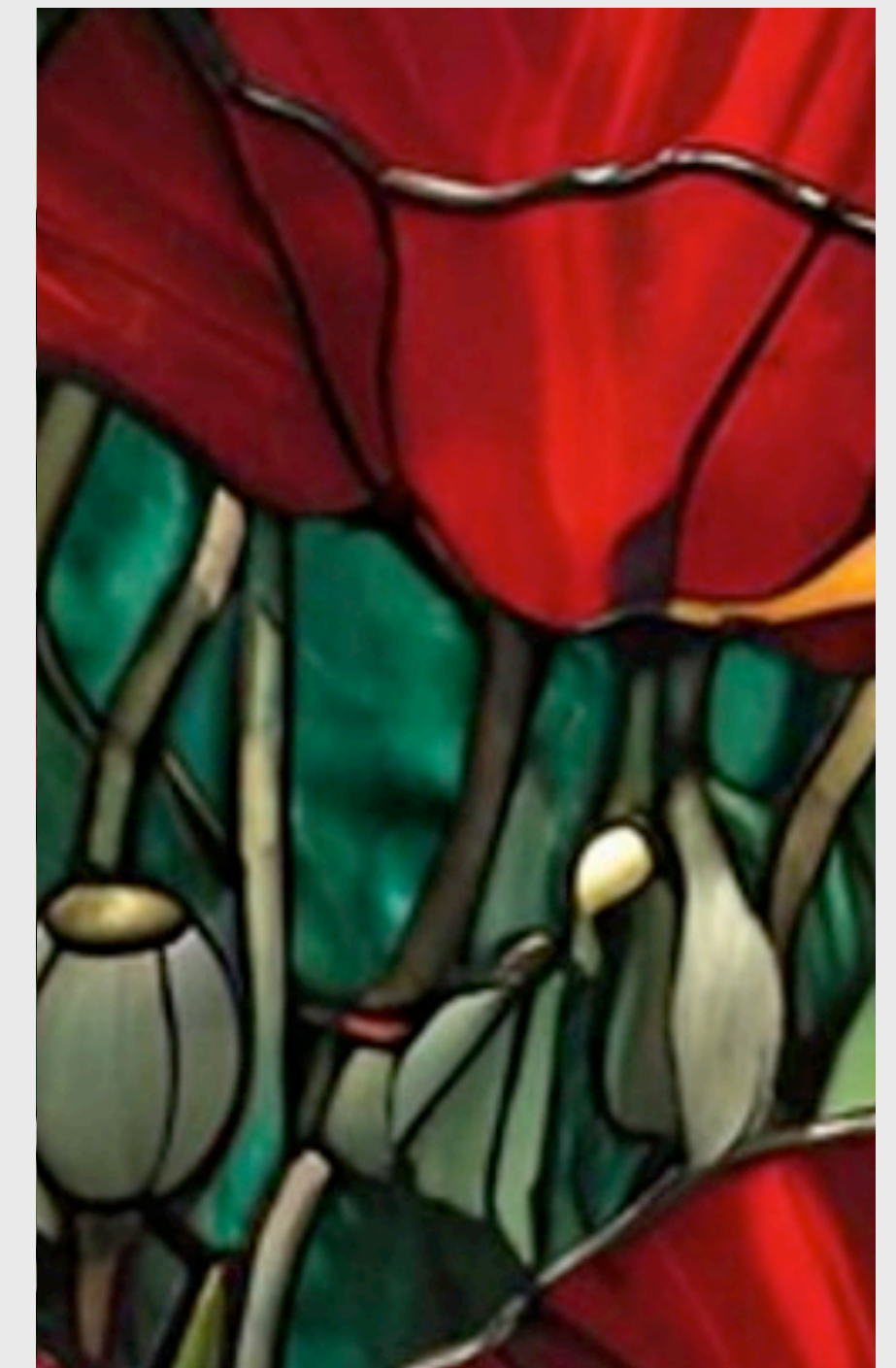
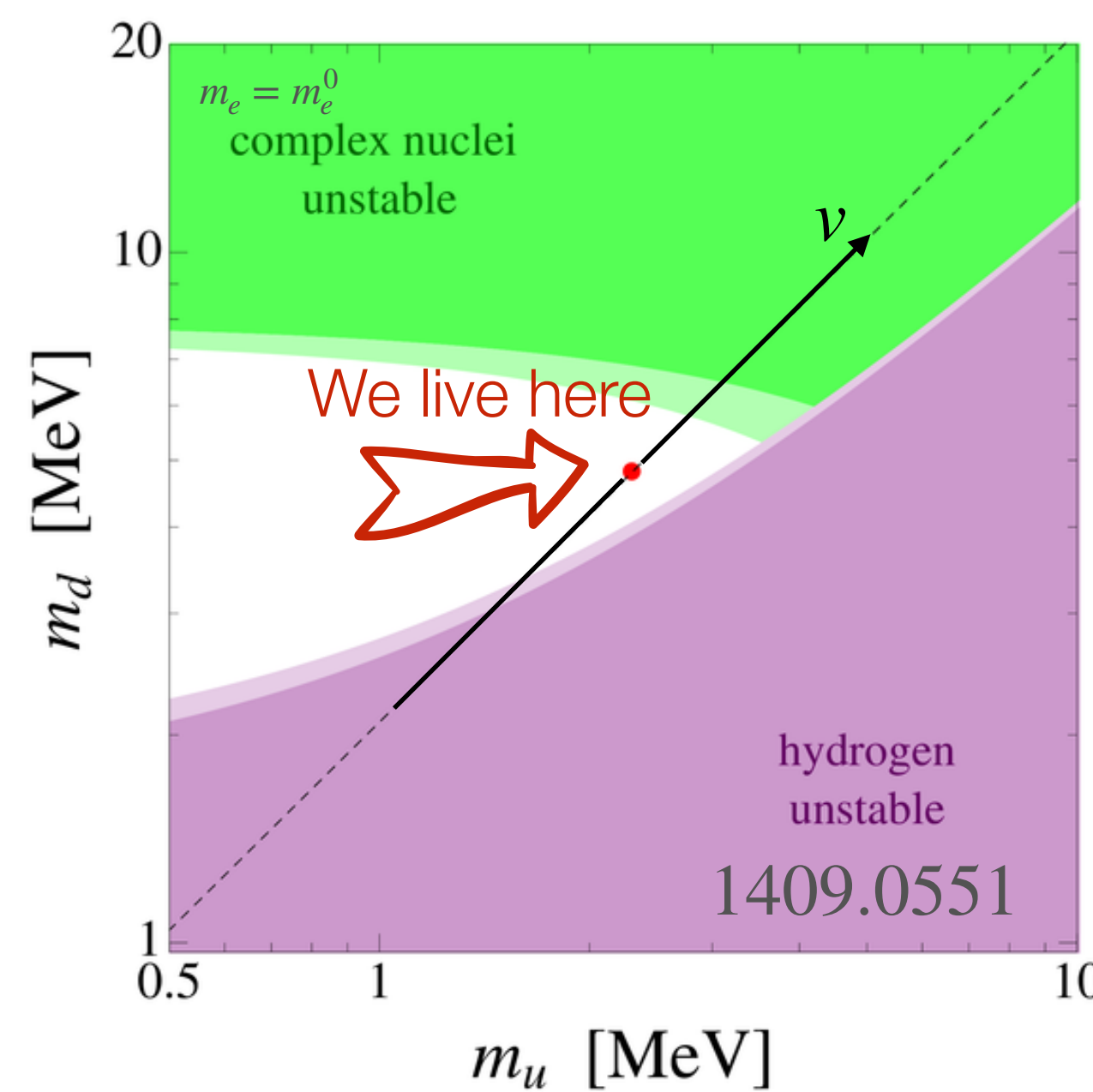
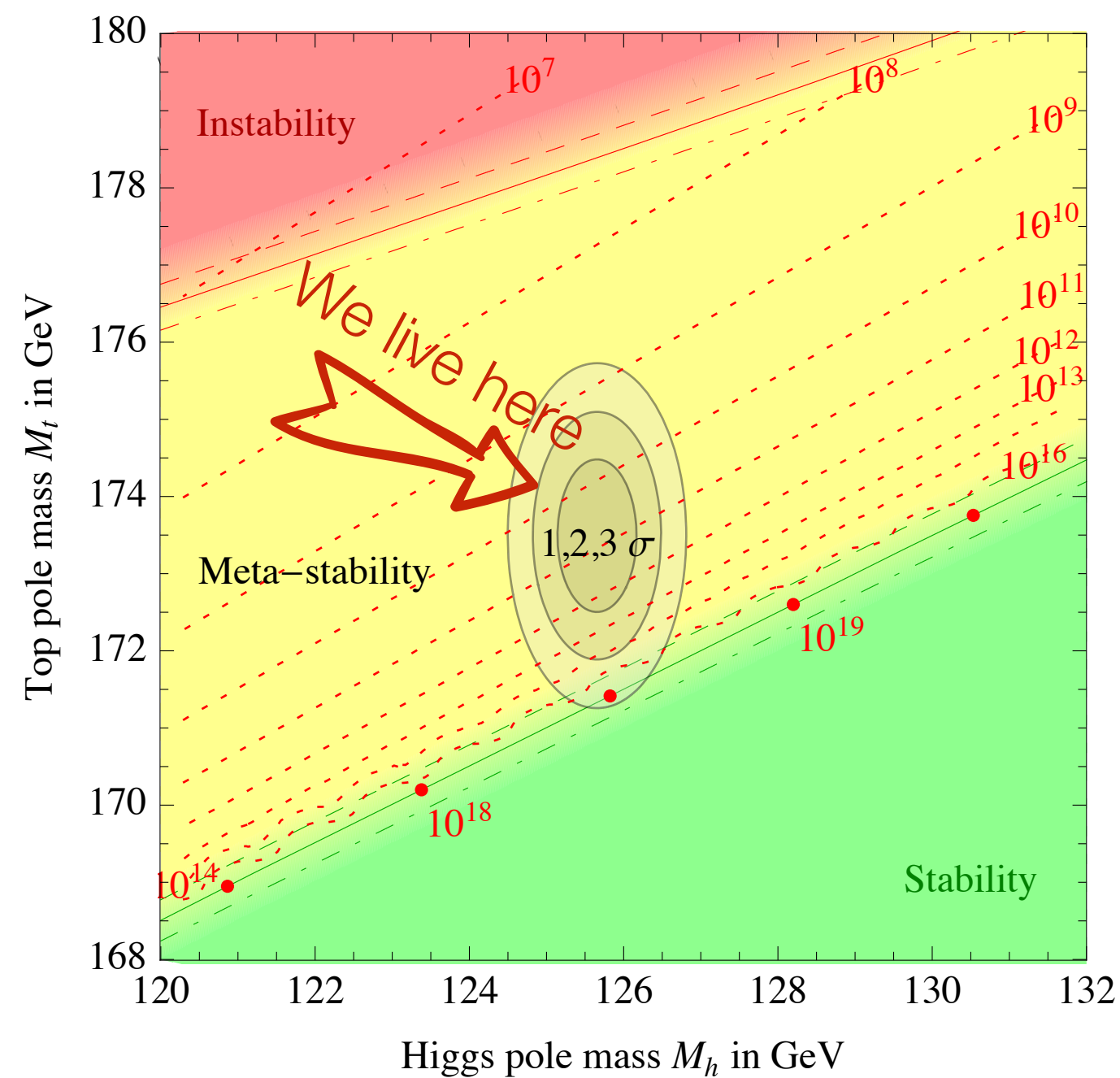
Dialing m_t, m_h, α_3

m_e, m_d, m_u, ν



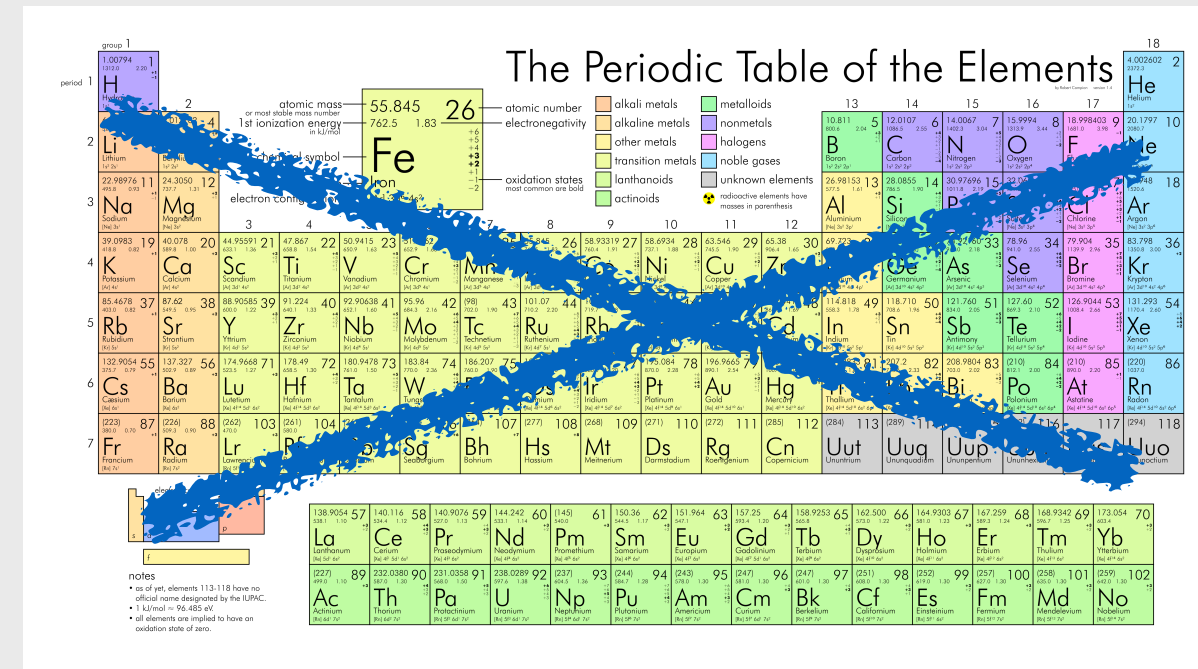
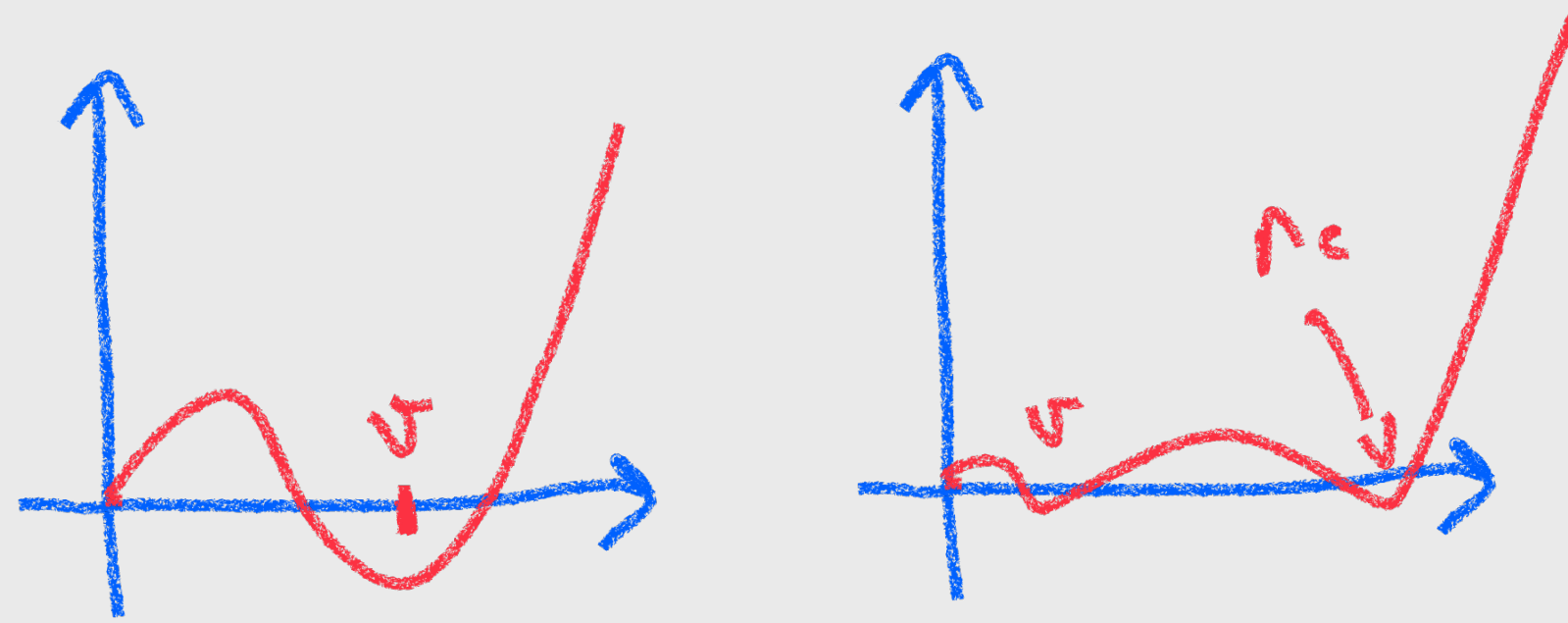
- if another vacuum exist we can tunnel into it

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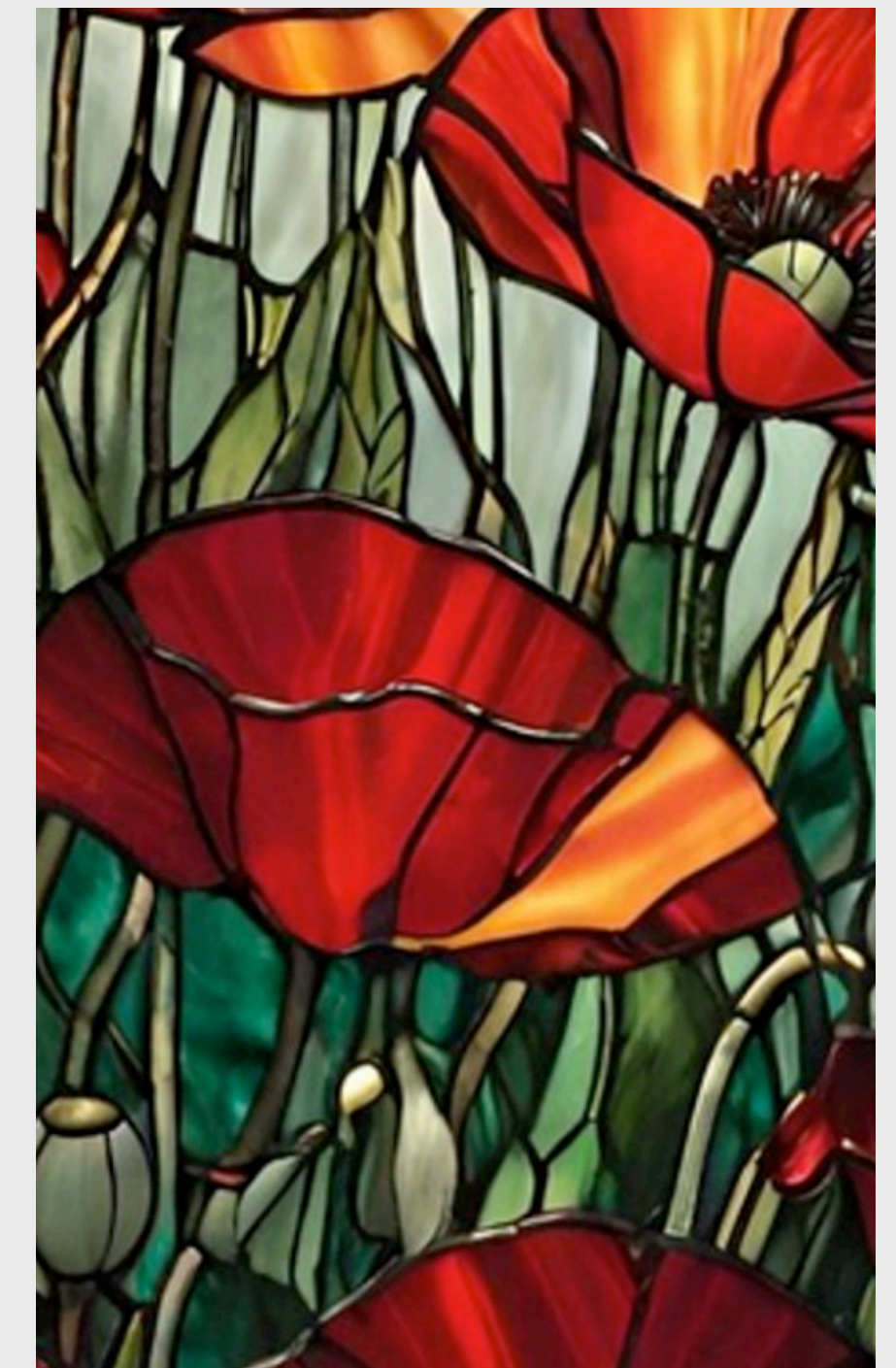
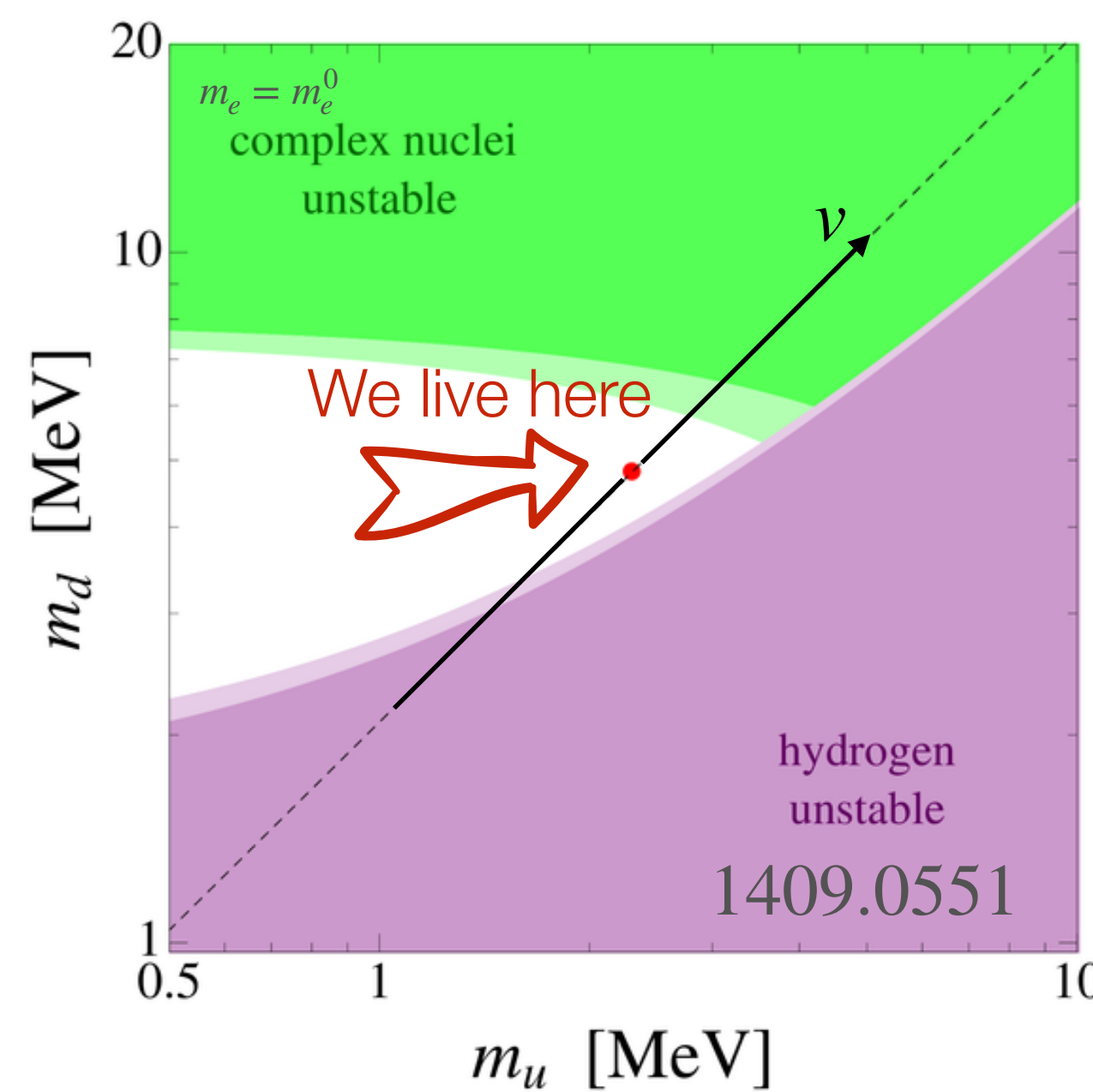
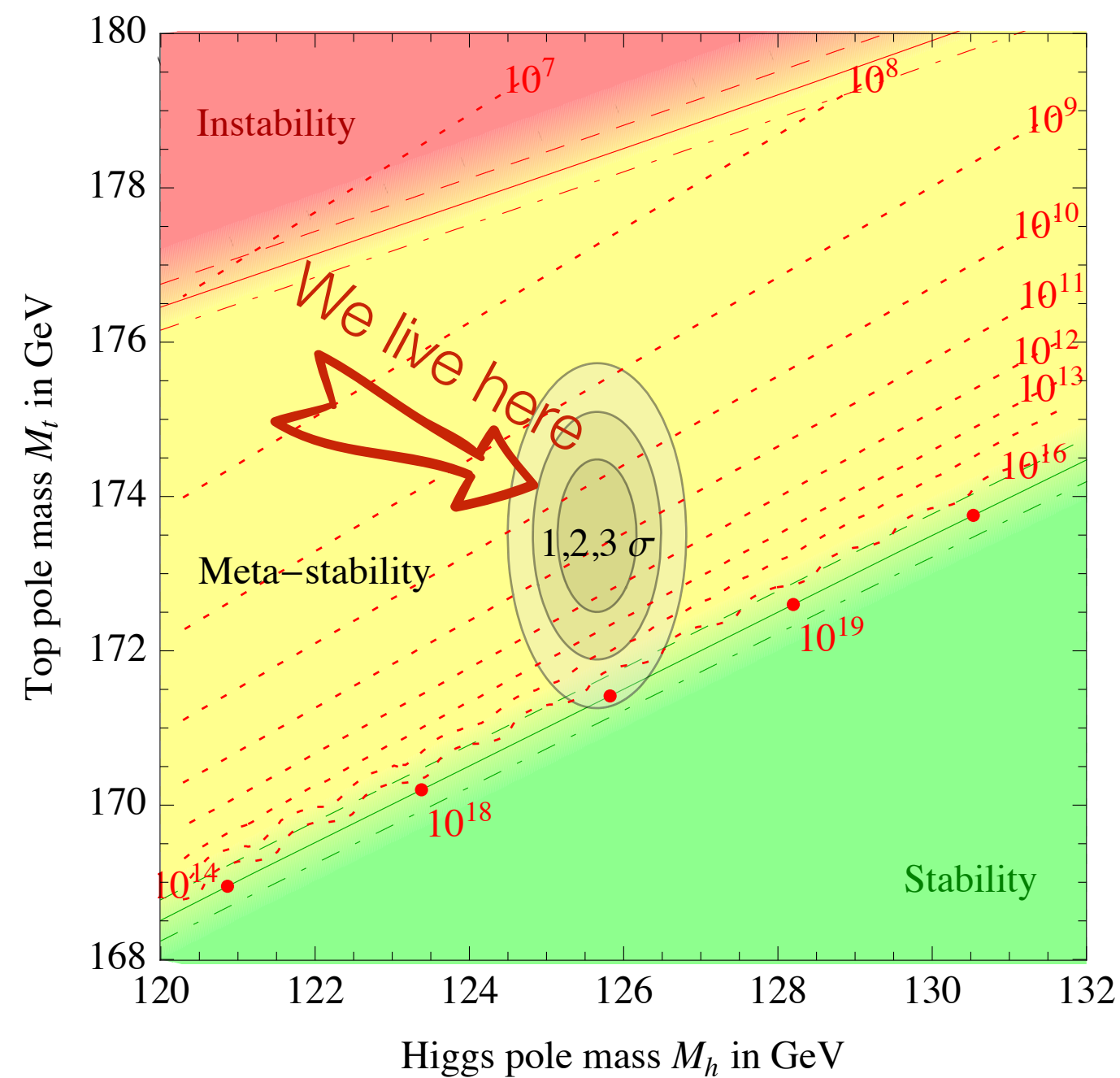
Dialing m_t, m_h, α_3

m_e, m_d, m_u, ν



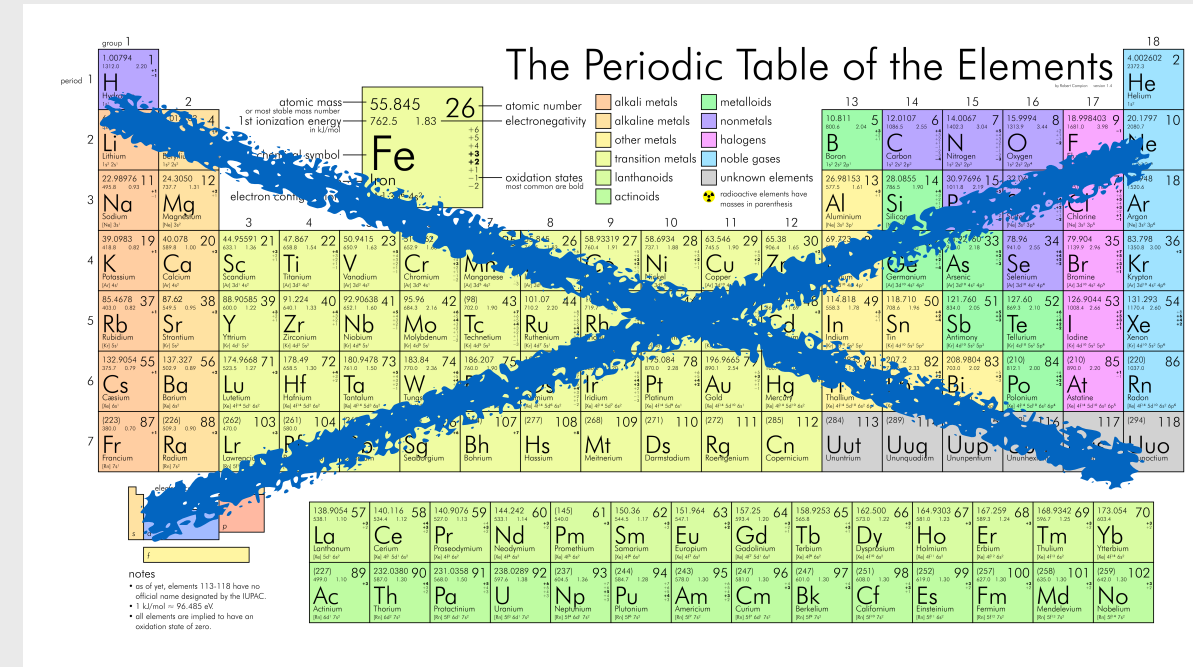
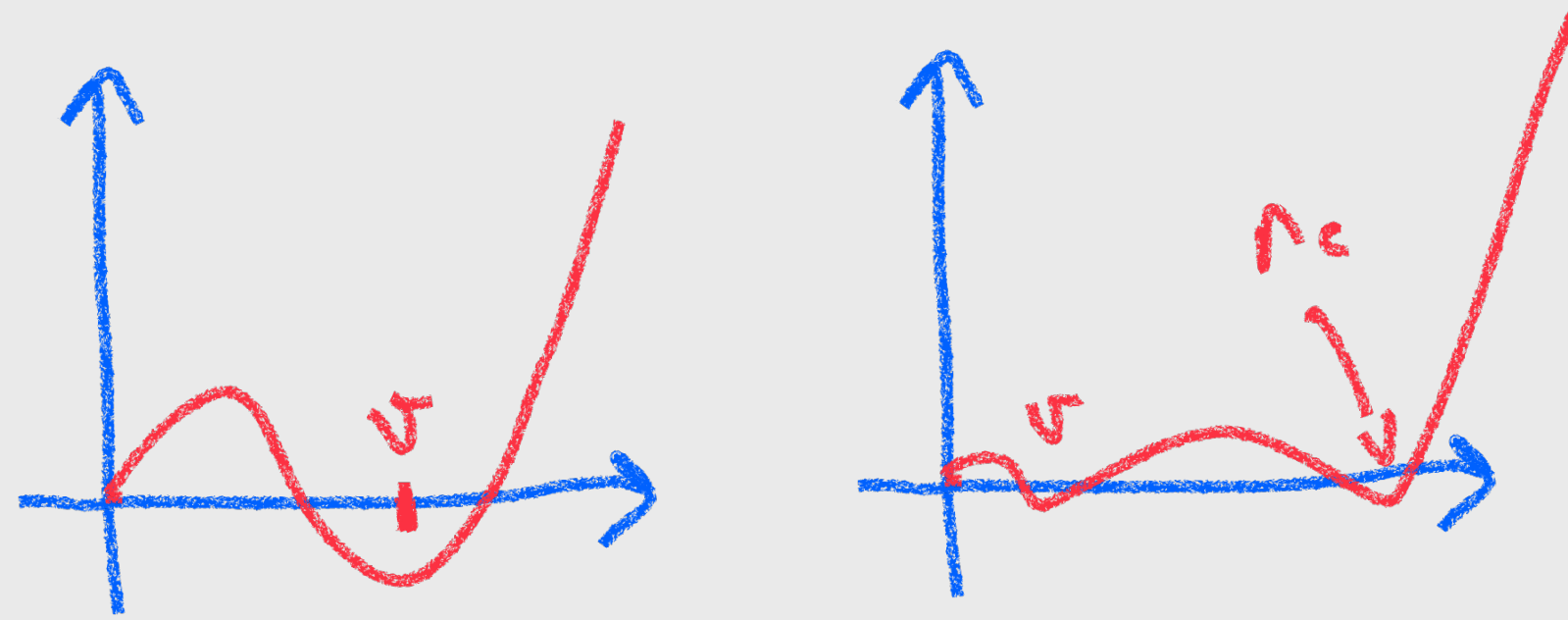
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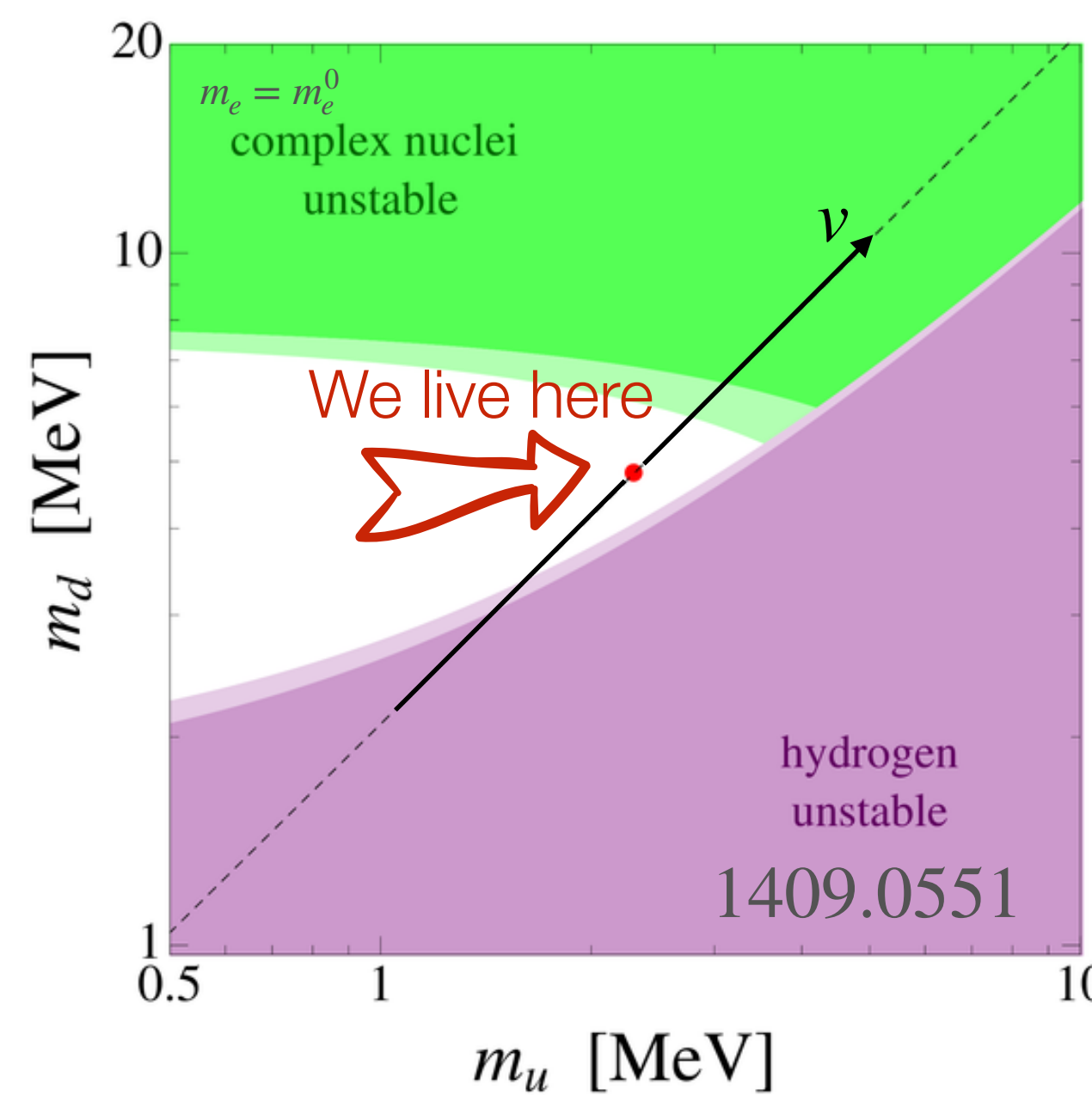
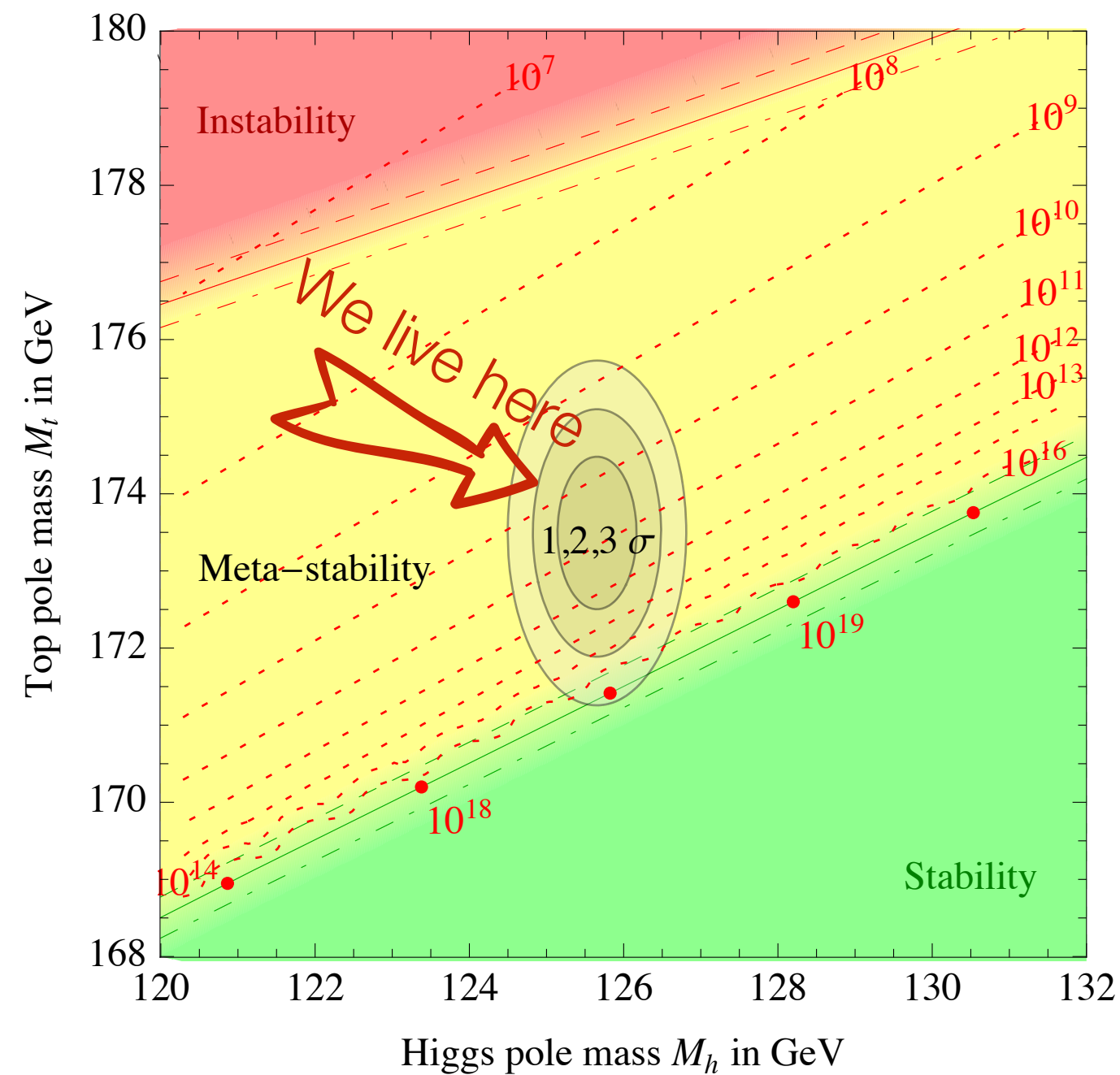
Dialing m_t, m_h, α_3

m_e, m_d, m_u, ν



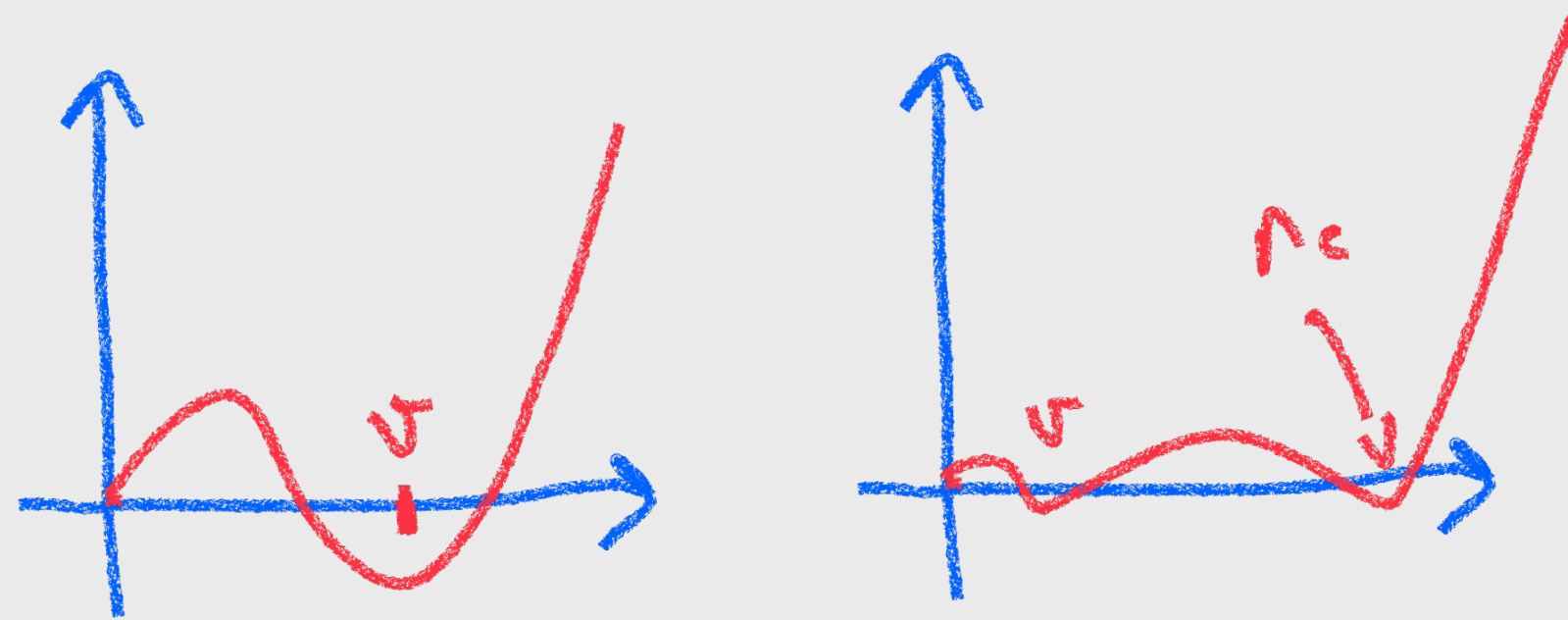
- if another vacuum exist we can tunnel into it

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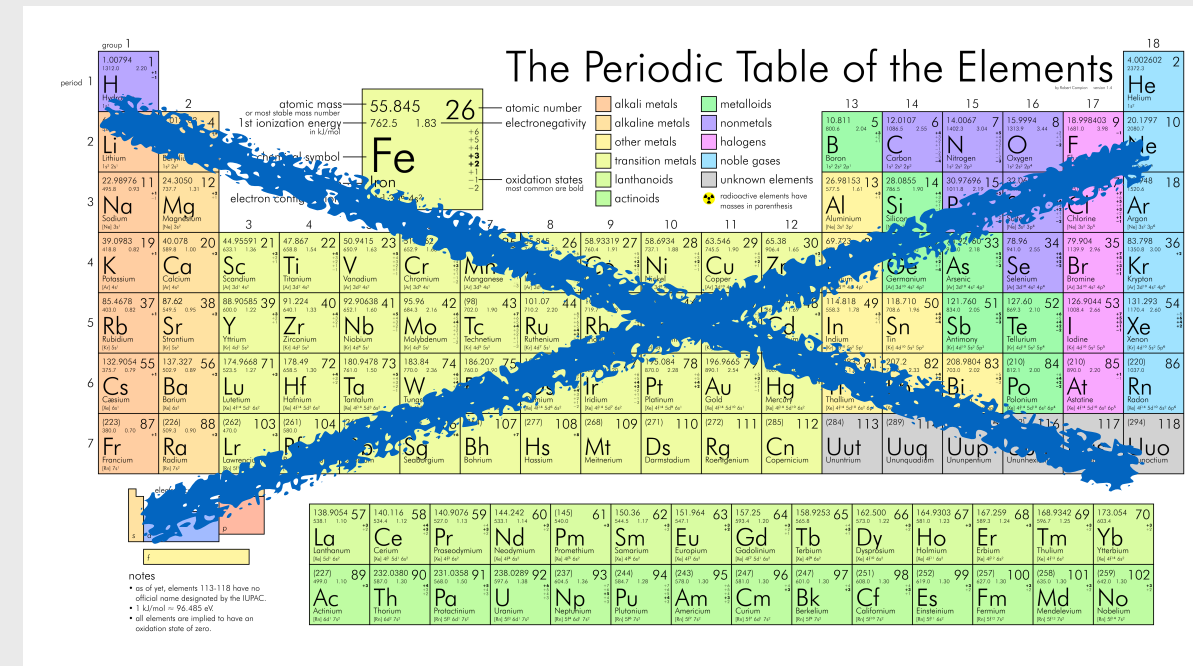


Dialing m_t, m_h, α_3

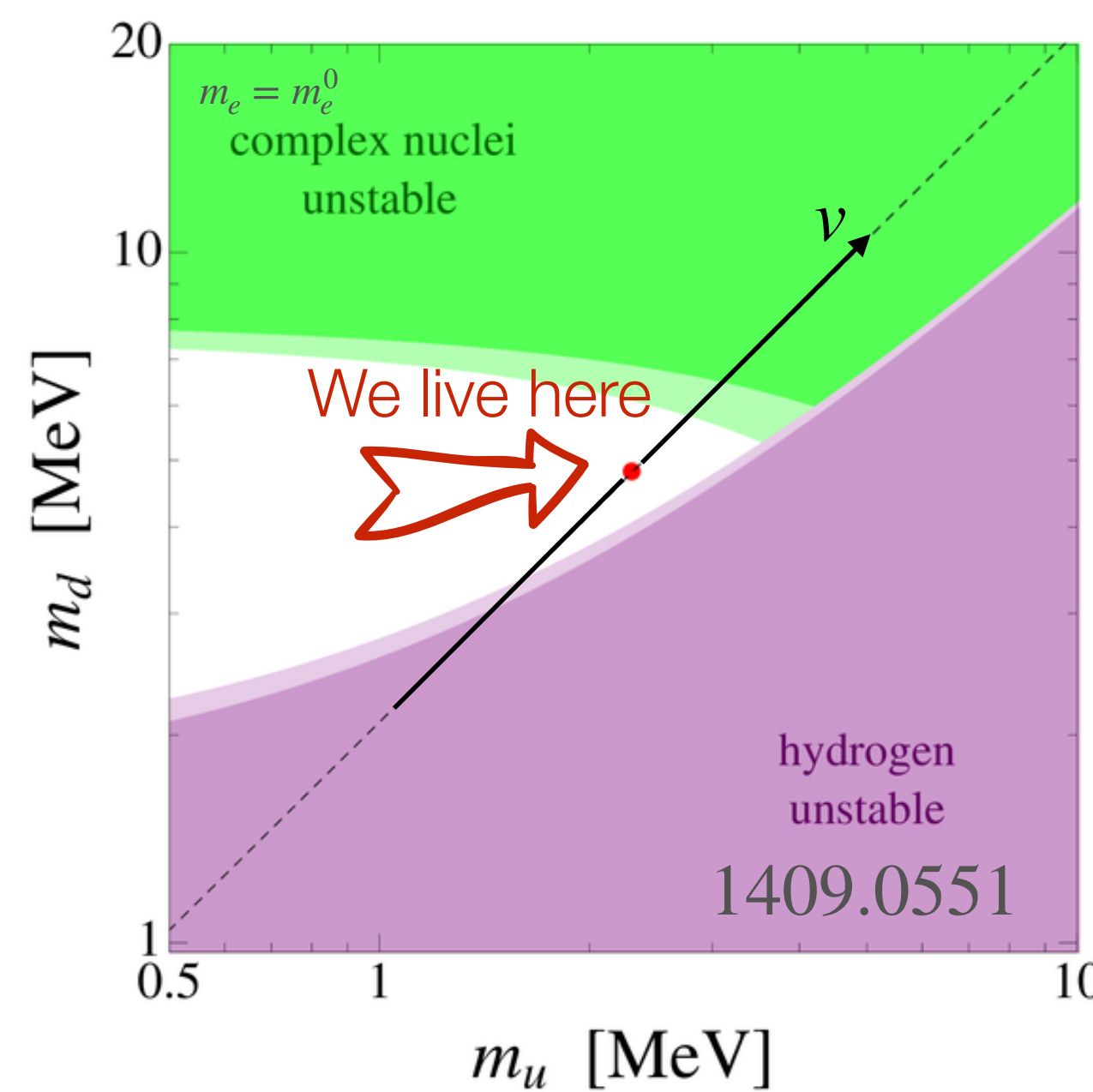
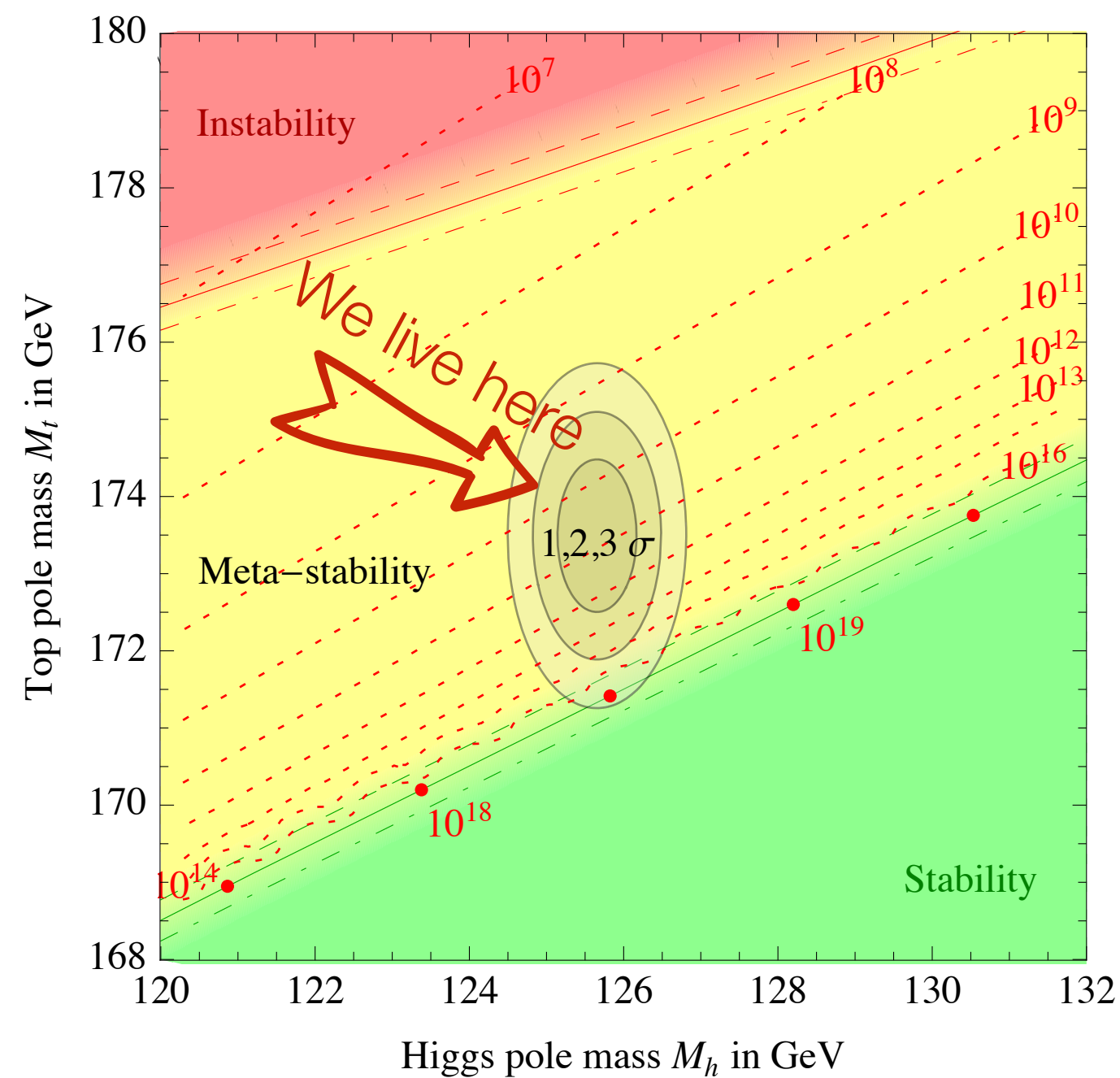
m_e, m_d, m_u, ν



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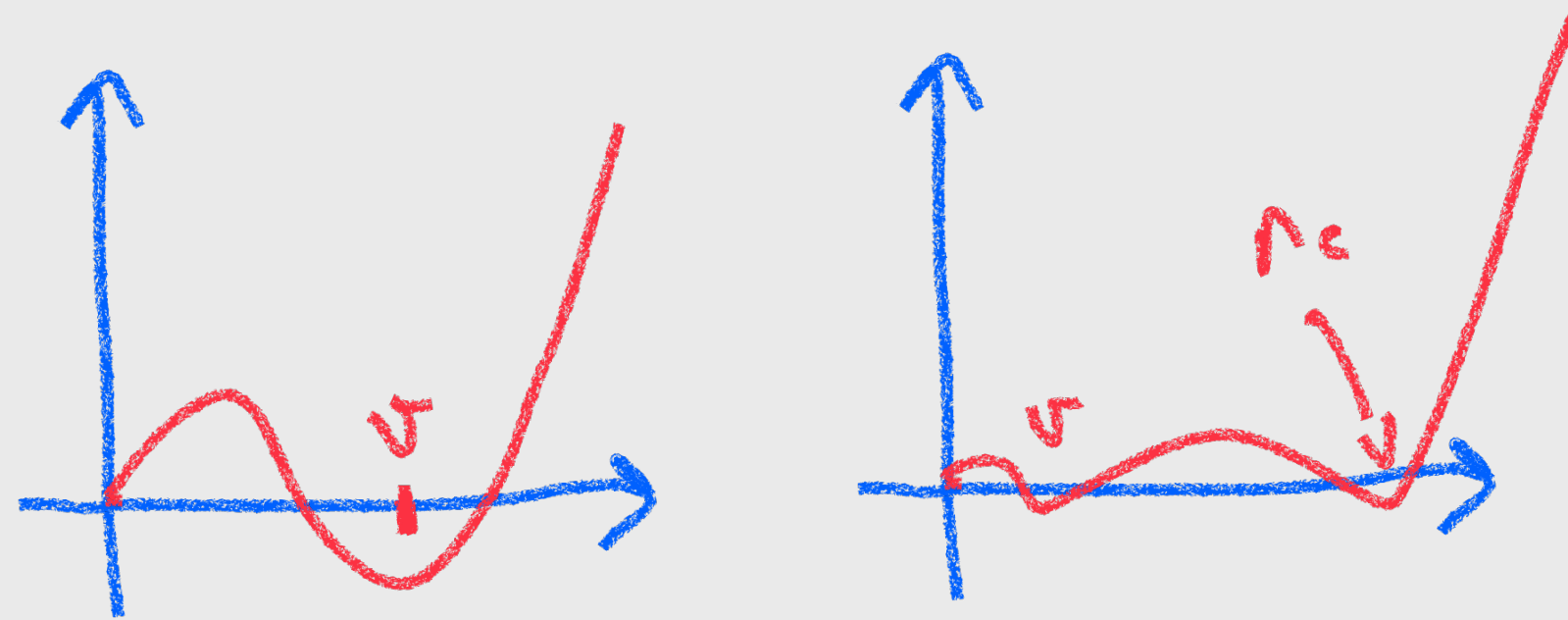


- all stars are neutron stars
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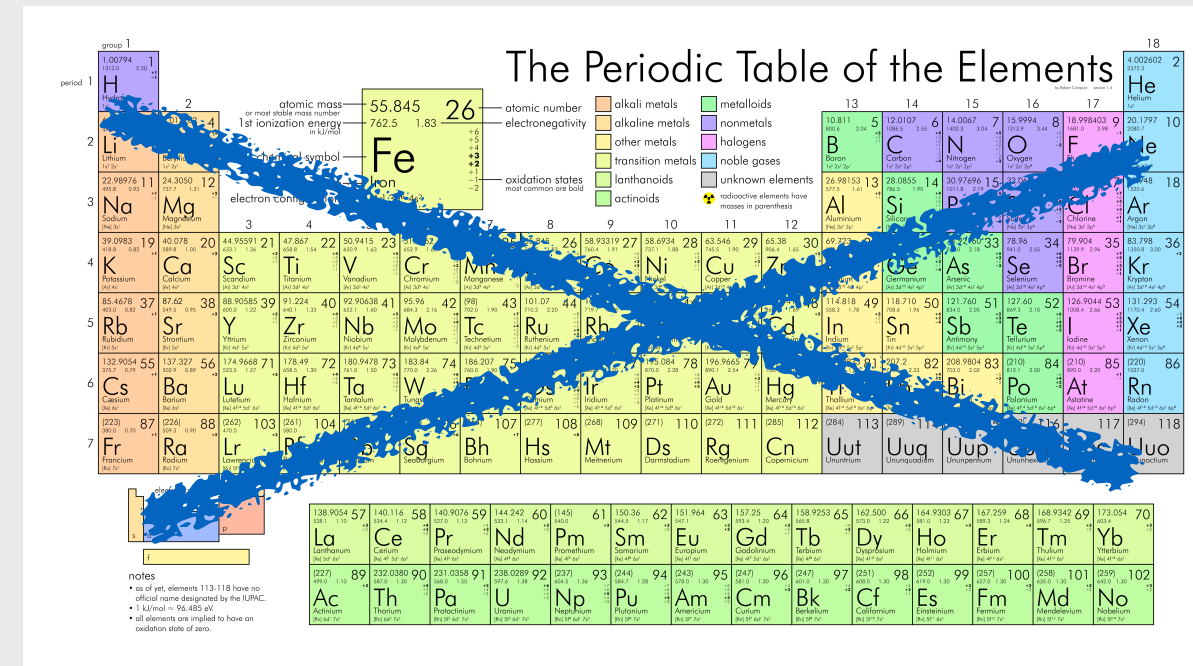


Dialing m_t, m_h, α_3

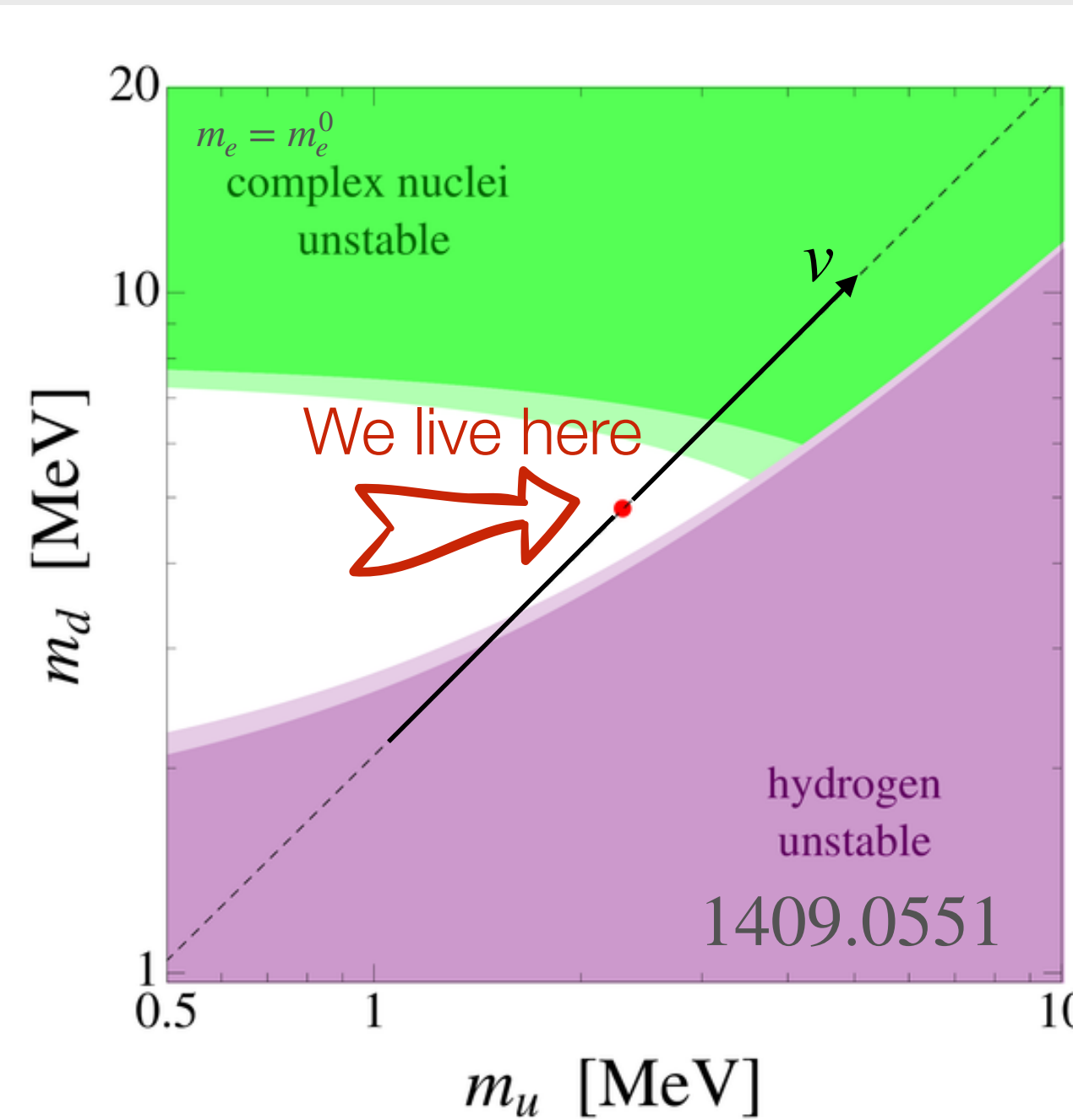
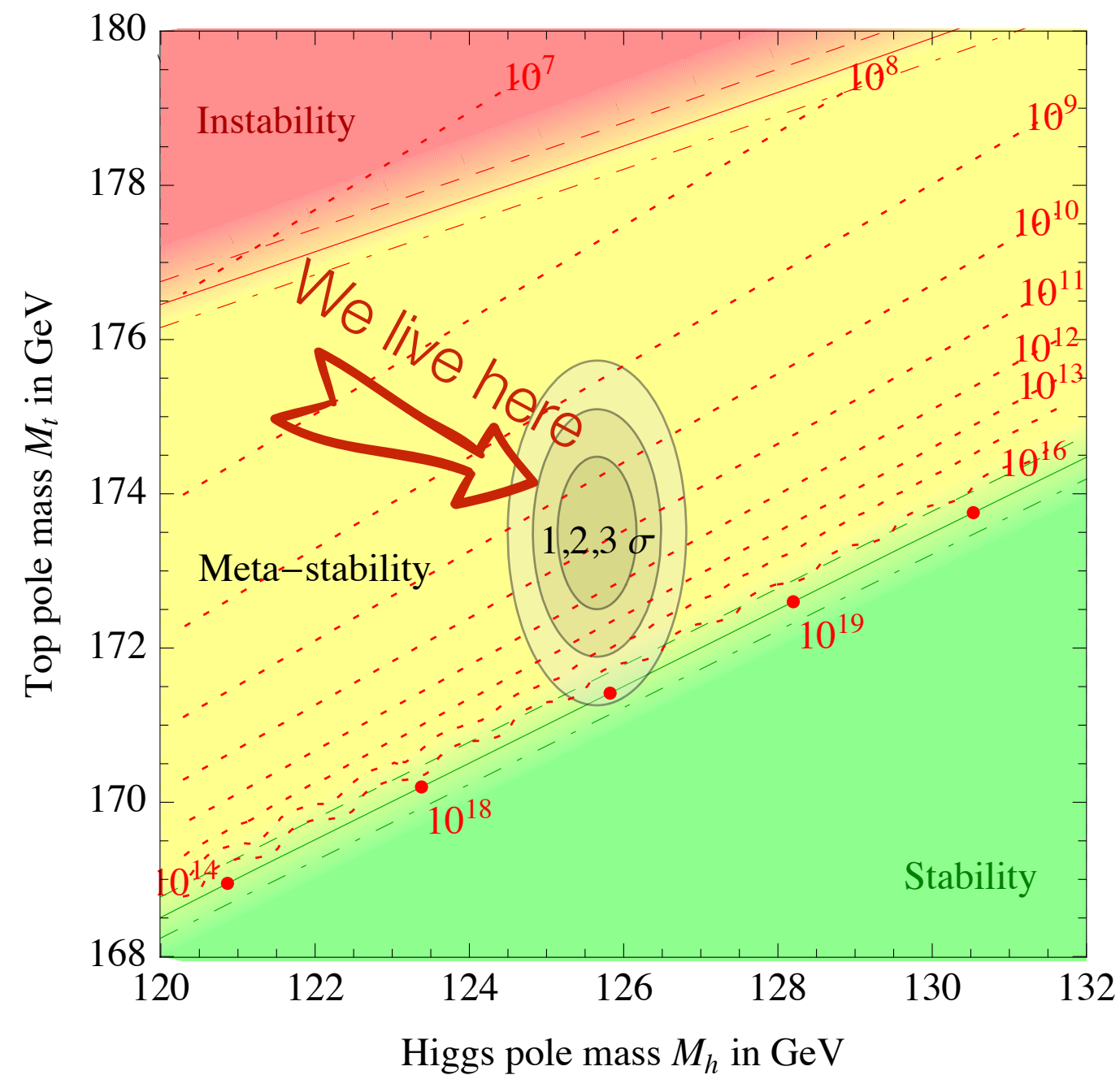
m_e, m_d, m_u, ν



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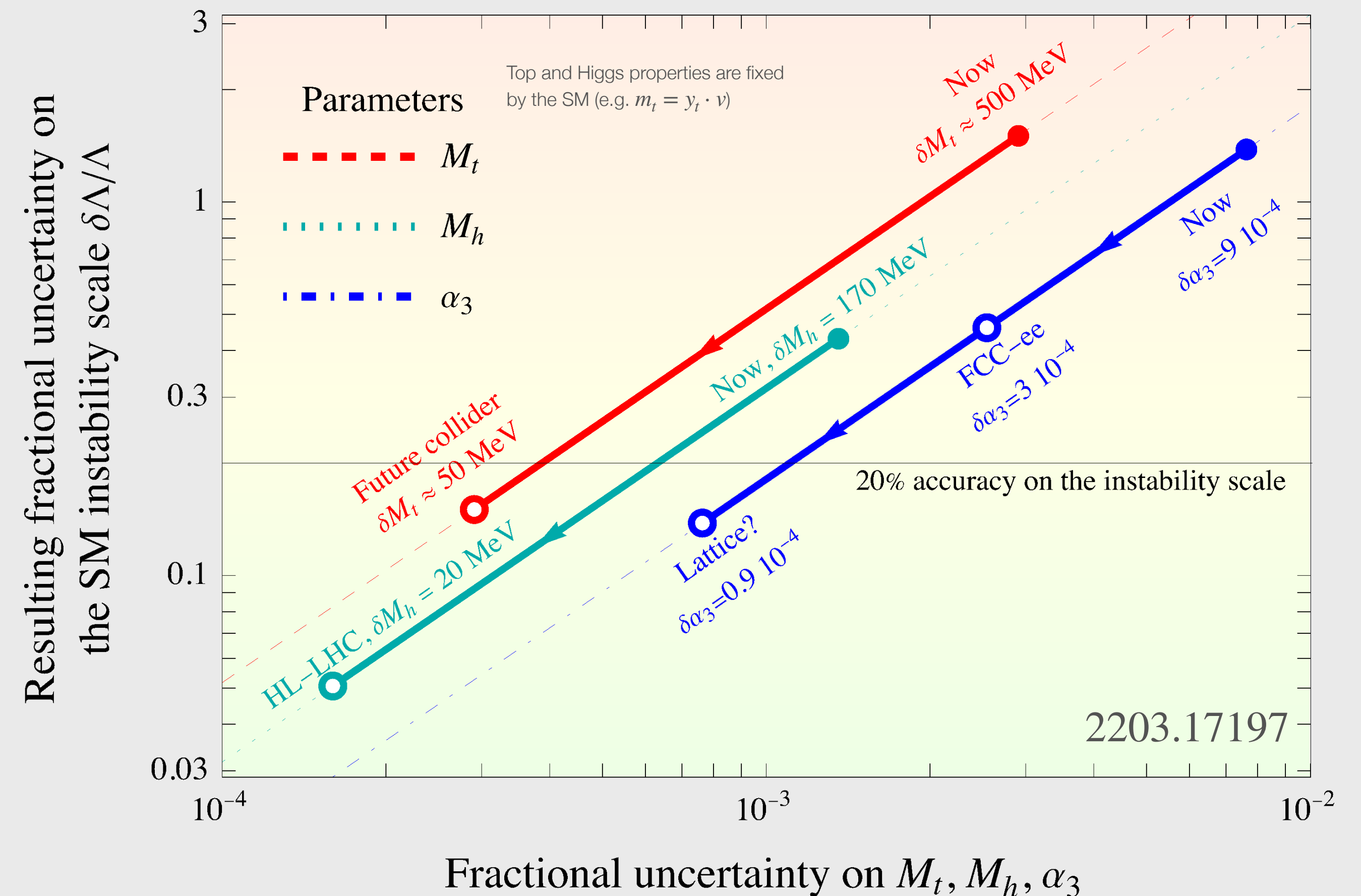
- all stars are neutron stars
- no nuclei beyond deuterium



Collider inputs we need to measure to settle this questions

- Higgs mass from HL-LHC will be good enough
- α_3 can be taken from Lattice QCD (in principle)

- **Top mass is the biggest player**
- **Can only be measured at colliders**



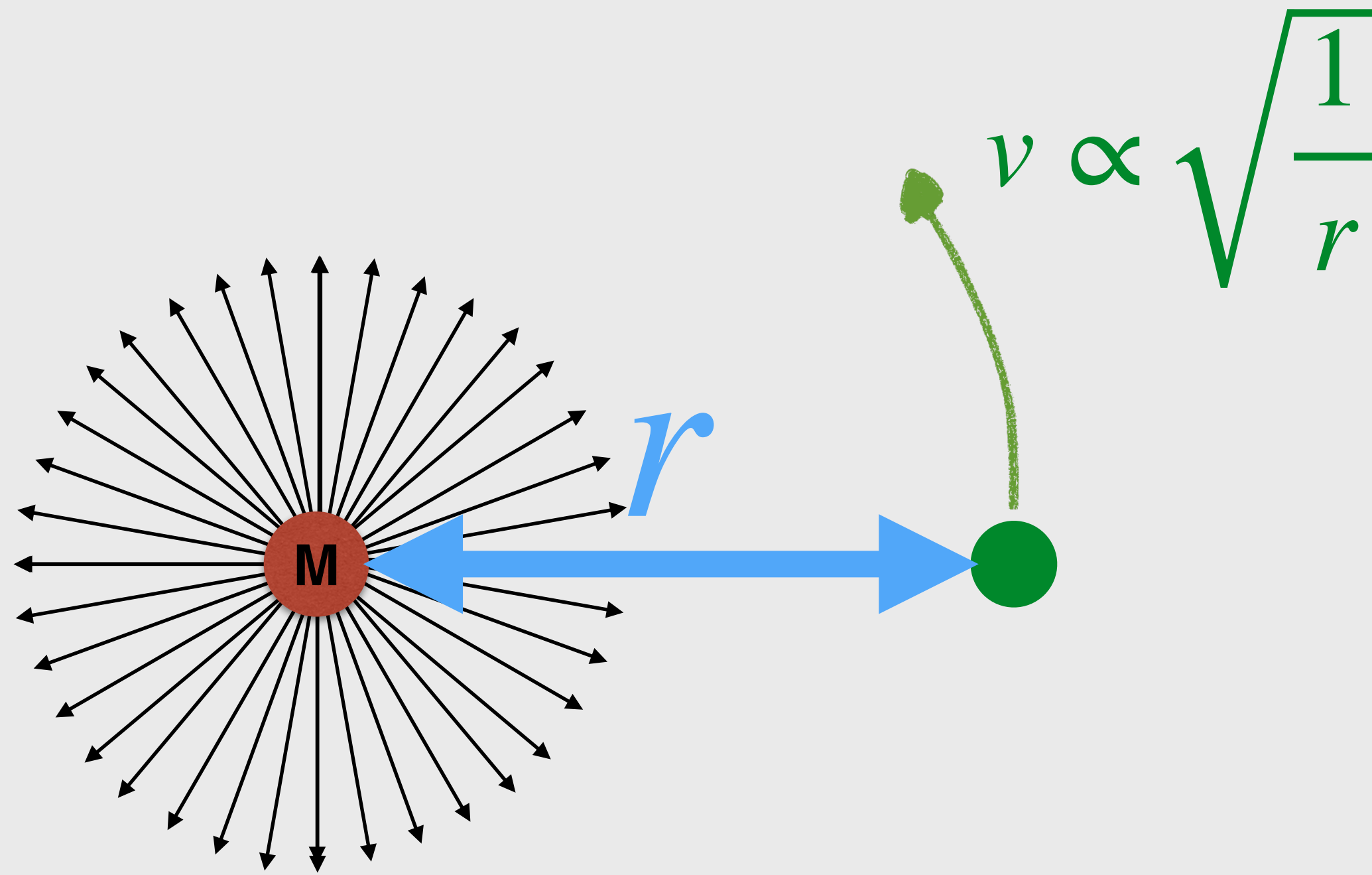
flashing concrete results for

Dark Matter at the weak scale

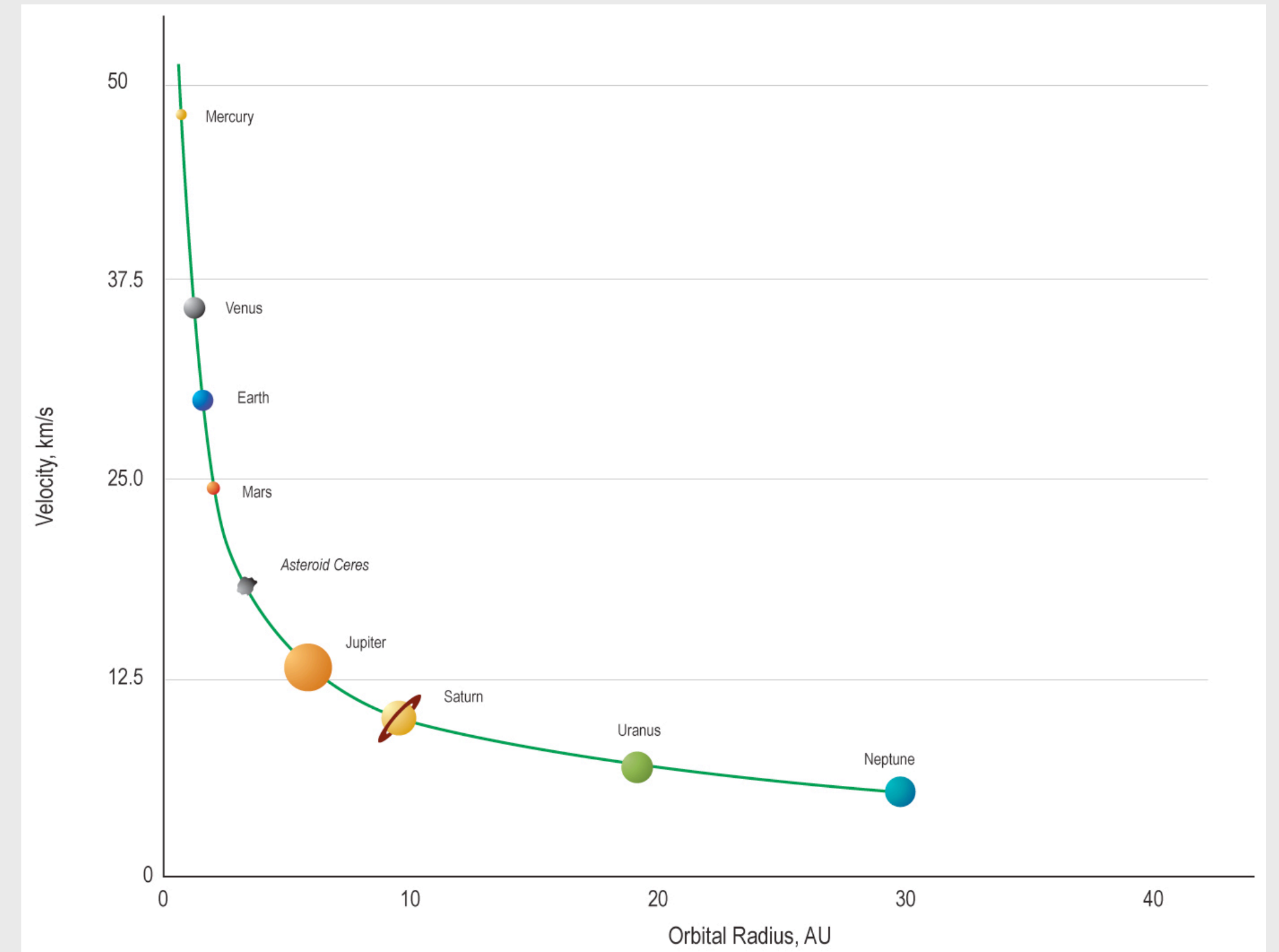
it's out there

NEWTONIAN

MECHANICS FAILS?



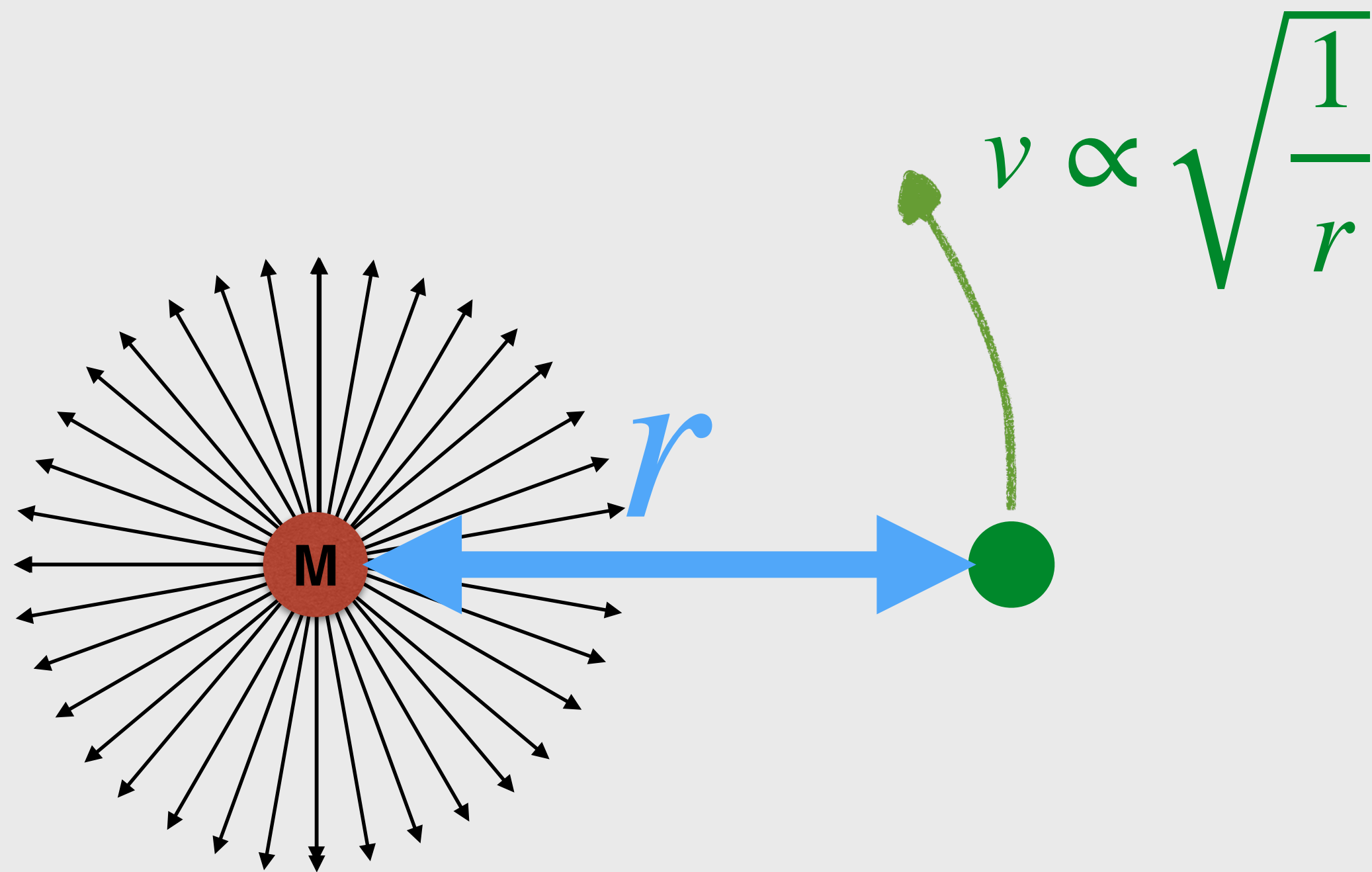
Perfect in our “neighborhood”



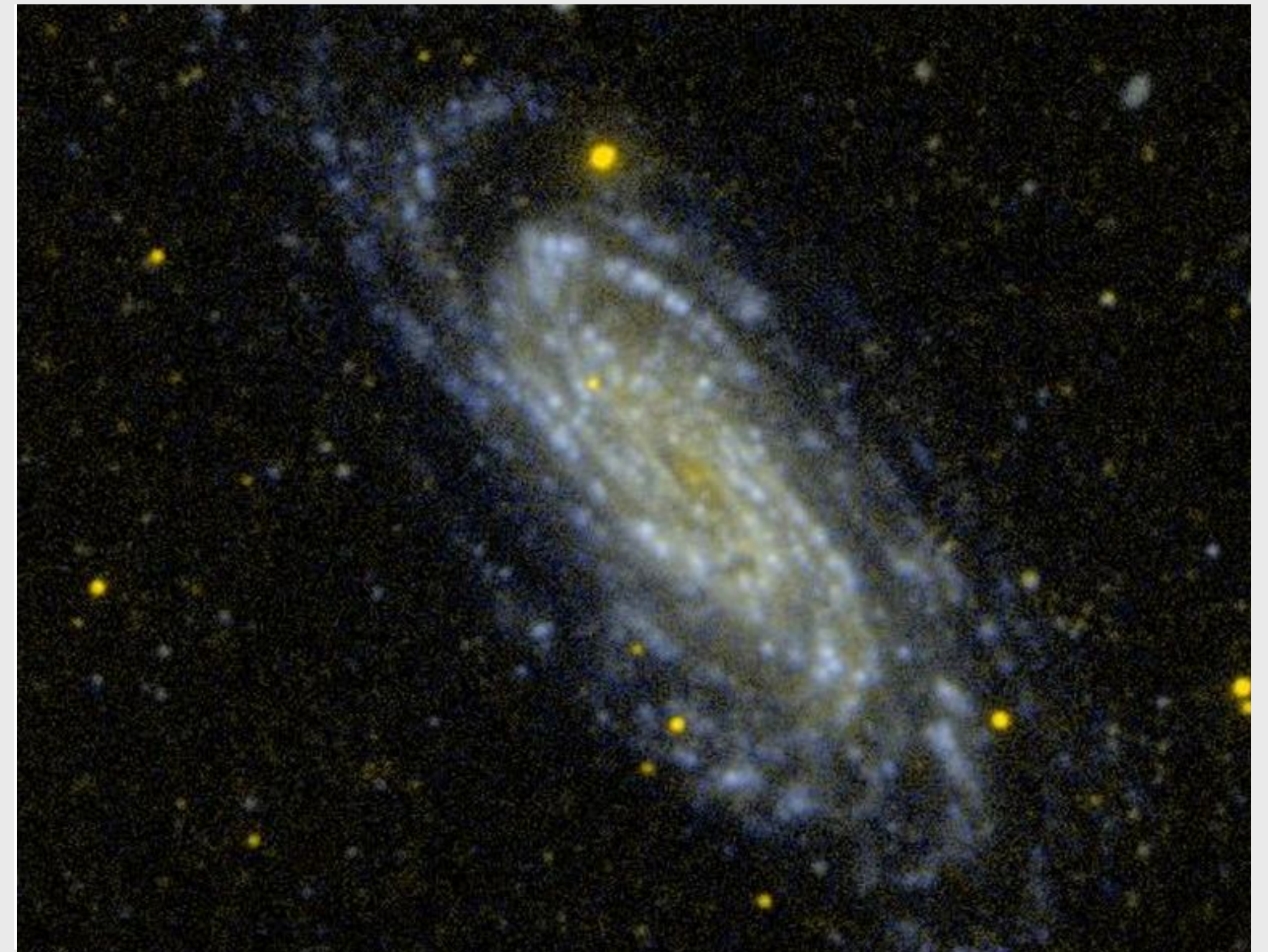
it's out there

NEWTONIAN

MECHANICS FAILS?



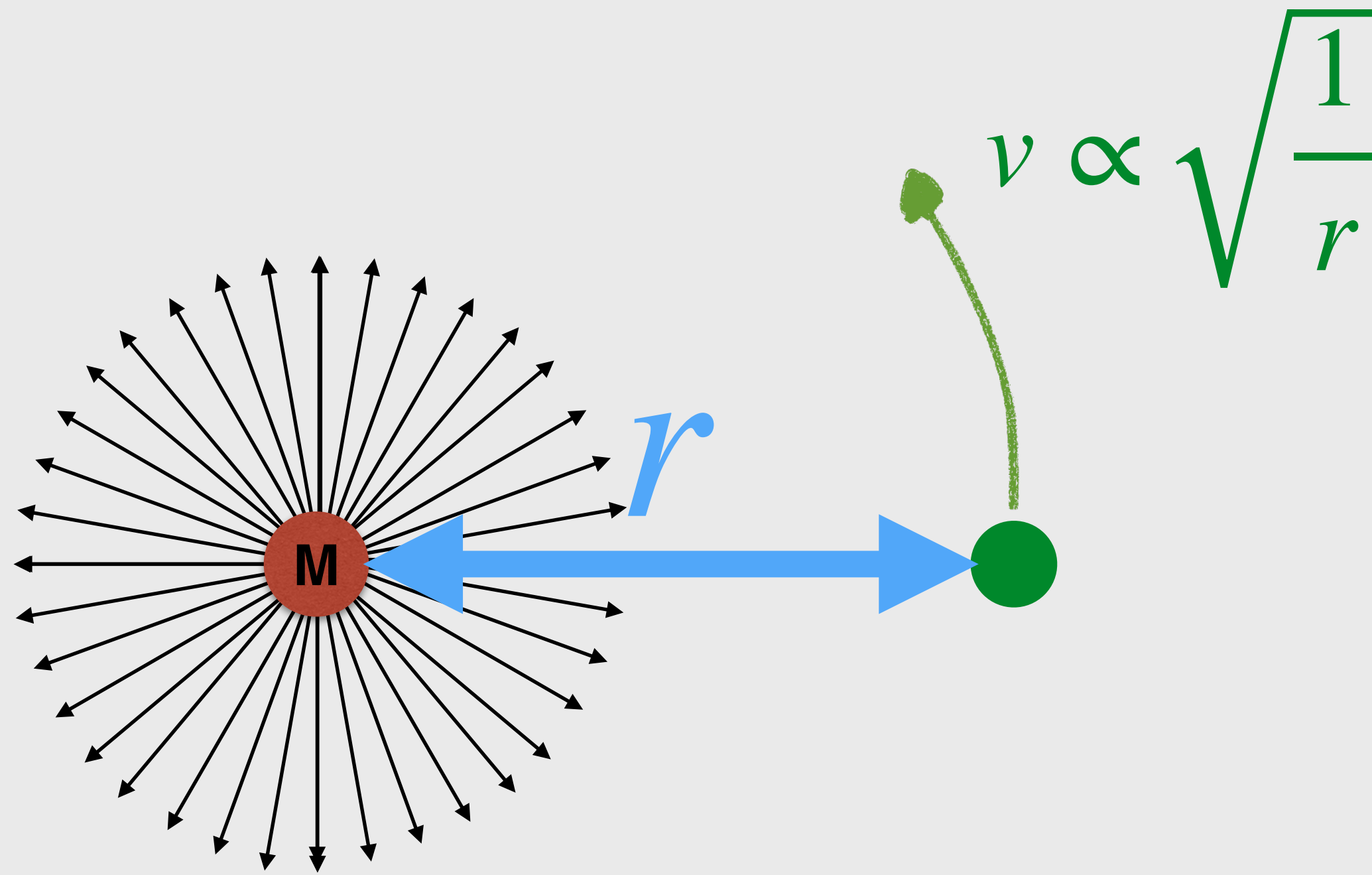
Perfect in our “neighborhood”



it's out there

NEWTONIAN

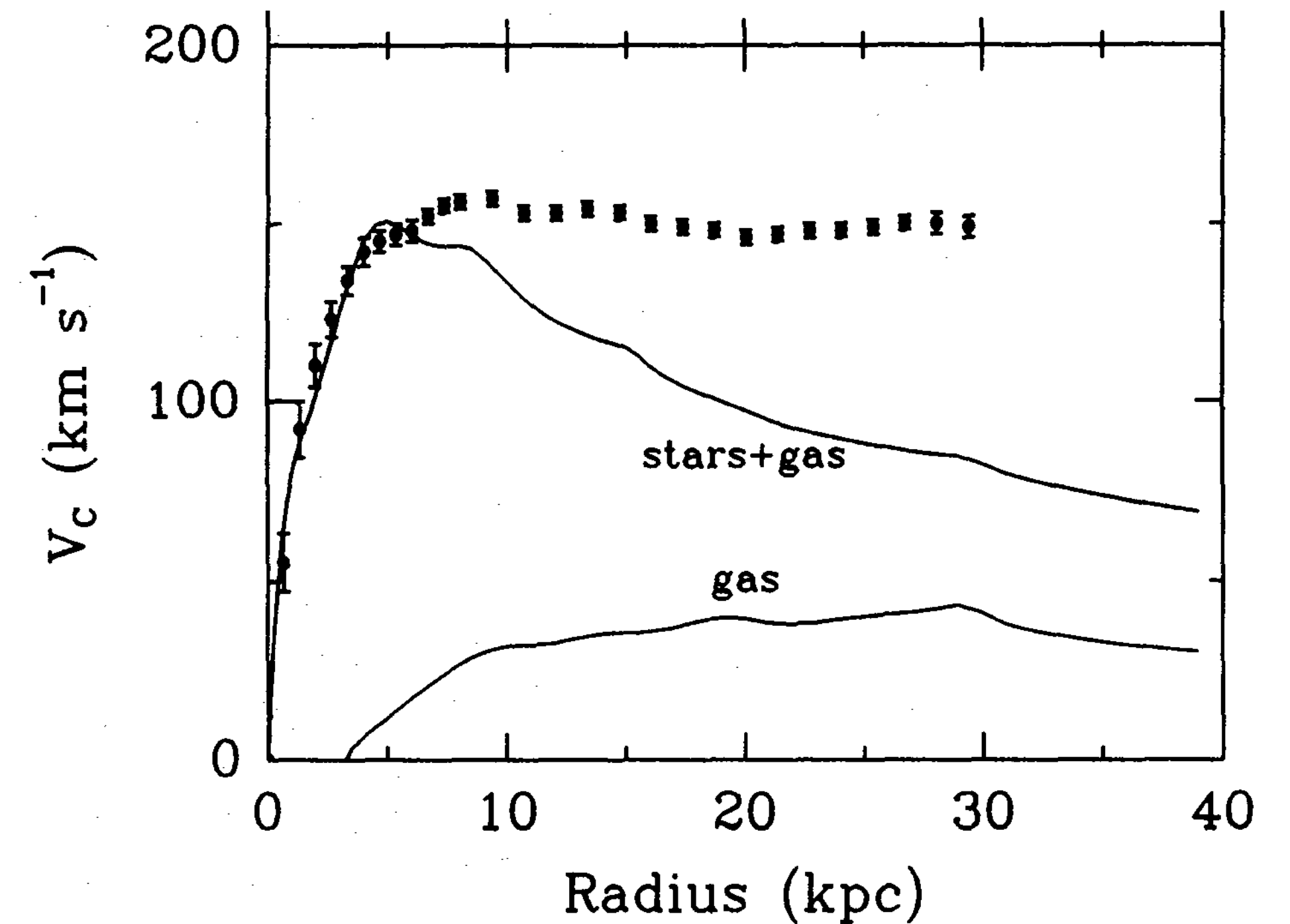
MECHANICS FAILS?



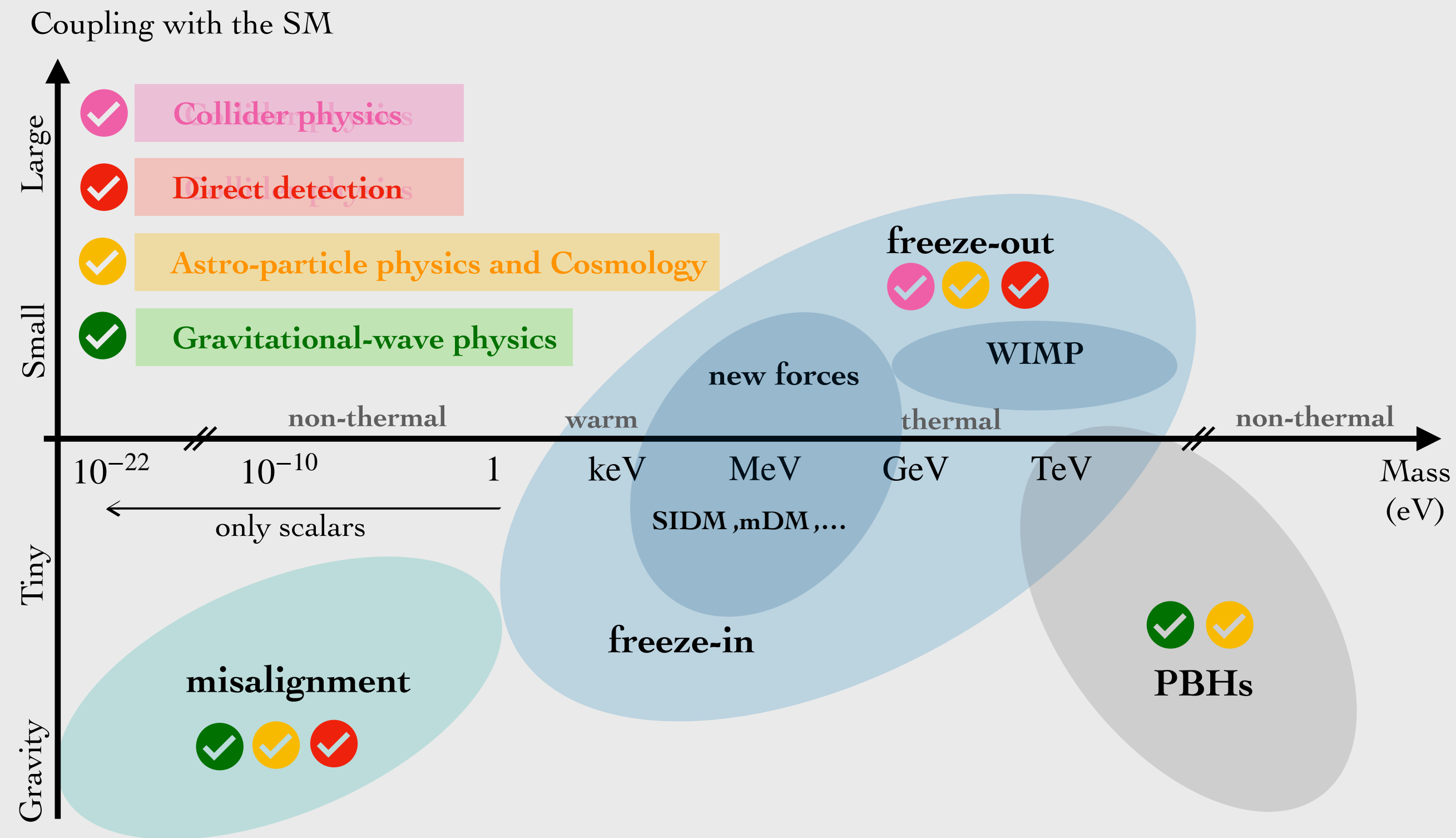
Perfect in our “neighborhood”

Begeman, K. 1989, A&A, 223, 47

NGC 3198



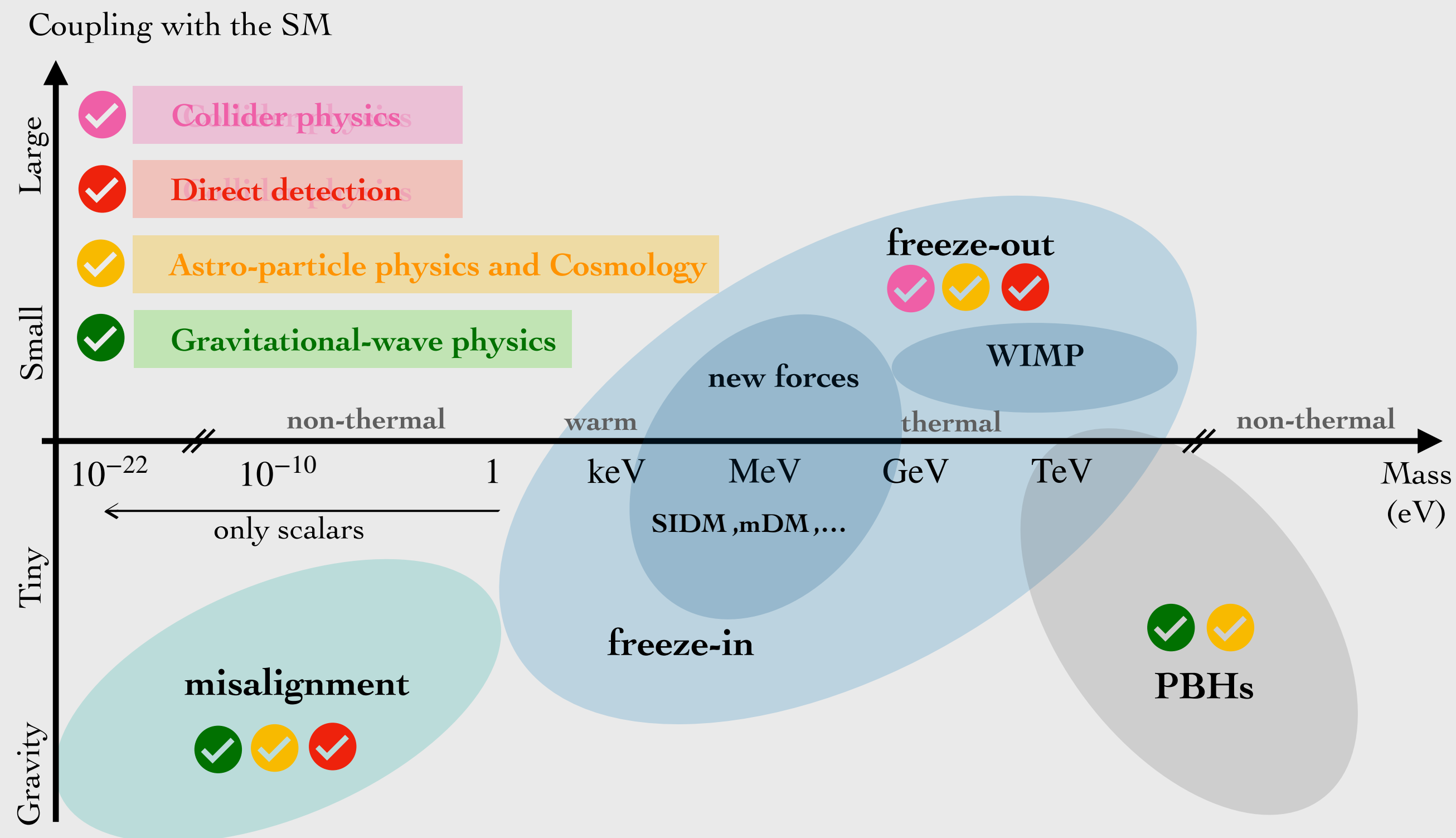
it's out there



plenty of ideas

Electroweak Dark Matter: LSP (+NLSP)

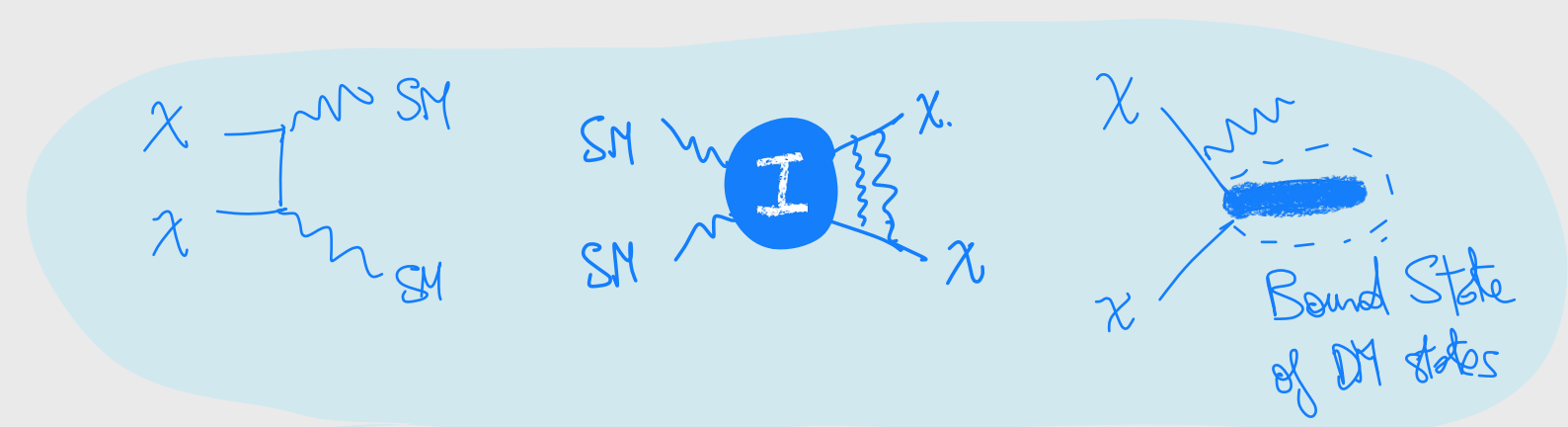
- The chessboard of DM is very large!



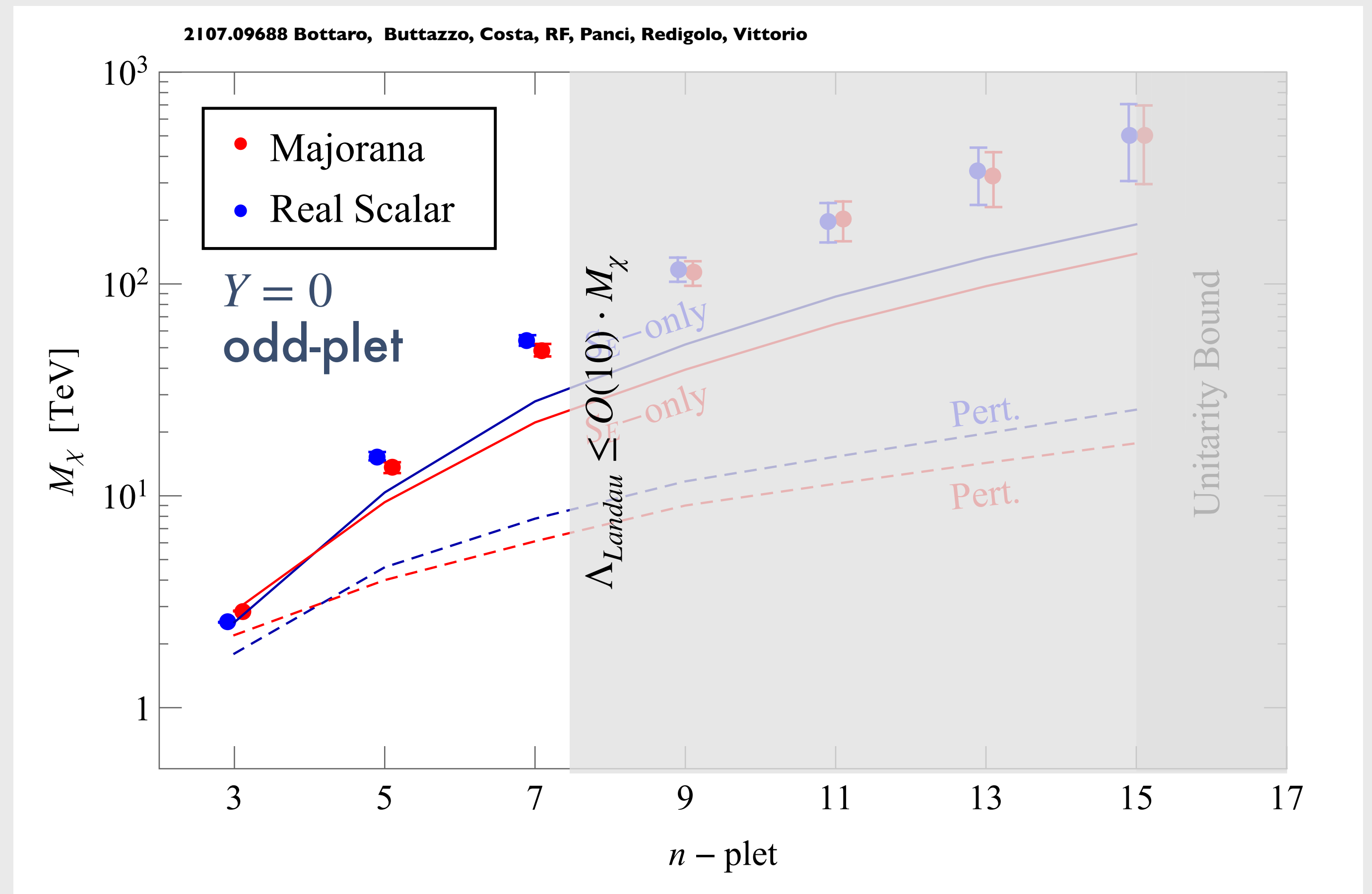
- High energy colliders are excellent and very robust probes of WIMPs!

An “interpolator” model

$$\Omega_{nr} \sim \frac{1}{\sigma_{ann}} \sim \frac{M^2}{C_n \cdot g^2}$$



given n the mass is predicted
understood as the maximal mass for that n

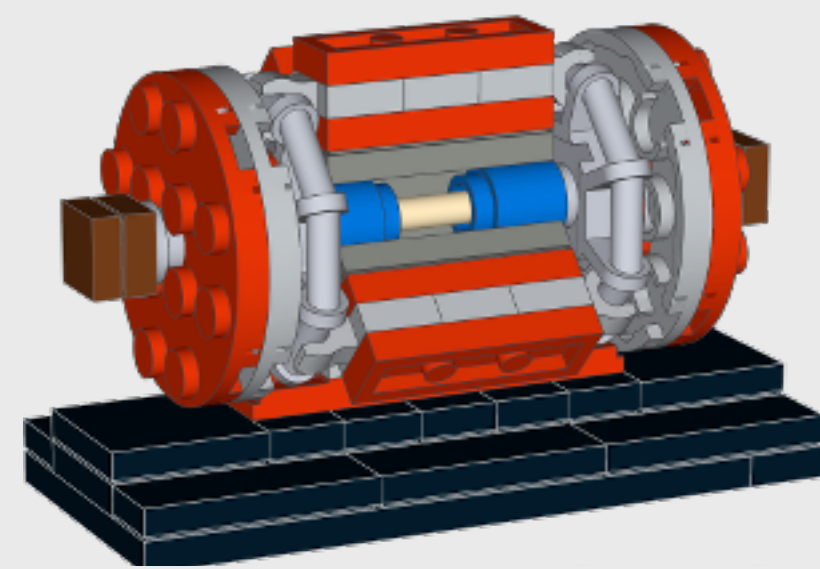


IF DARK MATTER FEELS SM WEAK INTERACTIONS WE CAN USE THE GENERAL n -PLET WIMP TO MEASURE HOW WELL WE ARE ABLE TO TEST THIS HYPOTHESIS AND POSSIBLY DISCOVER OR EXCLUDE ONE OR SEVERAL OR THE WHOLE CATEGORY OF DM CANDIDATES.

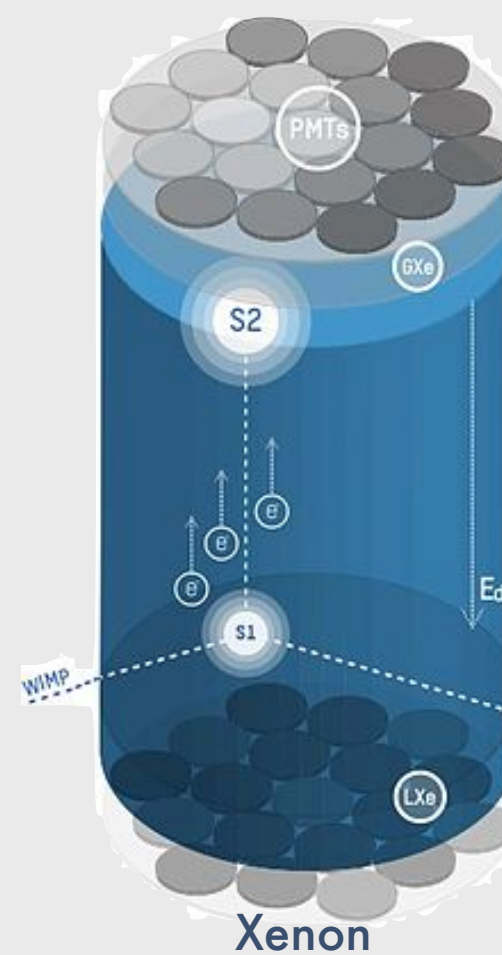
After decades of WIMPs we might start to see the end of the way (!)

HOW TO THOROUGHLY TEST IT?

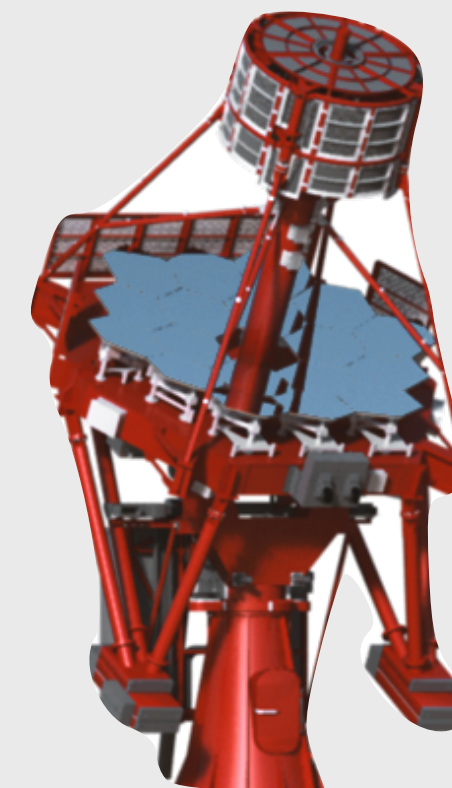
- Produce WIMPs in the lab
- Detect a WIMPs from natural source (big-bang)
- Observe WIMPs interactions (annihilation)
- Future Colliders sensitive to $O(100)$ TeV
- Upcoming nT Xe detectors
- Upcoming Cosmic Rays observatories



Future Collider



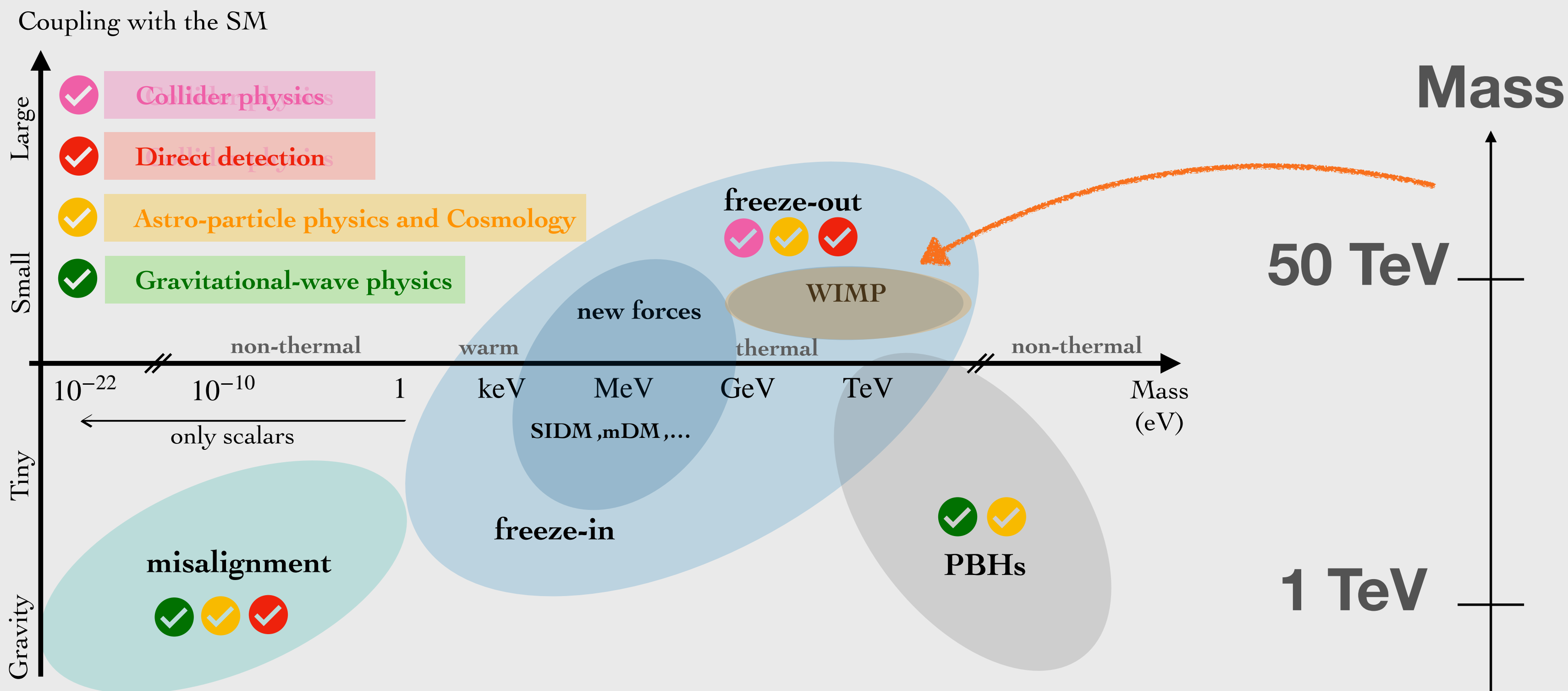
Xenon



CTA

Electroweak Dark Matter: LSP (+NLSP)

- The chessboard of DM is very large!



- High energy colliders are excellent and very robust probes of WIMPs!

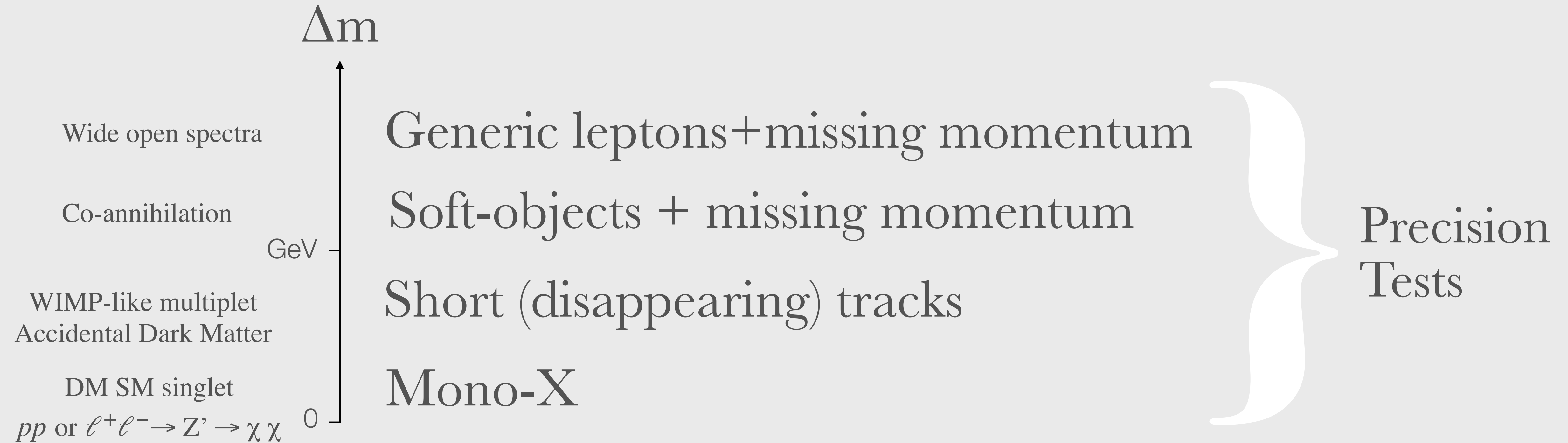


SUSY
WINO

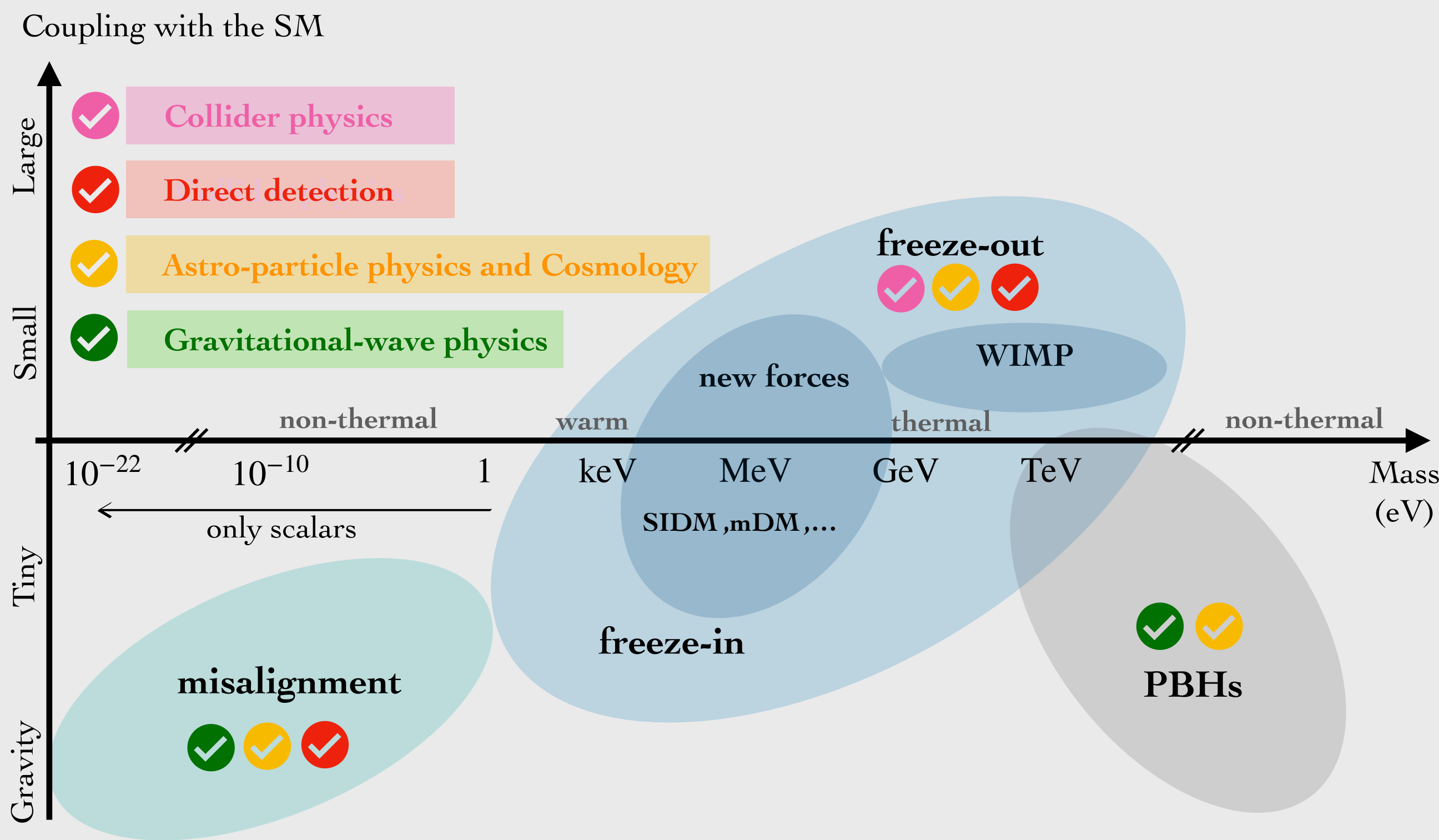
SUSY
HIGGSINO

“WIMP” Dark Matter

Electroweak Dark Matter: LSP (+NLSP)



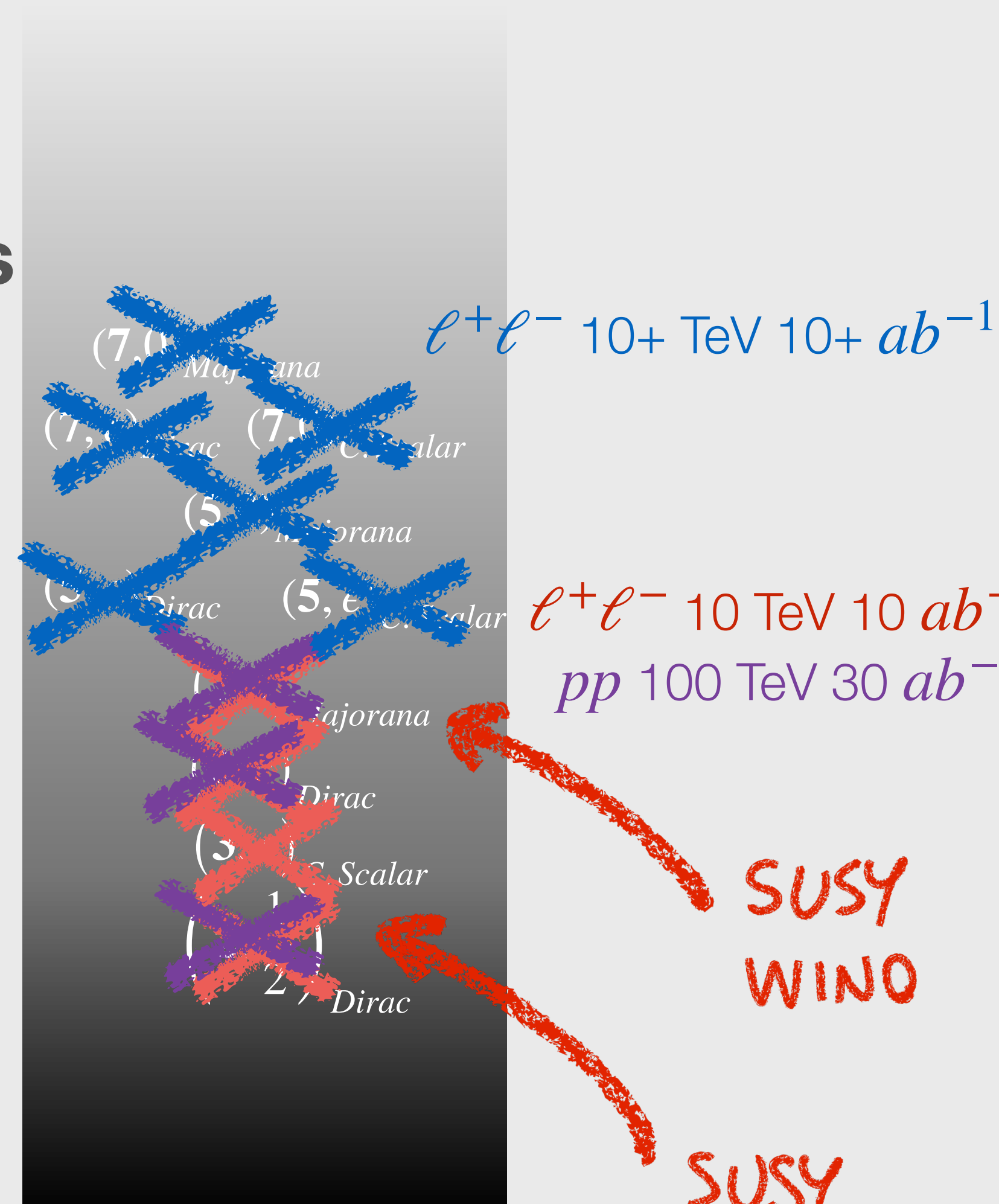
Electroweak Dark Matter: LSP (+NLSP)



Mass

50 TeV

1 TeV



“WIMP” Dark Matter

and much much more

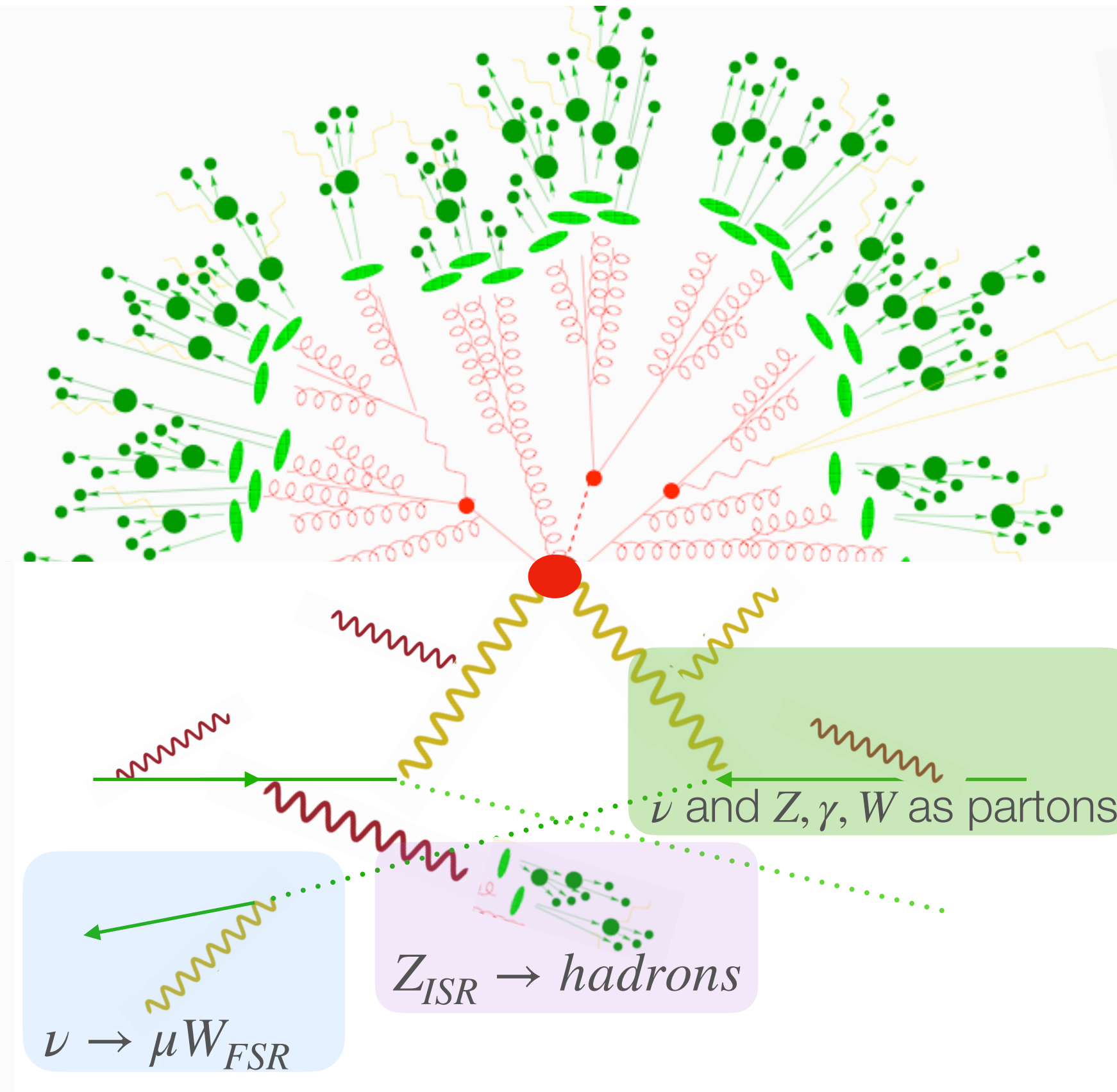
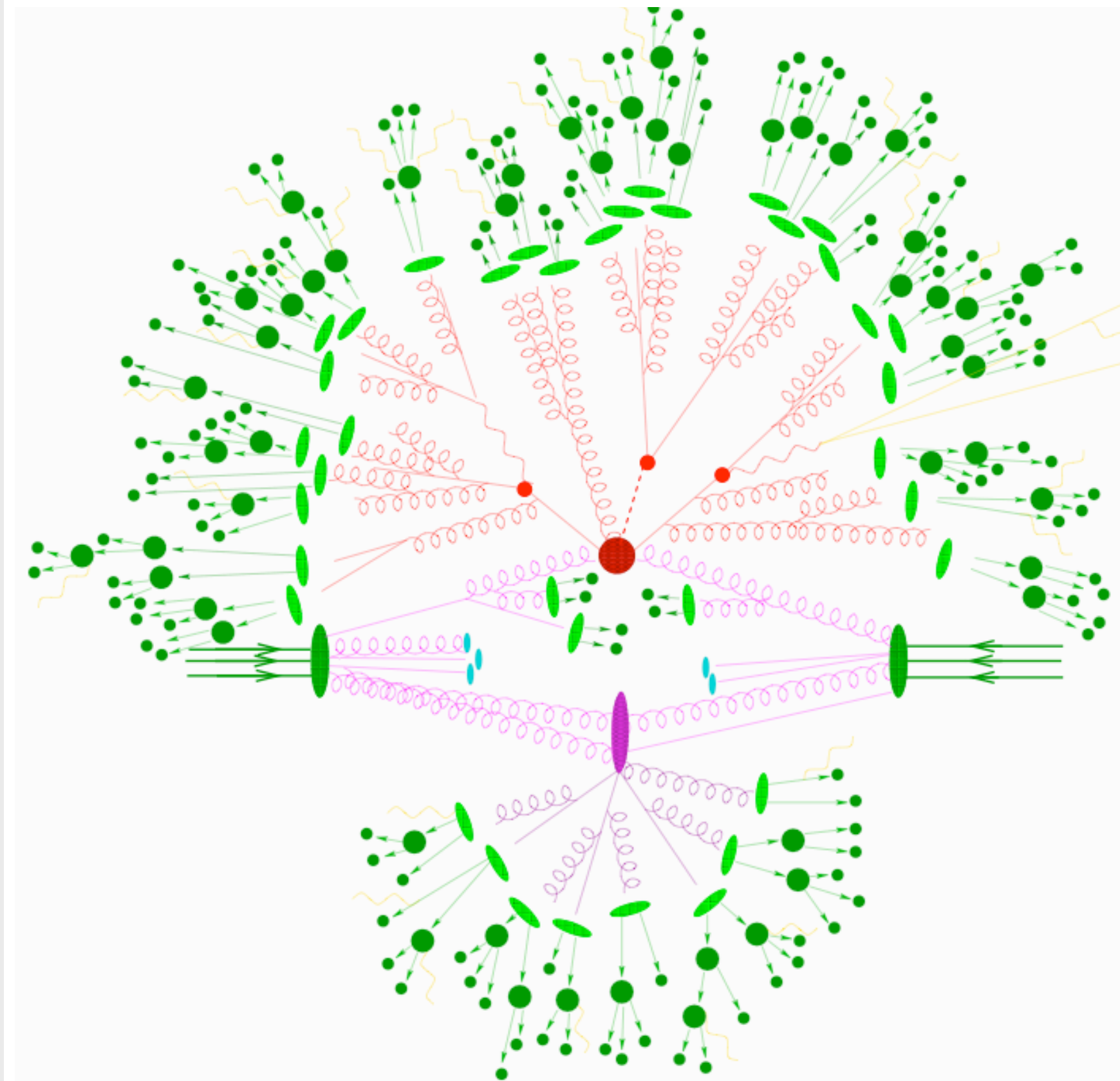
a rich and extensive program

UNBROKEN

PHASE OF THE ELECTROWEAK INTERACTIONS

tth production at the LHC (Fully hadronic)

tth production at the muC 100 TeV (F. Maltoni)



NEW PHENOMENA AND
NEW REGIMES IN pQFT

- unsuppressed weak corrections “electroweak is the new QCD”
- weak “partons”
- large EW logarithms
- a non-abelian charge (like color) becomes observable (like electric charge)

HIGHER ENERGIES \rightarrow W AND Z BOSON ARE NEARLY MASSLESS

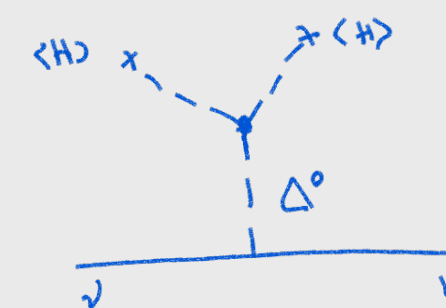
a rich and extensive program

LEPTON

NUMBER BREAKING

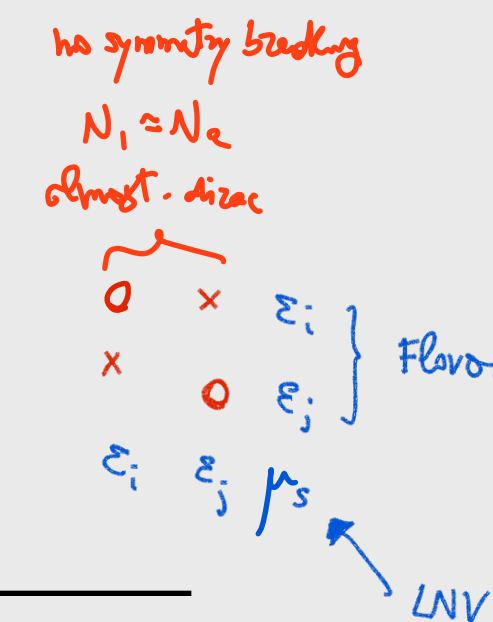
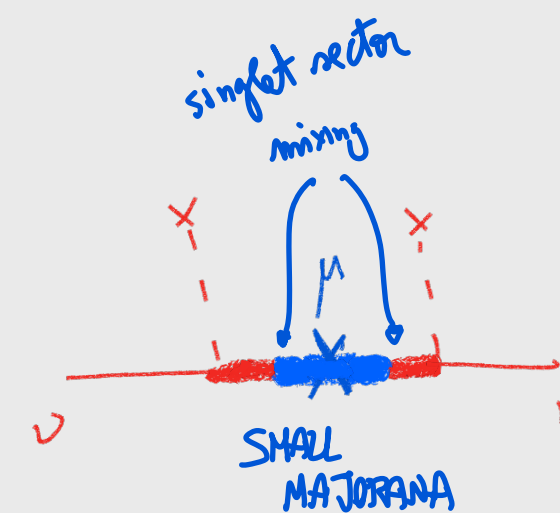
L – violation

(1,1,0) (at least 2)



(1,3,1) (1 is enough)

(1,1,0) (at least 2+1)

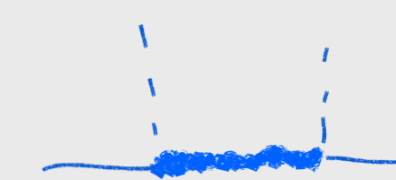


L – not accidental

new physics before 2012

$$d = 5 \quad (1,2,1/2) \quad \frac{(LH)^2}{\Lambda}$$

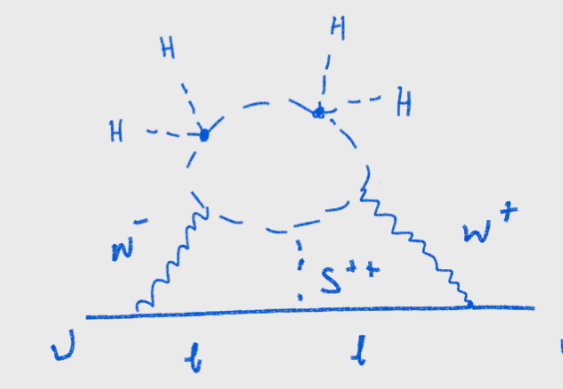
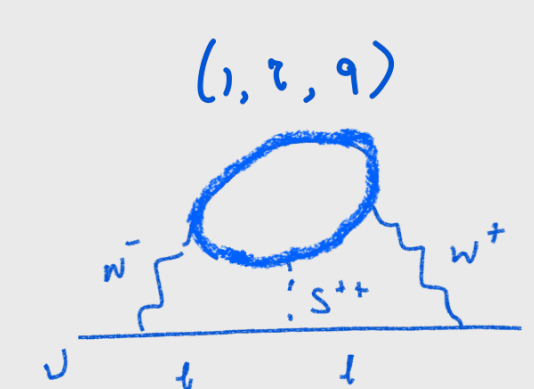
UV



(1, 2, 9)

$$d = 7 \quad (1,1,2) \quad \frac{(DH\sigma_2 H)^2 S^{--}}{\Lambda^3}$$

UV



L – gauged, SSB

$$SU(3) \otimes SU(2)_L \otimes SU(2)_L \otimes U(1)_{B-L}$$

$$(1,2,1,1), (1,1,2,1), (1,2,2,1), (1,1,1,2),$$

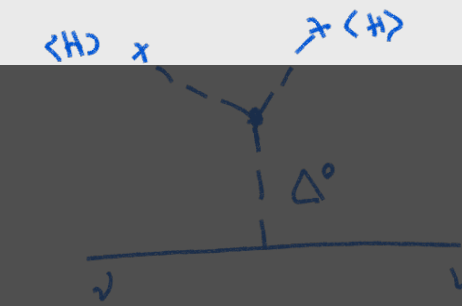
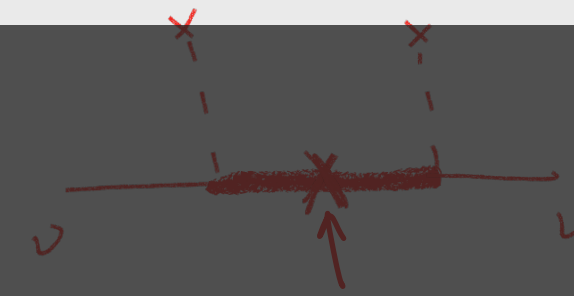
a rich and extensive program

LEPTON

NUMBER BREAKING

L – violation

(1,1,0) (at least 2)



(1,3,1) (1 is enough)

- Symmetry-based neutrino mass generation predicts new electroweak states at the TeV, where the next generation of machines can discover them!

(1,2,1,1), (1,1,2,1), (1,2,2,1), (1,1,1,2),

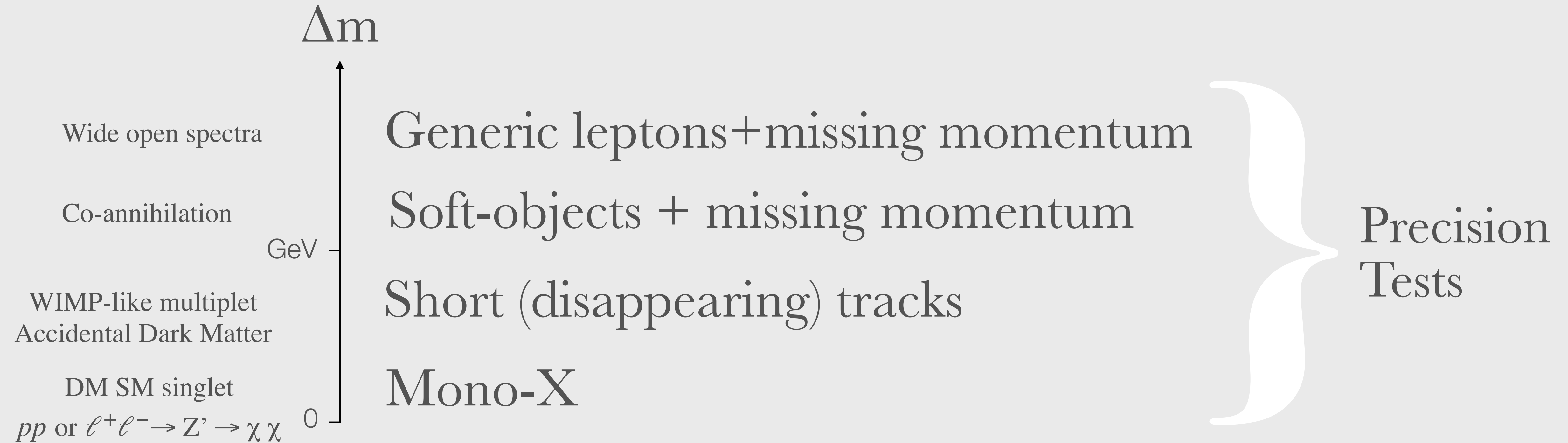
Conclusions

- The Higgs boson is a gold mine of questions of great importance for the understanding of fundamental interactions
- The next generation of colliders can study the Higgs boson with great precision and can establish its point-like nature up to an unprecedented degree, if there is more than one of them, and its possible role in generating the matter of the Universe, or even in keeping it from decaying.
- The next generation of colliders can probe thoroughly the issue of Dark Matter as a heavy particle, a great mystery that cuts physics across from cosmology, astrophysics to particle physics.
- The next generation of colliders enables new explorations of fundamental physics on a very broad field. The amount of knowledge we can foresee will be generated by a future collider is enormous.

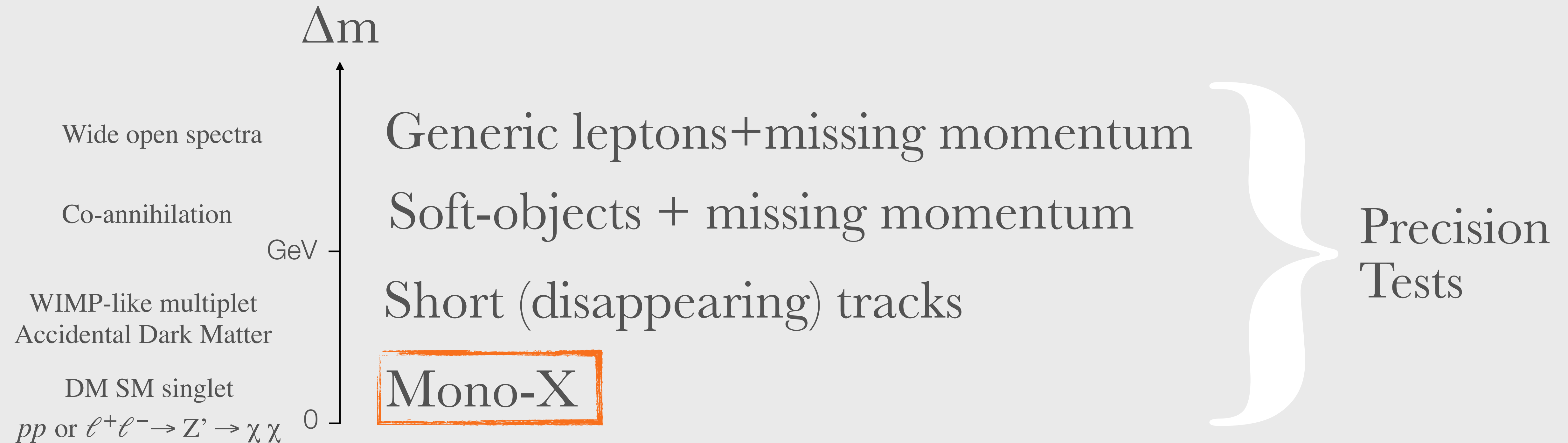
It's worth it!

Thank you!

Electroweak Dark Matter: LSP (+NLSP)



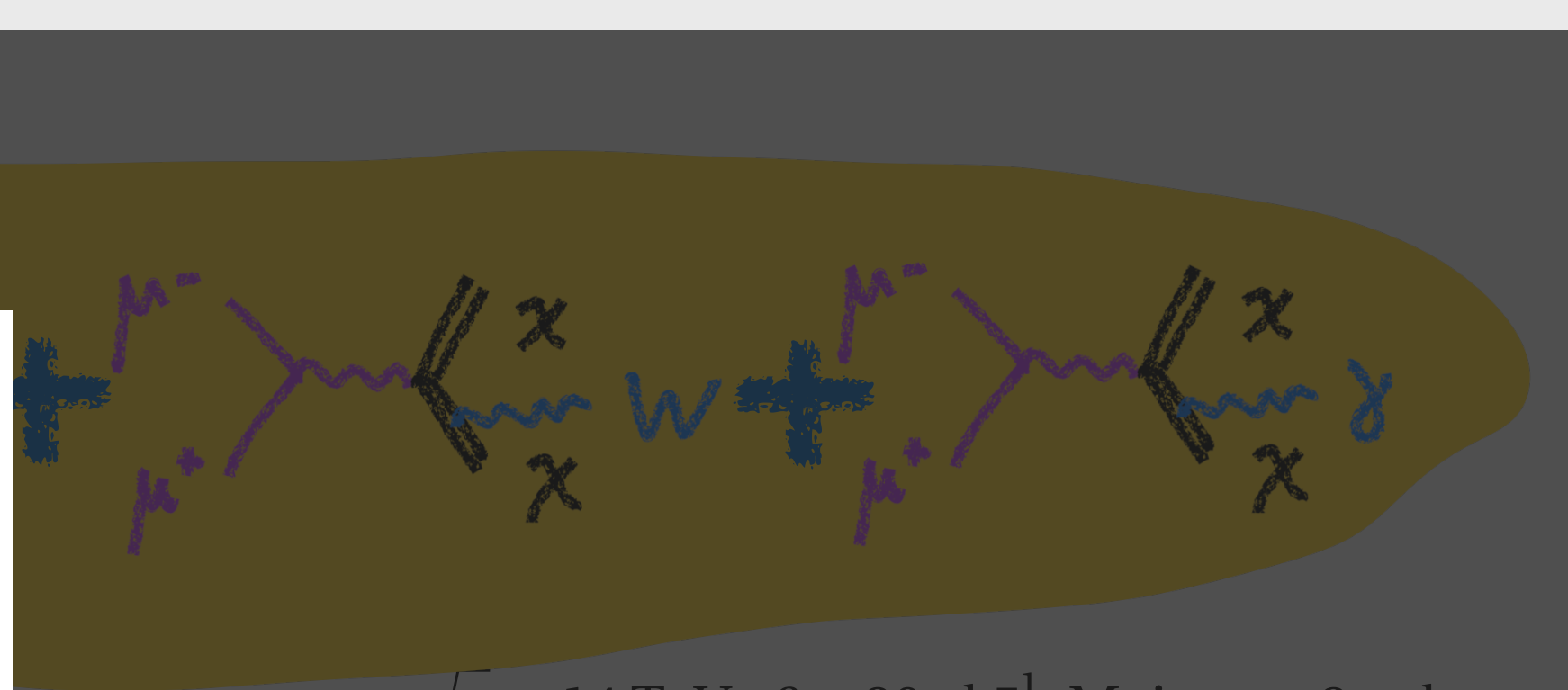
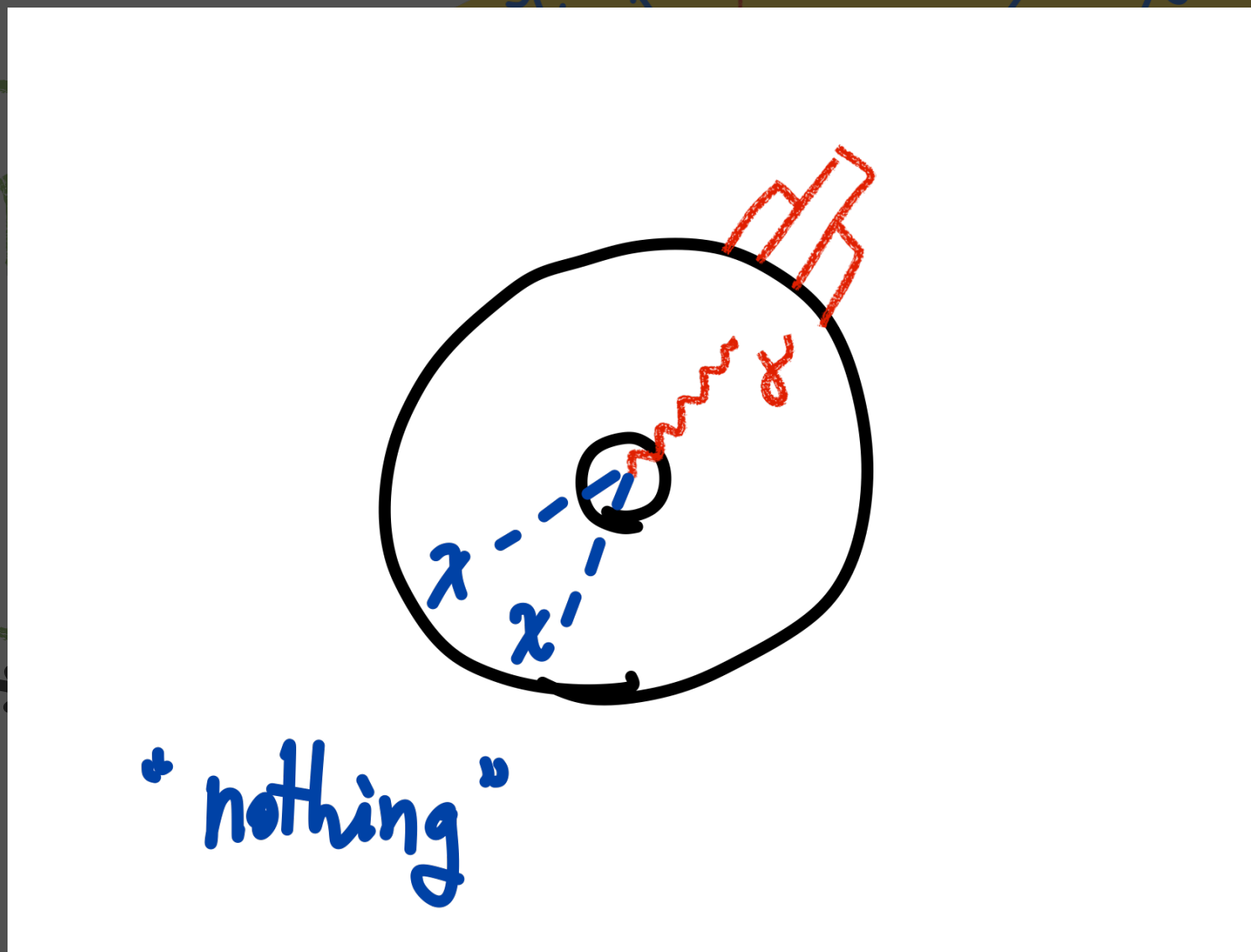
Electroweak Dark Matter: LSP (+NLSP)



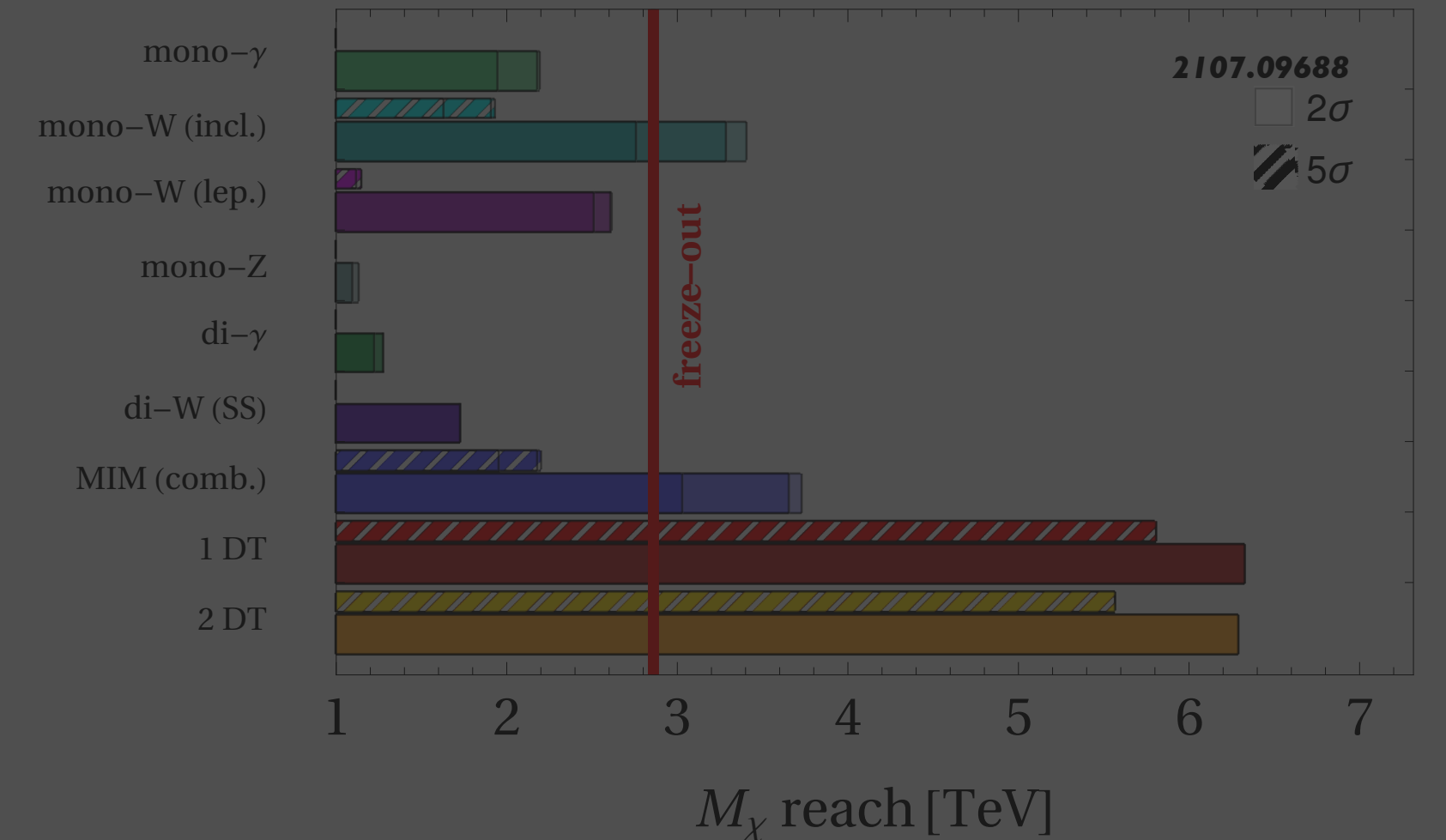
Recoil on “nothing”

GENERIC

SEARCH INTERPRETED FOR DARK MATTER



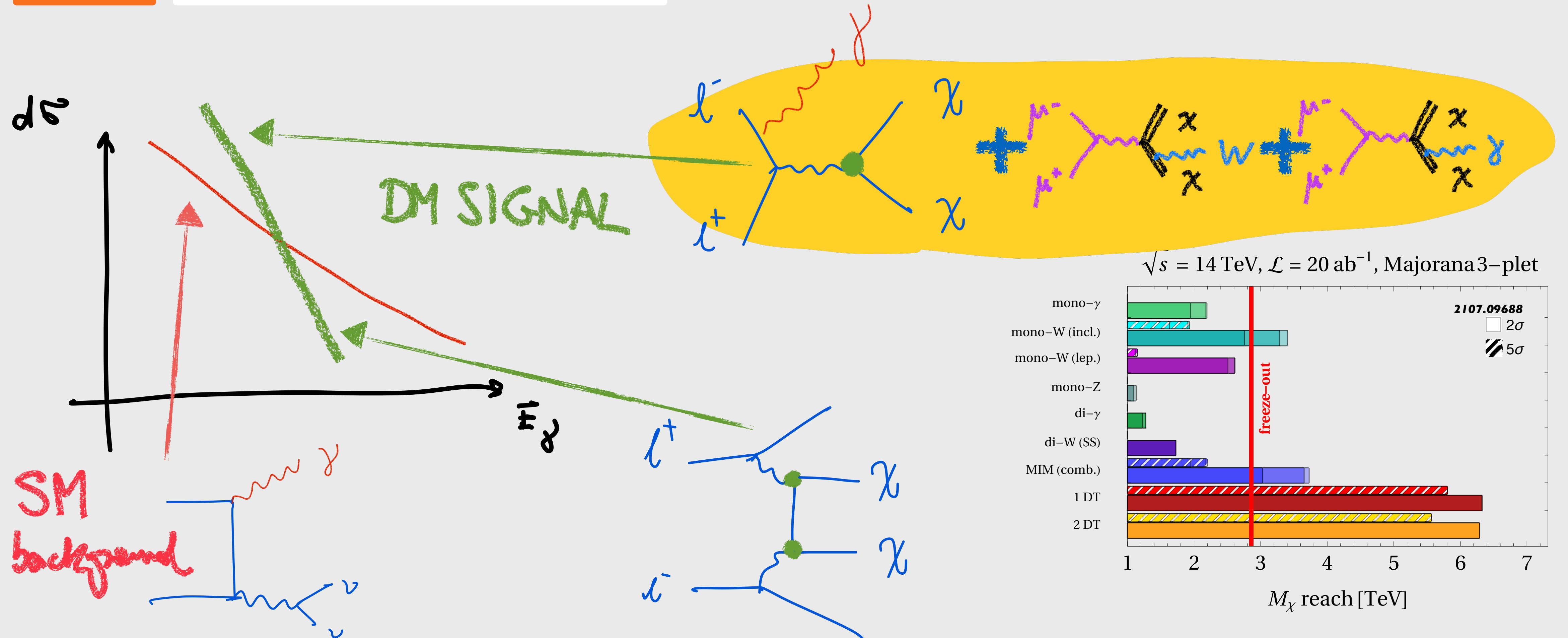
$\sqrt{s} = 14 \text{ TeV}, \mathcal{L} = 20 \text{ ab}^{-1}, \text{Majorana 3-plet}$



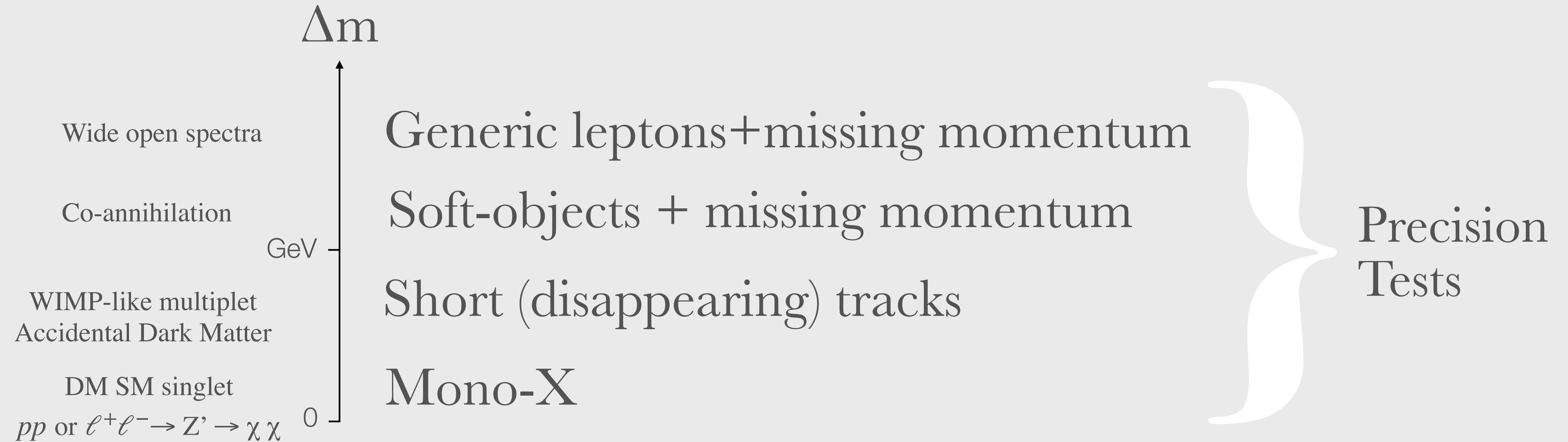
Recoil on “nothing”

GENERIC

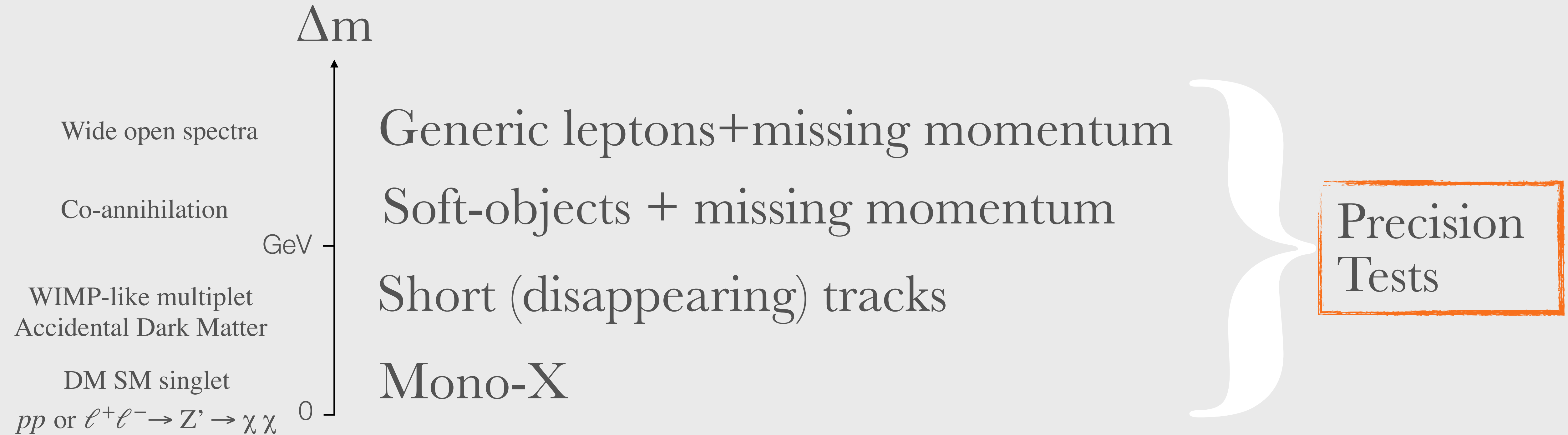
SEARCH INTERPRETED FOR DARK MATTER



Electroweak Dark Matter: LSP (+NLSP)



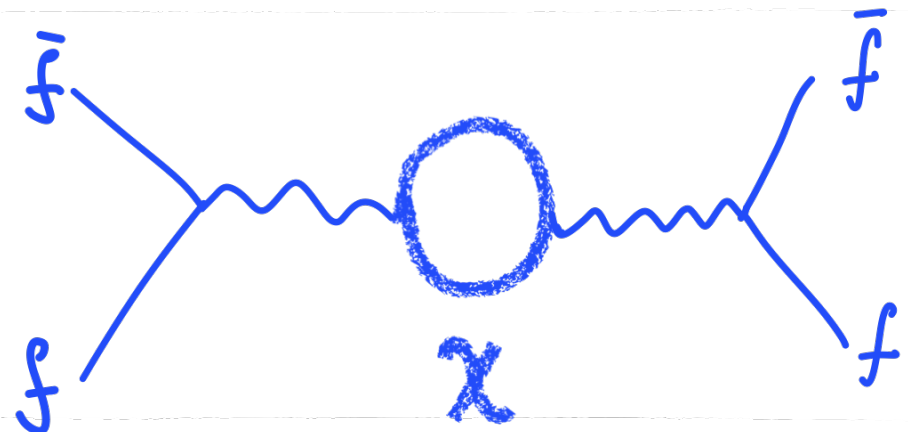
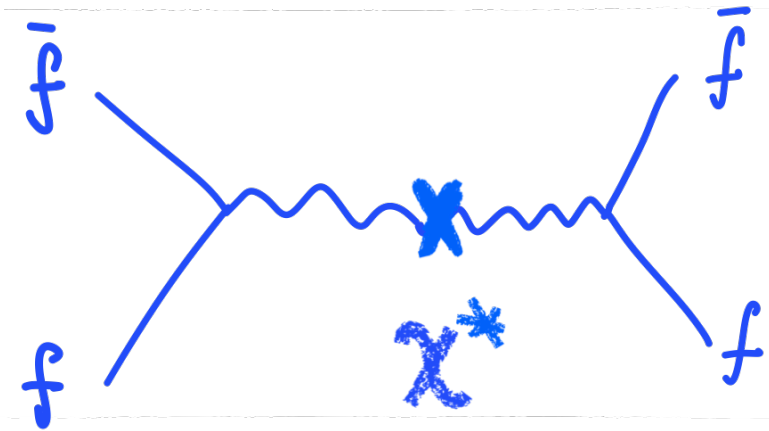
Electroweak Dark Matter: LSP (+NLSP)



$$pp \text{ or } \ell^+ \ell^- \rightarrow f\bar{f}, W^+W^-$$

PRECISION

TOTAL CROSS-SECTION

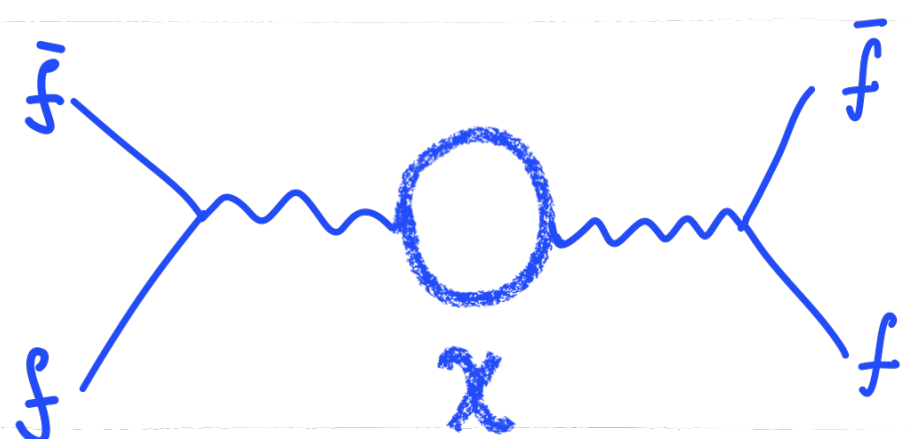
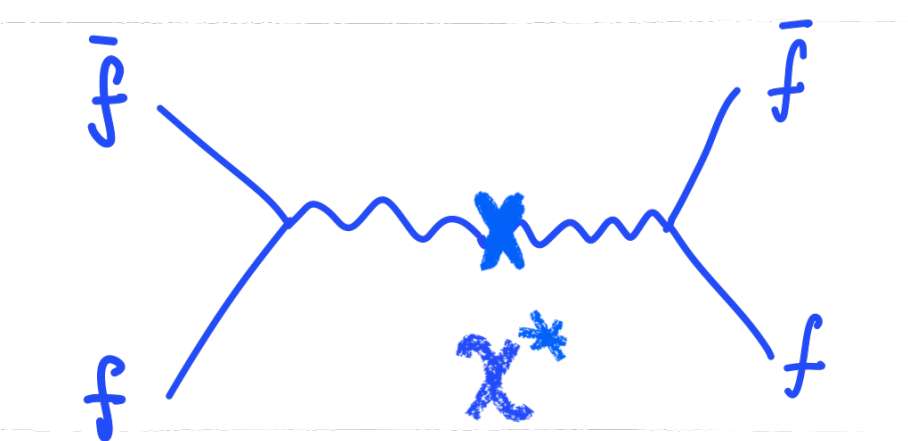
 χ is light new physics

 χ is heavy new physics


- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach

$$pp \text{ or } \ell^+ \ell^- \rightarrow f\bar{f}, W^+W^-$$

PRECISION

TOTAL CROSS-SECTION

 χ is light new physics χ is heavy new physics

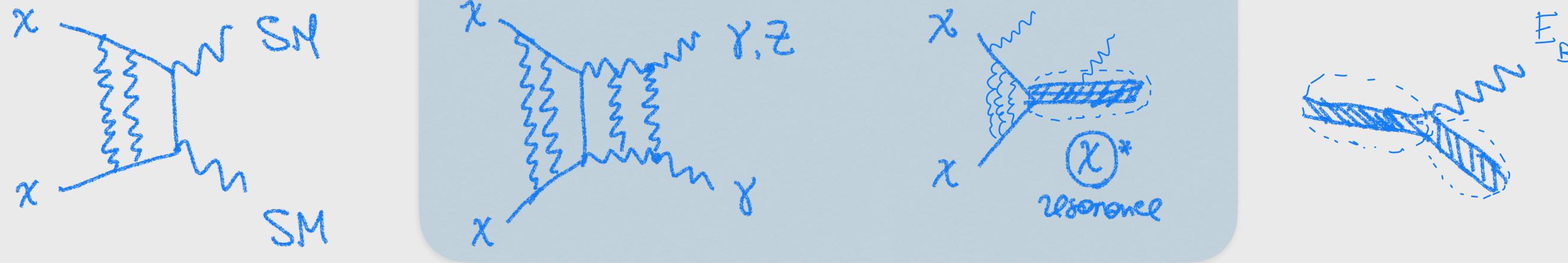
- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach

χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1, 2, 1/2)_{DF}$	1.1	–	–	–	0.4	0.6
$(1, 3, \epsilon)_{CS}$	1.6	–	–	–	0.2	0.2
$(1, 3, \epsilon)_{DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1, 3, 0)_{MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1, 5, \epsilon)_{CS}^*$	6.6	0.2	0.4	1.0	0.5 & [0.7, 1.6]	1.6
$(1, 5, \epsilon)_{DF}^*$	6.6	1.5	2.8	7.1	3.9	11
$(1, 5, 0)_{MF}$	14	0.9	1.8	4.4	2.9	3.5 & [5.1, 8.7]
$(1, 7, \epsilon)_{CS}$	54	0.6	1.3	3.2	2.4	2.5 & [3.5, 7.4]
$(1, 7, \epsilon)_{MF}$	48	2.1	4.0	11	6.4	18

- Comprehensive tool to explore new electroweak particles
- Can probe valid dark matter candidates!

INDIRECT DETECTION

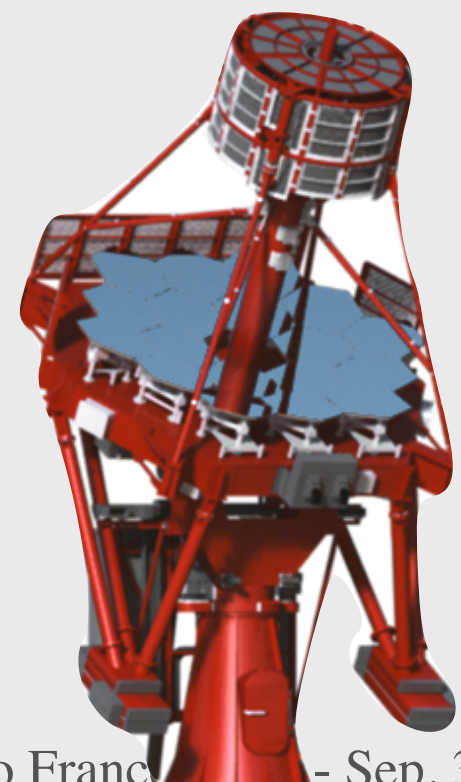
Thermal mass "lottery"



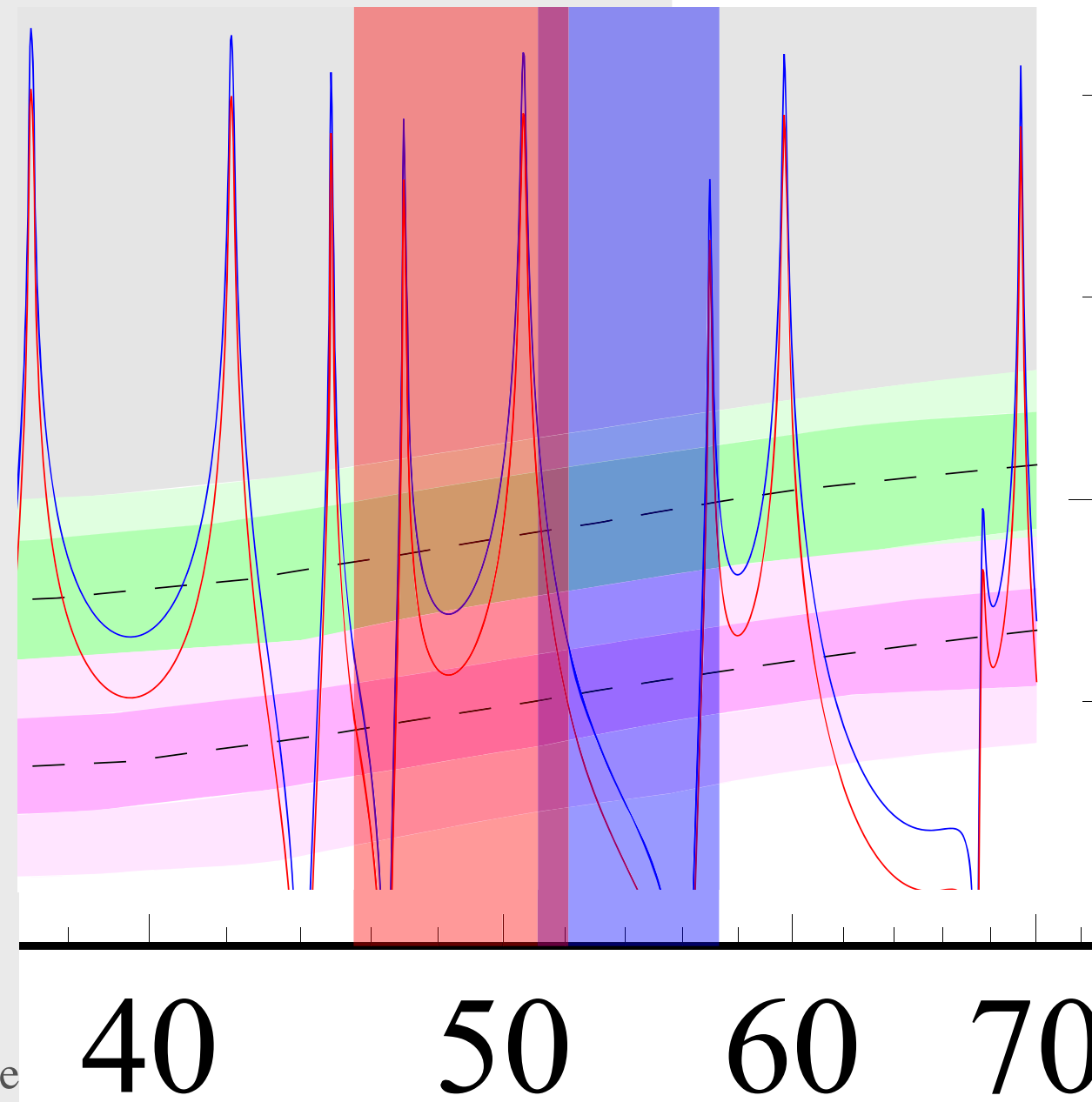
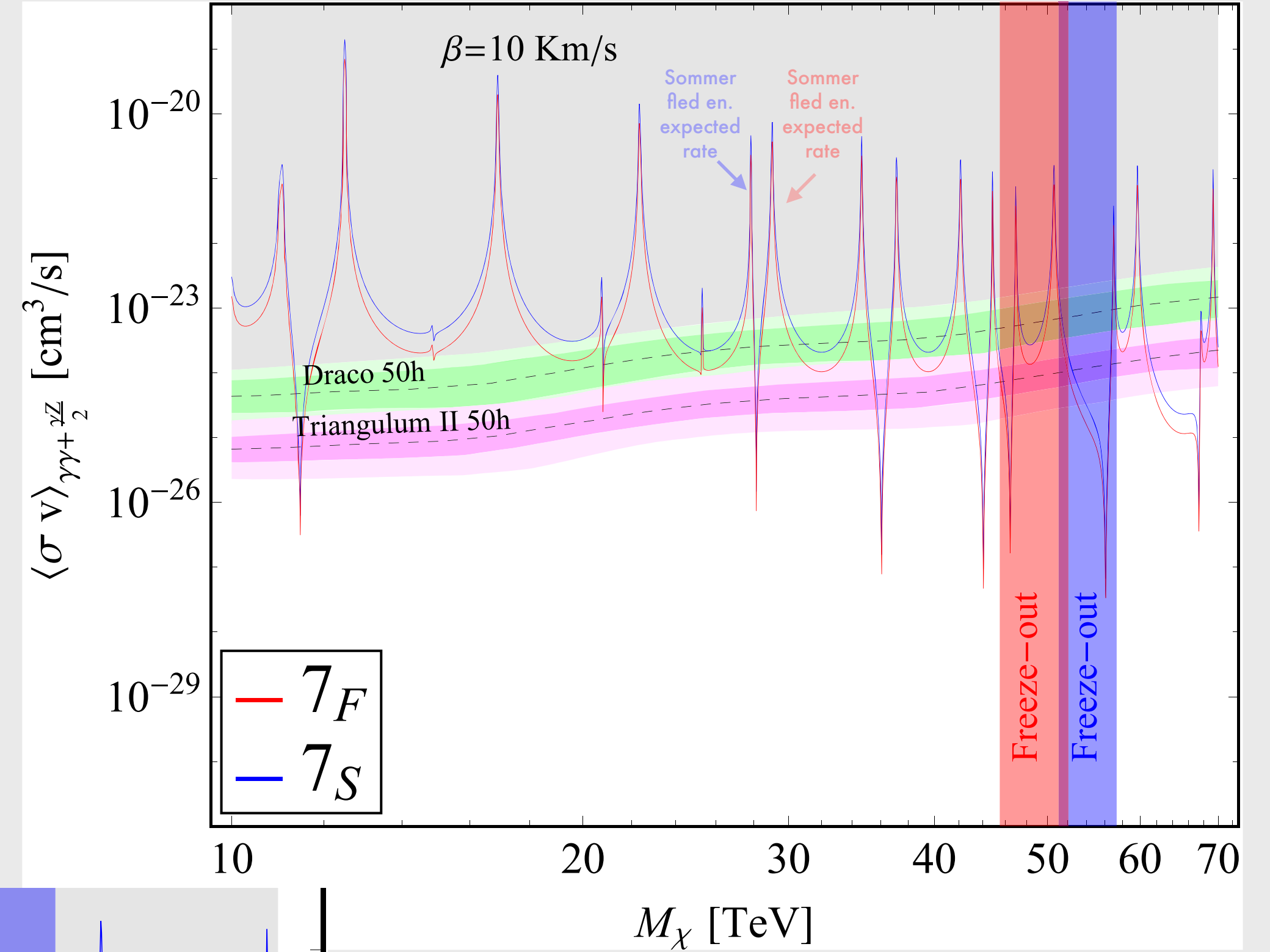
Annihilation in the astrophysical environment result in high-energy SM particle, which can be detector by cosmic rays observatories.

The signature depends on DM mass, possible resonant bound states formation and DM density profile

An excess on monochromatic multi-TeV photons would be quite convincing evidence of DM. The model can be even tested by the presence of multiple "lines" from bound states annihilations and lower energy de-excitation



2030s
 up to 300 TeV, $\frac{\Delta E}{E} \sim 10\%$



thermal mass "lottery": if the actual mass varies within the current theoretical uncertainty the signal strength changes by orders of magnitude!

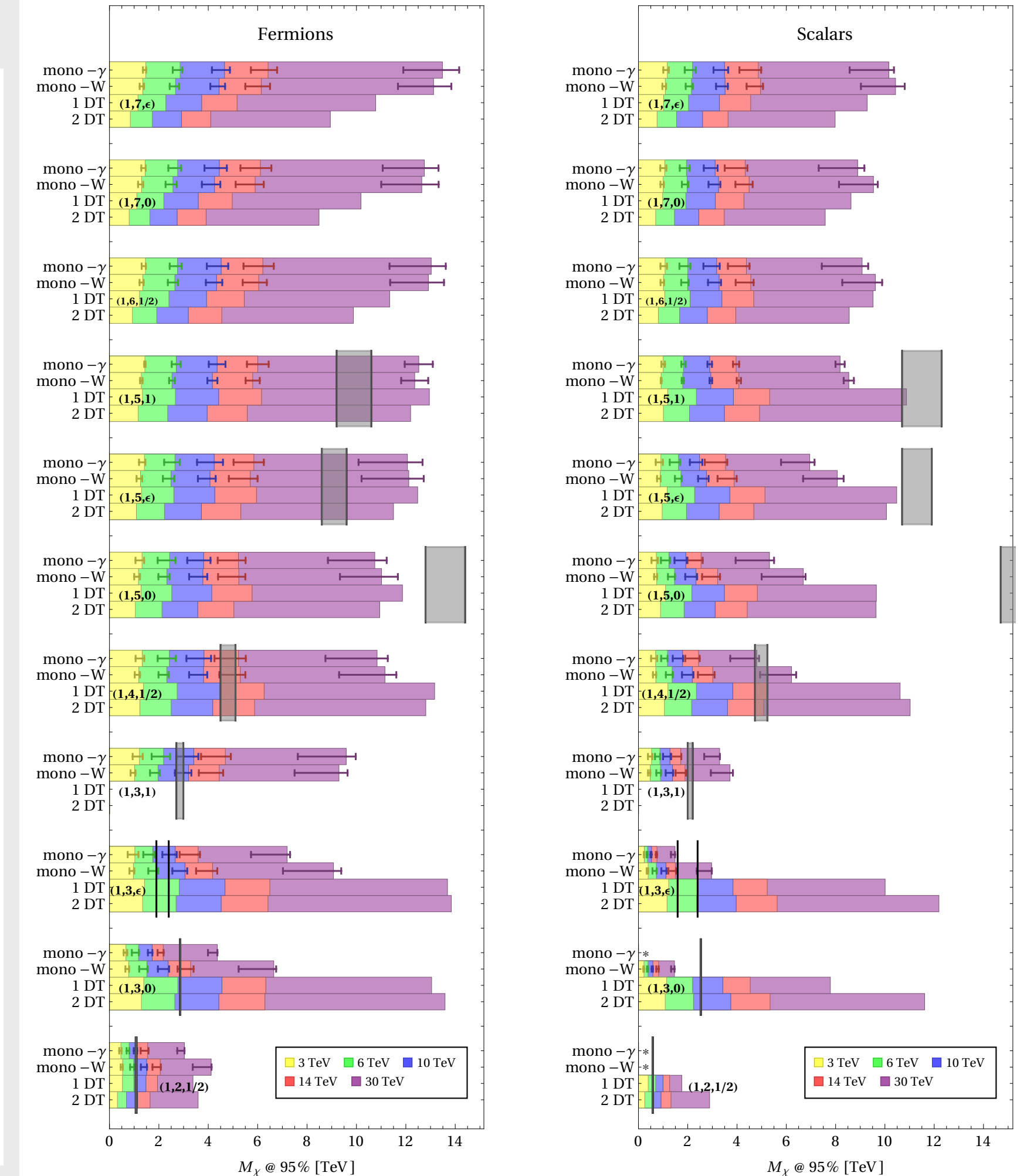
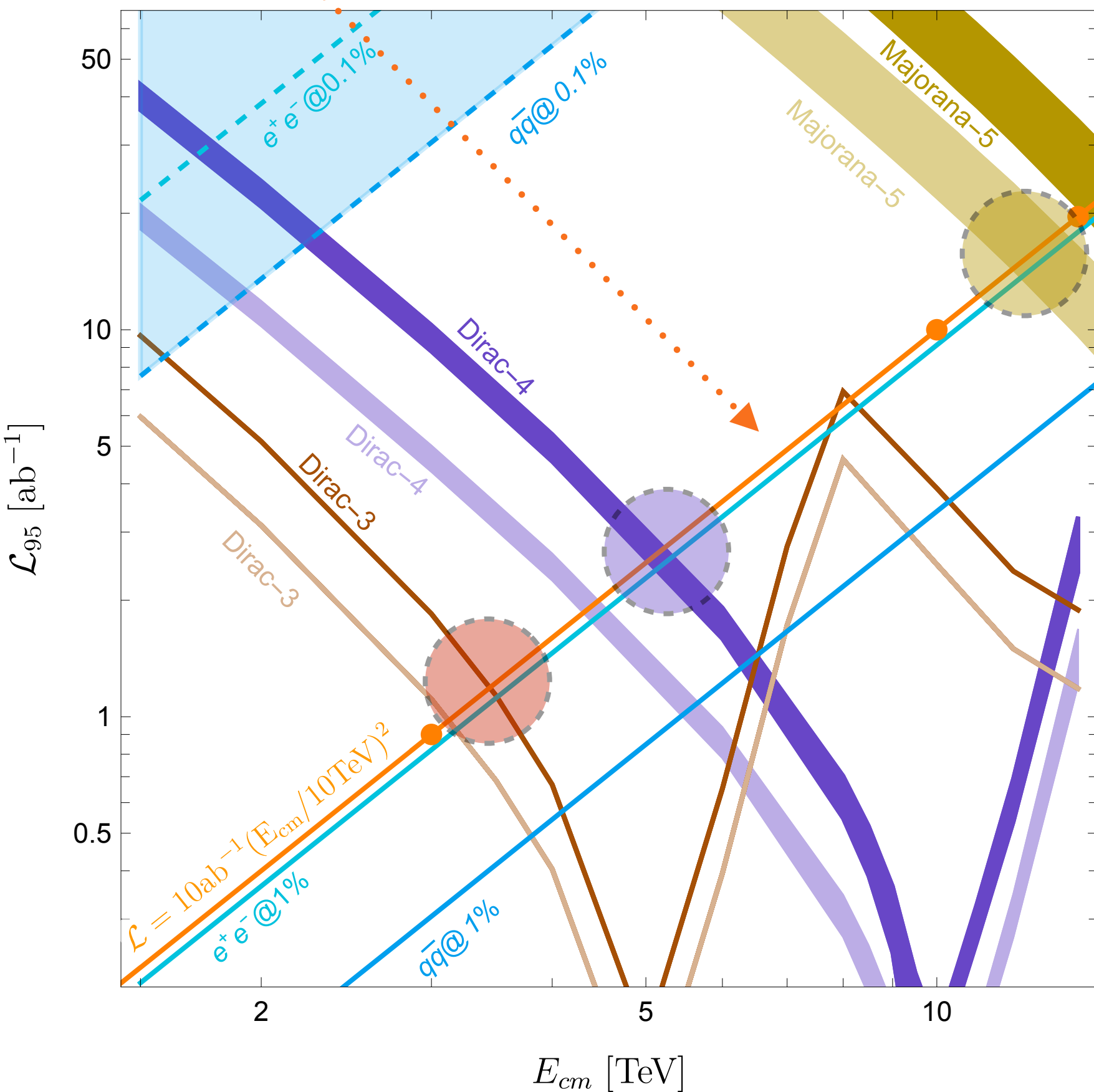
$$\ell^+ \ell^- \rightarrow f\bar{f}, Zh, W^+W^-, Wff'$$

$$\mu^+ \mu^- \rightarrow \chi\chi + X$$

SM

PRECISION MEASUREMENTS

$$\mathcal{L} = 10 \text{ ab}^{-1} \cdot (E_{com}/10 \text{ TeV})^2$$



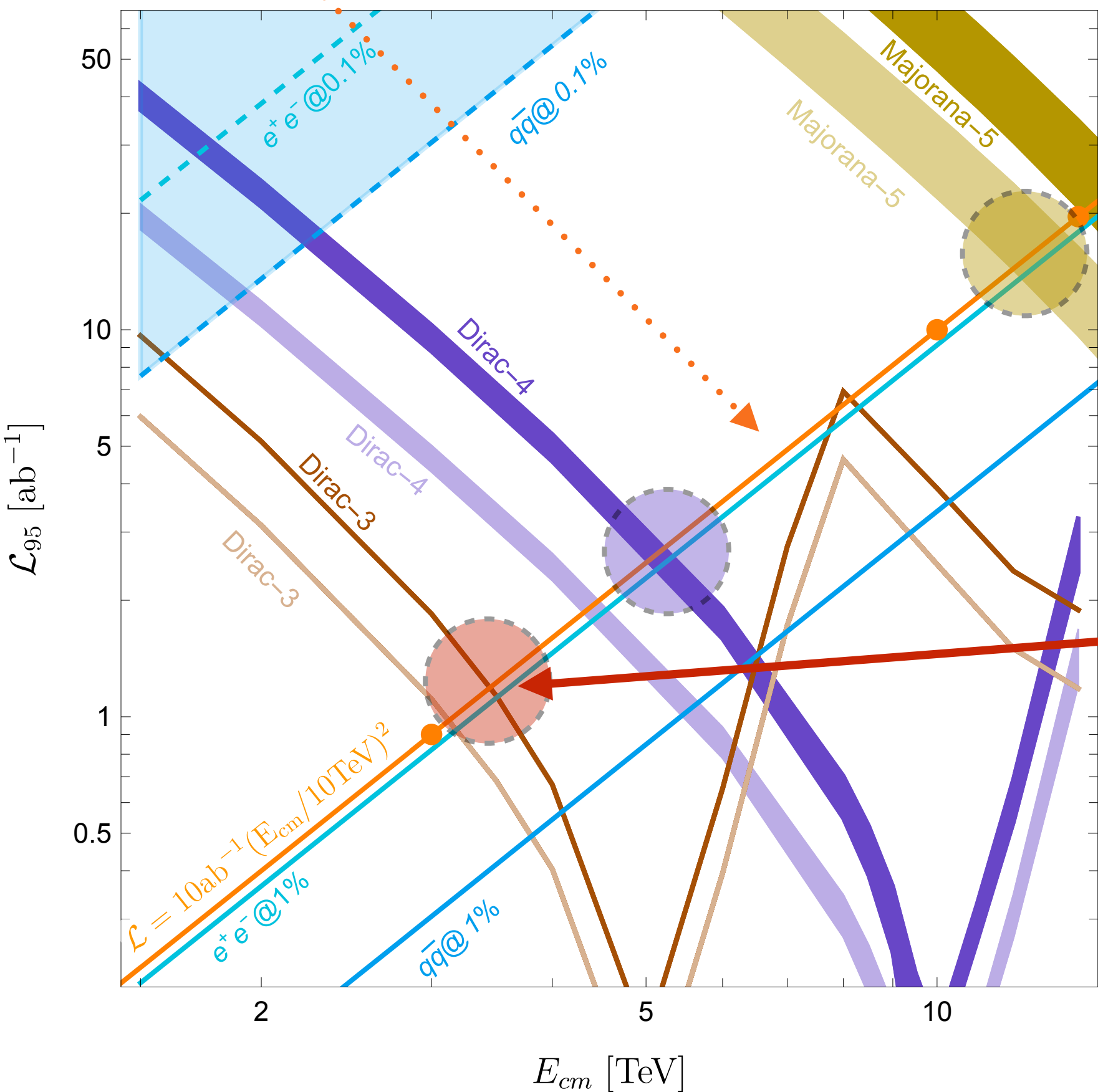
$$\ell^+ \ell^- \rightarrow f\bar{f}, Zh, W^+W^-, Wff'$$

$$\mu^+ \mu^- \rightarrow \chi\chi + X$$

SM

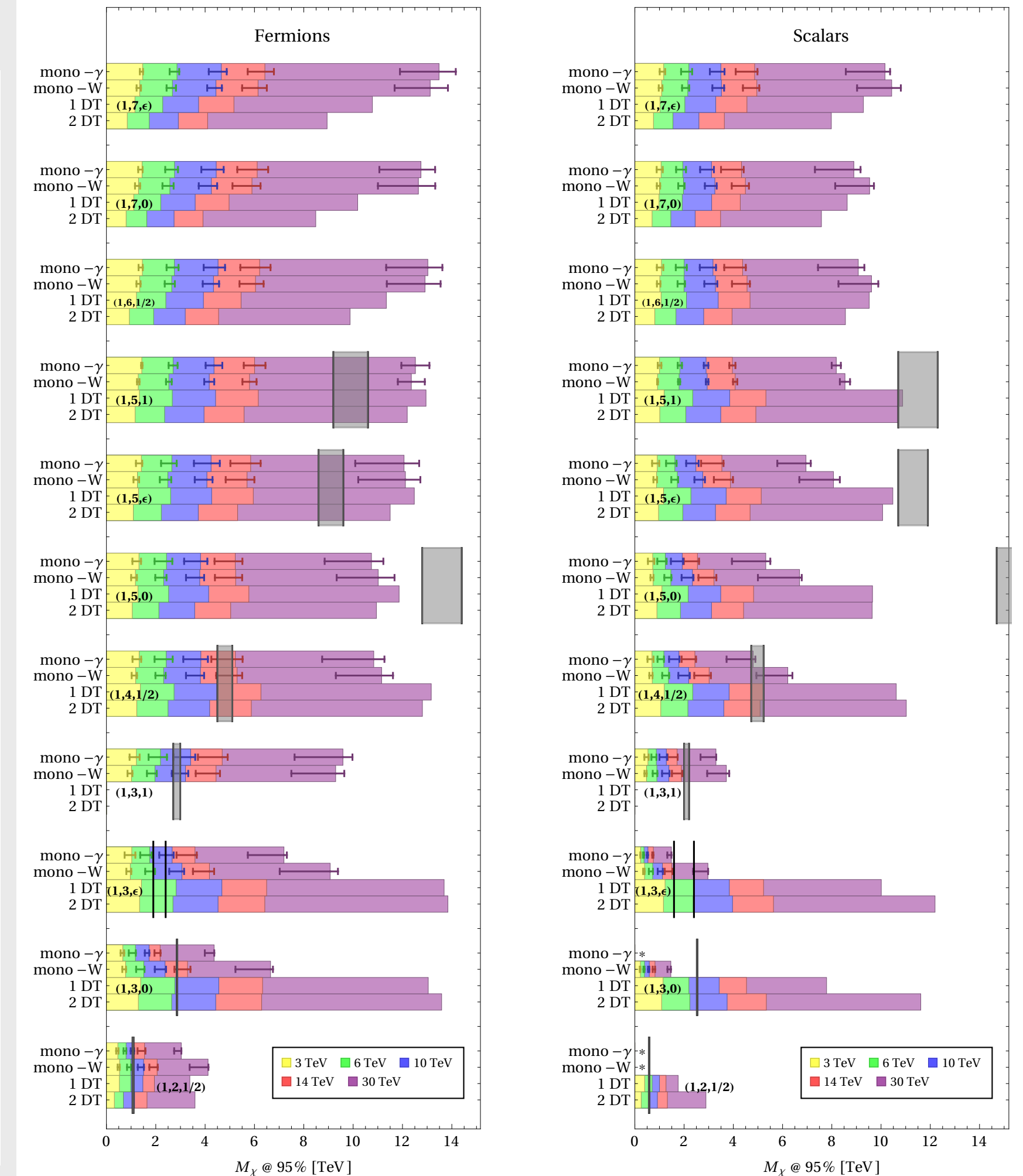
PRECISION MEASUREMENTS

$$\mathcal{L} = 10 \text{ ab}^{-1} \cdot (E_{com}/10 \text{ TeV})^2$$



$(3,0)$ Majorana
 $(3, \epsilon)$ Dirac
 $(2, \frac{1}{2})$ Dirac

$\ell^+ \ell^- 3 \text{ TeV } 1 \text{ ab}^{-1}$



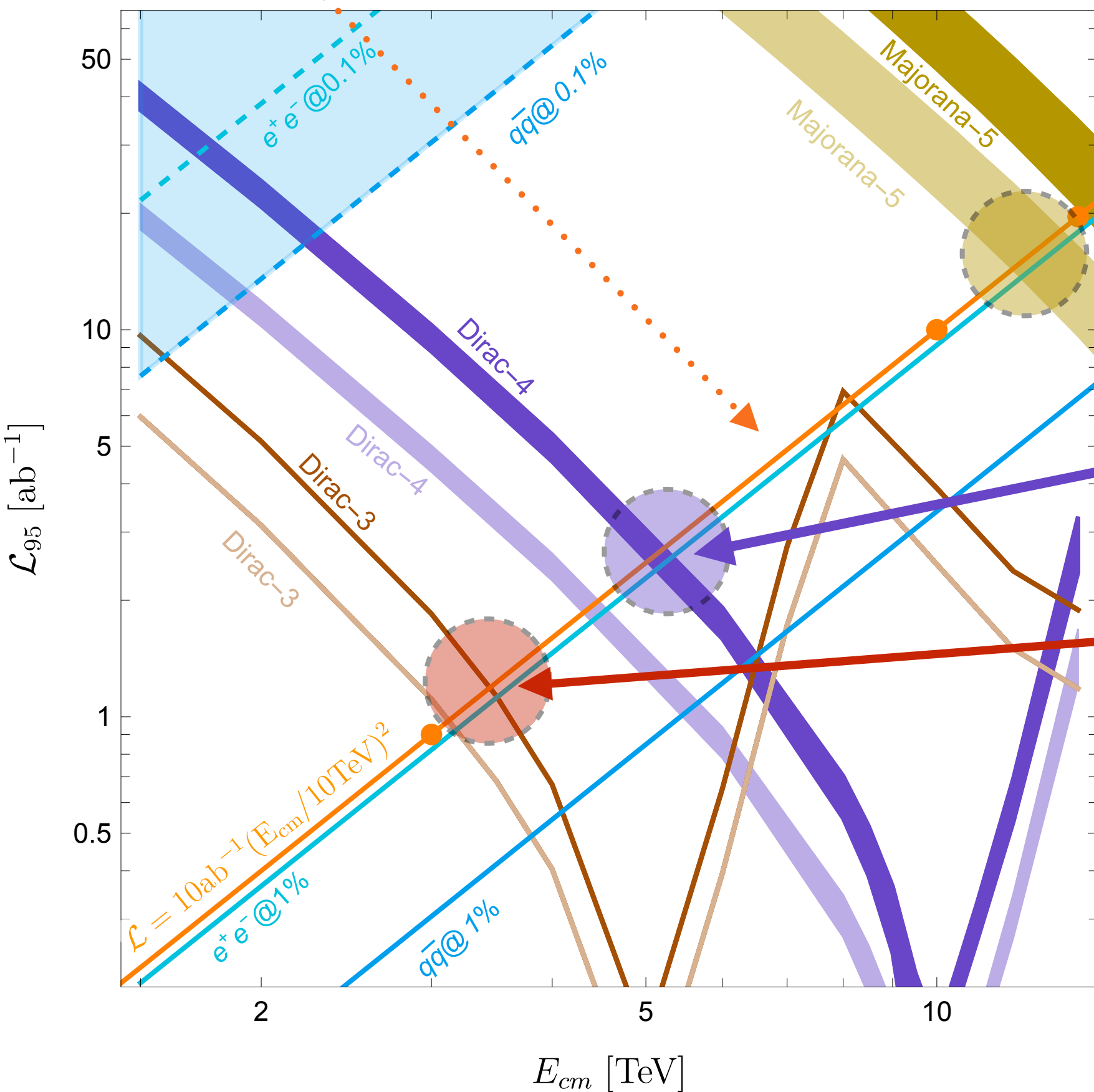
$$\ell^+ \ell^- \rightarrow f\bar{f}, Zh, W^+W^-, Wff'$$

$$\mu^+ \mu^- \rightarrow \chi\chi + X$$

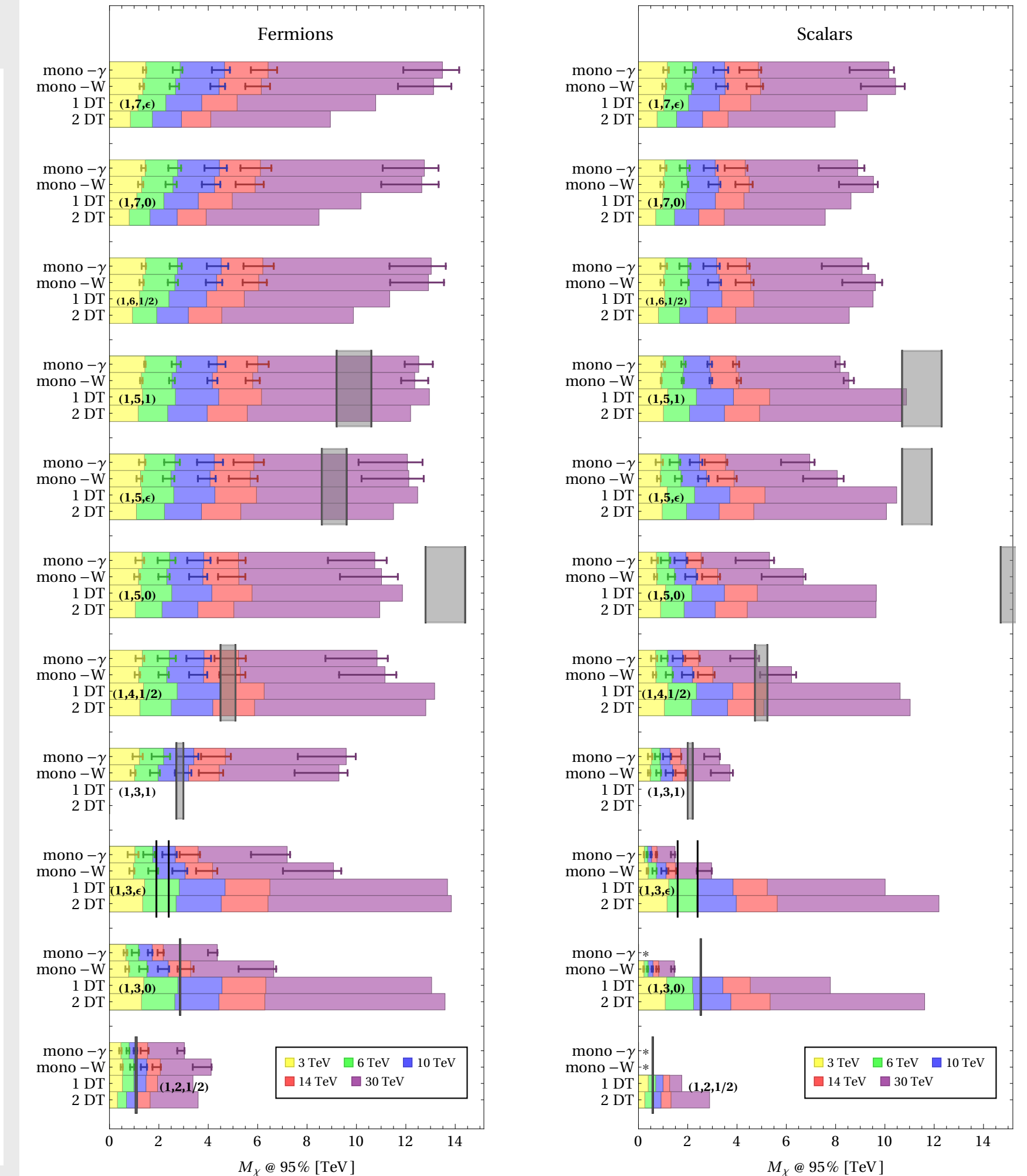
SM

PRECISION MEASUREMENTS

$$\mathcal{L} = 10 \text{ ab}^{-1} \cdot (E_{com}/10 \text{ TeV})^2$$



$(4, \frac{1}{2})$ Dirac $\ell^+ \ell^- 10 \text{ TeV } 10 \text{ ab}^{-1}$
 $(3, 0)$ Majorana
 $(3, \epsilon)$ Dirac $\ell^+ \ell^- 3 \text{ TeV } 1 \text{ ab}^{-1}$
 $(2, \frac{1}{2})$ Dirac



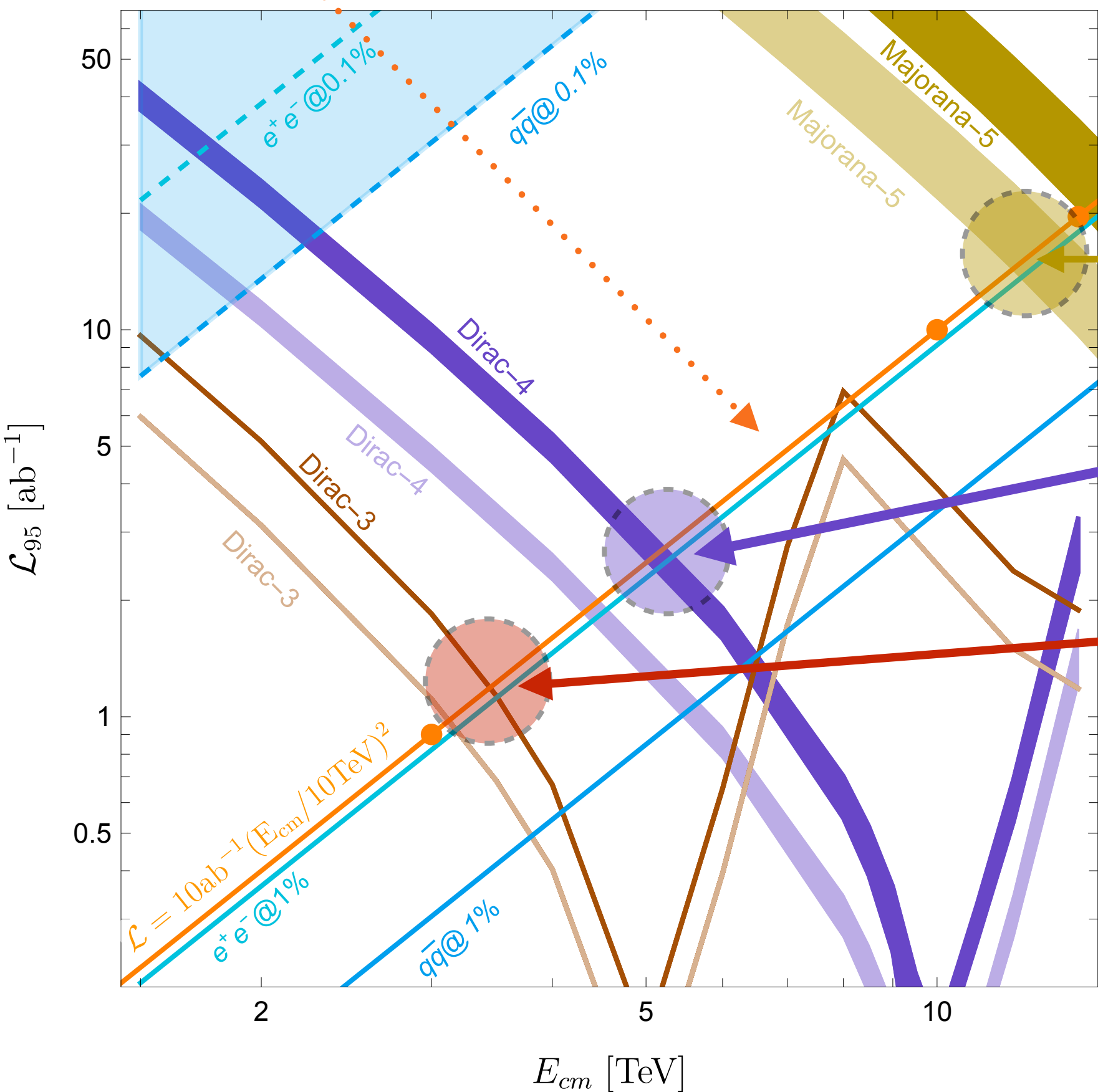
$$\ell^+ \ell^- \rightarrow f\bar{f}, Zh, W^+W^-, Wff'$$

$$\mu^+ \mu^- \rightarrow \chi\chi + X$$

SM

PRECISION MEASUREMENTS

$$\mathcal{L} = 10 \text{ ab}^{-1} \cdot (E_{com}/10 \text{ TeV})^2$$



$(7,0)_{Majorana}$

$(7,\epsilon)_{Dirac}$ $\ell^+ \ell^- 10+ \text{ TeV } 10+ \text{ ab}^{-1}$

$(5,0)_{Majorana}$

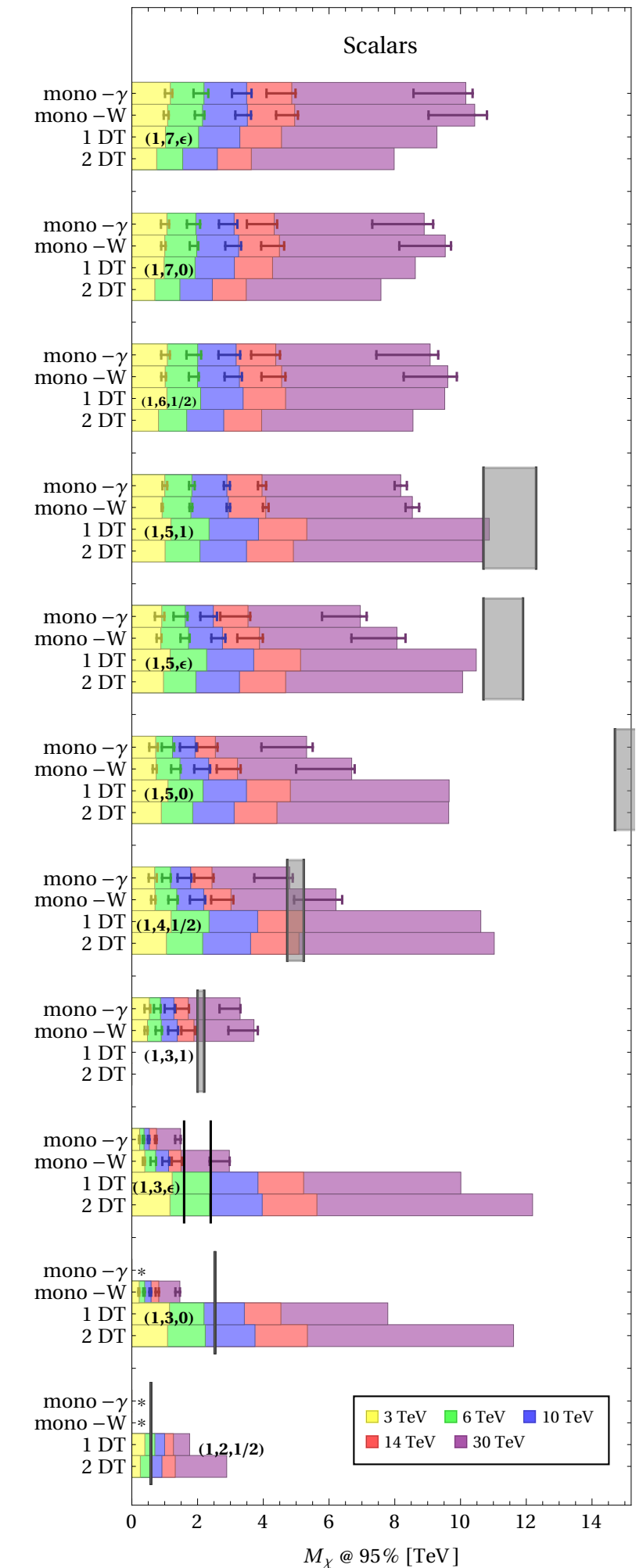
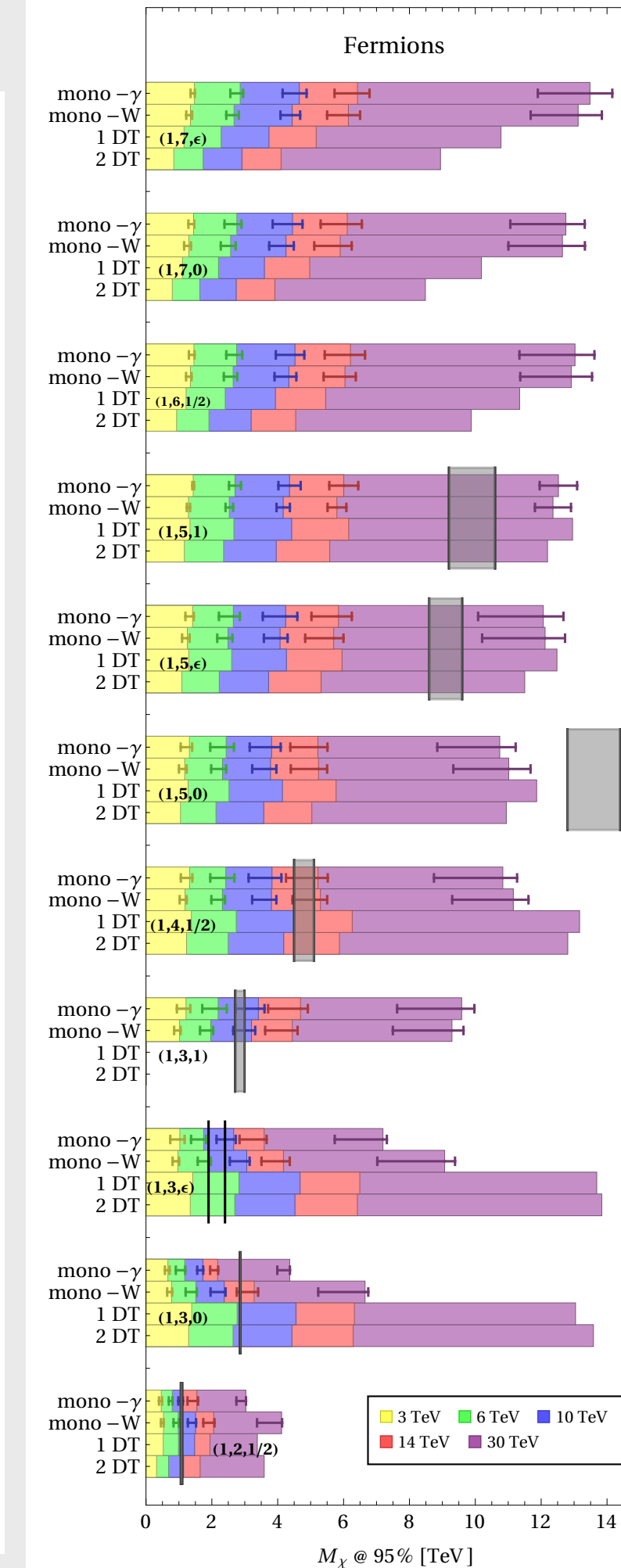
$(5,\epsilon)_{Dirac}$

$(4, \frac{1}{2})_{Dirac}$ $\ell^+ \ell^- 10 \text{ TeV } 10 \text{ ab}^{-1}$

$(3,0)_{Majorana}$

$(3,\epsilon)_{Dirac}$ $\ell^+ \ell^- 3 \text{ TeV } 1 \text{ ab}^{-1}$

$(2, \frac{1}{2})_{Dirac}$



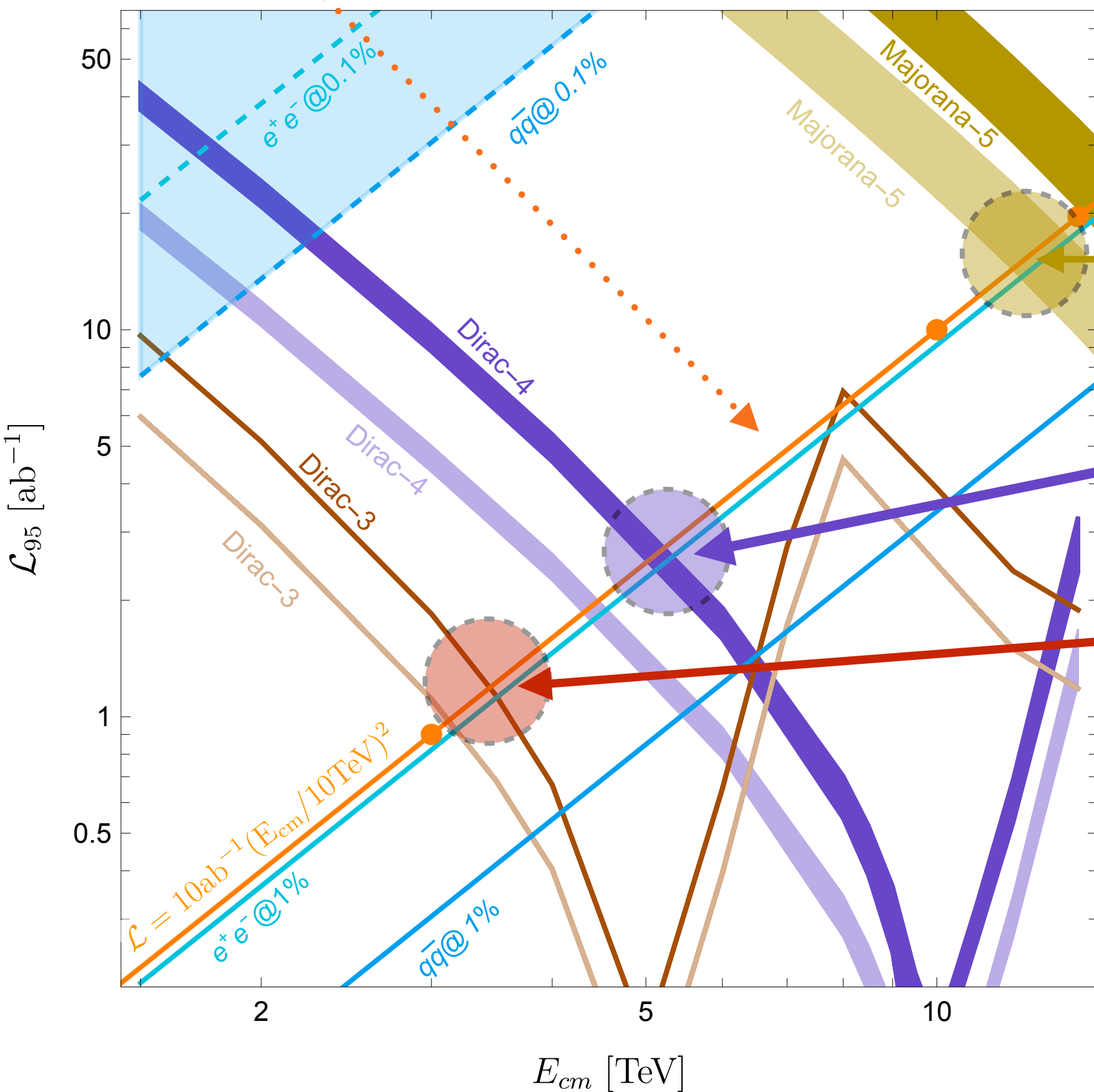
$$\ell^+ \ell^- \rightarrow f\bar{f}, Zh, W^+W^-, Wff'$$

$$\mu^+ \mu^- \rightarrow \chi\chi + X$$

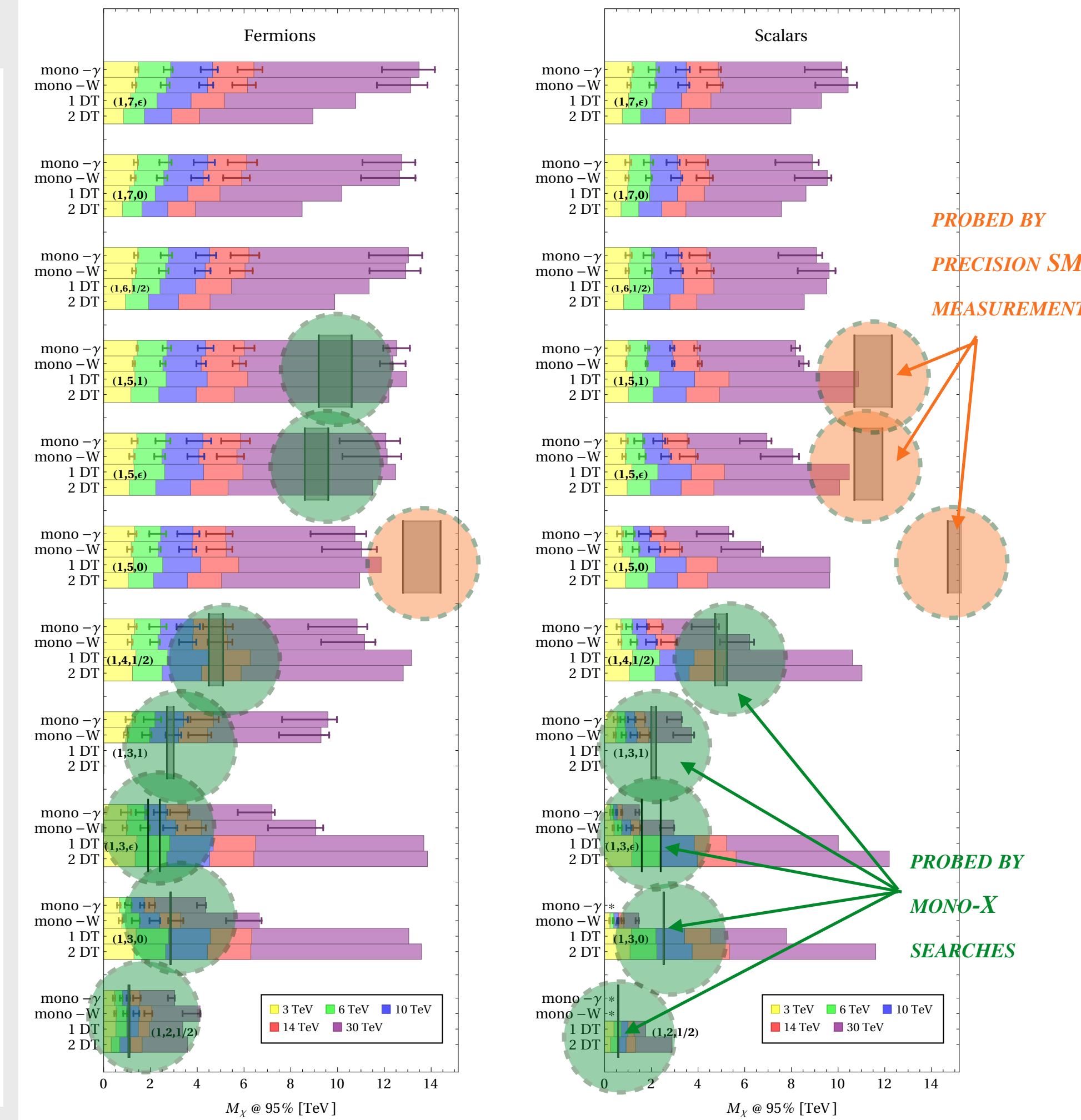
SM

PRECISION MEASUREMENTS








$$\mathcal{L} = 10 \text{ ab}^{-1} \cdot (E_{com}/10 \text{ TeV})^2$$






- $(7,0)_{Majorana}$
- $(7,\epsilon)_{Dirac}$ $\ell^+ \ell^- 10+ \text{ TeV } 10+ \text{ ab}^{-1}$
- $(5,0)_{Majorana}$
- $(5,\epsilon)_{Dirac}$
- $(4, \frac{1}{2})_{Dirac}$ $\ell^+ \ell^- 10 \text{ TeV } 10 \text{ ab}^{-1}$
- $(3,0)_{Majorana}$
- $(3,\epsilon)_{Dirac}$ $\ell^+ \ell^- 3 \text{ TeV } 1 \text{ ab}^{-1}$
- $(2, \frac{1}{2})_{Dirac}$



Open Questions on the “big picture” on fundamental physics as of 2020s

-  • what is the dark matter in the Universe?
-  • why QCD does not violate CP?
-  • how have baryons originated in the early Universe?
-  • what originates flavor mixing and fermions masses?
-  • what gives mass to neutrinos?
- EFT*  • why gravity and weak interactions are so different?
- EFT*  • what fixes the cosmological constant?

-  Need new matter (or even bigger modifications to the SM)
-  Adjusting one SM parameter might do
-  Adjusting several SM parameters might do
- EFT* Separation of scales as an organizing principle might fail

EACH of these issues one day will teach us a lesson

Open Questions on the “big picture” on fundamental physics as of 2020s

?	• what is the dark matter in the Universe?	✓	✓	WEAK INTERACTIONS
●	• why QCD does not violate CP?	✓		STRONG INTERACTIONS
●	• how have baryons originated in the early Universe?	✓		NEED SOME COSMOLOGY INPUTS
⚙	• what originates flavor mixing and fermions masses?	✓		
⚙	• what gives mass to neutrinos?	✓		
<i>EFT</i>	●	• why gravity and weak interactions are so different?	✓	
<i>EFT</i>	●	• what fixes the cosmological constant?	✓	