New developments in the S3 symmetric model

CATALINA ESPINOZA*

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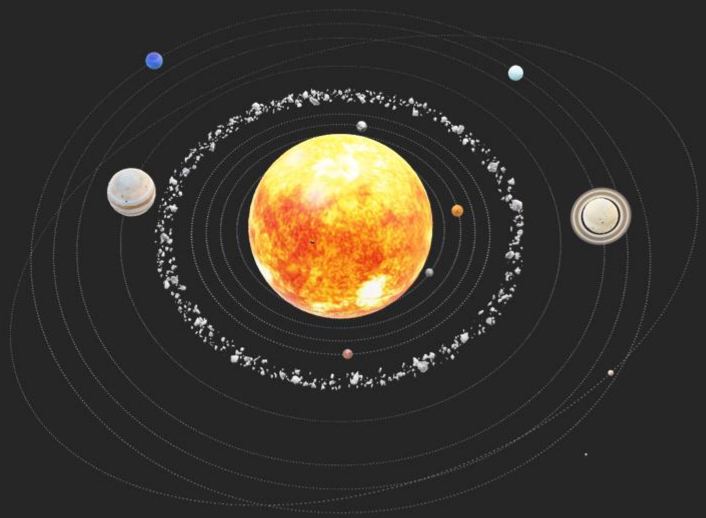
*In collaboration with M. Mondragón

Summary

- Motivation
- Phenomenological analysis strategy for BSM models
- The S3 symmetric model
- Adding a DM sector
- Phenomenology
- Conclusions

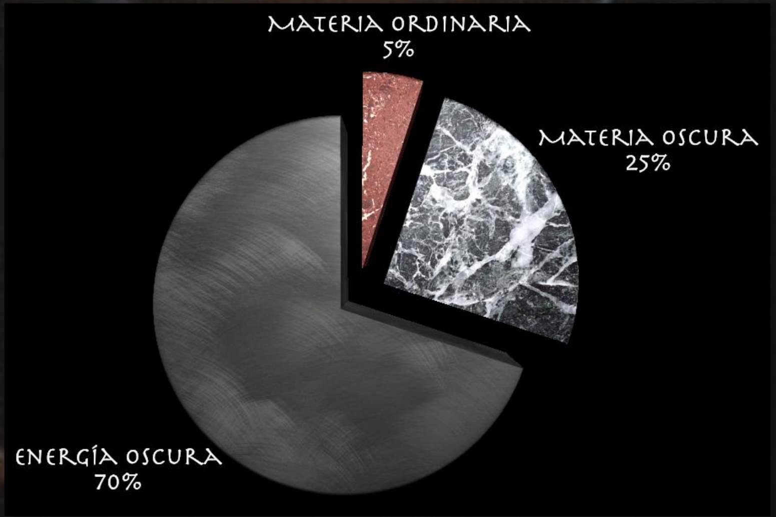


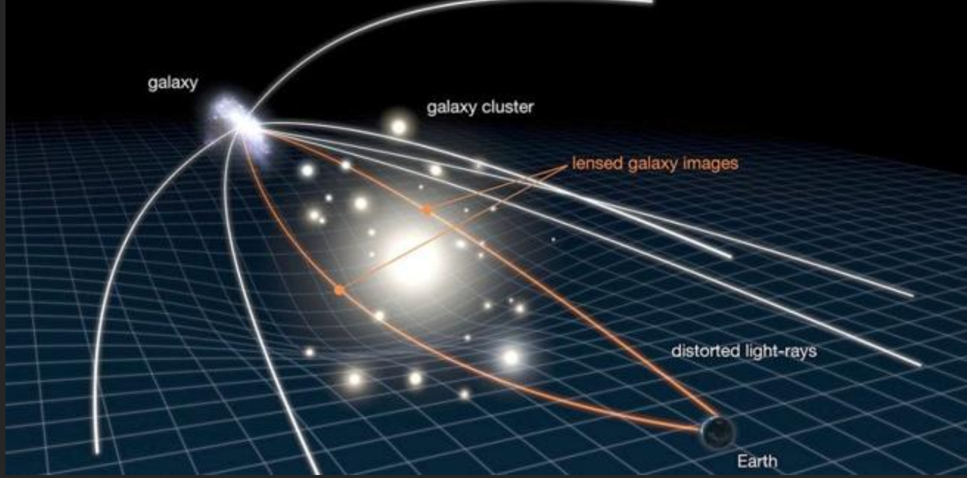
Motivation

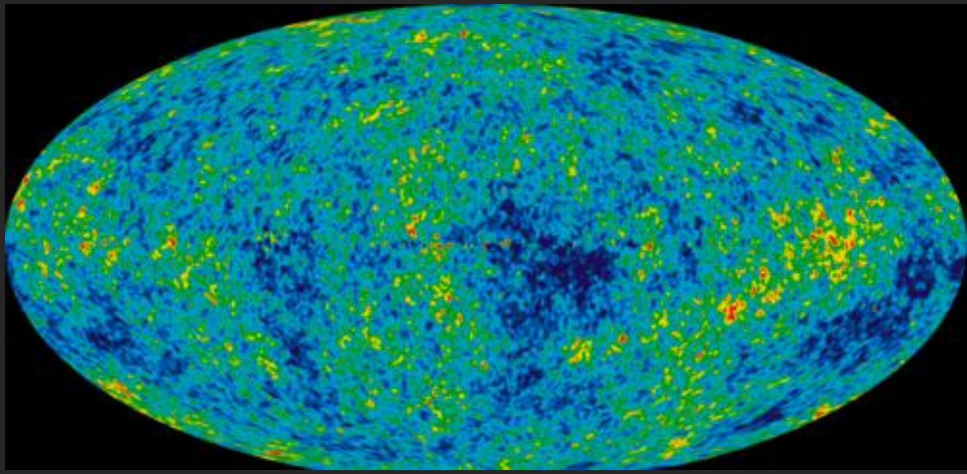
Evidence of Dark Matter and Dark Energy

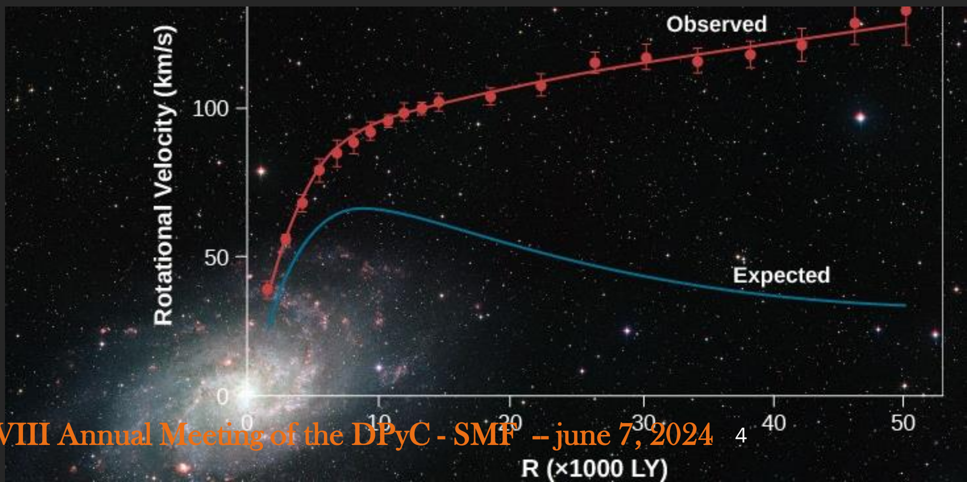
- ❑ The observational evidence of **Dark Matter** and Dark Energy ranges from rotational velocities of stars at the edges of galaxies, all the way through to the Cosmic Microwave Background anisotropies.

- ❑ The evidence indicates that dark matter makes up about 26.8% of the total mass-energy density of the Universe.





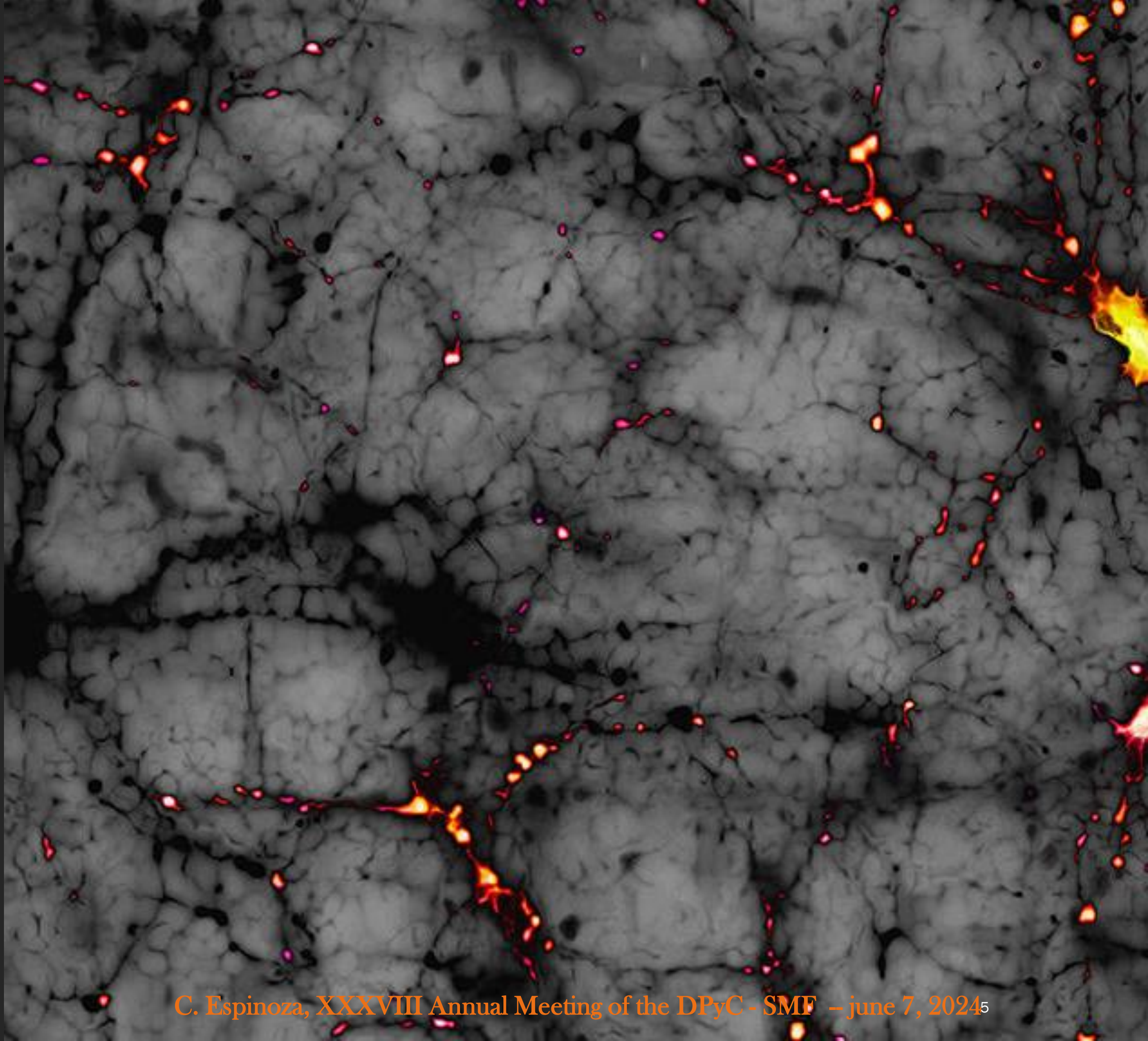




What is Dark Matter ...?

- The evidence for the existence of dark matter is overwhelming.
- Dark matter is invisible to us, but its effects on the Universe are clear.
- **We still do not know what dark matter is**, but we are working to understand it better.
- We'll focus on BSM theories where dark matter is an elementary particle

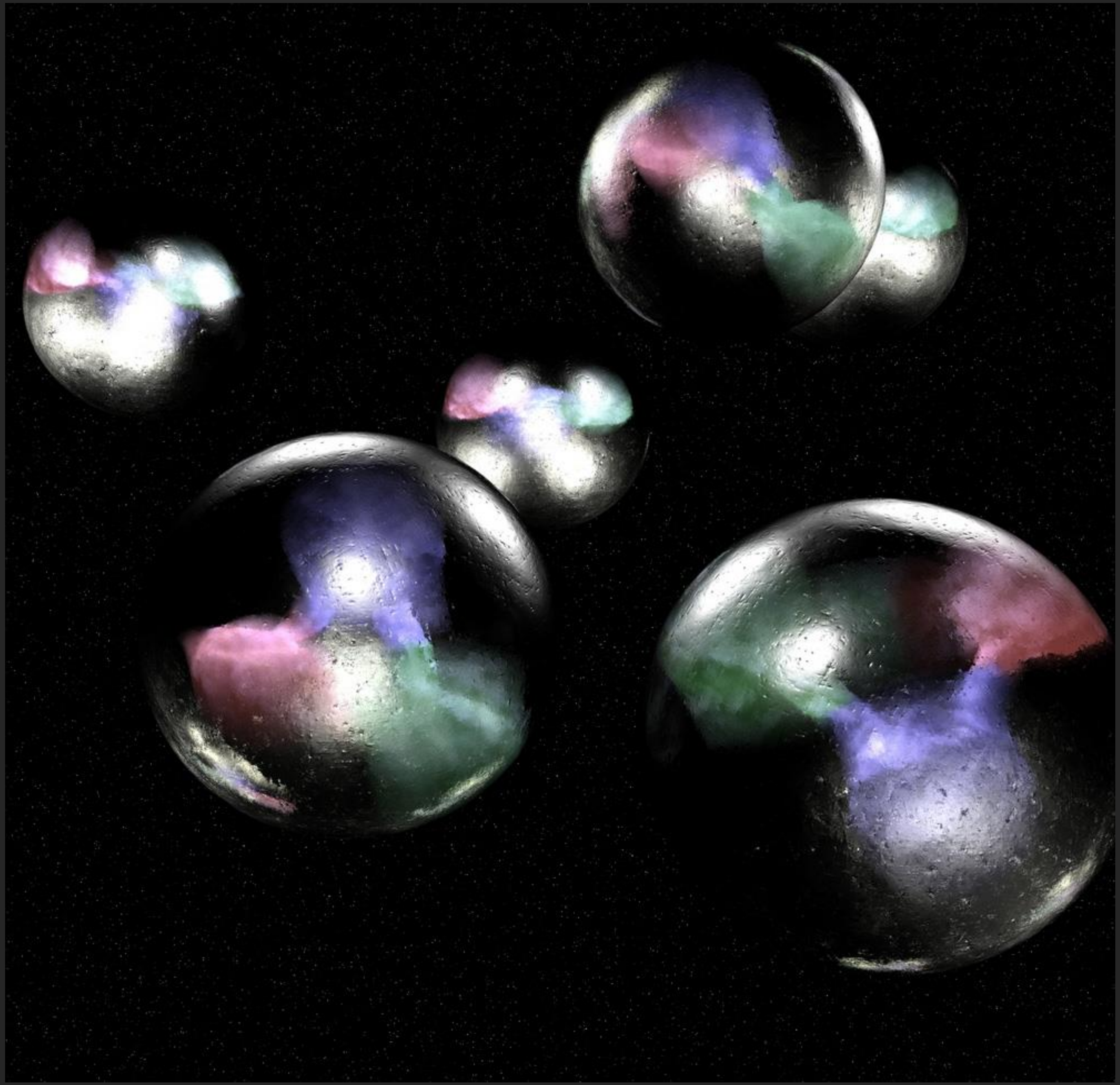
  → Corpuscular hypothesis.



The Standard Model of Elementary Particles

- The Standard Model (SM) is a theory that describes the basic building blocks of matter and the forces that govern their interactions.

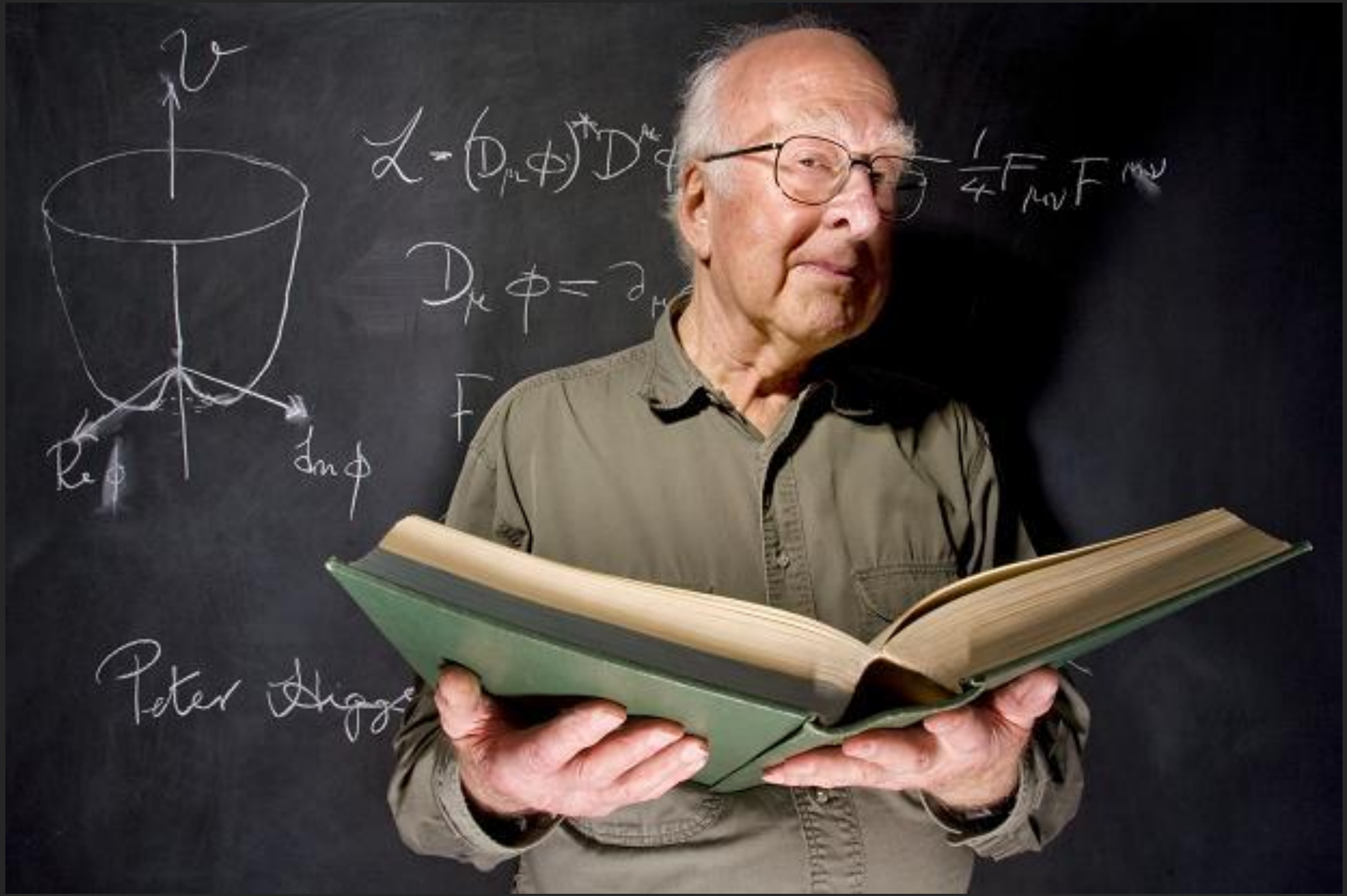
- The Standard Model has been extremely successful in describing the behavior of elementary particles and their interactions.



Comments

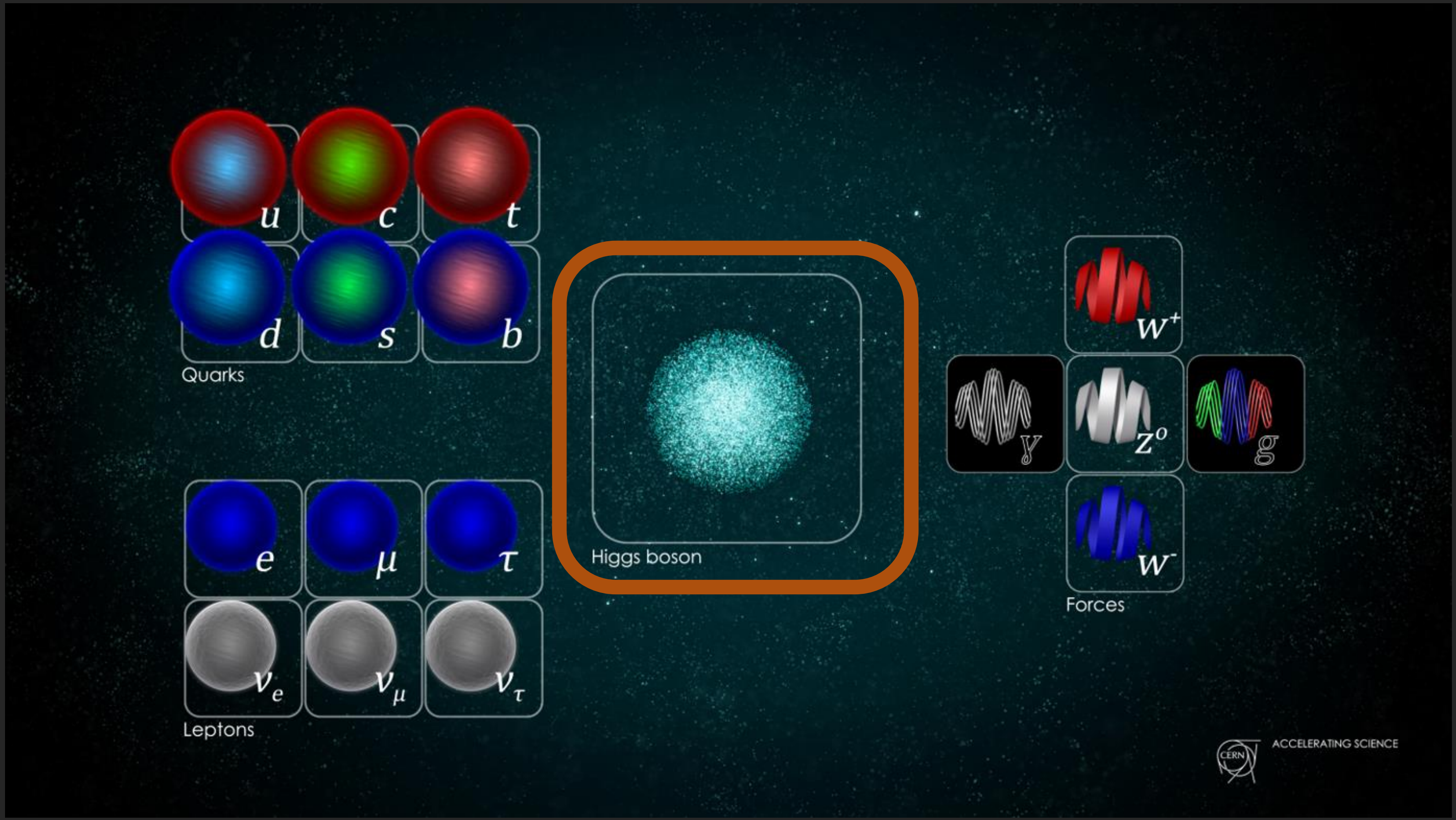
- The Standard Model has been tested and verified through countless experiments, including those performed at particle accelerators such as the Large Hadron Collider.

- One of the most significant successes of the Standard Model was the prediction and subsequent discovery of the Higgs boson.



The Higgs boson

- In the SM the nature of the Higgs boson is of particular importance since its existence ensures that the other elementary particles acquire masses in a consistent manner.
- However, it is well known that the SM cannot accommodate a particle of dark matter.

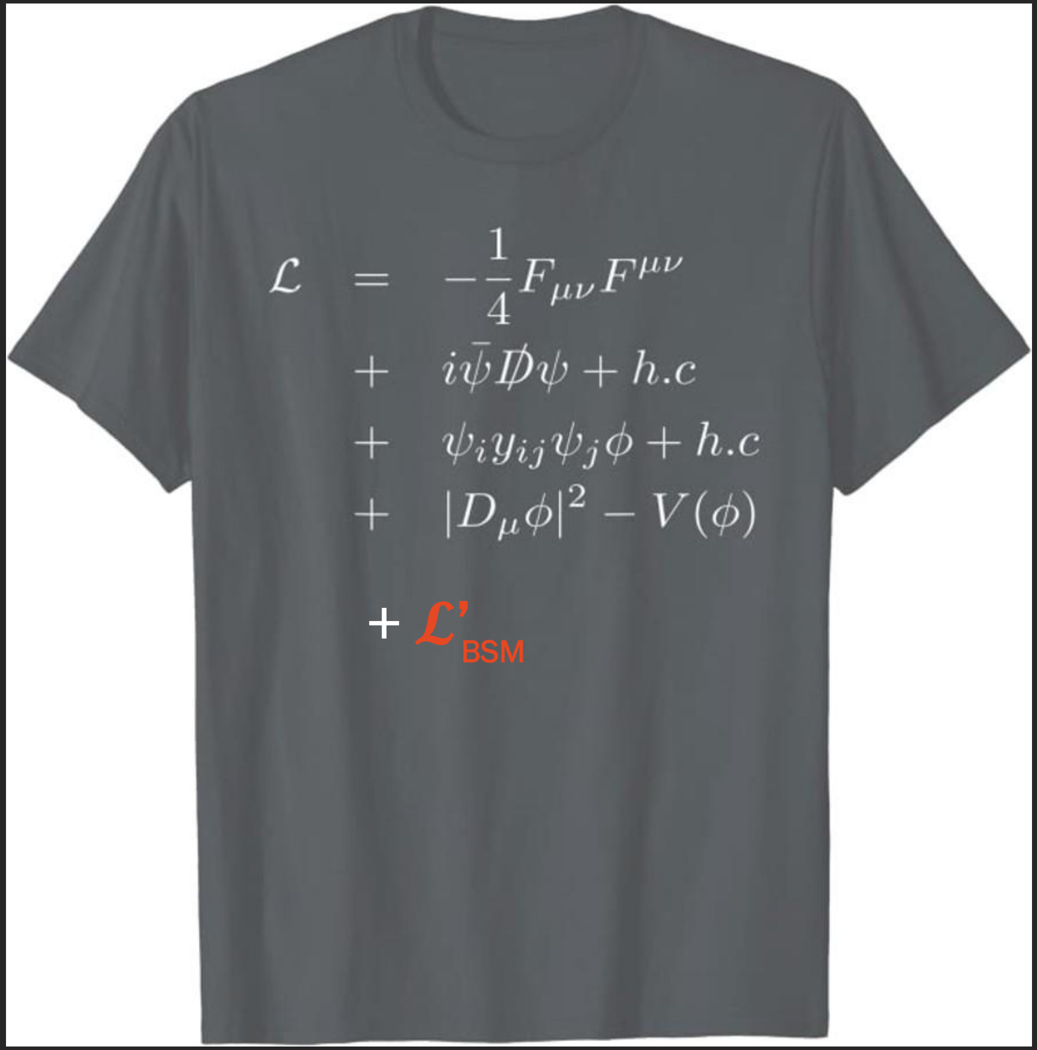


Model building

Defining a new model

- To accommodate DM it is therefore necessary to go 'Beyond the Standard Model' or BSM.

- We will focus in a 'bottom – up' approach, where:
  - A handful of **new fields and symmetries are added to the SM** with a 'phenomenological' motivation.

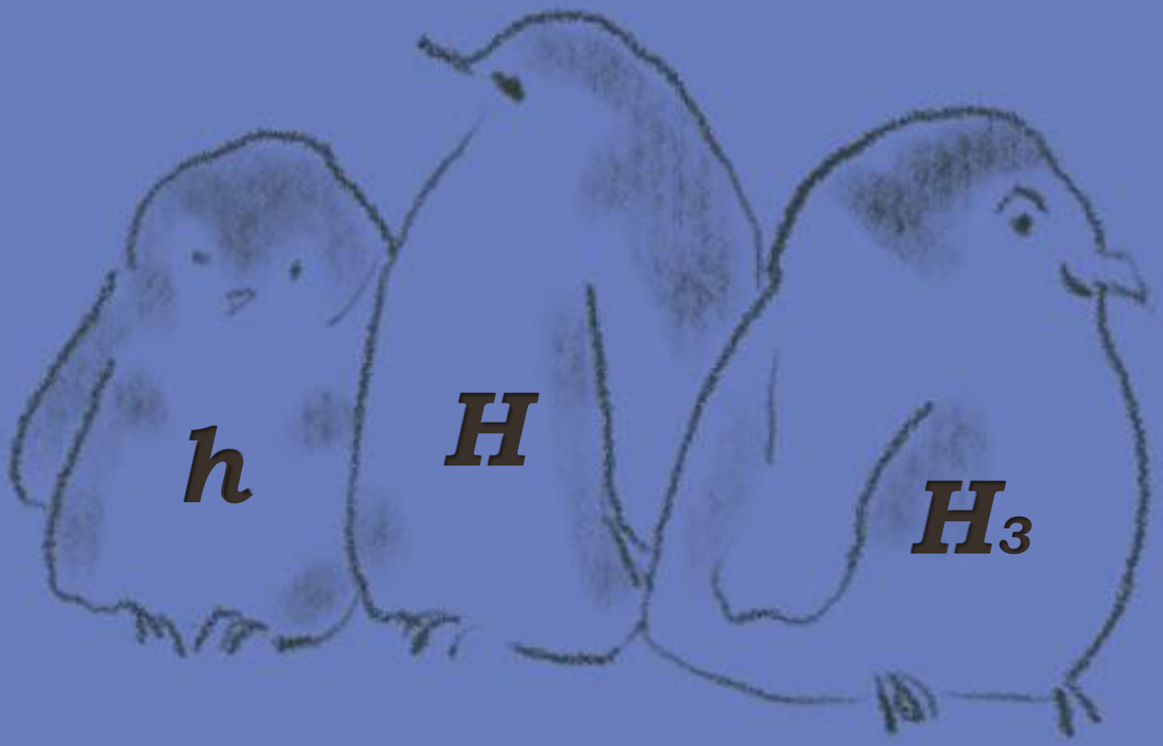


Additional BSM sectors

- In addition to the DM sector, there can be other sectors with new particles.
- Common examples are extended scalar sectors, where there are more Higgses than the one already discovered at CERN.

Multi-Higgs models

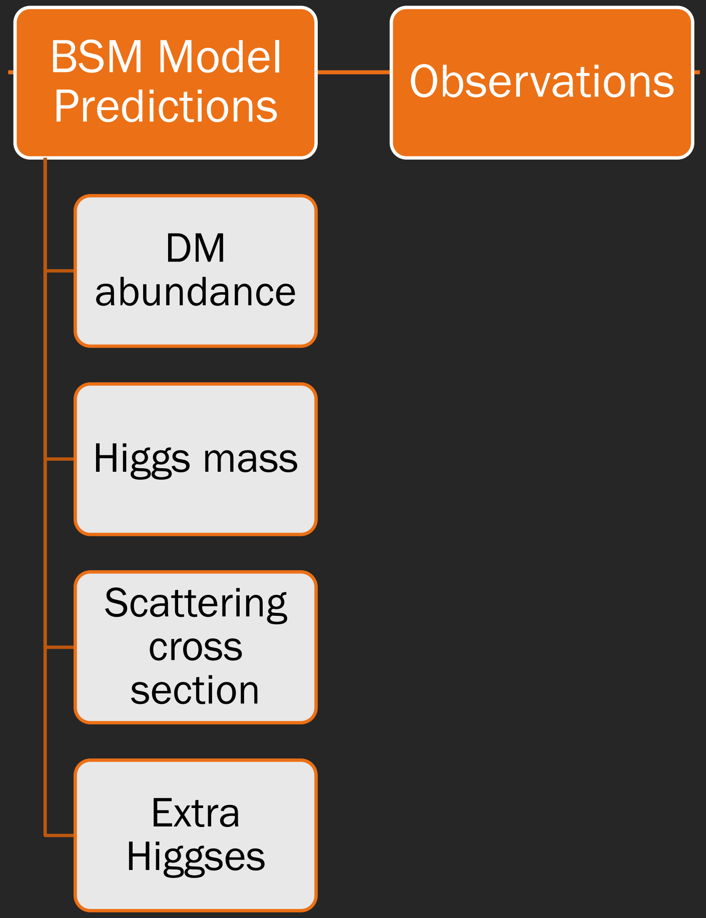
- In multi-Higgs models, there are more Higgs-like particles that might be discover in the LHC soon.
- For example, in a BSM model with 3 Higgs doublets, there are 2 physical scalars in addition to the SM Higgs h.
- These type of models have a very rich phenomenology.



Analysis strategy

Confronting BSM Model with observations

- From the BSM model predictions, the values of several observables are calculated.
- We compare these predictions with the experimental observations through statistical chi-square functions $\Delta\chi^2$.

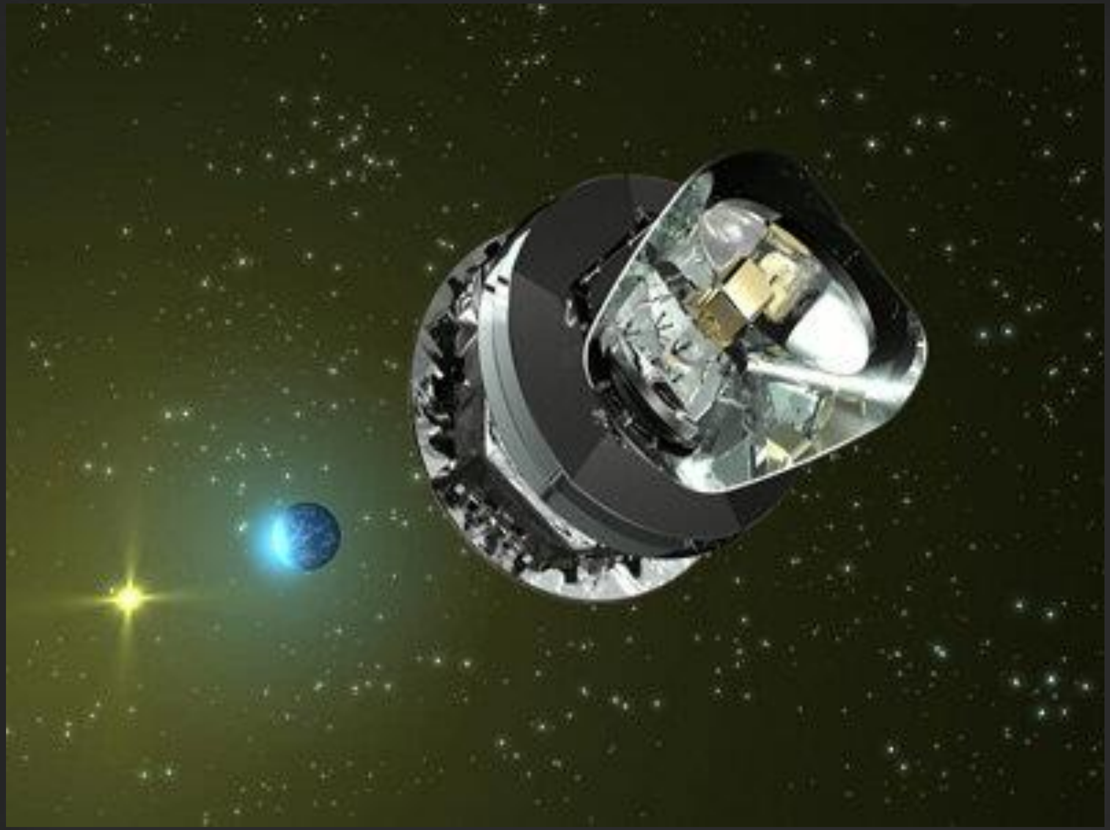


Confronting BSM Model with observations

- For the DM abundance, we compare with the ESA PLANCK satellite measurements.

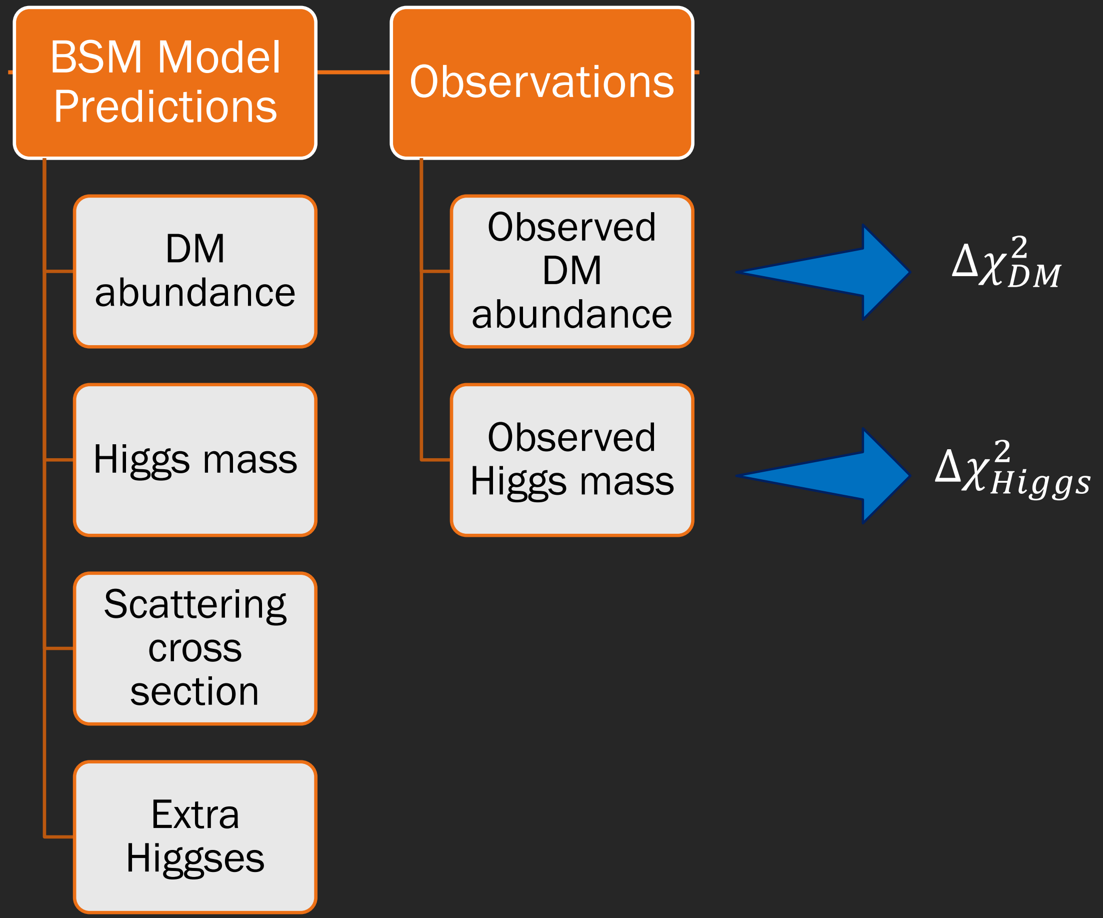
- BSM Model Predictions
  - DM abundance
  - Higgs mass
  - Scattering cross section
  - Extra Higgses
- Observations
  - Observed DM abundance

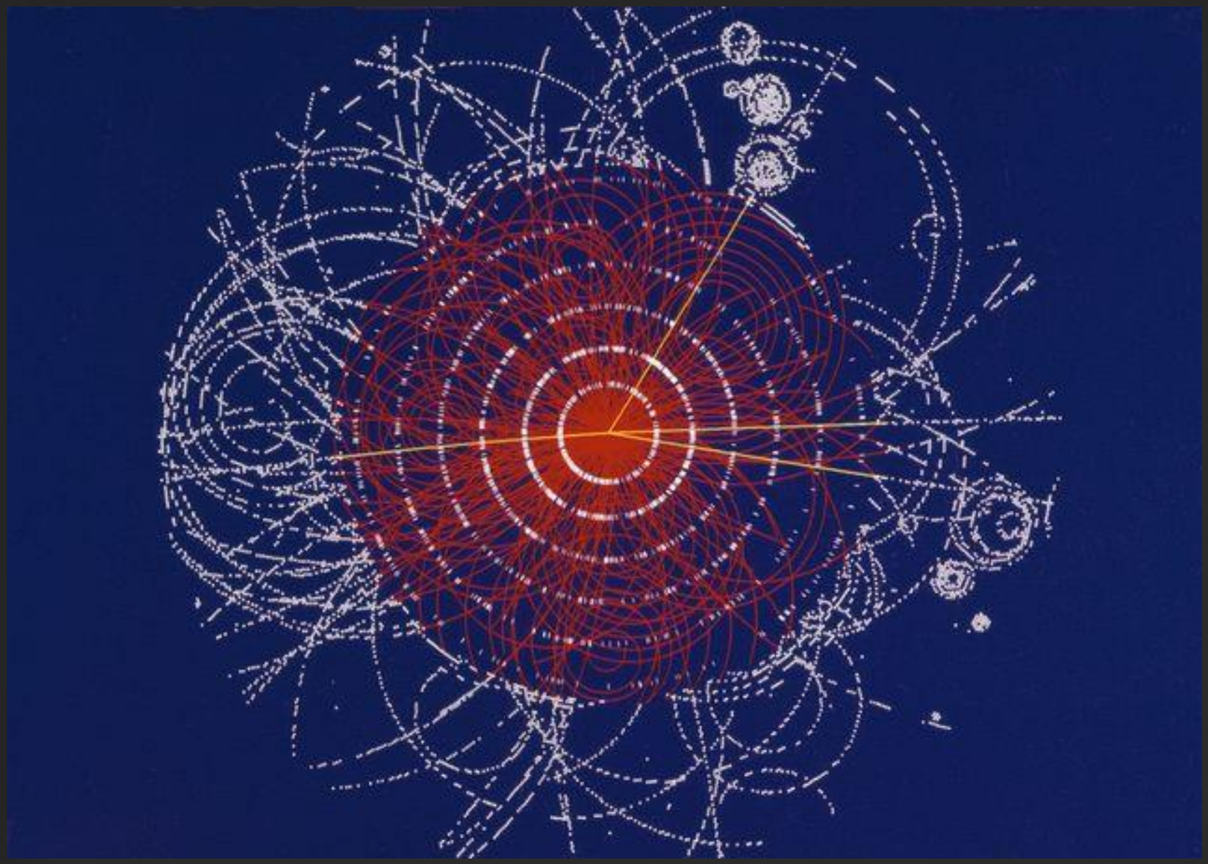
→ $\Delta\chi^2_{DM}$



Confronting BSM Model with observations

- For the Higgs mass and couplings, we compare with LHC experiments ATLAS and CMS data.

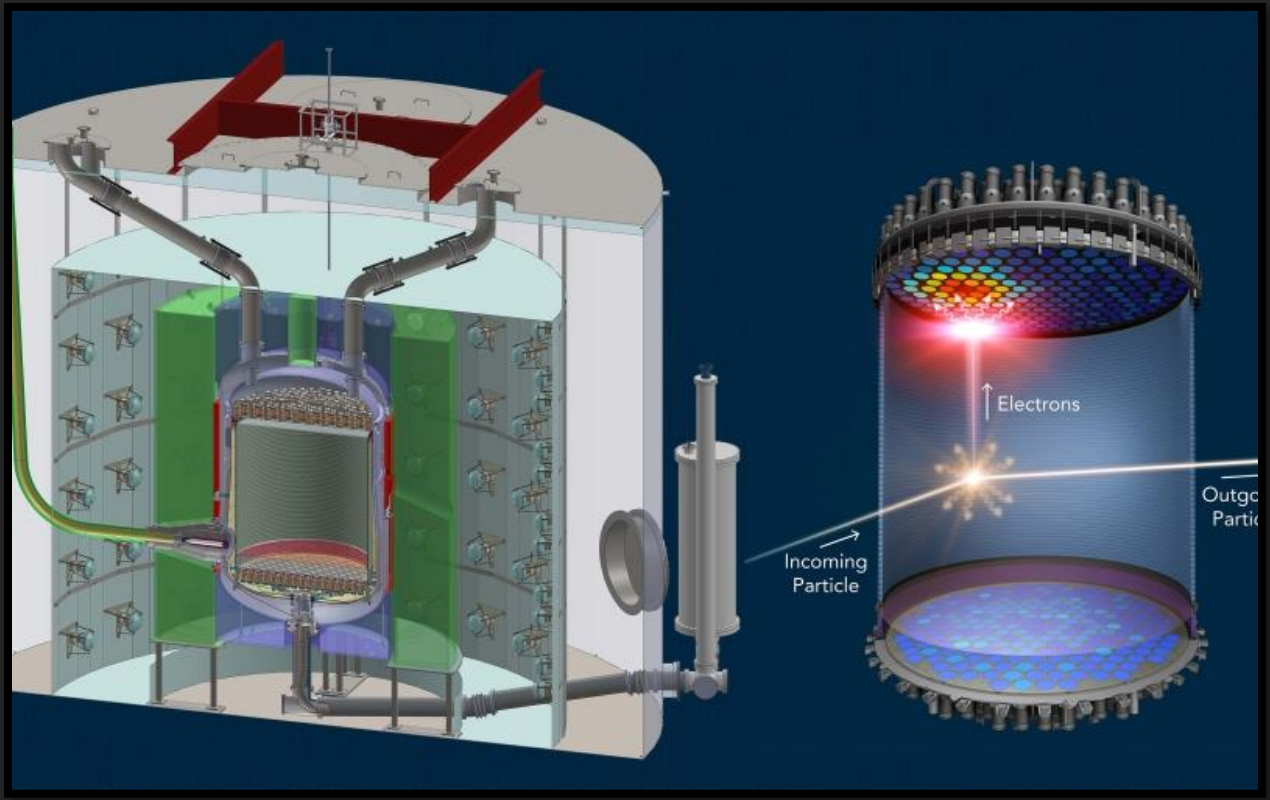




Confronting BSM Model with observations

- For Direct Detection of DM, we use limits from the no-observation of nuclear recoils in DD experiments.

BSM Model Predictions	Observations	
DM abundance	Observed DM abundance	→ $\Delta\chi^2_{DM}$
Higgs mass	Observed Higgs mass	→ $\Delta\chi^2_{Higgs}$
Scattering cross section	Limits from DD experiments	→ $\Delta\chi^2_{DD}$
Extra Higgses		



Confronting BSM Model with observations

- For extra Higgses or non-SM new particles we compare with limits from no-observation of such particles at the LHC and other colliders.

BSM Model Predictions	Observations	
DM abundance	Observed DM abundance	$\Delta\chi^2_{DM}$
Higgs mass	Observed Higgs mass	$\Delta\chi^2_{Higgs}$
Scattering cross section	Limits from DD experiments	$\Delta\chi^2_{DD}$
Extra Higgses	Limits from collider experiments	$\Delta\chi^2_{LHC}$

Likelihood functions

- Some experiments like those of DM Direct Detection or the **LHC** experiments publish their limits in terms of tabulated likelihood functions $\mathcal{L}$.
- From this tables and given the BSM free parameters values, one can infer the chi-square values from this relation.

$$\Delta\chi^2 = -2\log[\frac{\mathcal{L}}{\mathcal{L}_{max}}]$$

Composite Likelihood Function

- We can sum the log-likelihood functions to construct a global or **composite likelihood function** (or chi-square).

$$\log\mathcal{L} = \log\mathcal{L}_{DD} + \log\mathcal{L}_{\Omega h^2} + \log\mathcal{L}_{m_h} + \log\mathcal{L}_{ATLAS}$$

- The composite likelihood function measures how well the predictions compare with all the observations.

Composite Likelihood Function

- This composite likelihood is a function of the free parameters of the BSM model.
- The task is now to explore the parameter space of the model to find the regions that are best compatible with the observations.
- The preferred regions of parameter space will be those maximizing the composite likelihood function (or minimizing the corresponding composite chi-square function).

$$\log\mathcal{L} = \log\mathcal{L}_{DD} + \log\mathcal{L}_{\Omega h^2} + \log\mathcal{L}_{m_h} + \log\mathcal{L}_{ATLAS}$$

The S3 symmetric model

The S3 symmetric model

Matter content:

- In this model the particle content is assigned to irreps of the **S3** permutational symmetry group
- Two families of left-handed fermion **doublets**, and two scalar doublets are taken as **doublets** of S3.
- The third fermion family and third scalar doublet are taken as S3 **singlets**.

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \sim \mathbf{2} \quad , \quad \begin{pmatrix} Q_{1L} \\ Q_{2L} \end{pmatrix} \sim \mathbf{2}$$

$$H_S \sim 1_S \ , Q_{3L} \sim 1_S$$

Scalar potential and Yukawa lagrangian

- The terms in the most general renormalizable scalar potential are restricted by the symmetry, prohibiting many of the couplings.
- The same happens in the Yukawa Lagrangian.
- The point is that the form of these terms is dictated by the properties of the S3 symmetry group.

$$V = \sum a_{ij} H_i^{\dagger} H_j + \sum \boldsymbol{\lambda}_{ijkl} H_i^{\dagger} H_j H_k^{\dagger} H_l$$

The mass matrices

- It was well known (e.g. F. González, A. Mondragón, M. Mondragón, U. J. Saldaña, L. Velasco, Phys.Rev.D 88 (2013) 096004) that the mass matrices of either the fermions or the scalars can be rotated to this form.
- Provided the tangent of the angle of rotation γ is the quotient of the two scalar vevs of H1 and H2.

$$\tan\gamma = v_1/v_2$$

$$M \to R(\gamma) M R^T(\gamma) = \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

The intermediate basis

- It was later argued (D. Das, U. K. Dey, B. Pal, Phys.Lett.B 753 (2016) 315-318) that for a specific alignment between these two vevs (which follows from stability of the potential), the mass matrices are block-diagonal.

$$\tan\gamma = v_1/v_2$$

$$v_1 = \sqrt{3}\, v_2$$

$$M \to R(\gamma) M R^T(\gamma) = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

The remnant Z2

- This is entirely a consequence of a remnant Z2 symmetry after EWSB.
- Among other things, this implies that one physical quark does not mixes with the other quarks.
- The CKM matrix is then block-diagonal.
- Its form will not be modified by loop corrections because of the unbroken Z2 symmetry!

$$\tan\gamma = v_1/v_2$$

$$v_1 = \sqrt{3}\, v_2$$

$$M \to R(\gamma) M R^T(\gamma) = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

Breaking the symmetry

- In order to obtain a realistic CKM matrix, (e.g. Das et. al.) it is necessary to break the S3 symmetry directly in the Lagrangian.
- They proposed to break it with **soft-breaking** mass terms.
- In this work we analyze the phenomenology of the model taking into account these terms.

$$V_{soft} = \mu_s (H_1^\dagger H_s + h.c.)$$

Adding a Dark Matter Sector

The Dark Matter Sector

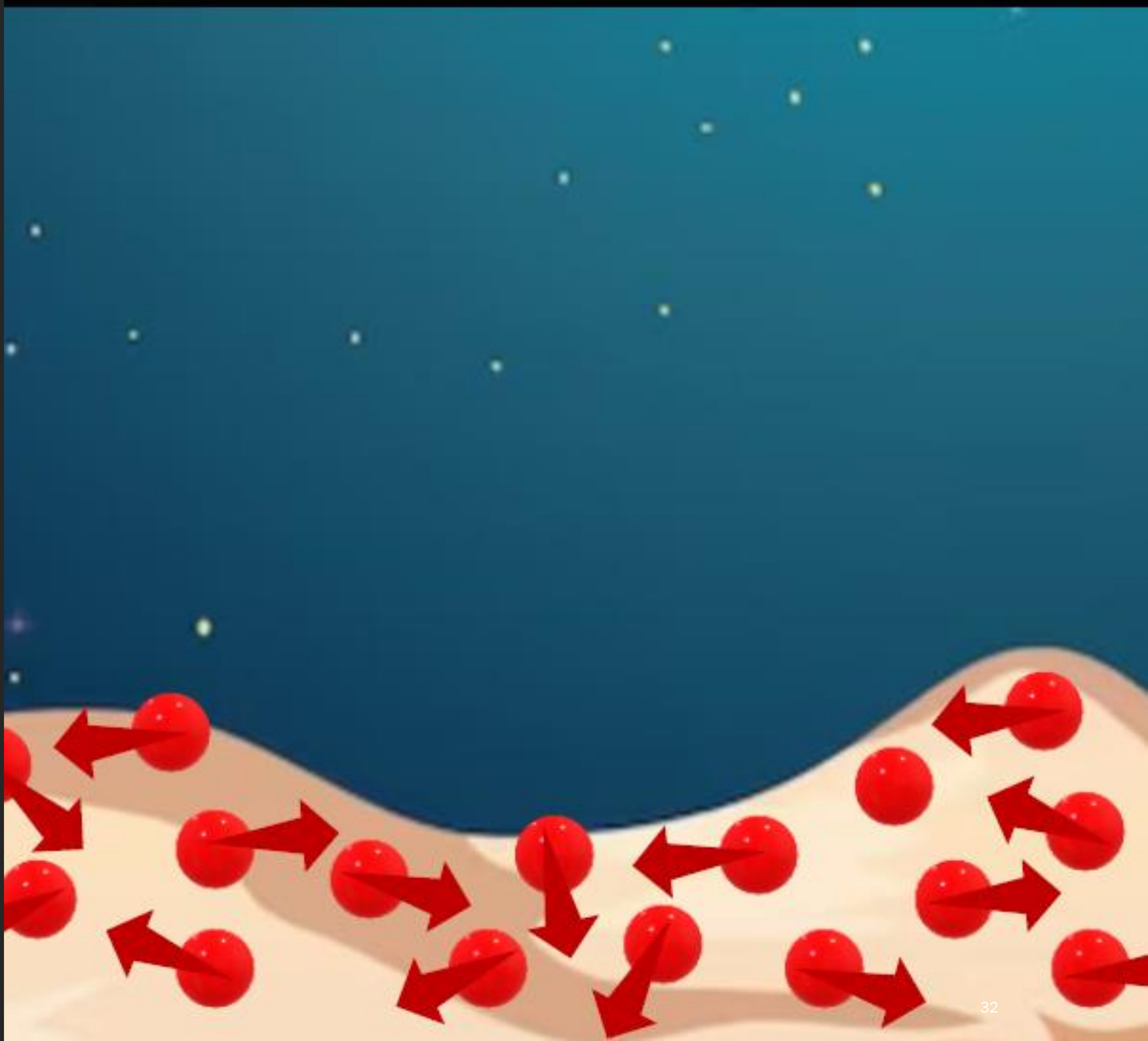
- In addition to considering the breaking of the S3 symmetry, we include a dark sector with a **scalar Higgs doublet** and **right-handed neutrinos**.
- We take all these fields as antisymmetric singlets under the S3 symmetry.
- The extra Z2 is for stabilizing the DM candidate.

$$H_a \sim 1_A \ , N_i \sim 1_A, \qquad \text{all } Z_2 \text{ odd}$$

Numerical analysysys

Technical details

- We have 22 free parameters (HUGE parameter space!):
  - 13 quartic couplings λ_i from the scalar potential
  - 1 independent squared mass parameter of the dark scalar doublet.
  - 1 soft-breaking mass parameter.
  - 1 angle ($\tan\theta = 2v_2/v_3$)
  - 3 masses of the right-handed neutrinos.
  - 3 Yukawa couplings of the right-handed neutrinos.



Technical details

- ❑ The equations for the masses are not analytically invertible → they are not free parameters but derived ones!
- ❑ This means we must reject a very large portion of the sampled points, because of the wrong prediction of the Higgs mass at 125 GeV.

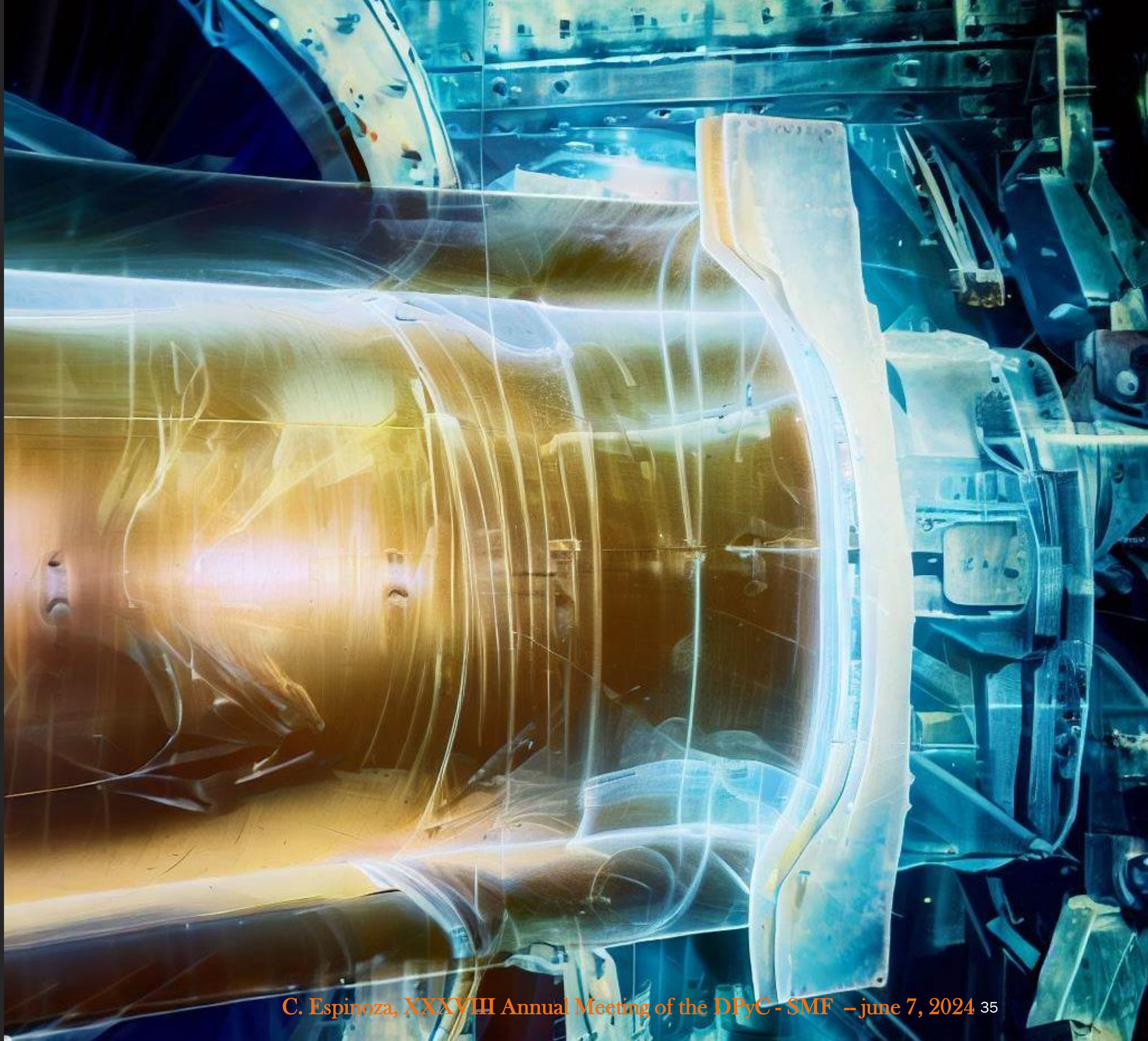
Technical details

- In addition, the theoretical constraints such as:
  - Unitarity of the S-matrix → restrictions on quartic and trilinear couplings.
  - Stability of the vacuum.

and …

Technical details

- The experimental constraints on extra scalars and new particles, such as limits from scalar searches on colliders from decades of observations, e.g. LEP, Tevatron, LHC.



Technical details

- All this greatly complicates the computing time.
- I will show preliminary results, but this is still work in progress.

Numerical tools

- ❑ Positivity and stability of the scalar potential:
  - ❑ EVADE, JHEP **03** (2019), 109

git clone https://gitlab.com/jonaswittbrodt/EVADE.git

- ❑ Exclusion limits from scalar searches:
  - ❑ HiggsBounds, Eur.Phys.J.C 80 (2020) 12, 1211

git clone https://gitlab.com/higgsbounds/higgsbounds.git

Numerical tools

- Implementation and couplings of the 125 GeV SM Higgs-like scalar:
  - SARAH, Adv. High Energy Phys., (2015), 840780
  - SPheno, Comput. Phys. Commun. **183** (2012), 2458-2469
- https://sarah.hepforge.org/
- https://spheno.hepforge.org/

- Gluon fusion and b-quark associated production of scalars and their decay rates to tau leptons:
  - SUSHI, Comput. Phys. Commun. 184 (2013), 1605-1617
- https://sushi.hepforge.org/

Numerical tools

- ❑ DM-nucleon scattering cross sections and relic density:
  - ❑ MicrOmegas, Comput. Phys. Commun. 231 (2018), 173-186

https://lapth.cnrs.fr/micromegas/

- ❑ LHC measurements for couplings to the SM Higgs-like scalar h:
  - ❑ HiggsSignals, Eur. Phys. J. C, 81 (2021) no.2, 145

git clone https://gitlab.com/higgsbounds/higgssignals.git

Numerical tools

- ❑ Direct detection limits:
  - ❑ DDcalc, Eur. Phys. J. C,77 (2017) no.12, 831

Git clone https://github.com/GambitBSM/DDCalc.git

- ❑ Numerical optimizer:
  - ❑ Diver, Eur. Phys. J. C,77 (2017) no.11, 761

Git clone https://github.com/patscott/Diver.git

Experimental information

- ATLAS (LHC) for scalar production via gluon fusion and b-quark associated production:
  - ATLAS, Phys. Rev. Lett. 125 (2020) no.5, 051801

- XENON 1T for DM direct detection limits:
  - XENON 1T, Phys. Rev. Lett. 121 (2018) no.11, 111302

- PLANCK for DM relic density:
  - PLANCK, Astron. Astrophys. 641 (2020), A6

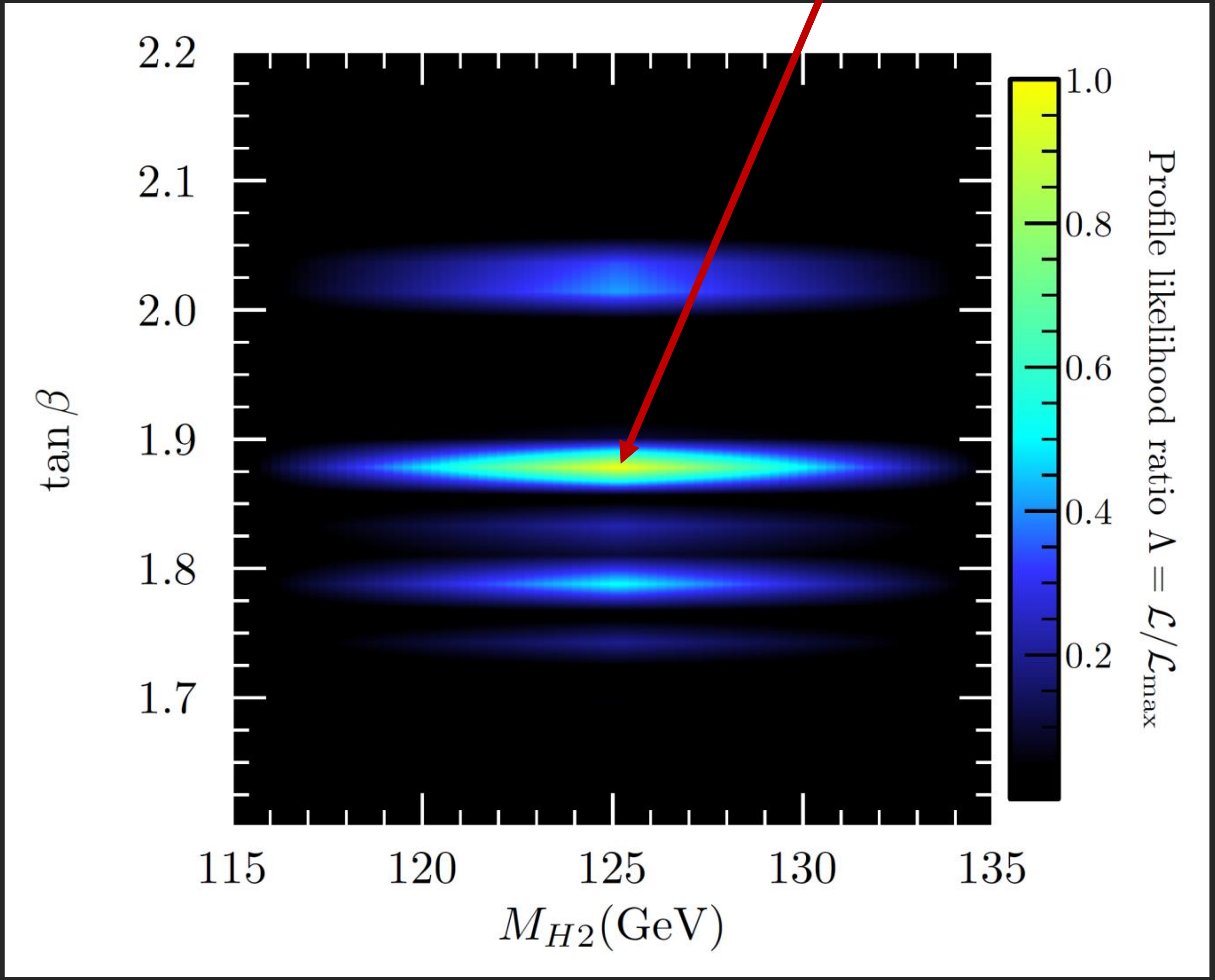
Phenomenology

The Scalars

The SM Higgs Mass

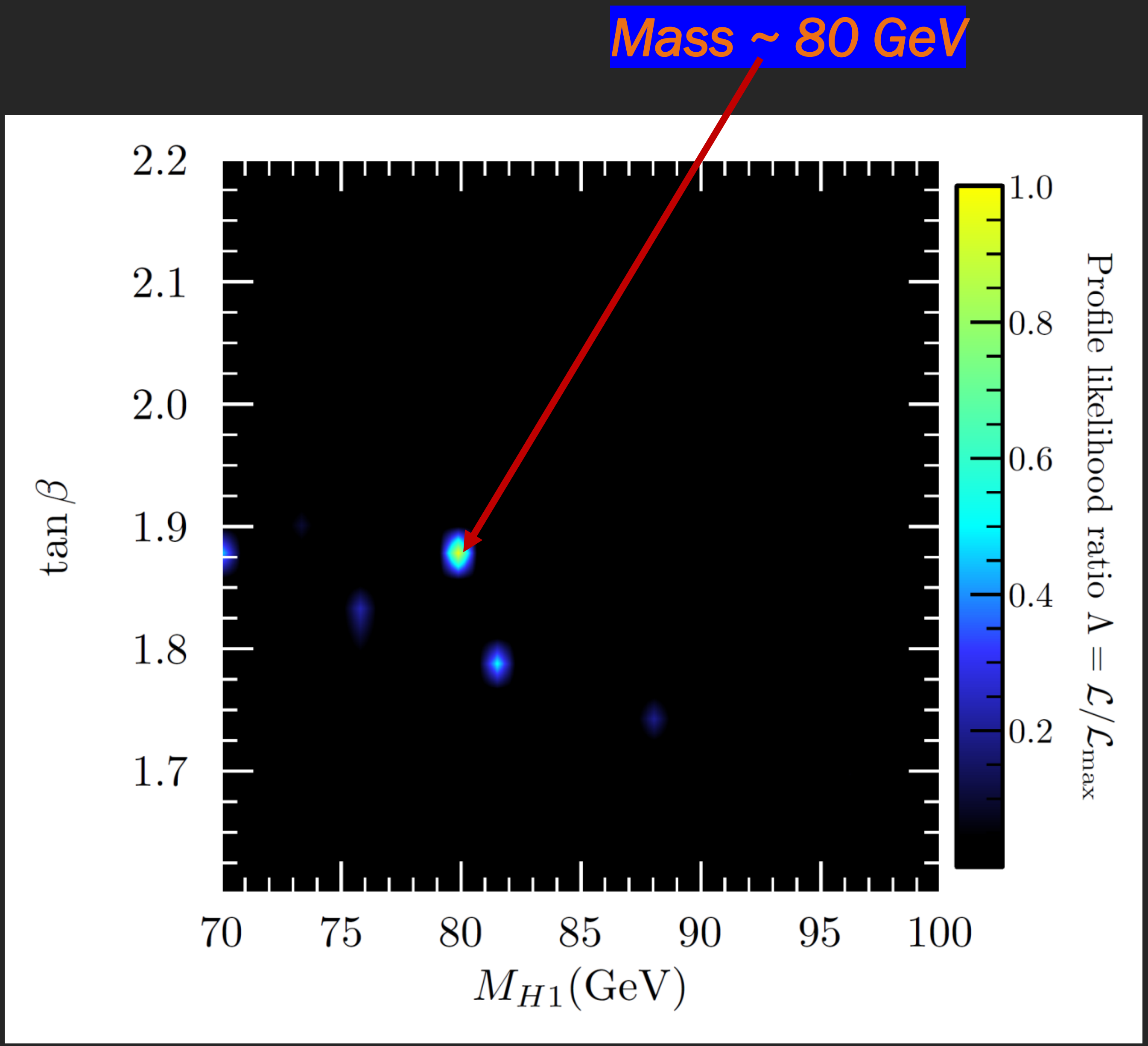
- We find a region of parameter space where the model correctly predicts the known mass for the SM Higgs boson.
- The tangent of beta is defined as the quotient of two of the vacuum expectation values of the Higgses.
- The brightest region contains the best fit point (BFP), the point in parameter space that best predicts the observables.
- Dark regions are points which poorly predict the observables.

Mass ~ 125 GeV



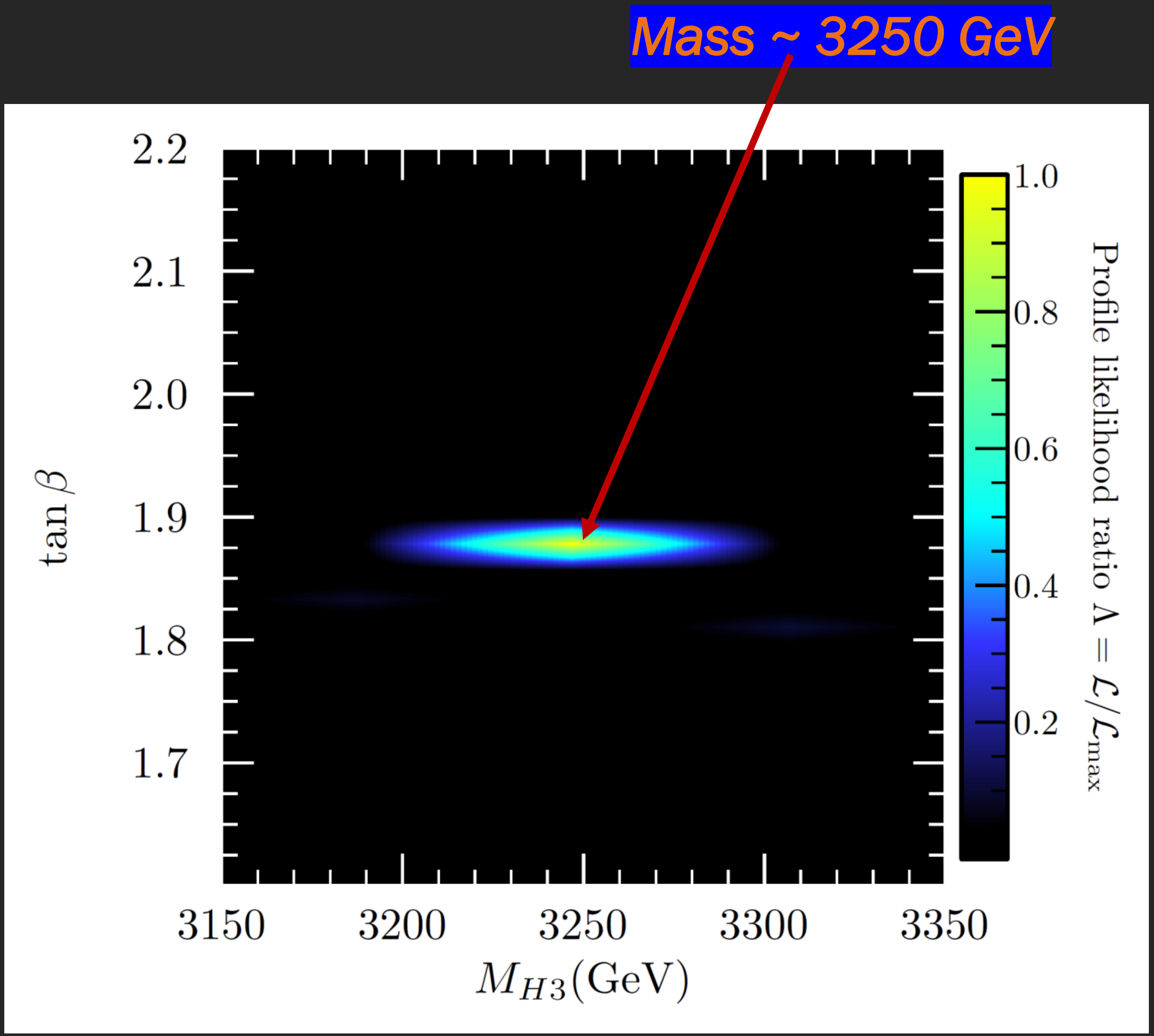
The light scalar

- This is the likelihood profile for the scalar H1.
- Interestingly, the analysis predicts its mass to be around 80 GeV.
- The fact that this is a highly constrained region (highly localized), might be because of the small number of points in the scan.
- We still need to further deepen the scanning of the parameter space.



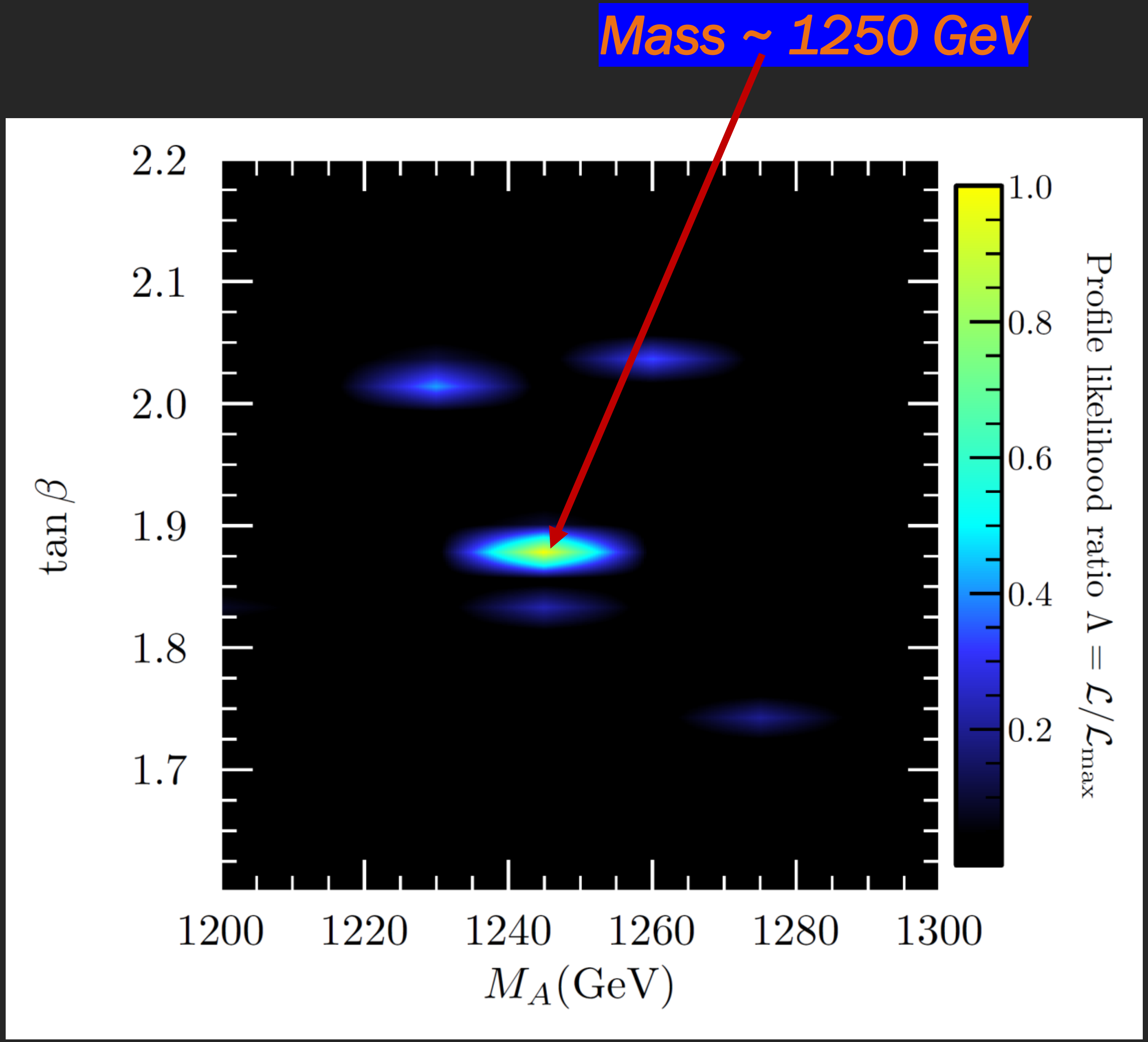
The heavy scalar masses

- The rest of the scalars are much heavier.
- This is the likelihood profile for the scalar H3.
- The analysis predicts its mass to be around 3250 GeV.



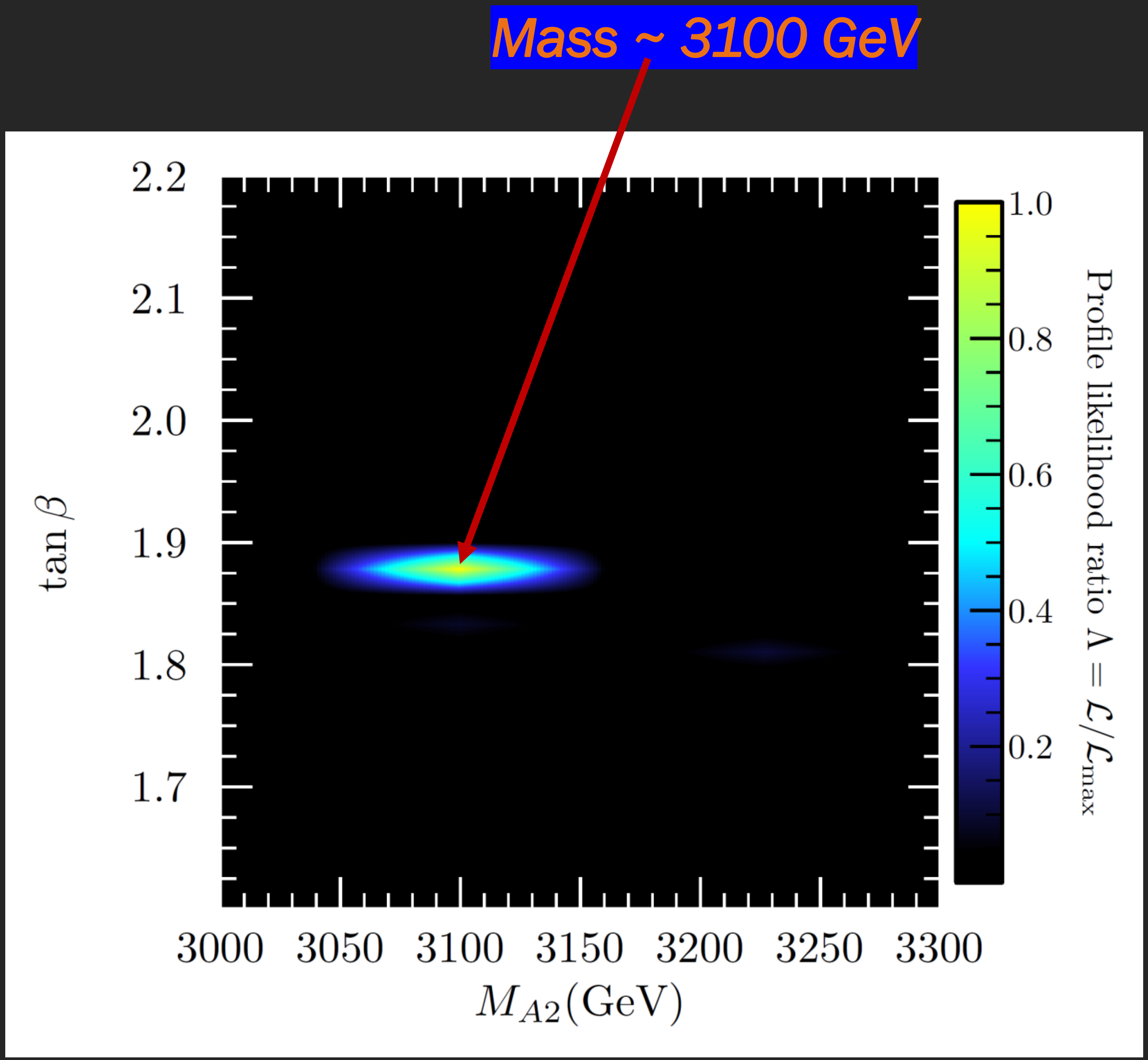
The pseudo scalar masses

- This is the profile for the pseudo scalar A.
- The analysis predicts a mass of ~1250 GeV for this scalar.



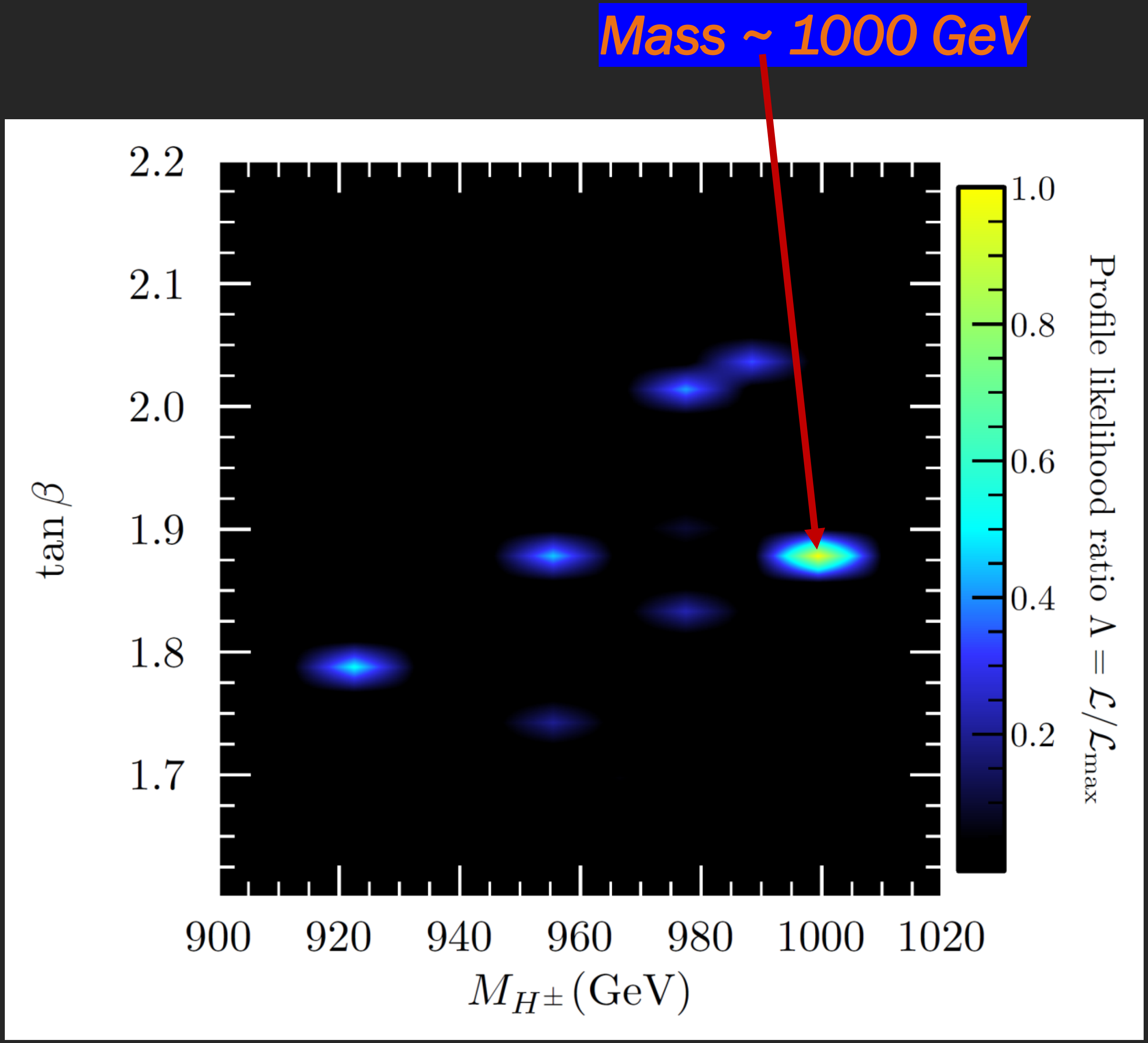
The pseudo scalar masses

- ❑ This is the profile for the second pseudo scalar A2.
- ❑ The analysis predicts a mass of ~3100 GeV for this scalar.



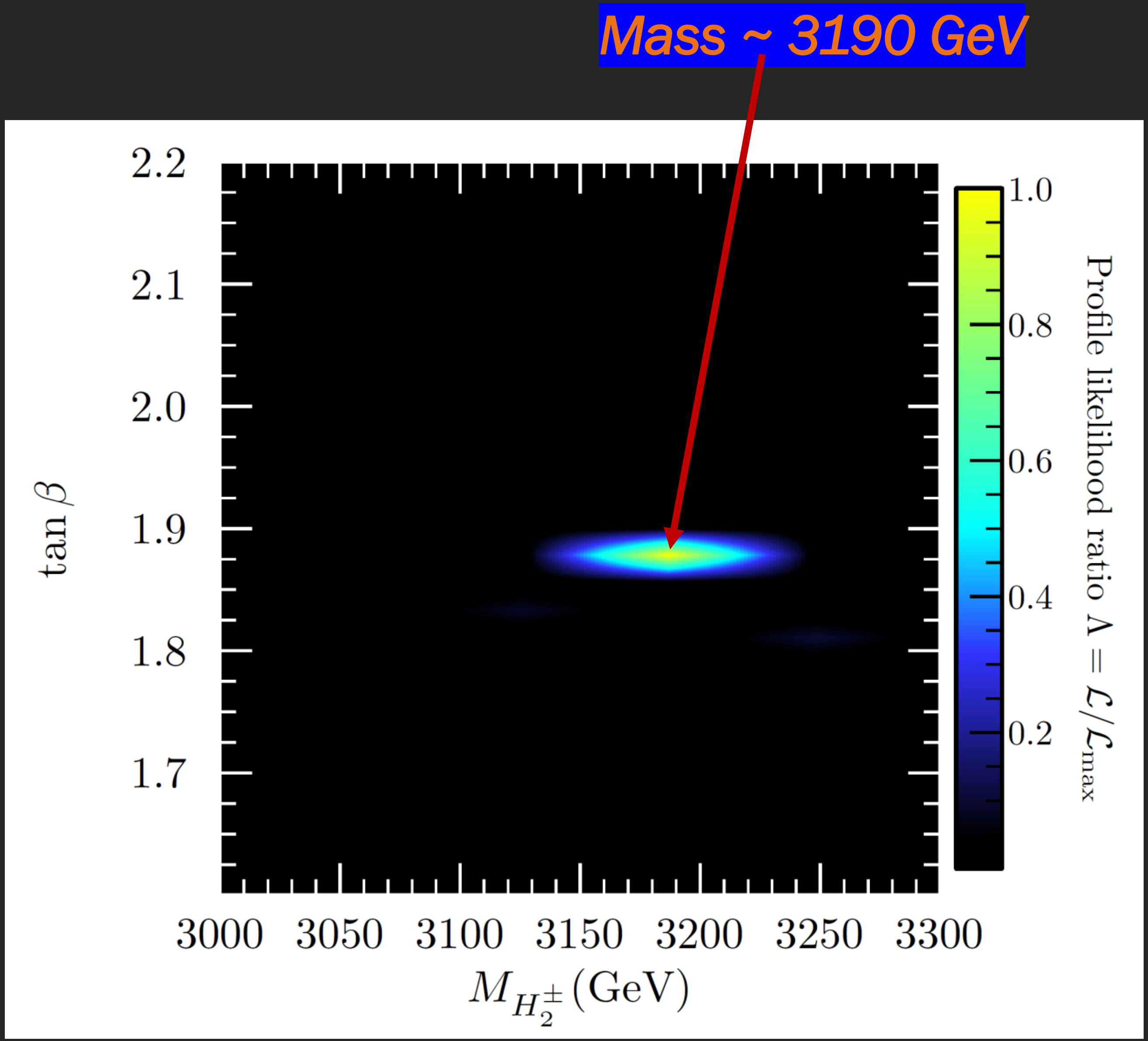
The charged scalar masses

- This is the profile for the first charged scalar H^+.
- The analysis predicts a mass of ~1000 GeV for this scalar.



The charged scalar masses

- This is the profile for the second charged scalar H_2^+.
- The analysis predicts a mass of ~3190 GeV for this scalar.

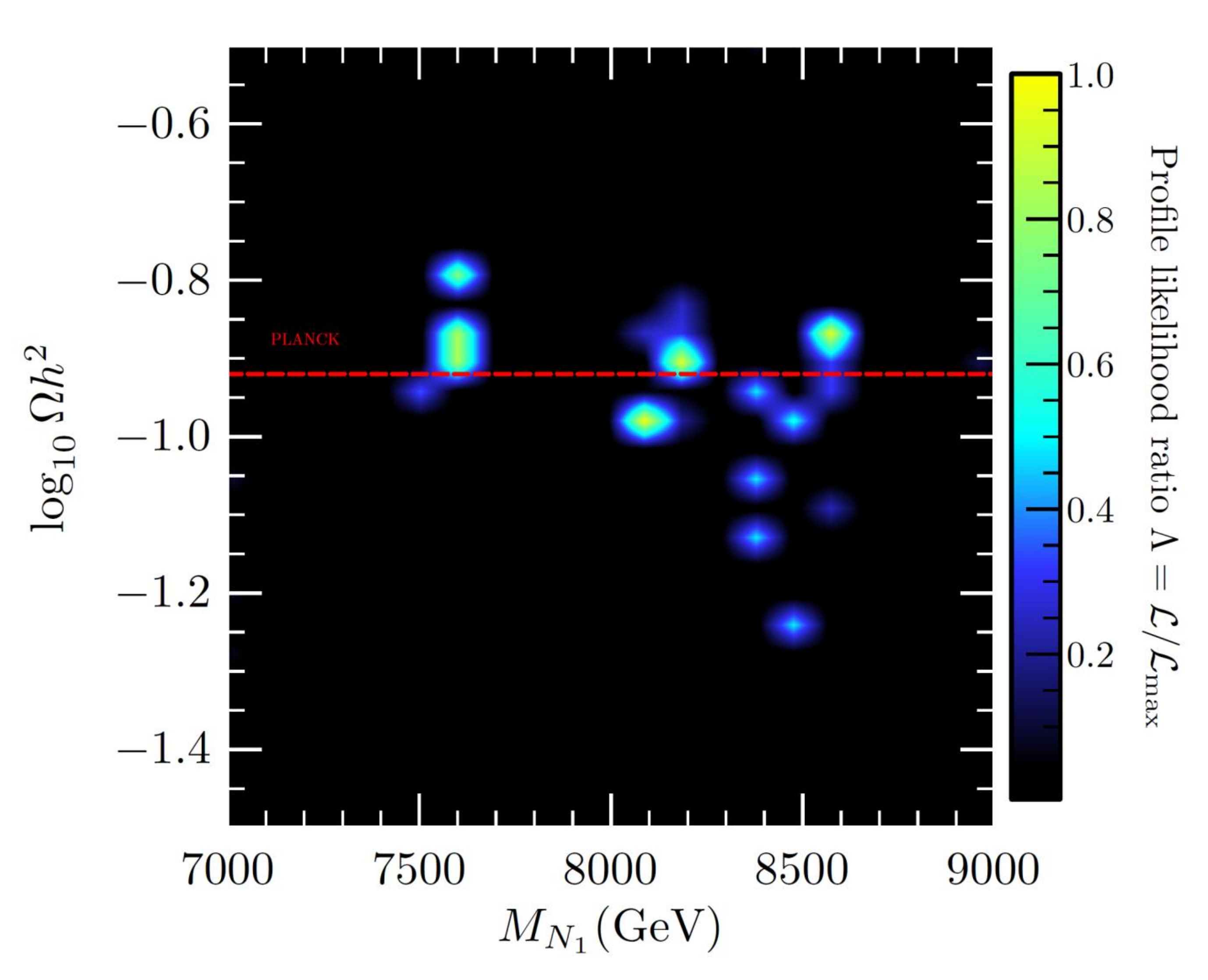


The Dark Sector

Fermion DM candidate

The DM abundance

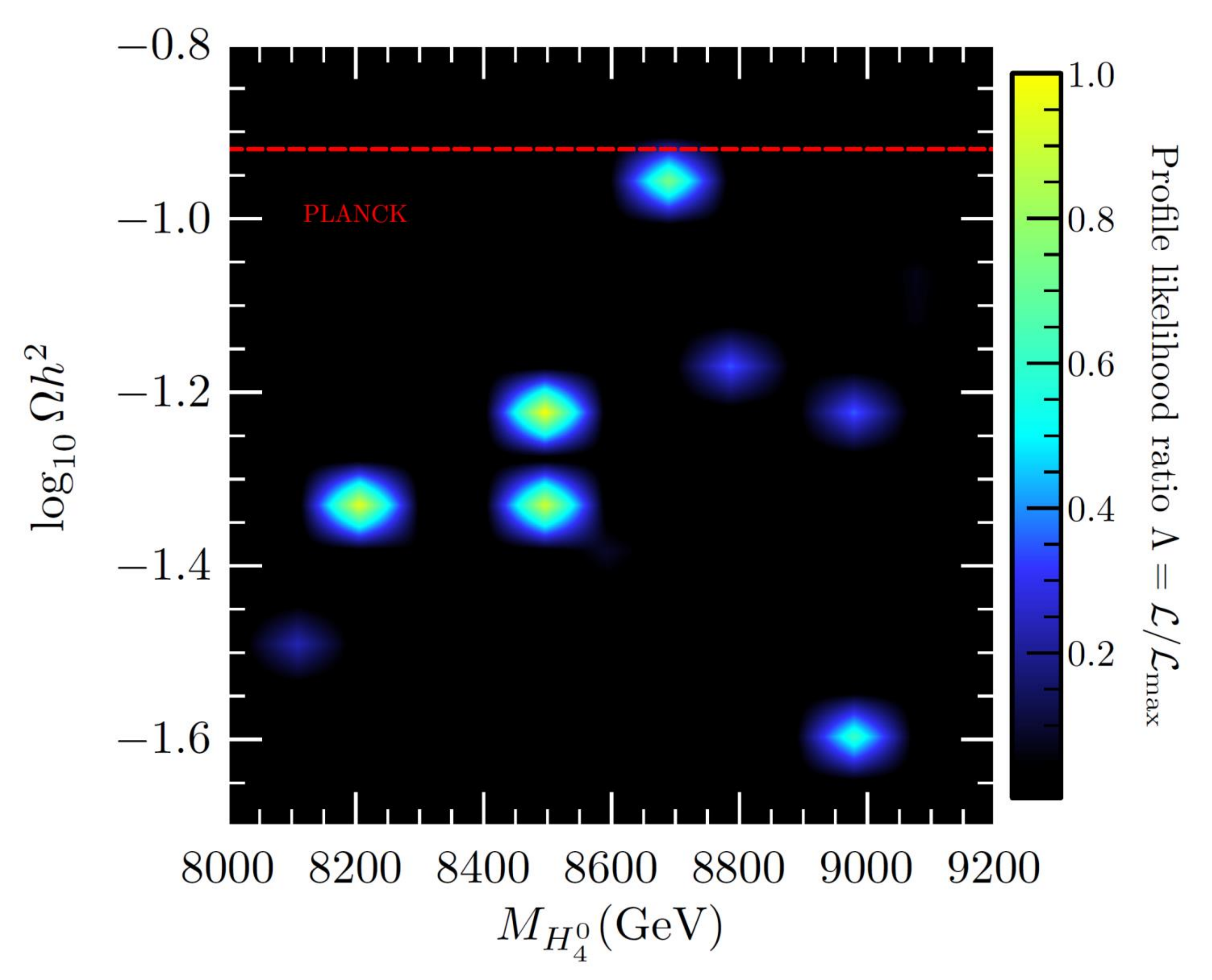
- This is the profile for the dark matter abundance of the fermion candidate.
- The red dashed line is the Planck measured value.
- The analysis allows us to infer that only (some) DM candidate masses in the interval ~ 7.5 TeV – 8.7 TeV can predict the correct value of the observed relic abundance.



Scalar DM candidate

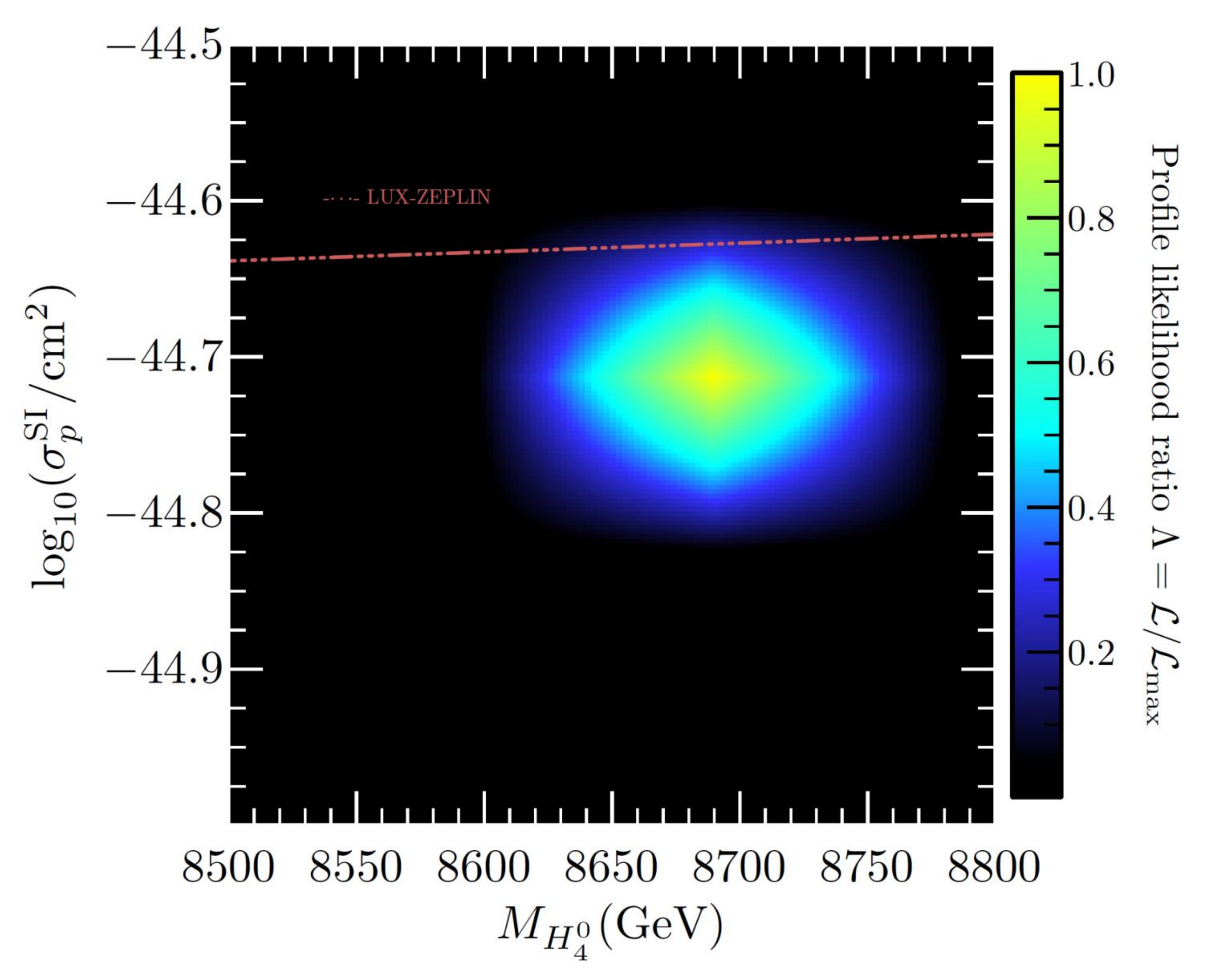
The DM relic abundance

- This is the likelihood profile for the relic abundance of the scalar DM candidate.
- The red dashed line is the Planck measured value.
- The analysis finds that the model predicts the correct DM abundance only for a handful of masses around 8.7 TeV.



The DM-proton scattering cross section

- This is the likelihood profile for the DM-proton scattering cross section for the scalar DM candidate.
- The analysis predicts a DM mass around 8.7 TeV at the BFP.
- The experiment LUX-ZEPLIN has the current strongest constraints on the model.



Work in progress

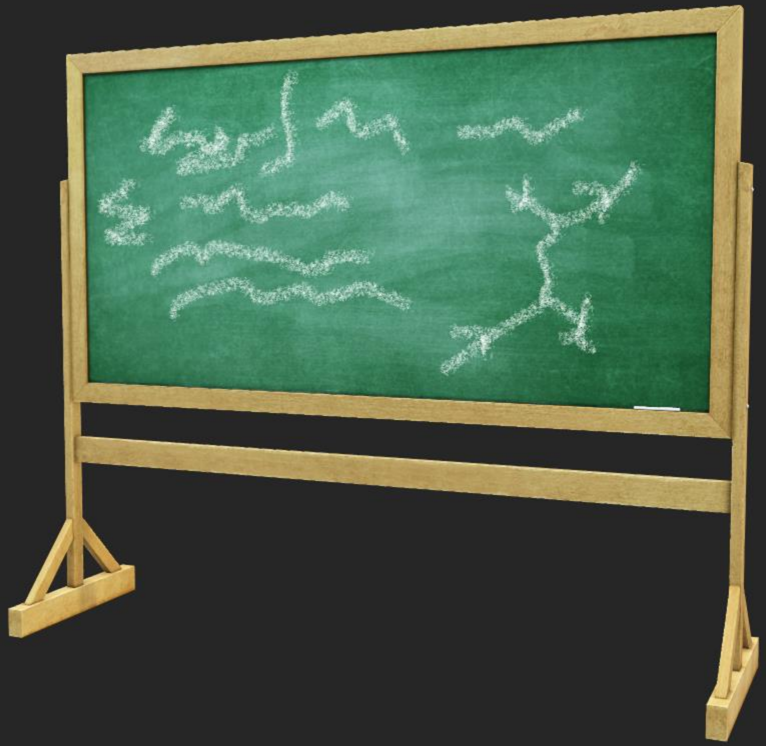
Additional posibilities

- Inclusion of constraints from flavor violation observables.
- Indirect detection constraints would be interesting since the DM is heavy.
- Long lived particles searches.

Conclusions

Concluding remarks

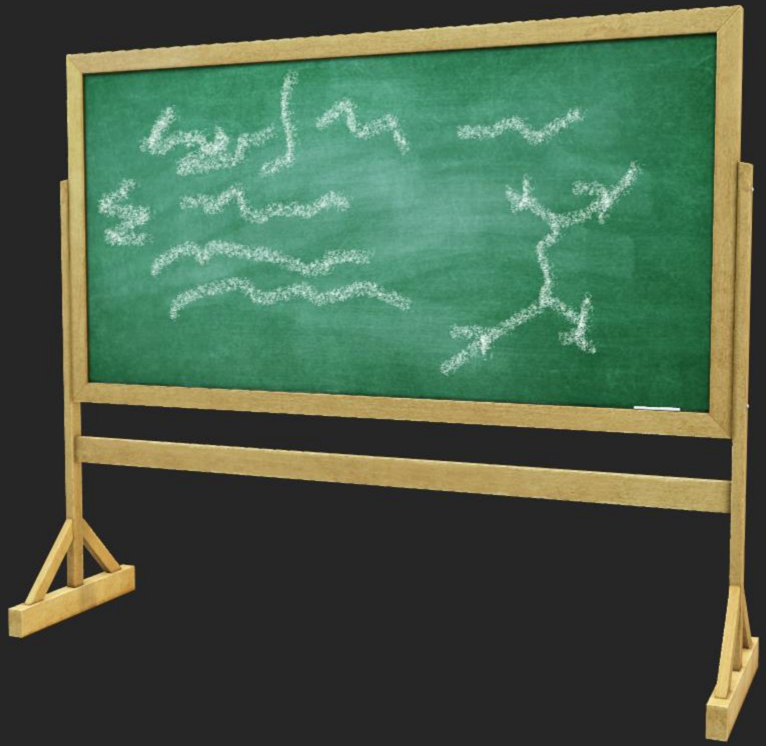
- The nature of DM is one of the greatest mysteries of our time.
- Given the important role that the Higgs boson plays among elementary particles, it would be interesting the existence of additional Higgses including in the DM sector.



Concluding remarks

- We are studying a BSM model featuring the permutational symmetry S3, several Higgses and a dark sector.

- Interesting results from the analysis range from a light Higgs to a DM sector with heavy particles on the ~10 TeV scale.



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Thank you for your attention!