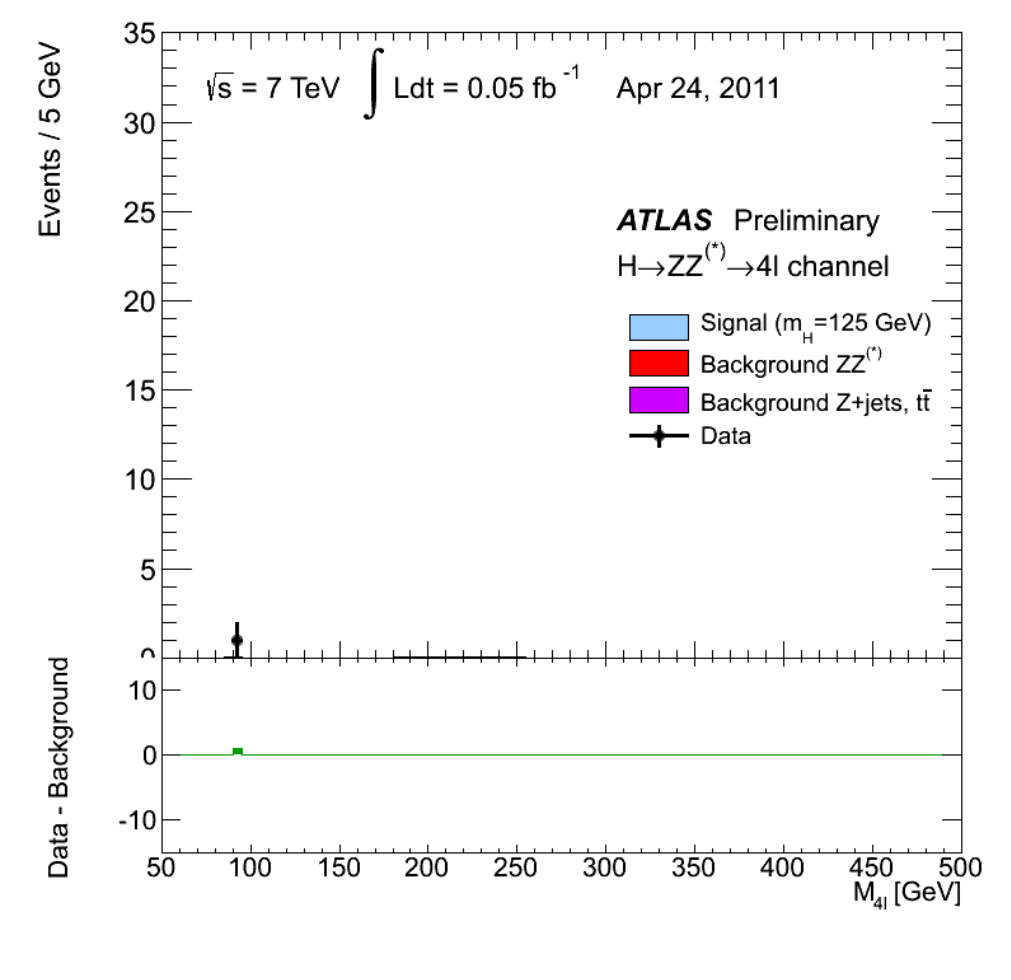
What is beyond the Standard Model?

- Could it be hiding at the SPS? -

Richard Jacobsson

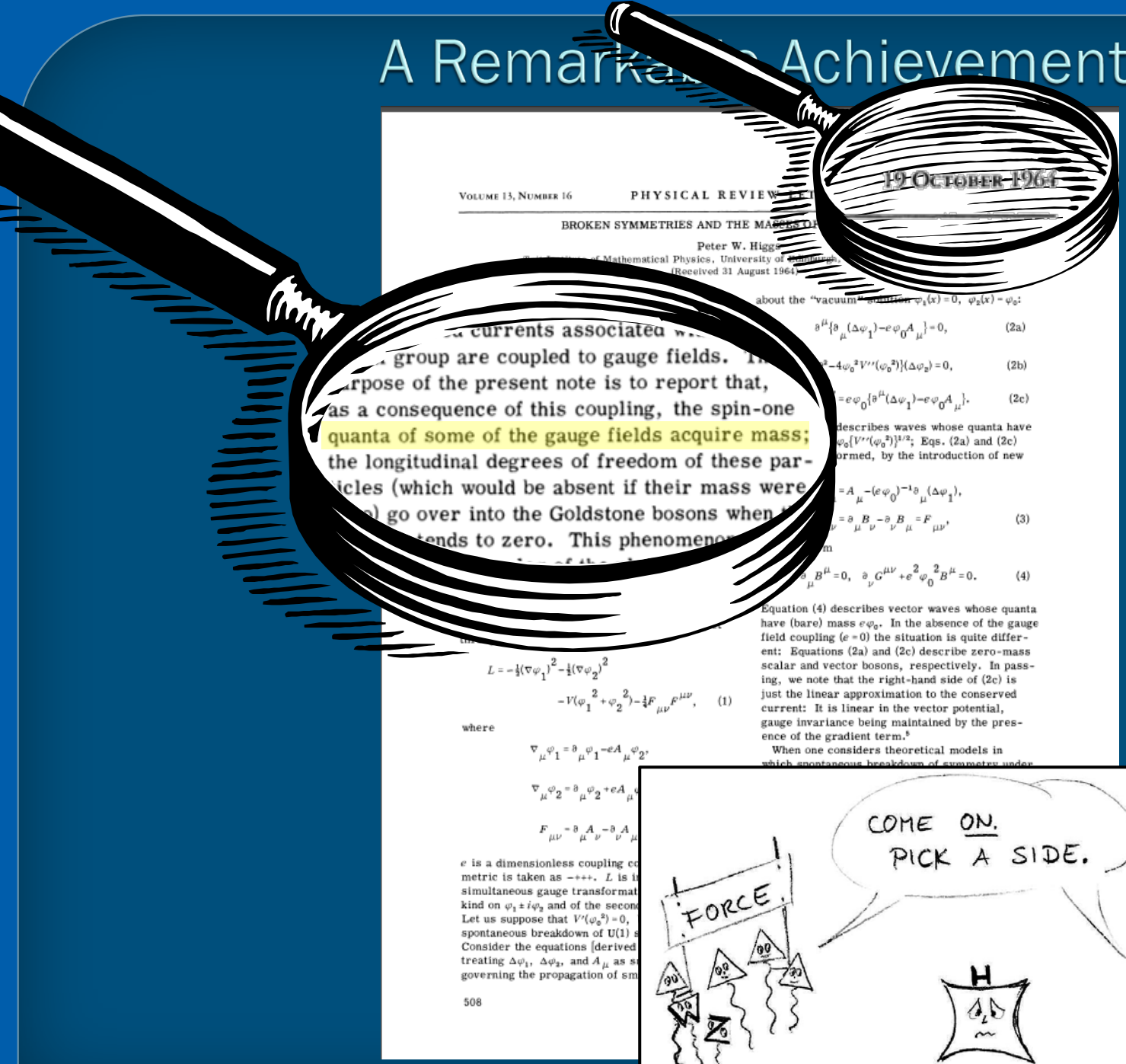
- Recapitulation of the results from LHC Run 1 (apologies to Alice!)
- Validity of the Standard Model
- Fundamental unanswered questions
- Possible solutions

Run 1: What did we find?



- ~1 - 5 Higgs per minute without us knowing!.... O(1 million) at production in total!
  - ATLAS+CMS: 1400 Higgs events after selection cuts
- Mass of the Higgs is equivalent to the total mass of 130 protons!

A Remarkable Achievement



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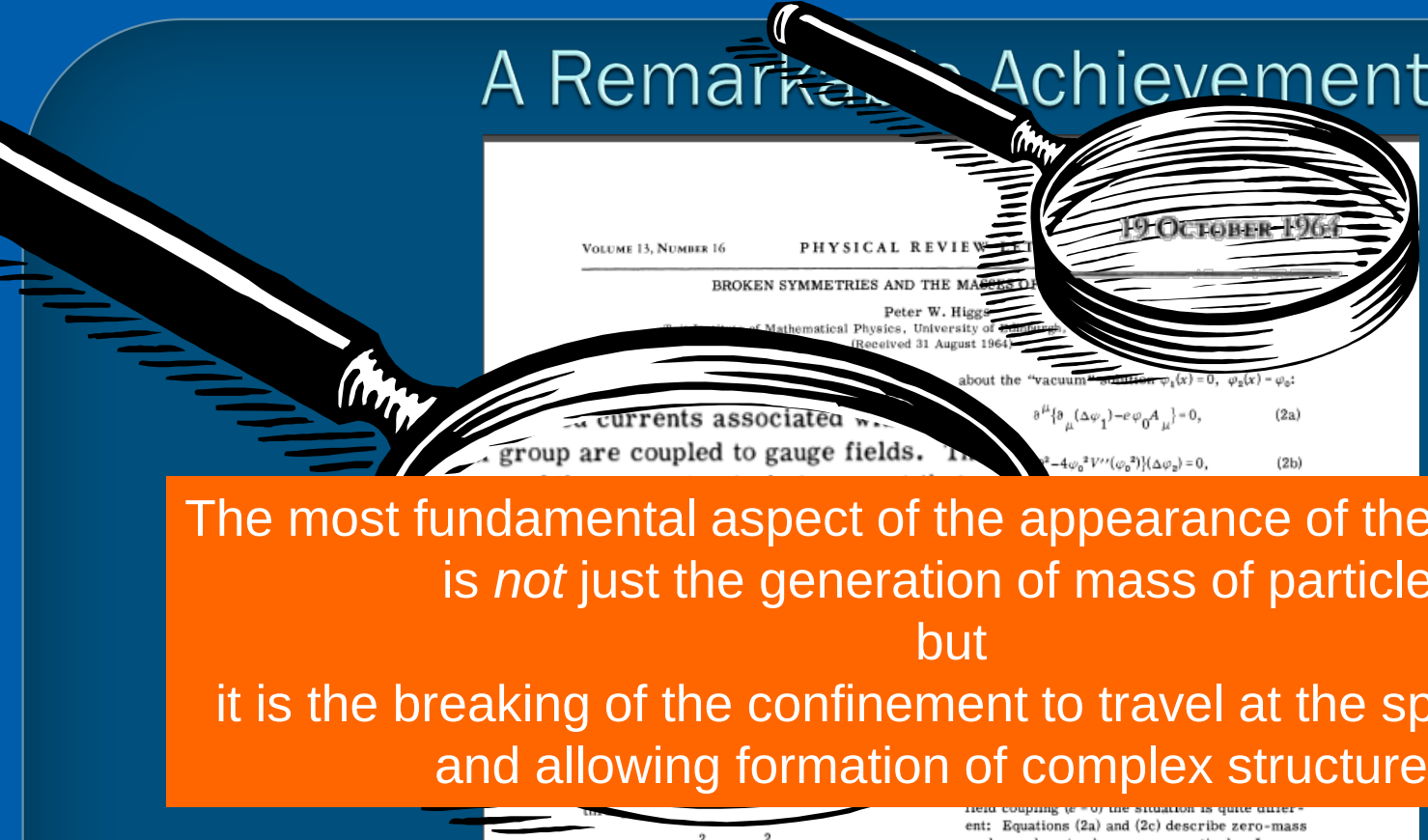
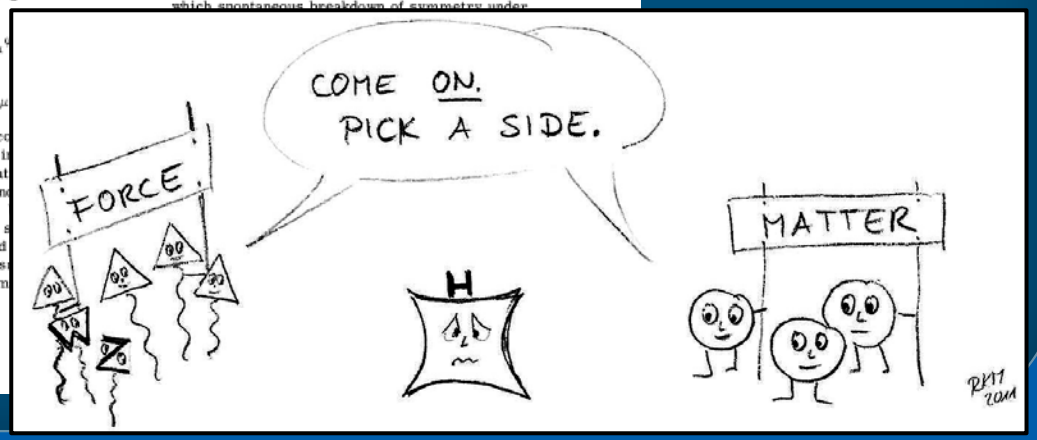


The most fundamental aspect of the appearance of the Higgs field is *not* just the generation of mass of particles

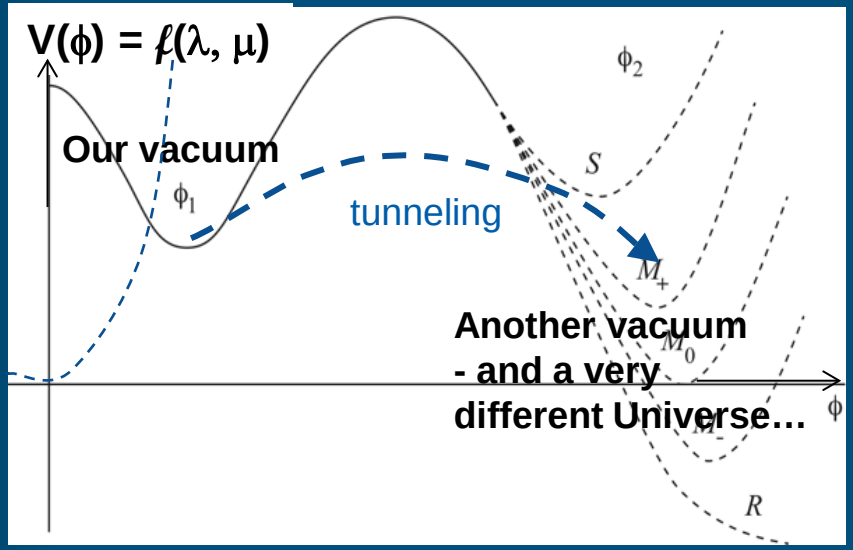
but

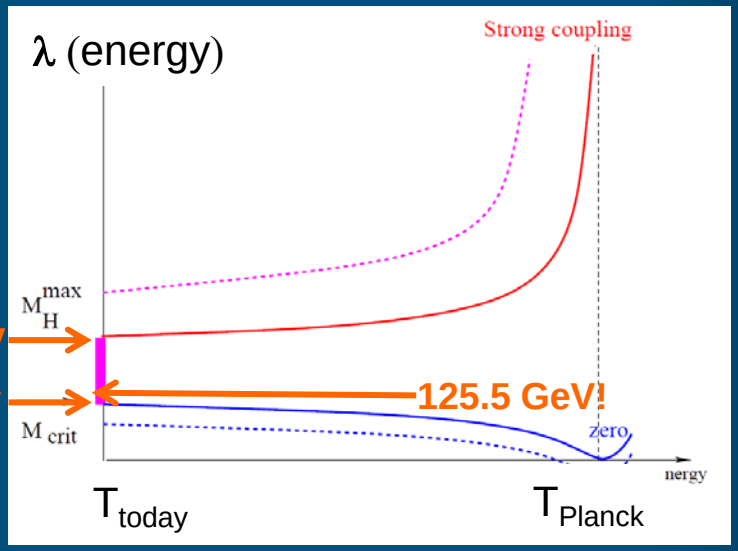
it is the breaking of the confinement to travel at the speed of light and allowing formation of complex structures!



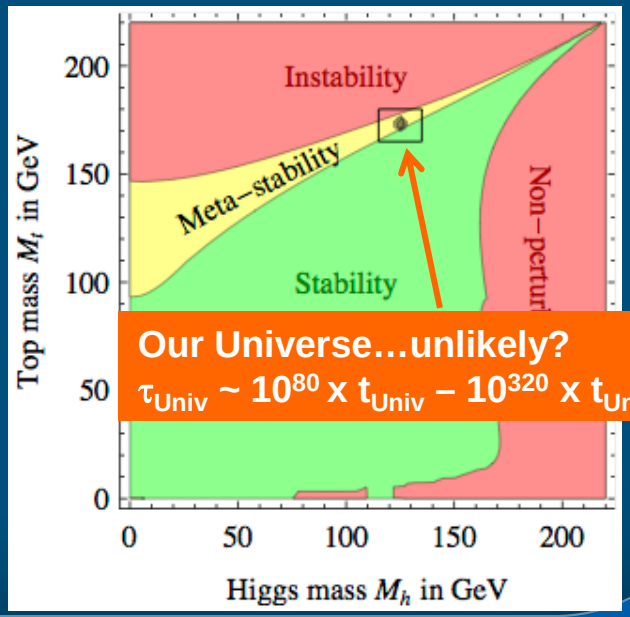
Is our vacuum – the Universe - stable?

- Probably, but just with a hair fine margin!
  - At least up to now as we are here to talk about it!



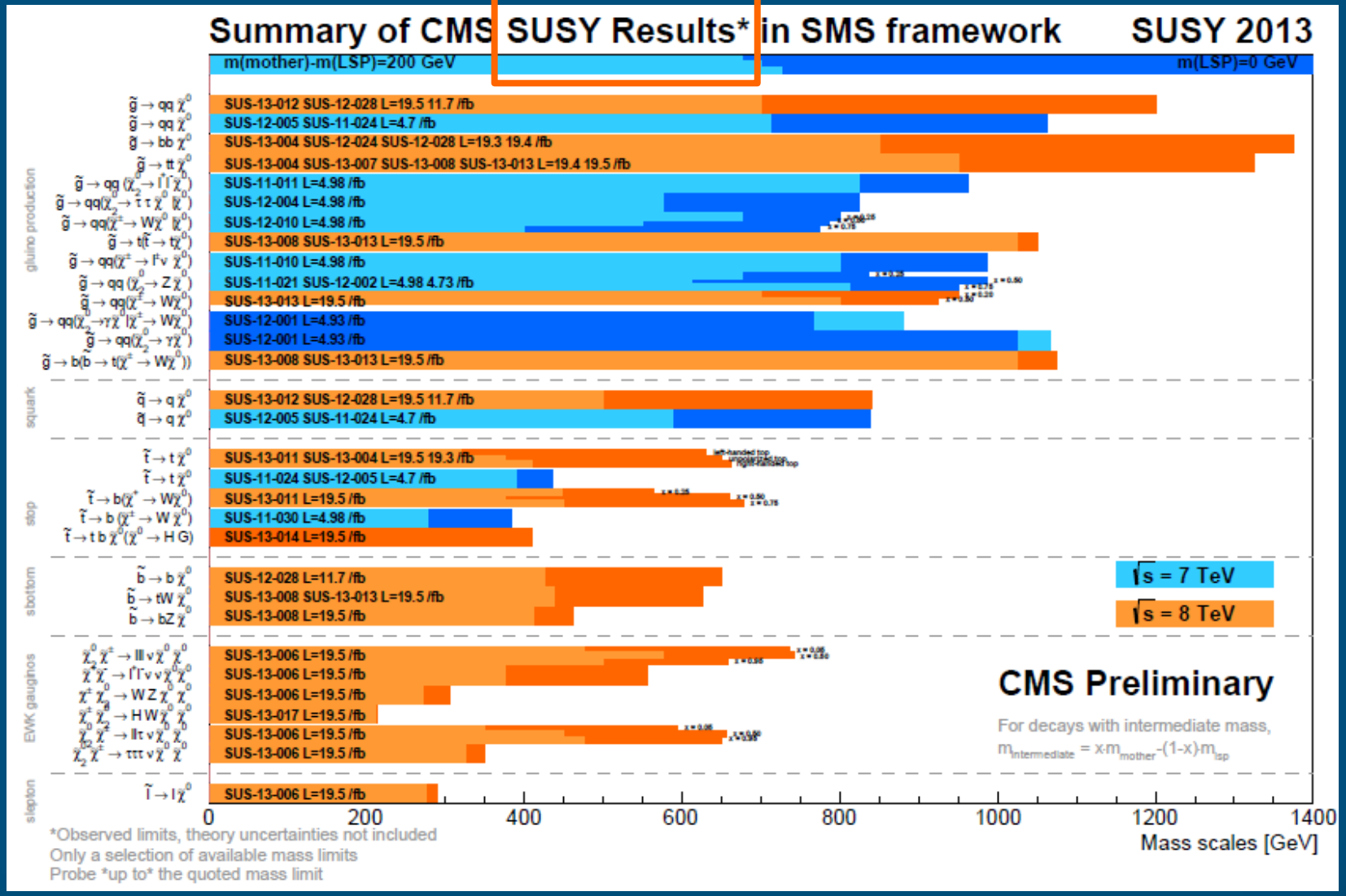


- If not:
  - A true vacuum could seed anywhere like a bubble and expand….
  - The current laws of physics would be lost and replaced for another version of the same fields….



Run 1 Searches: What did we not find....?

- LHC : A theory killer!



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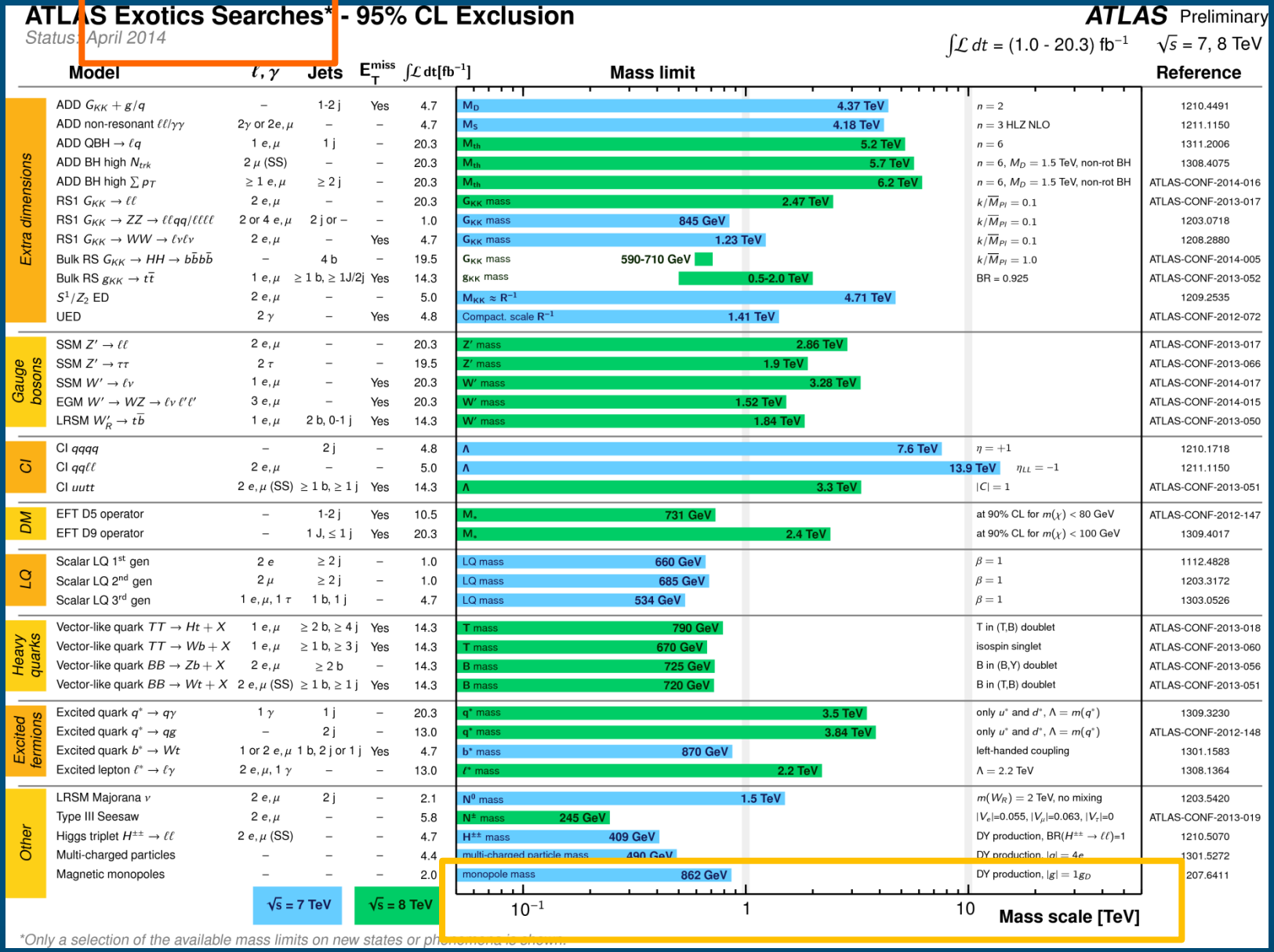


Run 1: Precision measurements?

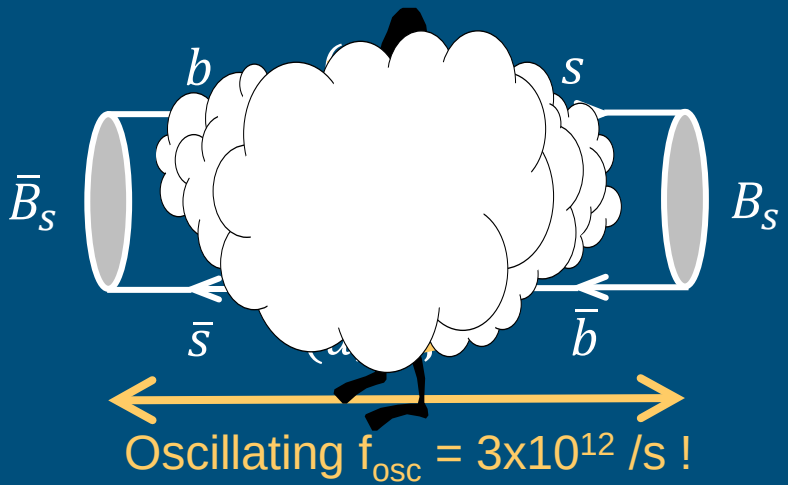
Recipe:

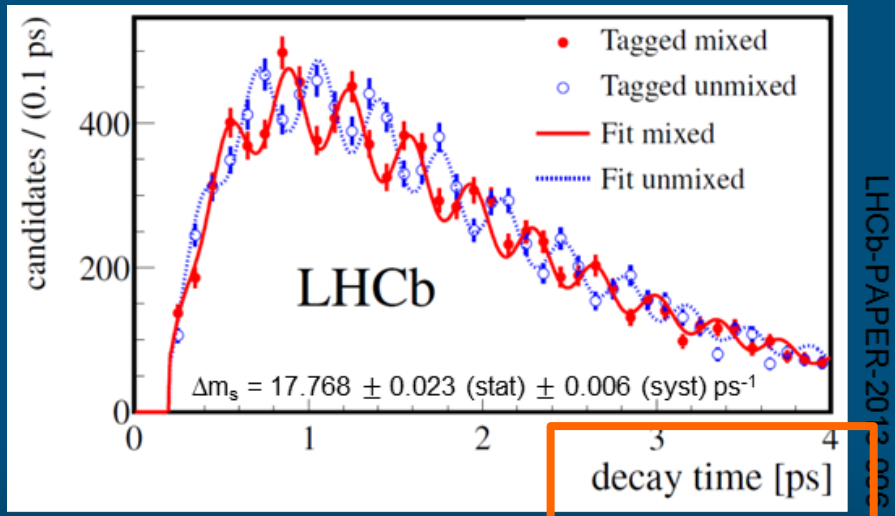
- Choose processes which are rare and calculable to high precision in SM
  - ➔ Indirectly find evidence for New Physics as discrepancy from SM prediction!
  - ➔ Virtual effects allow probing energies much higher than the E_{cms} of the LHC

Ex. B_s meson "adolescent identity problem"

$$\Phi_s^{exp} = \Phi_s^{SM} + \Phi_s^{NP}$$

Φ_s^{NP} contribution from New Physics





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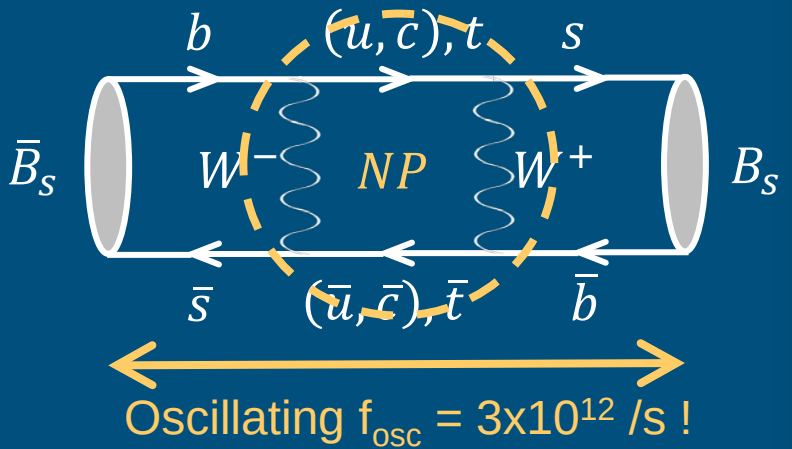
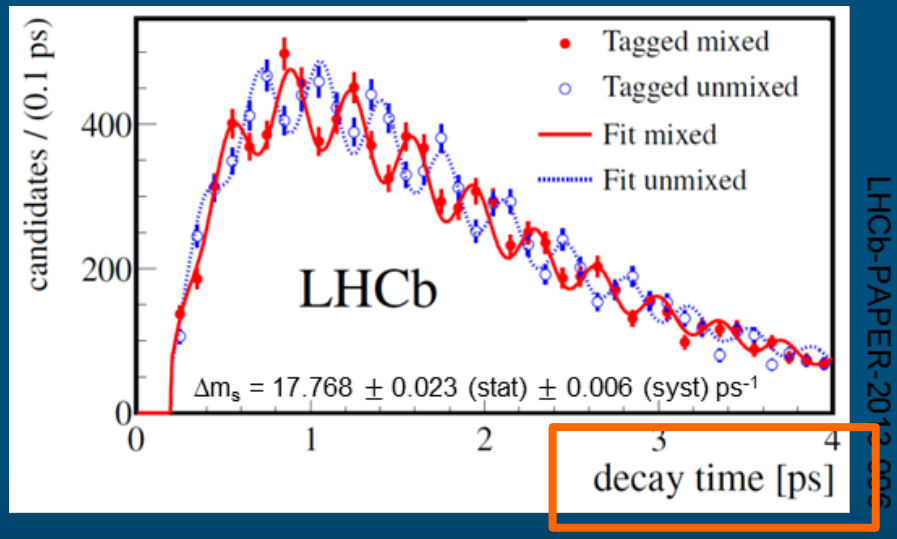
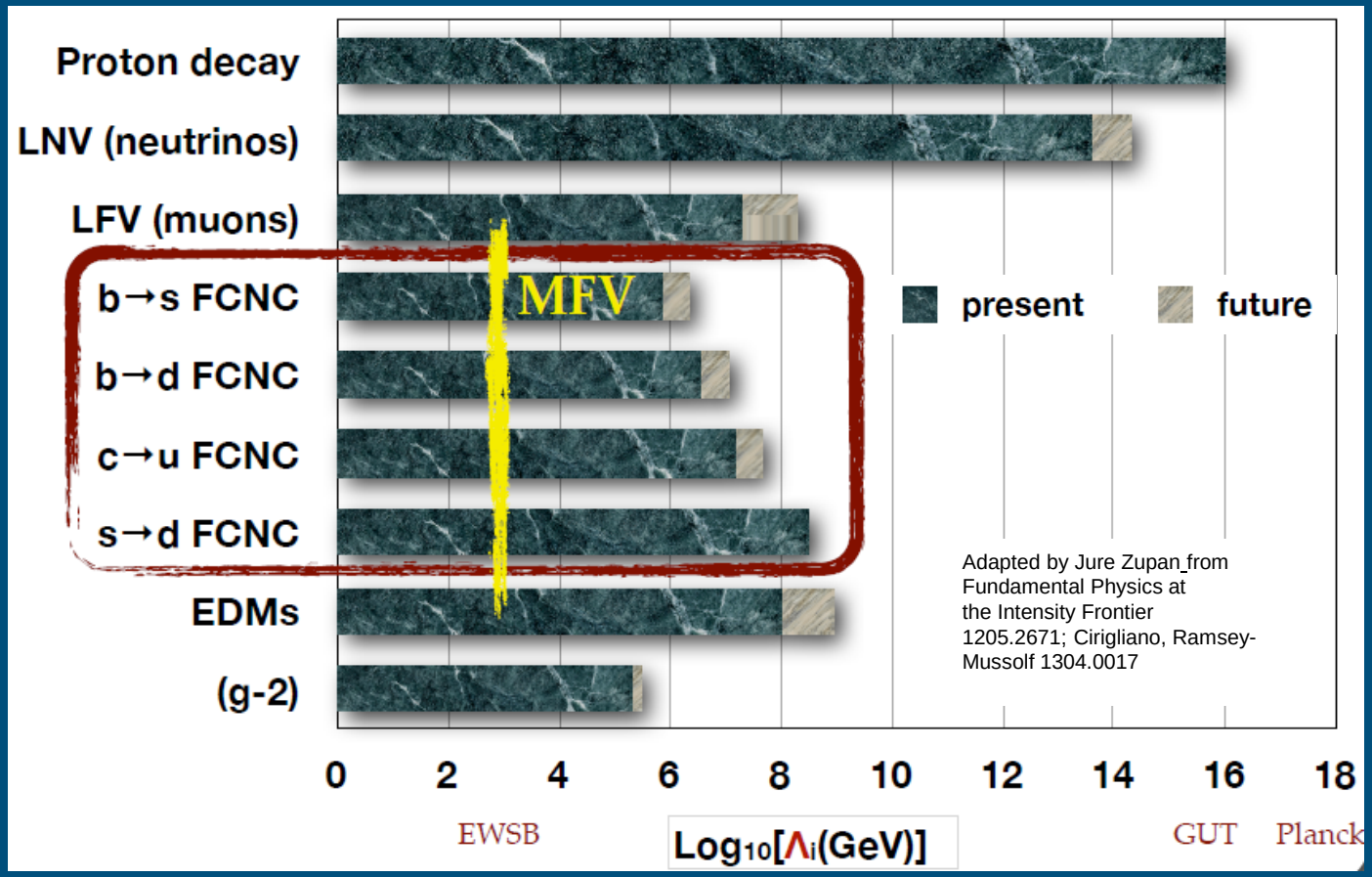




Run 1 Precision – What did we not find?

Push precisions! $\sigma_{stat+sys+th} < \Phi_s^{NP}$



No new particles in sight up to 10^4 TeV with coupling to flavour!! = 10 000 x direct reach of LHC!

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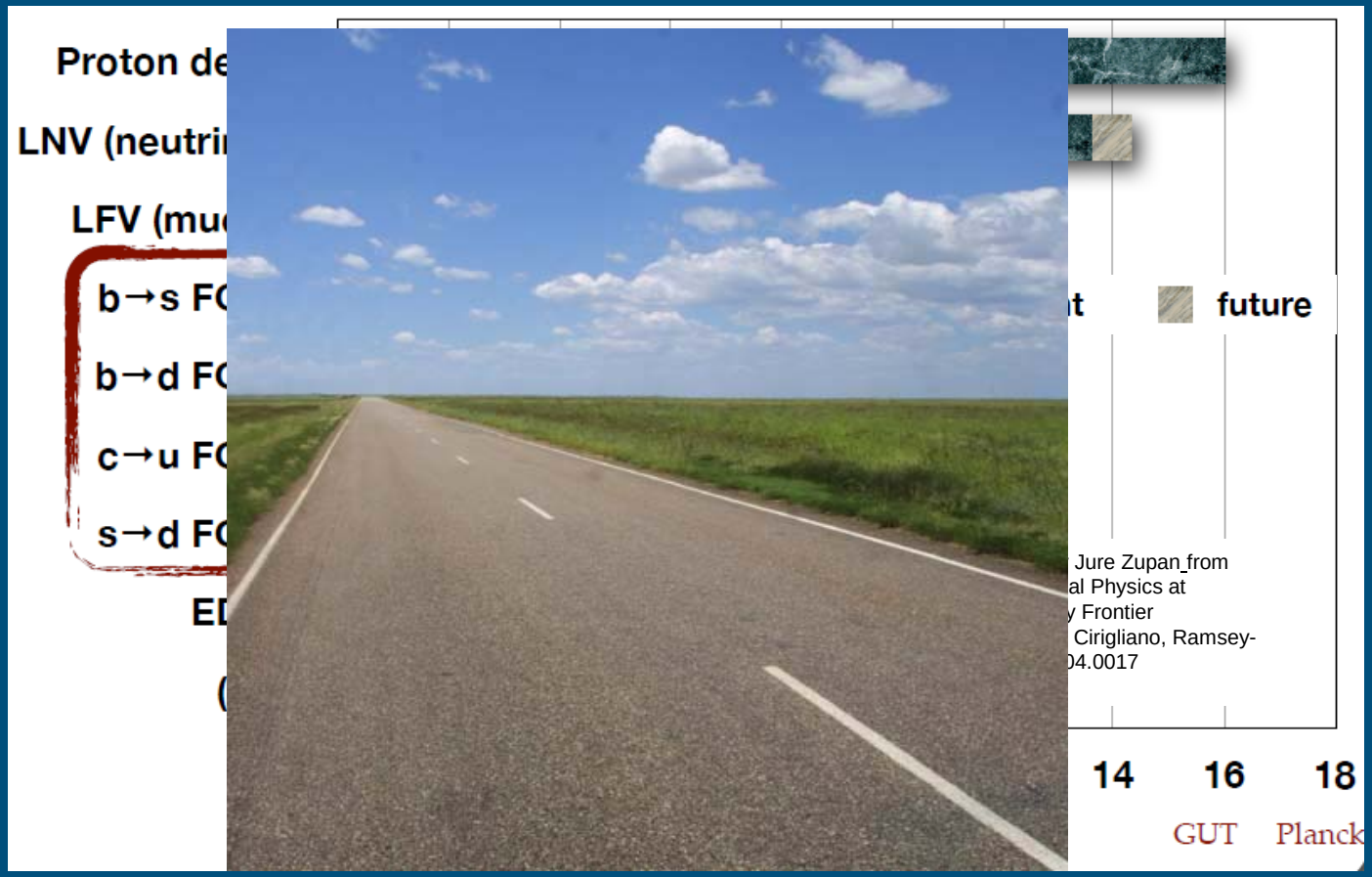

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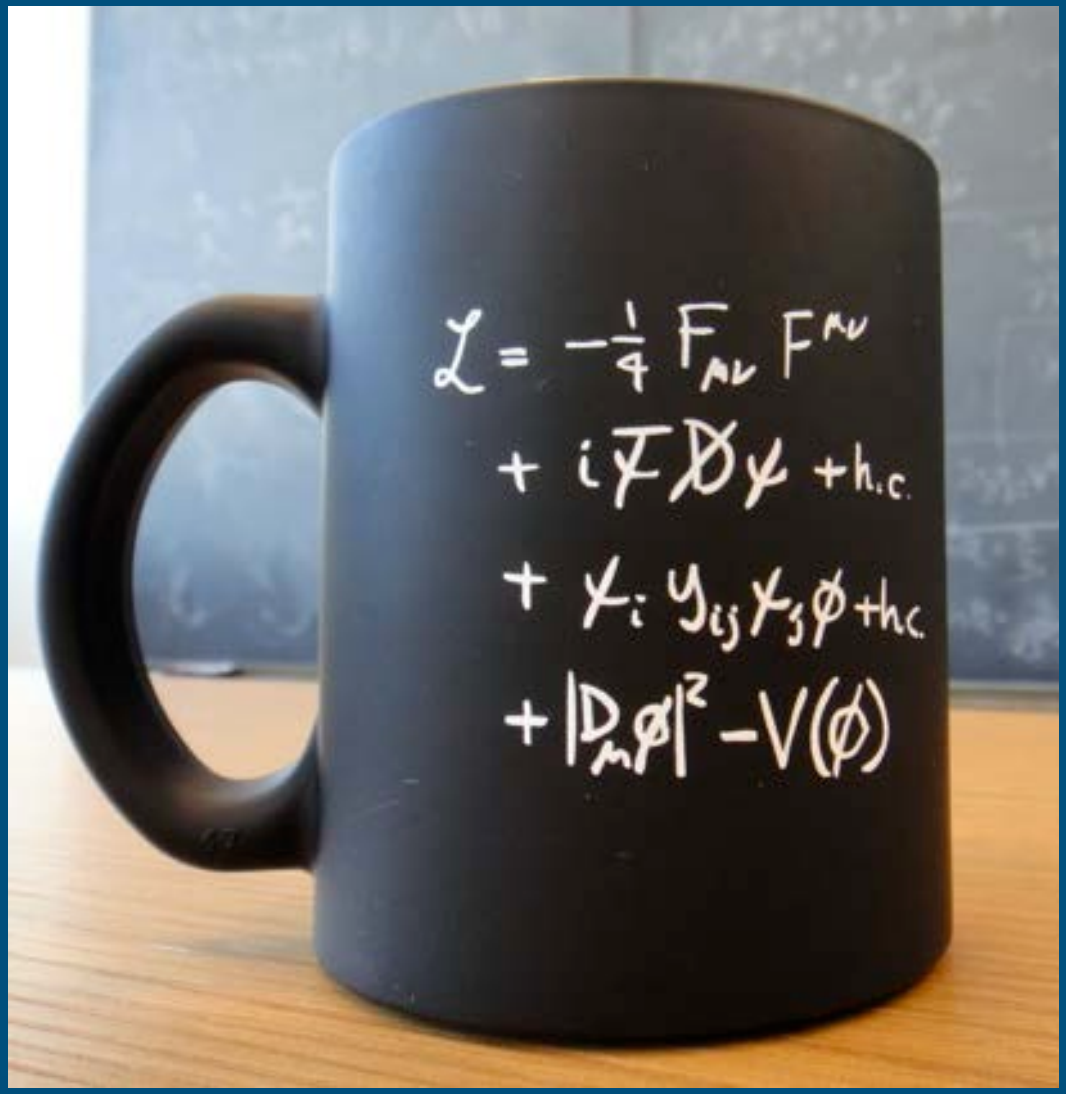
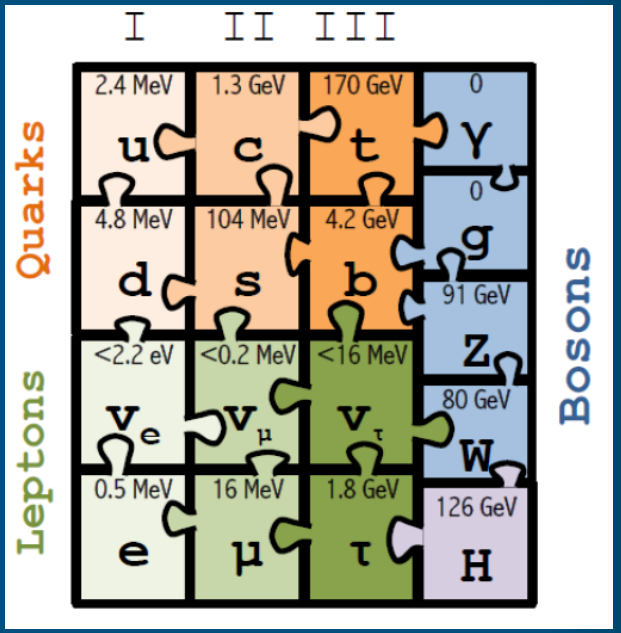
Universe 0 K – 10^{16}K++ in one formula?

- So, is it just this simple…??

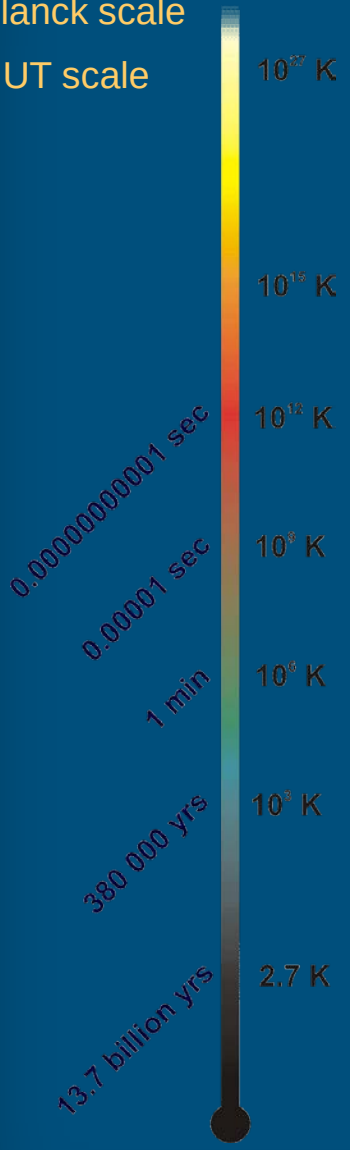




Validity of SM

Planck scale

GUT scale



New Physics (SUSY, extra dimensions, GUT, …)

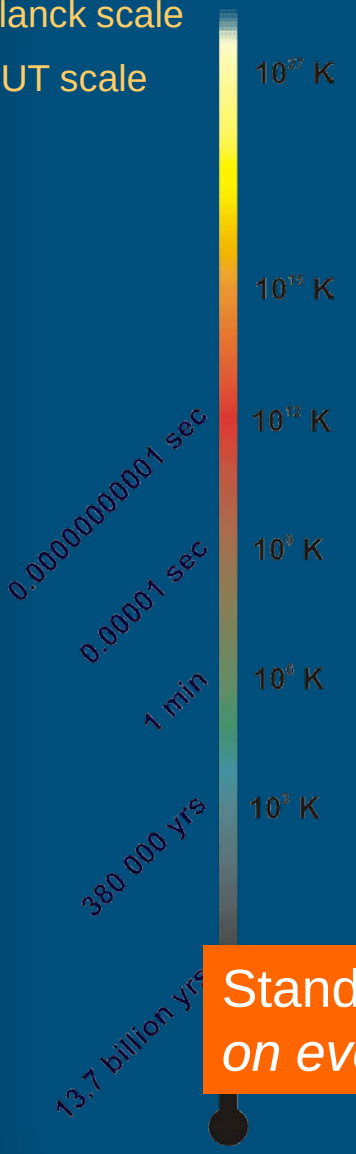
Standard Model

What we thought, or *hoped*….
And still do…

Validity of SM

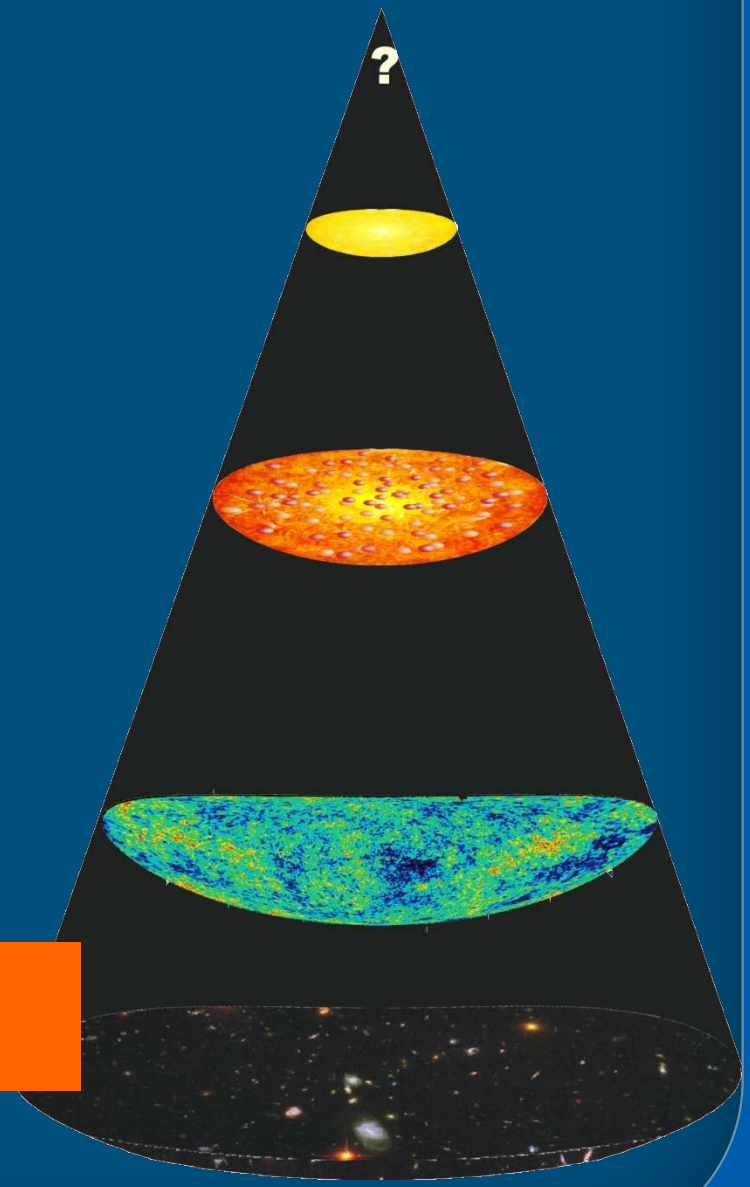
Planck scale

GUT scale



New Physics

Standard Model



Standard Model works perfectly well
on everything it attempts to explain

Validity of SM

Planck scale

GUT scale

10^{27} K

10^{15} K

10^{13} K

10^{9} K

10^{6} K

10^{3} K

2.7 K

0.000000000001 sec

0.00001 sec

1 min

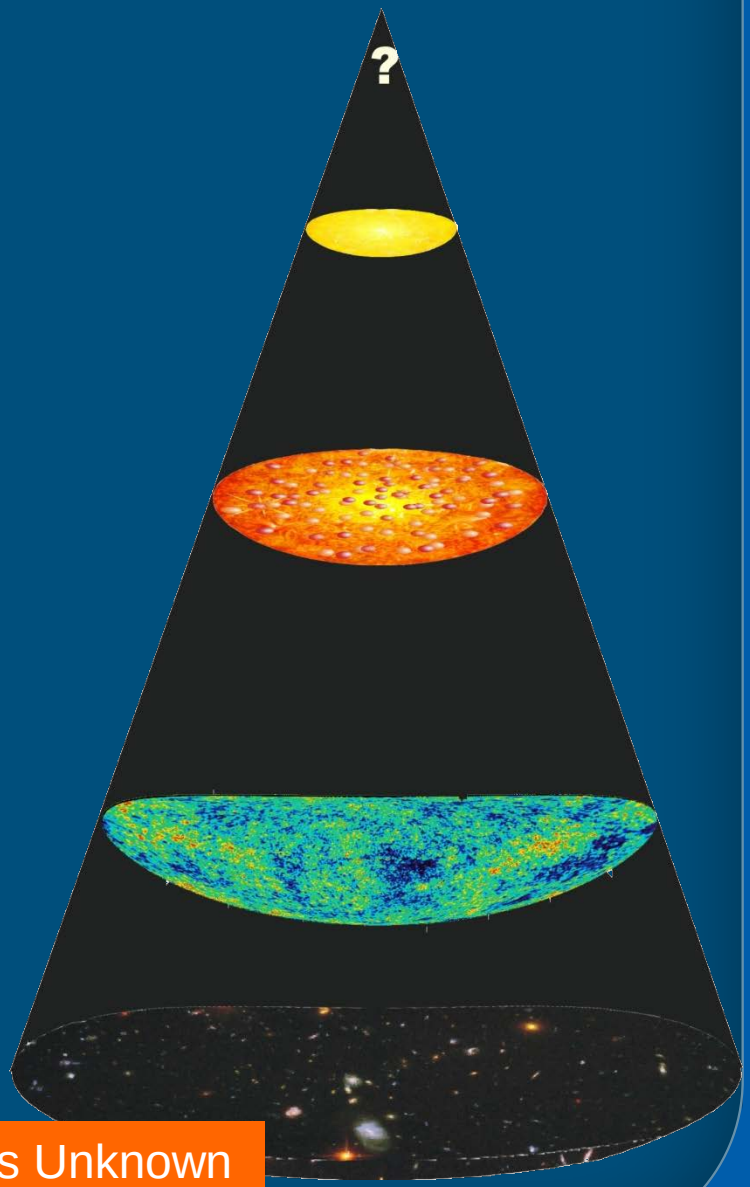
380 000 yrs

13,7 billion yrs

GUT - SUT

Standard Model

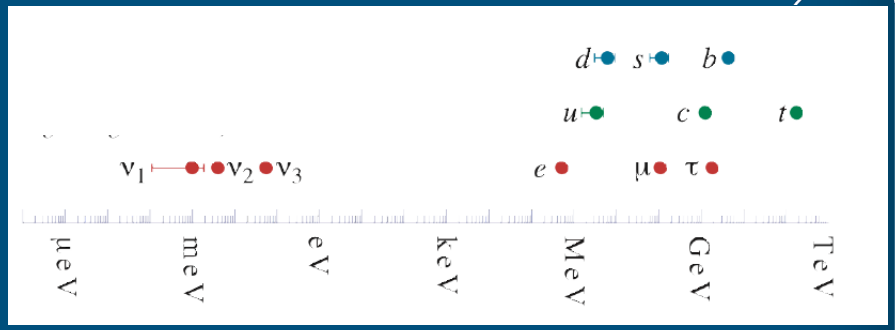
Hidden Sector??



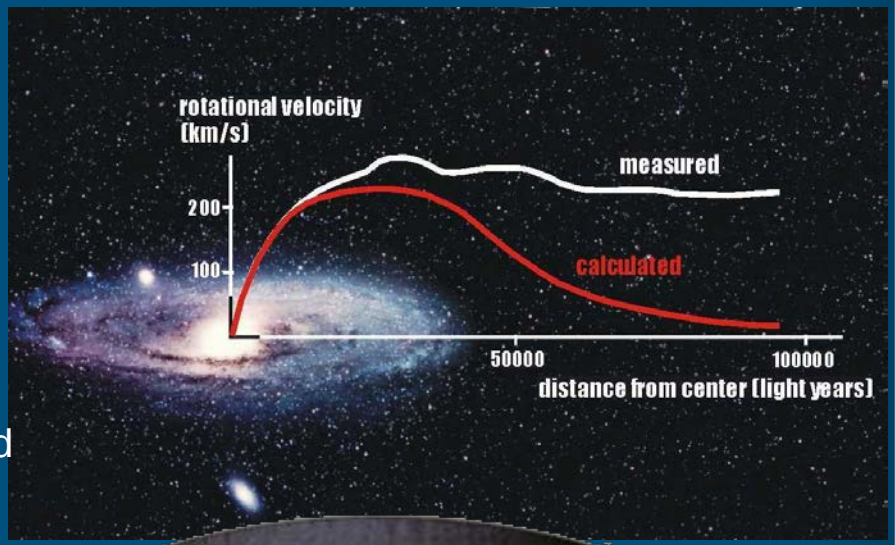
96% of energy content in Universe today is Unknown

Unresolved Experimental Evidence beyond SM

- **Neutrino oscillations**
  - → *Tiny* masses and flavour mixing

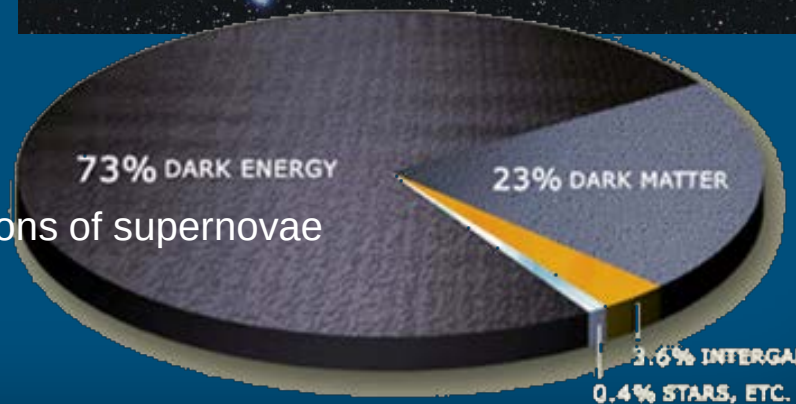


- **Baryon asymmetry of the Universe**
  - → BBN and CMB $\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim 6 \times 10^{-10}$
  - → CP violation in quark sector ➔ $\eta \sim 10^{-20}$!!



- **Dark Matter**
  - → Non-baryonic, neutral and stable or long-lived

- **Dark Energy**
  - → From apparent luminosity-distance observations of supernovae

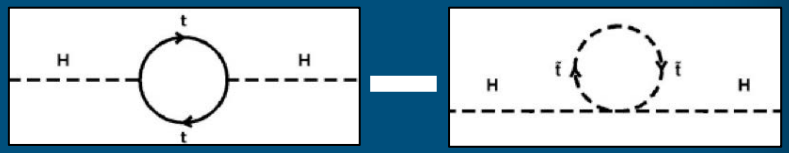


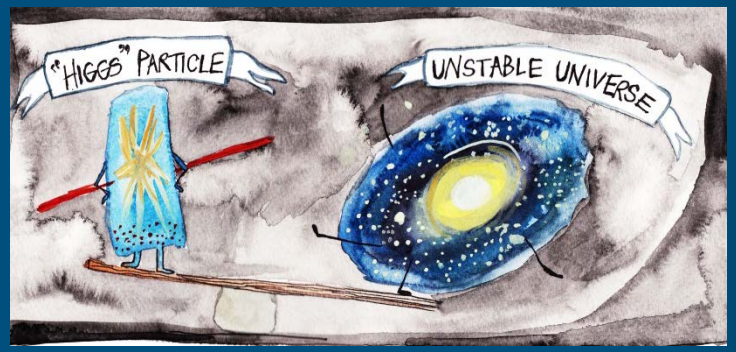
Unresolved Theoretical "Evidence" beyond SM

Prejudice…: "Universe is fine-tuned by chance or *driven* by obligation?"

Below GUT scale:

- Hierarchy problem
  → Stability of Higgs mass

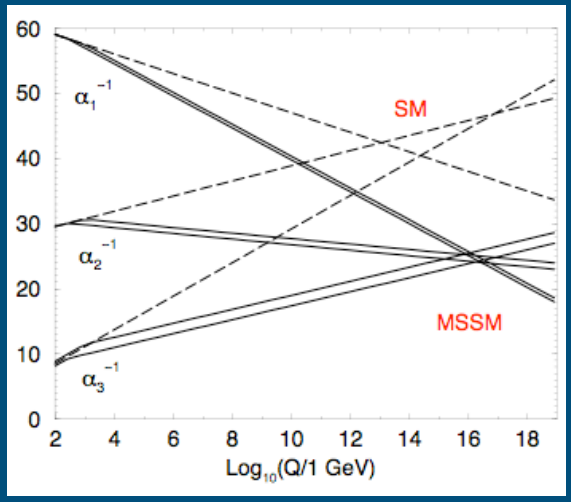




- SM flavour structure

- Strong CP problem
  - In principle, strong interaction comes with a naturally large CP violation, why suppressed?

- Unification of coupling constants



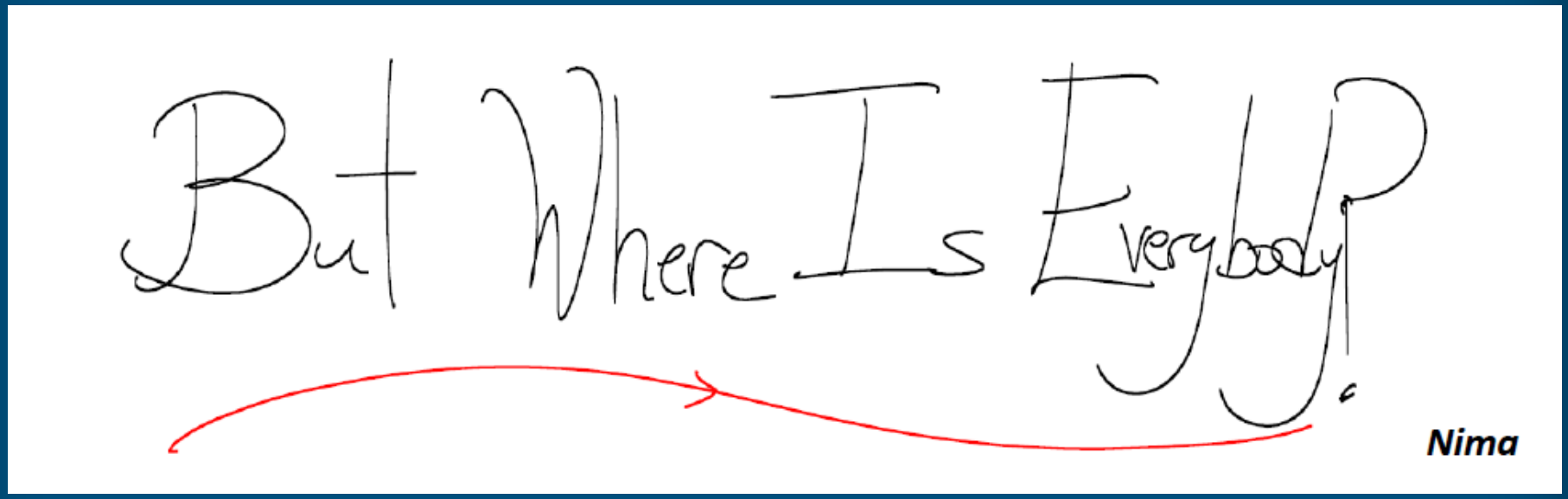
- Gravity

Above GUT scale (next time!)

- Event horizon problem, flatness, density variation which lead to structure formation,

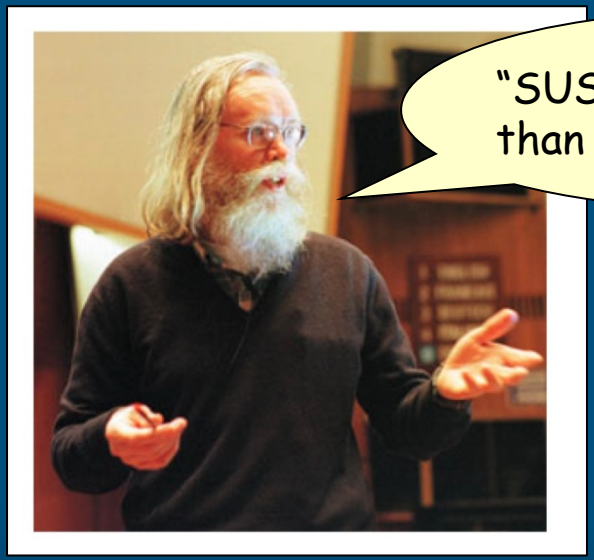
While we had bounds for the Higgs, no hard evidence for the next scale….

??



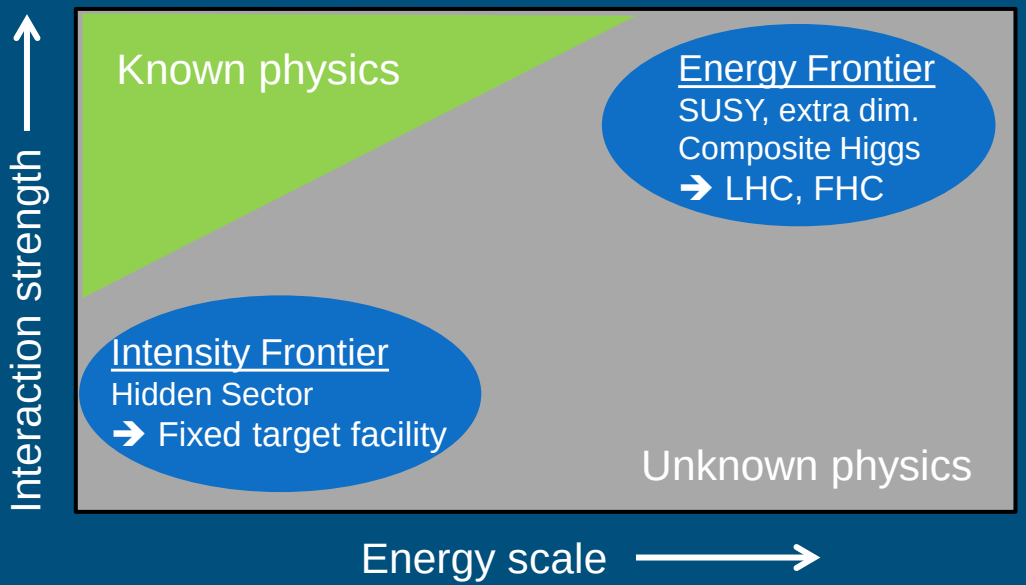
Why still SUSY searches in 2040++ ?

Indeed, even if fine-tuned,
it makes our universe more likely



On the contrary - What if...?

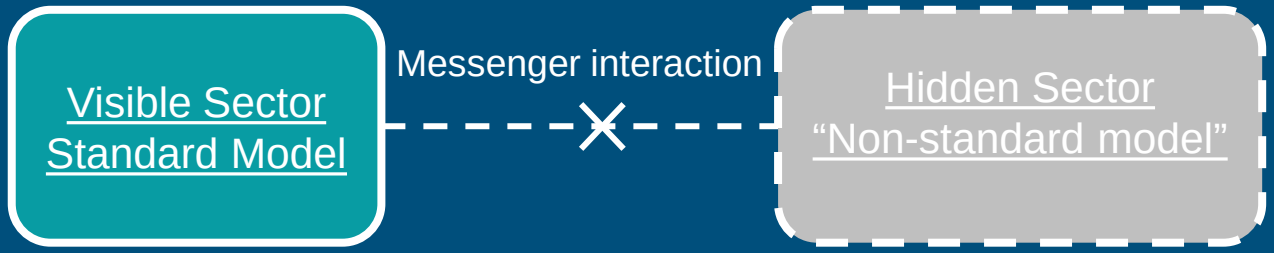
What about solutions to (some) these questions *below* the mass of the W boson?



➔Must have very weak couplings ➔ Hidden Sector

Hidden Sector?

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



- Most Hidden Sector particles have none of the charges of SM, only make up mass!
  - Hidden Sector may have their own charges and dynamics! ➔ Mirror World

- Some may have both SM and HS charges!

$$\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{HS}^{(k)} \mathcal{O}_{SM}^{(l)}}{\Lambda^n}$$

  ➔ "Portals" to the Hidden Sector !

  ➔ Dynamics of Hidden Sector may drive dynamics of Visible Sector!
    - Dark Matter
    - Higgs mass
    - Neutrino oscillations
    - Baryon asymmetry
    - Dark Energy
    - Inflaton
    - ……

Examples of Portals to Hidden Sector

- Standard Model portals:
  - D = 2: Vector portal
    - Kinetic mixing with massive dark/secluded/paraphoton V : $\frac{1}{2}\varepsilon F_{\mu\nu}^{SM} F_{HS}^{\mu\nu}$

    ➔ Interaction with ‘mirror world’ constituting dark matter

  - D = 2: Higgs portal
    - Mixing with dark scalar χ : $(\mu\chi + \lambda\chi^2)H^\dagger H$

    ➔ Mass to Higgs boson and right-handed neutrino, and function as inflaton in accordance with Planck and BICEP measurements

  - D = 5/2: Neutrino portal
    - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $YH^\dagger \bar{N} L$

    ➔ Neutrino oscillation, baryon asymmetry, dark matter

  - D = 4: Axion portal
    - Mixing with axion like particles, pseudo-scalars, axial vectors : $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

    ➔ Solve strong CP problem

  - And higher dimensional operator portals and supersymmetric portals (light sgoldstino, light neutralino,…)

Common features of 'Portals' to Hidden Sector

"Direct detection" through both portals in and out:

- Cosmologically interesting and accessible $m_{HS} \sim \mathcal{O}(MeV - GeV)$
  - ➔ Production through meson decays (π, K, D, B)
  - ➔ Decay to $l^+l^-,\ \pi^+\pi^-, l\pi,\ l\rho,\ \gamma\gamma$, etc

- Production and decay rates are very suppressed relative to SM.
  - Production branching ratios $\mathcal{O}(10^{-10})$
  - Long-lived objects
  - Travel unperturbed through *ordinary* matter

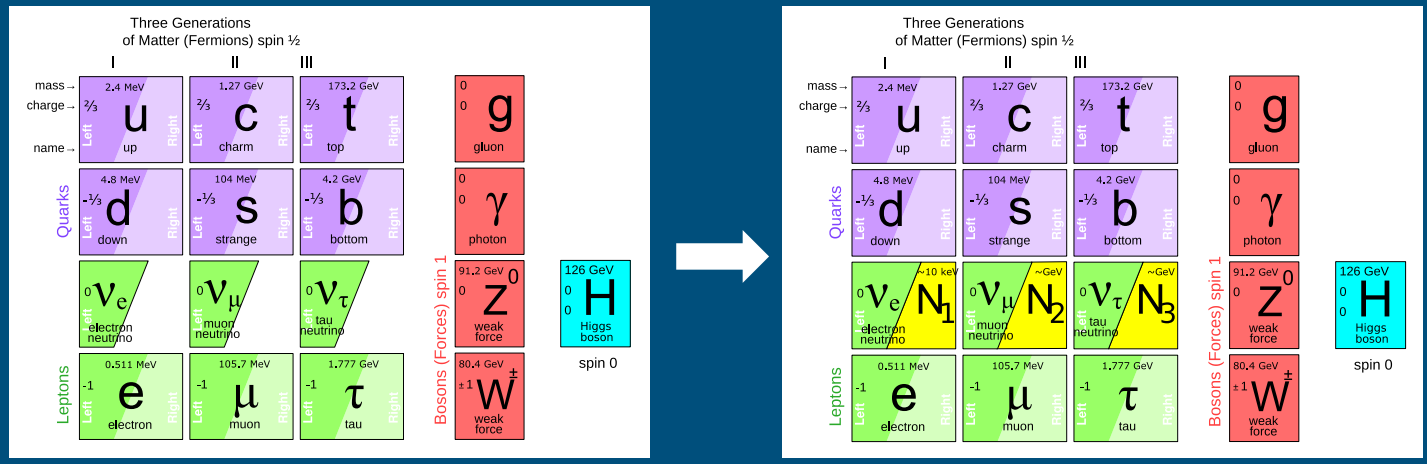
➔ Fixed-target experiment

➔ Large number of protons on target and large decay volume!

Experimental challenge ➔ Intensity Frontier

➔ Complementary physics program to searches for new physics by LHC!

Ex. Right-handed Majorana neutrinos



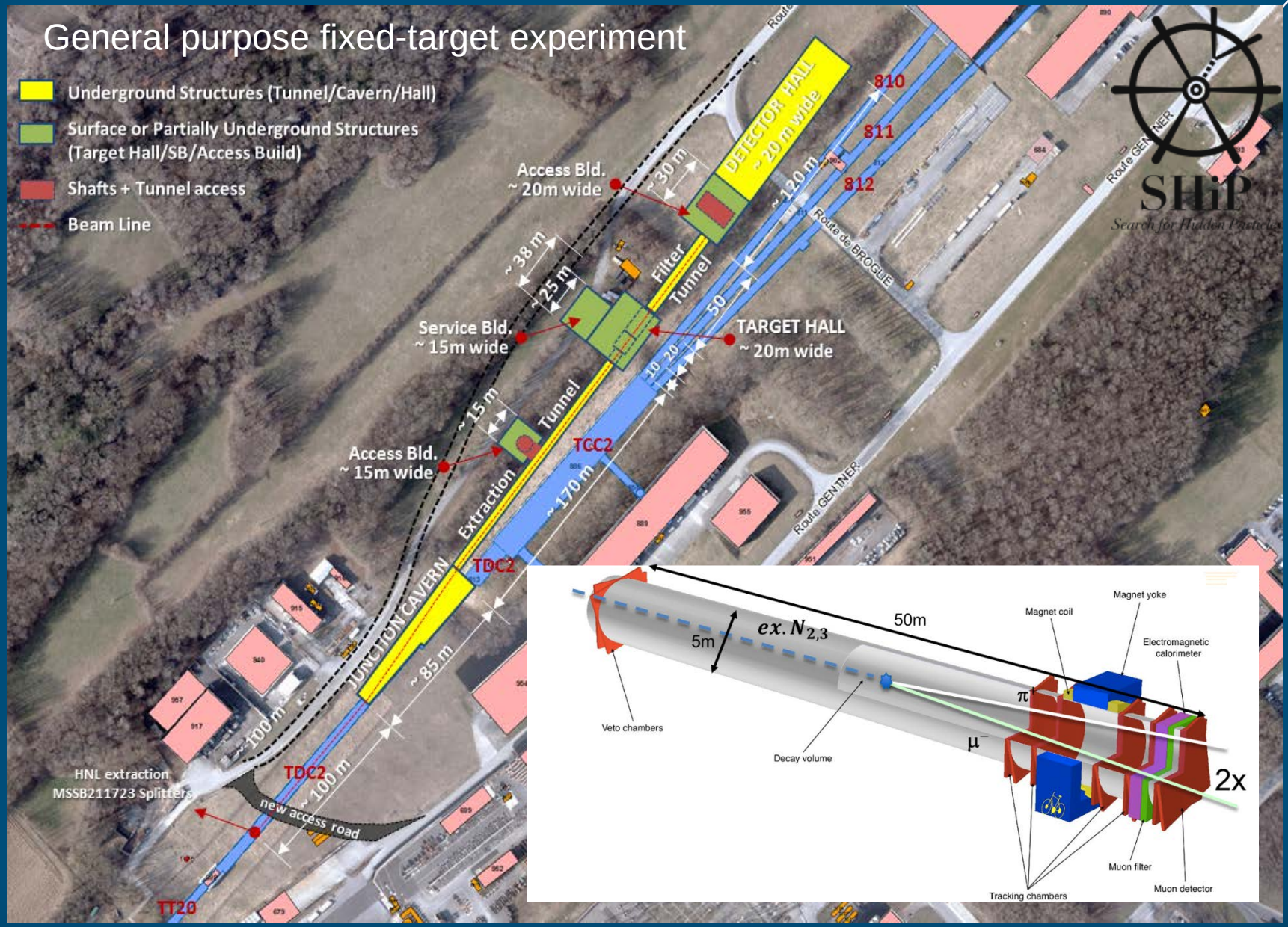
- Ex. νMSM with Heavy Neutral Leptons by Asaka and Shaposhnikov

Role of N_1 with a mass of $\mathcal{O}$(keV)
➔ Dark Matter

Role of N_2 and N_3 with a mass of $\mathcal{O}(m_q/m_{l^\pm})$ (100 MeV – GeV):
➔ Neutrino oscillations and mass, and matter-antimatter asymmetry

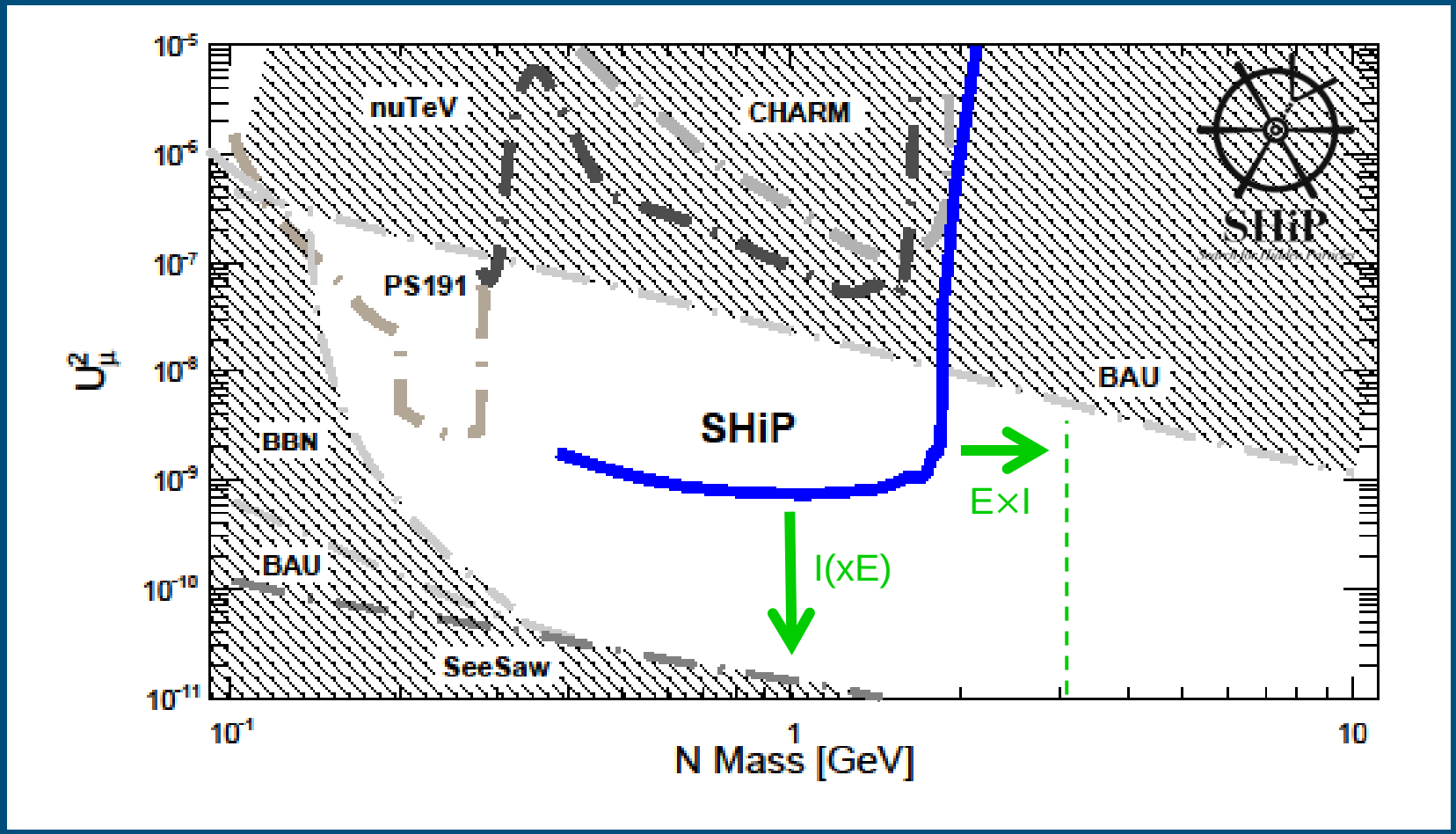
Simple extension and no new energy scale!

Proposal: Search for Hidden Particles



Ex. Expected Sensitivity to $N_{2,3} \rightarrow \mu\pi$

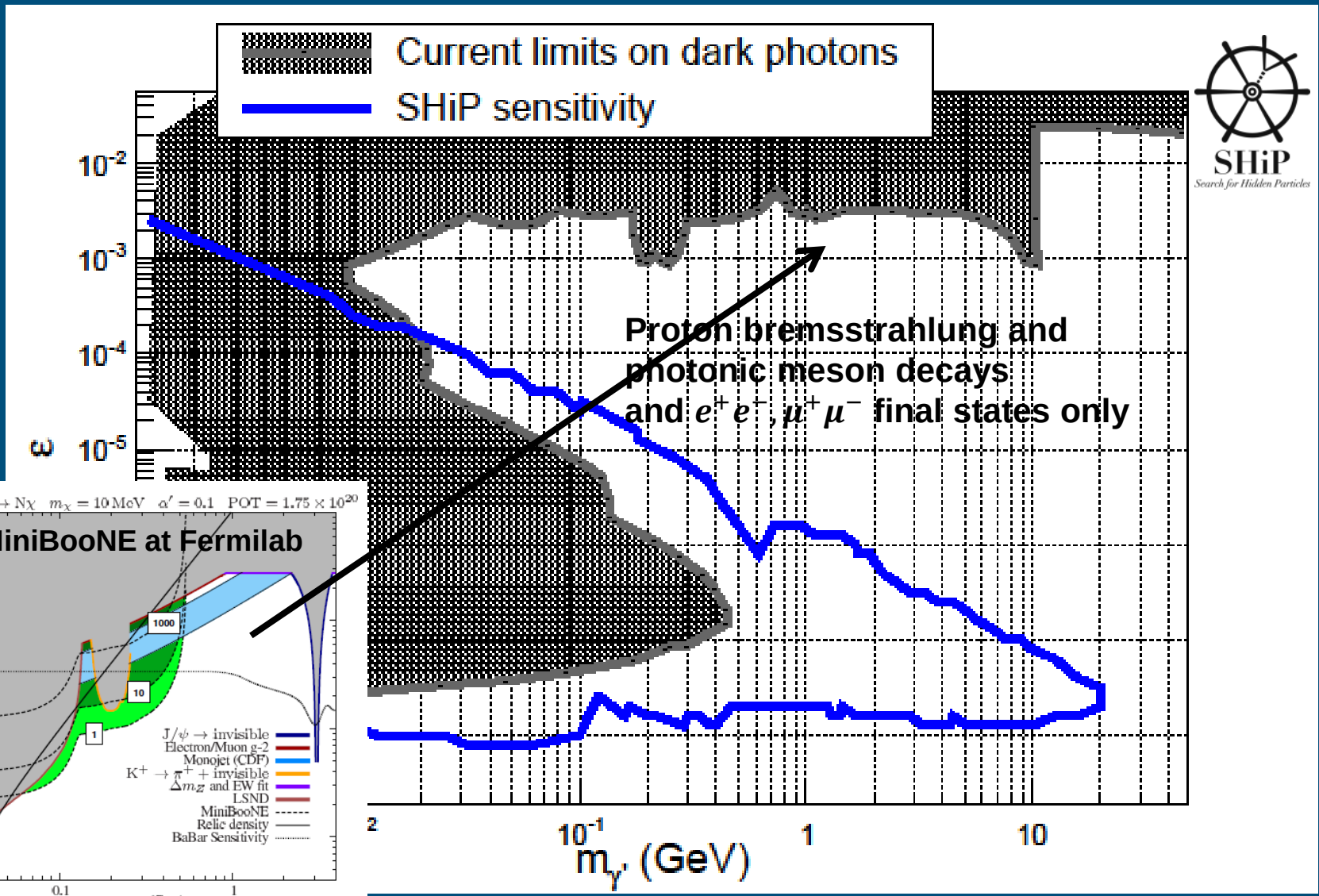
Sensitivity based on current SPS with 2×10^{20} p.o.t in ~5 years of CNGS-like operation



→ Colliders out of luck

- LHC ($\sqrt{s}$ = 14 TeV): with 1 ab^{-1}, i.e. 3-4 years: ~ 2×10^{16} in 4π
- SPS@400 ($\sqrt{s}$ = 27 GeV) with 2×10^{20} pot, i.e. ~5 years: ~ 2×10^{17}

Ex. Expected sensitivity to Dark Photons



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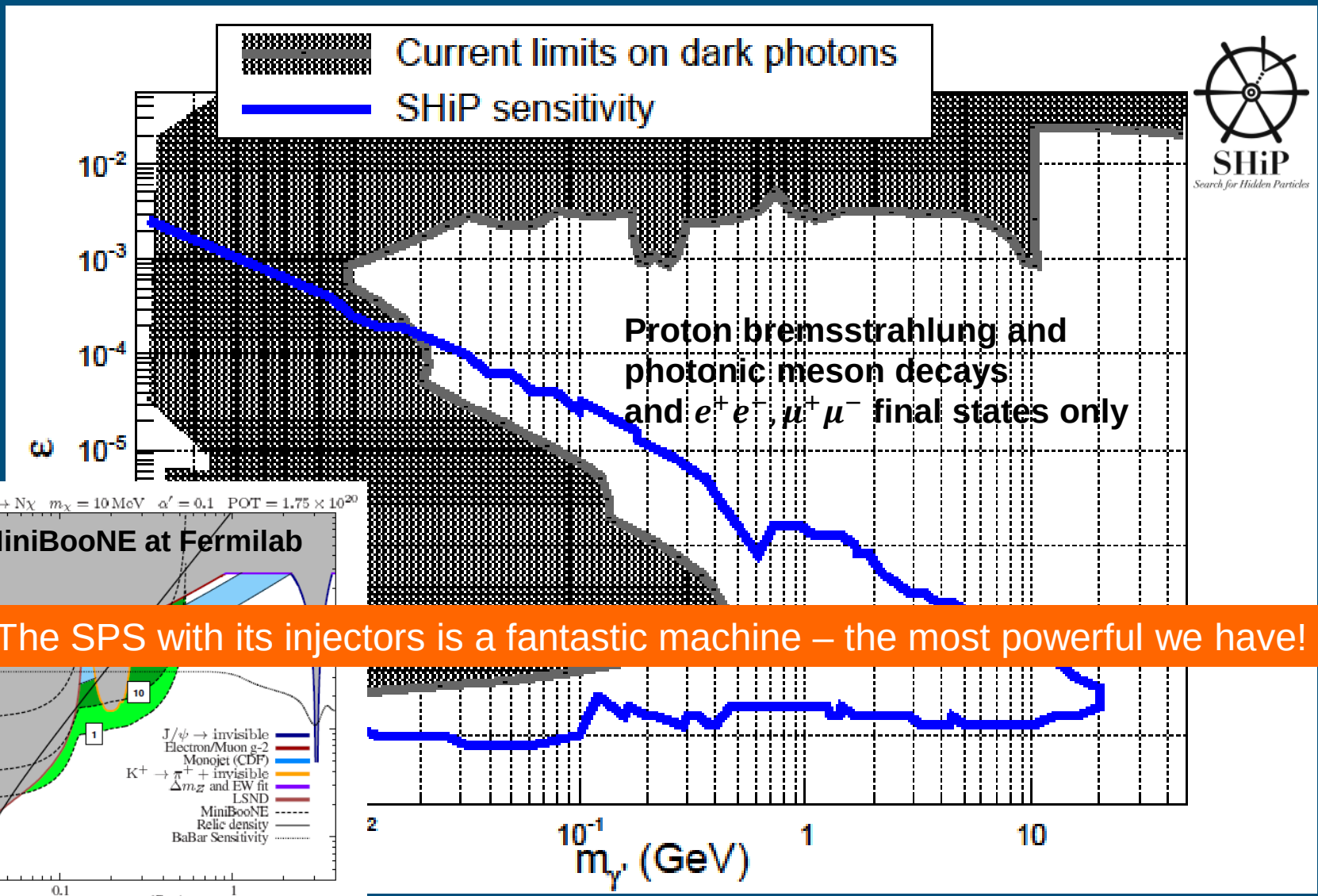

The SPS with its injectors is a fantastic machine – the most powerful we have!

Conclusions

We worried about finding just a Standard Model Higgs….

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…but taking all experimental results together with the remarkable progress in cosmological observations and theory makes the situation even more intriguing!

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…but taking all experimental results together with the remarkable progress in cosmological observations and theory makes the situation even more intriguing!

- The future requires a very open strategy and multiple points of attack!
  - Continued searches with the opening of a new energy domain at ~13 TeV
  - Precision measurements of Higgs and the top quark
  - Precision measurements in flavour physics

  …and…
  - Searches for a Hidden Sector!
- SPS is the most powerful machine there is around
- However, it remains clear, whatever is found or not found will require
  - Future colliders

  …and…
  - Future (fast cycling!) injectors for fixed target experiments!

Conclusions

We worried about finding just a Standard Model Higgs….

…but taking all experimental results together with the remarkable progress in cosmological observations and theory makes the situation even more intriguing!

- The future requi… …f attack!
  - Continued sea… …~13 TeV
  - Precision mea…
  - Precision mea…

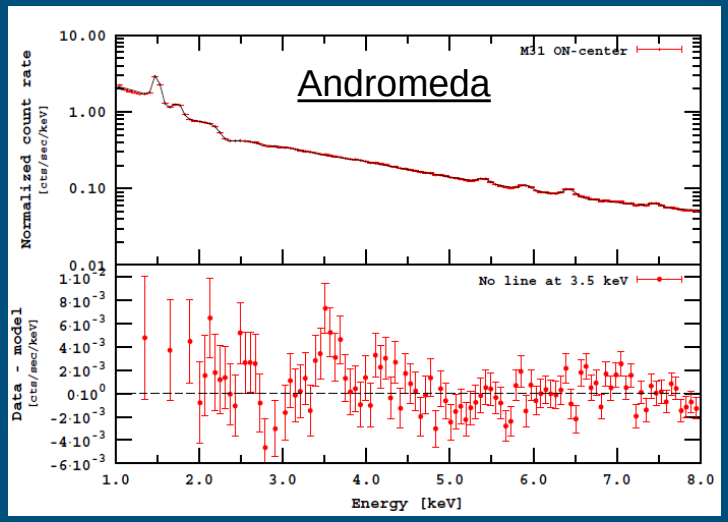
  …and…
  - Searches for a…
- SPS with its inje… …round
- However, it rema… …require
  - Future colliders

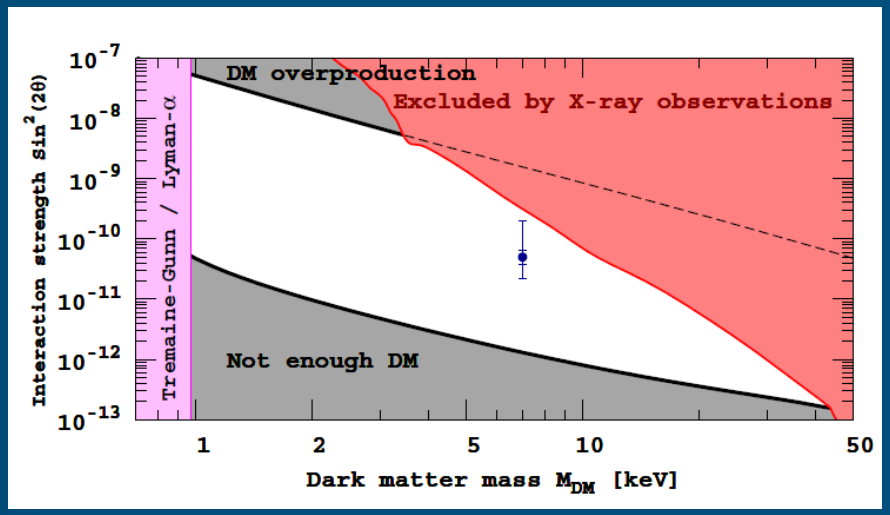
  …and…
  - Future (fast cycling!) injectors for fixed target experiments!

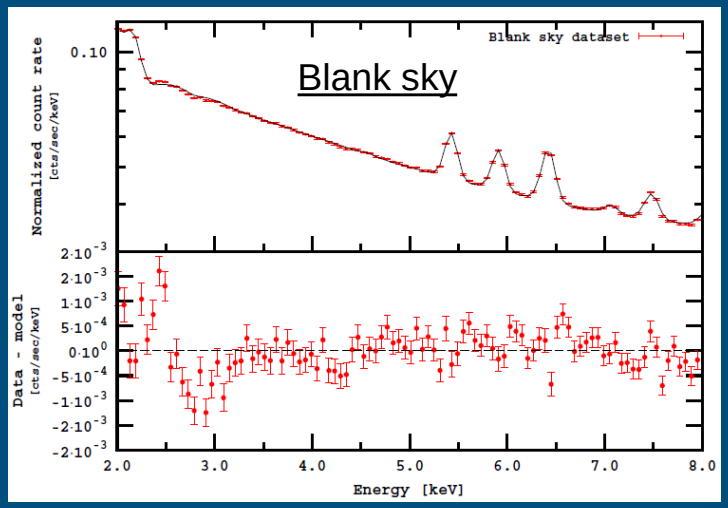
Reserve

Intriguing hints from galaxy spectrum?

- Two recent publications:
  - ➔ arXiv:1402.2301 : Detection of an unidentified emission line in the stacked XMM-Newton X-ray spectra of Galaxy Clusters at $E_\gamma \sim (3.55 - 3.57) \pm 0.03 keV$
  - ➔ arXiv:1402.4119 : An unidentified line in the X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster at $E_\gamma \sim 3.5\ keV$







Confirmation by Astro-H with better energy resolution required