Beyond the Standard Model: The theories & their practice

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The Standard Model:

Triumph in science!

With the Higgs discovery, completion of the SM:

Talks by David Kaplan, Luca Silvestrini, Margarete Muhlleitner, Kun Liu, Biagio Di Micco …

- A relativistic & quantum-mechanical
- Perturbative & unitary
- Renormalizable & ultra-violet (UV) complete

→ potentially valid up to an exponentially high scale, perhaps to the Planck scale!

All known physics

$$W = \int_{k<\Lambda} [\mathcal{D}g \ldots] \; \exp\left\{ \frac{i}{\hbar} \int d^4x \sqrt{-g} \left[\frac{1}{16\pi G} R - \frac{1}{4} F^2 + \bar{\psi} i \not{D} \psi - \lambda \phi \bar{\psi} \psi + |D\phi|^2 - V(\phi) \right] \right\}$$

amplitude | current understanding | quantum mechanics | spacetime | gravity | strong & electroweak | matter | Higgs

An eminent physicist remarked:

"... most of the grand underlying principles have been firmly established. The future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

Michelson–Morley experiment (1887):
"the moving-off point for the theoretical aspects of the second scientific revolution"

Will History repeat itself (soon)?

Lessons -- 温故知新
from the SM in the making:
1. "UV completion" as a guide has NOT served us well … ☹

- QED is UV complete, but doesn't go beyond O(GeV)

  e.g. $(g\text{-}2)_e$ versus $(g\text{-}2)_\mu$ Talks by Aida El-Khadra, Hogan Nguyen
- QCD is UV complete, could be dynamically extrapolated to an exponentially high scale Q

$$\alpha_s(Q^2) \approx 1/\ln(Q^2/\Lambda^2_{QCD}) \Rightarrow \Lambda_{QCD} \approx Q\exp(-1/2\alpha_s)$$

  But new physics comes in at $v \sim 250$ GeV
- The SM with the Higgs IS UV complete,

but what confidence do we have to extrapolate it to $O(M_{PL})$?

→ Go for BSM!

Lessons

from the SM in the making:
2. "Naturalness" guides the intuition, BUT facing the challenge … ☹

- In chemistry/AMO, m_e sets the scale, naturally :

$$a_{Bohr} = 1/\alpha m_e \sim 0.05 \text{ nm}, \quad E_{atom} \sim \alpha^2 m_e \sim 30 \text{ eV}$$

- Weak decay sets the scale: $1/\sqrt{G_F} \sim v \sim 250$ GeV

→ the gauge boson mass, naturally:

$$M_W = \frac{1}{2} g v \approx 80 \text{ GeV}, \quad \Delta M_W^2 \sim M_W^2 \ln(\Lambda/M_W)$$

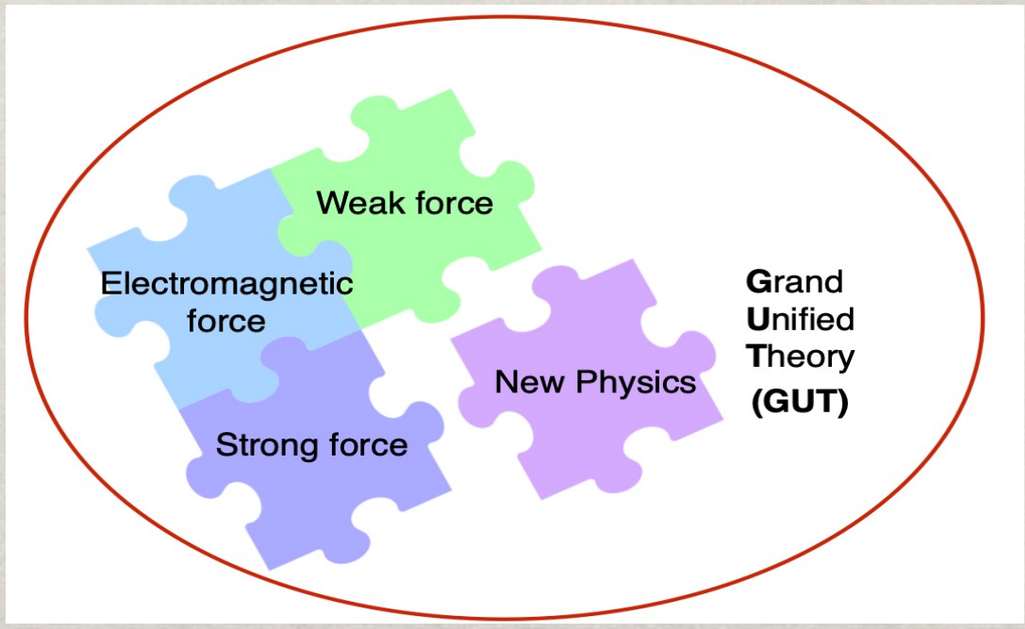
- But the Higgs mass fails our intuition, in the Wilsonian sense:

$$m_H = \sqrt{2}\,\boldsymbol{\mu} = (2\lambda)^{1/2}\, v = 125 \text{ GeV} \qquad \delta m_H^2 \propto -\frac{k^2}{4\pi^2}\Lambda^2$$

What is $\boldsymbol{\Lambda}$? $\boldsymbol{\Lambda} \sim 4\pi v$, or M_{SUSY}, or M_{PL} ?

Lessons
from the SM to beyond:
3. "Unification" reveals deep principles

- Newtonian universal gravitation unified the terrestrial & celestial forces & motion 👍
- Maxwell equations unified the electricity & magnetism
- The SM unifies the electromagnetism (**γ**) & weak force ($W^{\pm}$, Z^0) to "electroweak"
- "Grand unification"?



Gauge symmetry unification:

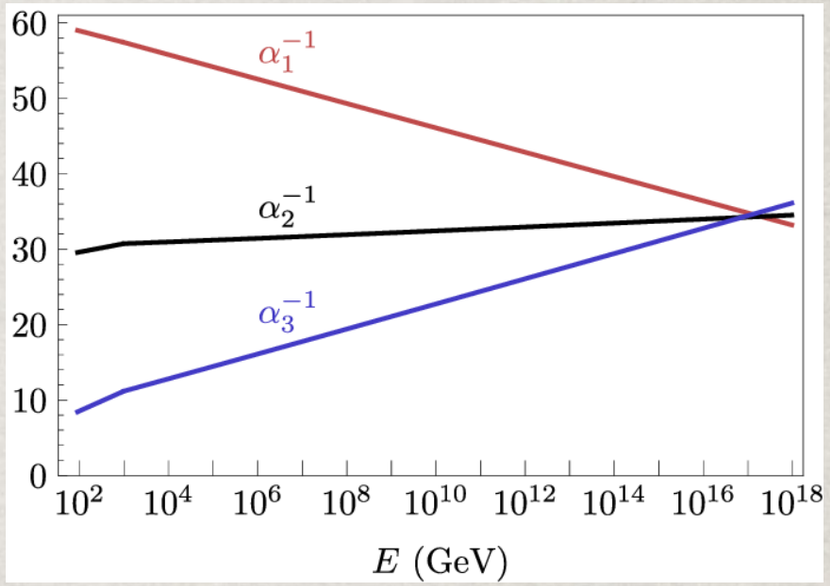
$G_{GUT} \supset G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$G_{GUT} = SU(5);\ SO(10)$

$SU(4)_c \otimes SU(2)_L \otimes SU(2)_R$

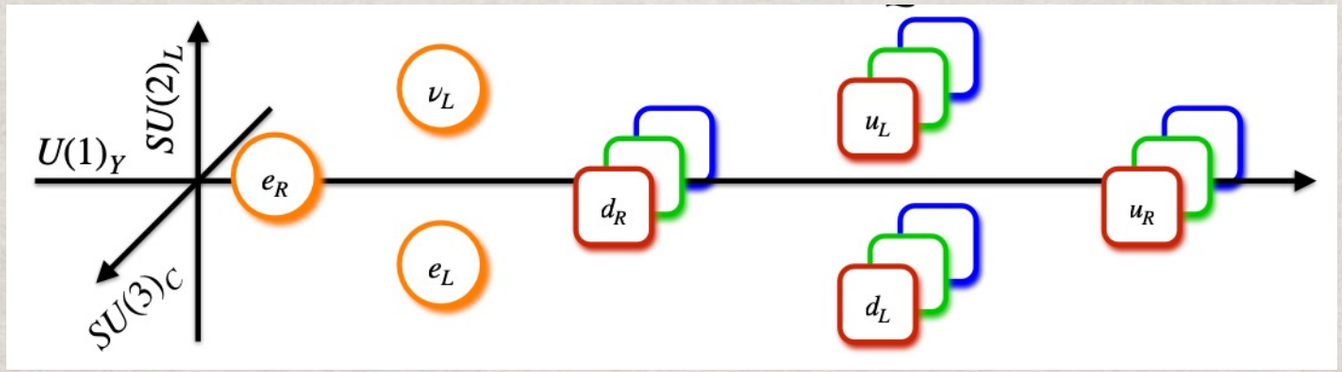
Coupling constant unification:

at M_{GUT} : $g_1 \approx g_2 \approx g_3$

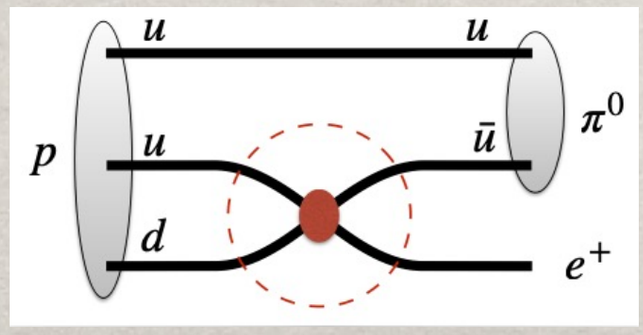


Particle content unification:

Quarks ←→ leptons in the same multiplets



Observationally: the proton decay or $n - \bar{n}$ oscillation



$$\tau_p \propto M_{GUT}^4 / m_p^5$$

$$\tau_{exp} > 1.67 \times 10^{34} \text{ years (SuperK)}$$

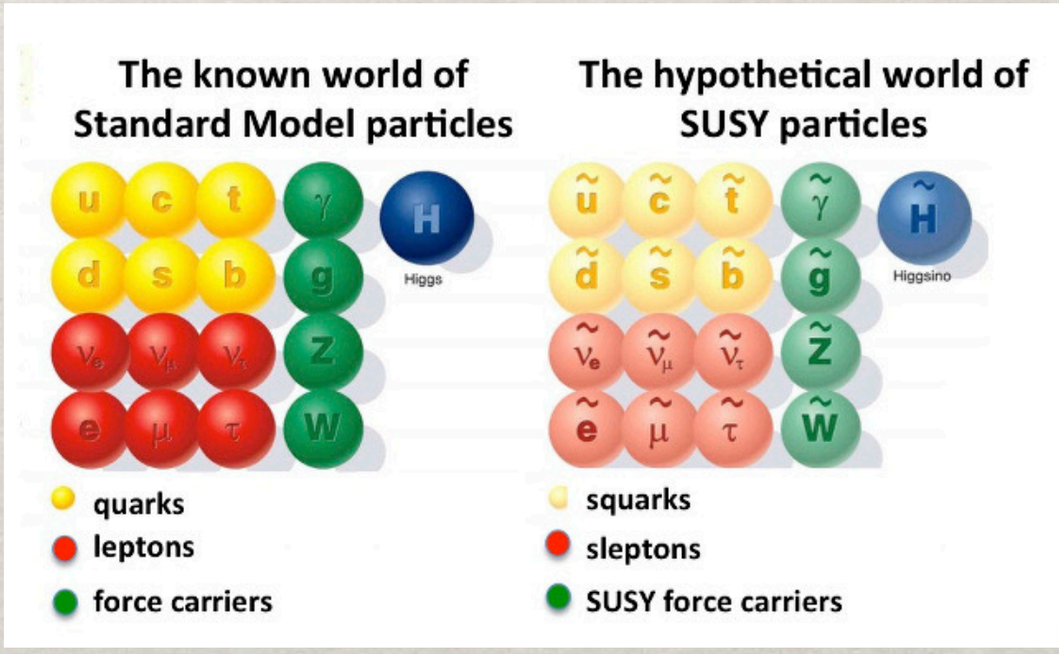
$$\Rightarrow M_{GUT} > 2 \times 10^{16} \text{ GeV}$$

Lessons
from the SM to beyond:
4. "Symmetry" governs dynamics

- Time translation → energy conservation 👍
- Spatial translation → momentum conservation
- 3D rotation → angular momentum conservation
- Poincare invariance → mass & spin of states
- "higher symmetry" of space-time & S-matrix
  Supersymmetry? Bosons ←→ Fermions

Observationally:
hopefully near the EW scale O(100 GeV)

Talk by Margarete Muhlleitner



Supersymmetry in theory:

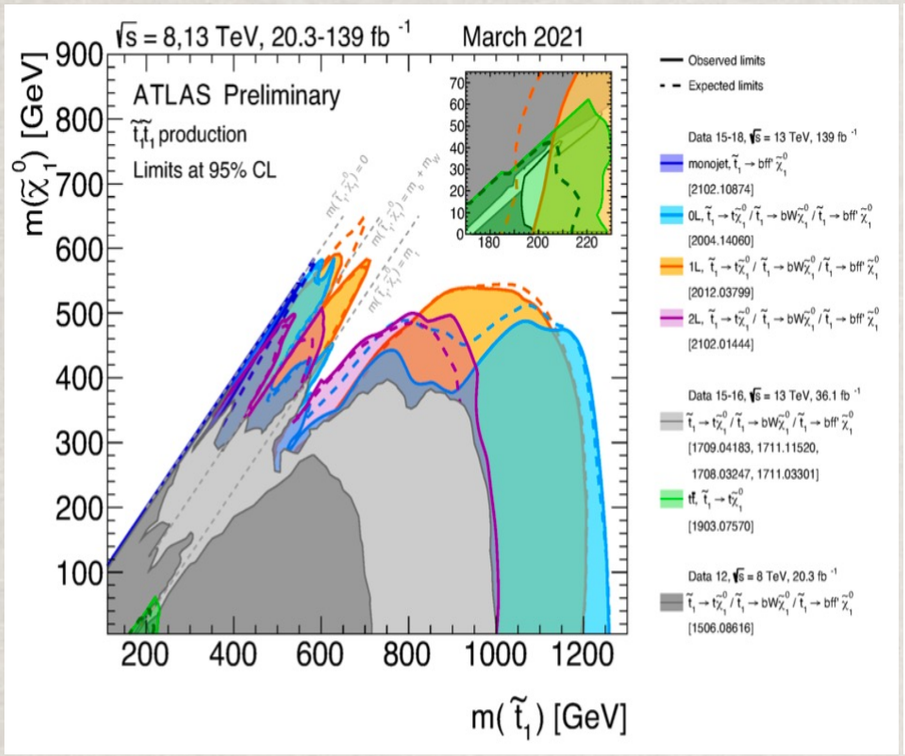
- SUSY unification
- Super-gravity
- Super-string/M theory
- Swampland

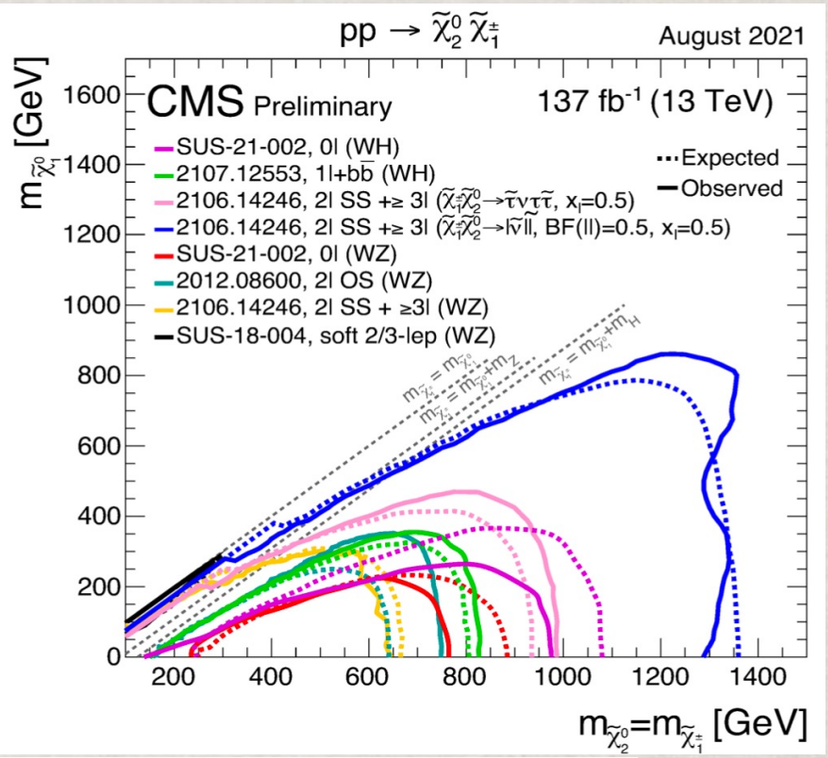
Supersymmetry in practice:

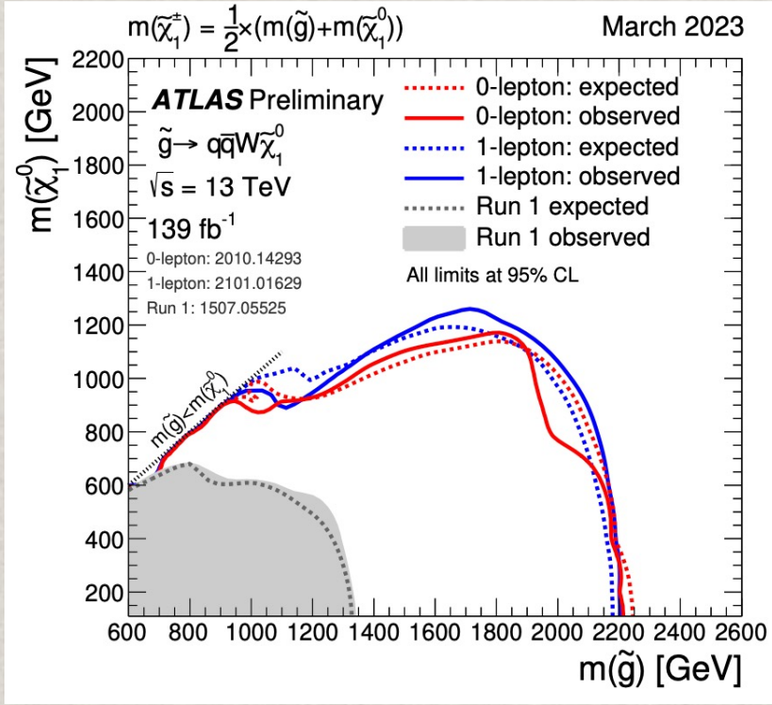
- Understanding Higgs scalars
- Predicting cold DM
- Baryogenesis & proton decay
- Neutrino mass & flavor physics
- Early universe cosmology

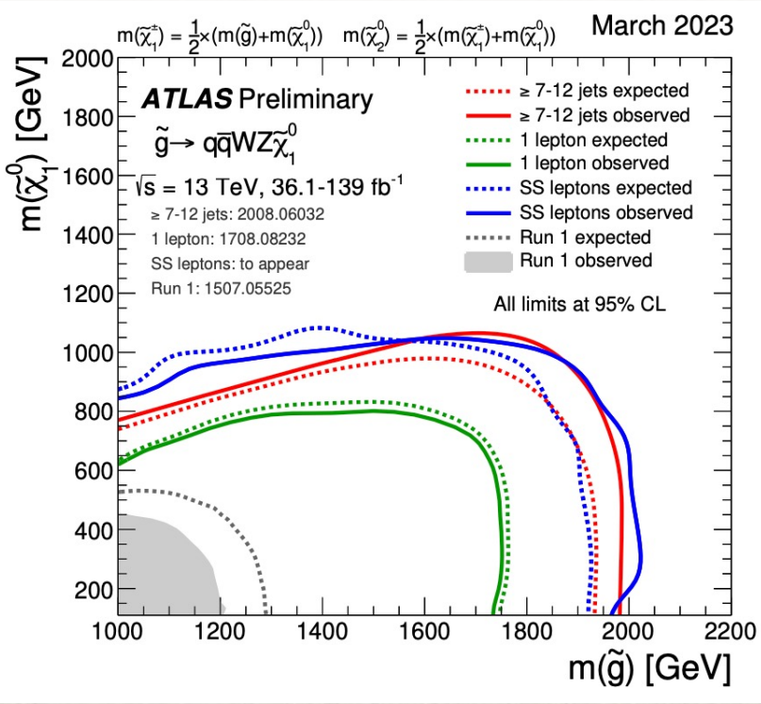
→ (arguably) most attractive theory for BSM

SUSY in the Search @ LHC









Talks by C. Herwig, Stefano Passagio, Evan Carlson …

Stringent mass bounds > 1 – 2 TeV!

The search continues at colliders as well as precision physics.

5. Dynamical scale generation is natural!

QCD inspired strong interacting theory:
Dynamical scale ("Technicolor") can be generated by "dimensional transmutation":

$$\Lambda_{TC} \approx \Lambda \ \exp(-\frac{1}{2\alpha_{TC}}) \approx 4\pi v.$$

Observationally:

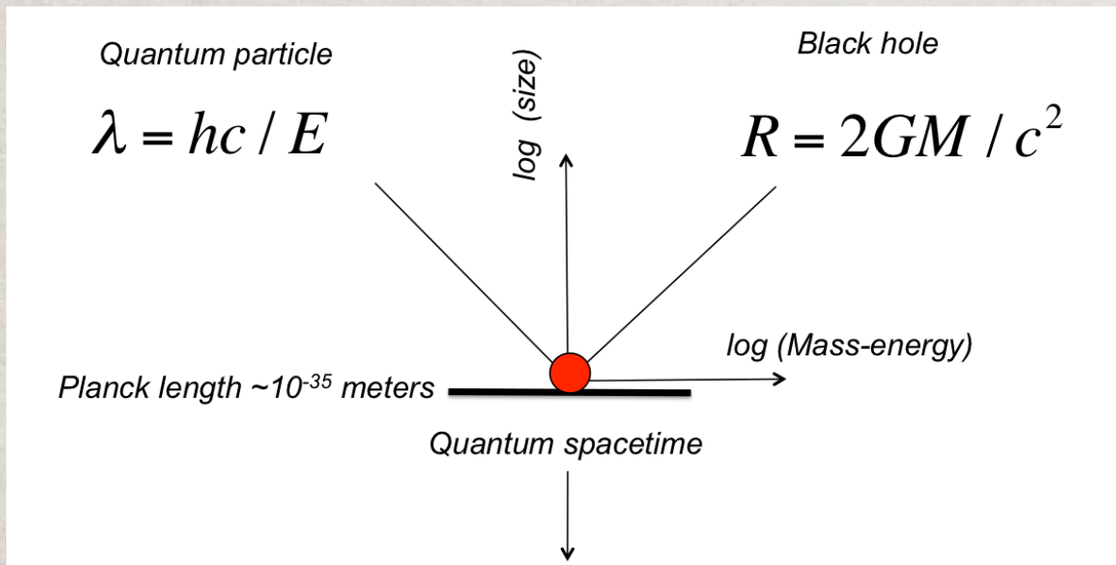
New dynamics not far from O(1 TeV)
Higgs composite → couplings, form factors?
and "partners": $T^{\pm}$, $\boldsymbol{\rho}^{\pm,0}$, $\boldsymbol{\Pi}^{\pm,0}$ …

Collider searches actively on-going …
The absence of the signal signifies
the "Little hierarchy"

6. The marriage of Relativity & Quantum mechanics is the ultimate destiny ✊

When approaching the Planck scale, the world is necessarily relativistic & Quantum-mechanical.

$$l_p = \sqrt{\frac{G\hbar}{c^3}} = 1.616 \times 10^{-35}\, meters$$



We do not have a unitary, renormalizable formulation …
Perhaps string theory? but how to test?

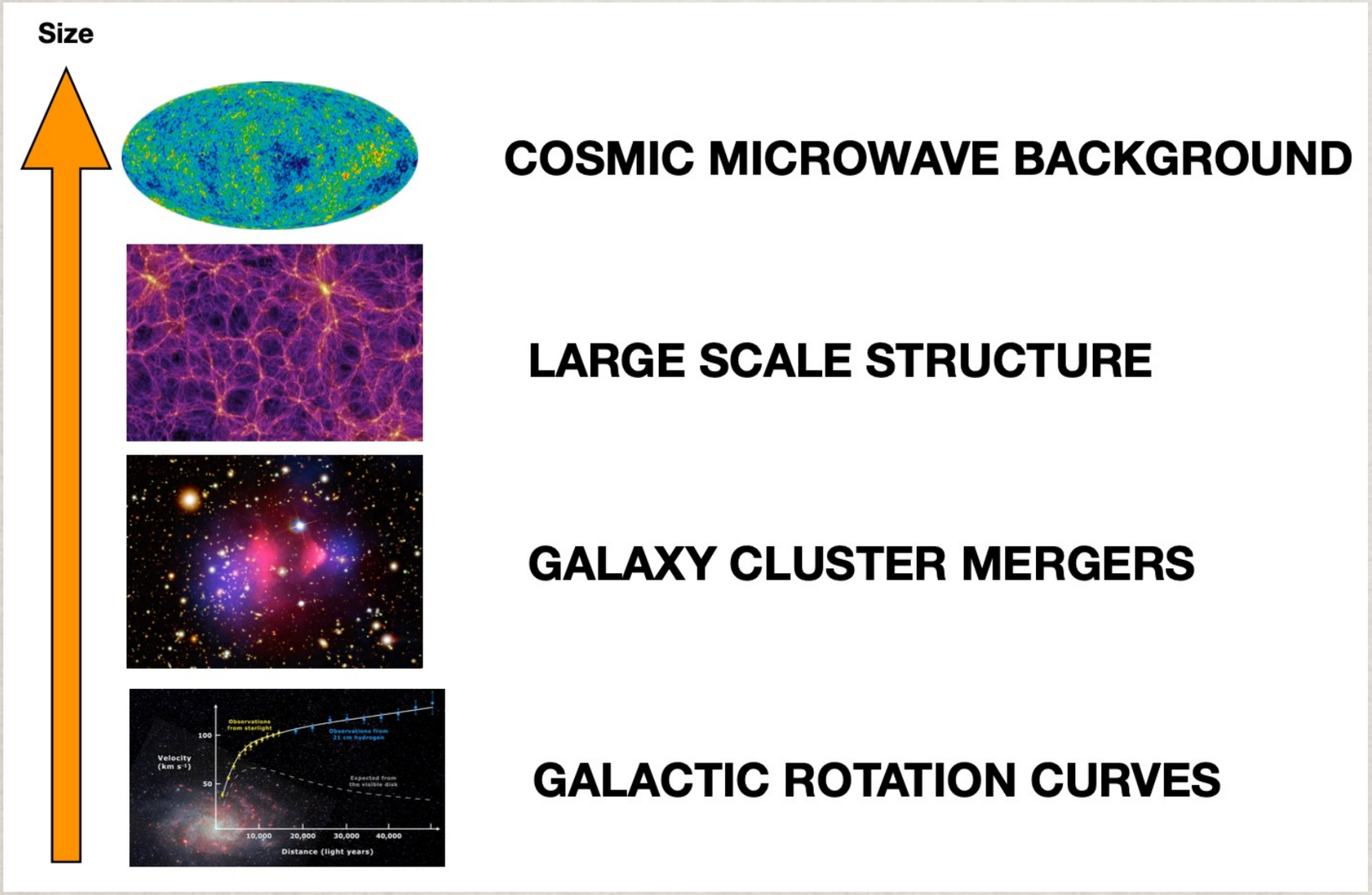
Talk by David Kaplan, John Kovac

In practice,
primordial GW & BH observation may shed light on.

Problems with SM

that need a BSM solution

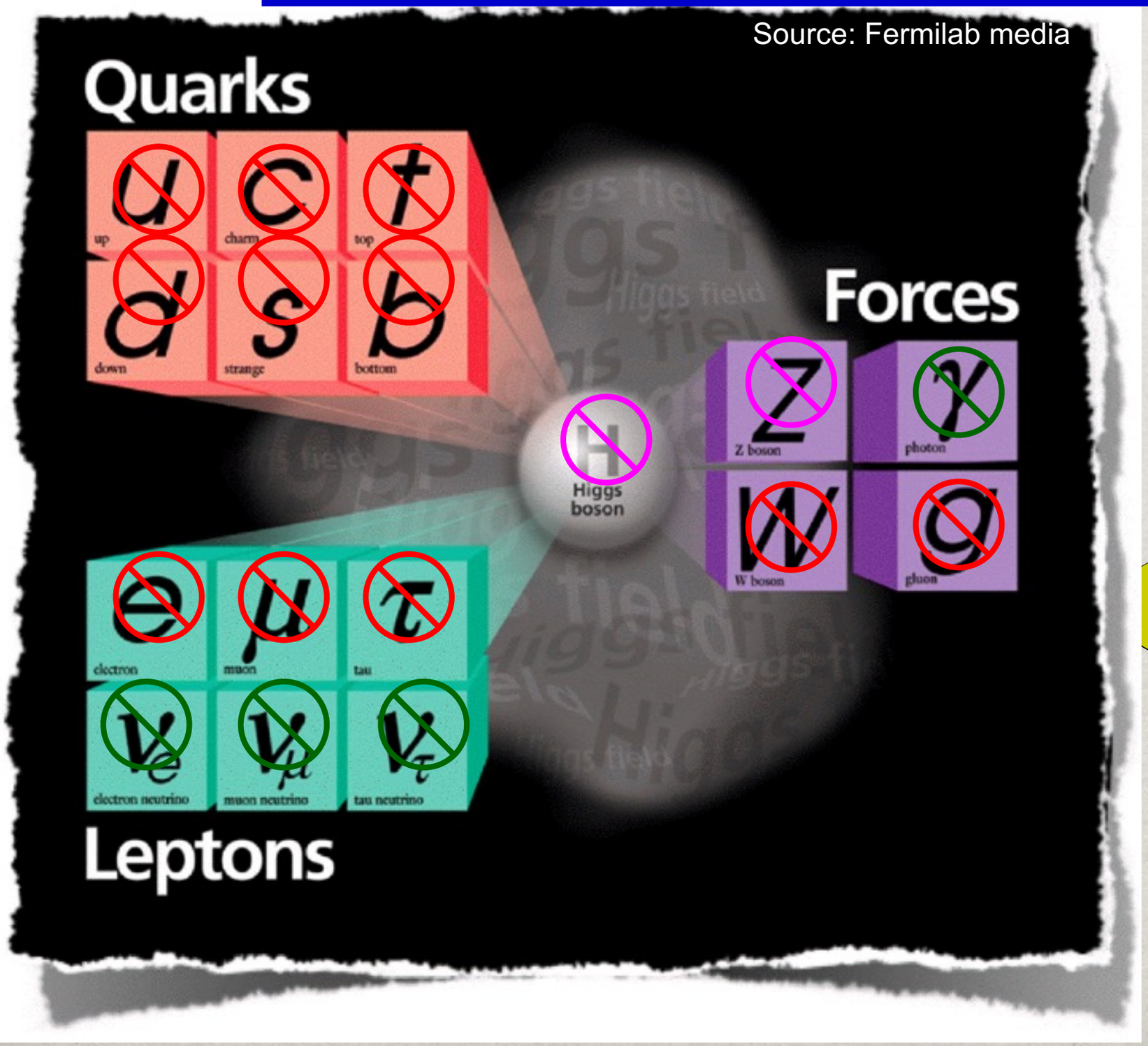
1. The Dark Matter exists



Talks by Fei Gao, Celine Boehm, Andrew Long …

It's most likely particle physics origin, but BSM:

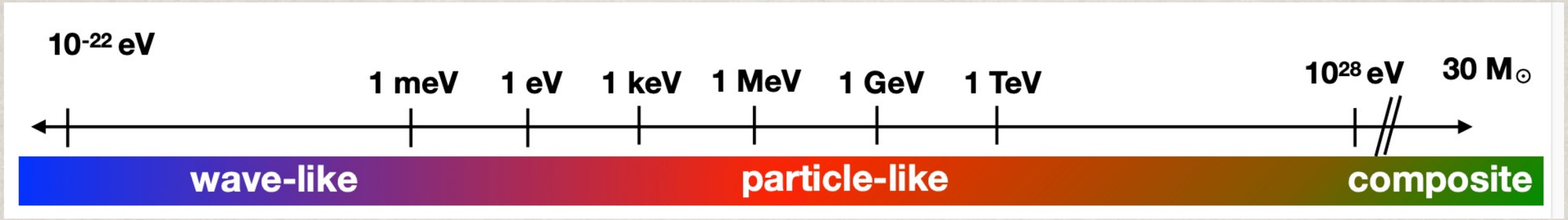
No good candidate for CDM in SM



CDM requirements

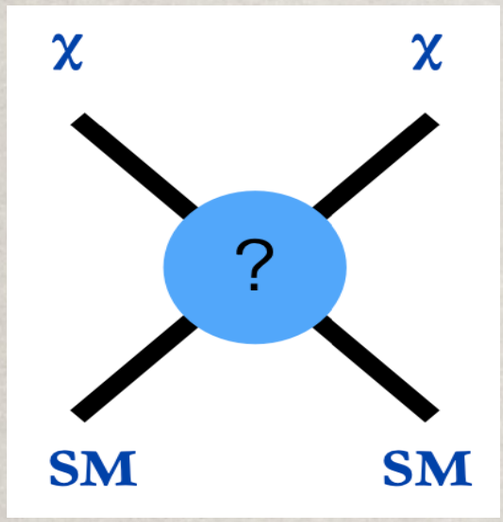
- Stable
- Non-baryonic
- Neutral
- Cold (massive)
- Correct density
- Gravitational interacting

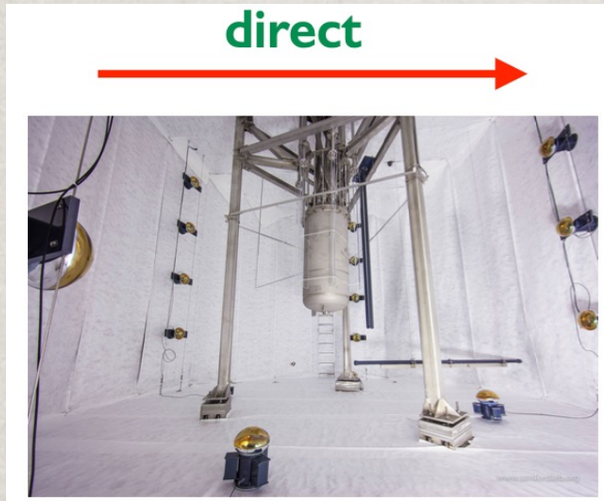
Dark Matter in theory: "embarrassment of riches"

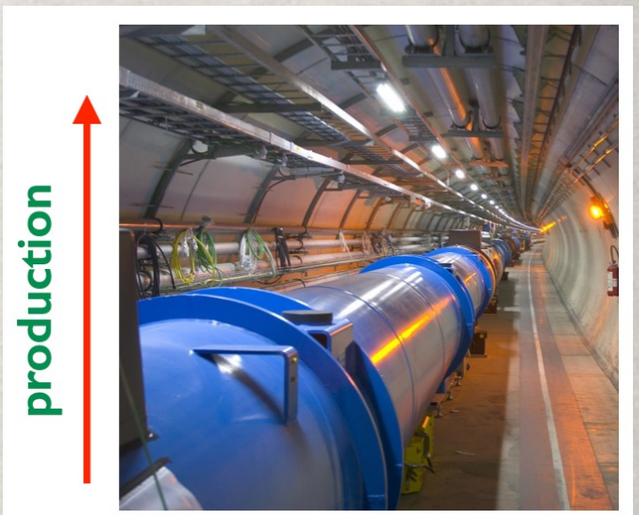


axions, dark photons … sterile ν's WIMPs WIMPzillas PBH?

Dark Matter in practice:







Much more recent activities in light DM detection!

- DM-electron scattering in noble liquids, semi-conductor, organic molecules
- DM-nuclear scattering through Migdal scattering & bremsstrahlung
- Light DM absorption: axion-like particles (LLP), dark photons
- DM scattering off collective modes in molecules & crystals

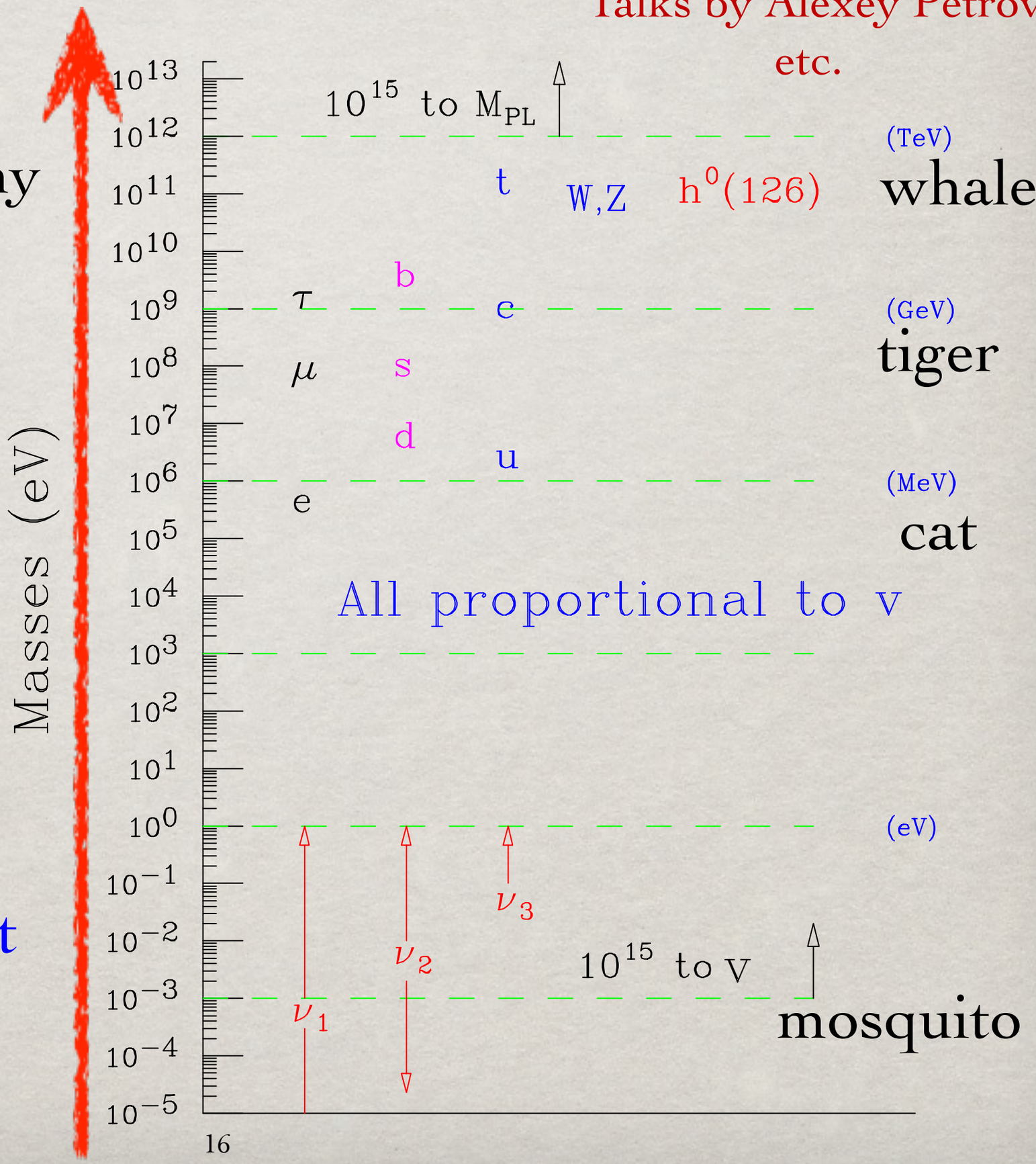
(phonosn, plasmons, magnons Talks by R. Laha, Nhan Tran, F. Scutti, M. Citron

2. The "Flavor Puzzle"

Talks by Alexey Petrov etc.

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- Tiny neutrino masses!
- New CP-violation sources?

Higgs Yukawa couplings as the pivot for all !



Flavor physics in theory: a serious challenge!

BSM: **much harder** to accommodate!

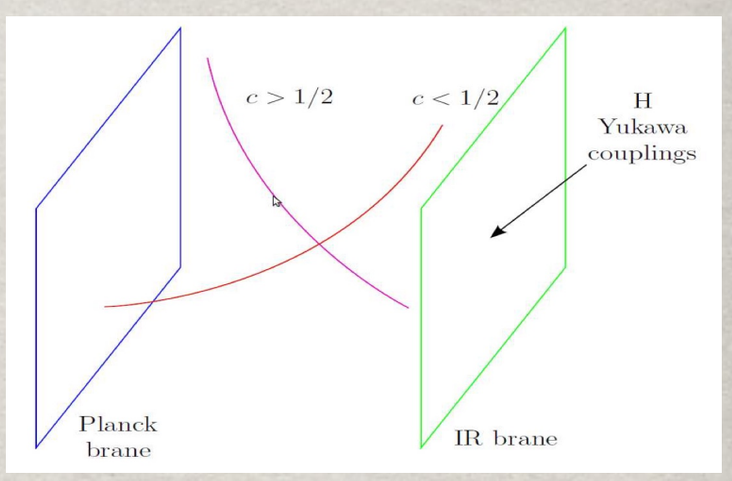
- Generate multiple mass scales
- Avoid FCNC
- Avoid Excessive CP violation

- Why the flavor mixing aligned with the SM Yukawa form?

→ Minimal Flavor Violation (MFV)

- Horizontal flavor symmetry: Froggatt-Nielson mechanism

$$(Y_u)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[u_j]}, \qquad (Y_d)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[d_j]}$$



- Warped extra-dimension: Couplings determined by the overlap with the EW brane.
- Radiative generation of m_f:

  light generation masses loop suppressed ~ $1/16\pi^2 \sim 10^{-2}$.

Vibrant field in experimental explorations!

3. Neutrino Masses

ν's: the most elusive/least known particle in the SM:

- How many species: 3 $\boldsymbol{\nu}_L$'s + N_R?
- Absolute mass scale: $m_{\boldsymbol{\nu}} \sim y_{\boldsymbol{\nu}}\, v < 1$ eV?

  or a new physics scale via "see-saw": $m_\nu \sim \kappa \dfrac{\langle H^0 \rangle^2}{M}$

- Flavor oscillations & CP violation?
- Mixing with sterile ν's?
- Portal to dark sector?

Studying neutrino physics has been rewarding:
6+ Nobel Prizes related to ν's!

Great playground for theory & experimentation!

Talks by Joachim Kopp,
Son Cao, Mikhail Danilov

SM → ν SM: the seesaw spirit

The leading SM gauge invariant operator is at dim-5:*

$$\frac{1}{\Lambda}\,(y_\nu L H)(y_\nu L H) + h.c. \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda}\,\overline{\nu_L}\,\nu_R^c.$$

*S. Weinberg, Phys. Rev. Lett. 1566 (1979)

- Theoretical: **Λ** → new scale / particles, implies an underlying (UV) theory!

→ There are three possibilities @ tree-level:

- Type I: New fermion singlets N $\otimes(\mathrm{L\,H})_S$
- Type II: New scalar triplet **Φ** $\otimes(\mathrm{L\,L})_T$
- Type III: New fermion triplets T $\otimes(\mathrm{L\,H})_T$

- Observational: Talks by Mikhail Danilov, Ruben Saakyan

  ΔL=2 → Majorana mass (Majorana neutrinos)

  → much activity on-going:

  $0\nu2\beta$ decay, meson decays, collider searches …

4. Baryon # & CP Asymmetry

The observed baryon dominance → BSM

Sakharov conditions:

- Baryon # violation (EW sphalerons)
- C & CP violation (BSM)
- Out of equilibrium (1st order PT, BSM)

Many BSM theories to accommodate

- Affleck-Dine mechanism (primordial universe)
- Lepto-genesis (ΔB = ΔL via sphalerons)
- EW baryogenegis (1st order PT, BSM)

Morrissey & Remsey-Musolf, arXiv:1206.2942

Observationally,

ΔB ≠ 0 → proton decay, $n - \bar{n}$ oscillation

ΔL ≠ 0 → Majorana neutrinos

Plus extra Higgs bosons to search for

SUMMARY

The Standard Model: A triumph in science!

Lessons from SM in the making, on

UV completion? Naturalness?

Unification; Higher symmetry;

Strong dynamics; Quantum Gravity

Problems that need a BSM solution

Dark matter; Neutrino mass;

Baryon asymmetry & CP violation

Challenging model-building &
exciting experimental programs ahead!