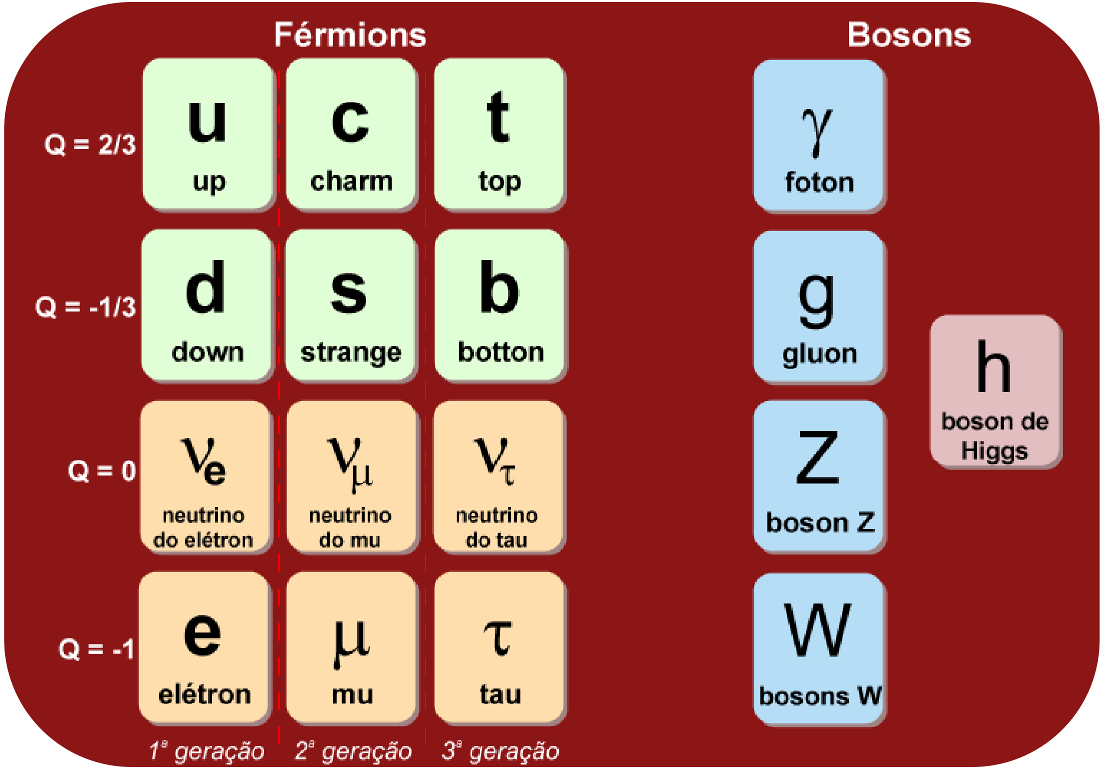
Physics Beyond the Standard Model

Ricardo D. Matheus

IFT-UNESP

The Standard Model in 1 slide (or so...)



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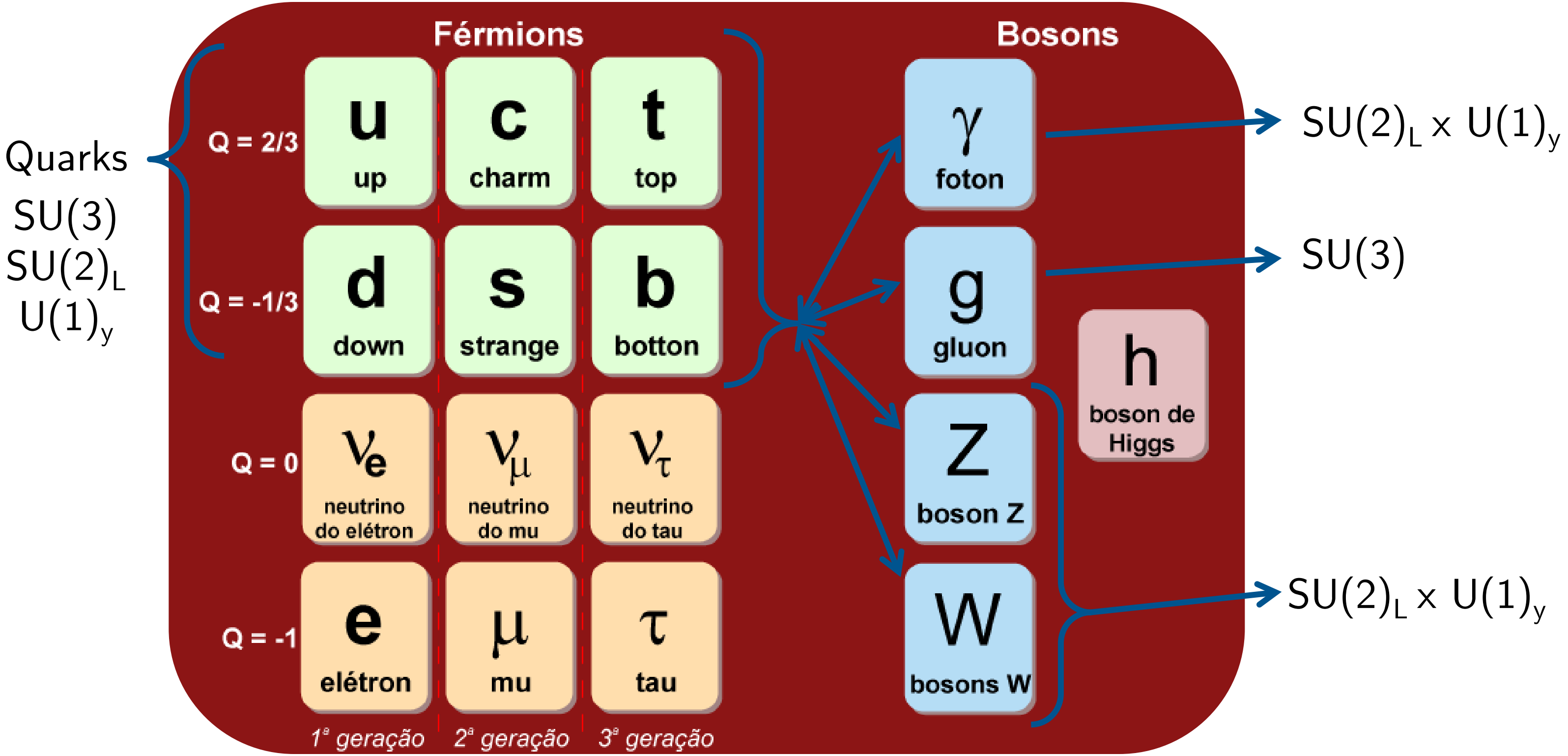

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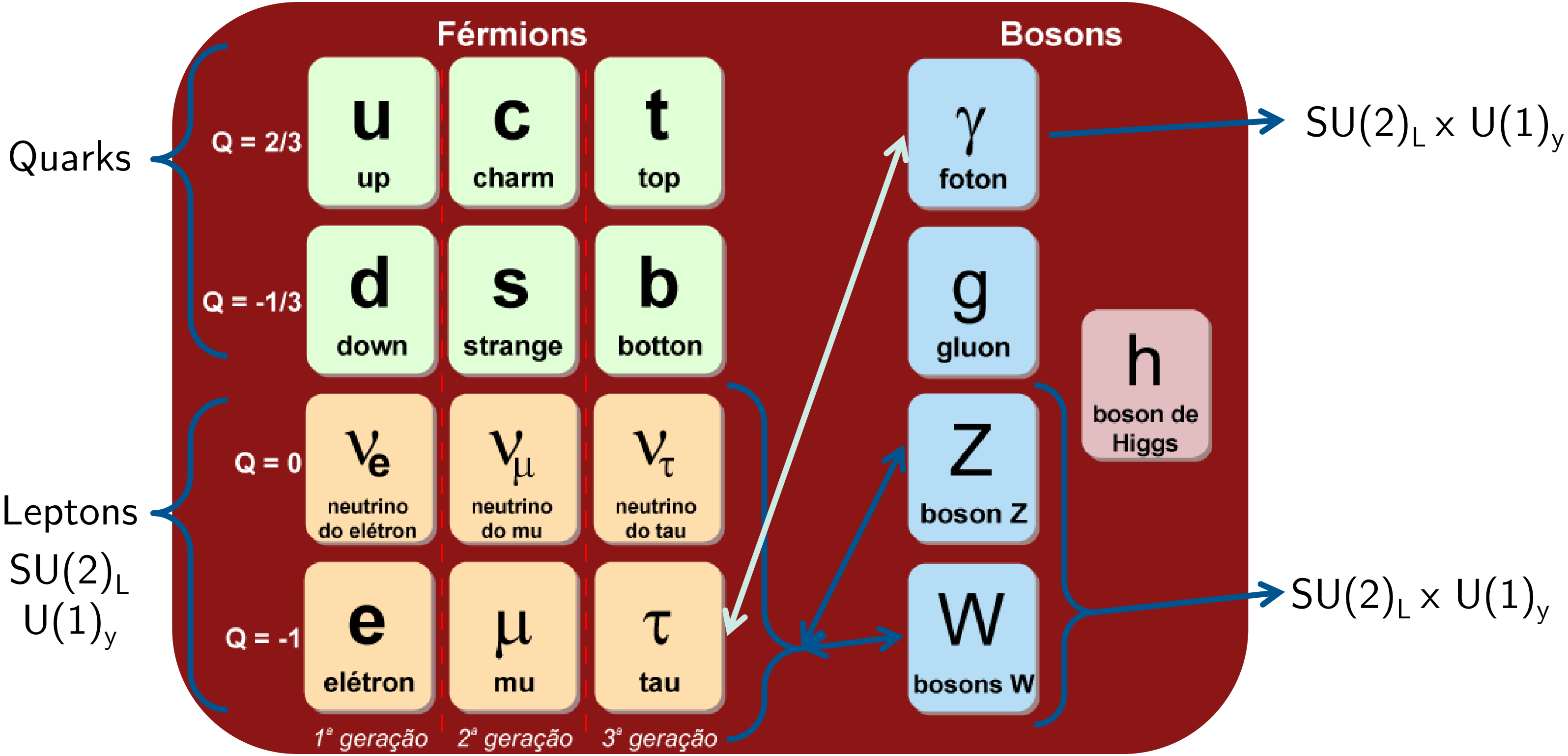

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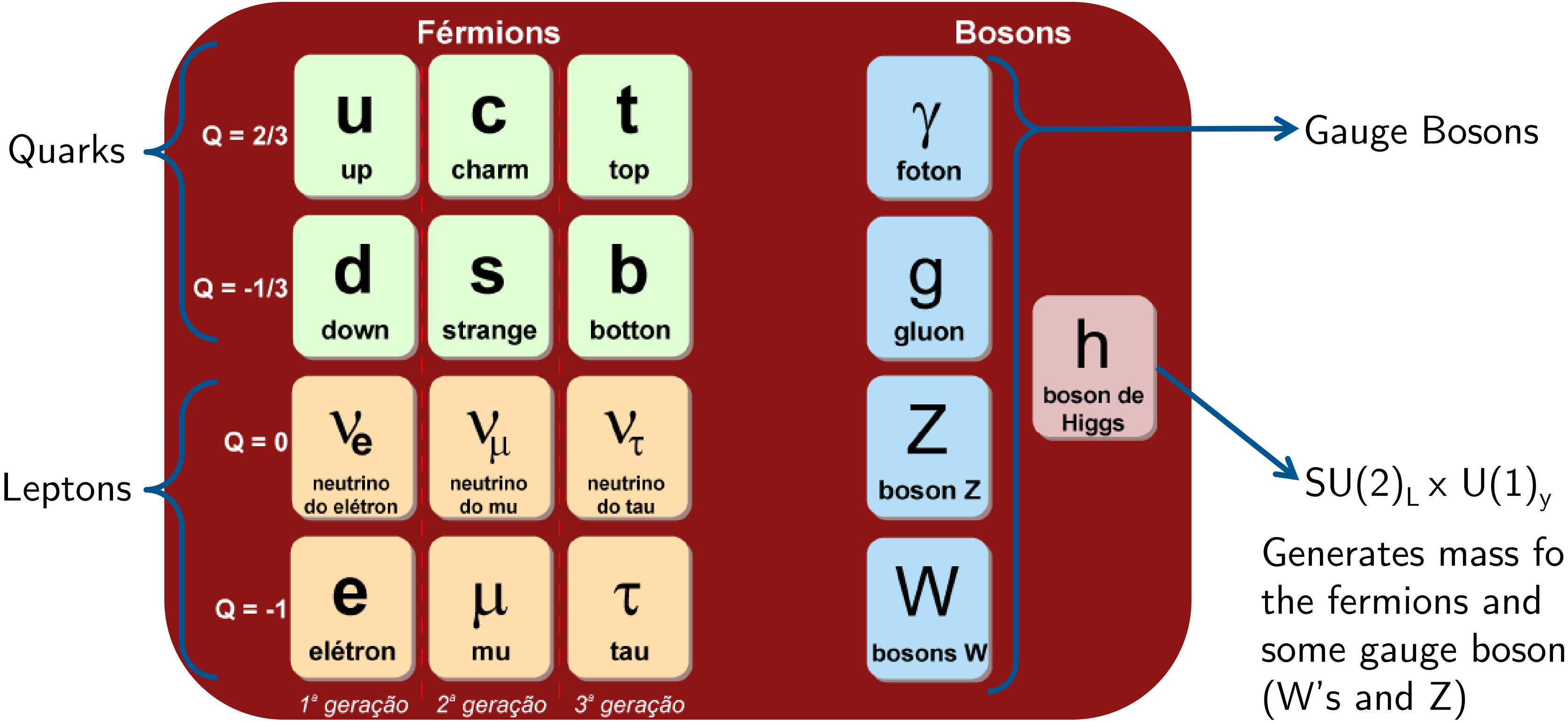

Generates mass for the fermions and some gauge bosons (W's and Z)

The physics flavor/family structure (shortcoming)

$$\mathcal{L}_Y = y_\psi \left(\bar{\psi}_L \phi \psi_R \right) + h.c.$$

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Electroweak Symmetry Breaking

$$\phi = \begin{pmatrix} 0 \\ \mathrm{h} + \mathrm{v} \end{pmatrix}$$

$$\mathcal{L}_Y = \frac{v}{\sqrt{2}} y_\psi \bar{\psi}_L \psi_R + h.c.$$

$$m_\psi = y_\psi \frac{v}{\sqrt{2}}$$

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$$v \approx 246 \text{ GeV}$$

These "Yukawa" couplings are chosen to fit all the fermion masses (plus mixings in the CKM and CP violation)

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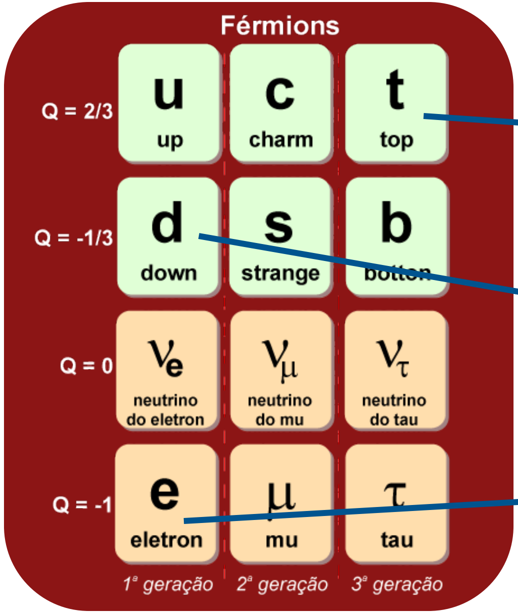

$$m_t = 171 GeV \qquad Y_t \sim 1$$

$$m_d = 5 MeV \qquad Y_d \sim 10^{-5}$$

$$m_e = 0.5 MeV \qquad Y_e \sim 10^{-6}$$

Fermion mass hierarchy (which is technically natural)

The physics flavor/family structure (shortcoming)

m_e	Electron mass	511 keV
m_μ	Muon mass	105.7 MeV
m_t	Tau mass	1.78 GeV
m_u	Up quark mass	1.9 MeV
m_d	Down quark mass	4.4 MeV
m_s	Strange quark mass	87 MeV
m_c	Charm quark mass	1.32 GeV
m_b	Bottom quark mass	4.24 GeV
m_t	Top quark mass	173.5 GeV
θ_{12}	CKM 12-mixing angle	13.1°
θ_{23}	CKM 23-mixing angle	2.4°
θ_{13}	CKM 13-mixing angle	0.2°
δ	CKM CP violation Phase	0.995
g'	U(1) gauge coupling	0.357
g	SU(2) gauge coupling	0.652
g_s	SU(3) gauge coupling	1.221
θ_{QCD}	QCD vacuum angle	~ 0
v	Higgs vacuum expectation value	246 GeV
m_H	Higgs mass	125.09 ± 0.24 GeV

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All of these are equivalent to fixing Yukawa couplings, in total we have 13 parameters (12 modules and 1 complex phase)

This is the majority of the 19 parameters of the standard model!

Hierarchy of Scales (Problem?)

$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) - V\left(H^\dagger H\right)$$

$$V\left(H^\dagger H\right) = \kappa\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2$$

At "tree level" this will produce scalar resonances with mass:

$$m_h^2 = -\kappa = 2\lambda v^2$$

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But once I take quantum corrections into consideration, I get extra terms, e.g.:

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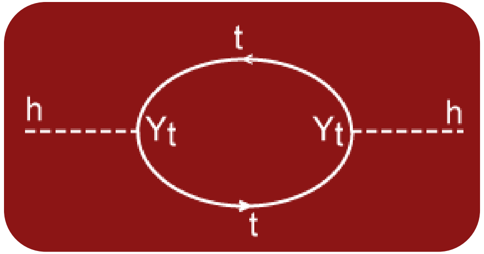

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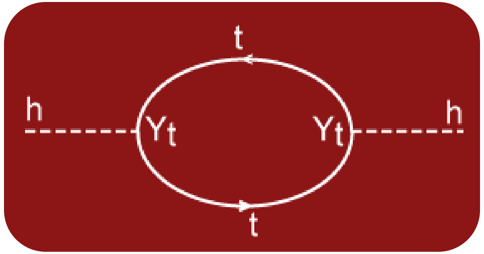

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This is a parameter of the low energy theory, **ideally independent of energies away from the regime you are measuring**

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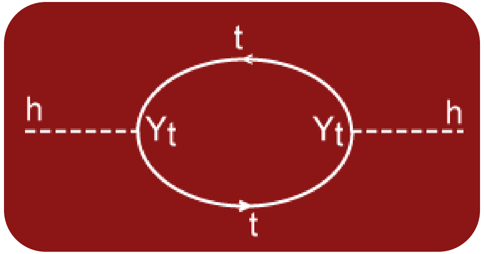

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Q&A

Q: Is this impossible? A: No

Q: Is this unlikely? A: The question makes no sense (to me).

Q: Is it interesting?

Q: Is it worth investigating?

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New physics at O(1000 GeV)!

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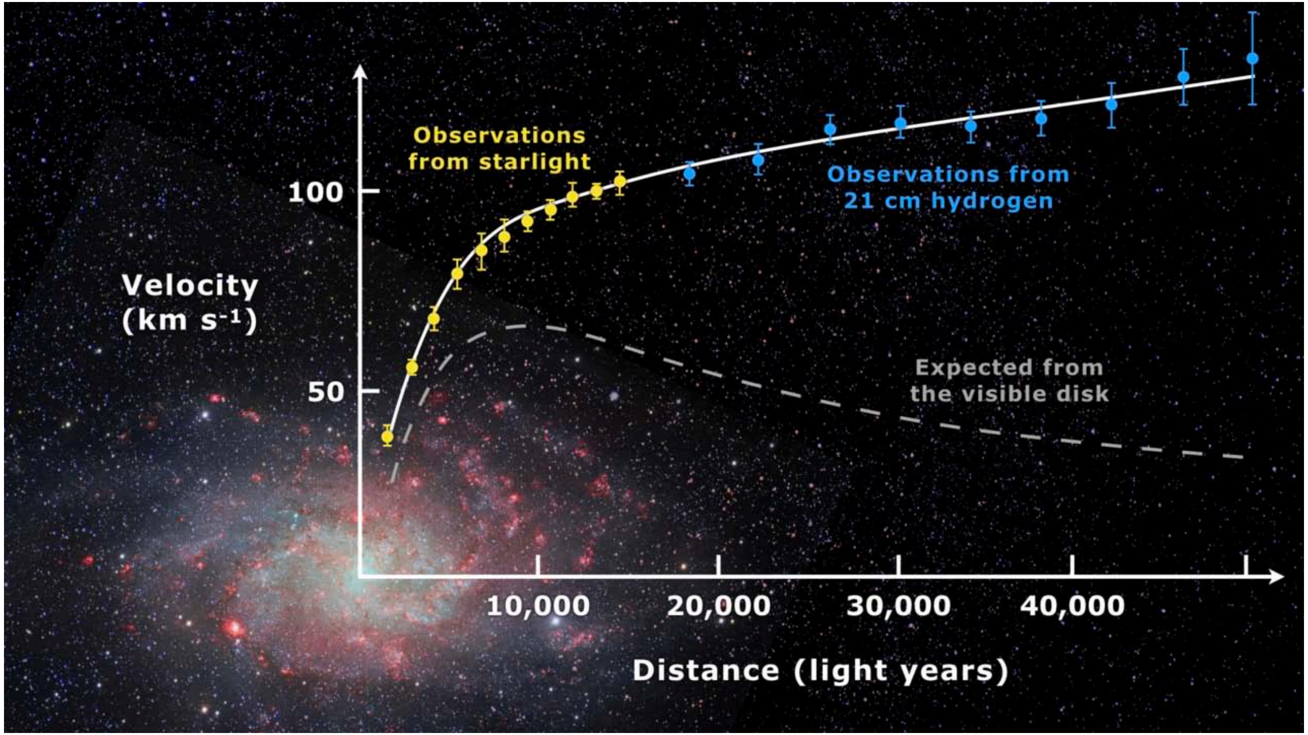
Q: All good then? Experimentalist A: Well... no new physics has been found (yet)...

Dark Matter (Problem)

There is something dark* out there:



Rotation curve of spiral galaxy Messier 33, source: wikipedia

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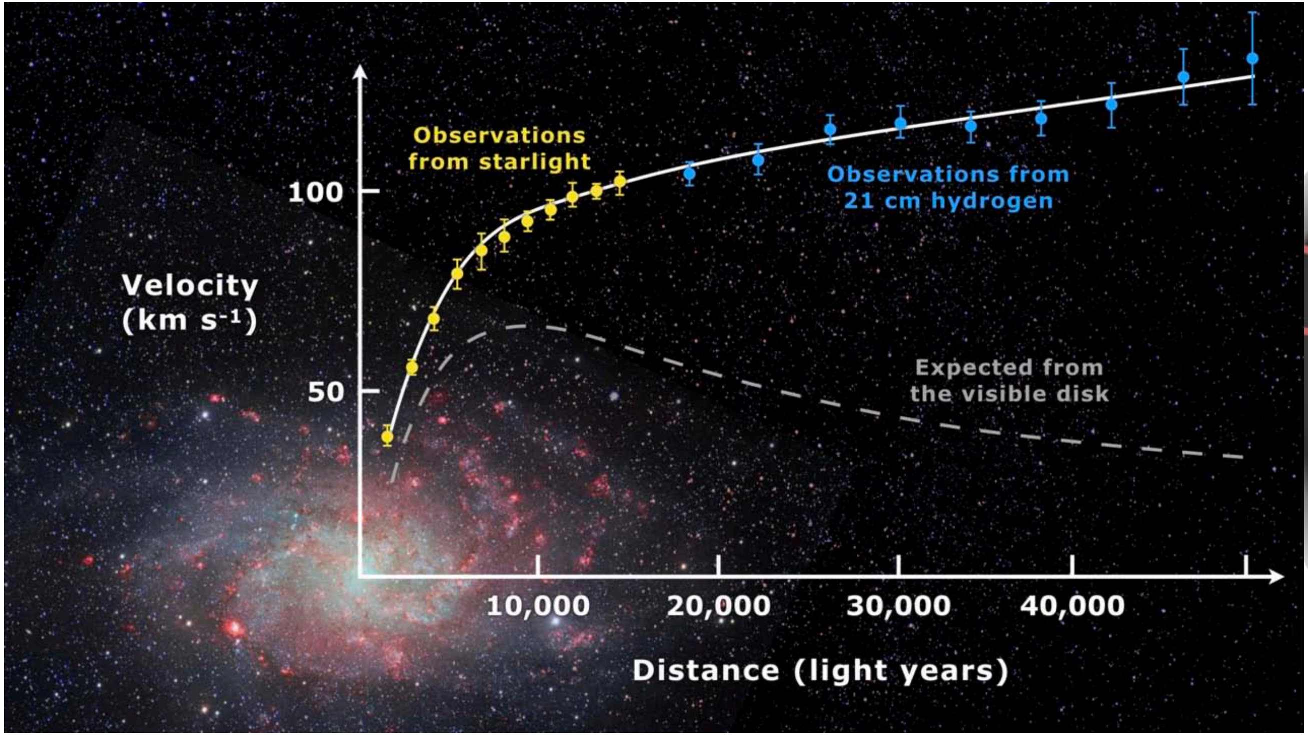

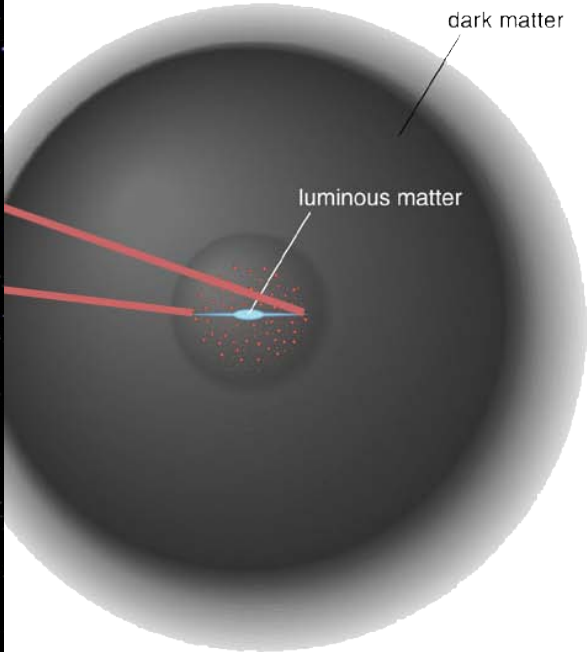

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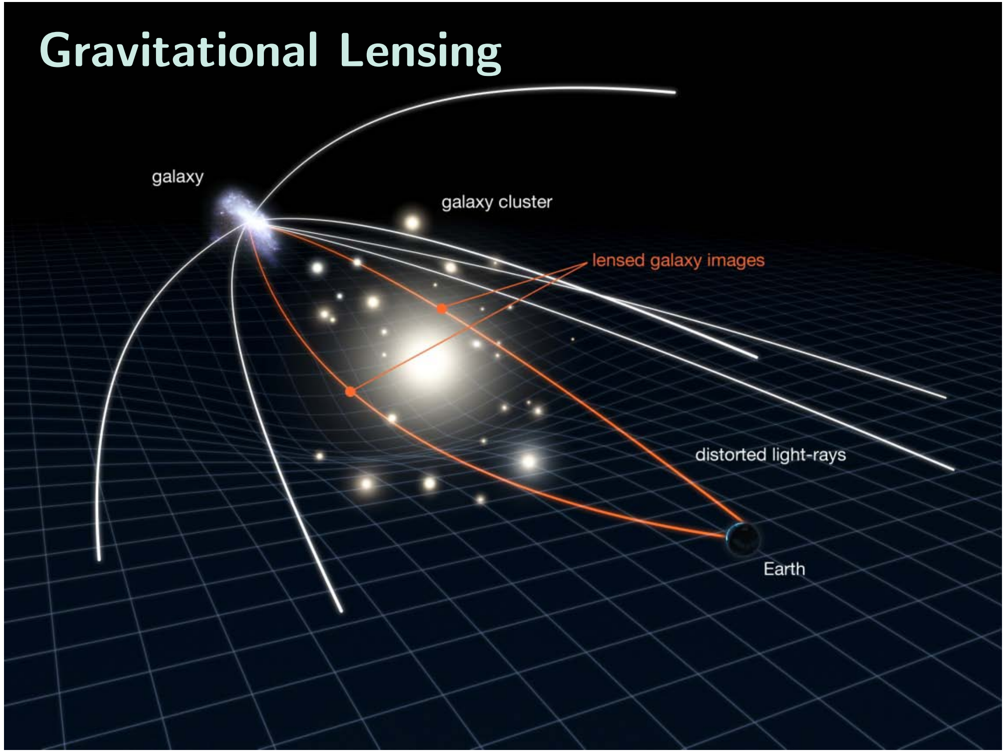

Credit: NASA, ESA & L. Calçada

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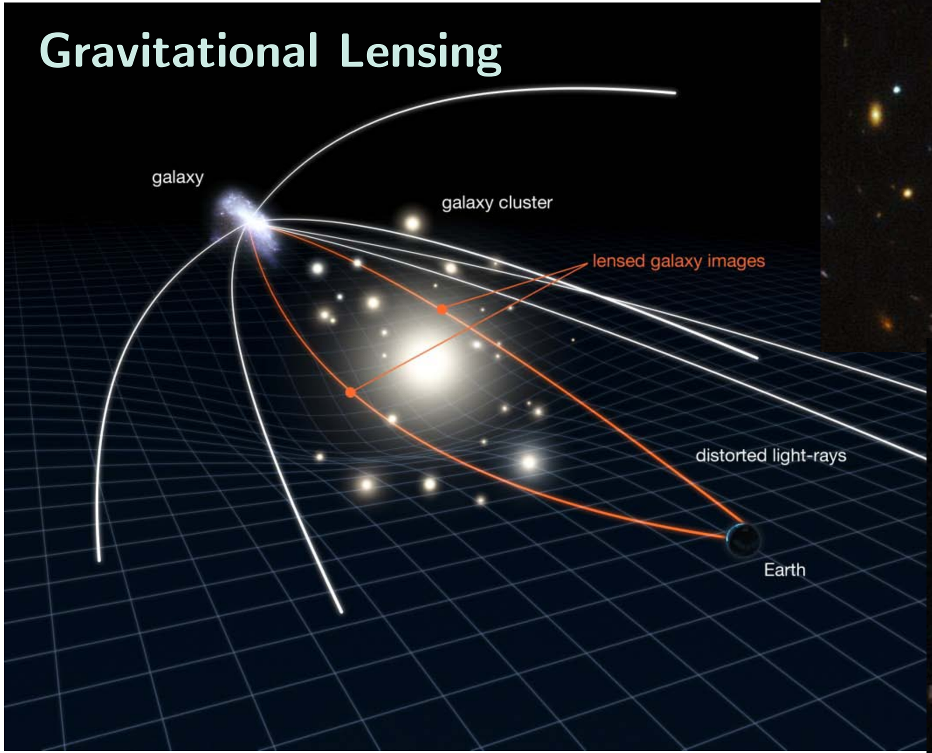

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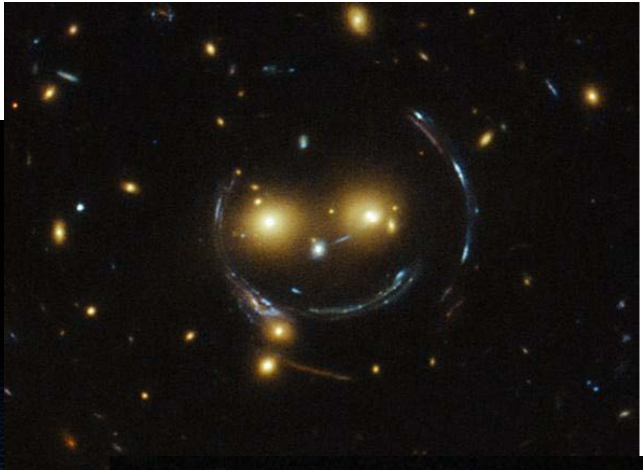

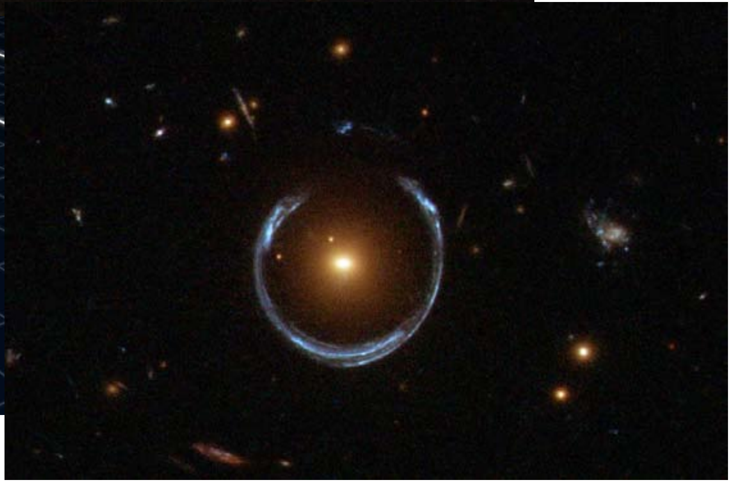

Allows careful mapping of mass, and there is much more than the "shiny stuff" can account for.

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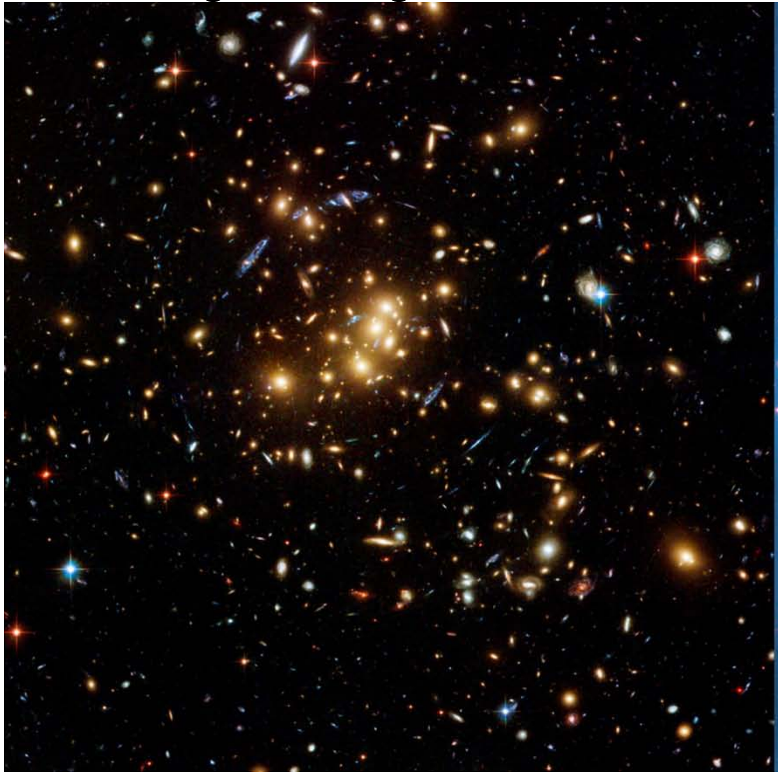
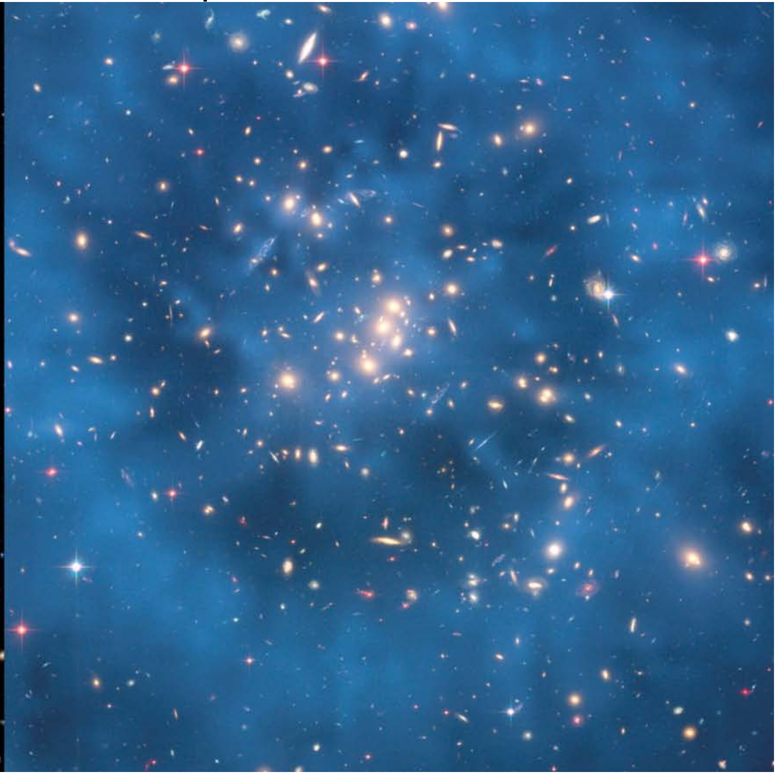
Electromagnetic image



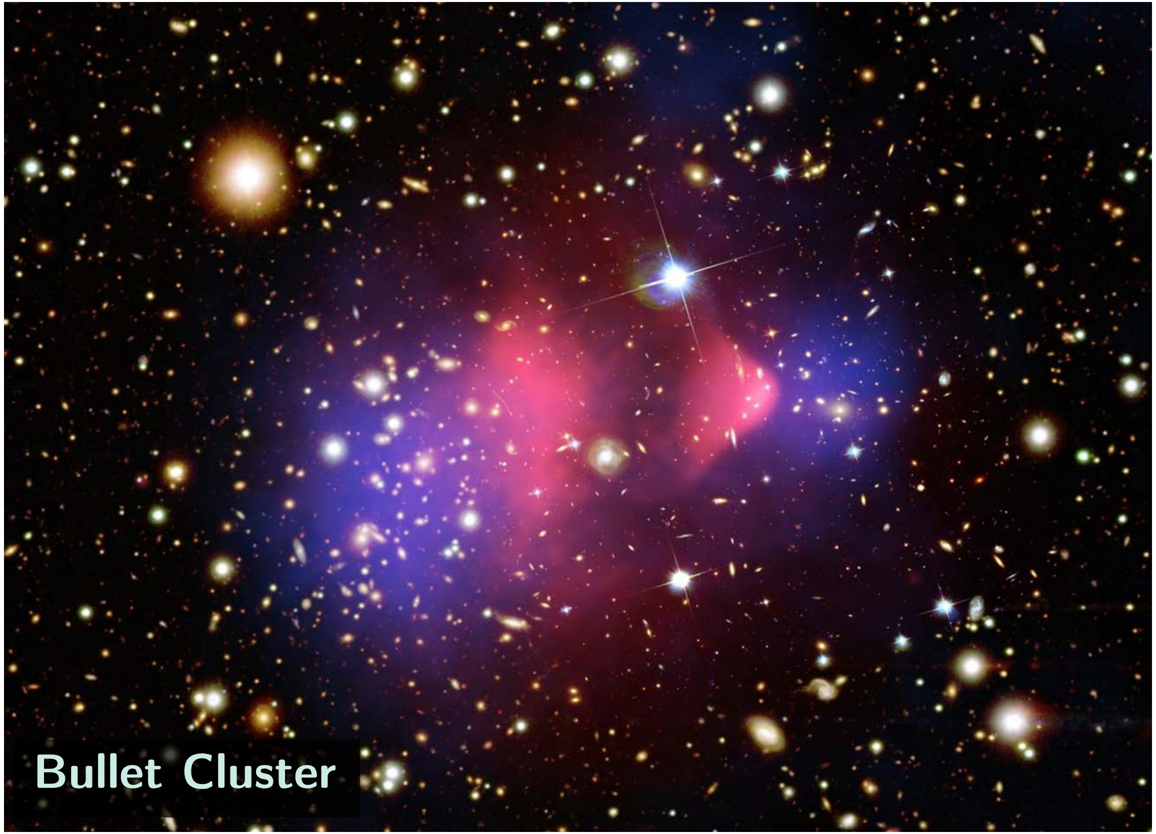
Mass Map



Credit: NASA, ESA, M. J. Jee and H. Ford (Johns Hopkins University) NEWS RELEASE: 2007-17

Dark Matter (Problem)

Maybe it is just gravity working outside Einstein's GR? Well, then you have to explain these:



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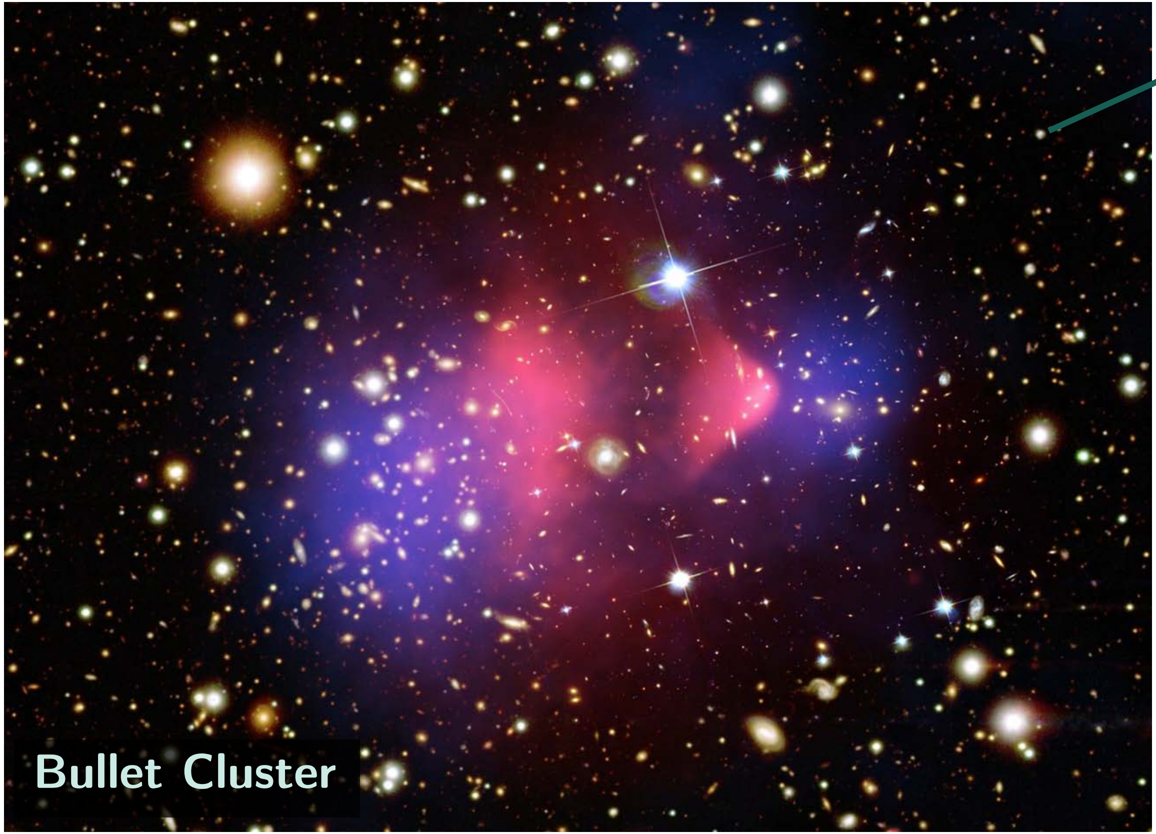

Visible Galaxies

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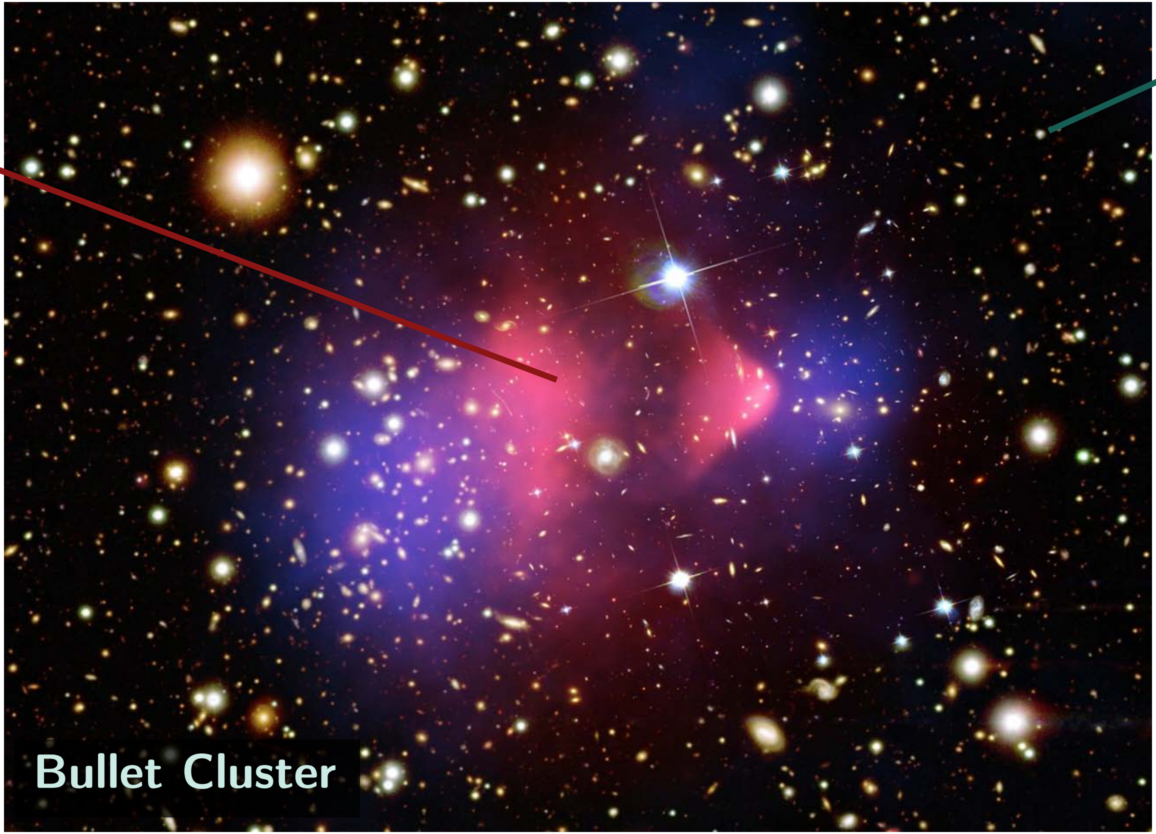

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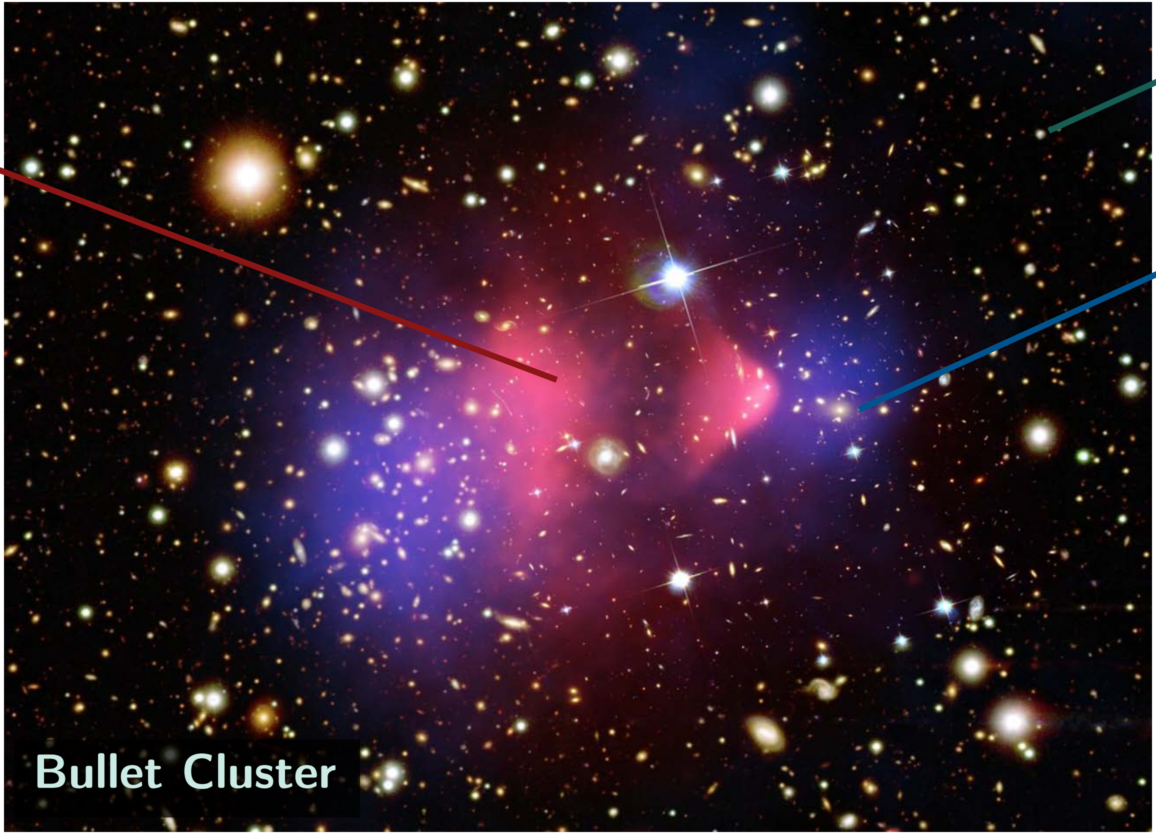

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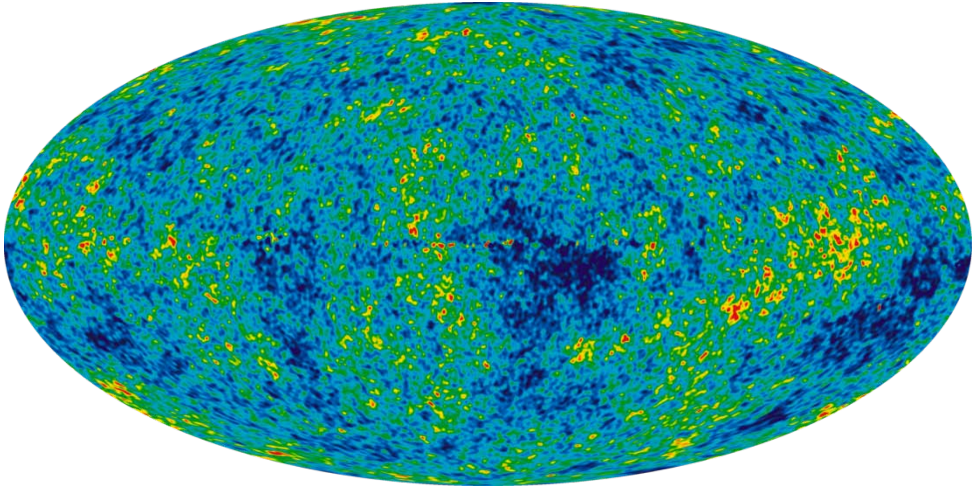
Visible Galaxies

This is where the gravitational well is deeper (according to lensing). We believe this to be the distribution of Dark Matter

Dark Matter (Problem)

Also, from cosmology:



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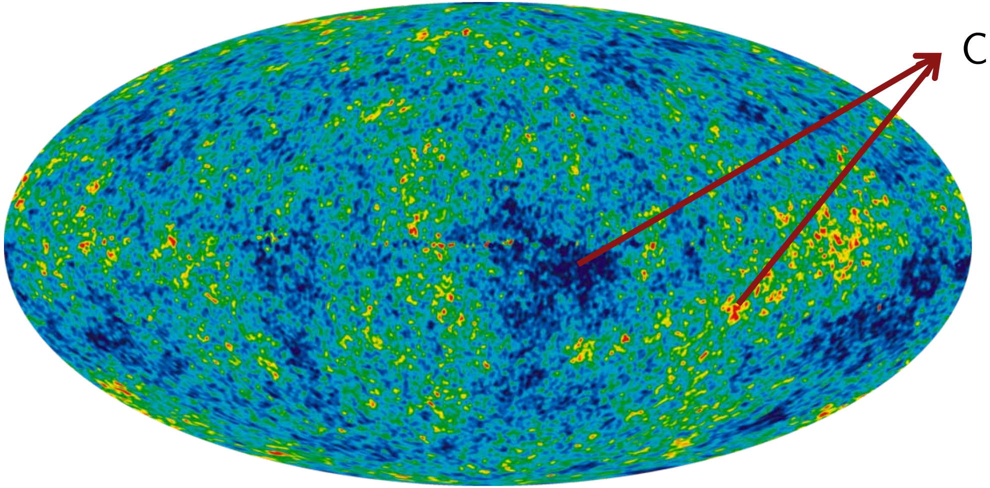
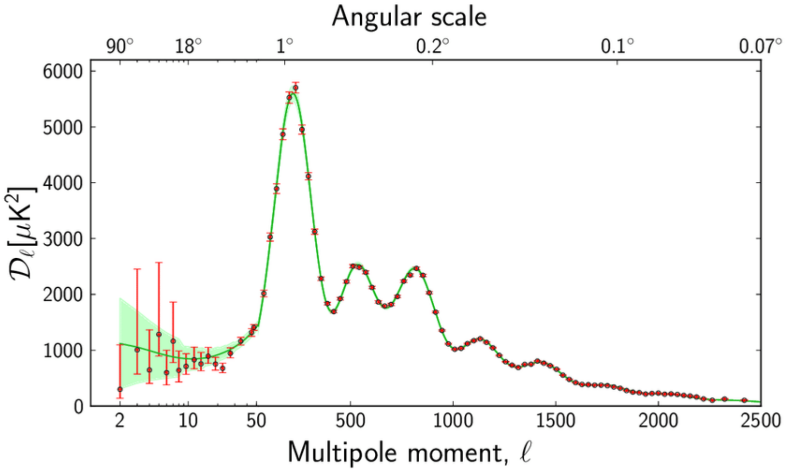


CMB temperature fluctuations:



https://arxiv.org/abs/1506.01907

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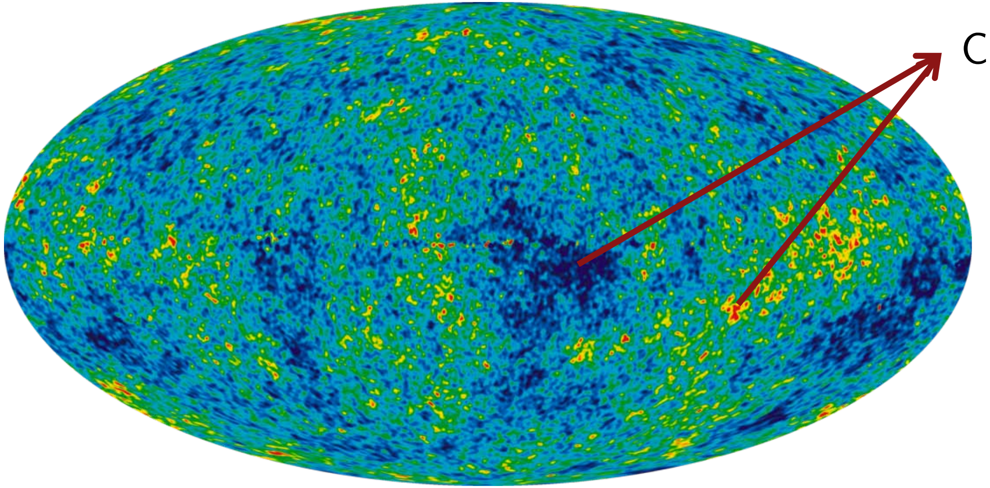

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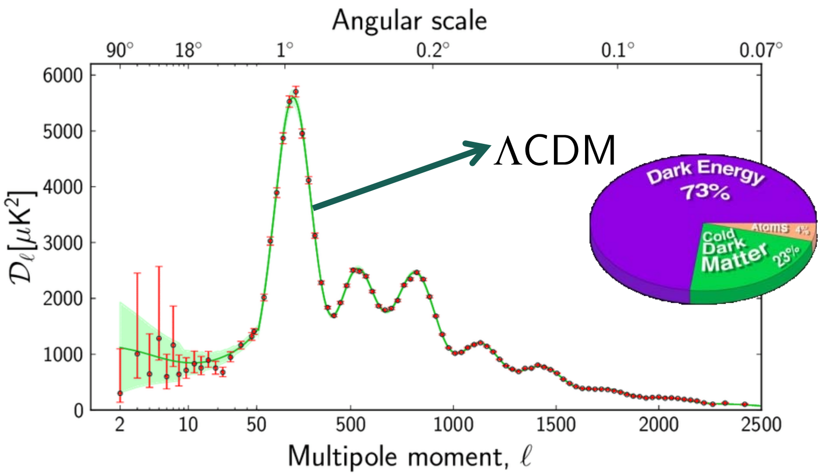

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Cosmological Constant (later)

ΛCDM = Lambda Cold Dark Matter

Means dark matter must be also non-relativistic at the time, which implies it is quite heavy (GeV-ish, bare minimum around keV, but that is already "warm")

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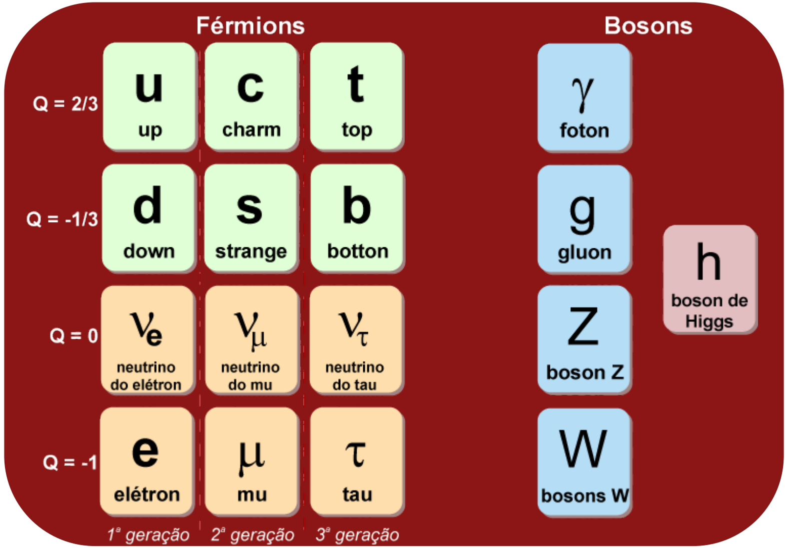
So, how can we fit Dark Matter in the SM?



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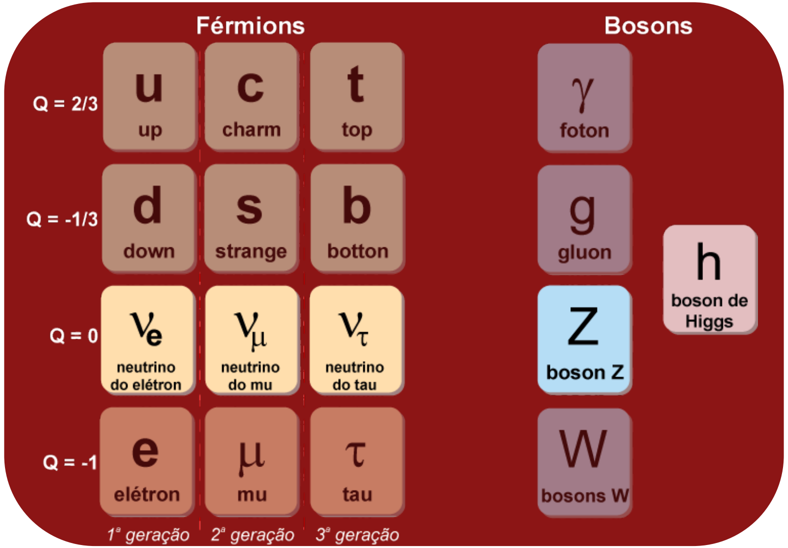

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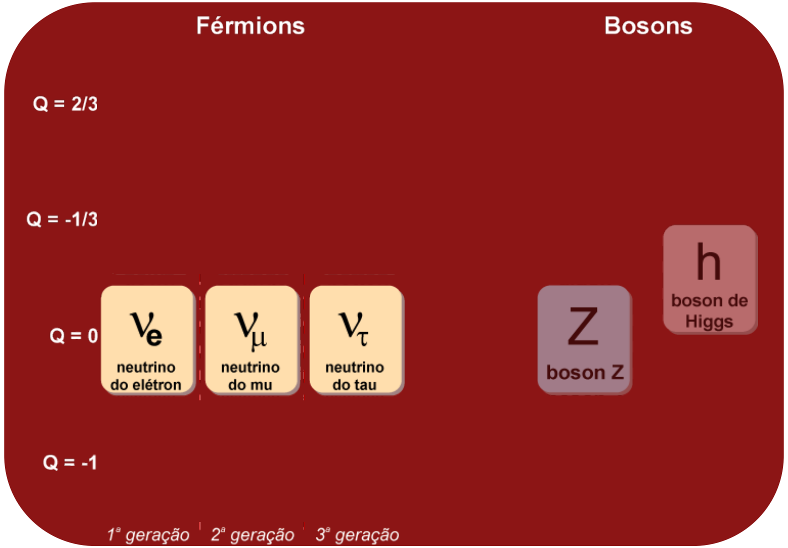

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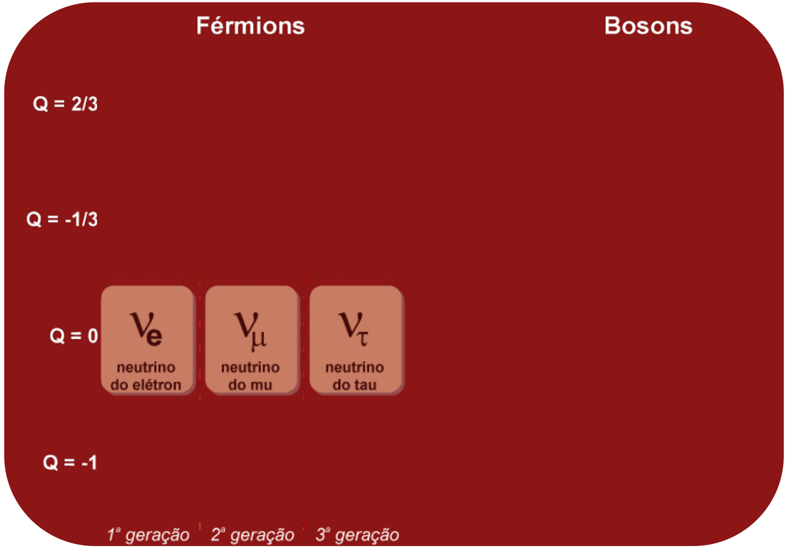

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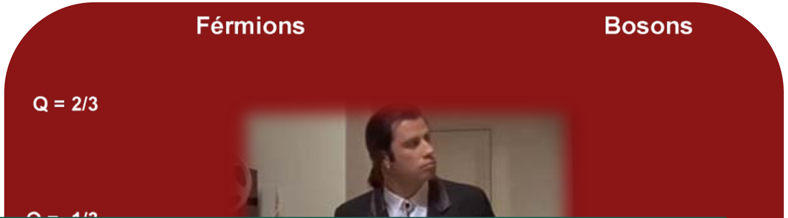
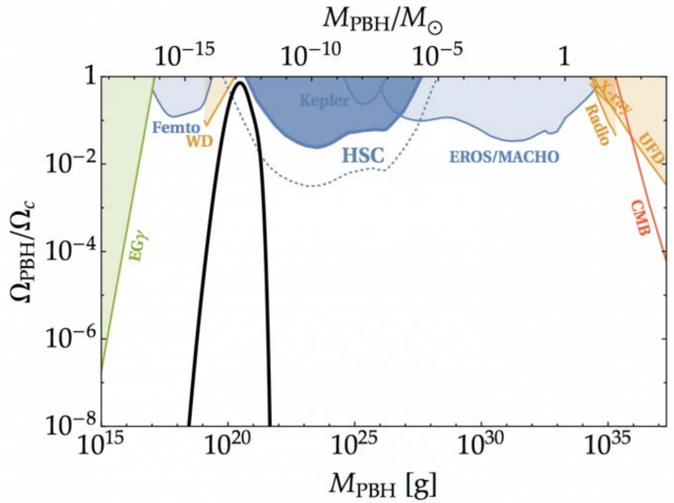


Disclaimer: there is still a space for DM being composed of MACHOs (**MA**ssive **C**ompact **H**alo **O**bject), but it is small.

e.g. PBH



https://arxiv.org/abs/1701.02544 [astro-ph.CO]

Neutrinos have Masses! (Problem)

Neutrino Oscillations imply masses for the neutrinos (sub eV)

But in the SM masses are given by: $\frac{v}{\sqrt{2}} y_\psi \bar{\psi}_L \psi_R$

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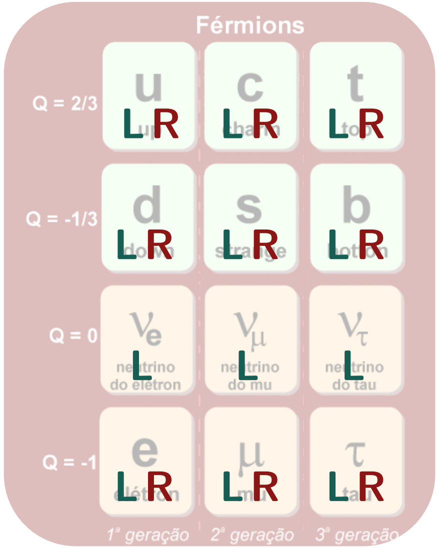

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□ Postulating a ν_R just to take care of masses means extending the SM by one (unobserved) degree of freedom

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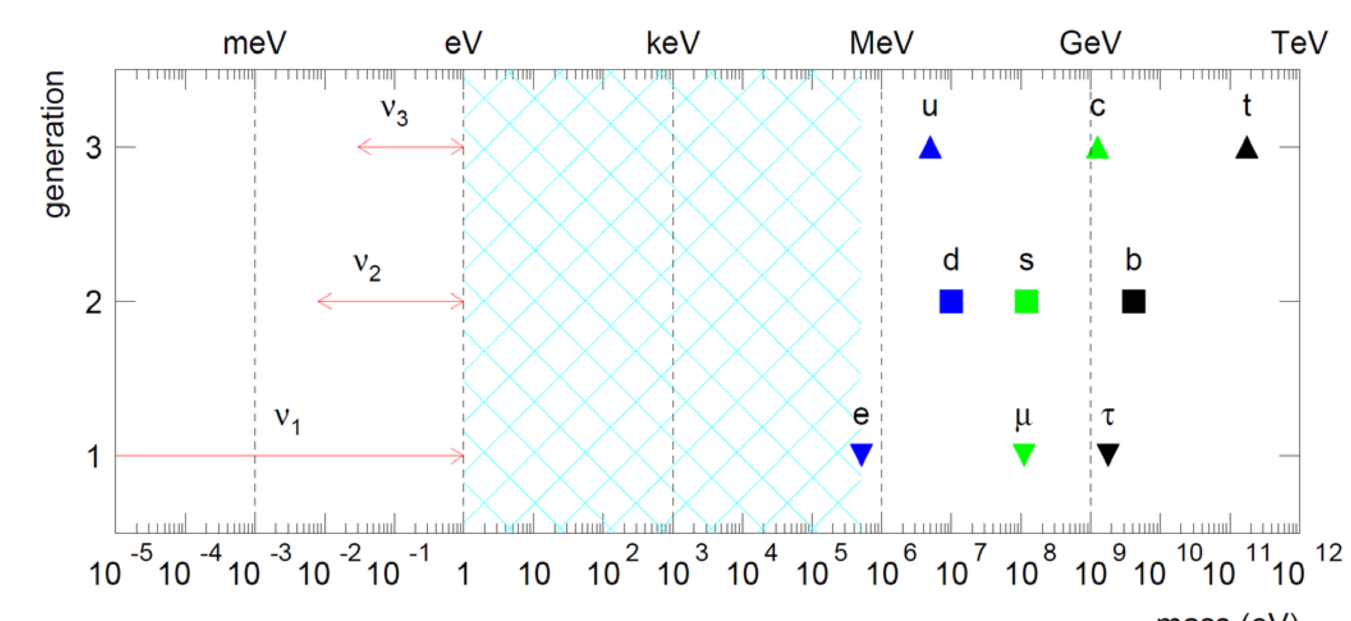
Neutrino (

But in

☐ No r
expect

☐ Post
SM by

Theoreticians don't like it that much, $y_\nu < 10^{-12}$ ...



https://arxiv.org/abs/hep-ph/0503086

...but it is a possibility

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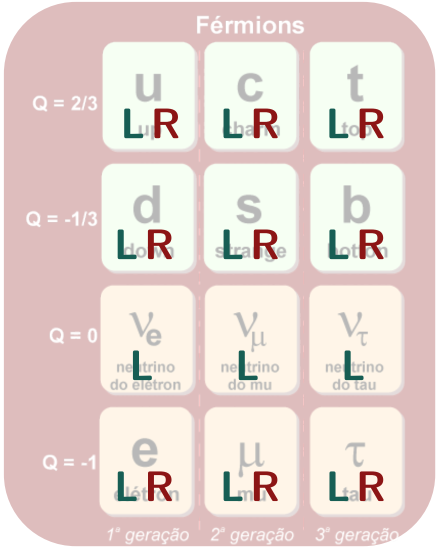

□ No right handed neutrinos were ever observed (nor would you expect to, as they would have almost no interactions)

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Since neutrinos are neutral and can be their own anti-particle, one can also postulate a Majorana mass coming from the operator:

$\tilde{H}_i = \epsilon_{ij}(H_j)^*$

$$\mathcal{L}_5 = \frac{c_5}{\Lambda}\left(\tilde{H}^\dagger L_{f_1}\right)^T C \left(\tilde{H}^\dagger L_{f_2}\right)$$

But that also means postulating new physics (at the scale Λ)

Matter / Antimatter asymmetry and baryogenesis (Problem)

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CP violation from QCD, strong CP problem (Fine tuning. Problem?)

We simply did not include an allowed operator:

$$\mathcal{L}_{SCP} \backsim \theta F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Experimentally θ is constrained to be smaller than 10^{-9}, but quantum effects should generate a θ of O(1)

Cosmological Constant (Shortcoming? Fine tuning?)

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No graviton (Shortcoming)

Well... no quantum gravity for us yet

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Conclusion

I hope I have convinced you there are enough reasons to look for physics:

Beyond the Standard Model (BSM)

so we move on to that next...

The Effective Approach

The SM works! (Very well indeed). So whatever new theory I cook up, it must reduce to the SM in some limit. Is there hope for that?

The Effective Approach

m_W m_Z m_h m_t Λ

E

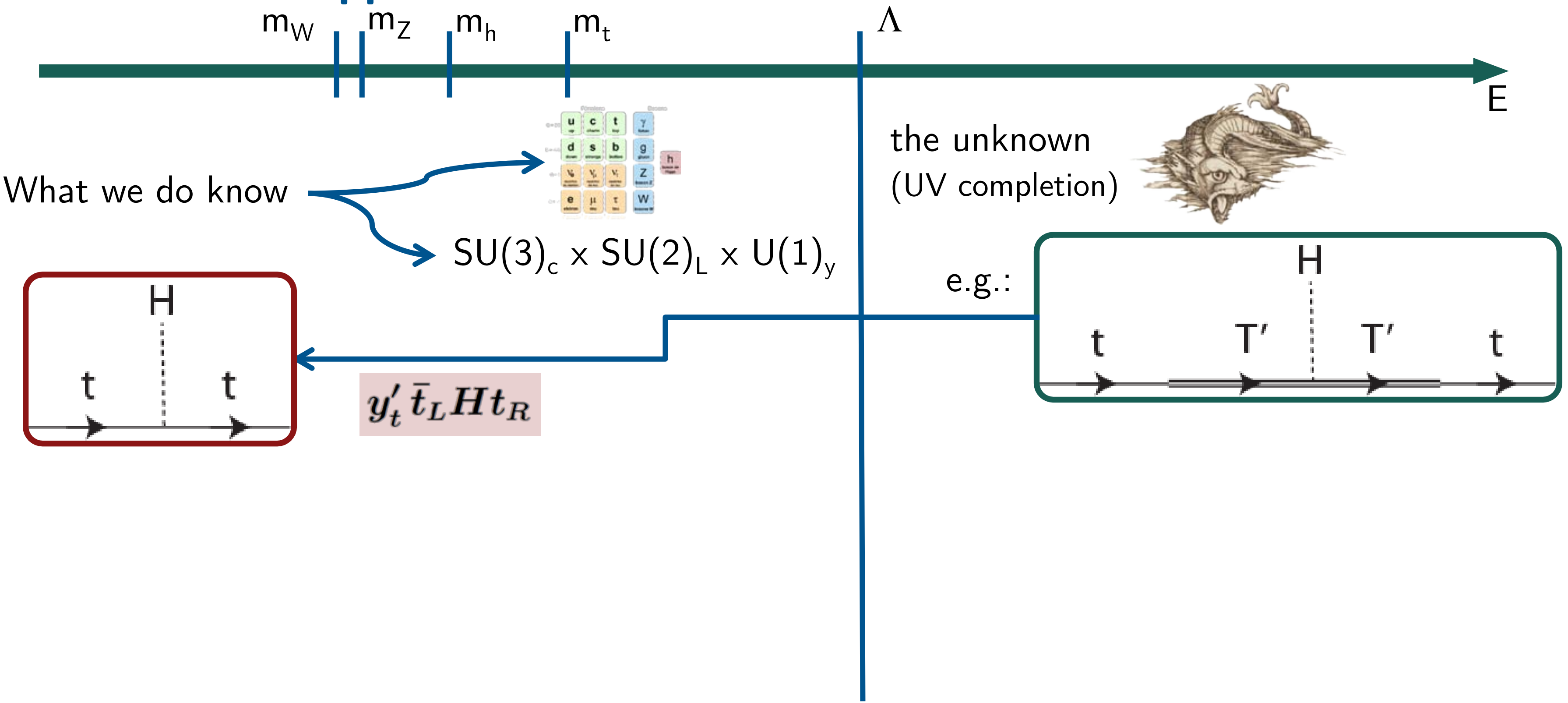
What we do know

$SU(3)_c \times SU(2)_L \times U(1)_y$

the unknown
(UV completion)

Physics Beyond the Standard Model (BSM)

The Effective Approach



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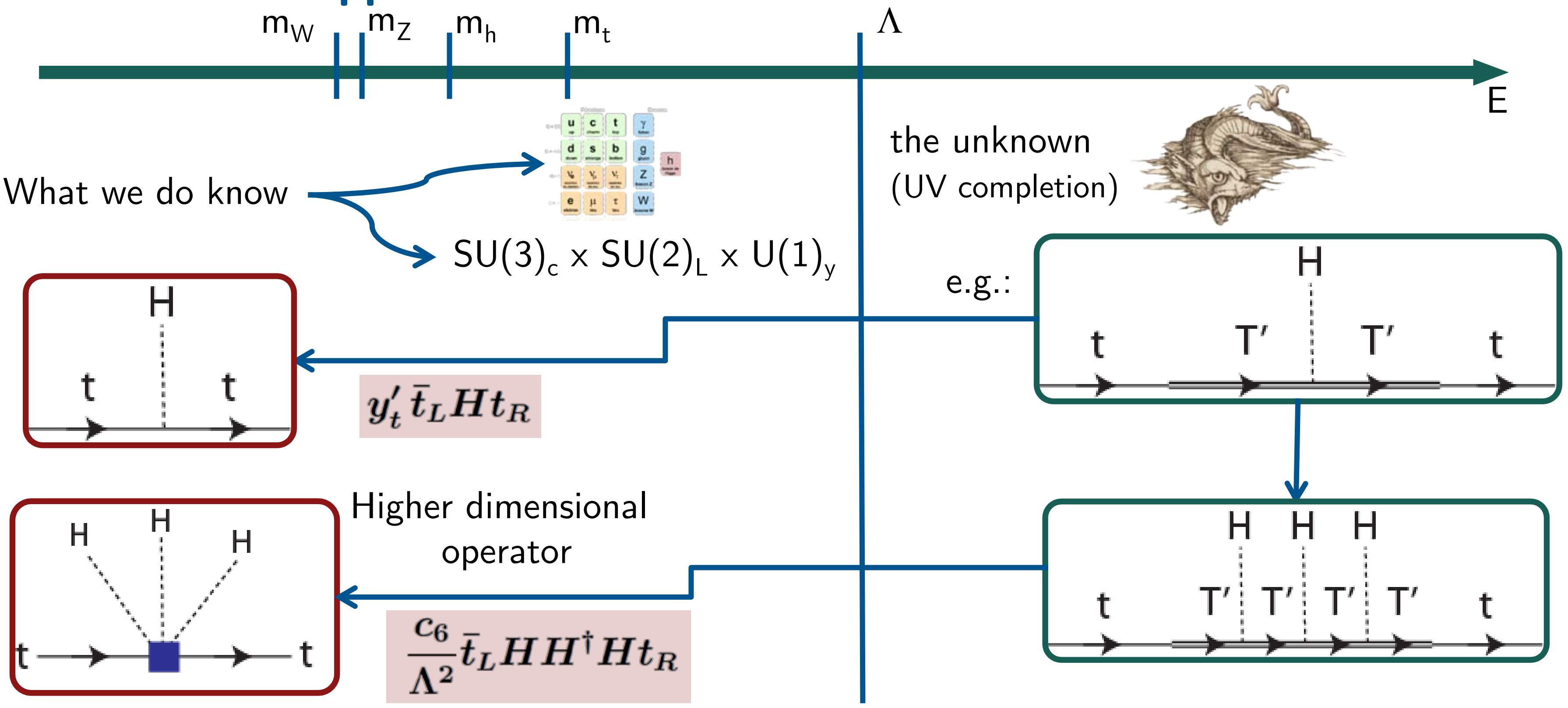

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We can then approach the problem in the following way:

Unknown UV can generate all Higher Dimensional Operators that...

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$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_{d\,i}$$

The full SM EFT has:

- ☐ 1 operator of dimension 5 (Majorana mass)
- ☐ 59 operators of dimension 6

} Not counting flavor indexes (if you do, it is around 2500 operators!)

See https://arxiv.org/abs/1008.4884

Case Study: Lepton Flavor Violation (LFV)

The operator below, for instance, can induce LFV (otherwise absent in the SM):

$$-\frac{\lambda'_{ij}}{\Lambda^2}\left(\bar{\psi}^i_L \psi^j_R\right) H \left(H^\dagger H\right)$$

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λ'_{ij} → Matrix in flavor space

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$$M^{ij}\bar{\psi}^i_L \psi^j_R \qquad M = \frac{v}{\sqrt{2}}\left[\lambda + \frac{v^2}{2\Lambda^2}\lambda'\right]$$

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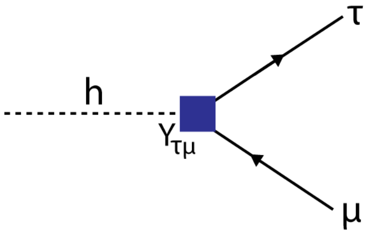
In the SM I can diagonalize M and Y with the same rotation, the new operator makes that impossible. That will generate flavor changing interactions with the Higgs:



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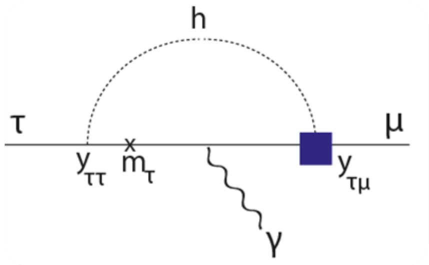

$\tau \to \mu\gamma$ has never been observed, that puts a limit on λ'/Λ^2

Which can mean: Λ is large (New physics is far away)

λ' is small (operator is suppressed or forbidden in the UV)

... or even both!

Case Study: Gauge boson scattering

Life is not always that easy though, consider the following operators (d = 6):

$$
\begin{aligned}
\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}] \\
\mathcal{O}_{\tilde{W}} &= (D_\mu \Phi)^\dagger \tilde{W}^{\mu\nu} (D_\nu \Phi) \\
\mathcal{O}_{\Phi d} &= \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right) \\
\mathcal{O}_{\Phi W} &= \left(\Phi^\dagger \Phi\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}] \\
\mathcal{O}_{\Phi B} &= \left(\Phi^\dagger \Phi\right) B^{\mu\nu} B_{\mu\nu}
\end{aligned}
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\mathcal{O}_{\tilde{W}W} &= \Phi^\dagger \tilde{W}_{\mu\nu} W^{\mu\nu} \Phi \\
\mathcal{O}_{\tilde{B}B} &= \Phi^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu} \Phi
\end{aligned}
$$

Case Study: Gauge boson scattering

They contribute to a lot of different scatterings:

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	X	X					X	X	X	X
$\mathcal{O}_{W}$	X	X	X	X	X		X	X	X	
$\mathcal{O}_{B}$	X	X		X	X					
$\mathcal{O}_{\Phi d}$			X	X						
$\mathcal{O}_{\Phi W}$			X	X	X	X				
$\mathcal{O}_{\Phi B}$				X	X	X				
$\mathcal{O}_{\tilde{W}WW}$	X	X					X	X	X	X
$\mathcal{O}_{\tilde{W}}$	X	X	X	X	X					
$\mathcal{O}_{\tilde{W}W}$			X	X	X	X				
$\mathcal{O}_{\tilde{B}B}$				X	X	X				

arXiv:1310.6708 and arXiv:1309.7890

It can be a lot harder to set limits to their coefficients

UV models

Another approach is to write possible UV models that contain the SM in some limits

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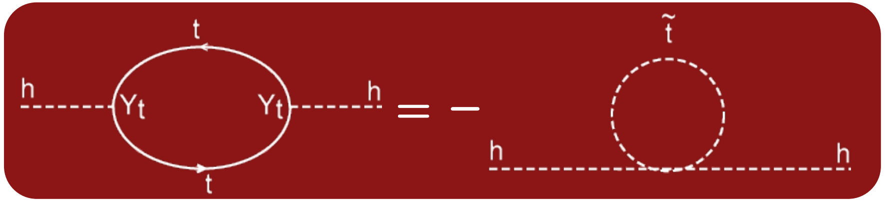
The traditional solutions to the hierarchy problem can be roughly divided in two classes:

- ☐ There is a light fundamental scalar & cancel quantum corrections



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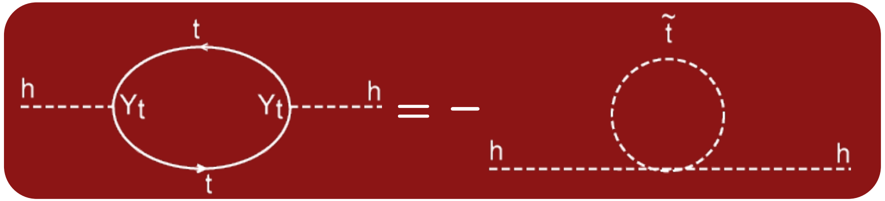

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□ The light scalar is not fundamental & quantum corrections only make sense up to the compositeness scale

(Composite Higgs Models)

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In most cases there is a DECOUPLING LIMIT where, by making the scale Λ associated with the new physics very big, one gets a theory increasingly SIMILAR to the SM. New physics effects DECREASE with INCREASING Λ.

Precision measurements
Agreement with SM
→ Pushes Λ away!

The models are never really gone, just pushed away.

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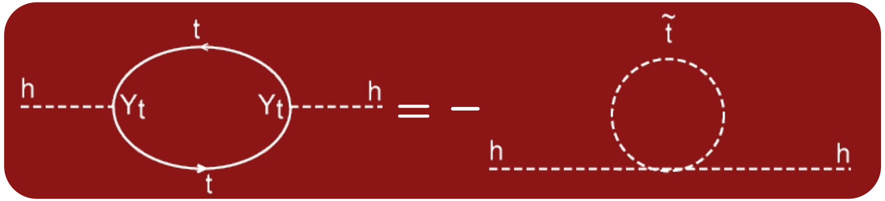
The hierarchy problem is thus reintroduced, e.g.:



Cancelation only works if the masses of top and stop are equal

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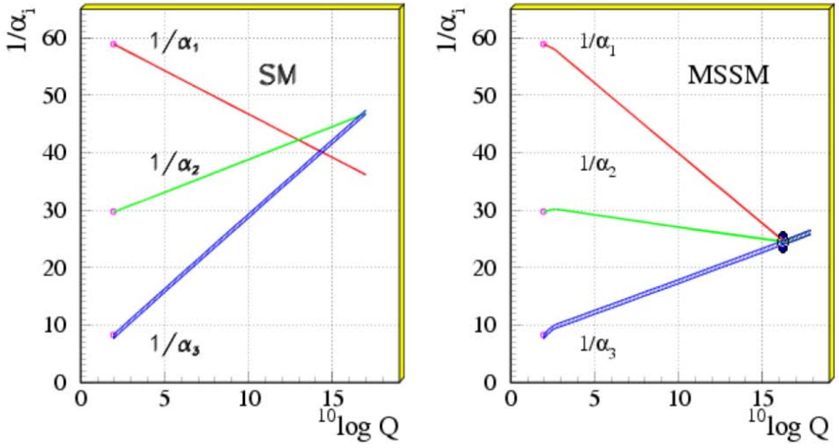

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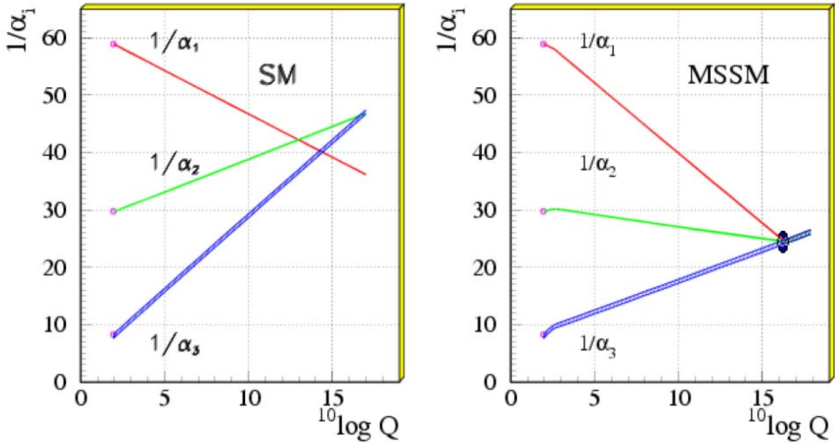

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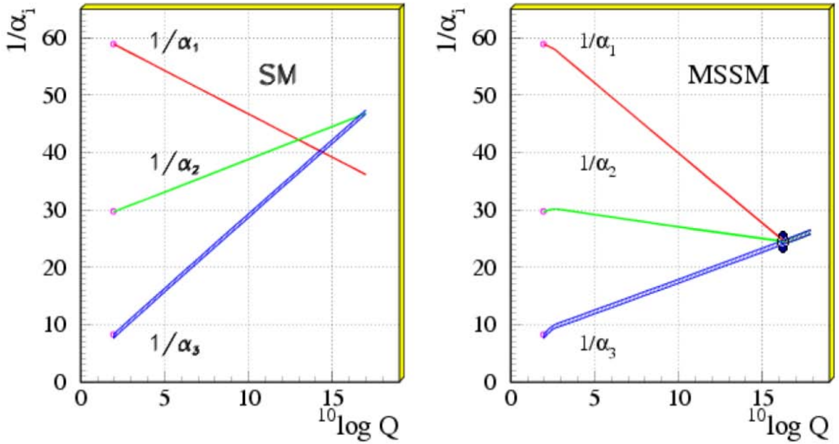

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- ☐ UV completion / Strings

Composite Higgs Models

Broad class that can refer to a lot of different models (including some extra dimensional models). Nowadays used more in connection with the Higgs being a pNGB of some broken global symmetry. The motivations are more empirical:

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- Has been realized in nature time and again, at various scales (pions, Cooper pairs)
- Some models also implement unification

DM candidates and portals

It is fairly easy to "plug-in" a Dark Matter candidate to an existing model, you just have to add some ad-hoc symmetry to stabilize some particle, but it is much more interesting when the model already has candidates due to its own symmetries (as is the case of the MSSM or some strongly coupled models).

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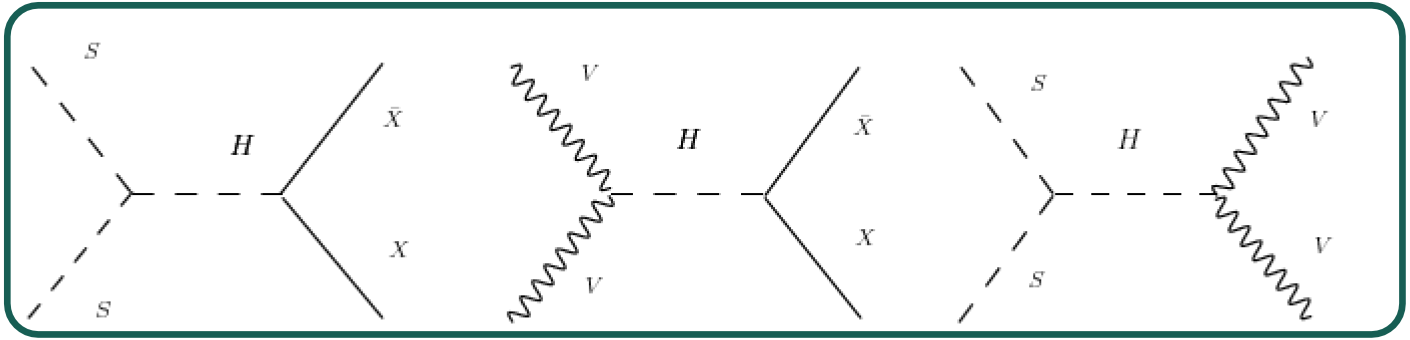

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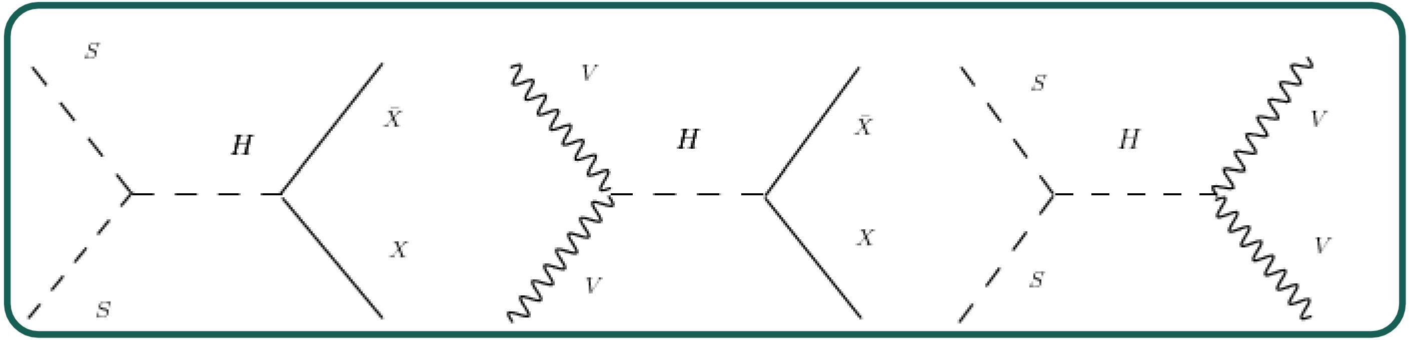

The challenge lies in having the right couplings / masses to get the abundance we see today and avoid direct detection experiments

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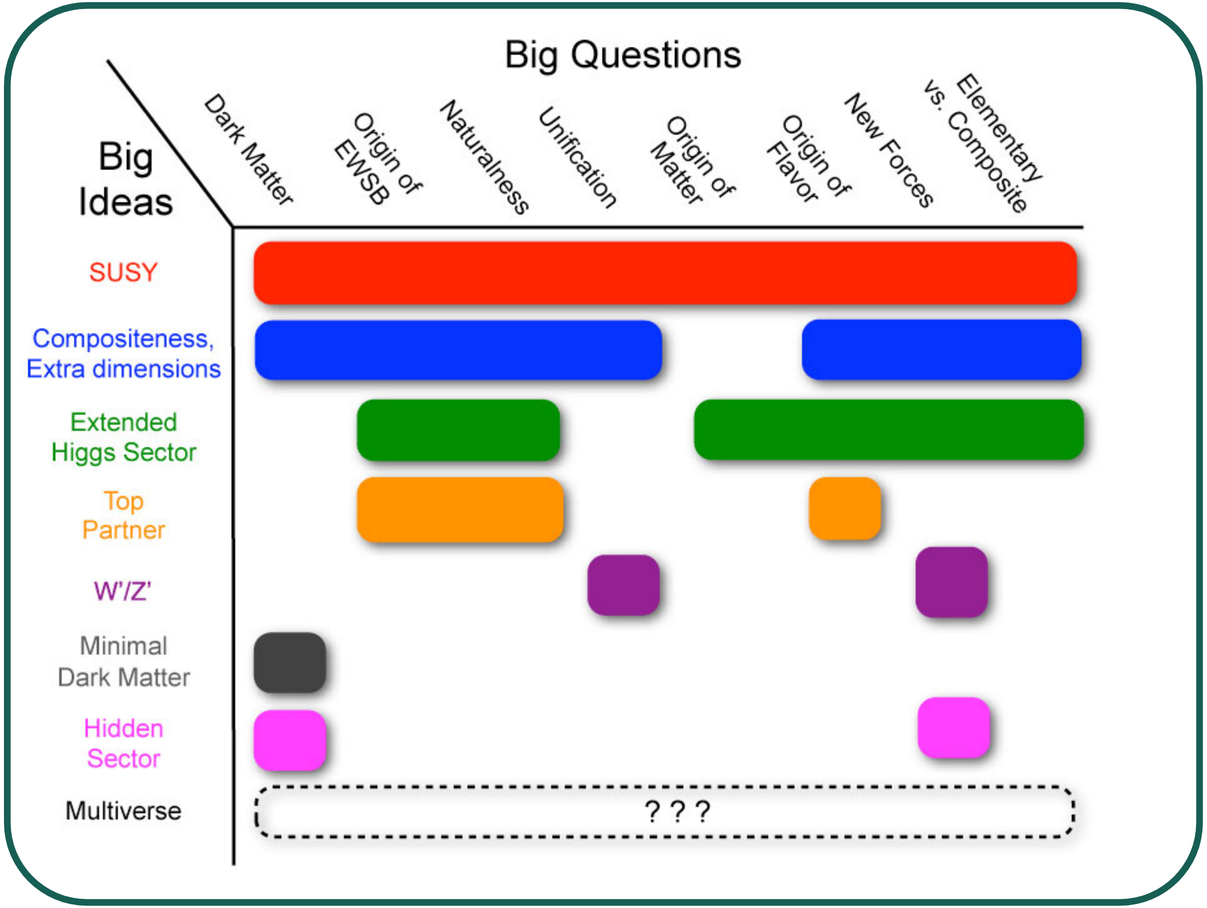
Of course people have found much more complicated models, but the main question at this moment is whether the neutrinos are Dirac or Majorana Fermions. This question might be answered experimentally in the next 10 years.

The list goes on...

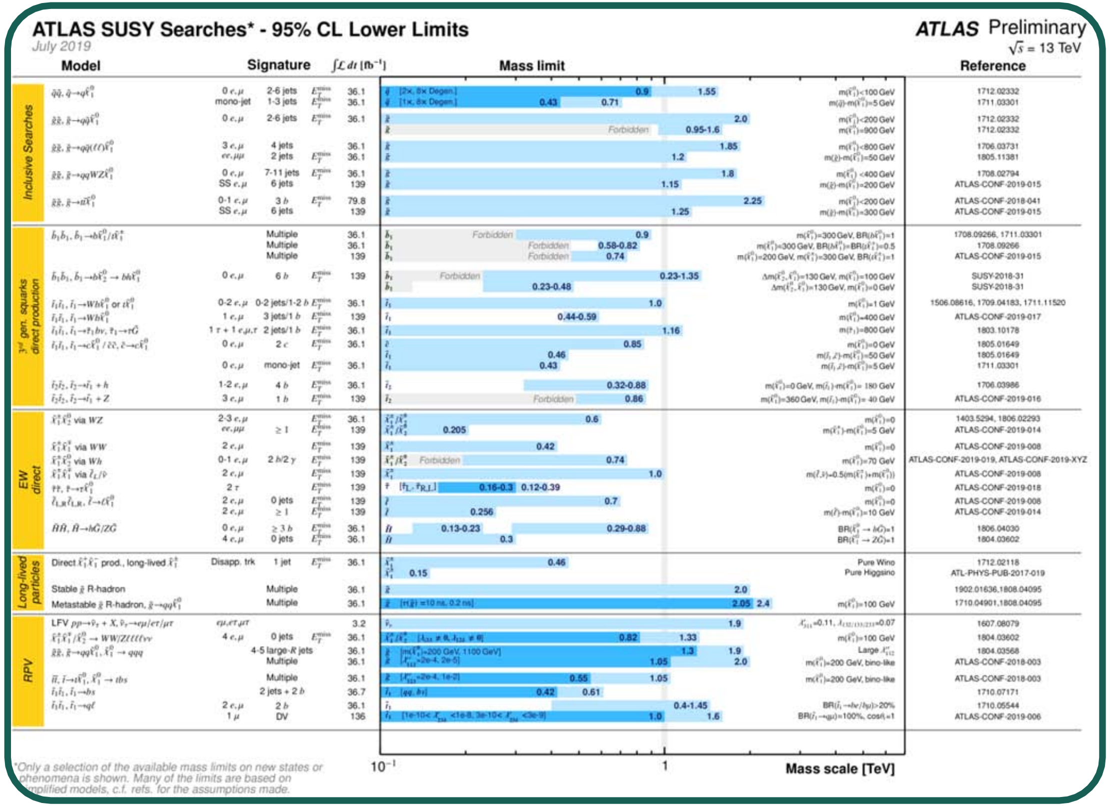


New Particles Working Group
Report of the Snowmass 2013
Community Summer Study,
arXiv:1504.07551

In one sentence: nothing to see here!

The search for BSM physics

But it is a very complicated “nothing”, so there might still be something hiding in the details:



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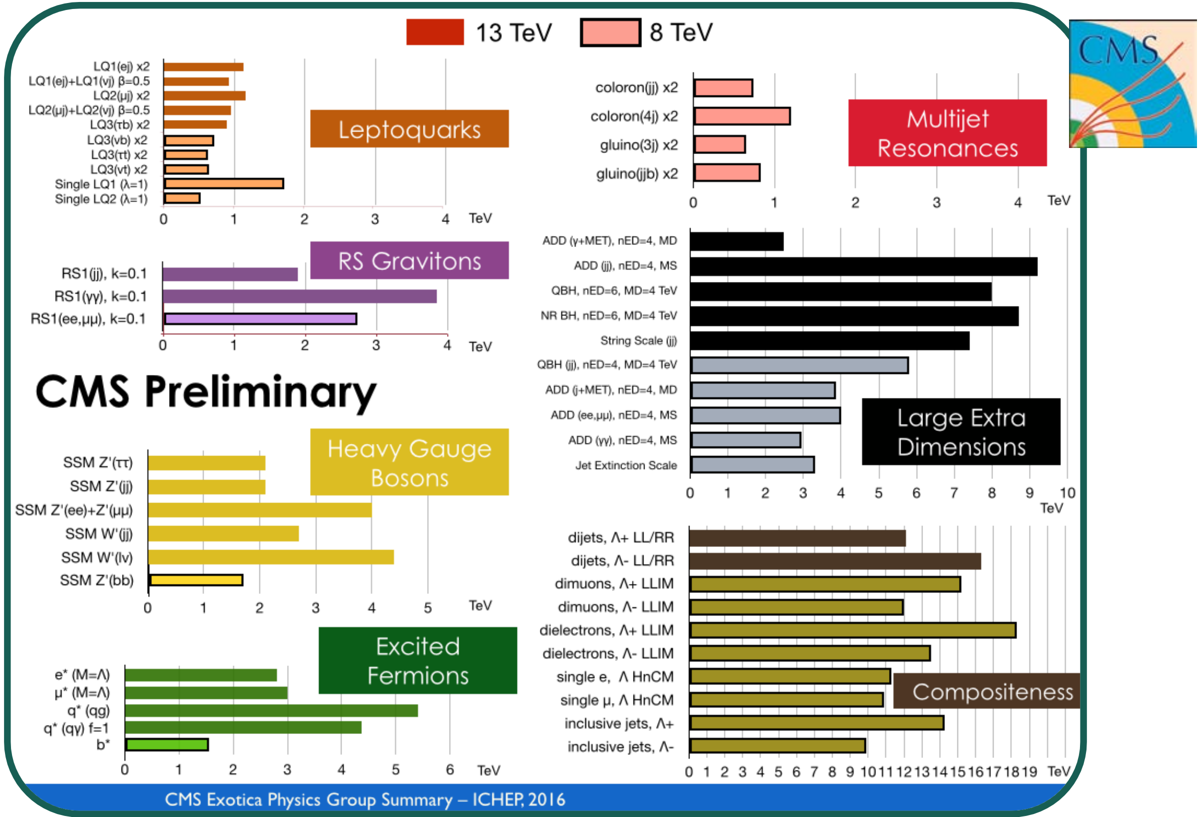

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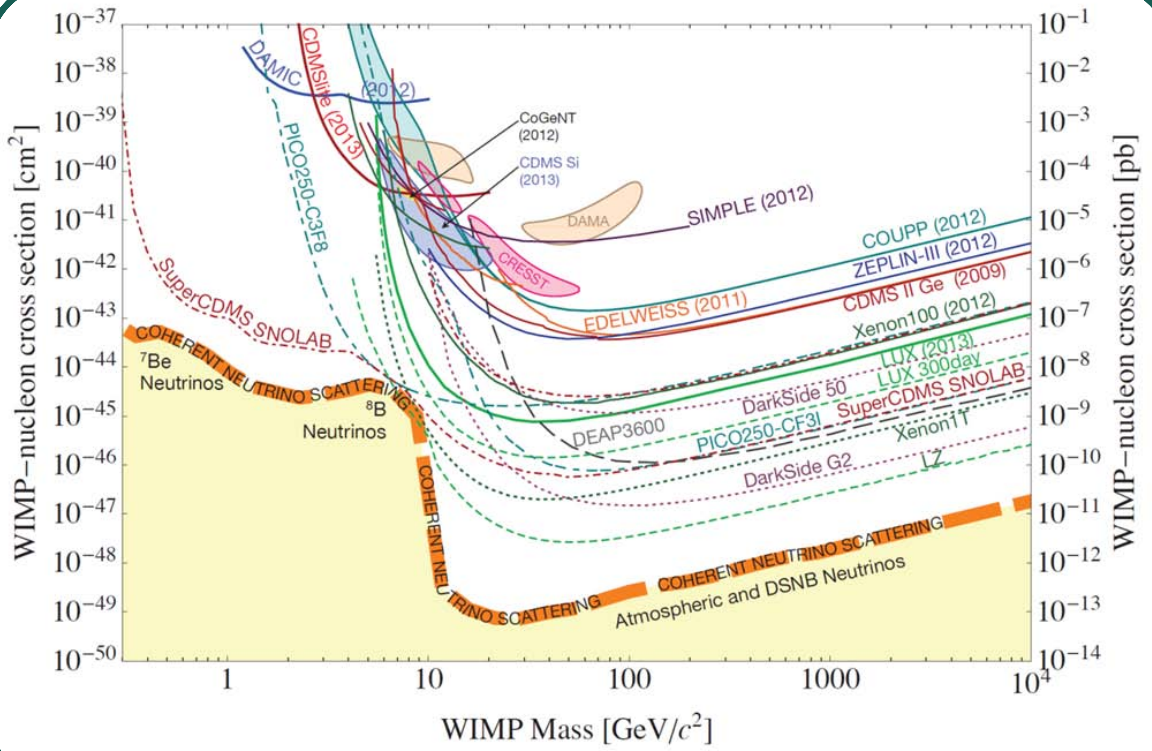

https://arxiv.org/abs/1410.4960

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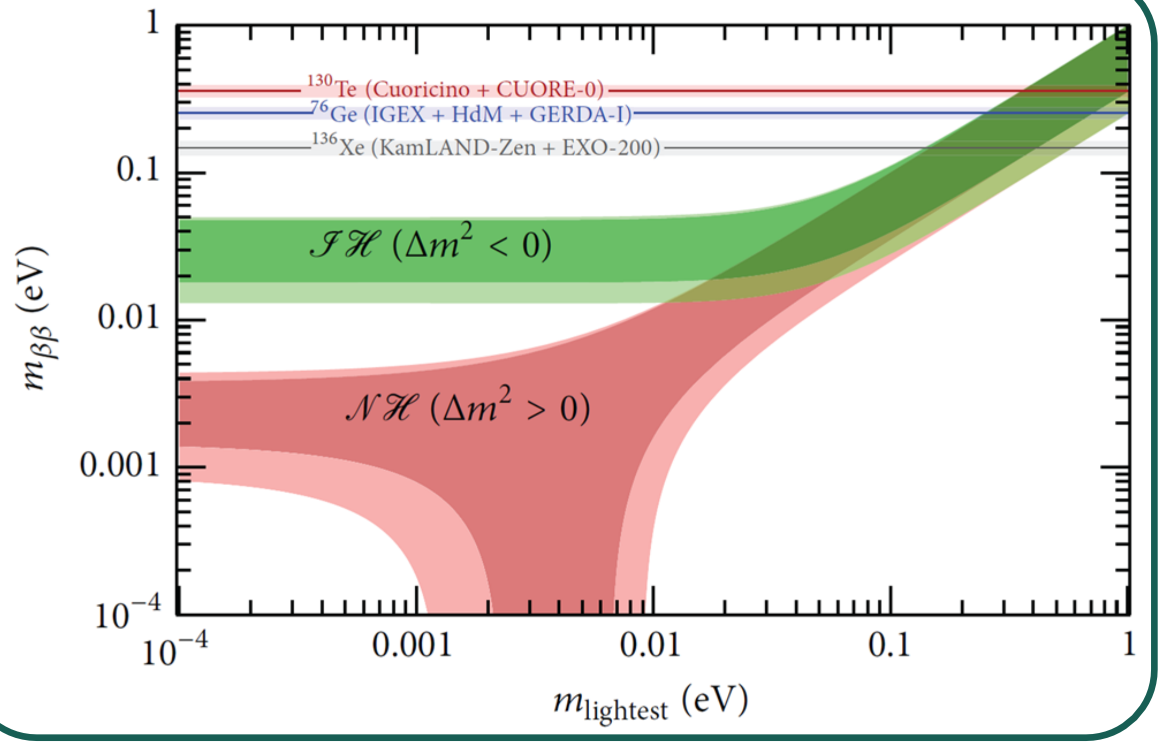

https://arxiv.org/abs/1601.07512

The only sensible thing to do right now...

... is to keep looking