Title: Cosmological non-Constant Problem

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Abstract: I will discuss how studying the gravitational effects of UV physics on large (astrophysical) scales precludes new mass scales in BSM physics beyond 600 GeV.

Asymptotic Safety in a Dark Universe

Perimeter Institute

June 5, 2018

Cosmological non-Constant (CnC) Problem:

Astrophysical Limits of Particle Physics

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Outline

- Prelude: Hierarchy in Nature
- Cosmological Non-Constant (CnC) Problem
  - Why CnC?
  - CnC in Astrophysics:
    - Cosmic Microwave Background
    - Pulsar Timing Observations
- Epilogue: The folly of the Effective Field Theory

Cosmological Constant (CC) Problem

- General Relativity

$$G_{\mu\nu}(x) = \kappa\, T_{\mu\nu}(x)$$

curvature

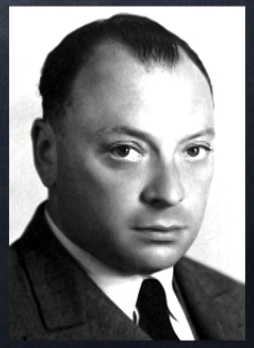
energy/momentum

- Quantum Mechanics (Standard Model)

$$\langle T_{\mu\nu}(x)\rangle_{\rm SM} \sim \pm 10^{45}\ {\rm eV}^4 \times g_{\mu\nu}$$

- Real World!

$$\kappa\langle G_{\mu\nu}(x)\rangle_{\rm cosm.} \sim 10^{-12}\ {\rm eV}^4 \times g_{\mu\nu}$$



HEP Hierarchy problem(s)

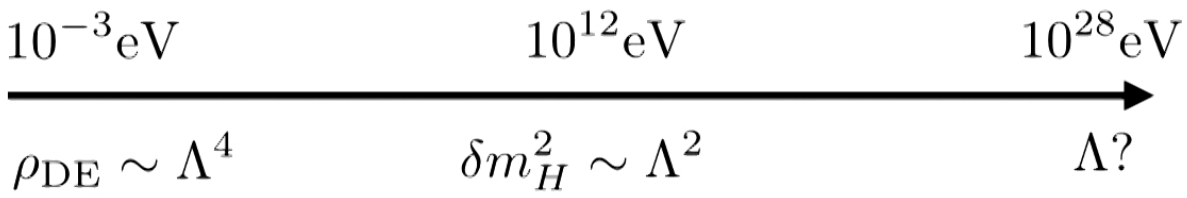
old cosmological constant (CC) problem

- neutrino mass
- dark energy

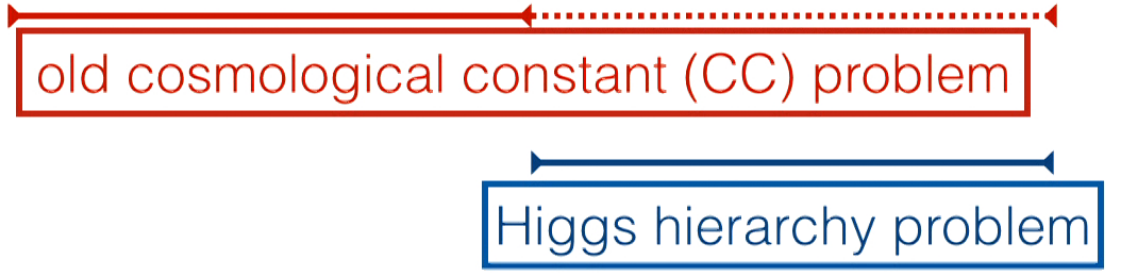
Higgs, Electroweak

LHC

GUT…Planck



HEP Hierarchy problem(s)

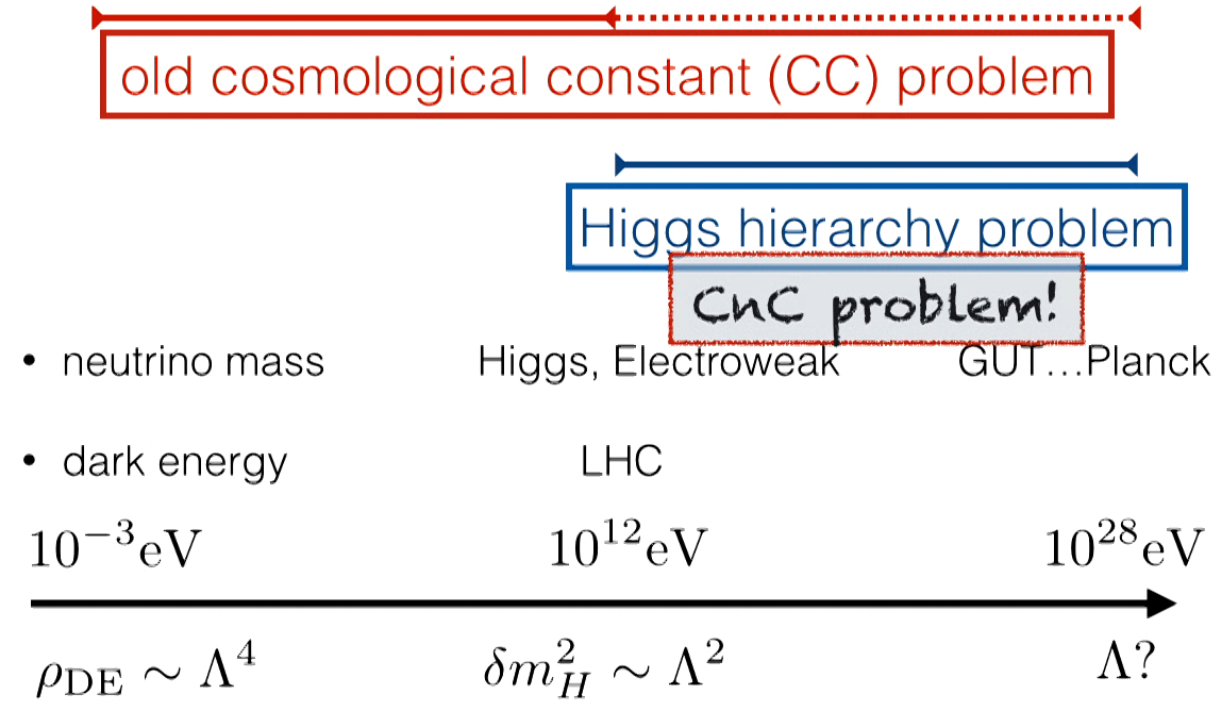


- neutrino mass — Higgs, Electroweak — GUT…Planck
- dark energy — LHC

$10^{-3}\mathrm{eV}$ $10^{12}\mathrm{eV}$ $10^{28}\mathrm{eV}$

$\rho_{\mathrm{DE}} \sim \Lambda^4$ $\delta m_H^2 \sim \Lambda^2$ $\Lambda?$

HEP Hierarchy problem(s)



Punchline!

- Gravity is different! Observables non-local
- UV physics -> IR noise in geometry
- No new scale in QFT+GR $\gtrsim$ TeV!

→ ~~High-scale SUSY, GUT, (almost all) Inflation models~~

→ TeV-scale QG, Large Extra Dimensions

→ Strongly coupled UV completion (Asymptotic Safety?)

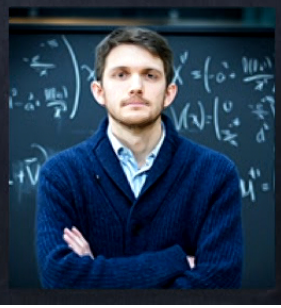
A very vibrant vacuum

- Quantum Fluctuations do fluctuate!

$$\langle T_{\mu\nu} T_{\alpha\beta} \rangle \neq \langle T_{\mu\nu} \rangle \langle T_{\alpha\beta} \rangle$$

- What is the analog of CC for the covariance of stress fluctuations?
- Can these fluctuations have an observable gravitational signature on large scales?

with Elliot Nelson, Phys. Rev. D 93, 083505



Vacuum Fluctuations in Linear Gravity

- Linearized Perturbations around FRW space-time

$$ds^2 = a^2(\eta)\left[-(1+2\phi)d\eta^2 + 2V_i dx_i d\eta + (1-2\psi)d\mathbf{x}^2\right]$$

- Einstein constraint sector: scalars in longitudinal gauge and vectors

$$-k^2\psi = 4\pi G\left(\delta T_{00} - \frac{3\mathcal{H}}{k^2} ik^i \delta T_{i0}\right),$$

$$-k^2\phi = 4\pi G\left(\delta T_{00} - \frac{3\mathcal{H}}{k^2} ik^i \delta T_{i0} + \left(\delta^{ij} - 3\frac{k^i k^j}{k^2}\right)\delta T_{ij}\right),$$

- $$k^2 V_i = 16\pi G(\delta_{ij} - \hat{k}_i\hat{k}_j)\delta T_{j0},$$

CnC: *the upshot!*

- Random stress fluctuations at UV scale Λ

$$\langle T_{ij}^{(V)}(\mathbf{x}) T_{kl}^{(V)}(\mathbf{y}) \rangle \sim \delta^3(\mathbf{x}-\mathbf{y})\Lambda^5$$

- Einstein eq. for anisotropic stress

$$k^2\Phi \sim M_{\rm p}^{-2} A^{ij} T_{ij}$$

- Variance of Metric perturbations grows as distance

$$\left(\Delta_\Phi^{(V)}\right)^2 \sim \frac{\Lambda^5}{M_p^4 k}$$

- A UV/IR Heisenberg uncertainty relation

$$\Lambda_{\rm IR} = \frac{\Lambda_{\rm UV}^5}{M_p^4}$$

Spectral Representation

- Most general expectation for stress correlators from *Unitarity*+*Lorentz symmetry*

$$\langle T_{\mu\nu}(x)T_{\alpha\beta}(y)\rangle = \int \frac{d^4k}{(2\pi)^4} e^{ik\cdot(x-y)} \int_0^\infty d\mu \left[\rho_0(\mu)P_{\mu\nu}P_{\alpha\beta} + \rho_2(\mu)\left(\frac{1}{2}P_{\mu\alpha}P_{\nu\beta} + \frac{1}{2}P_{\mu\beta}P_{\nu\alpha} - \frac{1}{3}P_{\mu\nu}P_{\alpha\beta}\right)\right] \theta(k^0)2\pi\delta(k^2+\mu),$$

- ρ's must positive.

$$P_{\mu\nu} \equiv \eta_{\mu\nu} - k_\mu k_\nu / k^2$$

- *Cosmological* constraints will roughly translate to

$$\int \frac{d\mu}{\sqrt{\mu}} \rho_2(\mu) \lesssim (10 \text{ TeV} - 1 \text{ PeV})^5$$

- *Pulsar Timing* constraints

$$\int \frac{d\mu}{\sqrt{\mu}} \rho_2(\mu) \lesssim (600 \text{ GeV})^5$$

E.g., a free scalar field

- For a weakly coupled scalar field

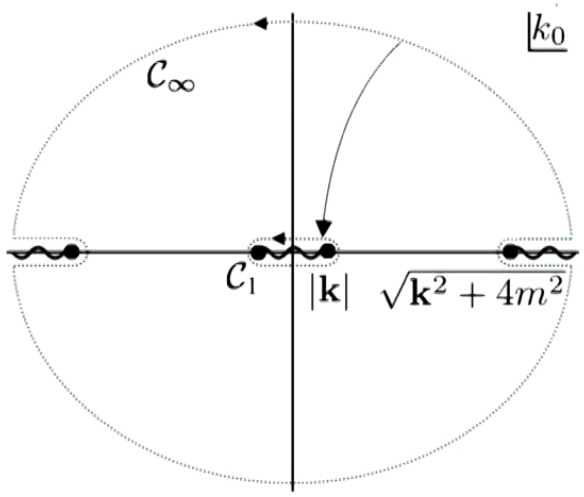
$$-\mu = k_0^2 - |\mathbf{k}|^2$$

$$\rho_2(\mu) = \frac{\mu^2}{120\pi^2}\sqrt{\frac{1}{4} - \frac{m^2}{\mu}}\left[\frac{1}{4} - \frac{m^2}{\mu}\right]^2 \Theta(\mu - 4m^2)$$

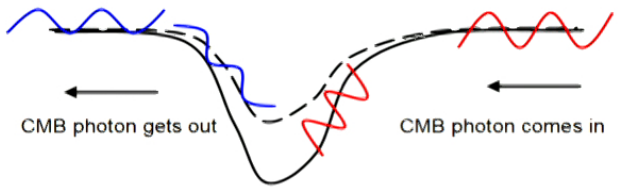
- For large scale, real-space correlations, one can deform the contour to get

$$\rho_{2,\mathrm{eff}}(\mu) = \frac{m^5}{120\pi^2\sqrt{-\mu}}\Theta(-\mu)$$

- *Described by Poisson model*



CMB anisotropies



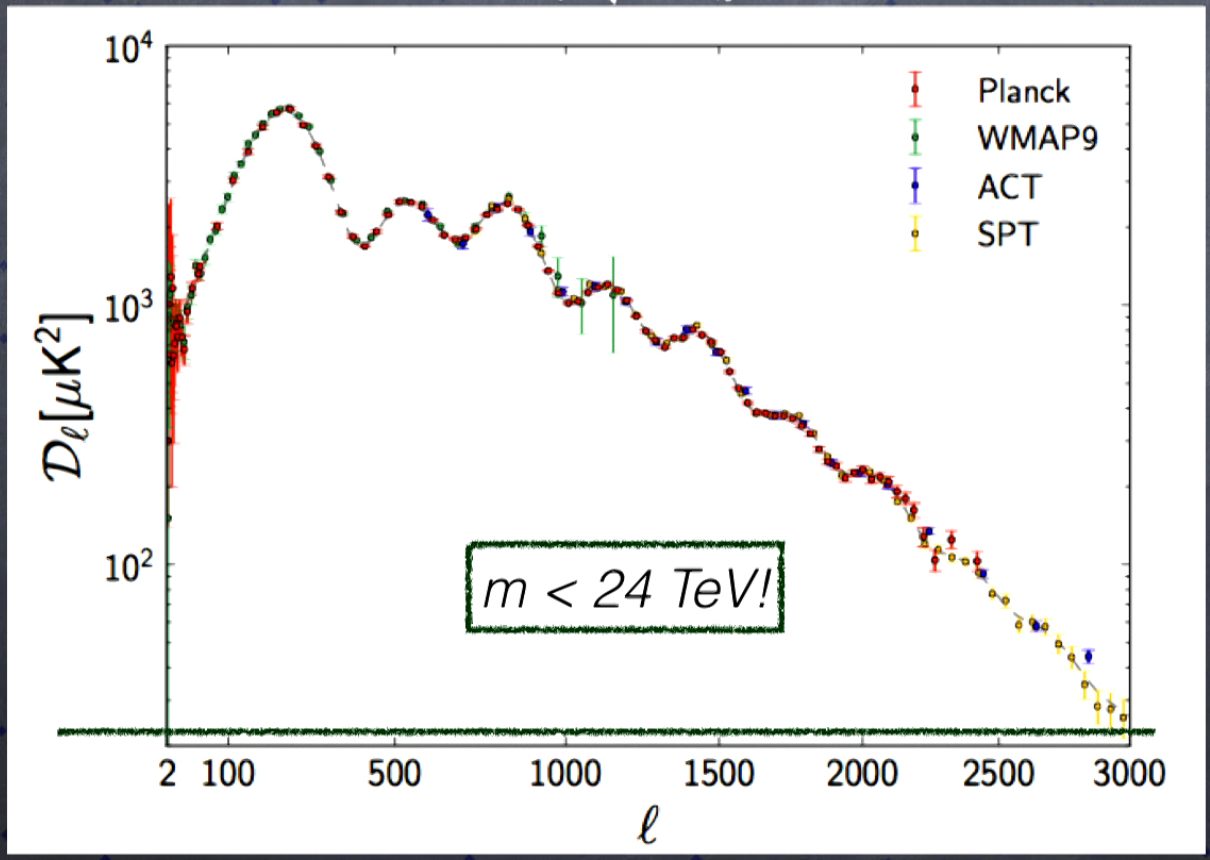
- Integrated Sachs-Wolfe (ISW) effect

$$\frac{\delta T^{\rm ISW}(\hat{\mathbf{r}})}{T} = \int_{\eta_{LSS}}^{\eta_{\rm today}} d\eta(\phi' + \psi' + V_i'\hat{r}^i),$$

- ISW effect due to metric fluctuations, due to a scalar vacuum

$$(\Delta_l^2)^{\rm ISW} \equiv \frac{l(l+1)C_l^{\rm ISW}}{2\pi} = \frac{49}{2880\pi^2}\frac{m^5 t_0}{M_p^4}$$

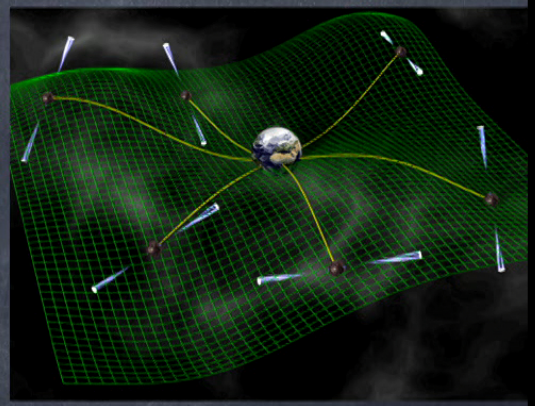
power spectrum of CMB



NA, Kim & Nelson 2017

Pulsar Timing

- Same as ISW effect, exc. @ different times, not directions



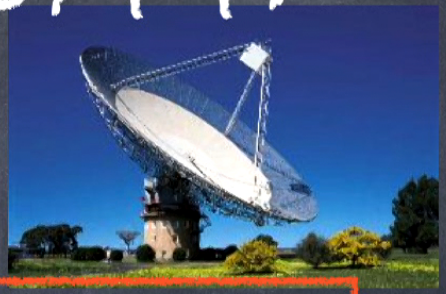
$$(Pf)^2 \Phi_{TN}(f) = \frac{h^2_{c,\mathrm{eq}}}{12\pi^2 f}$$

$$\begin{aligned}
c_X &= 1 \quad (X = \phi,\ \text{real}) \\
&= 2 \quad (X = \phi,\ \text{complex}) \\
&= 2 \quad (X = \psi,\ \text{Majorana}) \\
&= 4 \quad (X = \psi,\ \text{Dirac}) \\
&= 3 \quad (X = A_\mu,\ \text{real}) \\
&= 6 \quad (X = A_\mu,\ \text{complex}).
\end{aligned}$$

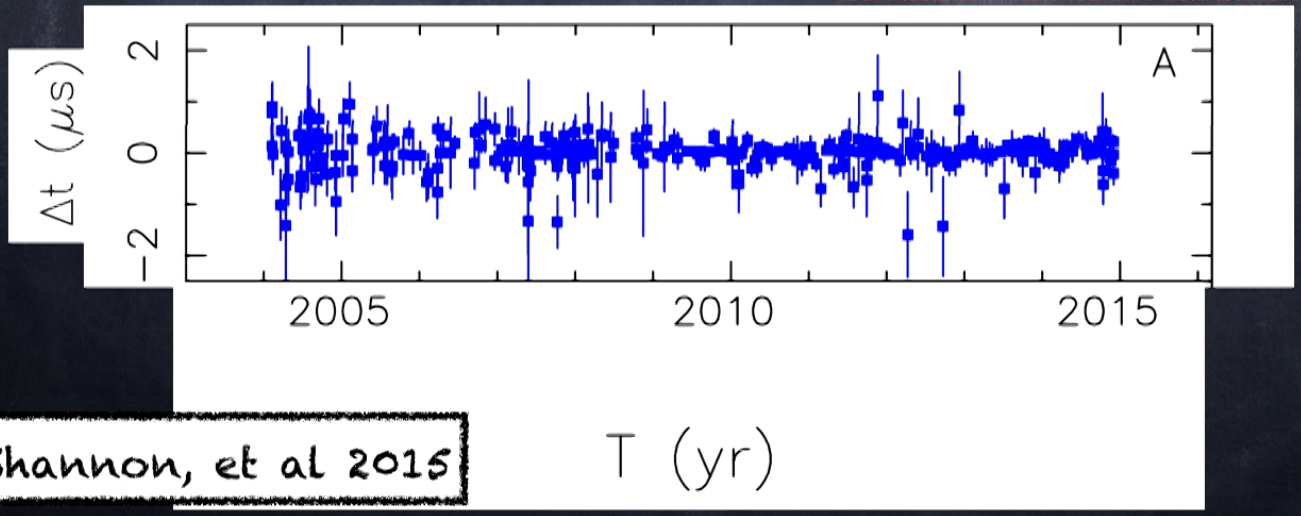
$$(h^2_{c,\mathrm{eq}})^{(X)} \approx -c_X \frac{7}{480\pi^3} \frac{m^5}{M_p^4 \omega} \left[\sqrt{4\pi\omega L} + \ln(k_{\max} L)\right]$$

$$\approx -4 \times 10^{-30} c_X \left(\frac{m}{600\ \mathrm{GeV}}\right)^5 \sqrt{\frac{2\pi L(\mathrm{kpc})}{\omega(\mathrm{yr}^{-1})}}$$

Meet PSR J1909-3744!

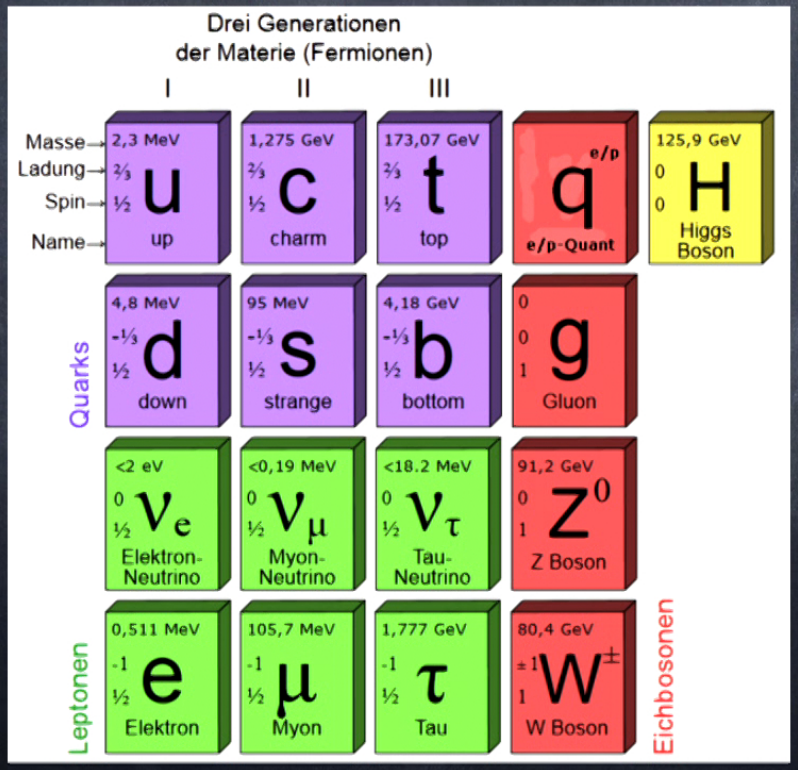


- P=2.947 ms, d=1.26 kpc
- $h_c < 3.2 \times 10^{-15}$ @f=0.2/yr → $m_\varphi < 600$ GeV



Shannon, et al 2015

No Physics "beyond" Standard Model?



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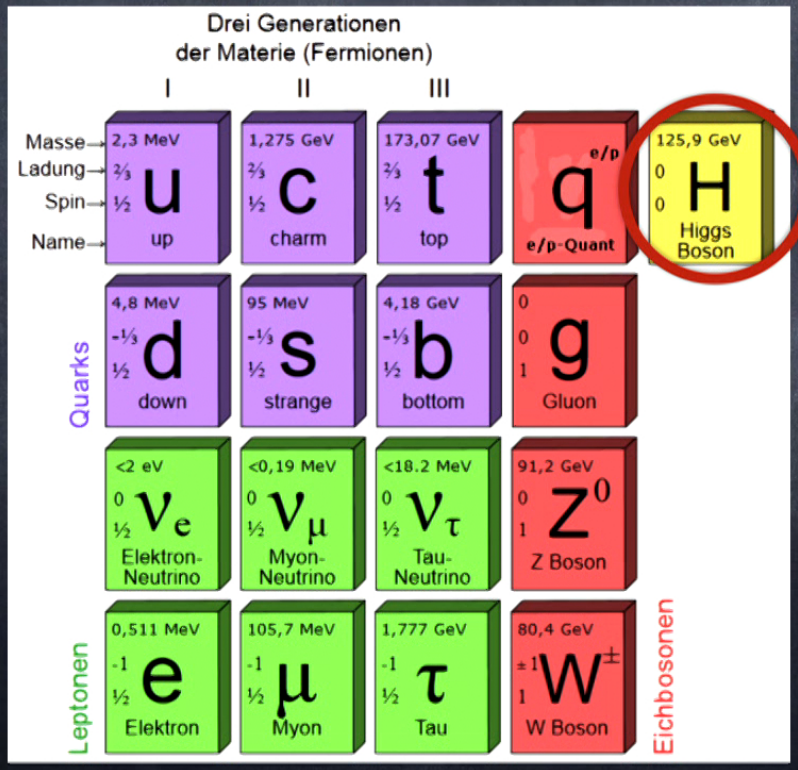

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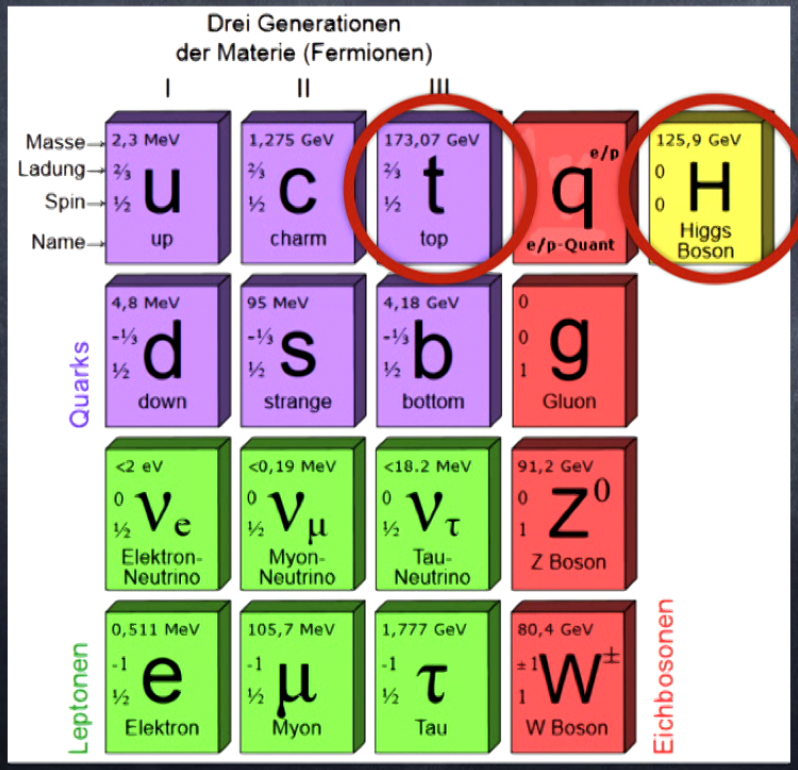
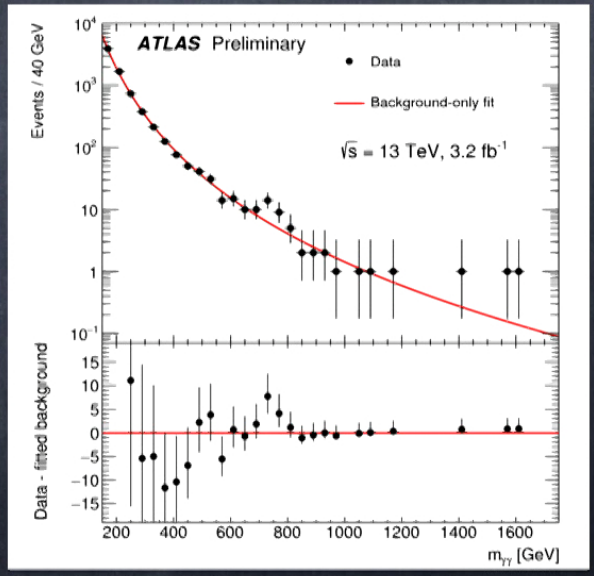


Remember Di-photon excess?

- 3σ di-photon excess in LHC/CMS
- A new particle at 750 GeV?
- If so, in contrast with CnC constraint from pulsar timing!



My slide from May 2016 at NBI, Copenhagen!

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Cosmological Non-Constant (CnC) problem

- Vacuum energy-momentum fluctuations can also source gravity
- They change the gravitational constraint sector in the IR, thru equal-time correlators
- Heisenberg Uncertainty principle for UV/IR observables
- CnC problem is more severe than the old CC problem, due to the positivity of the spectral functions or entropy, i.e. fine-tuning doesn't work

Open Questions

- What about the early universe/inflation/Dark Matter?
- The damned minutes sign!!
- What happens beyond linear order?
- Nature of IR cut-off? massive gravity, Dark Energy?
- Connection to holography [Ask me if interested!]

Final Thoughts

- CnC: Quantum Gravity couples UV and IR
  - Astrophysics → no Particle scale beyond
    - 24 TeV (CMB), 600 GeV (pulsar timing)
  - Also motivated by solving the Higgs hierarchy problem, e.g. Large Extra Dimensions, conformal Higgs
  - Target for LISA/LIGO?
- EFT: Just think outside the box!