Cosmological constant & vacuum energy

\* Einstein - Hilbert action S= Stek FF. Ret Lorents invariance, in fact defices morphism invariance ibits [R]= L<sup>2</sup> N's <u>akt</u> (or poweral covariance) other actions R<sup>MV</sup> R<sub>MU</sub>, R<sup>°</sup>, R<sup>MVSt</sup> R<sub>MU</sub>pp not all ind. Matter Lagrangian (density) Lan  $S = Sd^{4}x F_{2} Sun winnelly coupled. The = <math>g_{\mu\nu} 2m - 2 \frac{\delta S_{\mu\nu}}{\delta 2m}$ + variations work to the . ; integration by part SS = SUFKE-3 SOMO (-KRS Grov + 2 Tro) Ruo = Ruo - 2 Juo R  $\therefore \quad f_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi}{c^2}T_{\mu\nu}$ Shoin = a - Inain Ltes: geometry, RHS: matter conserved. Blanchi releastify \* Cosmological constant or vacuum energy Que > Que + N Zue or Tue > Tru + The, The = - AE Jue Show in = 0 at the mouse A is just a constant of theory or constant density everyohore (= vacuum everyy) in terms of perfect fluid The = SUMAN + P(SHO + ULLO) SA = -PA = Act in fact the only draiter for vacuum energy density - Suce you - Suce you - Suce you - Suce you

all physics except gravity : independent of absolute everyy but only difference gravity knows the absolute every : zero (no interaction) soverage kinetic everyy by going to negative

 $H = \frac{1}{2m}p^2 + \frac{1}{2}m\omega^2 q^2 \qquad E = \frac{1}{2}\pi\omega(1+2n) \qquad \text{Sound state (n-20)}$  here are - 1+...+ Quarteen Modanics : A Simple hermonic escillator \* Quantum field:  $9 \rightarrow \phi(k)$ ,  $p \rightarrow \pi(k) = 2 \int_{2} \phi(k)$  infinite dof QM  $H = \left(\frac{N^2 p}{2\pi} E_p \left(\frac{N_p}{4\pi} + \frac{1}{2} E_{p}, 9_{p}^{+}\right)\right) = E_p^{\perp} = m^{2} + p^{2}$  all frequency  $\Rightarrow E_{vacuum} - S_{(2\pi)}^{(3p)} = \frac{1}{2} V S_{(2\pi)}^{(3p$ Suce= = Stars = ~ Sdip2 + ~ phone

\* cut-of scales Planck scale mp<sup>2</sup> = the/G ~ (10<sup>-9</sup>Gel)<sup>2</sup>~ (10<sup>-5</sup>g)<sup>2</sup>, 2p~10<sup>-3</sup>m to ~ (0 sec GUT Move ~ (0" GeV Standard model Mate ~ (Tel ~ 103 Gel

\* observations:  $S_A \sim (10^{-12} \text{ Grel})^4 \implies (10^{-12} \text{ nr}^4)^4 \rightarrow (10^{-12} \text{ nr}^4)^4$ = | meV or NGO arders (standard)

**Cosmological constant problem** 120 order difference. Over with std model. 60 ordere, really problem? noted thous \* A top madel in QFT  $\Sigma_{\phi} = \frac{1}{2} (36)^{2} - \frac{1}{2} m_{0}^{2} \phi^{2} - \frac{1}{4} \phi^{4} - P_{0}$ bane quantities with o bane quantities are renormalized 2 only the renormalized match to experiments or observetions -> have quantities - not predicted, us physical \* Matching Prenorm ~ So (Mart) + Mart = Pobs implies 60-120 order digit the tuning & RED dection mass: Mnework ~ Ma (1+ 30 log ment) 2 \* Higgs mass (hierardy probe) = millings ~ moi + milling  $= ((o^{2} GeV)^{2} ~ ((0^{19} GeV)^{2})$ L> depends on particle cantents it m>> meta (vs. vacuum) still all this fine tuning arguaged may not be real, as have has no physical meaning

Cosmological constant as Einstein's biggest blunder

Einstein formulated GR in 1917 & applied to the Universe (or MW) Jaking) before the discovery of the flubble expansion (extra galaxies) gravity of matter pulls things together & collepte Expetein wonted some static & infinite universe, so add positile A to counter balance the pull prob. - A is constant, but matter distribution is not -> unstable Hubble expansion was discovered **Cosmological redshift** 1+2 = Kobs / Knest e.g. Lyd Oronaition 1216Å -> 8517Å at 2-6 tanilar phenomenon from Doppler effect, but V>C in asmology? things are not maing. spacefine betosen too points expands photon 4-vector in the next frame K? = w((. n?) K? K. 20 in FRW word,  $K^{\mu} = \frac{\omega}{2} (1, n^2)$ geodesic eq. temporel o=K"K", = K"K", + Took" + Took" + Took KK  $=\frac{\omega}{a}\left(\frac{\omega}{a}\right)^{2} + 24\left(\frac{\omega}{a}\right)^{2}$ ⇒ wa /a or λ a a \_. (+ 2 = <u>a,obs</u> acmit