METAPHOR FOR DARK ENERGY

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DAWN OF RELATIVITY

Newton's $1/r^2$ Law + Special Relativity

+ Equivalence Principle

Couple to Energy

$m=0$, spin-2

Couple to Mass

$m=0$, spin-0

Nordstrom '13

CURVED SPACETIME

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = T_{\mu\nu}$$

Einstein '15

⋮

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$$R = g^{\mu\nu} T_{\mu\nu}$$

$$C^{\text{Weyl}}_{\mu\nu\rho\sigma} = 0$$

Einstein, Fokker '14

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Einstein, Fokker '14

⋮

Analog (quantum) gravity
+ Cosmological Const. Problem
+ Modified gravity

Sundrum '03

LEAVE NO STONE UNTURNED

BETWEEN US & DARK ENERGY

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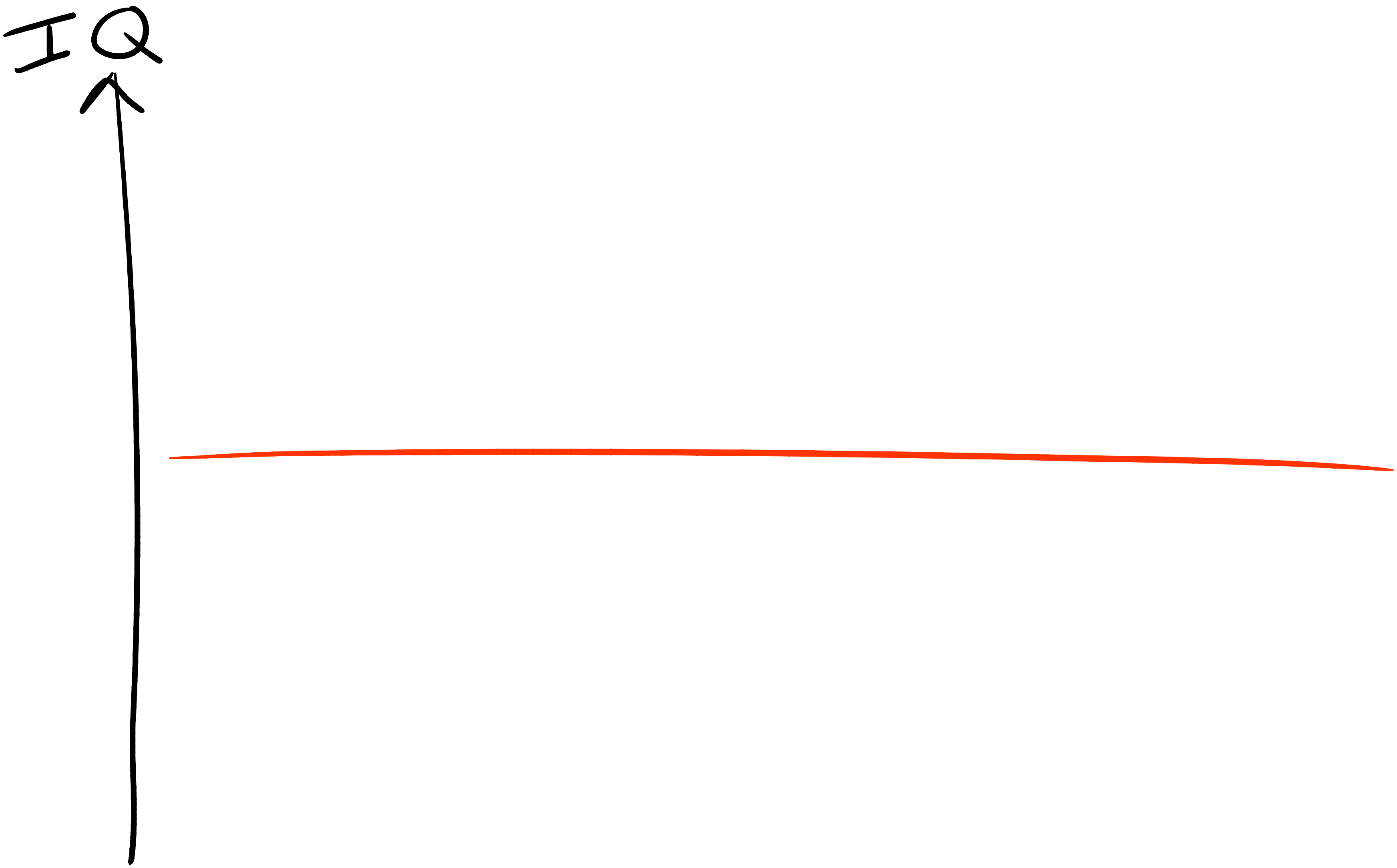


LEAVE NO STONE UNTURNED BETWEEN US & DARK ENERGY

Classical/Tree treatment

$$\mathcal{L} = (\partial \tilde{\varphi})^2 + \sum_j \bar{\psi}_j (i\not{\partial} - y_j \tilde{\phi} - m_j)\psi_j$$

$$F_{ij} = -y_i y_j / r^2$$

$$\propto \quad -m_i m_j / r^2 \Rightarrow m_i = y_i M$$

for some M

$$\Rightarrow \quad G_{\text{Newton}} = \frac{1}{M^2}\,,$$ M is Planck scale.

$$\therefore \mathcal{L} = (\partial\varphi)^2 + \sum_j \overline{\Psi}_j (i\not{\partial} - y\phi)\Psi_j$$

$$\varphi(x) \equiv \tilde{\varphi}(x) + M$$

$\Rightarrow$ Spontaneously Broken scale (conformal) symmetry by $\langle\phi\rangle = M$

$\tilde{\varphi}(x)$ is Goldstone Boson

$\equiv$ "Dilaton"

Dilaton NOT derivatively-coupled

Generally, $S \supset \int d^4x \, J^\mu_{\text{(other fields)}} \, \partial_\mu \pi(x) / f_\pi$

$$= \int d^4x \, J^\mu_{\text{scale}} \, \partial_\mu \tilde{\varphi} / M$$

But $J^\mu_{\text{scale}} \sim T^{\mu\nu}_{(x)} x_\nu \Rightarrow$

$$S \supset \int d^4x \, T^{\mu\nu} x_\nu \, \partial_\mu \tilde{\varphi} / M$$

$$\underset{\int \text{parts}}{=} \int d^4x \, T_\mu{}^\mu \, \tilde{\varphi}/M = \int d^4x \, \frac{\tilde{\varphi}}{M} \sum_j \bar{\psi}_j m_j \psi_j$$

Light . . .

Scale invariance $\Rightarrow$

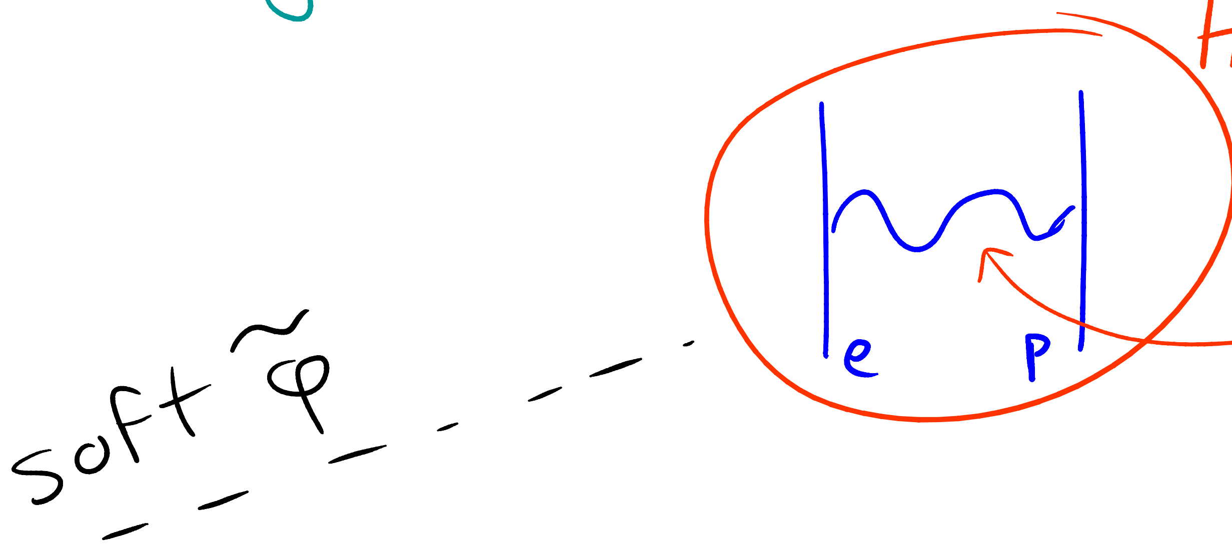
$$\mathcal{L} = (\partial \varphi)^2 + \sum_j \overline{\Psi}_j (i\not{\partial} - y_j \phi) \Psi_j - \frac{1}{4e^2} F_{\mu\nu}^2$$

. . . does not bend!

Dead as theory of real gravity . . .

. . . but great as an analogy

$m_{grav} = m_{inertial}$ for atoms



Hydrogen

Does binding energy gravitate?

(no $\sim\!\sim$)

$$m_H = m_e + m_p - \frac{\alpha^2 m_e m_p}{m_e + m_p} = \left(y_e + y_p - \alpha^2 \frac{y_e y_p}{y_e + y_p} \right) M$$

But M only appears in $\phi = \tilde{\phi} + M$ combo

$$\Rightarrow \quad m_H \left(1 + \frac{\tilde{\varphi}}{M} \right)$$

Similarly for planets, despite no

Scalar Gravity = Curved Spacetime !

= Dilaton Chiral Lagrangian

Einstein, Fokker '14

Isham, Salam, Strathdee '71

Weyl transformation $\Rightarrow$

$$\mathcal{L} = \sqrt{-g}\left\{ \bar{\psi}\left(i\gamma^a e_a{}^\mu \overset{\text{em+grav}}{D_\mu} - m\right)\psi - \frac{1}{4e^2} g^{\mu\nu} g^{\alpha\beta} F_{\mu\alpha} F_{\nu\beta} - M^2 R \right\}$$

opposite sign to usual

$$\underbrace{g_{\mu\nu}(x) = \left(\frac{\phi(x)}{M}\right)^2 \eta_{\mu\nu}}_{\text{generally covariantly}} \,,\quad e_a{}^\mu = \frac{\phi(x)}{M}\delta_a{}^\mu \,,\quad R \text{ Ricci scalar}$$

$C^{\text{Weyl}}_{\mu\nu\rho\sigma}[g] = 0$

conformal transformation $\subset$ general coordinate transformations

Dynamical spacetime, fixed mass scales, m_j, M $\longleftrightarrow$ flat spacetime dynamical mass scales, $\phi(x)$, $y_j\phi(x)$

Weyl Anomaly

Eg. $\mathcal{L}_{\phi+QCD} = (\partial\phi)^2 + \bar{\psi} i \not{D} \psi - \underbrace{\frac{1}{4g^2(\mu\frac{\phi}{M})}}_{\frac{1}{4}\left(\frac{1}{g^2(\mu)} + \frac{b}{16\pi^2}\ln\frac{\phi}{M}\right)} G^{a\,2}_{\mu\nu}$

$\ln\frac{\phi}{M} \sim \frac{\phi}{M}$

$\Rightarrow$ Non-renormalizable

Dilaton + light matter + radiation

Chiral Lagrangian $\ll M$, ~~symmetry~~ scale

Equivalence Principle for Hadrons

$$m_{proton} \sim \mu e^{-\frac{16\pi^2}{b g^2(\mu)}} \rightarrow \mu e^{-\frac{16\pi^2}{b g^2(\mu)} + \ln\phi/M}$$

$$= m_{proton} \frac{\phi}{M}$$

Einstein loved it

Einstein hated it

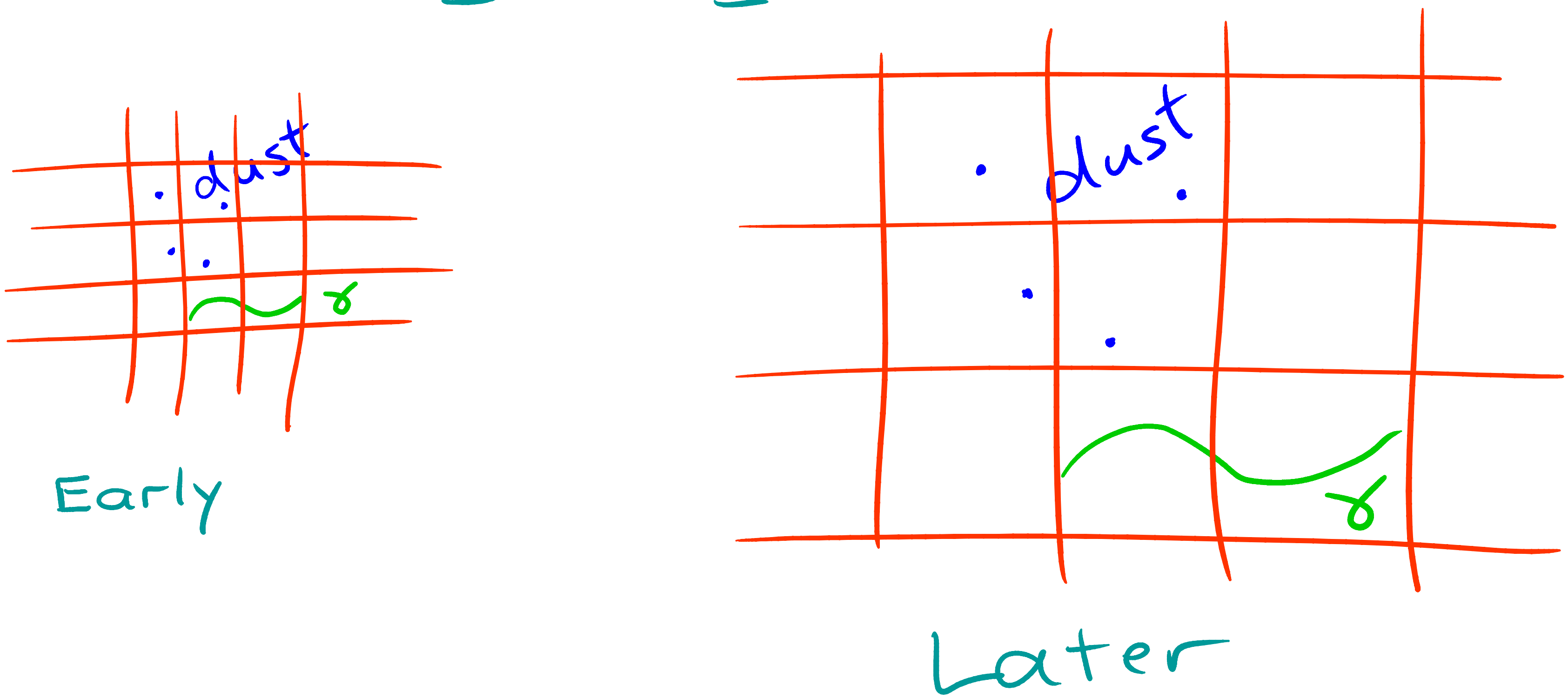
Standard Cosmology in Conformal Coordinates

Co-moving coords. $ds^2 = d\tau^2 - a^2(\tau)\, d\vec{x}^2$

$$= \frac{\varphi^2(t)}{M^2} \big(\underbrace{dt^2 - d\vec{x}^2}_{\eta_{\mu\nu} dx^\mu dx^\nu} \big)$$ Conformal coords

$$\underset{\text{Proper time}}{d\tau} = \frac{\varphi(t)}{M} \underset{\text{Conformal time}}{dt} \qquad a(\tau) = \frac{\varphi(t)}{M}$$

SPACE



But $\hat{E} \longleftrightarrow t = \phi / M \, E_{physical} \longleftrightarrow \tau$

Dust co-moving density $\equiv \hat{n}_{dust} = \text{constant}$

Radiation co-moving $\hat{E}$-density $\equiv \hat{\rho}_{rad} = \text{constant}$

$\therefore$ Physical energy densities

$$\rho_{rad} = \hat{\rho}_{rad}\left(\frac{M}{\phi(t)}\right)^4 = \hat{\rho}_{rad}/a^4(\tau)$$

$$n_{dust} = \hat{n}_{dust}\left(\frac{M}{\phi(t)}\right)^3$$

$$\rho_{dust} = m\,\hat{n}_{dust}\left(\frac{M}{\phi(t)}\right)^3 = \frac{m\,\hat{n}_{dust}}{a^3(\tau)}$$

FRIEDMAN EQUATION

$$H = \frac{\dot{a}}{a} \qquad \xleftarrow{\partial_\tau} \qquad H^2 = G_N\left(\frac{m\hat{n}_{dust}}{a^3} + \frac{\hat{\rho}_{rad}}{a^4} + \rho_{vac}\right)$$

$$\Longleftrightarrow \quad \overset{\partial_t \rightarrow}{\dot{\varphi}^2} = \frac{m\,\hat{n}_{dust}\,\phi}{M} + \hat{\rho}_{rad} + \frac{\rho_{vac}\,\phi^4}{M^4}$$

$$\frac{H}{M} = \frac{\dot{\varphi}}{\phi^2}$$

$$\Longleftrightarrow \quad \mathcal{H} = \frac{m\,\hat{n}_{dust}\,\phi}{M} + \hat{\rho}_{rad} + \frac{\rho_{vac}\,\phi^4}{M^4} - \dot{\phi}^2 = 0$$

energy density

Hamiltonian constraint

"wrong-sign" conformal mode of standard GR

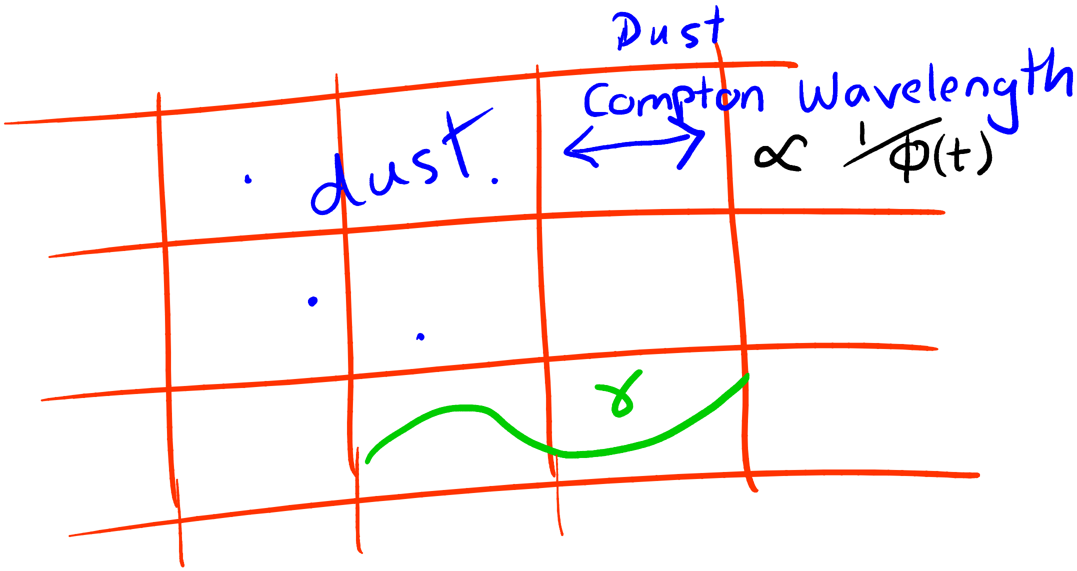
Cosmology of Scalar Gravity

Conserved

$$\mathcal{H} = \frac{m}{M}\hat{n}_{dust}\,\phi + \hat{\rho}_{rad} + \frac{\rho_{vac}}{M^4}\phi^4 + \dot{\phi}^2 \neq 0$$

right-sign kinetic term

conformally invariant $\lambda\phi^4$ coupling



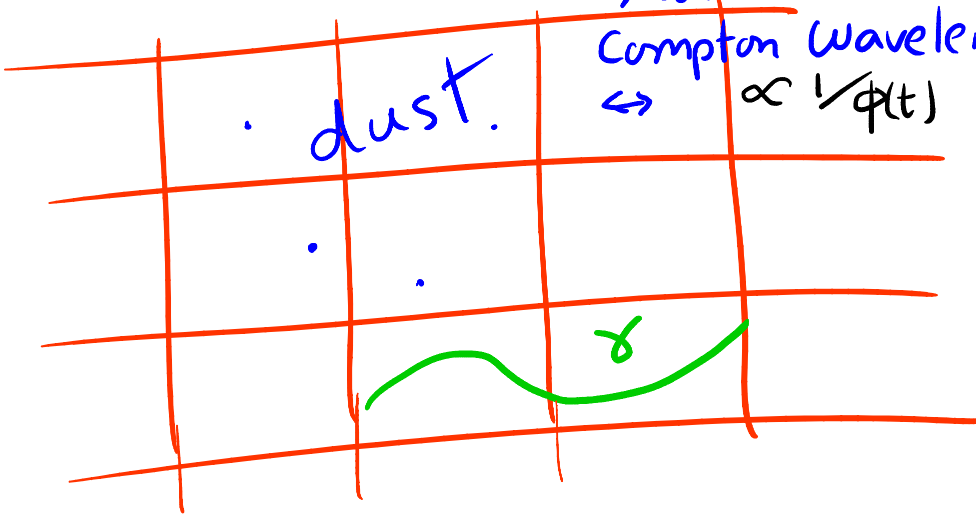
EARLY

Cosmology of Scalar Gravity

Conserved

$$\mathcal{H} = \frac{m}{M}\hat{n}_{dust}\,\phi + \hat{\rho}_{rad} + \frac{\rho_{vac}}{M^4}\phi^4 + \dot{\phi}^2 \neq 0$$

Dust Compton wavelength $\leftrightarrow \;\propto 1/\phi(t)$



LATER

GR Equivalences

Cosmological Constant $\equiv -\rho_{vac}$

$\gtrless 0$ in GR $\quad\quad$ $\gtrless 0$ scalar grav.

Radiation type energy $\equiv \mathcal{H} - \hat{P}_{rad}$

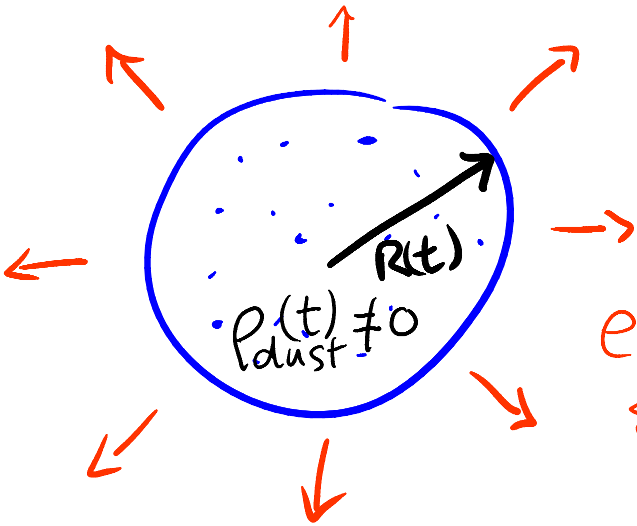
> 0 in GR $\quad\quad$ $\gtrless 0$ scalar grav.

Dust energy $\equiv -\frac{m}{M}\phi\,\hat{n}_{dust} < 0$ scalar grav.

> 0 in GR

Naively, no matter-dominated cosmology $\approx$ isotropic + homogeneous. BUT...

Newtonian Cosmology



empty space

Exploding ball with Newtonian (scalar) attraction

$$-\cancel{\partial_t^2 \tilde{\phi}} + \nabla^2 \tilde{\phi} = \frac{\rho_{dust}}{M}$$

non-rel. limit

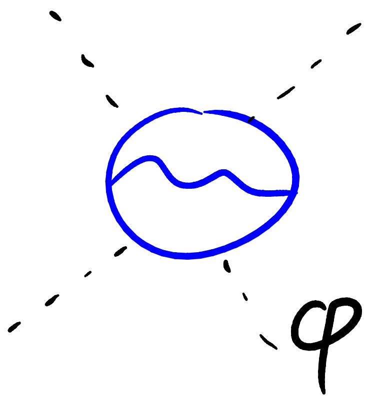
$$R(t) \equiv R_0\, a(t), \qquad \rho_{dust}(t) = \rho_0 \left(\frac{a_0}{a(t)}\right)^3$$

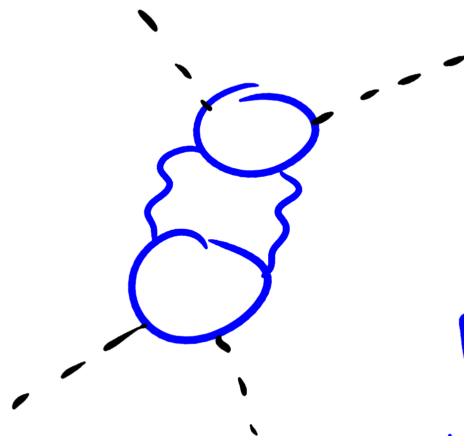
$$\mathcal{H} = m_{ball} \dot{R}^2 - \frac{m_{ball}^2}{M^2 R}$$

$$\Longleftrightarrow \quad \left(\frac{\dot{a}}{a}\right)^2 = \rho/M^2 + \underbrace{\frac{\mathcal{H}}{m_{ball} R_0^2}}_{\text{Fake ``spatial curvature'' term}} \frac{1}{a^2}$$

$\approx$ Galilean invariance makes physics inside ball $\approx$ homogeneous + isotropic

Vacuum Energy





Instead of general Coleman-Weinberg potentials $\varphi^4 \ln\varphi, \varphi^2,$ which are ~~conformal~~

we can only get $\rho_{vac}\sqrt{-g} \equiv \frac{\rho_{vac}}{M^4}\phi^4$

$\Rightarrow$ Cosmological Constant Problem of Scalar Gravity

Sundrum '03

Even Weinberg's No-Go Theorem for CCP '89 applies to scalar gravity

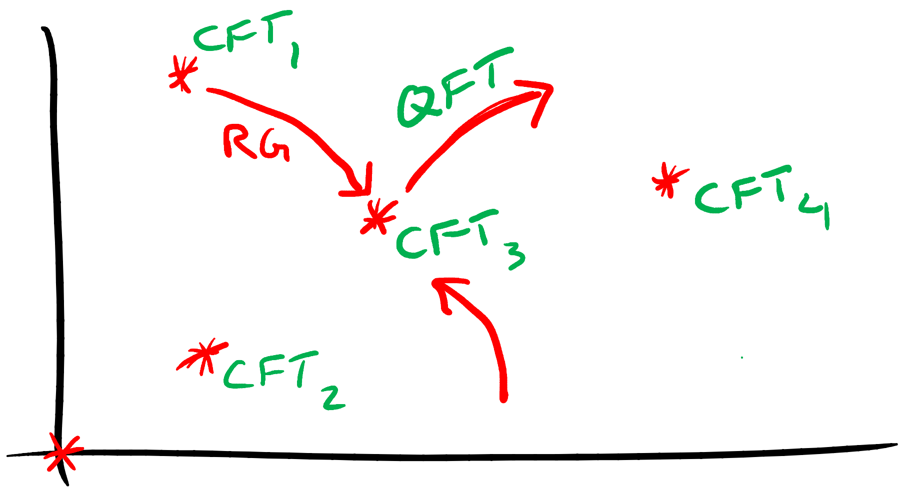
UV Completion

of Chiral Lagrangian of Spontaneous ~~conformal~~

= CFT with $\doteq$ MODULI SPACE $\equiv$ Dilaton

MODIFIED GRAVITY $\equiv$ QFT

$\equiv$ ~~Equivalence Principle~~



Space of QFT's & RG flows

Running is above the "Planck scale" $\langle\phi\rangle \equiv M$!

CONTINUUM LIMIT

about FP with single IR-relevant coupling

$$\mathcal{L}(x) = \mathcal{L}_{CFT}(x) + \sigma^{\gamma}\, \mathcal{O}(x)$$

mass parameter of continuum theory

relevant coupling, scaling dimension $4-\gamma$

Consider "critical exponent"

$\gamma \ll 1$ parametrically

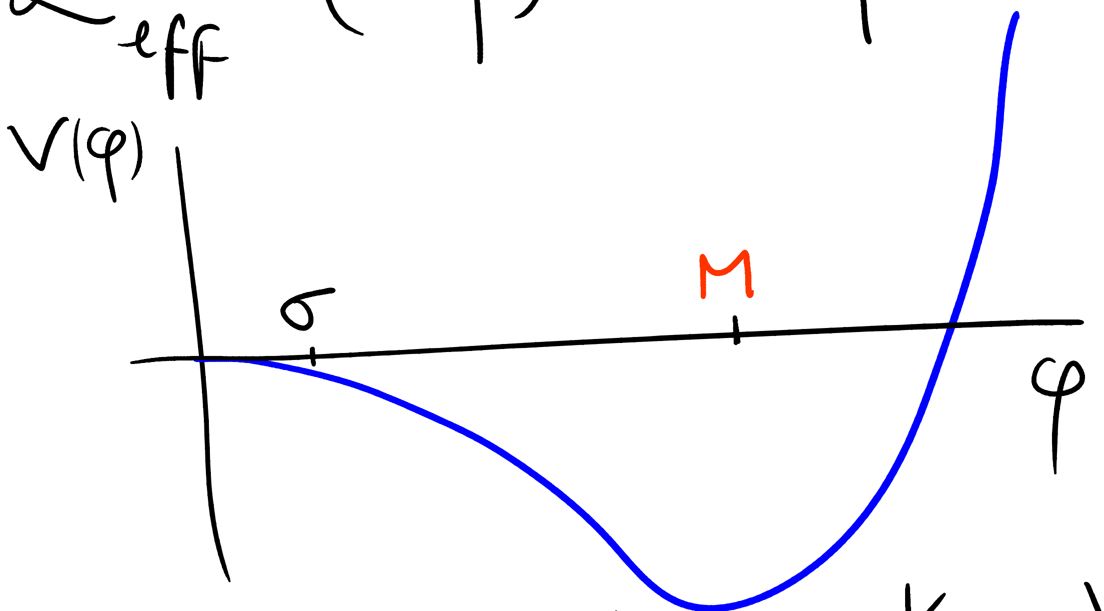
We will assume $\sigma \ll \langle\phi\rangle$ & check self-consistency, so we can expand perturbatively in $(\sigma/\varphi)^{\gamma} < 1$

$\sigma^{\gamma} \equiv$ explicit ~~conformal~~ spurion. $\gamma > 0 \equiv$ soft breaking

Cosmological Constant Suppression!

Contino, Pomarol, Rattazzi
(talk by Rattazzi, "Planck 2010")

$$\mathcal{L}_{eff} = (\partial\varphi)^2 - \lambda\varphi^4 + \lambda'\varphi^4\left(\frac{\sigma}{\varphi}\right)^\gamma$$



$$\left(\frac{\sigma}{M}\right)^\gamma = \frac{4}{4-\gamma}\,\frac{\lambda}{\lambda'}$$

$$V(\varphi) = \lambda\varphi^4\left(1 - \left(\frac{e^{1/4}M}{\varphi}\right)^\gamma\right)$$

Normally only relative scale factors (φ) physical, but now absolute scale factor (relative to σ) is.

Useful Approximation

$$V \approx -\gamma\lambda\varphi^4 \ln \frac{e^{1/4} M}{\varphi}$$

if $\quad \gamma \left|\ln M/\varphi\right| \ll 1 \qquad M e^{-1/\gamma} \ll \varphi \ll M e^{\frac{1}{\gamma}}$

Recalling $\quad H^2/M^2 \equiv \dot{\varphi}^2/\varphi^4$

$$\mathcal{H}_{\text{conserved}} = \dot{\varphi}^2 + V(\varphi)$$

$$a \equiv \phi/M$$

$\Rightarrow$ Friedman Eq.

$$H^2 \doteq G_N\left(\mathcal{H}_{\text{conserved}}/a^4 - \gamma\lambda M^4 \ln \frac{e^{1/4}M}{\varphi}\right)$$

fake "radiation" cosmo. const. λ

$\rightarrow \gamma\lambda \ln M/\varphi \; (\ll \lambda)$

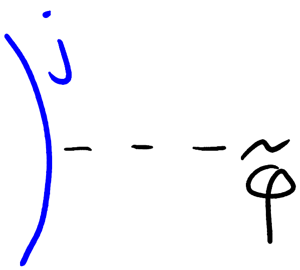
$\lambda = \rho_{vac}/M^4 \gtrsim 10^{-60} \Rightarrow \gamma \sim 10^{-60}$! Dark Energy!

~~Equivalence Pr.~~

Sundrum (to appear)

$$\mathcal{L} = (\partial\varphi)^2 - V(\varphi) + \sum_j \bar{\psi}_j \left[i\not\partial - \varphi\left(y_j + y_j'\left(\frac{\sigma}{\varphi}\right)^{\gamma}\right)\right]\psi_j$$

$$m_j = \left[y_j + y_j'\left(\frac{\sigma}{M}\right)^{\gamma}\right] M$$



$$= y_j + y_j'(1-\gamma)\left(\frac{\sigma}{M}\right)^{\gamma}$$

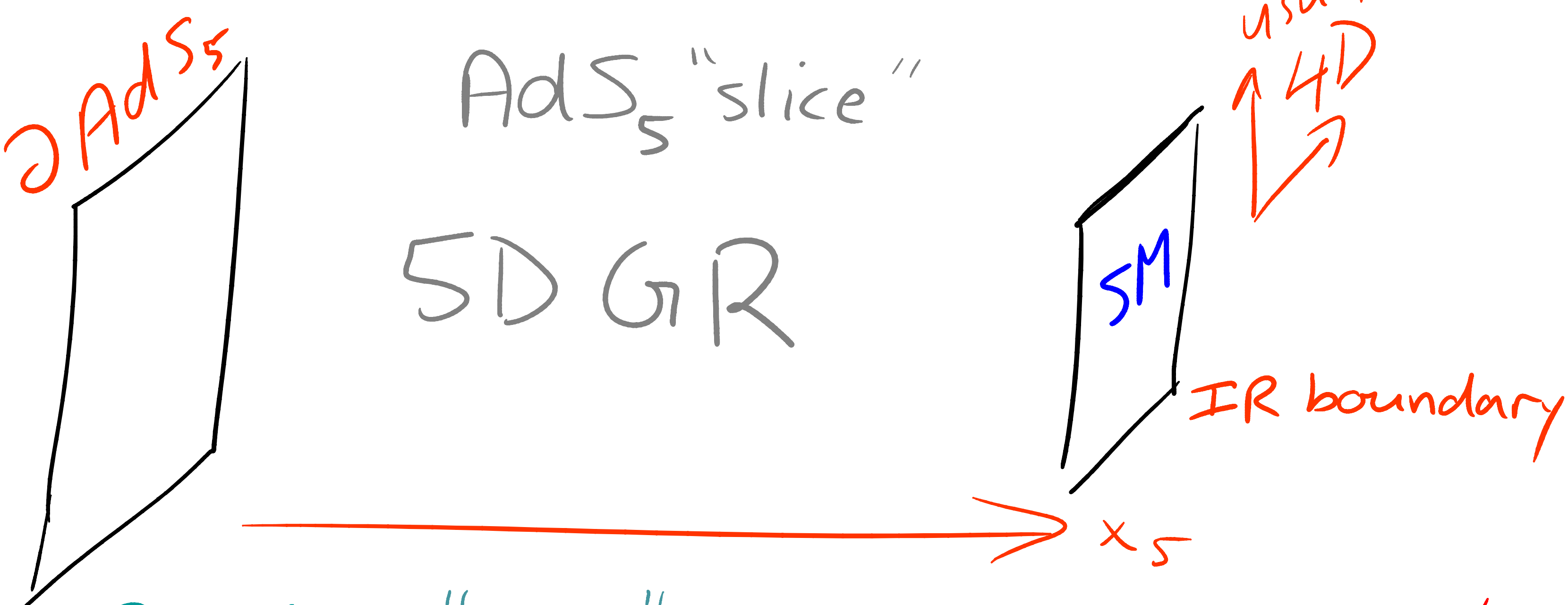
$\sim$ fractional error in equivalence

Effect on v. long-range gravity

$$m_\varphi^2 \sim \gamma\lambda M^2 \sim \rho_{vac}/M^2$$

$\gamma \ll 1$ Naturalness

AdS/CFT Dual $\equiv$ RS I + Goldberger–Wise Stabilization



Radion = "$g_{55}(x)$"

$\equiv \varphi(x)$

= Dilaton

Randall, Sundrum '99

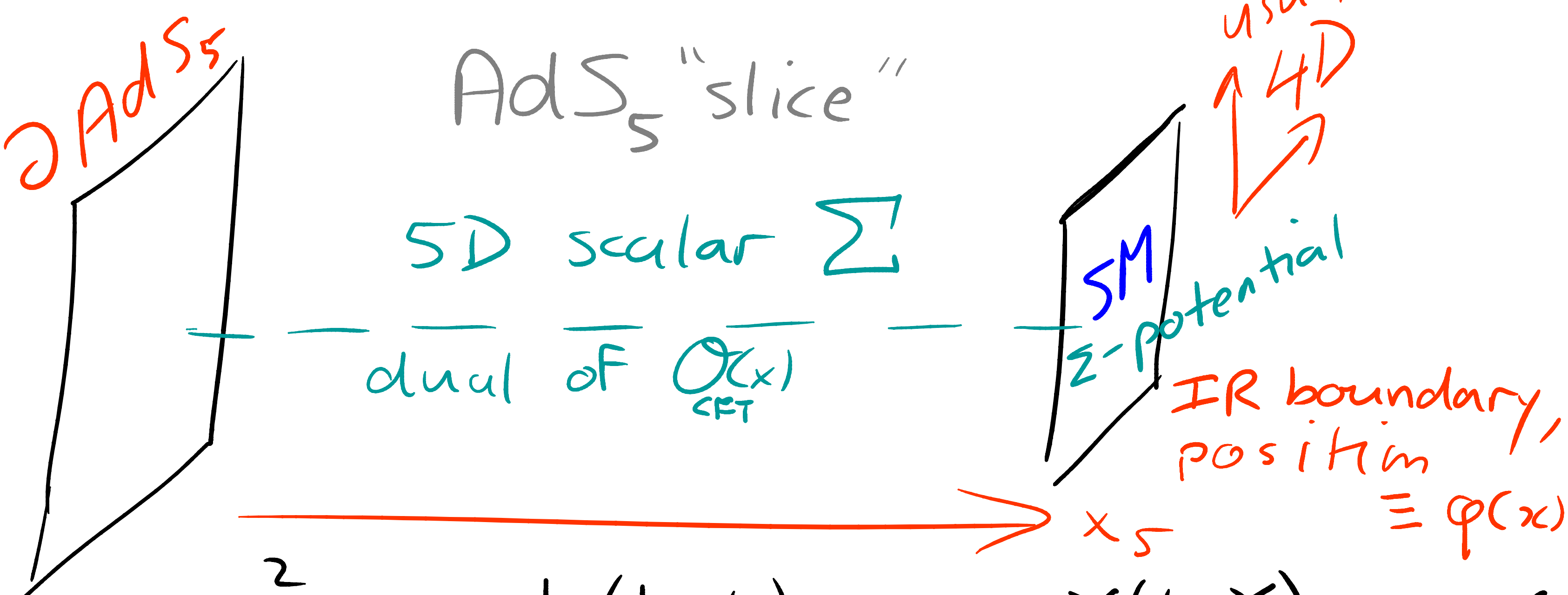
Goldberger, Wise '99

Arkani-Hamed, Porrati, Randall '00

Rattazzi, Zaffaroni '00

$\gamma \ll 1$ Naturalness

AdS/CFT Dual $\equiv$ RS1 + Goldberger-Wise



$$m^2_{\Sigma,5D} = \frac{d_\theta(d_\theta-4)}{R^2_{AdS}} = -\frac{\gamma(4-\gamma)}{R^2_{AdS}} \approx -\frac{4\gamma}{R^2_{AdS}}$$

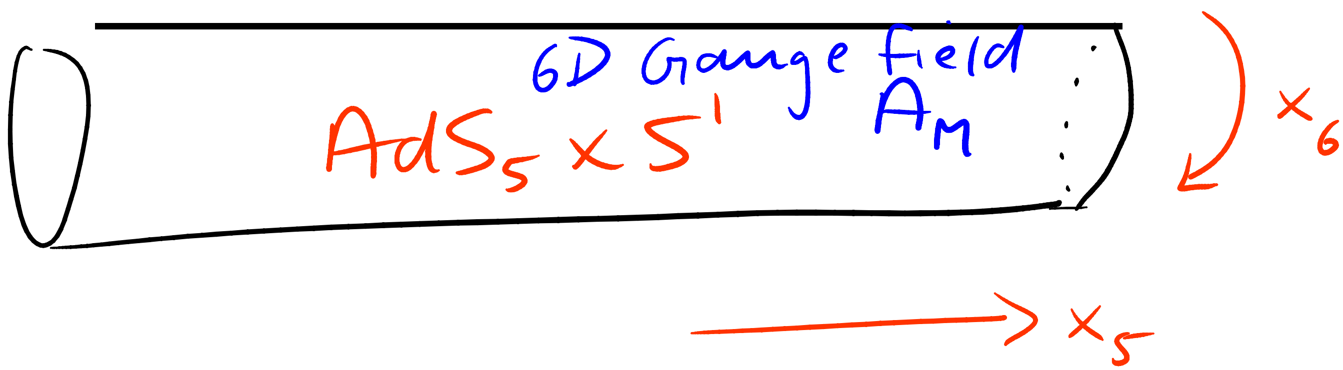
nearly massless "good" tachyon.

Σ nearly massless$_{5D}$ naturally because
= 5D Pseudo-Goldstone Boson

Rattazzi Planck 2010 talk

PGB protection from Quantum Gravity?

Agrawal, Sundrum
(to appear)



$$\Sigma \equiv A_6 \Rightarrow m^2_{\Sigma, 5D} \sim e^{-m_{6D\,\text{charge}} R_6} \equiv \gamma$$

via Hosotani mechanism

naturally extremely small

But can have light charges on IR brane

$\Rightarrow$ brane-localized Σ-potential

Modified Cosmology

Sundrum (to appear)

γ- suppression of cosmological constant if $\ln M/\varphi_{(\text{today})} \sim O(1)$.

Seems mild, but obviously tiny part of phase space of model.

Such tuning in phase space may be no better than the continuum landscape story in standard GR.

but sensible field theory, while the GR continuum landscape $\ni$ Super-Planck VEVs.

Phase transition

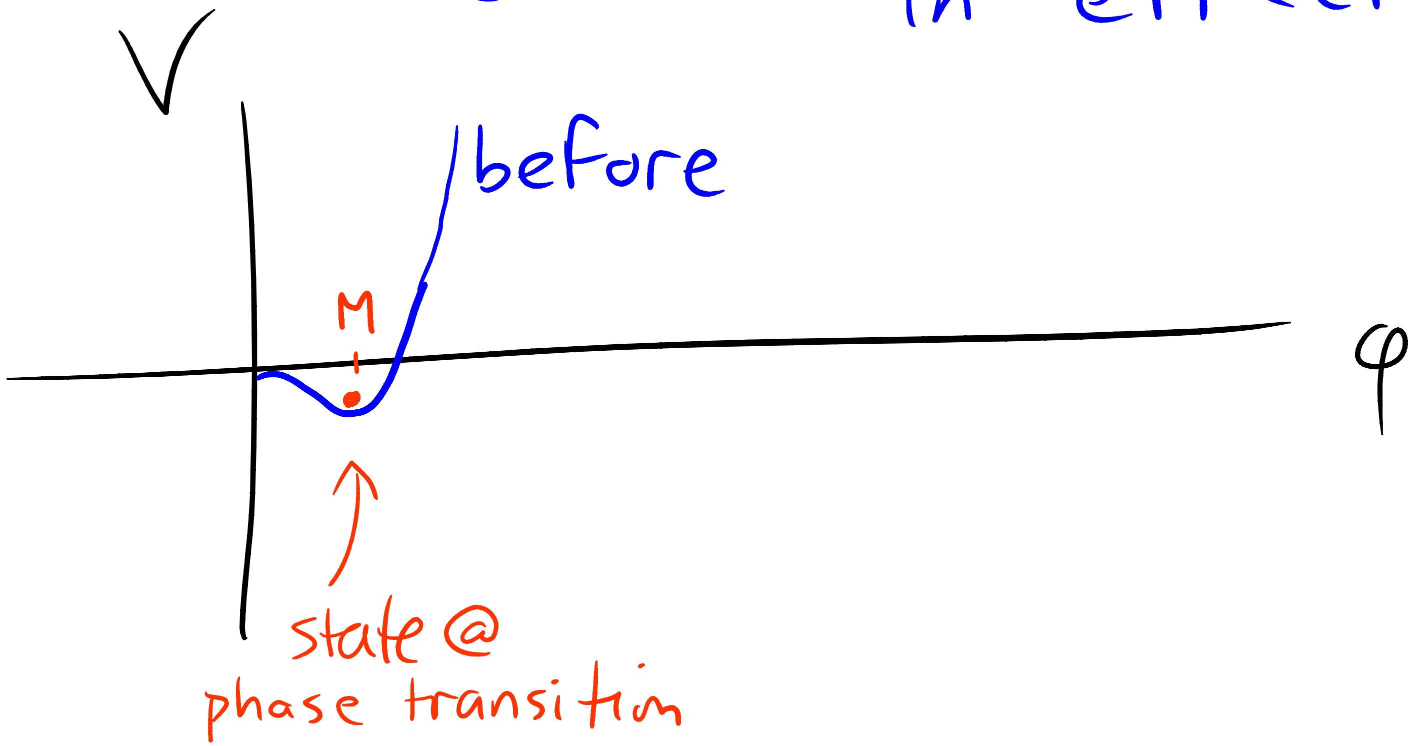
in matter sector suddenly changes vacuum energy $\lambda \to \xi\lambda$

Consider $\xi \lesssim 1$, λ' unchanged say:

Potential $V(\varphi) = \lambda\varphi^4\left(1 - \left(\frac{e^{1/4}M}{\varphi}\right)^\gamma\right)$

$$\to \lambda\varphi^4\left(1 - \left(\frac{e^{1/4}M}{\xi^{1/\gamma}\varphi}\right)^\gamma\right)$$

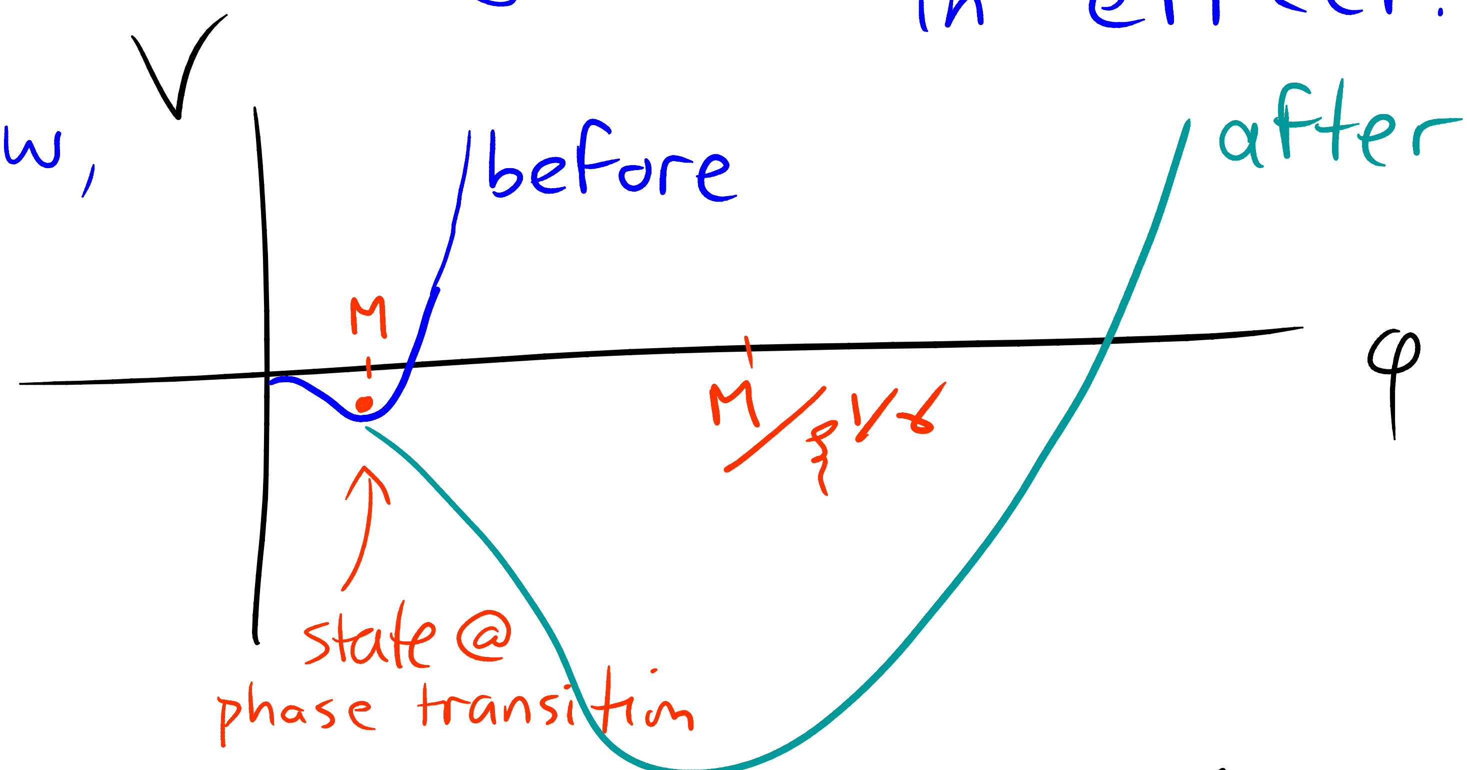
Suppose originally $\varphi \sim O(M)$
so cosmological constant cancelation in effect.



Suppose originally $\varphi \sim O(M)$

so cosmological constant cancelation in effect.

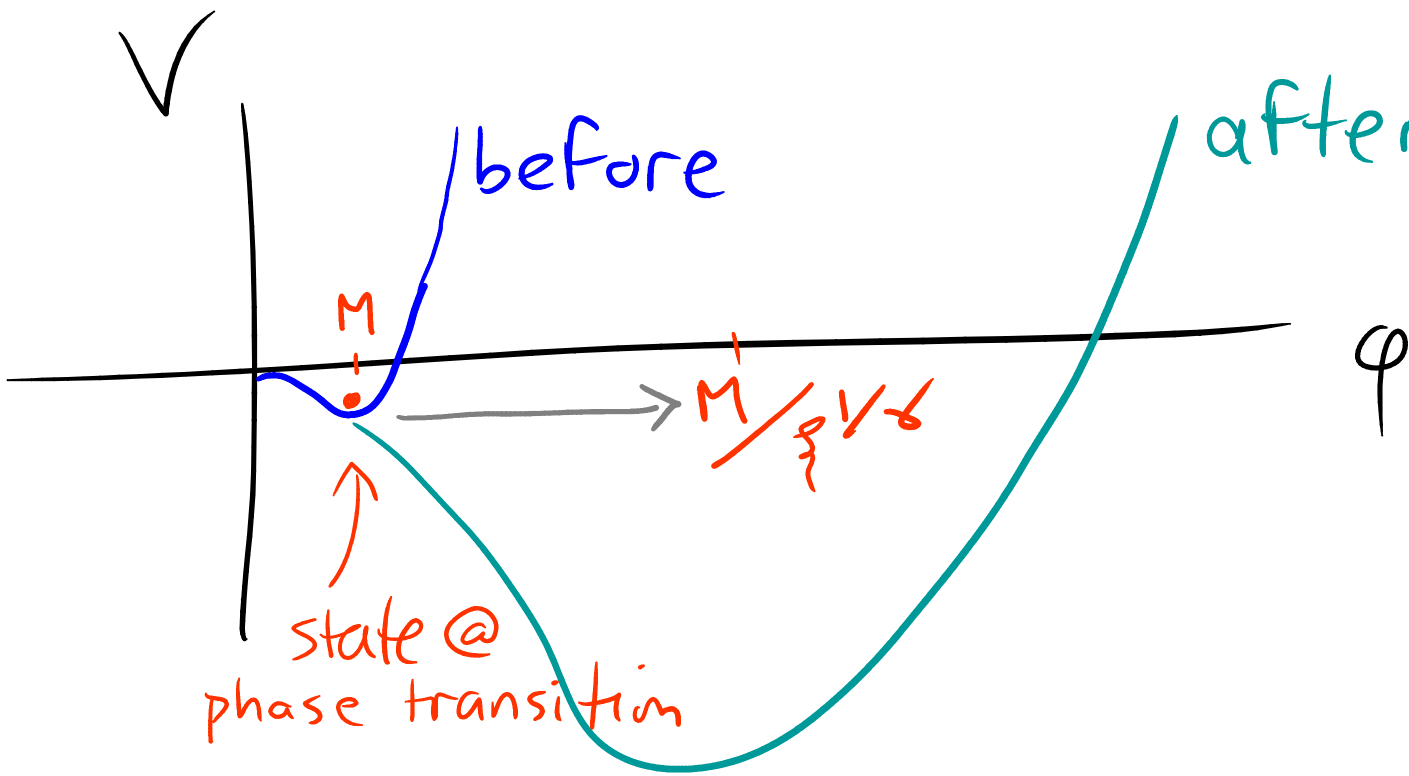
Now,



We thereby "start" new phase $\ln \frac{M}{\xi^{1/\gamma}\varphi} \sim O\left(\frac{1}{\gamma}\right)$ without γ-suppression. In fact $-\lambda\varphi^4(\sigma/\varphi)^\gamma$ dominates $\equiv$ HIGH INFLATION!

Eventually inflation ends

as $\varphi \sim O\left(M/\xi^{1/\gamma}\right)$ & γ-suppression returns.



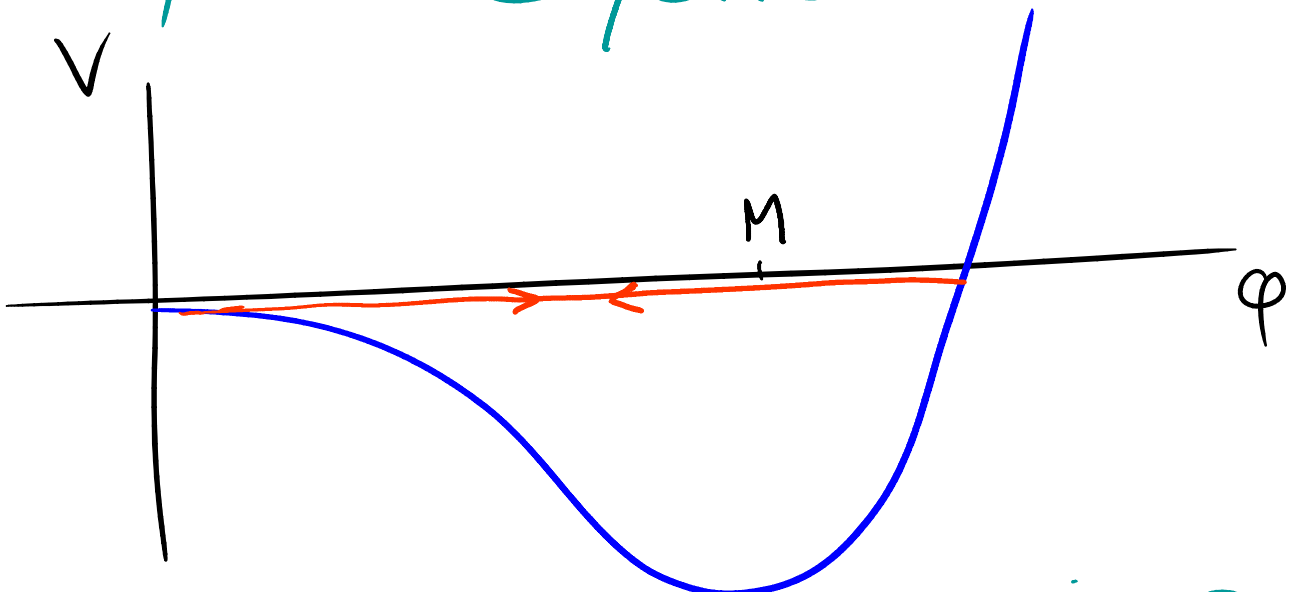
But by then $\sim 1/\gamma$ e-foldings have inflated away any original matter/radiation.

REHEATING AFTER AUTO-INFLATION

Phase-transition-robust initial conditions,

$$\varphi \sim 0_+ , \quad \dot{\varphi} \sim 0_+ , \quad V = \lambda \varphi^4 \left(1 - \left(\frac{e^{1/4} M}{\varphi}\right)^\gamma\right)$$

naively $\Rightarrow$ Cyclic Cosmology



But this neglects Cosmological Particle Production

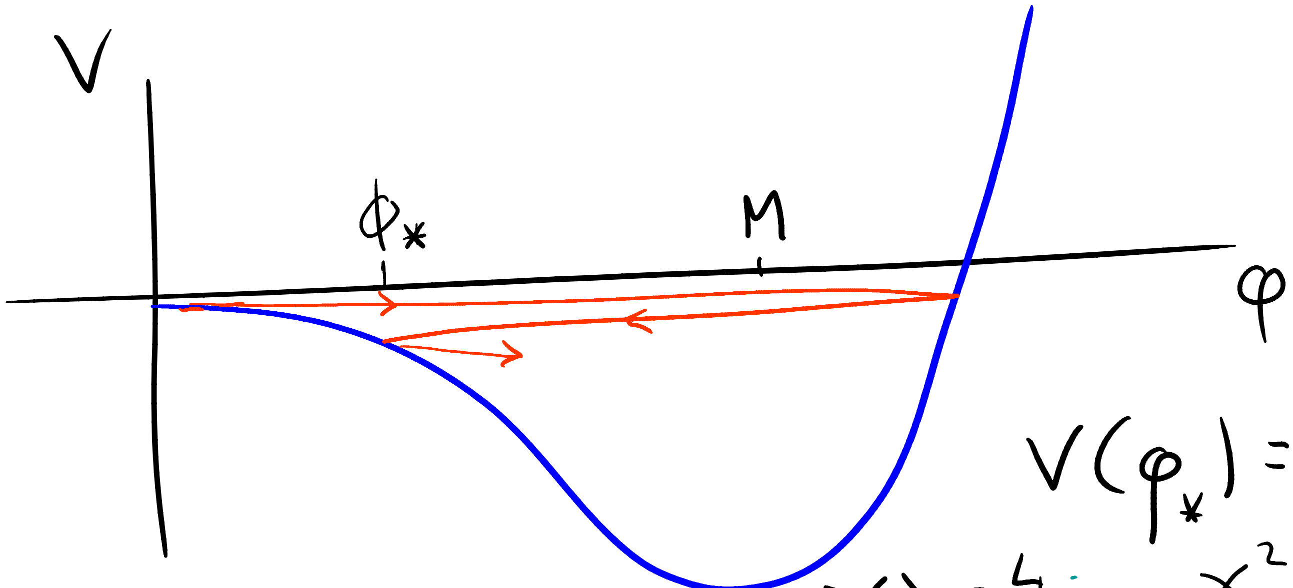
Eg. into (real) radiation $T_{rad} \sim H$

requires some mass scale in radiation, eg. massless QED

REHEATING AFTER AUTO-INFLATION

maximal (in absolute terms, not Planck units)
when $\varphi \sim O(M)$, $T_{rad} \sim \sqrt{\gamma\lambda}\, M$

$\Rightarrow$ Energy in φ reduced from O_+ by $T_{rad}^4 \sim \gamma^2\lambda^2 M^4$



$V(\varphi_*) = -T_{rad}^4$

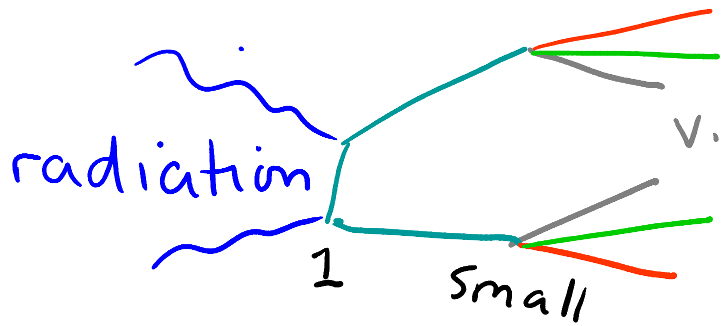
$\gamma\lambda\varphi_*^4 \sim \gamma^2\lambda^2 M^4$

In Planck units,
at first bounce $T_{rad}/M \sim \sqrt{\gamma\lambda}$
but after 2nd bounce $T_{rad}/\varphi_* \sim (\gamma\lambda)^{1/4} \equiv 3°K$ radiation!

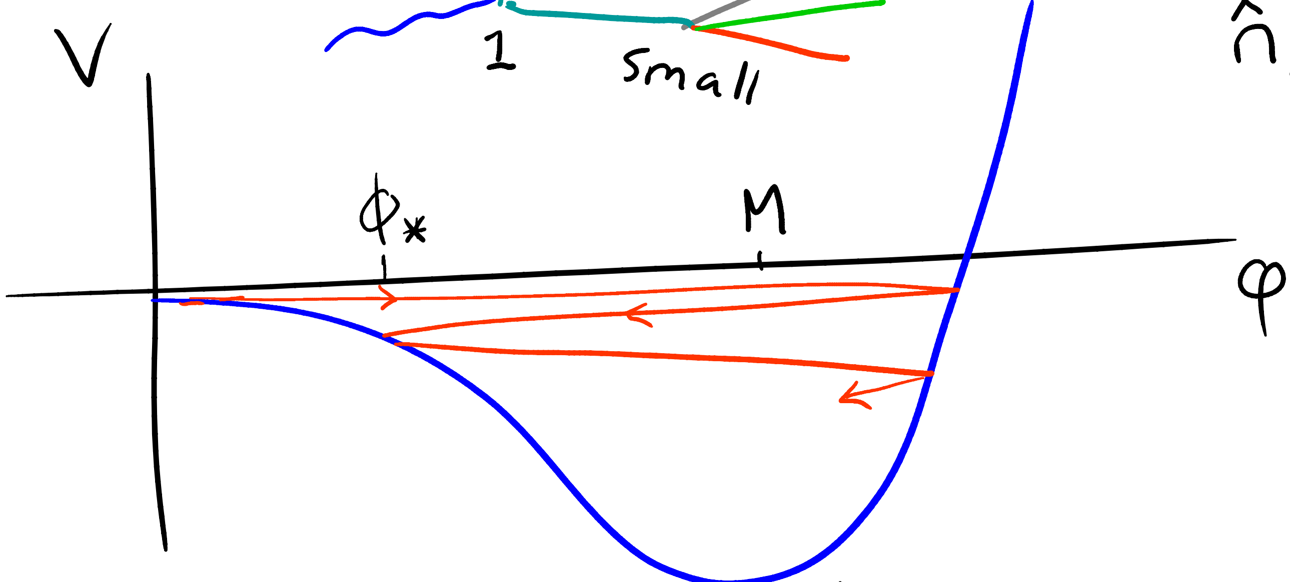
BUT NO "BARYONS"...

"BARYONS" ($m \gg (\rho_{vac,today})^{1/4} \sim 10^{-3}\,\mathrm{eV}$)

Imagine particles with "ν-like" masses so that radiation can annihilate into them $\gtrsim \phi_*$:



v. Few "ν" re-annihilate back to radiation: $\hat{n}_\nu \sim T_{rad}^3$ conserved



Suppose ν decays @ $\phi \sim \alpha(M)$, each to $N \gg 1$ "γ"s

(Eg. $Z^0 \to$ many hadrons ∋ many $\pi^0 \to$ many γs.)

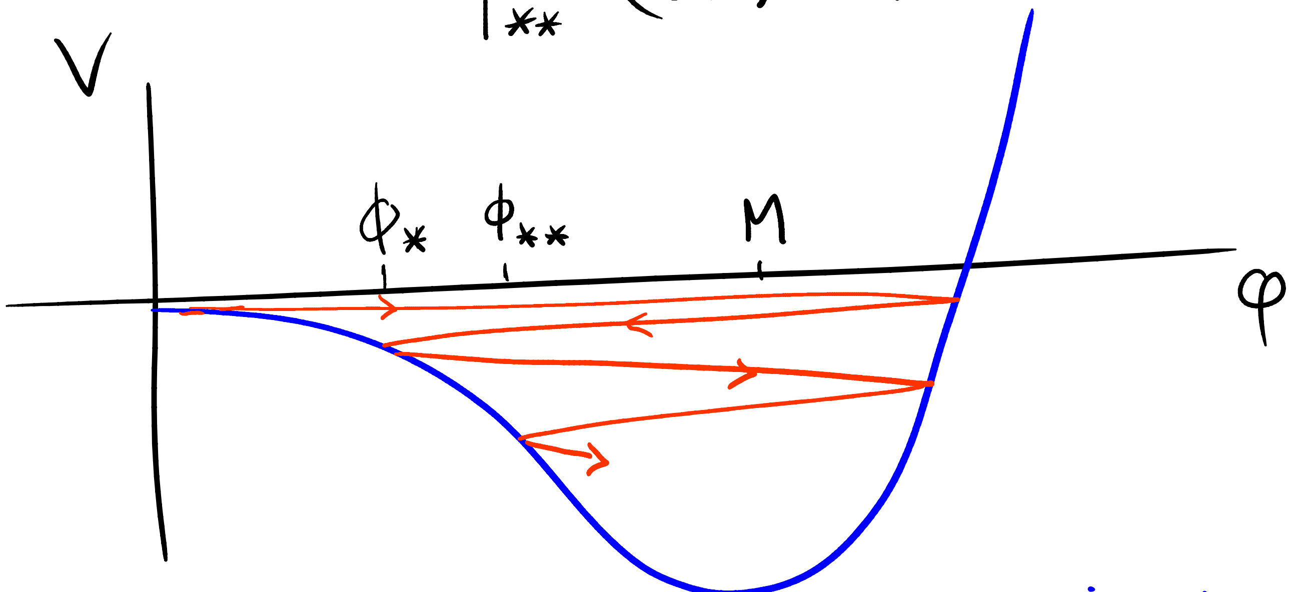
$\Rightarrow \hat{n}_\gamma \sim N \hat{n}_\nu \sim N T_{rad}^3 \sim N M^3 (\gamma\lambda)^{3/2}$, $E_\gamma \sim y_\nu M/N \sim (\gamma\lambda)^{1/4} M/N$.

"BARYONS" $(m \gg (\rho_{vac,\,today})^{1/4} \sim 10^{-3}\,eV)$

Energy density thereby dumped into radiation & lost to φ $\sim \hat{n}_\gamma E_\gamma \sim (\gamma\lambda)^{7/4} M^4$.

$\Rightarrow$ ~~4th~~ bounce @ ϕ_{**}: $\gamma\lambda\,\varphi_{**}^4 \sim (\gamma\lambda)^{7/4} M^4$

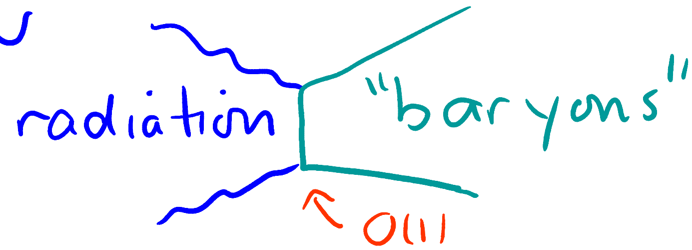
$$\phi_{**} \sim (\gamma\lambda)^{3/16} M$$



In Planck units, the radiation can be quite energetic $E_\gamma / \varphi_{**} \sim (\gamma\lambda)^{1/16} / N$

"BARYONS" $\left(m \gg (\rho_{vac,\,today})^{1/4} \sim 10^{-3}\,\mathrm{eV}\right)$

can be produced now



$$\frac{m_{baryon}}{\varphi_{**}} \sim \frac{E_\gamma}{\varphi_{**}} \sim (\gamma\lambda)^{1/16}/N$$

at a rate/vol. $\sim \hat{n}_\gamma^2\, \sigma_{\gamma\gamma\to baryons}$ $\quad \sigma_{\gamma\gamma\to baryons} \sim \frac{1}{m^2_{baryon}}$

$$\text{Rate/volume} \sim \hat{n}_\gamma^2\, \sigma_{\gamma\gamma\to baryons} \sim N^2 M^6 (\gamma\lambda)^3 \frac{N^2}{(\gamma\lambda)^{1/2} M^2}$$

$\sigma_{\gamma\gamma\to baryons} \sim \frac{1}{m^2_{baryon}}$

$$\sim N^4 M^4 (\gamma\lambda)^{5/2}$$

over Period $H^{-1} \sim \frac{1}{(\gamma\lambda)^{1/2}\varphi_{**}}$

$$\Rightarrow \frac{\rho_{baryons}}{\varphi_{**}^4} \sim m_{baryon} H^{-1} \hat{n}_\gamma^2 \sigma / (\gamma\lambda)^{3/4} M^4 \sim N^3 (\gamma\lambda)^{21/16}$$

but $< \frac{\rho_{rad}}{\varphi_{**}^4} \sim \gamma\lambda$

Saturating, $m_{baryon} \sim (\gamma\lambda)^{1/6}\varphi_{**}$ $\equiv$ "10 MeV", $N \sim 10^{12}$

DARK ENERGY EQUATION OF STATE $w \equiv P/\rho$

Generally, $\rho \propto a^{-3(1+w)} \propto \phi^{-3(1+w)}$

For Dark Energy $\rho_{DE} \underset{w+1 \ll 1}{\propto} 1 - 3(1+w) \ln \phi/\phi_{**}$

We have $\rho/M^4 \equiv \gamma\lambda \ln \phi/M \propto \ln \phi/\phi_{**} + \ln \phi_{**}/M$

$$\propto 1 + \frac{\ln \phi/\phi_{**}}{\ln \phi_{**}/M}$$

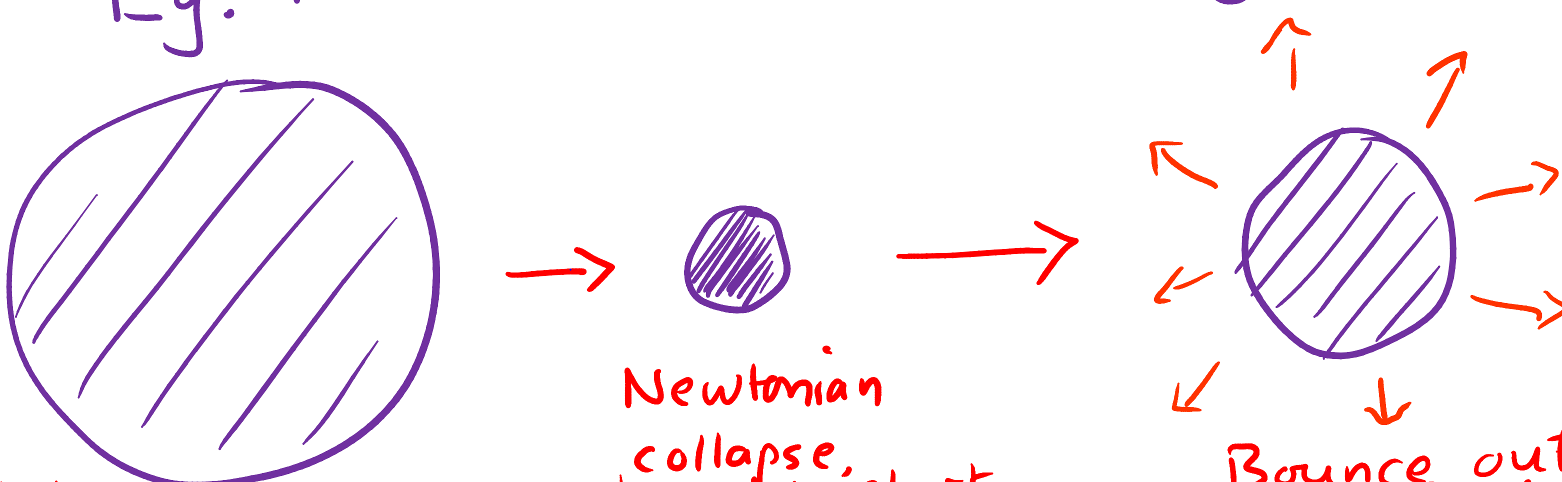
$\Rightarrow w+1 \sim \frac{1}{\ln \phi_{**}/M} \sim 1\%$

CENTRAL THORNY ISSUE
for good analogy

Our scalar cosmo ≡ "Cold" Big Bang
~3°K
while we have evidence in real world
of "Hot" Big Bang (eg BBN)

Can hot follow cold?

Eg. Newtonian Matter Cosmology



v. dilute matter ball at rest

Newtonian collapse, stopped by short range matter repulsion

Bounce outwards ⇒ illusion of high density matter dominated cosmology

MODIFIED spin-2 GR ?

Egs. Dvali - Gabadadze - Porrati '00
Einstein-Aether Jacobson, Mattingly '01
Ghost Condensate Arkani-Hamed, Cheng, Luty, Mukohyama '04
Horava-Lifshitz '09

Moral I draw from scalar gravity:

deform holographic (non-redundant) description

harder for real GR!

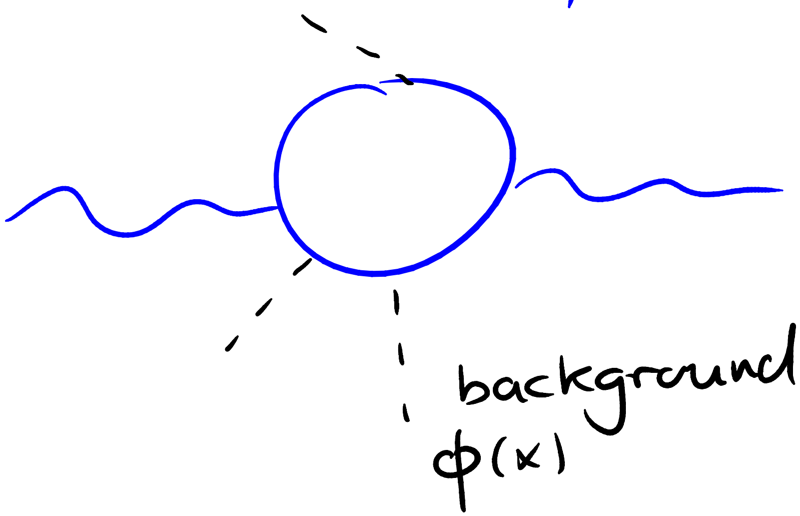
Eg. deforming CFT → Modified AdS gravity Sundrum '07

BACKUP

SLIDES

Radiative Corrections

Scale anomaly of QED + classical φ



Dim. Reg. + $\overline{\text{MS}}$ $\quad \mathcal{L}_{4+\varepsilon D} = \bar{\psi}(i\not{\partial} - y\phi)\psi - \frac{\mu^\varepsilon}{4e^2} F_{\mu\nu}^2$

$$\Pi(q) \sim \frac{1}{e^2(\mu)} + \frac{1}{16\pi^2} \ln \frac{\mu^2}{y^2\phi^2 + q^2}$$

V. Long distances

$$\mathcal{L}_{eff} = -\frac{1}{4}\left(\frac{1}{e^2(\mu)} + \frac{1}{16\pi^2}\ln\frac{\mu^2}{y^2\phi^2}\right)F_{\mu\nu}^2$$

Light bends!

Gravity picture

must maintain general covariance in $4+\epsilon$

$\supset$ conf. symmetry

$$\mathcal{L}_{4+\epsilon D} = \sqrt{-g}\left\{\bar{\psi}(i\not{D}_{\substack{em\\+grav}} - m)\psi - \frac{\mu^\epsilon}{4e^2}g^{\mu\nu}g^{\alpha\beta}F_{\mu\alpha}F_{\nu\beta}\right\}$$

$$= \bar{\psi}(i\not{D}_{em} - y\phi)\psi - \frac{\left(\frac{\mu\phi}{M}\right)^\epsilon}{4e^2}F_{\mu\nu}^2$$

$g_{\mu\nu} = \phi^2/M^2\,\eta_{\mu\nu}$

$\psi \to \psi\left(\frac{M}{\phi}\right)^{\frac{3+\epsilon}{2}}$

Note

Long Distances $\mathcal{L}_{eff} = -\frac{1}{4}\left(\frac{1}{e^2} + \frac{1}{16\pi^2}\ln\frac{\mu\cancel{\phi}/M}{y\cancel{\phi}}\right)F_{\mu\nu}^2$ no bending!

MORAL Scale invariant theory $\equiv$

$$\mathcal{L} = -\frac{1}{4e^2\left(\frac{\mu\phi}{M}\right)} F_{\mu\nu}^2 + \bar{\psi}(i\not{D}_{em} - y\phi)\psi$$

$$= -\frac{1}{4}\left(\frac{1}{e^2(\mu)} + \frac{1}{16\pi^2}\left(\frac{\tilde{\Phi}}{M} + \frac{\tilde{\Phi}^2}{M^2} + \dots\right)\right)F_{\mu\nu}^2 + \bar{\psi}(i\not{D} - y\phi)\psi$$

price is non-renormalizability

Non-ren. Chiral Lagrangian for dilaton + light matter/radiation $< M$

MORAL Scale invariant theory $\equiv$

$$\mathcal{L} = -\frac{1}{4e^2\left(\frac{\mu\phi}{M}\right)} F_{\mu\nu}^2 + \bar{\psi}(i\not{D}_{em} - y\phi)\psi$$

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$$+ \bar{\psi}(i\not{D} - y\phi)\psi$$

price is non-renormalizability

Non-ren. Chiral Lagrangian for dilaton + light matter/radiation $< M$

UV-completed by CFT with $\doteq$ modulus ϕ & other light ($\ll \langle\phi\rangle$) matter/radiation.

$m_{grav} = m_{inertial}$ for proton?

$$\mathcal{L}_{\substack{QCD \\ m_{quarks}=0 \\ +\varphi}} = -\frac{1}{4}\left(\frac{1}{g^2(\mu)} - \frac{1}{16\pi^2}\ln\frac{\phi}{M}\right) G^{a\,2}_{\mu\nu} + \bar{\psi}\, i \not{D}_{QCD}\, \psi$$

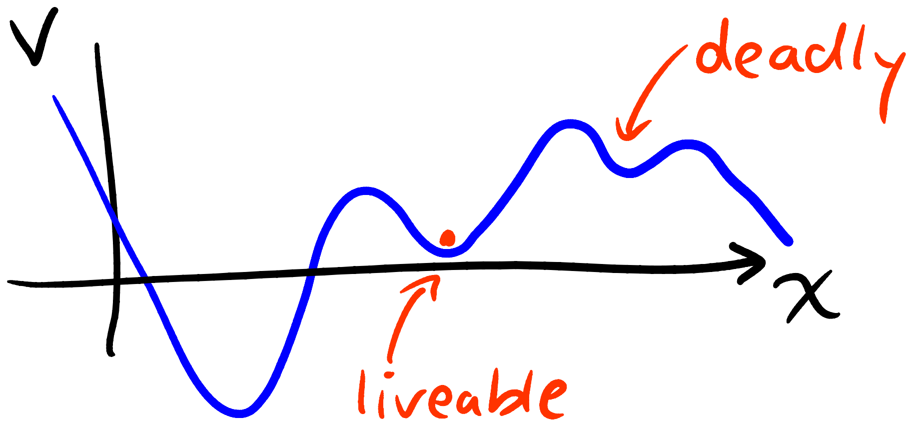
$$= -\frac{1}{4g^2\left(\frac{\mu\phi}{M}\right)} G^2_{\mu\nu} + \bar{\psi}\, i \not{D}\, \psi$$

Normally, $m_{proton} = \# \underbrace{\mu\, e^{-16\pi^2/g^2(\mu)}}_{\text{RG-invariant}}$

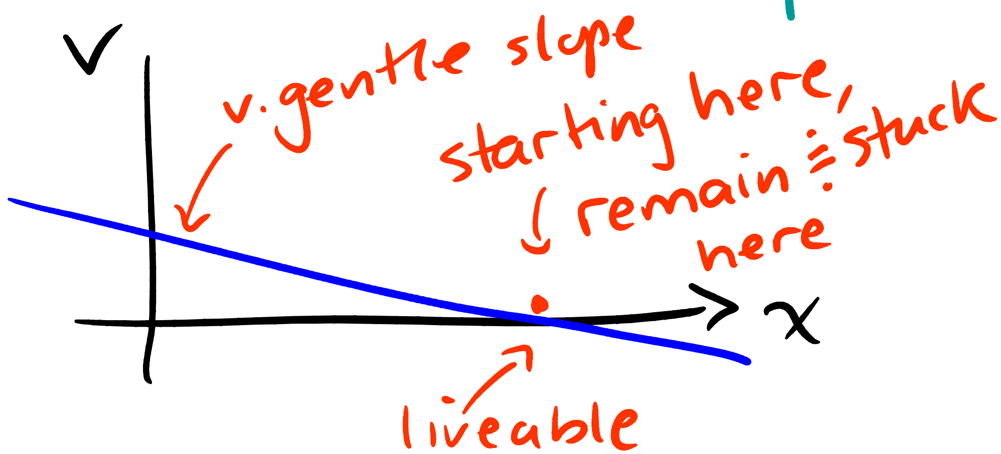
$$\xrightarrow{+\text{ soft } \varphi(x)} \# \mu\, e^{-16\pi^2/g^2(\mu) + \ln\phi/M} \equiv m_{proton}\frac{\phi}{M}$$

ADJUSTMENT MECHANISMS OF STANDARD GR

DISCRETUM

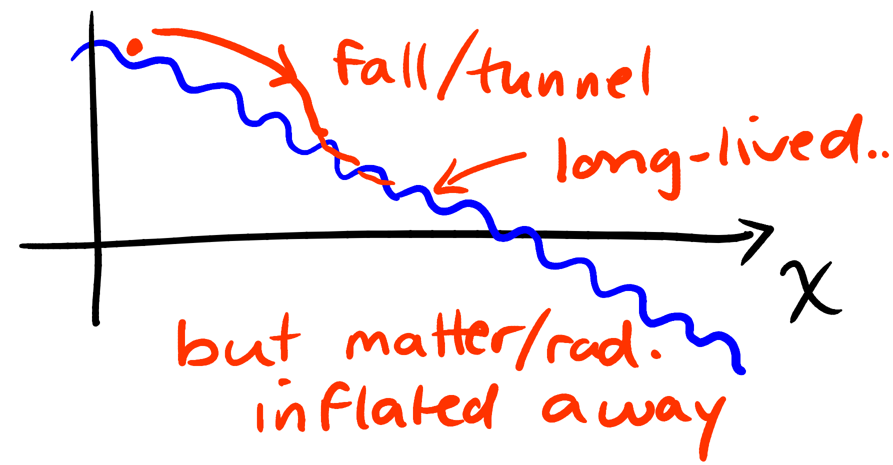


Continuum Landscape



Garriga, Vilenkin '03; Dimopoulos, Thomas '03

ABBOTT '85



CAN BE BORROWED.

ANYTHING NEW?