X.D.

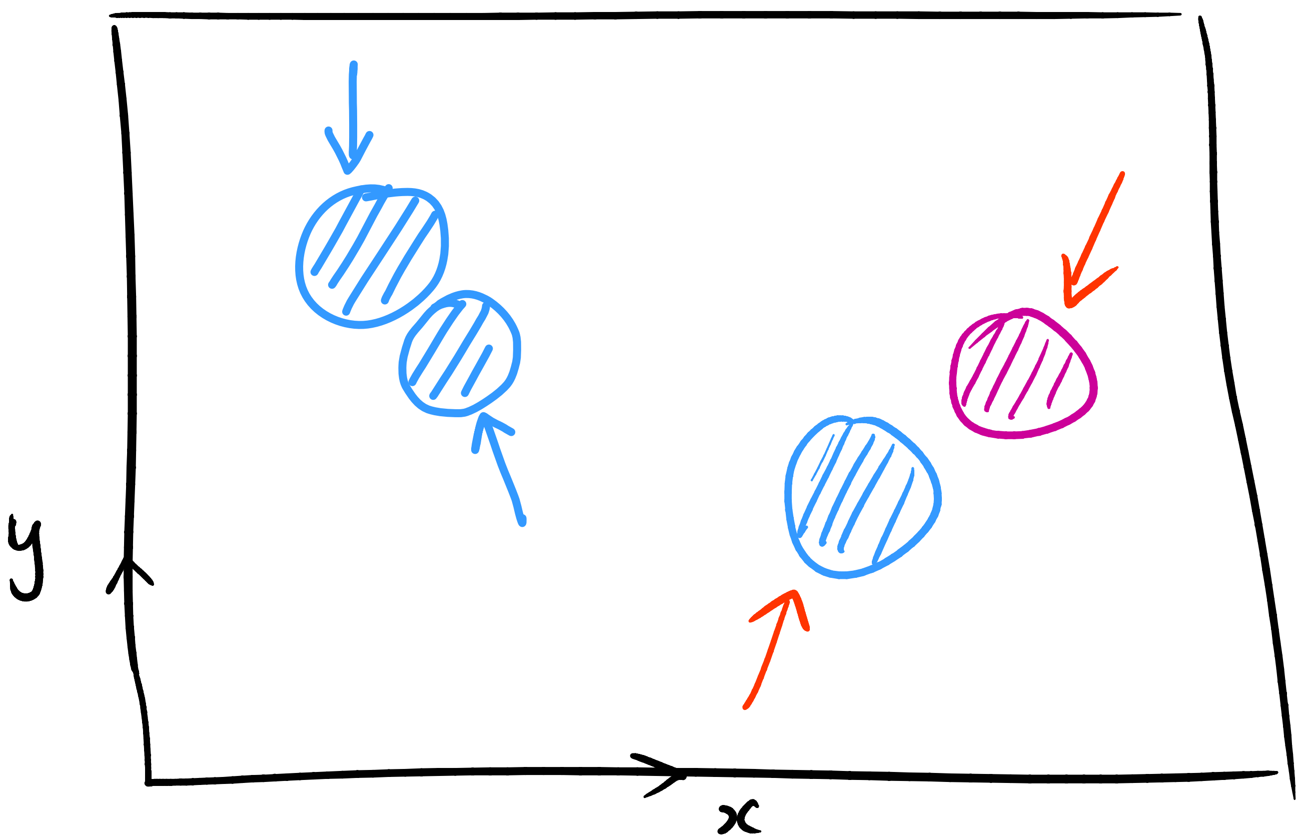
&

D.E.

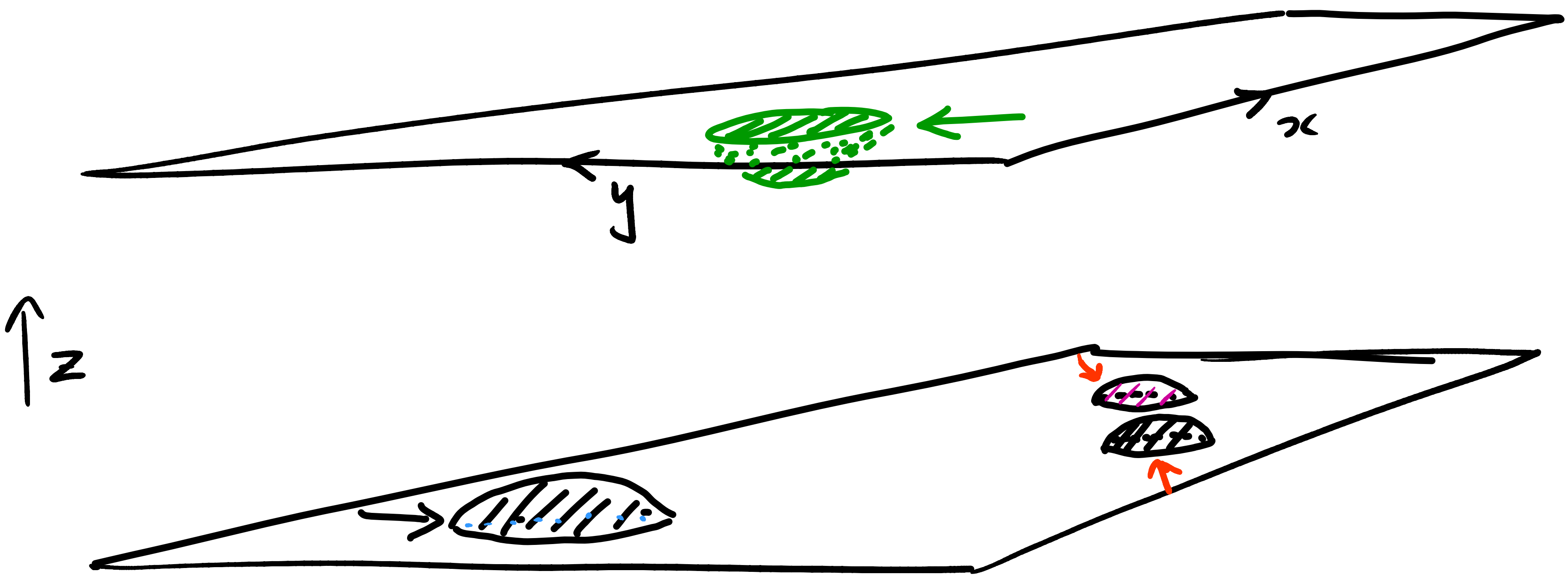
Raman Sundrum

U. Maryland, College Park

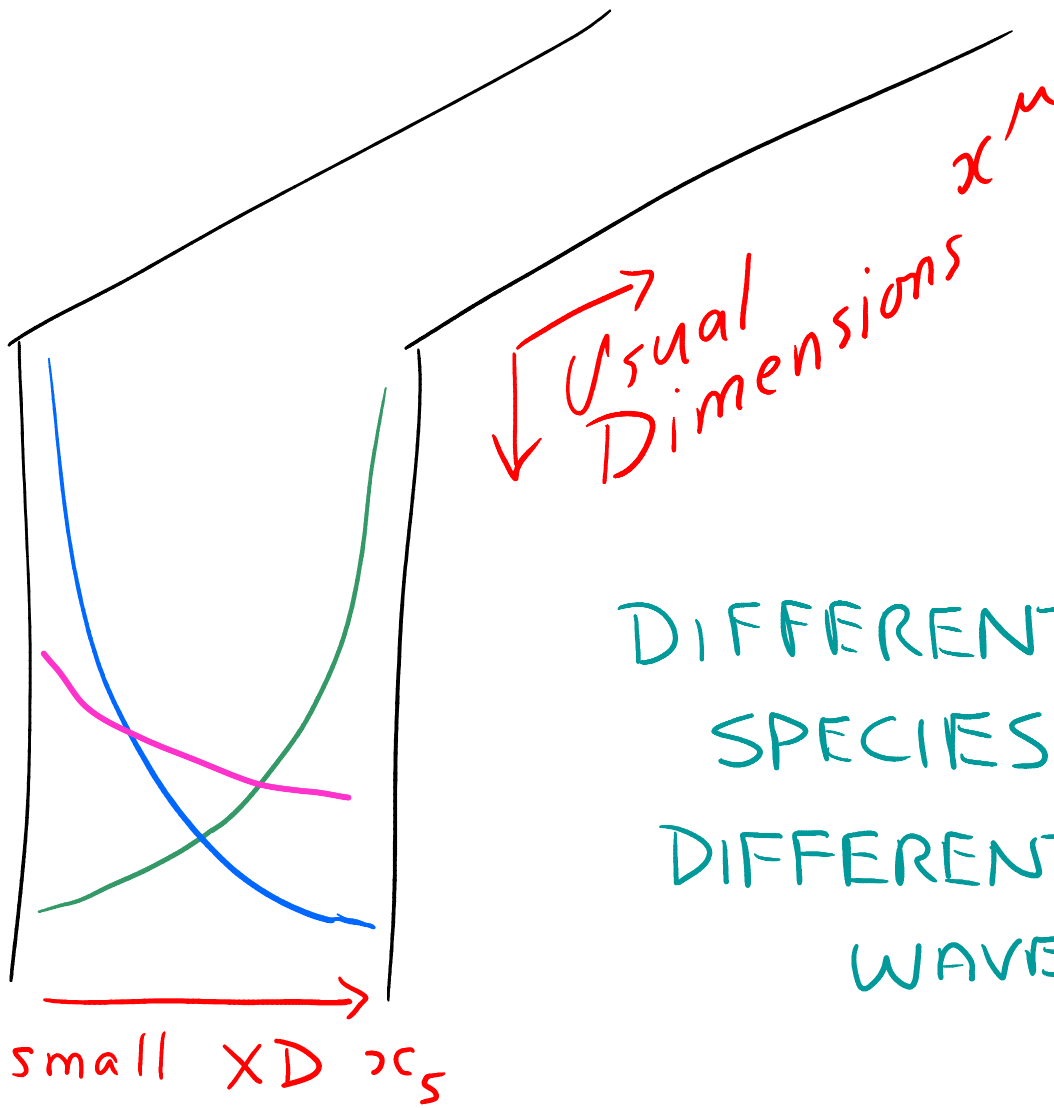
WHICH PAIR WILL COLLIDE?



HIDDEN DIMENSIONS CAN HOLD THE ANSWERS...



XD



DIFFERENT PARTICLE SPECIES HAVE DIFFERENT XD WAVEFUNCTIONS

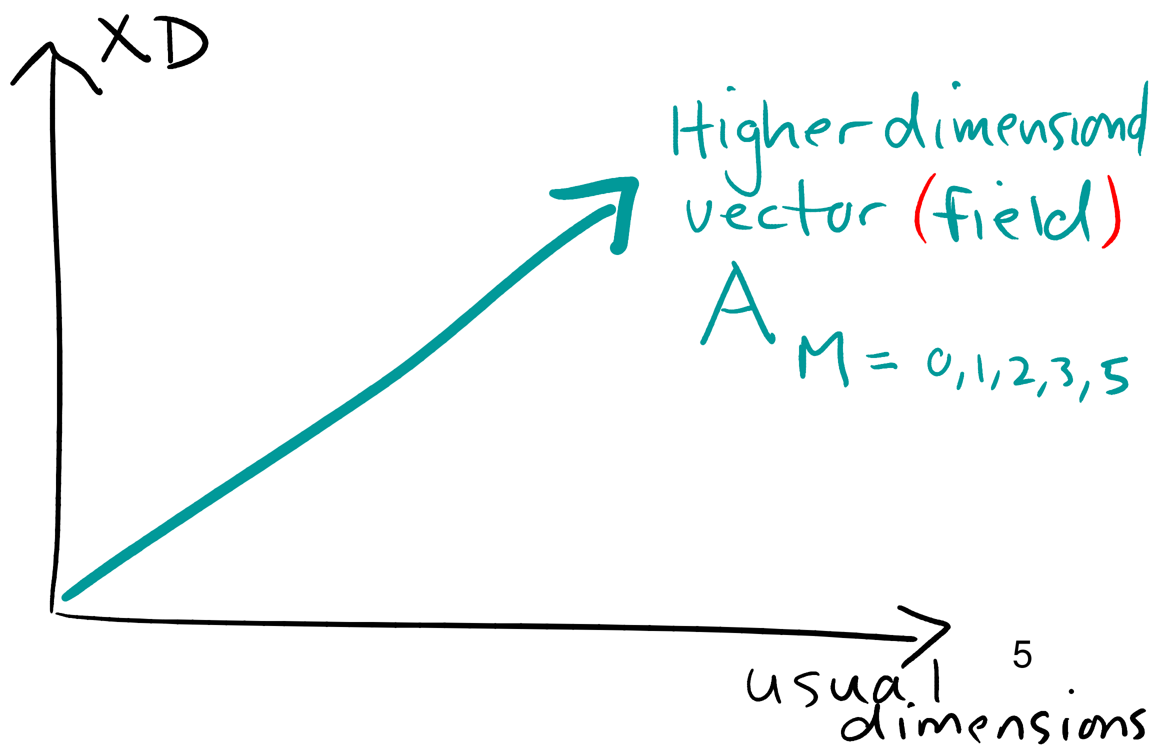
FEATURES

Higher Symmetry – x^μ — x_5

Lorentz invariance

x_5 translations

Unification



FEATURES

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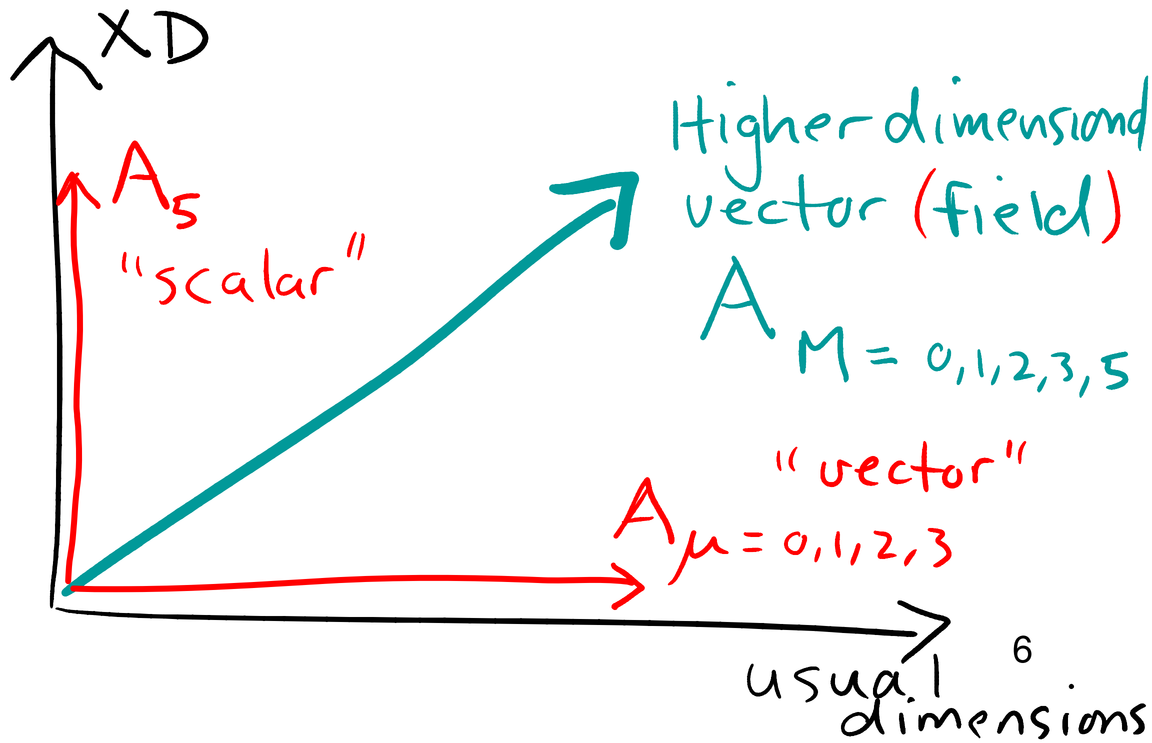
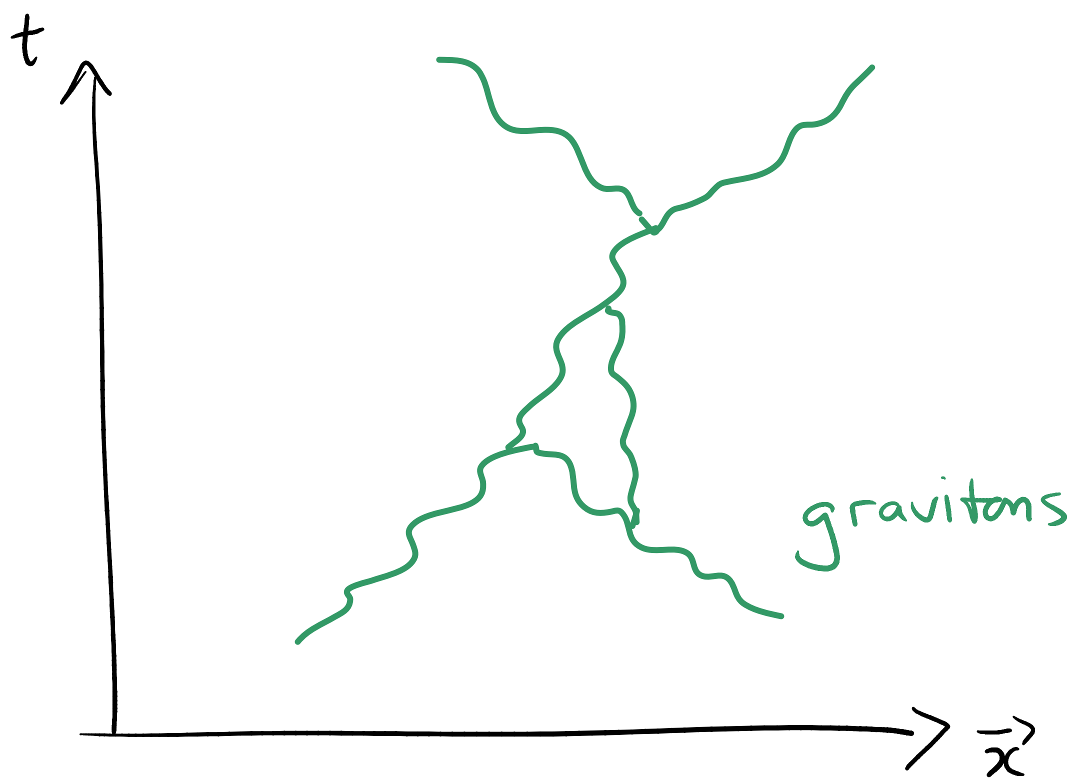
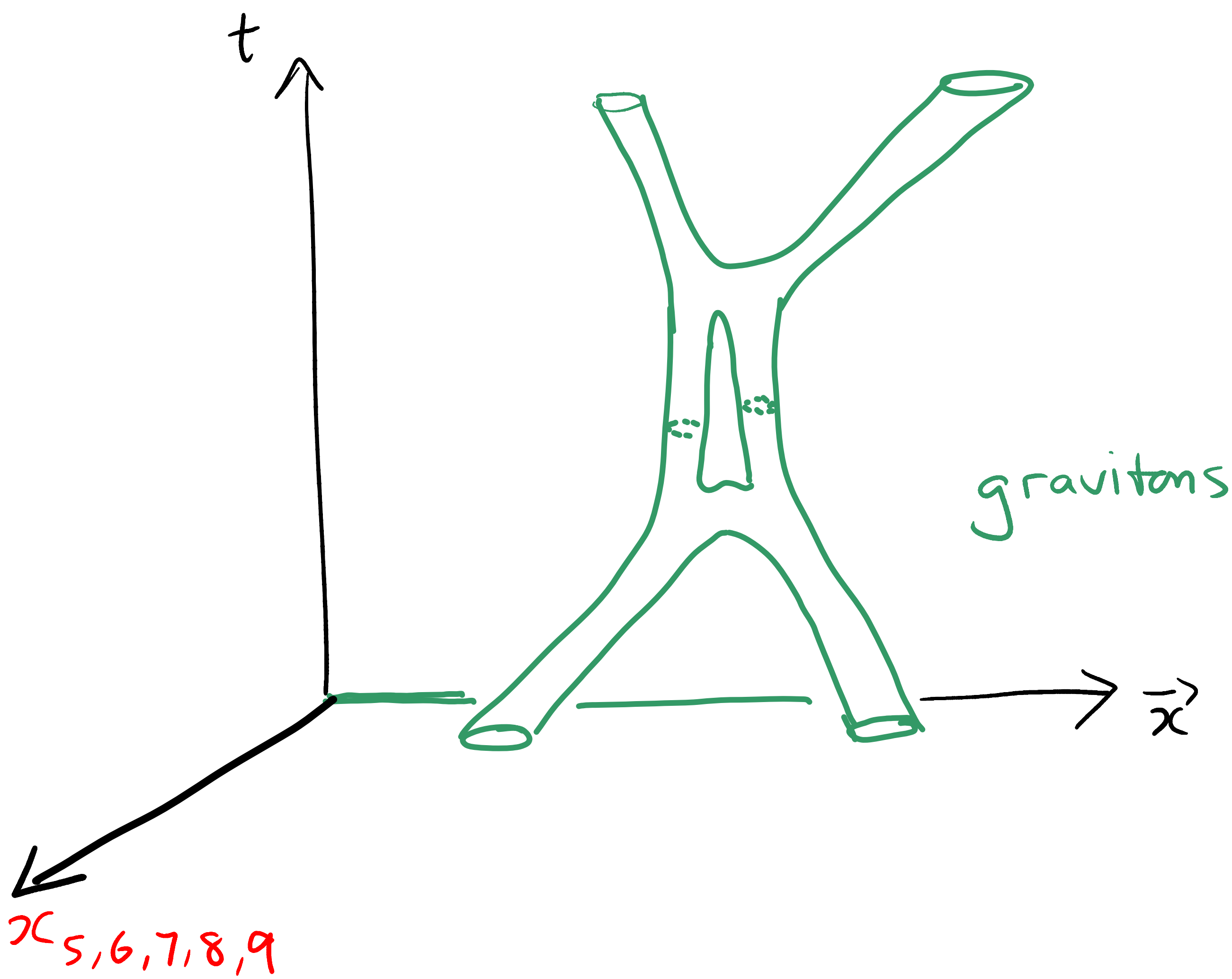


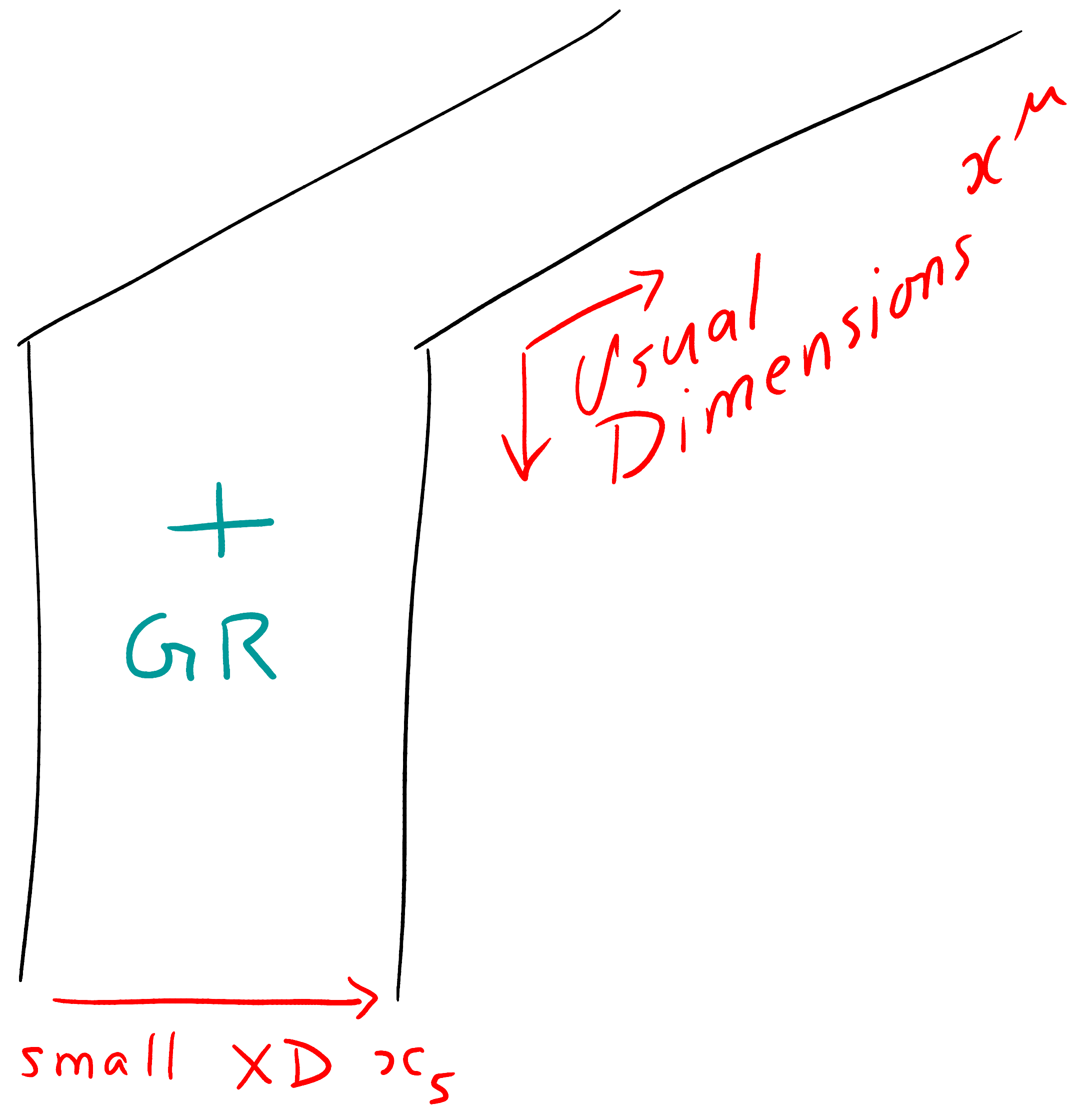
STRINGS & XD NEED EACH OTHER



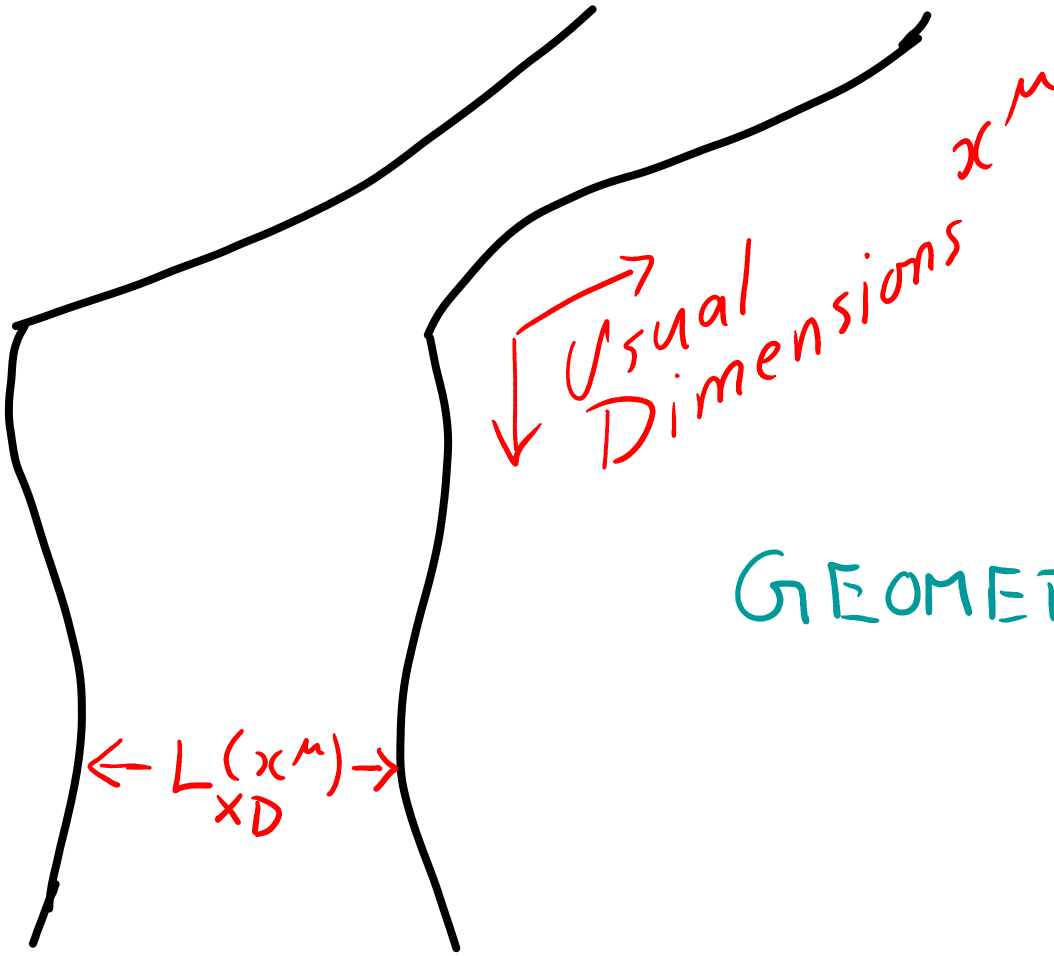
STRINGS & XD NEED EACH OTHER



XD



XD



GEOMETRIZE (Q)FT

STRONGLY COUPLED QFT

CAN BE GEOMETRIZED !

AdS/CFT Correspondence

Maldacena '97

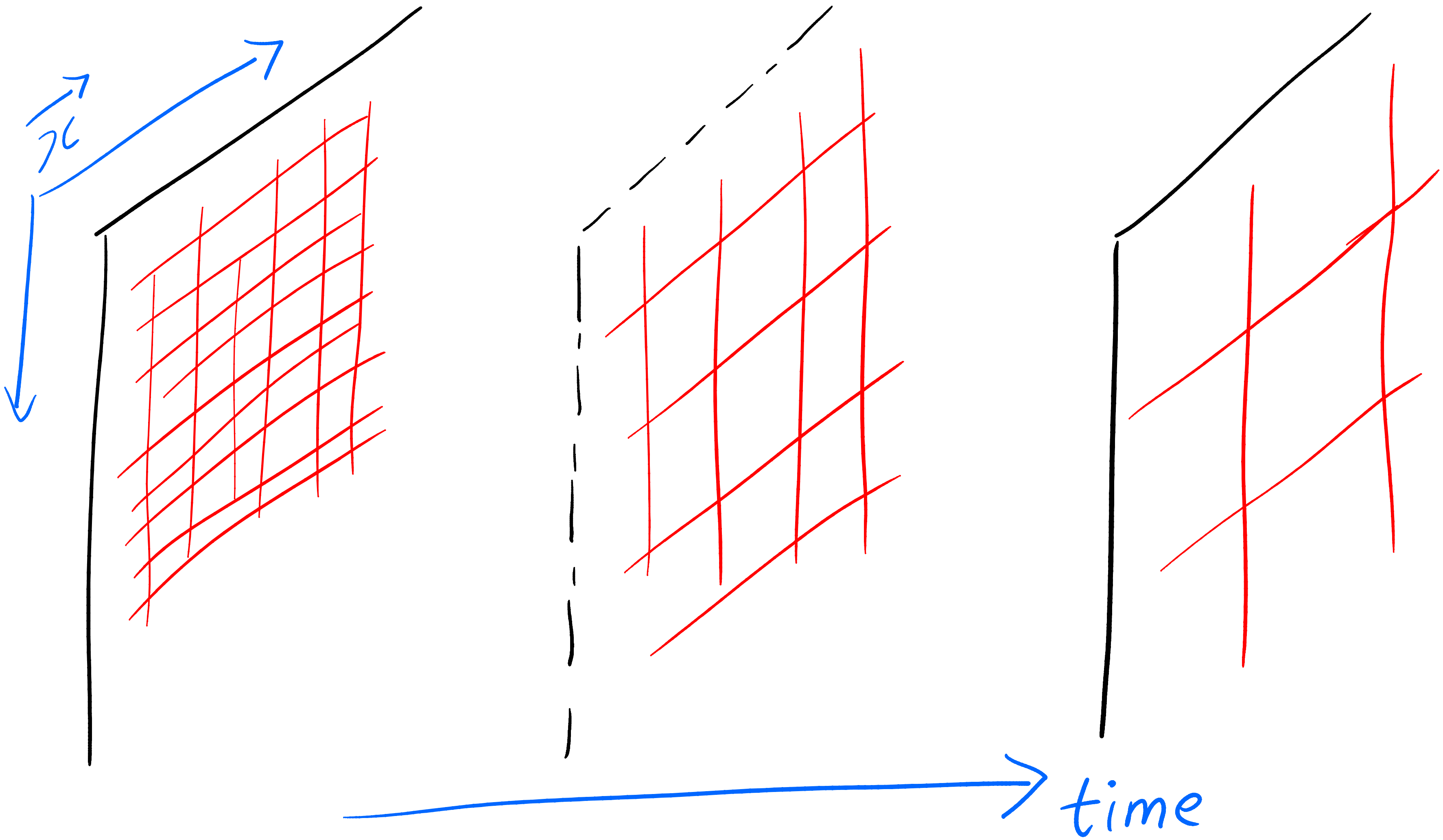
Gubser, Klebanov, Polyakov '97

Witten '98

$\approx$ EMERGENT XD

COSMOLOGY

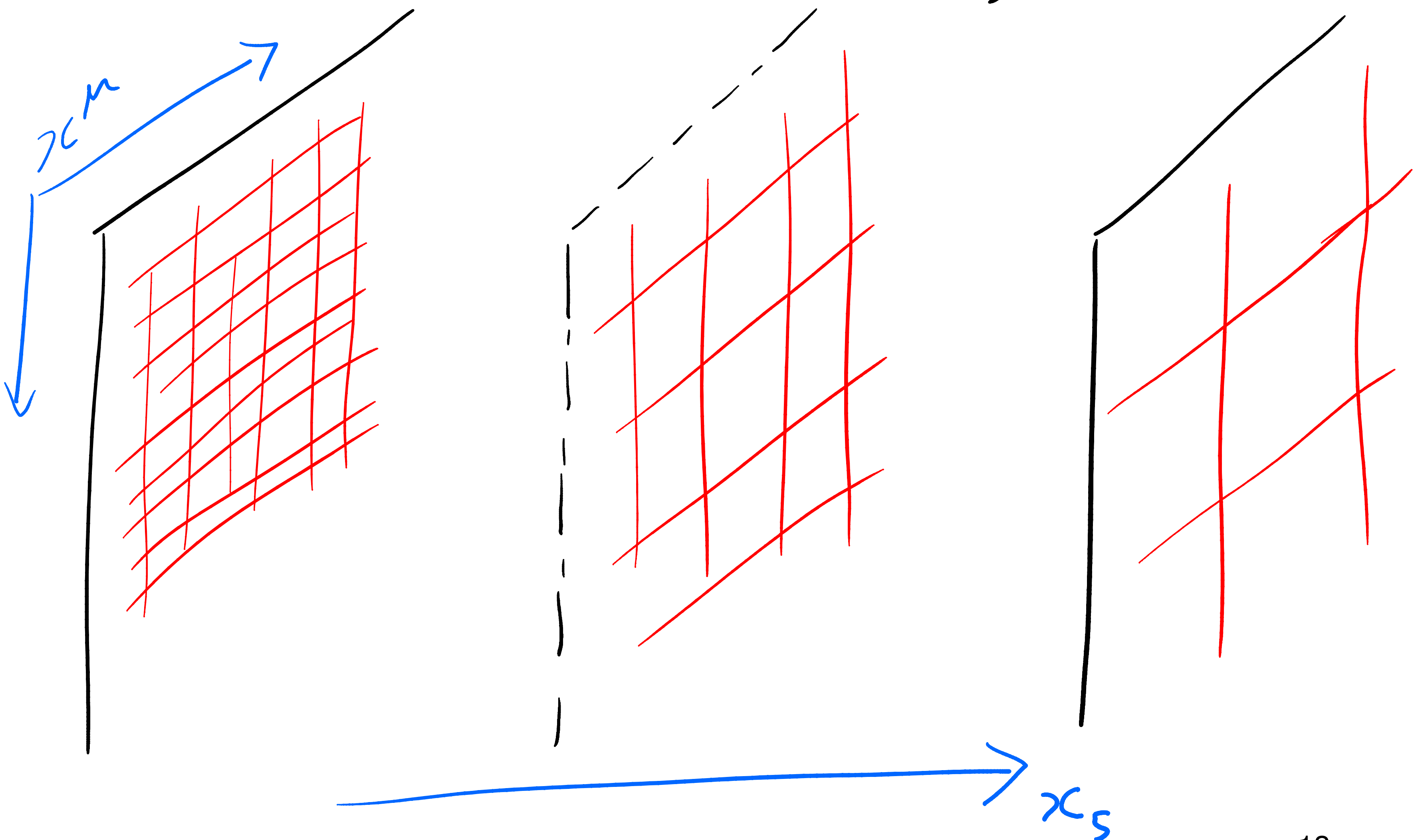
$$ds^2 = dt^2 - a^2(t)\, d\vec{x}^2$$



$a(t) \sim e^t$ de Sitter $\Rightarrow$ LARGE HIERARCHIES

WARPING

$$ds^2 = -dx_5^2 + w^2(x_5)\,dx^{\mu 2}$$



$w(x_5) \sim e^{x_5}$ Anti de Sitter => LARGE HIERARCHIES

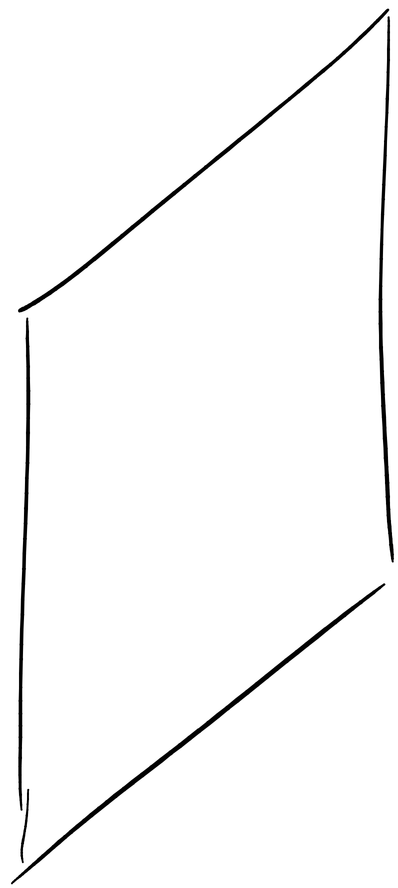
Elementary Objects in XD

particle

Elementary Objects in XD

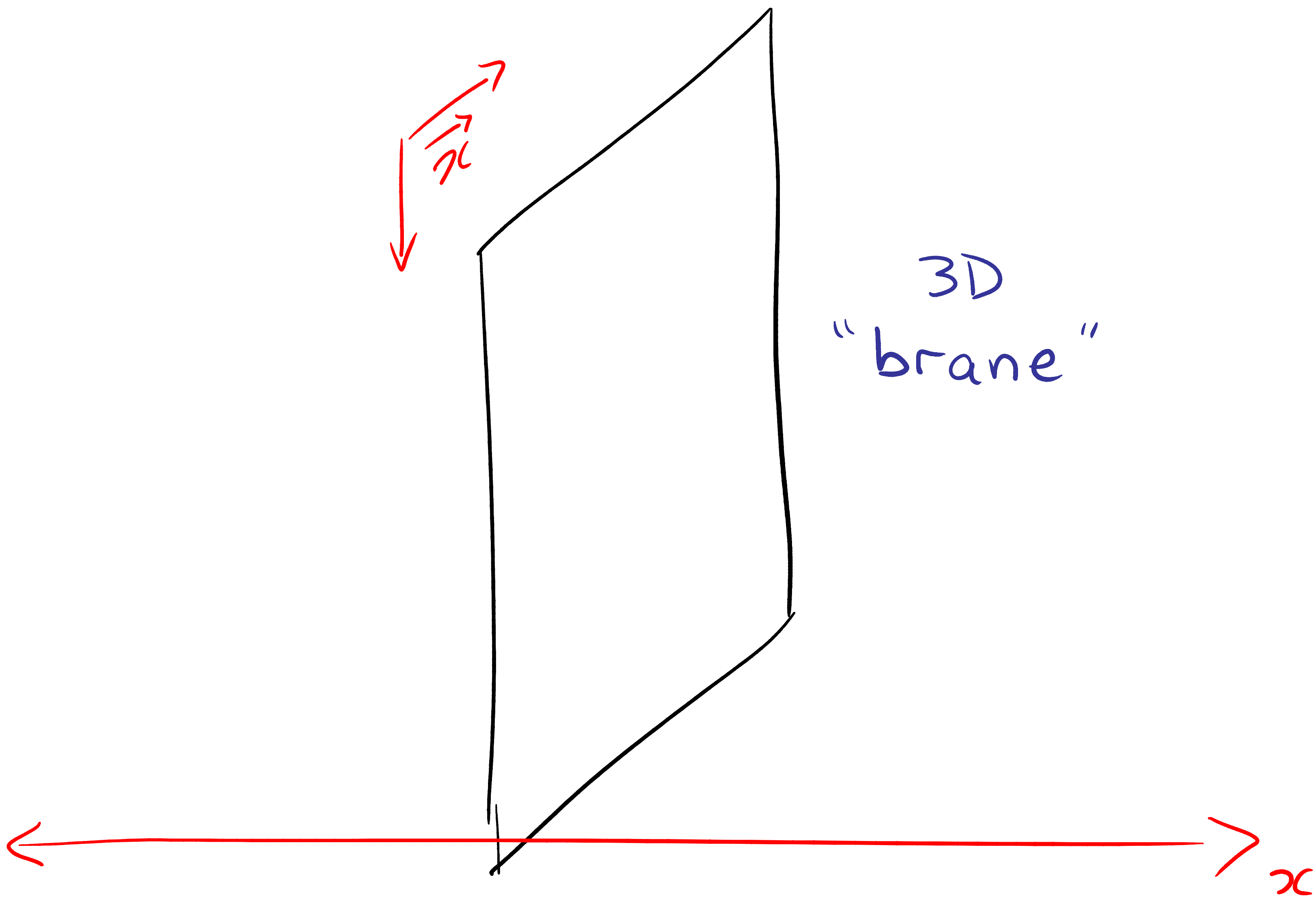
string

Elementary Objects in XD

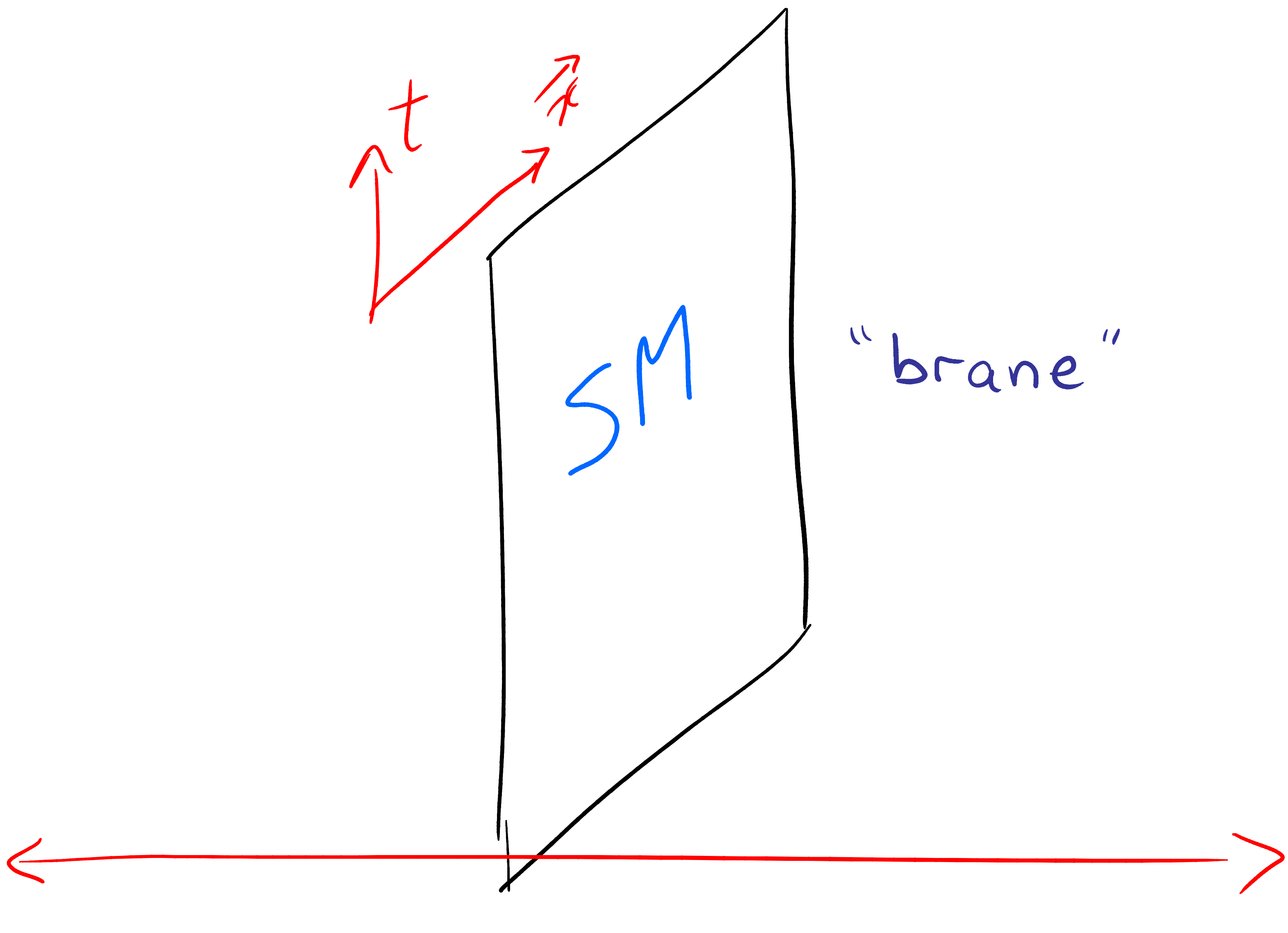


membrane

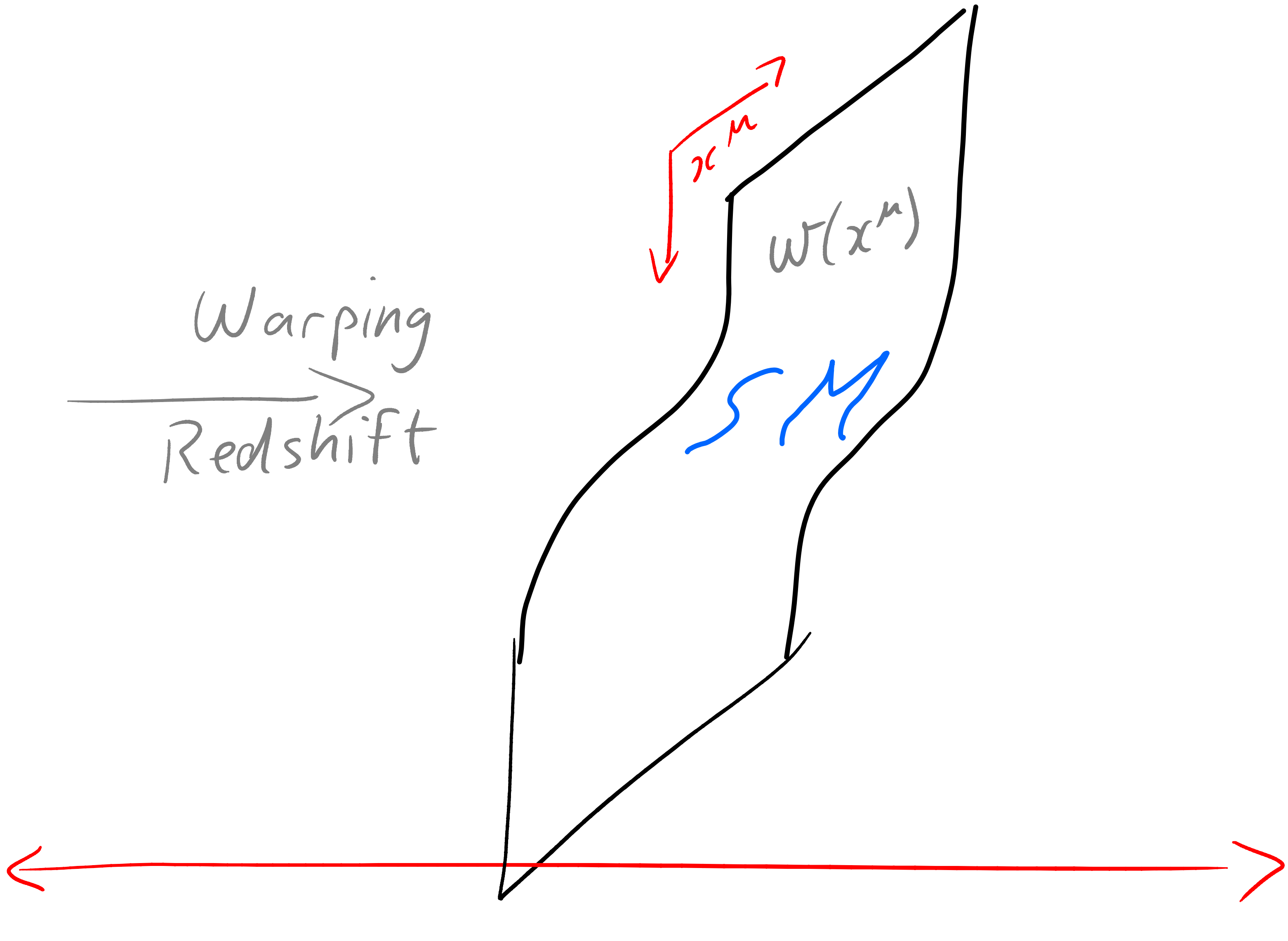
XD WITH BRANES



BRANEWORLD

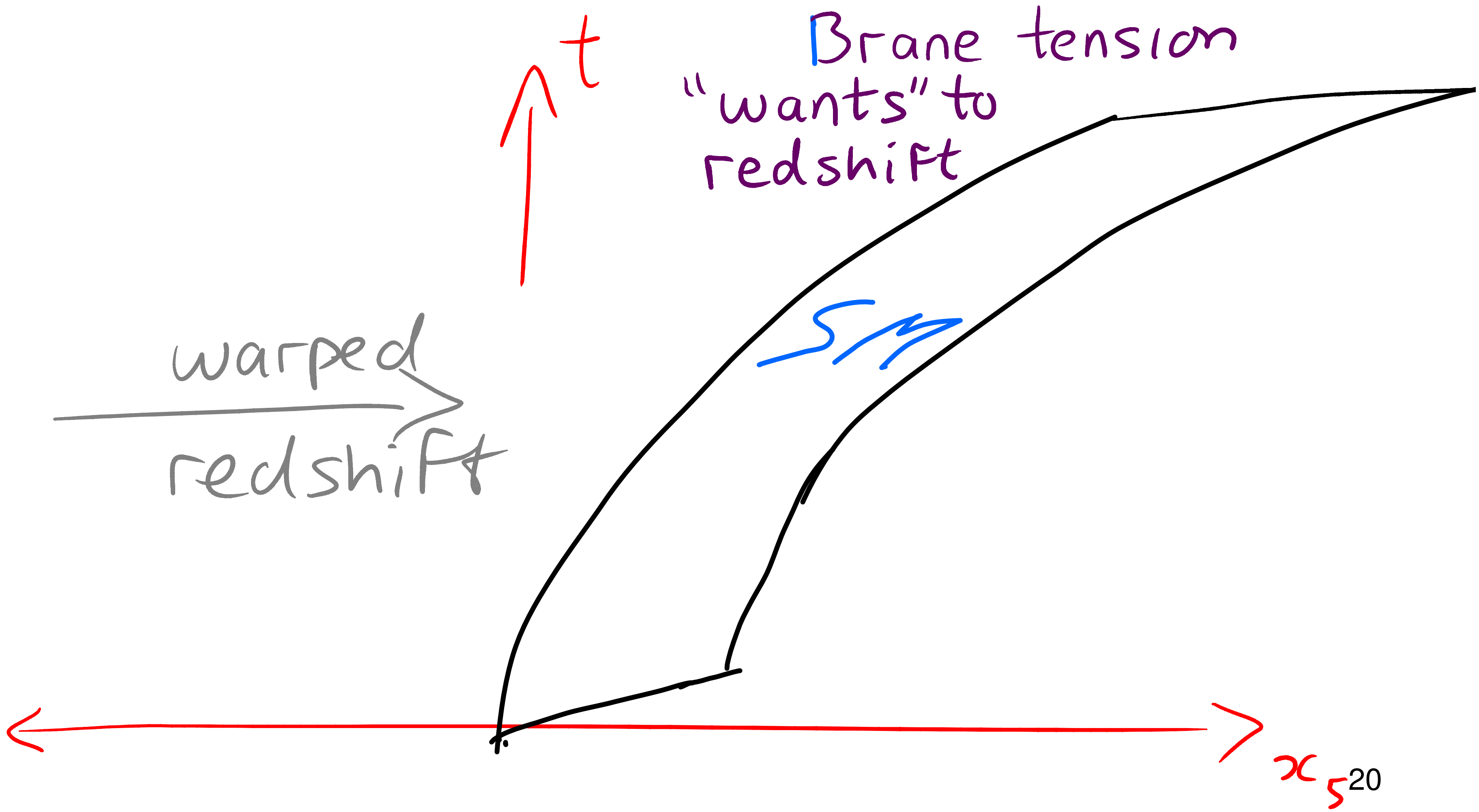


XD WITH BRANES

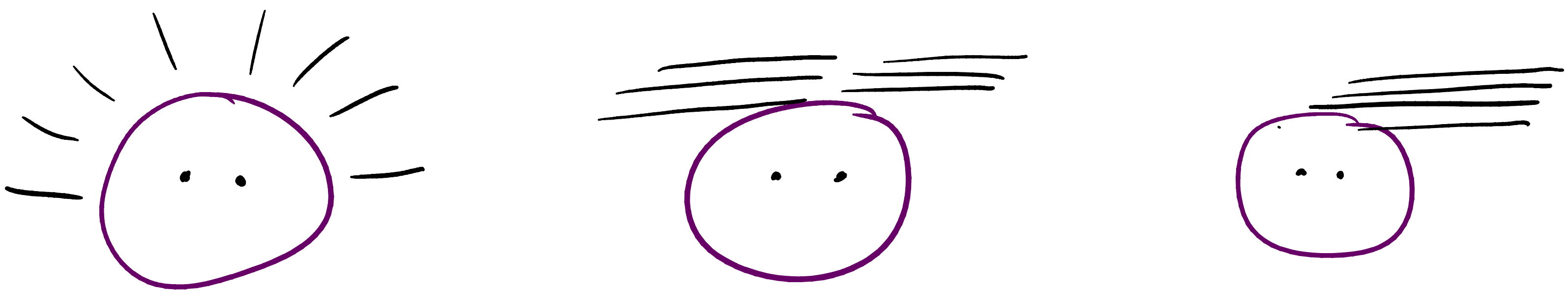


RUNAWAY BRANE

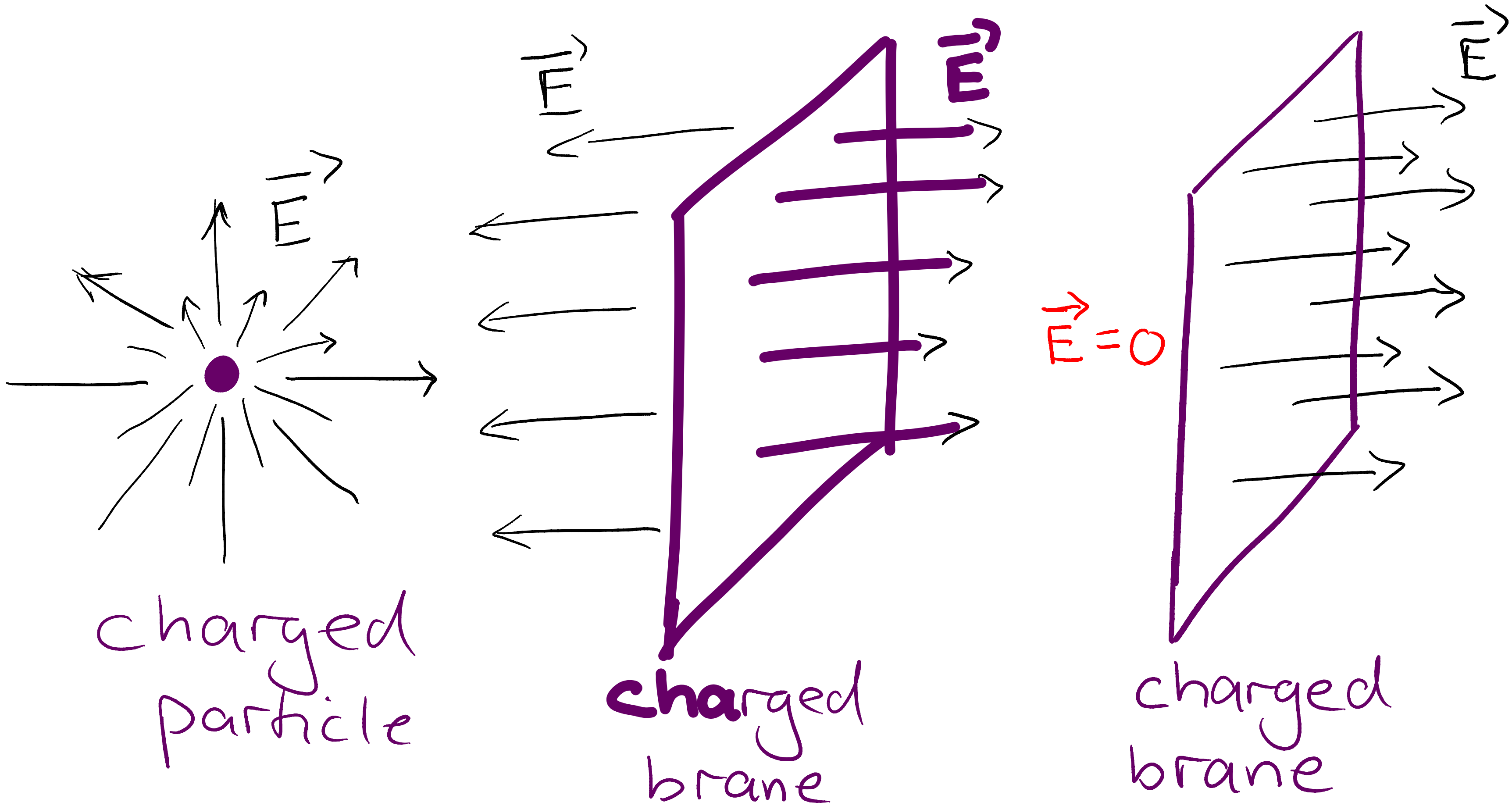
A Story of High Tension



HAIRSTYLES



HAIRSTYLES



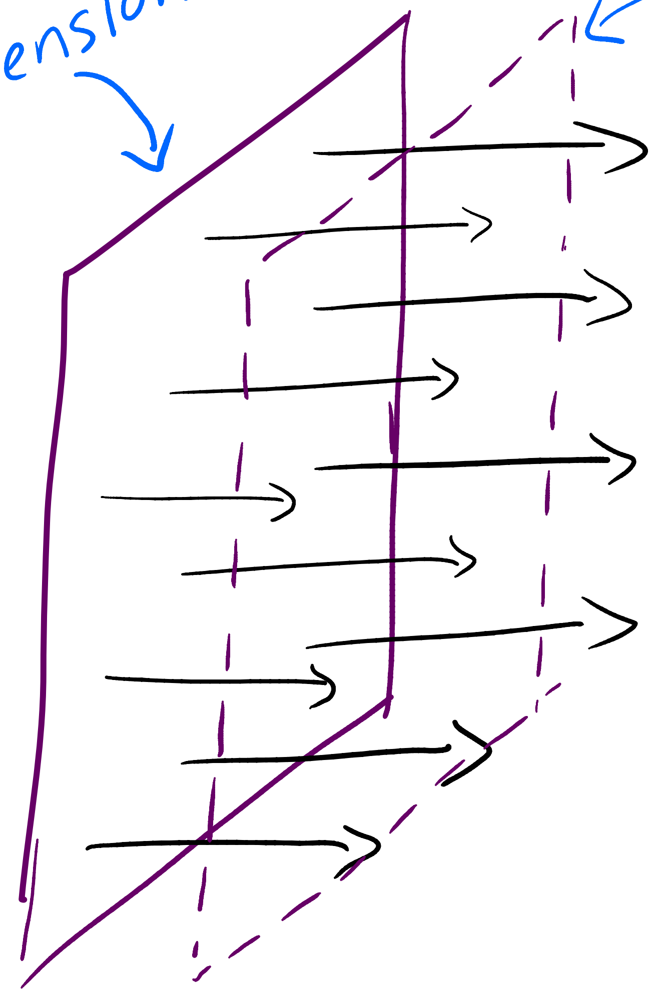
$\vec{E}$
charged particle
$\vec{E}$
$\vec{E}$
charged brane
$\vec{E} = 0$
$\vec{E}$
charged brane

STATIC MINKOWSKI BRANE

For suitable tension

Tension

redshifted tension



$\vec{E}$

Cosmological constant $\Lambda < 0$

AdS_5

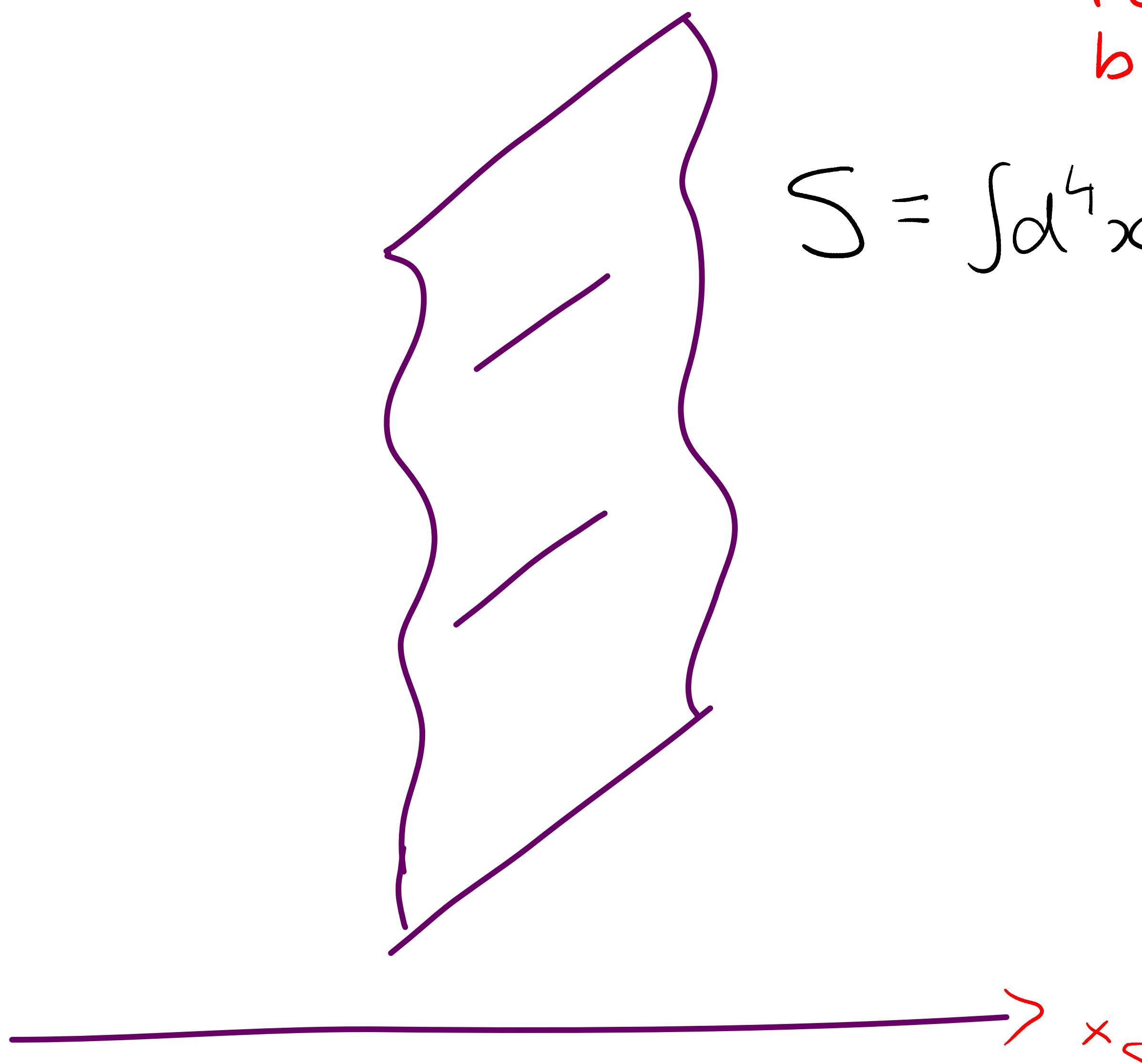
$$\Lambda_{eff} = \Lambda - \vec{E}^2 < \Lambda$$

AdS_5'

x_5

WARPING

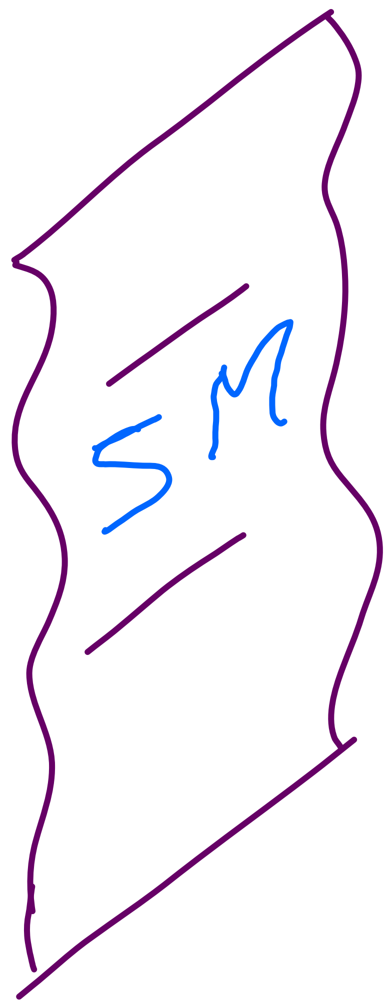
BRANE FLUCTUATIONS



redshift of brane

$$S = \int d^4x \left(\partial_\mu \varphi\right)^2$$

+ BRANEWORLD



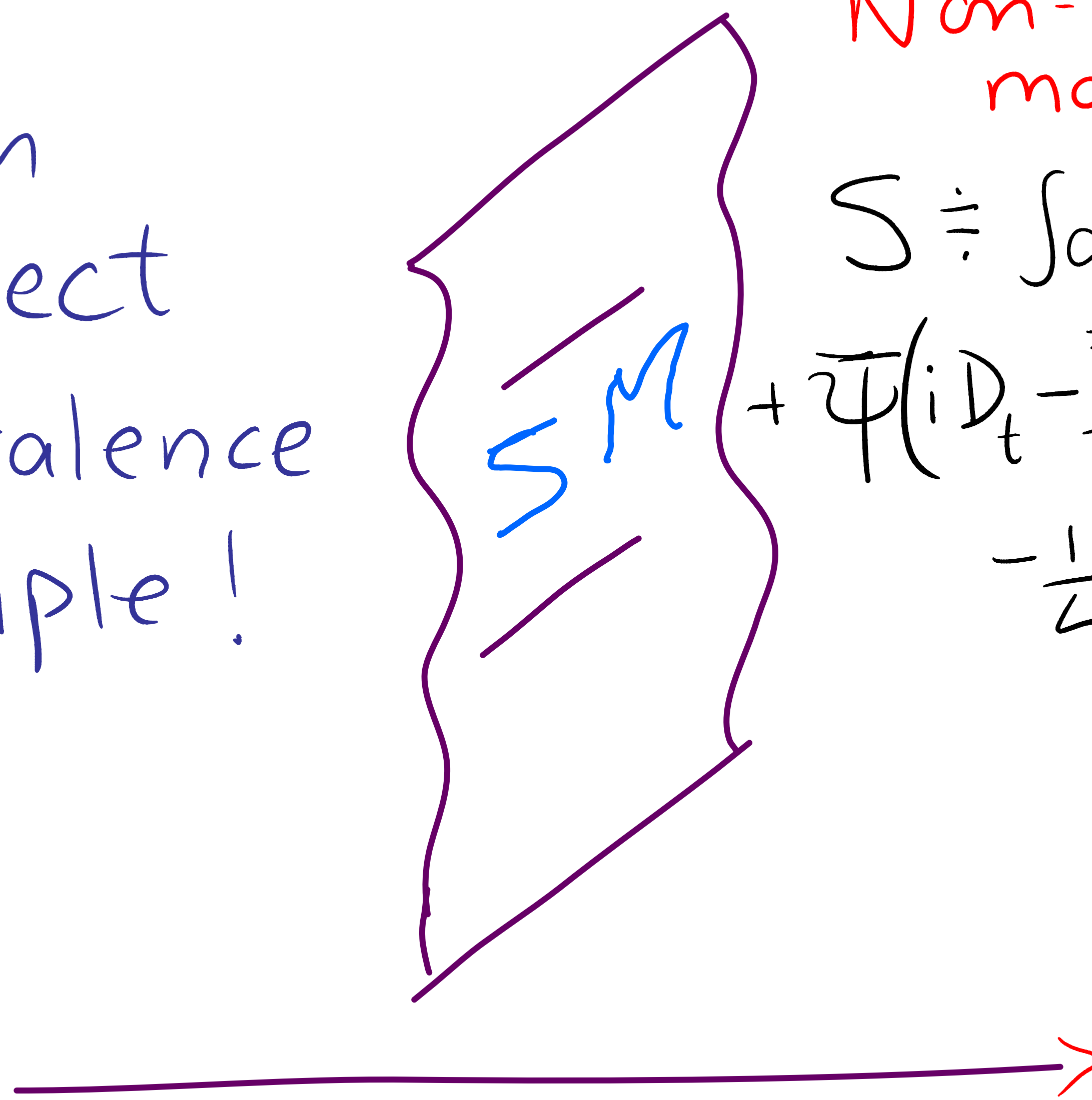
redshift of brane

$$S = \int d^4x \, (\partial_\mu \varphi)^2 - \frac{1}{4} F_{\mu\nu}^2 + \bar{\psi}\, i \not{D}\, \psi - m \frac{\varphi}{\varphi_0} \bar{\psi} \psi$$

redshifted mass

Scalar (3+1)D Gravity

with perfect Equivalence Principle!



x_s

Non-relativistic matter,

$$S \doteq \int d^4x \, -(\nabla\phi)^2 + \bar{\psi}\left(iD_t - \frac{\vec{D}^2}{2m} - \frac{m\phi}{\phi_0}\right)\psi - \frac{1}{4}F_{\mu\nu}^2$$

$$G_{Newton} = \frac{1}{\phi_0^2}$$

Newton's $1/r^2$ Law

+ Equivalence Principle + Special Relativity

m=0 spin-2

m=0 spin-0

Nordstrom '13

CURVED SPACETIME

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

Einstein '15

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

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

Einstein, Fokker '14

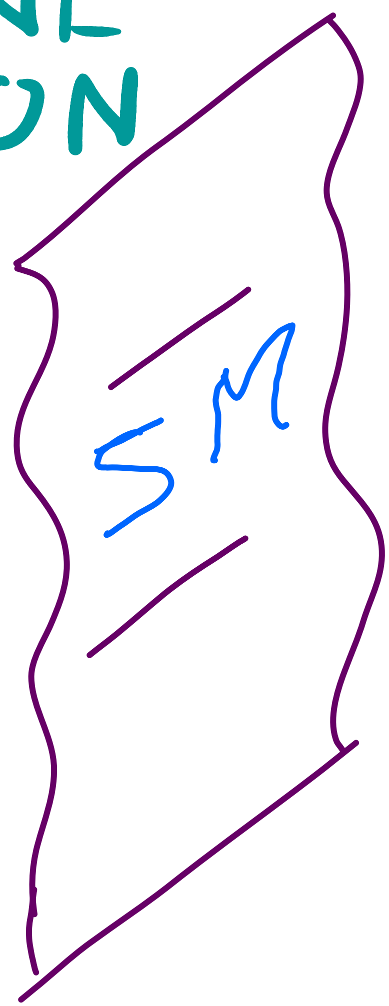
⟶ Modernized + QFT

Sundrum '03

SM VACUUM ENERGY

→ BRANE TENSION

destabilizes Minkowski brane!



x_s

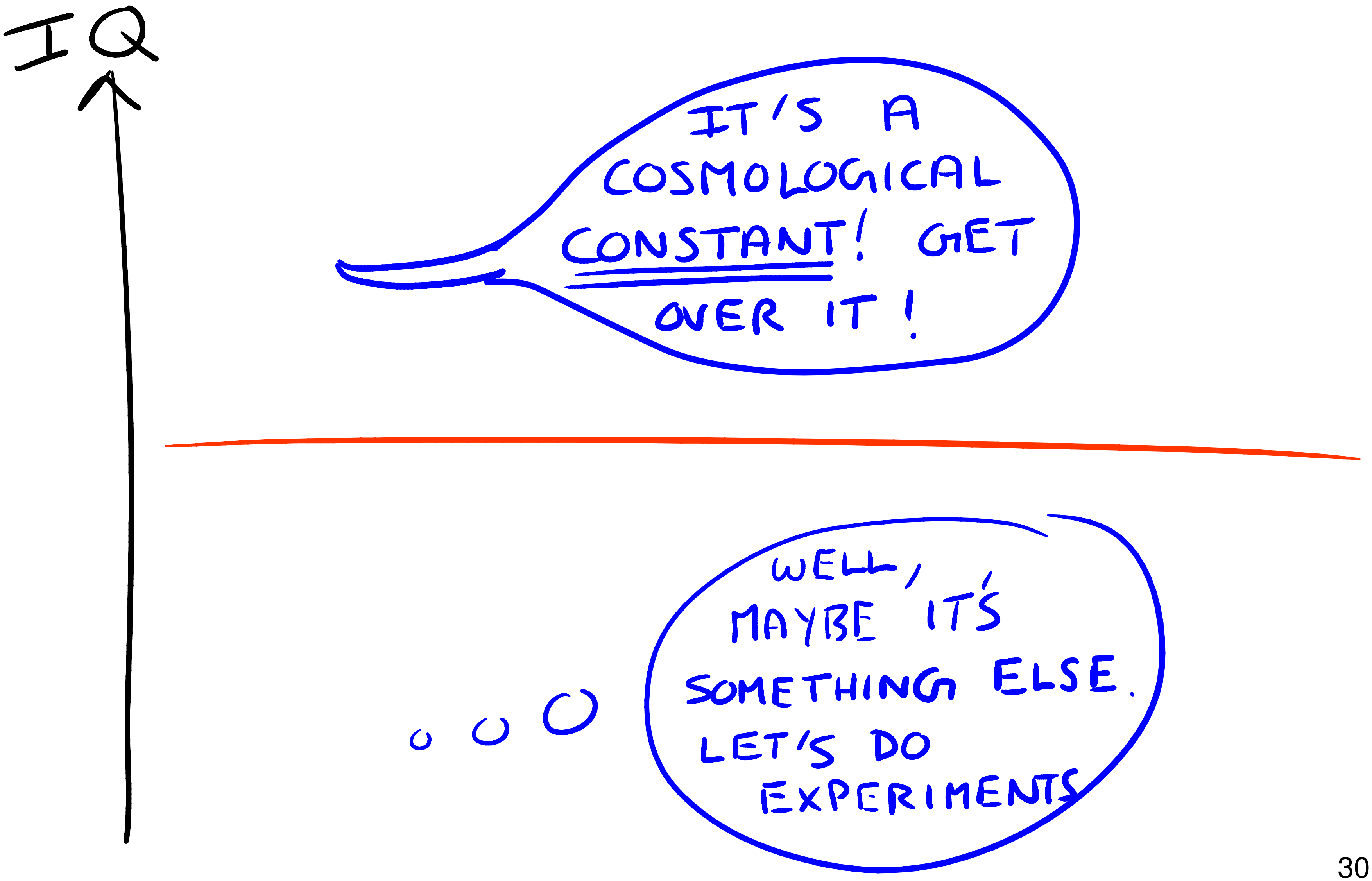
redshift of brane

$$S = \int d^4x \, (\partial_\mu \varphi)^2 - \frac{1}{4} F_{\mu\nu}^2 + \bar{\psi} i \not{D} \psi - \frac{m\varphi}{\varphi_0} \bar{\psi} \psi - \rho_{vacuum} \frac{\phi^4(x)}{\phi_0^4}$$

METAPHOR FOR DARK ENERGY?

+ other subtle problems

THE GREAT DIVIDE



Standard Cosmology in Conformal Coordinates

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

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

$$d\tau = \frac{\varphi(t)}{M}\, dt \qquad a(\tau) = \frac{\varphi(t)}{M}$$

$$S = \underset{\text{Note}}{-}(\partial_\mu \phi)^2 + \bar{\Psi}\left(i\not{D} - m\frac{\phi}{M_{Pl}}\right) - \frac{1}{4}F_{\mu\nu}^2$$

FRIEDMAN EQUATION

$\partial_t \to \dot{\ }$

$$\mathcal{E} = -\dot{\phi}^2 + m\frac{\overset{\text{conserved}}{n_{dust}}\,\phi}{M} + \rho_{rad} + \underset{\rho_{vac}/M^4}{\lambda}\,\phi^4$$

FRIEDMAN EQUATION

conserved

$$\mathbf{0} = \mathcal{E} = -\overset{\partial_t \to}{\dot{\phi}^2} + \frac{m\, \overset{\downarrow}{n_{dust}}\, \phi}{M_{Pl}} + \rho_{rad} + \lambda \phi^4$$

Hamiltonian constraint

λ: ρ_{vac}/M^4

$$\Longleftrightarrow \quad H/M_{Pl} \equiv \frac{\overset{\partial_\tau \to}{\dot{a}}}{a M_{Pl}} = \dot{\varphi}/\varphi^2$$

$$H^2 = G_N \left(\frac{m\, n_{dust}}{a^3} + \frac{\rho_{dust}}{a^4} + \rho_{vac} \right)$$

FRIEDMAN EQUATION

conserved

$\partial_t \rightarrow$

$$0 = \mathcal{E} = -\dot{\phi}^2 + \frac{m\, n_{dust}\, \phi}{M} + \rho_{rad} + \lambda \phi^4$$

ρ_{vac}/M^4

$\partial_t \rightarrow$

$$\Longleftrightarrow \quad H/M \equiv \frac{\dot{a}}{aM} = \dot{\varphi}/\varphi^2$$

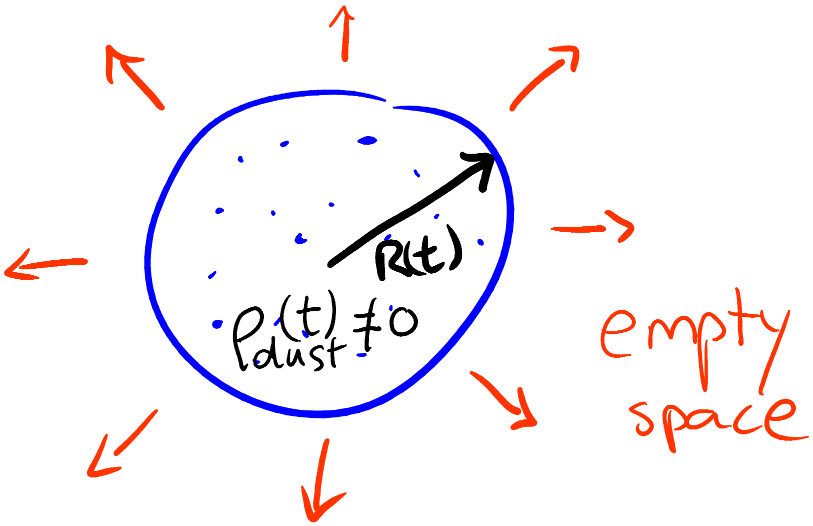
$$H^2 = G_N \left(\frac{m\, n_{dust}}{a^3} + \frac{\rho_{dust}}{a^4} + \rho_{vac} \right)$$

SCALAR GRAVITY

$$0 \neq \mathcal{E} = +\dot{\varphi}^2 + \frac{m\, n_{dust}\, \phi}{\phi_0} + \rho_{rad} + \lambda \phi^4$$

$$\Rightarrow \lambda_{\substack{scalar\\grav}} \equiv -\lambda_{\substack{real\\grav}} \; ; \; (\mathcal{E} - \rho_{rad})_{\substack{scalar\\grav}} \equiv \rho_{\substack{rad\\real\\grav}} \; ; \; n_{\substack{dust\\scalar\\grav}} \equiv -n_{\substack{dust\\real\\grav.}} \; !!$$

but Newtonian Cosmology matches!



Exploding ball with Newtonian (scalar) attraction

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

non-rel. limit

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

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

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

∴ Galilean invariance makes physics inside ball ∴ homogeneous + isotropic

MODIFIED Scalar GRAVITY

$\equiv$ ~~EQUIVALENCE PRINCIPLE~~ small

$\equiv$ ABSOLUTE SCALE FACTOR

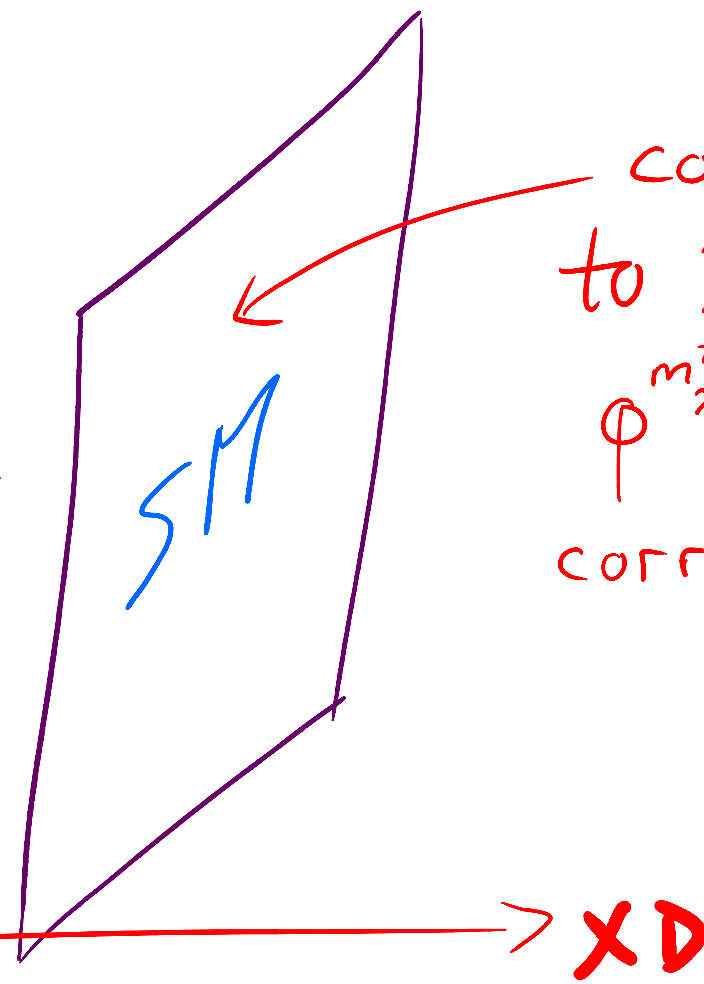
Goldberger-Wise

5D Scalar Field

$$\partial_w w^3 \partial_w \chi = m_\chi^2 \chi w^5$$

w: warp factor coordinate

$$\chi(w) \sim w_{AdS}^{m_\chi^2 R_{AdS}^2}$$



couplings to $\chi \Rightarrow$

$$\phi^{m_\chi^2 R_{AdS}^2}$$

corrections

Cosmological Constant Suppression in (modified) Scalar Gravity

Contino, Pomarol, Rattazzi
(Rattazzi talk @ Planck 2010)

New small parameter:

$\varepsilon \sim m_\chi^2 R_{AdS}^2 <<< 1$ natural if

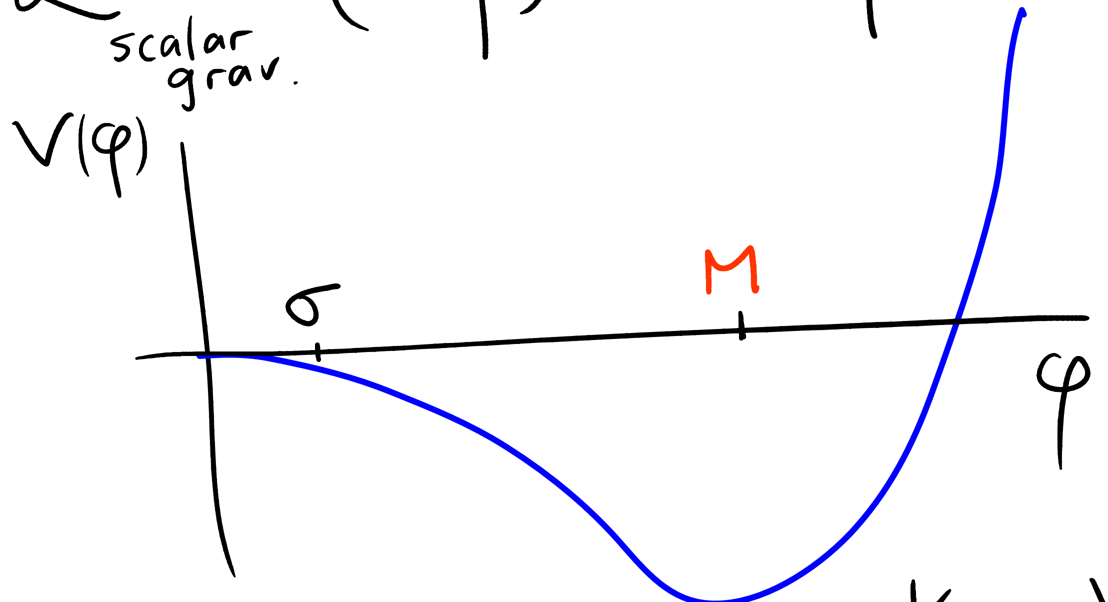
χ = 5D Pseudo Nambu-Goldstone Boson

$\chi = A_6$ gauge field $\quad \varepsilon \sim e^{-m_6^{\pm} L_6}$

Sundrum

$\sigma \equiv$ typical modification scale

$$\mathcal{L}_{\text{scalar grav.}} = (\partial\varphi)^2 - \lambda\varphi^4 + \lambda'\varphi^4\left(\frac{\sigma}{\varphi}\right)^{\varepsilon}$$



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

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

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

Useful Approximation

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

if $\quad \varepsilon\left|\ln M/\varphi\right| \ll 1 \qquad Me^{-1/\varepsilon} \ll \varphi \ll Me^{1/\varepsilon}$

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

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

$$a \equiv \phi/M$$

$\Rightarrow$ Friedman Eq.

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

fake "radiation" $\qquad$ cosmological const.

$\lambda \to \varepsilon\lambda \ln M/\varphi \, (\ll \lambda)$

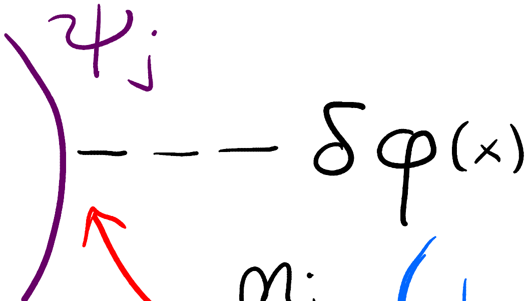
$\lambda = \rho_{vac}/M^4 \sim O(1) \Rightarrow \varepsilon \sim 10^{-123}$!! $\qquad$ Dark Energy!

What I'm working on...

~~Equivalence Principle~~

small

$$\mathcal{L} = (\partial_\mu \varphi)^2 - V(\varphi) + \sum_j \bar{\psi}_j \left[i\not{D} - m_j \frac{\varphi}{M} \left(1 + \left(\frac{\sigma_j}{\varphi} \right)^{\varepsilon} \right) \right] \psi_j$$



$$\frac{m_j}{M} \left(1 - \varepsilon \left(\frac{\sigma_j}{M} \right)^{\varepsilon} \right)$$

tiny anomalous accelerations

Effect on gravity . . .

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

. . . only on today's horizon scale

Cosmology

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

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

Hidden tuning?

Phase transition

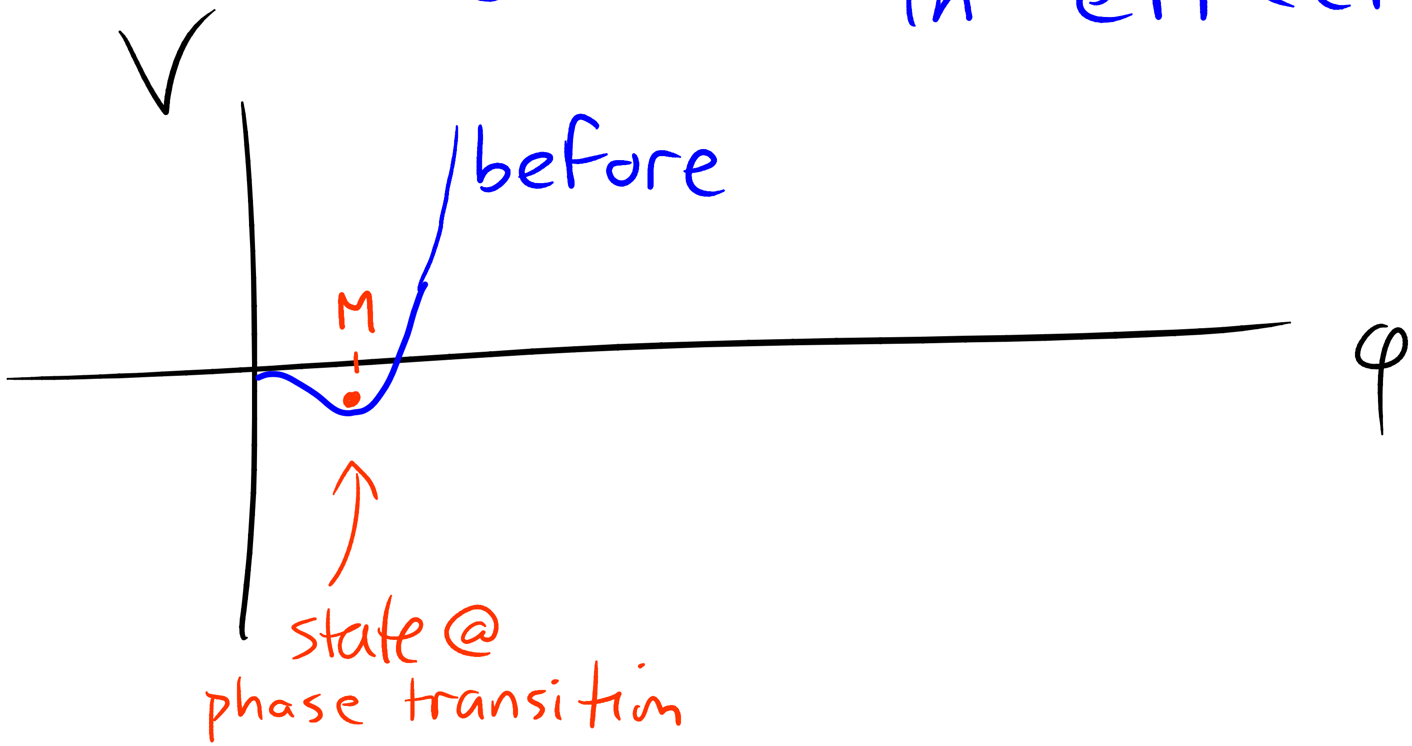
in matter sector suddenly changes vacuum energy $\lambda \to \xi\lambda$ (& lesser extent λ').

Consider $\xi \lesssim 1$, λ' unchanged.

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

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

so cosmological constant cancelation in effect...

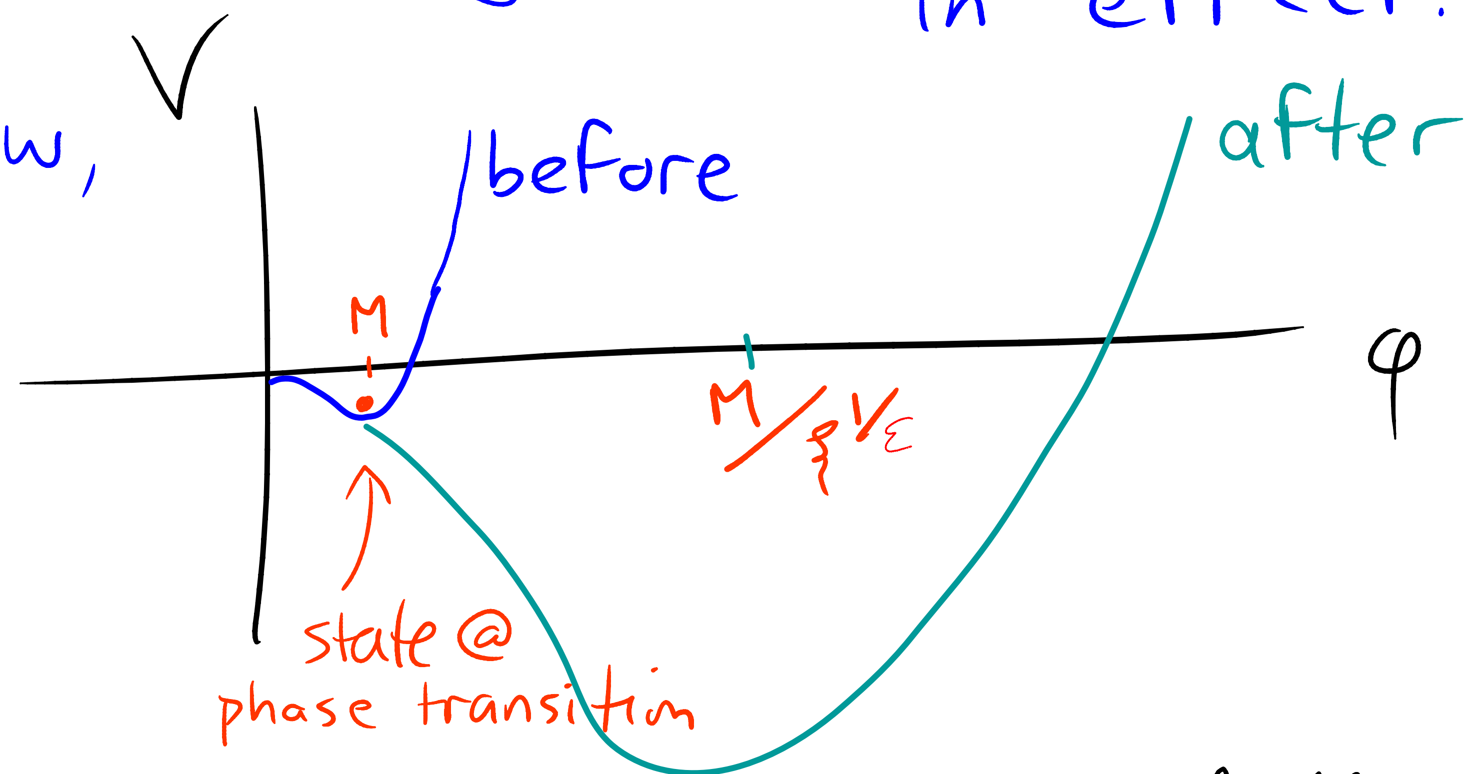


... & LIFE IS GOOD

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

so cosmological constant cancelation in effect.

Now,



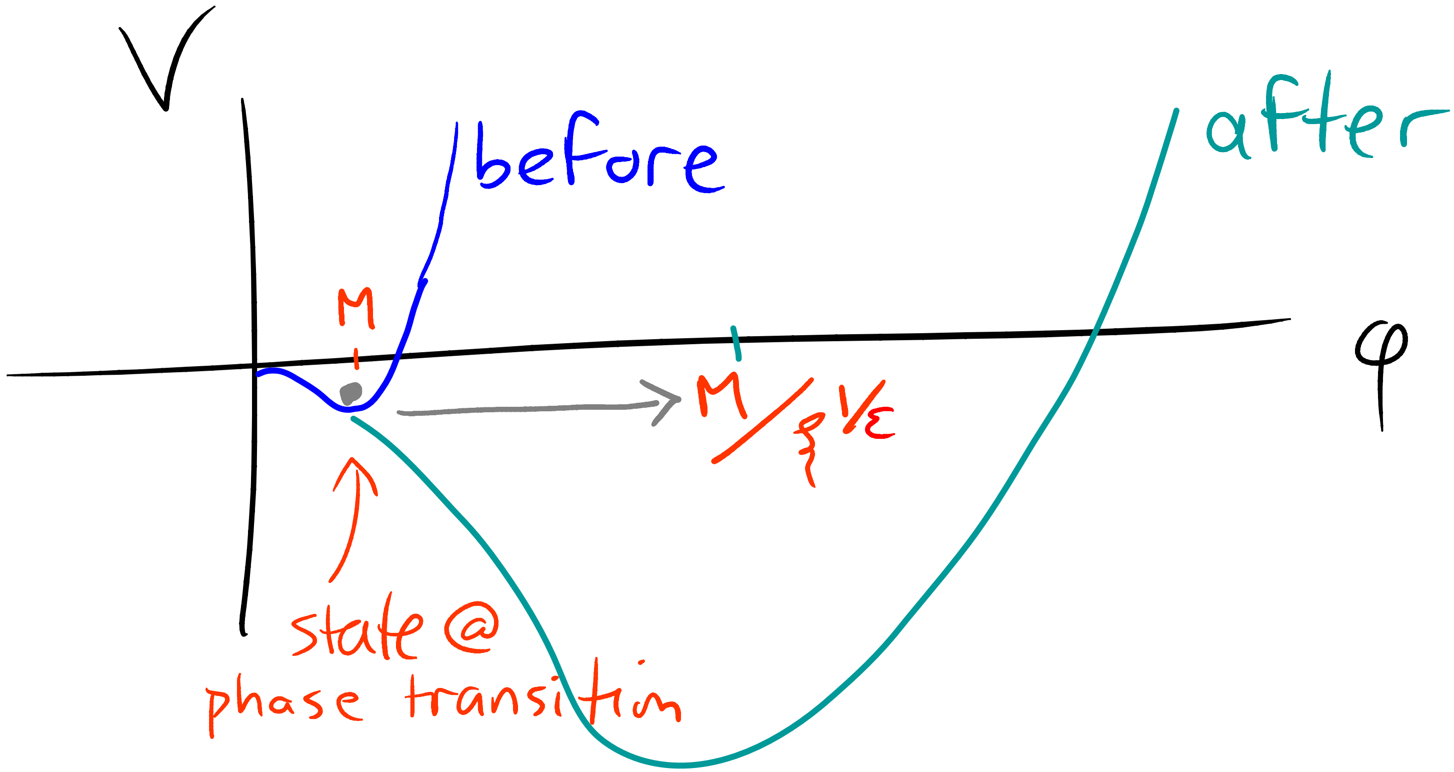
We thereby "start" new phase $\ln \frac{M}{\xi^{1/\varepsilon}\varphi} \sim O\left(\frac{1}{\varepsilon}\right)$

without ε-suppression. In fact

$-\lambda \varphi^4 (\sigma/\varphi)^\varepsilon$ dominates $\equiv$ HIGH INFLATION!

Eventually inflation ends

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



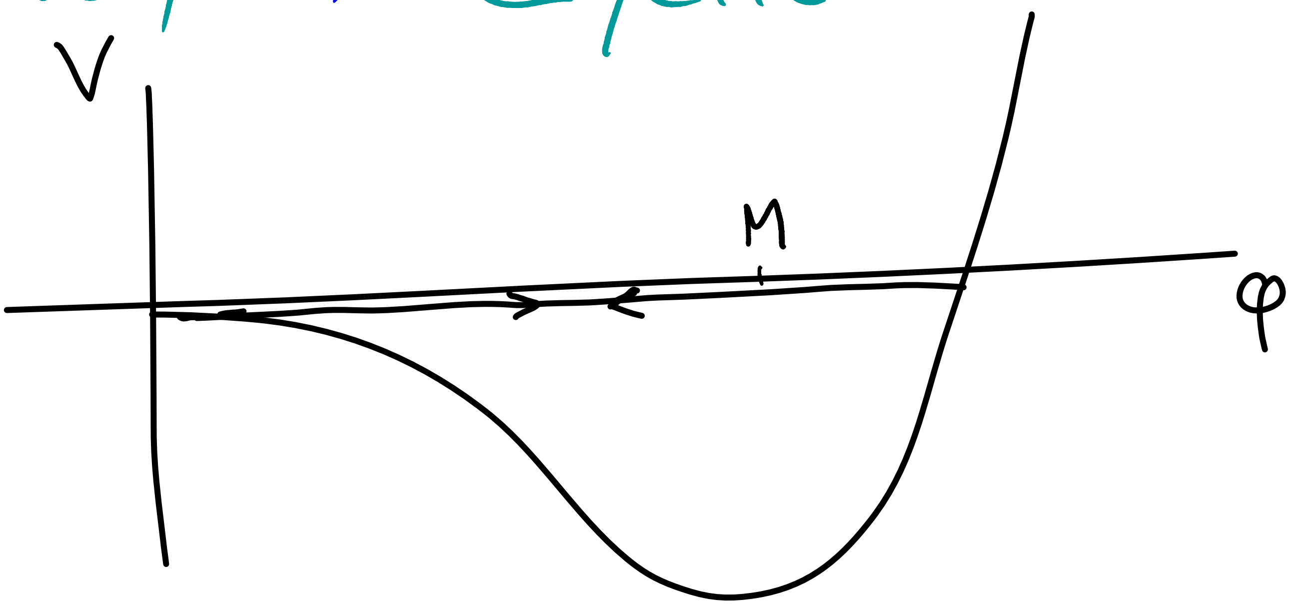
But by then $\sim 1/\varepsilon$ e-foldings have inflated away any original matter/radiation.

REHEATING AFTER AUTO-INFLATION?

Phase-transition-robust initial conditions,

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

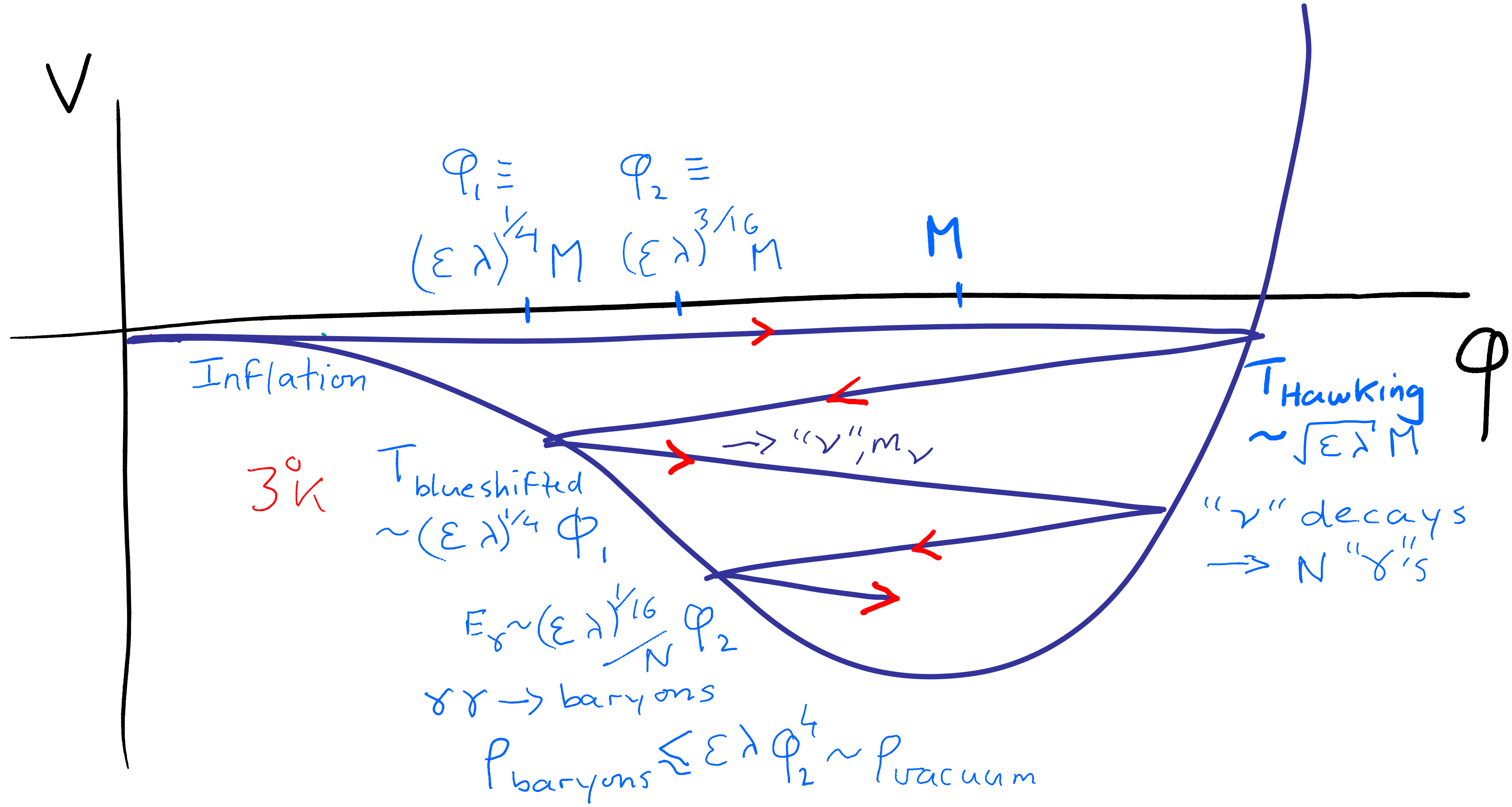
naively ⇒ Cyclic Cosmology



BUT MUST ACCOUNT FOR COSMOLOGICAL PARTICLE PRODUCTION

Eg. Hawking Radiation

REHEATING AFTER AUTO-INFLATION



GROWTH OF INHOMOGENEITIES . . .

(THE OTHER) w

$$\rho_{vacuum} \propto a^{-3(1+w)} \propto \varphi^{-3(1+w)}$$

$$\underset{w \approx -1}{\approx} 1 - 3(1+w) \ln \phi/\phi_{now}$$

For us, $\rho_{vacuum} \propto \varepsilon\lambda \ln \phi/M = \varepsilon\lambda \ln \frac{\phi}{\phi_2} + \varepsilon\lambda \ln \frac{\phi_2}{M}$

$$\propto 1 + \frac{\ln \phi/\phi_2}{\ln \phi_2/M}$$

$$w = -1 - \frac{1}{3 \ln \phi_2/M}$$

$$= -1 - \frac{1}{3 \ln (\varepsilon\lambda)^{3/16}} \approx -1 + \frac{1}{\frac{9}{16} \ln 10^{123}}$$

CONCLUSIONS

XD: plausible, powerful set of field theory mechanisms,

applicable to INFLATION

ELECTROWEAK PHYSICS

DARK MATTER

STRONG COUPLING

CONCLUSIONS

DE: (VERY)^{123} HARD PROBLEM!

XD ⇒ TOY MODEL

of how a subtle break in Equivalence Principle evades Cosmological Constant Problem with observational consequences

TOY MODEL ⟶ REAL GRAVITY?

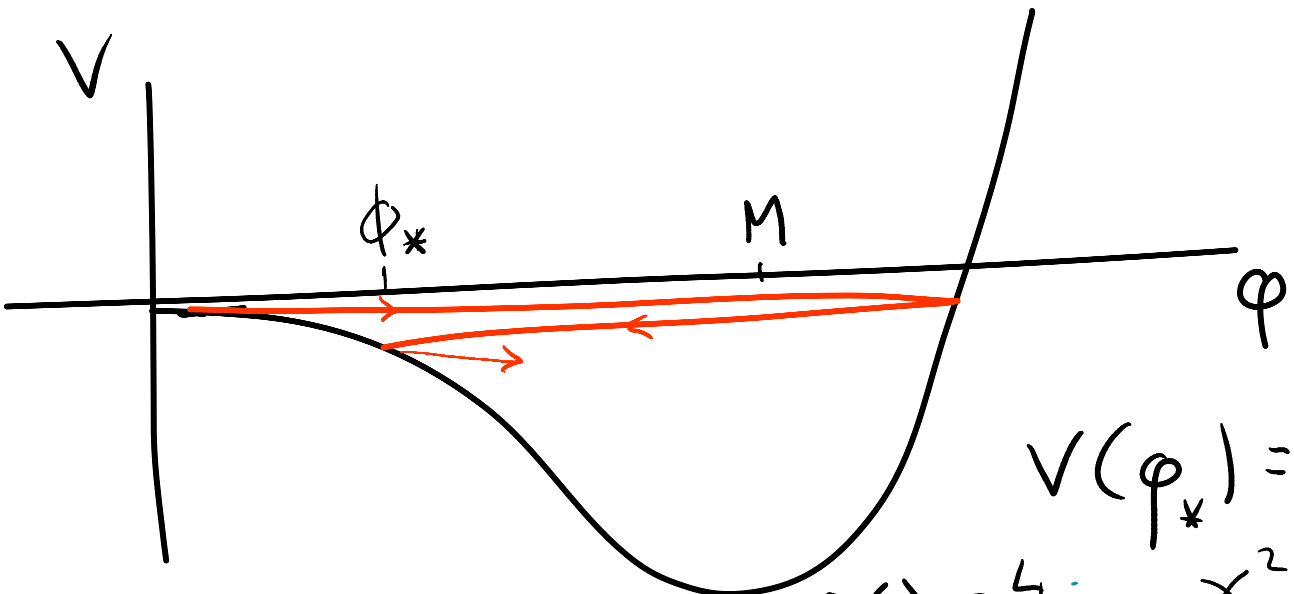
Keep pushing toy model ⟶ structure, higher matter/rad densities

Can even toy model guide experiments?

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 $T_{rad}^4 \sim \gamma^2\lambda^2 M^4$



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

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

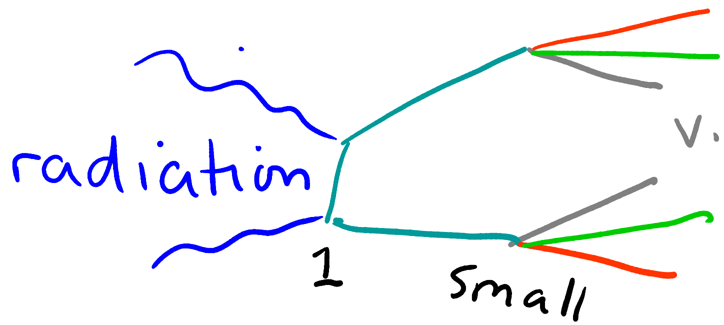
In Planck units, at first bounce $T_{rad}/M \sim \sqrt{\gamma\lambda}$

but after 2nd bounce $T_{rad}/\varphi_* \sim (\gamma\lambda)^{1/4} \equiv 3°K$ radiation!

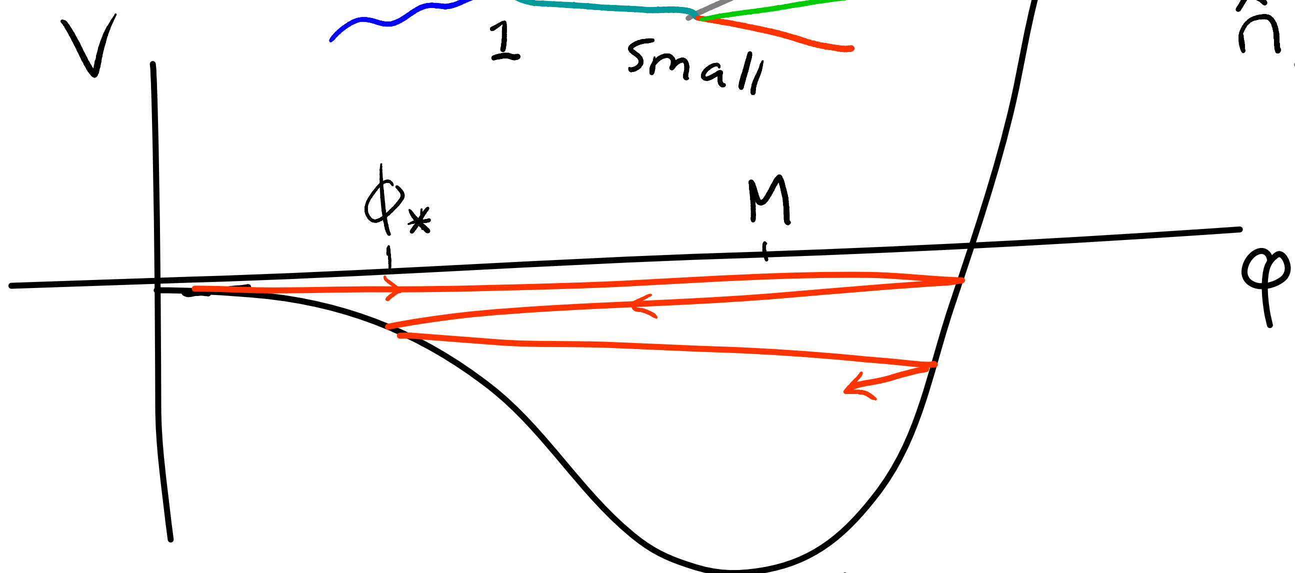
BUT NO "BARYONS"...

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

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 @ $\phi \sim \mathcal{O}(M)$, each to $N \gg 1$ "γ"s

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

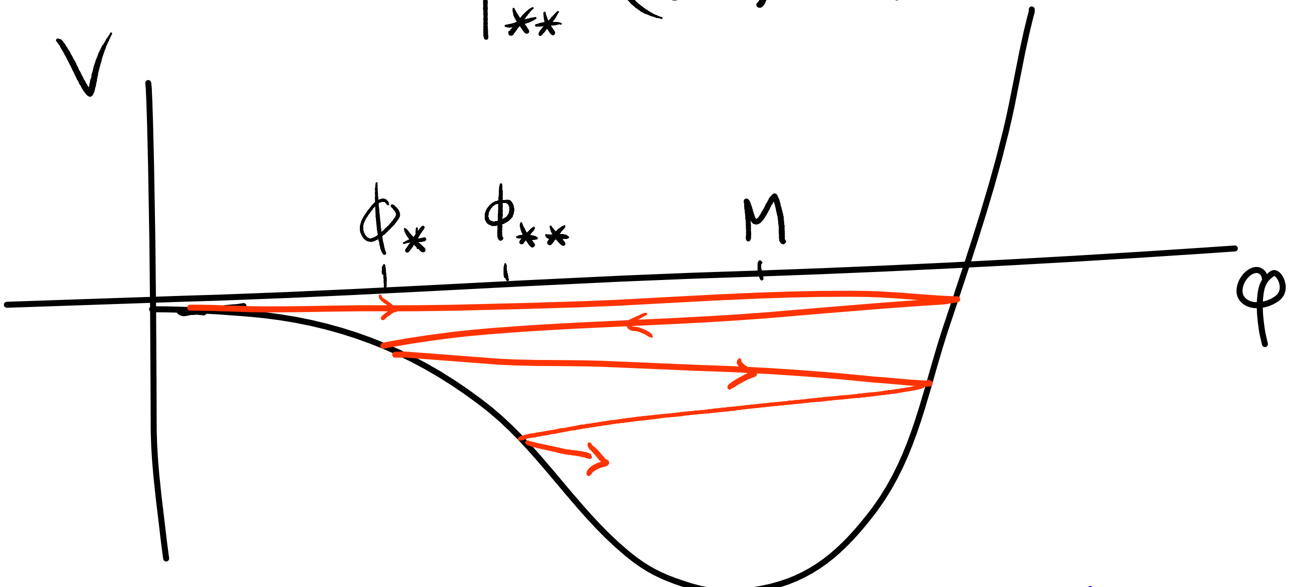
$$\Rightarrow \hat{n}_\gamma \sim N \hat{n}_\nu \sim N T_{rad}^3 \sim N M^3 (\gamma\lambda)^{3/2}, \quad E_\gamma \sim y_\nu M/N \sim (\gamma\lambda)^{1/4} M/N.$$

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

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

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

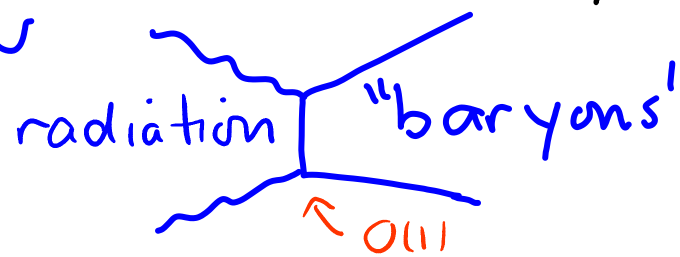
$$\varphi_{**} \sim (\gamma\lambda)^{3/16} M$$



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. $\sim \hat{n}_\gamma^2\, \sigma_{\gamma\gamma\to baryons}$

$\sim \frac{1}{m^2_{baryon}}$

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

$\sim \frac{1}{m^2_{baryon}}$

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

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

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

$\sim N^3 (\gamma\lambda)^{21/16}$ up to max. of $\rho_{rad}/\varphi_{**}^4 \sim \cancel{\gamma}\lambda$

$$\frac{\rho_{\text{baryon}}}{\varphi_{**}^4} \sim \gamma\lambda \quad \text{for} \quad N \sim \frac{1}{(\gamma\lambda)^{5/48}}$$

$$\equiv \frac{m_{\text{baryon}}}{\varphi_{**}} \sim \frac{(\gamma\lambda)^{1/16}}{N} \sim (\gamma\lambda)^{1/6}$$

$m_{\text{baryon}} \sim 10\,\text{MeV}$

w - LAST

Generally, $\rho_{vac} \propto a^{-3(1+w_{\text{eq. of state}})} \propto \varphi^{-3(1+w)}$

$$\underset{w \approx -1}{\propto} 1 - 3(1+w)\ln \varphi/\varphi_*$$

We have $\rho_{vac} \propto \gamma\lambda \ln \varphi/M \underset{\varphi \sim \varphi_{**}}{\propto} \ln \varphi/\varphi_{**} + \ln \frac{\varphi_{**}}{M}$

$$w = -1 + \frac{1}{\ln \varphi_{**}/M} \sim O(1\%)$$