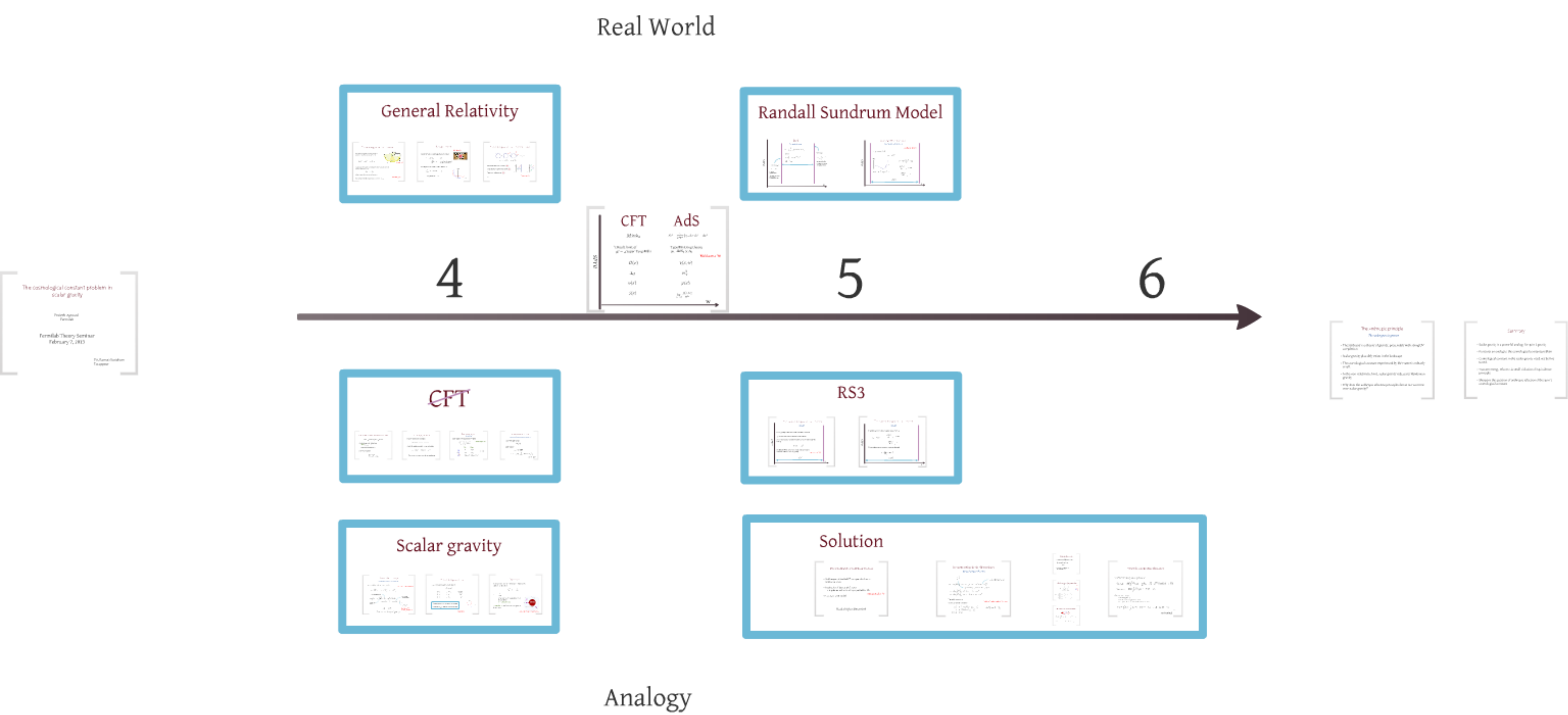


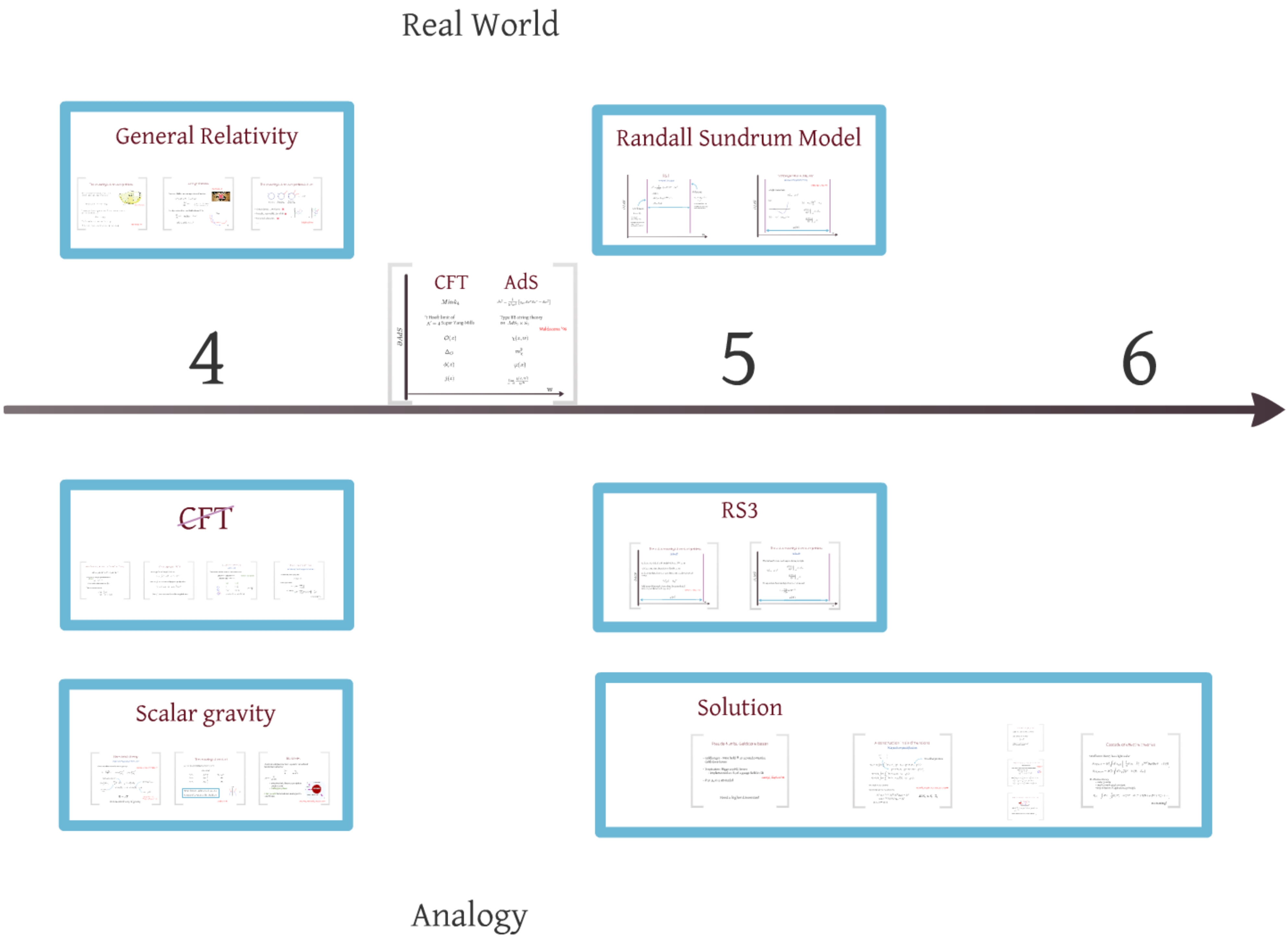
The cosmological constant problem in scalar gravity
Fermilab Theory Seminar
February 7, 2013
Real World
General Relativity
Randall Sundrum Model
CFT
AdS
4
5
6
CFT
RS3
Scalar gravity
Solution
Analogy

The cosmological constant problem in scalar gravity

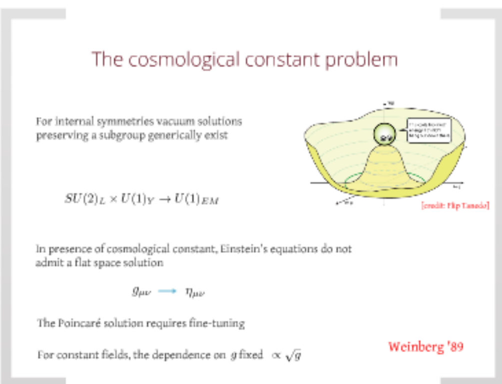
Prateek Agrawal
Fermilab

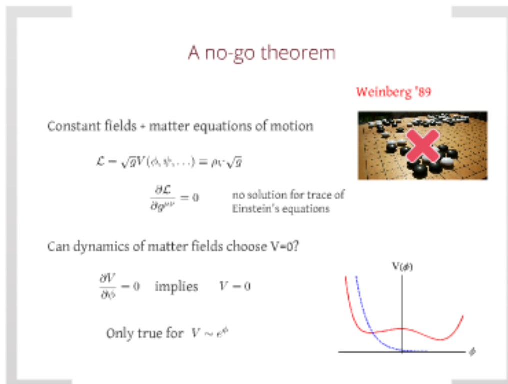
Fermilab Theory Seminar
February 7, 2013

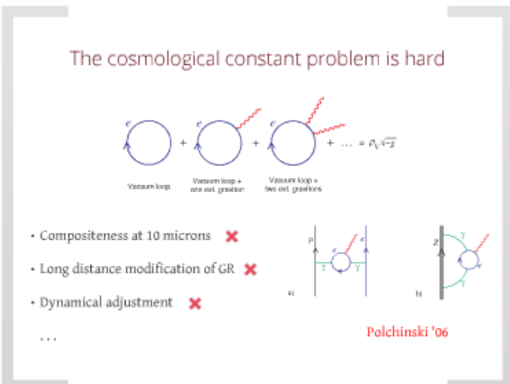
PA, Raman Sundrum
To appear


Real World
General Relativity
Randall Sundrum Model
CFT
AdS
4
5
6
CFT
RS3
Scalar gravity
Solution
Analogy

General Relativity

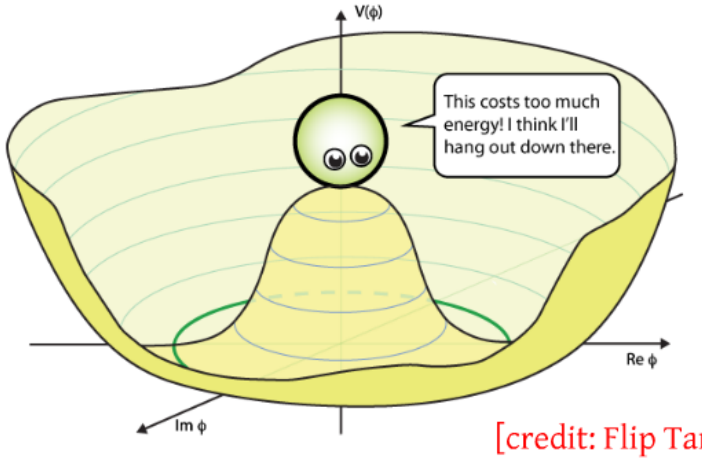






The cosmological constant problem

For internal symmetries vacuum solutions preserving a subgroup generically exist



[credit: Flip Tanedo]

$$SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

In presence of cosmological constant, Einstein's equations do not admit a flat space solution

$$g_{\mu\nu} \longrightarrow \eta_{\mu\nu}$$

The Poincaré solution requires fine-tuning

For constant fields, the dependence on g fixed $\propto \sqrt{g}$

Weinberg '89

A no-go theorem

Weinberg '89

Constant fields + matter equations of motion

$$\mathcal{L} = \sqrt{g} V(\phi, \psi, \ldots) \equiv \rho_V \sqrt{g}$$

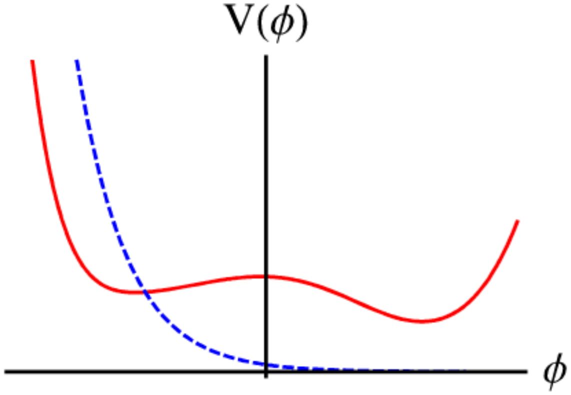
$$\frac{\partial \mathcal{L}}{\partial g^{\mu\nu}} = 0$$

no solution for trace of Einstein's equations

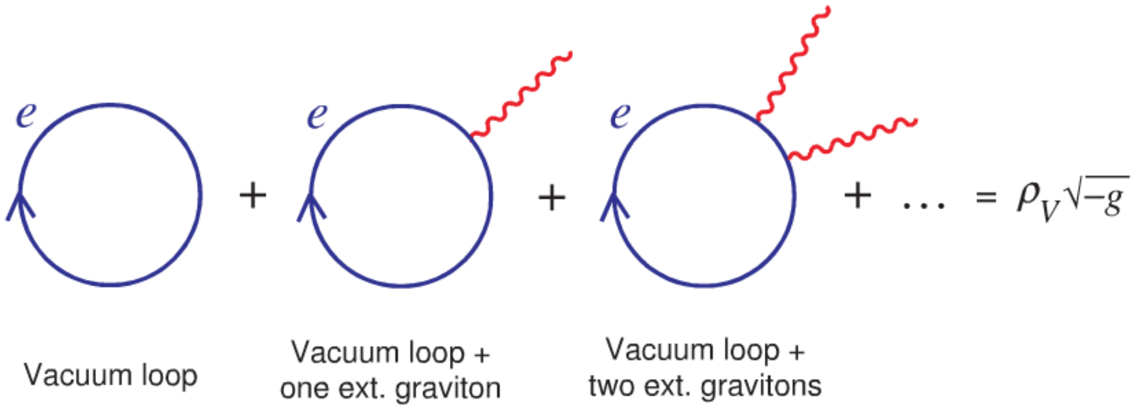
Can dynamics of matter fields choose V=0?

$$\frac{\partial V}{\partial \phi} = 0 \quad \text{implies} \quad V = 0$$

Only true for $V \sim e^{\phi}$

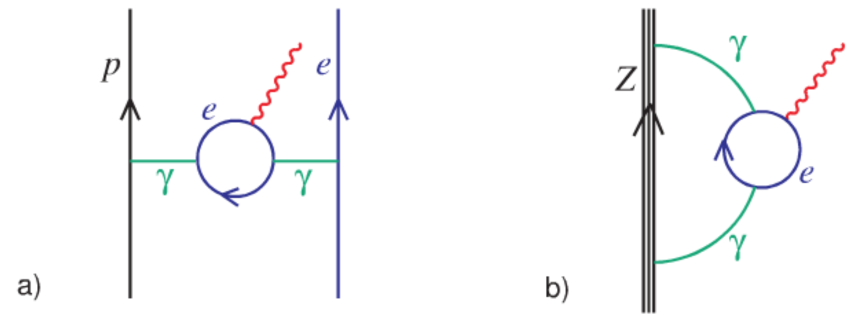


The cosmological constant problem is hard



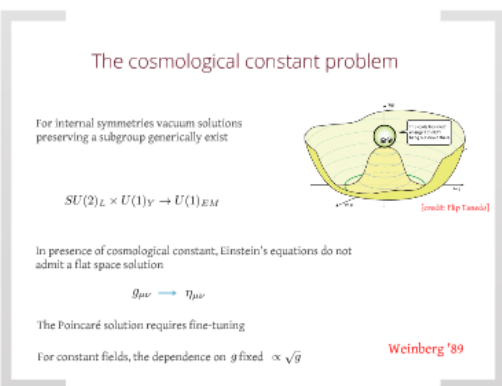
- Compositeness at 10 microns ✖
- Long distance modification of GR ✖
- Dynamical adjustment ✖

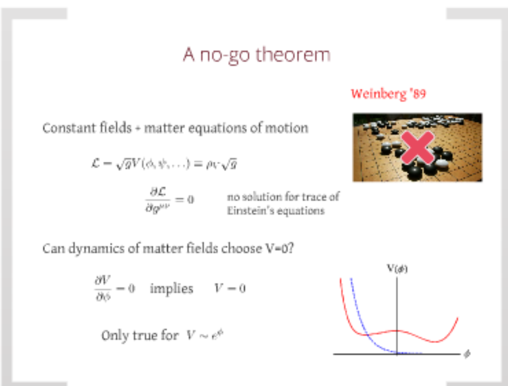
…

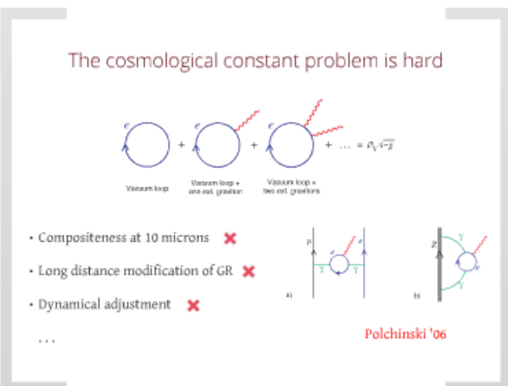


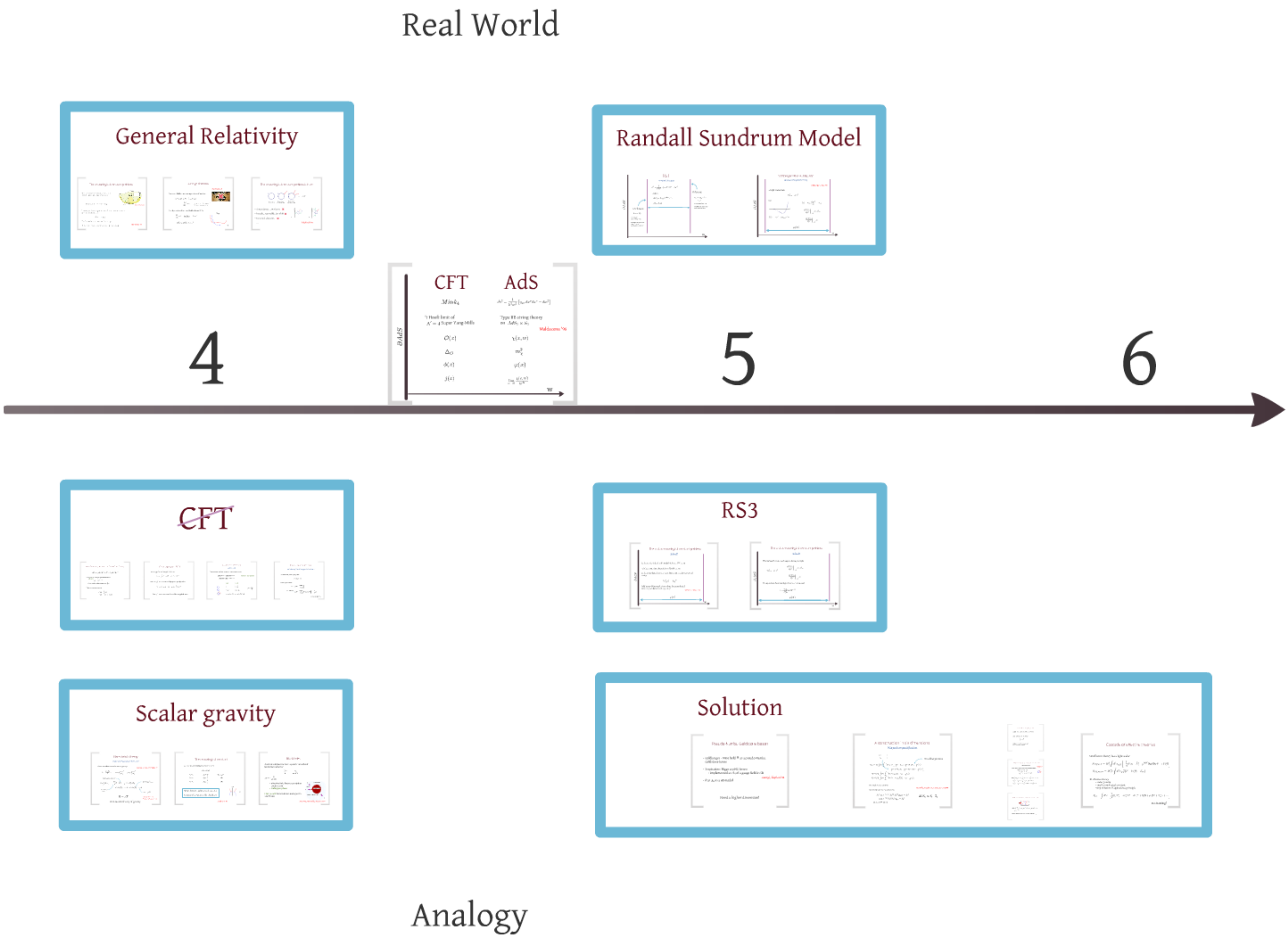
Polchinski '06

General Relativity



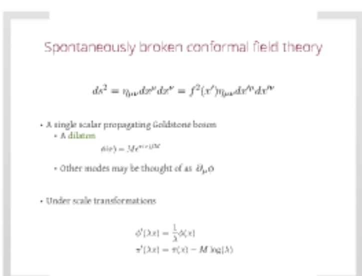


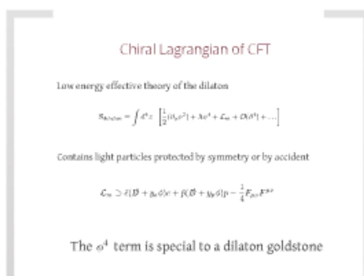


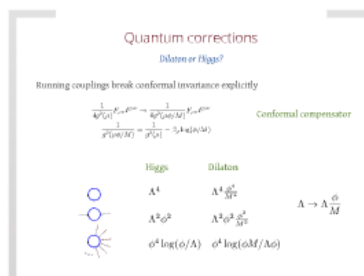


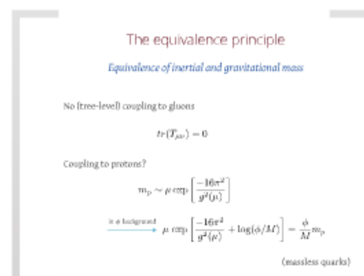
Real World
General Relativity
Randall Sundrum Model
CFT
AdS
4
5
6
CFT
RS3
Scalar gravity
Solution
Analogy

~~CFT~~


Spontaneously broken conformal field theory
A single scalar propagating Goldstone boson
A dilaton
Other modes may be thought of as
Under scale transformations


Chiral Lagrangian of CFT
Low energy effective theory of the dilaton
Contains light particles protected by symmetry or by accident
The ϕ^4 term is special to a dilaton goldstone


Quantum corrections
Dilaton or Higgs?
Running couplings break conformal invariance explicitly
Conformal compensator
Higgs
Dilaton
Λ^4
$\Lambda^2\phi^2$
$\phi^4 \log(\phi/\Lambda)$
$\Lambda \to \Lambda \frac{\phi}{M}$


The equivalence principle
Equivalence of inertial and gravitational mass
No (tree-level) coupling to gluons
$tr(T_{\mu\nu}) = 0$
Coupling to protons?
$m_p \sim \mu \exp\left[\frac{-16\pi^2}{g^2(\mu)}\right]$
(massless quarks)

Spontaneously broken conformal field theory

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu = f^2(x') \eta_{\mu\nu} dx'^\mu dx'^\nu$$

- A single scalar propagating Goldstone boson
    - A dilaton

$$\phi(x) = M e^{\pi(x)/M}$$

    - Other modes may be thought of as $\partial_\mu \phi$

- Under scale transformations

$$\phi'(\lambda x) = \frac{1}{\lambda} \phi(x)$$
$$\pi'(\lambda x) = \pi(x) - M \log(\lambda)$$

Chiral Lagrangian of CFT

Low energy effective theory of the dilaton

$$S_{dilaton} = \int d^4x \ \left[\frac{1}{2}(\partial_\mu\phi^2) + \Lambda\phi^4 + \mathcal{L}_m + \mathcal{O}(\partial^4) + \ldots\right]$$

Contains light particles protected by symmetry or by accident

$$\mathcal{L}_m \supset \bar{e}(\not{D} + y_e\phi)e + \bar{p}(\not{D} + y_p\phi)p - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

The ϕ^4 term is special to a dilaton goldstone

Quantum corrections

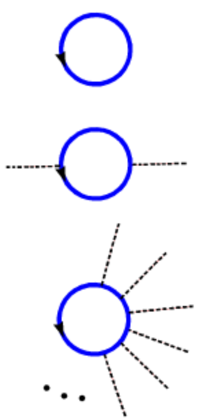
Dilaton or Higgs?

Running couplings break conformal invariance explicitly

$$\frac{1}{4g^2(\mu)} F_{\mu\nu}F^{\mu\nu} \to \frac{1}{4g^2(\mu\phi/M)} F_{\mu\nu}F^{\mu\nu}$$

$$\frac{1}{g^2(\mu\phi/M)} = \frac{1}{g^2(\mu)} - \beta_g \log(\phi/M)$$

Conformal compensator



Higgs	Dilaton
Λ^4	$\Lambda^4 \frac{\phi^4}{M^4}$
$\Lambda^2\phi^2$	$\Lambda^2\phi^2 \frac{\phi^2}{M^2}$
$\phi^4 \log(\phi/\Lambda)$	$\phi^4 \log(\phi M/\Lambda\phi)$

$$\Lambda \to \Lambda \frac{\phi}{M}$$

The equivalence principle

Equivalence of inertial and gravitational mass

No (tree-level) coupling to gluons

$$tr(T_{\mu\nu}) = 0$$

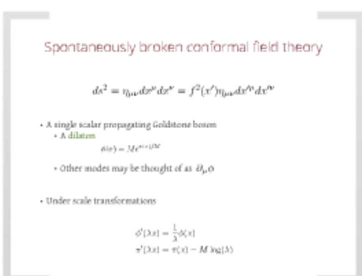
Coupling to protons?

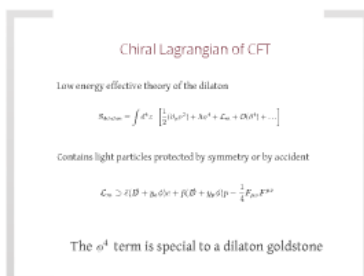
$$m_p \sim \mu \exp\left[\frac{-16\pi^2}{g^2(\mu)}\right]$$

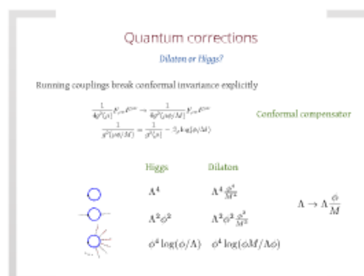
$$\xrightarrow{\text{in } \phi \text{ background}} \mu \exp\left[\frac{-16\pi^2}{g^2(\mu)} + \log(\phi/M)\right] = \frac{\phi}{M} m_p$$

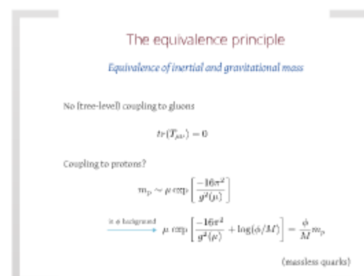
(massless quarks)

CFT


Spontaneously broken conformal field theory
$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu = f^2(x') \eta_{\mu\nu} dx'^\mu dx'^\nu$
• A single scalar propagating Goldstone boson
• A dilaton
• Other modes may be thought of as $\partial_\mu \phi$
• Under scale transformations
$\phi'(\lambda x) = \frac{1}{\lambda}\phi(x)$
$\pi'(\lambda x) = \pi(x) - M \log(\lambda)$


Chiral Lagrangian of CFT
Low energy effective theory of the dilaton
Contains light particles protected by symmetry or by accident
The ϕ^4 term is special to a dilaton goldstone


Quantum corrections
Dilaton or Higgs?
Running couplings break conformal invariance explicitly
Conformal compensator
Higgs
Dilaton
Λ^4
$\Lambda^2\phi^2$
$\phi^4 \log(\phi/\Lambda)$
$\phi^4 \log(\phi M/\Lambda\phi)$
$\Lambda \to \Lambda \frac{\phi}{M}$


The equivalence principle
Equivalence of inertial and gravitational mass
No (tree-level) coupling to gluons
$tr(T_{\mu\nu}) = 0$
Coupling to protons?
$m_p \sim \mu \exp\left[\frac{-16\pi^2}{g^2(\mu)}\right]$
$\mu \exp\left[\frac{-16\pi^2}{g^2(\mu)} + \log(\phi/M)\right] = \frac{\phi}{M} m_p$
(massless quarks)

Scalar gravity

Nordström's theory

Understand the gravity of the situation

Covariant description for scalar gravity

Isham, Salam, Strathdee '71

$$g_{\mu\nu} = \frac{\phi^2(x)}{M^2}\eta_{\mu\nu} \qquad e \to e\left(\frac{\phi}{M}\right)^{\frac{3}{2}} \qquad p \to p\left(\frac{\phi}{M}\right)^{\frac{3}{2}}$$

Cosmological constant

$$S = \int d^4x\,\sqrt{-g}\left[-\frac{M^2}{12}R + \Lambda M^4 - \frac{1}{4}g^{\mu\nu}g^{\alpha\beta}F_{\mu\alpha}F_{\nu\beta} + \bar{e}(i\gamma^a e^\mu_a D_\mu - m_e)e + \bar{p}(i\gamma^a e^\mu_a D_\mu - m_p)p\right]$$

Gauge + gravity covariant derivative

Opposite sign from GR

$m_\psi = y_\psi M$

$$R = \kappa T$$

Nordström '13
Einstein, Fokker '14

First metric theory of gravity

The cosmological constant

$\Lambda\phi^4$ is the cosmological constant term

$$\partial^2\phi = 4\Lambda\phi^3$$

$\Lambda = 0$	$\langle\phi\rangle = M$	Poincaré
$\Lambda > 0$	$\langle\phi\rangle \propto \frac{1}{z}$	AdS_4
$\Lambda < 0$	$\langle\phi\rangle \propto \frac{1}{t}$	dS_4

No-go theorem applies to scalar gravity

Presence of ϕ^4 potential for the dilaton

Sundrum '03

Black holes

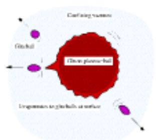
Classical solutions far from a point mass exhibit Newtonian behavior

$$\frac{\phi(r)}{M} = 1 - \frac{m}{4\pi M^2 r}$$

At $r \sim \frac{m}{4\pi M^2}$

- effective field theory description breaks down
- Unhiggsed phase

Plasma-balls have features analogous to black holes



Aharony, Minwalla, Wiseman '07

Nordström's theory

Understand the gravity of the situation

Covariant description for scalar gravity

Isham, Salam, Strathdee '71

$$g_{\mu\nu} = \frac{\phi^2(x)}{M^2}\eta_{\mu\nu} \qquad e \to e\left(\frac{\phi}{M}\right)^{\frac{3}{2}} \qquad p \to p\left(\frac{\phi}{M}\right)^{\frac{3}{2}}$$

Cosmological constant

Gauge + gravity covariant derivative

$$S = \int d^4x\,\sqrt{-g}\left[-\frac{M^2}{12}R + \Lambda M^4 - \frac{1}{4}g^{\mu\nu}g^{\alpha\beta}F_{\mu\alpha}F_{\nu\beta} + \bar{e}(i\gamma^a e_a^\mu D_\mu - m_e)e + \bar{p}(i\gamma^a e_a^\mu D_\mu - m_p)p\right]$$

Opposite sign from GR

$$m_\psi = y_\psi M$$

$$R = \kappa T$$

Nordström '13
Einstein, Fokker '14

First metric theory of gravity

The cosmological constant

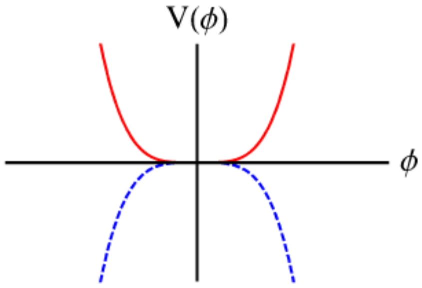
$\Lambda\phi^4$ is the cosmological constant term

$$\partial^2\phi = 4\Lambda\phi^3$$

$\Lambda = 0$	$\langle\phi\rangle = M$	Poincaré
$\Lambda > 0$	$\langle\phi\rangle \propto \frac{1}{z}$	AdS_4
$\Lambda < 0$	$\langle\phi\rangle \propto \frac{1}{t}$	dS_4

No-go theorem applies to scalar gravity

Presence of ϕ^4 potential for the dilaton



Sundrum '03

Black holes

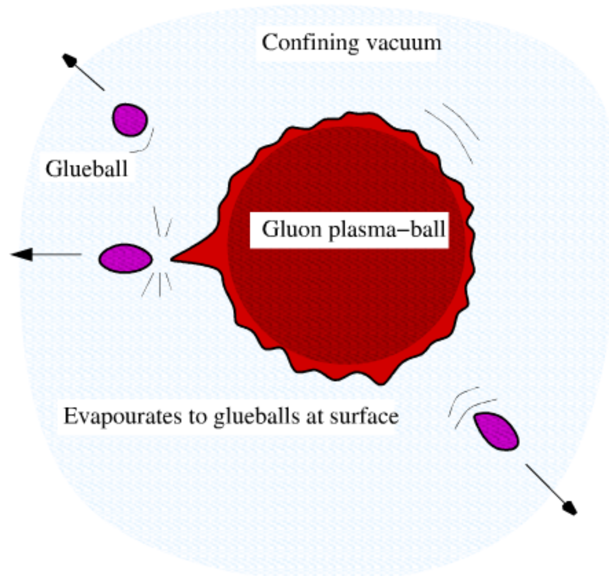
Classical solutions far from a point mass exhibit Newtonian behavior

$$\frac{\phi(r)}{M} = 1 - \frac{m}{4\pi M^2 r}$$

At $r \sim \dfrac{m}{4\pi M^2}$

- effective field theory description breaks down
- Unhiggsed phase

Plasma-balls have features analogous to black holes



Aharony, Minwalla, Wiseman '07

Scalar gravity

Nordström's theory

Understand the gravity of the situation

Covariant description for scalar gravity

Isham, Salam, Strathdee '71

$$g_{\mu\nu} = \frac{\phi^2(x)}{M^2}\eta_{\mu\nu} \qquad e \to e\left(\frac{\phi}{M}\right)^{\frac{3}{2}} \qquad p \to p\left(\frac{\phi}{M}\right)^{\frac{3}{2}}$$

Cosmological constant

Gauge + gravity covariant derivative

$$S = \int d^4x\sqrt{-g}\left[-\frac{M^2}{12}R + \Lambda M^4 - \frac{1}{4}g^{\mu\nu}g^{\alpha\beta}F_{\mu\alpha}F_{\nu\beta} + \bar{e}(i\gamma^a e^\mu_a D_\mu - m_e)e + \bar{p}(i\gamma^a e^\mu_a D_\mu - m_p)p\right]$$

Opposite sign from GR

$m_\phi = y_\phi M$

$$R = \kappa T$$

Nordström '13
Einstein, Fokker '14

First metric theory of gravity

The cosmological constant

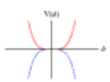
$\Lambda\phi^4$ is the cosmological constant term

$$\partial^2\phi = 4\Lambda\phi^3$$

$\Lambda = 0$	$\langle\phi\rangle = M$	Poincaré
$\Lambda > 0$	$\langle\phi\rangle \propto \frac{1}{z}$	AdS_4
$\Lambda < 0$	$\langle\phi\rangle \propto \frac{1}{t}$	dS_4

No-go theorem applies to scalar gravity

Presence of ϕ^4 potential for the dilaton



Sundrum '03

Black holes

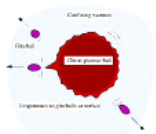
Classical solutions far from a point mass exhibit Newtonian behavior

$$\frac{\phi(r)}{M} = 1 - \frac{m}{4\pi M^2 r}$$

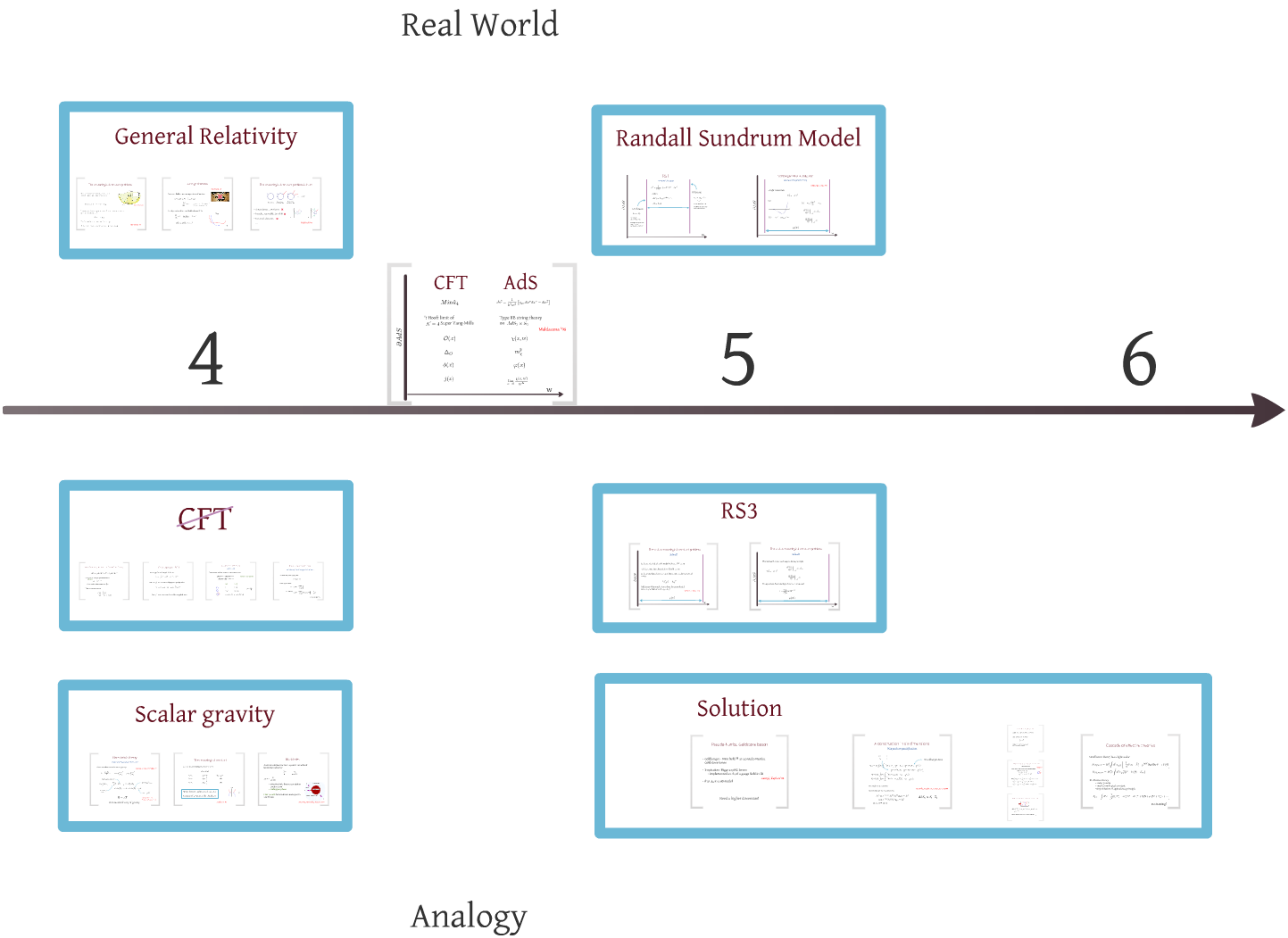
At $r \sim \frac{m}{4\pi M^2}$

- effective field theory description breaks down
- Unhiggsed phase

Plasma-balls have features analogous to black holes



Aharony, Minwalla, Wiseman '07

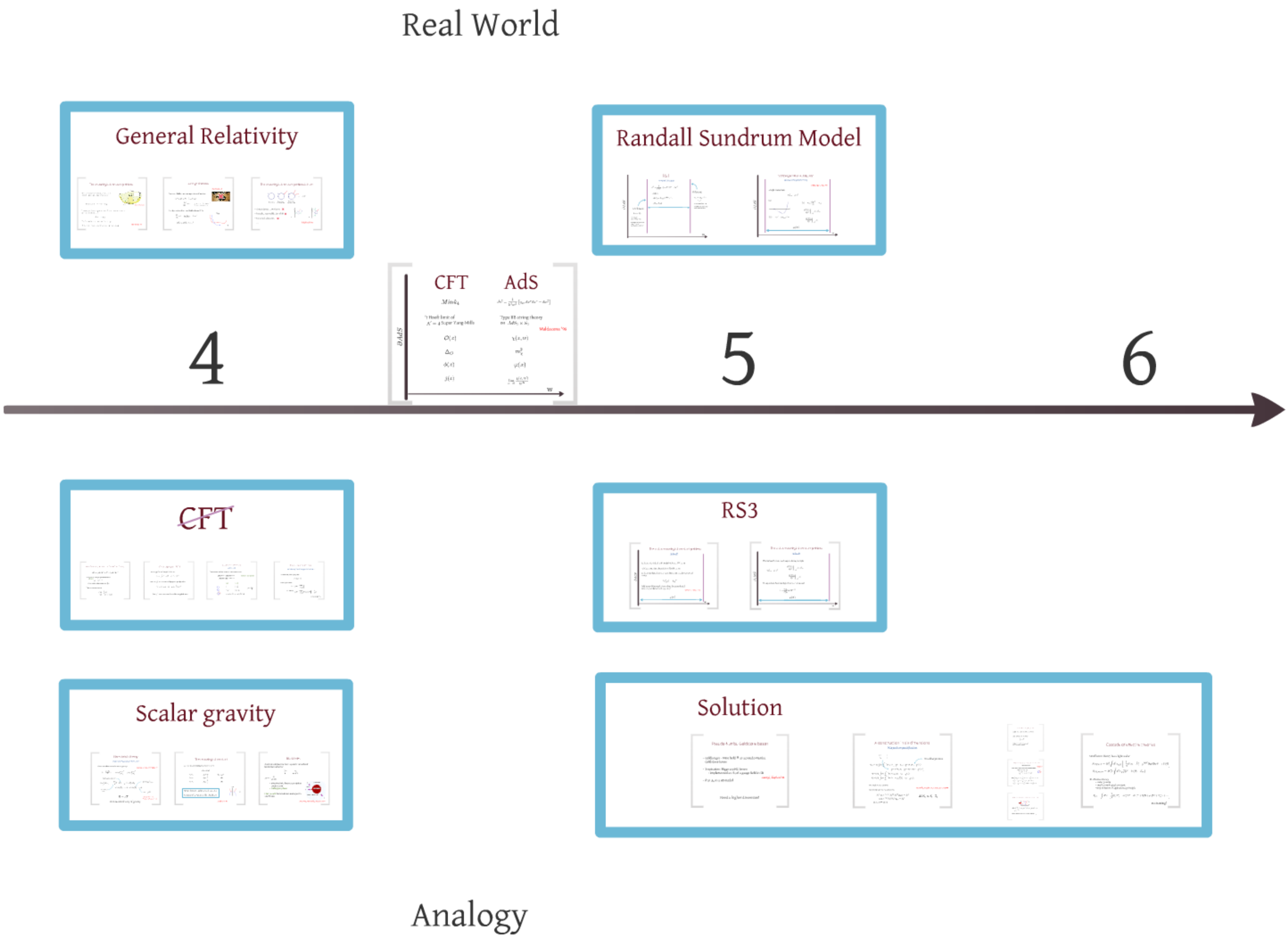


Real World
General Relativity
Randall Sundrum Model
CFT
AdS
4
5
6
CFT
RS3
Scalar gravity
Solution
Analogy

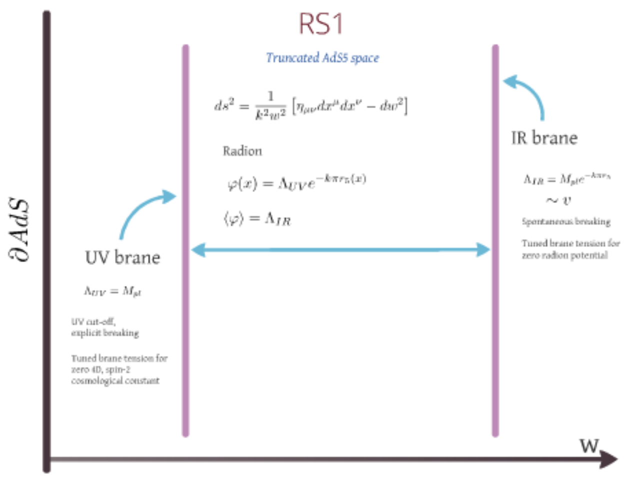
∂AdS

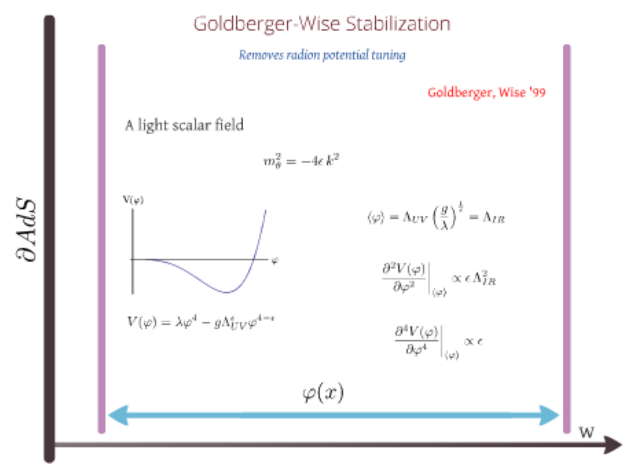
CFT	AdS
$Mink_4$	$ds^2 = \frac{1}{k^2 w^2}\left[\eta_{\mu\nu} dx^\mu dx^\nu - dw^2\right]$
't Hooft limit of $\mathcal{N} = 4$ Super Yang-Mills	Type IIB string theory on $AdS_5 \times S_5$
	Maldacena '98
$\mathcal{O}(x)$	$\chi(x, w)$
$\Delta_{\mathcal{O}}$	m_χ^2
$\phi(x)$	$\varphi(x)$
$j(x)$	$\lim_{w \to 0} \frac{\chi(x, w)}{w^\Delta}$

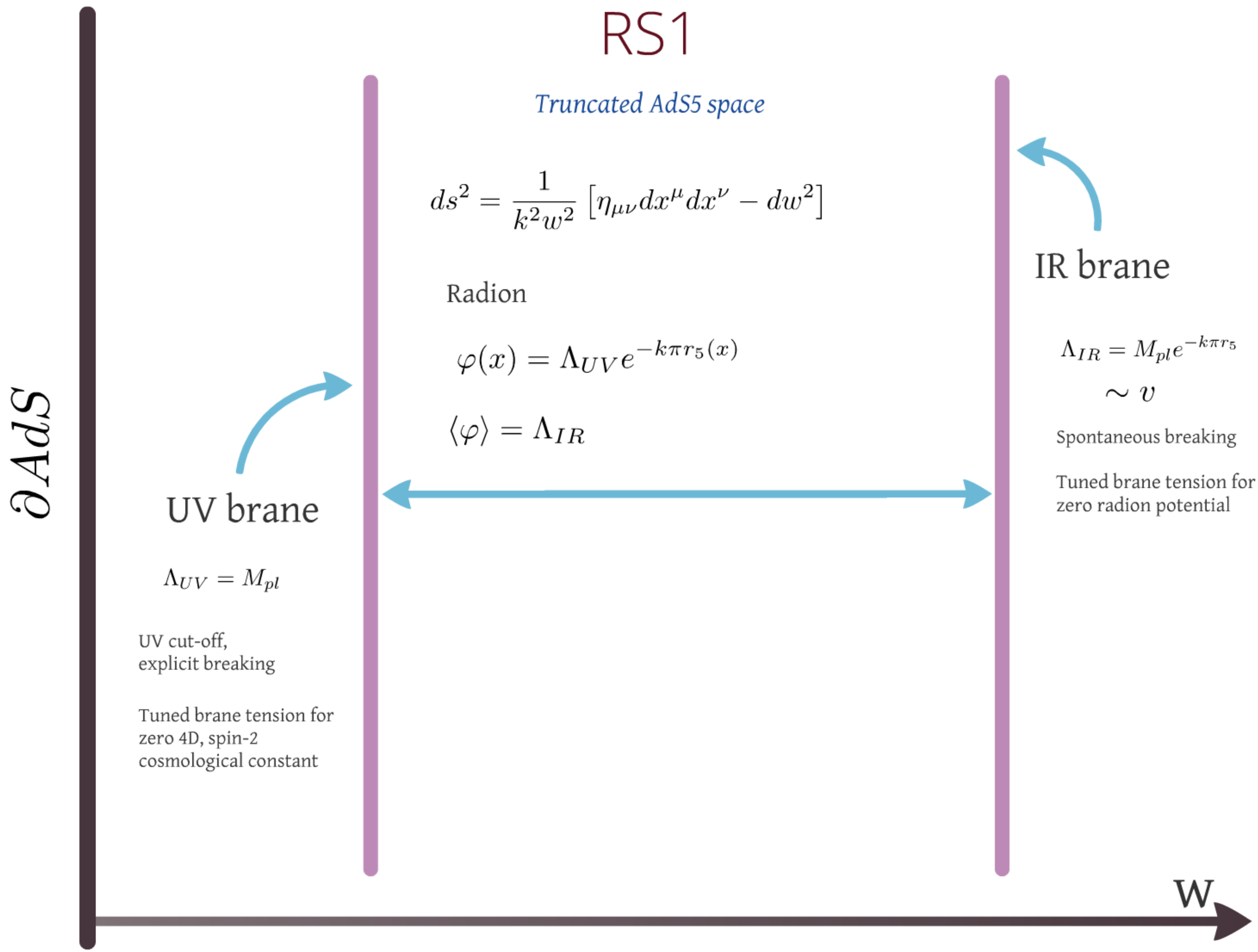
w


Real World
General Relativity
Randall Sundrum Model
CFT
AdS
4
5
6
CFT
RS3
Scalar gravity
Solution
Analogy

Randall Sundrum Model





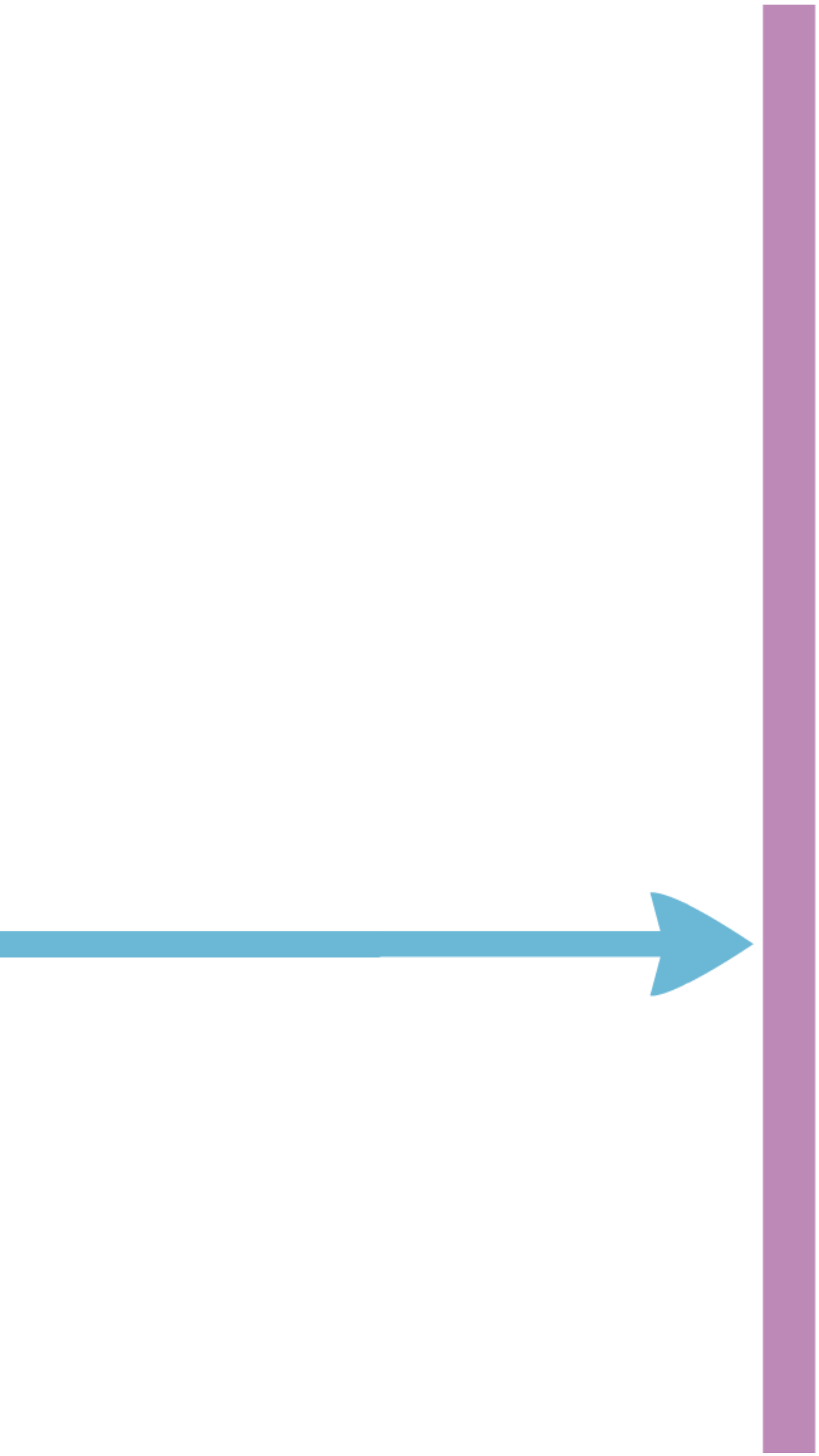

RS1
Truncated AdS5 space
$ds^2 = \frac{1}{k^2 w^2}\left[\eta_{\mu\nu} dx^\mu dx^\nu - dw^2\right]$
Radion
$\varphi(x) = \Lambda_{UV} e^{-k\pi r_5(x)}$
$\langle \varphi \rangle = \Lambda_{IR}$
IR brane
$\Lambda_{IR} = M_{pl} e^{-k\pi r_5}$
$\sim v$
Spontaneous breaking
Tuned brane tension for
zero radion potential
∂AdS
UV brane
$\Lambda_{UV} = M_{pl}$
UV cut-off,
explicit breaking
Tuned brane tension for
zero 4D, spin-2
cosmological constant
W

UV brane

$$\Lambda_{UV} = M_{pl}$$

UV cut-off,
explicit breaking

Tuned brane tension for
zero 4D, spin-2
cosmological constant



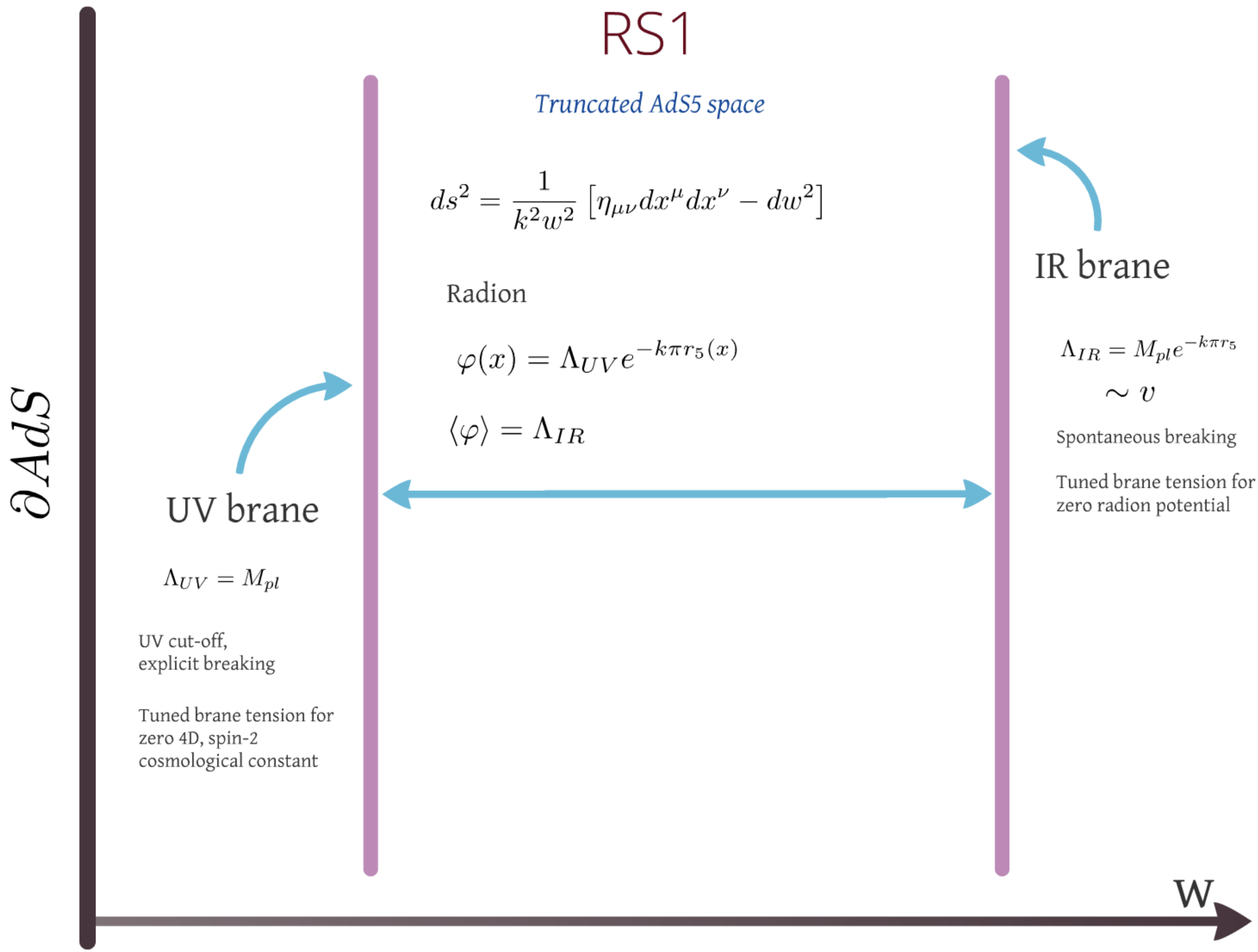
IR brane

$$\Lambda_{IR} = M_{pl} e^{-k\pi r_5}$$

$$\sim v$$

Spontaneous breaking

Tuned brane tension for zero radion potential



RS1
Truncated AdS5 space
$ds^2 = \frac{1}{k^2 w^2}\left[\eta_{\mu\nu}dx^\mu dx^\nu - dw^2\right]$
Radion
$\varphi(x) = \Lambda_{UV} e^{-k\pi r_5(x)}$
$\langle\varphi\rangle = \Lambda_{IR}$
IR brane
$\Lambda_{IR} = M_{pl} e^{-k\pi r_5}$
$\sim v$
Spontaneous breaking
Tuned brane tension for zero radion potential
∂AdS
UV brane
$\Lambda_{UV} = M_{pl}$
UV cut-off, explicit breaking
Tuned brane tension for zero 4D, spin-2 cosmological constant
W

Goldberger-Wise Stabilization

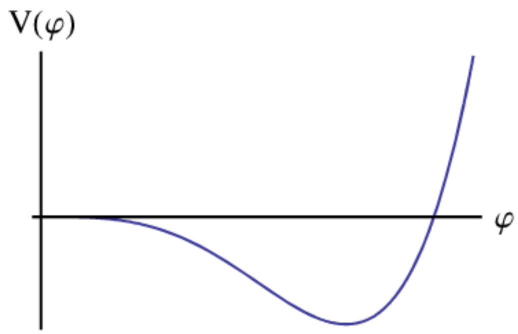
Removes radion potential tuning

Goldberger, Wise '99

∂AdS

A light scalar field

$$m_\theta^2 = -4\epsilon\, k^2$$



$$V(\varphi) = \lambda\varphi^4 - g\Lambda_{UV}^{\epsilon}\varphi^{4-\epsilon}$$

$$\langle\varphi\rangle = \Lambda_{UV}\left(\frac{g}{\lambda}\right)^{\frac{1}{\epsilon}} = \Lambda_{IR}$$

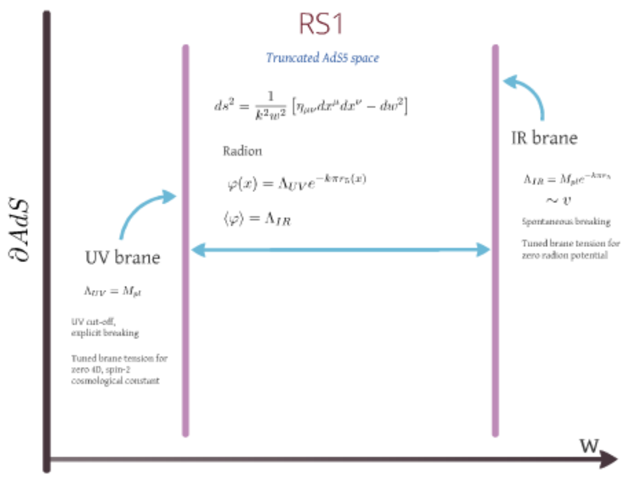
$$\left.\frac{\partial^2 V(\varphi)}{\partial\varphi^2}\right|_{\langle\varphi\rangle} \propto \epsilon\,\Lambda_{IR}^2$$

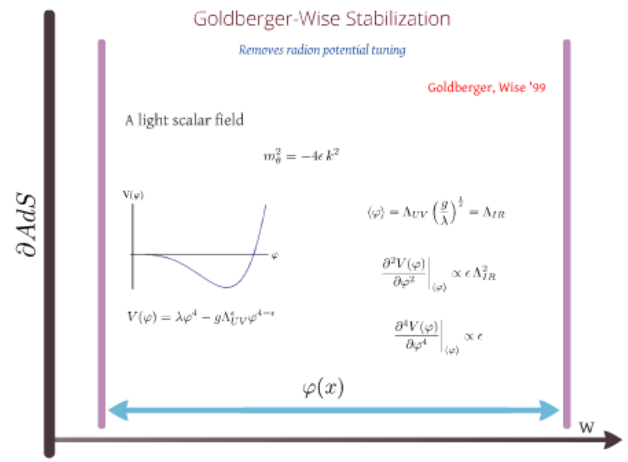
$$\left.\frac{\partial^4 V(\varphi)}{\partial\varphi^4}\right|_{\langle\varphi\rangle} \propto \epsilon$$

$$\varphi(x)$$

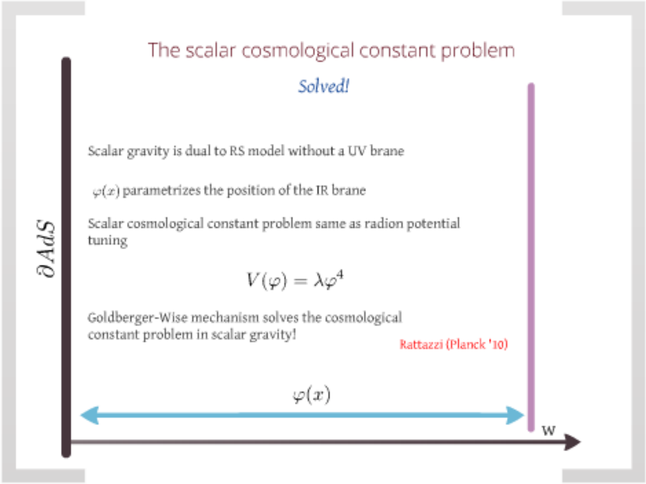
w

Randall Sundrum Model

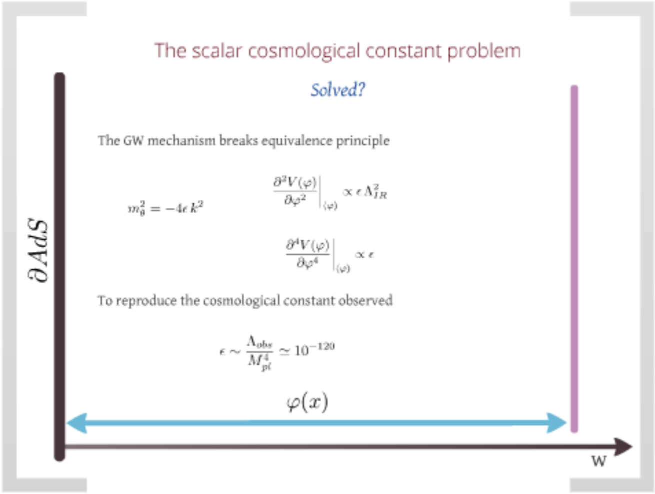




RS3



The scalar cosmological constant problem
Solved!
Scalar gravity is dual to RS model without a UV brane
$\varphi(x)$ parametrizes the position of the IR brane
Scalar cosmological constant problem same as radion potential tuning
$V(\varphi) = \lambda \varphi^4$
Goldberger-Wise mechanism solves the cosmological constant problem in scalar gravity!
Rattazzi (Planck '10)
∂AdS
$\varphi(x)$
w



The scalar cosmological constant problem
Solved?
The GW mechanism breaks equivalence principle
$m_\theta^2 = -4\epsilon\, k^2$
$\left.\frac{\partial^2 V(\varphi)}{\partial \varphi^2}\right|_{\langle\varphi\rangle} \propto \epsilon\, \Lambda_{IR}^2$
$\left.\frac{\partial^4 V(\varphi)}{\partial \varphi^4}\right|_{\langle\varphi\rangle} \propto \epsilon$
To reproduce the cosmological constant observed
$\epsilon \sim \frac{\Lambda_{obs}}{M_{pl}^4} \simeq 10^{-120}$
∂AdS
$\varphi(x)$
w

The scalar cosmological constant problem

Solved!

Scalar gravity is dual to RS model without a UV brane

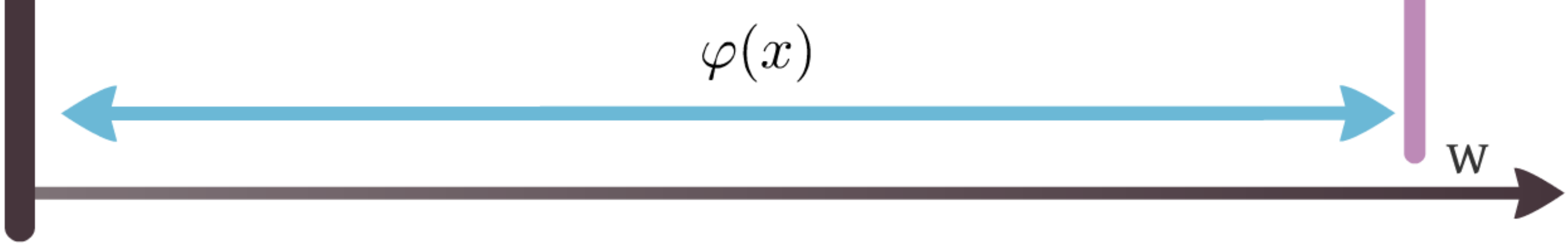
$\varphi(x)$ parametrizes the position of the IR brane

Scalar cosmological constant problem same as radion potential tuning

$$V(\varphi) = \lambda\varphi^4$$

Goldberger-Wise mechanism solves the cosmological constant problem in scalar gravity!

Rattazzi (Planck '10)



The scalar cosmological constant problem

Solved?

The GW mechanism breaks equivalence principle

$$m_\theta^2 = -4\epsilon\, k^2$$

$$\left.\frac{\partial^2 V(\varphi)}{\partial \varphi^2}\right|_{\langle\varphi\rangle} \propto \epsilon\, \Lambda_{IR}^2$$

$$\left.\frac{\partial^4 V(\varphi)}{\partial \varphi^4}\right|_{\langle\varphi\rangle} \propto \epsilon$$

To reproduce the cosmological constant observed

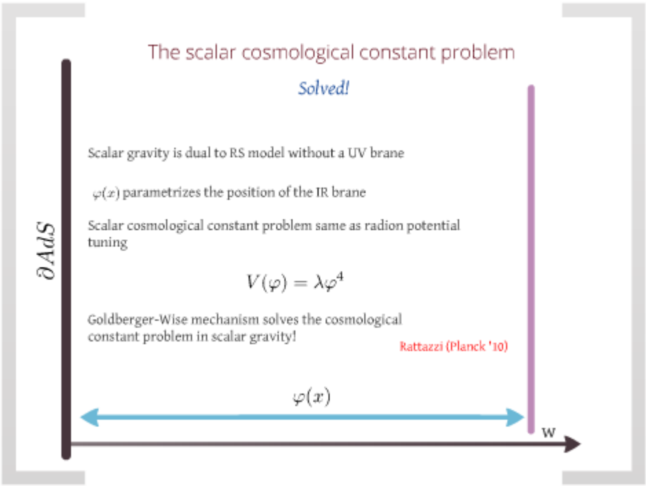
$$\epsilon \sim \frac{\Lambda_{obs}}{M_{pl}^4} \simeq 10^{-120}$$

∂AdS

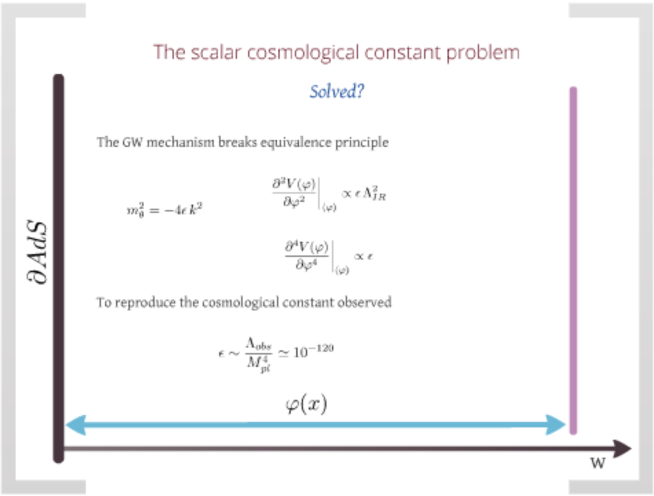
$\varphi(x)$

w

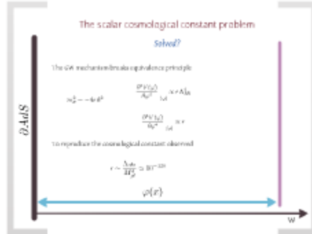
RS3



The scalar cosmological constant problem
Solved!
Scalar gravity is dual to RS model without a UV brane
$\varphi(x)$ parametrizes the position of the IR brane
Scalar cosmological constant problem same as radion potential tuning
$V(\varphi) = \lambda\varphi^4$
Goldberger-Wise mechanism solves the cosmological constant problem in scalar gravity!
Rattazzi (Planck '10)
∂AdS
$\varphi(x)$
w



The scalar cosmological constant problem
Solved?
The GW mechanism breaks equivalence principle
$m_\theta^2 = -4\epsilon\, k^2$
$\left.\frac{\partial^2 V(\varphi)}{\partial\varphi^2}\right|_{\langle\varphi\rangle} \propto \epsilon\, \Lambda_{IR}^2$
$\left.\frac{\partial^4 V(\varphi)}{\partial\varphi^4}\right|_{\langle\varphi\rangle} \propto \epsilon$
To reproduce the cosmological constant observed
$\epsilon \sim \frac{\Lambda_{obs}}{M_{pl}^4} \simeq 10^{-120}$
∂AdS
$\varphi(x)$
w



Solution

Pseudo-Nambu Goldstone boson

- Goldberger - Wise field θ as a pseudo-Nambu Goldstone boson
- Inspiration: Higgs as pNG boson
  - implemented as A_5 of a gauge field in 5D

Georgi, Kaplan '84

- θ as A_6 in a 6D model

Need a higher dimension!

A construction in six dimensions

Warped compactification

[illegible]

$AdS_5 \times S_1/Z_2$

Cascade of effective theories

5D effective theory has a light scalar

$$S_{5D,bulk} = M_5^3 \int d^5x \sqrt{g} \left[-\frac{1}{4} R_{5D} + k_5^2 + g^{MN} \partial_M \theta \partial_N \theta + \epsilon V(\theta) \right]$$

$$S_{5D,brane} = M_5^3 k \int d^4x \sqrt{g} \left[T + V(\theta) + \mathcal{L}_{SM} \right]$$

4D effective theory
- scalar gravity
- small cosmological constant
- tiny violation of equivalence principle

$$S_{4D} = \int d^4x \left[\frac{1}{2}(\partial_\mu \pi^2) - m_\pi^2 \pi^2 - \Lambda_{CC} \phi^4 + \bar{\psi}(i\partial\!\!\!/ + y_e(M + \pi))e + \ldots \right]$$

no tuning!

Pseudo-Nambu Goldstone boson

- Goldberger - Wise field θ as a pseudo-Nambu Goldstone boson
- Inspiration: Higgs as pNG boson
  - implemented as A_5 of a gauge field in 5D

Georgi, Kaplan '84

- θ as A_6 in a 6D model

Need a higher dimension!

A construction in six dimensions

Warped compactification

$$A_M : (-,-)$$
$$A_6 : (+,+)$$

6D Goldberger-Wise

$$S_{bulk} = M_6^4 \int d^5x \int_0^{\pi r_6} du \, \sqrt{-G}\left[-\frac{1}{4}R + \Lambda_{bulk} + \frac{1}{2}G^{ab}\partial_a\chi\partial_b\chi - \frac{1}{2}m_\chi^2\chi^2 \right.$$
$$\left. -\frac{1}{4}G^{ac}G^{bd}F_{ab}F_{cd} + \frac{1}{2}G^{ab}(D_a\psi)^\dagger D_b\psi - \frac{1}{2}m_\psi^2\psi^2\right]$$
$$S_1 = k_6 M_6^4 \int d^5x \int_0^{\pi r_6} du \, \delta(u)\sqrt{g_1}[T_1 + \lambda_1\chi + \frac{1}{2}\mu_2\chi^2]$$
$$S_2 = k_6 M_6^4 \int d^5x \int_0^{\pi r_6} du \, \delta(u-\pi r_6)\sqrt{g_2}[T_2 + \lambda_2\chi + \frac{1}{2}\mu_2\chi^2]$$

Untuned brane tensions

DeWolfe, Freedman, Gubser, Karch 2000

Maximally symmetric solutions

$$ds^2 = e^{-2\sigma(u)}dx^M dx^N \bar{g}_{MN} - du^2$$
$$\bar{g} = e^{-2ky}dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$
$$\chi(x,u) = \chi(u)$$

$$AdS_5 \times S_1/Z_2$$

Potential for 6D gauge field

- Gauge invariance prohibits 6D mass term

- Other potential terms absent

$$\int du\ \partial_u A^6$$

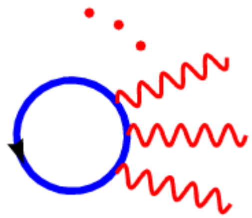
- Potential arises from non-local Aharanov-Bohm effect

Wilson loops using Schwinger proper time

(flat spacetime case)

Strassler '92

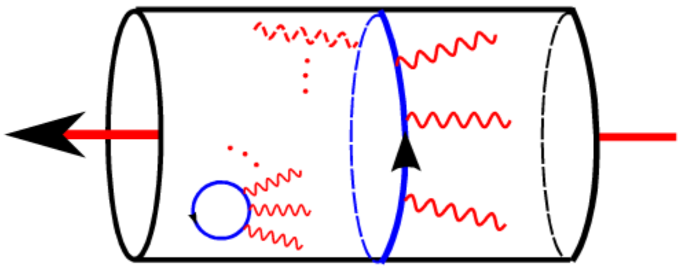
Effective action as a path integral over charged particle worldlines



$$\Gamma[A] = -\log\left(det(-D^2 - m_\psi^2)\right)$$
$$= -tr\ \log\left(-D^2 - m_\psi^2\right)$$
$$= \int_0^\infty \frac{dT}{T}\ tr\ \exp\left(\frac{1}{2}\mathcal{E}T(-D^2 - m_\psi^2)\right)$$

$$\Gamma[A] = \int_0^\infty \frac{dT}{T} \int \mathcal{D}x\,\mathcal{D}p\ \exp\left[\int_0^T d\tau\ ip\cdot\dot{x}\right] \exp\left[-\frac{1}{2}\mathcal{E}\int_0^T d\tau\,(p - eA)^2 + m_\psi^2\right]$$
$$= \int_0^\infty \frac{dT}{T}\,\mathcal{N}\int \mathcal{D}x\ \exp\left[-\int_0^T d\tau\ \frac{1}{2\mathcal{E}}\dot{x}^2 + \frac{\mathcal{E}}{2}m_\psi^2 + ieA(x)\cdot\dot{x}\right]$$
$$= \int_0^\infty \frac{dT}{T}\,\mathcal{N}\int \mathcal{D}x\ \exp\left[-m_\psi\int_0^T d\tau\sqrt{\eta_{\mu\nu}\dot{x}^\mu\dot{x}^\nu}\right] \exp\left[ig\oint dx\cdot A(x)\right]$$

Wilson loops using Schwinger proper time



$$V_{eff}[A] \propto \int_0^\infty \frac{dT}{T} \int \mathcal{D}x \ \exp\left[-m_\psi \int_0^T d\tau \sqrt{\eta_{\mu\nu}\dot{x}^\mu \dot{x}^\nu}\right] \exp\left[ig \oint dx \cdot A(x)\right]$$

$$\propto e^{i\theta} e^{-2\pi m_\psi r_6}$$

Charged matter needs to be only modestly heavier than $\frac{1}{r_6}$

Cascade of effective theories

5D effective theory has a light scalar

$$S_{5D,bulk} = M_5^3 \int d^5x\sqrt{g}\left[-\frac{1}{4}R_{5D} + \hat{k}_5^2 + g^{MN}\partial_M\theta\partial_N\theta + \epsilon V(\theta)\right]$$

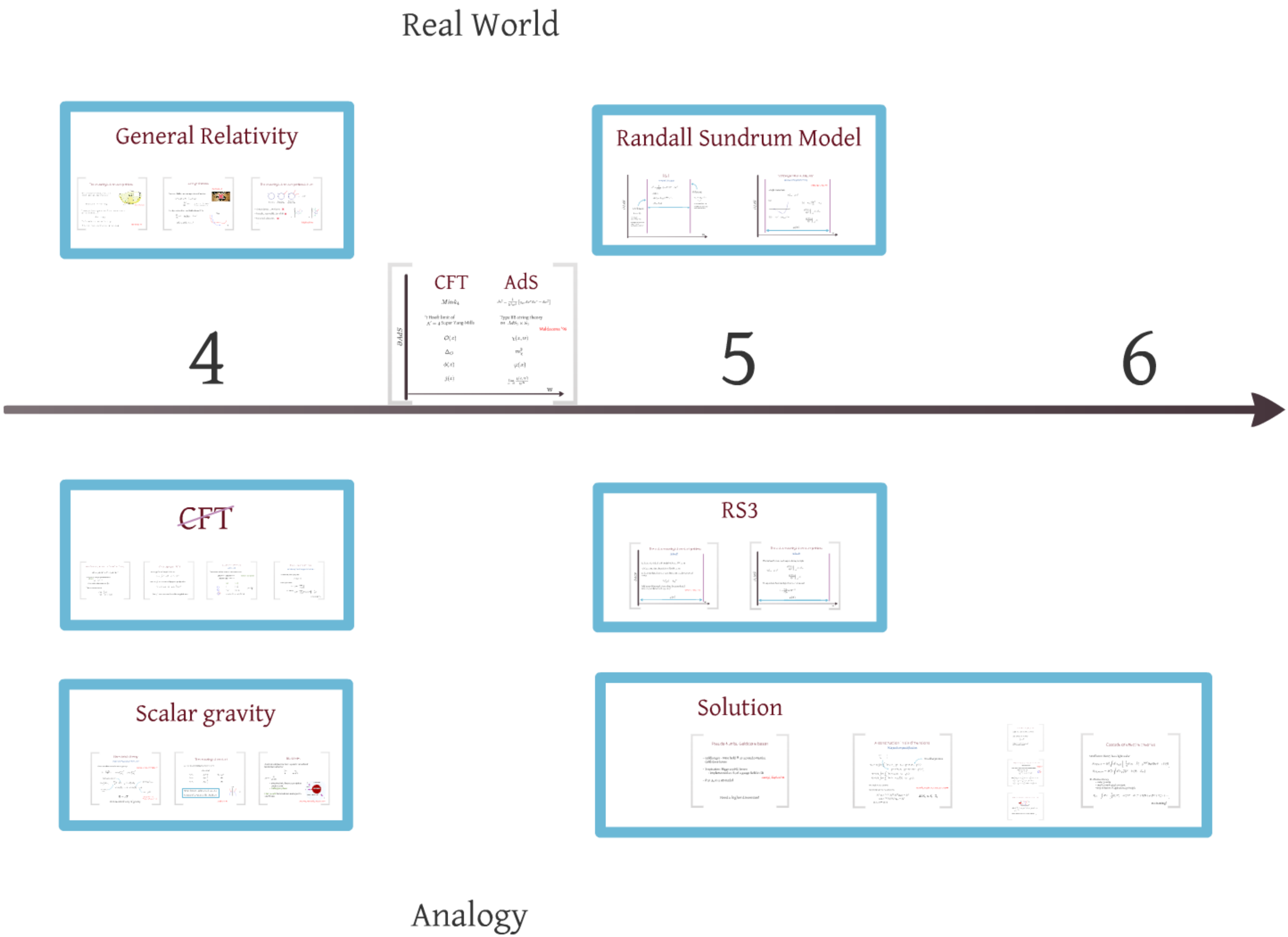
$$S_{5D,brane} = M_5^3 k \int d^5x\sqrt{g}\left[T + V(\theta) + \mathcal{L}_m\right]$$

4D effective theory

- scalar gravity
- small cosmological constant
- tiny violation of equivalence principle

$$S_{4D} = \int d^4x \ \left[\frac{1}{2}(\partial_\mu\pi^2) - m_\pi^2\epsilon\pi^2 - \Lambda\epsilon\phi^4 + \bar{e}(\not{D} + y_e(M+\pi))e + \ldots\right]$$

no tuning!


Real World
General Relativity
Randall Sundrum Model
CFT
AdS
4
5
6
CFT
RS3
Scalar gravity
Solution
Analogy

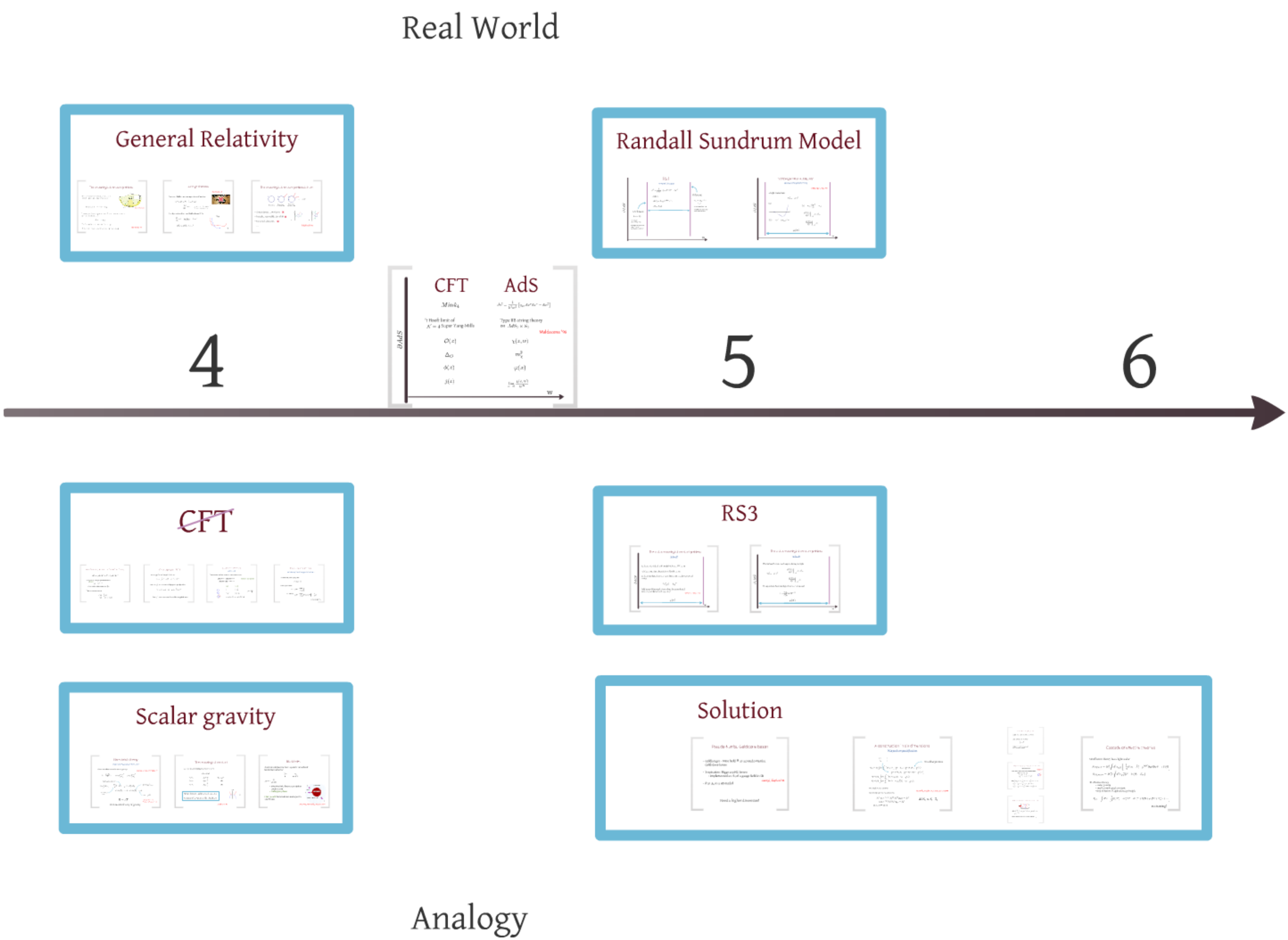
The Anthropic principle

The scalar grass is greener

- The 5D theory is a theory of gravity, presumably with string UV completion
- Scalar gravity plausibly exists in the landscape
- The cosmological constant experienced by SM matter is robustly small.
- In the non-relativistic limit, scalar gravity reduces to Newtonian gravity
- Why does the anthropic selection principle choose our universe over scalar gravity?

Summary

- Scalar gravity is a powerful analogy for spin-2 gravity
- Possesses an analog to the cosmological constant problem
- Cosmological constant in the scalar gravity need not be fine-tuned.
- Vacuum energy relaxes via small violation of equivalence principle
- Sharpens the question of anthropic selection of the spin-2 cosmological constant



Real World
General Relativity
Randall Sundrum Model
CFT
AdS
4
5
6
CFT
RS3
Scalar gravity
Solution
Analogy