LIFE ON THE EDGE:
observational signatures of braneworld models

Sanjeev S. Seahra

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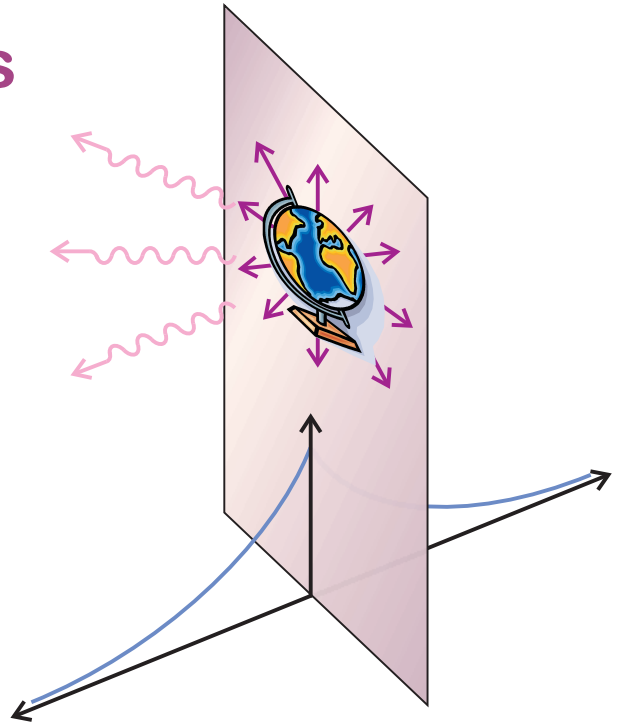

Current status of gravitational theory

Quick history of gravitation

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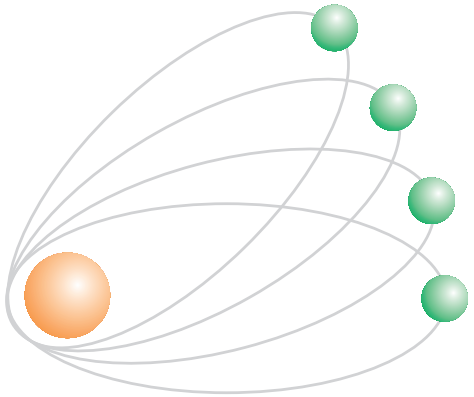

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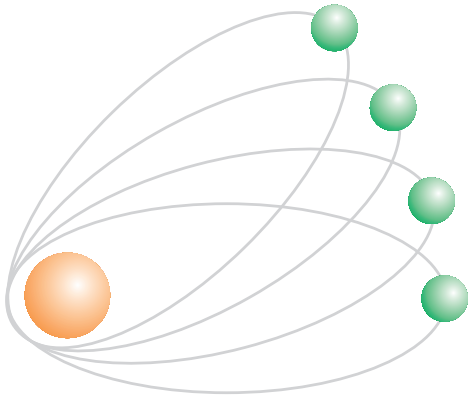

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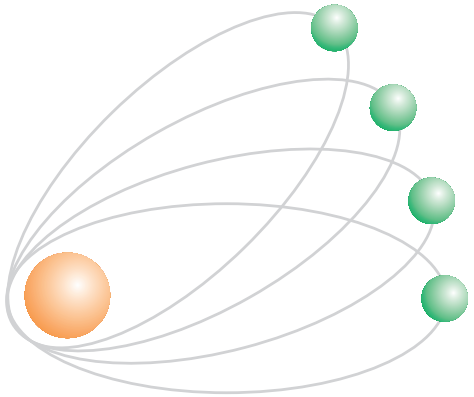

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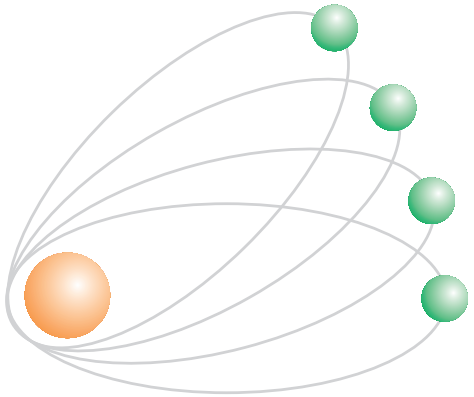

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  - explained Mercury's orbit without the "dark planet"

Testing general relativity

GR has many other testable predictions

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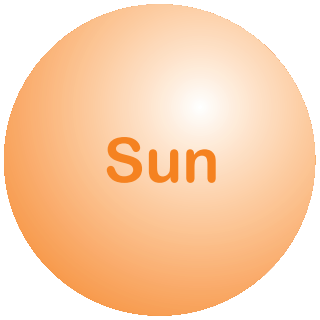

Earth

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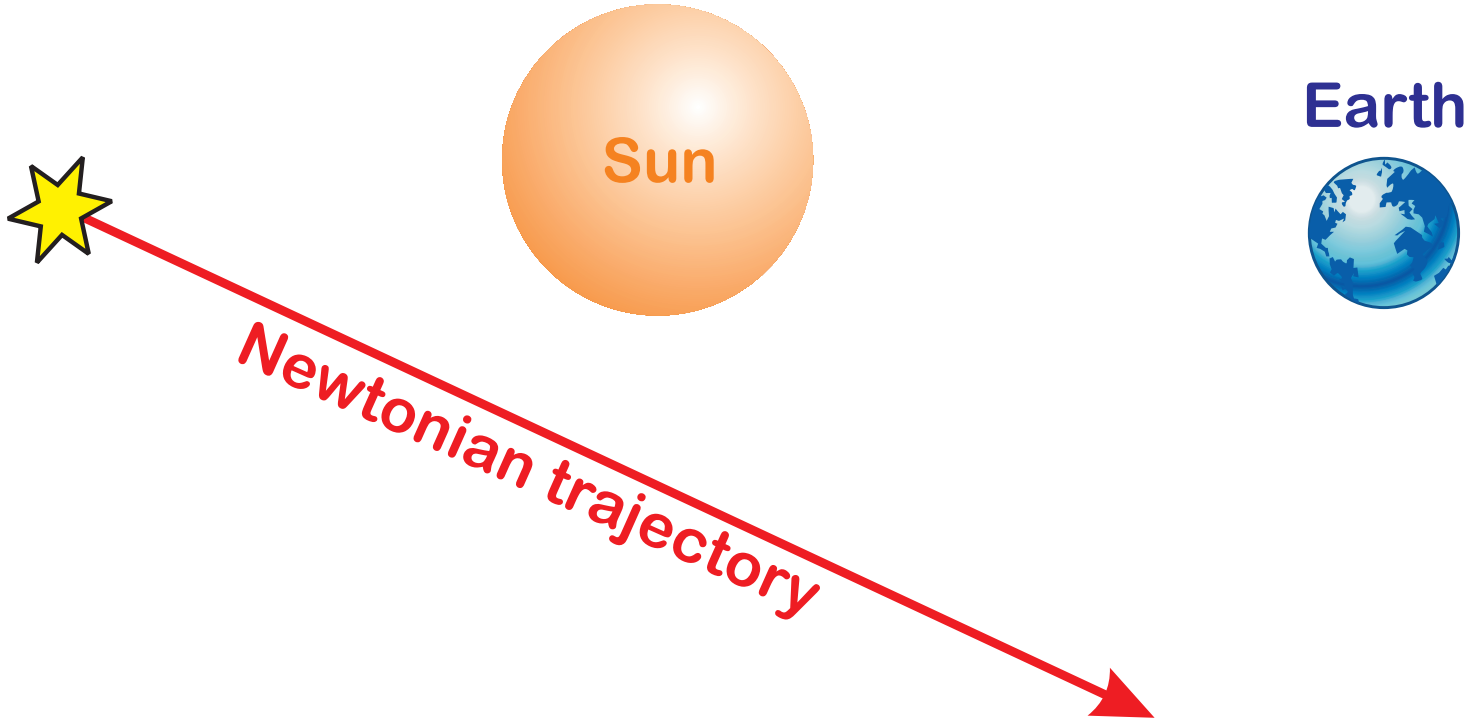

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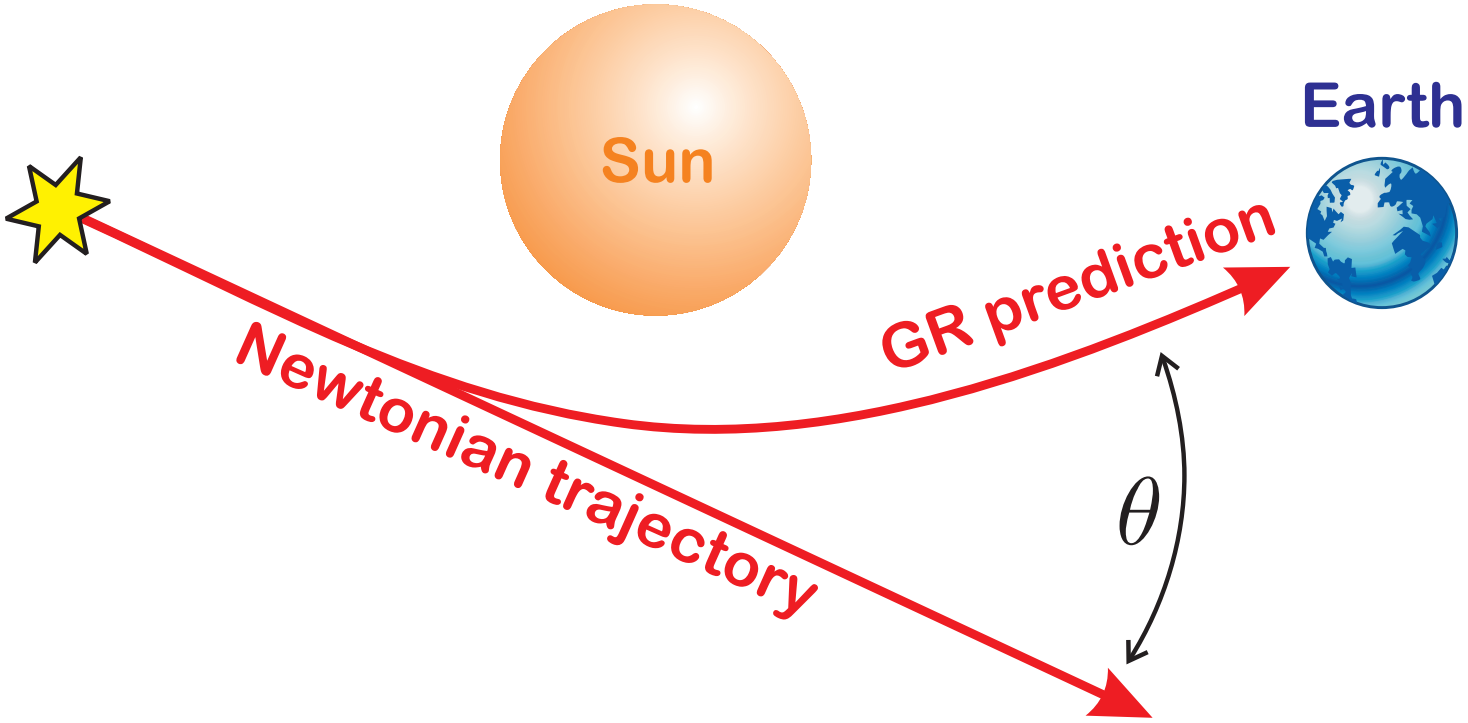

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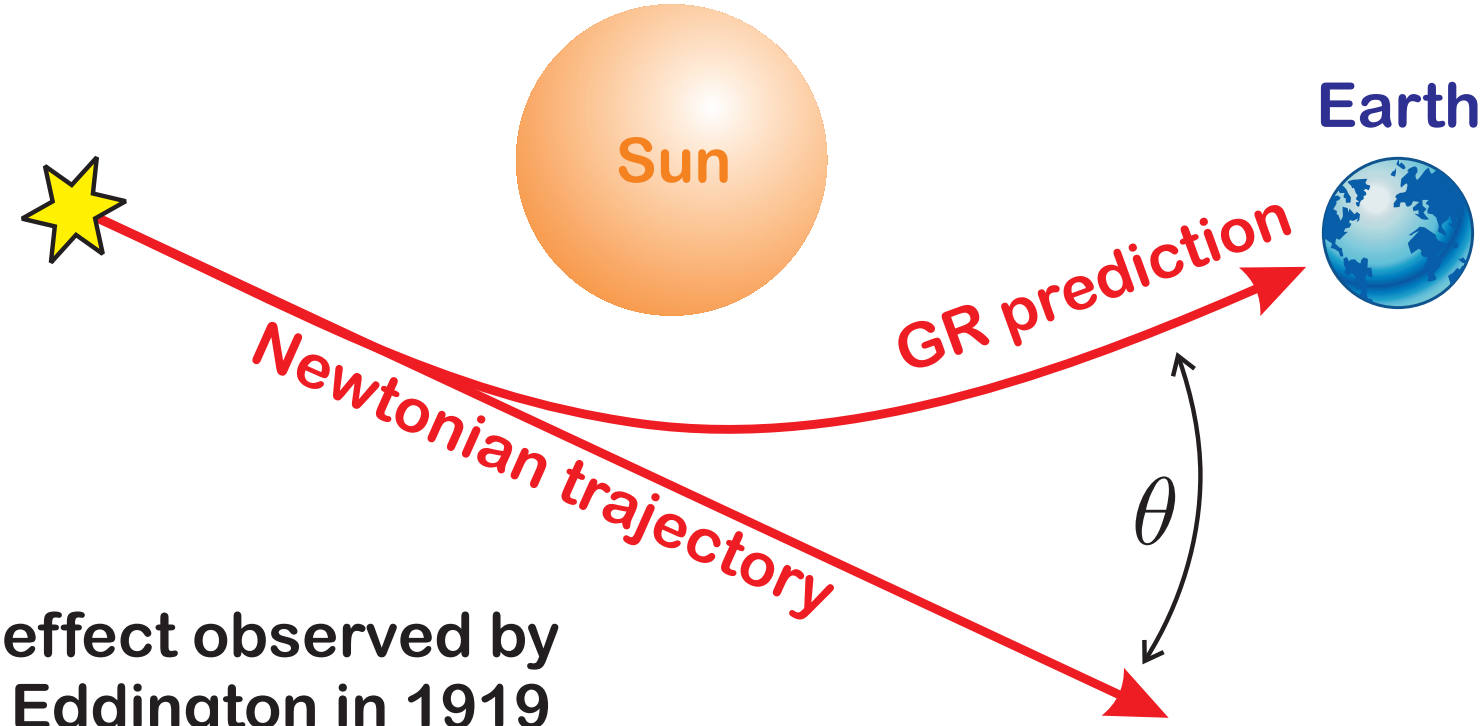

effect observed by Eddington in 1919

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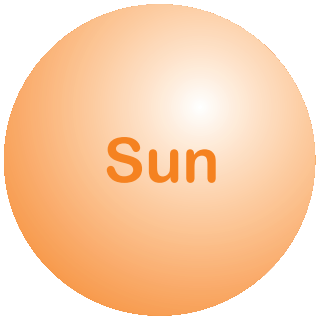

Cassini spacecraft

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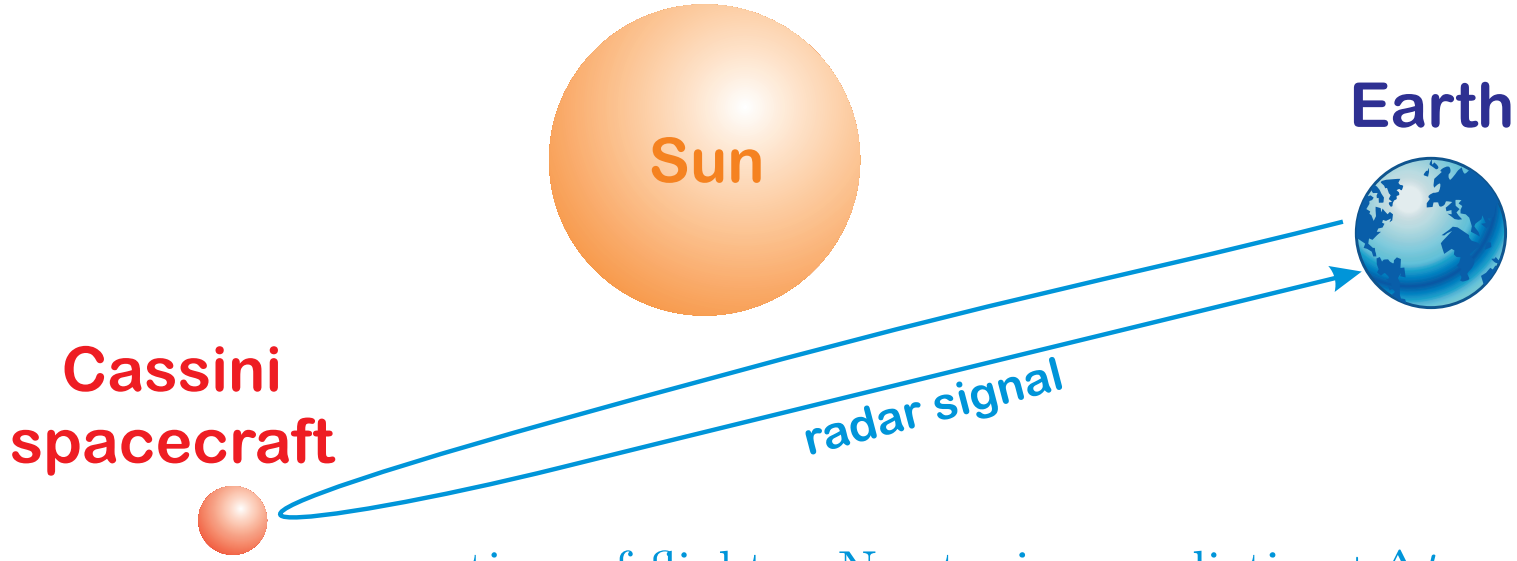

$$\text{time of flight} = \text{Newtonian prediction} + \Delta t_{\rm GR}$$

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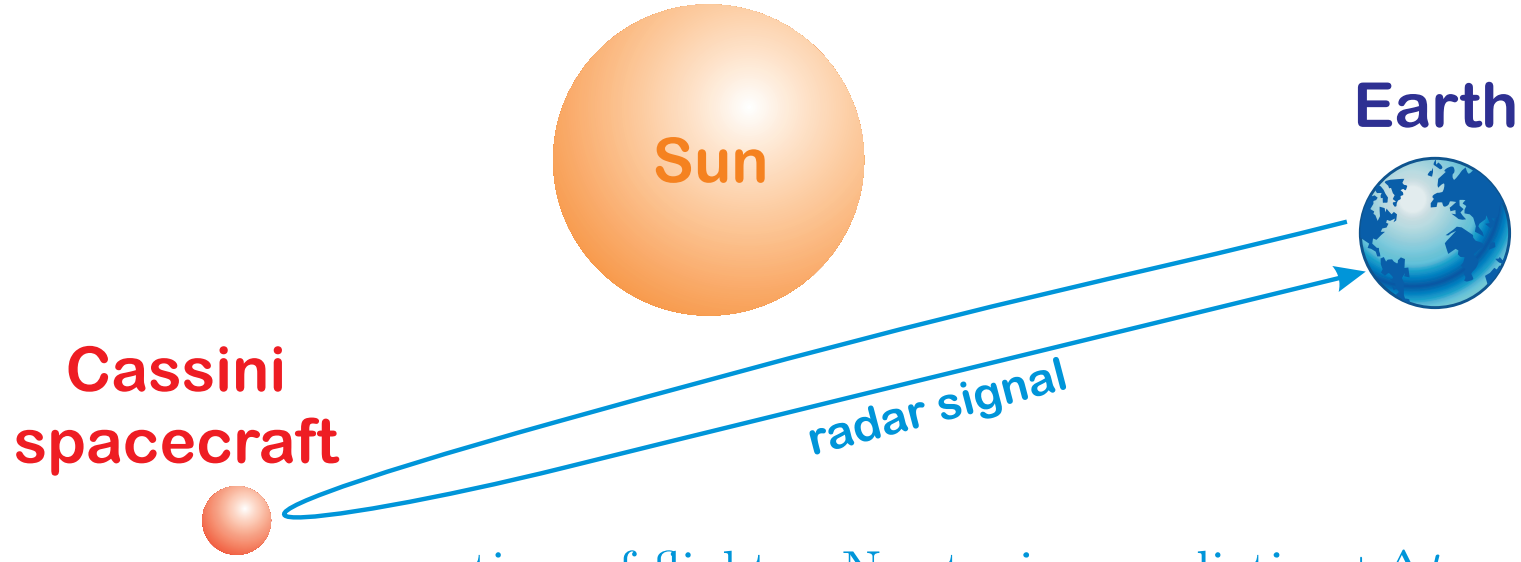

measured Δt matches GR prediction to accuracy 10^{-5}

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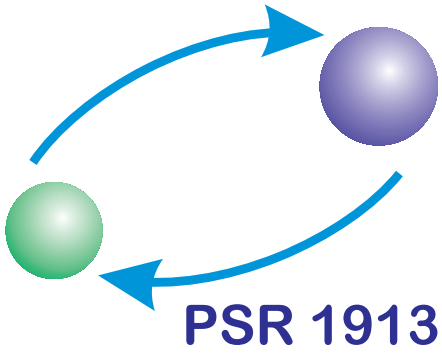

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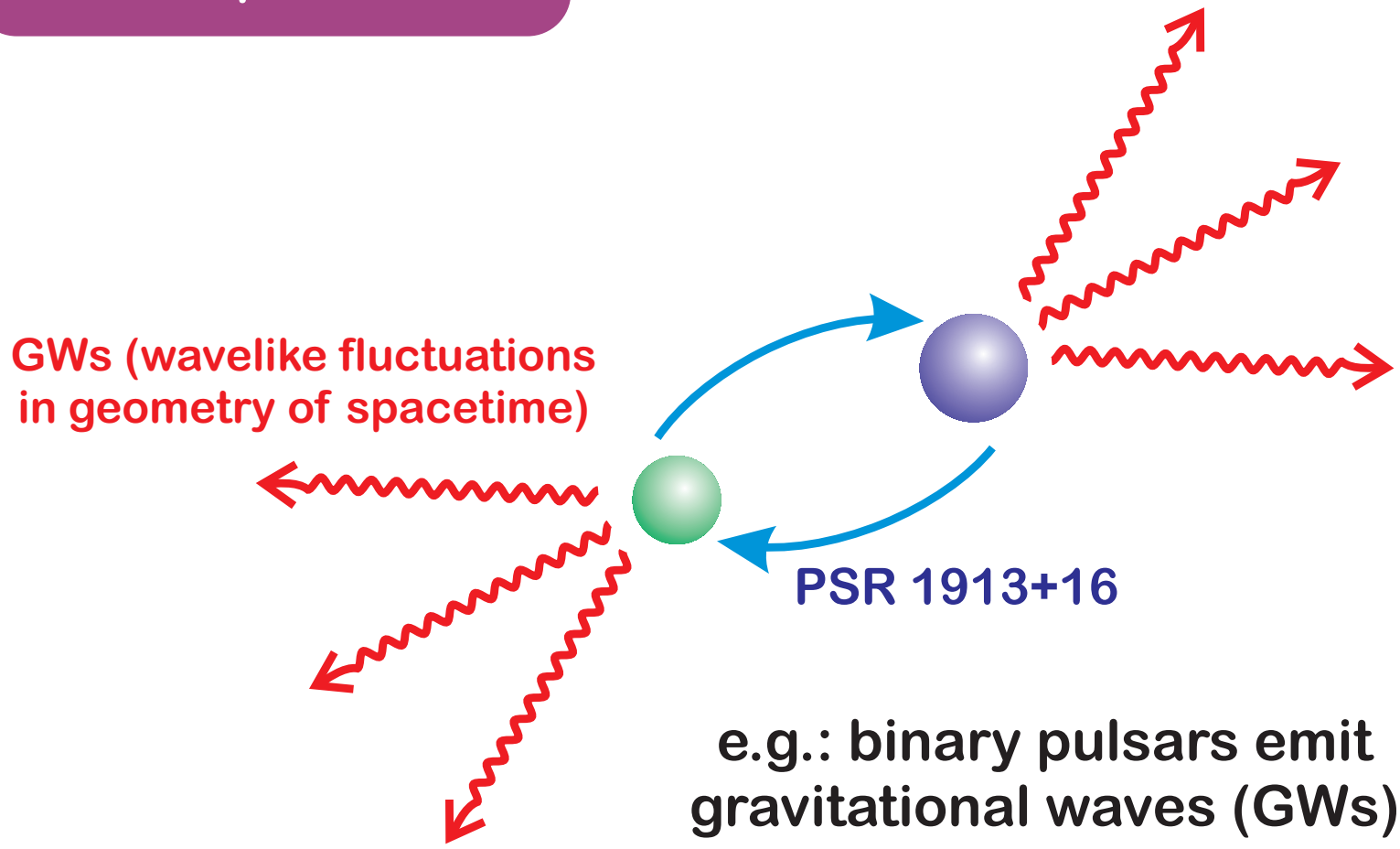

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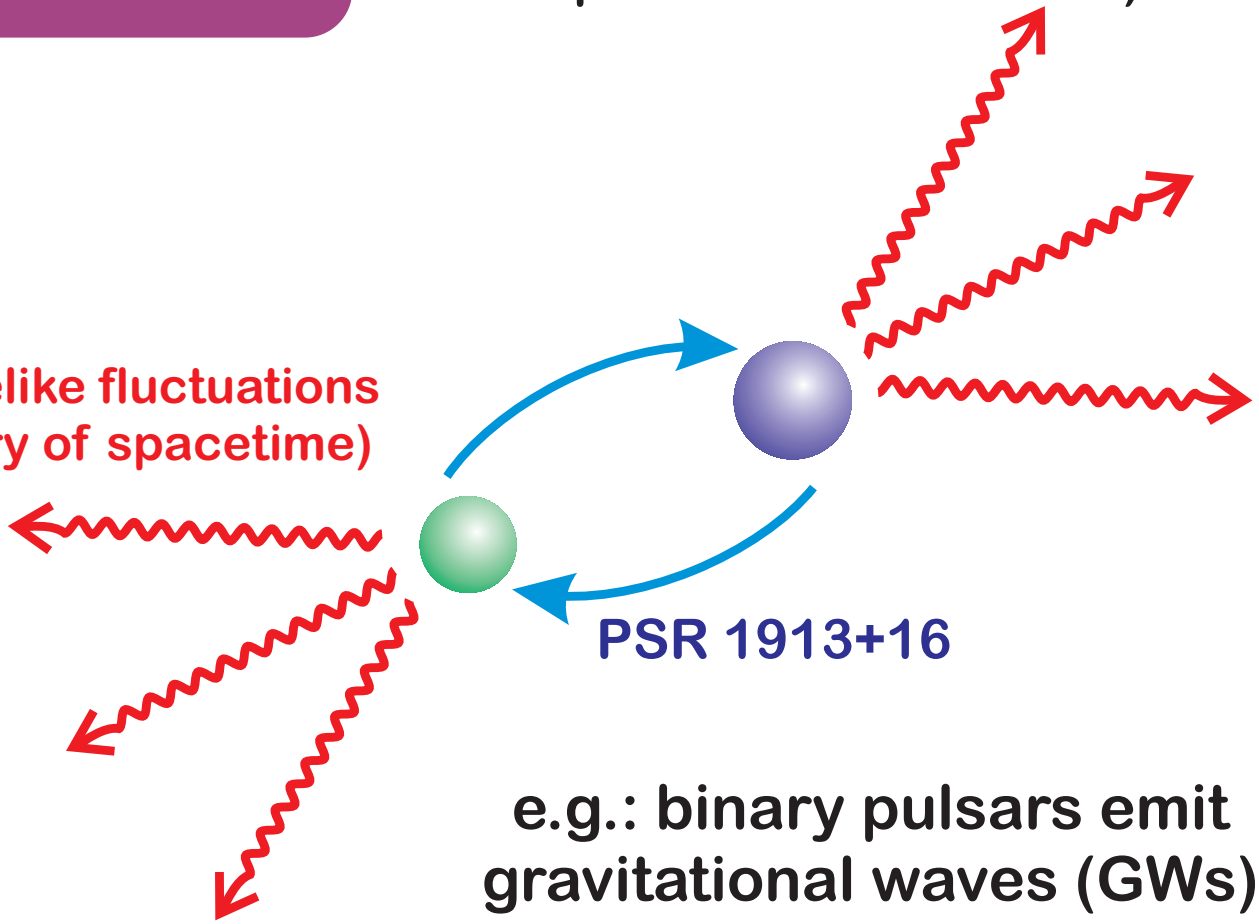

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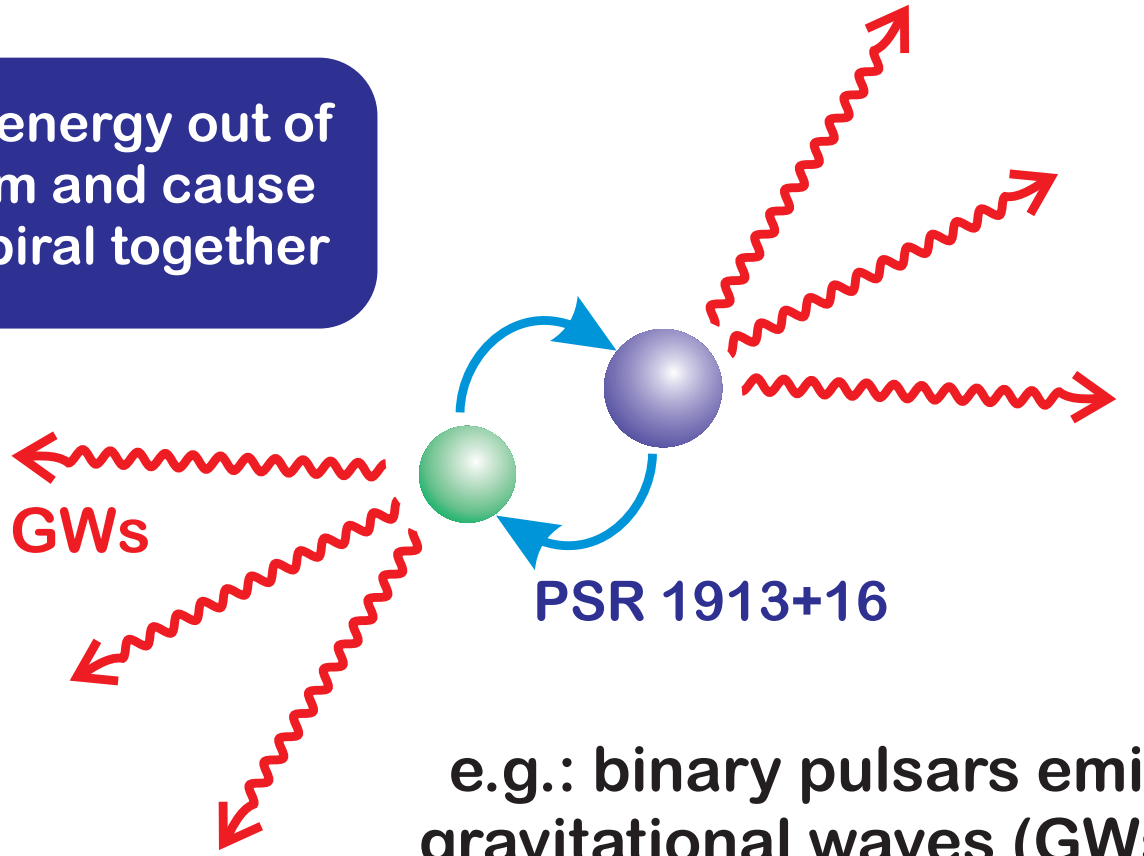

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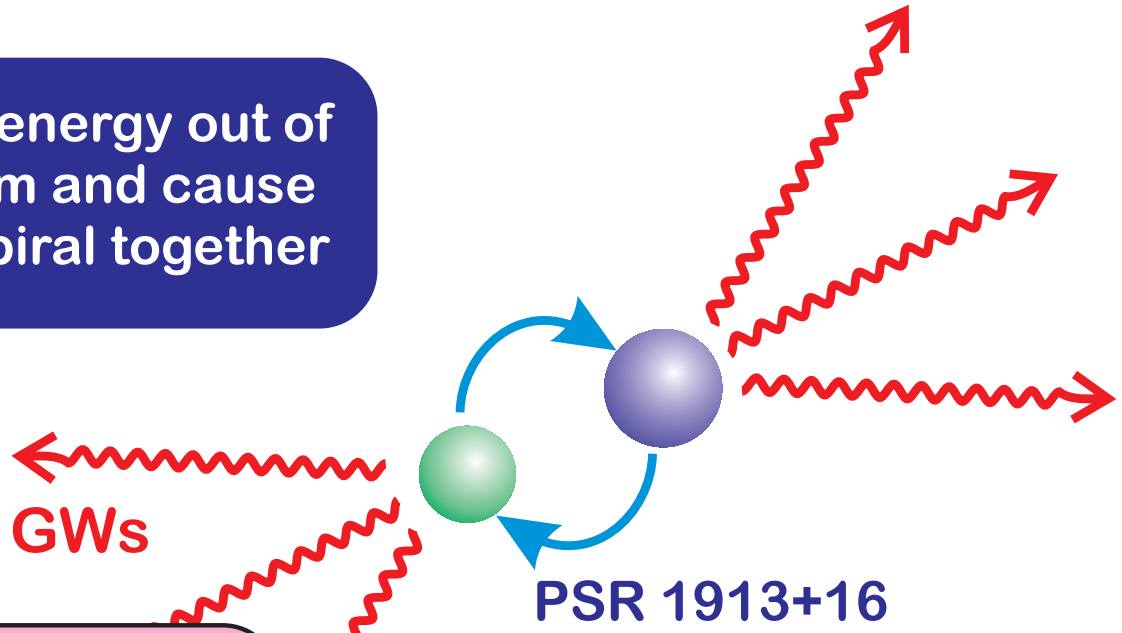

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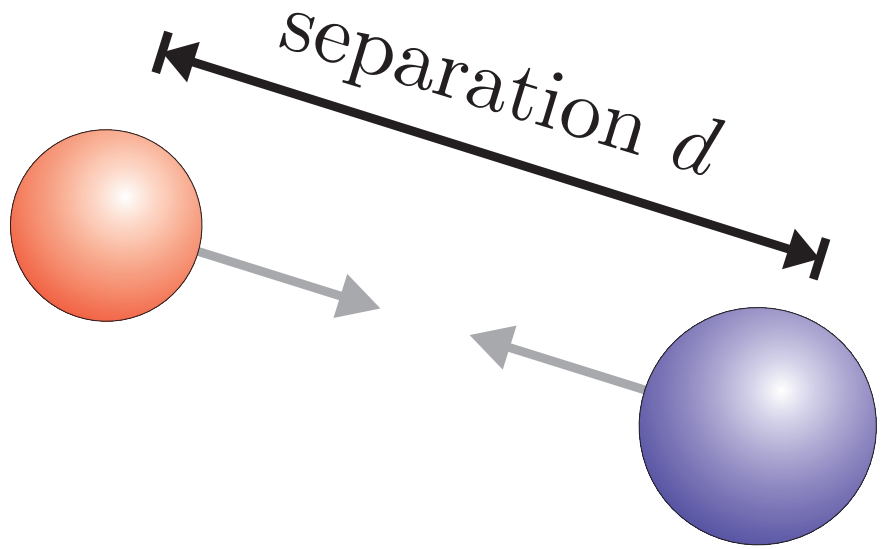

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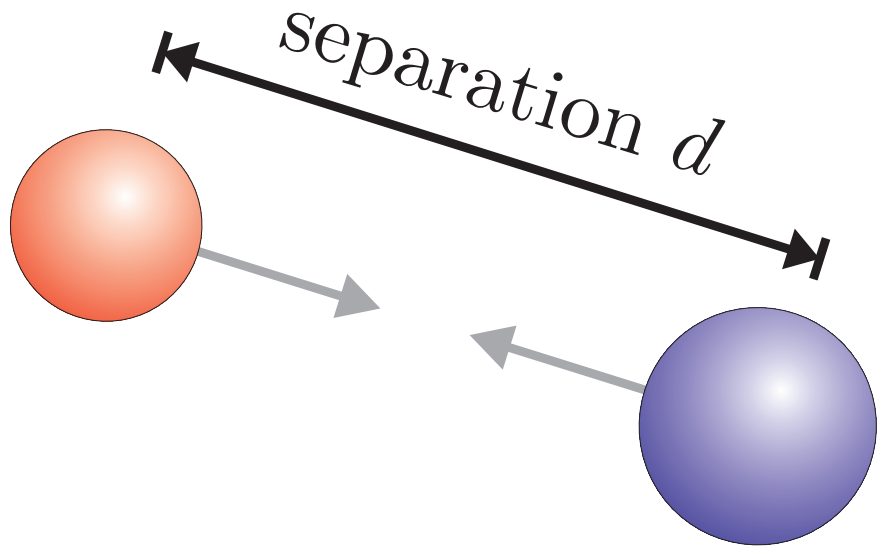
GR prediction confirmed for $d \gtrsim 50\,\mu\mathrm{m}$



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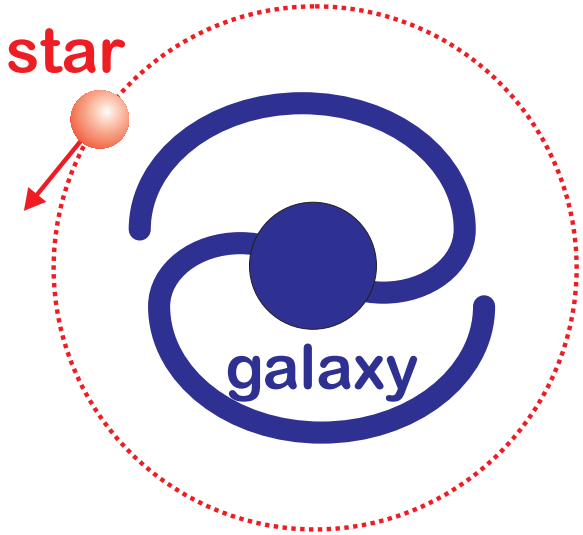

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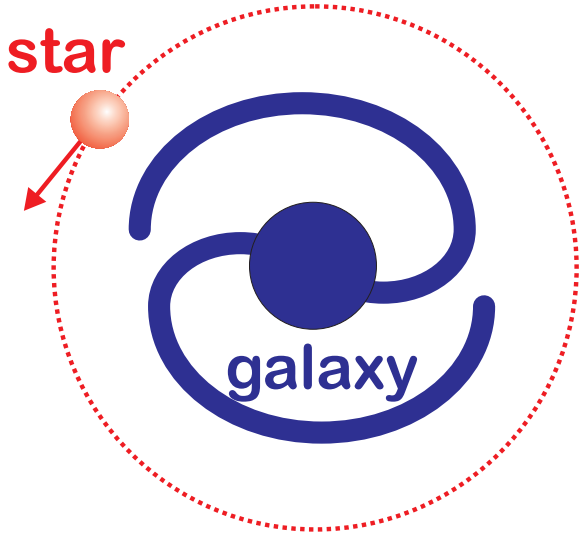

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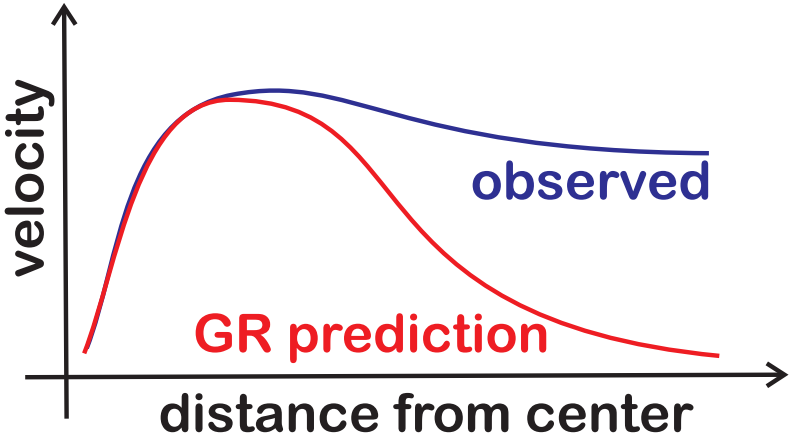

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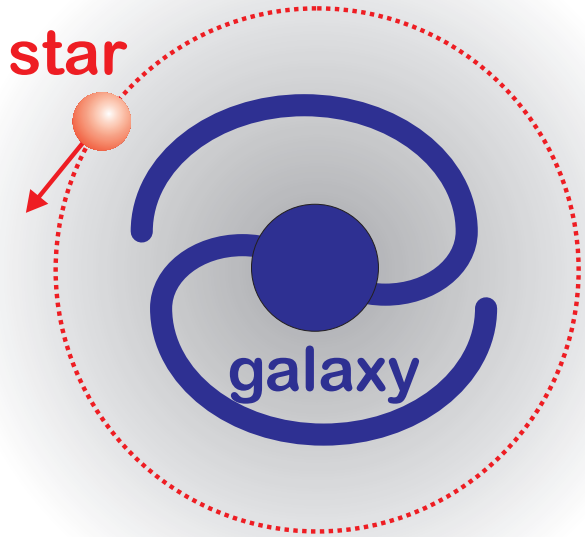

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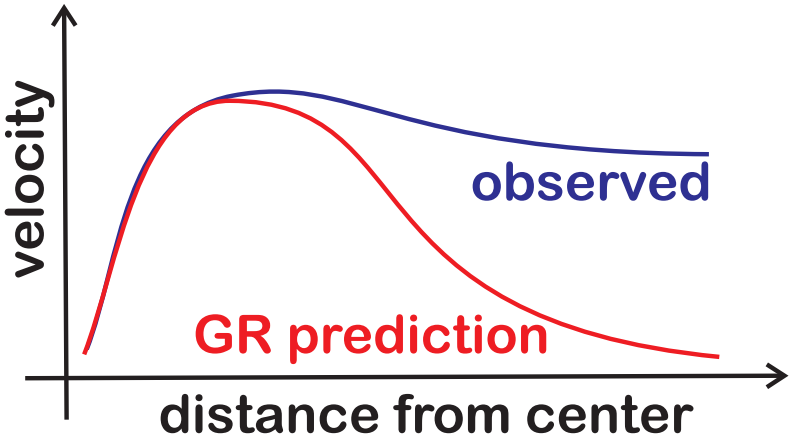

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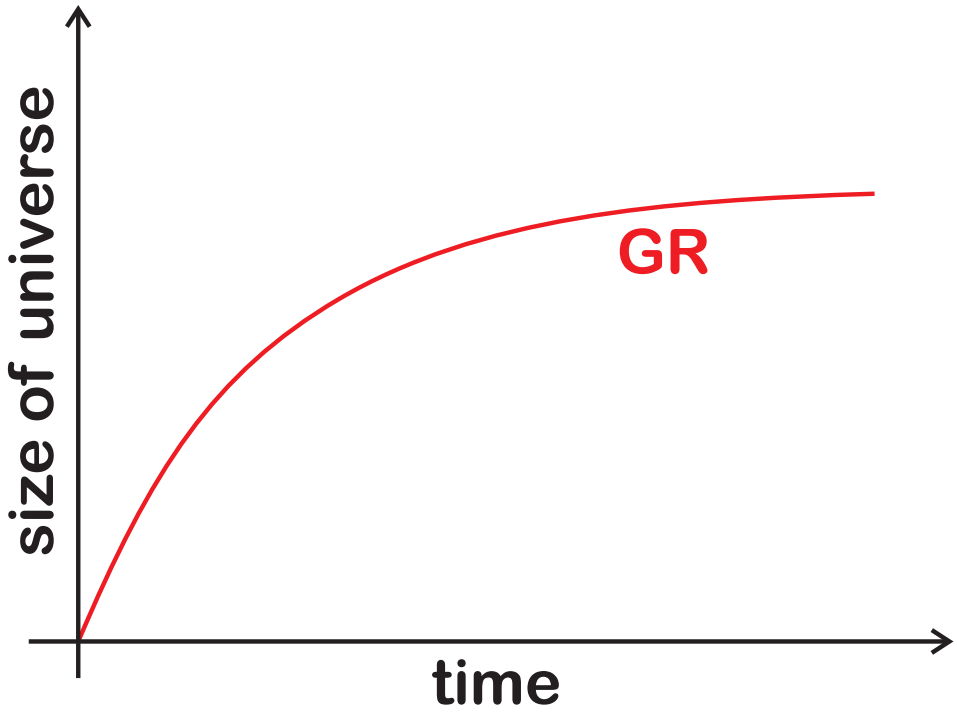

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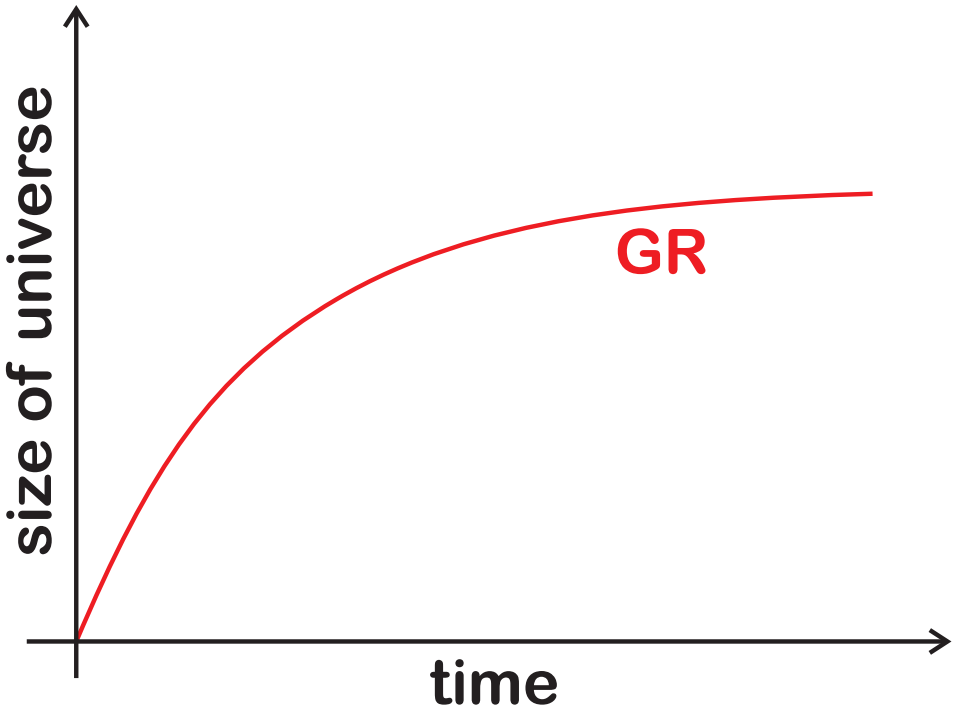

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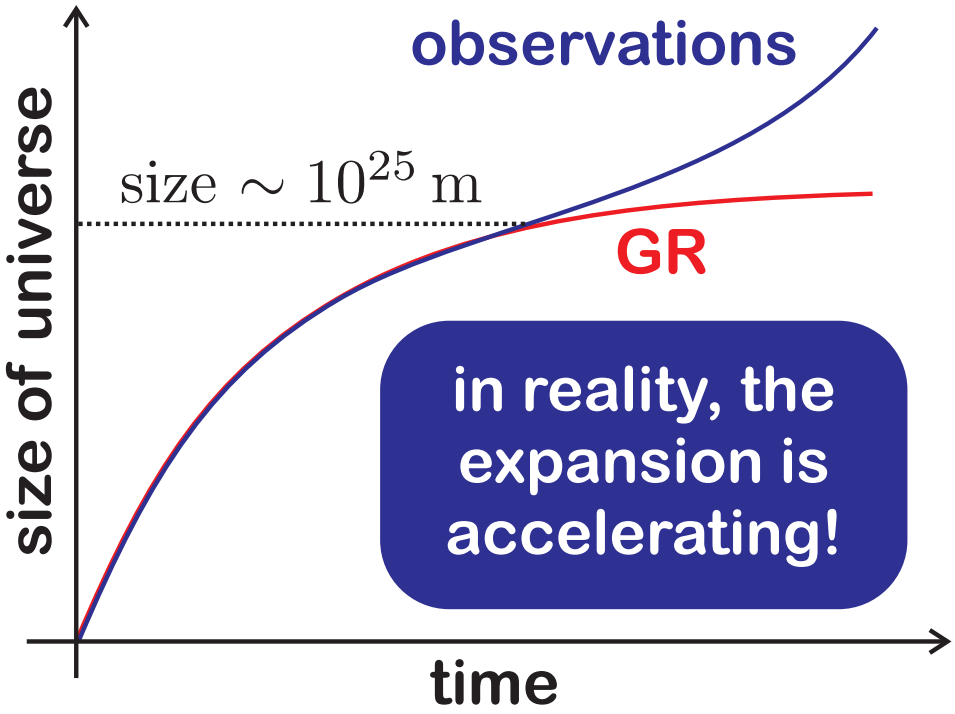

in reality, the expansion is accelerating!

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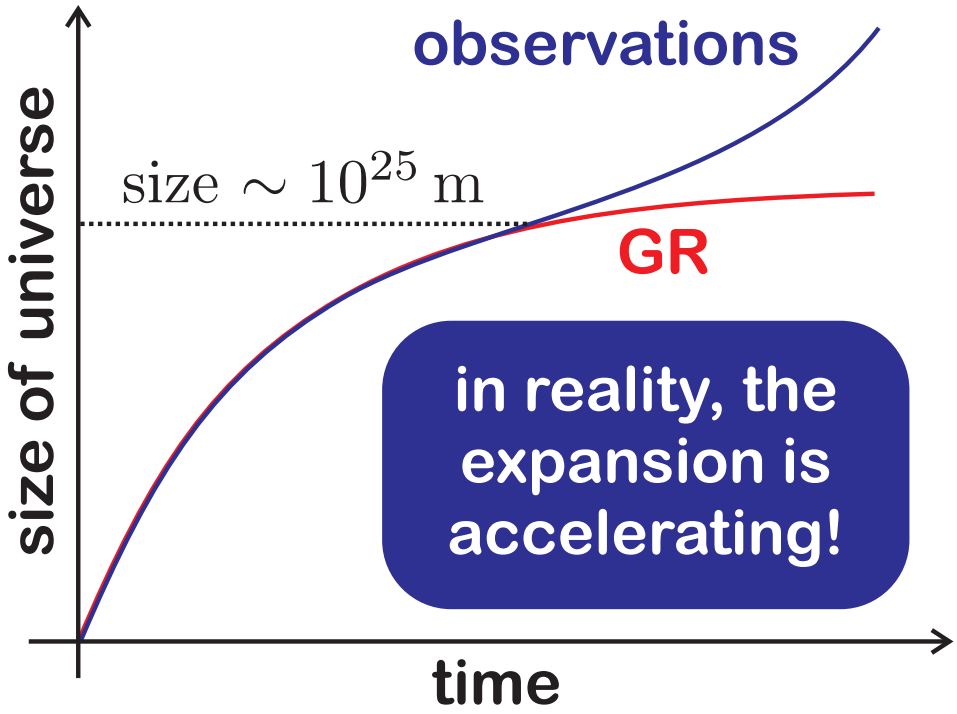

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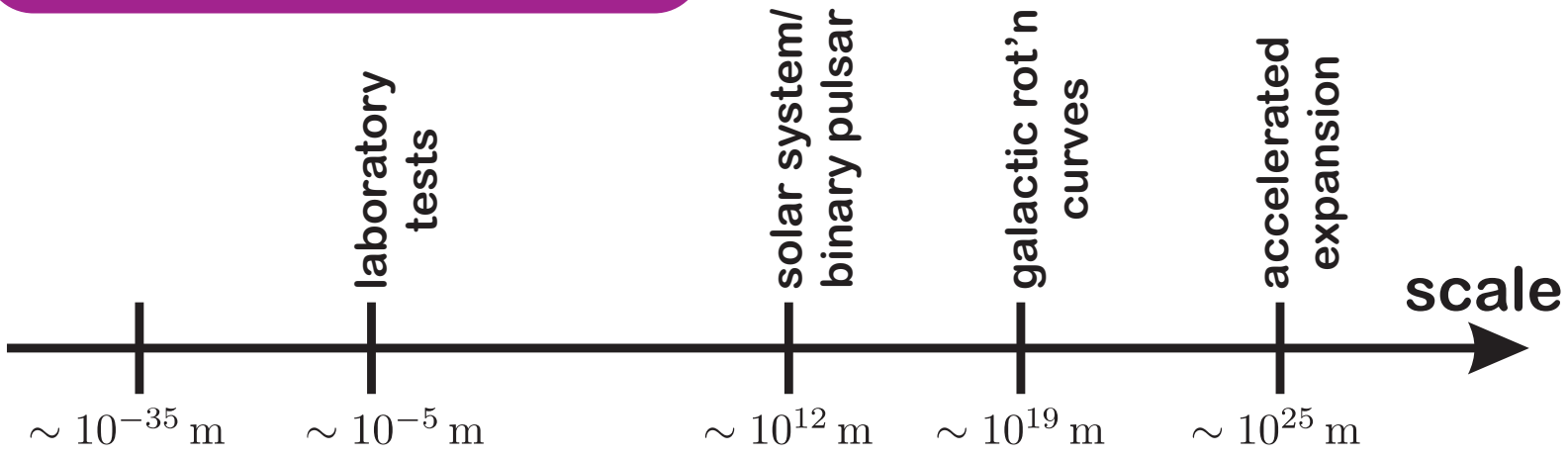

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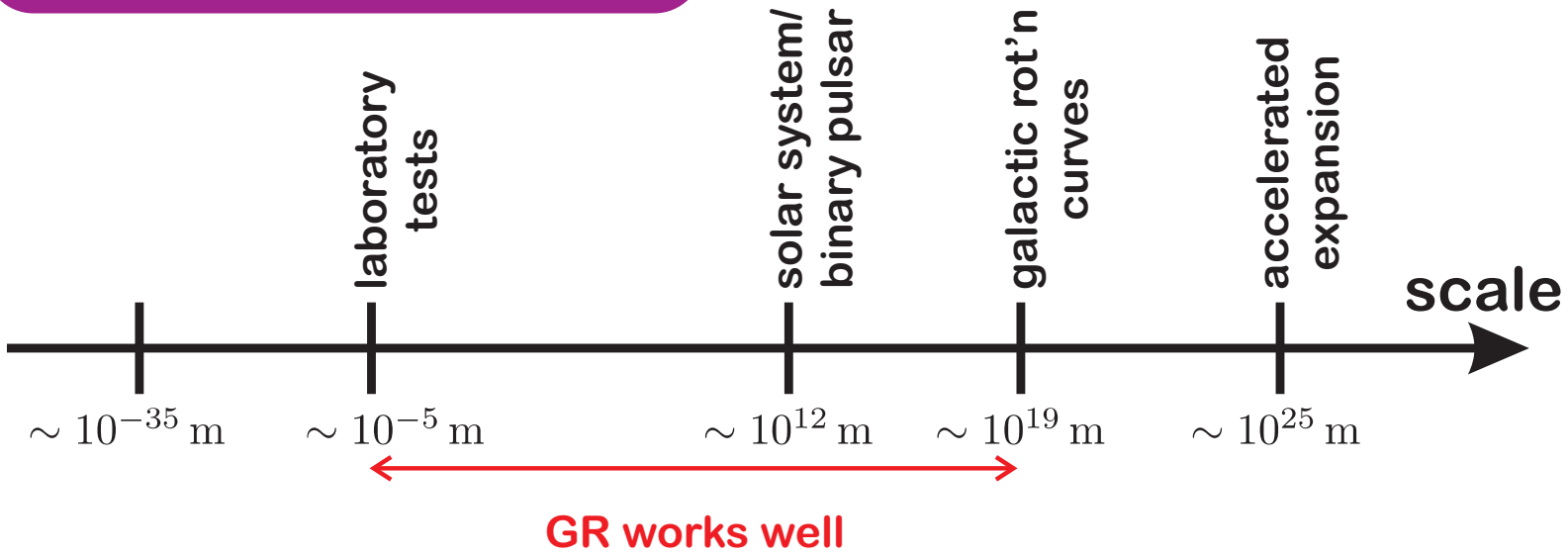

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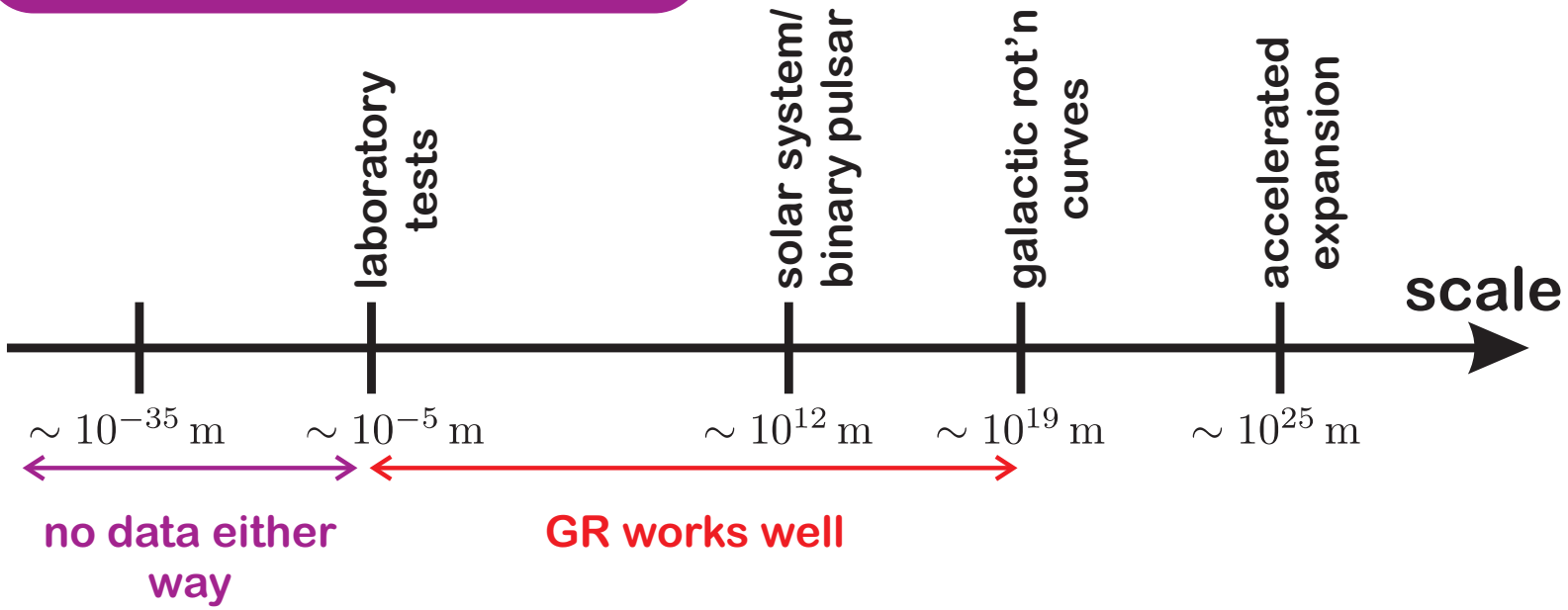

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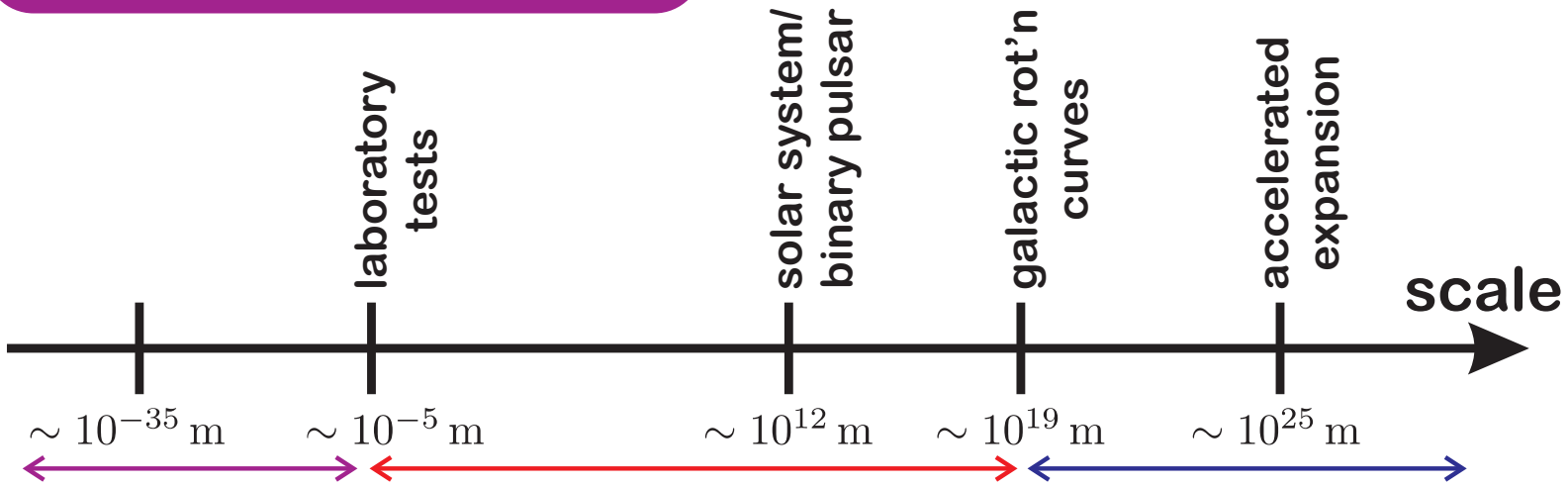

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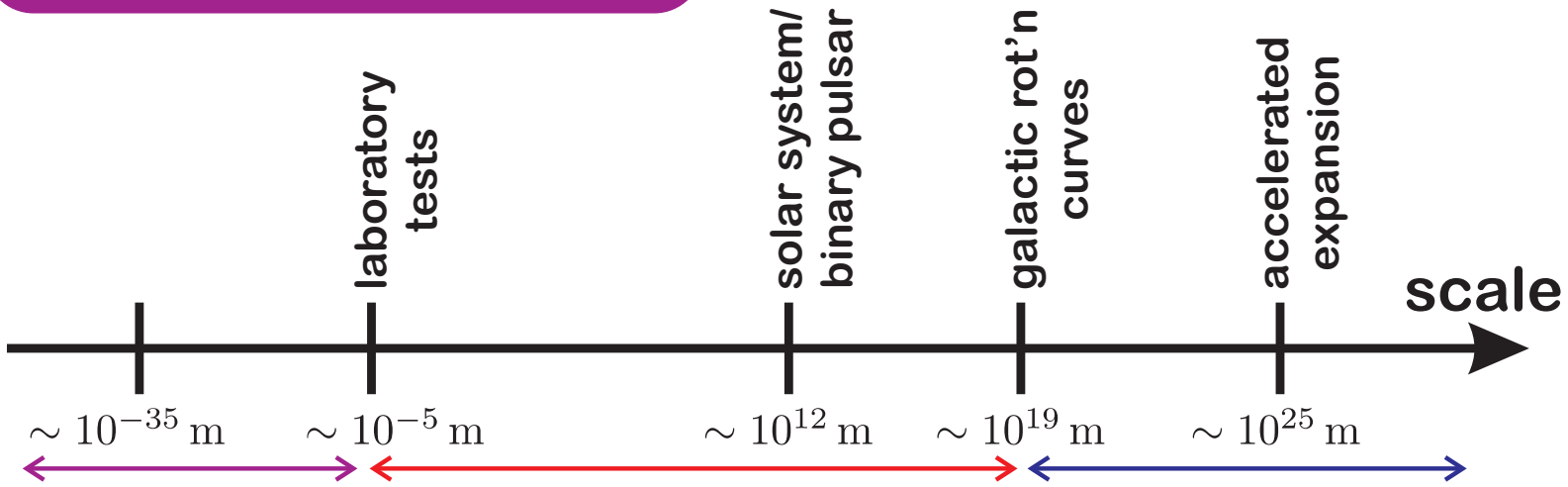

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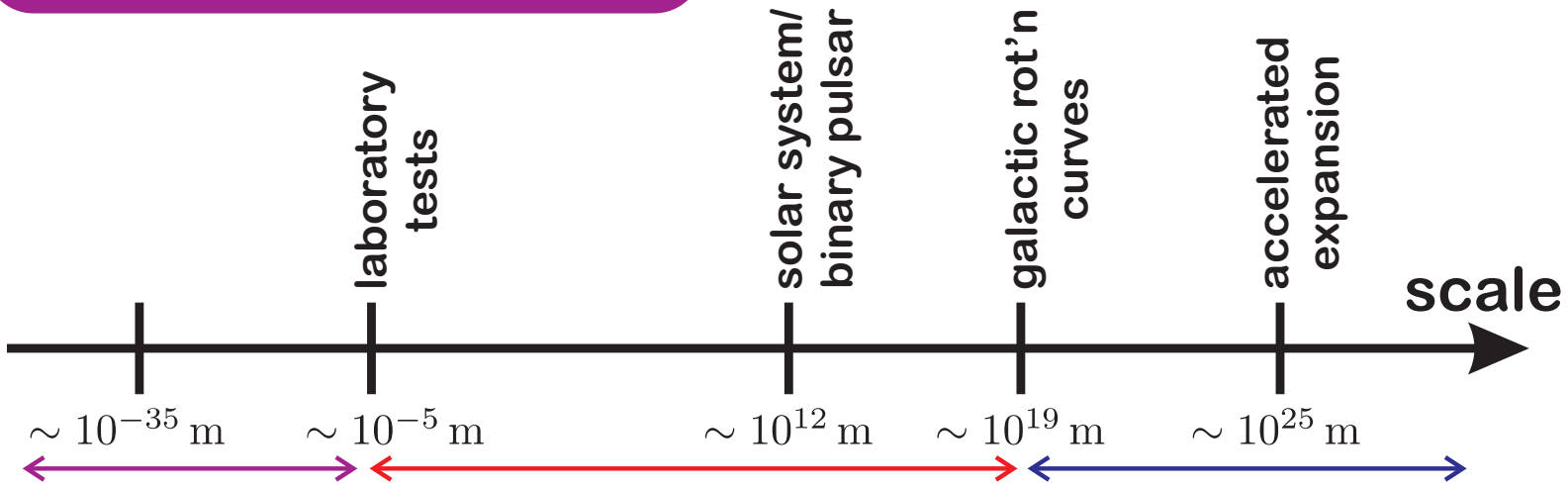

no data either way

GR works well

GR needs help from the dark side

is GR the right theory on small scales?

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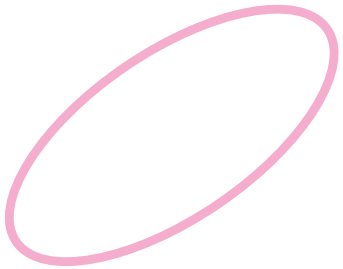
  - somewhat surprisingly, it can also gives large scale modifications

Introducing braneworlds

A brief tour of string theory

in string theory the fundamental objects are... strings



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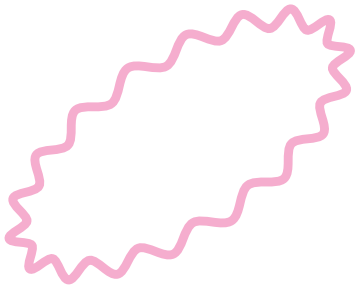

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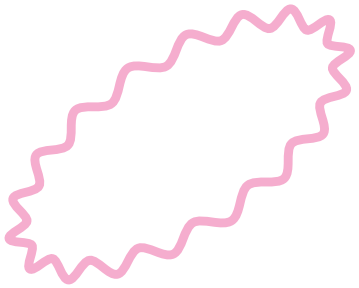

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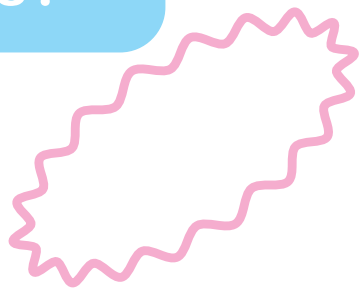

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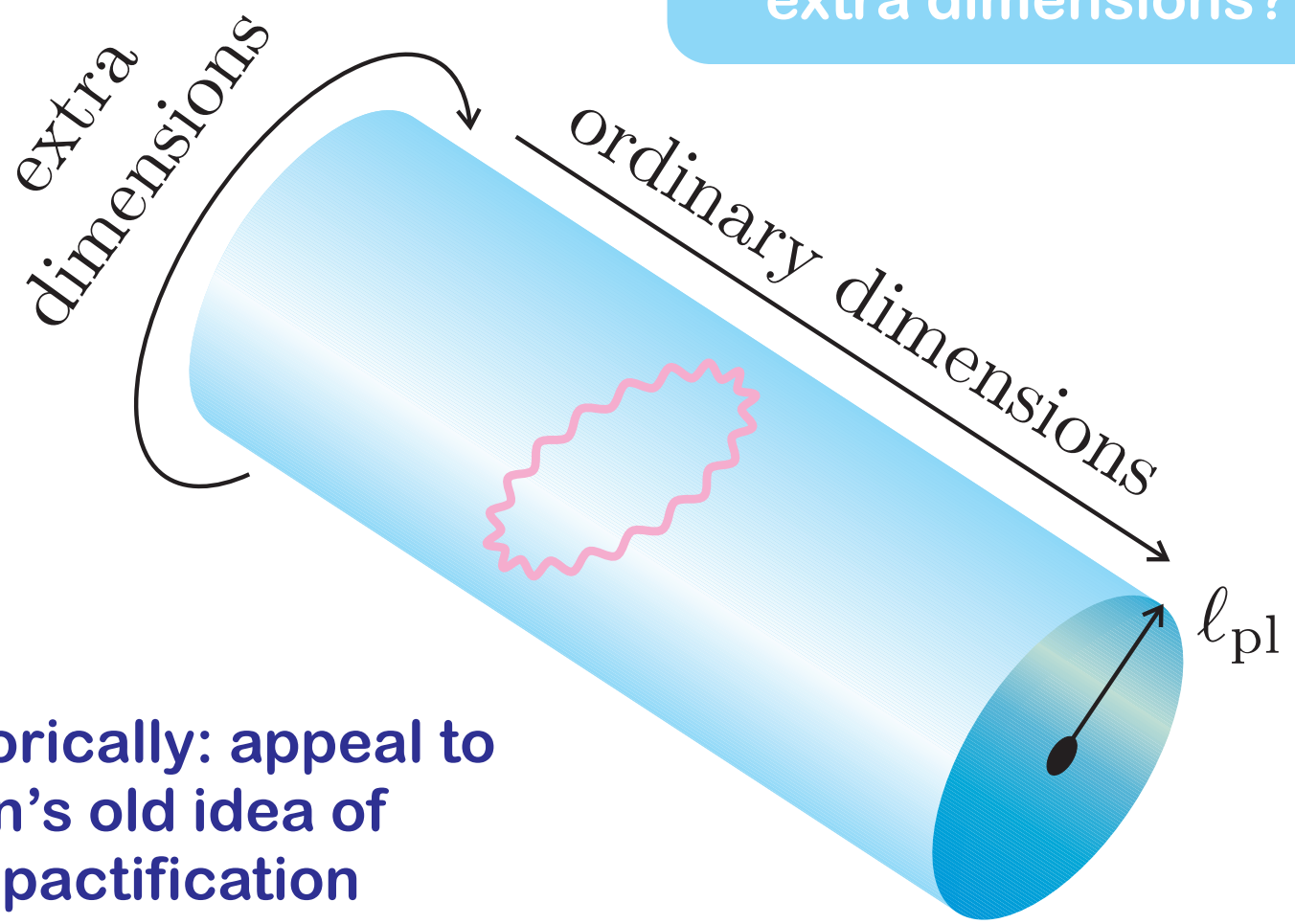

historically: appeal to Klein's old idea of compactification

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brane: object on which the ends of open strings reside

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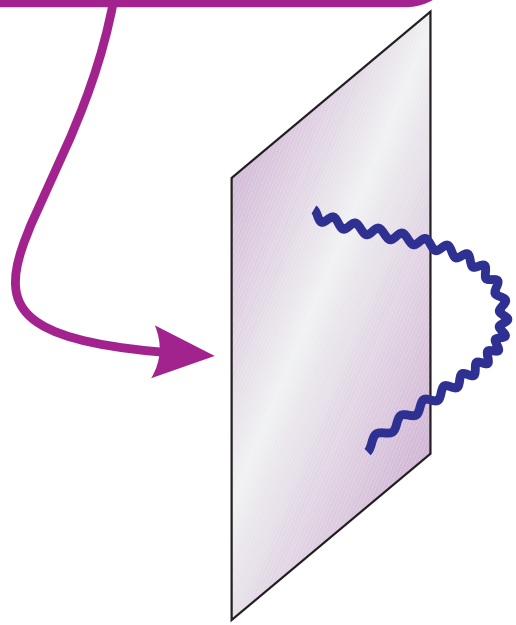

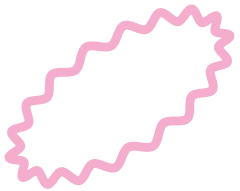

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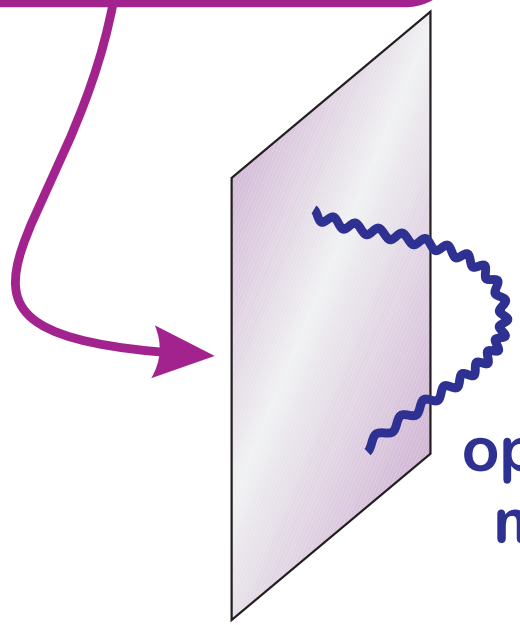
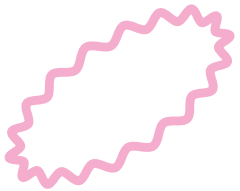


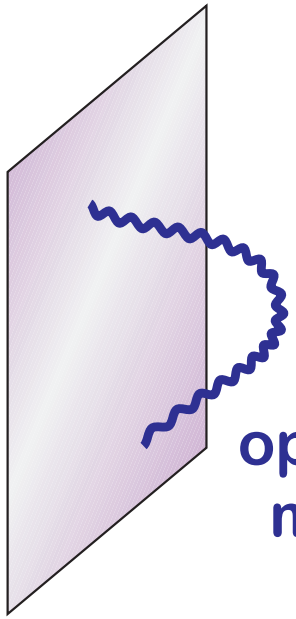
closed strings: carry gravitational DOFs



open strings: carry standard model degrees of freedom

A brief tour of string theory

a natural picture emerges where ordinary matter is confined to a brane while gravity propagates in the bulk



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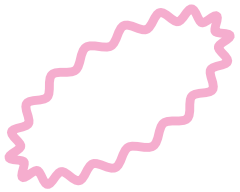

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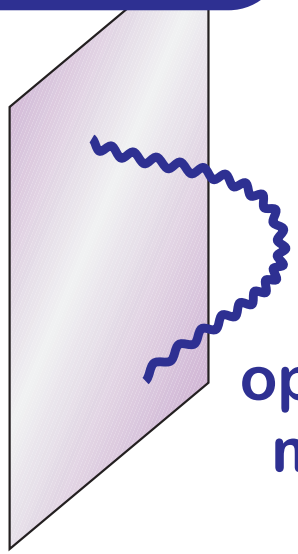
braneworld idea: identify our universe with a 4D brane



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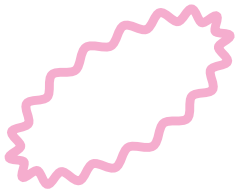

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Braneworld paradigm

- don’t need compactification because **non-gravitational** physics naturally confined to the 4D brane

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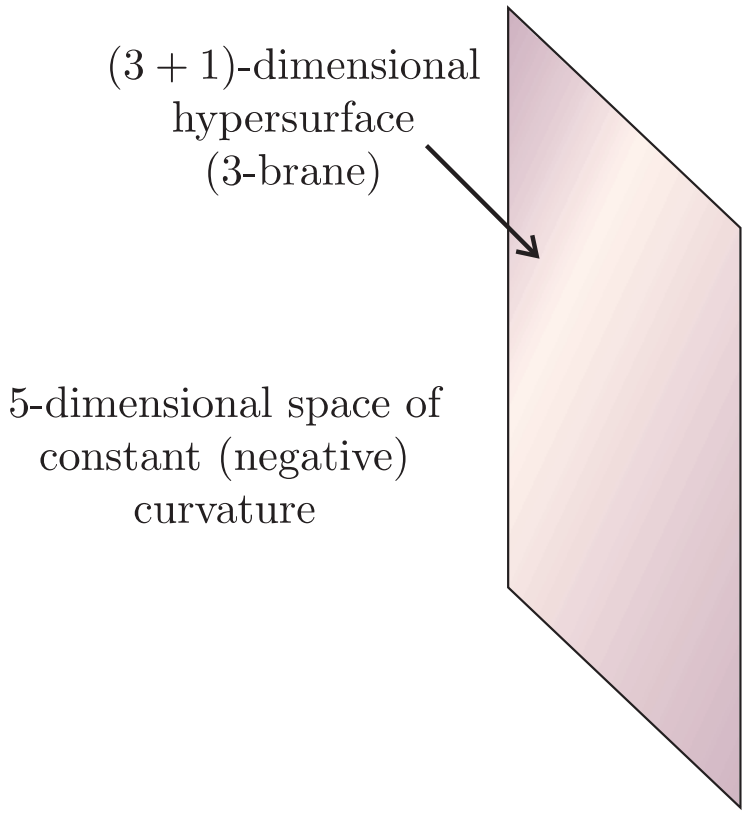
Randall-Sundrum braneworlds



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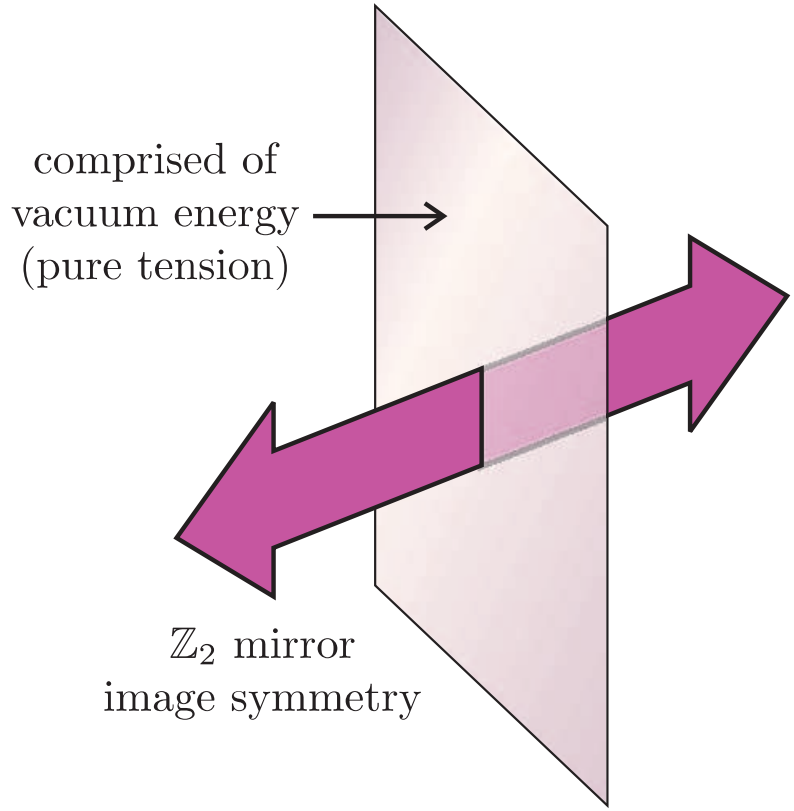

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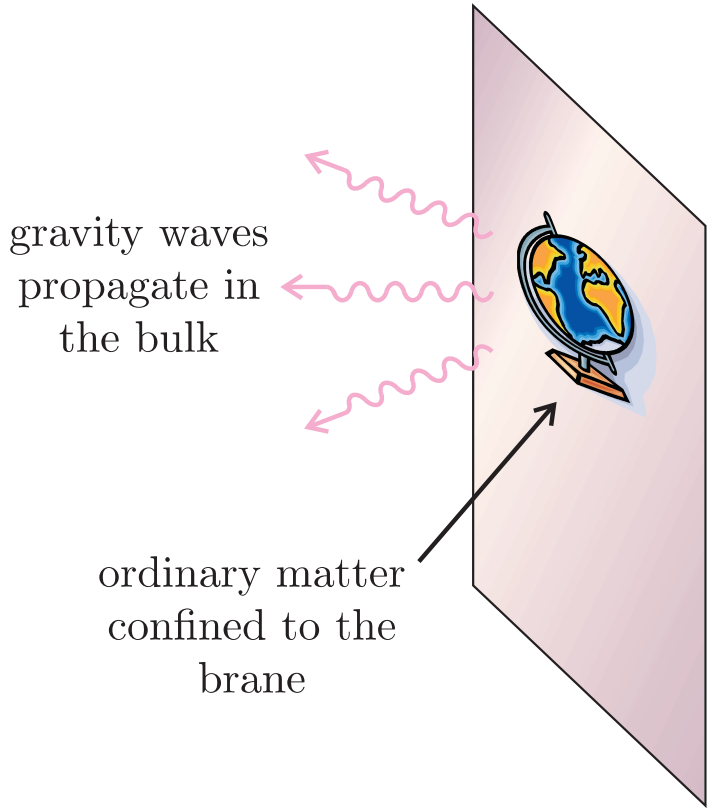
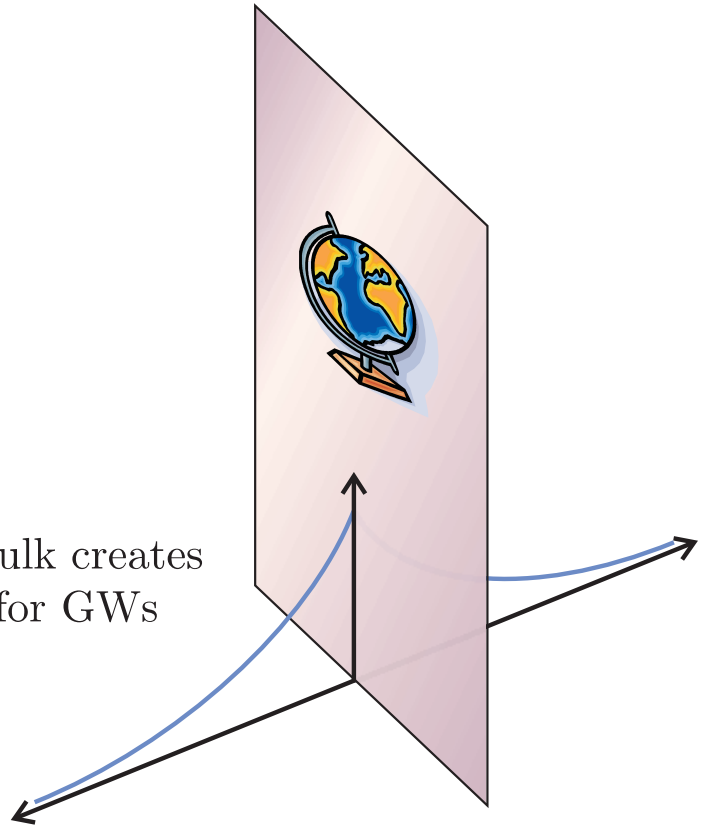


Randall-Sundrum braneworlds

curvature of bulk creates
a potential for GWs



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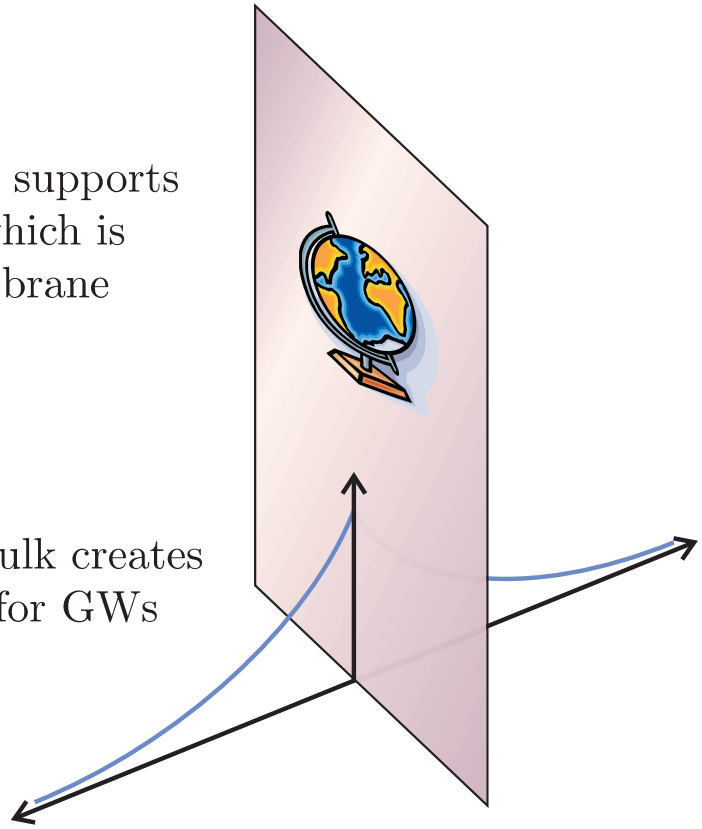

Randall-Sundrum braneworlds

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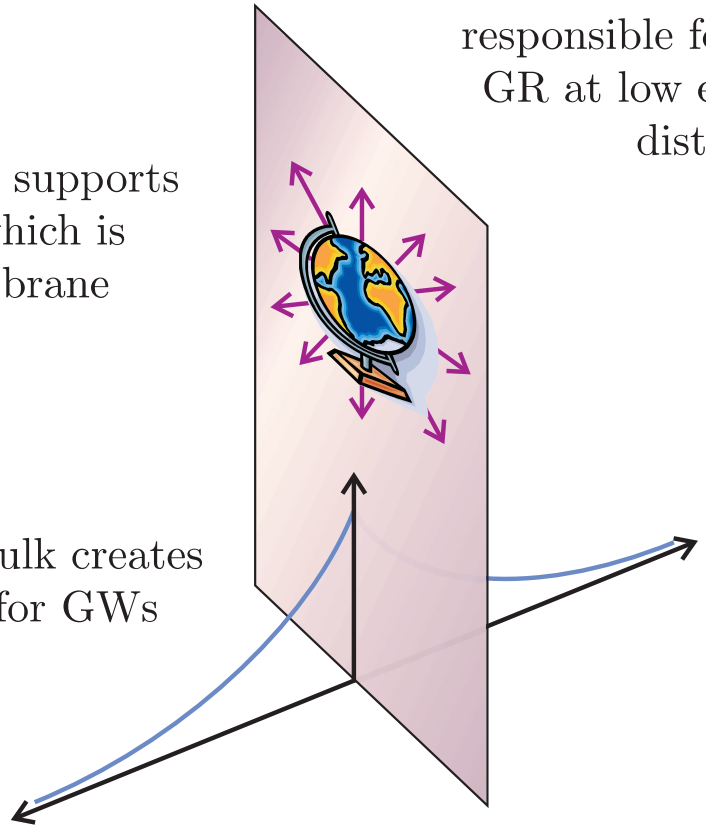
the bound state is responsible for reproducing GR at low energies/large distances



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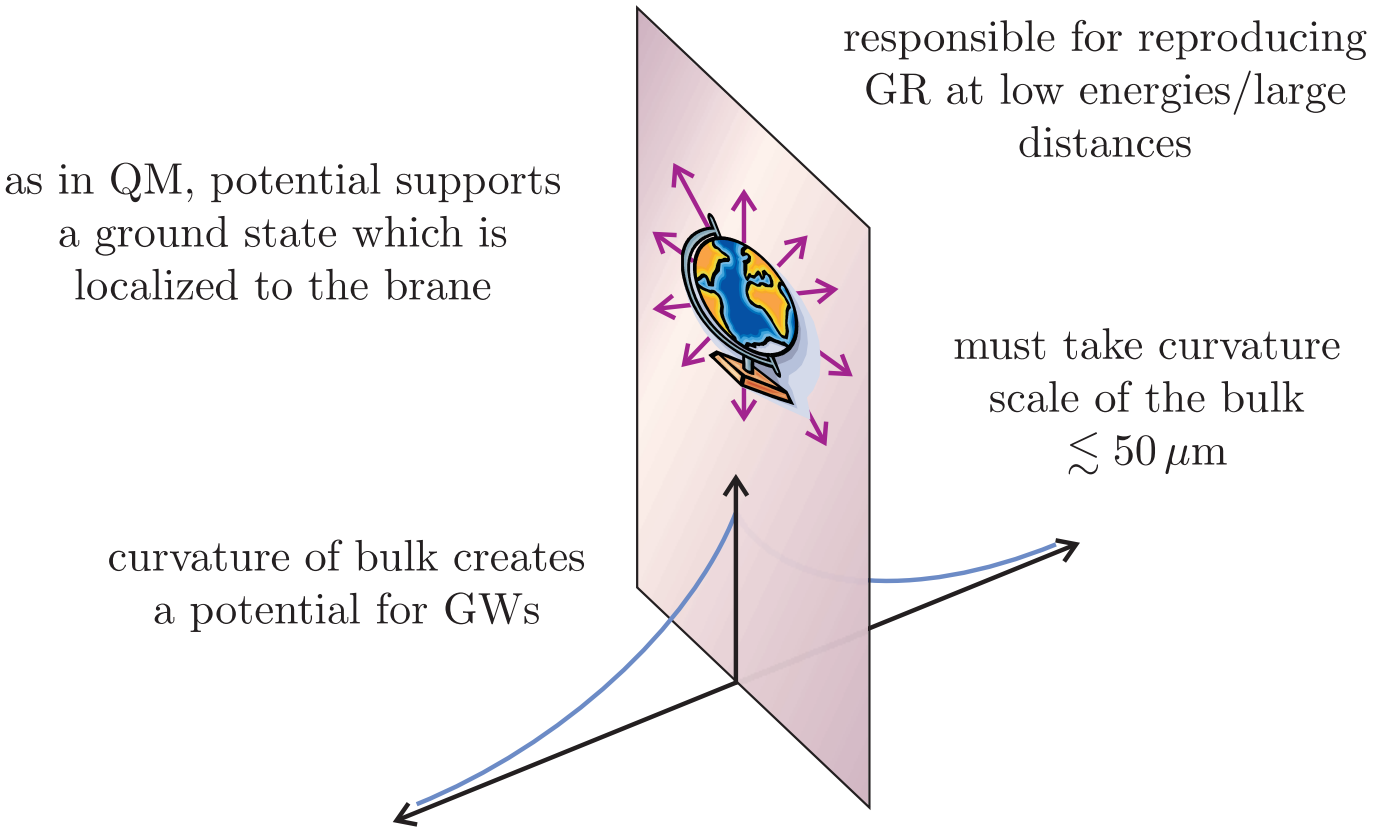
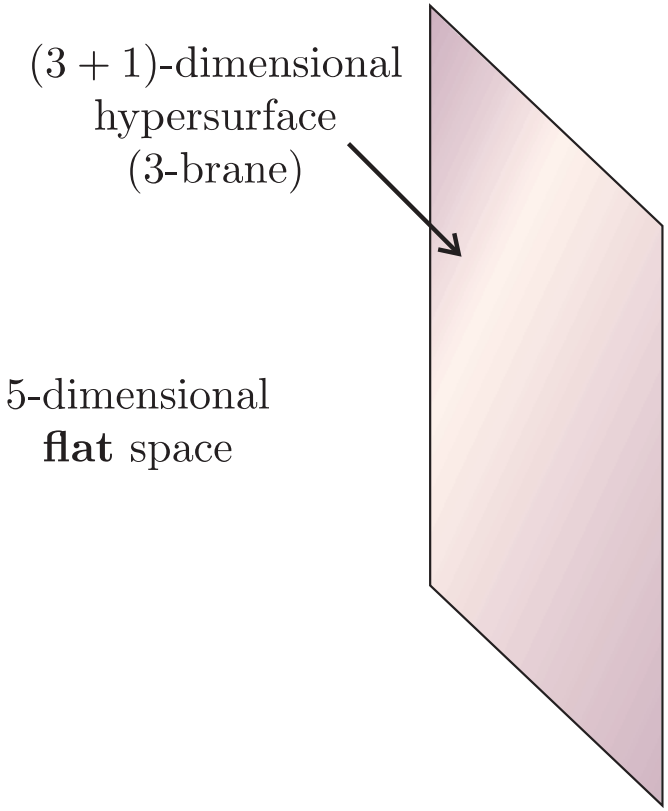


DGP braneworlds



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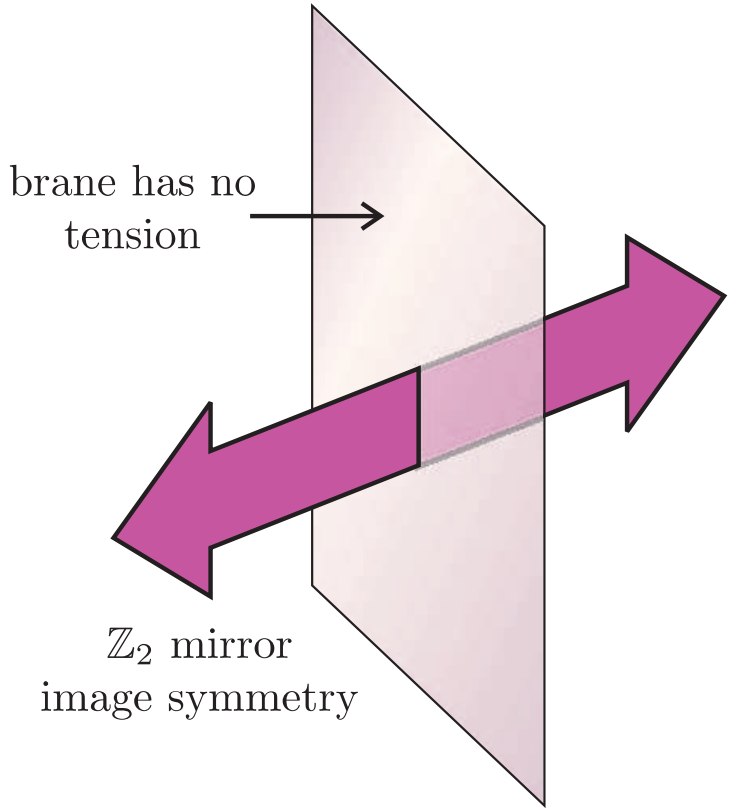

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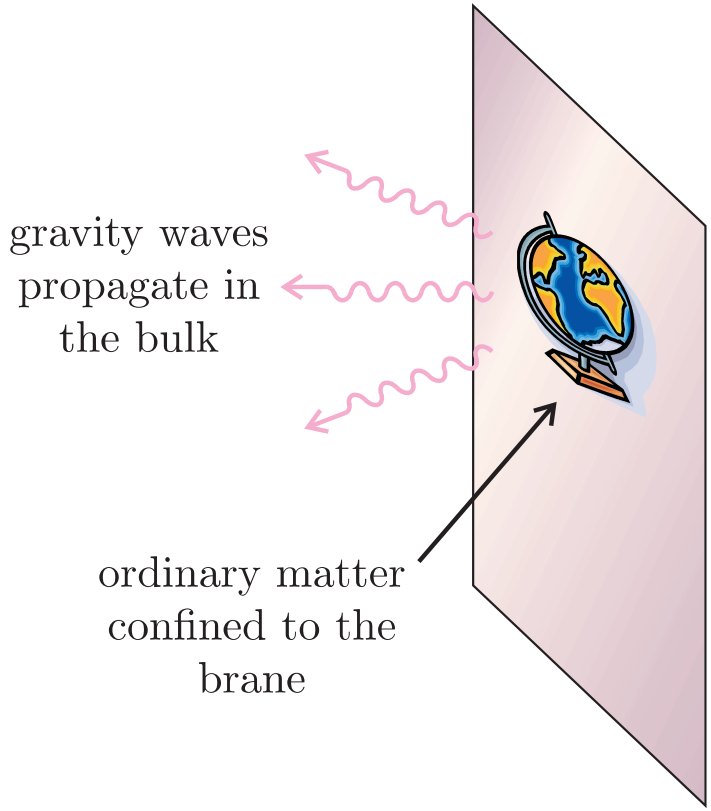

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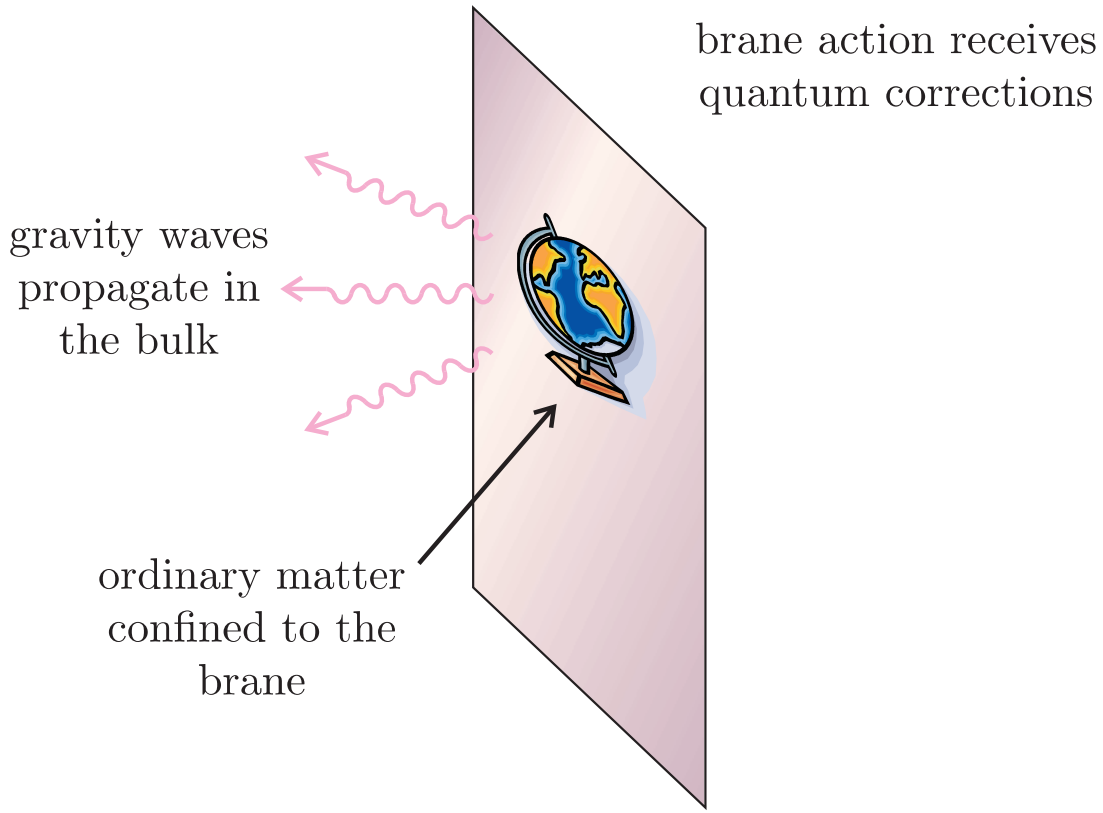

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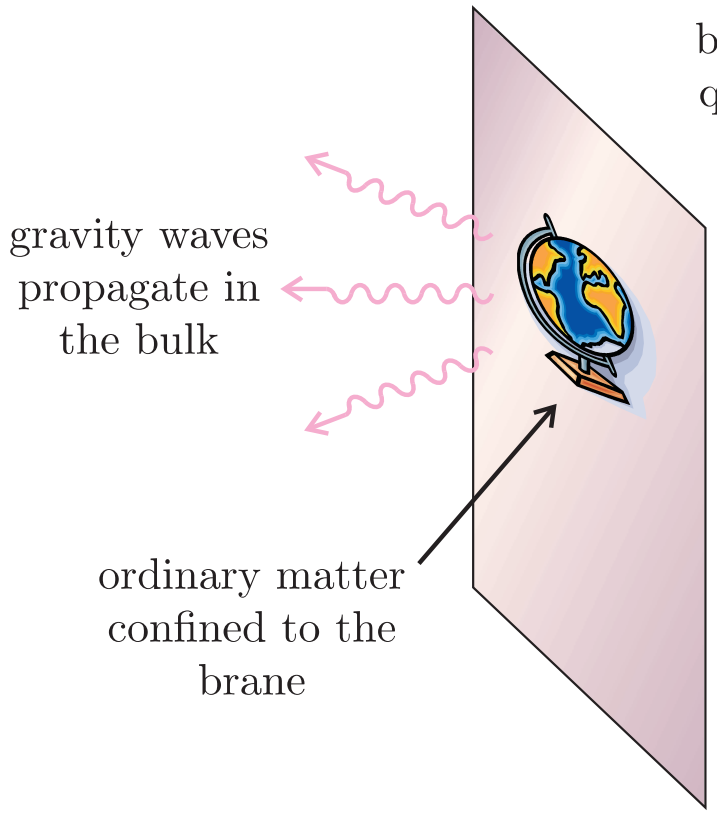

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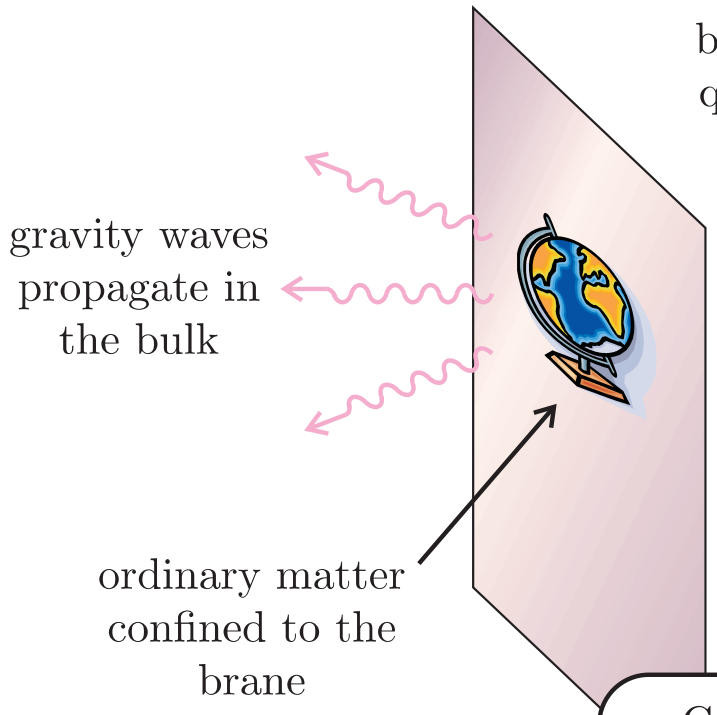
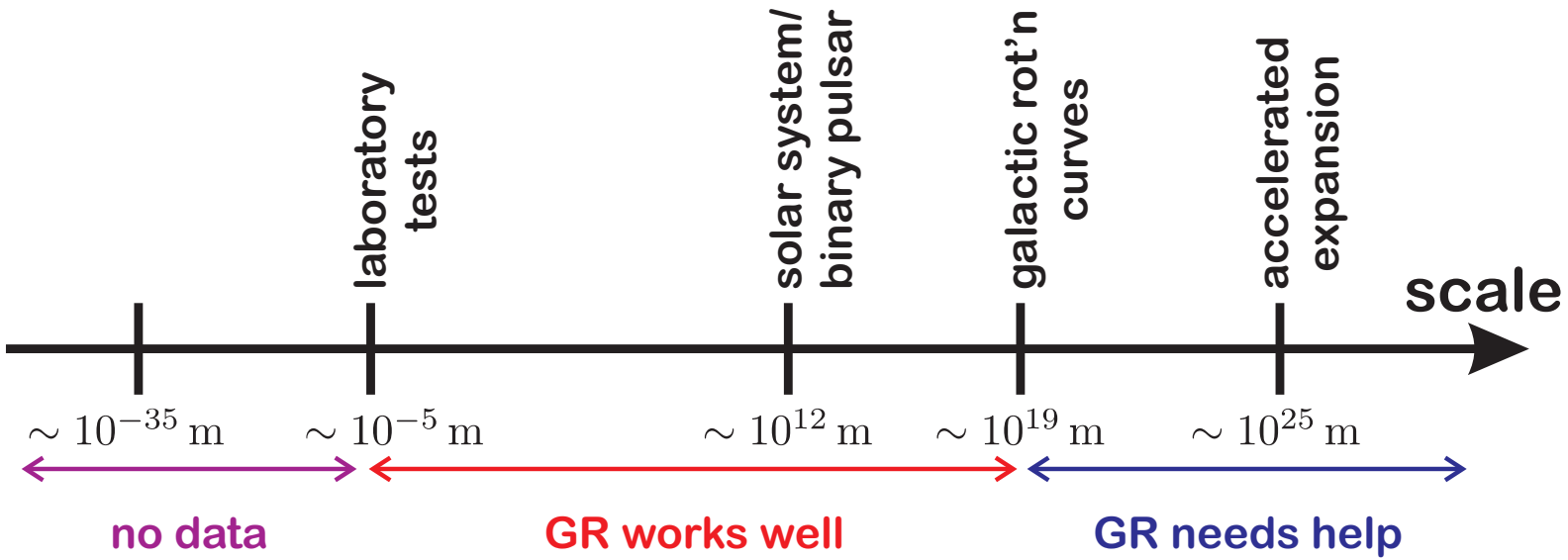


Braneworld observational signatures



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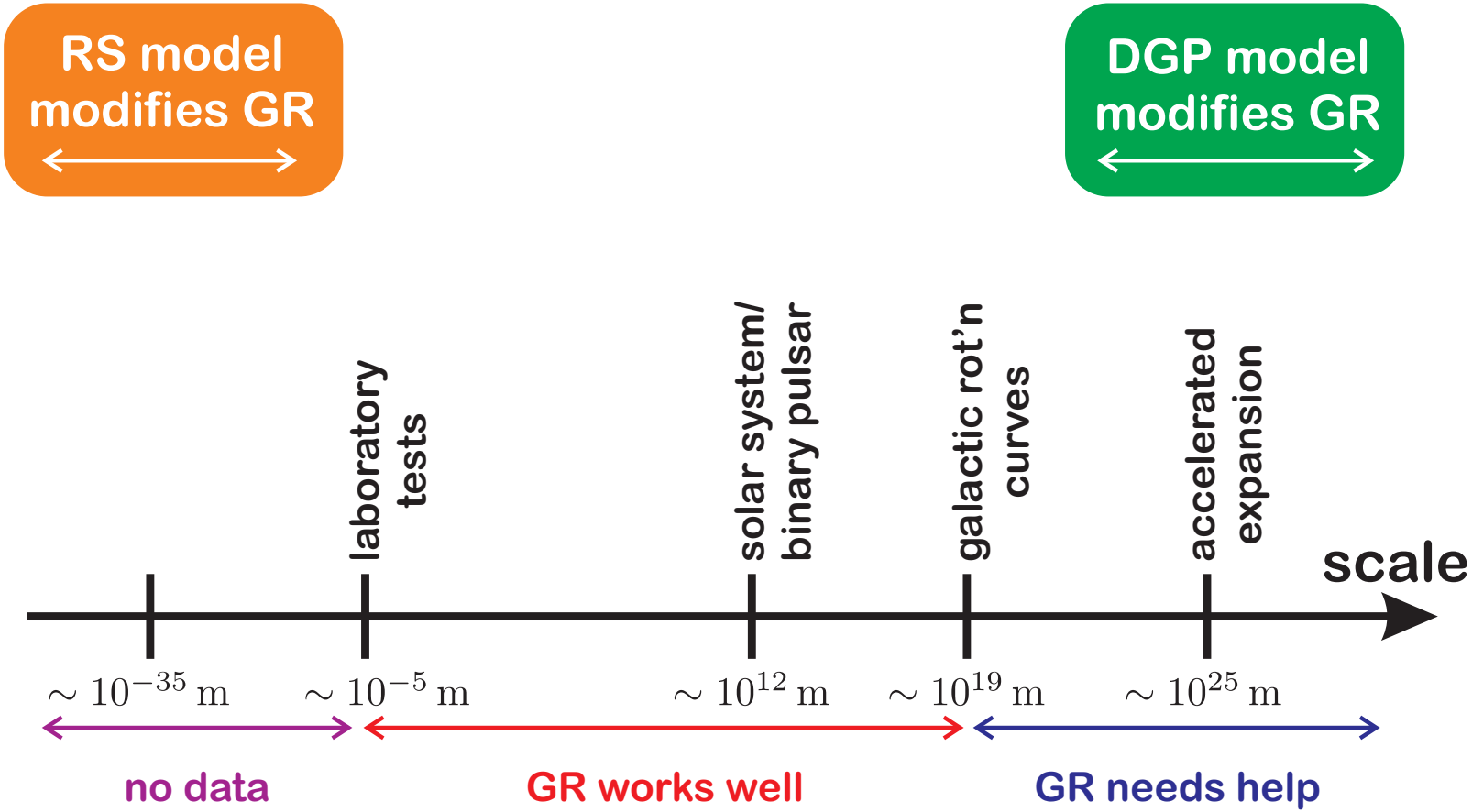
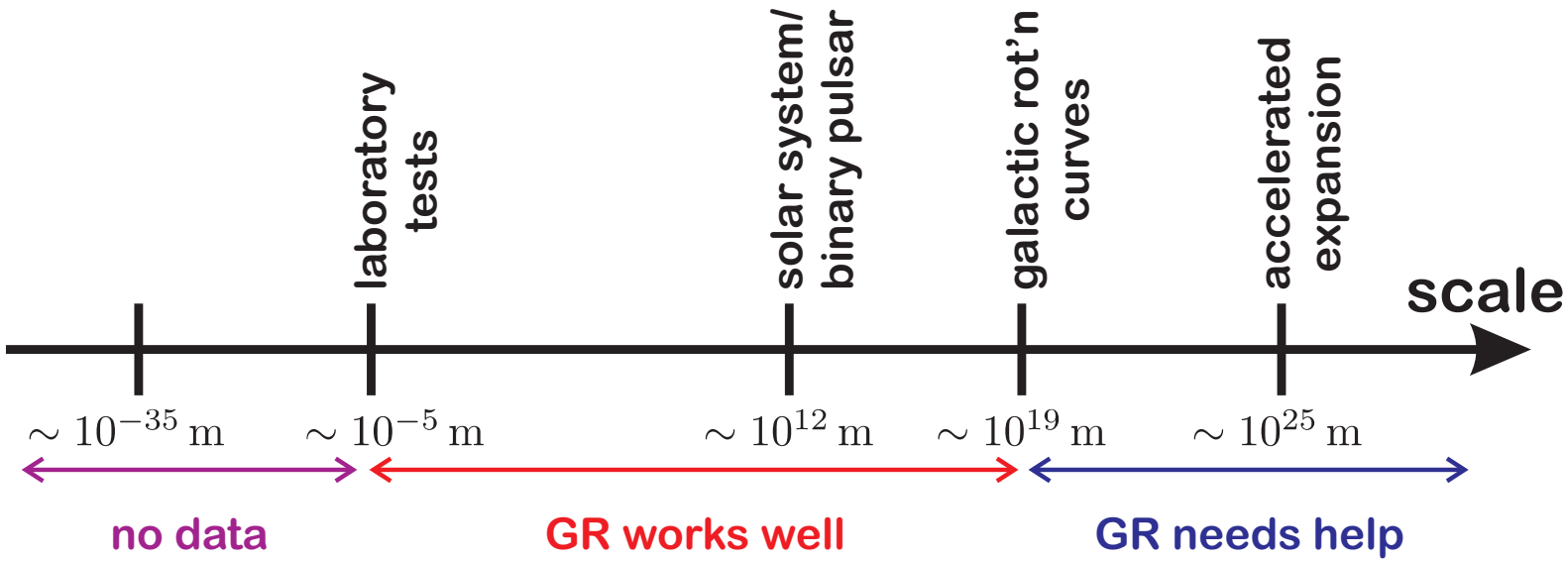


Braneworld observational signatures

RS model modifies GR ⟷

where to look for observational signatures?

DGP model modifies GR ⟷



Braneworld observational signatures

short wavelength GWs or early universe

observations of nearby cosmology

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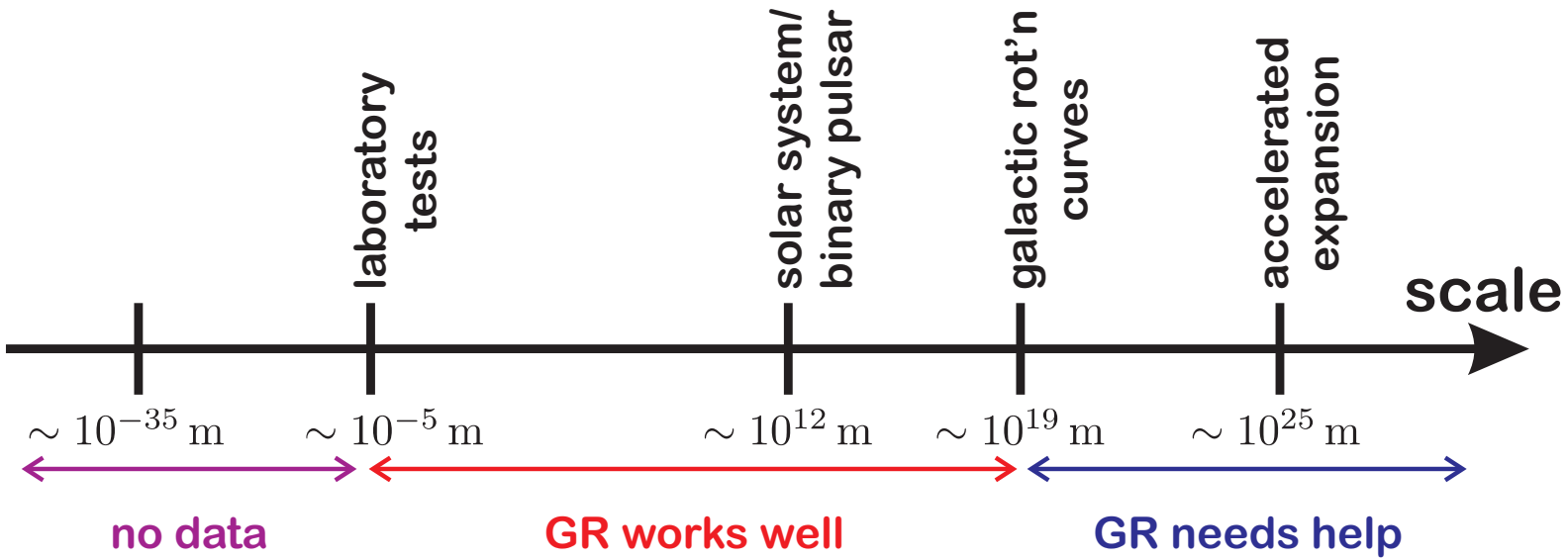
⟷ **DGP model modifies GR**



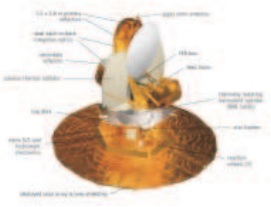
Braneworld cosmology

Cosmological probes

we observe the universe in a number of different ways:

cosmic microwave background (CMB)

Planck



WMAP

large scale structure (LSS)

SDSS

supernovae type Ia (SNeIa)

HST + ground telesopes

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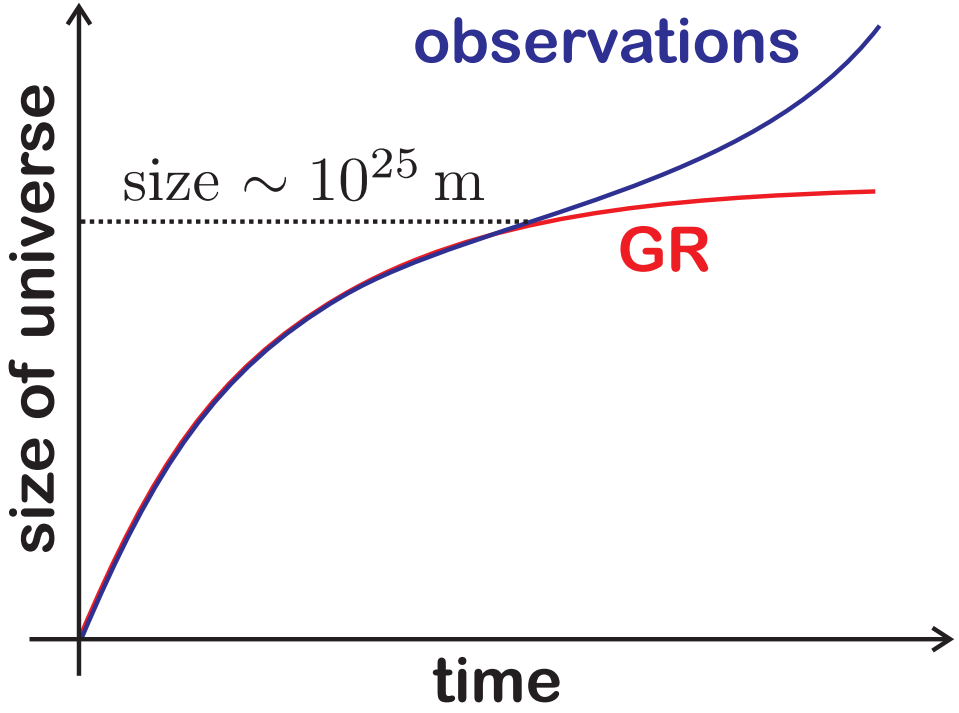
SNela's provide a direct measure of the expansion rate of the universe



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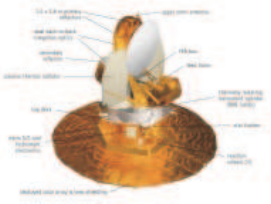
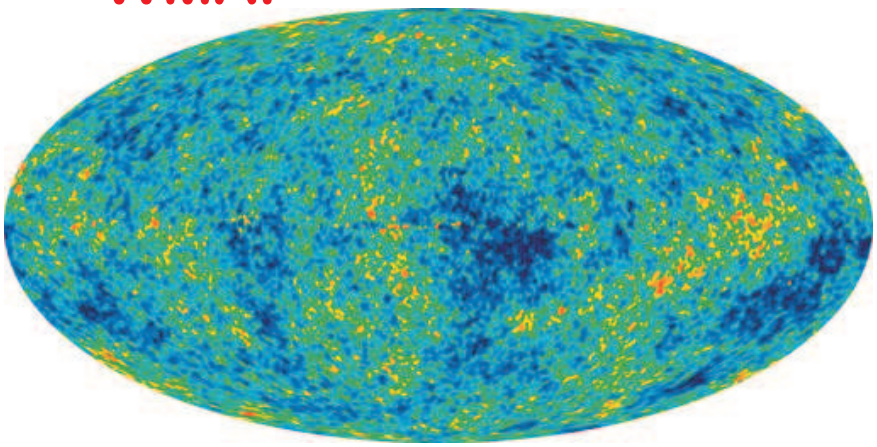


WMAP

CMB experiments directly measure thermal relics of the early universe



all sky map of temperature fluctuations in cosmic blackbody radiation

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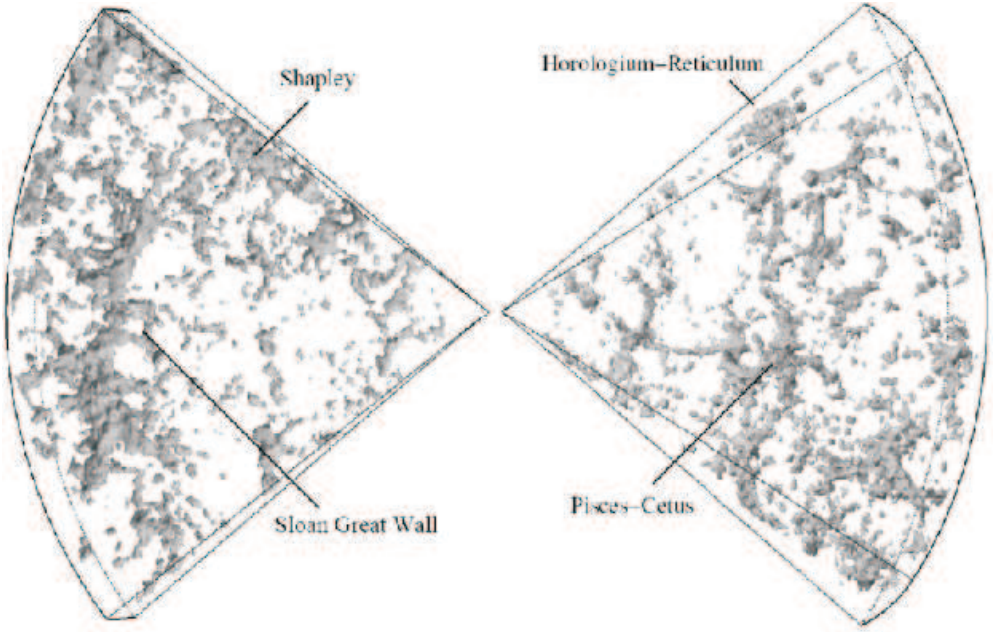

large scale structure (LSS)

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probes of LSS measure the distribution of nearby galaxies

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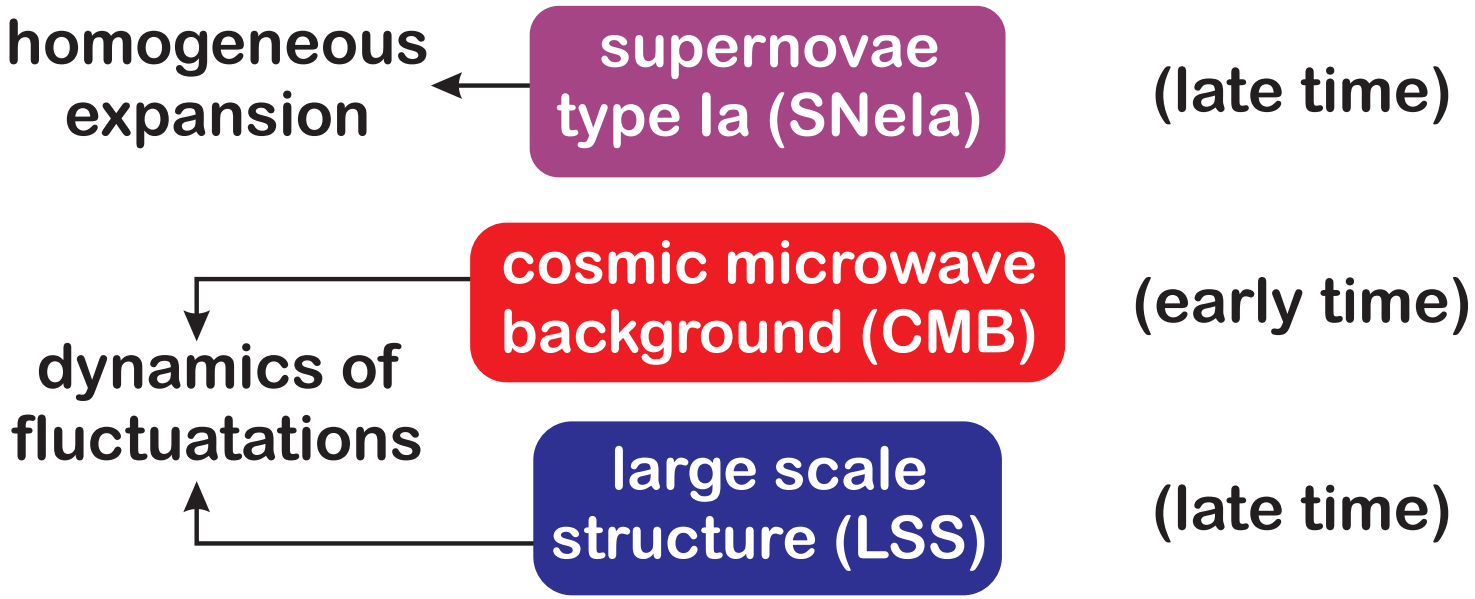

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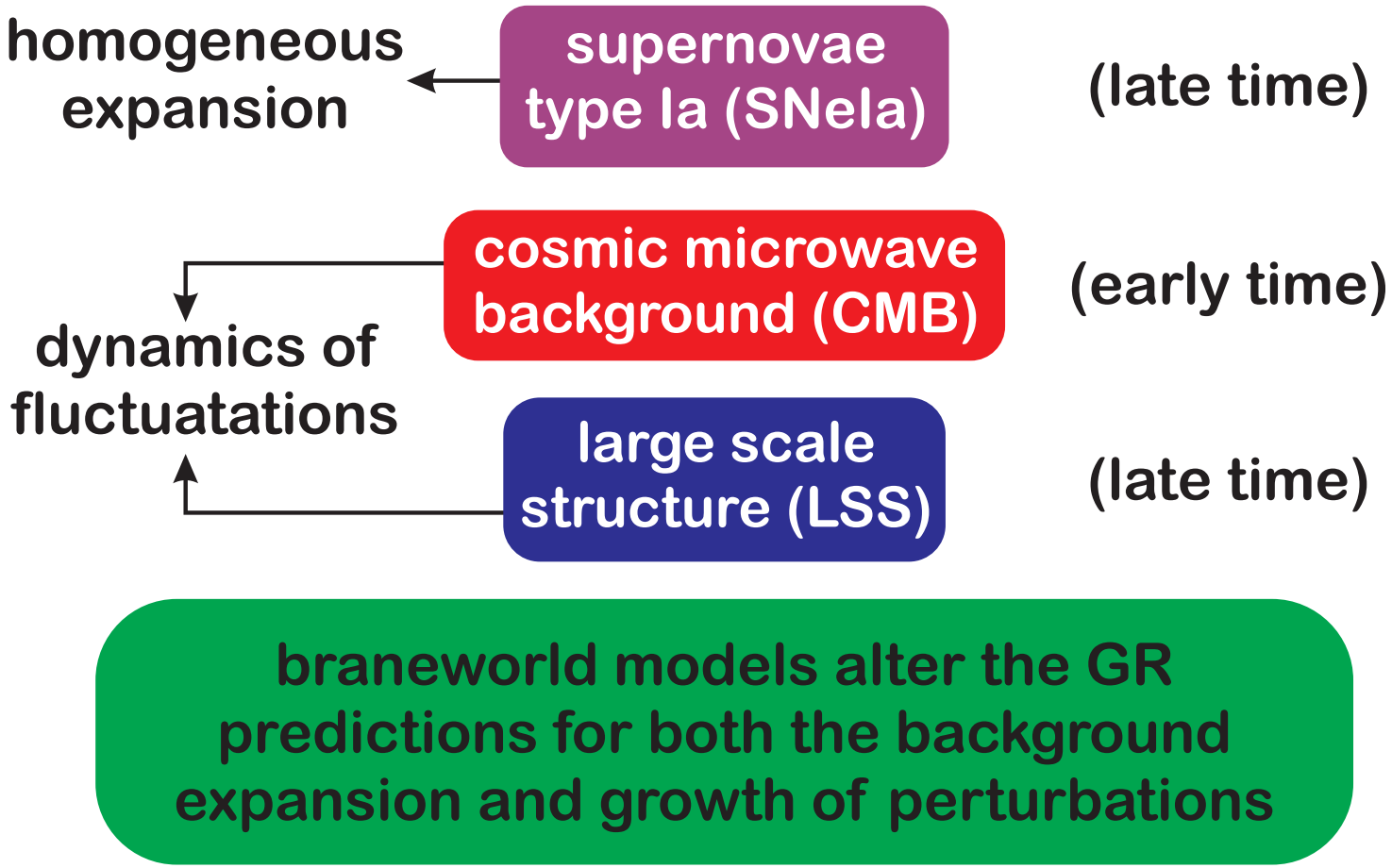
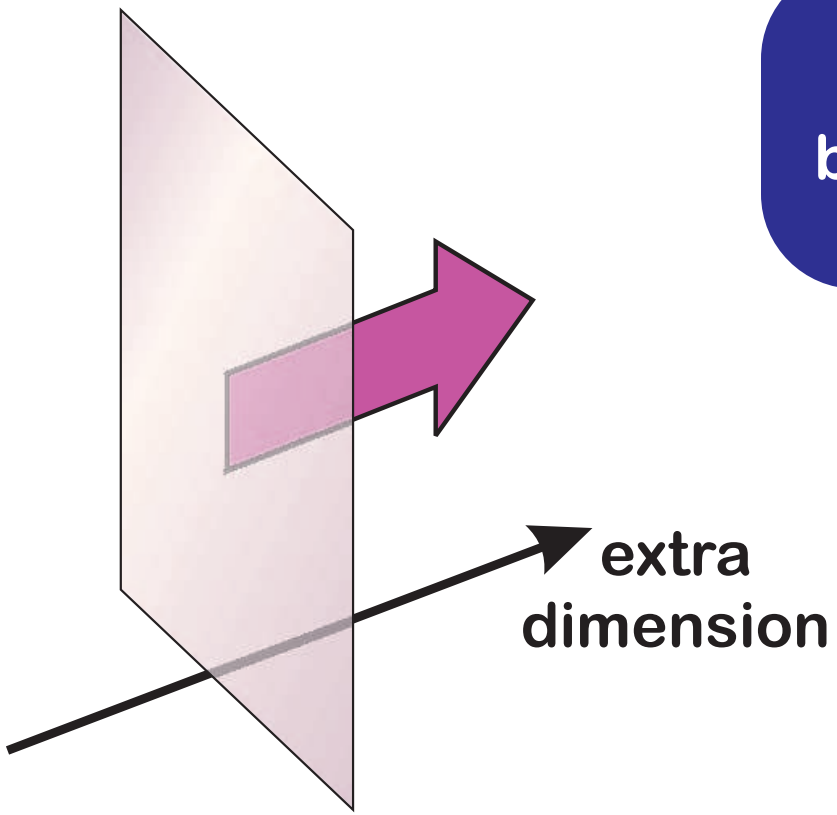


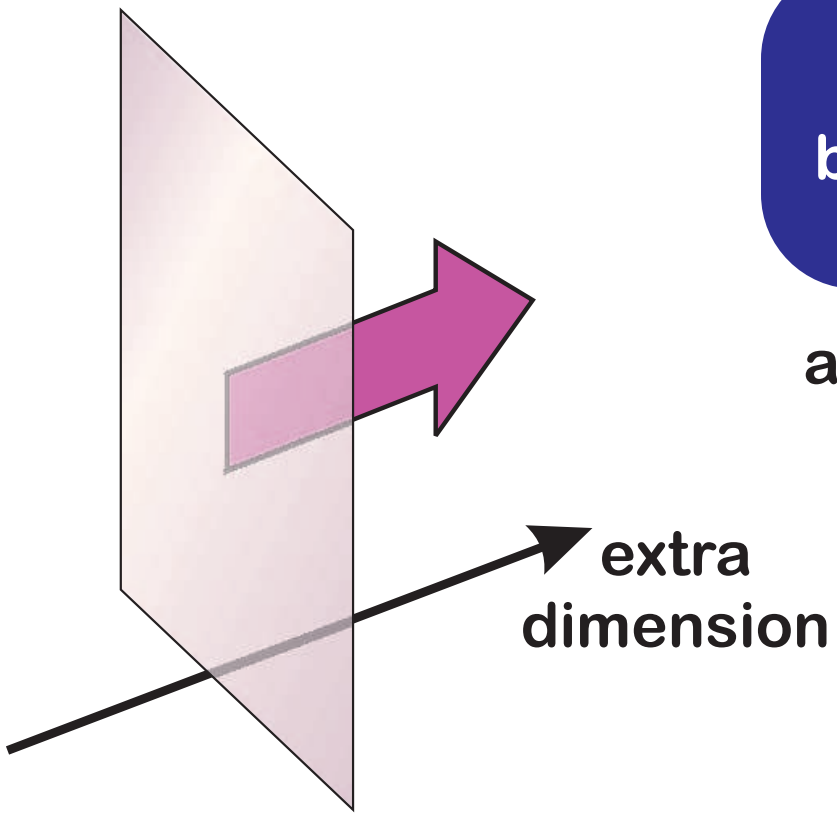
Modifications to the expansion



in braneworld cosmology, the brane moves in the extra dimension

Modifications to the expansion

brane motion = cosmological expansion



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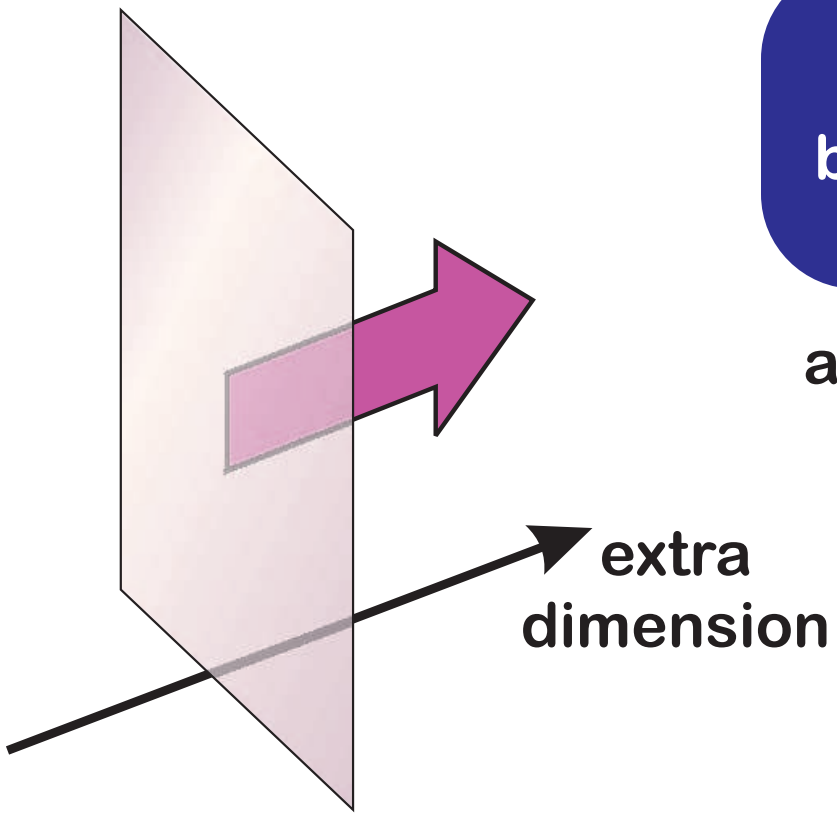


in braneworld cosmology, the brane moves in the extra dimension

as the brane moves, its size changes

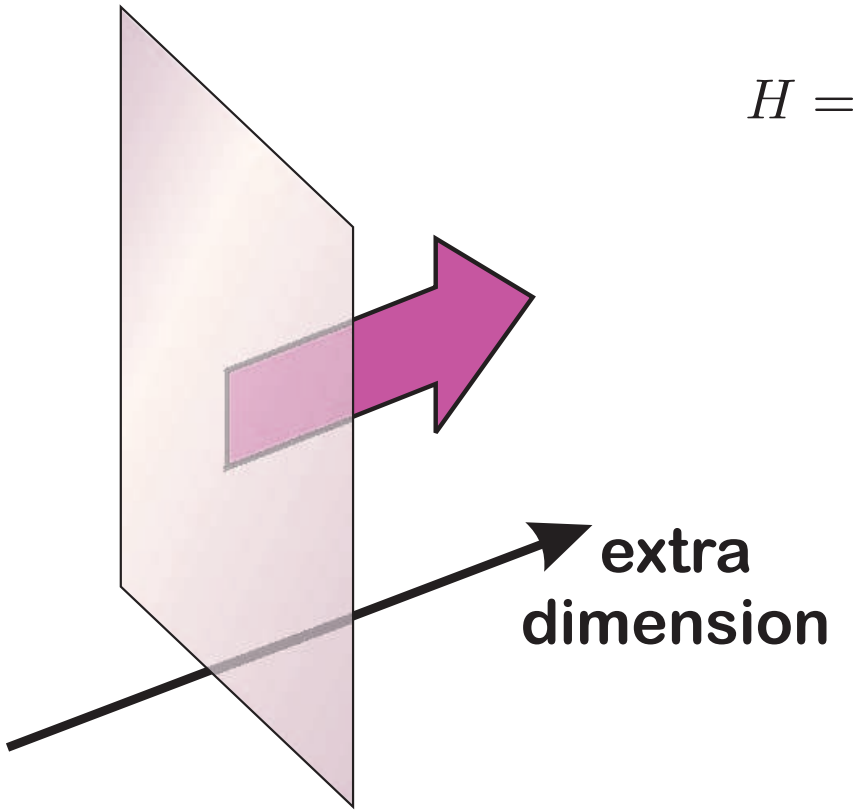
“if the universe is expanding, what is it expanding into?”

Modifications to the expansion

brane motion = cosmological expansion

$$a = \text{relative brane size}$$

$$H = \text{Hubble rate} = \frac{1}{a}\frac{da}{dt}$$



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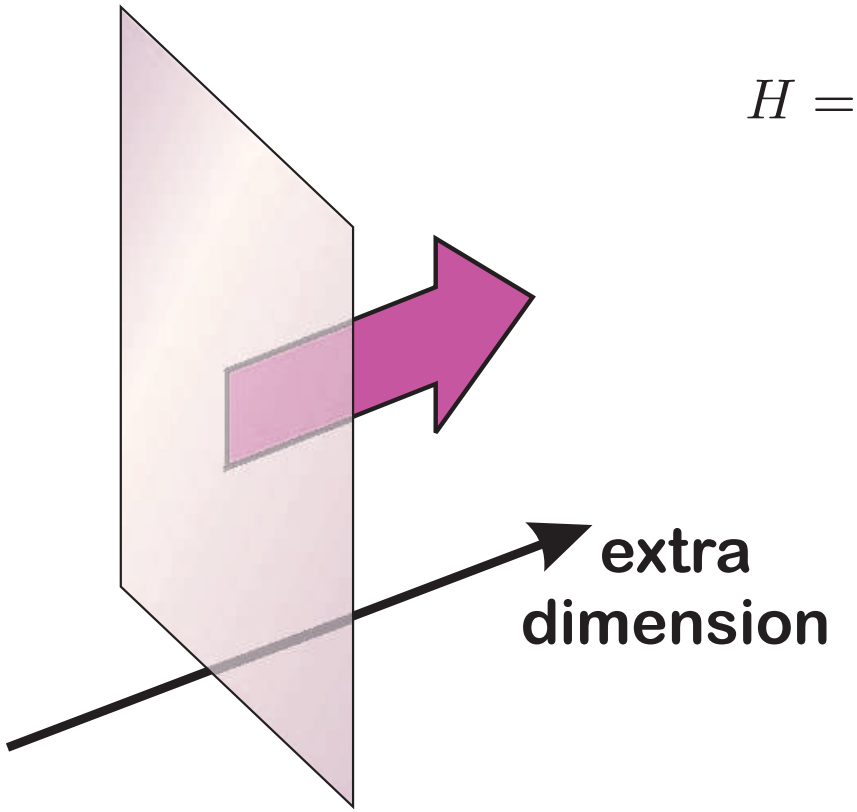
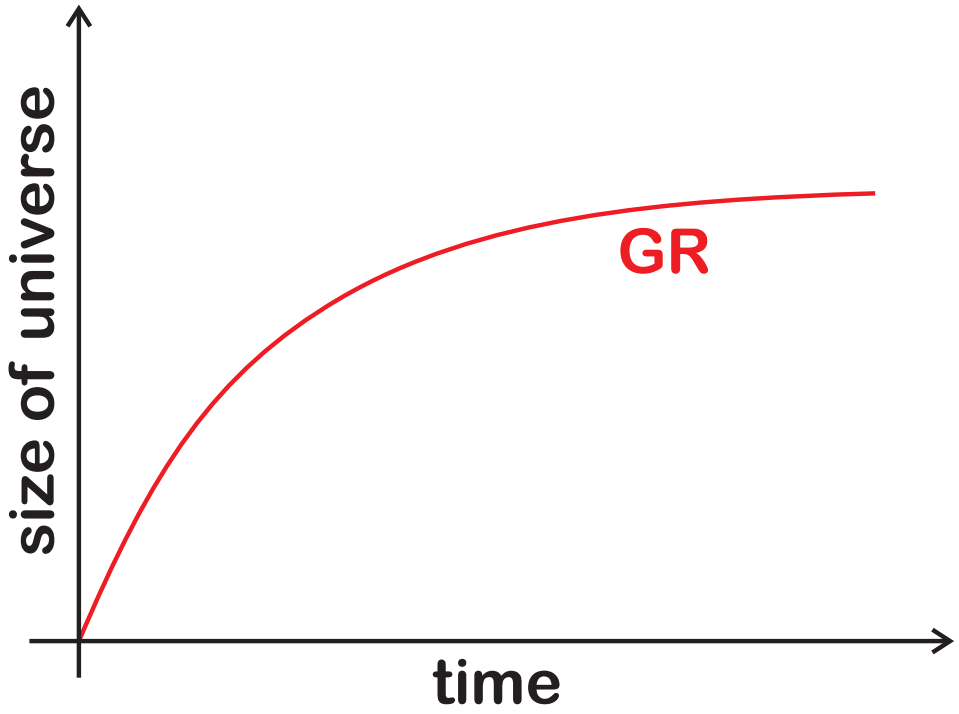


RS modifies GR expansion when $H\ell \gtrsim 1$ ($\ell \lesssim 50\,\mu\text{m}$)

DGP modifies GR expansion when $Hr_c \lesssim 1$ ($r_c \gtrsim 3000\,\text{Mpc}$)

Modifications to the expansion



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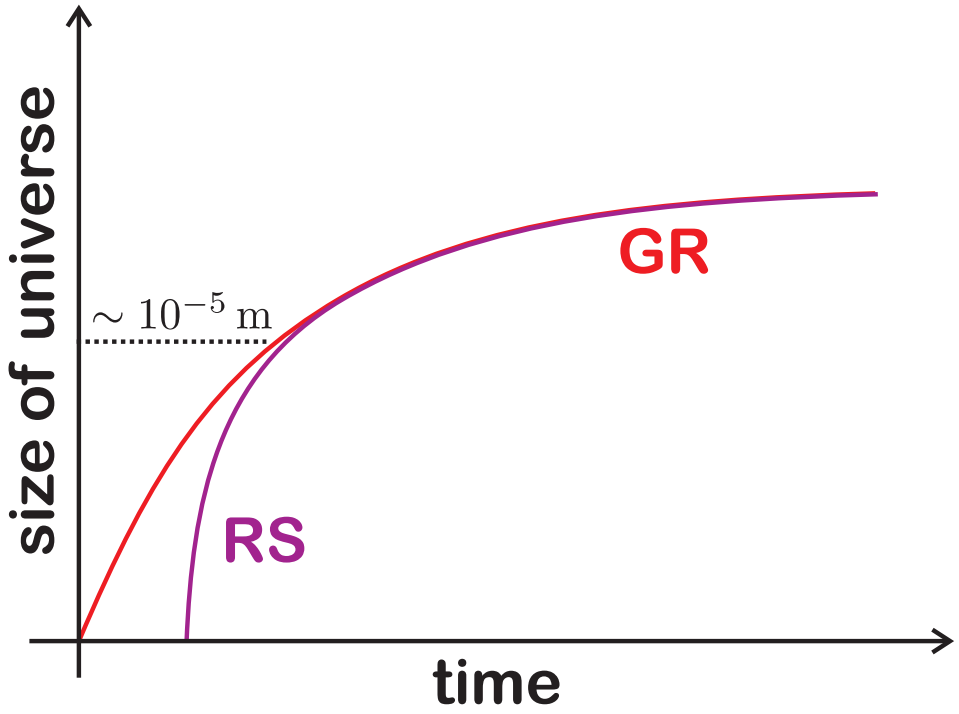

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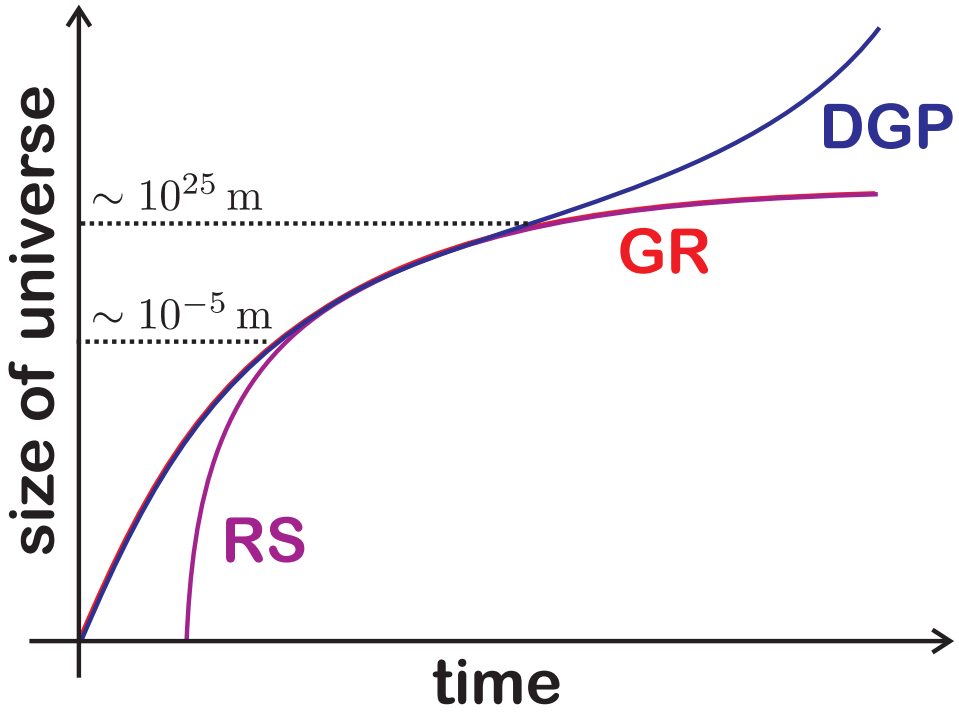

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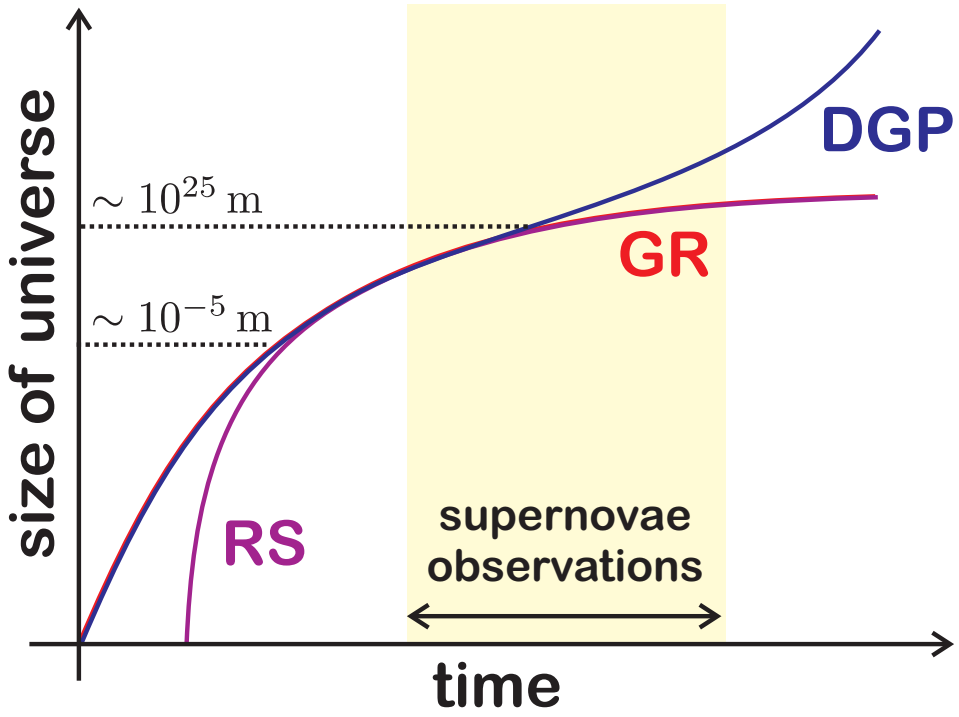
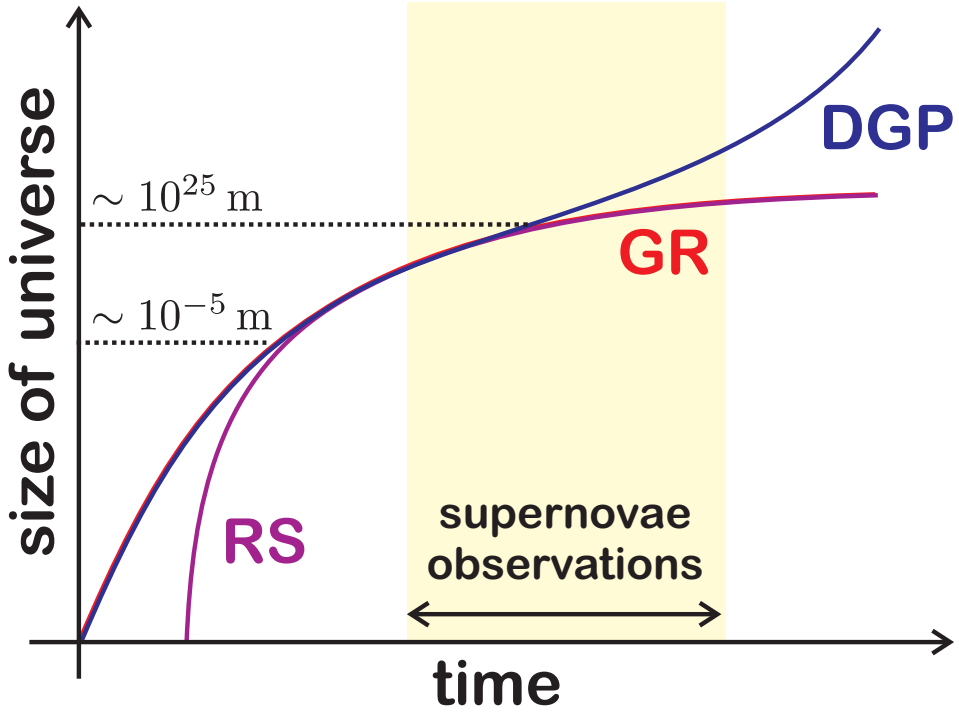


Modifications to the expansion

DGP actually predicts late time acceleration!



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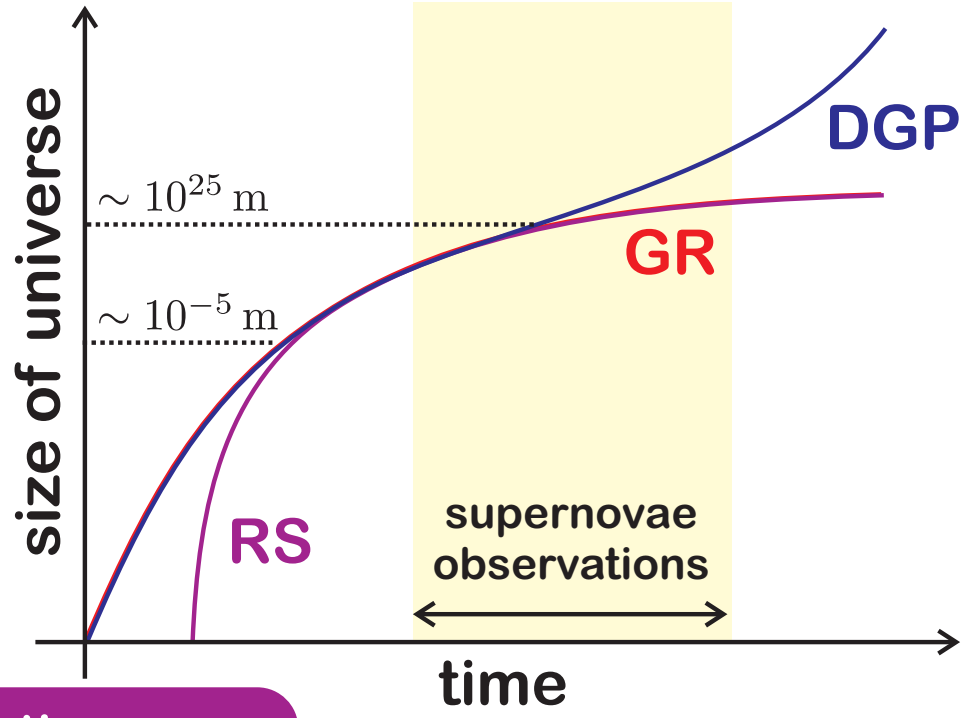
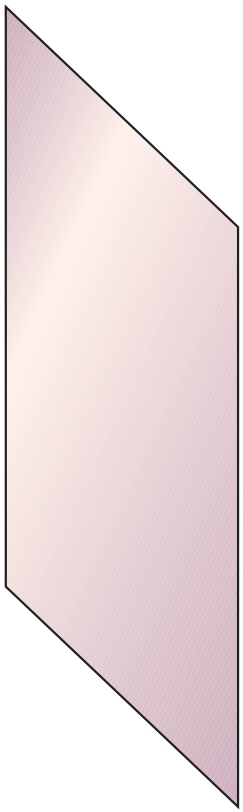


RS corrections are too early too observe directly

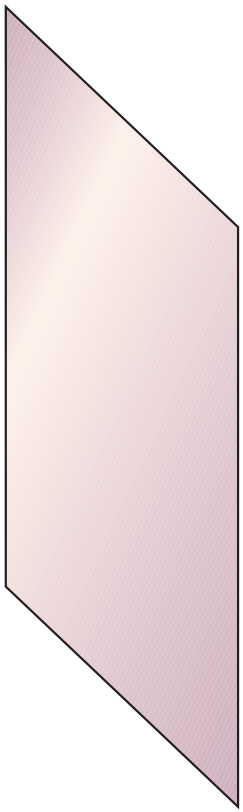
Modifications to perturbations



supernovae observations alone are not enough to discriminate between DGP and other “dark energy” models

they also shed no light on RS scenarios

Modifications to perturbations



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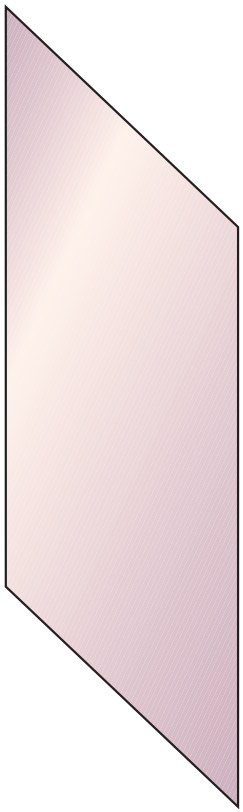
...look to perturbations of the model to get more information

Modifications to perturbations



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Modifications to perturbations

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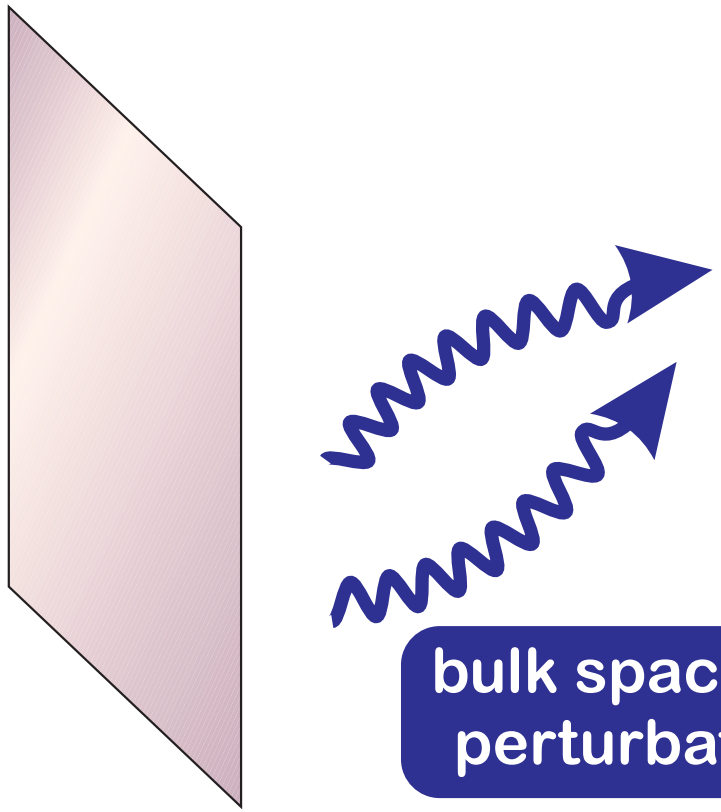
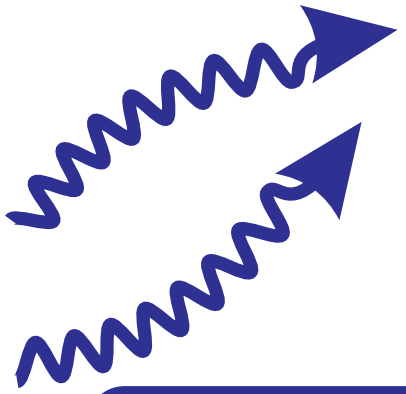


bulk spacetime perturbations

Modifications to perturbations

inhomogeneties in brane matter



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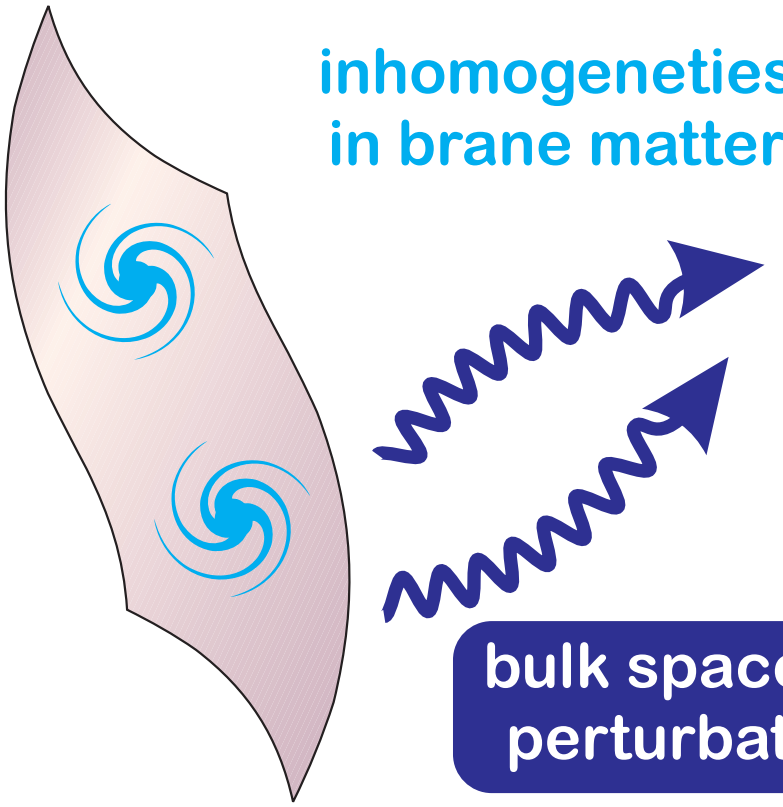
Modifications to perturbations

fluctuations in brane geometry

inhomogeneties in brane matter



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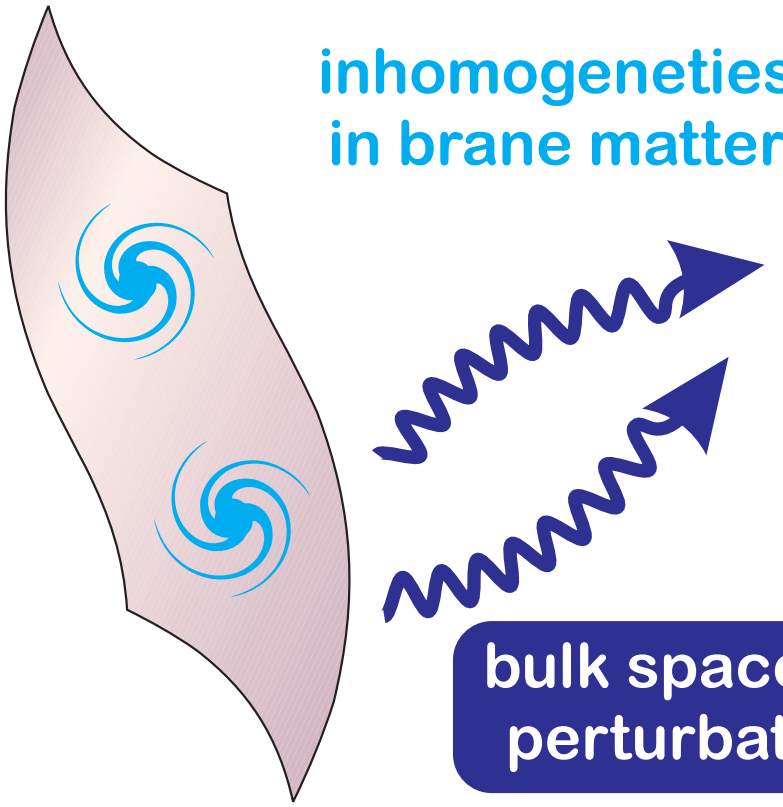

bulk spacetime perturbations

in braneworld model, there are lots of different perturbations to consider

plus the brane is moving --- complicated problem that needs simulations

Modifications to perturbations

RS: corrections come in early universe

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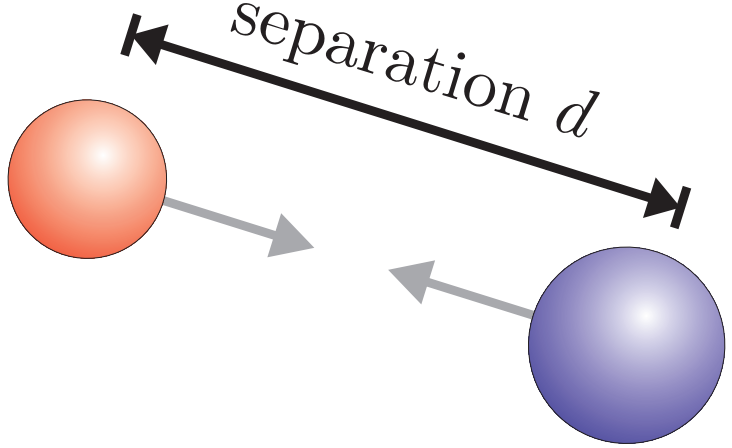

in early universe, overdense regions are close together

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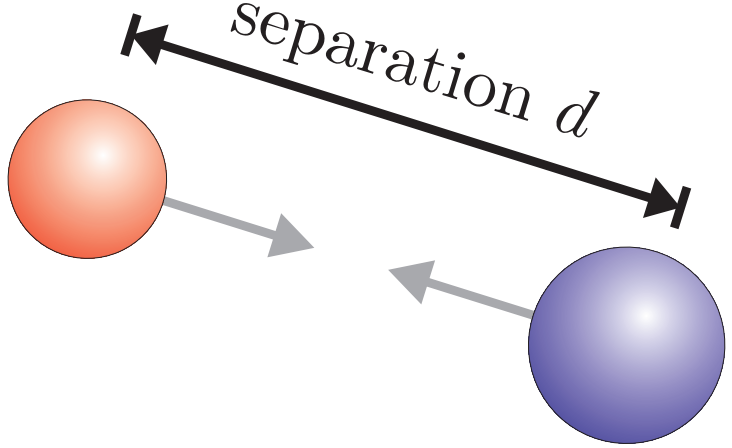

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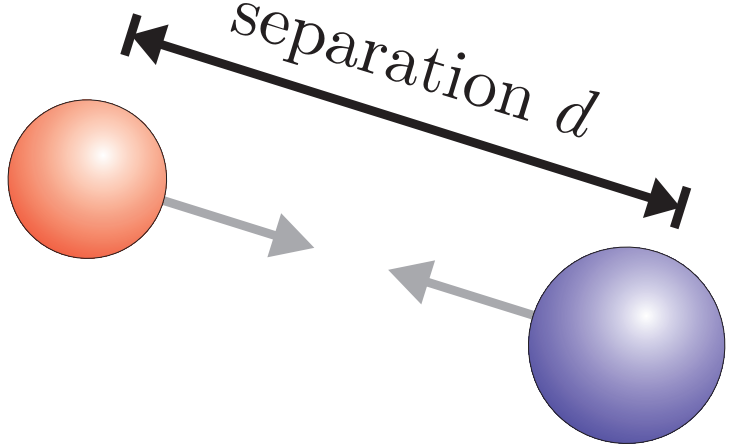


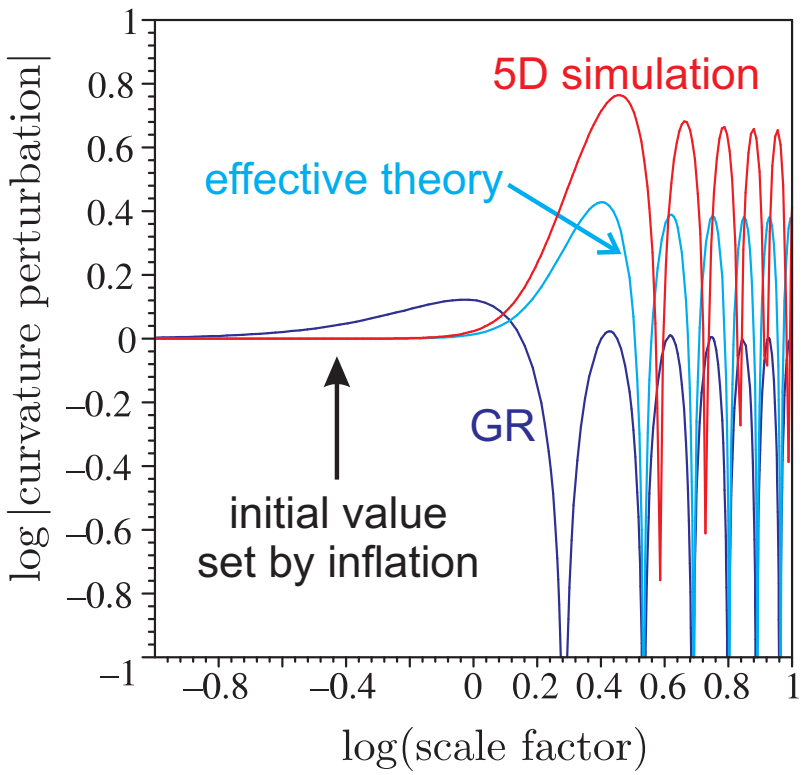
force of gravity in RS enhanced for separations less than curvature scale

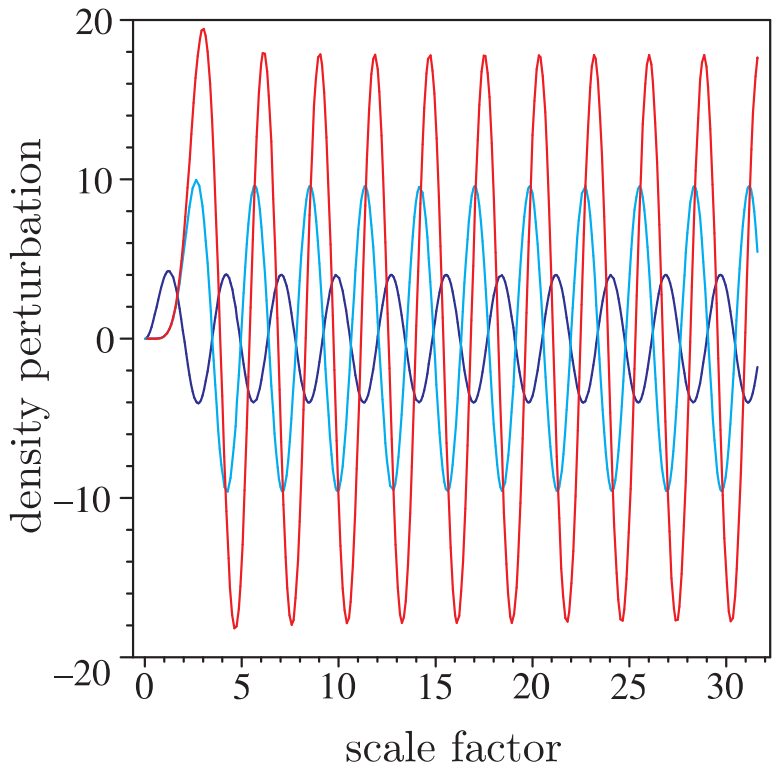
in early universe, overdense regions are close together

hence, perturbations should grow faster than in GR

Modifications to perturbations

Cardoso, Hiramatsu, Koyama & SSS; JCAP (2007)





enhancement in amplitude of perturbations seen in simulations

Modifications to perturbations

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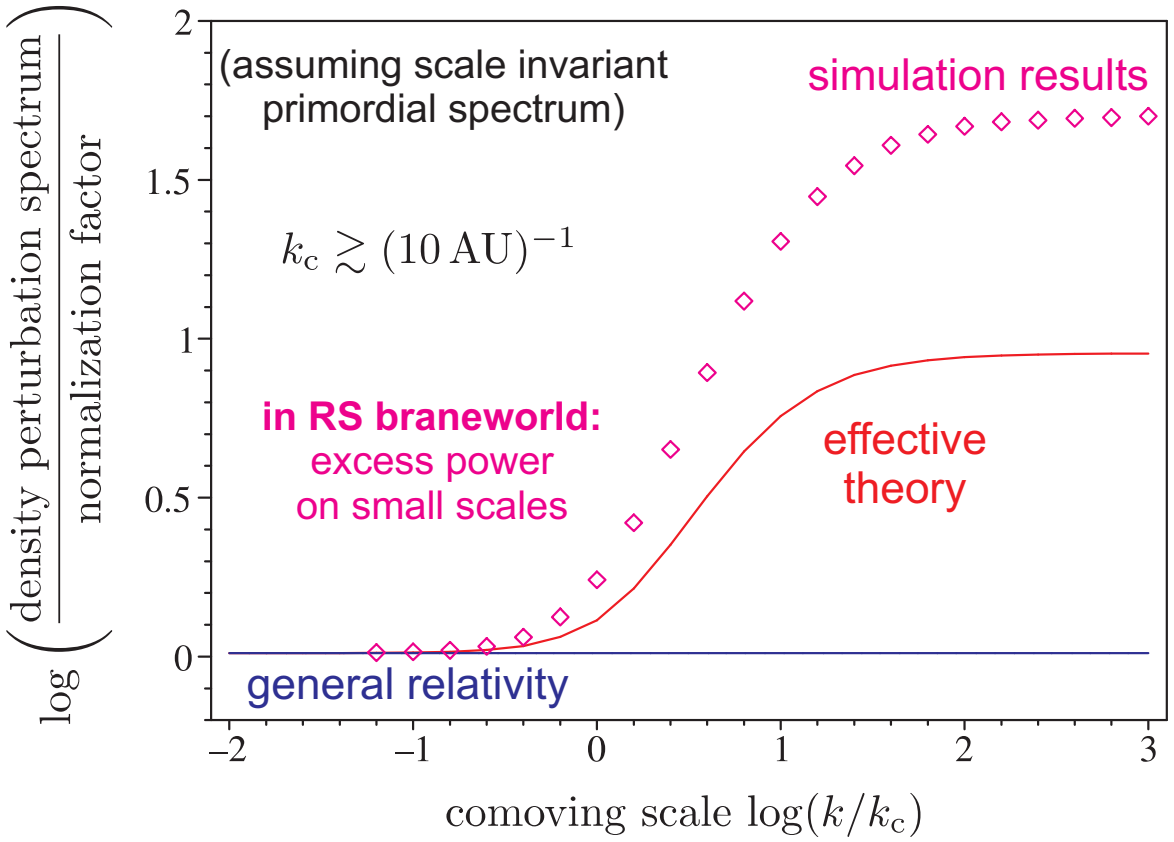

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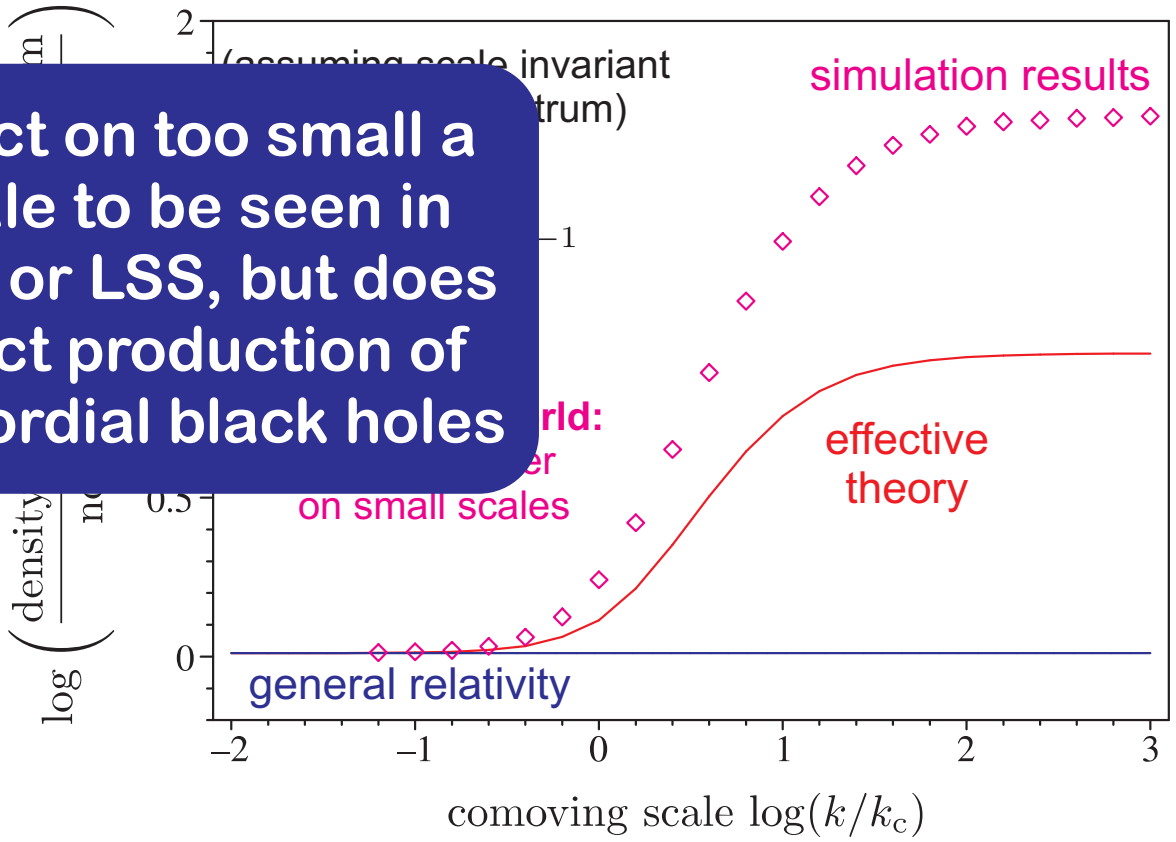

effect on too small a scale to be seen in CMB or LSS, but does affect production of primordial black holes

results in an amplification in the power spectrum of density perturbations on small scales

Modifications to perturbations

DGP: corrections come in late universe

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best seen in the integrated Sachs-Wolfe effect

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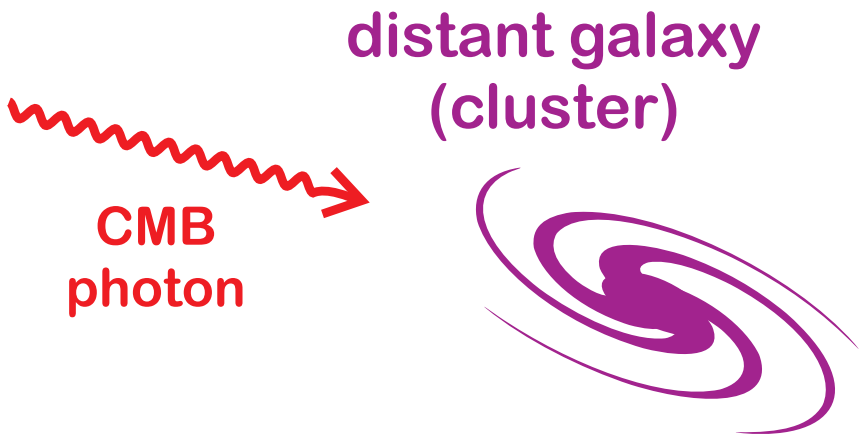

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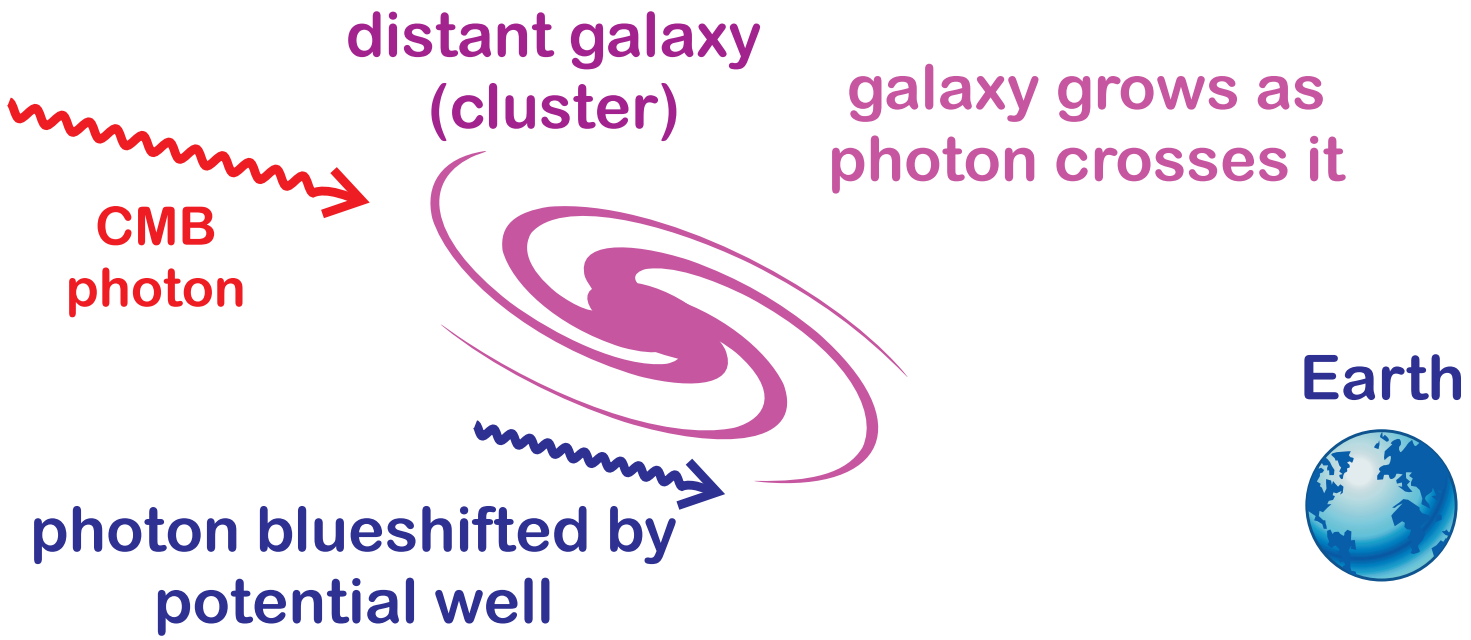

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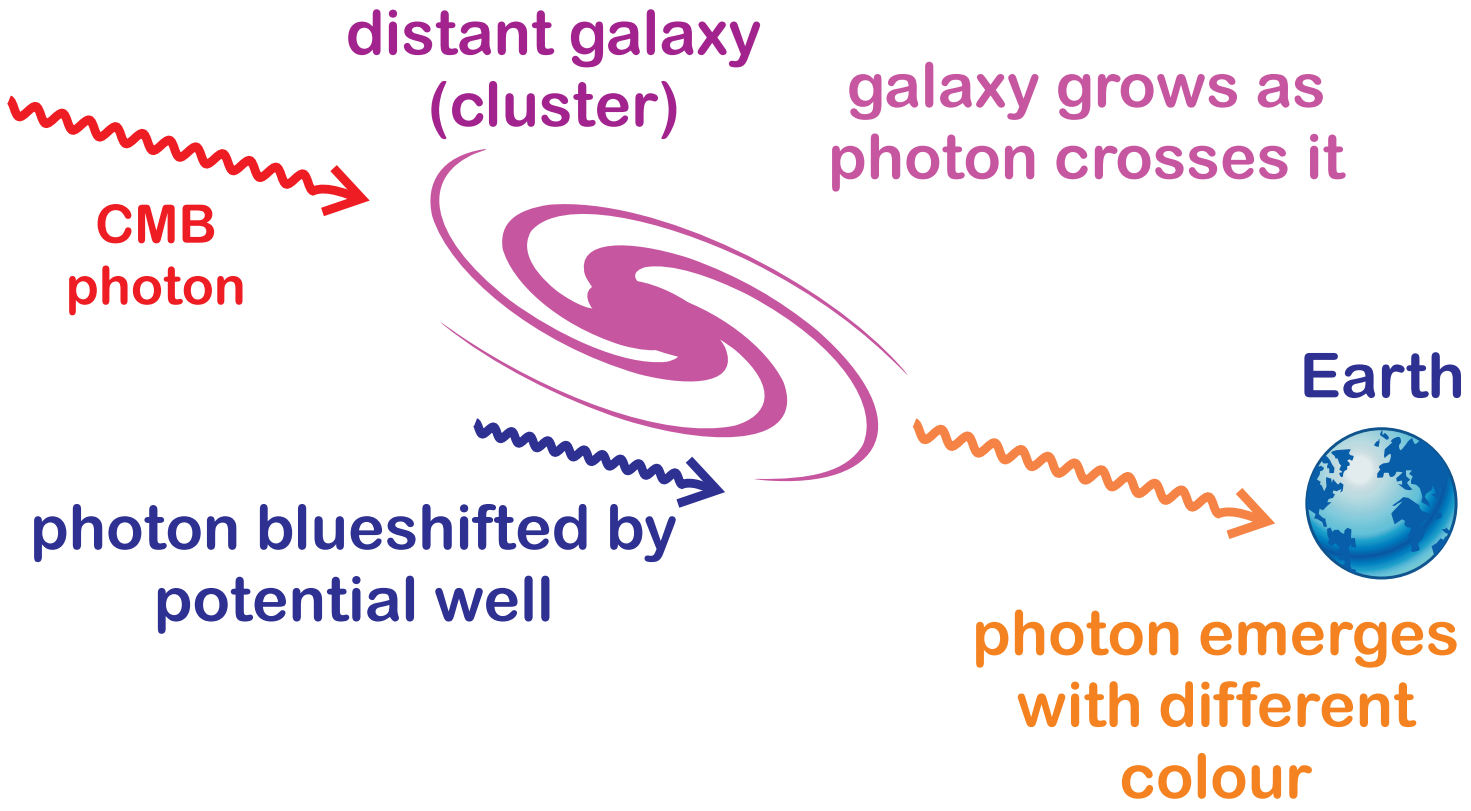

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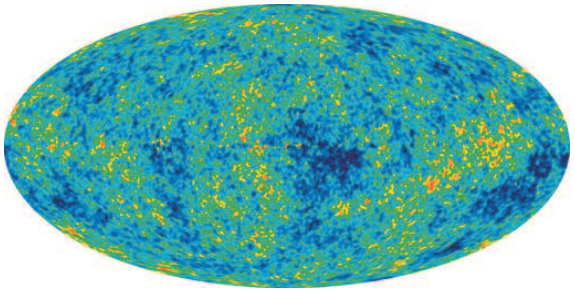
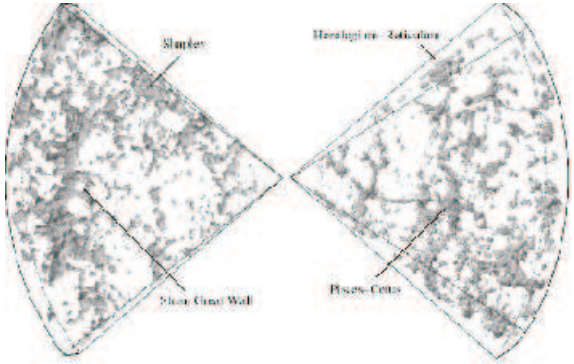


correlated

LSS



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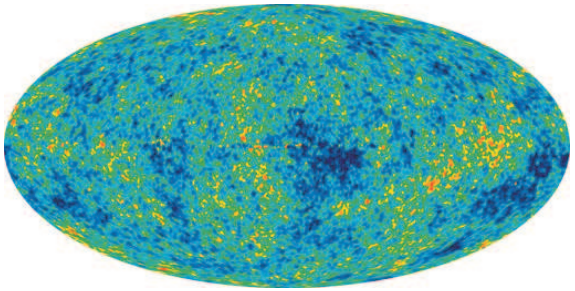

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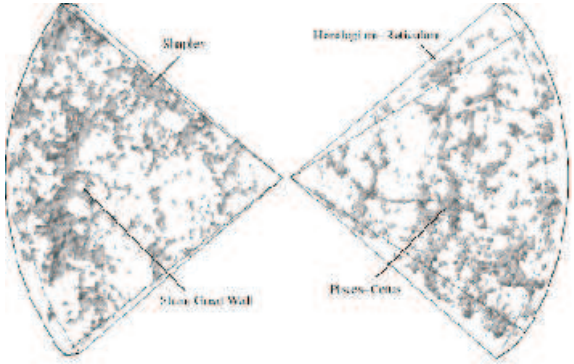
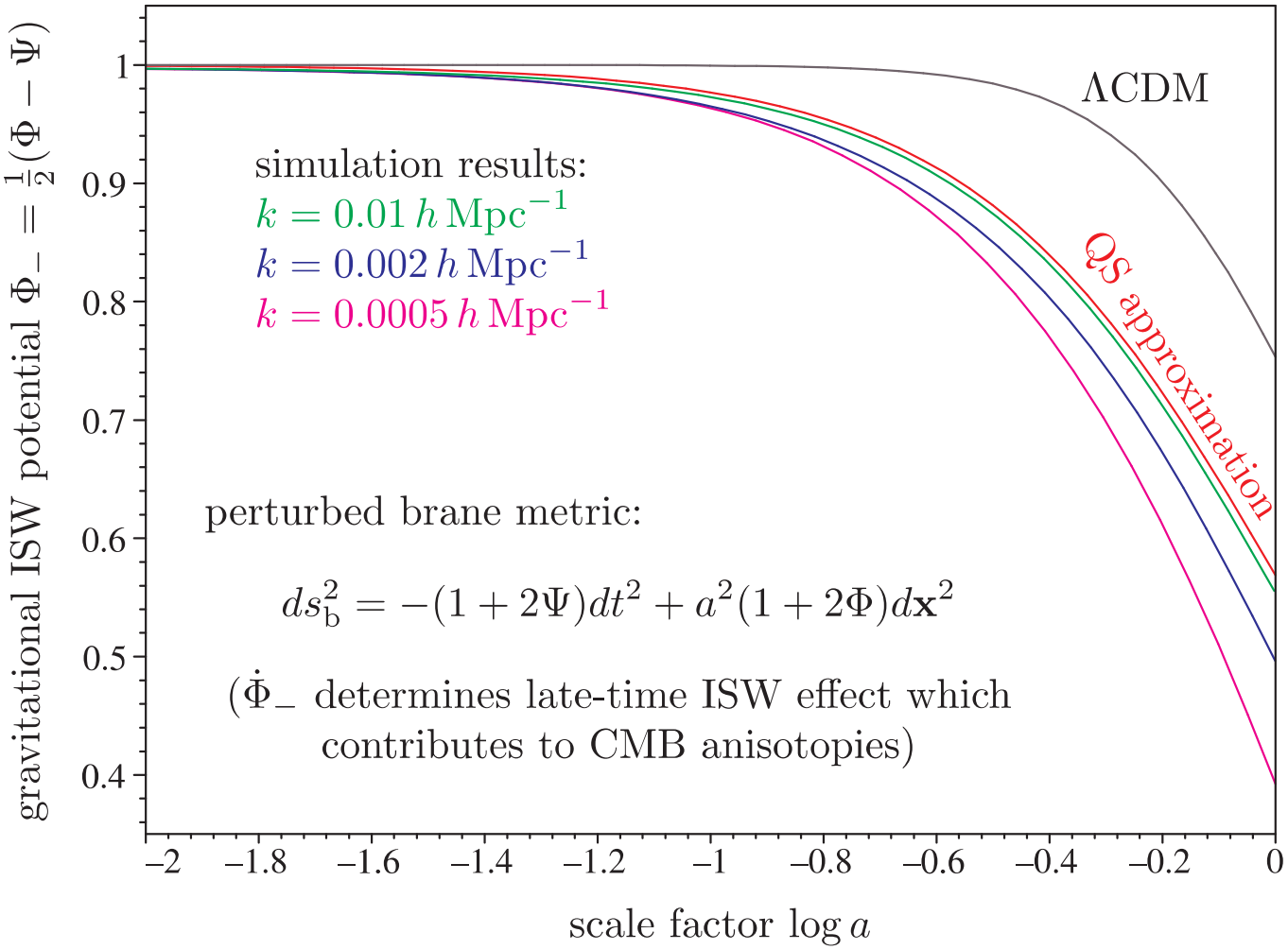


the DGP model predicts a different evolution for LSS than GR, hence the degree of CMB/LSS cross correlation changes

Modifications to perturbations

Cardoso, Koyama, SSS, Silva; arXiv:0711.2563



Braneworld black holes

Detecting gravitational waves

how does one detect GWs?

Detecting gravitational waves

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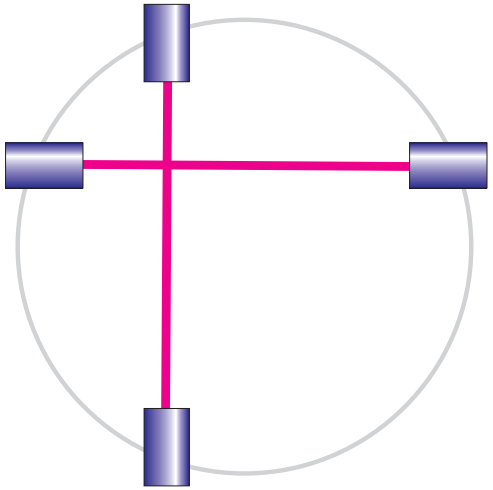
interferometer



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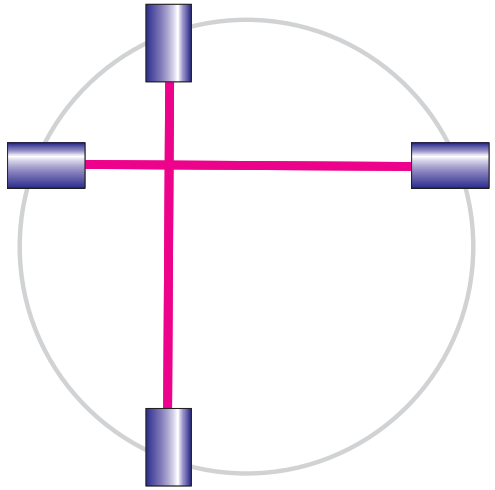

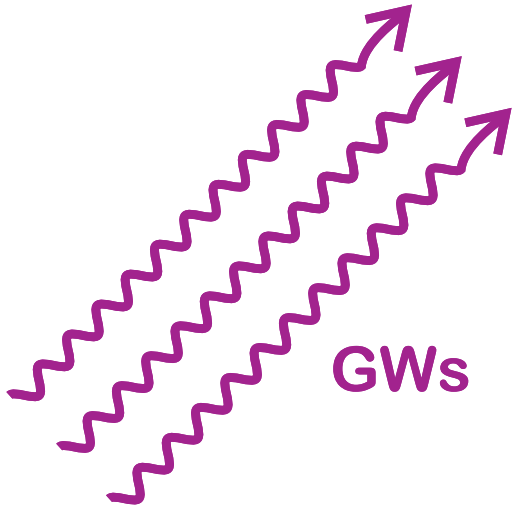

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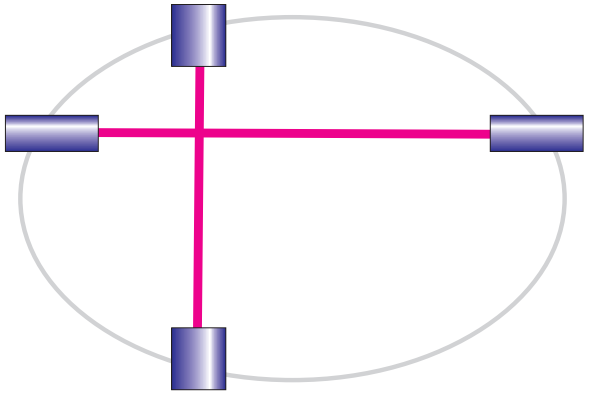

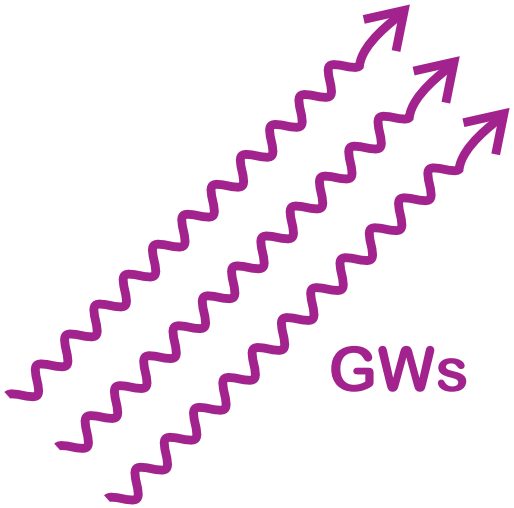

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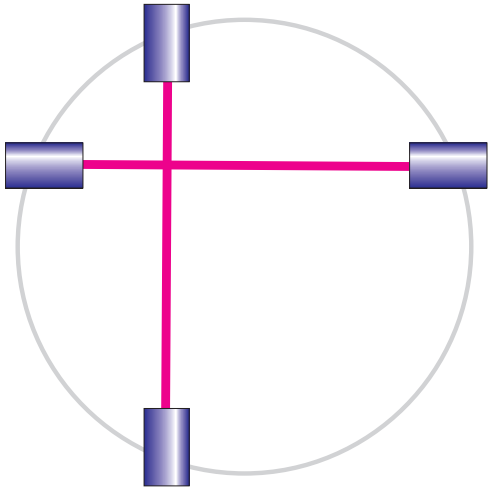

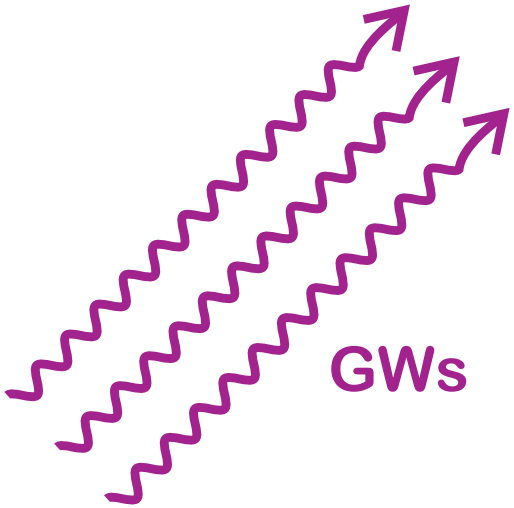

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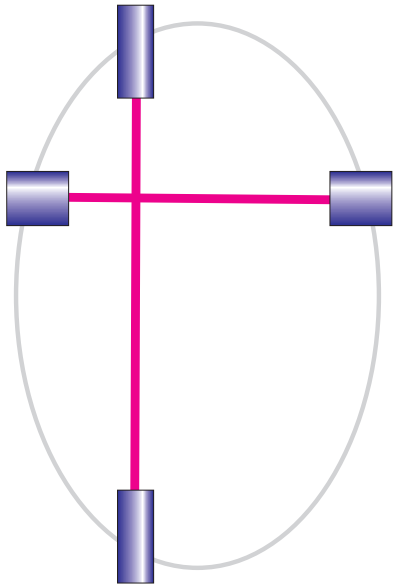

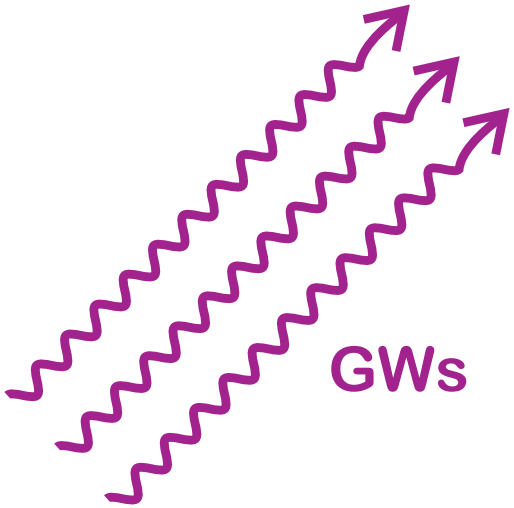

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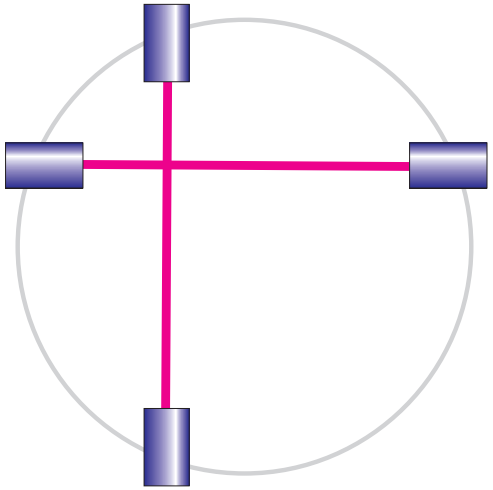

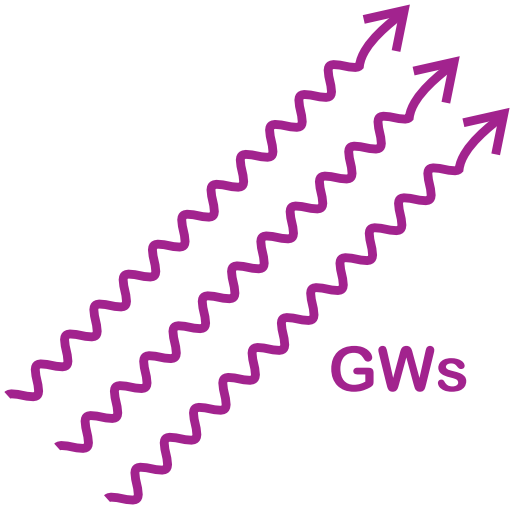

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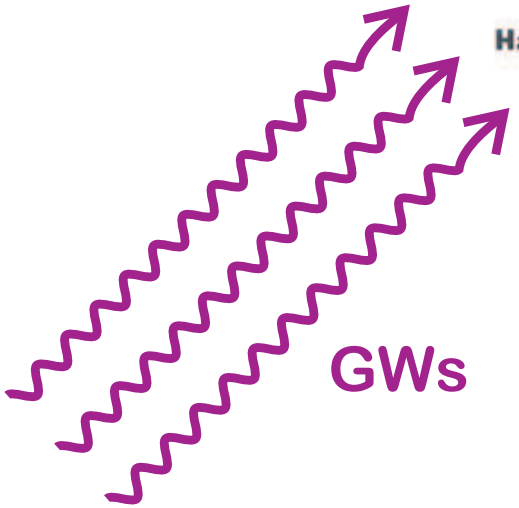
LIGO (4 km arms, kHz)

(in operation)



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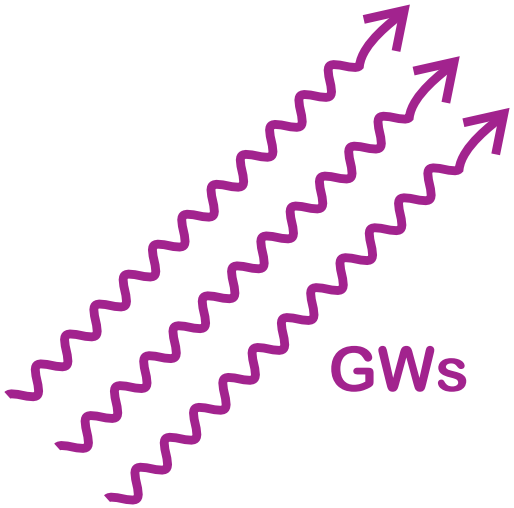
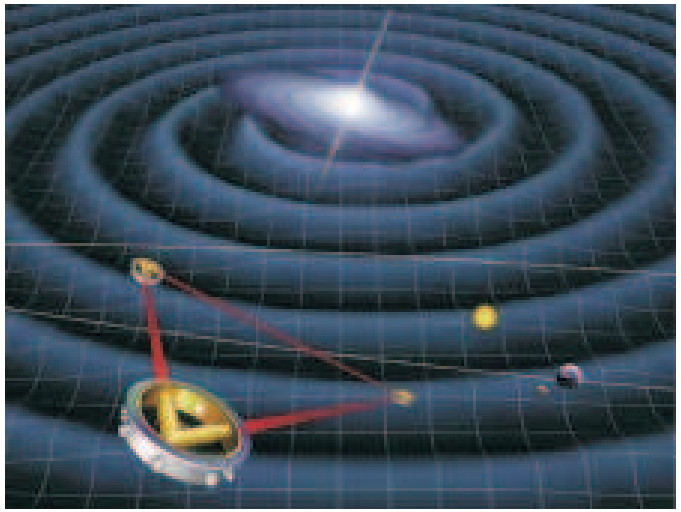


LISA (Gm arms, 10 mHz)



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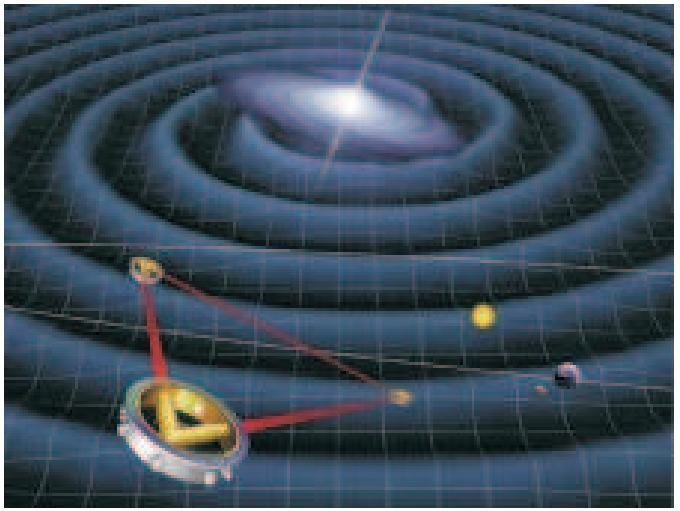

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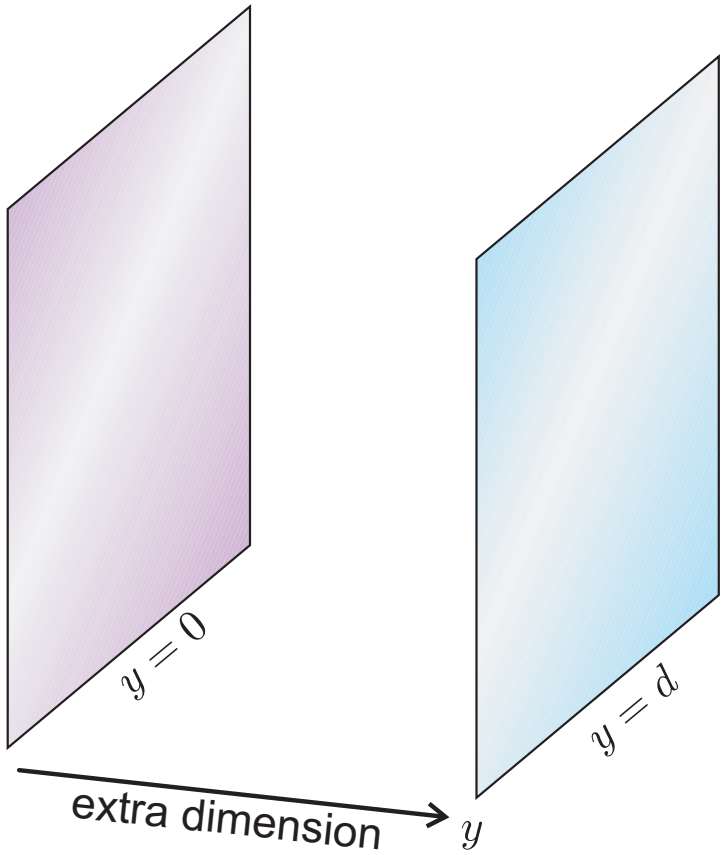
black holes are important sources, are there any braneworld signatures?

The black string braneworld

Our braneworld black hole model involves the two-brane variant of the RS setup:



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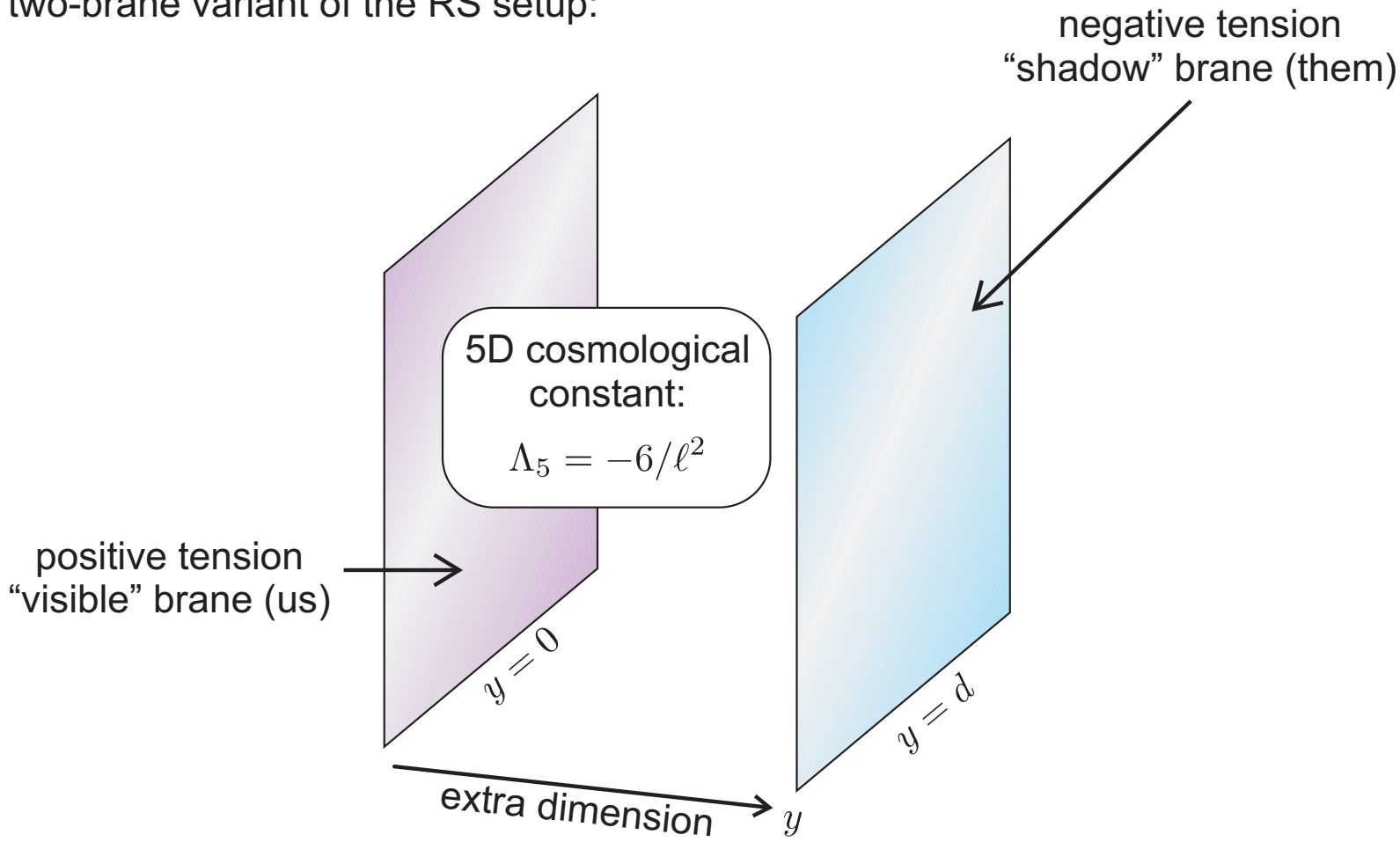

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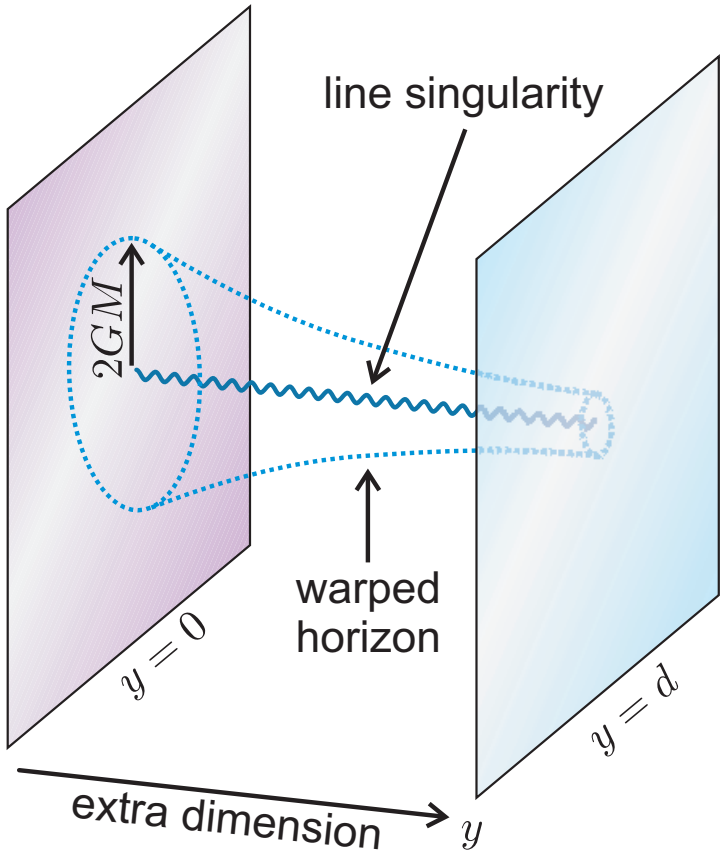

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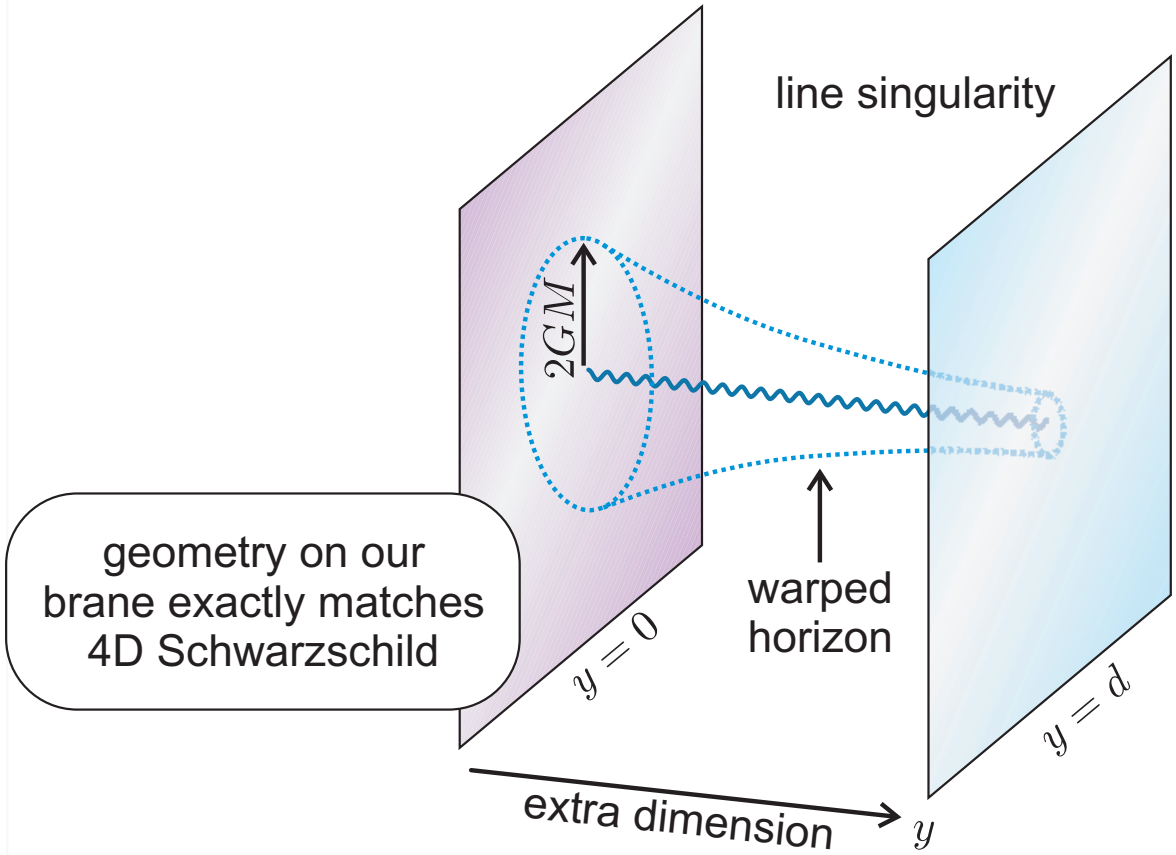

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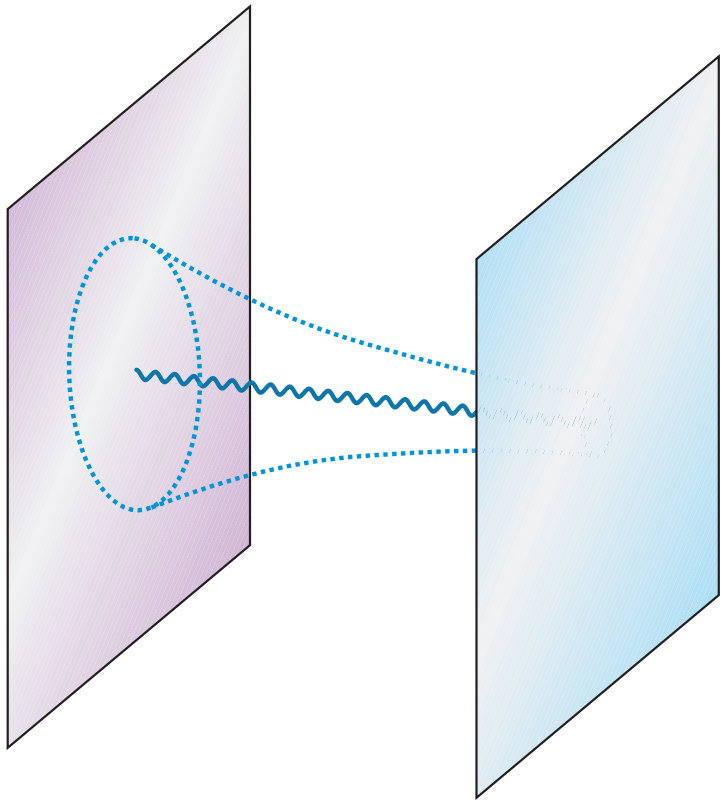

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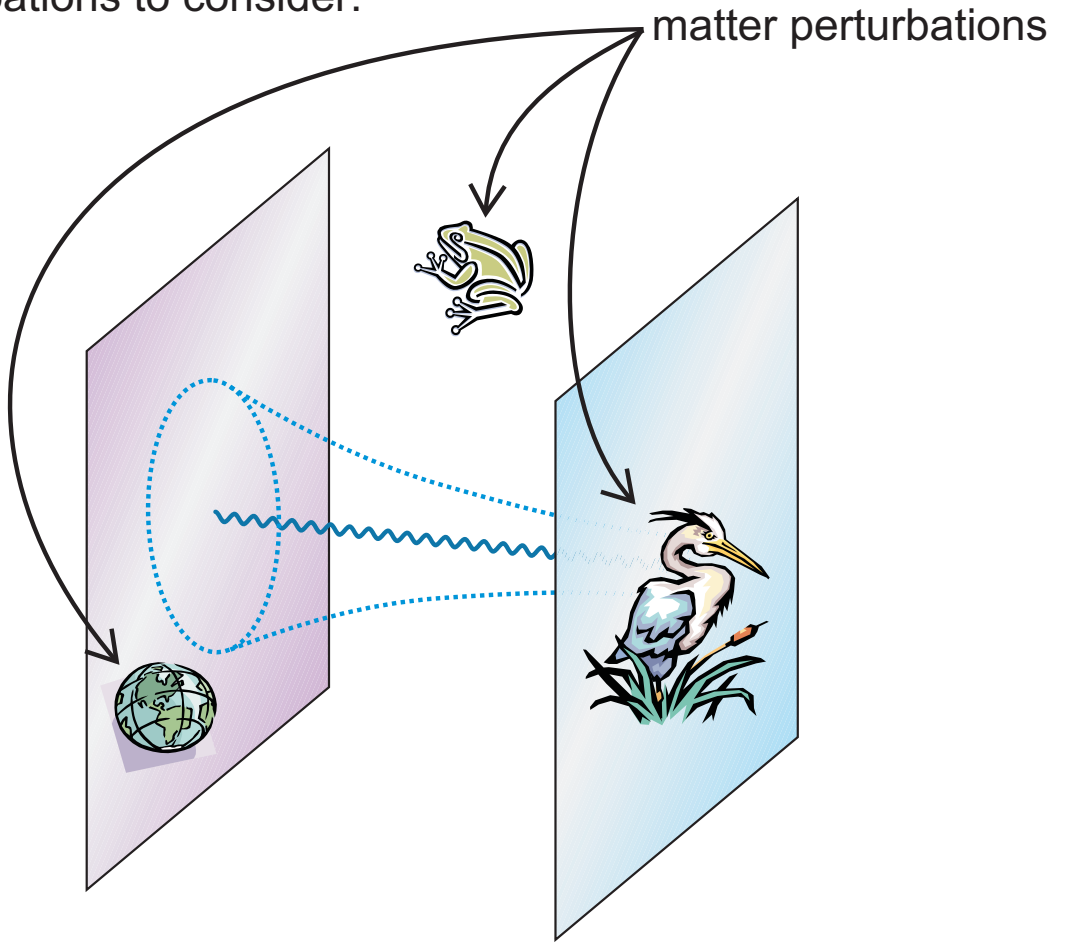

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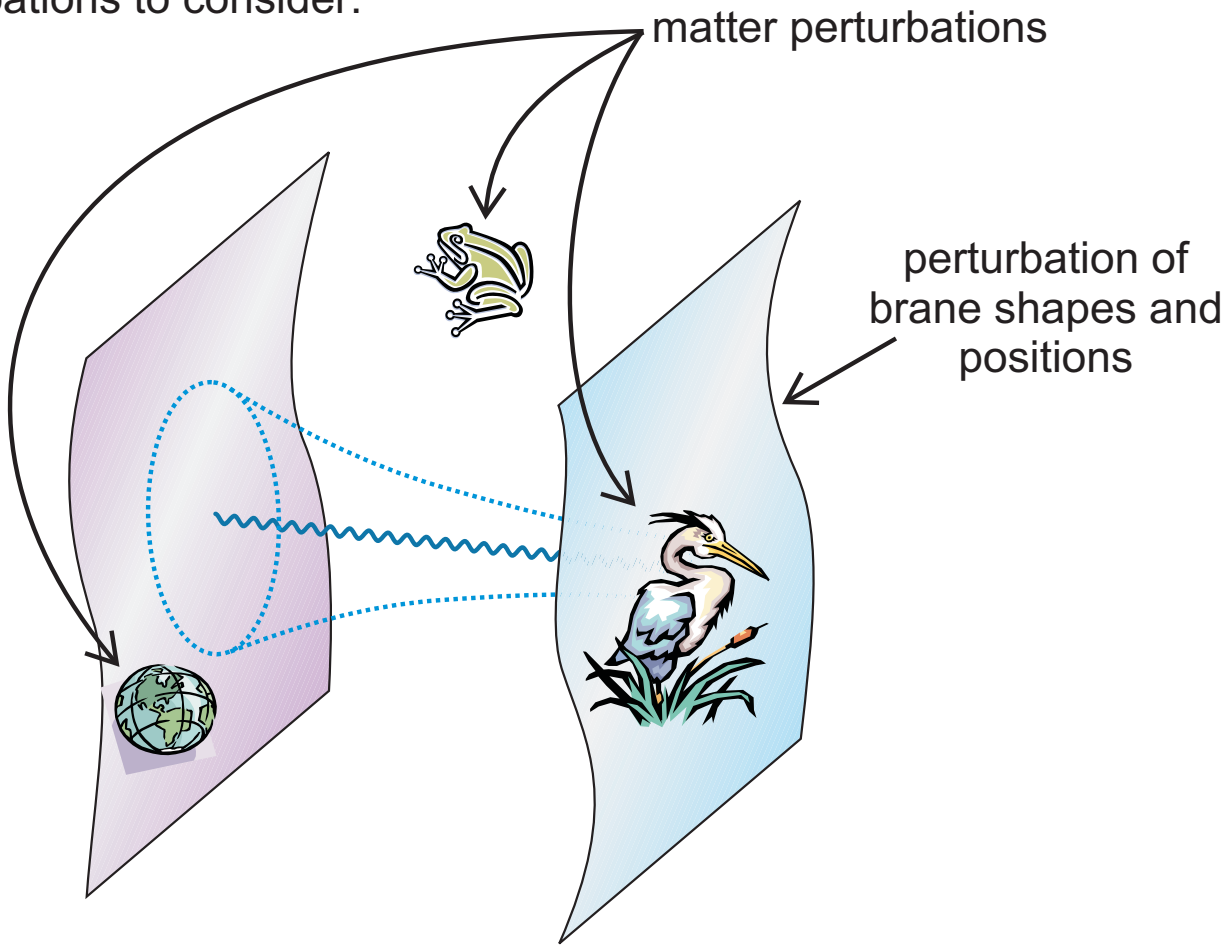

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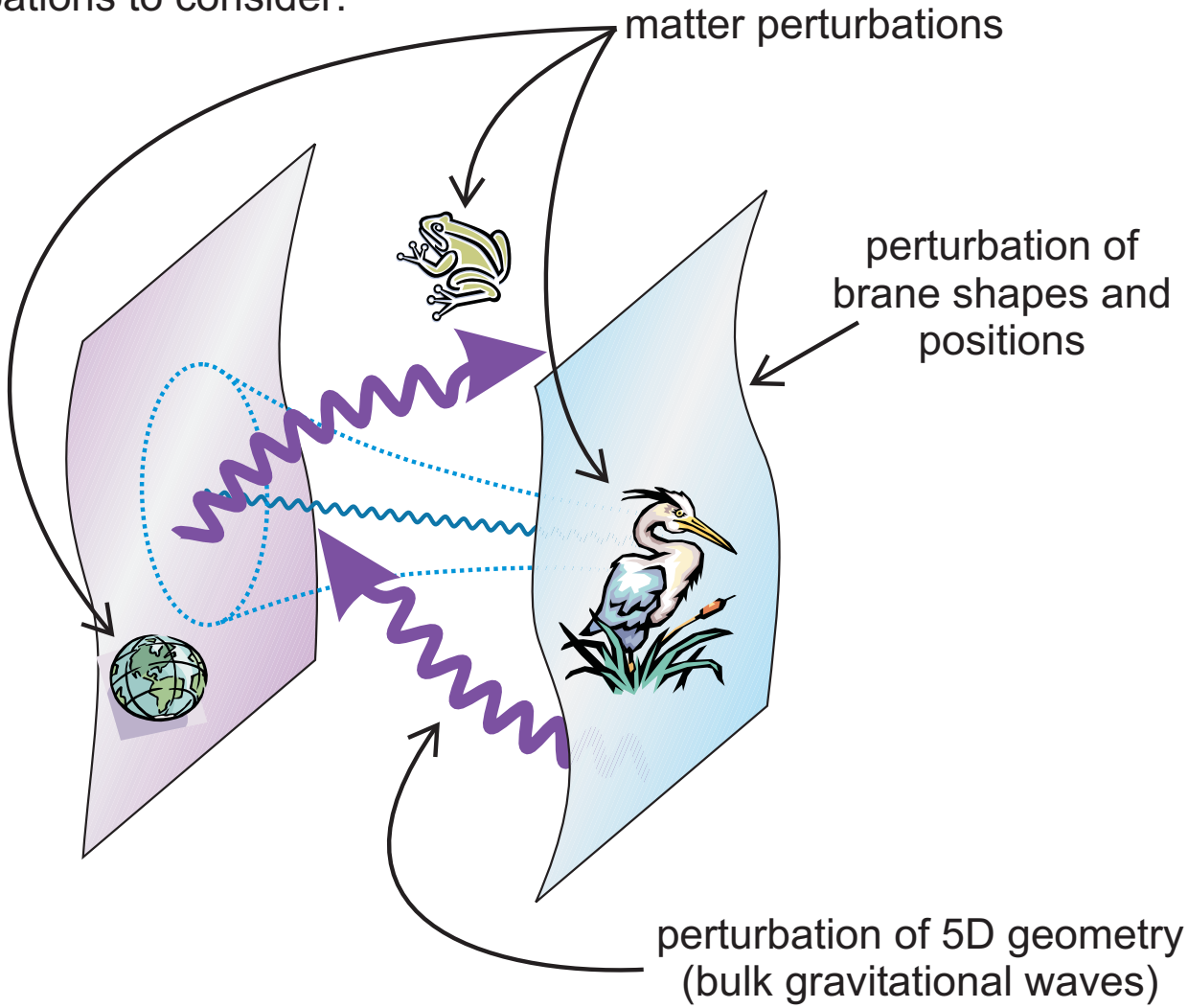

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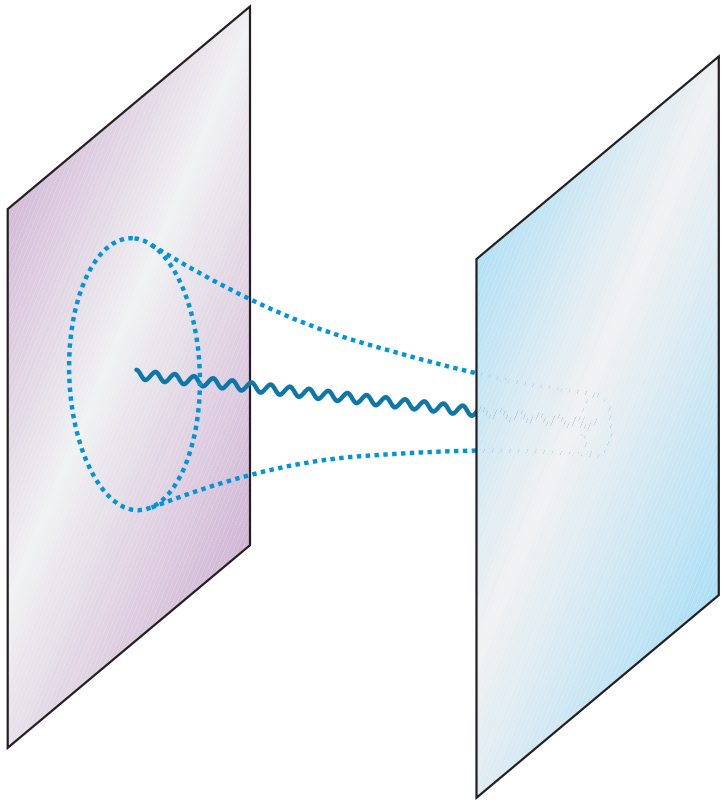

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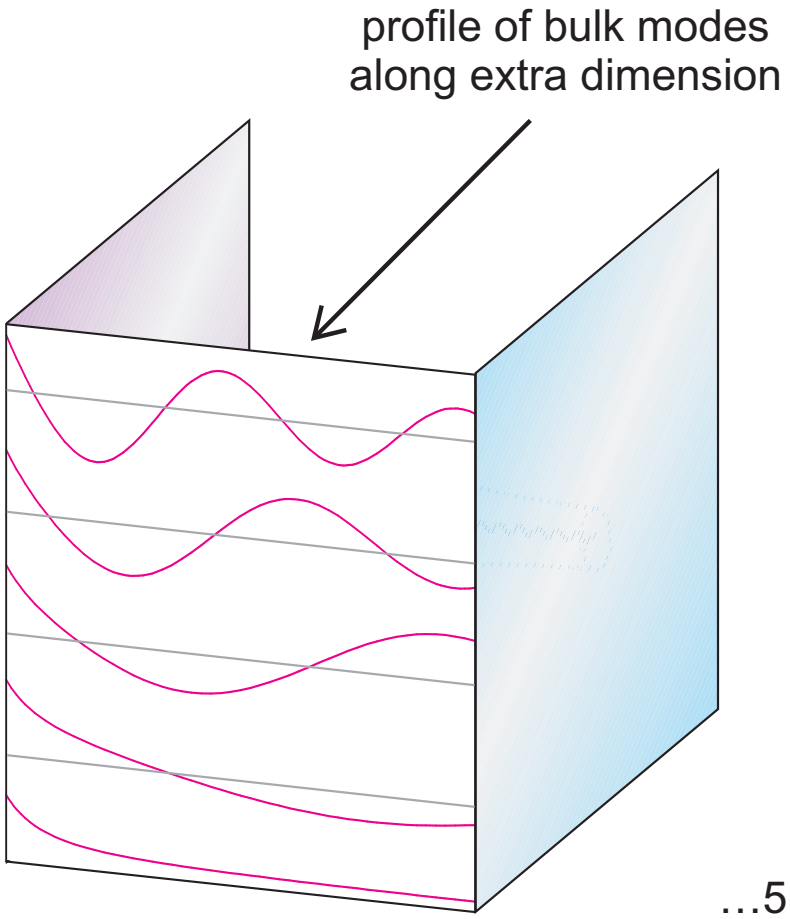

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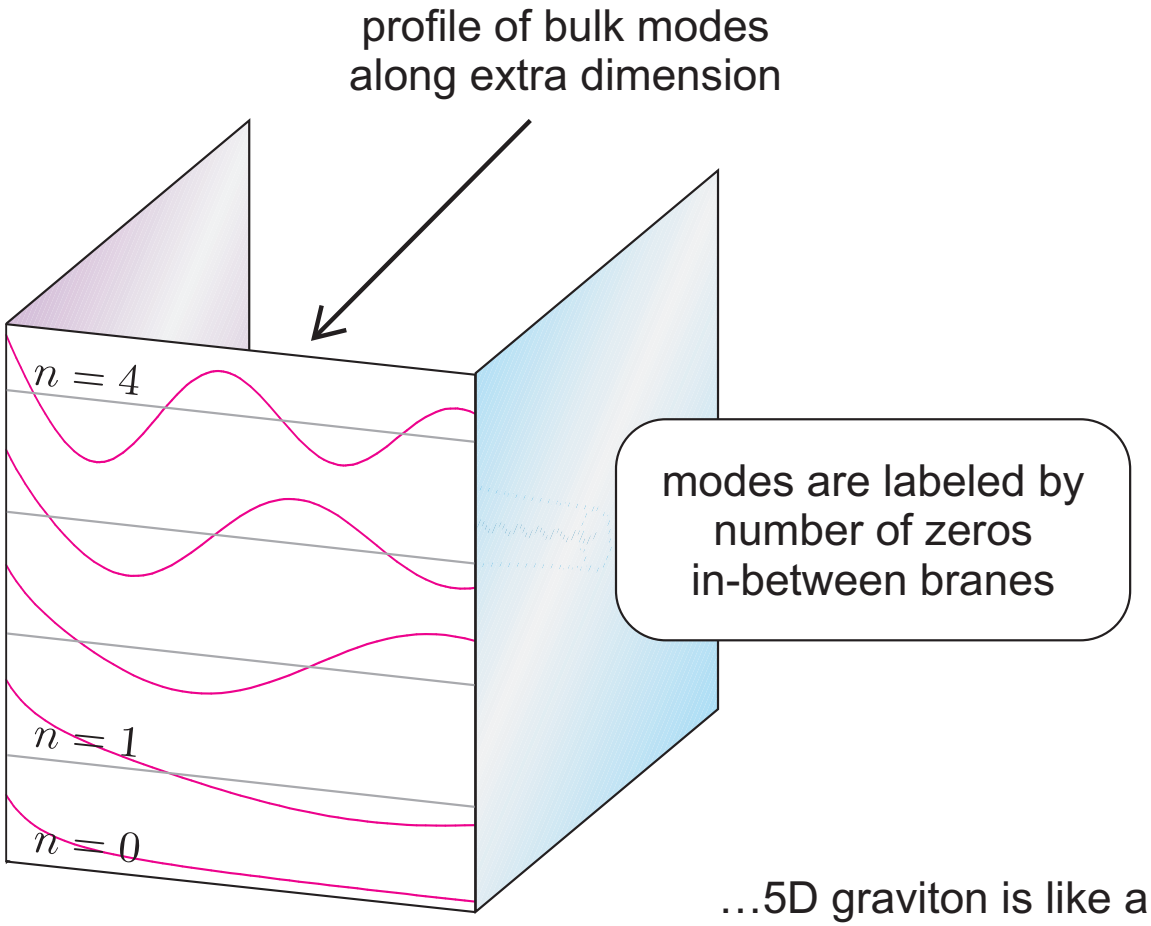

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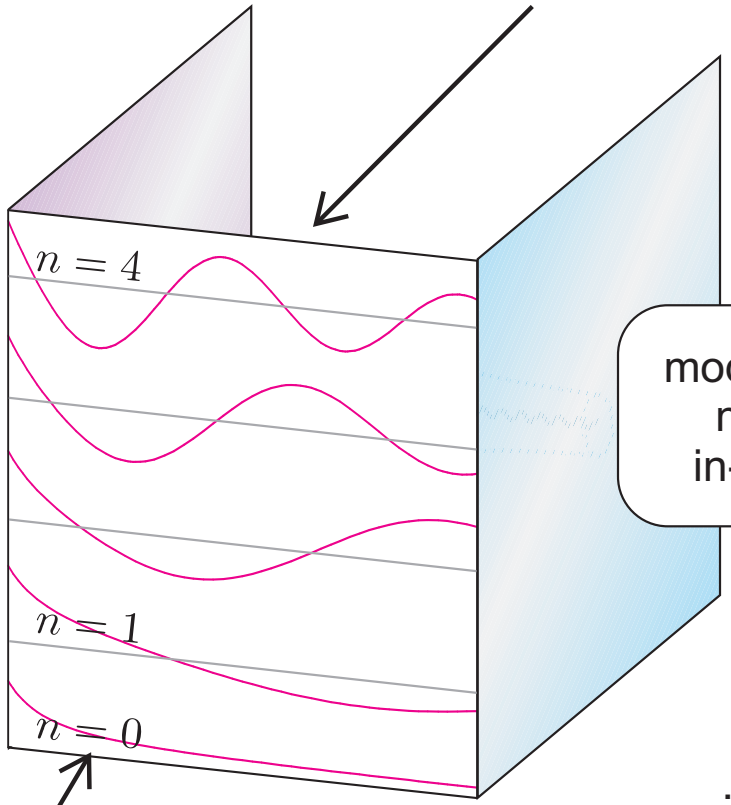

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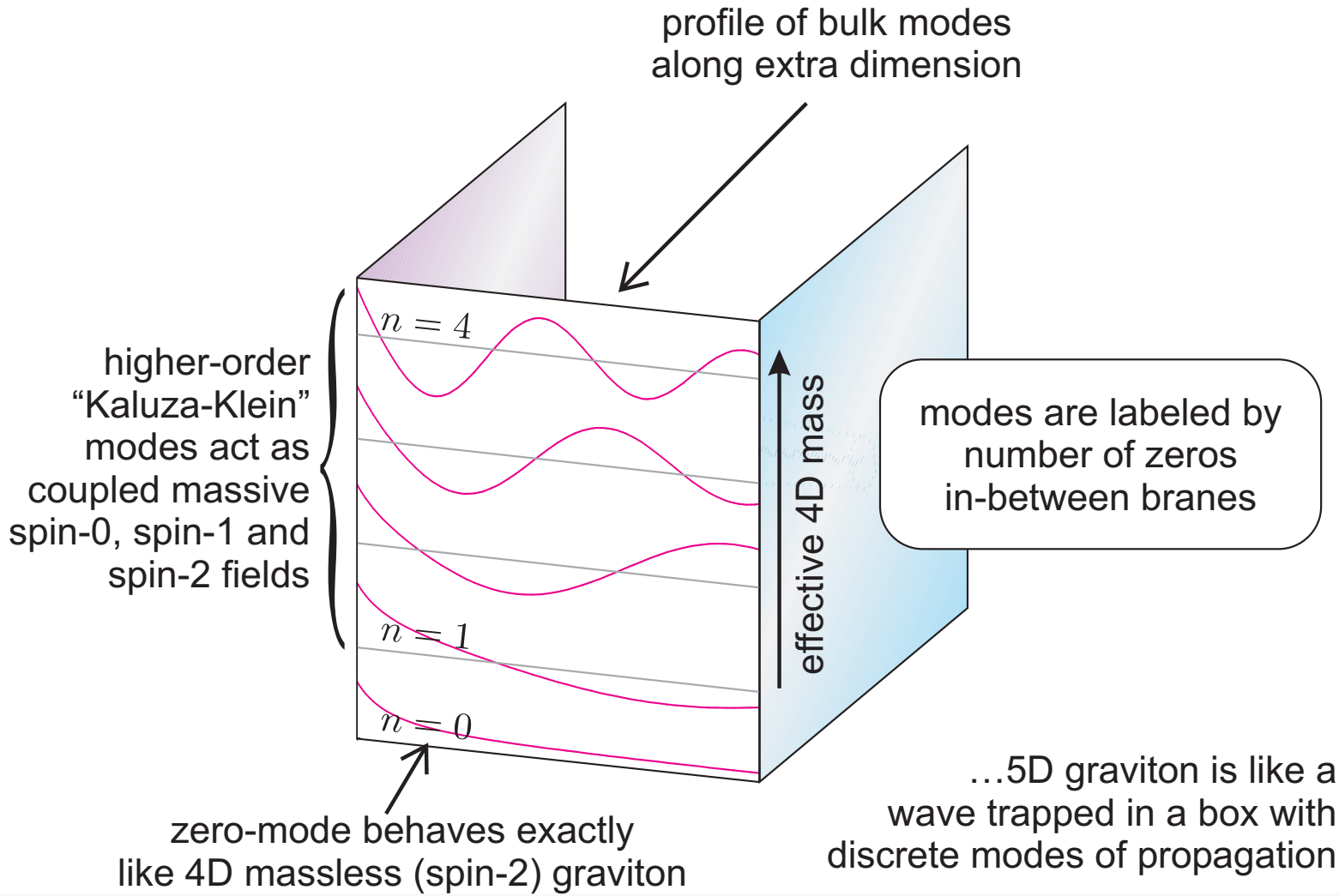

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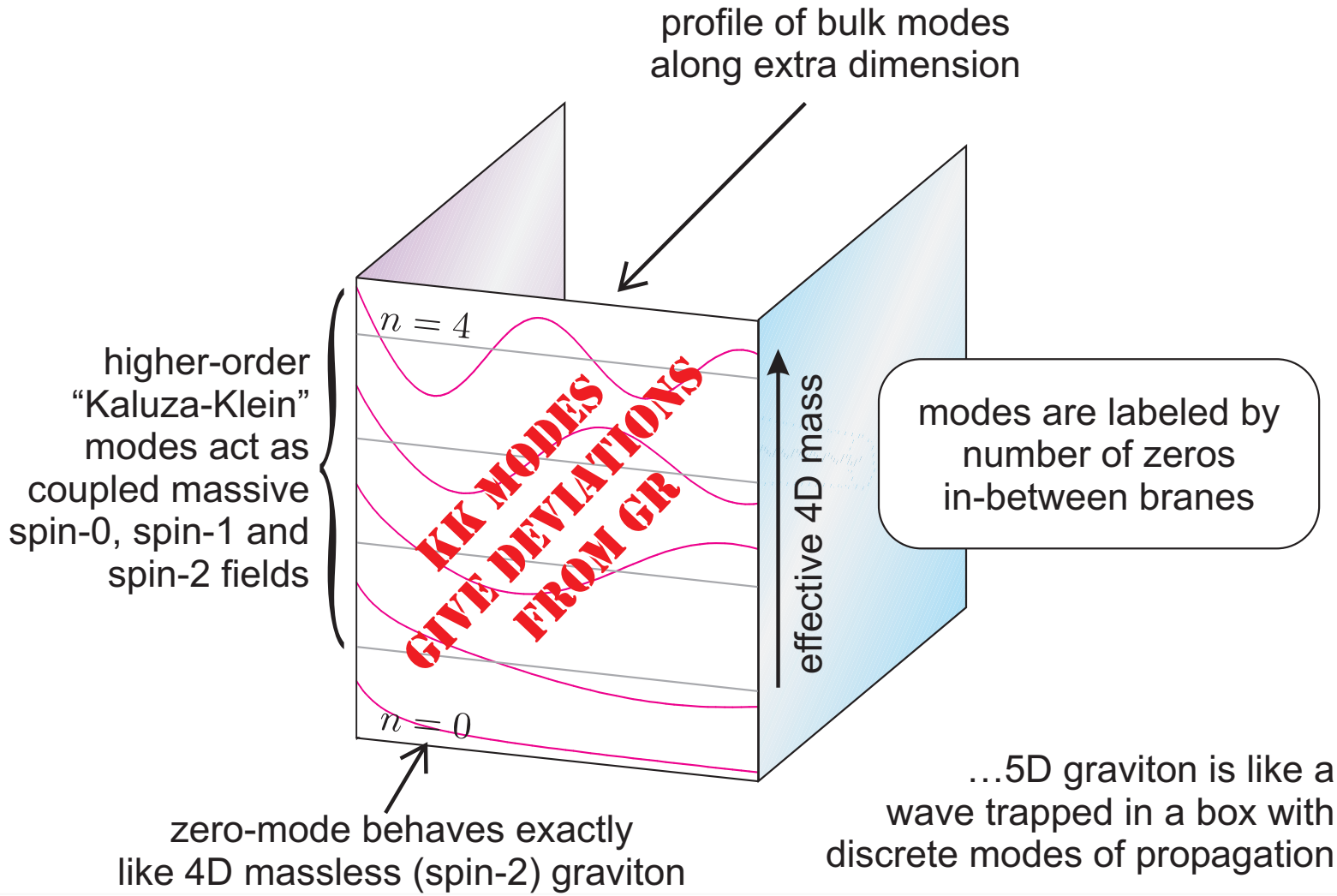

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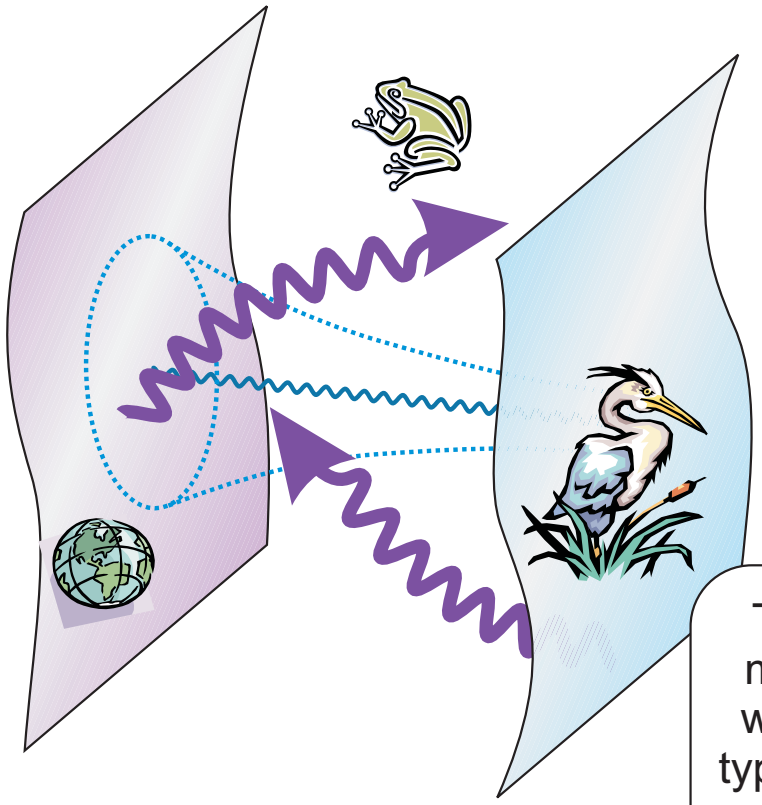
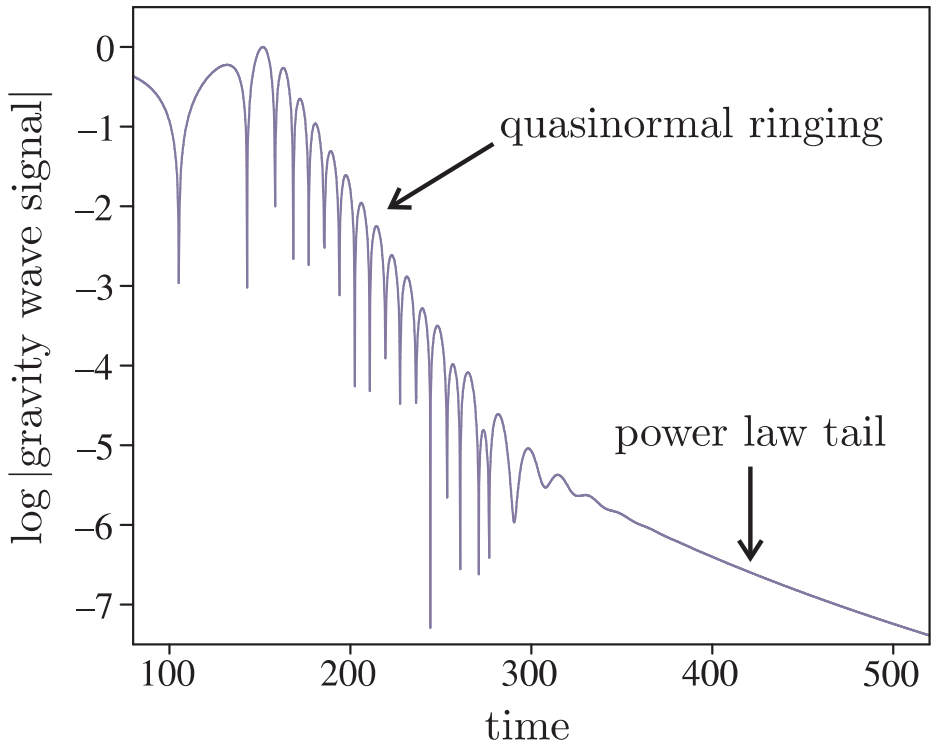


To quantify the KK modes, we need to worry about how all types of perturbations couple to/source one another

GW signal from the black string

typical gravity wave signal from a black hole in 4-dimensions:



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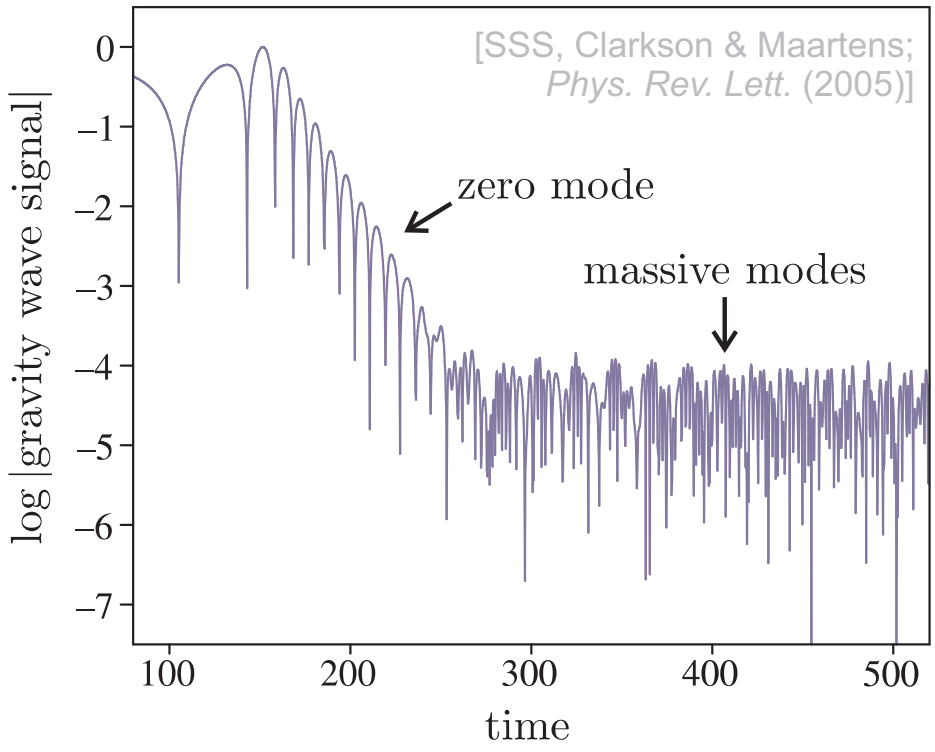

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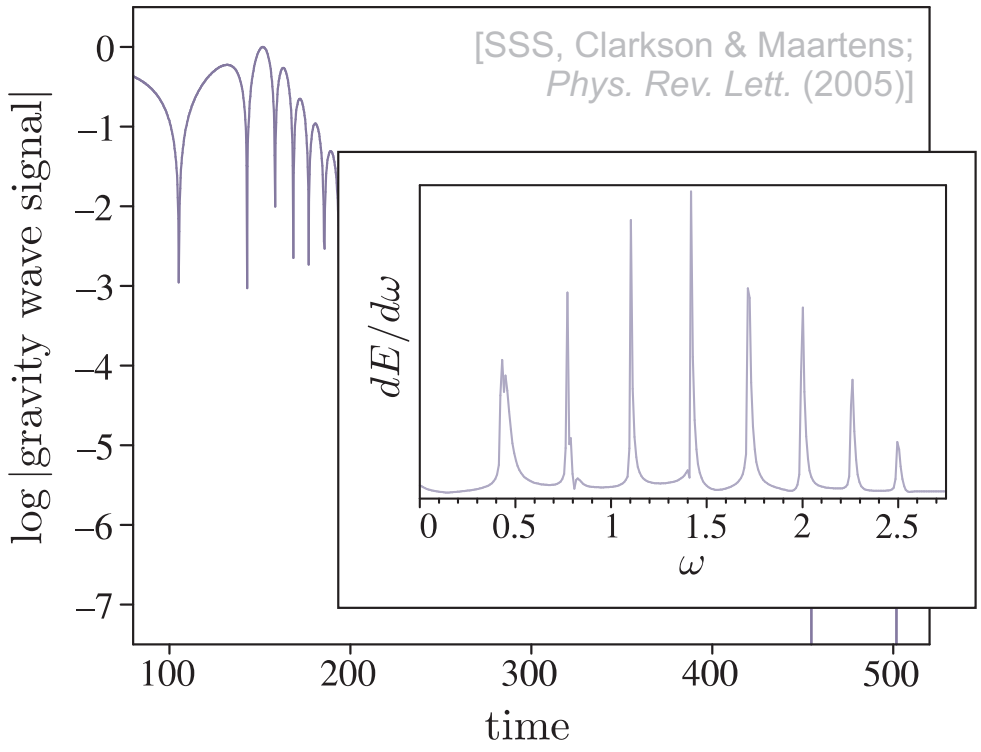
detecting extra dimensions with gravity wave spectroscopy:



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- amplitudes are tiny, several orders of magnitude less than the GR case

Detectability of massive modes

- depending on parameters, massive mode signal are 10^4 to 10^{11} Hz
- generally higher frequencies than LIGO or LISA were designed to detect
  - may need high frequency GW detectors to really get a handle on the system
- amplitudes are tiny, several orders of magnitude less than the GR case
- nevertheless, they are long lived suggesting they may be detectable with a long integration time

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