The Canadian Association of Physicists

L'Association canadienne des physiciens et physiciennes

The 2014 CAP Undergraduate Lecture Tour

Celebrating and promoting:

- Current developments in physics
- Physics research and education in Canada
- the CAP !

www.cap.ca

WITH SPECIAL THANKS TO

All Contributors to the CAP Foundation which supports this tour, including:

- Individual Members
- Member Departments
- Corporate Members
- Science Atlantic

What is the Canadian Association of Physicists?

- A national network of 1600 member physicists working in Canadian educational, industrial, and research settings
- A strong and effective advocacy group for support of, and excellence in, physics research and education

Join the CAP today at www.cap.ca

What can CAP do for you?

- **A professional certification program for practicing physicists**
- **Events and activities, including:**
  - CAP annual congress
  - Our journal: ***Physics in Canada***
  - Canadian Undergraduate Physics Conference
  - University Prize Examination
  - Stoicheff Memorial Graduate Scholarship
  - and more!

- **Free memberships to:**
  - undergraduate physics students*.
  - Physics graduate students* (one year's free full membership and reduced fees in first four years after graduation.)

Join the CAP today at www.cap.ca

*in Canada

Participate in student poster or oral paper competition!

The 2014 CAP Undergraduate Lecture Tour

Special thanks to our National and Regional Coordinators, the CAP Office, volunteer fund raisers, our sponsors, CAP member/host physics departments, our outstanding CAP volunteer speakers, Canadian physics student societies and
YOU – our audience !

We hope you enjoy this event!

What's the matter with gravity?

Sanjeev Seahra (University of New Brunswick, Fredericton)

CAP Undergraduate Lecture Series: Winter 2014

Gravitation is the most familiar force in our everyday lives, but it remains an active area of physics research. Why is that?

Successes and failures

Quick history of gravitation

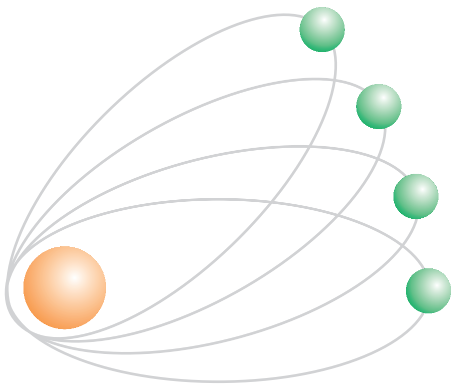
- **1605:** Kepler used observations by Tycho Brahe to find his three empirical laws of planetary motion

Quick history of gravitation

- **1605:** Kepler used observations by Tycho Brahe to find his three empirical laws of planetary motion
- **1677:** Newton proposed inverse-square law of gravitation from which he derived Kepler’s laws

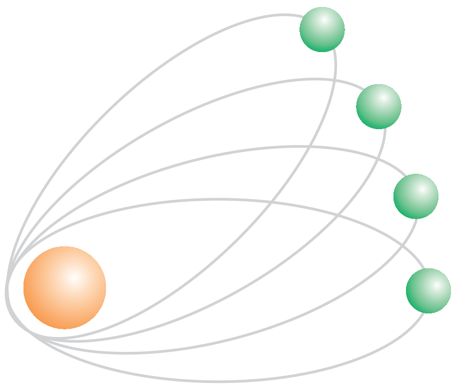
Quick history of gravitation

- **1605:** Kepler used observations by Tycho Brahe to find his three empirical laws of planetary motion
- **1677:** Newton proposed inverse-square law of gravitation from which he derived Kepler's laws
- **1800s:** observations of orbit of Mercury were found to be inconsistent with Kepler's laws
  - the "dark planet" Vulcan was proposed to explain the discrepancy



Quick history of gravitation

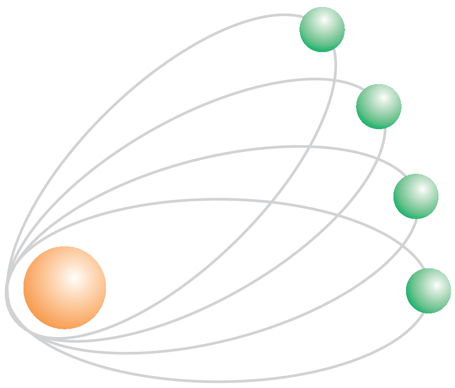
- **1605:** Kepler used observations by Tycho Brahe to find his three empirical laws of planetary motion
- **1677:** Newton proposed inverse-square law of gravitation from which he derived Kepler's laws
- **1800s:** observations of orbit of Mercury were found to be inconsistent with Kepler's laws
  - the "dark planet" Vulcan was proposed to explain the discrepancy



- **1915:** Einstein put forth the theory of general relativity (GR)

Quick history of gravitation

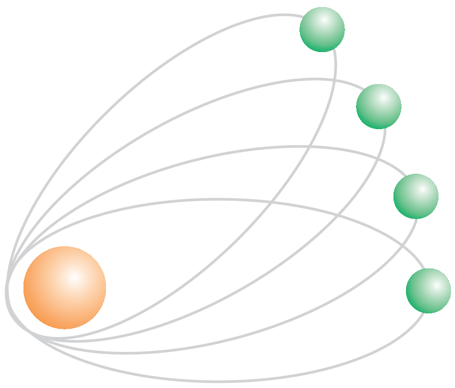
- **1605:** Kepler used observations by Tycho Brahe to find his three empirical laws of planetary motion
- **1677:** Newton proposed inverse-square law of gravitation from which he derived Kepler's laws
- **1800s:** observations of orbit of Mercury were found to be inconsistent with Kepler's laws
  - the "dark planet" Vulcan was proposed to explain the discrepancy



- **1915:** Einstein put forth the theory of general relativity (GR)
  - interpreted curvature of spacetime as gravity

Quick history of gravitation

- **1605:** Kepler used observations by Tycho Brahe to find his three empirical laws of planetary motion
- **1677:** Newton proposed inverse-square law of gravitation from which he derived Kepler’s laws
- **1800s:** observations of orbit of Mercury were found to be inconsistent with Kepler’s laws
  - the “dark planet” Vulcan was proposed to explain the discrepancy



- **1915:** Einstein put forth the theory of general relativity (GR)
  - interpreted curvature of spacetime as gravity
  - explained Mercury’s orbit without the “dark planet”

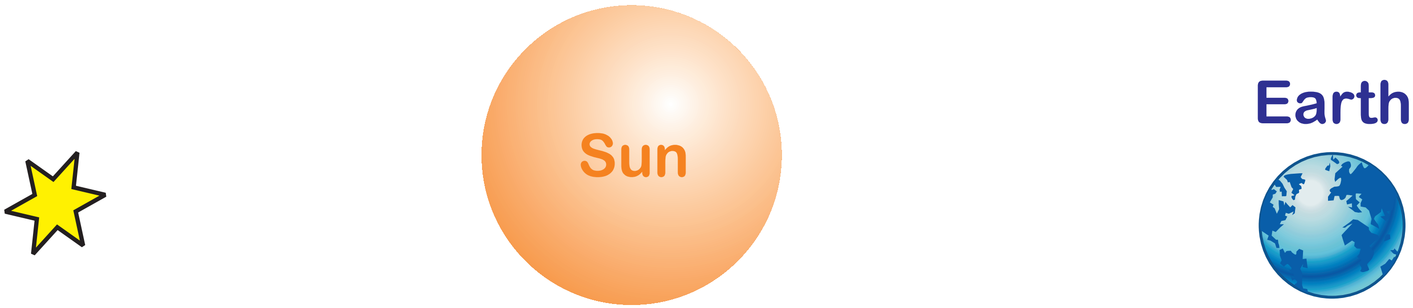
GR has many other testable predictions

GR has many other testable predictions

e.g.: photon trajectories deflected by massive bodies

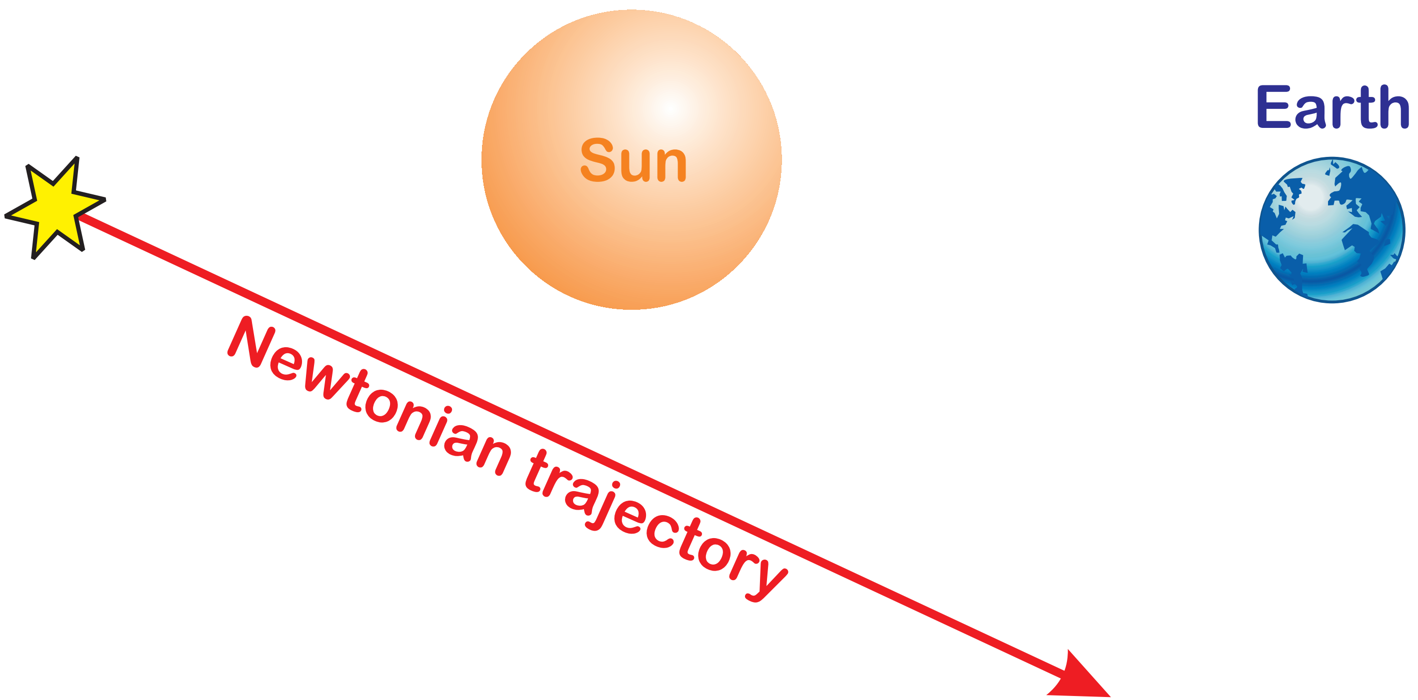
GR has many other testable predictions

e.g.: photon trajectories deflected by massive bodies



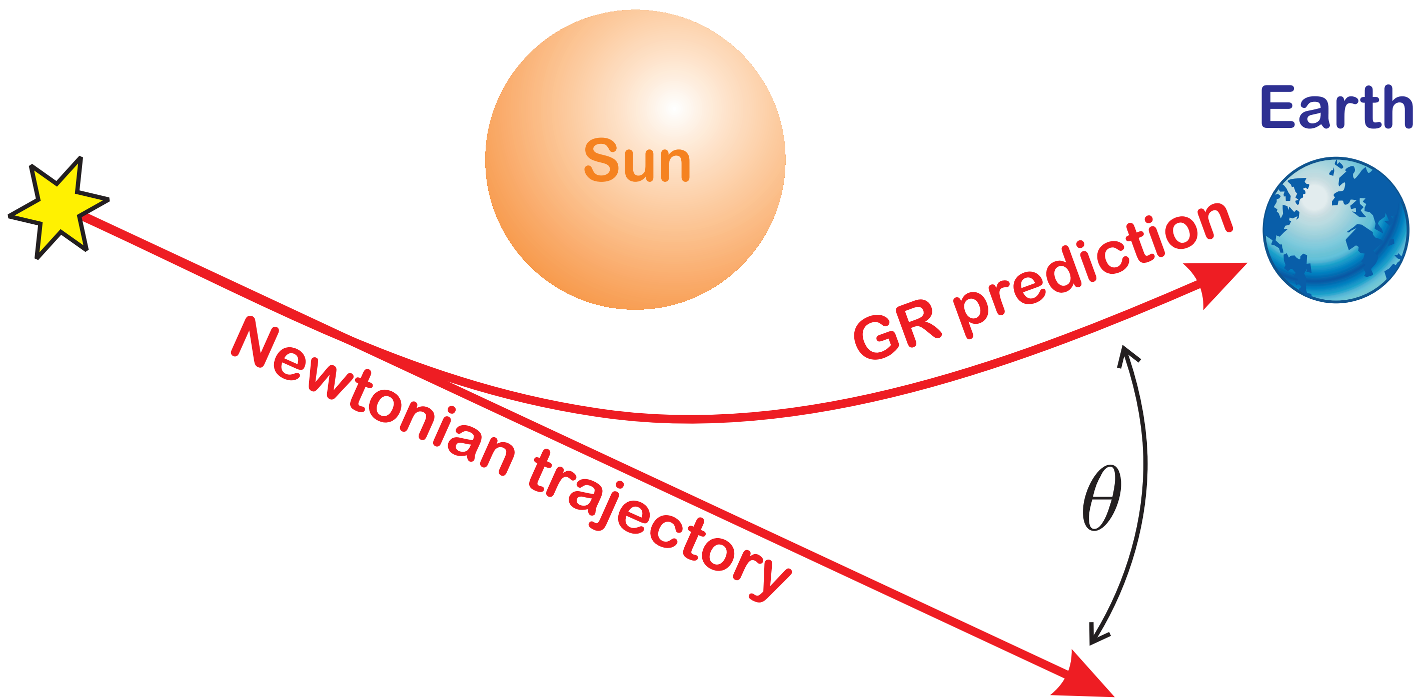
GR has many other testable predictions

e.g.: photon trajectories deflected by massive bodies



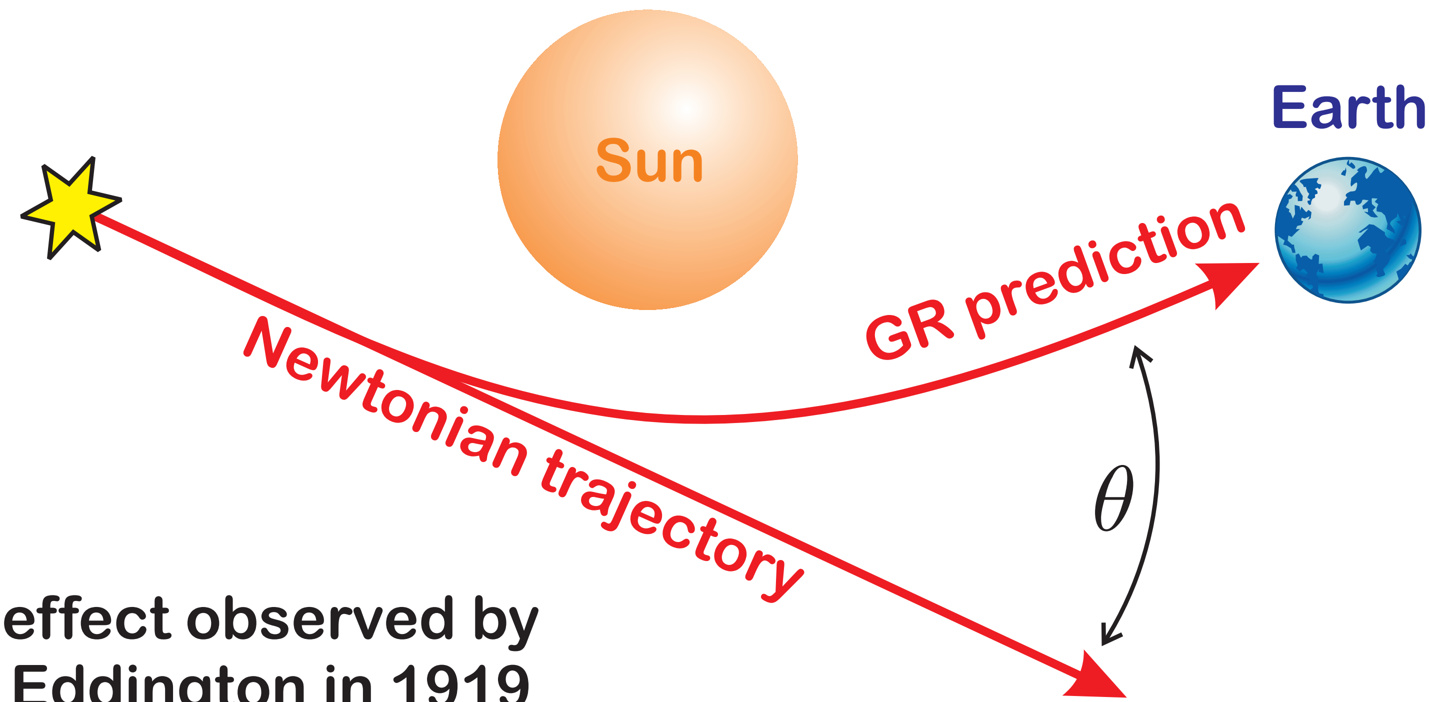
GR has many other testable predictions

e.g.: photon trajectories deflected by massive bodies



GR has many other testable predictions

e.g.: photon trajectories deflected by massive bodies

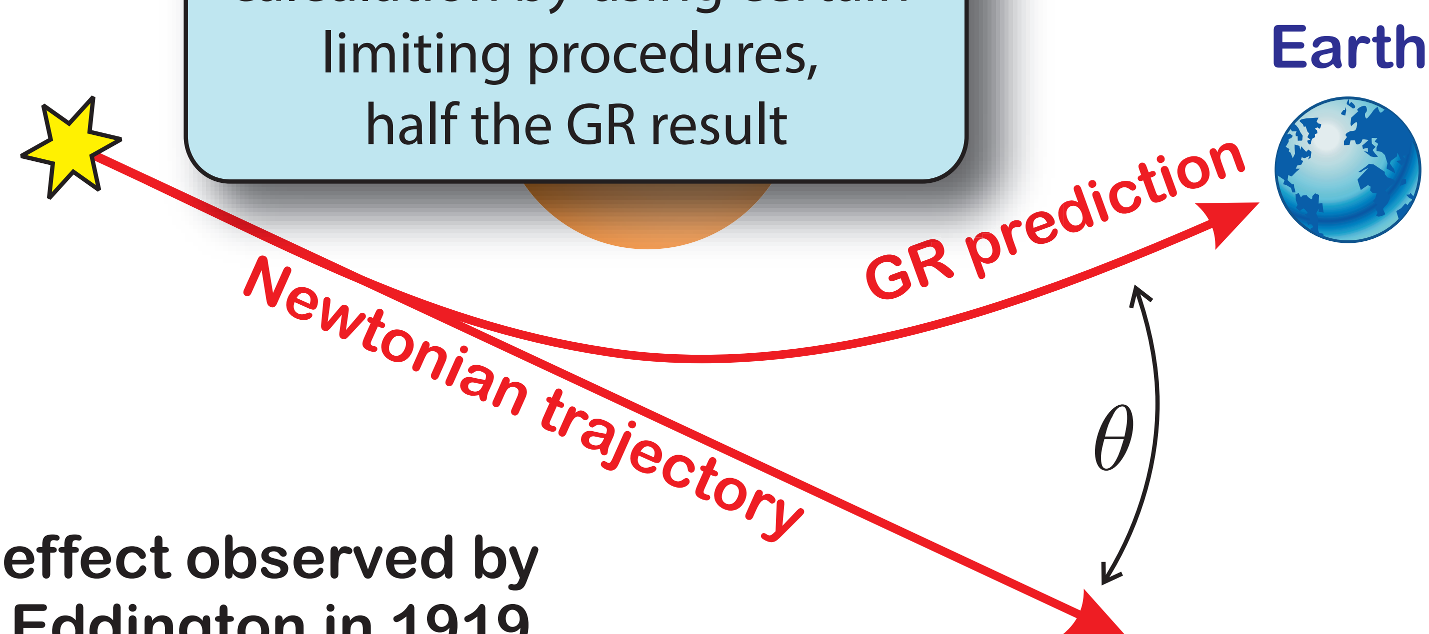


effect observed by Eddington in 1919

GR has many other testabl

e.g.: photon trajectories ed by massive bodies

disclaimer: can also get light deflection in Newtonian calculation by using certain limiting procedures, half the GR result



effect observed by Eddington in 1919

Testing general relativity

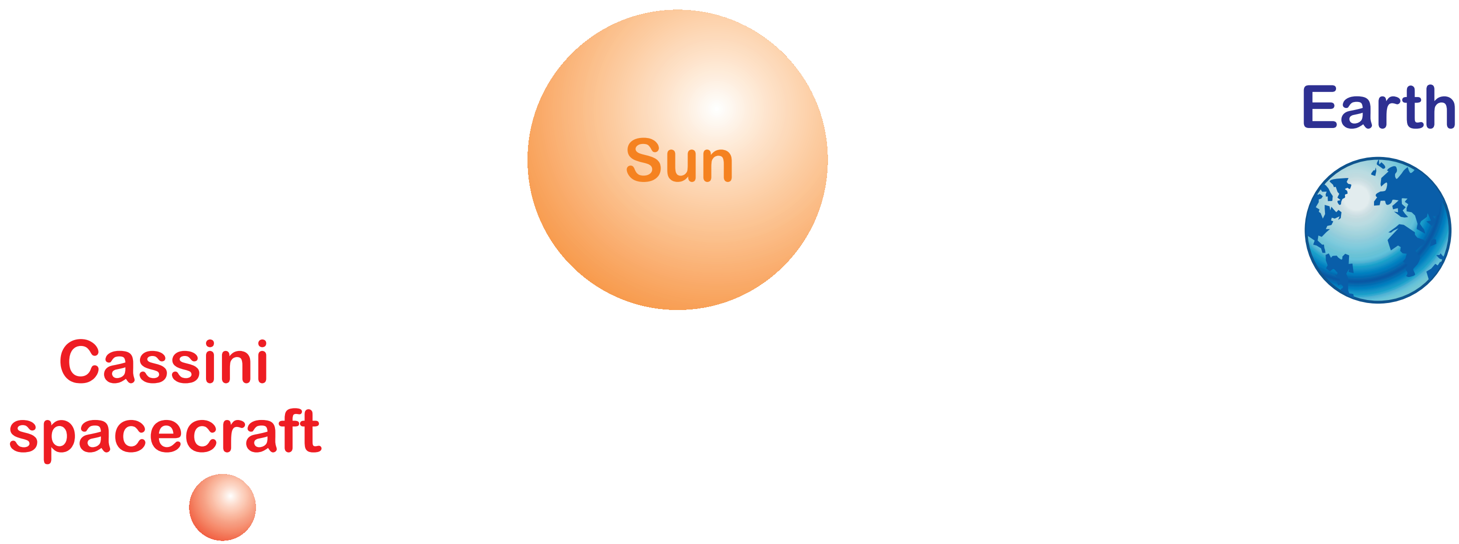
GR has many other testable predictions

e.g.: radar signals are delayed when they travel near massive bodies

Testing general relativity

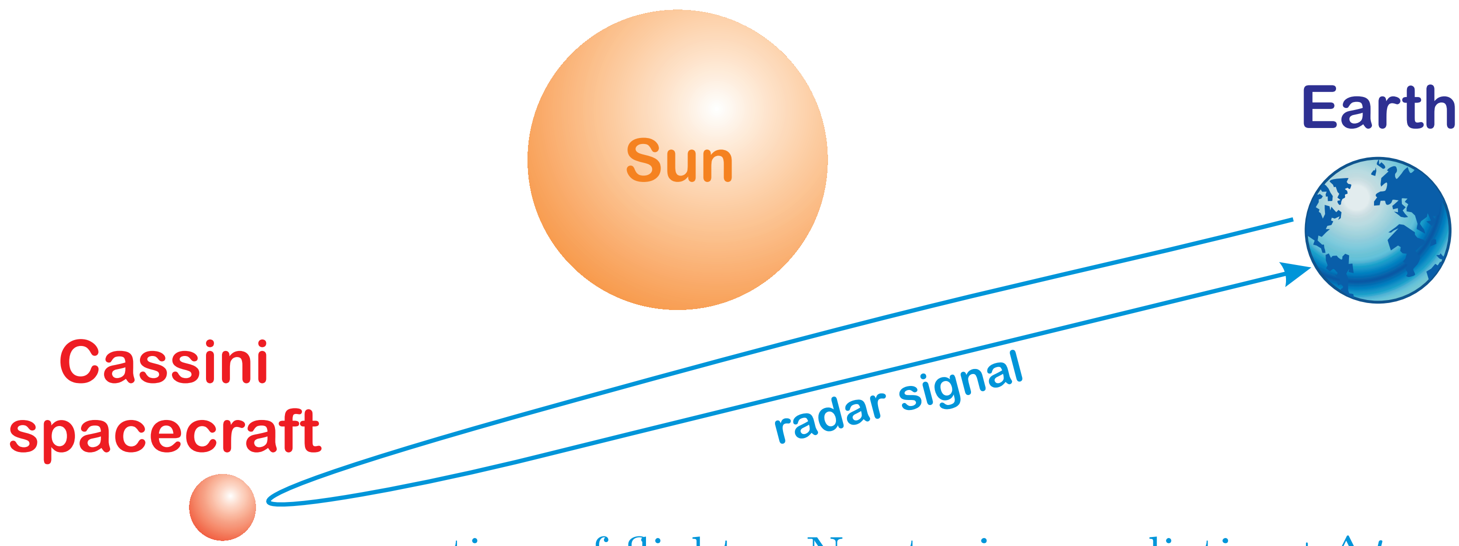
GR has many other testable predictions

e.g.: radar signals are delayed when they travel near massive bodies



GR has many other testable predictions

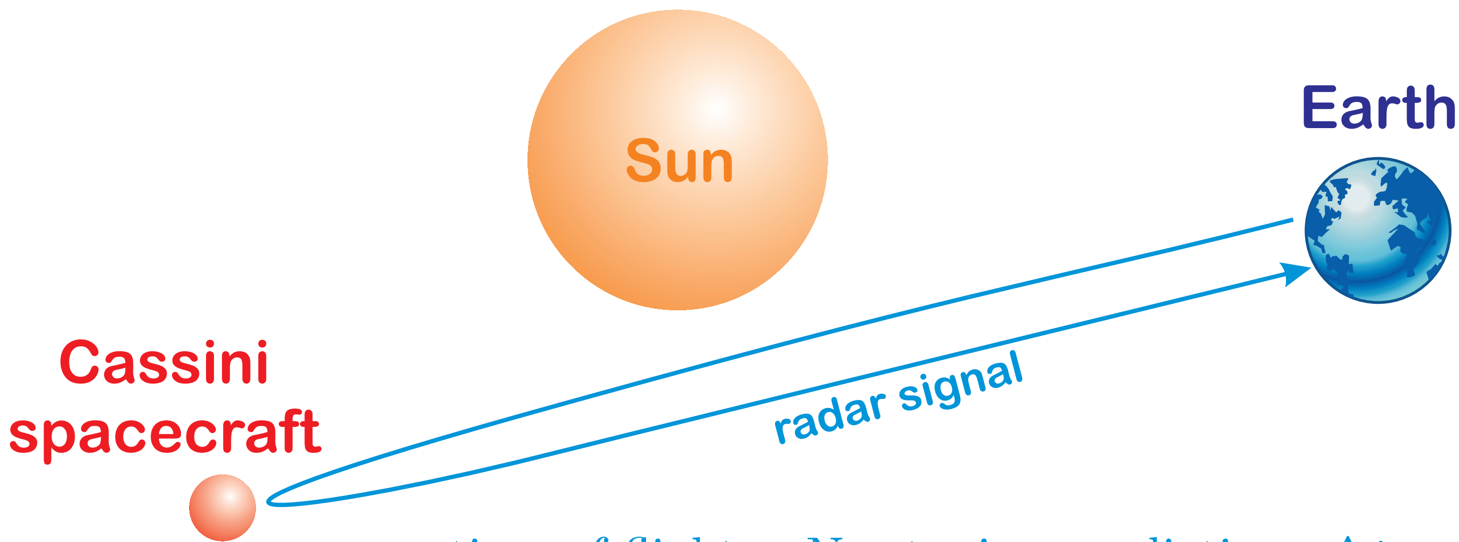
e.g.: radar signals are delayed when they travel near massive bodies



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

GR has many other testable predictions

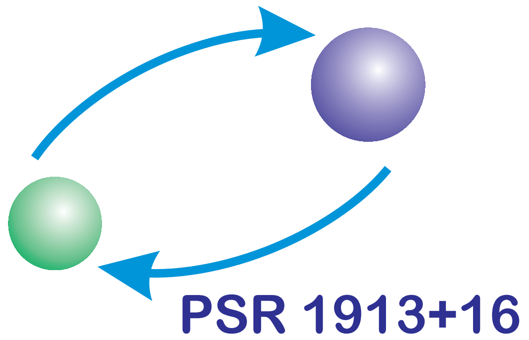
e.g.: radar signals are delayed when they travel near massive bodies



time of flight = Newtonian prediction+Δt_{GR}

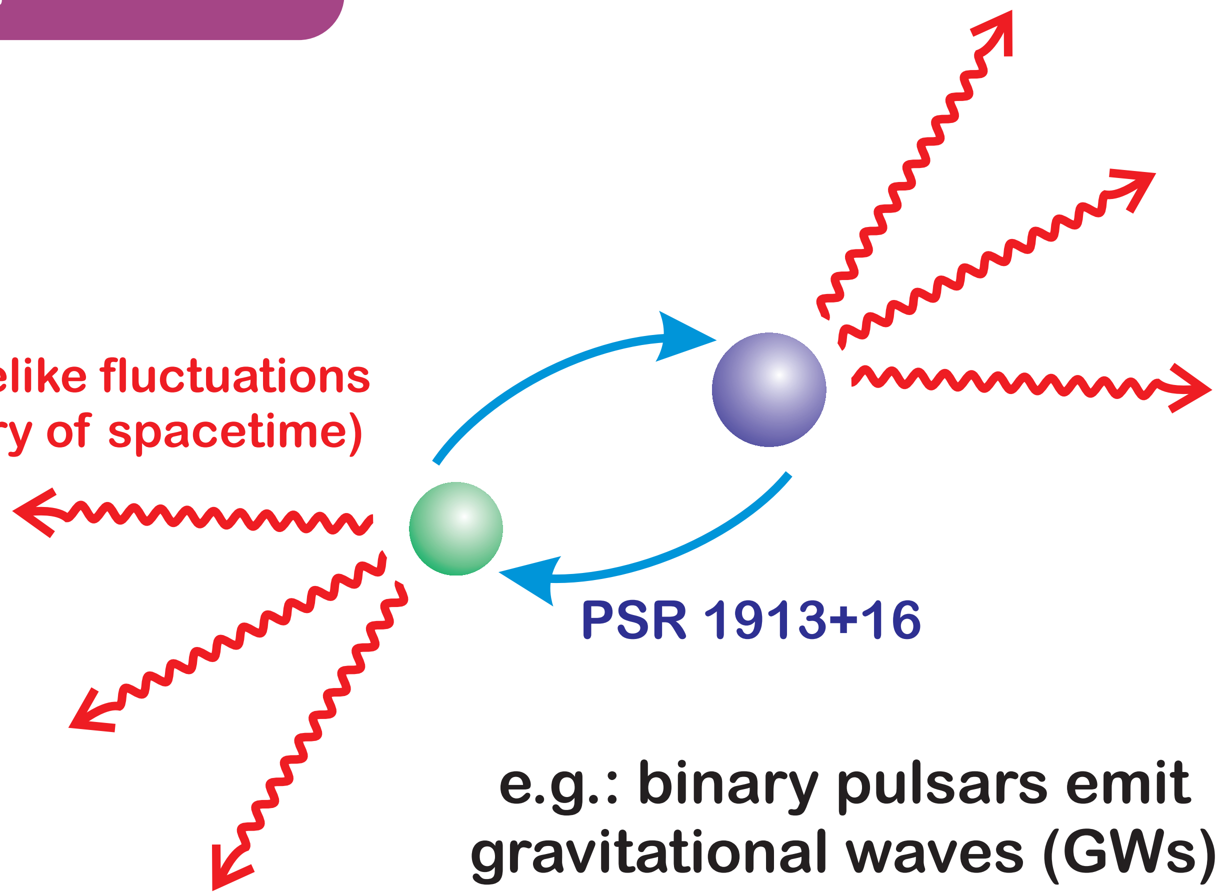
measured Δt matches GR prediction to accuracy 10^{-5}

GR has many other testable predictions



e.g.: binary pulsars emit gravitational waves (GWs)

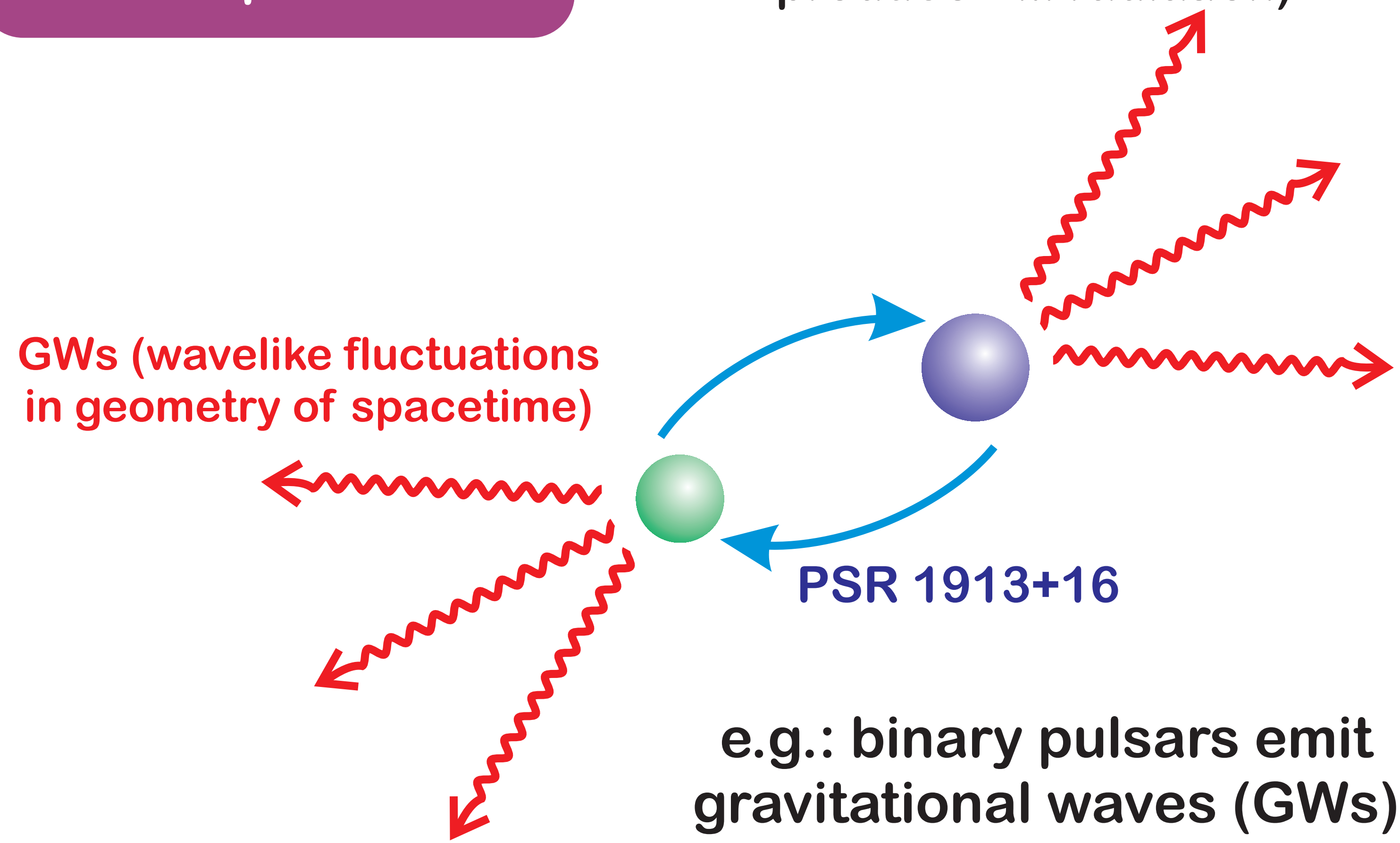
GR has many other testable predictions



e.g.: binary pulsars emit gravitational waves (GWs)

GR has many other testable predictions

(same effect as in Maxwell's theory: accelerating charges produce EM radiation)

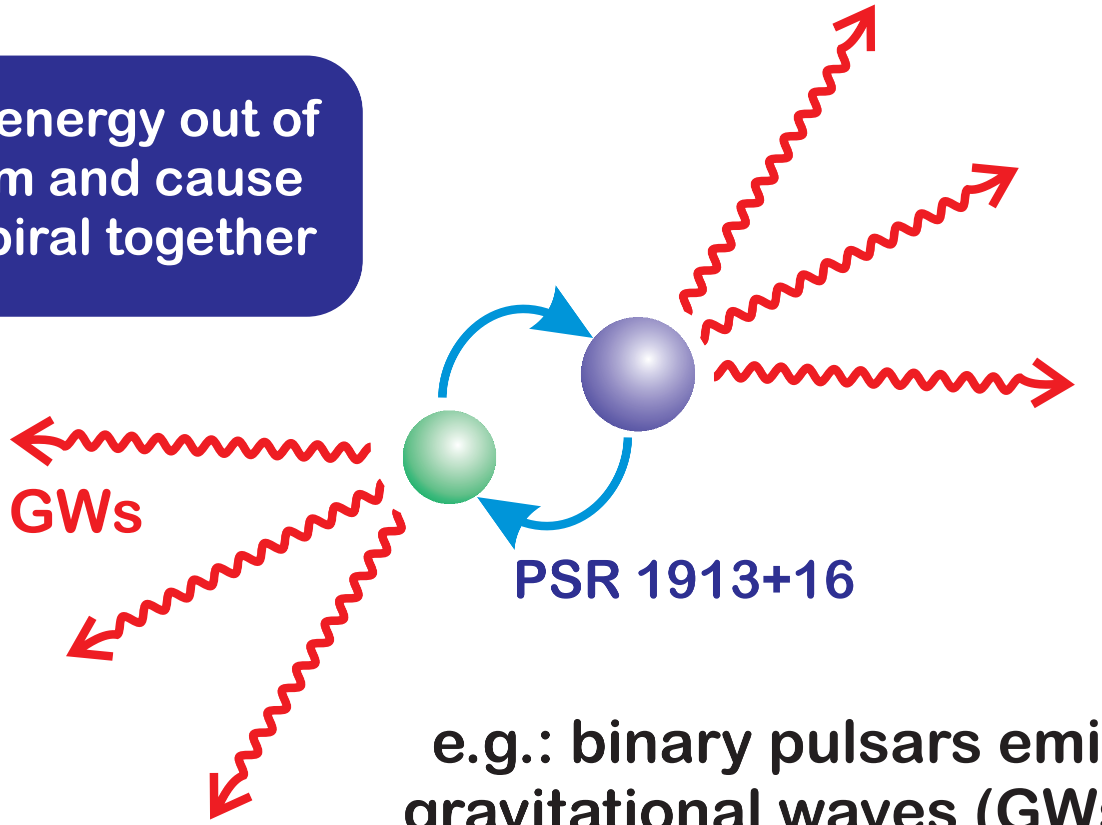


e.g.: binary pulsars emit gravitational waves (GWs)

GR has many other testable predictions

(same effect as in Maxwell's theory: accelerating charges produce EM radiation)

GWs take energy out of the system and cause stars to spiral together



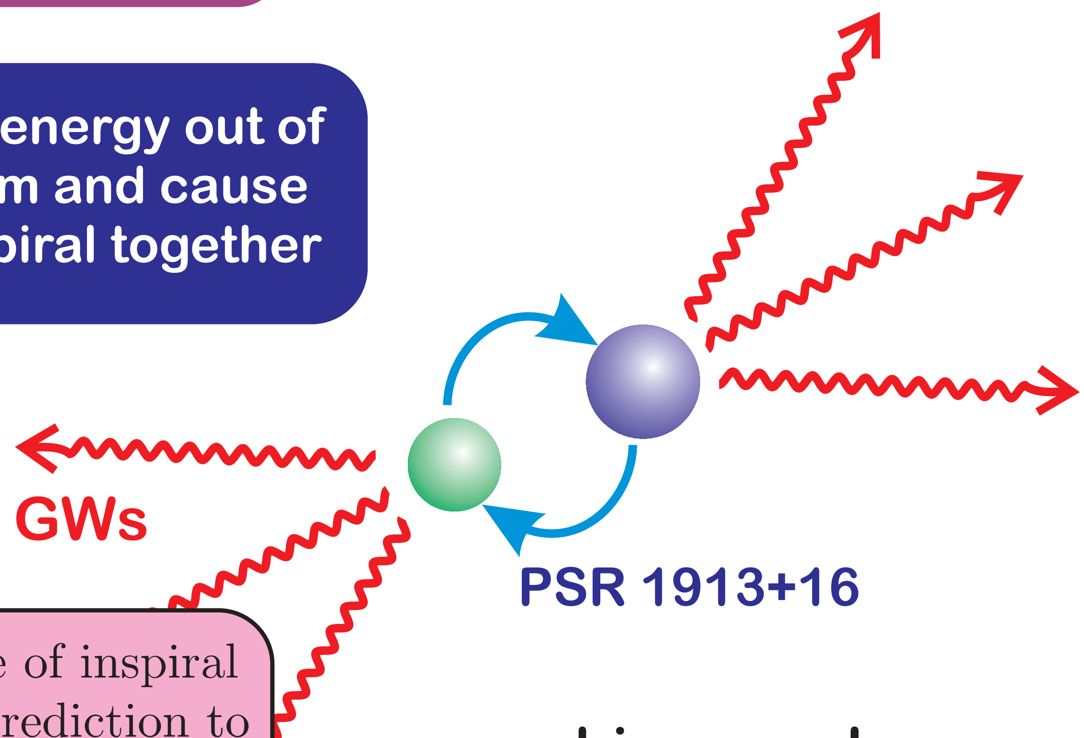
e.g.: binary pulsars emit gravitational waves (GWs)

Testing general relativity

GR has many other testable predictions

(same effect as in Maxwell’s theory: accelerating charges produce EM radiation)

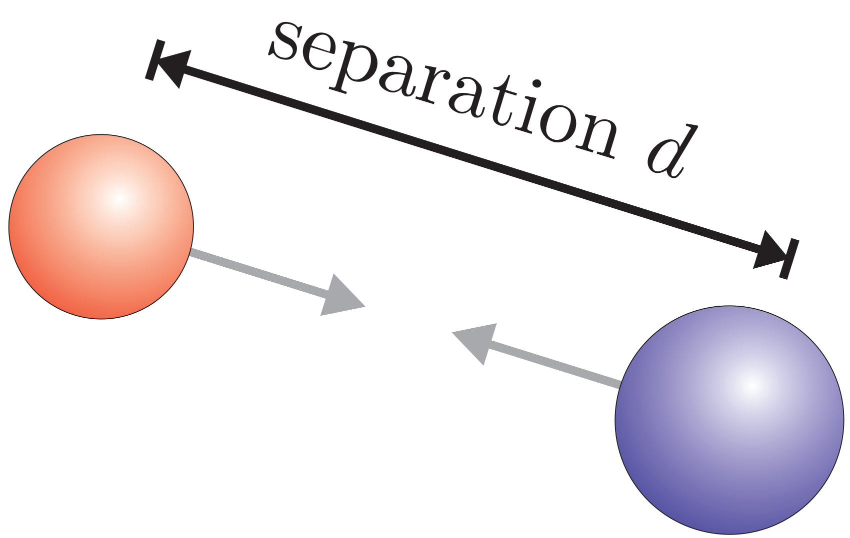
GWs take energy out of the system and cause stars to spiral together



measured rate of inspiral matches GR prediction to accuracy 10^{-3}

e.g.: binary pulsars emit gravitational waves (GWs)

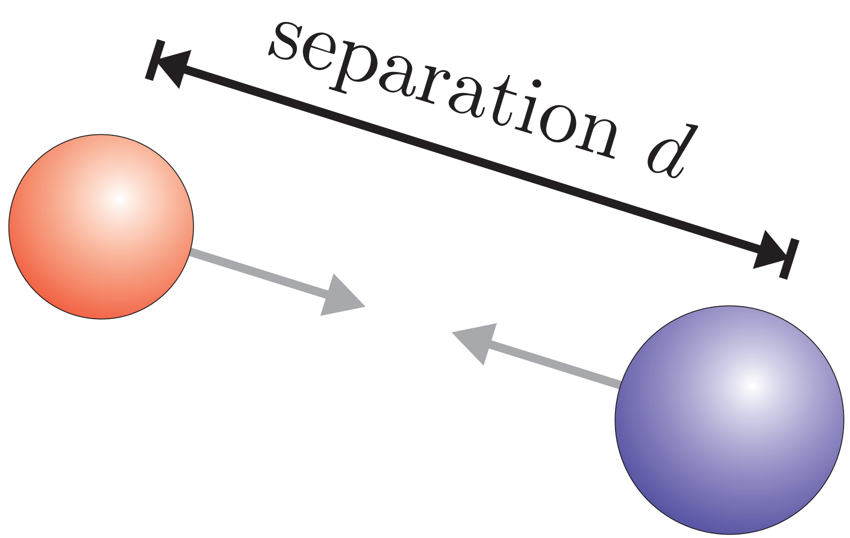
GR has many other testable predictions



can also test GR in the lab by measuring gravitational attraction directly

GR has many other testable predictions

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



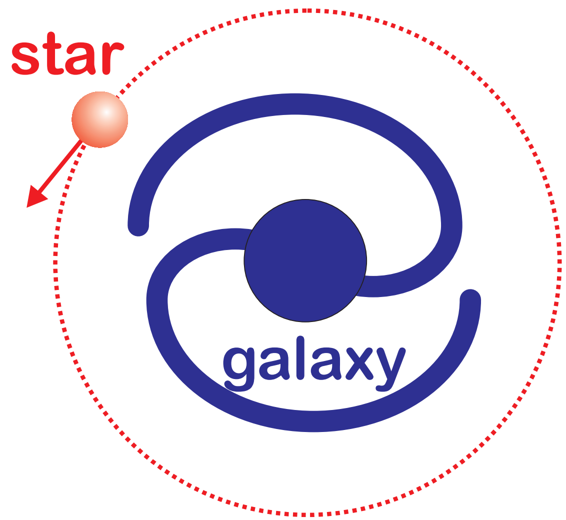
can also test GR in the lab by measuring gravitational attraction directly

however, GR doesn’t explain everything...

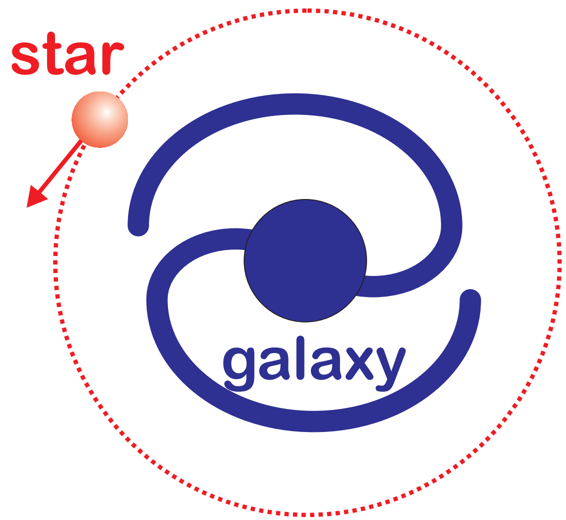
e.g.: galactic rotation curves

however, GR doesn’t explain everything...

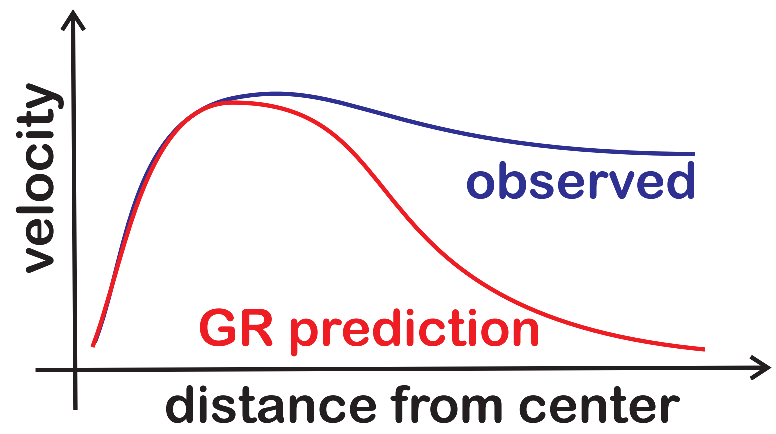
e.g.: galactic rotation curves



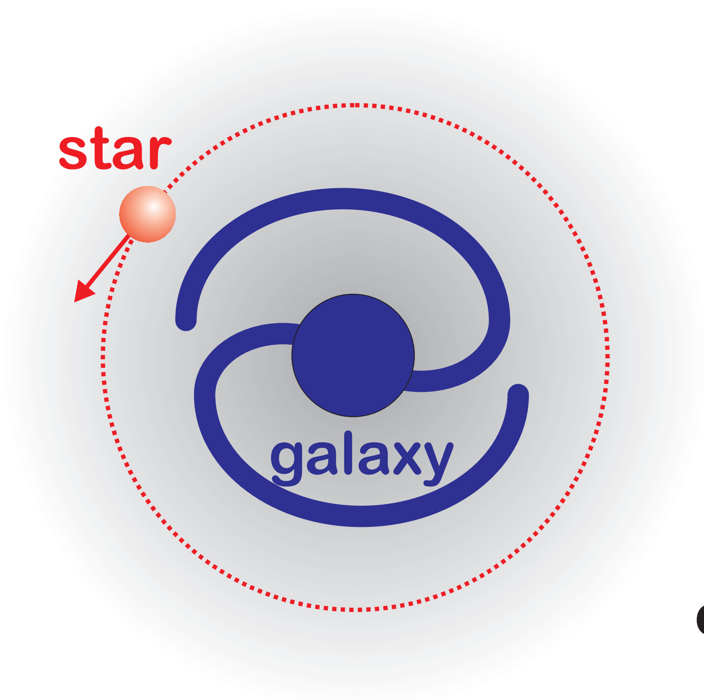
however, GR doesn’t explain everything...



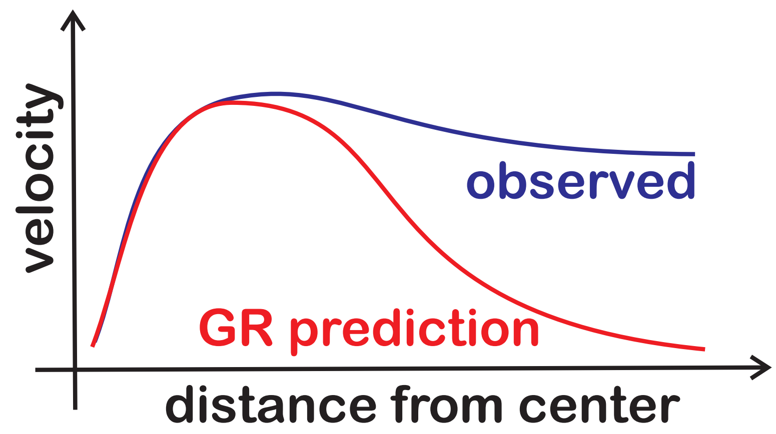
e.g.: galactic rotation curves



however, GR doesn’t explain everything...



e.g.: galactic rotation curves



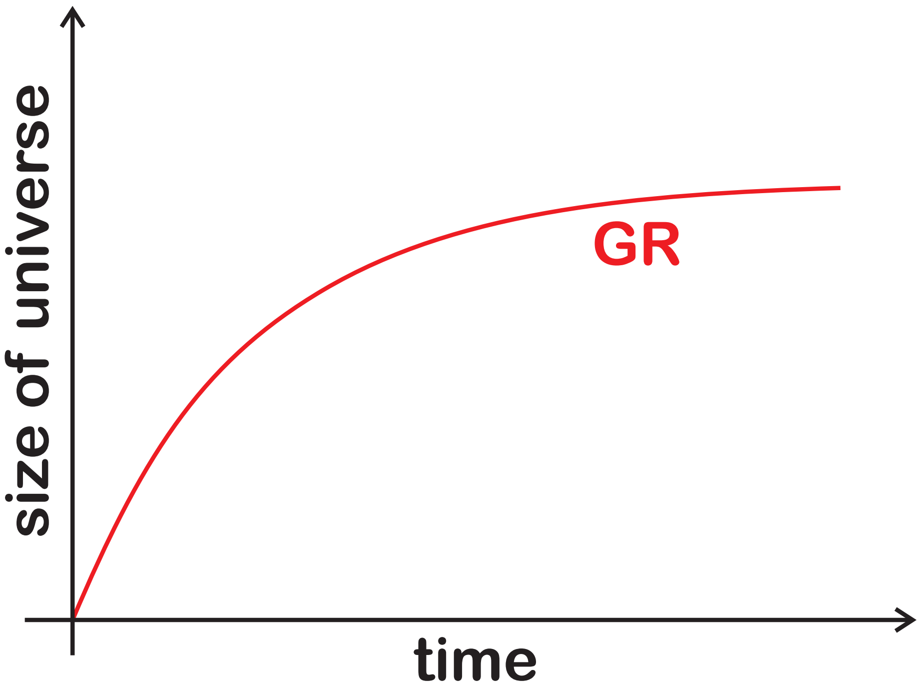
discrepancy usually explained by the existence of “dark matter” haloes

however, GR doesn’t explain everything...

one of the key predictions of GR is the expansion of the universe...

however, GR doesn’t explain everything...

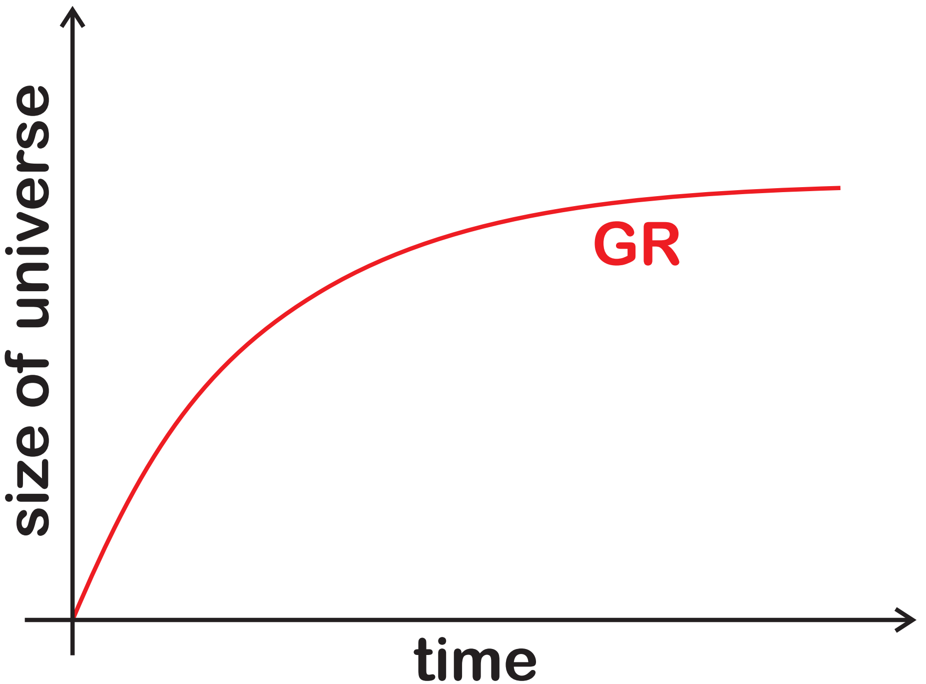
one of the key predictions of GR is the expansion of the universe...



however, GR doesn’t explain everything...

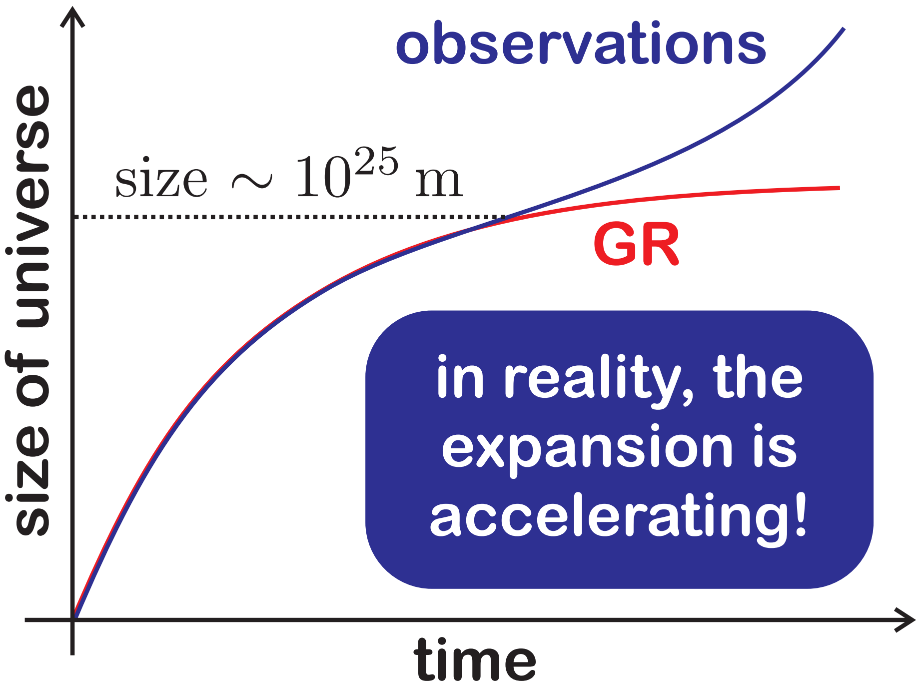
one of the key predictions of GR is the expansion of the universe...

in GR, gravity is an attractive force: so expansion should decelerate



however, GR doesn't explain everything...

one of the key predictions of GR is the expansion of the universe...

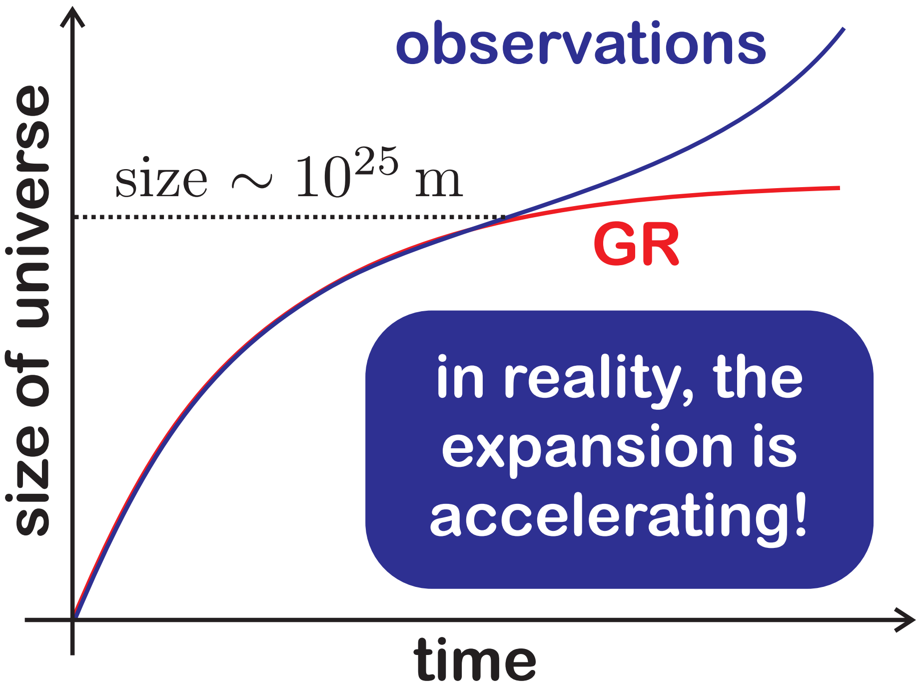


in reality, the expansion is accelerating!

in GR, gravity is an attractive force: so expansion should decelerate however, GR doesn’t explain everything...

one of the key predictions of GR is the expansion of the universe...

discrepancy usually explained by existence of exotic “dark energy”

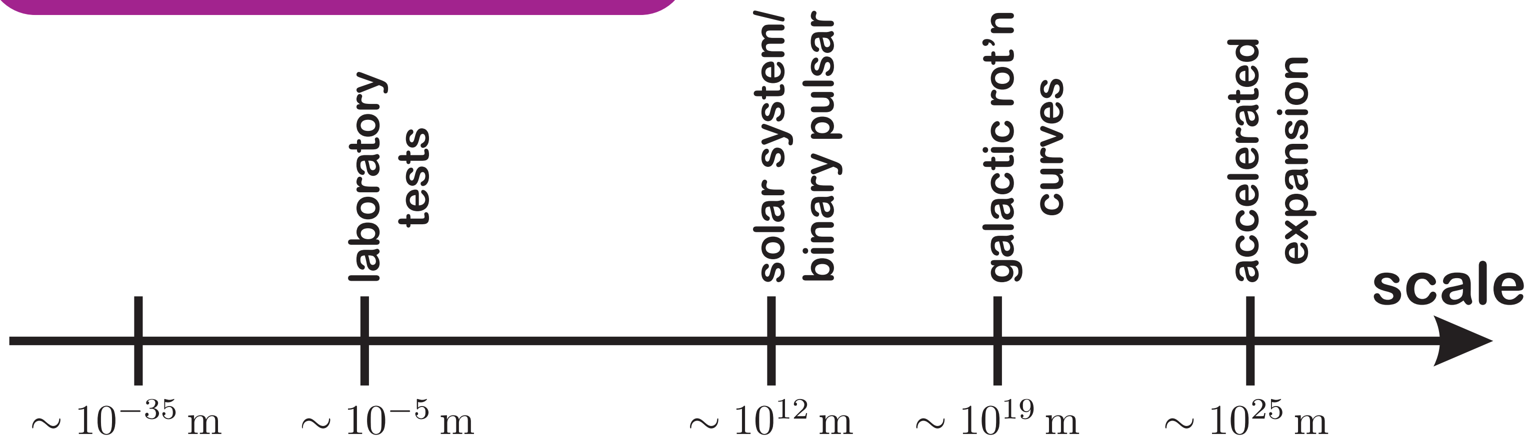


in GR, gravity is an attractive force: so expansion should decelerate

in reality, the expansion is accelerating!

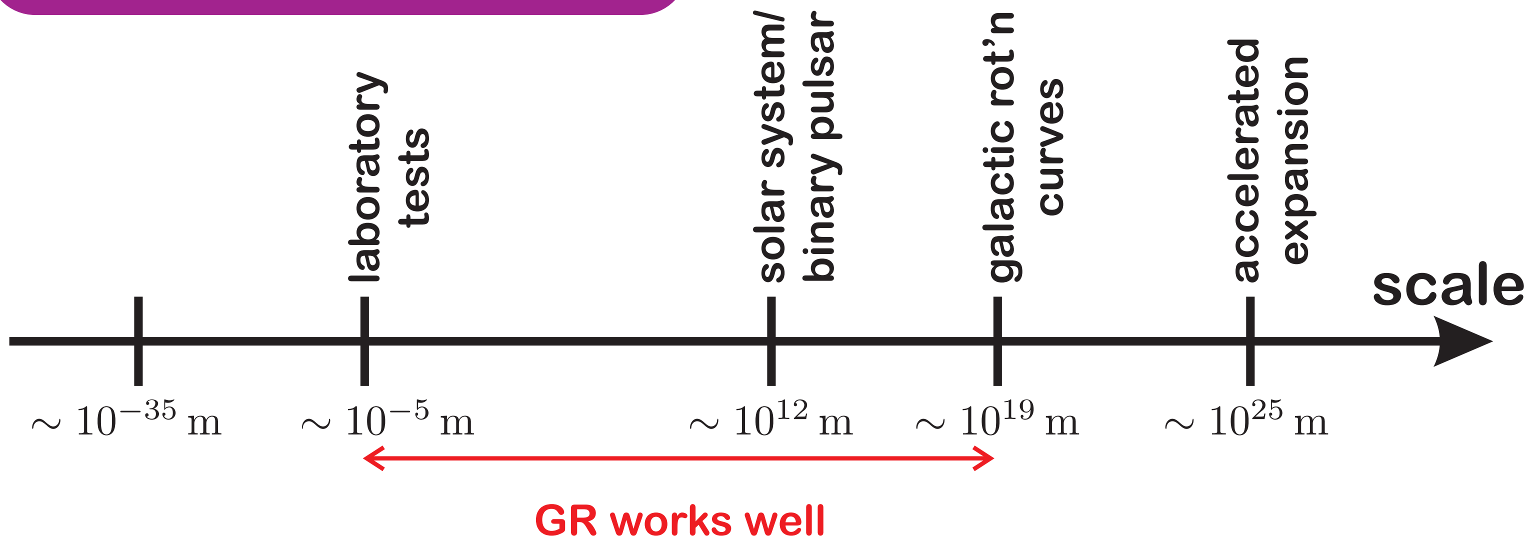
however, GR doesn't explain everything...

different effects probe gravity at different scales



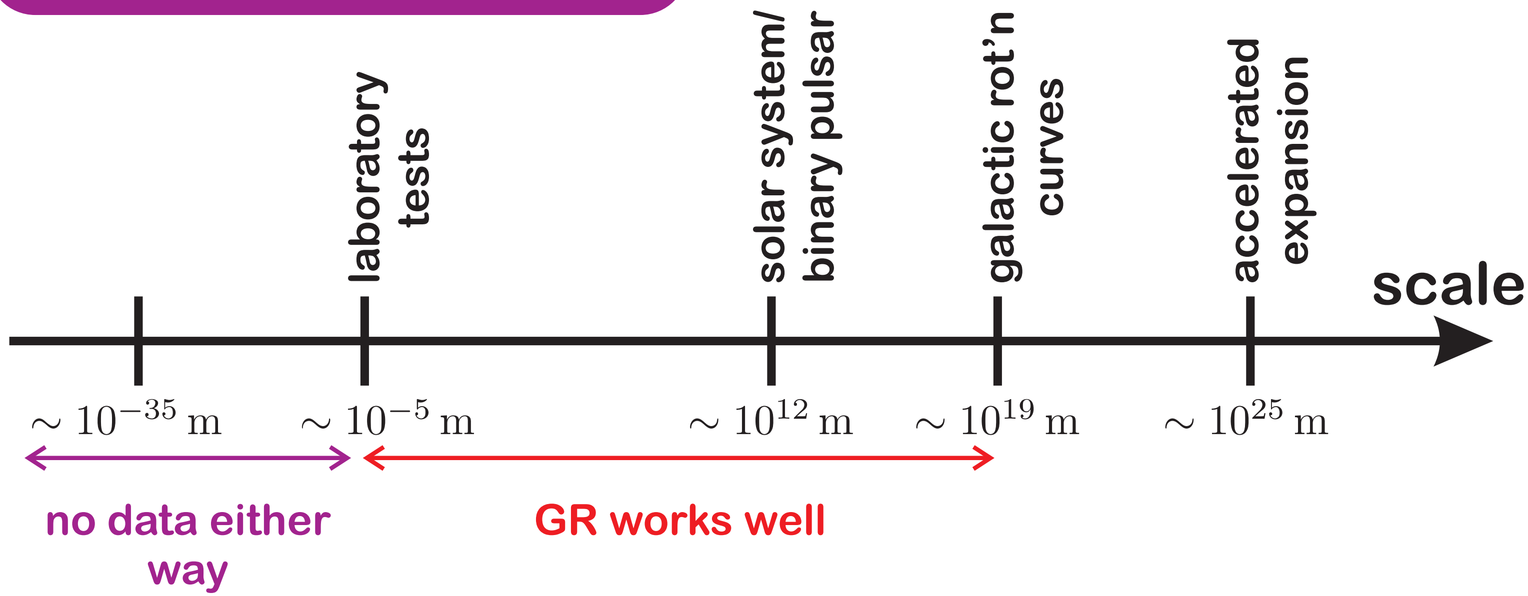
however, GR doesn’t explain everything...

different effects probe gravity at different scales



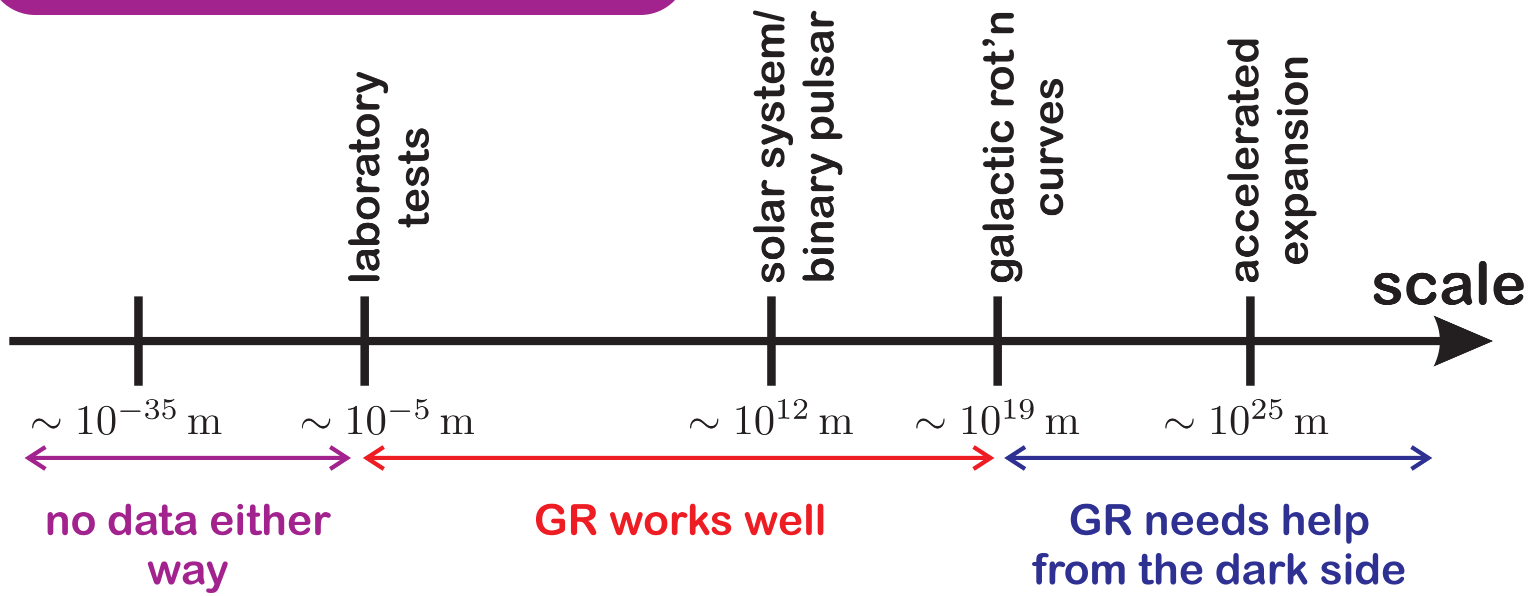
however, GR doesn't explain everything...

different effects probe gravity at different scales



however, GR doesn't explain everything...

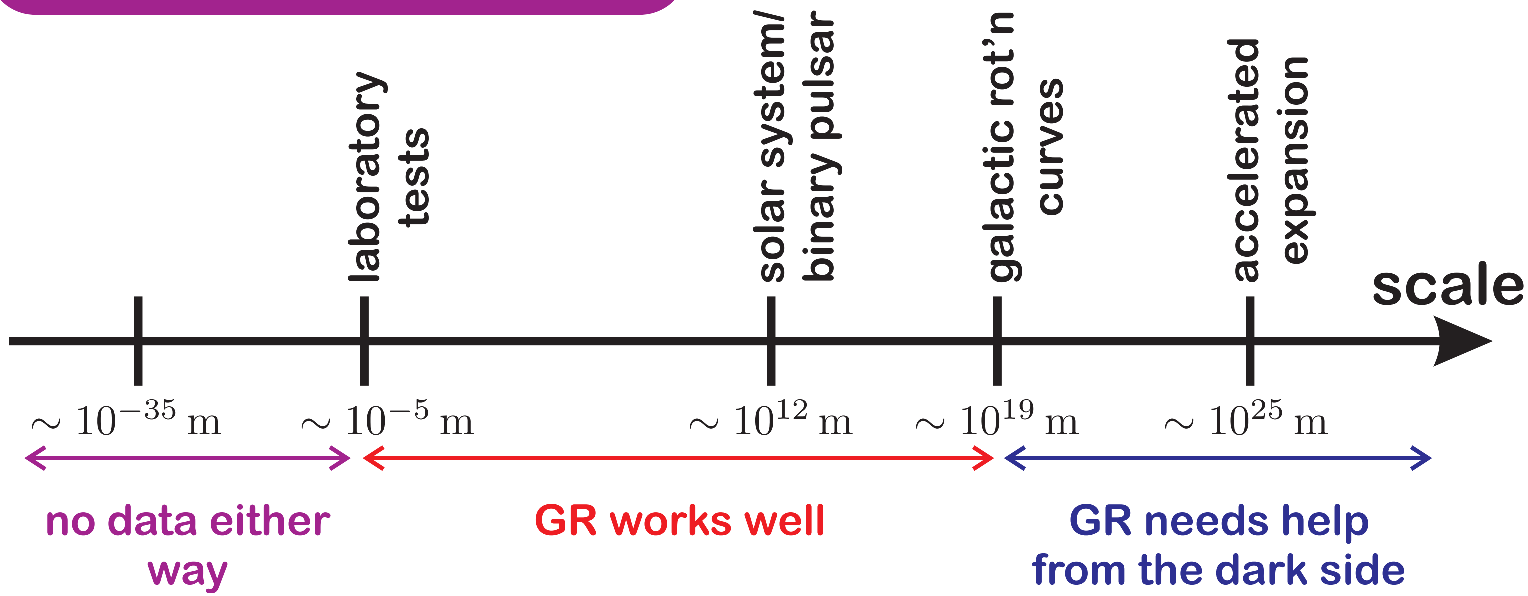
different effects probe gravity at different scales



Shortcomings of GR

however, GR doesn’t explain everything...

different effects probe gravity at different scales



...or GR is not the correct theory of gravity on large scales

Shortcomings of GR

however, GR doesn’t explain everything...

different effects probe gravity at different scales

laboratory tests — solar system/ binary pulsar — galactic rot’n curves — accelerated expansion — **scale**

$\sim 10^{-35}\,\mathrm{m}$ | $\sim 10^{-5}\,\mathrm{m}$ | $\sim 10^{12}\,\mathrm{m}$ | $\sim 10^{19}\,\mathrm{m}$ | $\sim 10^{25}\,\mathrm{m}$

no data either way (from $\sim 10^{-35}$ m to $\sim 10^{-5}$ m)

GR works well (from $\sim 10^{-5}$ m to $\sim 10^{19}$ m)

GR needs help from the dark side (beyond $\sim 10^{19}$ m)

is GR the right theory on small scales?

...or GR is not the correct theory of gravity on large scales

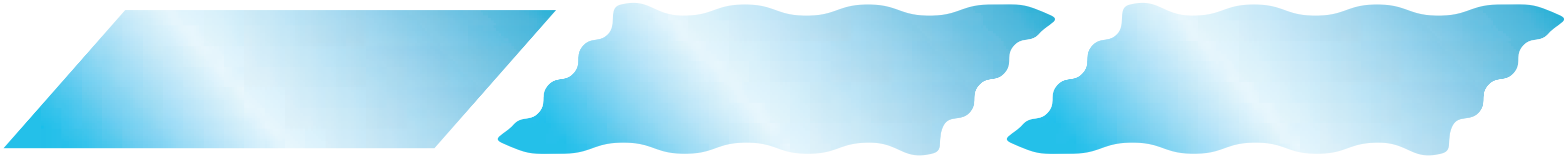
- small scales $\Rightarrow$ quantum mechanics

How not to quantize gravity

- small scales $\Rightarrow$ quantum mechanics
- classical GR is governed by a system of nonlinear PDEs

How not to quantize gravity

- small scales $\Rightarrow$ quantum mechanics
- classical GR is governed by a system of nonlinear PDEs
- standard approach: quantize perturbations about a simple solution



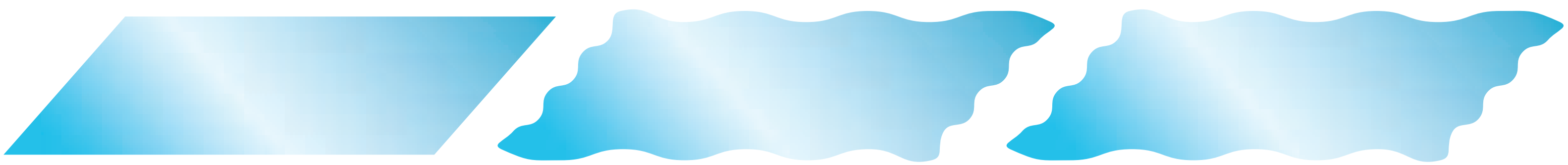
step 1: start with flat space

step 2: add wiggles

step 3: quantize wiggles in perturbation series

How not to quantize gravity

- small scales $\Rightarrow$ quantum mechanics
- classical GR is governed by a system of nonlinear PDEs
- standard approach: quantize perturbations about a simple solution



step 1: start with flat space

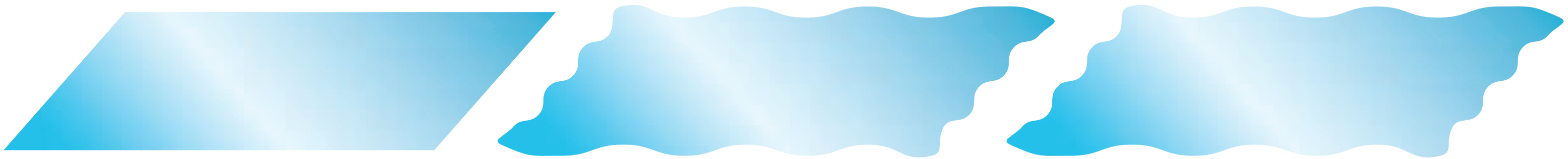
step 2: add wiggles

step 3: quantize wiggles in perturbation series

- this works fine for GR at the linear level

How not to quantize gravity

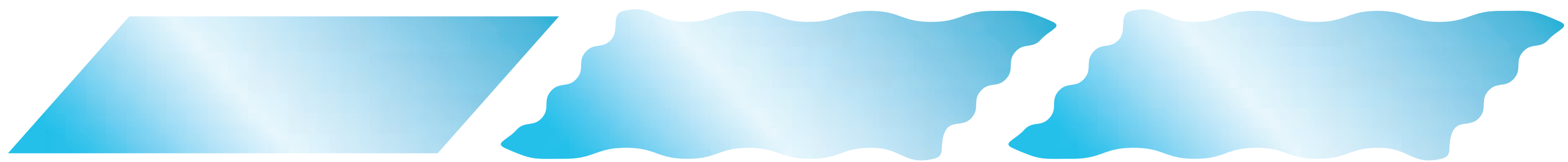
- small scales $\Rightarrow$ quantum mechanics
- classical GR is governed by a system of nonlinear PDEs
- standard approach: quantize perturbations about a simple solution



- this works fine for GR at the linear level
- adding nonlinear terms back in results in a quantum field theory with non-removable divergences and no predictive power

How not to quantize gravity

- small scales $\Rightarrow$ quantum mechanics
- classical GR is governed by a system of nonlinear PDEs
- standard approach: quantize perturbations about a simple solution



step 1: start with flat space   **step 2:** add wiggles   **step 3:** quantize wiggles in perturbation series

- this works fine for GR at the linear level
- adding nonlinear terms back in results in a quantum field theory with non-removable divergences and no predictive power
  - that is, perturbative quantum gravity is non-renormalizable

Is this a problem?

- why do we even want to quantize gravity?

Is this a problem?

- why do we even want to quantize gravity?
  - everything else is quantum, why not gravity?

Is this a problem?

- why do we even want to quantize gravity?
  - everything else is quantum, why not gravity?
  - Einstein field equations state

$$\text{spacetime curvature} \Leftrightarrow \text{matter content}$$

Is this a problem?

- why do we even want to quantize gravity?
  - everything else is quantum, why not gravity?
  - Einstein field equations state

$$\text{spacetime curvature} \Leftrightarrow \text{matter content}$$

- somewhat inconsistent to treat gravity classically and matter quantum mechanically

Is this a problem?

- why do we even want to quantize gravity?
  - everything else is quantum, why not gravity?
  - Einstein field equations state

    $$\text{spacetime curvature} \Leftrightarrow \text{matter content}$$

    - somewhat inconsistent to treat gravity classically and matter quantum mechanically
  - GR implies spacetime singularities at the centre of black holes and at the beginning of the universe (the big bang)

Is this a problem?

- why do we even want to quantize gravity?
  - everything else is quantum, why not gravity?
  - Einstein field equations state

    $$\text{spacetime curvature} \Leftrightarrow \text{matter content}$$

    - somewhat inconsistent to treat gravity classically and matter quantum mechanically
  - GR implies spacetime singularities at the centre of black holes and at the beginning of the universe (the big bang)
    - many believe quantum gravity will "cure" these

Is this a problem?

- why do we even want to quantize gravity?
  - everything else is quantum, why not gravity?
  - Einstein field equations state

    $$\text{spacetime curvature} \Leftrightarrow \text{matter content}$$

    - somewhat inconsistent to treat gravity classically and matter quantum mechanically
  - GR implies spacetime singularities at the centre of black holes and at the beginning of the universe (the big bang)
    - many believe quantum gravity will "cure" these
- these seem like theoretical prejudices

Is this a problem?

- why do we even want to quantize gravity?
  - everything else is quantum, why not gravity?
  - Einstein field equations state

$$\text{spacetime curvature} \Leftrightarrow \text{matter content}$$

    - somewhat inconsistent to treat gravity classically and matter quantum mechanically
  - GR implies spacetime singularities at the centre of black holes and at the beginning of the universe (the big bang)
    - many believe quantum gravity will "cure" these
- these seem like theoretical prejudices
  - is there any experimental information available?

“Observable” quantum gravity?

- how big are quantum gravity effects?

“Observable” quantum gravity?

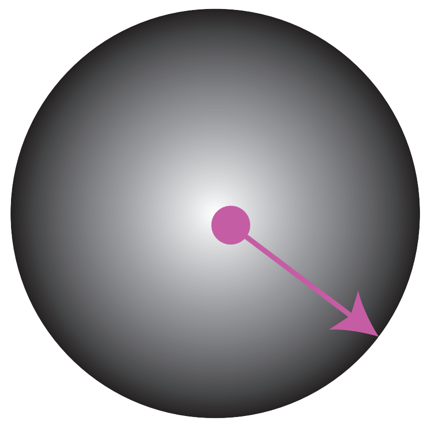
- how big are quantum gravity effects?
- the dimensionful constants in the theory:
  - Newton’s constant G
  - Planck’s constant $\hbar$
  - the speed of light c

- how big are quantum gravity effects?
- the dimensionful constants in the theory:
  - Newton's constant G
  - Planck's constant $\hbar$
  - the speed of light c
- these define the Planck mass/energy and length:

$$M_{\rm Pl} = \sqrt{\frac{\hbar c}{G}} \sim \frac{10^{19}\,{\rm GeV}}{c^2} \qquad \ell_{\rm Pl} = \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35}\,{\rm m}$$

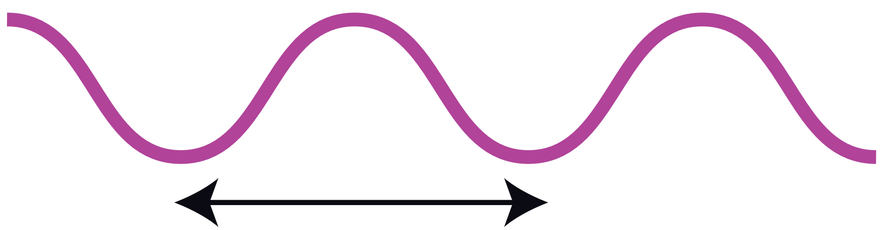
“Observable” quantum gravity?

black hole of mass M



radius $\dfrac{2GM}{c^2}$

quantum particle of mass M



Compton wavelength $\dfrac{2\pi\hbar}{Mc}$

set them equal: $M = \sqrt{\dfrac{\pi\hbar c}{G}} = \sqrt{\pi}M_{\rm Pl}$

a black hole with mass $M_{\rm Pl}$ has a radius $\approx$ Compton wavelength

“Observable” quantum gravity?

- how big are quantum gravity effects?
- the dimensionful constants in the theory:
  - Newton’s constant G
  - Planck’s constant $\hbar$
  - the speed of light c
- these define the Planck mass/energy and length:

$$M_{\rm Pl} = \sqrt{\frac{\hbar c}{G}} \sim \frac{10^{19}\,{\rm GeV}}{c^2} \qquad \ell_{\rm Pl} = \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35}\,{\rm m}$$

- physics intuition: quantum gravity effects will become tangible for (individual particle) energies $\gtrsim M_{\rm Pl}$ or distances $\lesssim \ell_{\rm Pl}$

Hard to see

This means its not easy to observe quantum gravity effects:

phenomenon	typical size ℓ	$\ell_{\rm Pl}/\ell$
solar mass black hole	$10^{3}\,\mathrm{m}$	10^{-38}
hydrogen atom	$10^{-10}\,\mathrm{m}$	10^{-25}
proton	$10^{-15}\,\mathrm{m}$	10^{-20}

This means its not easy to observe quantum gravity effects:

phenomenon	typical size ℓ	$\ell_{\rm Pl}/\ell$
solar mass black hole	10^3 m	10^{-38}
hydrogen atom	10^{-10} m	10^{-25}
proton	10^{-15} m	10^{-20}

phenomenon	typical energy E	$E/M_{\rm Pl}c^2$
hydrogen atom	10^{-9} GeV	10^{-28}
large hadron collider	10^3 GeV	10^{-16}
ultra high energy cosmic rays	10^9 GeV	10^{-8}
cosmological inflation	10^{16} GeV	10^{-3}

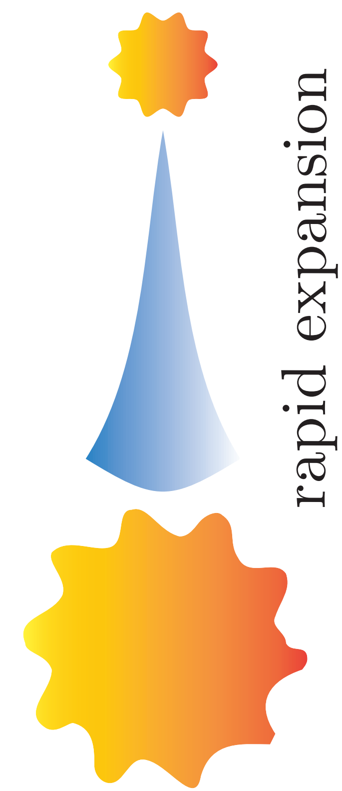
Inflation as a Planck scale microscope

inflation provides a mechanism for the generation of structure in the early universe

Inflation as a Planck scale microscope

inflation provides a mechanism for the generation of structure in the early universe

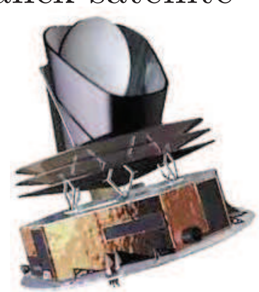
quantum fluctuations when universe is small

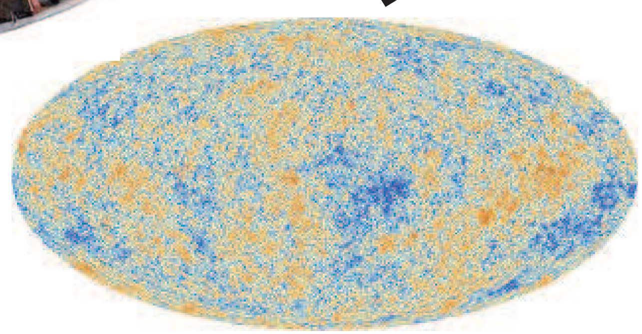


macroscopic inhomogenieties

leads to predictions for the cosmic microwave background

Planck satellite



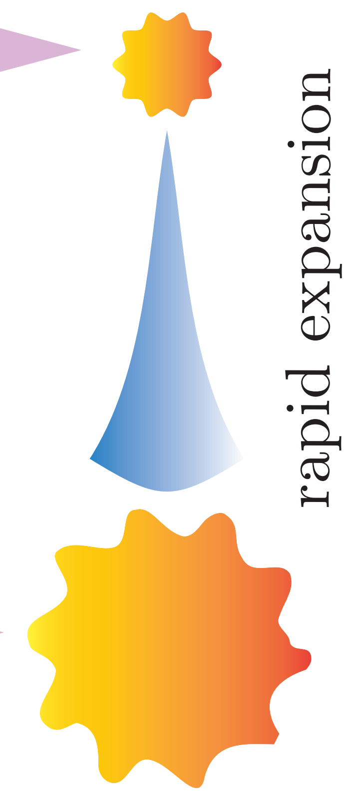


temperature anisotropies

Inflation as a Planck scale microscope

quantum fluctuations when universe is small

these have wavelength $\ll \ell_{\mathrm{Pl}}$ and should be sensitive to quantum gravity



Kempf: “A Planck scale microscope”

these are big enough to see in the distribution of objects in the sky

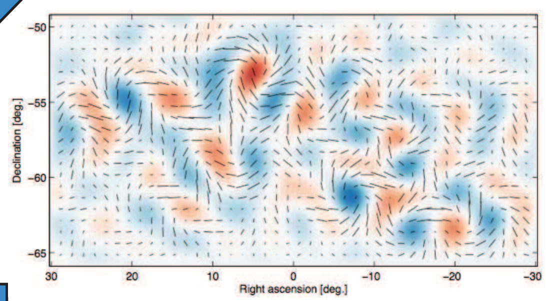
macroscopic inhomogenieties

$\Rightarrow$ we could see quantum gravity effects in large scale structure of universe

Primordial GWs: testable prediction?

tensor modes: purely gravitational fluctuations enhanced during inflation

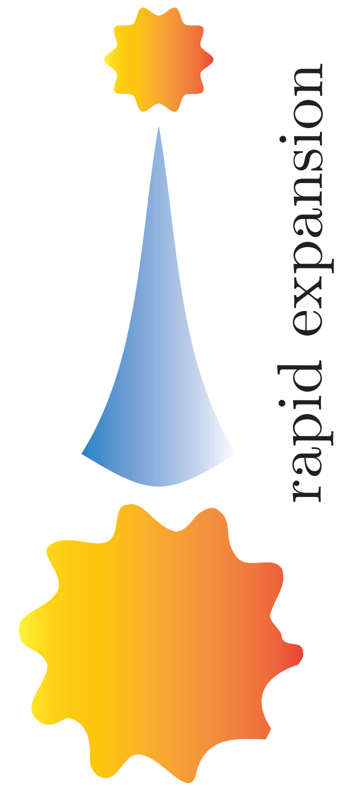
give rise to characteristic polarization in CMB



observation would provide circumstantial evidence for quantized linear gravitation perturbations

finiteness would suggest that gravity ought to be quantized and renormalizable

quantum fluctuations when universe is small

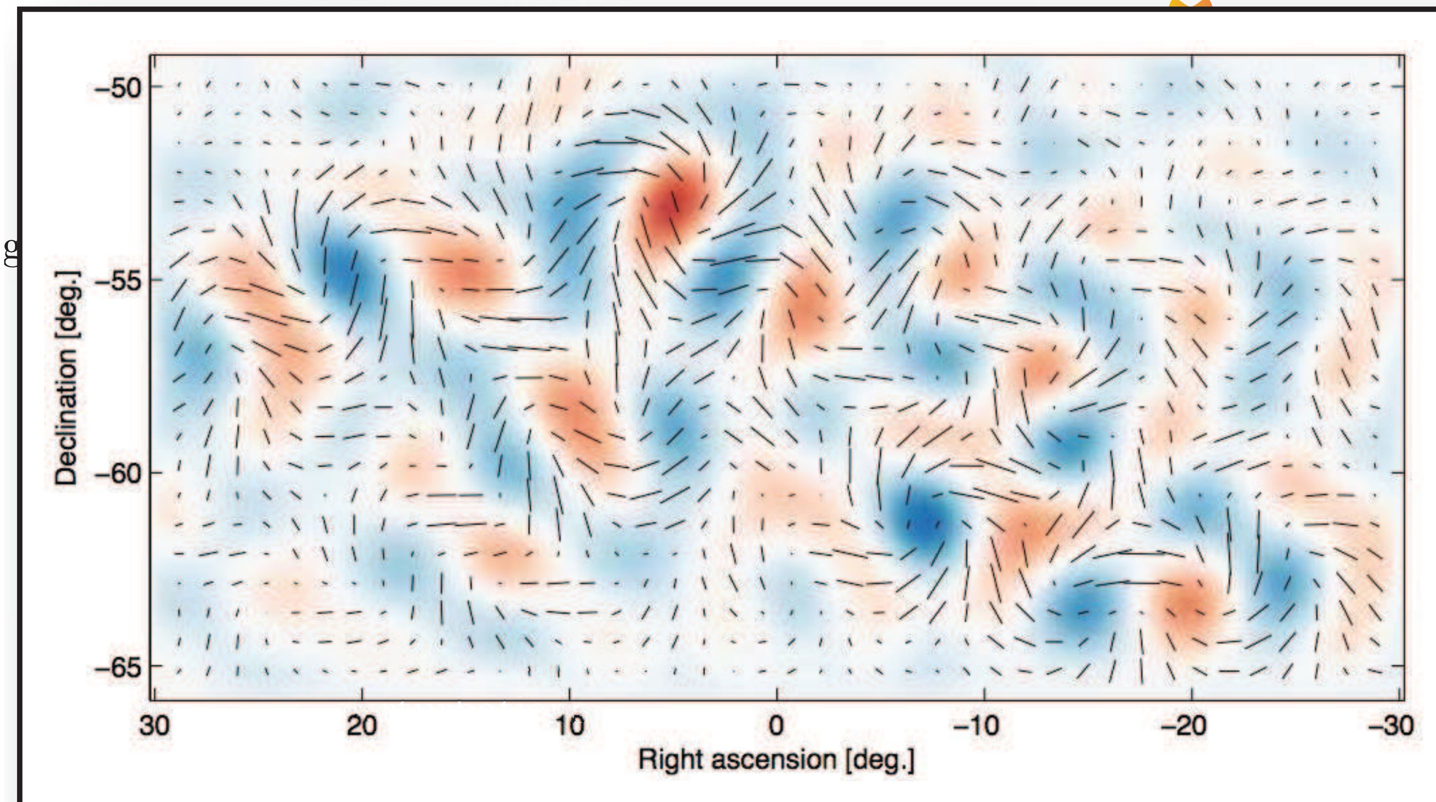


macroscopic inhomogenieties

Primordial GWs: testable prediction?

tensor modes: purely gravitational fluctuations enhanced during inflation

quantum fluctuations when universe is small



macroscopic inhomogenieties

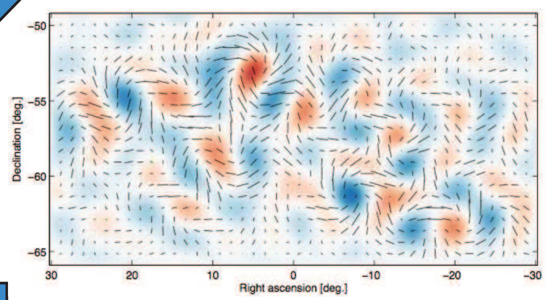
finiteness would suggest that gravity ought to be quantized and renormalizable

Primordial GWs: testable prediction?

tensor modes: purely gravitational fluctuations enhanced during inflation

↓

give rise to characteristic polarization in CMB



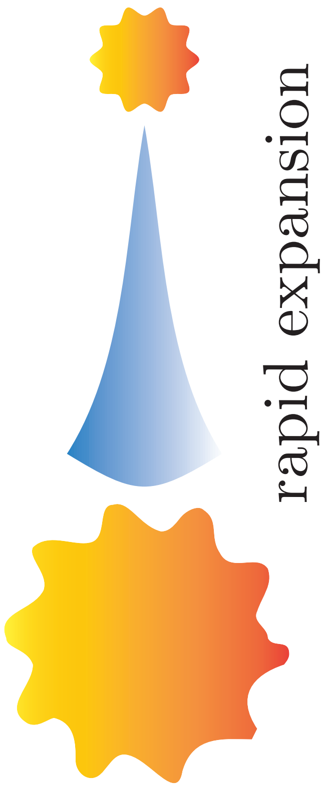
↓

observation would provide circumstantial evidence for quantized linear gravitation perturbations

↓

finiteness would suggest that gravity ought to be quantized and renormalizable

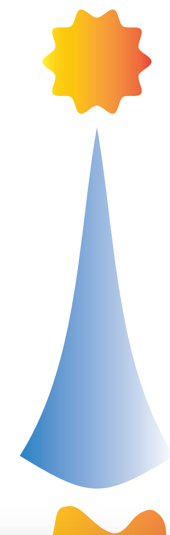
quantum fluctuations when universe is small



macroscopic inhomogenieties

Primordial GWs: testable prediction?

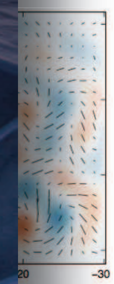
quantum fluctuations when universe is small



rapid expansion

give

p



observation would provide circumstantial evidence for quantized linear gravitation perturbations

finiteness would suggest that gravity ought to be quantized and renormalizable

DETECTION ANNOUNCED MONDAY, MARCH 17 BY BICEP2!

macroscopic inhomogenieties

Small scale patches

Solution 1: quantizing the wrong theory

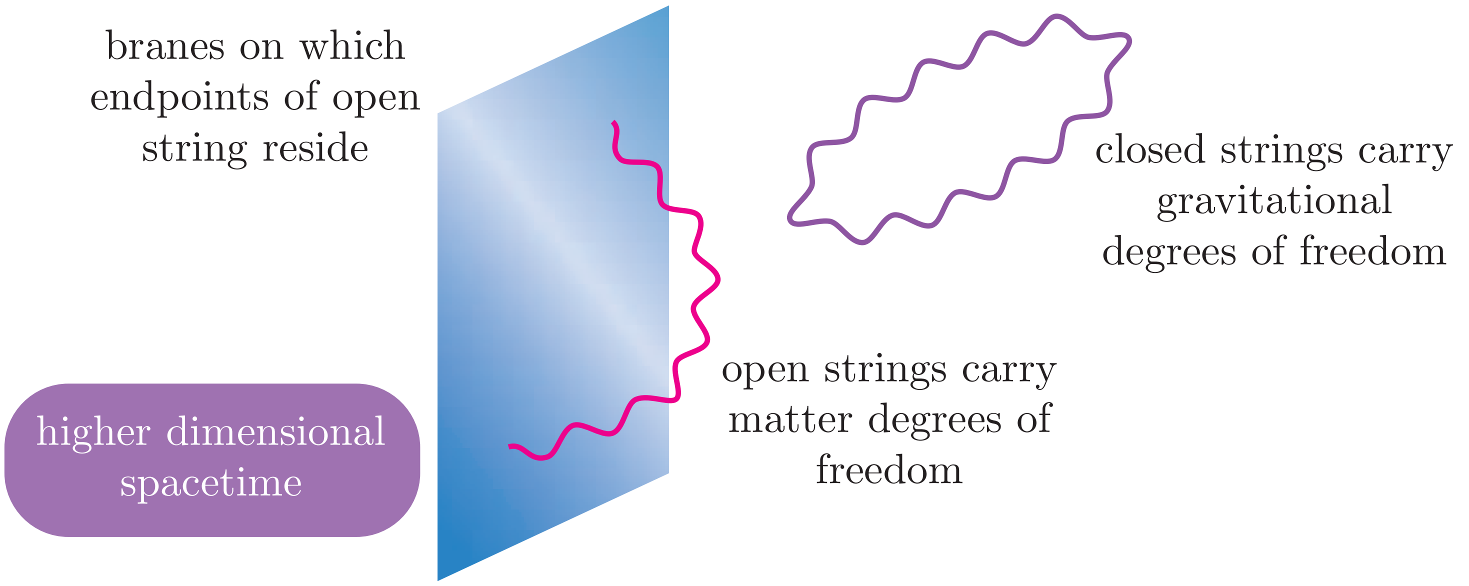
- if GR is cannot be consistently quantized, maybe it is not the correct theory of gravity

Solution 1: quantizing the wrong theory

- if GR is cannot be consistently quantized, maybe it is not the correct theory of gravity
- some options:

Solution 1: quantizing the wrong theory

- if GR is cannot be consistently quantized, maybe it is not the correct theory of gravity
- some options:
  - **string theory:** gravitational field is actually induced by vibrations of higher dimensional objects (strings and branes)



Solution 1: quantizing the wrong theory

- if GR is cannot be consistently quantized, maybe it is not the correct theory of gravity
- some options:
  - **string theory:** gravitational field is actually induced by vibrations of higher dimensional objects (strings and branes)
    - **pros:** vibrations of strings governed by 2D conformal field theory which is nicely behaved

Solution 1: quantizing the wrong theory

- if GR is cannot be consistently quantized, maybe it is not the correct theory of gravity
- some options:
  - **string theory:** gravitational field is actually induced by vibrations of higher dimensional objects (strings and branes)
    - **pros:** vibrations of strings governed by 2D conformal field theory which is nicely behaved
  - **higher curvature and Horava-Lifshitz theories:** GR is effective version of a more complicated (4D) theory that can be consistently quantized

Solution 1: quantizing the wrong theory

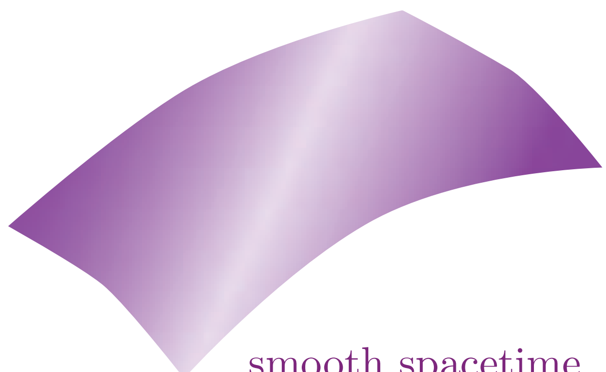
- if GR is cannot be consistently quantized, maybe it is not the correct theory of gravity
- some options:
  - **string theory:** gravitational field is actually induced by vibrations of higher dimensional objects (strings and branes)
    - **pros:** vibrations of strings governed by 2D conformal field theory which is nicely behaved
  - **higher curvature and Horava-Lifshitz theories:** GR is effective version of a more complicated (4D) theory that can be consistently quantized
    - **pros:** the theories are selected to avoid divergences when quantized

Solution 2: right theory but wrong quantization

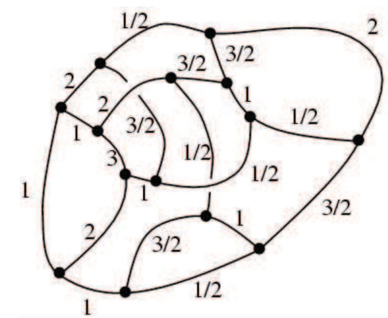
- if we try to quantize gravitational perturbations and get inconsistent results, maybe we ought to try something else?

Solution 2: right theory but wrong quantization

- if we try to quantize gravitational perturbations and get inconsistent results, maybe we ought to try something else?
- **loop quantum gravity:** tries to quantize GR non-perturbatively



smooth spacetime geometry

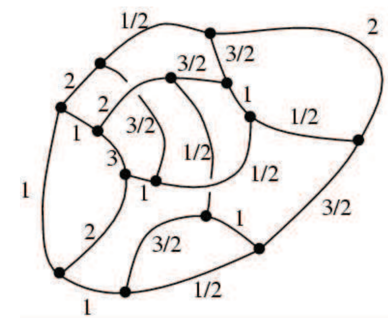


connected graph labelled by spin indices

Solution 2: right theory but wrong quantization

- if we try to quantize gravitational perturbations and get inconsistent results, maybe we ought to try something else?
- **loop quantum gravity:** tries to quantize GR non-perturbatively

smooth spacetime geometry



connected graph labelled by spin indices

- **pros:** no exotic classical theory of gravity; succeeds because of choice of variables and non-standard polymer quantization

. . . and the answer is

?

. . . and the answer is

- in the absence of experimental facts, the only way to distinguish models is consistency checks/theoretical bias

. . . and the answer is

- in the absence of experimental facts, the only way to distinguish models is consistency checks/theoretical bias
- there are criticisms of each approach:

. . . and the answer is

- in the absence of experimental facts, the only way to distinguish models is consistency checks/theoretical bias
- there are criticisms of each approach:
  - string theory involves a background higher dimensional spacetime; i.e. not really a quantization of geometry

. . . and the answer is

- in the absence of experimental facts, the only way to distinguish models is consistency checks/theoretical bias
- there are criticisms of each approach:
  - string theory involves a background higher dimensional spacetime; i.e. not really a quantization of geometry
  - really hard to calculate things in loop quantum gravity; not even sure how classical GR is recovered

Large scale fixes

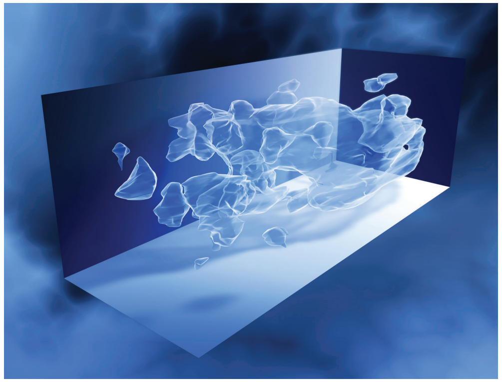
- do we need to modify gravity to account for dark matter?

- do we need to modify gravity to account for dark matter?
- probably not . . . lots of evidence for dark matter other than galactic rotation curves

The dark matter problem

- do we need to modify gravity to account for dark matter?
- probably not . . . lots of evidence for dark matter other than galactic rotation curves
  - for example: weak gravitational lensing lets us map dark matter distribution in galactic clusters

distortions in galactic shapes



map of dark matter distribution

- do we need to modify gravity to account for dark matter?
- probably not . . . lots of evidence for dark matter other than galactic rotation curves
  - for example: weak gravitational lensing lets us map dark matter distribution in galactic clusters
- however . . .

The dark matter problem

- do we need to modify gravity to account for dark matter?
- probably not . . . lots of evidence for dark matter other than galactic rotation curves
  - for example: weak gravitational lensing lets us map dark matter distribution in galactic clusters
- however . . .
  - what is it?

- do we need to modify gravity to account for dark matter?
- probably not . . . lots of evidence for dark matter other than galactic rotation curves
  - for example: weak gravitational lensing lets us map dark matter distribution in galactic clusters
- however . . .
  - what is it?
  - **direct searches:** observe dark matter interaction with dense materials in isolated labs

The dark matter problem

- do we need to modify gravity to account for dark matter?
- probably not . . . lots of evidence for dark matter other than galactic rotation curves
  - for example: weak gravitational lensing lets us map dark matter distribution in galactic clusters
- however . . .
  - what is it?
  - **direct searches:** observe dark matter interaction with dense materials in isolated labs
  - **indirect searches:** observe by-products of dark matter annihilations in the Milky Way

The dark energy problem

- problem of explaining the late time acceleration of universe one of the biggest in physics

The dark energy problem

- problem of explaining the late time acceleration of universe one of the biggest in physics
- if it has a resolution like dark matter, the matter is very strange indeed

The dark energy problem

- problem of explaining the late time acceleration of universe one of the biggest in physics
- if it has a resolution like dark matter, the matter is very strange indeed
- simplest answer is to add a constant Λ to Einstein's equation

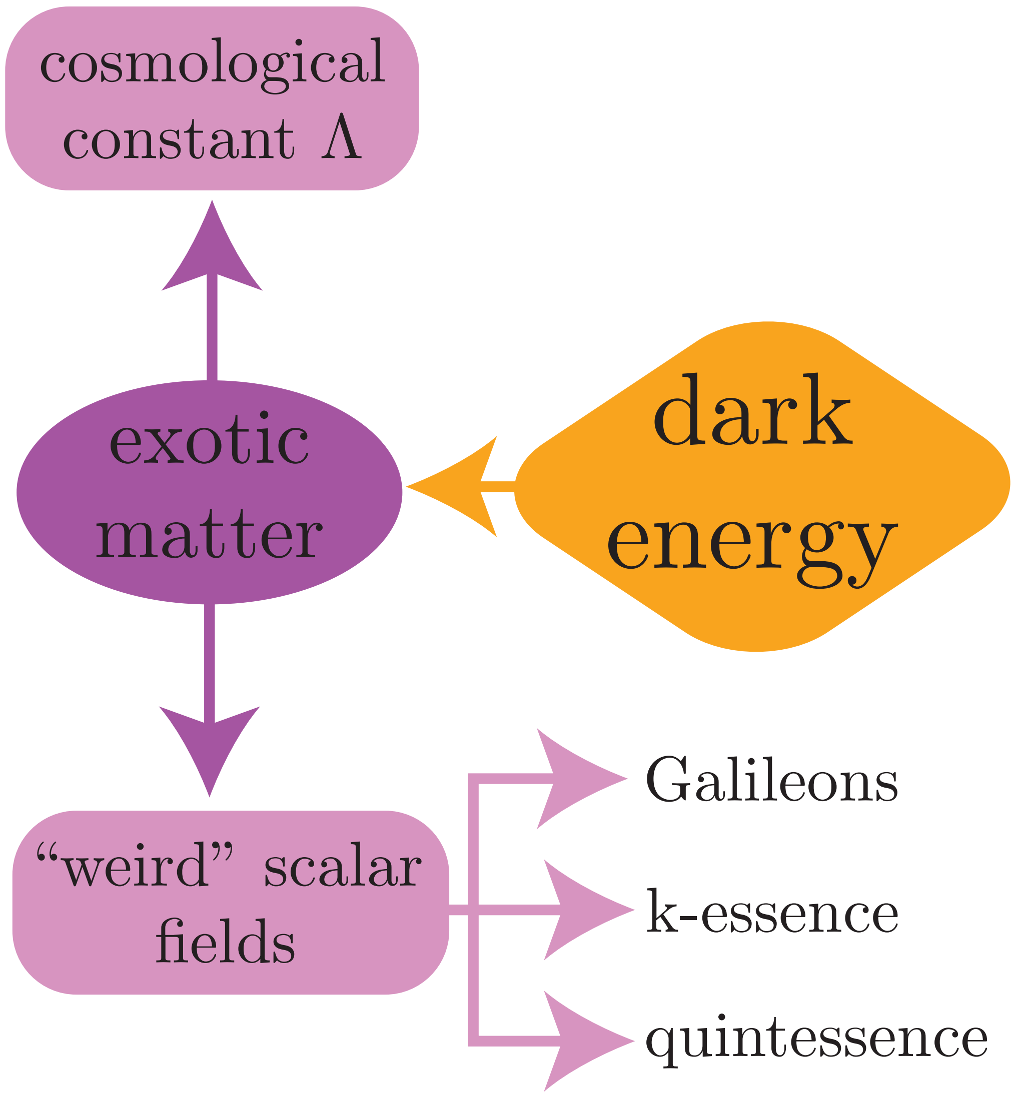
The dark energy problem

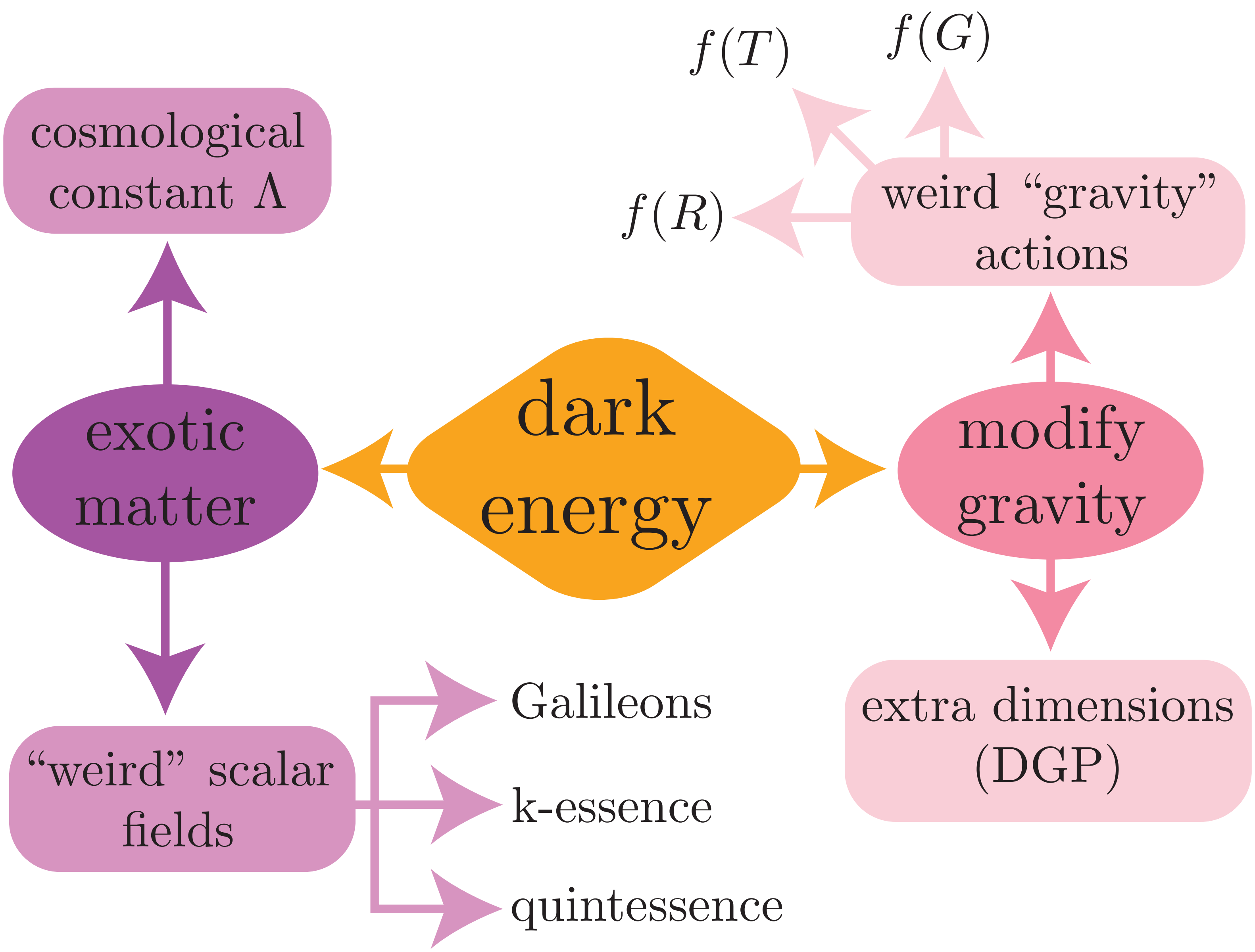
- problem of explaining the late time acceleration of universe one of the biggest in physics
- if it has a resolution like dark matter, the matter is very strange indeed
- simplest answer is to add a constant Λ to Einstein's equation
  - Einstein tried this to get rid of the expansion of the universe: called it "his greatest blunder"

The dark energy problem

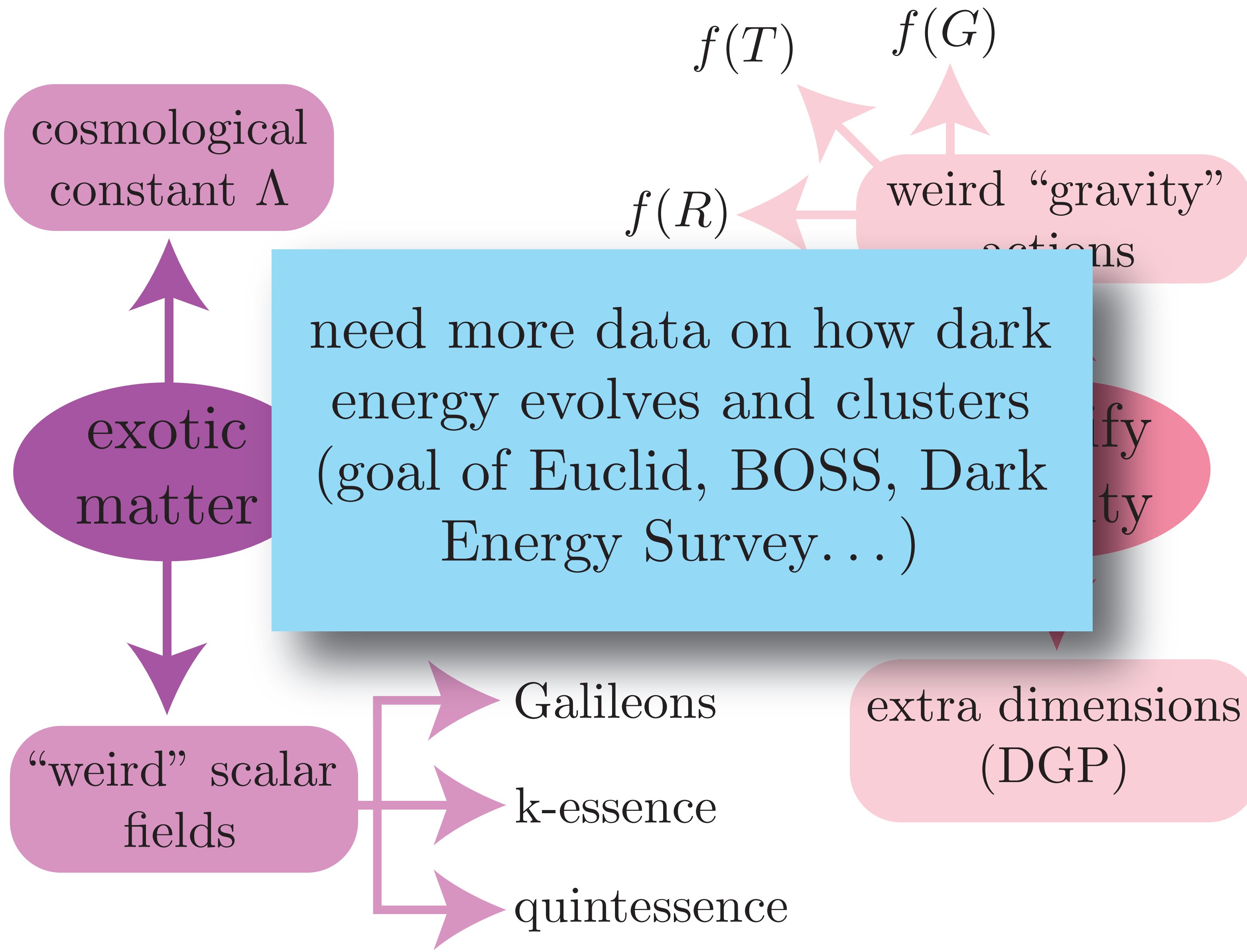
- problem of explaining the late time acceleration of universe one of the biggest in physics
- if it has a resolution like dark matter, the matter is very strange indeed
- simplest answer is to add a constant Λ to Einstein's equation
  - Einstein tried this to get rid of the expansion of the universe: called it "his greatest blunder"
  - observational value of Λ is ridiculously small, hard to "explain" it from other theories with dimensionful constants

Other ideas


cosmological constant Λ
exotic matter
dark energy
"weird" scalar fields
Galileons
k-essence
quintessence


$f(T)$
$f(G)$
cosmological constant Λ
$f(R)$
weird "gravity" actions
exotic matter
dark energy
modify gravity
Galileons
"weird" scalar fields
k-essence
quintessence
extra dimensions (DGP)

Other ideas



need more data on how dark energy evolves and clusters (goal of Euclid, BOSS, Dark Energy Survey. . .)

Where do we stand?

- GR works perfectly well for most astrophysical phenomena if supplemented with dark matter

- GR works perfectly well for most astrophysical phenomena if supplemented with dark matter
  - on the very largest scales, the late time acceleration means that we have to live with another very exotic type of matter (dark energy) or we have to modify gravity

Assessment

- GR works perfectly well for most astrophysical phenomena if supplemented with dark matter
  - on the very largest scales, the late time acceleration means that we have to live with another very exotic type of matter (dark energy) or we have to modify gravity
- traditional approaches to quantizing gravity fail

Assessment

- GR works perfectly well for most astrophysical phenomena if supplemented with dark matter
  - on the very largest scales, the late time acceleration means that we have to live with another very exotic type of matter (dark energy) or we have to modify gravity
- traditional approaches to quantizing gravity fail
  - ~~no~~ direct observational evidence that we are obliged to quantize gravity; cosmological tensor modes are ~~**forthcoming**~~ **here** $\Rightarrow$ **quantum gravity is real (probably)**

Assessment

- GR works perfectly well for most astrophysical phenomena if supplemented with dark matter
  - on the very largest scales, the late time acceleration means that we have to live with another very exotic type of matter (dark energy) or we have to modify gravity
- traditional approaches to quantizing gravity fail
  - ~~no~~ direct observational evidence that we are obliged to quantize gravity; cosmological tensor modes are ~~forthcoming~~ **here $\Rightarrow$ quantum gravity is real (probably)**
  - on the quantum gravity side theoretical motivations drive research $\Rightarrow$ distinguishing theories remains hard to do

Assessment

- GR works perfectly well for most astrophysical phenomena if supplemented with dark matter
  - on the very largest scales, the late time acceleration means that we have to live with another very exotic type of matter (dark energy) or we have to modify gravity
- traditional approaches to quantizing gravity fail
  - ~~no~~ direct observational evidence that we are obliged to quantize gravity; cosmological tensor modes are ~~forthcoming~~ **here $\Rightarrow$ quantum gravity is real (probably)**
  - on the quantum gravity side theoretical motivations drive research $\Rightarrow$ distinguishing theories remains hard to do
- want to learn more? apply to grad school at UNB . . .