Modelling the most catastrophic events in the universe: a journey into Einstein’s theory of gravity

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Plan of the talk

- a brief introduction of gravity
- Einstein’s view of gravity
- black holes, neutron stars, and gravitational waves
- numerical relativity
- simulating catastrophic events
Our experience of gravity
Our experience of gravity

★ Instinctive notion
Our experience of gravity

- Instinctive notion
- Intuitive notion
Our experience of gravity

- Instinctive notion
- Intuitive notion
- Imaginative notion
The fathers of gravity

In 1679 Newton publishes his theory of gravitation.

Gravity is an instantaneous **force** between two masses proportional to the masses and inversely proportional to the square of the distance.

\[ \vec{F} = -\frac{G M m}{c^2 r^2} \hat{e}_r \]

With this theory he could explain essentially **all astronomical** observations of his time.
The fathers of gravity

In 1915 Einstein publishes his theory of gravitation (Allgemeine Relativitätstheorie) changing our understanding of gravity.

According to Einstein, gravity is the manifestation of spacetime curvature.

Any form of mass/energy curves the spacetime.

Implications of this view are: black holes, neutron stars, gravitational waves.
Einstein equations

\[ G_{\mu\nu} = 8\pi T_{\mu\nu} \]
Einstein equations

Einstein tensor

stress-energy tensor

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Einstein tensor
stress-energy tensor

spacetime curvature
mass and energy in the spacetime
There is a relation between the curvature and mass/energy.

Gravity is the manifestation of spacetime curvature.

\[ G_{\mu\nu} = 8\pi T_{\mu\nu} \]
What is spacetime curvature?
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Let's consider a region of space and time (spacetime) void of matter and energy. It will have zero curvature and will therefore be flat.
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Let’s consider a region of space and time (spacetime) void of matter and energy. It will have zero curvature and will therefore be flat.

If instead it contains a mass $M$, it will also have a nonzero curvature and will therefore be a curved spacetime.
Let's consider the orbital motion of an object of small mass $m$ around an object of large mass $M$: (e.g. Earth around the Sun)

**Newton**: the orbit is the result of the balance between the gravitational force and the centrifugal one.
Gravity à la Einstein

Let’s consider the orbital motion of an object of small mass $m$ around an object of large mass $M$: (eg Earth around the Sun)

Einstein: the orbit is what the small object needs to do to avoid falling in the curvature produced by the large mass.
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A measure of the spacetime curvature is contained in the ratio $\frac{M}{R}$: where $M$ and $R$ are the mass and the size of the object. The larger this ratio the larger the gravity/curvature.
Small and large curvatures

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What is the curvature on Earth?

$$\frac{M_\oplus}{R_\oplus} \approx \frac{5.97 \times 10^{24} \text{ kg}}{6372 \text{ km}} \approx 3 \times 10^{-9} \approx 0.0000000003$$
Small and large curvatures

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In our neighbourhood, largest curvature is in the Sun

$$\frac{M_\odot}{R_\odot} \approx \frac{1.98 \times 10^{30} \text{ kg}}{6.95 \times 10^5 \text{ km}} \approx 2 \times 10^{-6} \approx 0.000002$$

In other words: spacetime is very hard to curve!
Consequences of Einstein’s gravity

Einstein’s revolutionary concept of gravity leads to three consequences, some of which he rejected:
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• Black holes
• Neutron Stars
• Gravitational Waves
Black Holes
Nature can produce objects with large $M$ and small $R$. A “gedanken experiment”: let’s take a star of mass $M$ and let’s compress it reducing $R$. This is what happens to the curvature as we increase $M/R$. 

$M/R = 0.00998$
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$$M/R = 0.09980$$
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$$\frac{M}{R} = 0.19230$$
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\[ M/R = 0.3125 \]
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$$M/R = 0.37037$$
Nature can produce objects with large $M$ and small $R$. A “*gedanken experiment*”: let’s take a star of mass $M$ and let’s compress it reducing $R$. This is what happens to the curvature as we increase $M/R$.

$$M/R = 0.44444$$

\[\sqrt{-g_{tt}}\]

*This is the limit curvature for an object with a solid surface (neutron star)*.
Nature can produce objects with large $M$ and small $R$. A "gedanken experiment": let's take a star of mass $M$ and let's compress it reducing $R$. This is what happens to the curvature as we increase $M/R$. We have gone beyond the limit and produced a black hole!
What is a black hole?

There are several ways to understand what a black hole is but the simplest is the concept of escape velocity \( v_f \) i.e. the velocity necessary to escape a gravitational field.
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It's possible to escape Earth's surface: need sufficient velocity.
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$$v_f = \sqrt{\frac{2GM}{R}}$$

It’s possible to escape Earth’s surface: need sufficient velocity.

It’s impossible to escape the black hole surface even for light.

$$c = \sqrt{\frac{2GM_{BH}}{R_{EH}}}$$

$M_{BH}$ : black hole mass

$R_{EH}$ : radius of event horizon
Neutron Stars

$T = 1.30\,\text{ms}$
Neutron stars are the most common end of the evolution of massive stars, i.e., stars with

$$10M_\odot \lesssim M \lesssim 100M_\odot$$

Such stars end their evolution as supernovae.
A spoon of this matter is as heavy as the Mont Blanc.

\[ M \approx 1.3 - 2.0 \, M_{\odot} \]

\[ R \approx 12 - 15 \, \text{km} \]

\[ \rho_c \approx 10^{15} \, \text{g/cm}^3 \]
Let's compare again sizes and curvatures

<table>
<thead>
<tr>
<th>Object</th>
<th>$R$</th>
<th>$M/R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>$R_\odot \simeq 70,000$ km; $M/R \simeq 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>White dwarf</td>
<td>$R_{\text{white dwarf}} \simeq 10,000$ km; $M/R \simeq 10^{-4} - 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Neutron star</td>
<td>$R_{\text{neutron star}} \simeq 12$ km; $M/R \simeq 0.15 - 0.25$</td>
<td></td>
</tr>
<tr>
<td>Black hole</td>
<td>$R_{\text{black hole}} \simeq 1.5$ km; $M/R = 0.5$</td>
<td></td>
</tr>
</tbody>
</table>
Compact Star vs Black Hole

When it comes to compactness, black holes and neutron stars are very similar and extreme!
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\[ \frac{M}{R} = 0.44 \]

\[ p_{\text{gt}} \]

\[ \frac{M}{R} = 0.50 \]

\[ p_{\text{gt}} \]

Two aspects are different: a compact star has a hard surface and the curvature is large but finite; a black hole has no surface and the curvature is infinite at the centre.
Gravitational waves
Gravitational waves: ripples in spacetime

We have seen that compact objects like black holes and neutron stars curve the spacetime near them.
Gravitational waves: ripples in spacetime

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- What happens to the curvature when they move?
- What happens if they orbit around the same center of mass?
Gravitational waves: ripples in spacetime

The mechanical analogy is very close: general relativity predicts that if masses are accelerated, they produce \textit{gravitational waves (GWs)}.
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- They are transverse waves moving at the speed of light: i.e. they produce changes in the direction orthogonal to the propagation one.
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- They are **transverse waves** moving at the speed of light: i.e. they produce changes in the direction orthogonal to the propagation one.
- They **distort space and time** in a quadrupolar manner; squeeze in one direction and stretch in the other one.
Comparing EM and GWs

Electromagnetic and gravitational waves provide information which is complementary.

- EM waves tell us of the thermodynamical properties of matter.
- GWs tell us of the dynamical properties of compact objects.

<table>
<thead>
<tr>
<th>Gravitational-wave spectrum</th>
<th>Electromagnetic spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>f</em> (Hz)</td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>$10^2$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$10^{12}$</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass (M☉)</th>
<th>400nm</th>
<th>700nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>supermassive BHs</td>
<td>$10^7$ M☉</td>
<td>$10^5$ M☉</td>
</tr>
<tr>
<td>stellar BHs</td>
<td>$10^2$ M☉</td>
<td>1 M☉</td>
</tr>
<tr>
<td>NSs</td>
<td>$10^3$ M☉</td>
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*scienceinthenews*
How do you produce gravitational waves?
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However, spacetime is hard to curve and GWs are also hard to produce (not possible in laboratories).

What is needed is:

• compact objects, i.e. large masses in small volumes
• velocities close to that of light
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Clearly, black holes and neutron stars are ideal sources, especially if in binary systems.
How do you detect gravitational waves?

GW detectors are giant interferometers: laser beams are sent to create interference. GWs produce differences in arm lengths

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$$\frac{\Delta L}{L} \approx 10^{-21}$$
Catastrophic events

Back-of-the-envelope calculation (Newtonian quadrupole approx.) shows the energy emitted in GWs per unit time is

\[ L_{GW} \approx \left( \frac{G}{c^5} \right) \left( \frac{M \langle v^2 \rangle}{\tau} \right)^2 \approx \left( \frac{c^5}{G} \right) \left( \frac{R_{Schw.}}{R} \right)^2 \left( \frac{\langle v \rangle}{c} \right)^6 \]
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Near merger the binary is very compact \((R_{Schw.} = 2GM/c^2)\) and moving at fraction of speed of light: GR is indispensable

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As a result, the GW luminosity is:

\[ L_{GW} \approx 10^{-8} \left( \frac{c^5}{G} \right) \approx 10^{50} \text{ erg s}^{-1} \approx 10^{17} L_\odot \]

This is roughly the combined luminosity of 1 million galaxies!
Numerical Relativity: solving Einstein equations on a computer
Numerical relativity

Einstein’s theory is as beautiful as *intractable* analytically
Numerical relativity

Einstein’s theory is as beautiful as intractable analytically

Numerical relativity solves Einstein/HD/MHD eqs. in regimes in which no approximation is expected to hold. To do this we build codes: our ”theoretical laboratories”.
Theoretical laboratories?
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Theoretical laboratories?

Think of them as a factory of "gedanken experiments"
Theoretical laboratories?

Think of them as a factory of “gedanken experiments”
Einstein would have loved them…
Do black holes really exist?...
The Milky Way

View of the full sky (north and south) in the optical.
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Frankfurt
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Sgr A*  
(Center of Milky Way)
The Milky Way

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8.3 kpc $\sim 10^{16}$ km $\sim 10,000$ light years
The Milky Way

View of the full sky (north and south) in the optical.

- Black hole size is proportional to its mass: \( R_S = \frac{2GM}{c^2} \)
- Biggest and largest BHs are at centers of galaxies
- The BH with largest diameter is at center of Milky Way
**Sgr A*: the “dark object” in the Galactic Center**

- Near-infrared telescopes (ESO) have measured orbits of individual stars.
- The stars orbit a dark object: the compact radio source Sgr A*.
- Study of orbits reveals a mass of 4.3 million times the mass of the Sun.

Gillessen/Eisenhauer/Genzel (MPE Garching)
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Images of the radio source

- The shorter the wavelength, the smaller the radio source.
- At $\lambda = 1.3$ mm the radio source becomes the size of the event horizon.

$\text{mas} = \text{milli-arcsecond} = 5 \times 10^{-9}$ rad

$\mu\text{as} = \text{micro-arcsecond} = 5 \times 10^{-12}$ rad
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Very Long Baseline Interferometry (VLBI)

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The Event Horizon Telescope

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What do we want to do?

• **Build a joint black hole camera**
  * image event horizon to the best of present VLBI technology

• **Hunt for pulsars near Sag-A**
  * detection of pulsars will provide unprecedented accuracy

• **Make theoretical predictions/interpretations**
  * use numerical simulations to produce synthetic images
  * interpret observations to constrain theories of gravity

Not easy, but another milestone of modern physics
black-hole binaries
This is the signal that needs to be measured by modern gravitational detectors.
merging neutron-star binaries
The two-body problem in GR

• The merger of BHs is easy to imagine:

\( \text{BH} + \text{BH} \rightarrow \text{BH} + \text{gravitational waves (GWs)} \)
The two-body problem in GR

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• For NSs the question is **subtle**: the merger leads to a star that is very massive (HMNS) but survive for some time (ms)

\[ \text{NS} + \text{NS} \rightarrow \text{HMNS} + \text{... ?} \rightarrow \text{BH} + \text{torus} + \text{... ?} \rightarrow \text{BH} \]
The two-body problem in GR

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  BH + BH $\rightarrow$ BH + gravitational waves (GWs)

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  NS + NS $\rightarrow$ HMNS + ... ? $\rightarrow$ BH + torus + ... ? $\rightarrow$ BH

All complications are in the intermediate stages:

• studying the HMNS we can learn how neutron stars are made, i.e. the equation of state (EOS) of nuclear matter.

• studying the BH+torus we can possibly understand catastrophic events such as short gamma-ray bursts.
$M = 1.6 \, M_\odot$
Quantitative differences are produced by:

- **differences induced by the gravitational MASS:**
  a binary with smaller mass will produce a HMNS further away from the stability threshold and will collapse at a later time

- **differences induced by the EOS:**
  a binary with an EOS with large thermal capacity (i.e., hotter after merger) will have more pressure support and collapse later
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  tidal disruption before merger; may lead to prompt BH
Total mass : $3.37 \, M_\odot$; mass ratio : $0.80$;
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  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse
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- **differences induced by RADIATIVE PROCESSES:**
  radiative losses will alter the equilibrium of the HMNS
Short Gamma-ray Burst

NASA
The most energetic explosions

- Short Gamma-ray bursts (SGRBs) have been observed for 40 years and we see essentially a few per week.
- Energies released are huge: $10^{48-50} \text{ erg}$.
- The merger of two neutron stars can release sufficient energy over the correct timescale.
- No self-consistent model has yet been produced to explain them but a relativistic jet seems necessary.
- Theoretical modelling has now reached level of maturity to shed light short SGRBs.
B-fields during inspiral phase

Typical evolution for a magnetized binary
(hot EOS) $M = 1.5 M_\odot, B_0 = 10^{12} \text{ G}$

Animations: LR, Koppitz
Magnetic fields in the HMNS have complex topology: dipolar fields are destroyed.
Crashing neutron stars can make gamma-ray burst jets

\[ \frac{J}{M^2} = 0.83 \quad M_{\text{tor}} = 0.063 M_\odot \quad t_{\text{accr}} \sim \frac{M_{\text{tor}}}{\dot{M}} \sim 0.3 \text{ s} \]
Conclusions
Conclusions

GSFC/NASA
Conclusions

GSFC/NASA

radio
far-IR
mid-IR
near-IR
optical
x-ray
gamma-ray
GWs

???
It has happened over and over in the history of astronomy: as a new “window” has been opened, a “new”, universe has been revealed. GWs will reveal Einstein’s universe of black holes and neutron stars.