Gravitas Simulation User Manual

1 Introduction

Gravitas is an open–source interactive simulation that models the gravitational interactions of celestial bodies. The program lets you explore everything from the orderly dance of planets in our solar system to the chaotic collisions of black holes and neutron stars. It uses Newtonian physics coupled with visual effects for phenomena such as accretion discs, relativistic jets and gravitational–wave ripples. This manual explains how to operate the simulation, describes its features, and provides scientific background for the many preset scenarios. All dates and times in this document are referenced to the *America/Chicago* time zone.

1.1 Purpose of the simulation

The simulation aims to help students, educators and enthusiasts visualise gravitational dynamics. By adjusting parameters such as object masses, velocities and the universal gravitational constant, you can observe how orbits change, how objects merge, and how gravity drives the large–scale structure of the Universe. Where possible, the simulation draws on real astronomical data (for example, the preset *Solar System* scenario uses approximate masses and orbits for the eight planets and some dwarf planets), but it is primarily a sandbox for experimentation rather than a precise astrophysical model.

1.2 Document organisation

This manual is divided into several sections:

- **Getting Started** – how to load the simulation and basic controls.
- **User Interface Overview** – description of panels, menus and on–screen tools.
- **Physics Engine and Features** – how Gravitas implements gravitational interactions, relativistic effects and visual elements like accretion discs and jets.
- **Objects** – the types of bodies available (stars, planets, black holes, neutron stars, etc.) and their properties.
- **Interacting with the Simulation** – guidance on creating objects, adjusting settings and exploring parameter space.
- **Preset Scenarios** – an exhaustive catalogue of the built–in demonstrations. Each entry summarises the scenario setup and gives scientific context based on current research.
- **Tips and Limitations** – practical advice, known limitations and performance considerations.

Readers who wish to jump directly to a particular scenario can consult the table of contents below.

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2 Getting Started

Gravitas is delivered as a web page containing embedded JavaScript code. To run the simulation you simply open the page (typically `index.html`) in a modern browser such as Chrome or Firefox. No installation is required. On initial load you will see a splash screen followed by a starfield canvas. A tutorial button appears in the lower right corner offering a guided tour of the interface; clicking it displays instructions about zooming, panning and resetting the view.

2.1 Basic controls

- **Play/Pause** – A button in the top–left corner toggles the simulation state. When paused, gravitational forces are not integrated and objects freeze; you can still inspect bodies or change settings.
- **Reset** – Clicking the "reset" icon returns the simulation to its initial state. For preset scenarios it reloads the default arrangement of bodies.
- **Zoom** – Use the mouse scroll wheel or pinch gesture on touch screens to zoom in and out. The scale bar in the bottom centre shows the current zoom level in astronomical units (AU) or kilometres.
- **Pan** – Click and drag the canvas to move your viewpoint across the starfield. Double–clicking the canvas recentres the view.
- **Step** – When the simulation is paused, a "step" button advances time by a single integration step (useful for analysing close encounters or mergers).

2.2 Loading scenarios

The "scenarios" button opens a modal listing dozens of preset configurations. Each entry contains a short description, which is derived from the `SCENARIO_INFO` table in the code base. Selecting a scenario automatically adjusts all relevant settings (number and type of bodies, masses, initial positions and velocities, zoom level, etc.) using the `apply_preset` function. You can return to the previous scenario by clicking the back arrow in the modal.

2.3 Settings menu

The settings gear opens a panel where you can customise physics parameters and the appearance of the simulation. Among the options are:

- **Gravitational constant (G)** – scale factor for Newton's law of gravitation. Increasing G makes gravity stronger relative to velocities, causing orbits to tighten and mergers to occur more quickly.
- **Time step** – controls the integration step size. Smaller steps improve accuracy but slow down the simulation. Larger steps may cause orbits to diverge or objects to pass through each other.
- **Mutual gravity** – toggles whether bodies attract each other or only respond to central forces. Disabling mutual gravity can approximate test particles orbiting a fixed mass.
- **BH accretion and jets** – enable visual effects for black holes, including accretion discs, relativistic jets and gravitational wave ripples when mergers occur.
- **Colour palette** – changes the colour scheme of stars and background to suit light or dark environments.

Adjustments take effect immediately, though some (such as changing the number of bodies) require resetting the simulation to apply.

3 User Interface Overview

The interface is composed of several layered elements:

1. **Starfield Canvas** – The largest element of the page. It renders bodies as coloured circles whose size scales with mass. Black holes appear as dark cores surrounded by glowing accretion discs and, when active, polar jets. Neutron stars and white dwarfs use distinct colours (often blue–white) to differentiate them from ordinary stars and planets. The canvas also shows coordinate axes and scale ticks.
2. **Top Bar** – Contains play/pause/step controls, scenario selector, settings, black hole mass display and a tutorial button. The scenario selector opens a modal listing all presets with icons and descriptions. The black hole mass display shows the mass of selected black holes (useful when merging bodies).
3. **Right Sidebar** – When the object inspector is opened, this panel lists properties of the selected body: mass, radius, velocity, composition (e.g., "black hole", "neutron star", "planet"), and allows renaming or deletion. Clicking on an object in the canvas selects it and centres the inspector on that object.

4. **Modals** – Several pop–up windows provide additional information:
   - *Scenario list* – choose preset scenarios and view their descriptions.
   - *Settings* – adjust physics constants, number of bodies, placement methods (random, circular rings, grid), velocity distribution and more.
   - *Black hole masses* – specify the mass of each black hole before creation. Mass values are in solar masses.
   - *Tutorial* – a simple guide to controls, recommended for first–time users.
5. **Footer** – Displays the simulation time, current zoom scale and any active notifications (e.g., "Two black holes have merged").

The layout is responsive and works on mobile devices as well as desktop browsers. On small screens some controls collapse into drop–down menus to save space.

4 Physics Engine and Features

4.1 Newtonian gravity

At the core of Gravitas is a Newtonian N–body solver. Each body exerts a gravitational force on every other body according to Newton's law of universal gravitation $F = G\frac{m_1 m_2}{r^2}$. The net force on each body determines its acceleration via $a = F/m$. Positions and velocities are updated using a simple time–integration scheme (a semi–implicit method similar to the leapfrog algorithm). You can adjust the gravitational constant G and the integration time step in the settings. Note that extremely large time steps or unrealistic G values may cause instability or objects to pass through each other.

4.2 Merging and accretion

When two bodies pass within a distance less than the sum of their radii they merge into a single body. For star–like objects this produces a larger star (with mass equal to the sum of the progenitors). For compact objects (white dwarfs, neutron stars and black holes) the behaviour is more complex:

- **Black hole mergers** – When two black holes collide the simulation displays an expanding ring of "gravity ripple" particles to indicate a burst of gravitational waves. The new black hole inherits the total mass minus a small fraction emitted as gravitational waves. In reality LIGO observed such an event in 2015 when two black holes of about 29 and 36 solar masses merged; approximately three solar masses of energy were radiated away in gravitational waves.

- **Neutron star mergers** – Two neutron stars spiralling together trigger a kilonova event. In the simulation the objects merge and a burst of ejecta appears; this is inspired by real observations where neutron star collisions produce heavy elements via the rapid neutron–capture process and eject material at a significant fraction of the speed of light.

- **White dwarf mergers** – If a binary white dwarf system grows above the Chandrasekhar limit ($1.44\ M_\odot$) a Type Ia supernova is triggered. The simulation visually shows an explosion, reflecting the runaway thermonuclear reaction that destroys the star.

4.3 Accretion discs and jets

Black holes in Gravitas can produce accretion discs and jets when gas and stars fall into them. The discs are rendered as swirling, glowing particles orbiting the black hole. If enabled, relativistic jets emerge perpendicular to the disc plane. These features are inspired by active galactic nuclei (AGN), where matter spiralling into a supermassive black hole heats up and emits enormous amounts of radiation. Some AGN produce narrow beams of energetic particles that travel nearly at the speed of light. Jet intensity and accretion disc particle count can be adjusted in the settings panel.

4.4 Gravitational wave ripples

During black hole and neutron star mergers the simulation emits expanding concentric rings to mimic gravitational waves. These visual cues are purely aesthetic but highlight that real mergers radiate energy through spacetime as ripples. Gravitational waves were predicted by Einstein's general relativity and were first directly detected in 2015 by the Laser Interferometer Gravitational–Wave Observatory (LIGO). Gravitational waves propagate at the speed of light and carry information about their violent origins.

4.5 Orbital placement options

When creating custom systems you can choose how to arrange objects:

- **Random** – positions bodies randomly within the selected area. Velocities can also be randomised.
- **Circular** – places bodies evenly on a circle around the origin with velocities set for approximate circular orbits. Useful for ring systems like the Solar System or rings of asteroids.
- **Multi–ring** – creates several concentric rings of bodies with adjustable inner and outer radii. A good option for Kuiper Belt or exoplanet laboratory scenarios.
- **Grid** – arranges bodies on a rectangular grid. Combined with small velocities this can simulate a star cluster forming from a molecular cloud.

5 Objects

Gravitas supports several types of celestial bodies, each with unique properties and visual cues. Table 1 summarises the options and provides brief scientific context.

Table 1: Object types and their scientific context

Object type	**Description and scientific context**
Planet	Earth–like planets have masses from 0.01–1 $M_\odot$ and radii scaled accordingly. They appear as coloured spheres with a thin atmosphere.
Gas giant	Larger planets (e.g., Jupiter or Saturn) with masses up to a few Jupiter masses. They are coloured differently to distinguish them from terrestrial worlds.

Object type	Description and scientific context
Star	Main–sequence stars with masses from ~ 0.1 to 50 $M_\odot$. They emit light based on mass; more massive stars are brighter and bluish, lower mass stars are redder.
White dwarf (WD)	Compact stellar remnants with masses $\leq$1.4 $M_\odot$. In reality white dwarfs are Earth–sized but contain roughly the mass of the Sun. They appear as small white or blue points. If two WDs merge and exceed the Chandrasekhar limit (1.44 $M_\odot$) they explode as a Type Ia supernova.
Neutron star (NS)	Extremely dense remnants of massive stars. A neutron star packs half a million Earth masses into a sphere roughly 20 km across; if rotating rapidly with a strong magnetic field it becomes a pulsar, emitting beams of radiation that sweep across space. Neutron star collisions produce kilonovae and heavy elements.
Black hole (BH)	Regions of spacetime where gravity is so strong not even light can escape. The simulation uses non–relativistic Newtonian dynamics but includes visual effects for accretion and relativistic jets. Black holes can merge and emit gravitational wave ripples.
Micro black hole	Hypothetical small black holes (¡1 $M_\odot$). They might have formed in the early universe and could evaporate via Hawking radiation. In the simulation they serve as test masses.

Each body has properties such as mass, radius, velocity, colour and composition, which you can edit via the object inspector. In the simulation, gravitational interactions depend solely on mass and distance; other properties affect only the rendering.

6 Interacting with the Simulation

6.1 Creating and editing bodies

From the settings panel you can choose how many objects of each type to create. For example, selecting two black holes and 100 planets will randomly distribute two black holes and one hundred planets according to the placement method. Once placed, you can:

1. **Select a body** – click on a body in the canvas; its properties appear in the inspector. The inspector lists mass, radius, velocity, type and other attributes. You can rename the object or delete it. Deleting a body removes it from the simulation and its mass is no longer considered in the gravitational calculation.

2. **Edit properties** – change the mass or velocity values in the inspector. After editing, click "apply" to update the simulation; the object will respond with new trajectories accordingly.

3. **Add bodies** – use the creation tools in the settings panel to spawn additional objects. Choose the object type, number and placement method, then click "place".

6.2 Adjusting simulation parameters

In addition to object properties, you can modify global settings:

- **Gravitational constant** – scales the strength of gravity. Setting G to zero stops all gravitational interactions, allowing bodies to drift with constant velocity. Increasing G emphasises gravitational attraction and leads to faster mergers and tighter orbits.
- **Time step** – controls how far the simulation advances each frame. Small steps improve stability; large steps accelerate time at the cost of accuracy.
- **Drag coefficient** – the simulation includes optional drag to damp velocities; this is not physically realistic in vacuum but can help achieve stable orbits in chaotic setups.
- **Enable/disable mutual gravity** – if off, bodies experience gravitational attraction only from black holes or stars marked as "central". This can approximate planetary systems around a fixed massive star.
- **Enable jets and accretion discs** – toggles visual effects around black holes.

Experimenting with these parameters teaches how gravitational systems respond to changes in fundamental constants and initial conditions.

7 Preset Scenarios

Gravitas includes a wide range of preset scenarios accessible from the scenario list. They illustrate many astrophysical phenomena, from simple planetary orbits to exotic compact–object interactions. This section describes each scenario, summarises the simulation configuration and offers scientific background based on current research.

7.1 Solar System

Summary: The simulation recreates our Solar System, including the eight major planets and several dwarf planets and comets. The planets orbit a central star at distances scaled appropriately; comets travel on elongated orbits.

Scientific background: The Solar System formed about 4.6 billion years ago from a protoplanetary disk of gas and dust. It consists of the Sun, eight planets, dwarf planets (e.g., Pluto, Eris), moons, asteroids and comets. Gravity from the Sun dominates the motion of these bodies. Inner planets (Mercury, Venus, Earth and Mars) are rocky, whereas outer planets (Jupiter, Saturn, Uranus and Neptune) are gas or ice giants. The Kuiper Belt beyond Neptune contains millions of icy objects and dwarf planets. Neptune's gravity prevented planet formation in this region and stirred up the disk.

7.2 Earth–Moon System

Summary: A close–up view of the Earth–Moon system illustrating tidal locking and orbital dynamics. The Earth appears larger with a single moon orbiting it.

Scientific background: The Earth–Moon system formed when a Mars–sized body collided with the proto–Earth, ejecting debris that coalesced into the Moon. The Moon's gravitational pull causes tides on Earth and gradually slows Earth's rotation while pushing the Moon farther away by about 3.8 cm per year. The Moon is tidally locked, meaning the same side always faces Earth. This scenario emphasises the gravitational dance of a binary planet–moon system.

7.3 TRAPPIST–1 System

Summary: Models the TRAPPIST–1 planetary system, an ultra–cool red dwarf star about 40.7 light–years away. Seven known planets orbit the star in periods ranging from 1.5 to 19 days, four of which lie within the habitable zone.

Scientific background: TRAPPIST–1's seven planets are all Earth–sized. Because the star is only about 9 % the mass of the Sun and cooler (surface temperature $\sim$ 2,566 K), its habitable zone is close to the star. The planets are likely tidally locked (one side always facing the star). This scenario demonstrates how multiple close–in planets interact gravitationally and shows orbital resonances (the planets' periods are nearly integer ratios).

7.4 GW150914 Gravitational–Wave Event

Summary: A recreation of the first gravitational wave detection, where two black holes of roughly 29 and 36 solar masses merged to form a new black hole of 62 solar masses with about three solar masses radiated away.

Scientific background: On 14 September 2015 LIGO detected gravitational waves from the merger of two stellar–mass black holes located about 1.3 billion light–years away. The event (named GW150914) confirmed Einstein's prediction that accelerating masses emit ripples in spacetime. In the simulation you can watch the black holes inspiral, merge and emit a visible ripple as a stand–in for the gravitational waves. Real gravitational waves propagate at the speed of light and distort spacetime by an incredibly small amount.

7.5 Binary Black Holes

Summary: Two black holes orbit each other at varying separations. Over time they emit gravitational waves and spiral inward, eventually merging. The simulation shows accretion discs and jets if enabled.

Scientific background: Binary black holes can form from massive binary star systems or through dynamical interactions in dense star clusters. As they orbit each other they lose energy and angular momentum by emitting gravitational waves. Eventually they merge into a single more massive black hole. LIGO and Virgo have detected many such events, including GW150914.

7.6 Triple Black Hole System

Summary: Three black holes of similar mass orbit each other in a chaotic dance. Depending on initial conditions, two may merge first, flinging the third away, or all three may interact for a long time before settling.

Scientific background: Triple black hole systems can arise in galactic centres following successive mergers. Their dynamics are complex: gravitational slingshots can eject one black hole or cause rapid mergers. Studying such systems helps understand gravitational wave signals and the evolution of galactic nuclei.

7.7 Supermassive Black Hole (Sagittarius A)

Summary: This scenario places a massive black hole (4 million $M_{\odot}$) at the centre with stars orbiting at various distances. It mimics the environment around Sagittarius A, the supermassive black hole at the Milky Way's centre.

Scientific background: Observations with Chandra and Hubble reveal that Sagittarius A has a mass of roughly four million times the Sun and is located about 26,000 light–years from Earth. Gas and stars orbit it, with only a small fraction of infalling material reaching the event horizon; much of it is ejected in winds or jets. The simulation allows you to explore how stars behave under the intense gravity of a supermassive black hole.

7.8 Star Cluster

Summary: Generates a dense cluster of thousands of stars with random positions and velocities. The cluster collapses or expands depending on gravitational interactions and initial conditions.

Scientific background: Star clusters are gravitationally bound groups of stars that formed together. *Globular clusters* contain tens of thousands to millions of stars, are spherical and ancient (8–13 billion years old), and span 50–450 light–years. *Open clusters* are looser groups of tens to thousands of stars, a few light years across, and typically less than a billion years old. *Stellar associations* are even more diffuse, with 10–10,000 stars spread over hundreds of light years. This scenario lets you study cluster dynamics, evaporation and core collapse.

7.9 Kuiper Belt

Summary: Simulates a ring of thousands of small icy bodies beyond Neptune. A central star and the four giant planets are included.

Scientific background: The Kuiper Belt occupies the region from about 30 AU to 50 AU beyond Neptune. It contains millions of icy bodies, including dwarf planets such as Pluto, Haumea and Makemake. These objects are remnants from the early Solar System and contain rock, water ice and frozen gases like methane. Neptune's gravitational influence prevented these objects from coalescing into a large planet and stirred them into a thick disc.

7.10 Sagittarius A

See the *Supermassive Black Hole* scenario above.

7.11 Binary Star System

Summary: Two stars orbit their common centre of mass. You can adjust mass ratios to observe the effects on orbital period and barycentre location.

Scientific background: Many stars exist in binary or multiple systems. Binary stars exchange mass and angular momentum through tidal interactions. If one star evolves into a compact object (WD, NS or BH), the system can produce X–ray binaries or eventually merge, creating a supernova or gravitational wave event. The orbital period depends on the masses and separation; Kepler's laws describe this relationship.

7.12 Slingshot (Gravity Assist)

Summary: A spacecraft (test particle) approaches a massive body and is accelerated using the planet's gravitational field. The simulation allows you to vary approach angle and velocity to observe the change in trajectory.

Scientific background: A gravity assist (or slingshot) uses a three–body interaction to change a spacecraft's velocity relative to a central body. When the spacecraft swings by a planet, it exchanges energy with the planet; relative to the Sun, the spacecraft gains (or loses) speed while the planet's change is negligible due to its huge mass. NASA's Cassini probe used gravity assists at Venus, Earth and Jupiter to reach Saturn. Cassini's Titan flybys changed the spacecraft's speed by about 800 m/s while Titan's speed changed by about 7 cm per million years.

7.13 Rogue Encounter

Summary: A star with its own planets passes near another planetary system. The gravitational perturbation can eject planets, capture them or send comets into the inner system.

Scientific background: Stars drift through the galaxy and occasionally pass close to the Sun. For example, Scholz's star (a red dwarf) likely grazed the Solar System's Oort Cloud about 70,000 years ago. Passing stars can perturb the orbits of comets and Kuiper Belt objects and send them into the inner Solar System. Such encounters happen roughly every 100,000 years, with closer flybys every few million years.

7.14 Neutron Star Collision

Summary: Two neutron stars orbit and spiral inward until they merge, releasing a burst of ejecta and gravitational waves.

Scientific background: Neutron stars are incredibly dense objects left over after supernovae. When two orbit each other they emit gravitational waves and eventually collide. The merger triggers a kilonova, ejecting material at 20–30 % of the speed of light and synthesising heavy elements like strontium via the r–process. The 2017 event GW170817 was accompanied by electromagnetic emissions across the spectrum.

7.15 Pulsar System

Summary: One or more neutron stars rotate rapidly and emit beams of radiation. The simulation shows pulsars as flashing points and allows you to explore their gravitational influence on nearby bodies.

Scientific background: Pulsars are rotating neutron stars with strong magnetic fields. Beams of radiation emanate from the magnetic poles; because the magnetic axis is often misaligned with the spin axis, the beams sweep through space like a lighthouse. When the beam crosses Earth, we observe pulses of radio waves. Pulsar periods can be milliseconds to seconds. The simulation emphasises the intense gravity of neutron stars and the periodic nature of pulsar emission.

7.16 White Dwarf Binary (Type Ia Supernova)

Summary: Two white dwarfs orbit each other. When the combined mass approaches the Chandrasekhar limit (1.44 $M_\odot$), they merge and explode as a Type Ia supernova.

Scientific background: A Type Ia supernova occurs in a binary system when a white dwarf accretes material from a companion or merges with another white dwarf. As the mass approaches the Chandrasekhar limit the carbon–oxygen core ignites, triggering a thermonuclear runaway that releases about 1×10^{44} J and completely unbinds the star. Type Ia supernovae have nearly uniform peak brightness, making them standard candles for measuring cosmic distances.

7.17 Stellar Graveyard

Summary: A mixture of black holes, neutron stars and white dwarfs interacts in a dense region. Frequent mergers and ejections occur.

Scientific background: Regions like globular clusters or galactic centres can harbour many compact objects. Dynamical interactions can lead to exchanges, hierarchical systems and collisions. Understanding such "compact object zoos" helps scientists interpret gravitational wave detections.

7.18 Galactic Centre

Summary: Models a dense star cluster around a supermassive black hole. Stars experience strong relativistic precession and may be tidally disrupted.

Scientific background: The Milky Way's centre hosts a cluster of young, massive stars orbiting Sagittarius A. Some stars follow highly eccentric orbits, while others reside in a disc. Stellar orbits probe the gravitational potential and test general relativity. Tidal disruption events occur when a star passes too close to the black hole and is torn apart. The simulation shows how stars can be captured or flung away by gravitational slingshots.

7.19 Supernova Remnant

Summary: A massive star explodes, leaving behind an expanding shell of gas. The simulation renders the shock wave and tracks the dynamics of the ejected material.

Scientific background: Supernova remnants (SNRs) are the remains of supernova explosions. Shell–type remnants display limb–brightened rings, while Crab–like remnants (plerions) contain pulsar wind nebulae. SNRs heat the interstellar medium, distribute heavy elements and accelerate cosmic rays. Studying SNRs provides insight into stellar evolution and cosmic ray physics.

7.20 Compact Object Zoo

Summary: A random assortment of black holes, neutron stars and white dwarfs interacts gravitationally. The system evolves chaotically with mergers, ejections and high–velocity encounters.

Scientific background: Dense environments like globular clusters or galactic nuclei can contain many compact objects. Because black holes are more massive, they sink to the centre (mass segregation). Dynamical interactions can produce binaries, triples or runaway stars. Observations of gravitational waves provide evidence for such environments.

7.21 Millisecond Pulsar

Summary: A rapidly rotating neutron star emits beams of radiation thousands of times per second. The simulation emphasises the extremely short pulsar period and its gravitational effect on nearby bodies.

Scientific background: Millisecond pulsars spin hundreds of times per second. They are often found in binaries and have been spun up ("recycled") by accreting material from a companion star. Millisecond pulsars are exceptionally stable clocks and are used to detect gravitational waves through pulsar timing arrays. The rapid rotation arises because angular momentum is transferred from the accreted matter.

7.22 Tidal Disruption Event

Summary: A star approaches a black hole on a nearly parabolic orbit. At pericentre the tidal forces tear the star apart. Some debris is ejected while the rest forms an accretion disc.

Scientific background: When a star gets too close to a black hole it experiences "spaghettification". The tidal force on the star's near side is much greater than on its far side, stretching and ultimately shredding the star. The debris forms an accretion disc and produces a bright flare that fades over months or years. Observations of events like ASASSN–14li have confirmed models of tidal disruption.

7.23 Intermediate–Mass Black Hole

Summary: Two relatively massive black holes (60–80 $M_{\odot}$) merge to form a black hole of intermediate mass (¿100 $M_{\odot}$), radiating energy as gravitational waves.

Scientific background: Intermediate–mass black holes (IMBHs) bridge the gap between stellar–mass and supermassive black holes. They have masses between 100 and 100,000 $M_{\odot}$. The gravitational wave event GW190521, detected in 2019, involved the merger of black holes of 85 $M_{\odot}$ and 65 $M_{\odot}$, producing a 142 $M_{\odot}$ black hole and radiating eight solar masses of energy. IMBHs may form through repeated mergers or collapse of massive stars.

7.24 Galactic Collision

Summary: Two galaxies merge. Stars are rarely involved in direct collisions but are gravitationally scattered, and supermassive black holes spiral inward to merge. The simulation often includes two star clusters and central black holes.

Scientific background: The Milky Way and Andromeda galaxies are expected to collide in about 4.5 billion years as Andromeda approaches at $\sim$ 110 km/s. Individual star collisions are unlikely due to vast interstellar distances, but some stars may be ejected into intergalactic space. The merger may also involve the smaller Triangulum Galaxy and ultimately produce a new elliptical galaxy. The final coalescence of the central black holes will radiate powerful gravitational waves.

7.25 Micro Black Hole Swarm

Summary: A swarm of hypothetical micro black holes interacts with each other and with normal stars. Because they are tiny, they can zip through the system quickly or evaporate.

Scientific background: Micro black holes (also known as mini black holes or quantum black holes) are hypothetical objects with masses much less than a solar mass. Stephen Hawking proposed that quantum effects could allow such tiny black holes to form in the early universe. They might evaporate by emitting Hawking radiation and would disappear quickly. In the simulation they serve as test particles, illustrating chaotic gravitational scattering and potential evaporation.

7.26 Exoplanet Lab

Summary: A laboratory of dozens of exoplanets orbiting a star or stars. You can vary orbital configurations and masses to explore stability and resonances.

Scientific background: Since 1992 astronomers have discovered thousands of exoplanets using methods such as transits and radial velocity. Many exoplanets orbit closer to their stars than Mercury does to the Sun and come in a range of sizes from super–Earths to mini–Neptunes. Studying multiple exoplanets in different configurations helps understand planet formation and migration.

7.27 Quasar Cannon

Summary: A supermassive black hole emits powerful jets that fling stars and gas away. The simulation shows jets hitting objects and accelerating them to high velocities.

Scientific background: In active galactic nuclei the accretion disc around a supermassive black hole can launch relativistic jets that travel near the speed of light. Quasars and blazars are AGN whose jets are pointed toward Earth, making them extremely luminous. The simulation exaggerates the effect to illustrate how jets can expel matter from the galactic centre.

7.28 Pinwheel Galaxy Core

Summary: A dense star cluster orbits the core of a spiral galaxy with long tidal arms. This scenario emphasises the tidal stripping and star formation triggered by galactic interactions.

Scientific background: The Pinwheel Galaxy (Messier 101) is a face–on spiral galaxy with a prominent nucleus and well–defined spiral arms. Interactions with companion galaxies can create tidal tails—streams of stars and gas pulled out by gravitational forces. In the Hubble image of the interacting galaxies NGC 4676 (the "Mice"), long tails of stars emanate from each galaxy due to tidal forces, and clusters of young stars form along the tails. Similar processes occur in real galactic mergers.

7.29 Star Frisbee

Summary: Stars are slung around a central mass and flung outwards like frisbees. This scenario tests extreme slingshots and gravitational interactions.

Scientific background: High–speed interactions near massive bodies can impart enough energy to eject stars from galaxies. The Milky Way contains *hypervelocity stars* travelling over 1,000 km/s, thought to have been ejected by interactions with Sagittarius A or by supernova explosions in binary systems.

7.30 Kessler Cascade

Summary: A ring of satellites (asteroids) orbit a planet. Collisions produce fragments that trigger further collisions, illustrating the Kessler Syndrome.

Scientific background: The *Kessler Syndrome* describes a cascade of orbital debris collisions. Donald Kessler and Burton Cour–Palais predicted in 1978 that as more spacecraft are launched, the likelihood of collisions increases; each smashup creates fragments that increase the probability of future collisions. The phenomenon could create a belt of debris around Earth more hazardous than natural meteoroids. In the simulation, the cascade is exaggerated to show how debris can proliferate.

7.31 Alien Dyson Swarm Collapse

Summary: Hundreds of artificial satellites orbit a star in a tight swarm. Small perturbations cause the swarm to collapse, leading to collisions and ejections.

Scientific background: A *Dyson sphere* is a hypothetical megastructure encircling a star to capture its energy. A Dyson *swarm* consists of many independent satellites orbiting the star. Such structures were popularised by Freeman Dyson as a thought experiment to illustrate how advanced civilisations might harvest stellar energy. In the simulation the swarm is unstable; tiny gravitational interactions cause collisions and catastrophic collapse.

7.32 Tidal Arm Tango

Summary: Two galaxies with spiral arms interact, forming tidal tails that twist and wrap around each other. Stars and gas are pulled out into elongated structures.

Scientific background: When galaxies interact, tidal forces stretch them, creating long streams of stars and gas known as *tidal tails*. In the interacting galaxies NGC 4676 ("The Mice"), tidal forces trigger star formation along the tails, and simulations show the pair will eventually merge into a single galaxy. The simulation reproduces this phenomenon on a simplified scale.

7.33 Hungry Hungry Holes

Summary: Multiple black holes orbit within a cluster of stars. They compete to accrete stars and small bodies, growing in mass and occasionally merging.

Scientific background: Dense star clusters may contain many stellar–mass black holes. Through dynamical friction they sink toward the centre where they interact, sometimes merging. Those with the most mass dominate, "eating" stars and smaller black holes. Such environments could produce repeated gravitational wave events.

7.34 Slingshot Gauntlet

Summary: A series of massive bodies is arranged like an obstacle course. A test particle must navigate the gauntlet, utilising slingshots while avoiding collisions.

Scientific background: Spacecraft such as Voyager and Cassini used multiple gravity assists to reach the outer planets. A chain of slingshots can dramatically increase a spacecraft's energy relative to the Sun. The slingshot gauntlet emphasises planning trajectories and timing to achieve a desired final velocity.

7.35 Black Hole Billiards

Summary: Multiple black holes interact on a billiard–table–like plane. Their gravitational interactions send them ricocheting across the system, merging or ejecting each other.

Scientific background: In dense environments, black holes can encounter each other and undergo gravitational slingshots. Some may be ejected at high speeds into intergalactic space, while others form binaries and merge. These interactions contribute to the population of free–floating black holes and gravitational wave sources.

7.36 Stellar Nursery

Summary: A large cloud of gas and dust collapses under gravity to form a cluster of protostars. The simulation uses many low–mass bodies arranged in a grid or random distribution with small velocities.

Scientific background: Stars form in cold, dense regions of interstellar molecular clouds. When parts of a cloud reach a critical mass they collapse under their own gravity, forming protostars. The collapse can be triggered by shock waves from supernovae, collisions with other clouds or gravitational instabilities. As the protostars grow, they may eject jets and drive turbulence. Observations of the Orion Nebula show more than 700 newborn stars, ranging from 100,000 to a million years old. Stellar nurseries are the birthplaces of stars and planets.

8 Tips and Limitations

- **Performance:** Gravitas runs entirely in the browser. Systems with many thousands of particles may slow down on older hardware. If the frame rate drops, try reducing the number of bodies, disabling visual effects or increasing the time step.
- **Accuracy:** The simulation uses Newtonian physics and does not include general relativity except via visual effects. Orbits around black holes will not show relativistic precession or gravitational redshift. The gravitational wave ripples are artistic representations and do not carry energy away from the system.
- **Collision handling:** Objects merge when their radii overlap. In reality many close encounters would result in tidal disruption or gravitational slingshots rather than perfect mergers. For educational purposes the simulation simplifies these interactions.
- **Units:** Masses are specified in solar masses ($M_\odot$) for stars and compact objects; planetary masses are relative to Earth or Jupiter. Distances are given in astronomical units (AU) or kilometres depending on the zoom level. Velocities are displayed in kilometres per second.
- **Random seeds:** Each random placement uses a seed to generate positions and velocities. Reloading the same scenario will produce similar but not identical distributions unless a seed is specified.
- **Custom modifications:** Advanced users can edit the JavaScript files to add new scenarios or customise physics. The `SCENARIO_INFO` object in `ui.js` describes each built–in scenario, and `apply_preset` sets the corresponding settings and object counts.

9 Further Reading

For readers interested in the science behind the simulation, the following resources provide accessible explanations:

- **Gravitational Waves:** LIGO's overview of gravitational waves explains how accelerating masses distort spacetime and describes recent detections.
- **Supermassive Black Holes:** NASA's Chandra and Hubble observations of Sagittarius A discuss the mass, distance and behaviour of the Milky Way's central black hole.
- **Star Formation:** The Center for Astrophysics article on star formation describes how molecular clouds collapse to form stars and planets.
- **Star Clusters:** NASA's article on star clusters differentiates between globular clusters, open clusters and associations, explaining their sizes and ages.
- **Neutron Stars and Pulsars:** NASA's "Imagine the Universe" site introduces neutron stars and pulsars and explains the lighthouse effect.
- **Kuiper Belt:** NASA's Kuiper Belt facts page describes the icy bodies beyond Neptune and explains how Neptune's gravity prevented planet formation.
- **Type Ia Supernovae:** Articles on Type Ia supernovae explain how white dwarf binaries explode when they exceed the Chandrasekhar limit.

- **Tidal Disruption Events:** The University of California's article on TDEs describes how stars are torn apart when approaching black holes.

This user manual has provided a comprehensive overview of Gravitas, its features and scientific context. By experimenting with the scenarios and creating your own systems, you will gain intuition about how gravity shapes the Universe—from the orbits of planets to the mergers of black holes.