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

Luciano Rezzolla

Institute for Theoretical Physics, Frankfurt, Germany

Frankfurt Institute for Advanced Studies, Frankfurt, Germany

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

erc European Research Council Established by the European Commission

Night of Science
Frankfurt,
June 19, 2015

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

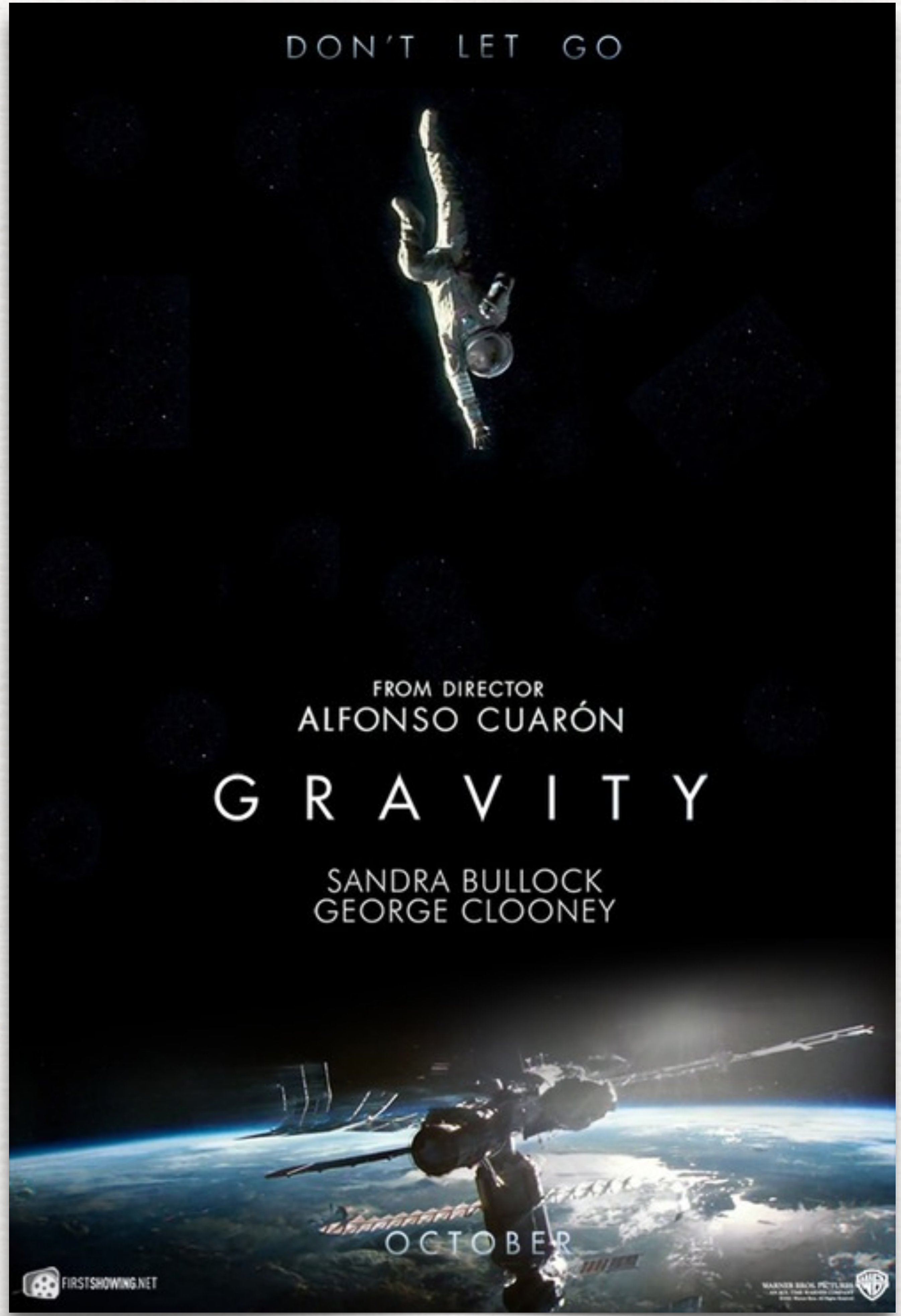
Our experience of gravity

- Instinctive notion

- Intuitive notion

Our experience of gravity

- Instinctive notion
- Intuitive notion
- Imaginative notion

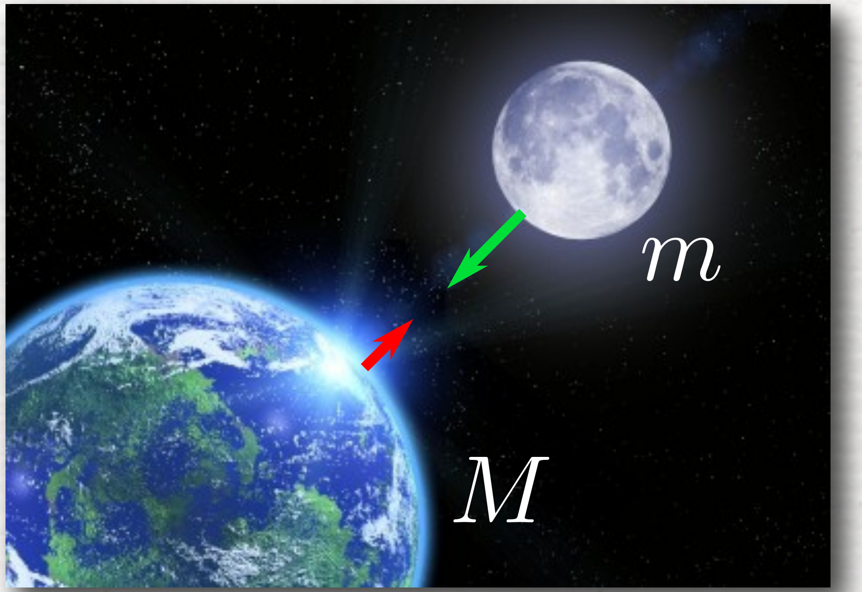


The fathers of gravity

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.

$$\vec{F} = -\frac{G}{c^2}\frac{Mm}{r^2}\vec{e_r}$$

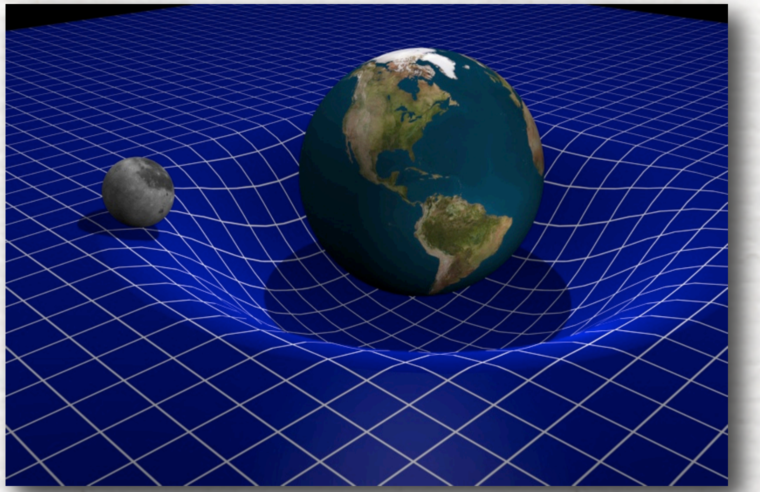


With this theory he could explain essentially **all astronomical** observations of his time.

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 → $G_{\mu\nu}$

stress-energy tensor → $T_{\mu\nu}$

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

Einstein equations

Einstein tensor

stress-energy tensor

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

spacetime
curvature

mass and energy
in the spacetime

Einstein equations

Einstein tensor

stress-energy tensor

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

spacetime curvature

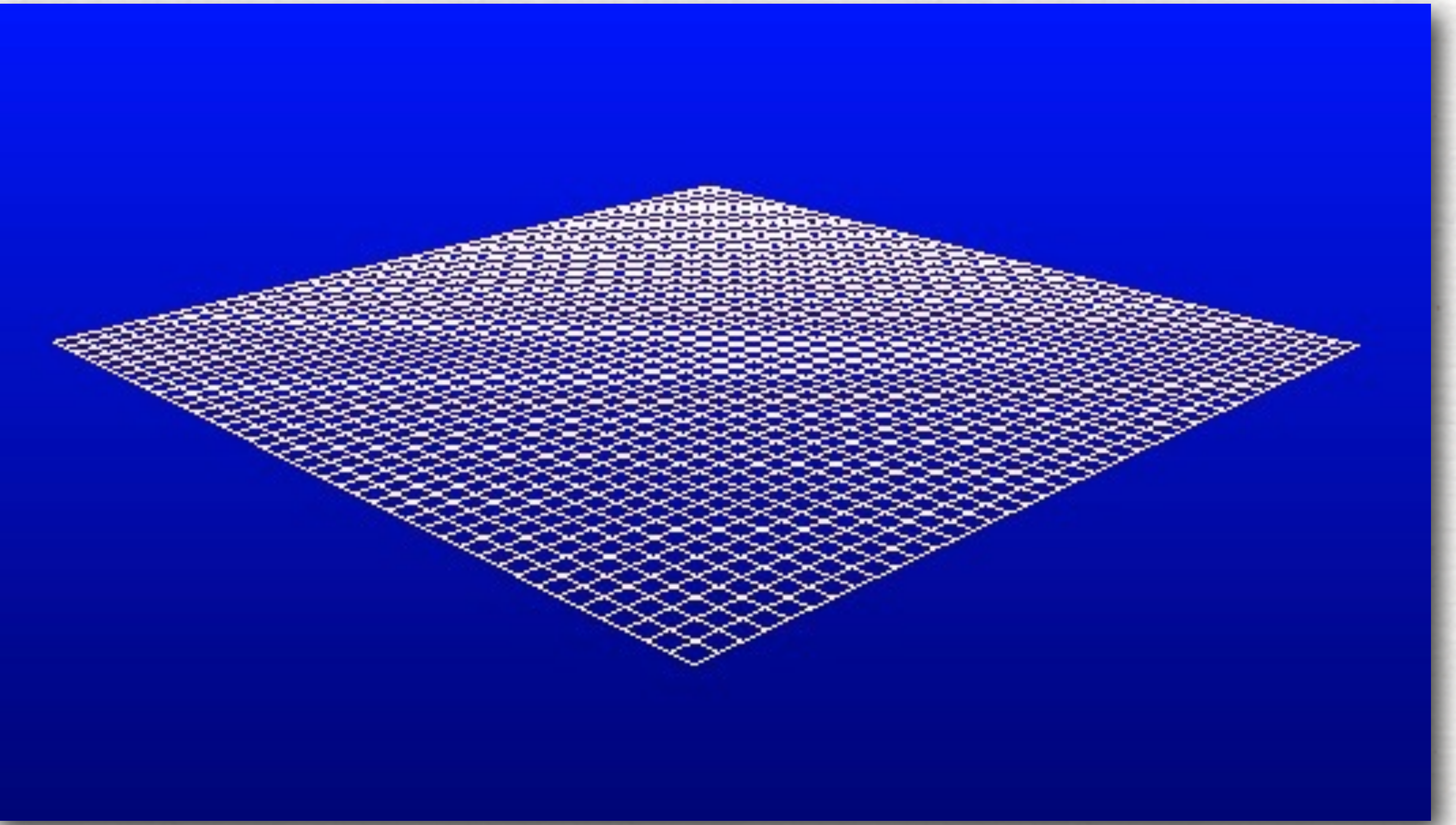
mass and energy in the spacetime

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

gravity is the manifestation of spacetime curvature

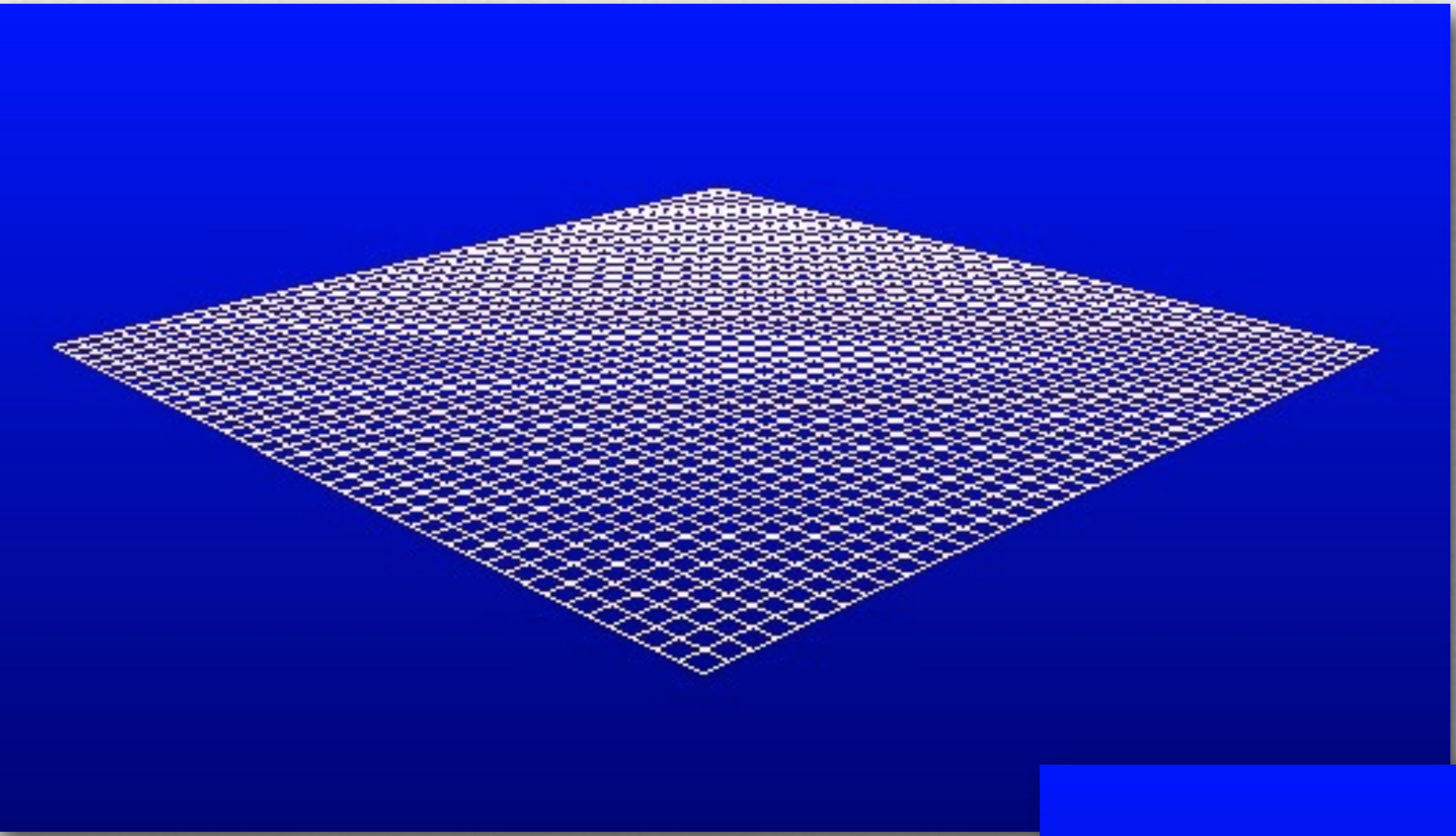
What is spacetime curvature?

What is spacetime curvature?



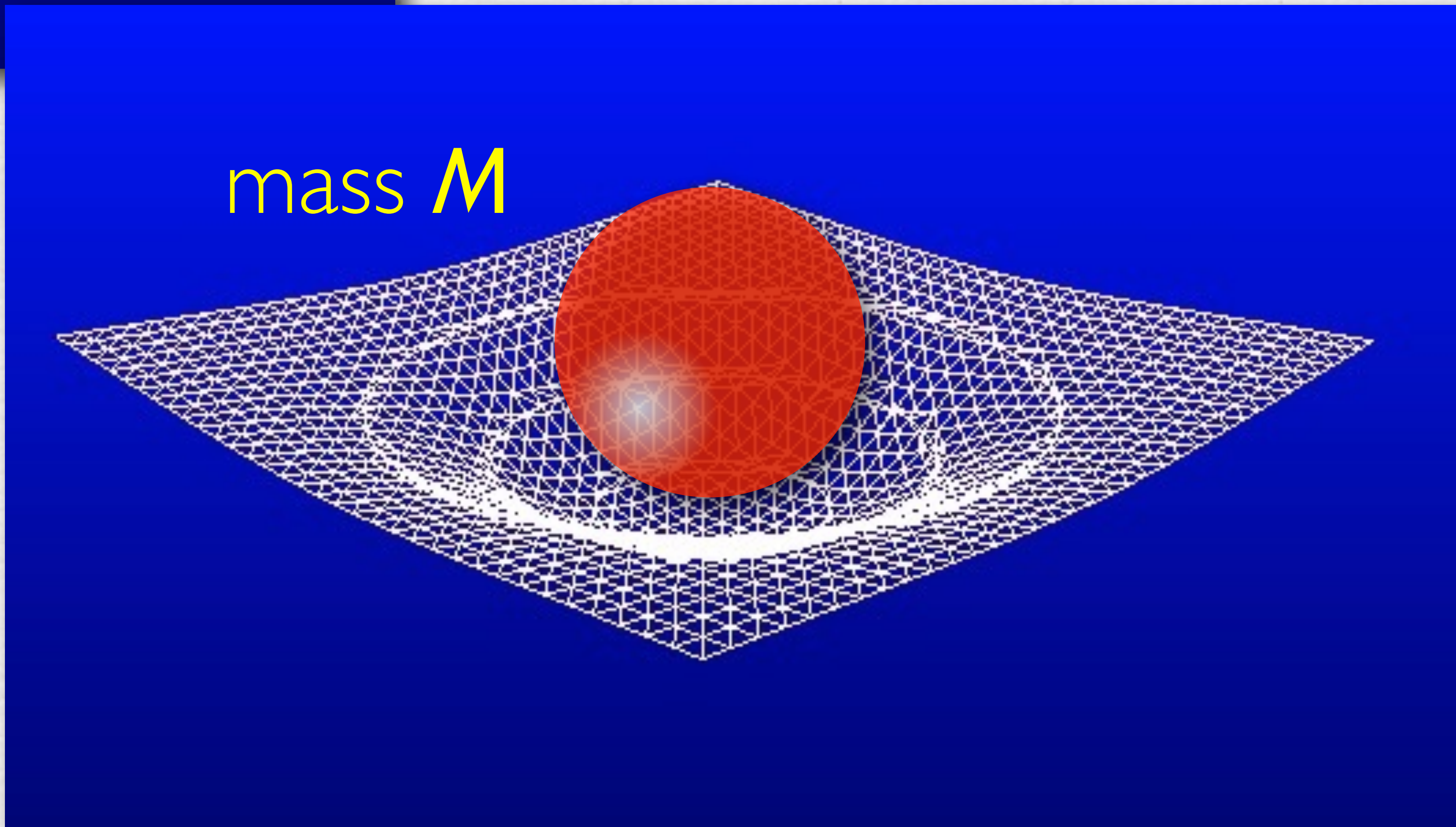
Let's consider a region of space and time (spacetime) void of matter and energy. It will have **zero** curvature and will therefore be ***flat***

What is spacetime curvature?



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***

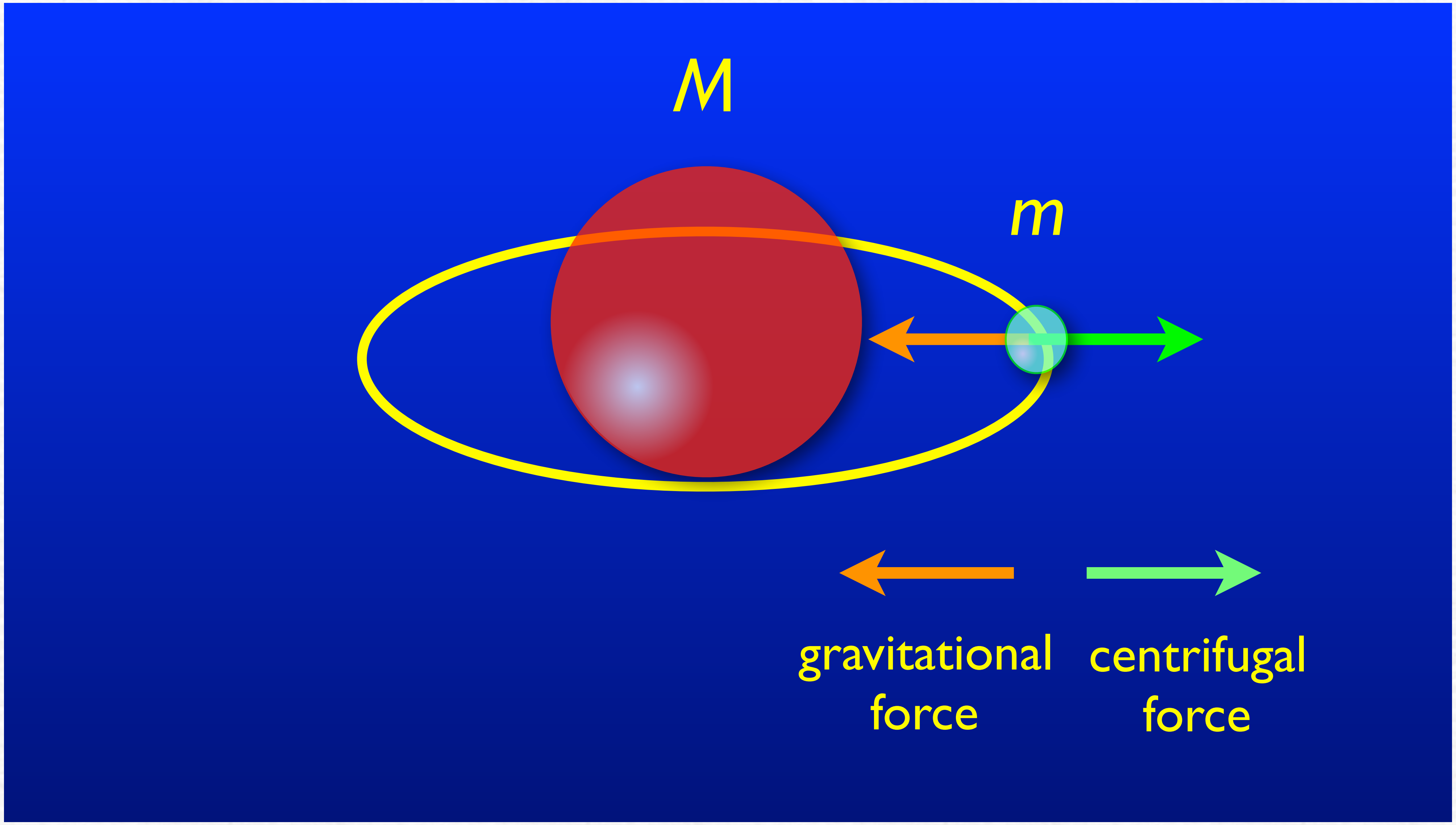
If instead it contains a mass ***M***, it will also have a nonzero curvature and will therefore be a ***curved spacetime***



Gravity à la Newton

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)

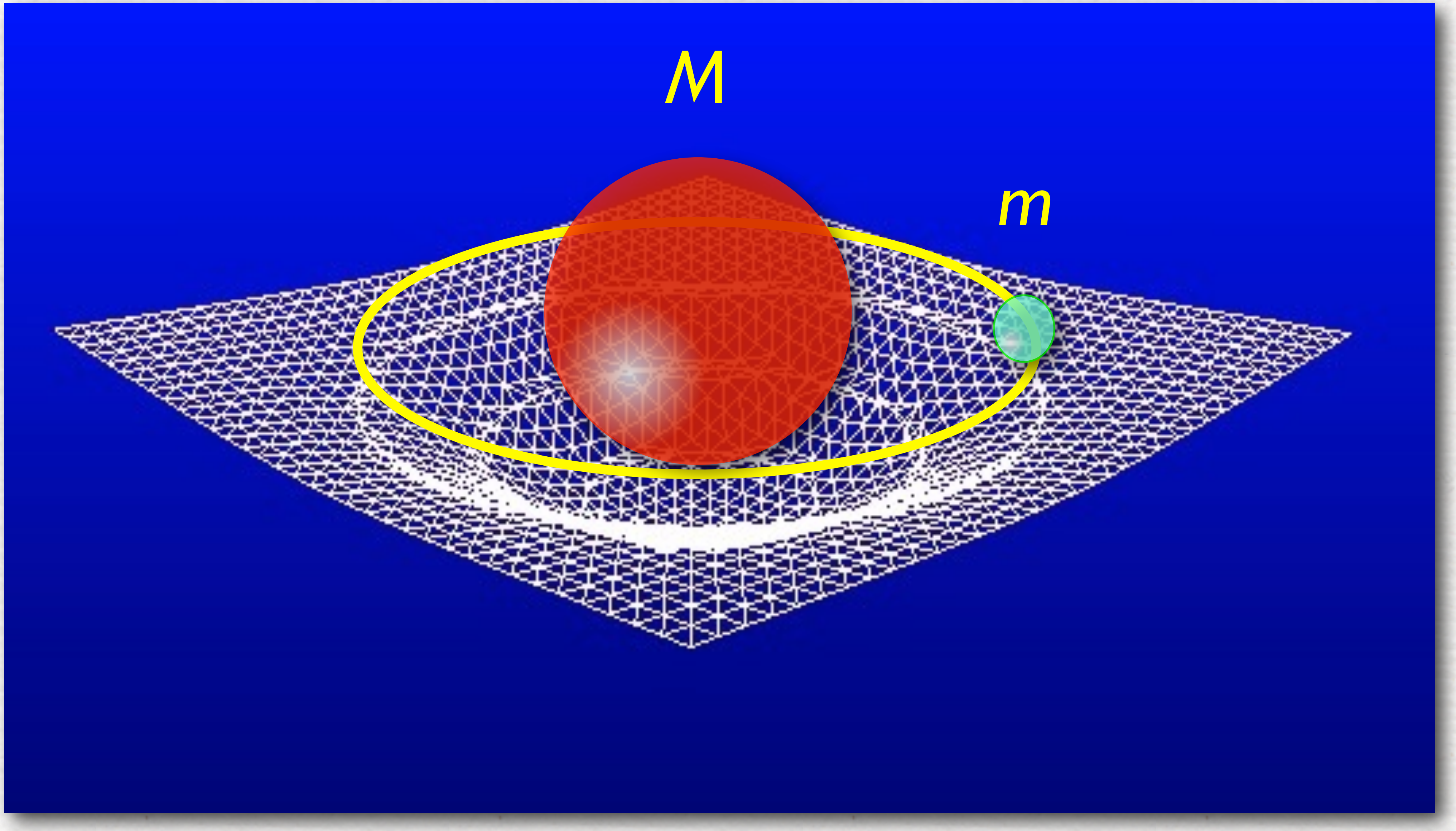
Newton*: the orbit is the result of the balance between the gravitational force and the centrifugal one*



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)

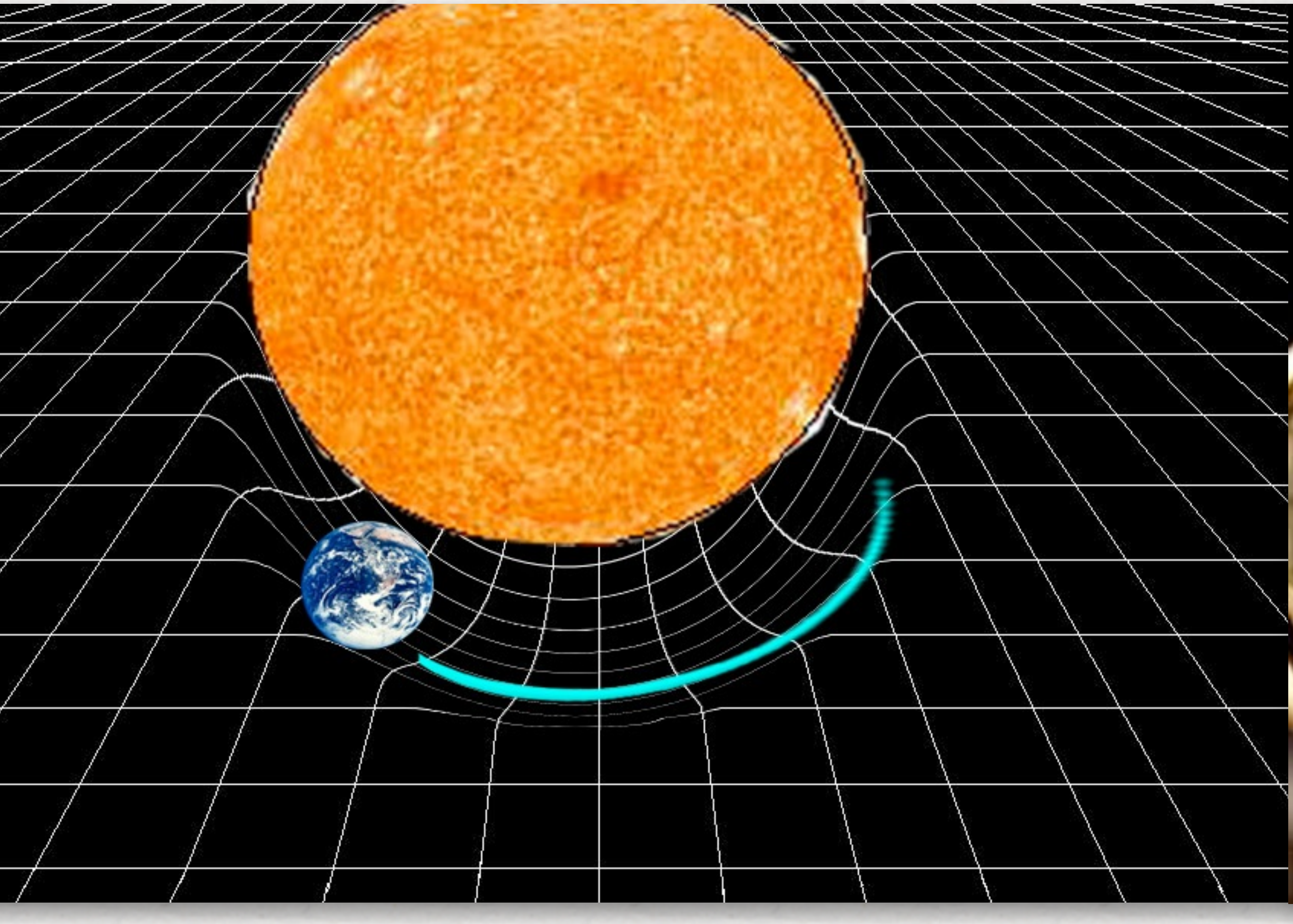
Einstein*: the orbit is what the small object needs to do to avoid falling in the curvature produced by the large mass*



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*



Small and large curvatures

A measure of the spacetime curvature is contained in the ratio ***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

A measure of the spacetime curvature is contained in the ratio ***M/R***: where ***M*** and ***R*** are the mass and the size of the object.

The larger this ratio the larger the gravity/curvature.

What is the curvature on Earth?

$$\frac{M_\oplus}{R_\oplus} \simeq \frac{5.97 \times 10^{24}\ \mathrm{kg}}{6372\ \mathrm{km}} \simeq 3 \times 10^{-9} \simeq 0.0000000003$$

Small and large curvatures

A measure of the spacetime curvature is contained in the ratio ***M/R***: where ***M*** and ***R*** are the mass and the size of the object.

The larger this ratio the larger the gravity/curvature.

What is the curvature on Earth?

$$\frac{M_\oplus}{R_\oplus} \simeq \frac{5.97 \times 10^{24}\ \mathrm{kg}}{6372\ \mathrm{km}} \simeq 3 \times 10^{-9} \simeq 0.0000000003$$

In our neighbourhood, largest curvature is in the Sun

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

In other words: spacetime is **very hard to curve!**

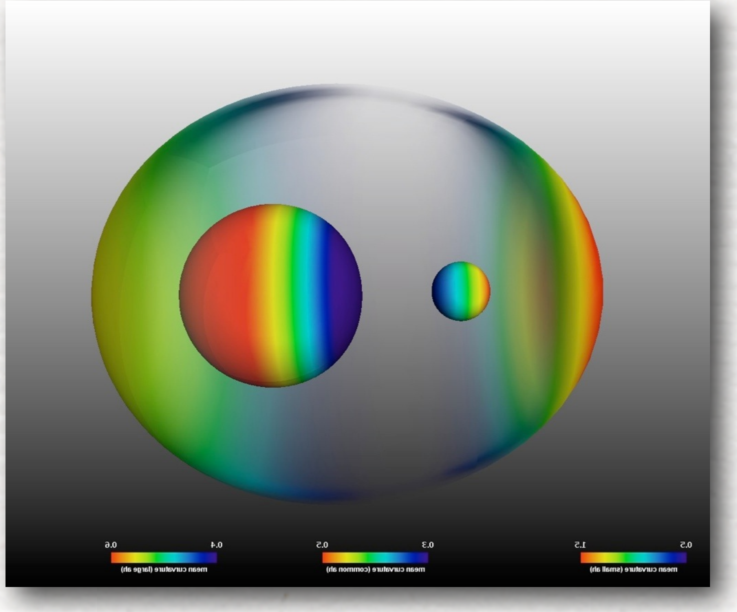
Consequences of Einstein's gravity

Einstein's revolutionary concept of gravity leads to three consequences, some of which he rejected:

Consequences of Einstein's gravity

Einstein's revolutionary concept of gravity leads to three consequences, some of which he rejected:

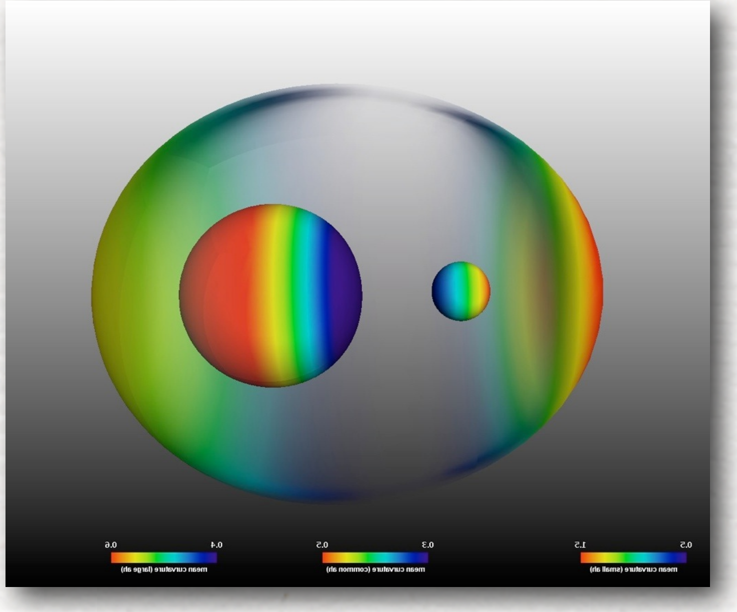
- Black holes



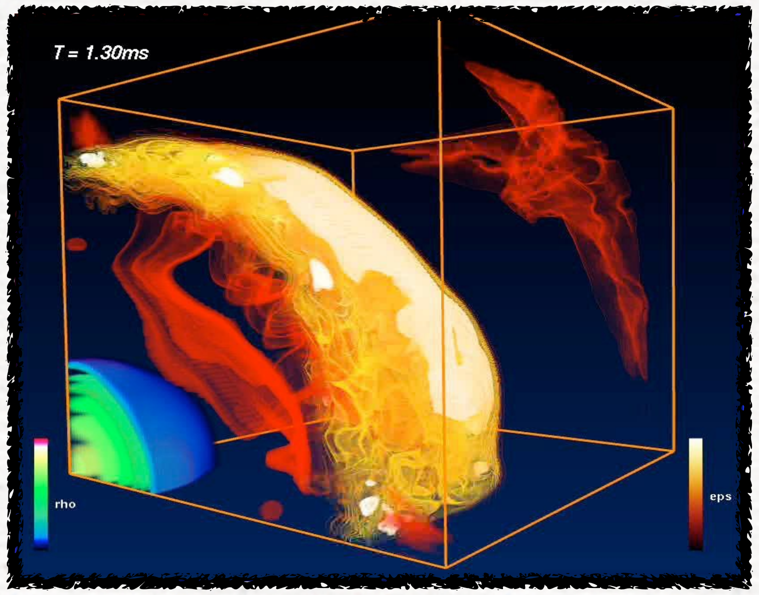
Consequences of Einstein's gravity

Einstein's revolutionary concept of gravity leads to three consequences, some of which he rejected:

- Black holes

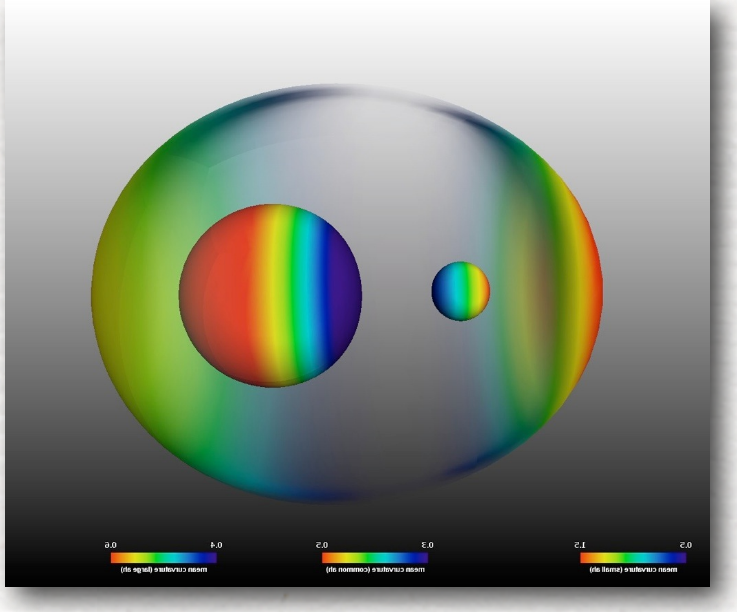


- Neutron Stars

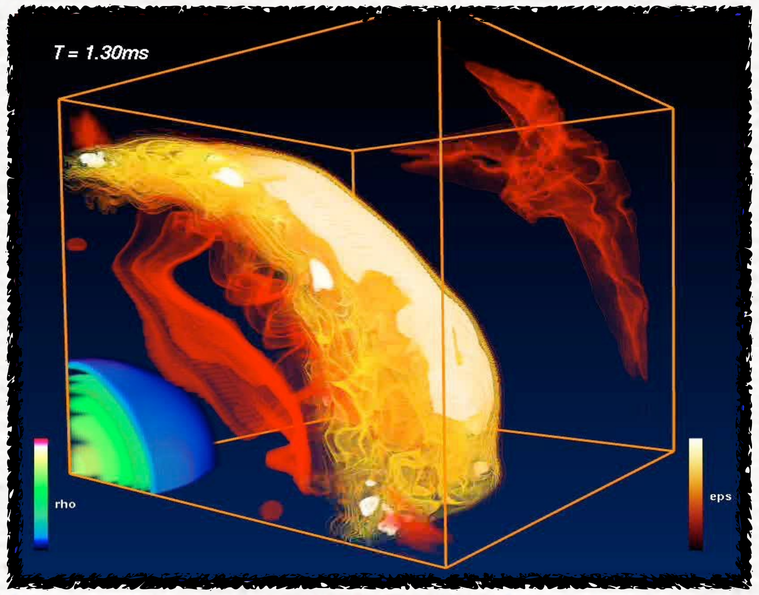


Consequences of Einstein's gravity

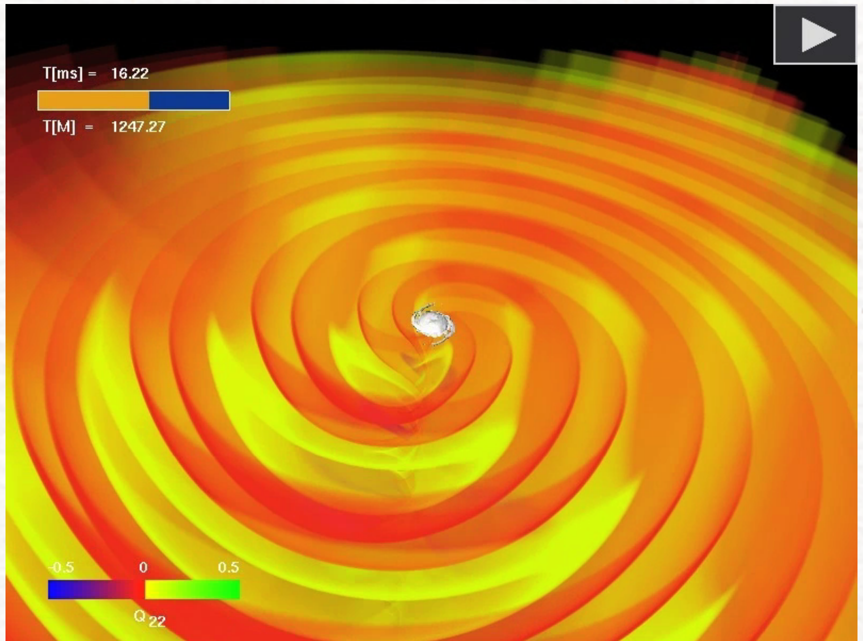
Einstein's revolutionary concept of gravity leads to three consequences, some of which he rejected:



- Black holes

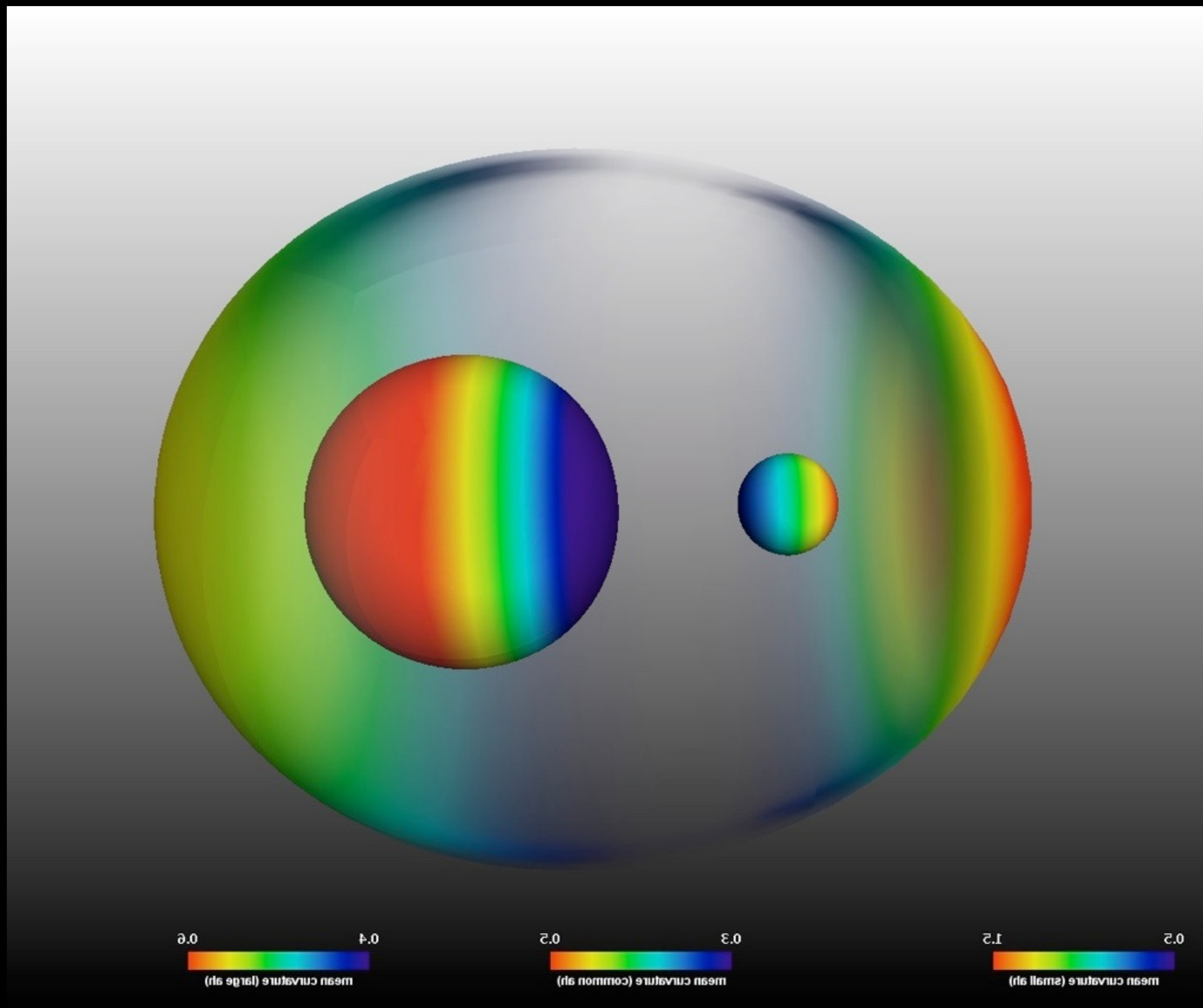


- Neutron Stars



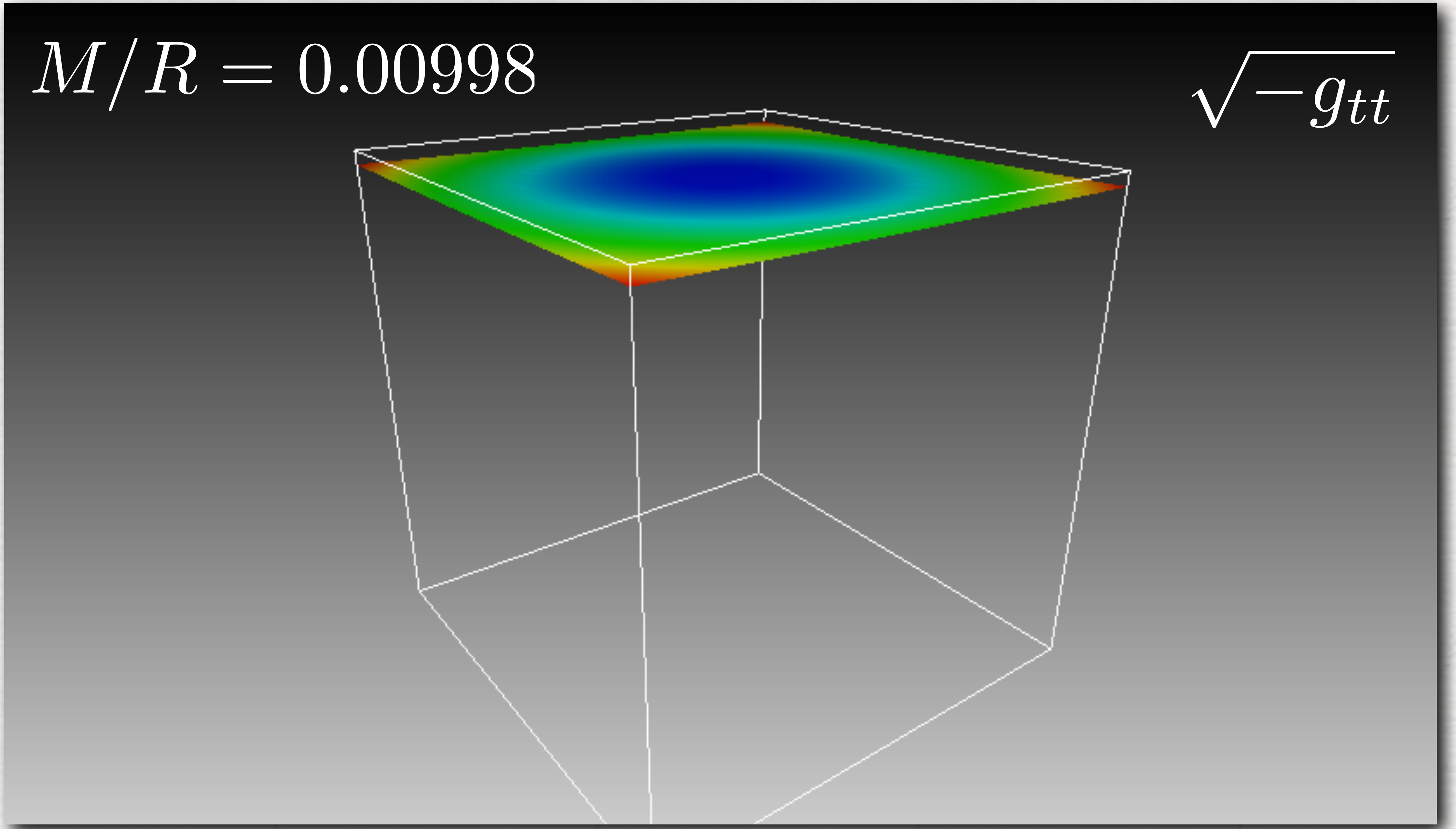
- Gravitational Waves

Black Holes

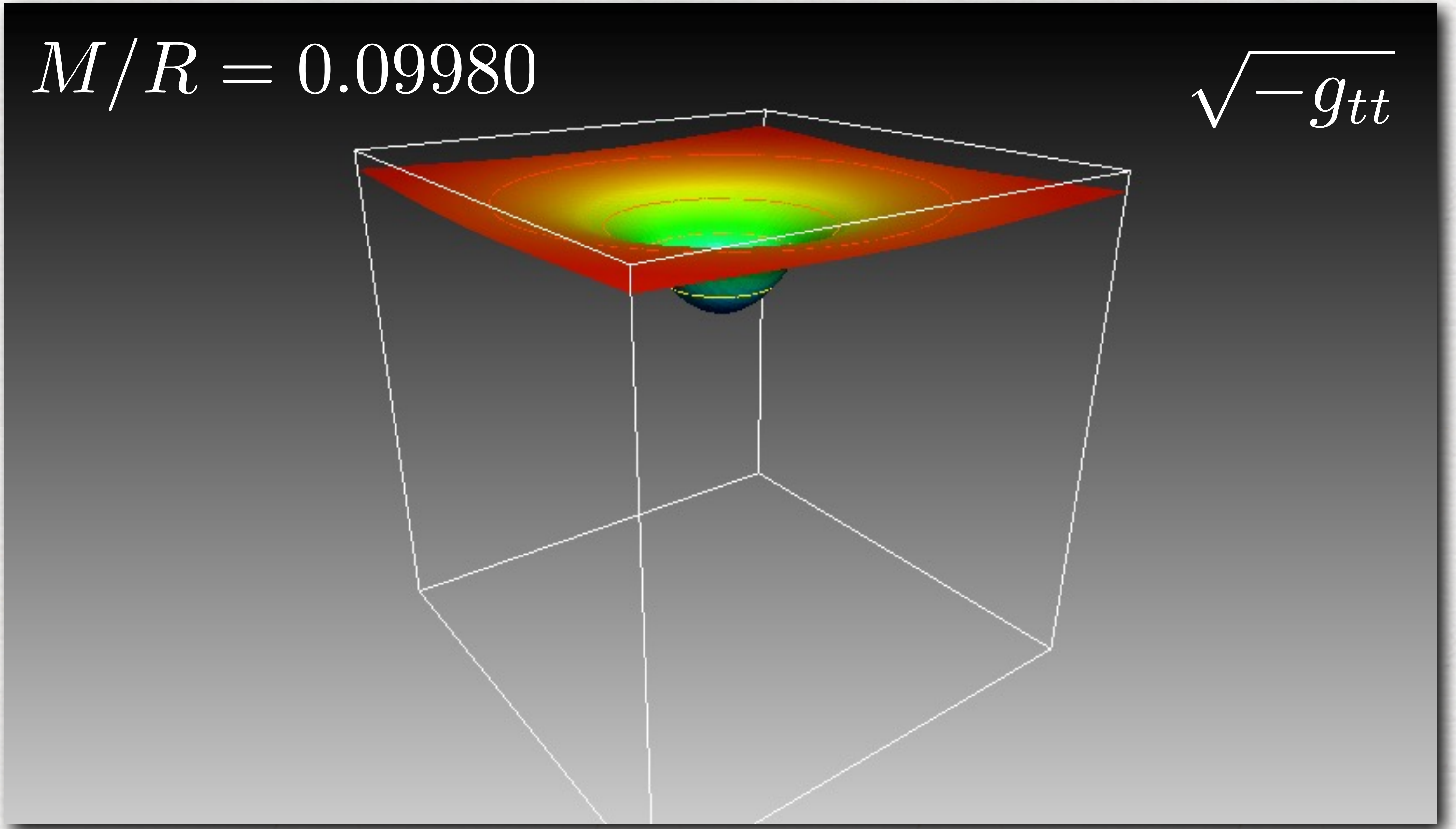


0.6
0.4
mean curvature (large ah)
0.5
0.3
mean curvature (common ah)
1.5
0.5
mean curvature (small ah)

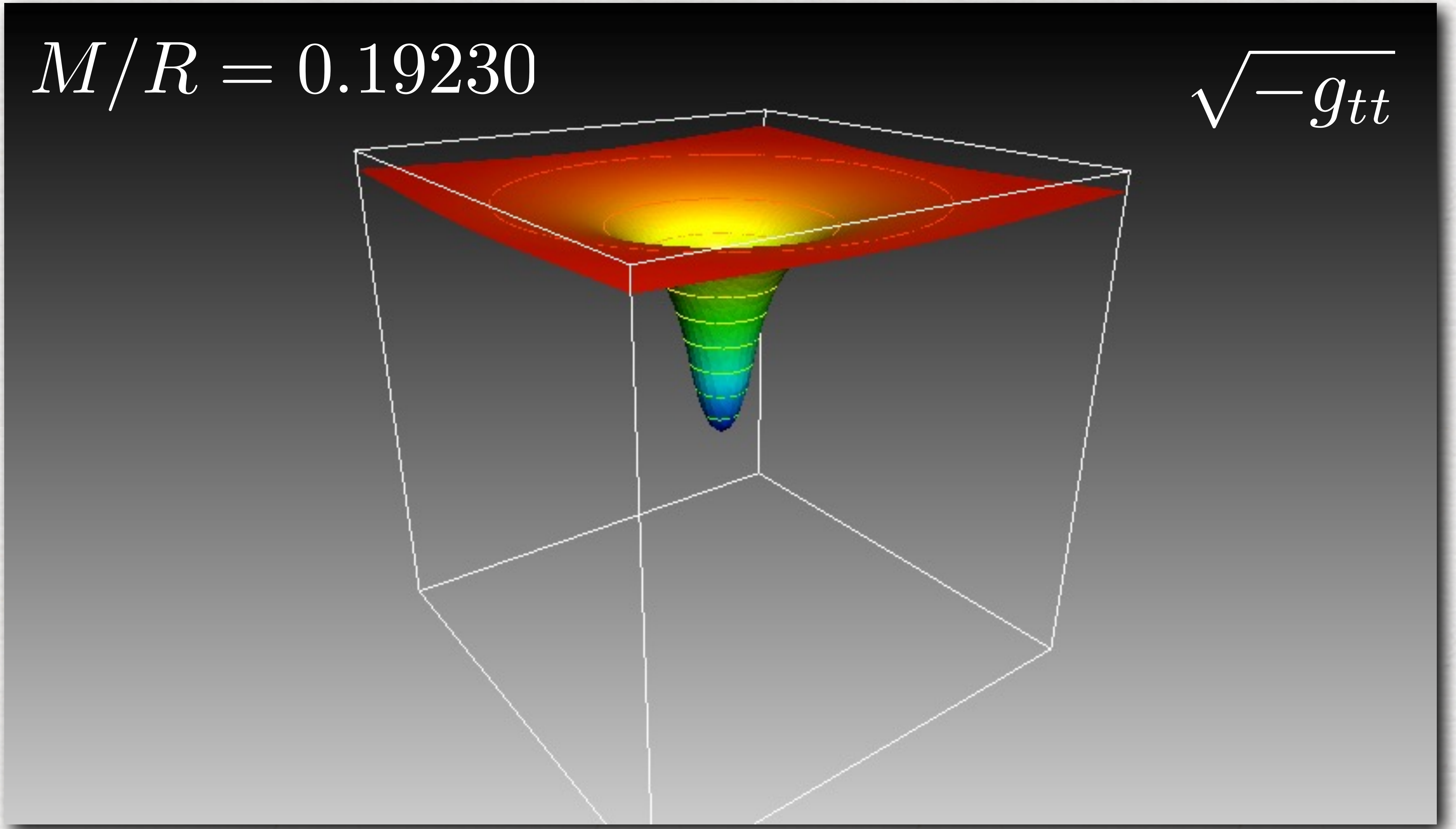
Nature can produce objects with large ***M*** and small ***R***. A *"gedanken experiment"*: let's take a star of mass ***M*** and let's compress it reducing ***R***. This is what happens to the curvature as we increase ***M/R***.



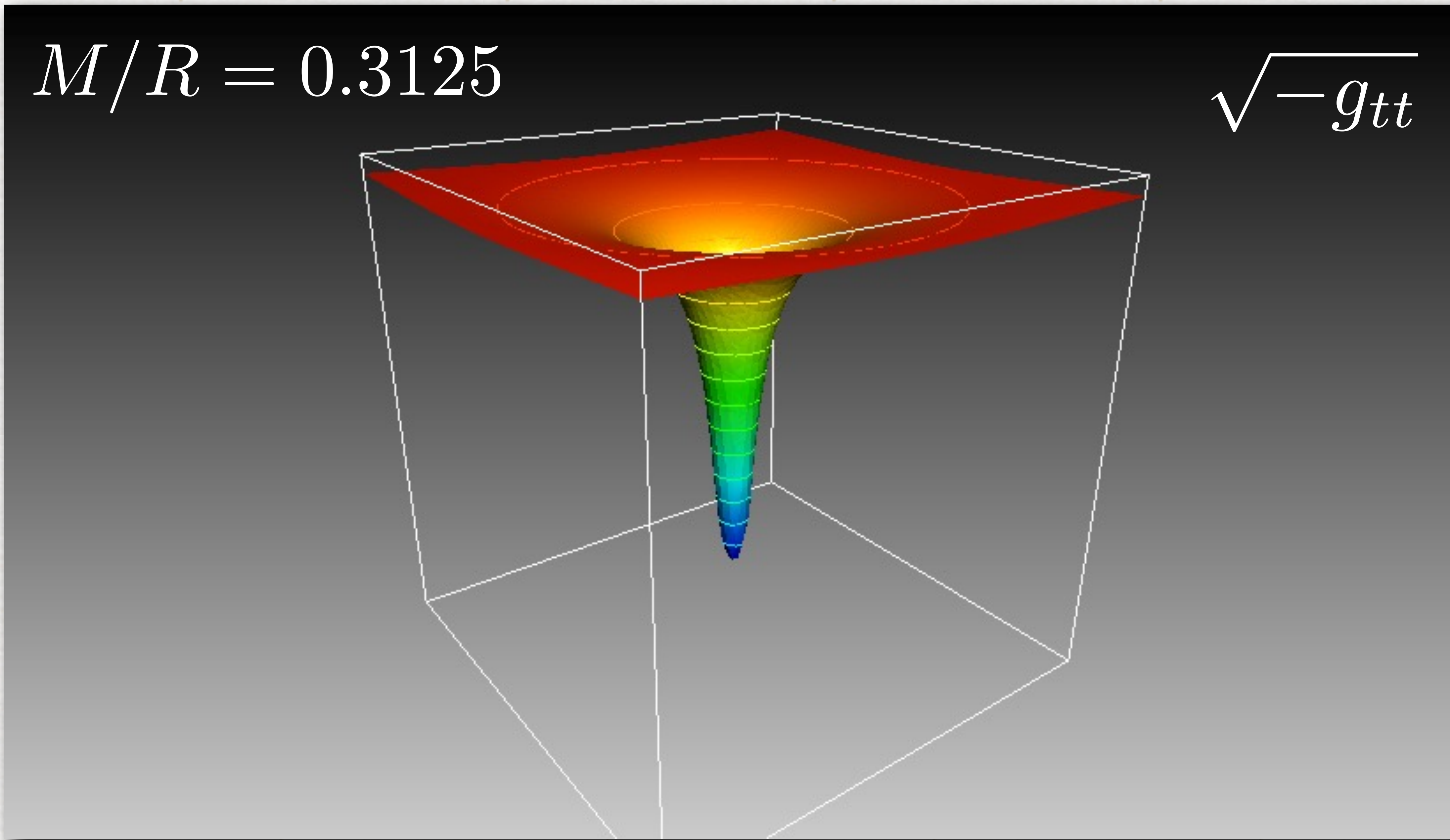
Nature can produce objects with large ***M*** and small ***R***.
A *"gedanken experiment"*: let's take a star of mass ***M*** and let's compress it reducing ***R***. This is what happens to the curvature as we increase ***M/R***.



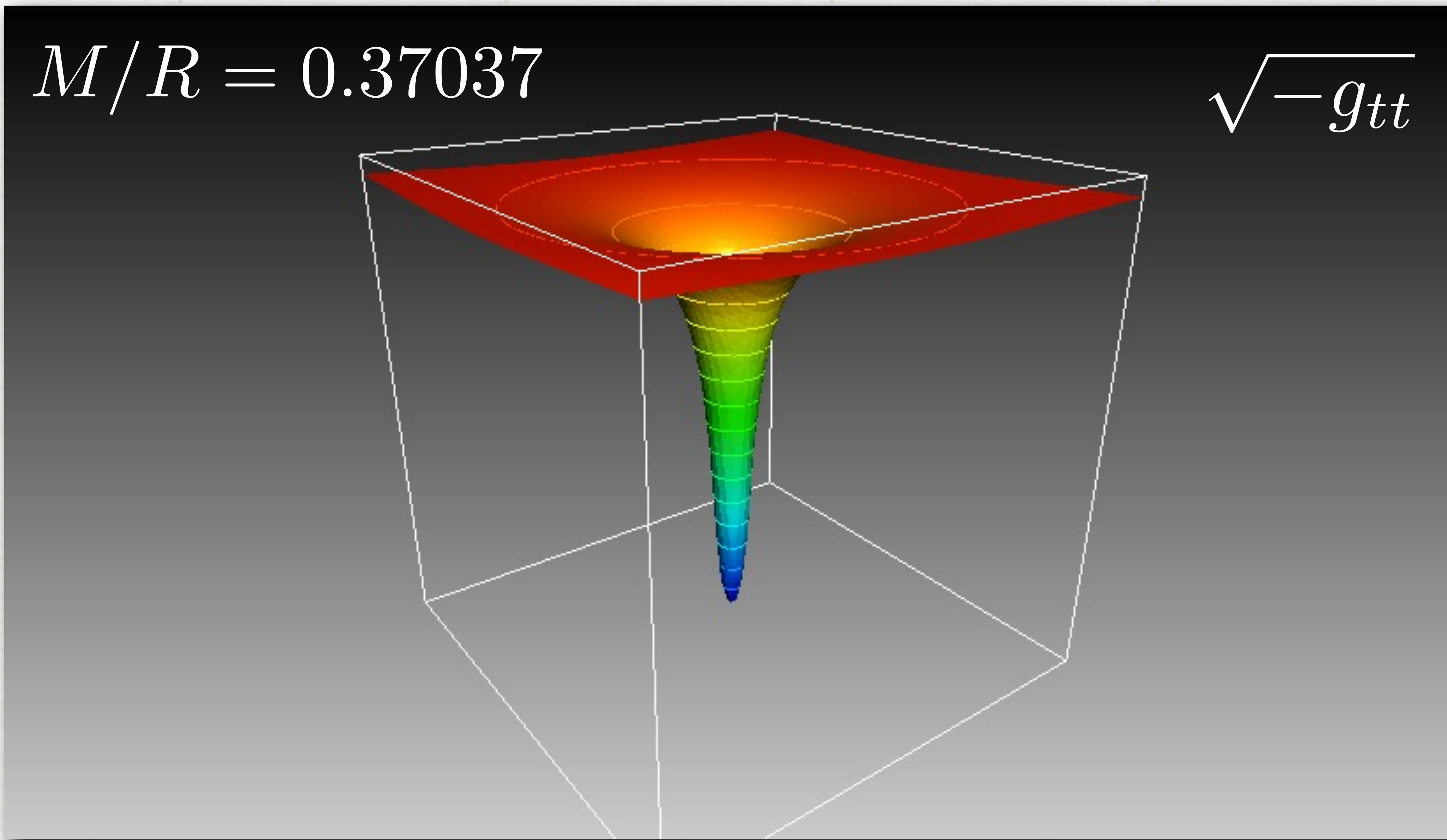
Nature can produce objects with large ***M*** and small ***R***. A *"gedanken experiment"*: let's take a star of mass ***M*** and let's compress it reducing ***R***. This is what happens to the curvature as we increase ***M/R.***



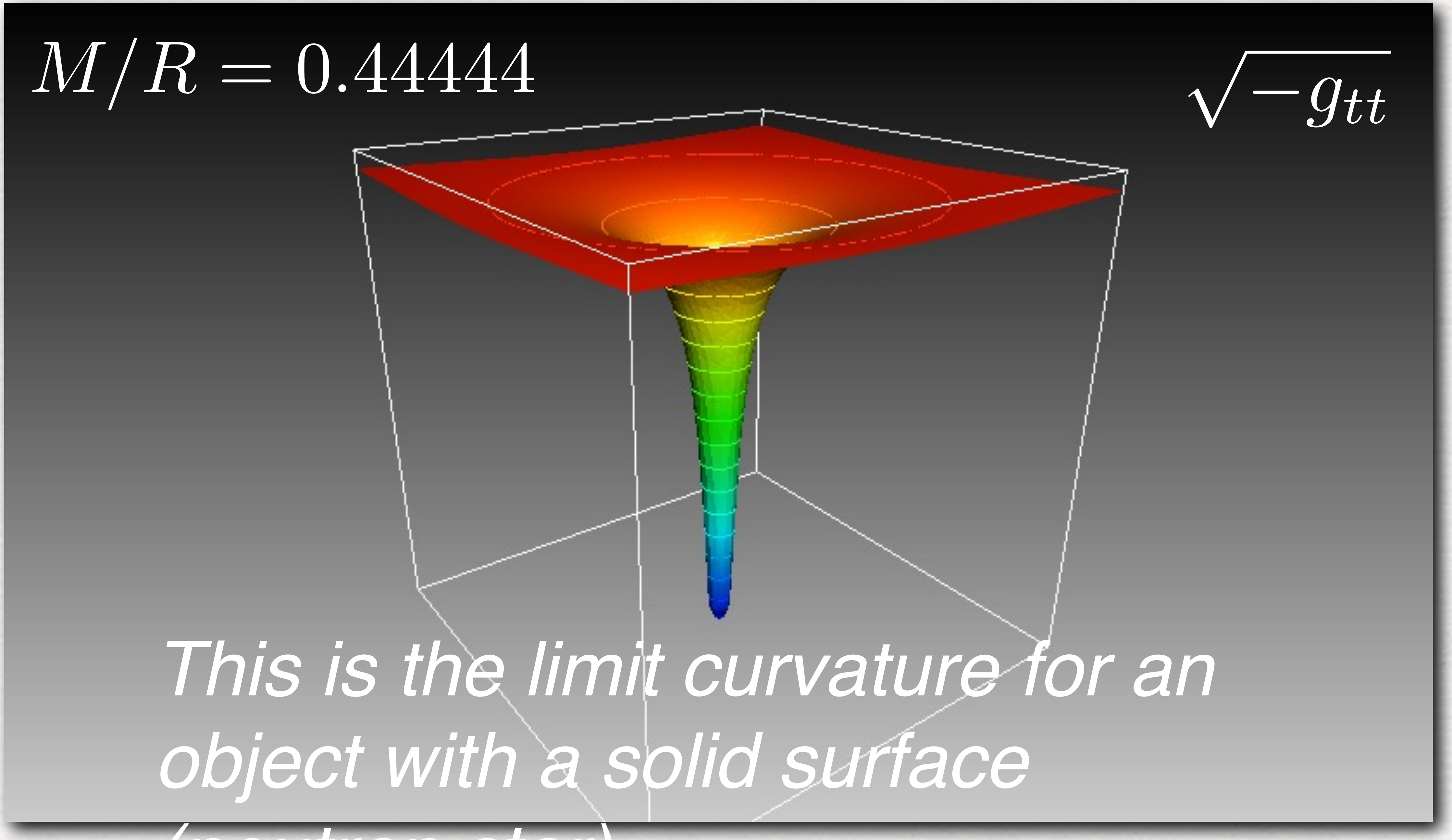
Nature can produce objects with large ***M*** and small ***R***.
A *"gedanken experiment"*: let's take a star of mass ***M*** and let's compress it reducing ***R***. This is what happens to the curvature as we increase ***M/R***.



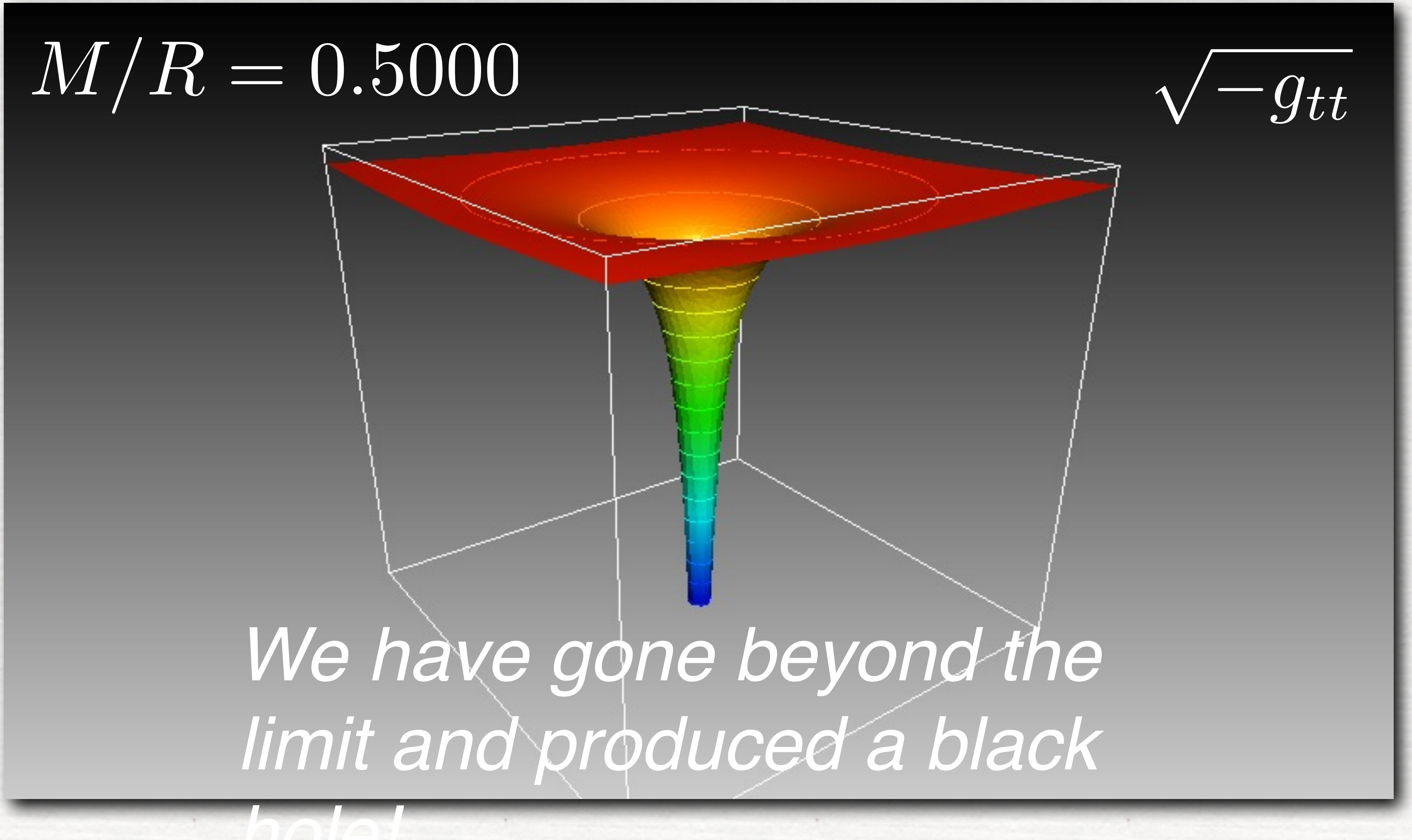
Nature can produce objects with large ***M*** and small ***R***.
A *"gedanken experiment"*: let's take a star of mass ***M*** and let's compress it reducing ***R***. This is what happens to the curvature as we increase ***M/R***.



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***.



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***.

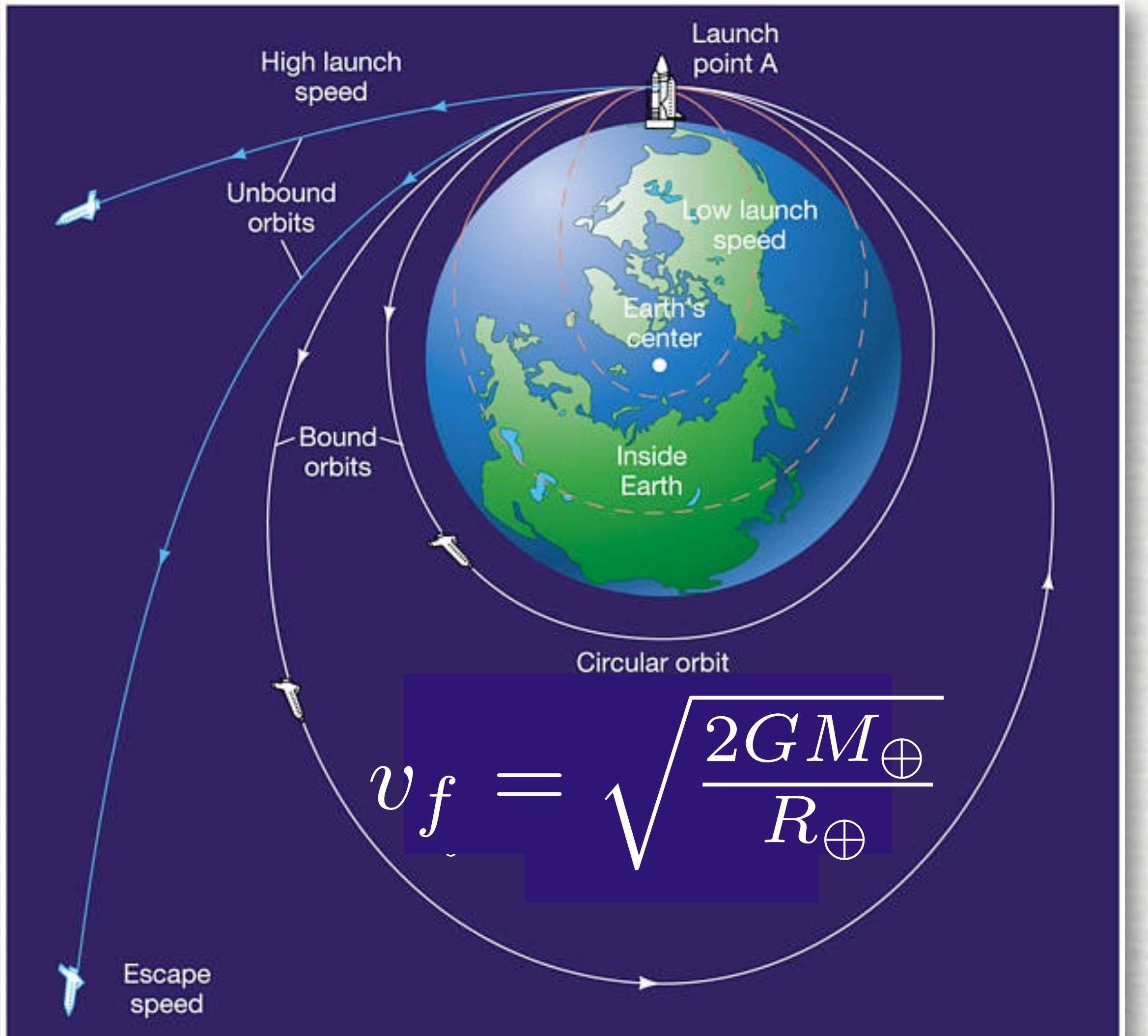


What is a black hole?

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

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



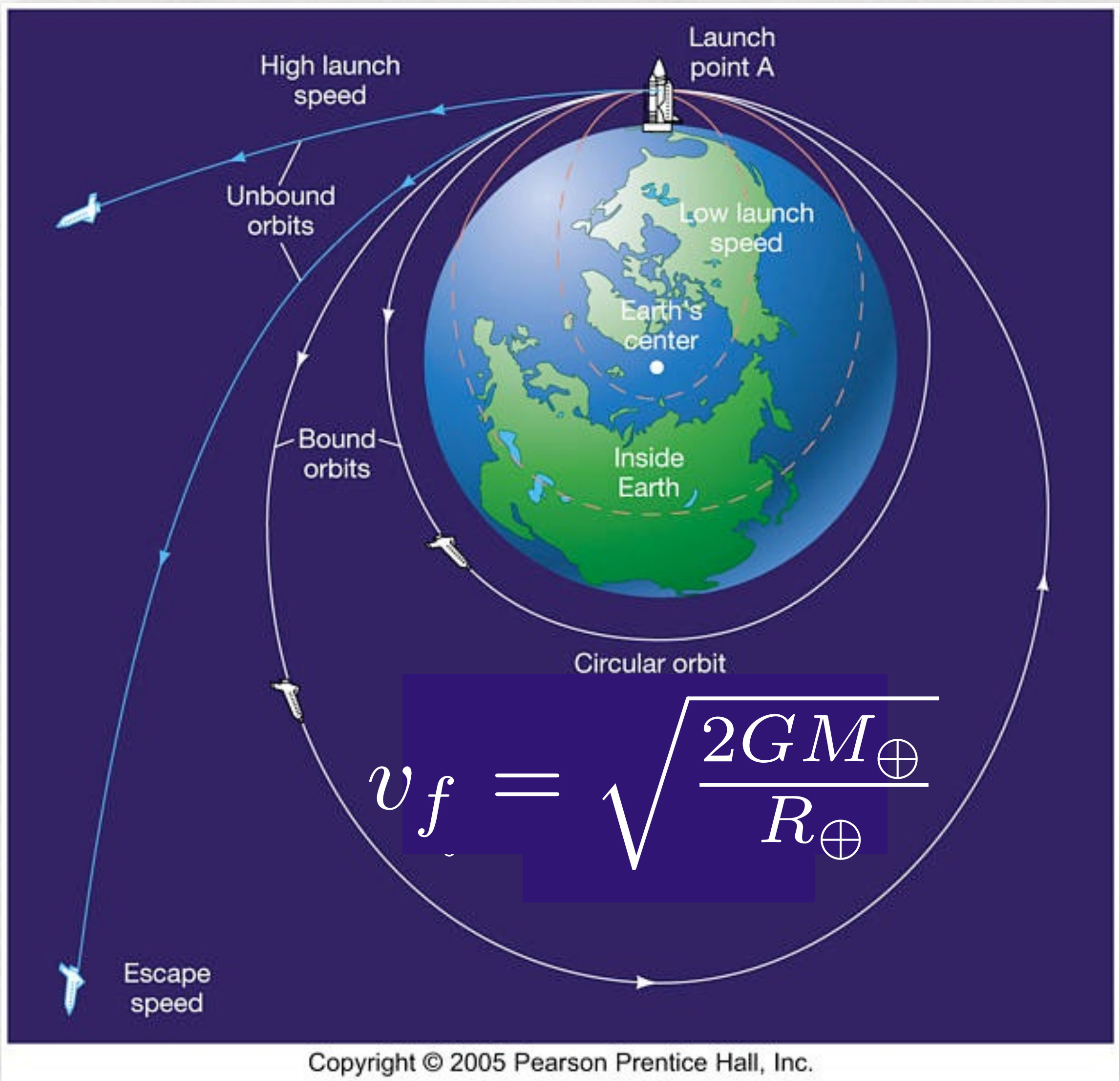
$$v_f = \sqrt{\frac{2GM_\oplus}{R_\oplus}}$$

Copyright © 2005 Pearson Prentice Hall, Inc.

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

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



$$v_f = \sqrt{\frac{2GM_\oplus}{R_\oplus}}$$

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

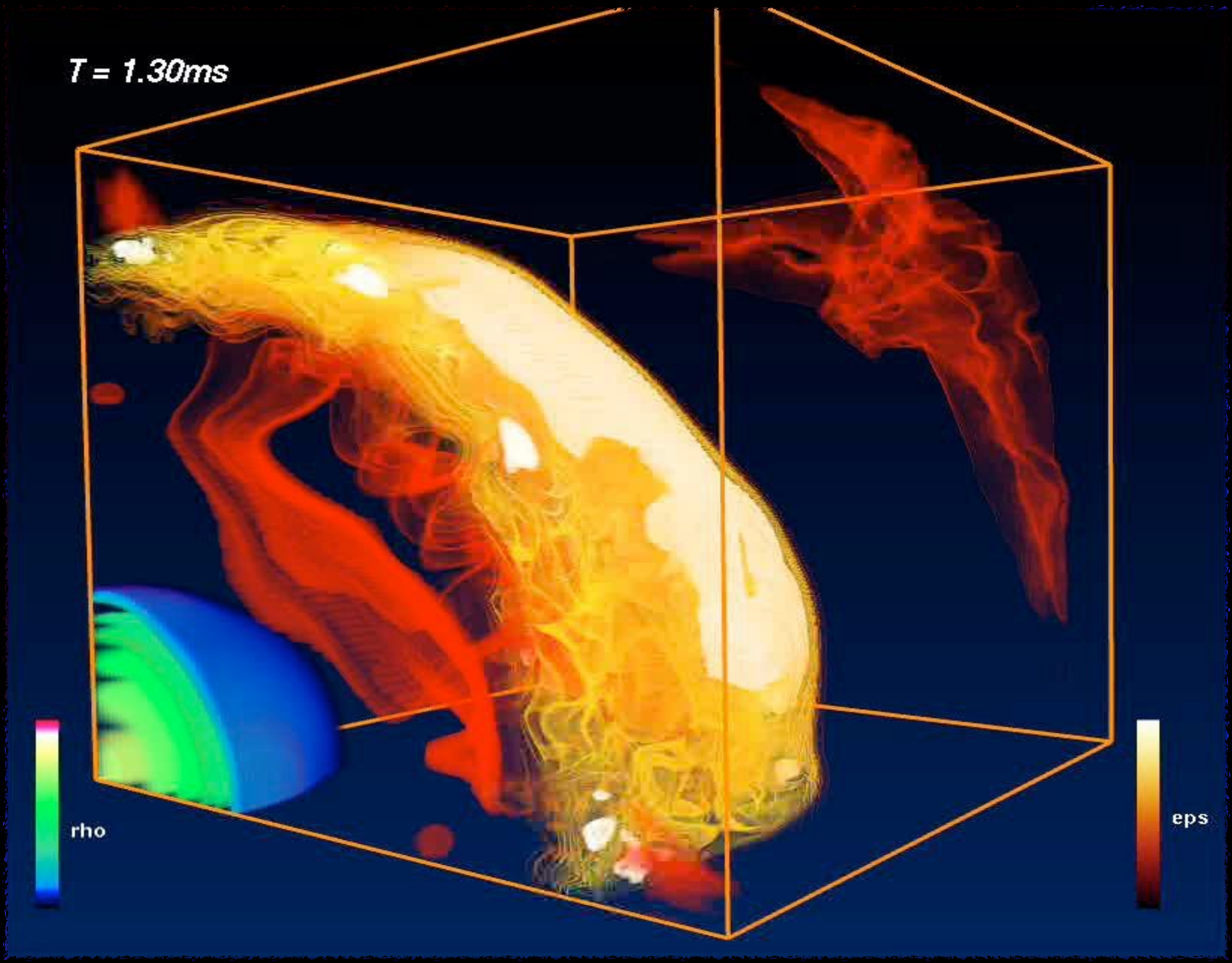
$M_{\rm BH}$: black hole mass

$R_{\rm EH}$: radius of event horizon

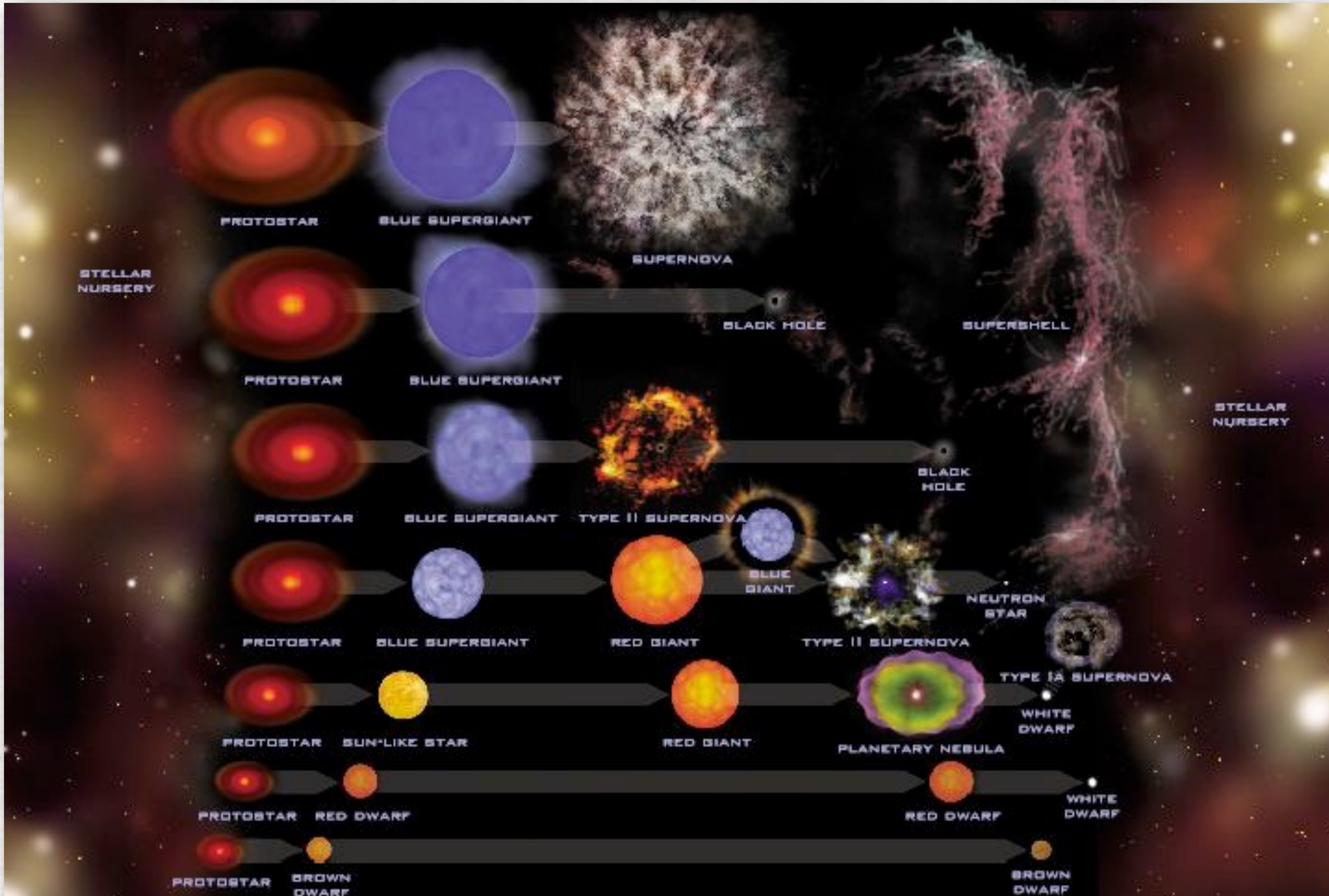
It's **possible** to escape Earth's surface: need sufficient velocity.

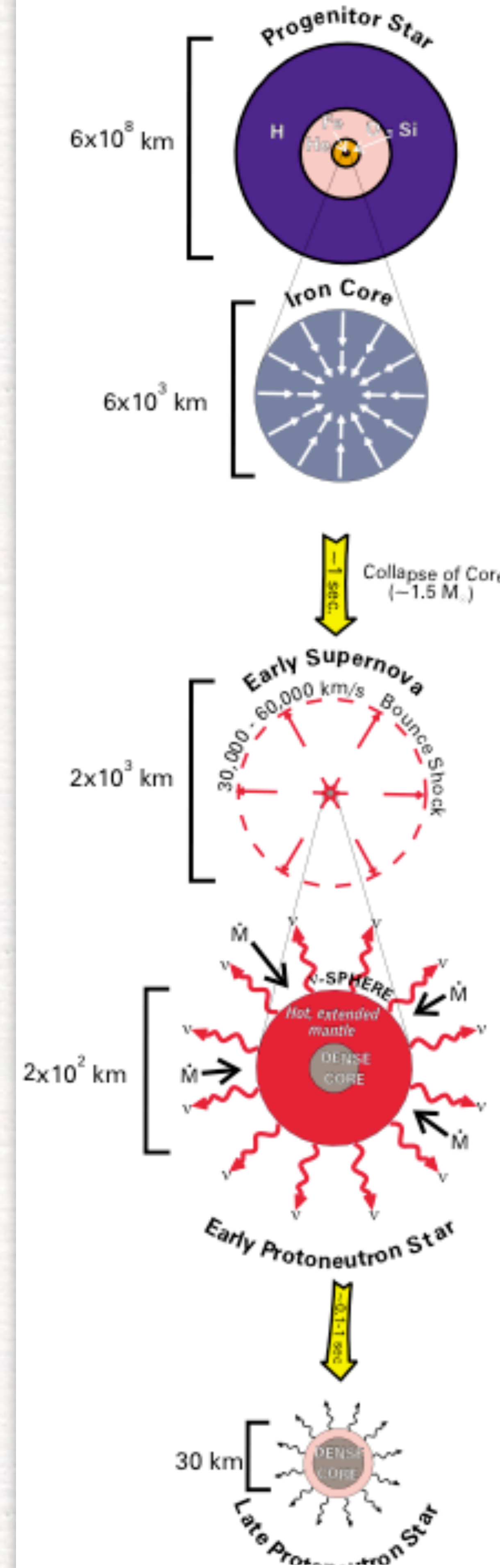
It's **impossible** to escape the black hole surface even for light

Neutron Stars



What is a neutron star?



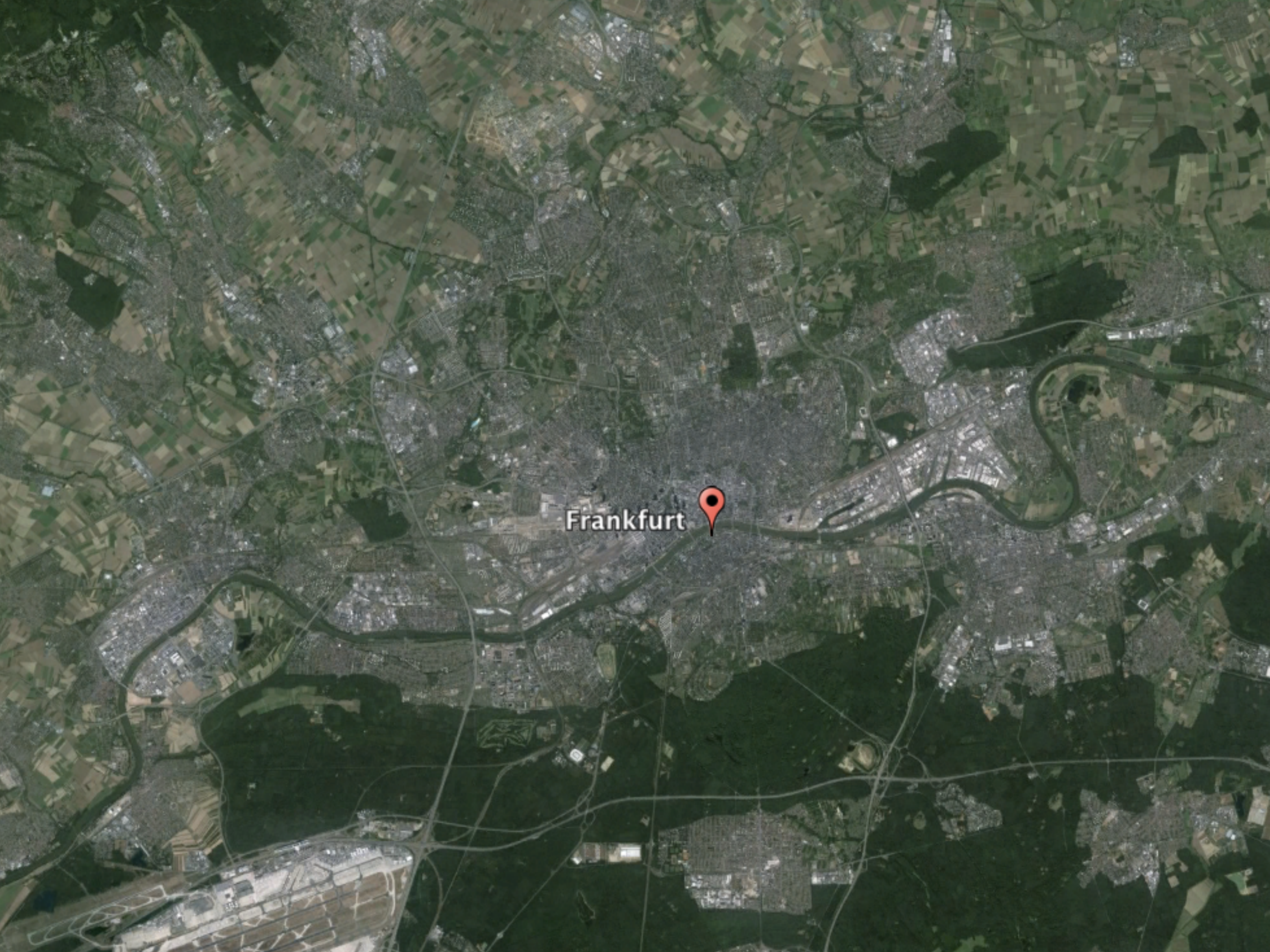


Burrows

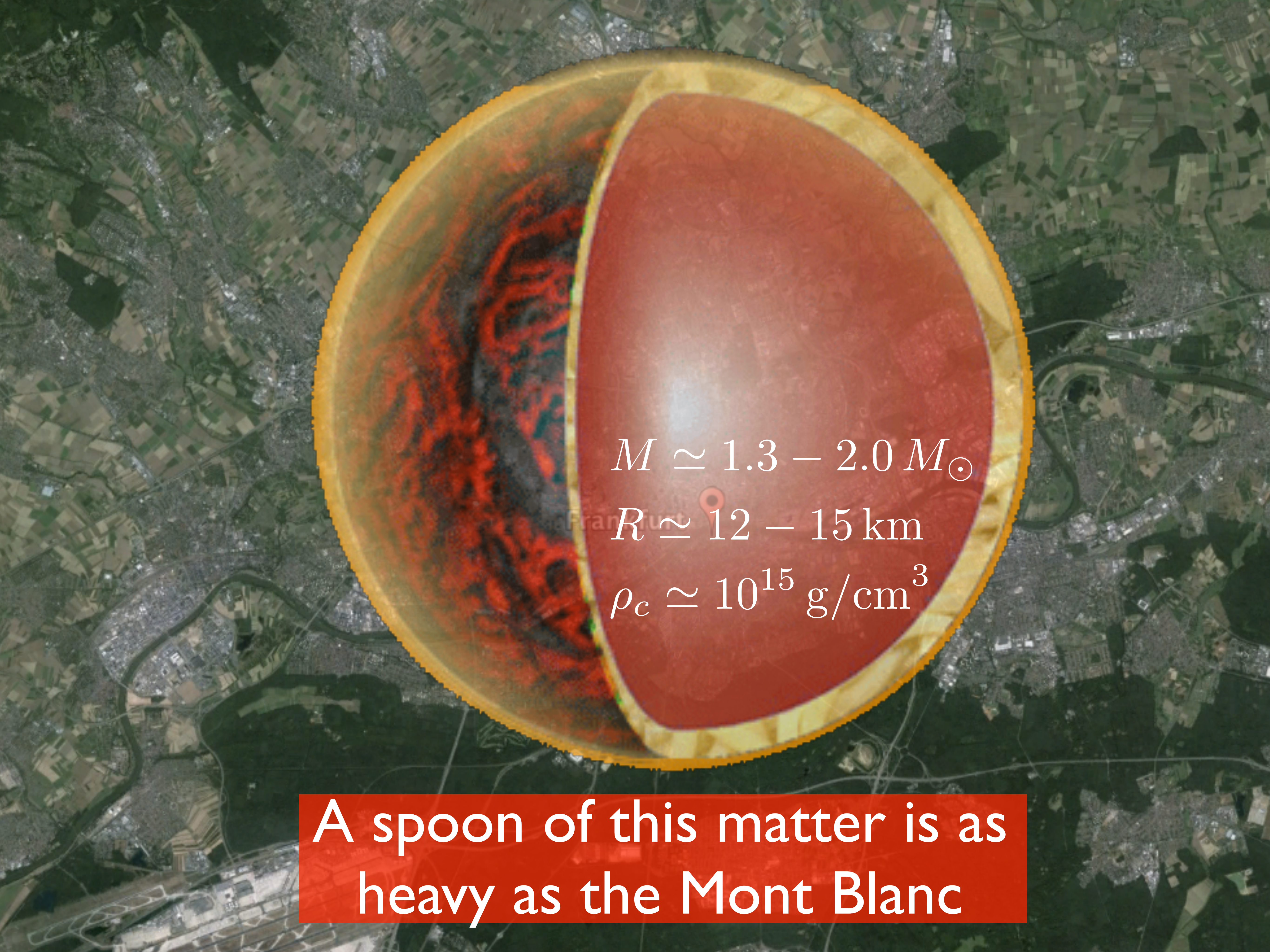
Neutron stars are the most common end of the evolution of massive stars, ie stars with

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

Such stars end their evolution as **supernovae**


Frankfurt

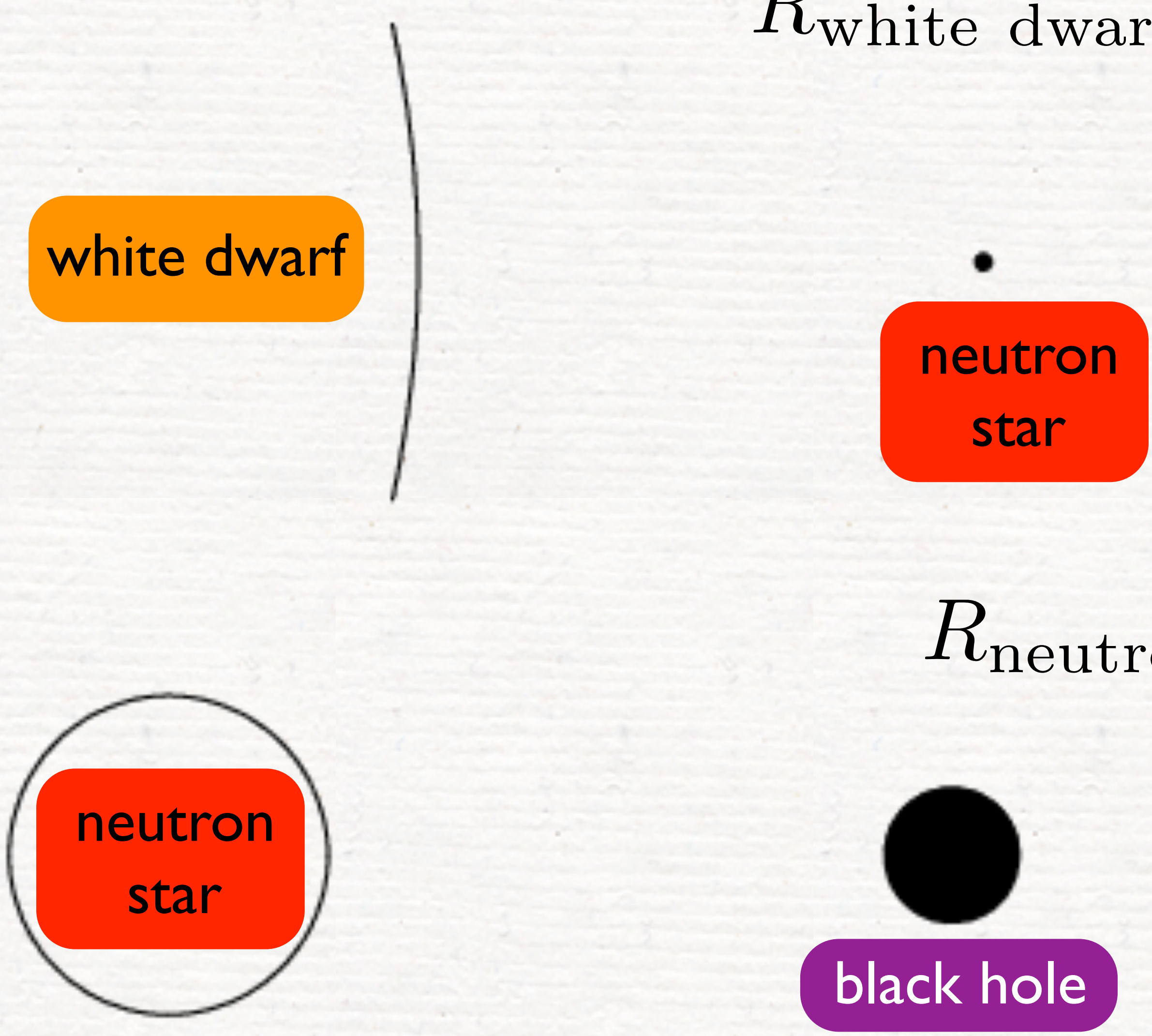

Frankfurt


$M \simeq 1.3 - 2.0\, M_\odot$
$R \simeq 12 - 15\, \mathrm{km}$
$\rho_c \simeq 10^{15}\, \mathrm{g/cm^3}$
A spoon of this matter is as heavy as the Mont Blanc

Let's compare again sizes and curvatures

$$R_\odot \simeq 70,000\,\mathrm{km};\ M/R \simeq 10^{-6}$$

$$R_{\mathrm{white\ dwarf}} \simeq 10000\,\mathrm{km};\ M/R \simeq 10^{-4} - 10^{-5}$$



$$R_{\mathrm{neutron\ star}} \simeq 12\,\mathrm{km};\ M/R \simeq 0.15 - 0.25$$

$$R_{\mathrm{black\ hole}} \simeq 1.5\,\mathrm{km};\ M/R = 0.5$$

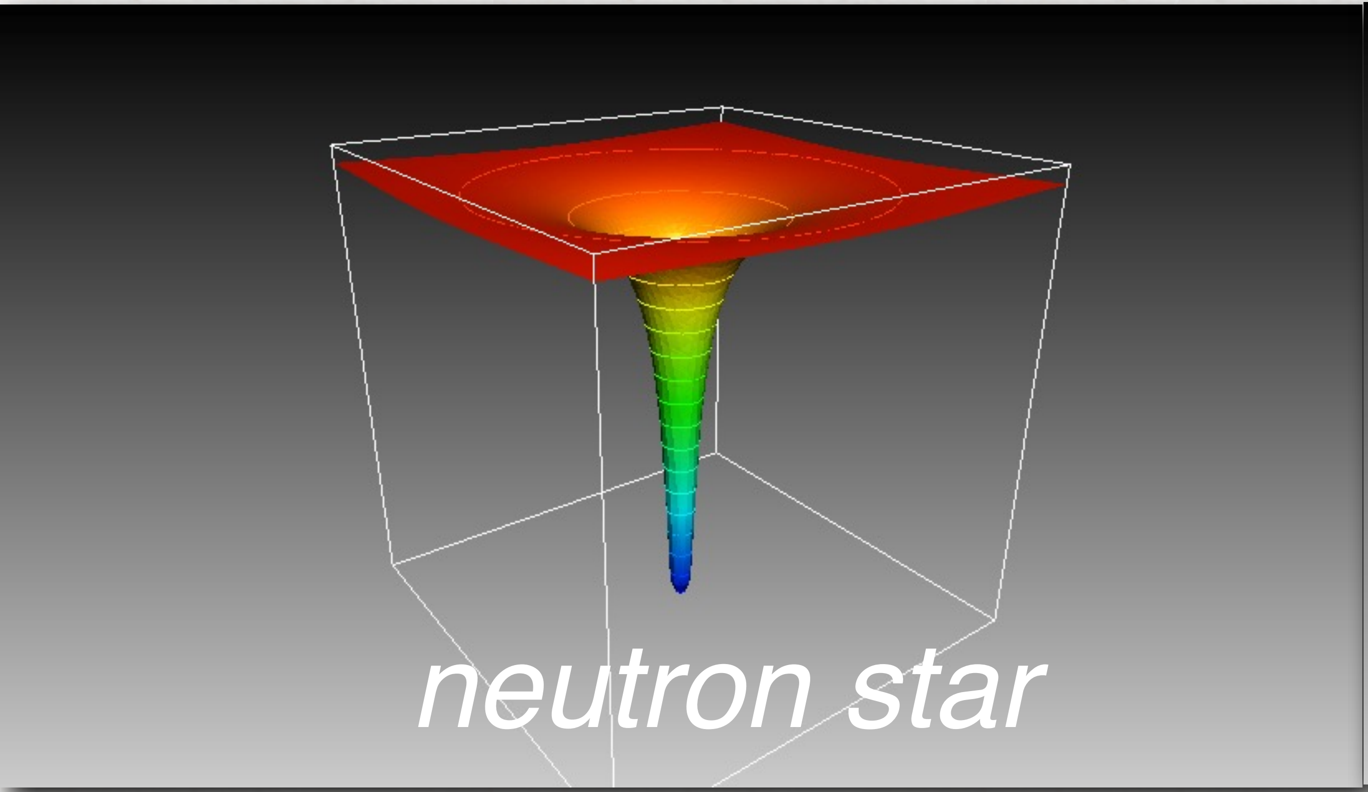
Compact Star vs Black Hole

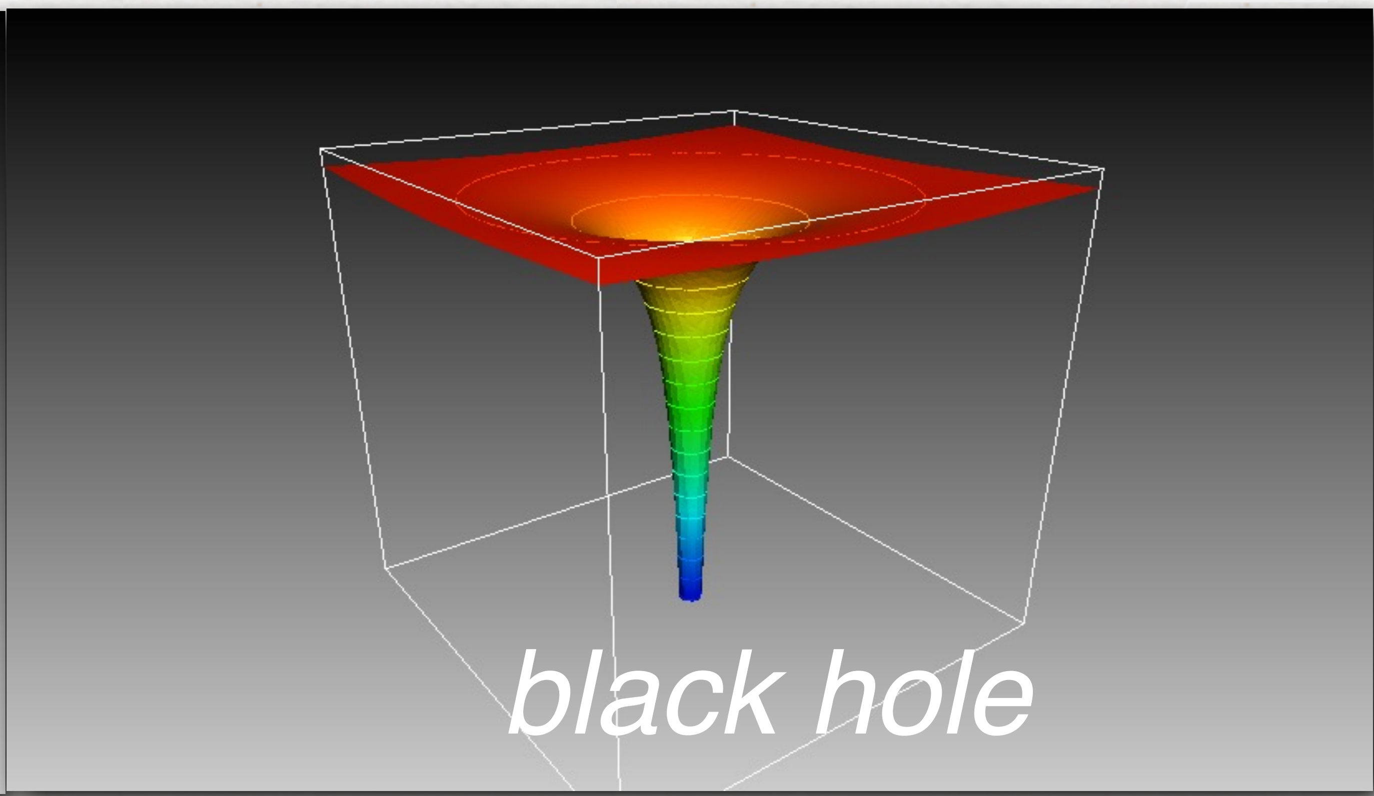
When it comes to compactness, black holes and neutron stars are very similar and extreme!

$M/R = 0.44444$ $\sqrt{-g_{tt}}$ $M/R = 0.5000$ $\sqrt{-g_{tt}}$

Compact Star vs Black Hole

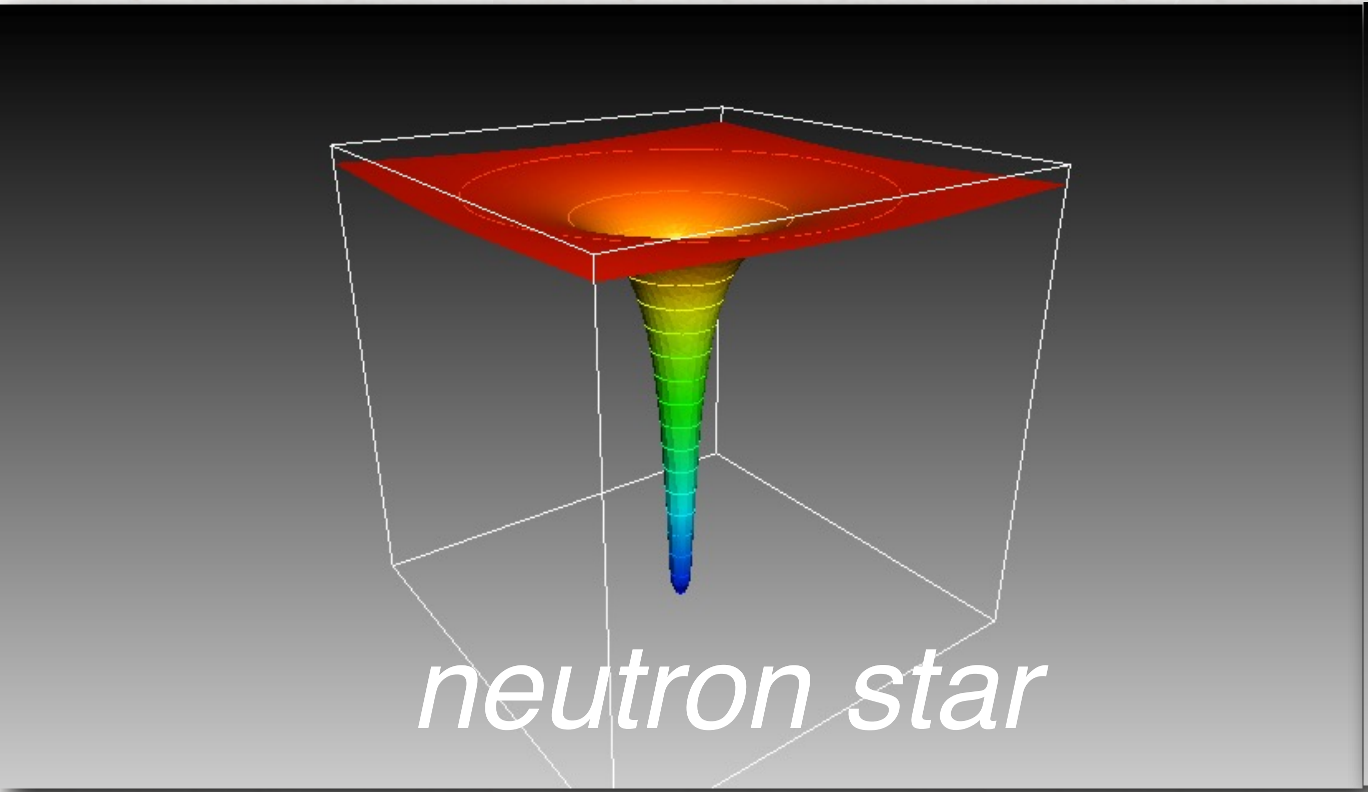
When it comes to compactness, black holes and neutron stars are very similar and extreme!

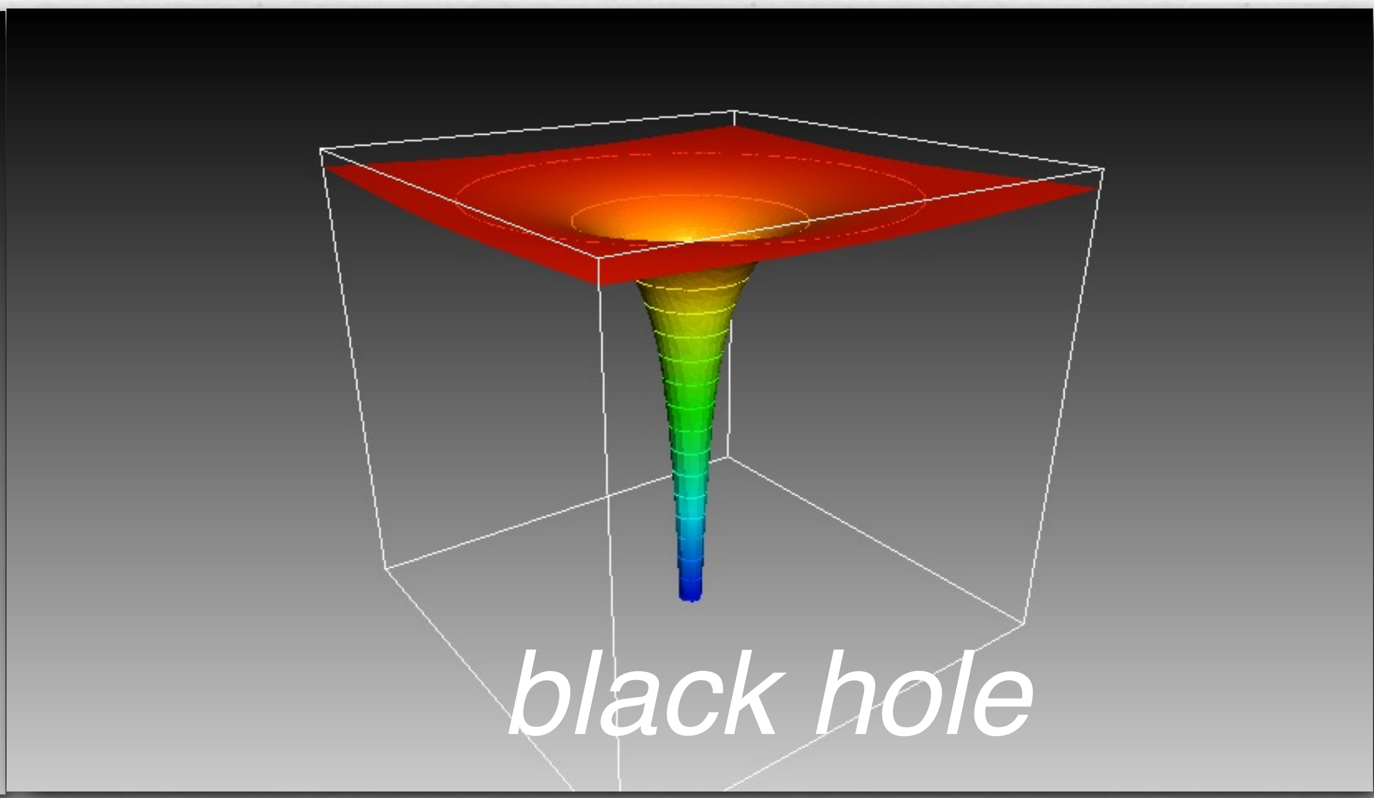




Compact Star vs Black Hole

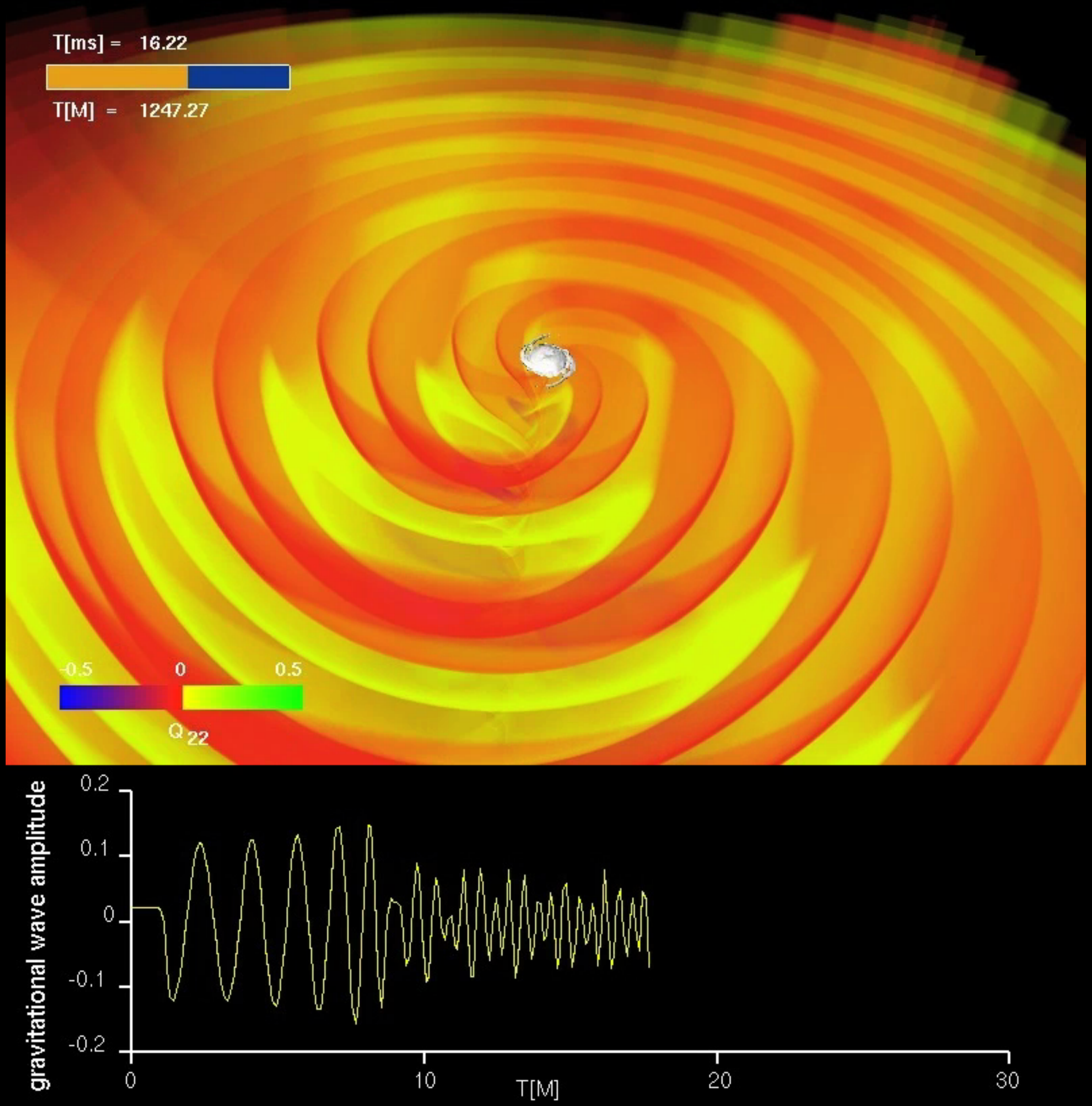
When it comes to compactness, black holes and neutron stars are very similar and extreme!





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

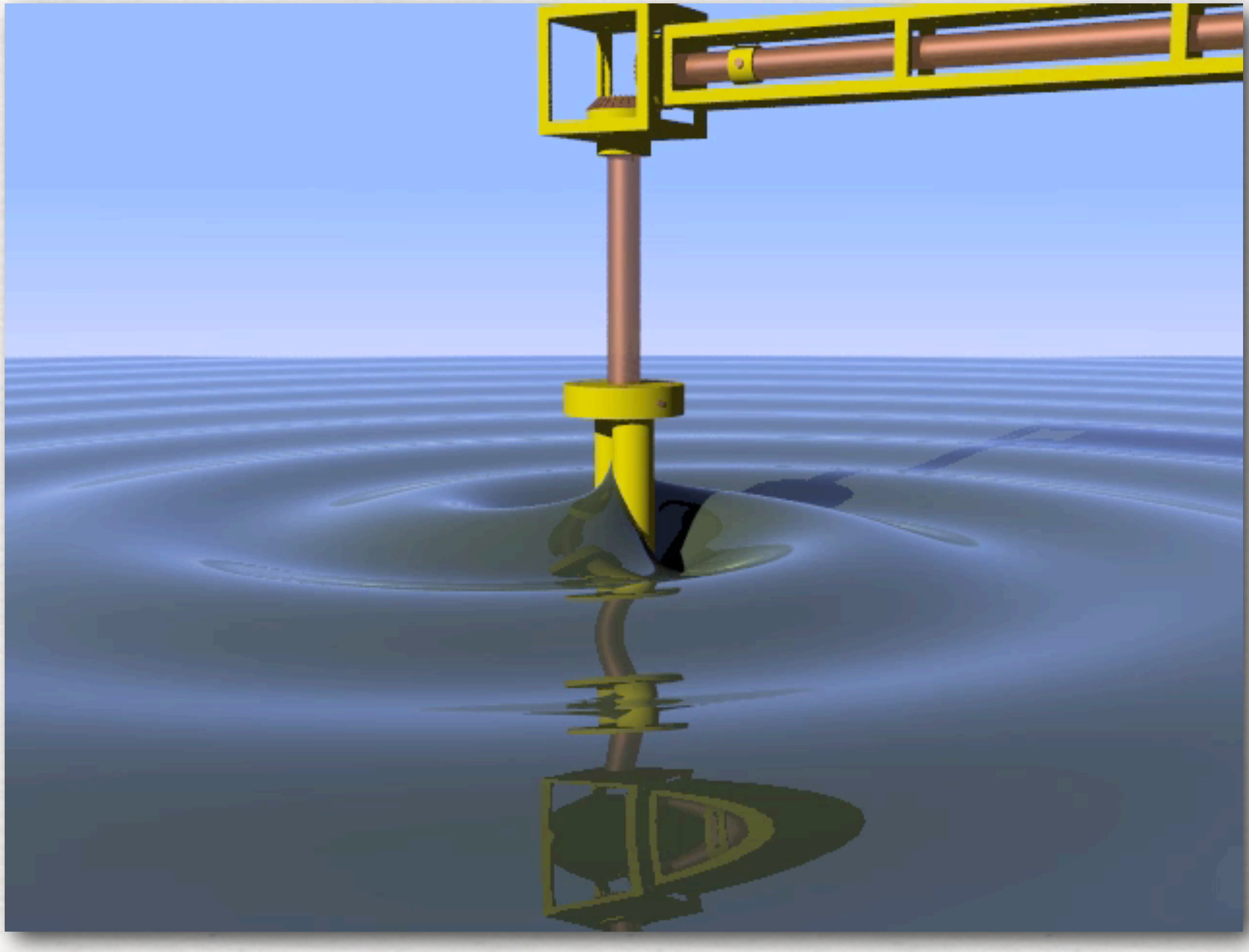
We have seen that compact objects like black holes and neutron stars curve the spacetime near them.

Gravitational waves: ripples in spacetime

We have seen that compact objects like black holes and neutron stars curve the spacetime near them.

- What happens to the curvature when they move?

- What happens if they orbit around the same center of mass?

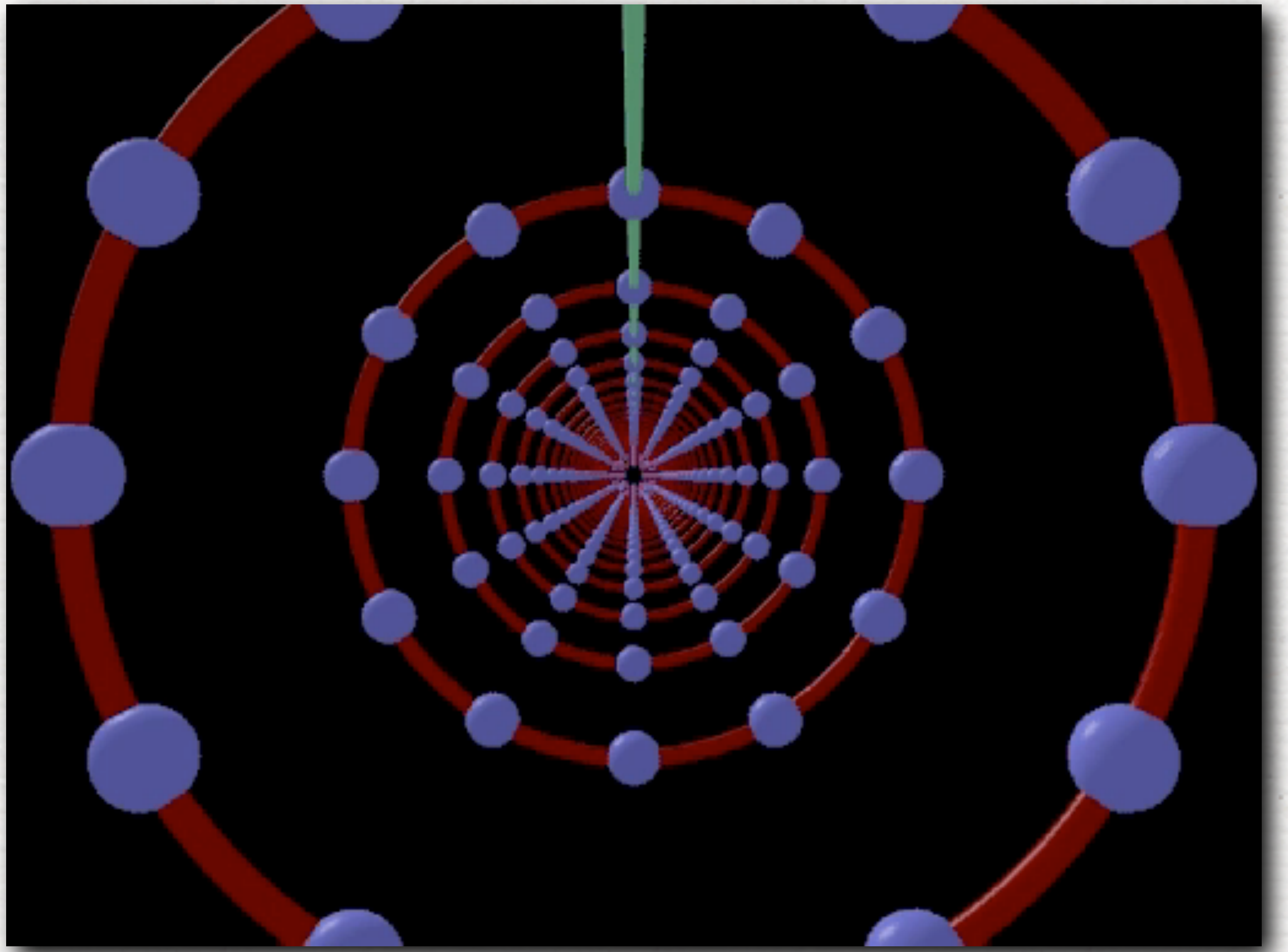


Gravitational waves: ripples in spacetime

The mechanical analogy is very close: general relativity predicts that if masses are accelerated, they produce ***gravitational waves (GWs)***

Gravitational waves: ripples in spacetime

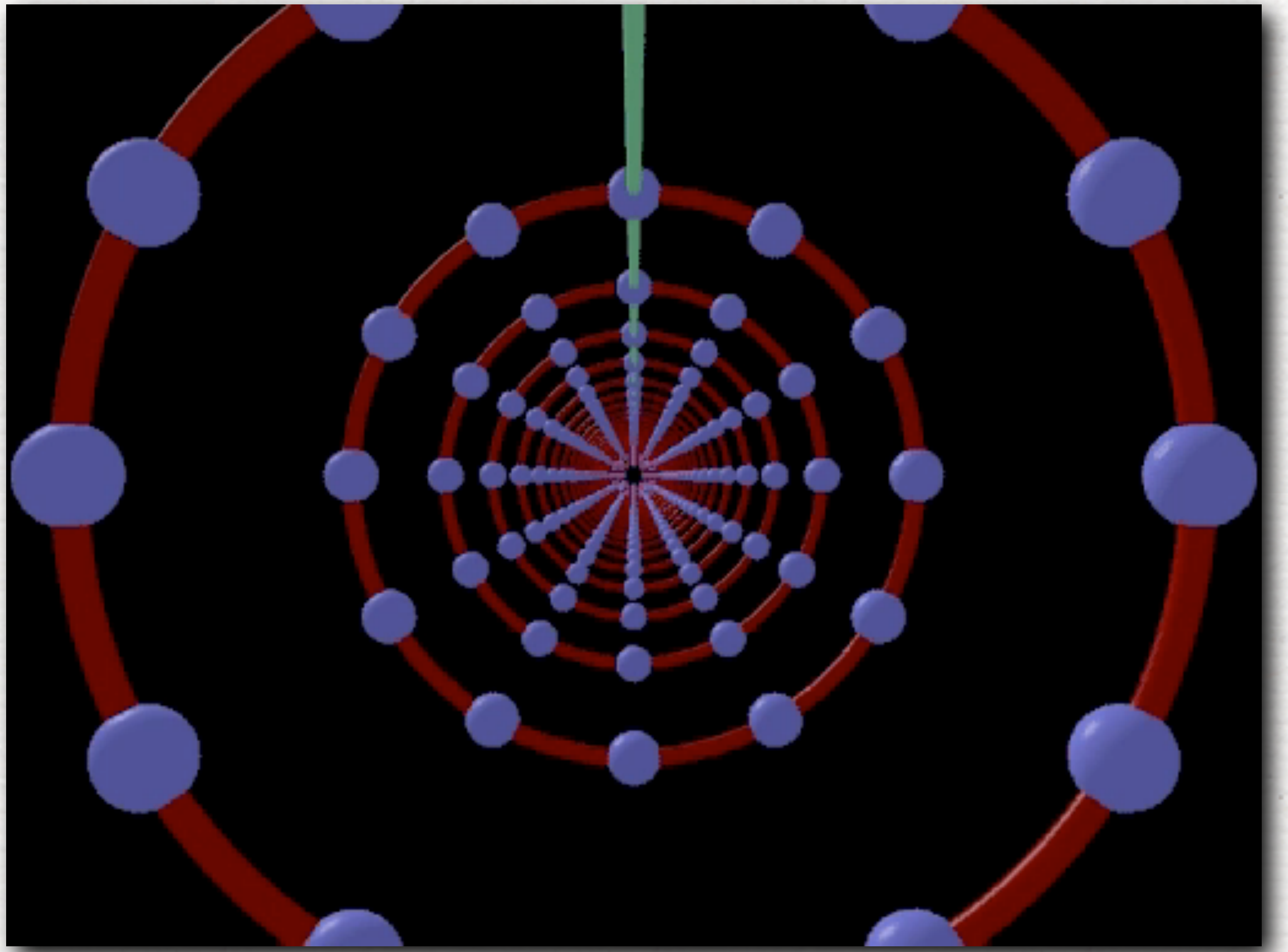
The mechanical analogy is very close: general relativity predicts that if masses are accelerated, they produce ***gravitational waves (GWs)***



Gravitational waves: ripples in spacetime

The mechanical analogy is very close: general relativity predicts that if masses are accelerated, they produce ***gravitational waves (GWs)***

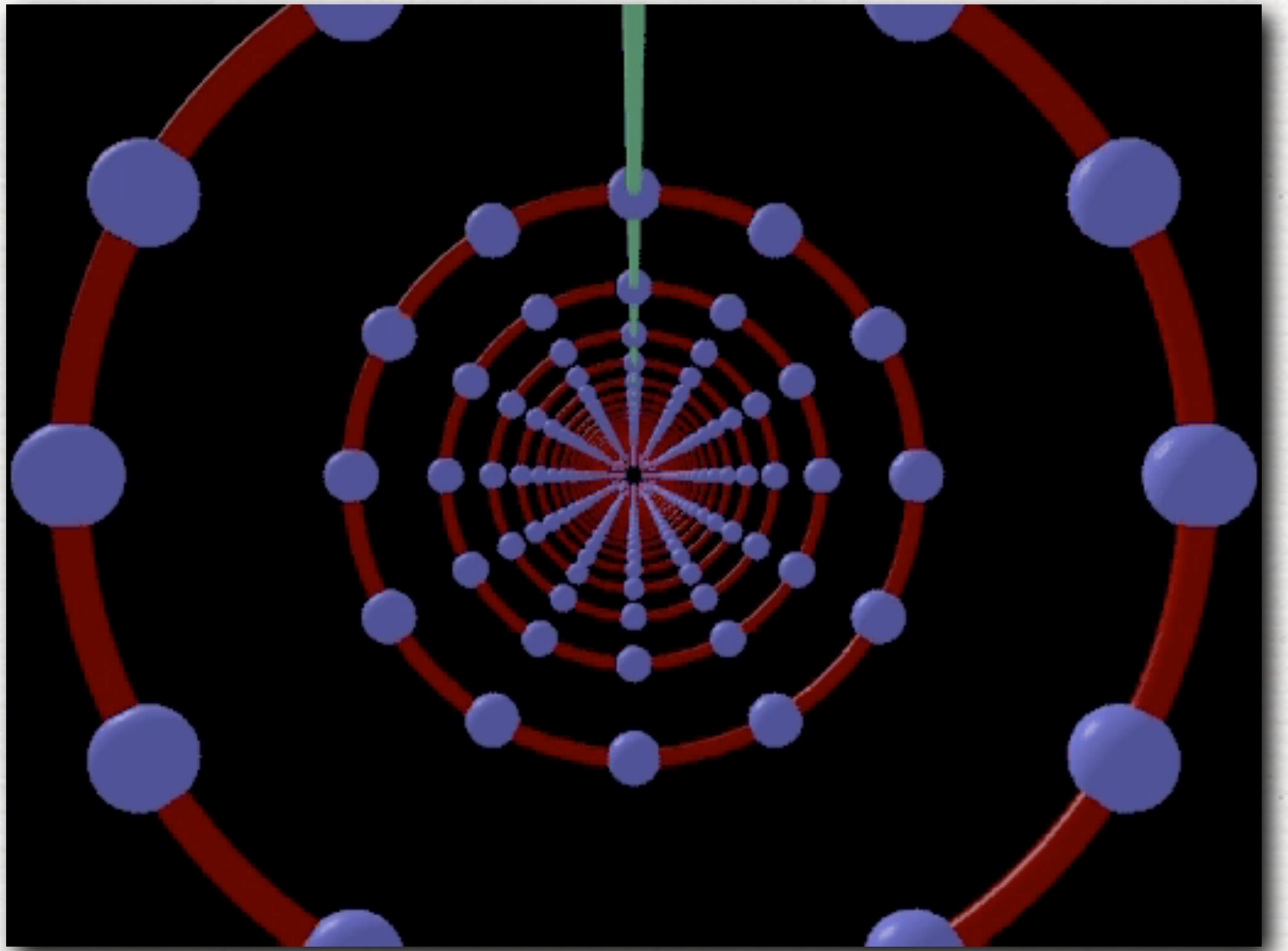
- They are **transverse waves** moving at the speed of light: i.e. they produce changes in the direction orthogonal to the propagation one



Gravitational waves: ripples in spacetime

The mechanical analogy is very close: general relativity predicts that if masses are accelerated, they produce ***gravitational waves (GWs)***

- 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.

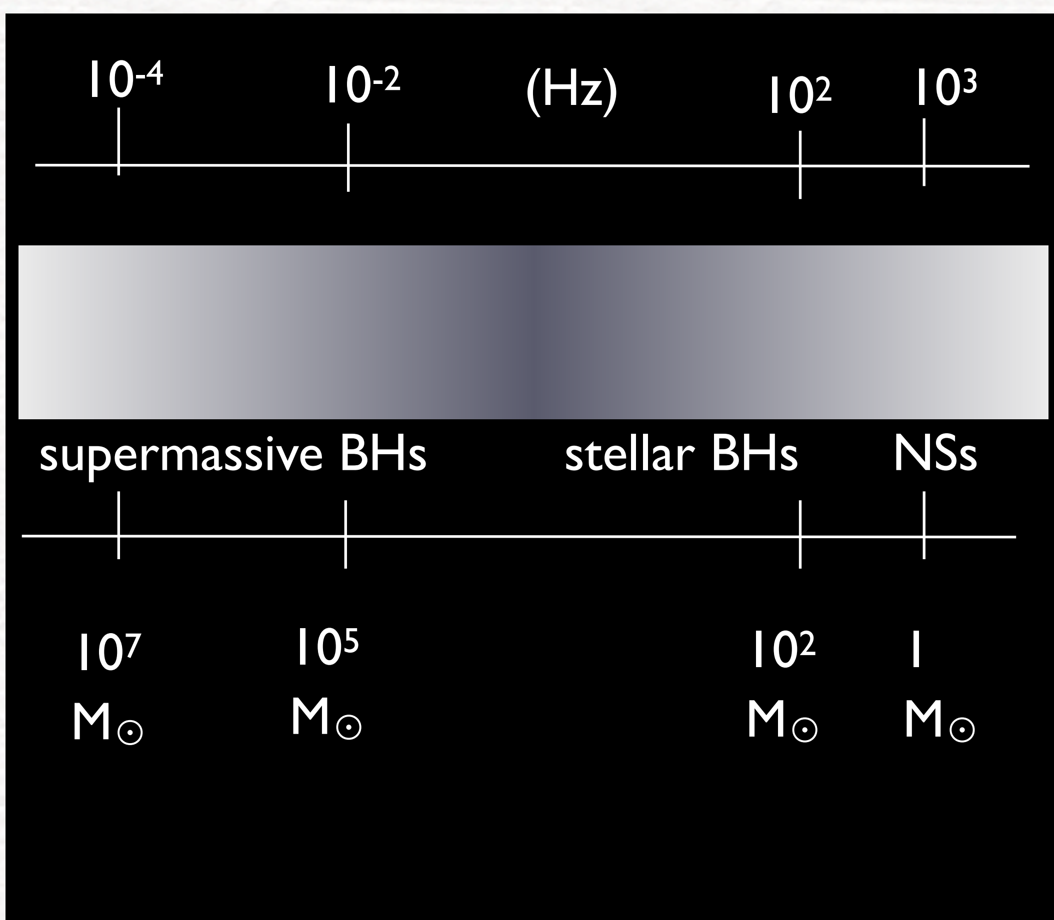


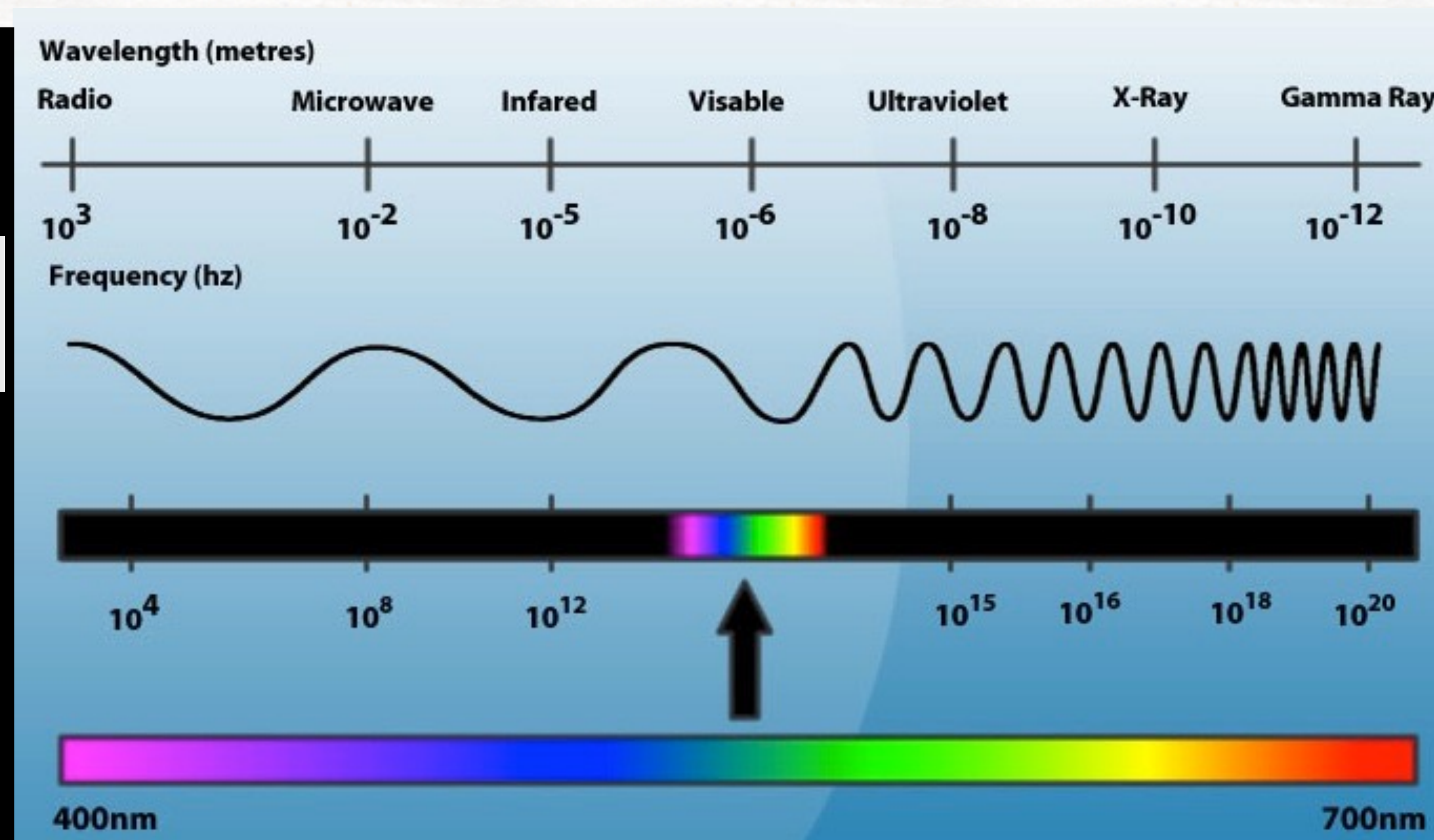
Comparing EM and GWs

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

gravitational-wave spectrum **electromagnetic spectrum**





scienceinthenews

How do you produce gravitational waves?

How do you produce gravitational waves?

GWs are produced when a **non-spherical** distribution of matter is accelerated.

How do you produce gravitational waves?

GWs are produced when a **non-spherical** distribution of matter is accelerated.

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

How do you produce gravitational waves?

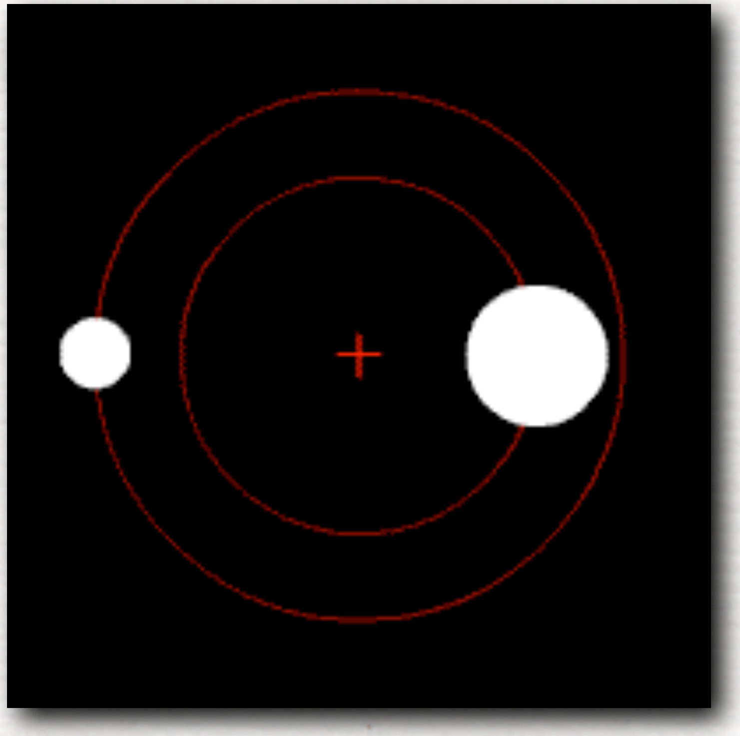
GWs are produced when a **non-spherical** distribution of matter is accelerated.

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

Clearly, **black holes** and **neutron stars** are ideal sources, especially if in **binary systems.**

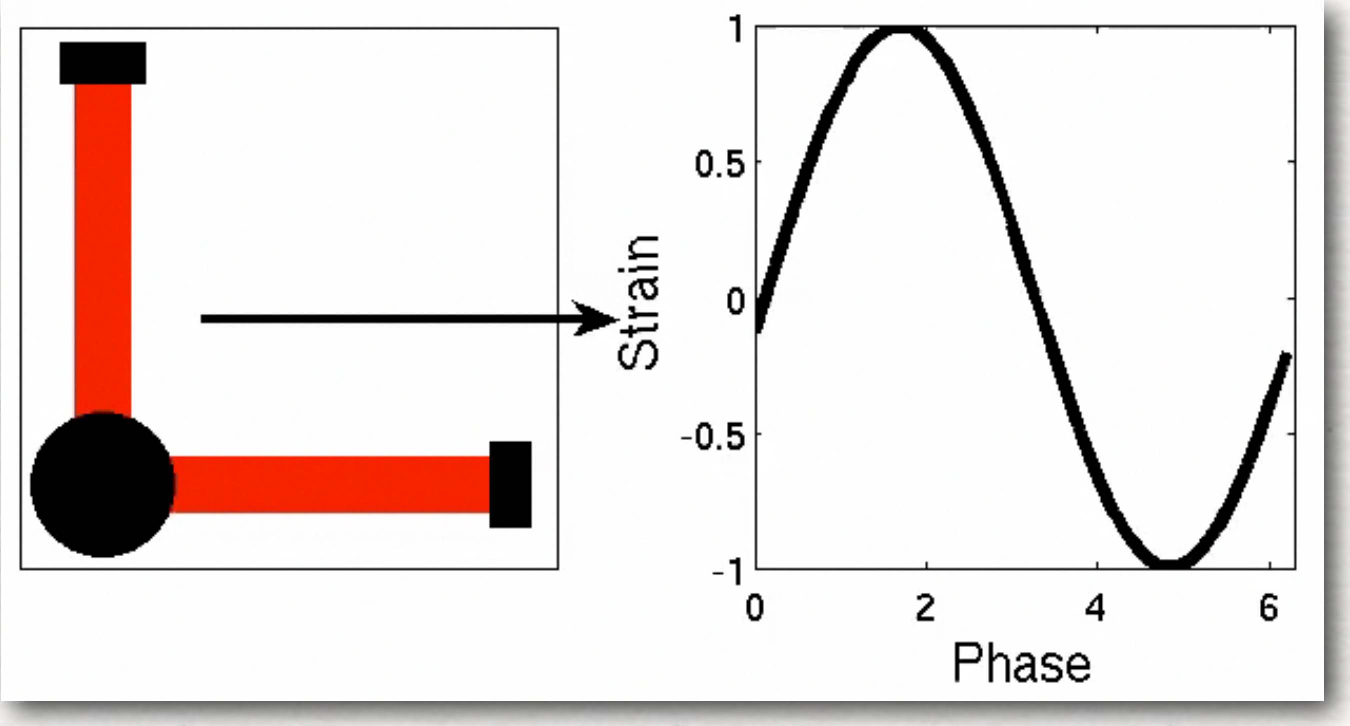


How do you detect gravitational waves?

GW detectors are giant interferometers: laser beams are sent to create interference.

GWs produce differences in arm lengths

$$\frac{\Delta L}{L} \simeq 10^{-21}$$

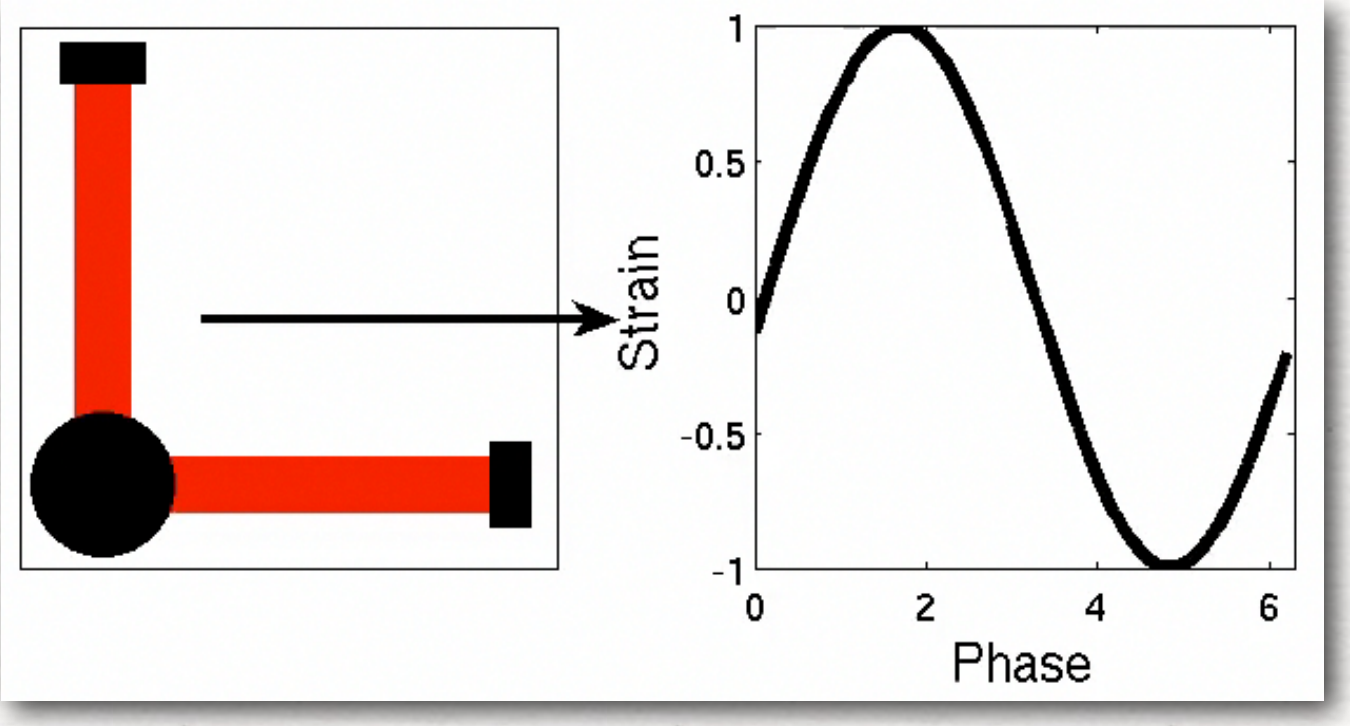


How do you detect gravitational waves?

GW detectors are giant interferometers: laser beams are sent to create interference.

GWs produce differences in arm lengths

$$\frac{\Delta L}{L} \simeq 10^{-21}$$



Catastrophic events

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

$$L_{\rm GW} \simeq \left(\frac{G}{c^5}\right)\left(\frac{M\langle v^2\rangle}{\tau}\right)^2 \simeq \left(\frac{c^5}{G}\right)\left(\frac{R_{\rm Schw.}}{R}\right)^2\left(\frac{\langle v\rangle}{c}\right)^6$$

Catastrophic events

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

$$L_{\rm GW} \simeq \left(\frac{G}{c^5}\right)\left(\frac{M\langle v^2\rangle}{\tau}\right)^2 \simeq \left(\frac{c^5}{G}\right)\left(\frac{R_{\rm Schw.}}{R}\right)^2\left(\frac{\langle v\rangle}{c}\right)^6$$

Near merger the binary is very compact ($R_{\rm Schw.}=2GM/c^2$) and moving at fraction of speed of light: GR is indispensable

$$R \simeq 10\, R_{\rm Schw.} \qquad \langle v\rangle \simeq 0.1\, c$$

Catastrophic events

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

$$L_{\rm GW} \simeq \left(\frac{G}{c^5}\right)\left(\frac{M\langle v^2\rangle}{\tau}\right)^2 \simeq \left(\frac{c^5}{G}\right)\left(\frac{R_{\rm Schw.}}{R}\right)^2\left(\frac{\langle v\rangle}{c}\right)^6$$

Near merger the binary is very compact ($R_{\rm Schw.}=2GM/c^2$) and moving at fraction of speed of light: GR is indispensable

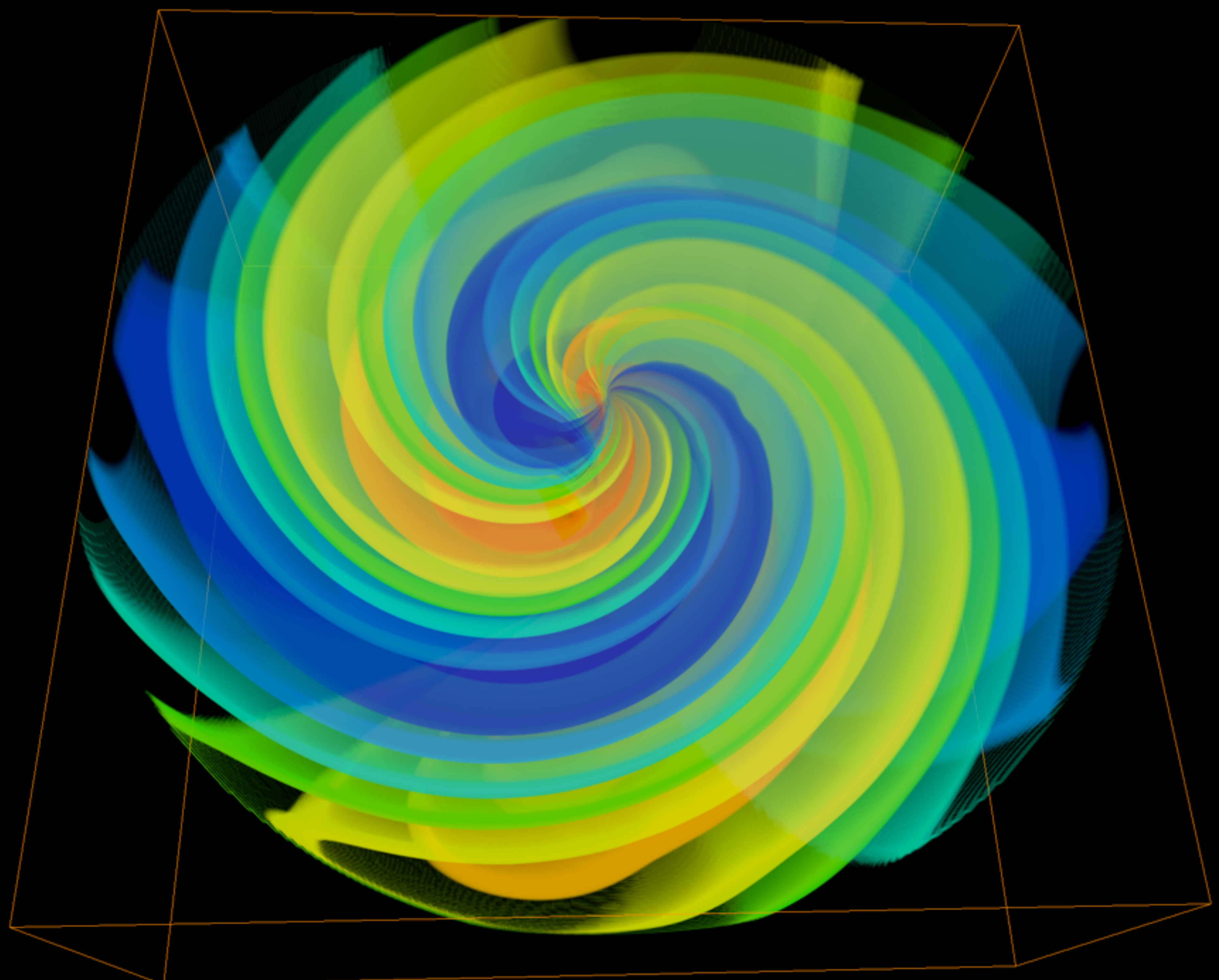
$$R \simeq 10\,R_{\rm Schw.} \qquad \langle v\rangle \simeq 0.1\,c$$

As a result, the GW luminosity is:

$$L_{\rm GW} \simeq 10^{-8}\left(\frac{c^5}{G}\right) \simeq 10^{50}\,{\rm erg\ s^{-1}} \simeq 10^{17}\,L_\odot$$

This is roughly the combined luminosity of 1million 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

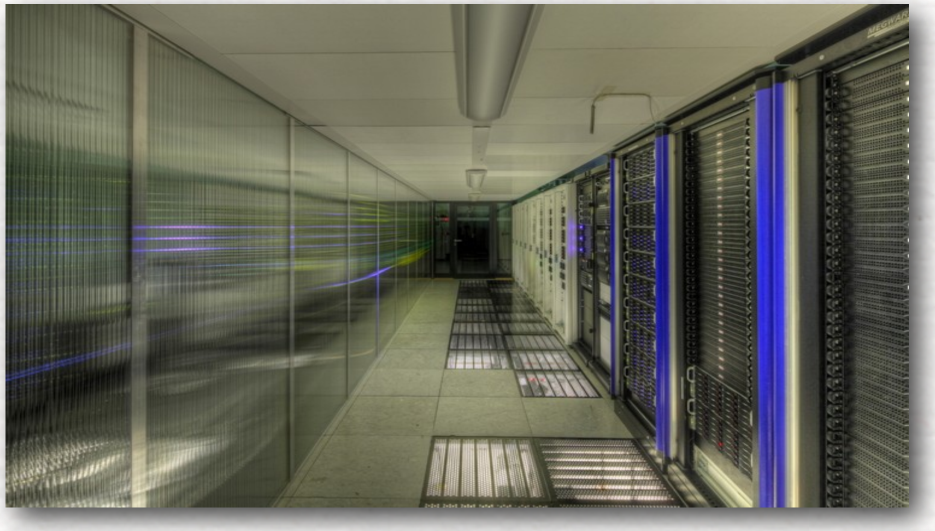
Numerical relativity solves Einstein/HD/MHD eqs. in regimes in which no approximation is expected to hold.

To do this we build codes: our **"theoretical laboratories"**.

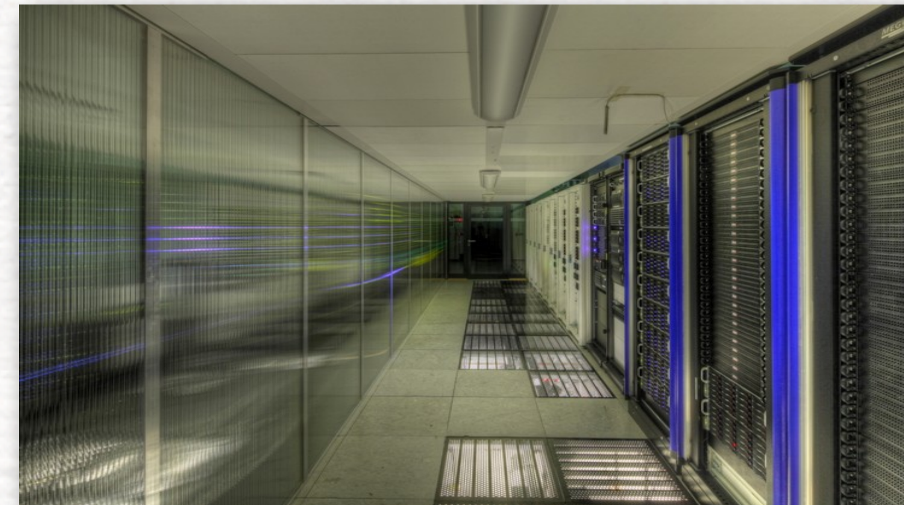
Theoretical laboratories?

Theoretical laboratories?

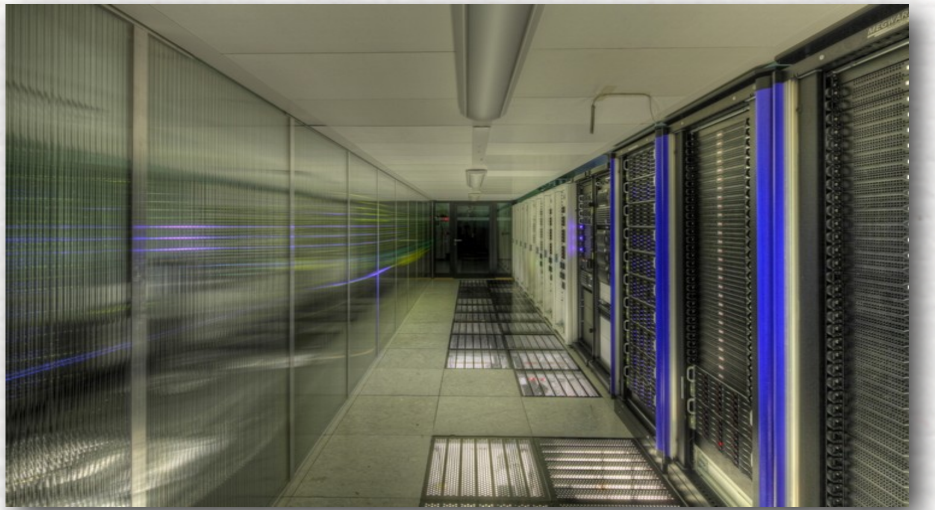
Theoretical laboratories?



Theoretical laboratories?



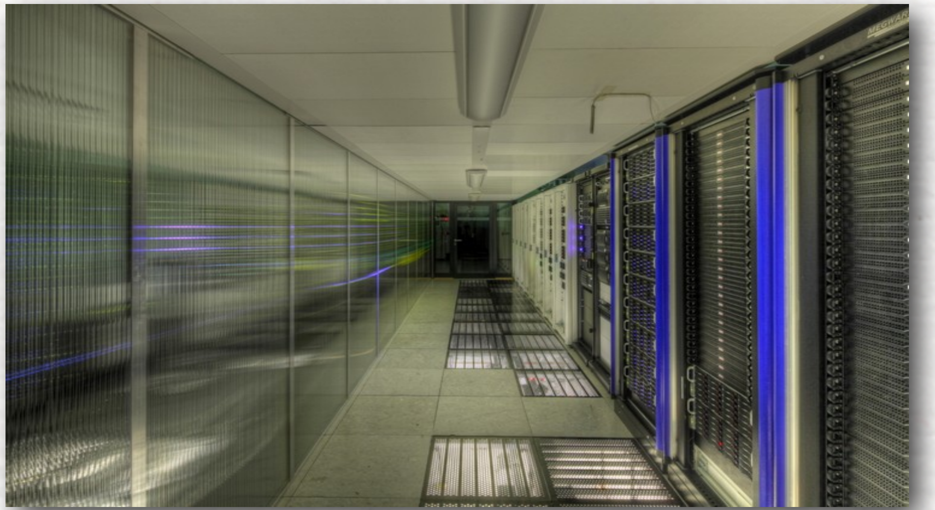
Theoretical laboratories?



$$G_{\mu\nu} = 8\pi G T_{\mu\nu},$$

$$\nabla_\mu T^{\mu\nu} = 0$$

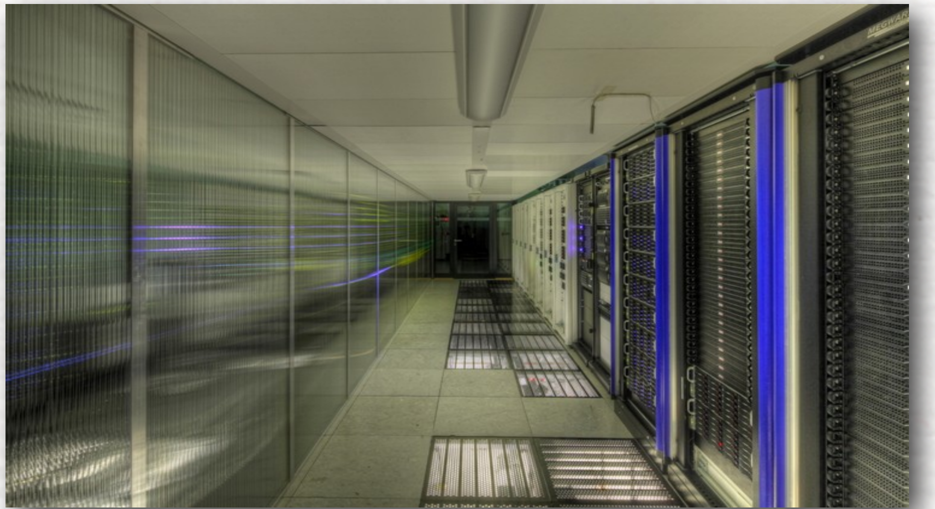
Theoretical laboratories?



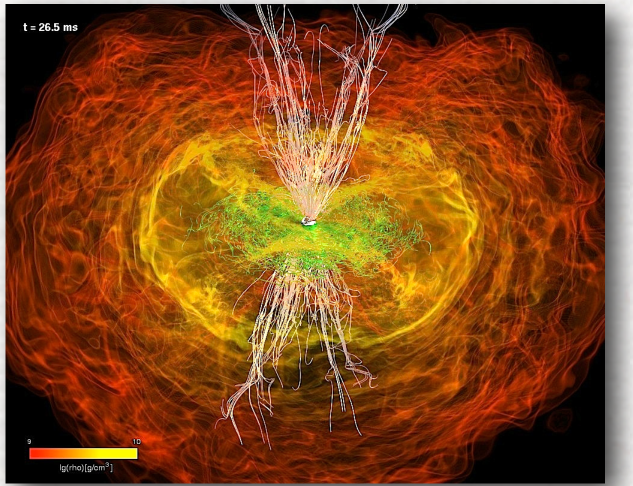
$$G_{\mu\nu} = 8\pi G T_{\mu\nu},$$

$$\nabla_\mu T^{\mu\nu} = 0$$

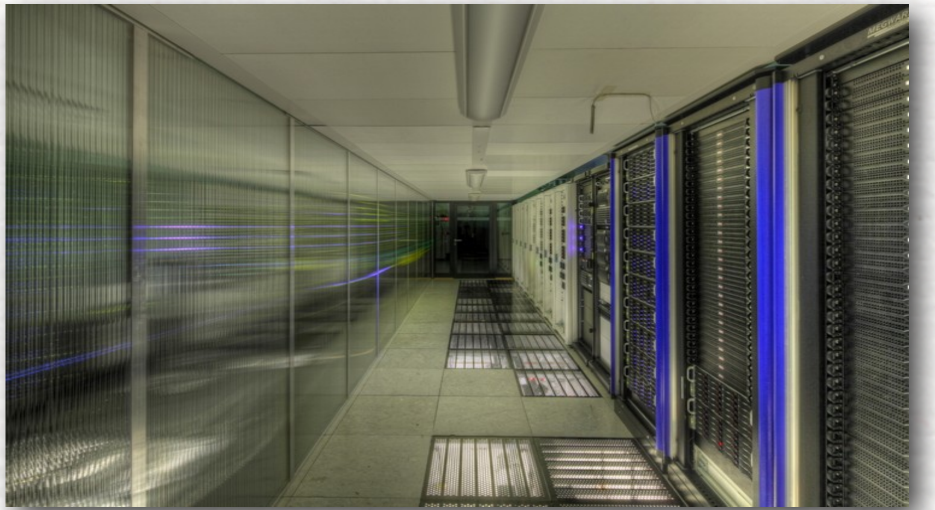
Theoretical laboratories?



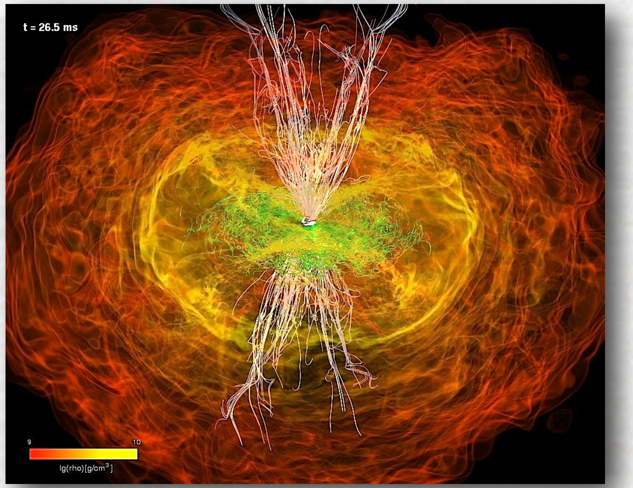
$$G_{\mu\nu} = 8\pi G T_{\mu\nu},$$
$$\nabla_\mu T^{\mu\nu} = 0$$



Theoretical laboratories?

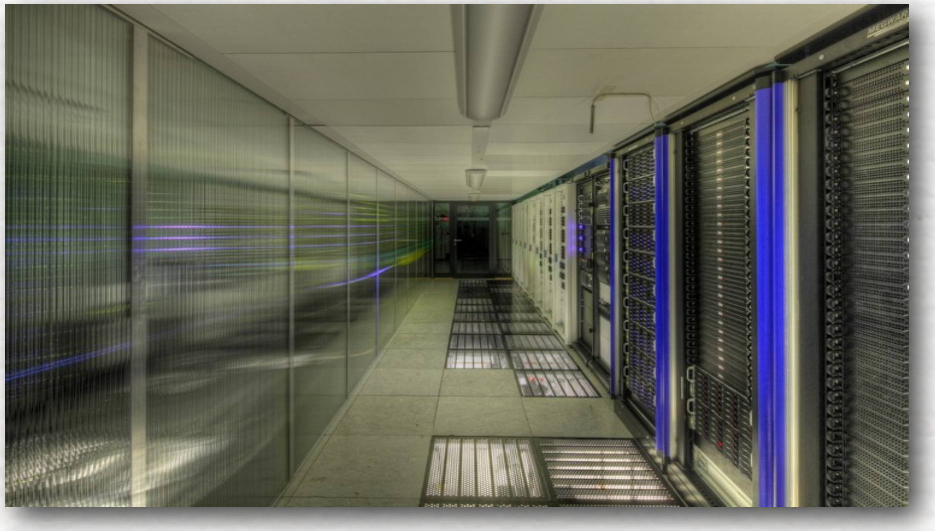


$$G_{\mu\nu} = 8\pi G T_{\mu\nu},$$
$$\nabla_\mu T^{\mu\nu} = 0$$

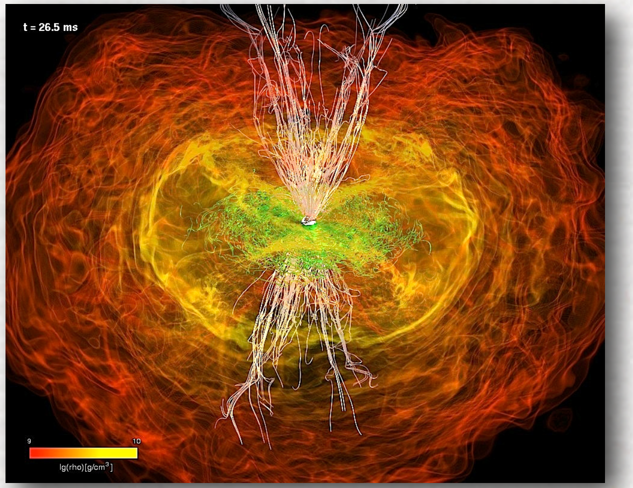


Think of them as a factory of "**gedanken experiments**"

Theoretical laboratories?



$$G_{\mu\nu} = 8\pi G T_{\mu\nu}\,,$$
$$\nabla_\mu T^{\mu\nu} = 0$$



Think of them as a factory of "**gedanken experiments**"

Einstein would have loved them…

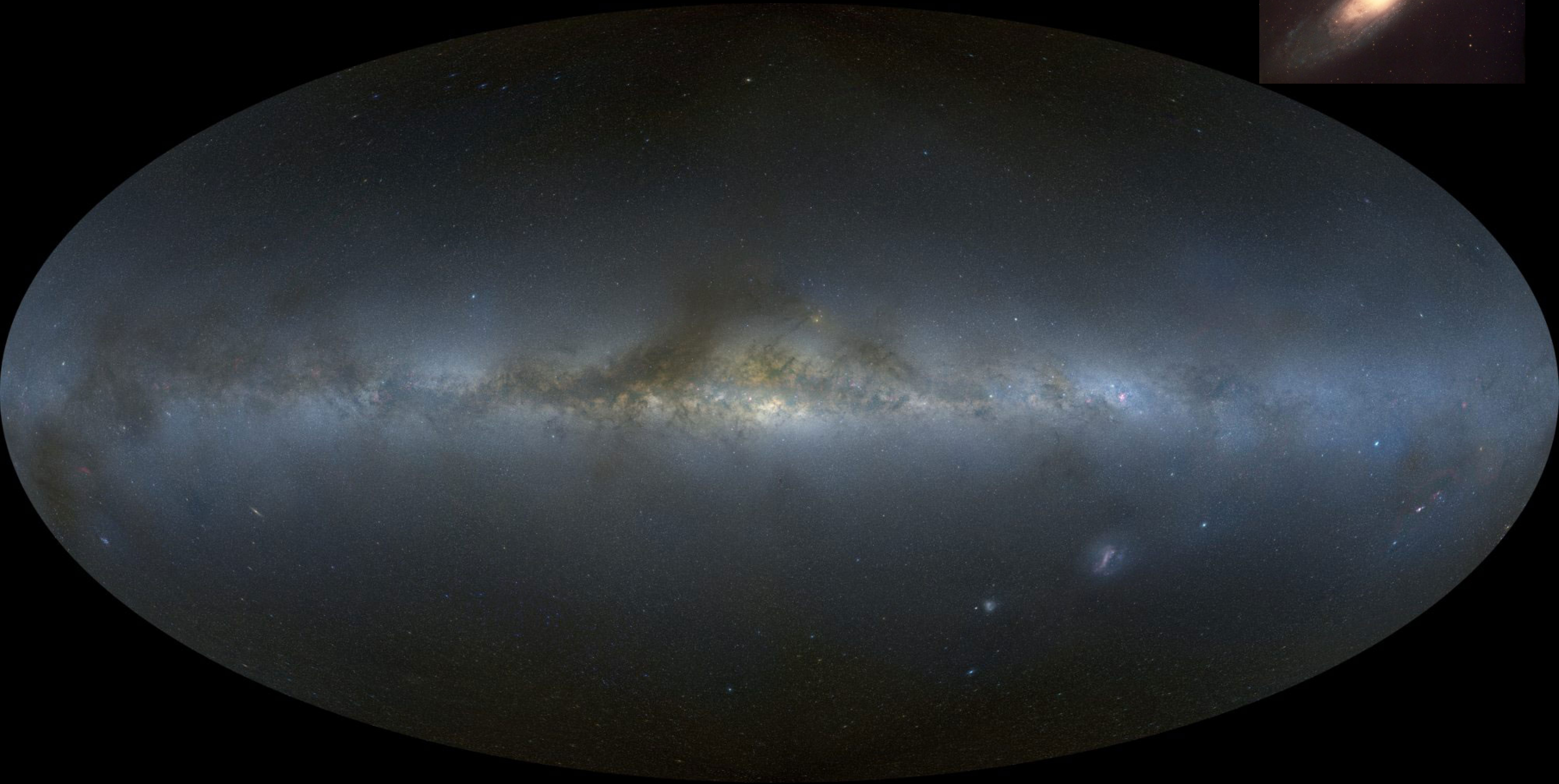
Do black holes really exist?…

The Milky Way

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

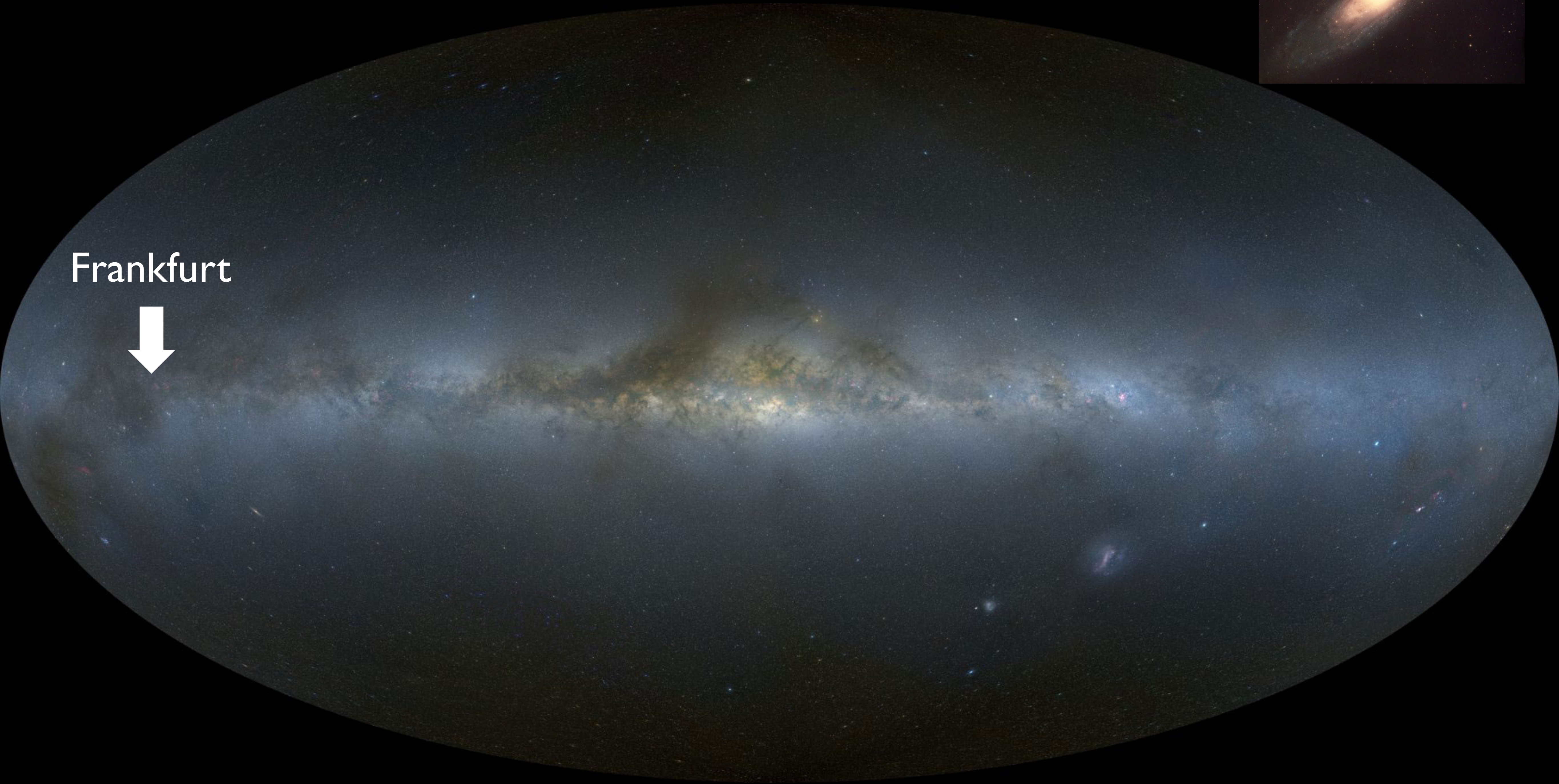
The Milky Way

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



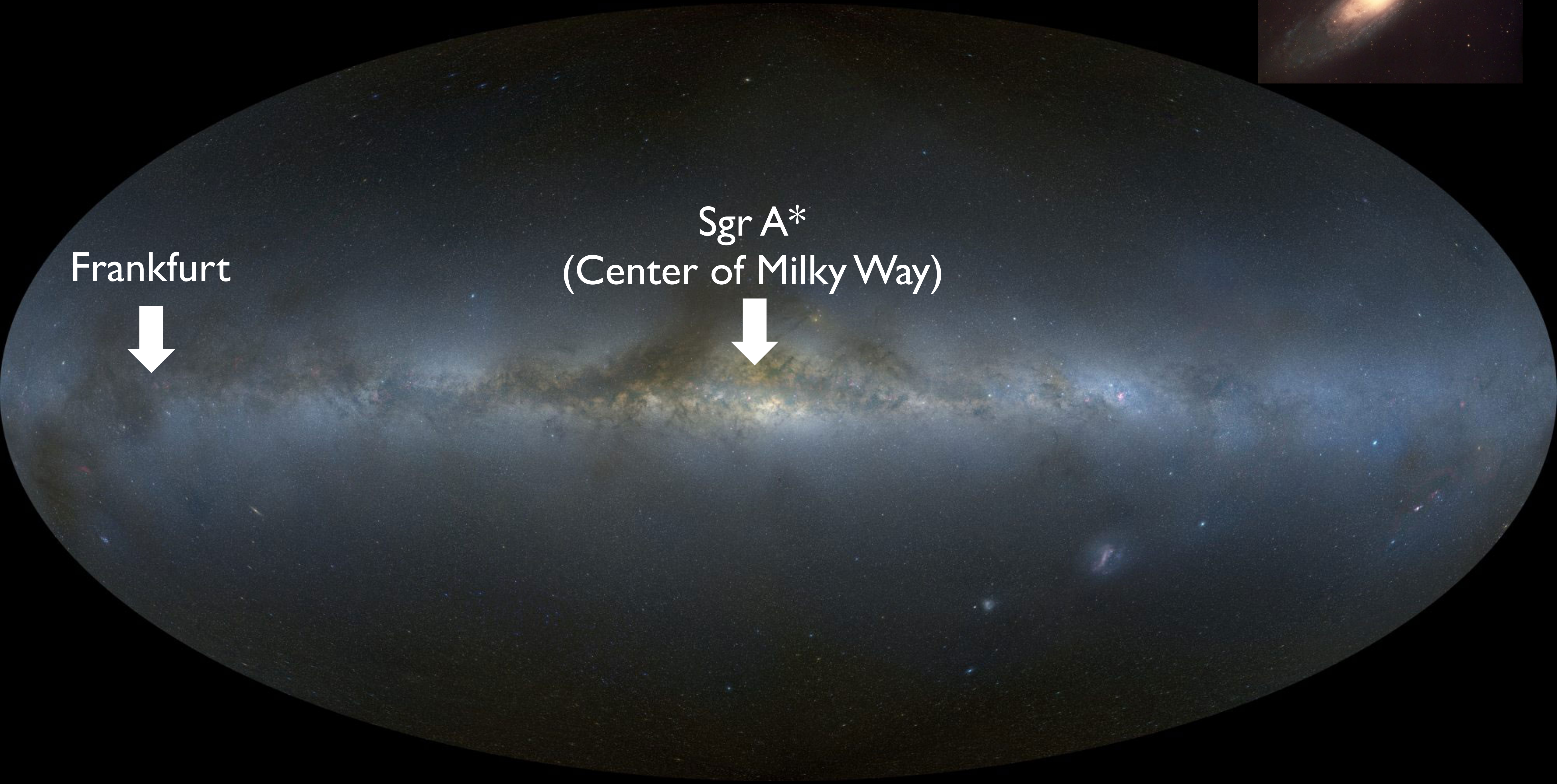
The Milky Way

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



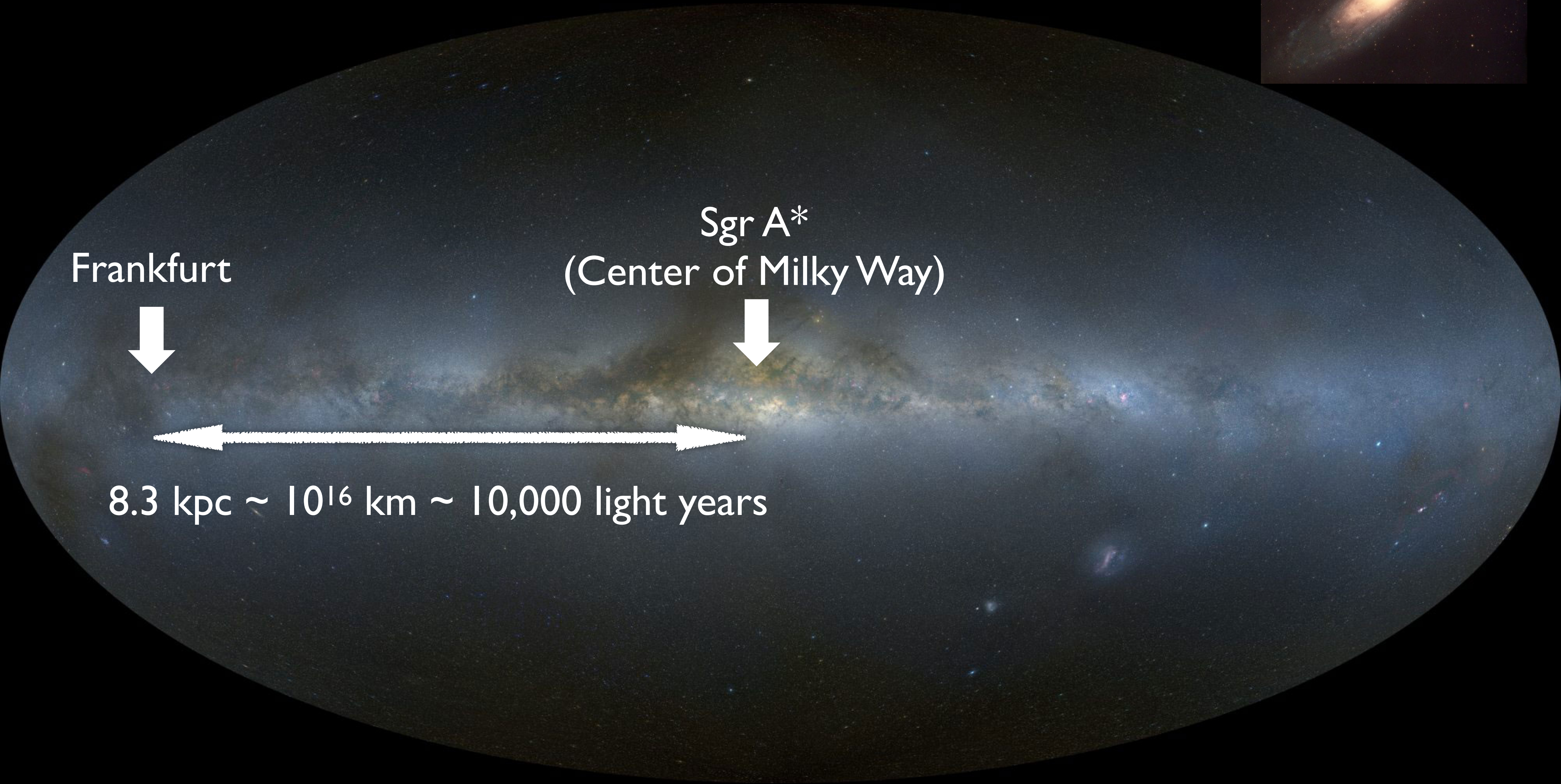
The Milky Way

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



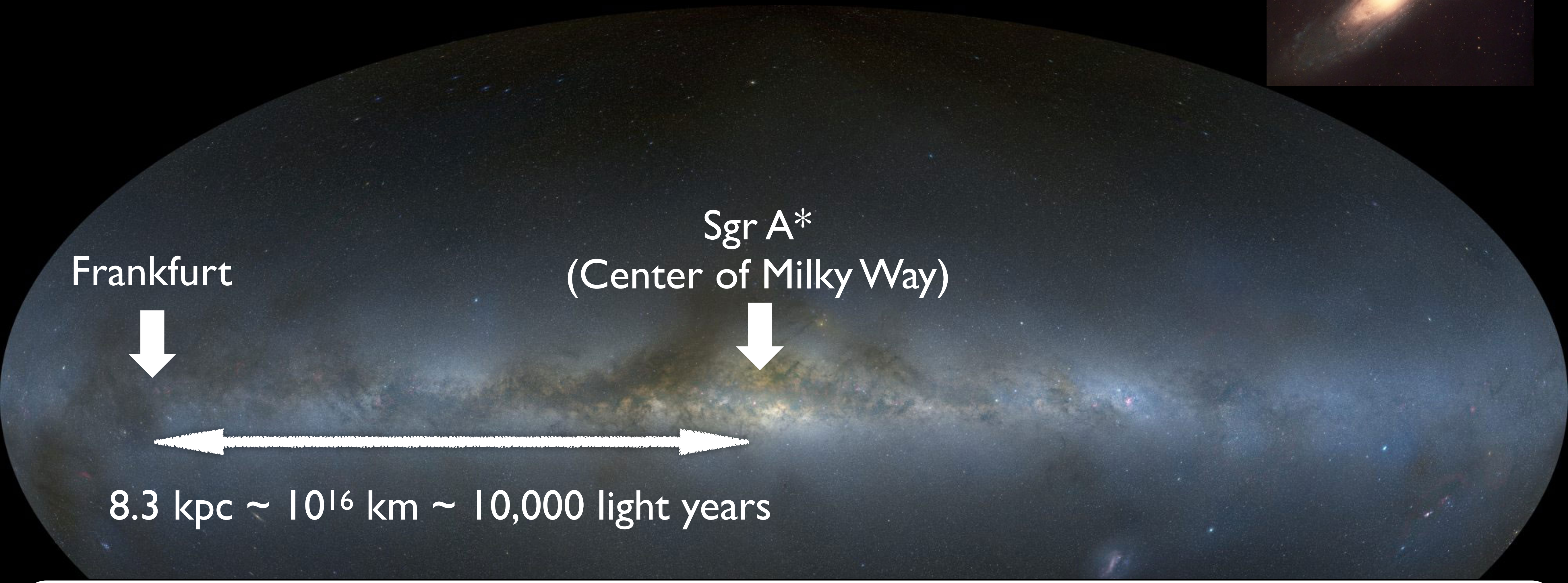
The Milky Way

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



The Milky Way

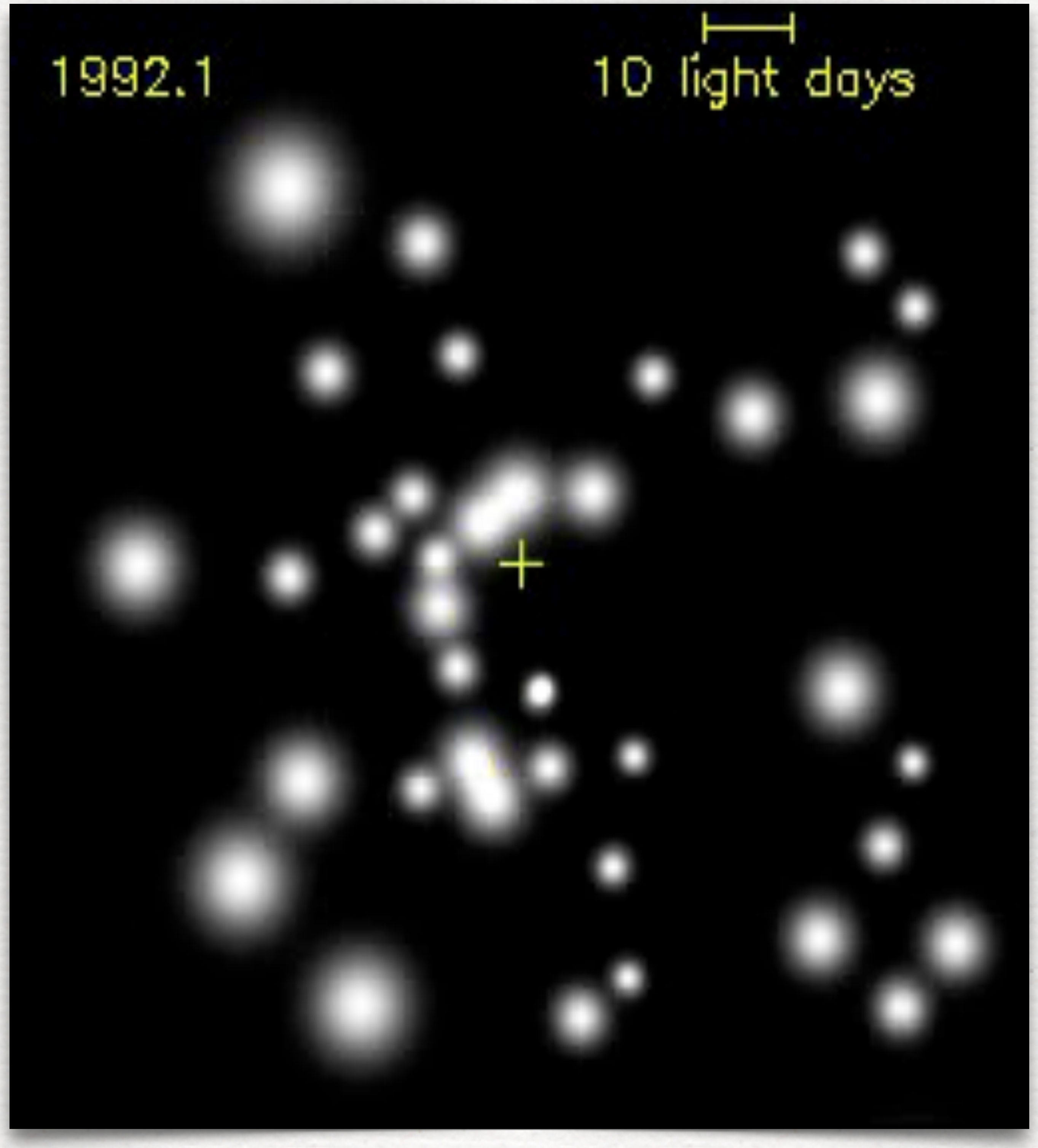
View of the full sky (north and south) in the optical.



- Black hole size is proportional to its mass: $R_S = 2GM/c^2$
- 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

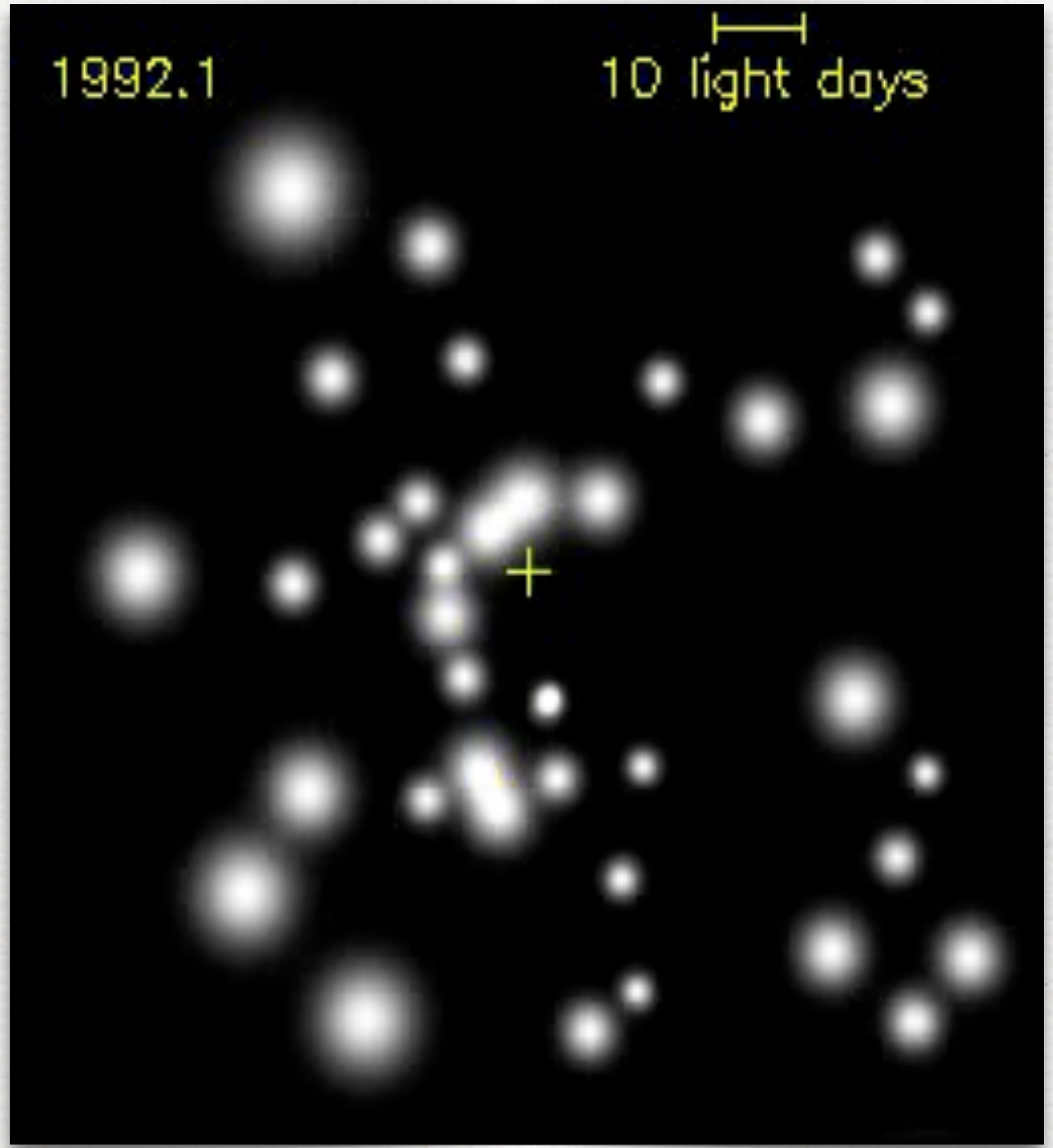
- Near-infrared telescopes (ESO) have measured orbits of individual stars.
- The stars orbit a dark object: the compact radio source Sgr A*.
- Study of orbits reveals a mass of 4.3 million times the mass of the Sun.



Gillessen/Eisenhauer/Genzel (MPE Garching)

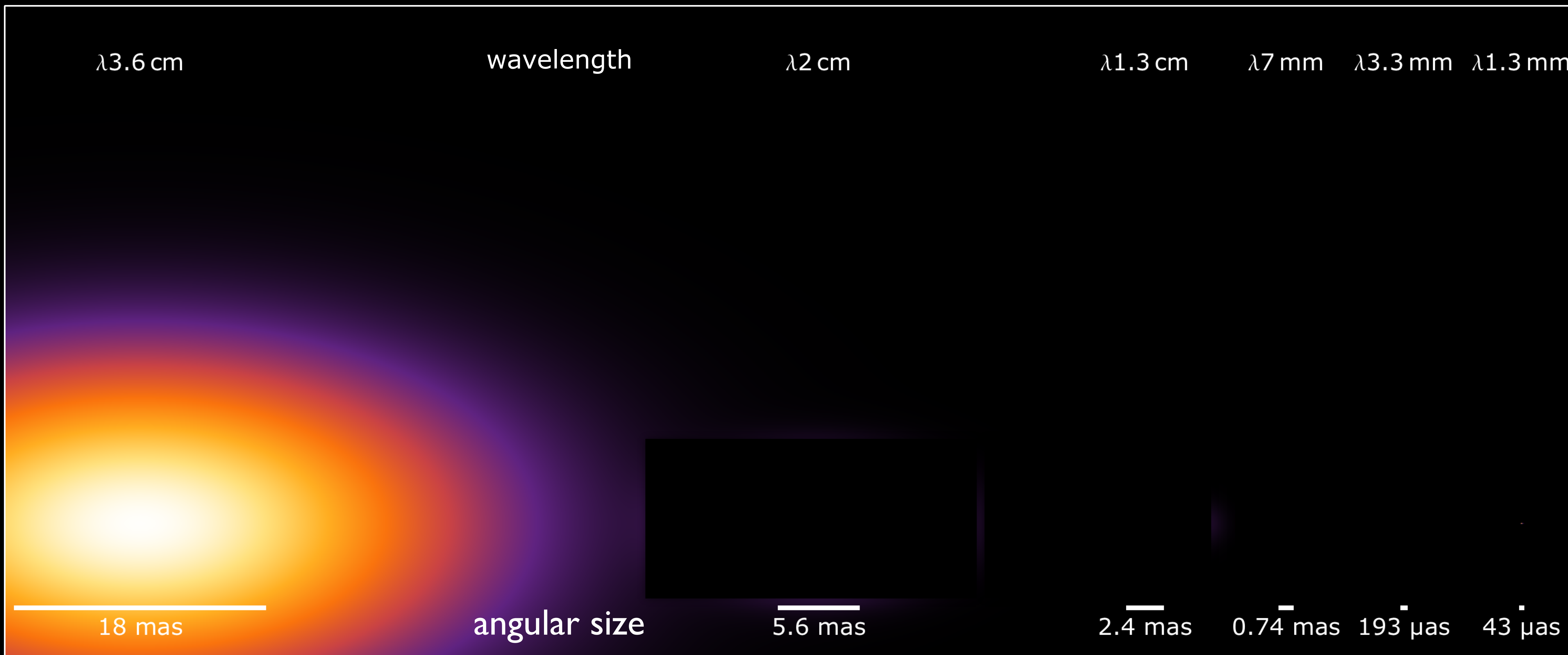
Sgr A*: the "dark object" in the Galactic Center

- 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)

Images of the radio source

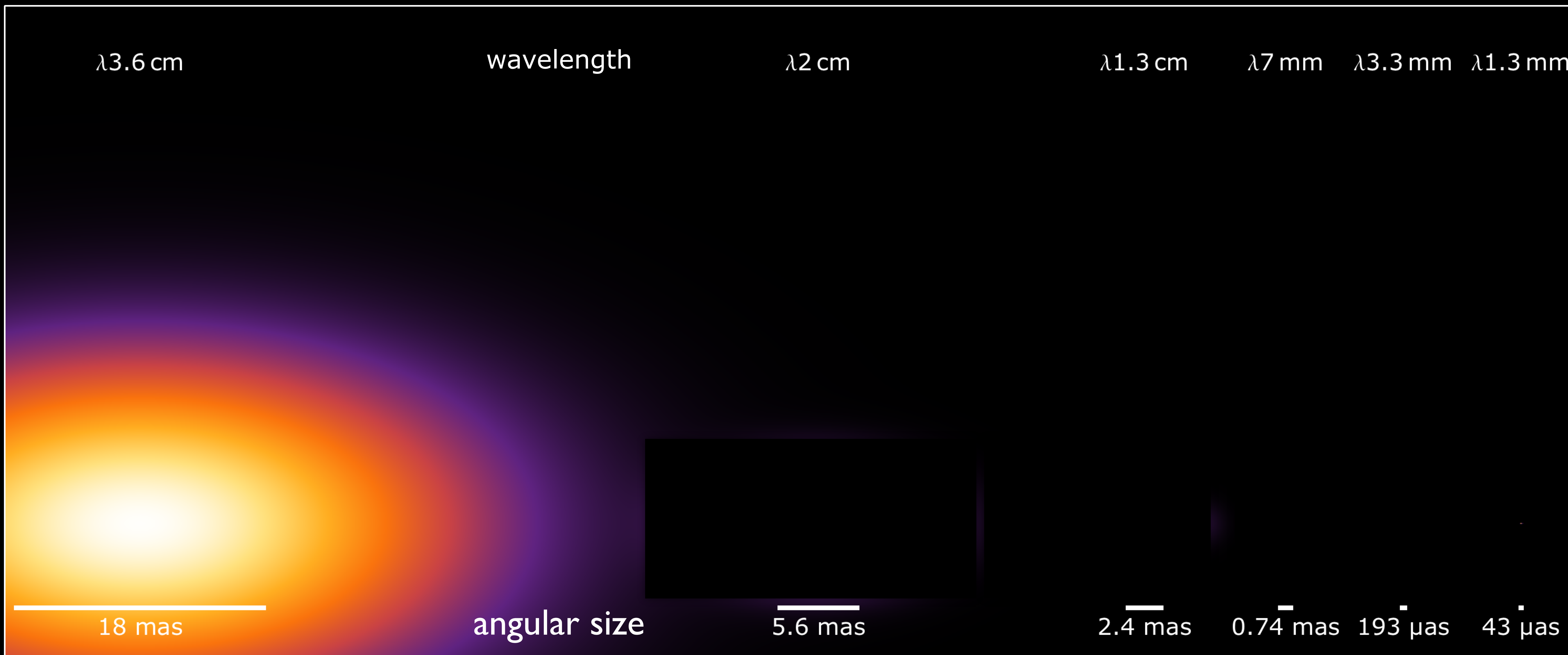


- The shorter the wavelength, the smaller the radio source.
- At λ=1.3 mm the radio source becomes the size of the event horizon.

mas = milli-arcsecond = 5×10^{-9} rad

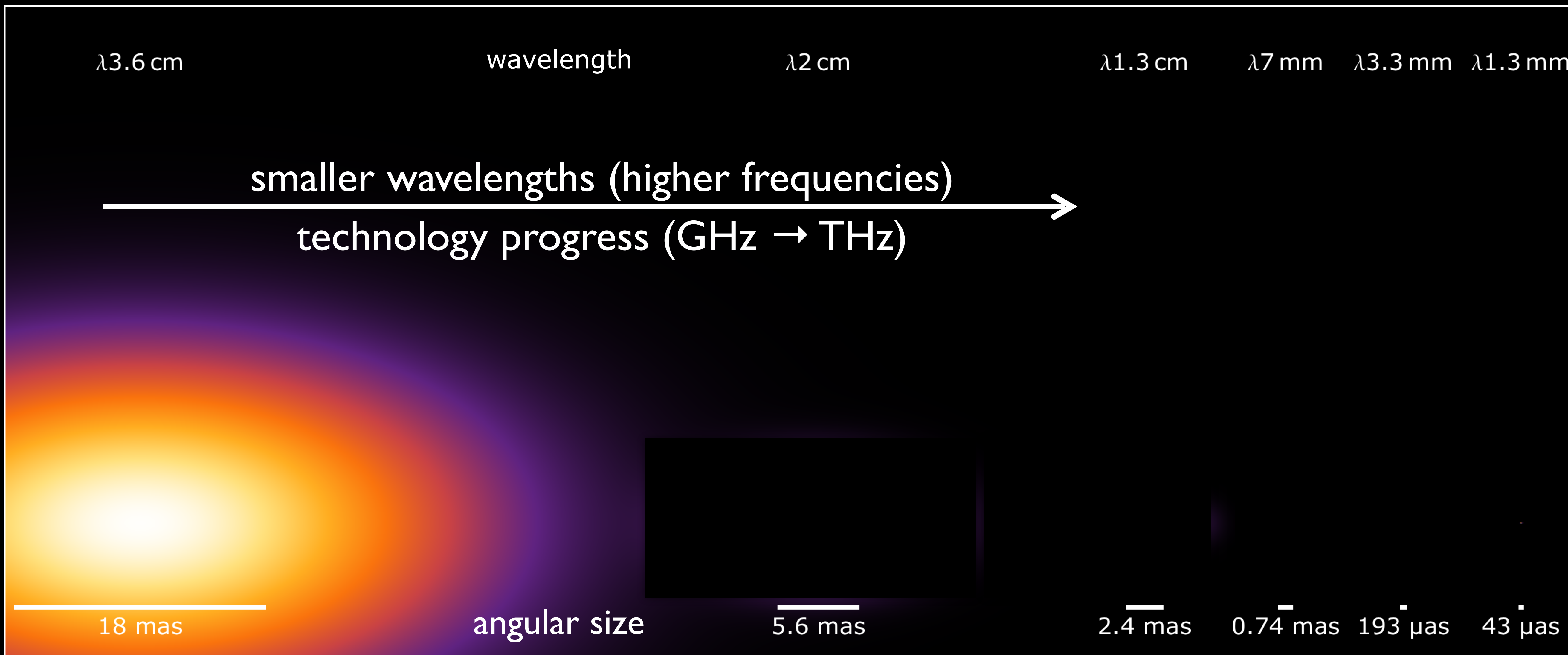
μas = micro-arcsecond = 5×10^{-12} rad

Images of the radio source



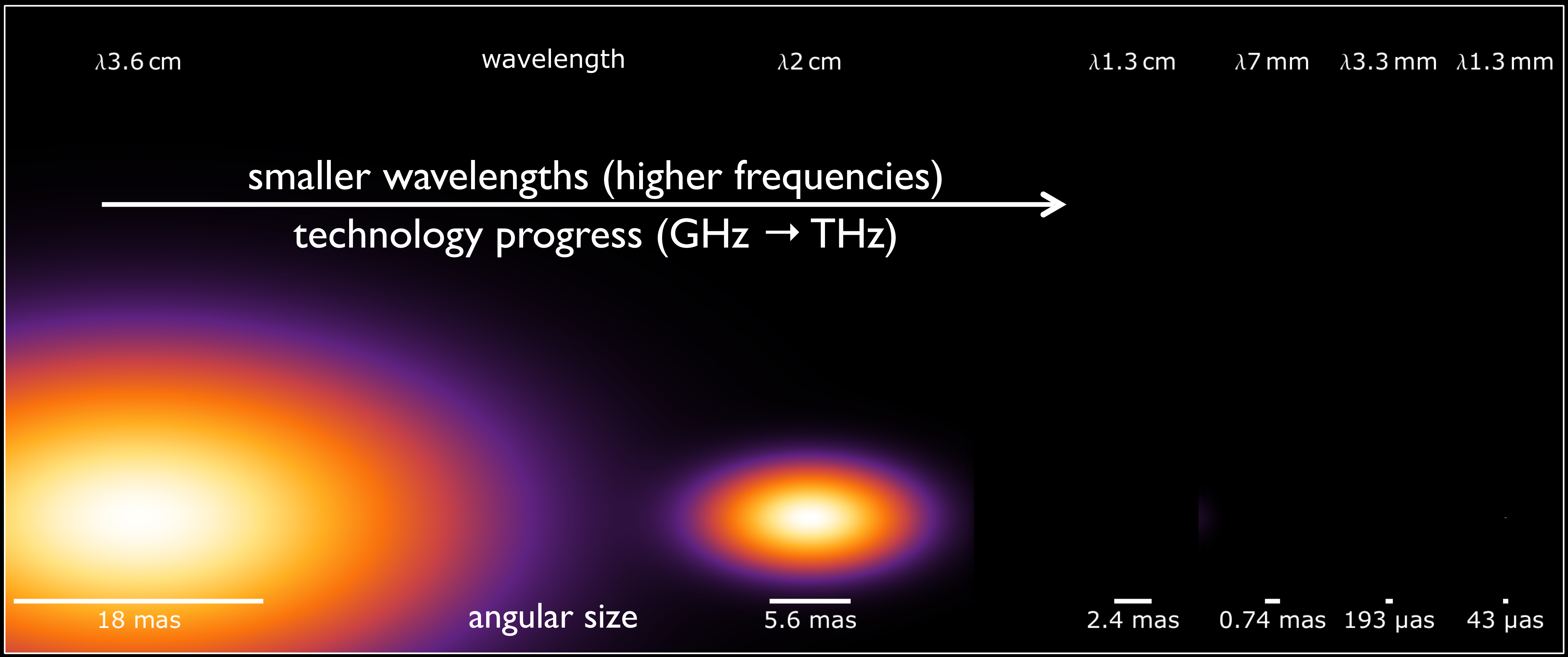
- The shorter the wavelength, the smaller the radio source.
- At λ=1.3 mm the radio source becomes the size of the event horizon.

Images of the radio source



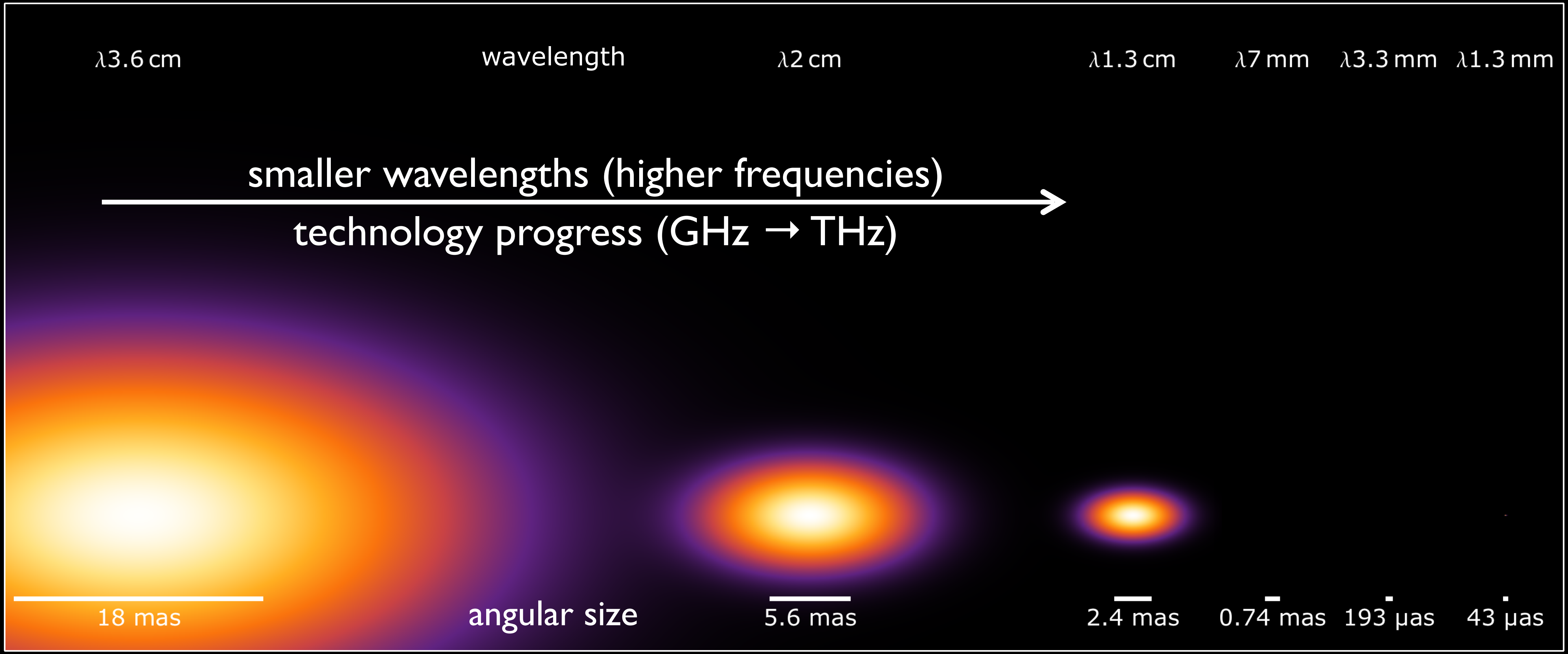
- The shorter the wavelength, the smaller the radio source.
- At λ=1.3 mm the radio source becomes the size of the event horizon.

Images of the radio source



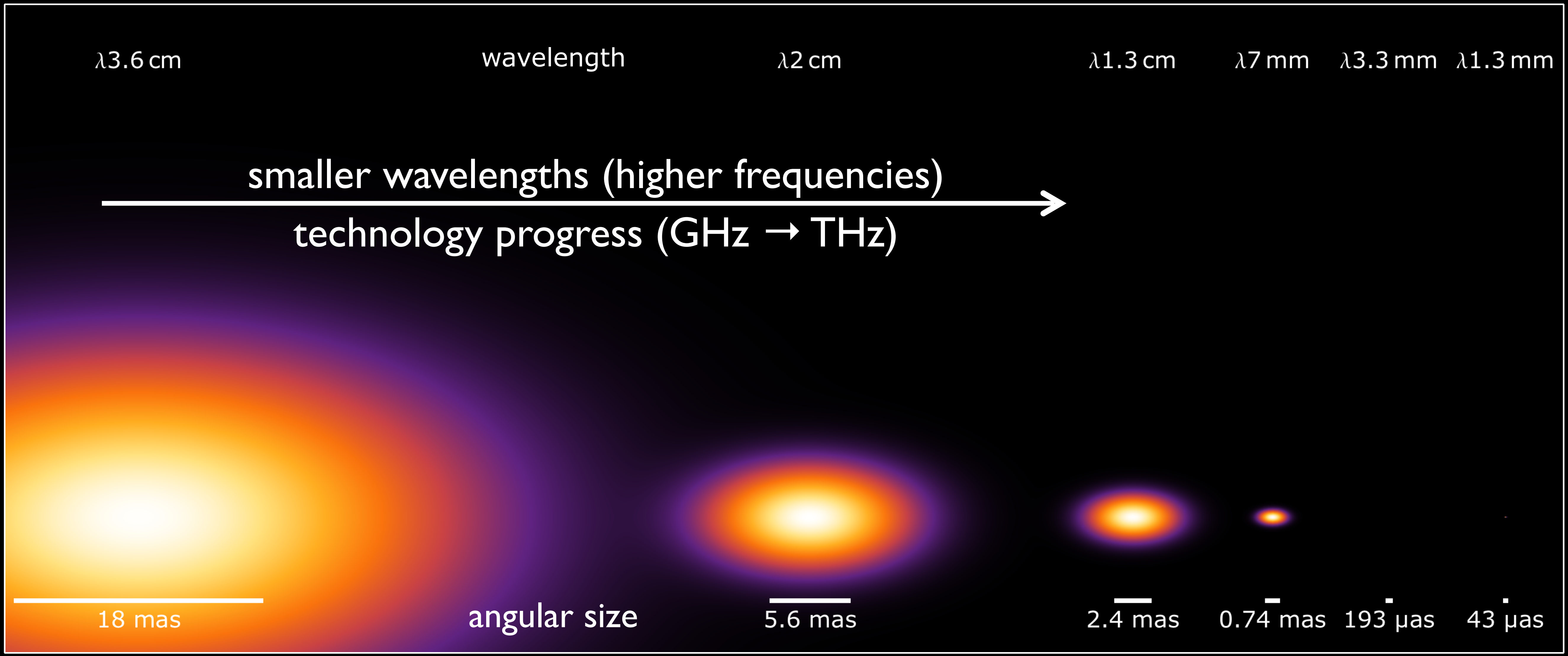
- The shorter the wavelength, the smaller the radio source.
- At λ=1.3 mm the radio source becomes the size of the event horizon.

Images of the radio source



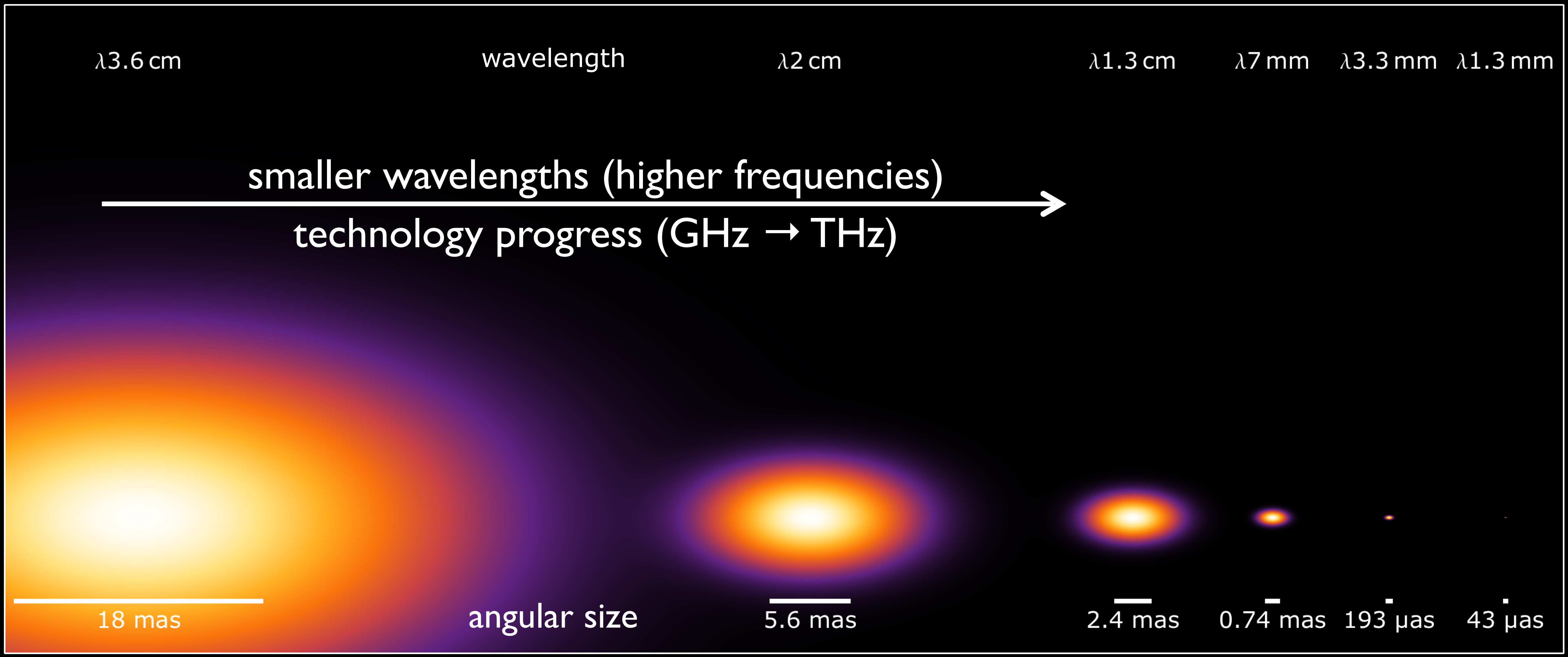
- The shorter the wavelength, the smaller the radio source.
- At λ=1.3 mm the radio source becomes the size of the event horizon.

Images of the radio source



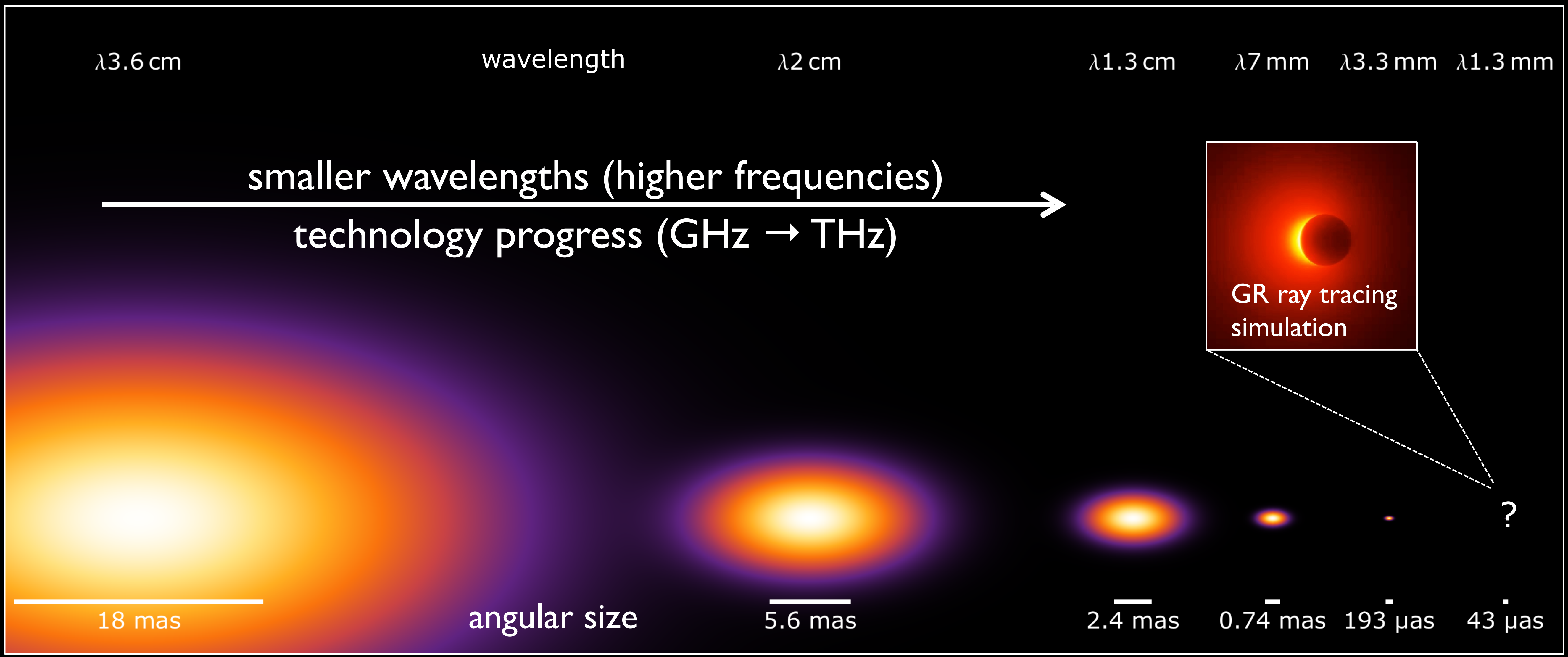
- The shorter the wavelength, the smaller the radio source.
- At λ=1.3 mm the radio source becomes the size of the event horizon.

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.

Images of the radio source



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

Very Long Baseline Interferometry (VLBI)

Very Long Baseline Interferometry (VLBI)

Very Long Baseline Interferometry (VLBI)

Create a virtual radio telescope the size of the Earth, using the shortest wavelength.

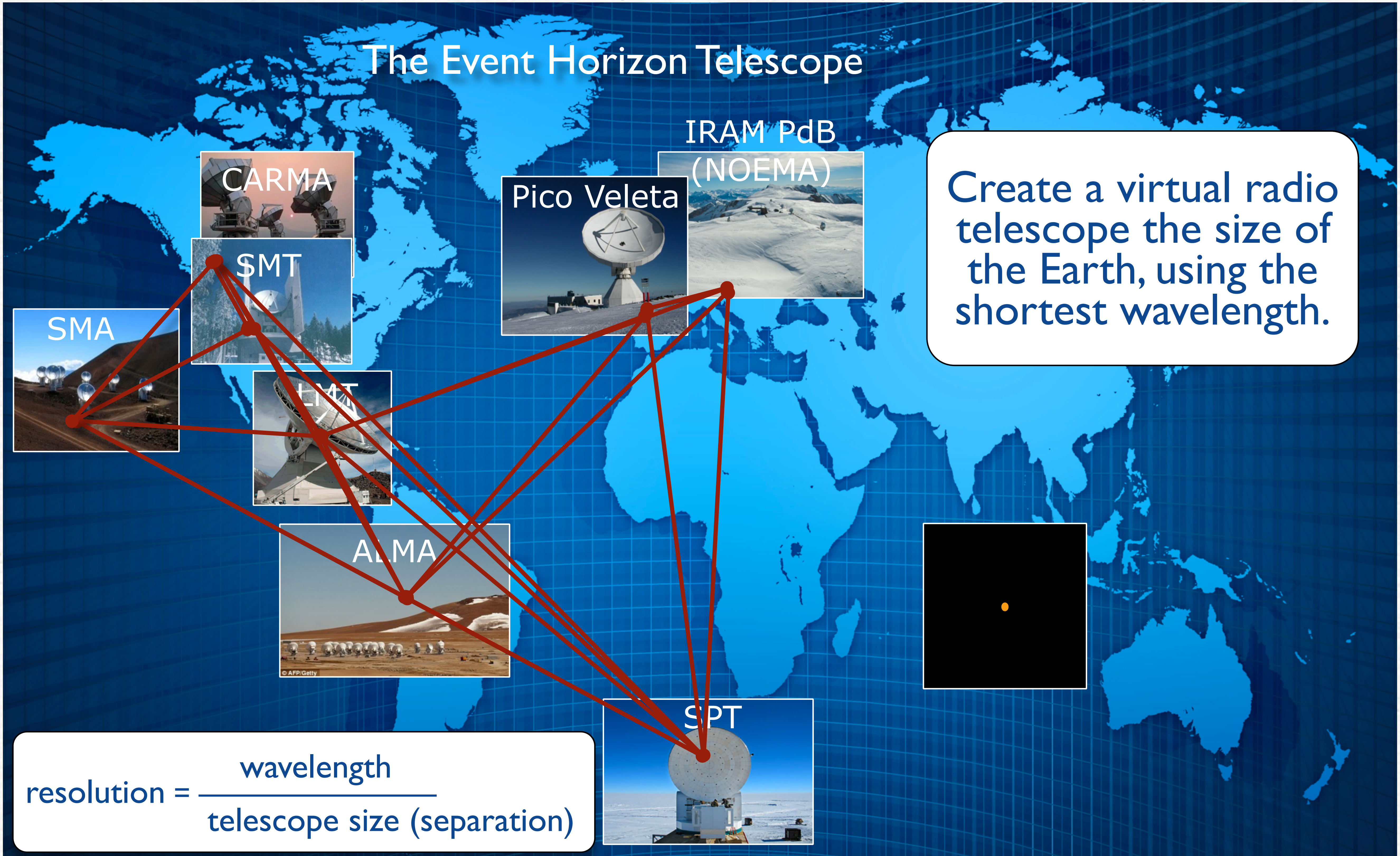
$$\text{resolution} = \frac{\text{wavelength}}{\text{telescope size (separation)}}$$

Very Long Baseline Interferometry (VLBI)

Create a virtual radio telescope the size of the Earth, using the shortest wavelength.

$$\text{resolution} = \frac{\text{wavelength}}{\text{telescope size (separation)}}$$

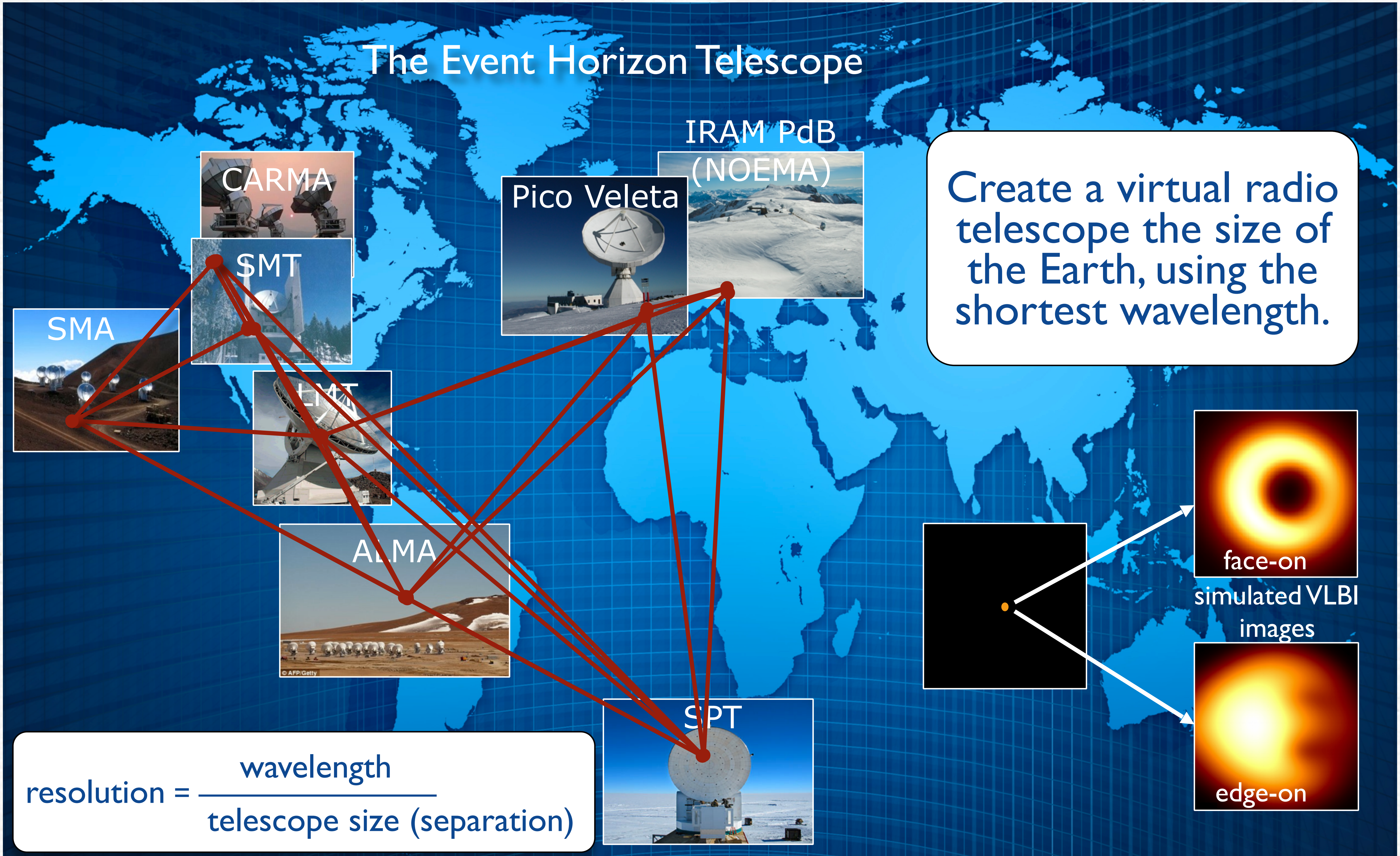
Very Long Baseline Interferometry (VLBI)



Create a virtual radio telescope the size of the Earth, using the shortest wavelength.

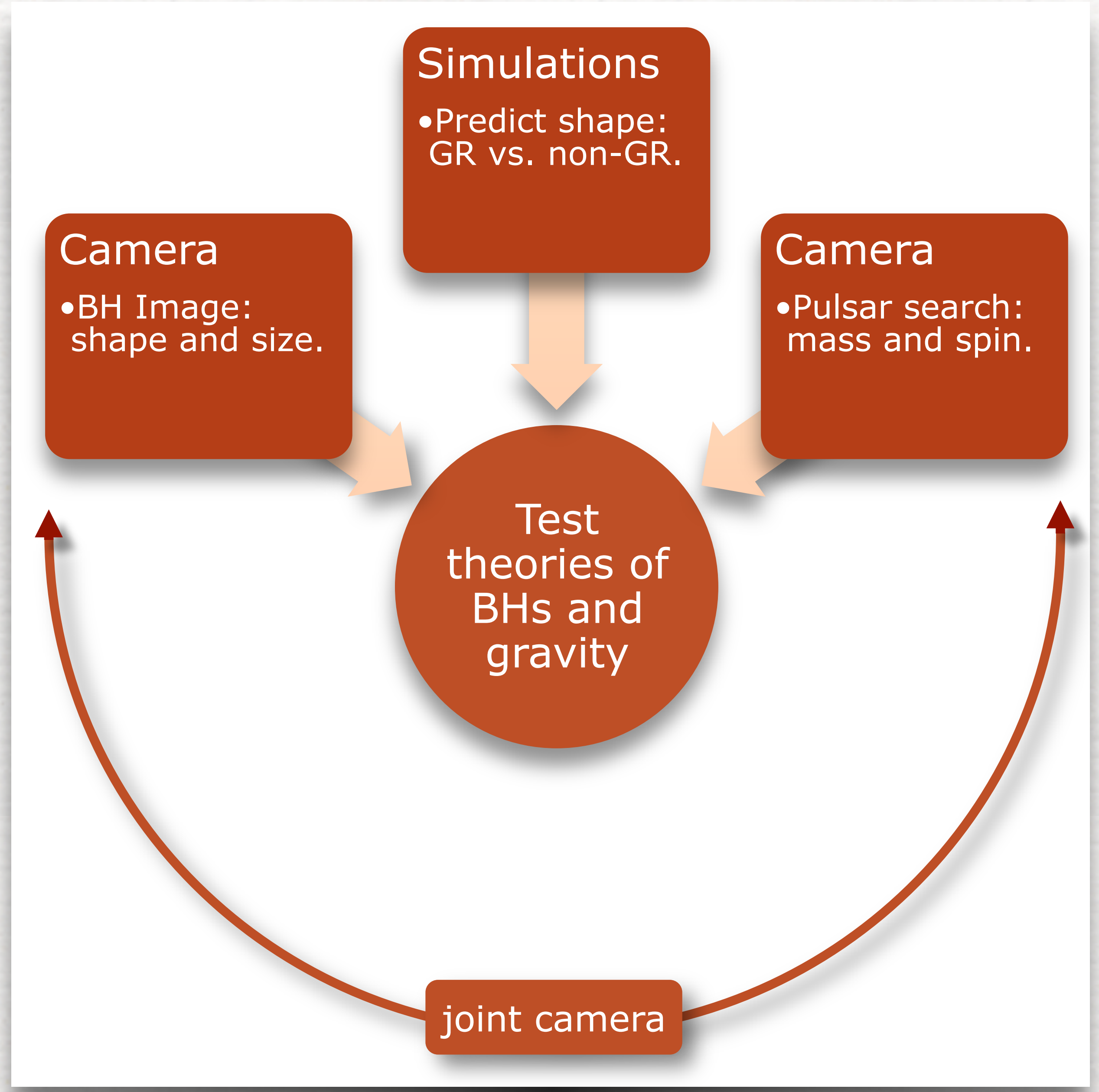
$$\text{resolution} = \frac{\text{wavelength}}{\text{telescope size (separation)}}$$

Very Long Baseline Interferometry (VLBI)



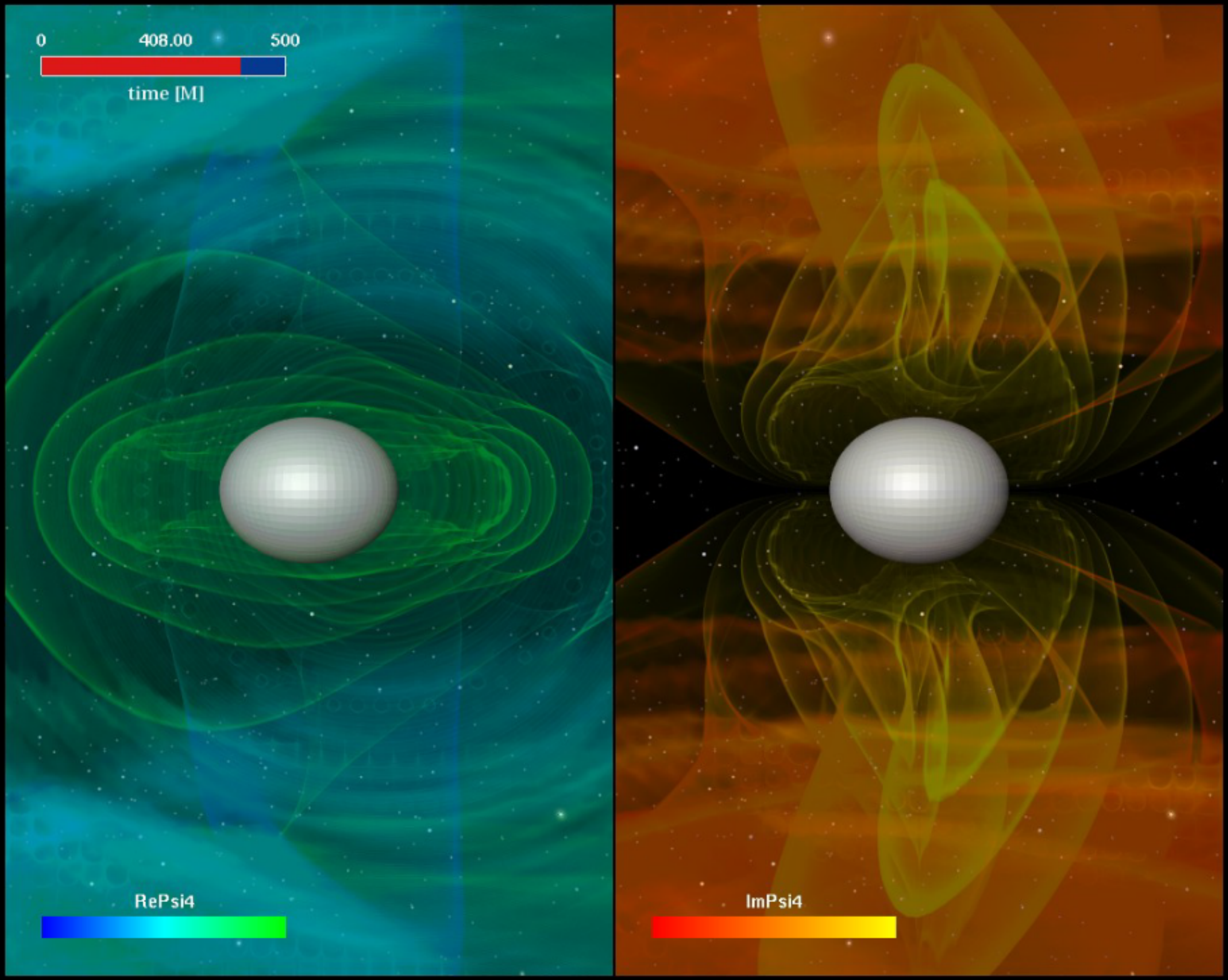
What do we want to do?

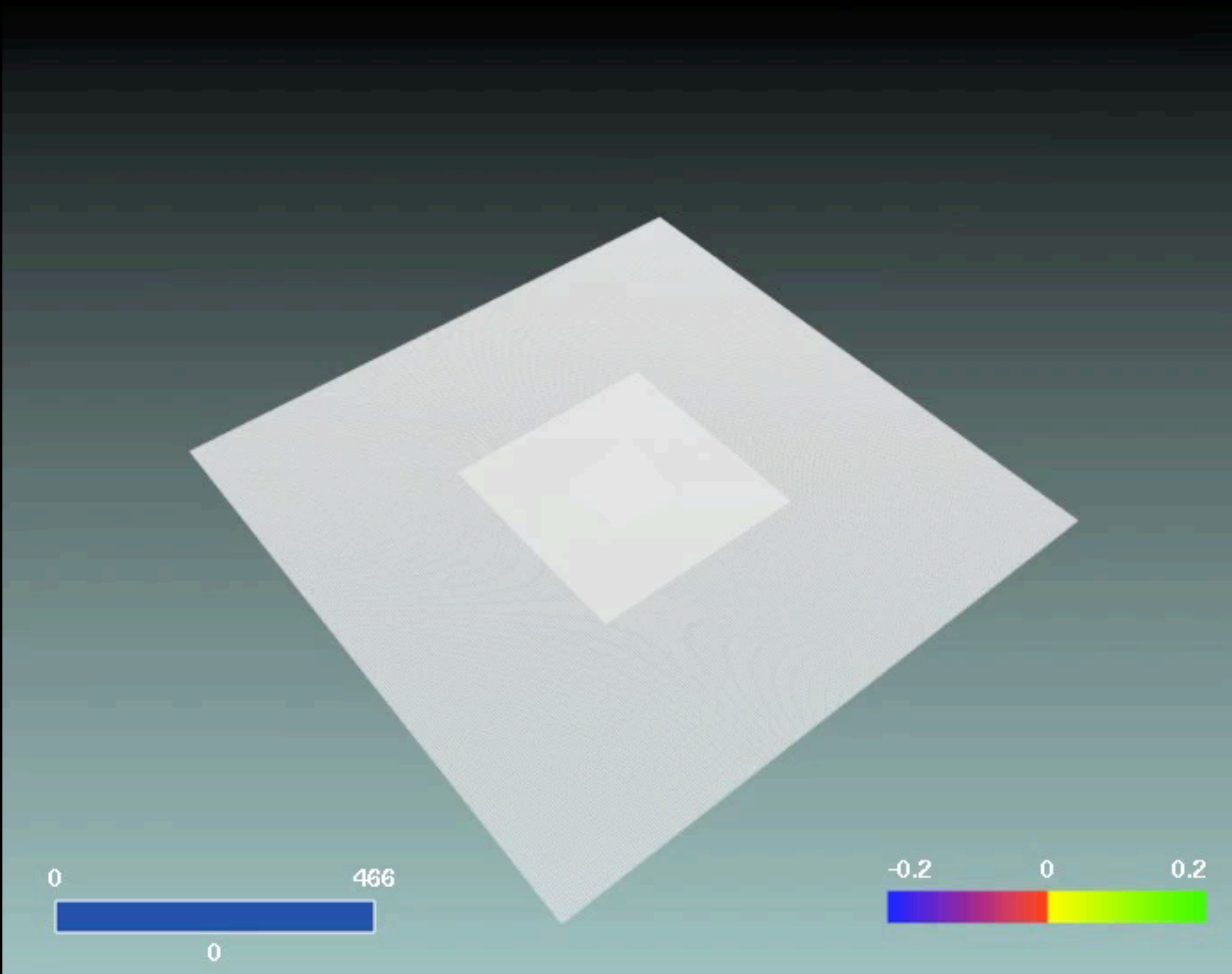
- **Build a joint black hole camera**
  - image event horizon to the best of present VLBI technology
- **Hunt for pulsars near Sag-A***
  - detection of pulsars will provide unprecedented accuracy
- **Make theoretical predictions/ interpretations**
  - use numerical simulations to produce synthetic images
  - interpret observations to constrain theories of gravity



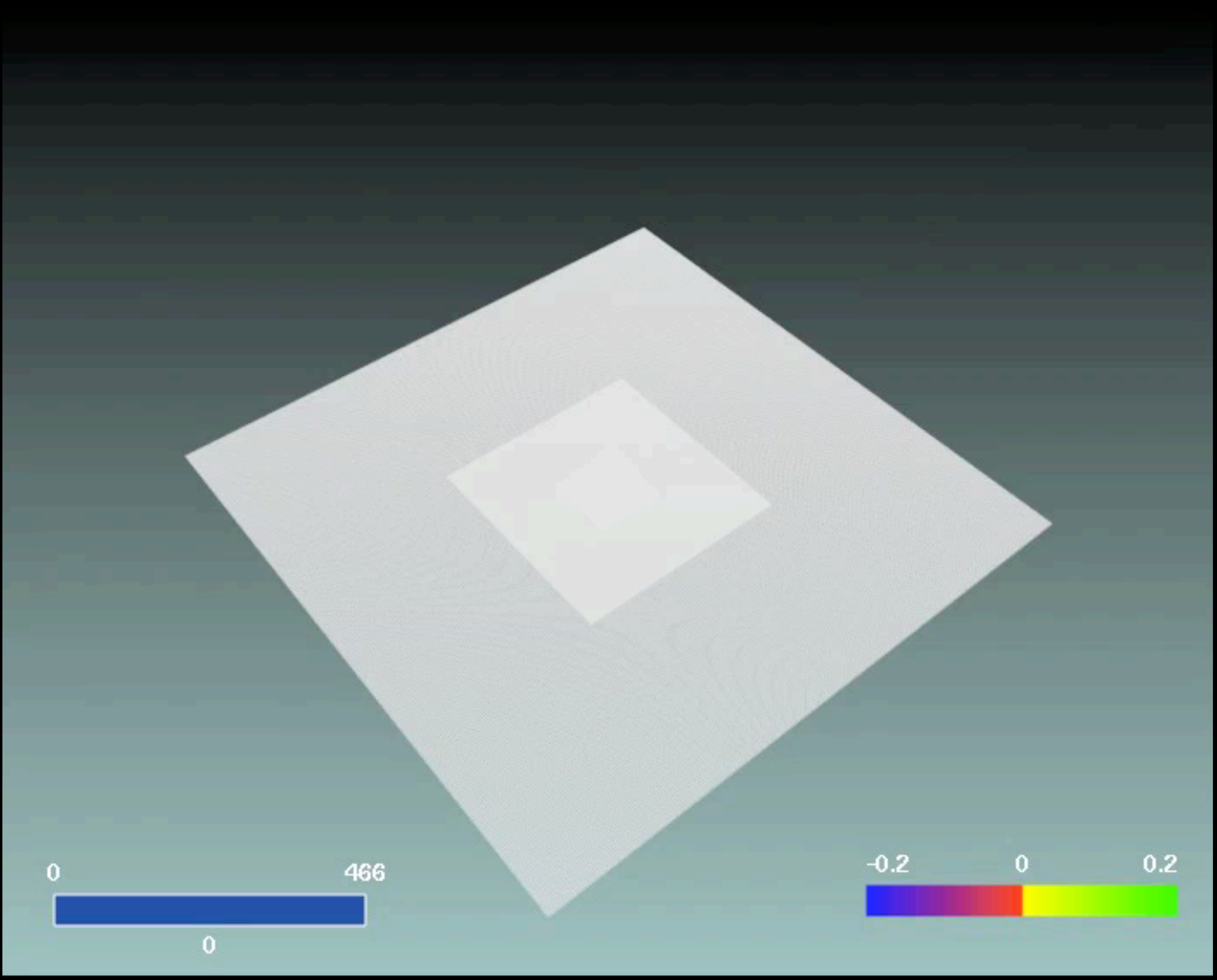
Not easy, but another milestone of modern physics

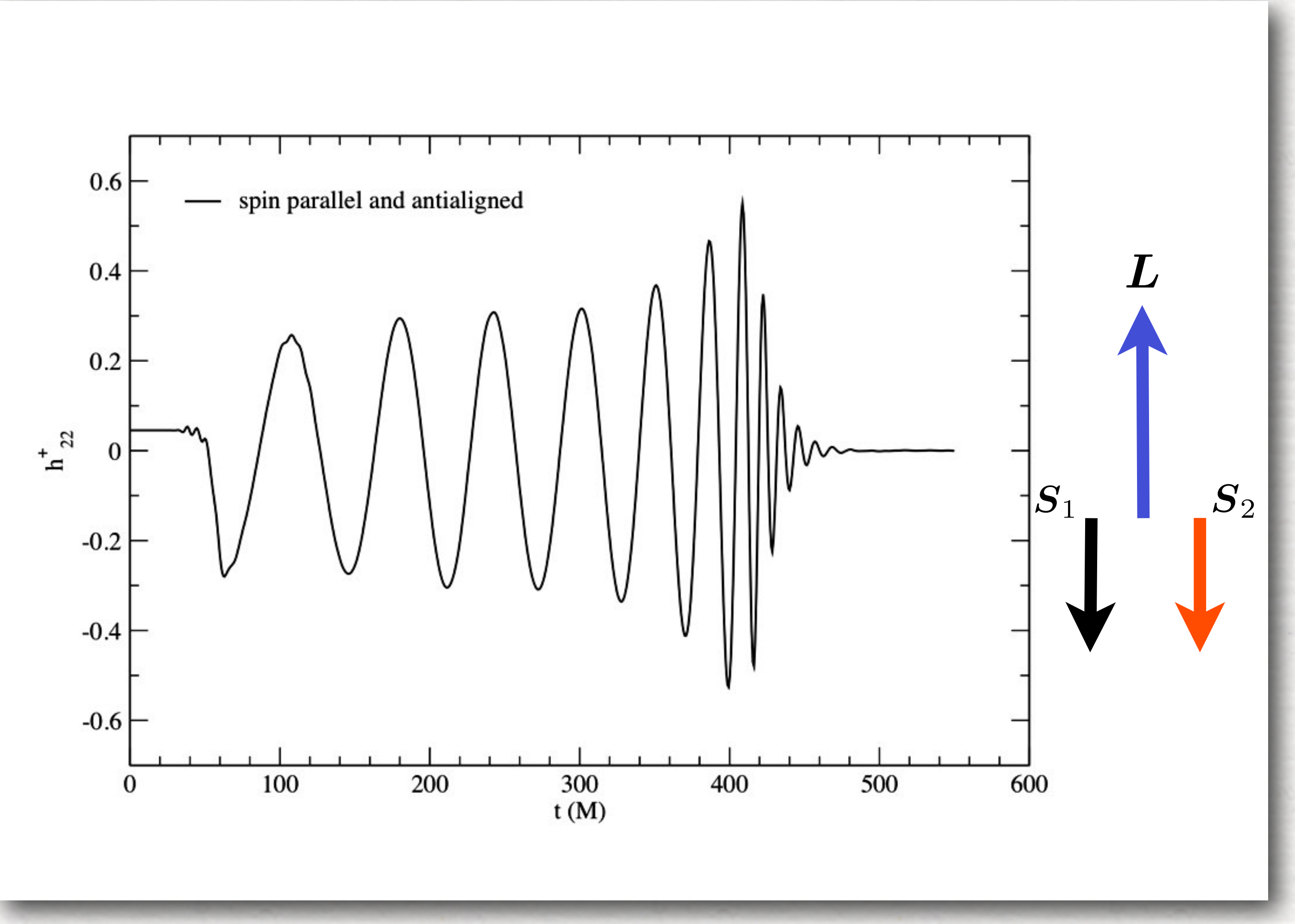
black-hole binaries



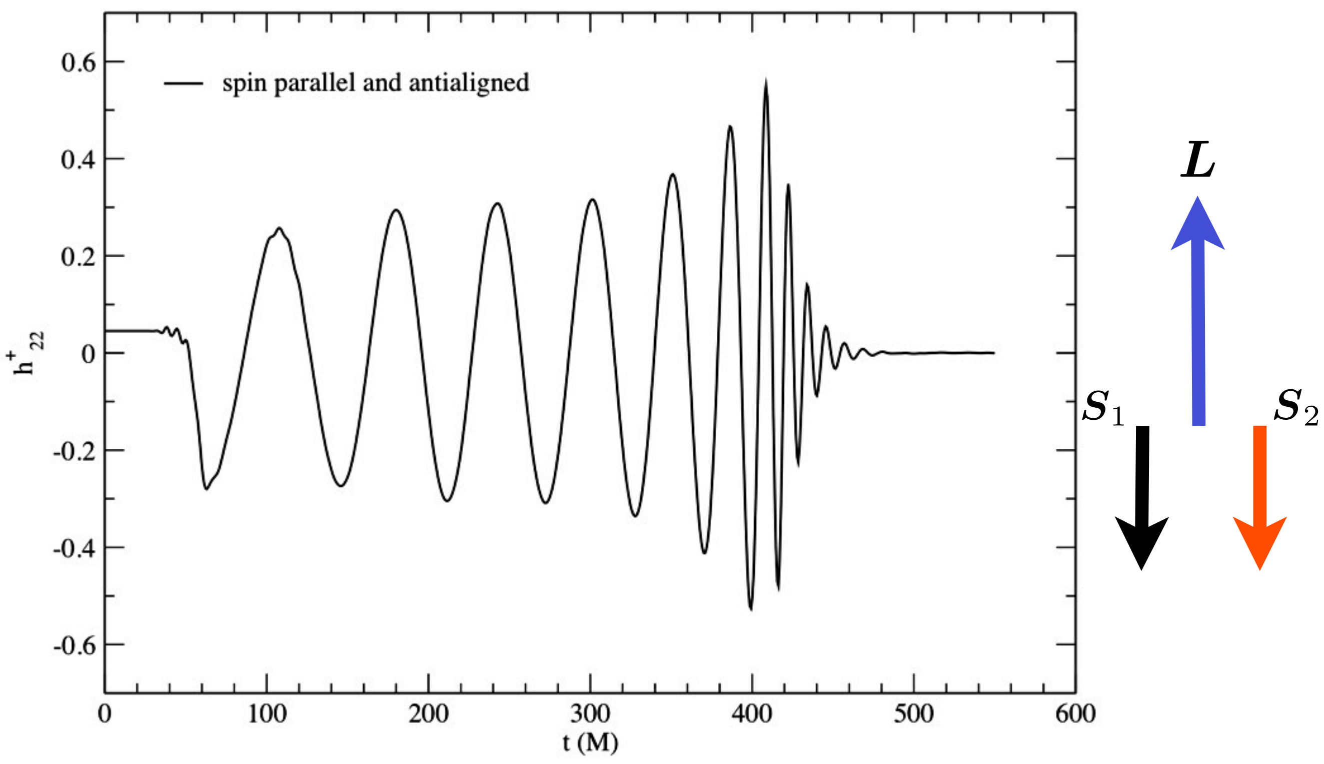


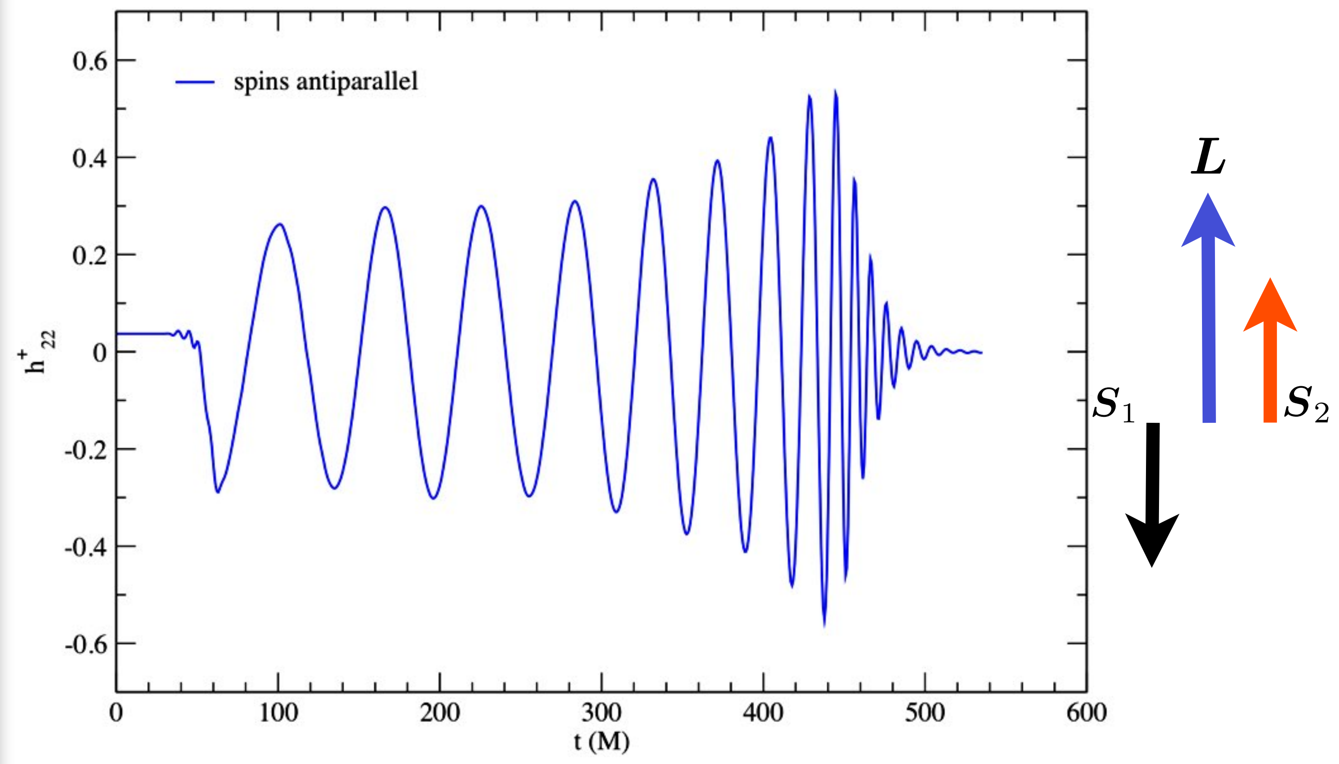
Animation by Kaehler, Reisswig, LR

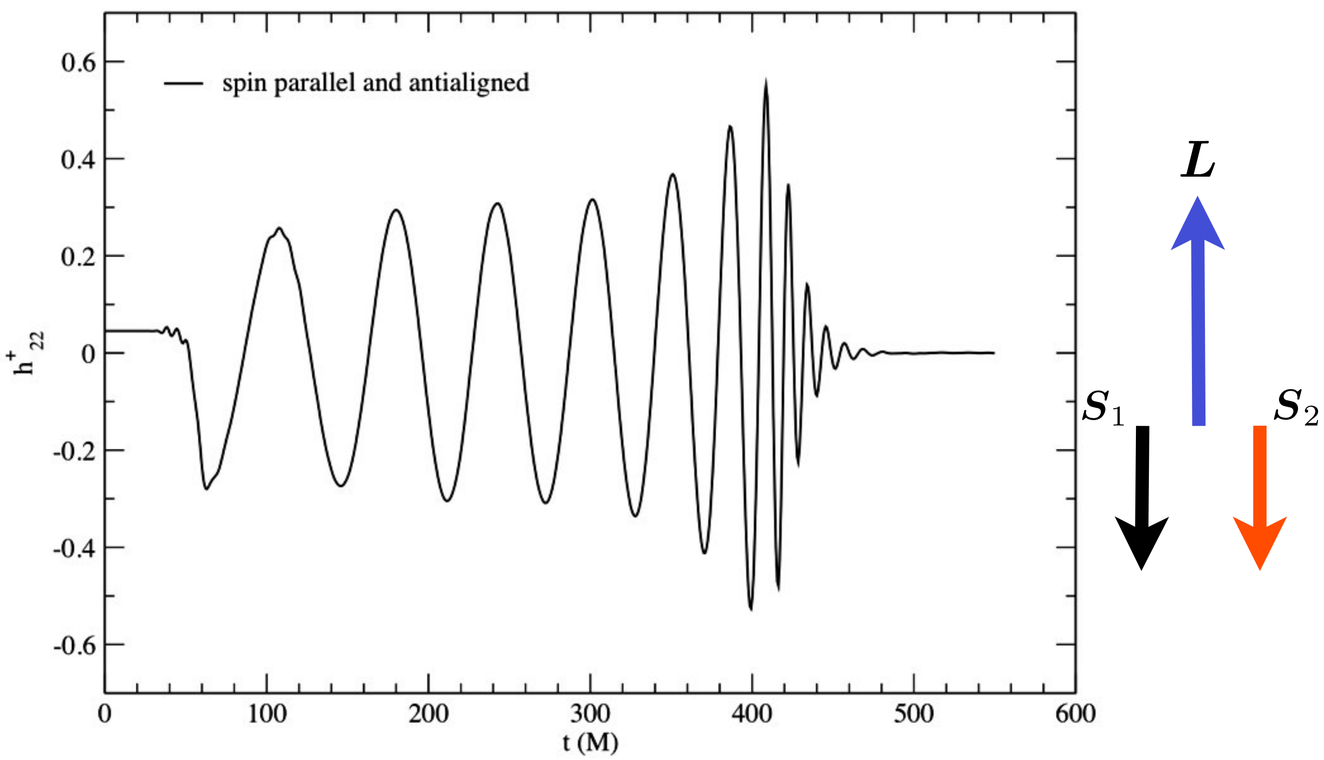

0
466
0
-0.2
0
0.2

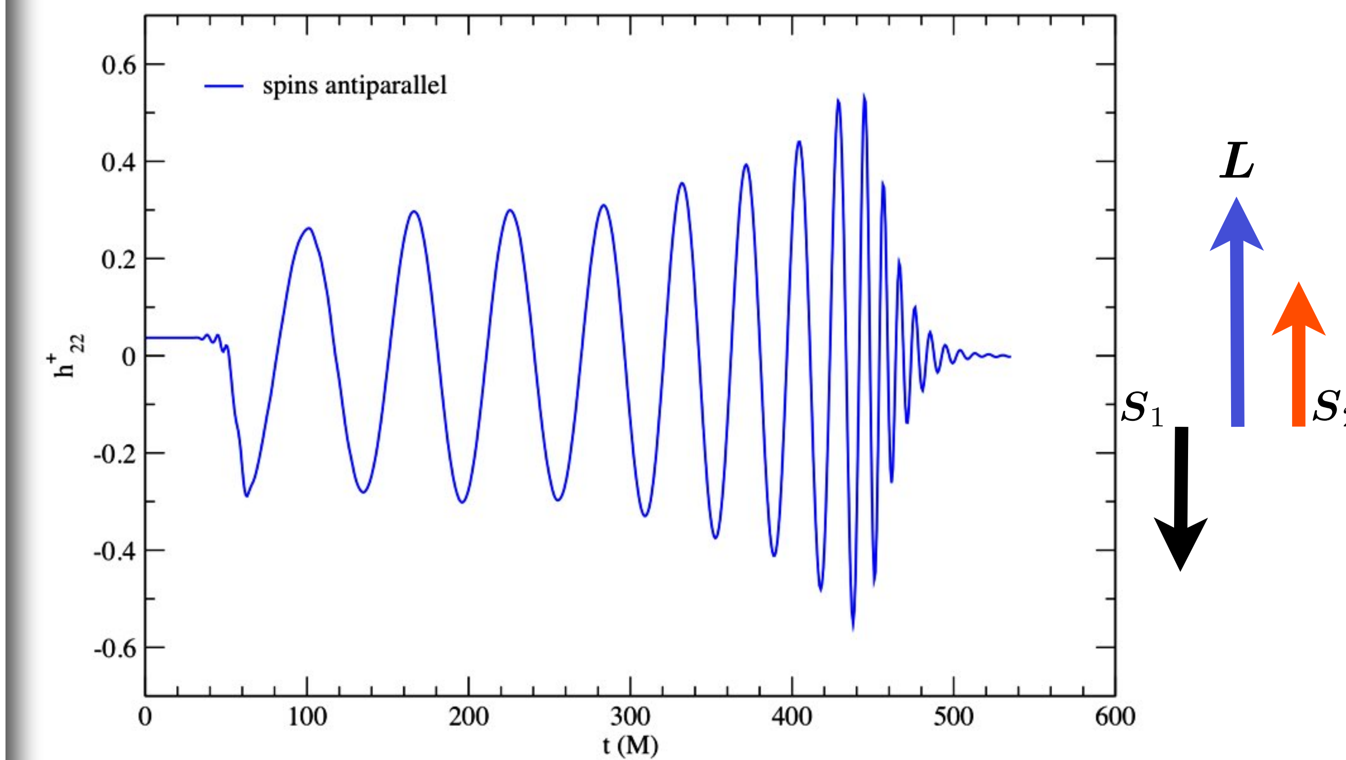


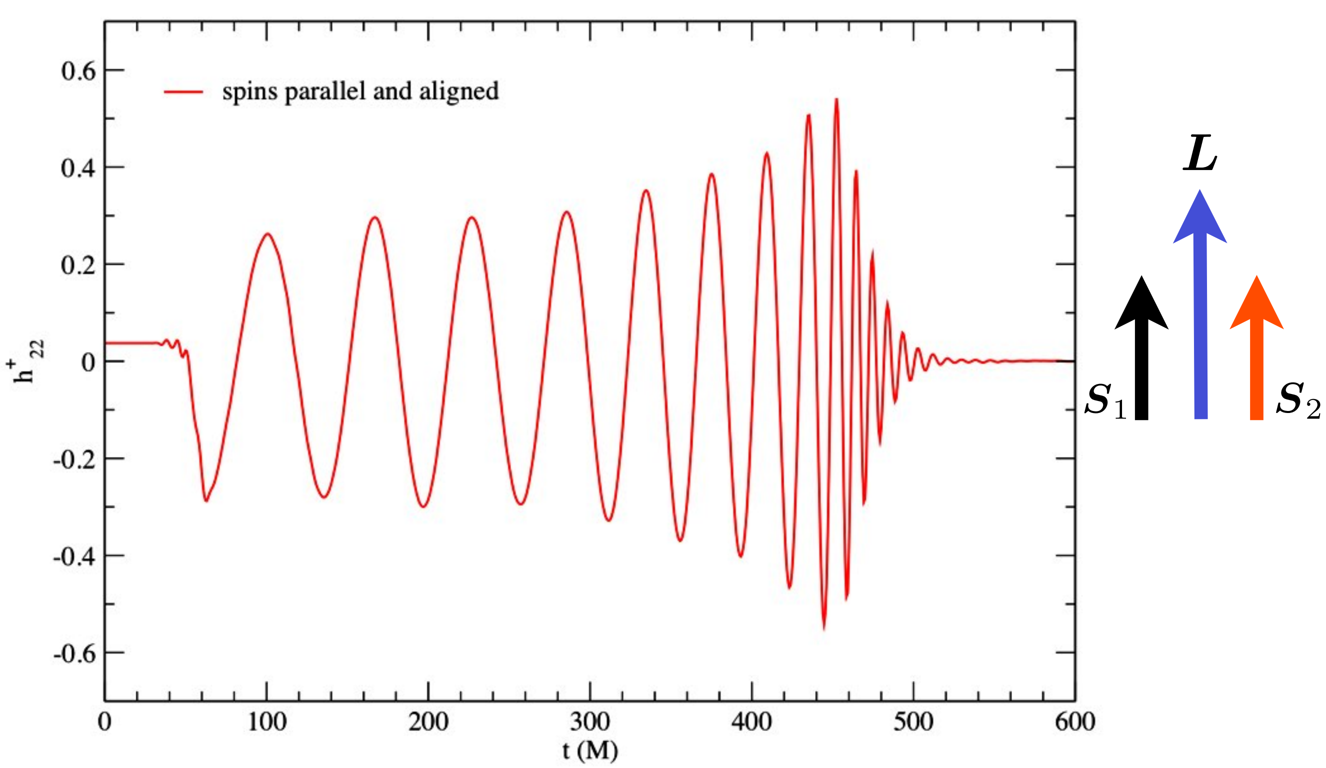
spin parallel and antialigned
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
100
200
300
400
500
600
t (M)
h^{+}_{22}
$\boldsymbol{L}$
$\boldsymbol{S}_1$
$\boldsymbol{S}_2$

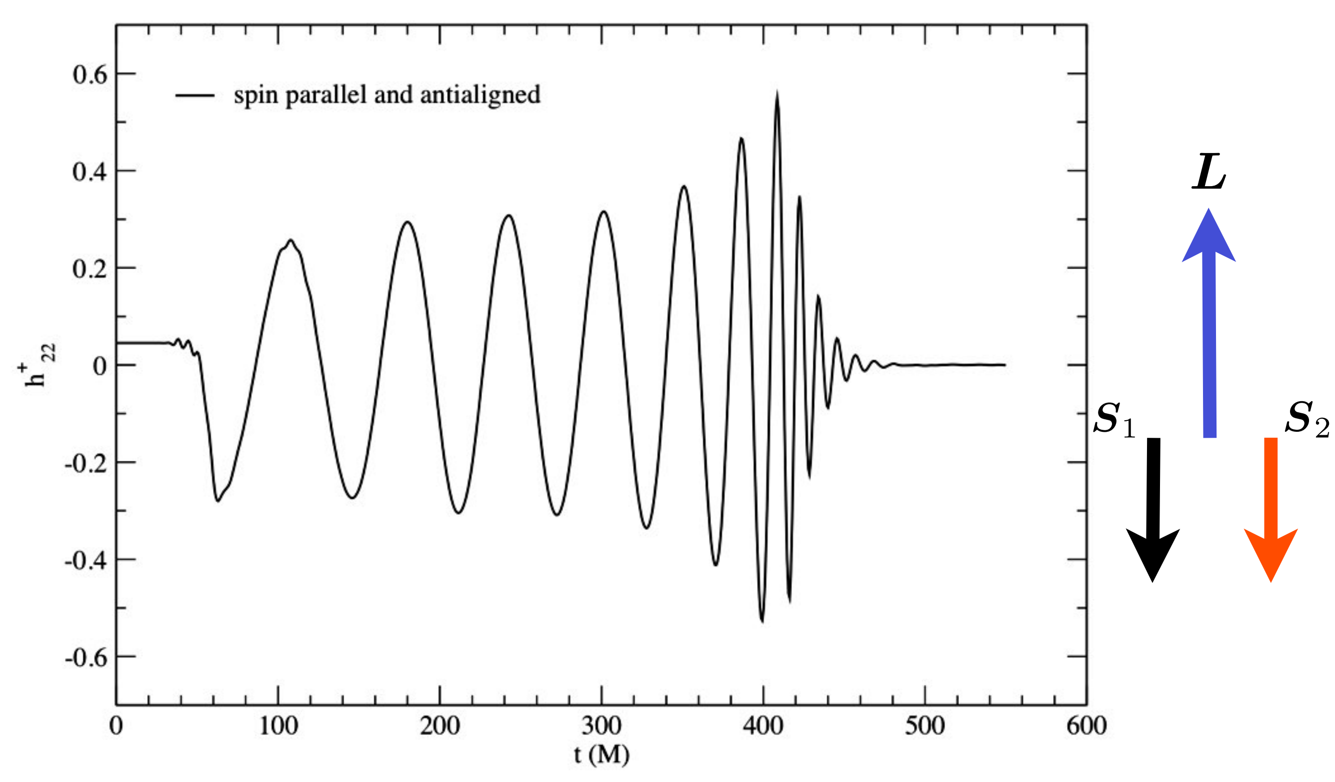

spin parallel and antialigned
h^+_{22}
t (M)
L
S_1
S_2

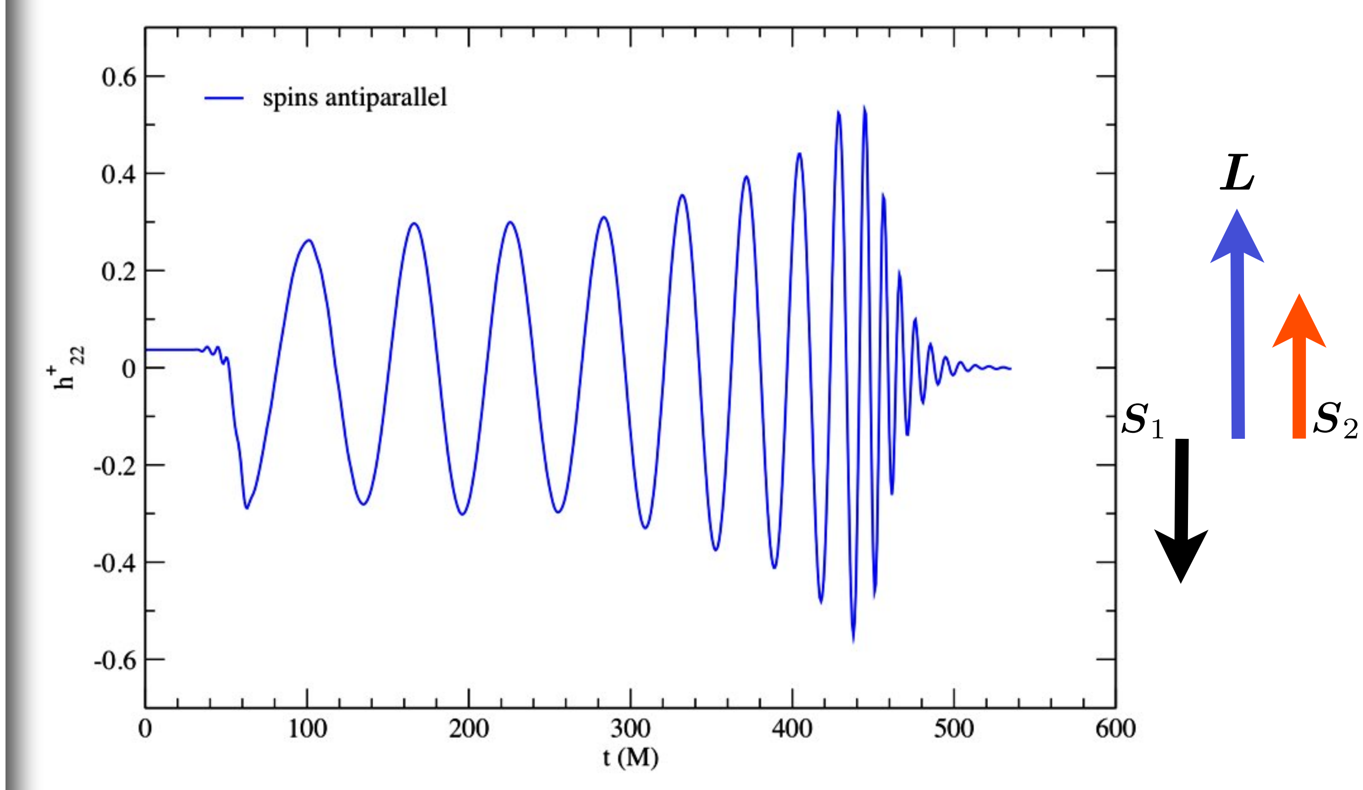

spins antiparallel
h^+_{22}
t (M)
L
S_1
S_2

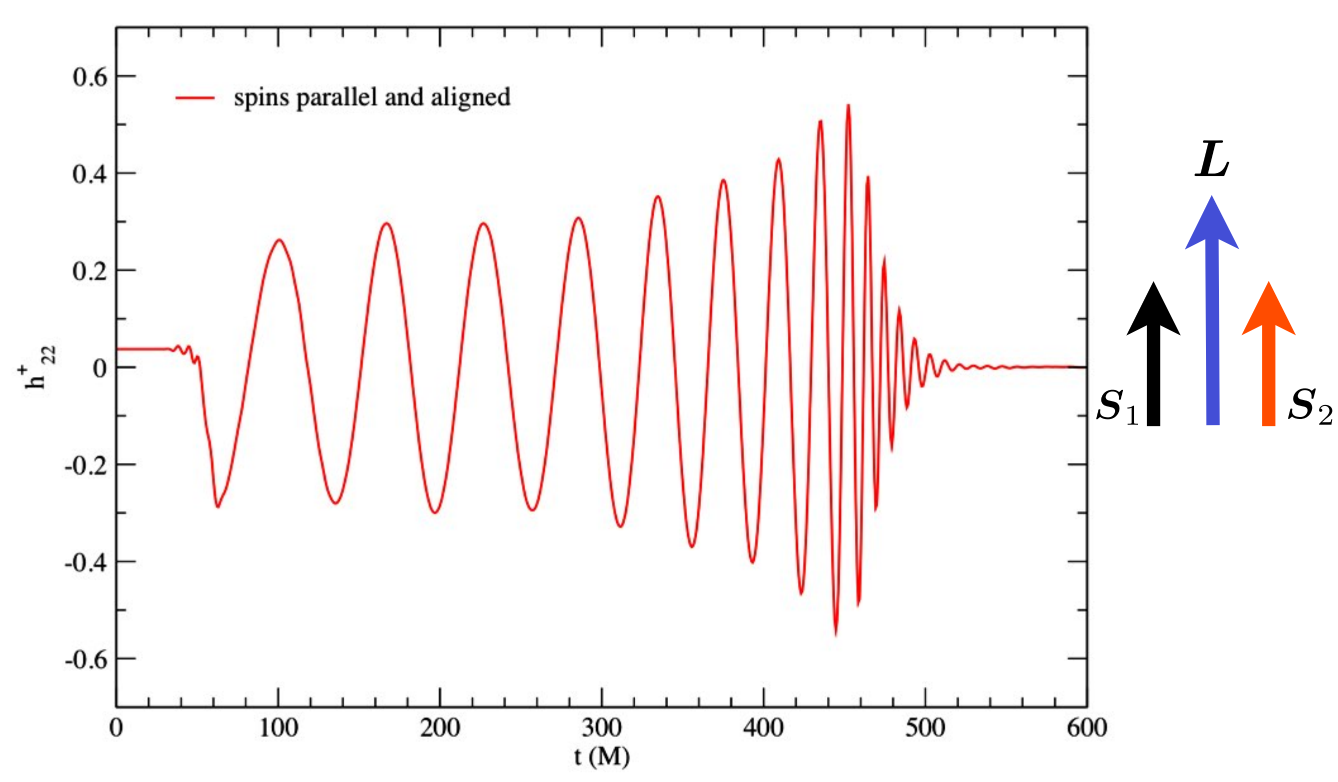

spin parallel and antialigned
h^{+}_{22}
t (M)
L
S_1
S_2


spins antiparallel
h^{+}_{22}
t (M)
L
S_1
S_2


spins parallel and aligned
h^{+}_{22}
t (M)
L
S_1
S_2

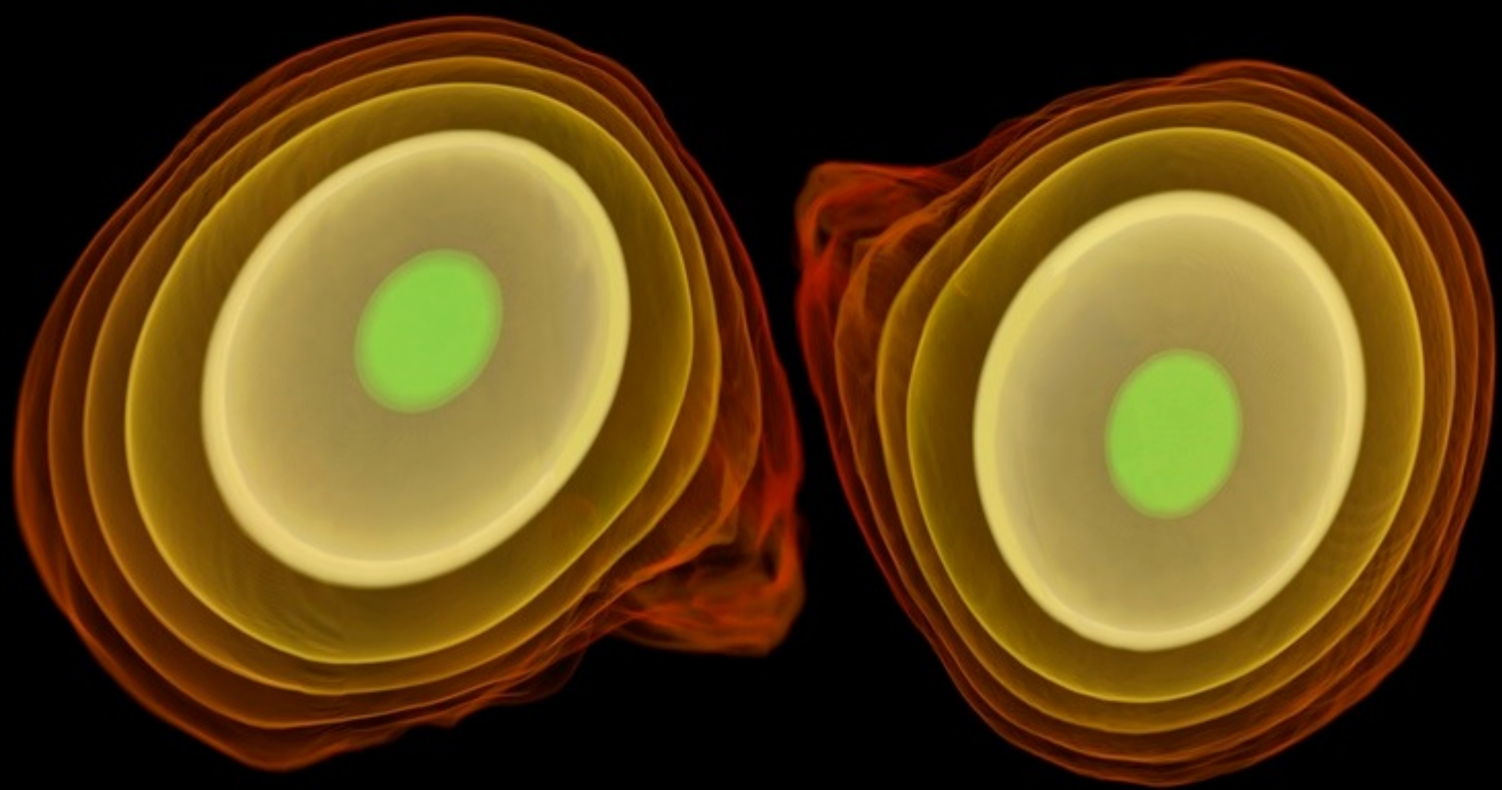






This is the signal that needs to be measured by modern gravitational detectors.

merging neutron-star binaries



The two-body problem in GR

- The merger of BHs is easy to imagine:

BH + BH ⟶ BH + gravitational waves (GWs)

The two-body problem in GR

- The merger of BHs is easy to imagine:

BH + BH ⟶ BH + gravitational waves (GWs)

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

NS + NS ⟶ HMNS + **... ?** ⟶ BH + torus + **... ?** ⟶ BH

The two-body problem in GR

- The merger of BHs is easy to imagine:

BH + BH ⟶ BH + gravitational waves (GWs)

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

NS + NS ⟶ HMNS + **... ?** ⟶ BH + torus + **... ?** ⟶ BH

All complications are in the intermediate stages:

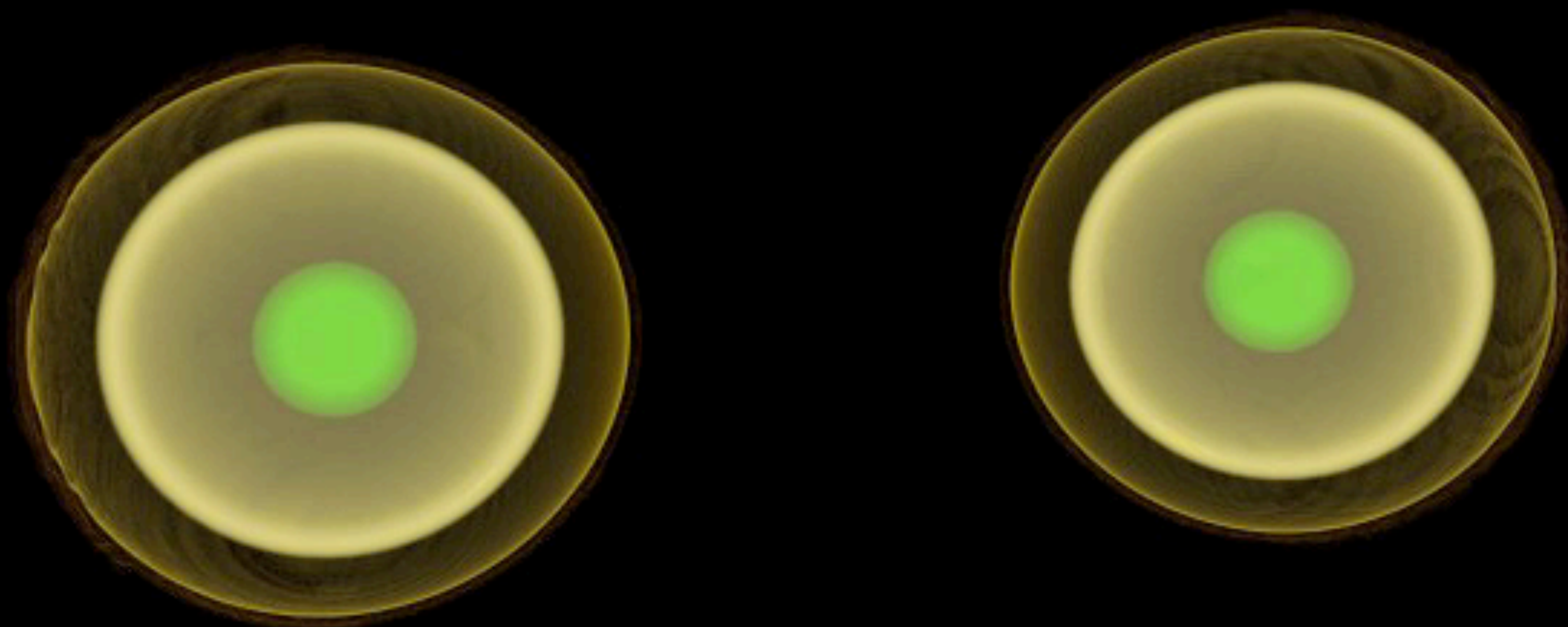
- studying the HMNS we can learn how neutron stars are made, i.e. the equation of state (EOS) of nuclear matter.

- studying the BH+torus we can possibly understand catastrophic events such as short gamma-ray bursts.

Animations: Kaehler, Giacomazzo, Rezzolla

T[ms] = 0.00

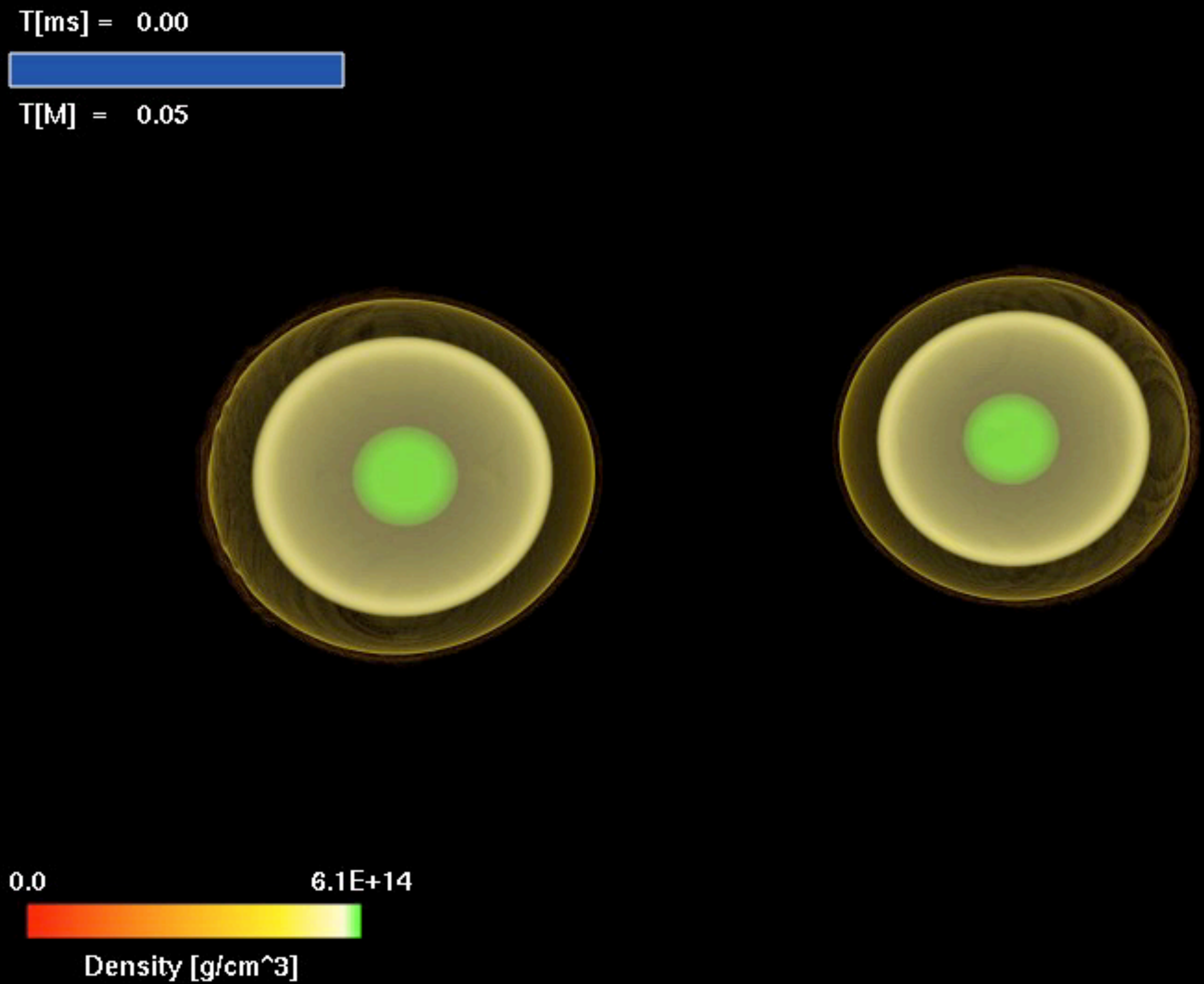
T[M] = 0.05



0.0 6.1E+14

Density [g/cm^3]

$$M = 1.6\,M_{\odot}$$


T[ms] = 0.00
T[M] = 0.05
0.0
6.1E+14
Density [g/cm^3]

"merger → HMNS → BH + torus"

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 (ie hotter after merger) will have more pressure support and collapse later

"merger → HMNS → BH + torus"

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:**

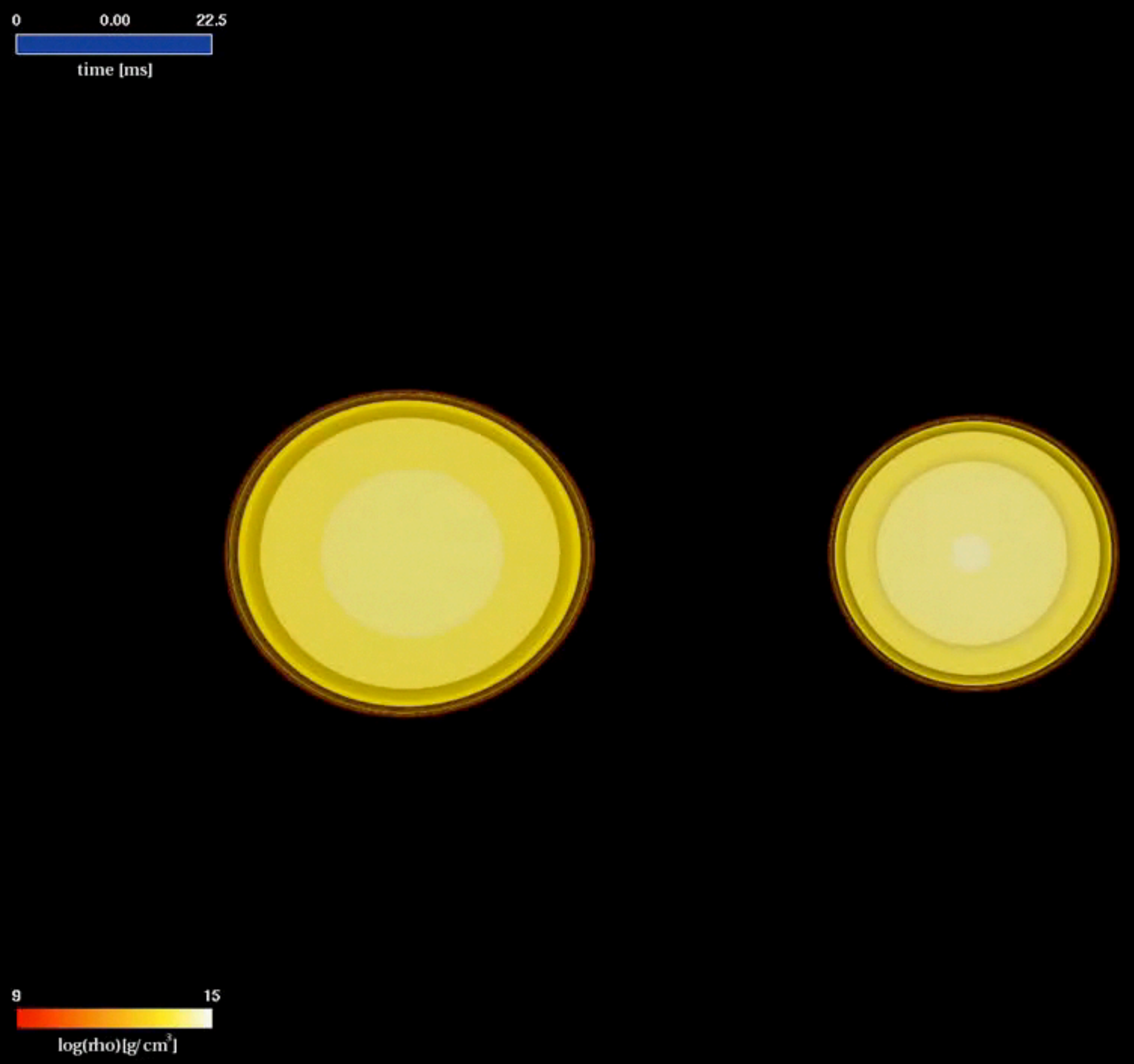
  a binary with an EOS with large thermal capacity (ie hotter after merger) will have more pressure support and collapse later

- **differences induced by MASS ASYMMETRIES:**

  tidal disruption before merger; may lead to prompt BH

Animations: Giacomazzo, Koppitz, LR

Total mass : $3.37\, M_{\odot}$; mass ratio :0.80;


0
0.00
22.5
time [ms]
9
15
log(rho)[g/cm3]

"merger → HMNS → BH + torus"

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 (ie hotter after merger) will have more pressure support and collapse later

- **differences induced by MASS ASYMMETRIES:**

  tidal disruption before merger; may lead to prompt BH

"merger → HMNS → BH + torus"

Quantitative differences are produced by:

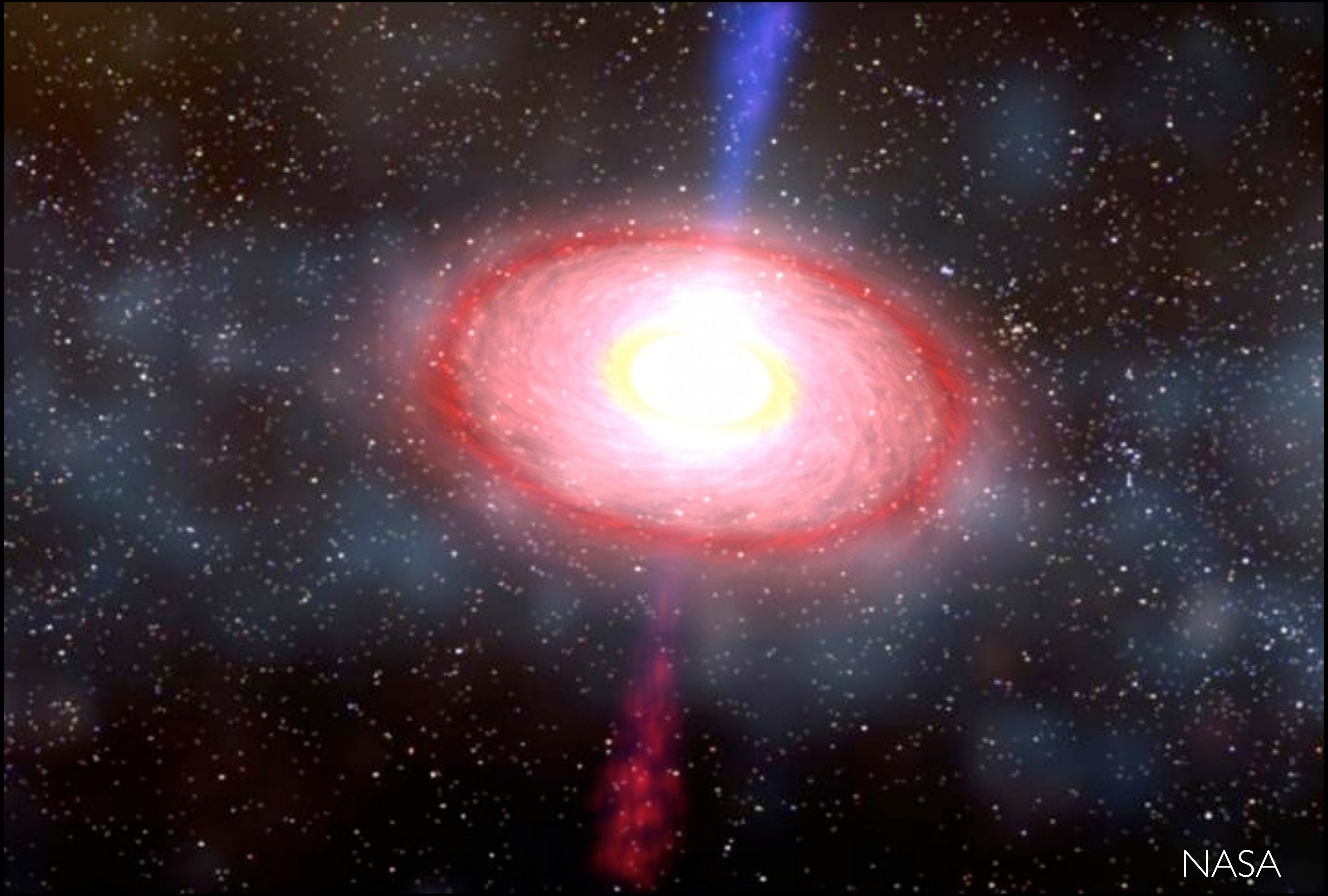
- **differences induced by the gravitational MASS:**
  a binary with smaller mass will produce a HMNS further away from the stability threshold and will collapse at a later time
- **differences induced by the EOS:**
  a binary with an EOS with large thermal capacity (ie hotter after merger) will have more pressure support and collapse later
- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH
- **differences induced by MAGNETIC FIELDS:**
  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse

“merger → HMNS → BH + torus”

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 (ie hotter after merger) will have more pressure support and collapse later
- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH
- **differences induced by MAGNETIC FIELDS:**
  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse
- **differences induced by RADIATIVE PROCESSES:**
  radiative losses will alter the equilibrium of the HMNS

Short Gamma-ray Burst



The most energetic explosions

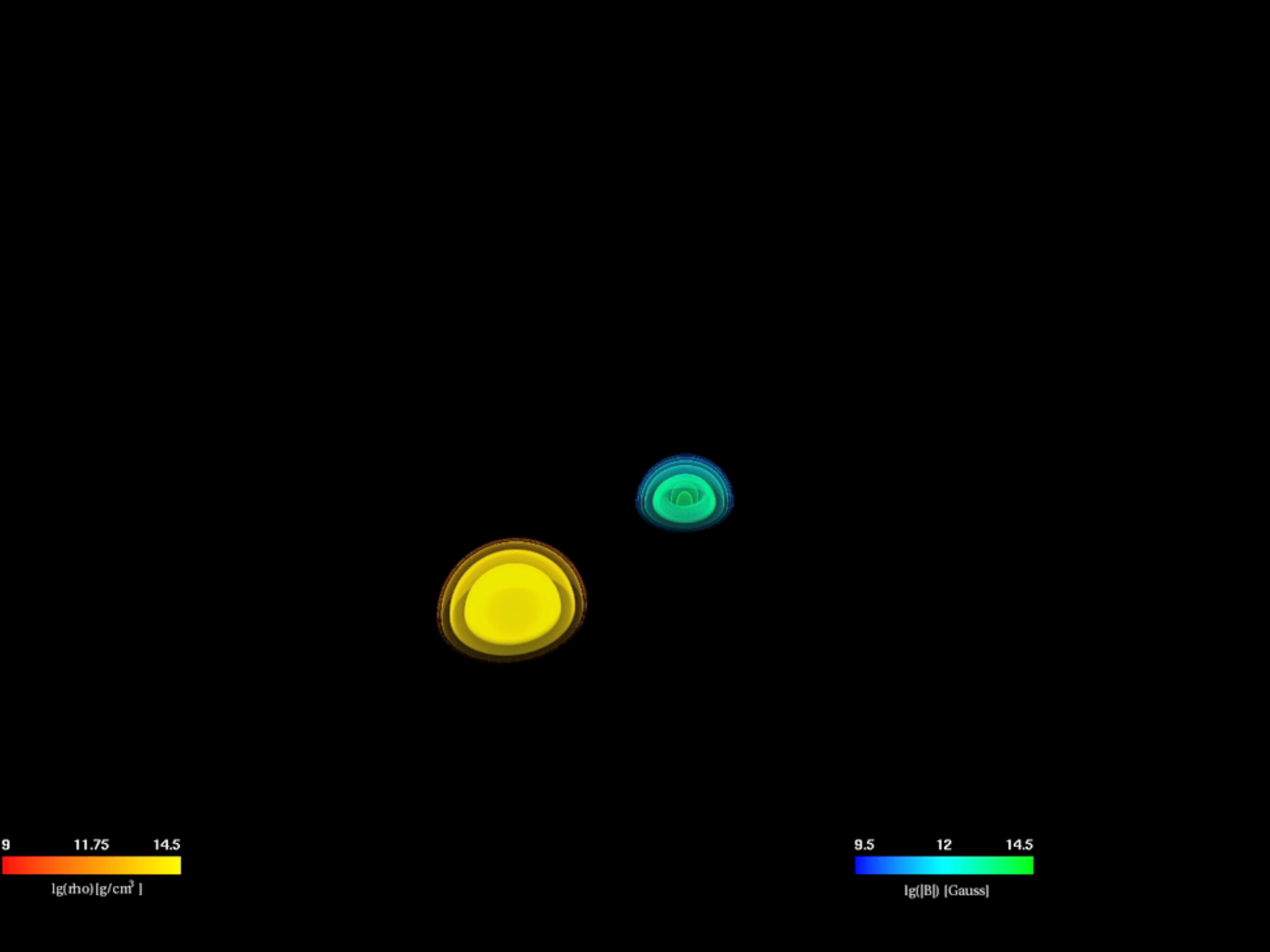
- Short Gamma-ray bursts (SGRBs) have been observed for 40 years and we see essentially a few per week.
- Energies released are huge: $\mathbf{10^{48\text{-}50}}$ **erg**.
- The merger of two neutron stars can release sufficient energy over the correct timescale.
- No self-consistent model has yet been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

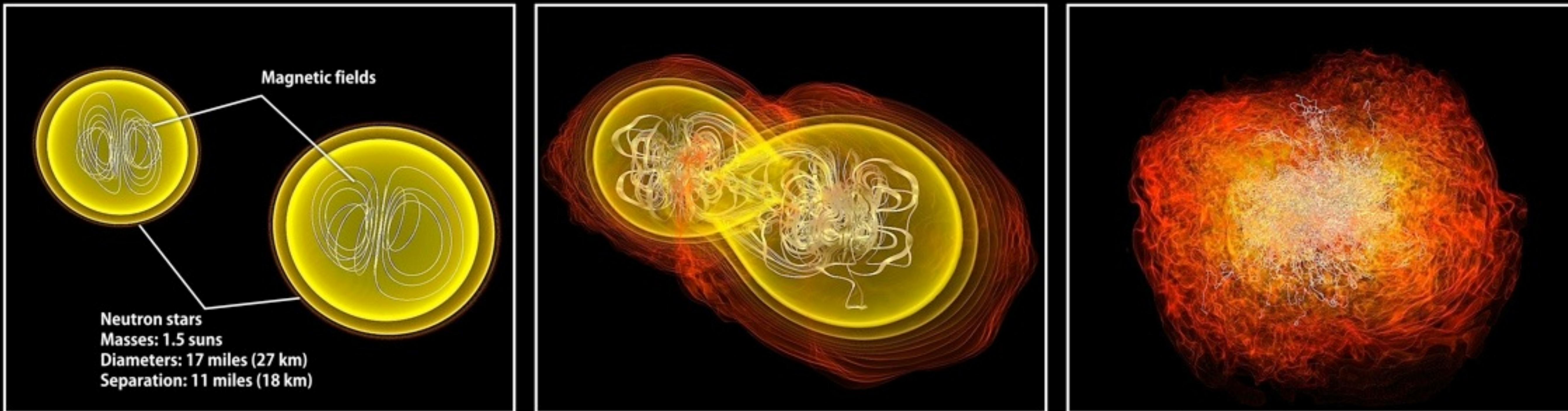
NASA
NASA

B-fields during inspiral phase

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

Animations:, LR, Koppitz


9
11.75
14.5
lg(rho) [g/cm3]
9.5
12
14.5
lg(|B|) [Gauss]

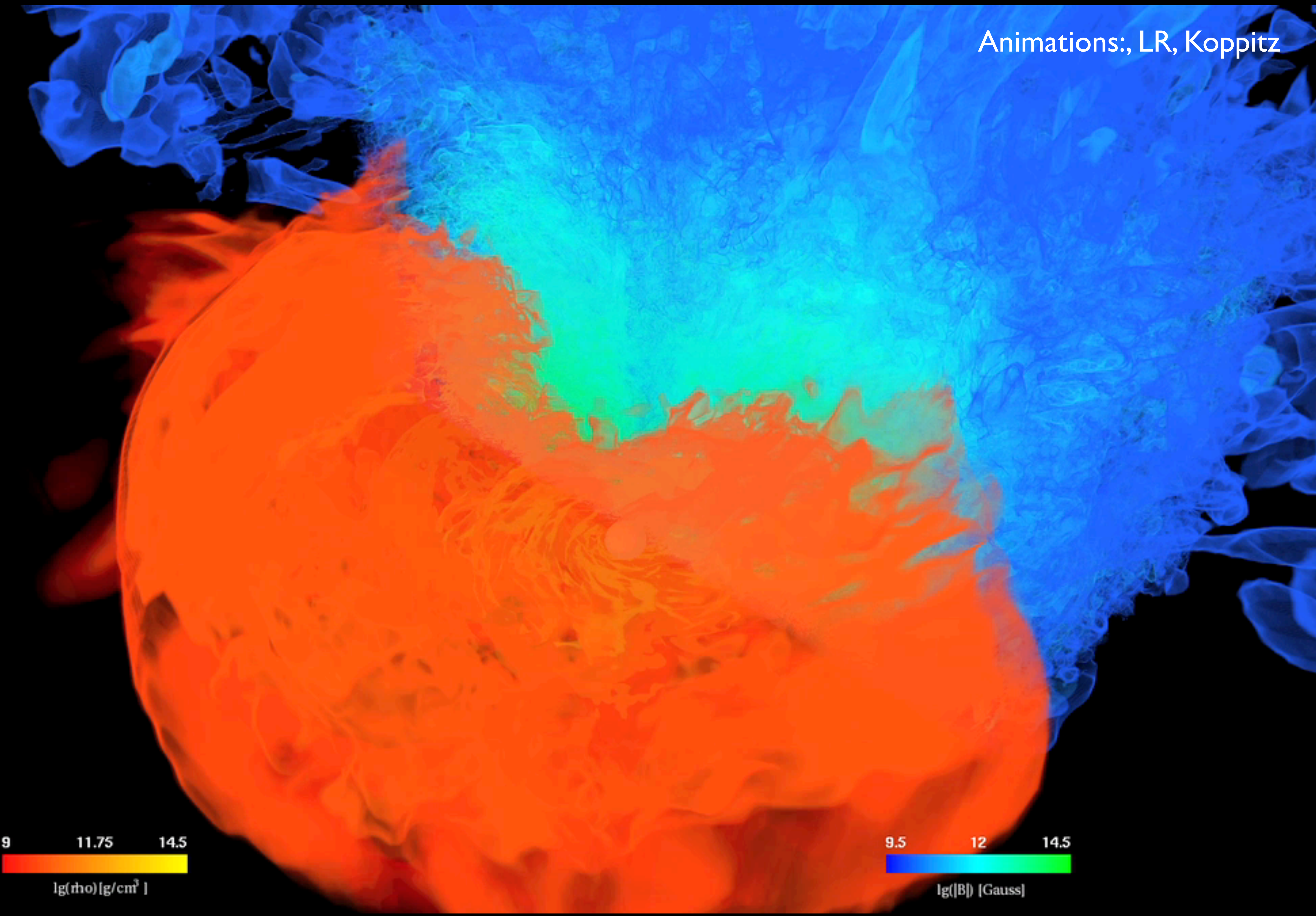


Simulation begins

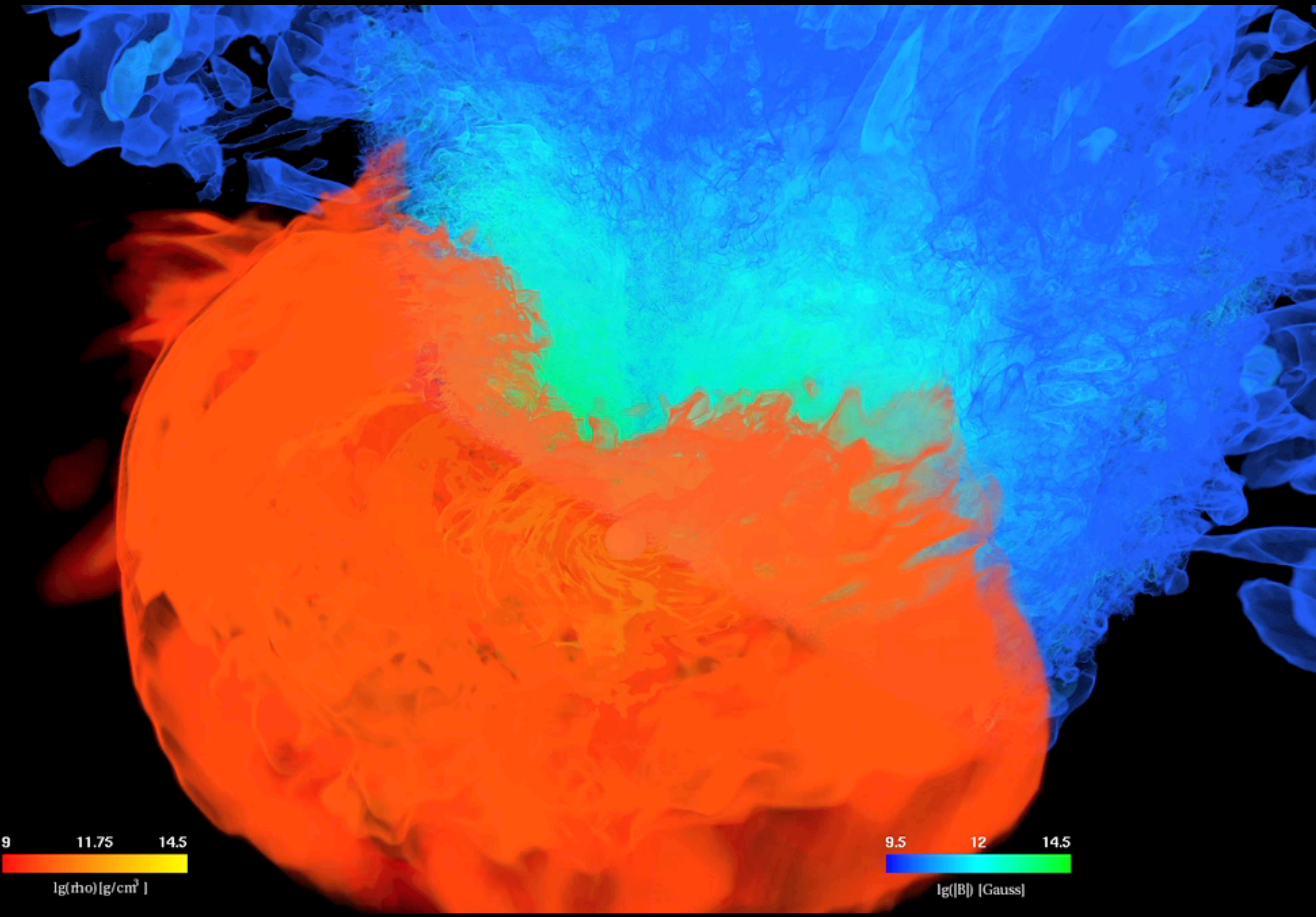
7.4 milliseconds

13.8 milliseconds

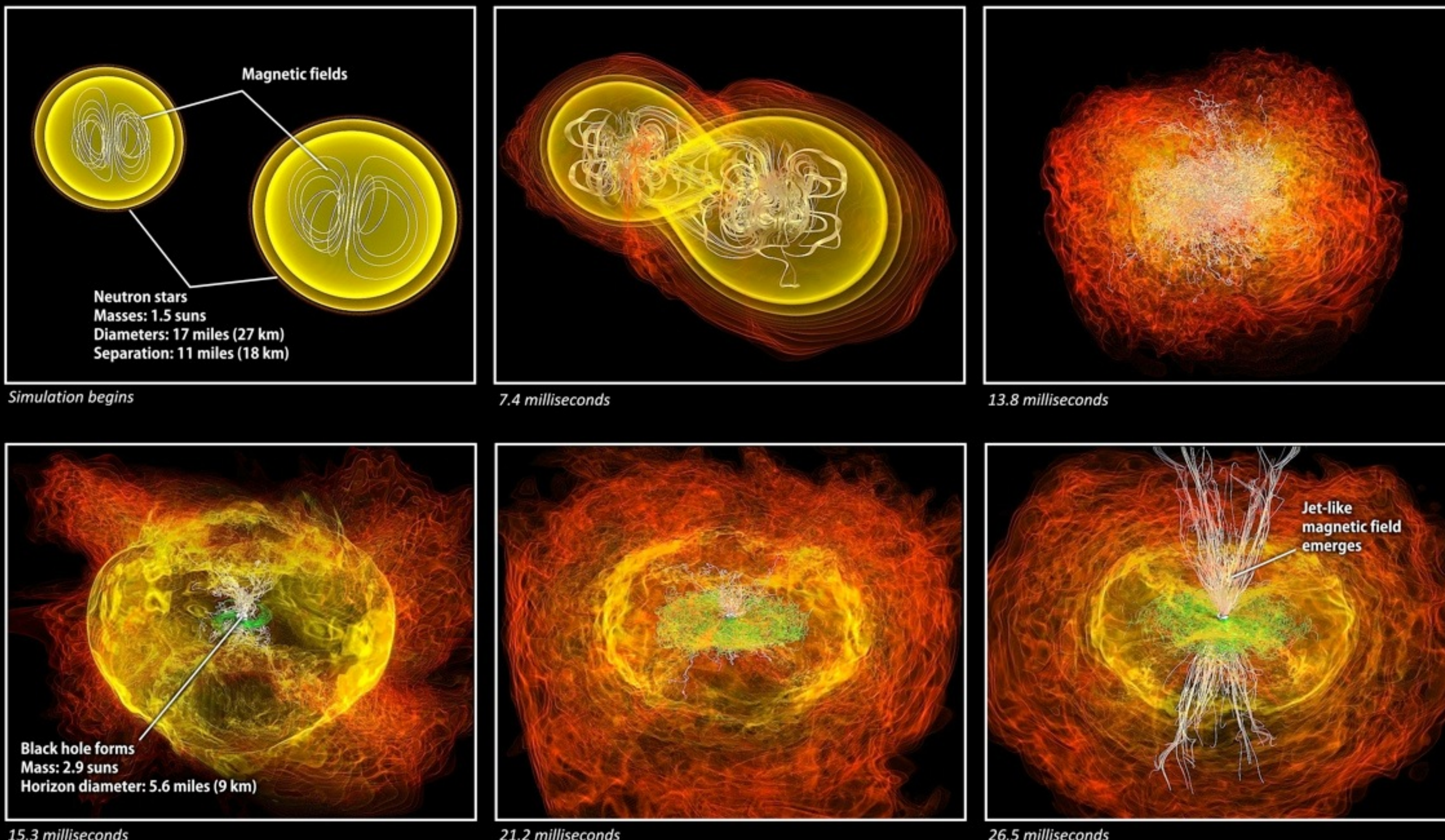
Magnetic fields in the HMNS have complex topology: dipolar fields are destroyed.



Animations:, LR, Koppitz
9
11.75
14.5
lg(rho) [g/cm³]
9.5
12
14.5
lg(|B|) [Gauss]

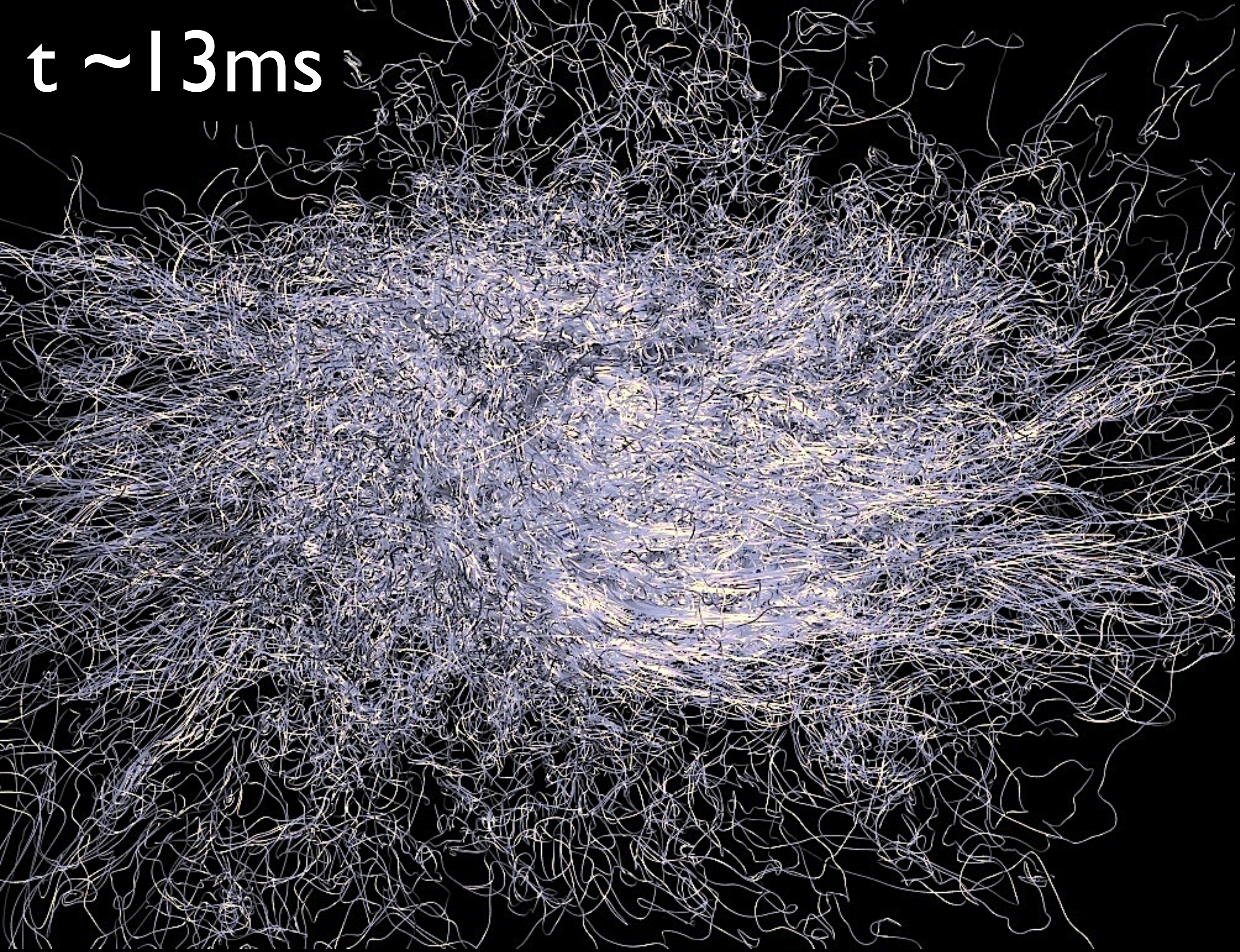

9
11.75
14.5
lg(rho) [g/cm^3]
9.5
12
14.5
lg(|B|) [Gauss]

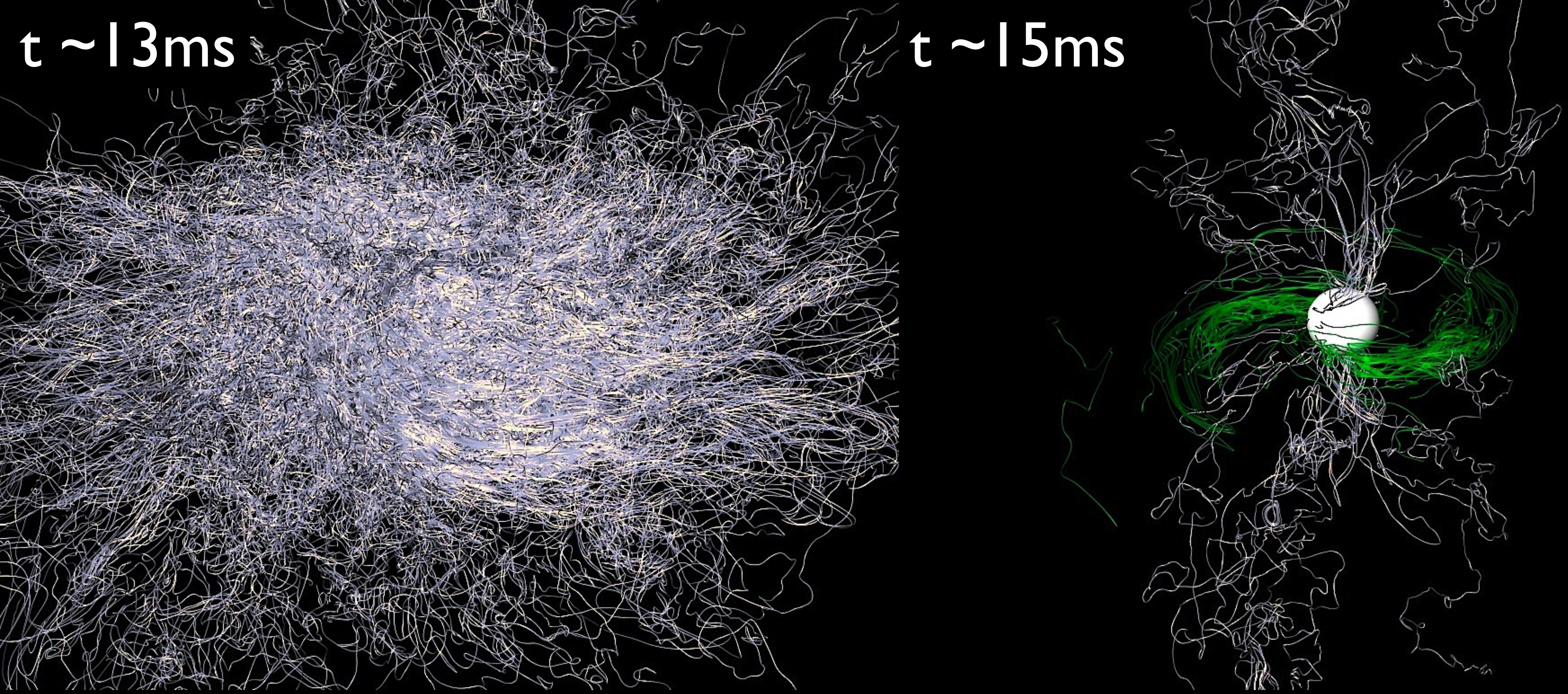
Crashing neutron stars can make gamma-ray burst jets

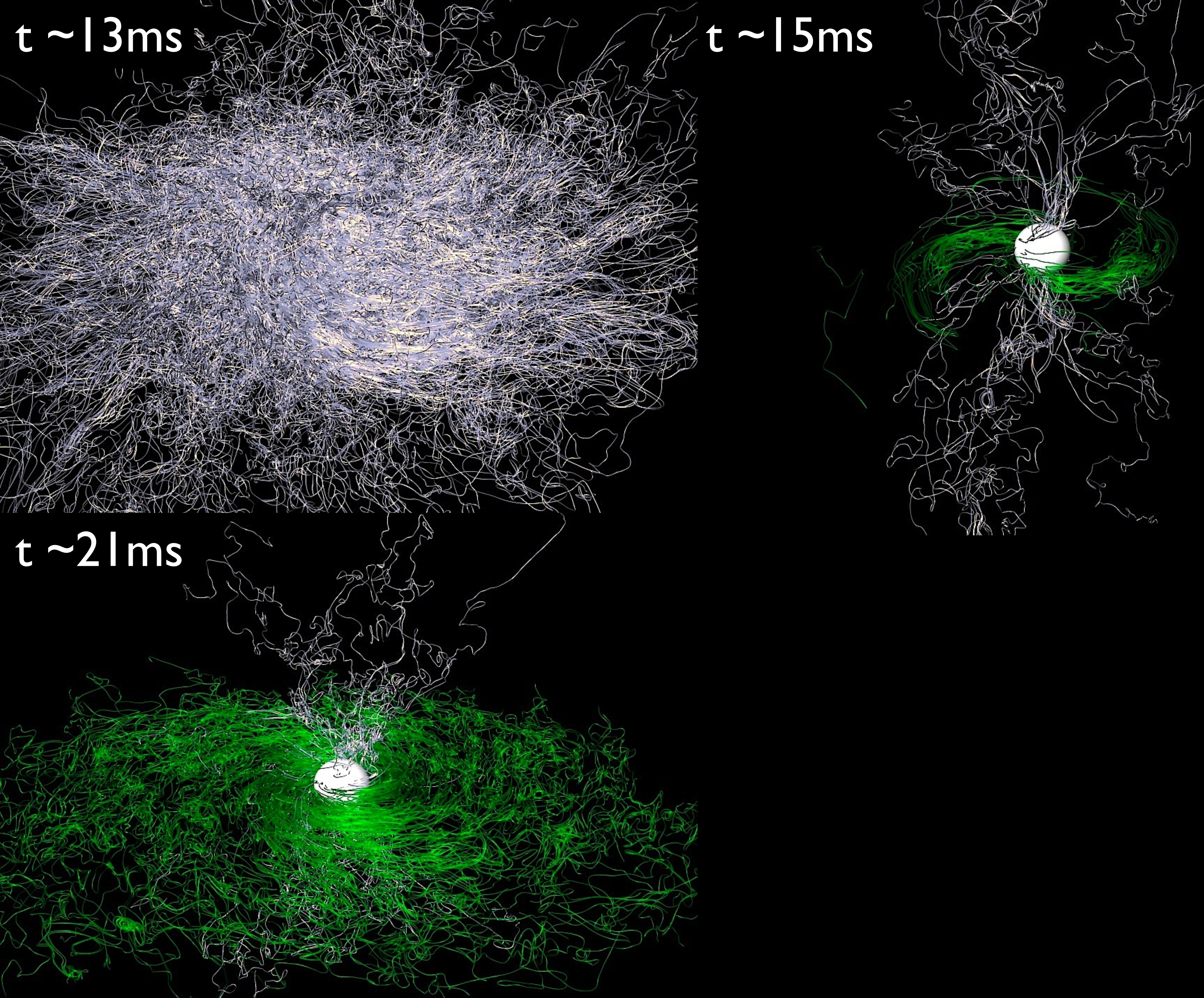


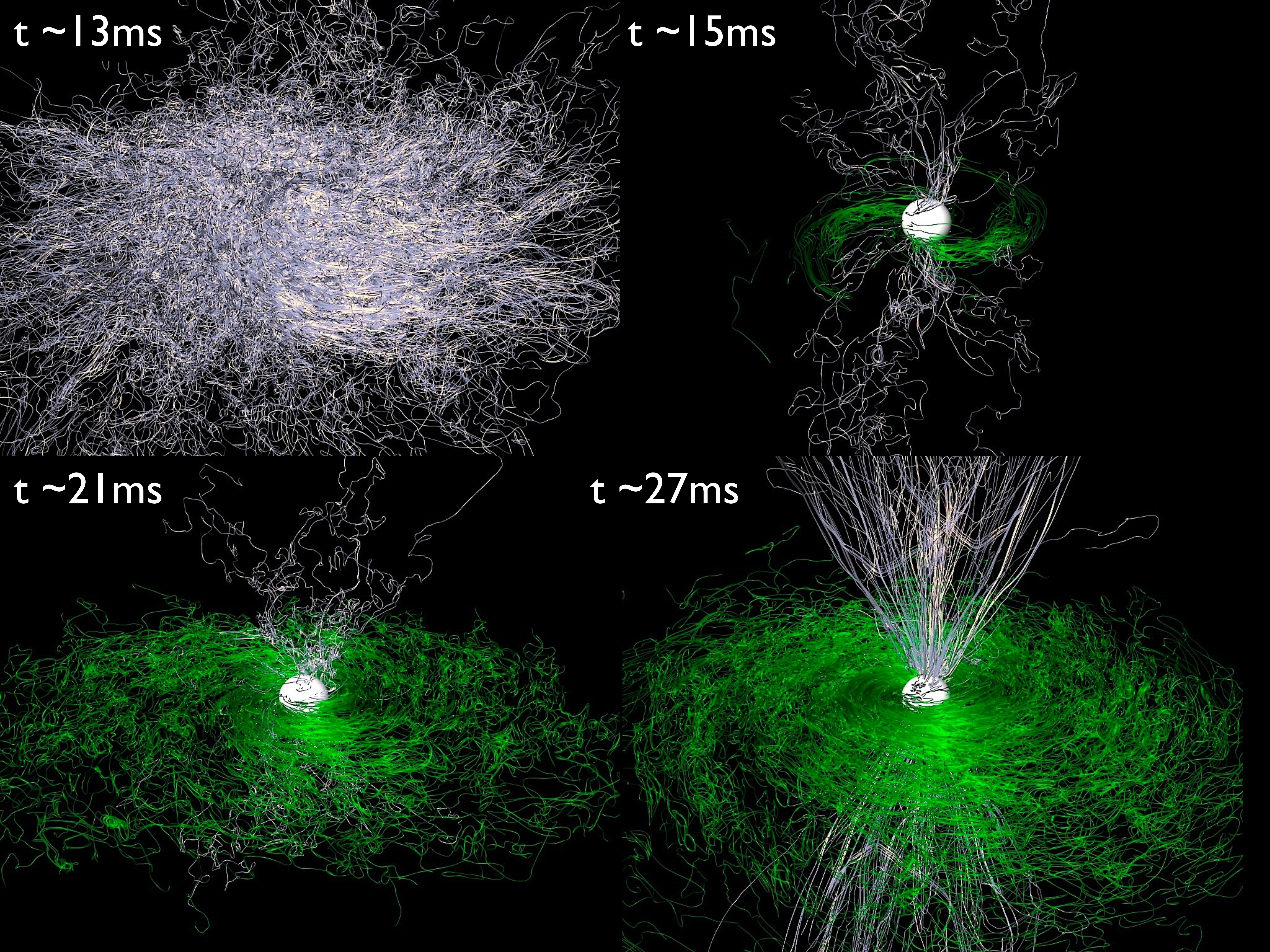
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

$J/M^2 = 0.83$ $\mathrm{M_{tor}} = 0.063 M_\odot$ $\mathrm{t_{accr}} \simeq M_{\mathrm{tor}}/\dot{M} \simeq 0.3\ \mathrm{s}$


t ~13ms


t ~13ms
t ~15ms

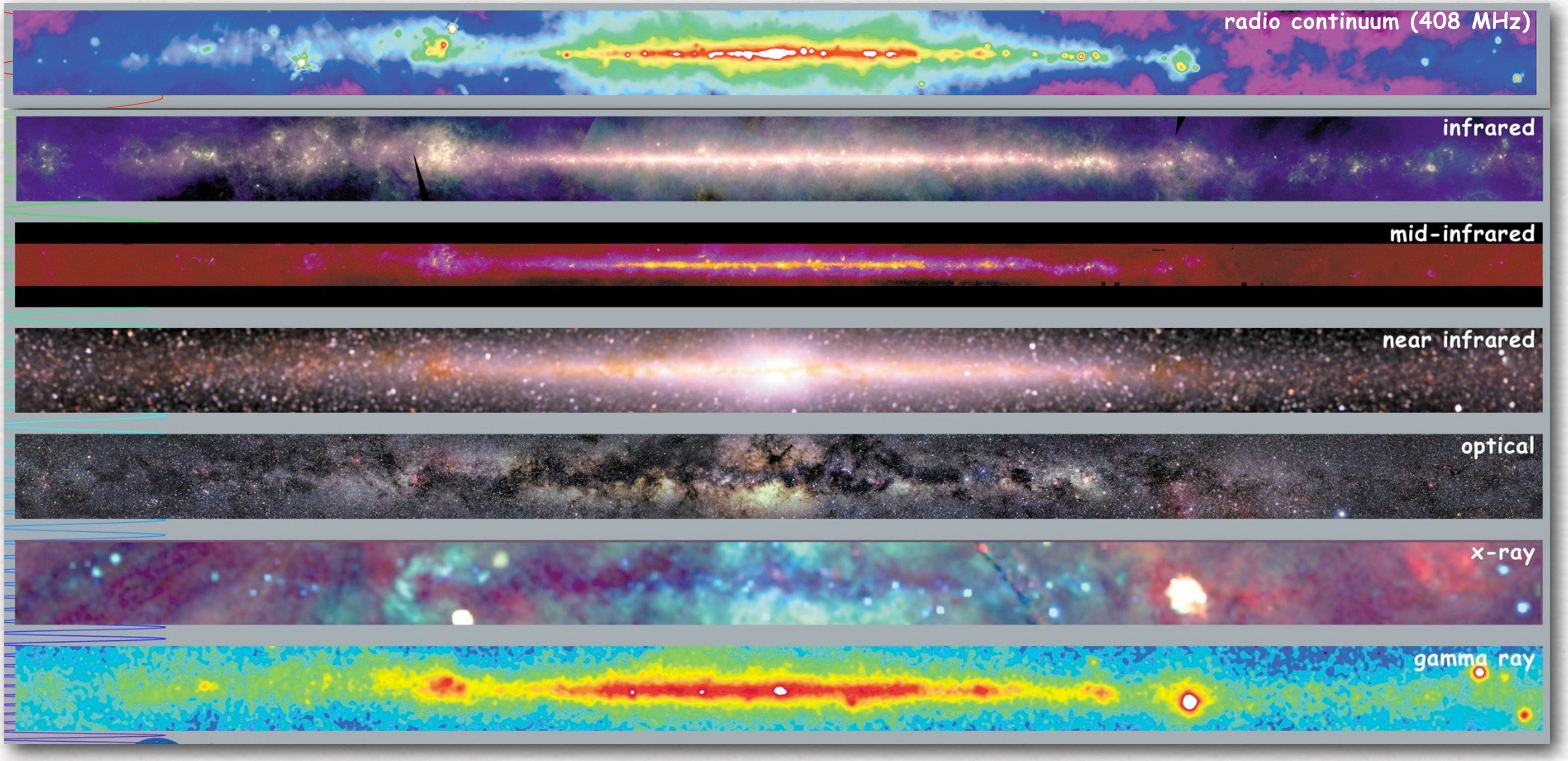

t ~13ms
t ~15ms
t ~21ms


t ~13ms
t ~15ms
t ~21ms
t ~27ms

Conclusions

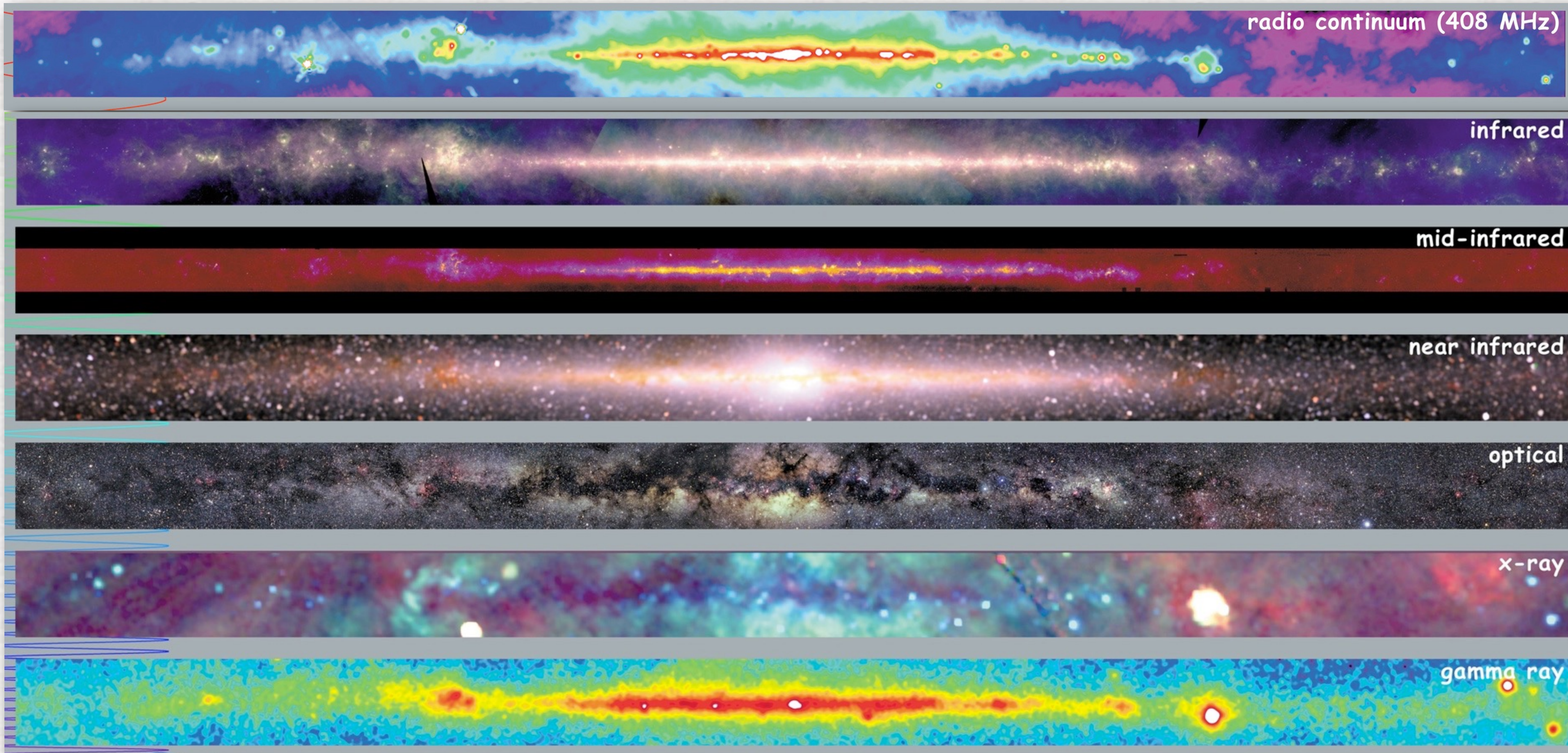
Conclusions

GSFC/NASA



Conclusions

GSFC/NASA



radio

far-IR

mid-IR

near-IR

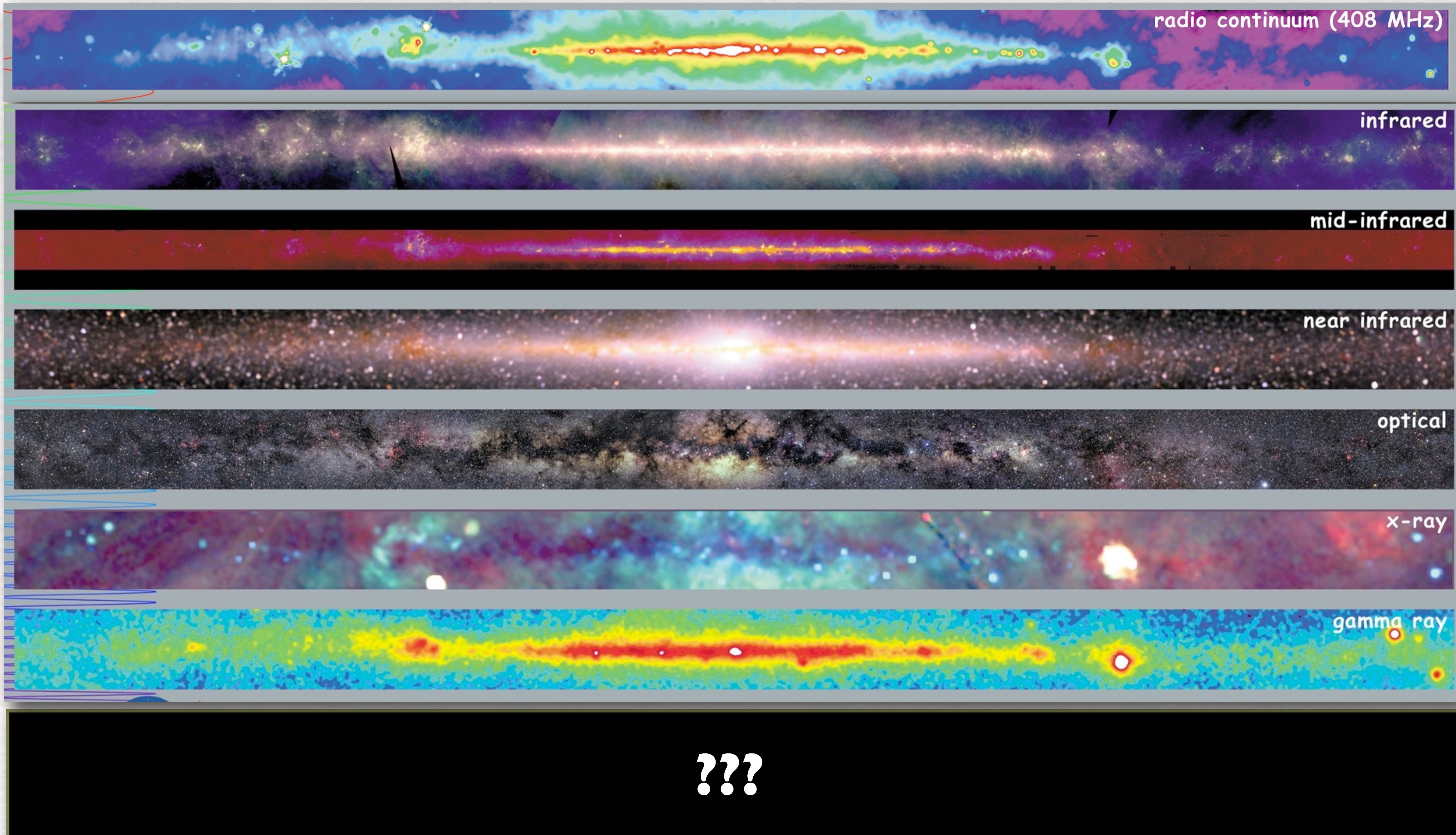
optical

x-ray

gamma-ray

Conclusions

GSFC/NASA



radio

far-IR

mid-IR

near-IR

optical

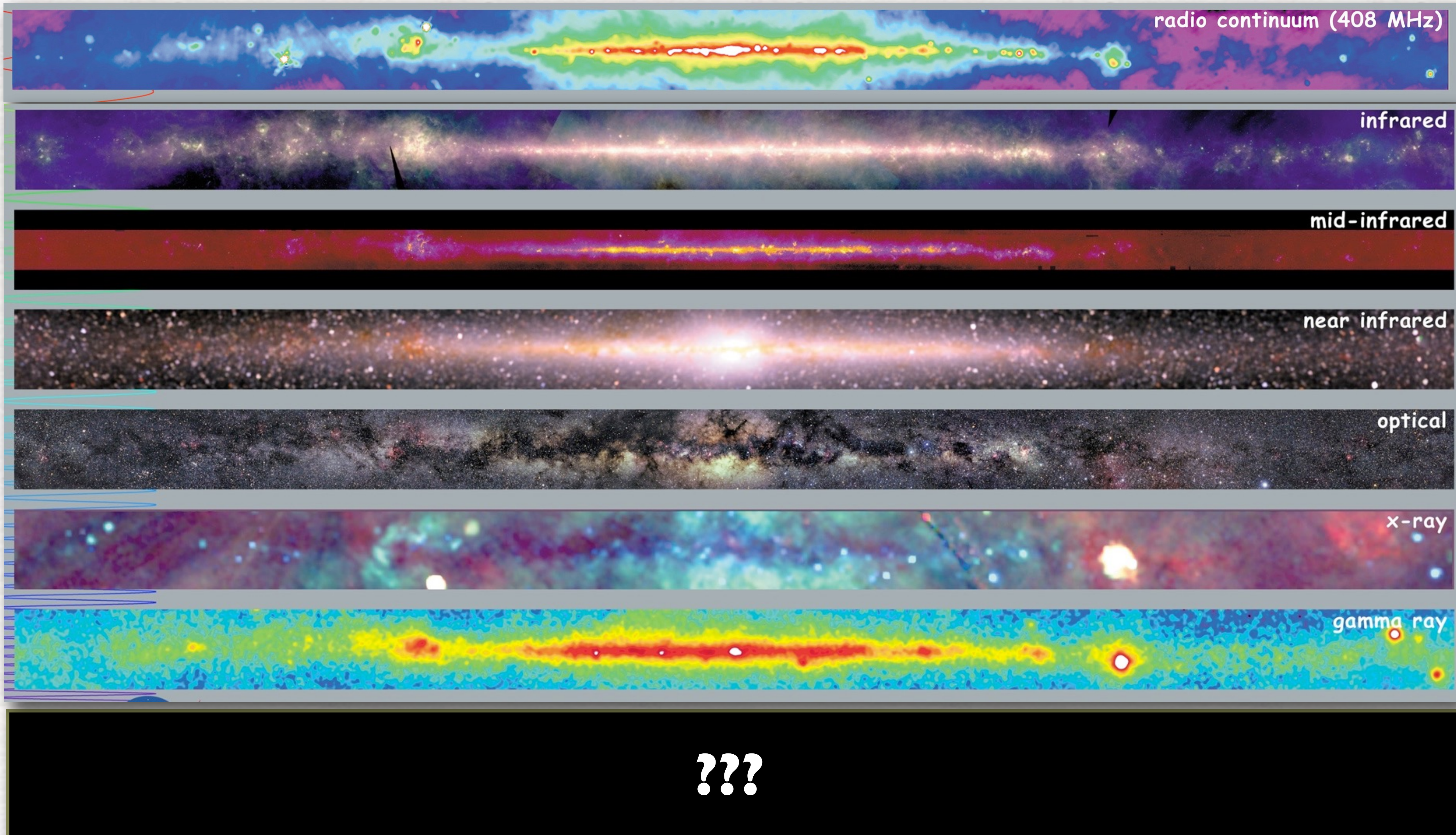
x-ray

gamma-ray

GWs

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