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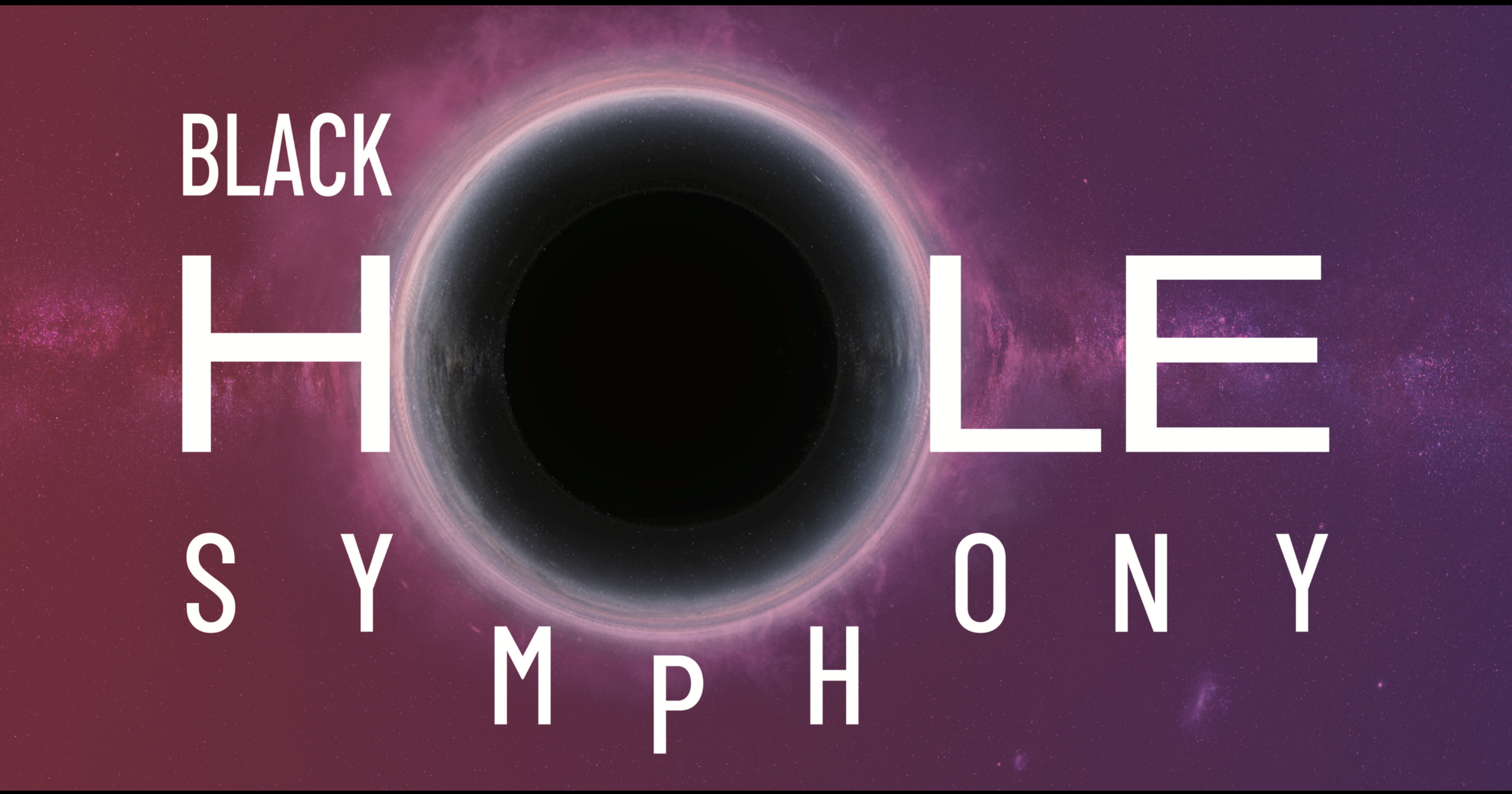

PRODUCED AND PRESENTED BY MULTIVERSE CONCERT SERIES AND THE MUSEUM OF SCIENCE, BOSTON

COMPOSED BY DAVID IBBETT

→ COSMIC TRAVELER'S GUIDE

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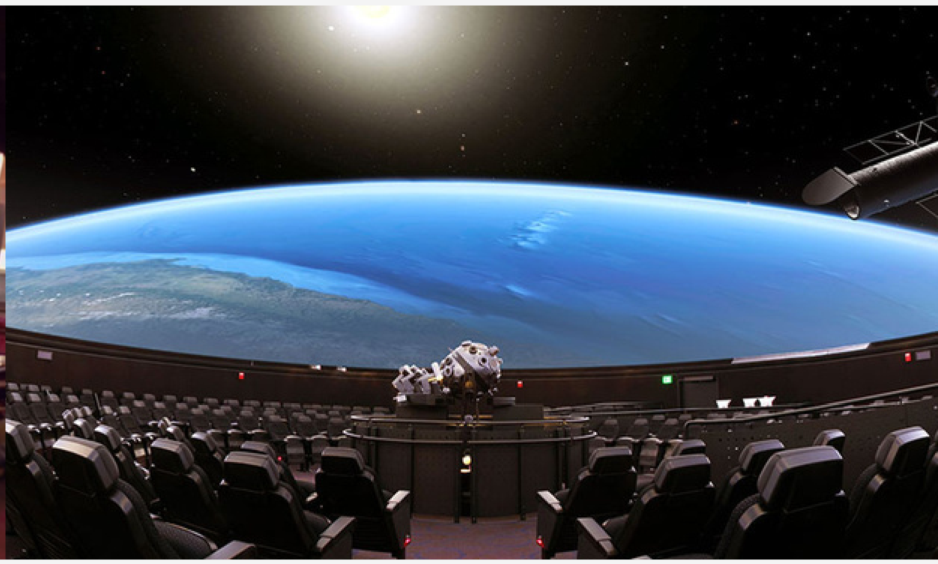
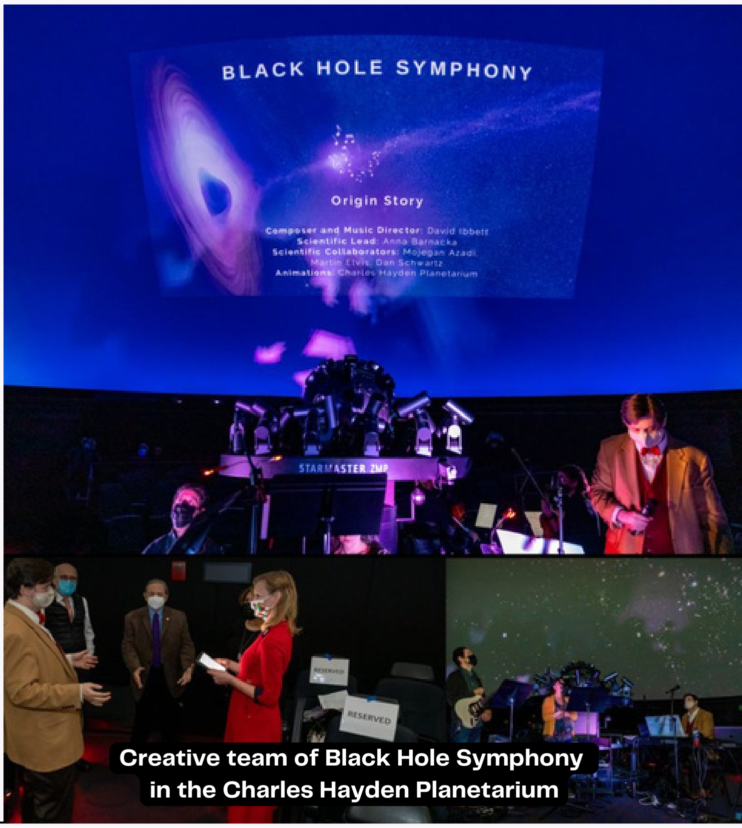


ORIGIN STORY

Black holes have long fascinated us — challenging our very notions of space and time. At the center of almost every galaxy is a black hole at least a million times more massive than our Sun! Instead of solely conjuring up images of menacing engines of destruction, we now know that they are powerful engines of light and creation — spinning matter into accretion disks that launch jets of relativistic plasma that shoot thousands of lightyears into intergalactic space.

Black holes are the silent conductors of an unfolding cosmic symphony.



Creative team of Black Hole Symphony in the Charles Hayden Planetarium

Our goal with **Black Hole Symphony** is to share the story of black holes in an immersive experience – **for everyone** – combining music, science, and groundbreaking Planetarium visuals.

From their first meeting in 2018, Composer David Ibbett and Astrophysicist Anna Barnacka decided to combine forces of music and science and create a 5-movement narrative that takes us on a journey through spacetime, traveling back billions of years to a moment when the stars were outshined by the activity of supermassive black holes at the centers of galaxies. Quickly the idea became reality when the team was joined by James Monroe and his team from the Museum of Science. The mission to create the most immersive fusion of science, art, and music in the universe began!

This journey is only possible through the unlimited power of human imagination and collaboration with a team of amazing scientists from the Harvard Smithsonian Center for Astrophysics and Black Hole Initiative, world-class musicians, and visual creative talent from the Museum of Science, Boston.

We invite you to join us and experience the wonder of our universe.

Multiverse and the Museum of Science

The Black Hole Symphony tells the story of phenomena that happened billions of years ago. To be clear, there will never be a rocket or time machine that can take us to these places in person. We have telescopes and satellites that allow us to detect light from different parts of the universe and these telescopes are as close as we can ever get to having a time machine.

If we ever want to experience these phenomena, we need art — and music — to conjure up a journey through space and time – one informed by real data from black holes and their surrounding galaxies.

We can use the arc of the symphony as a rocket to explore space and time. Like the instruments of an orchestra, a supermassive black hole system contains several key players, each producing a unique signal that we can detect with a variety of telescopes and sonify as musical harmonies.

Black holes are powerful engines governing the evolution of galaxies that can emit light spread through the whole electromagnetic spectrum – around 60 octaves of light.

Our eyes can see less than one of these octaves, but our ears are far more sensitive – translating the light from a black hole galaxy into sound allows us to experience what is out there in the universe with our own senses. Each frequency component of the black hole galaxy is represented by a different musical instrument; for example, piccolo as accretion disk, french horn as dust torus, electric guitar as relativistic jets.

But this is not just a symphony. The experience we are creating has the potential to inspire and bring people of all generations together to explore our place in the universe.

WHY SYMPHONY

I Sonata Allegro

1) X-ray sky
2) Relativistic jets

II Adagio

3) Heart of the galaxy

III Scherzo

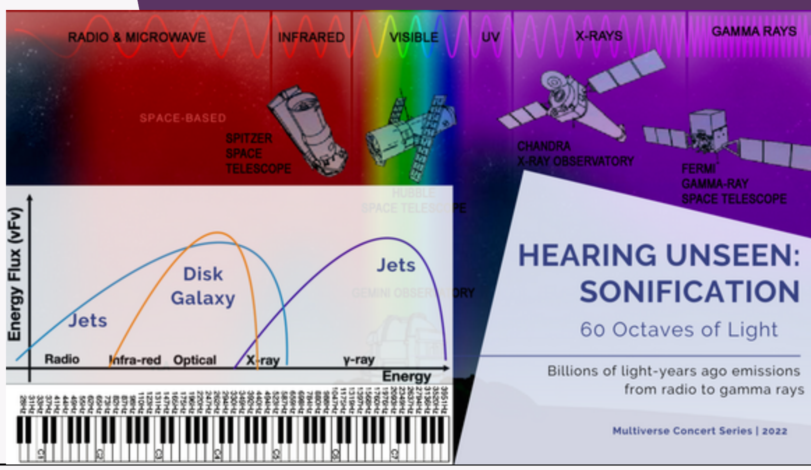
4) Dust torus
5) Broad line region
6) Accretion disk

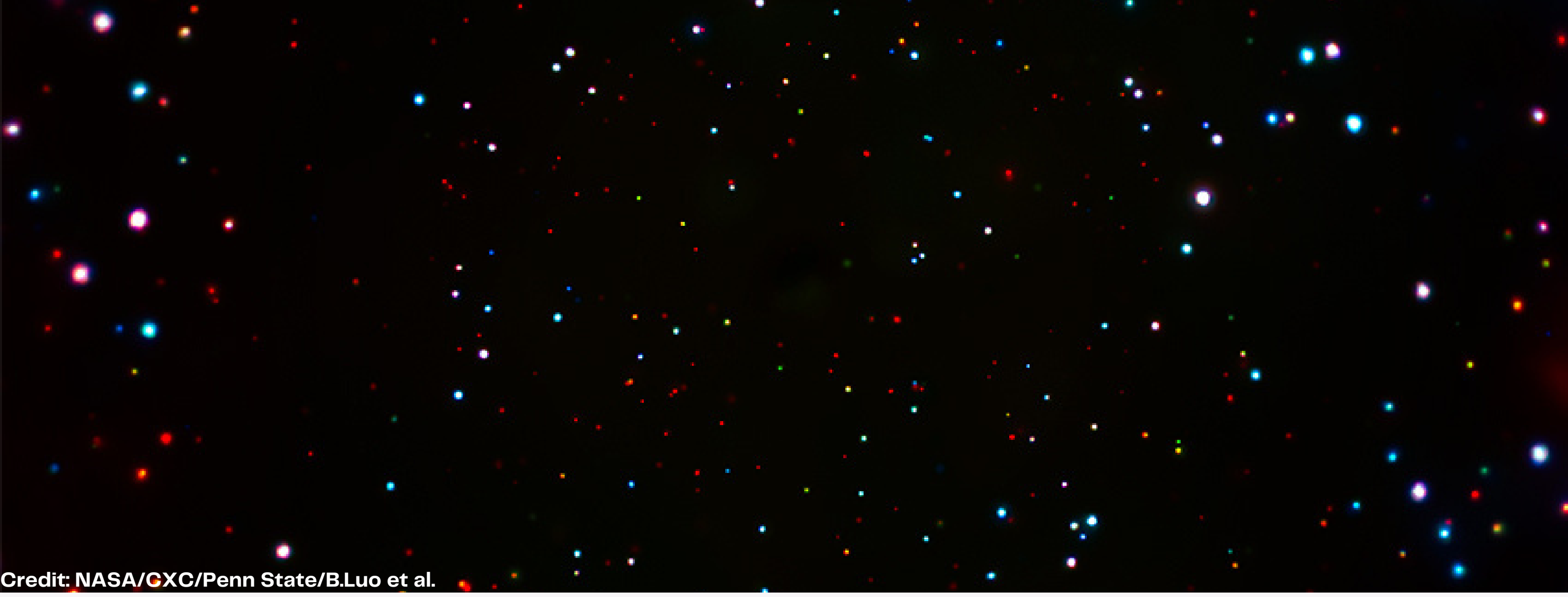
IV Moderato, Vivace

7) Dance of the merging black holes

V Allegro Ritmico

8) Waves coming home
9) Light will be shone





Credit: NASA/CXC/Penn State/B.Luo et al.

X-RAY SKY

"Each dot is not a star, but a black hole.
Nested at the heart of every galaxy, they are the conductors of a cosmic symphony."

When we look up at the sky we see stars. We can see them with our eyes because like most animals, we have evolved so that the one octave of electromagnetic radiation that we can image with our senses includes the form of the energy generated by our Sun. More precisely, the visible range is due to the radiation from the hot gas which is the outer surface of the Sun. The wavelengths comprising this light are determined by the temperature of the gas. For most stars, this temperature is in the range of a thousand to many tens of thousands of degrees.

With our eyes, we cannot see black holes. Using X-rays an entirely new view of the universe is opened to us. In the Milky Way and nearby galaxies, we see the remnants of supernova explosions, neutron stars, white dwarfs with huge magnetic fields, and hot gas clouds where new stars are being born. Far outside our galaxy, the X-ray sky shows us that the Universe is full of supermassive black holes.

What to listen for

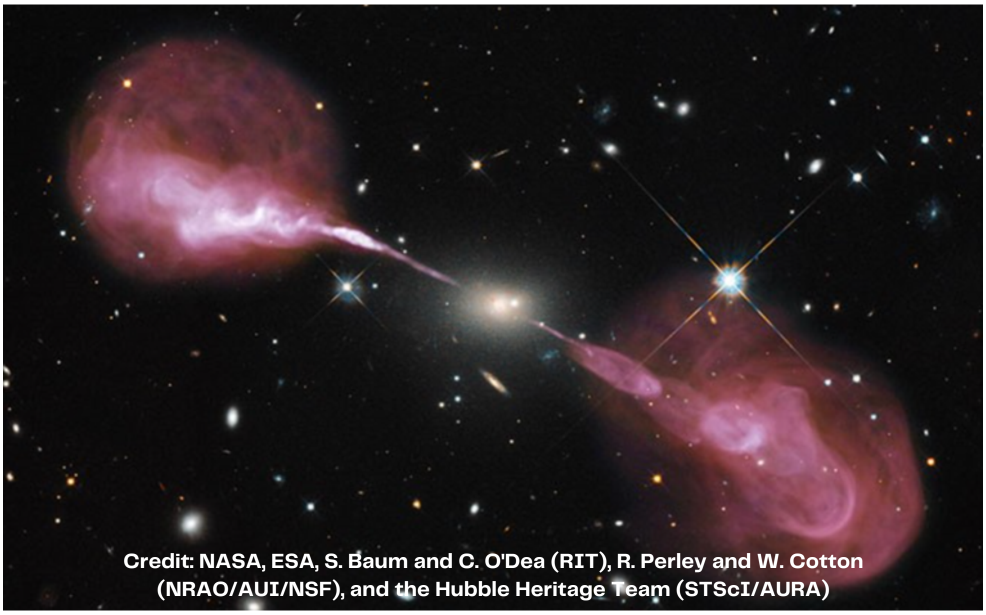
The piccolo plays the ***X-Ray Theme****, heard throughout the symphony. It is answered by the* ***Journey Theme****, played pesante by the horns, strings, and synth bass.*

While our naked eyes see a sky full of stars, X-ray telescopes reveal a sky full of supermassive black holes. Almost every colored dot indicates an X-ray emission from the area around a giant black hole in a galaxy far away, as the black holes' intense gravity churns the space around them.

The image above is the deepest ever X-ray map, taken with the Chandra X-Ray Observatory satellite. Almost every colored dot indicates an X-ray emission from a giant black hole in a galaxy far away. Light from those galaxies takes hundreds of millions to even more than 10 billion years to reach the Earth. Each black hole has a mass from one million to ten billion times that of our Sun. Of course, we can't see the X-rays. It takes a special satellite to detect such high-energy radiation. Astronomers construct images such as we see here, using computers to trace back the direction of each photon and determine its origin in the sky. Colors are chosen to enable us to visualize the information about the intensities and energies of the X-ray photons.

These supermassive black holes reside near the centers of galaxies but outshine their entire galaxy in both visible and X-ray light; this is why we see them as single points of emission. The supermassive black holes are swallowing starfulls of hot gas and converting them into energy with efficiencies of as much as 40%. That is more than 100 times the efficiency of stars.

RELATIVISTIC JETS



Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

"Jets of plasma approach the speed of light: a cosmic laser launched from the galaxy's heart, beaming radiation to the distant universe."

When the universe was about a few Giga-year old, galaxies were rapidly growing by merging with other galaxies. The universe was still full of hydrogen gas that was fueling star formation. The gas that was filling galaxies was falling also into their centers where the spinning supermassive black holes were residing.

Such a large amount of falling gas could not be accreted by the black hole. Instead, clouds of gas falling down from the outskirts of the galaxy rotate rapidly around the black hole. In such a cosmic thunderstorm, the spinning black hole helps trigger the formation of a cosmic tornado that shoots out of the very center of the system. Astrophysicists call these cosmic tornadoes - jets. Such a jet is made of blobs of plasma that move close to the speed of light. When objects move close to the speed of light, we have to use Einstein theory of relativity to explain the observations, and this is why we call these objects relativistic jets.

The above image shows the observation of spectacular jets powered by the gravitational energy of a super massive black hole in the core of the galaxy called Hercules A. This image illustrates the combined power of two of astronomy's cutting-edge tools, the Hubble Space Telescope, and Very Large Array radio telescope in New Mexico.

The yellowish part shows thermal emission of stars in the galaxy. When the pinkish light corresponds to the radio emission and shows the jets.

These jets are also highly collimated like a laser and can reach from the center of the galaxy into intergalactic space. These relativistic jets are the largest particle accelerators in the universe and produce radiation in the entire electromagnetic spectrum: from radio to the very high-energy gamma rays.

When stars can produce only a few octaves of light, these cosmic tornados produce emission that corresponds to 60 octaves!

The variability in the intensity of the emission of relativistic jets can change across the spectrum. In their quiet mode, changes in variability resemble pink to red noise that could best be described as a waterfall or rain.

But there are times when we see fast outbursts when emission can increase even hundreds of times in periods as short as days, adding to the complex nature of these sources.

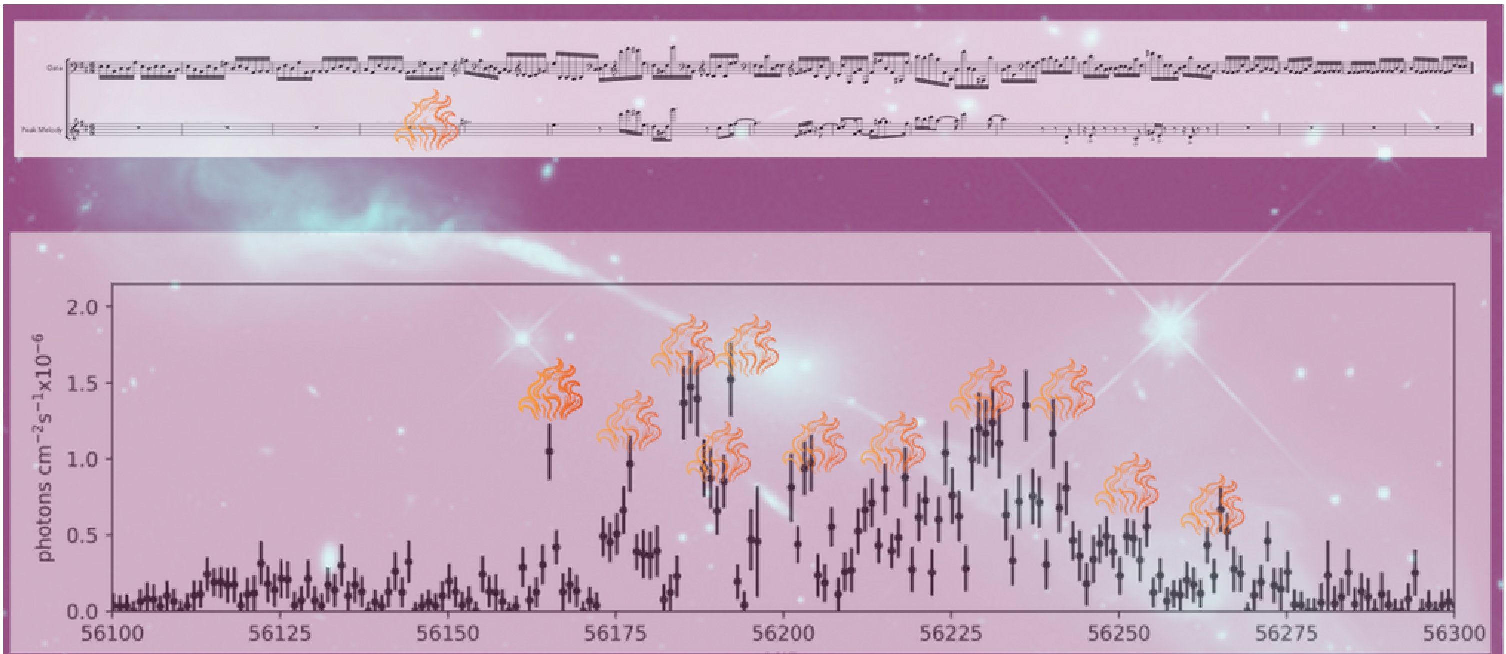
One of many of gamma-ray storms was observed by the FERMI satellite from an object that we called B2 0218+35. In the plot below we can see a gamma-ray thunderstorm that lasted for about 200 days and was used by David Ibbett as an inspiration.

What to listen for

*In the **Jets Theme** - a sonification - the intensity of the gamma flares corresponds to musical pitch. Each note represents one day of data, rising and falling with the gamma fluctuations over time. David Ibbett chose an electric guitar and rhythmic synth to drive the melody.*

What's most striking are the jagged peaks that pop out against the background. Ibbett draws out these notes in a second melodic layer, extending the peak notes to create an intensity barometer for the jet's flaring plasma. When you listen to the symphony, see if you can follow the flame markers as the piccolo and guitar highlight the most intense bursts of radiation.

SONIFICATION OF RELATIVISTIC JET



Anna Barnacka (2018) Physics Reports

HEART OF THE GALAXY

The heart of the galaxy
we perceive the jets' radio light
the visible gleam of the stars
the silicate grains of the torus
the shining elements of the
accretion disc.
The iron line with its twisting x-rays
and at the electromagnetic zenith -
the jet peak, blazing with gamma
rays.

Credit - ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

The image shows Centaurus A, which is one of the closest galaxies to us, powered by the supermassive black hole at its center.

To grasp the full picture, we need multiple telescopes that are sensitive to the light at different frequencies. We need X-ray telescopes to detect the light from the vicinity of the black hole. To capture the light from relativistic jets we need radio and gamma-ray telescopes. To see the stars in the galaxy we need telescopes like Hubble that are sensitive to visible light. Telescopes that can detect winds and particles of gas blowing outwards in all directions in the center of the galaxy.

To have a clear understanding of how our universe evolved to its present shape, we need all this information. In fact, putting the information from different telescopes sensitive to the light at different frequencies is like putting the pieces of a puzzle together.

People typically think of black holes as simply destructive. But thanks to the work of many scientists and a massive amount of observations from all kinds of telescopes, we know that black holes run the whole show, governing the formation and evolution of galaxies in a very efficient way.

The strong gravities of the black holes forms structures that generate the energies that has a significant impact on the formation and growth of the stars in the galaxy.

Without their supermassive black holes, galaxies might not be able to develop structures of billions of stars, as we see them today.

To better understand how our present universe came to be, we need to put the information from all these structures and the light from different telescopes detecting them together.

Similar to different instruments in an orchestra, different components of this complex system radiate at different frequencies. The galaxy and the rotating disk around the supermassive black hole in visible light. The jets at low frequencies where we have the radio and at the very high frequencies where have the gamma rays. The stars in the galaxy depending on their age can radiate across all frequencies, from X-ray and ultraviolet to infrared and radio.

All these pieces together create a cosmic symphony spanning 60 octaves of light.

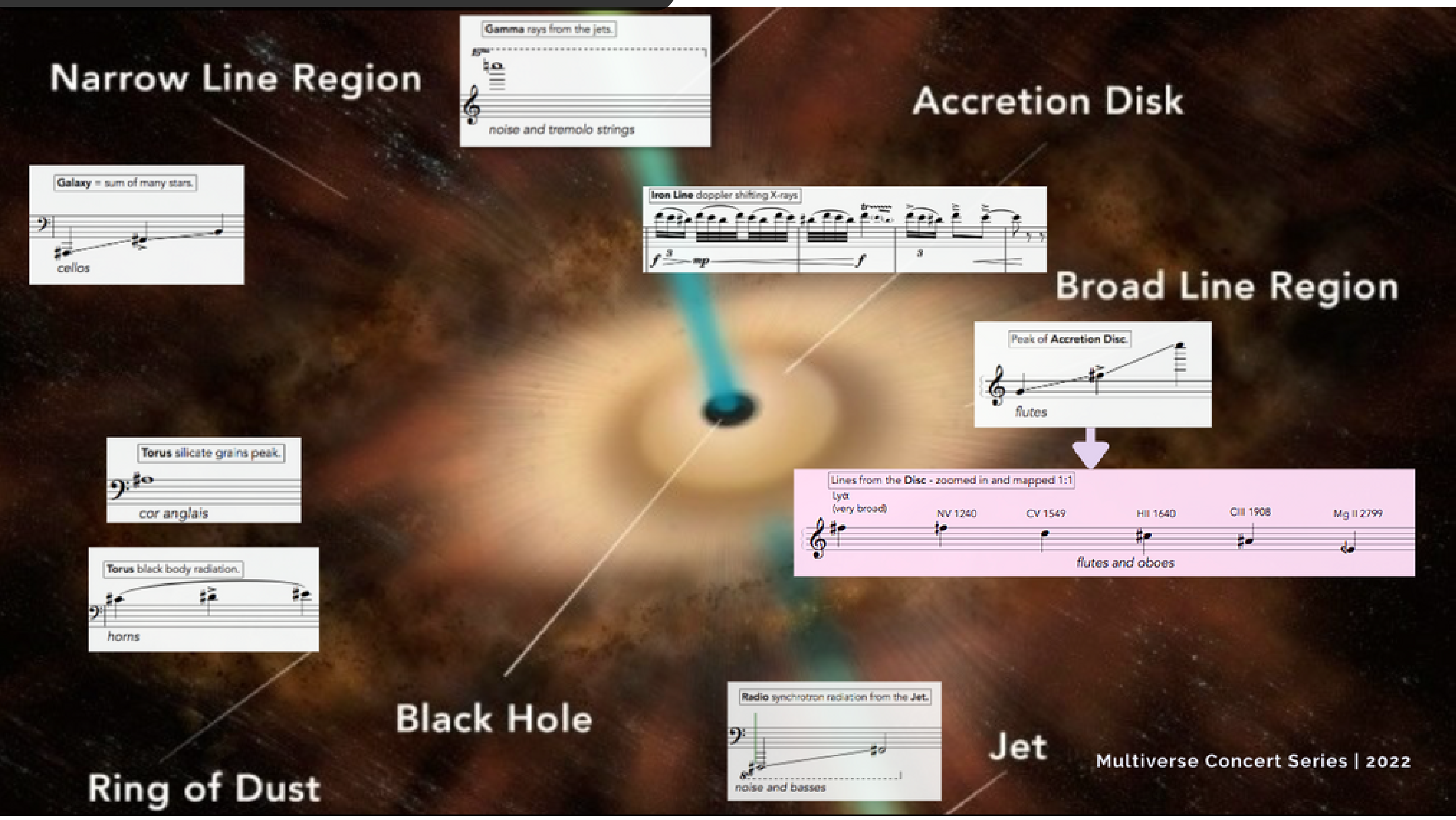
What to listen for

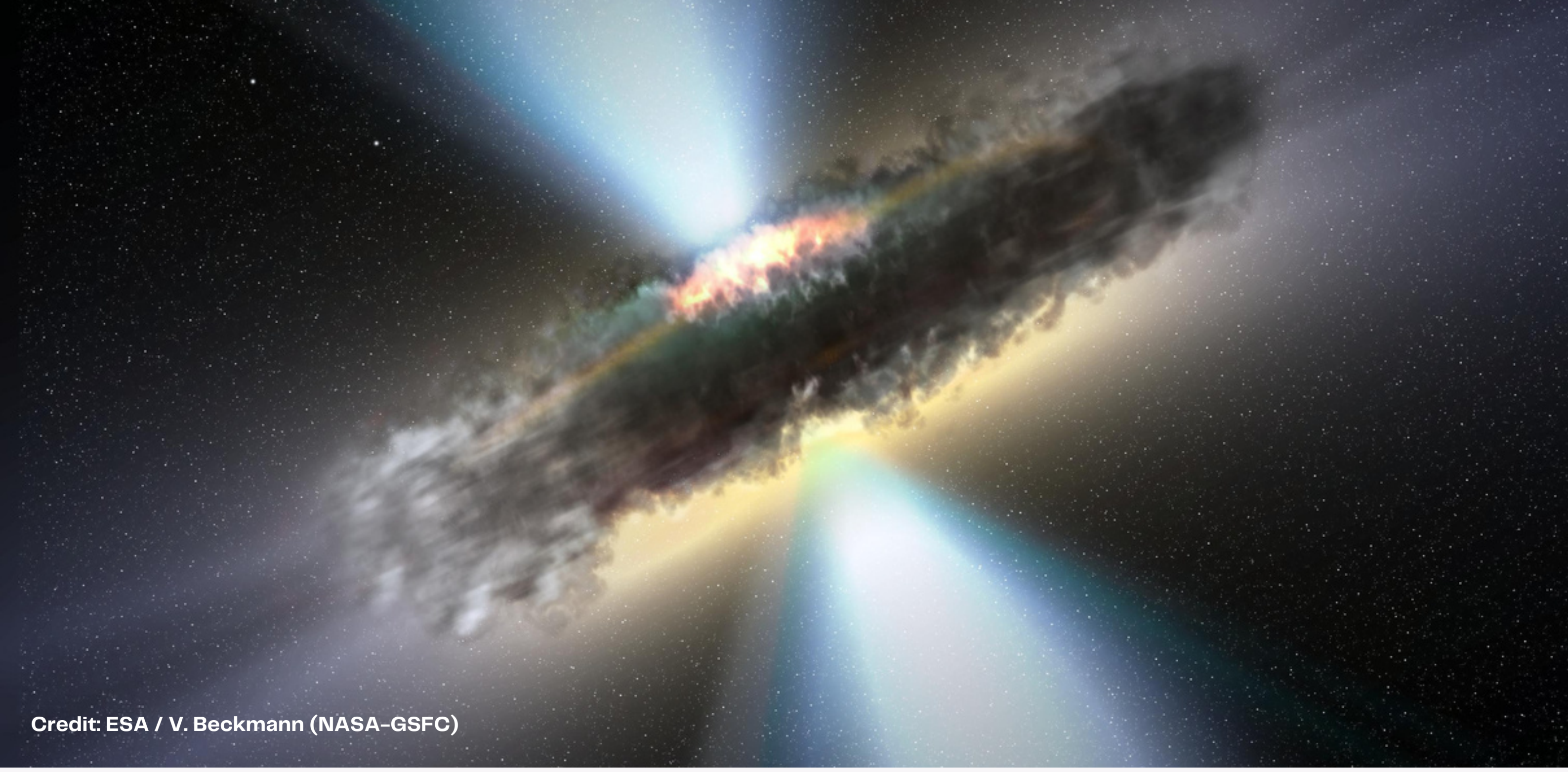
Our eyes can see just a small fraction of the universe's electromagnetic spectrum: less than one doubling of signal contains all of the colours we know. Musicians call one doubling one octave, and compared to the eye - the ear can perceive up to 10 octaves of sound!

Our goal with the Multiverse project is to translate the wonders of the universe into real experiences that we can share together. Black Hole Symphony uses the power of our ears to reveal a far wider range of frequencies than our eyes could ever experience.

Emission types from radio to gamma rays can be listen to, or sonified, as the notes of a giant piano. This works because light and sound are both waves. Musical chords then emerge because different components of the active galaxy emit very specific frequencies with intricate peaks and troughs, each corresponding to different elements and molecules. This gives rise to ***Black Hole Chord*** *- a sonification of the Active Galaxy's full radiation spectrum: the harmonic center of the Symphony.*

BLACK HOLE CHORD





DUSTY TORUS

"It's dark in the depths of the dust.
The torus surrounds the galaxy's inner region.
A layer of thick silicate grains, held in check by gravity
Let's delve inward."

Now if we zoom in to the center of the galaxy we will see structures around the supermassive black hole. The strong gravitational force from the black holes drags the nearby gas and stars and forms a rotating disk, called the accretion disk. Some of the photons originating from the accretion disk are absorbed by another structure called torus. This structure, which has a donut shape, surrounds the black hole and accretion disk and mainly consists of graphite grains. Astronomers call these grains dust. Infrared telescopes such as SPITZER can detect the light coming from the dust grains in the torus.

What to listen for

Our journey continues as we plunge into the Dust Torus - a dark and obscured environment filled with dense particles. Listen for the ***Torus Theme*** *played on french horn - drawn from the Black Hole Chord - joined by a rainstick and singing sands recorded from Earth's deserts.*

Gradually we pick up speed and hurtle joyfully towards the center of the galaxy. All of a sudden, we burst out from the Torus to the new environment of Broad Line Clouds...

BROAD LINE REGION

"Broad Line Clouds of superheated gas, resonant with pulses of light from a source within. On the horizon, the accretion disc."

As we move inwards from the dark and dusty region of the torus, we emerge into a space full of glowing clouds moving around the central black hole.

The clouds are held there by the gravity of the black hole. They must move very fast to stay in orbit, as much as 10% the speed of light, or fast enough to circle the Earth in a second.

Responding to the quasar light the clouds glow in single bright colors, similar to a sodium street lamp. These colors let us know what the gas around a black hole is made of.

Clouds nearer the black hole accretion disk glow in one color deep in the ultraviolet that comes from atoms of carbon; further out the clouds glow in a bright red, a sign of hydrogen atoms, while even further out the clouds glow blue thanks to magnesium atoms.

We know this because these precise colors have been measured in laboratories. The colors are smudged out by the fast motion of the clouds thanks to the Doppler effect that is familiar to us from police and ambulance sirens. They have been "broadened" to cover a range of nearby colors. That's why we call this cloudy region the "Broad Line Region."

No other objects in the Universe can maintain such high velocities year after year. From the amount of smudging we can tell how fast the clouds are moving and how far they are from the black hole.

What to listen for

The Broad Line Region of superheated gas is lit with echoes of light emitted from the accretion disc.

In Black Hole Symphony, these pulses are sonified as the ***Light Echoes Arpeggio****, played by the entire orchestra. In order to be perceived, the light waves are slowed down to form a cascade of sound - like a descending arpeggio - moving outwards from the high energy region at the center.*

David worked closely with scientist Martin Elvis to map each musical note to the resonant frequencies of elements present within the clouds.

Credit: NASA /JPL-Caltech

ACCRETION DISK

The bright light sent out by the accretion disk is an unsteady one; it flickers. Sometimes it can flash, doubling its brightness in a few days. We don't really understand how it does this yet.

But we can use those flashes as another way to measure how far away the bright clouds of the broad line region are from the black hole. To do so we use "light echoes."

The flash comes toward us with no delay. But the broad-line region is about the size of the solar system. It takes 8 minutes for light to reach us from the Sun, but a 5-6 hours to reach Pluto. Fortunately the Sun doesn't flash. When an accretion disk flashes each ring of clouds lights up in succession, but we only see them light up with a delay equal to the time it took for the flash of light to reach them. So the different colors light up in turn, making a pattern that David Ibbett turned into an arpeggio.

"At last, out of the clouds
the accretion disk blooms:
outshining all the stars of the galaxy."

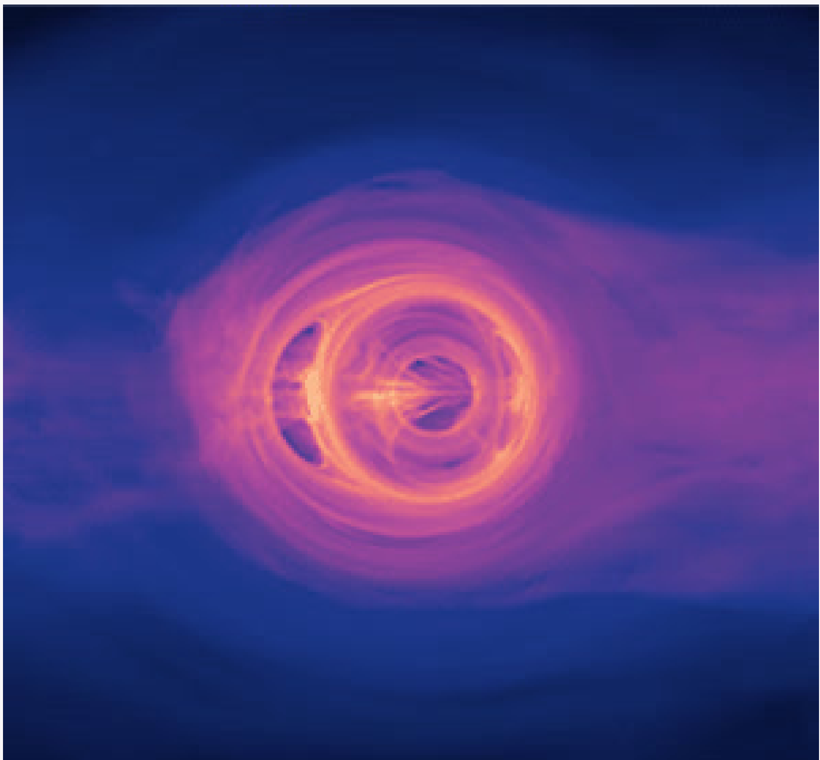
What to listen for

After escaping the boiling clouds of gas, we emerge triumphantly at the black hole's accretion disc. Here, the creative power of gravity unfolds a dense symphony of light and energy - a maestoso variation on the ***Journey Theme****, topped by a waltzing string melody. Many of the musical rhythms are drawn from square numbers to evoke objects falling at ever accelerating rates. 4 against 9, 16, 25, 36...*

As we approach the event horizon, the texture thins to reveal the ***Accretion Theme*** *on winds, then brass and strings. This melody is a variation on a Shepard Tone - an aural illusion that appears to rise and fall forever. Blasted back to the torus by jets of plasma, we eventually return to the disc, to be drawn inwards and accelerated to near-light speeds. Mass radiates away....*

DANCE OF THE MERGING BLACK HOLES

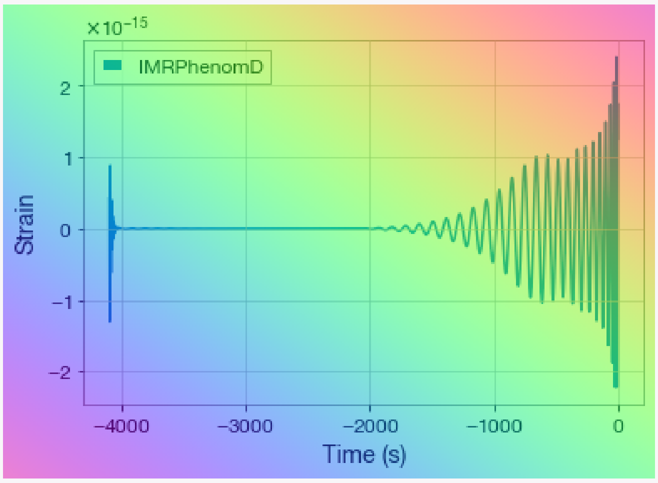
"Mass radiates away, and what remains is still unknown. In time, these singularities may find one another, engaging in a gravitational dance whose pulse can be felt throughout the universe."



Credit: NASA / Goddard Space Flight Center

Scientists learned through the massive amount of observations and simulations that galaxies can grow by merging with other galaxies. We also know that at the center of almost every galaxy there is a supermssive black hole. As such, we expect that black holes at the cores of colliding galaxies may combine to become even larger black holes. As they come within a fraction of a light-year of each other, they create ripples in the fabric of spacetime that undulate across the universe.

Unlike solar mass black holes that do not produce any light when merging because there is no floating gas around them, supermassive black hole binaries are surrounded by disks of glowing gas heated by magnetic and gravitational forces. Each black hole will have its own disk; a second, bigger one will ring both, like a bell, but this ringing gradually decreases as more energy is transmitted in the form of gravitational waves.



What to listen for

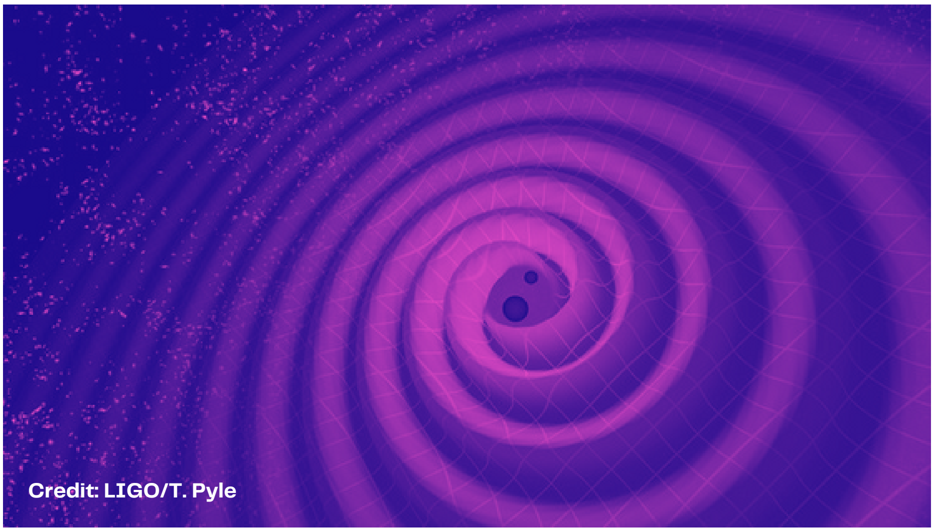
After passing the event horizon, we begin a new scene - perhaps occurring after millenia have passed. By chance, our black hole drifts within the gravitational influence of another of its kind, initiating a gravitational dance that will ultimately result in a violent merger.

The fourth movement of the symphony is a lilting 6/8 dance, beginning softly on guitar, growing steadily in intensity - and violence - as the masses are drawn inexorably together. The voice of the universe sings of loneliness, longing and destructive love.

When the energy reaches a critical threshold, the tempo increases rapidly. This final dance is a sonification of the gravitational waves released as black holes orbit one another in closing circles - provided from a simulation by scientist Fabio Pacucci (left). Here, the composer imagines a giant 'space trombone', playing sliding glissandi that are contorted by the stretching and squeezing of spacetime, mirrored by cascading orchestral arpeggios.

WAVES COMING HOME

"Einstein was right: these gravitational waves do resonate through spacetime itself. As they travel, our universe evolves around them – a ballet of gravity, matter and light, pulsing till the end of time.".



There are many astrophysical phenomena that are completely invisible in any form of light. Gravitational waves are a powerful new probe of the universe that uses gravity instead of light to take measure of dynamical astrophysical phenomena.

Gravitational waves were first theorized by Albert Einstein. Since the LIGO gravitational wave observatory came online in 2015 scientists discovered nearly 100 black hole mergers. But observatories like LIGO can "hear" ripples of spacetime created by "small" black holes with masses of the order of the Sun.

The discovery of merging supermassive black holes is yet to come. To capture ripples in the fabric of spacetime created by merging black holes billion times more massive than the Sun we need even bigger observatories than LIGO. We need observatory like the Laser Interferometer Space Antenna (LISA) with arms extending about a million miles in space. To capture even bigger gravitational waves we can use the entire galaxy by using pulsars that spin almost 1,000 times per second. Scientists can measure their rotation so precisely that we can use these pulsars to create a galactic-scale gravitational wave detector called Pulsar timing array (PTA).

What to listen for

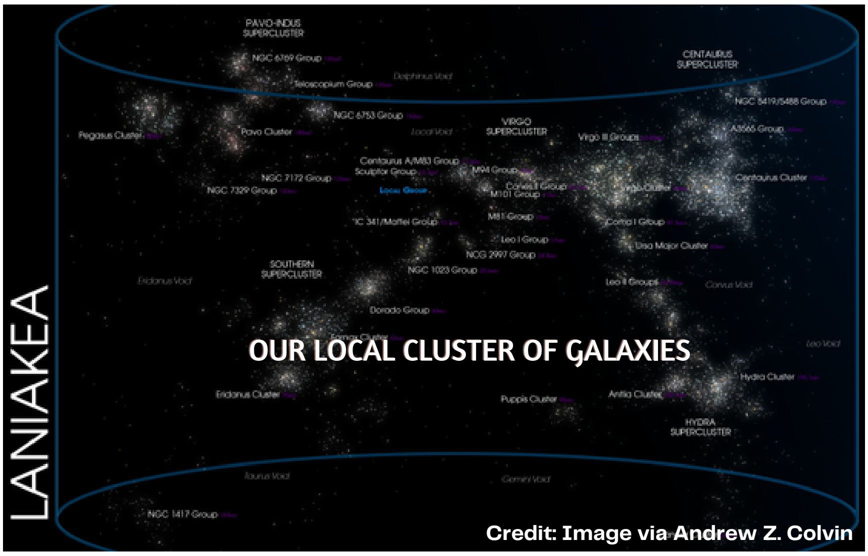
The fifth movement of the symphony follows the evolution of universal time experienced by a gravitational wave on its journey to us on Earth. Musical chimes and watch beeps enter one by one, building in intensity to a rhythmic march and orchestral tutti.

The voice of the universe reflects on our earthy perspective on these colossal events: how we see them written in the sky, how they have made us who we are, how they compel us to grow, understand and celebrate our place in the universal story.

"Our distant past adorns the sky,
Waves coming home, waves coming home
The trembling heart of a long dead star
Resonates freely, captures our memory

Like a searchlight on a mote of dust
Like a trumpet sounding out the void
Like a sun ray on a pale blue dot
Our universe sings! How shall we answer its call?"

LIGHTS WILL BE SHONE



"Black Holes; a story of destruction, radiation, creation and evolution. Inseparable from the story of the universe, and from the story of us. We are just beginning to draw back the veil."

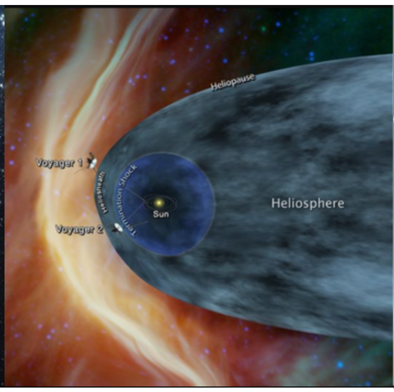
The advancement in science and technology in the last few decades exploded our understanding of the vast scale of the universe. Researchers use observations with the Hubble telescope to estimate that there are at least 2 trillion galaxies in the universe. Each galaxy has at least one supermassive black hole and on average 100 billion stars. Scientists estimate that there is at least one planet on average per star. One in five Sun-like stars is expected to have an "Earth-sized" planet in the habitable zone. But there is only one planet that we can call home.

What to listen for

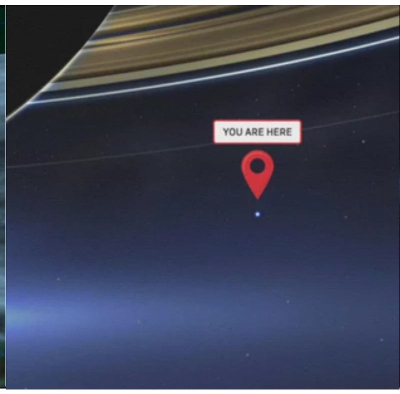
A final moment of reflection on the nature of time is marked by bells and a solemn chorale played by oboes and trumpets. As the music swells for one final time, the voice of the universe invites us to be thankful, and to look forward to ever more discoveries...

OUR PLACE IN THE GALAXY

OUR SOLAR SYSTEM



EARTH SEEN FROM SATURN



OUR ONLY HOME

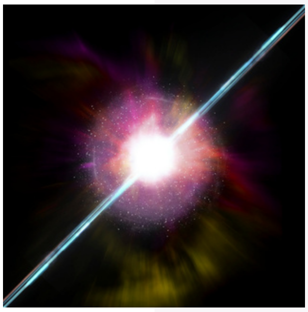
CREDITS

Black Hole Symphony

MUSIC BY DAVID IBBETT, DEDICATED TO ANNA BARNACKA

Visual design by the Charles Hayden Planetarium
at the Museum of Science, Boston

Produced by the Adult Programs & Theater Experiences
team at the Museum of Science, Boston
and Multiverse Concert Series



Science Research by

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Fabio Pacucci, Black Hole Initiative
Priya Natarajan, Yale, Black Hole Initiative
Dan Schwartz, CFA | Harvard & Smithsonian

Music by

Music Composed by David Ibbett
Lyrics by David Ibbett, inspired by Carl Sagan, Cecilia Payne-Gaposchkin and the women of the Harvard-Smithsonian Center for Astrophysics
Performed and Recorded by the Multiverse Symphony

Players:
Agnes Coakley Cox - Soprano
Andrew Harms - Trumpet
David Ibbett - Conductor
Johnny Mok - Cello
Meredith Moore - Horns
Matt Russo - Guitar
Ryan Shannon - Violin
Jessica Smith - Flute/Piccolo
Beth Sterling - Narrator

CREDITS

Audio Samples from:

Perseus Sonification – NASA/CXC/SAO/K.Arcand, SYSTEM Sounds (M. Russo, A. Santaguida)

Cosmic Microwave Background – Robert Wilson, Bell Labs

LIGO: Gravitational Wave Sonification September 14, 2015

NASA: Sound of a Black Hole – X-Ray Sonification of black hole GRS 1915+105 by Edward Morgan, MIT

Produced With Funding from:
Museum of Science, Boston
MathWorks
Massachusetts Music Teachers' Association

And Our Generous Kickstarter Backers,
Special Mention to:

Anna Barnacka
Winfield Perry
Sherie Bush
Chad Council
Kane Hadley
Charles Dornbush
Lily Symmonds
Dan and Vicky Schwartz
Martin Elvis
Tomasz Kierul
Jane, Roger and Chris Ibbett
Beth and John Titterington
Rajarajan Palanimurugan
Smitha Vishveshwara
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