NEUTRINO IN PHYSICS AND ASTROPHYSICS (supplement)

RELEVANT & IRRELEVANT

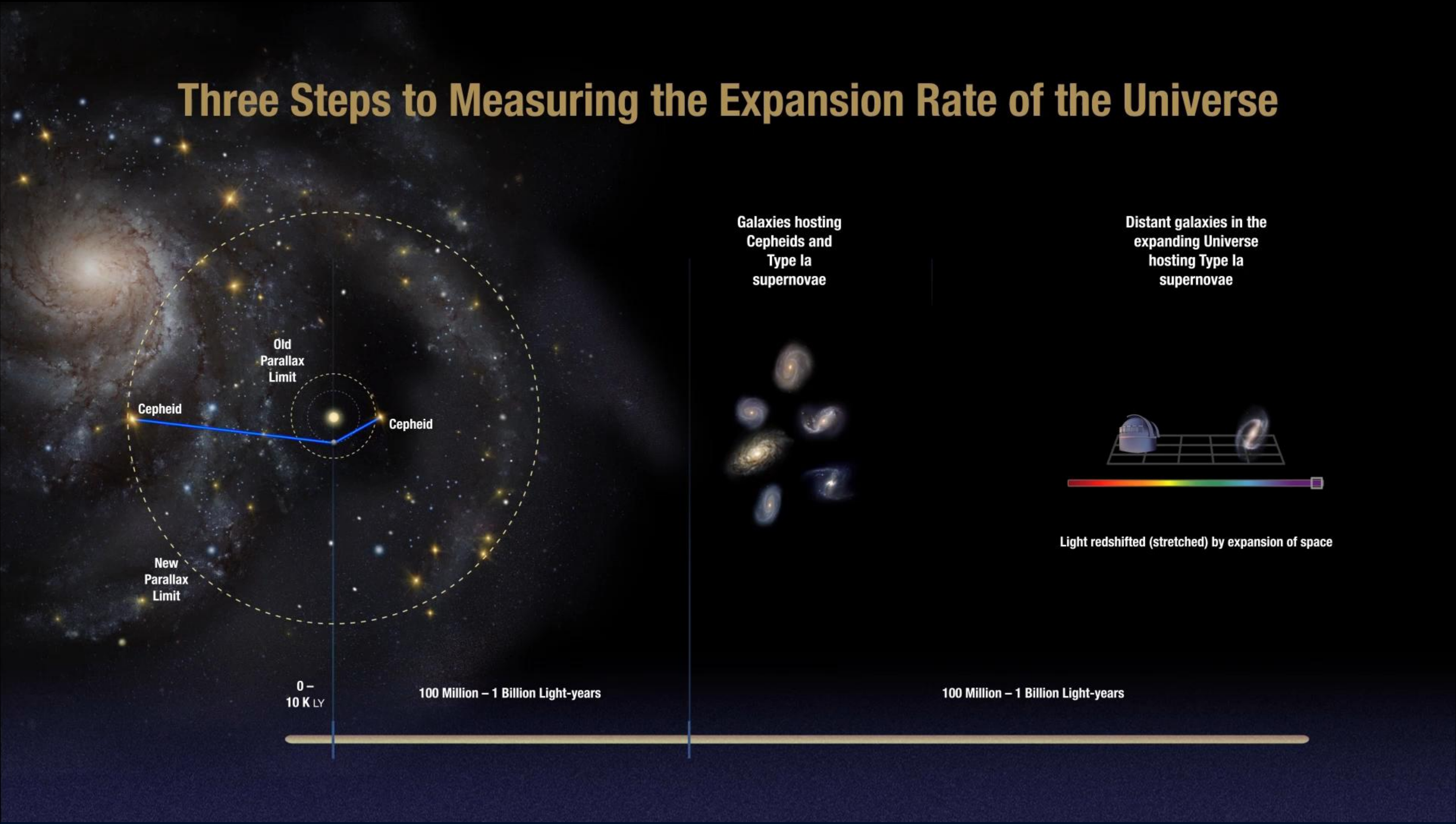
(non-systematic selection of slides on some topics covered in the lectures)

V. Naumov

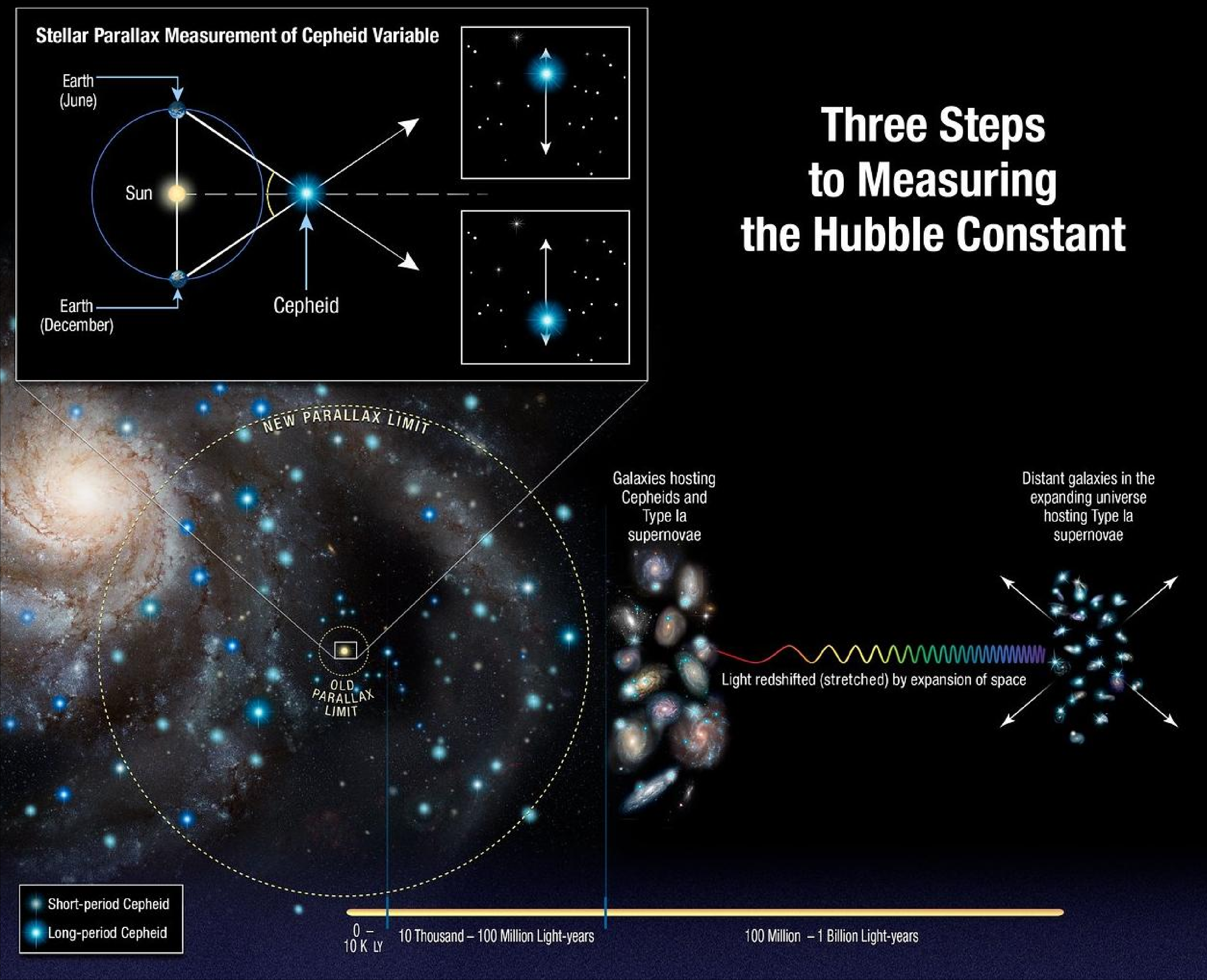
JINR, Fall Term 2023

v.01.11.2023

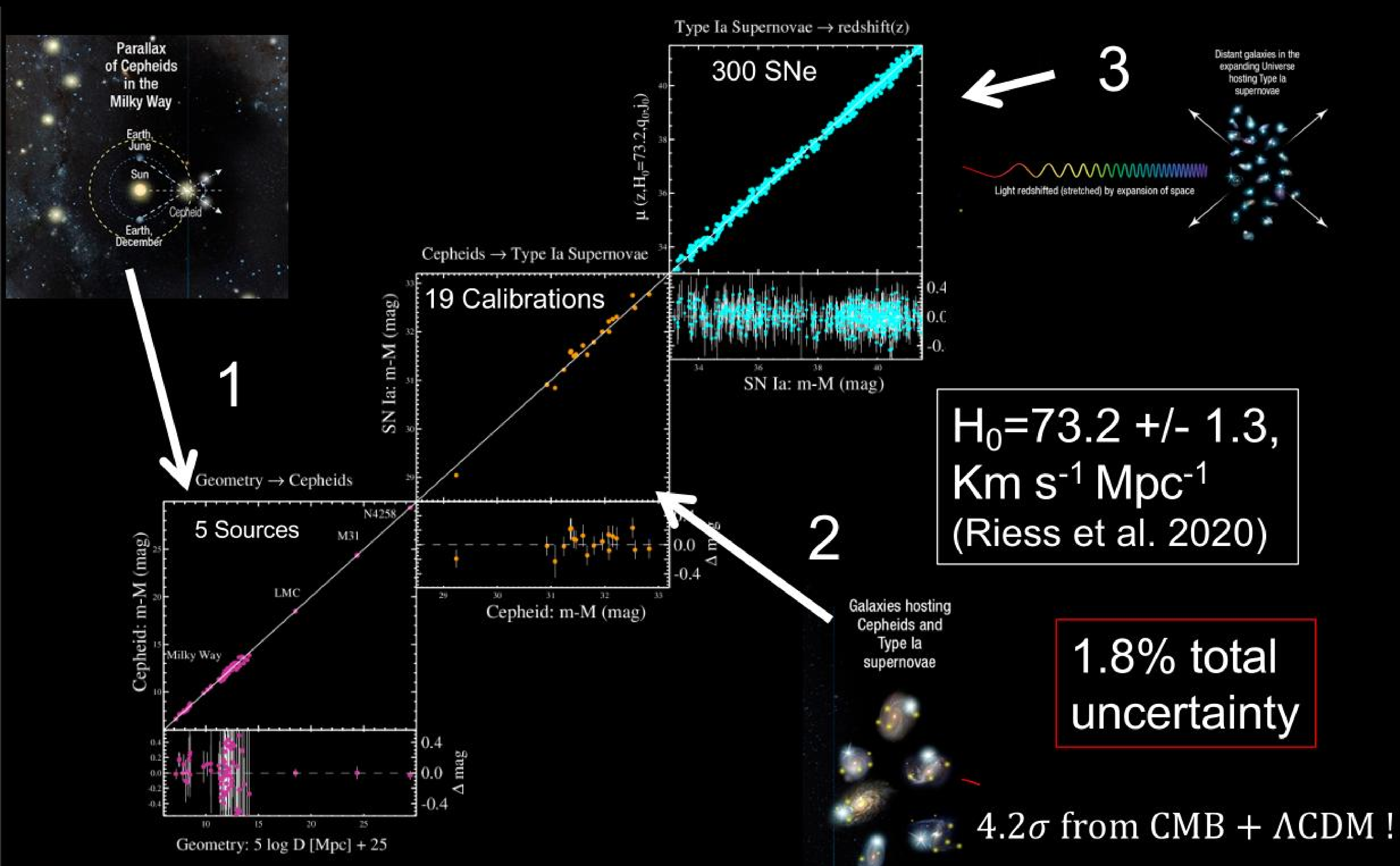
New determination of the Hubble constant with Gaia EDR3



From URL: https://supernova.eso.org/exhibition/videos/heic1611a/



From URL: https://www.eso.org/public/blog/first-rung-on-cosmic-distance-ladder/



*Simultaneous Fit: Retain interdependence of data and parameters

From A. Riess (SHoES Team), "New Determination of the Hubble constant with Gaia EDR3, Further evidence of excess expansion"; < https://indico.in2p3.fr/event/22845/attachments/61796/84379/2021seminar_shown.pdf >;for details and further references, see Riess et al. ApJL 908 (2021) L6, arXiv:2012.08534 [astro-ph.CO].

Gravitational waves (instrumnts)

Arecibo radio telescope

Operating wavelength range: from 3 cm to 1 m.
Operating radio frequency range: 300 MHz to 10 GHz
Focal length: 132.5 m.
Reflector mirror shape: spherical surface.
Reflector mirror diameter: 304.8 m.
Reflector mirror depth: 50.9 m.
Mirror area ≈ 73,000 m².
In operation: 1963 – 2020.

The telescope was built in a natural sluggy in Puerto Rico and was one of the largest radio telescopes in the world.

What really happened at the Arecibo observatory?

On the morning of December 1st, 2020, one of the most iconic astronomical instruments in the world collapsed. Cannot be restored.

Music of pulsars

From URL: https://www.youtube.com/watch?v=jJqeIIAQ2bo

Dark matter

Figure shows the "bullet cluster" 1E0657-56 and "baby bullet" MACSJ0025.4-1222.

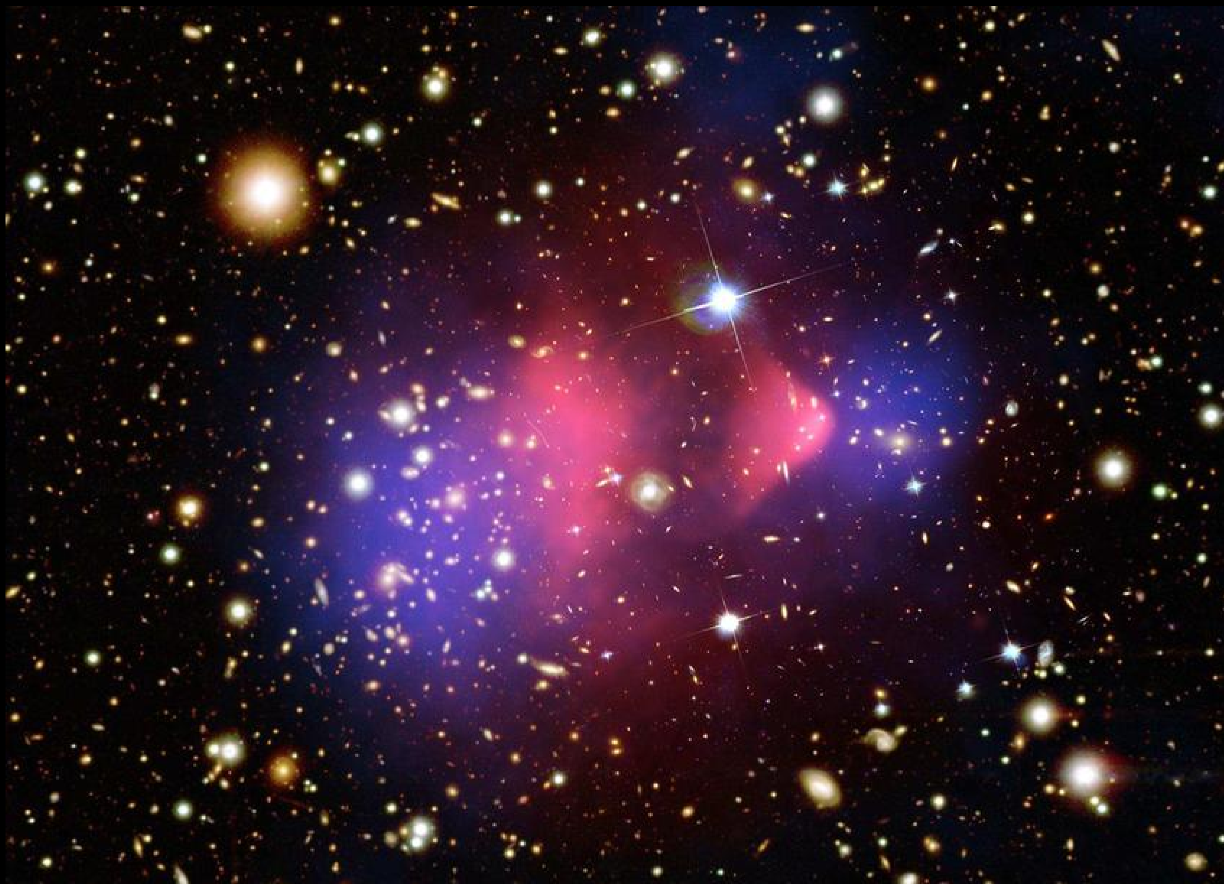


Figure credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.
Optical image: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
NASA/ESA/M.Bradac et al.

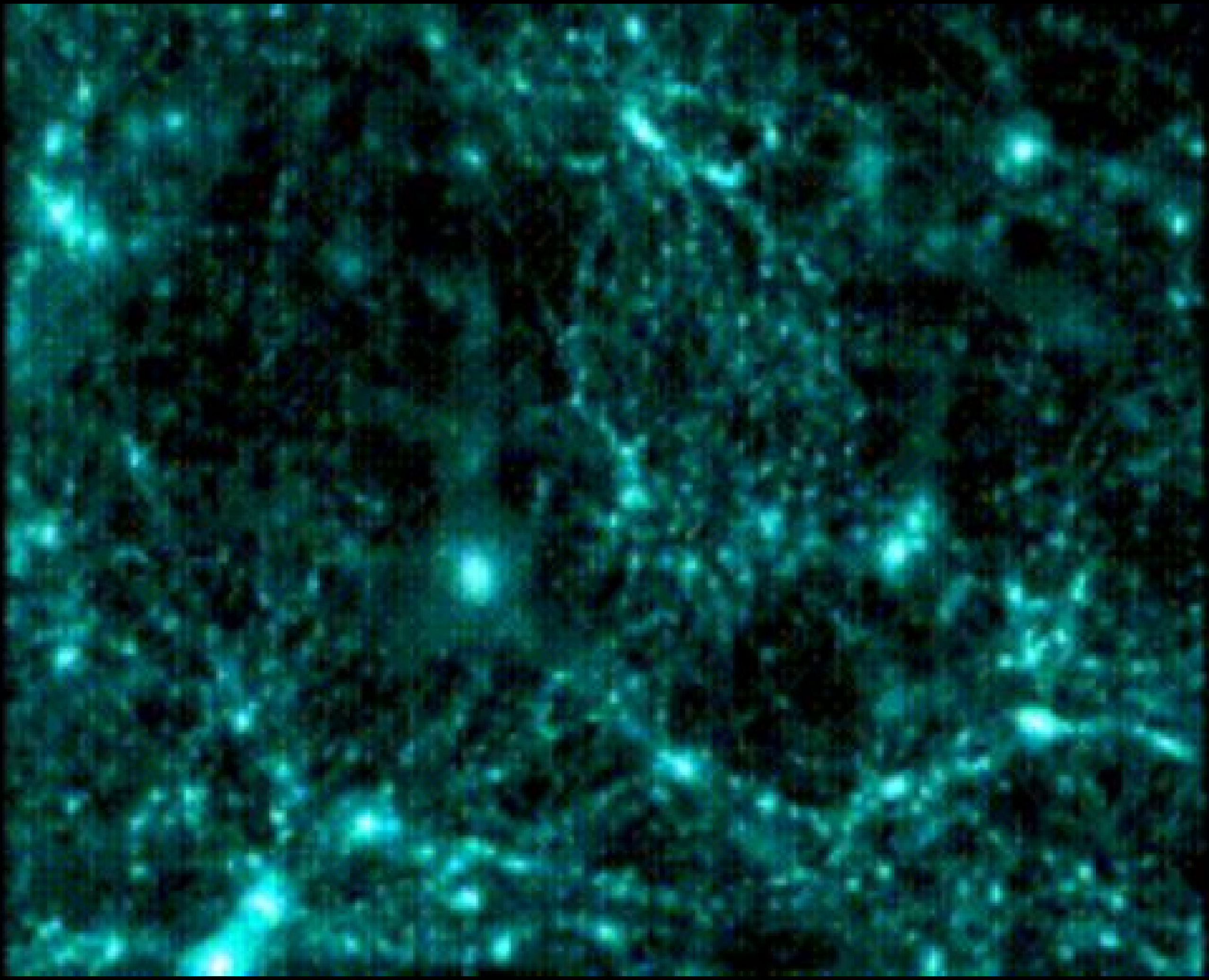
The background images show the location of galaxies, with most of the larger yellow galaxies associated with one of the clusters. The overlaid pink features show X-ray emission from hot, intra-cluster gas. Galaxies and gas are baryonic material. The overlaid blue features show a reconstruction of the total mass from measurements of gravitational lensing. This appears coincident with the locations of the galaxies, implying it has a similarly small interaction cross-section. However, there is far more mass than that present in the stars within those galaxies, providing strong evidence for the existence of an additional reserve of dark matter.

From https://www.researchgate.net/figure/The-bullet-cluster-1E0657-56-and-baby-bullet-MACSJ00254-1222-The-background_fig4_45894607

One of the best evidence for Dark Matter
Abell 520

This false-color image shows giant blobs of dark matter left inside galaxy cluster Abell 520 after collisions between many galaxies there. Dark matter can be inferred by its gravitational effects on nearby light rays.

From https://nautil.us/blog/the-best-evidence-for-dark-matter--the-uncertainty-therein

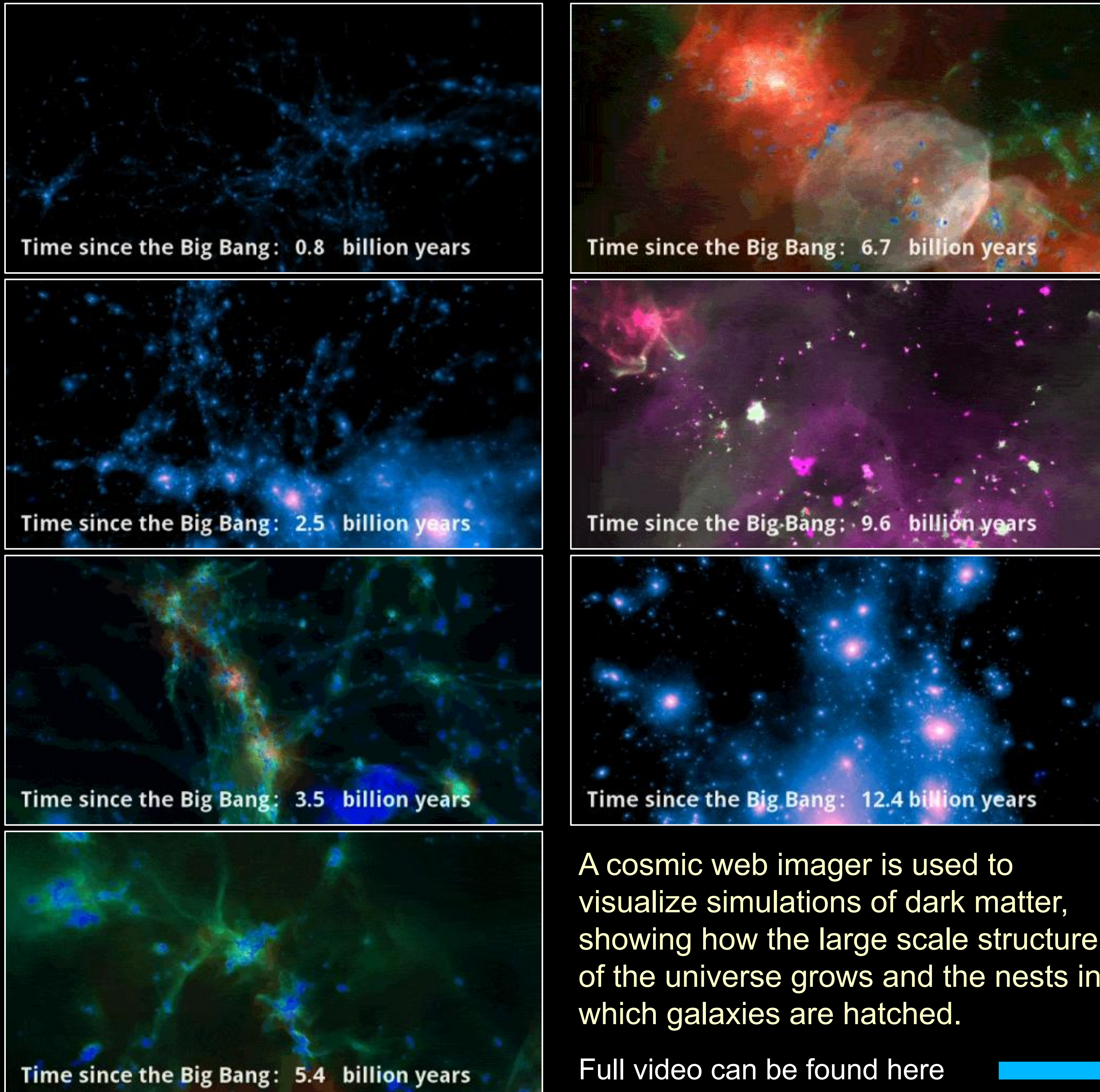


A computerized visualization showing the possible large-scale structure of dark matter in the universe.

(Credit: Amit Chourasia and Steve Cutchin/NPACI Visualization Services; Enzo)

From https://newscenter.lbl.gov/2016/05/24/3-knowns-3-unknowns-dark-matter/

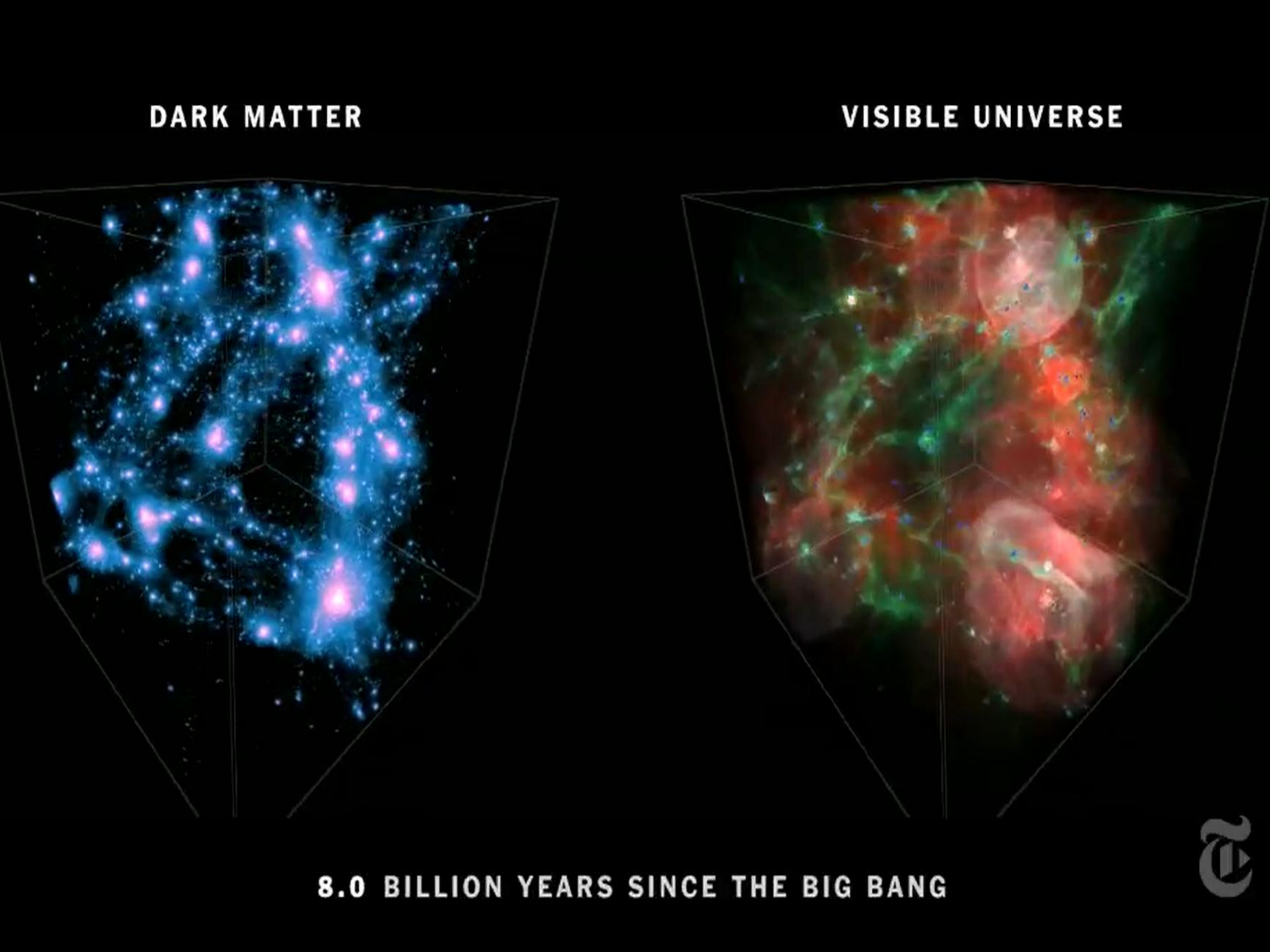
Another computer simulation

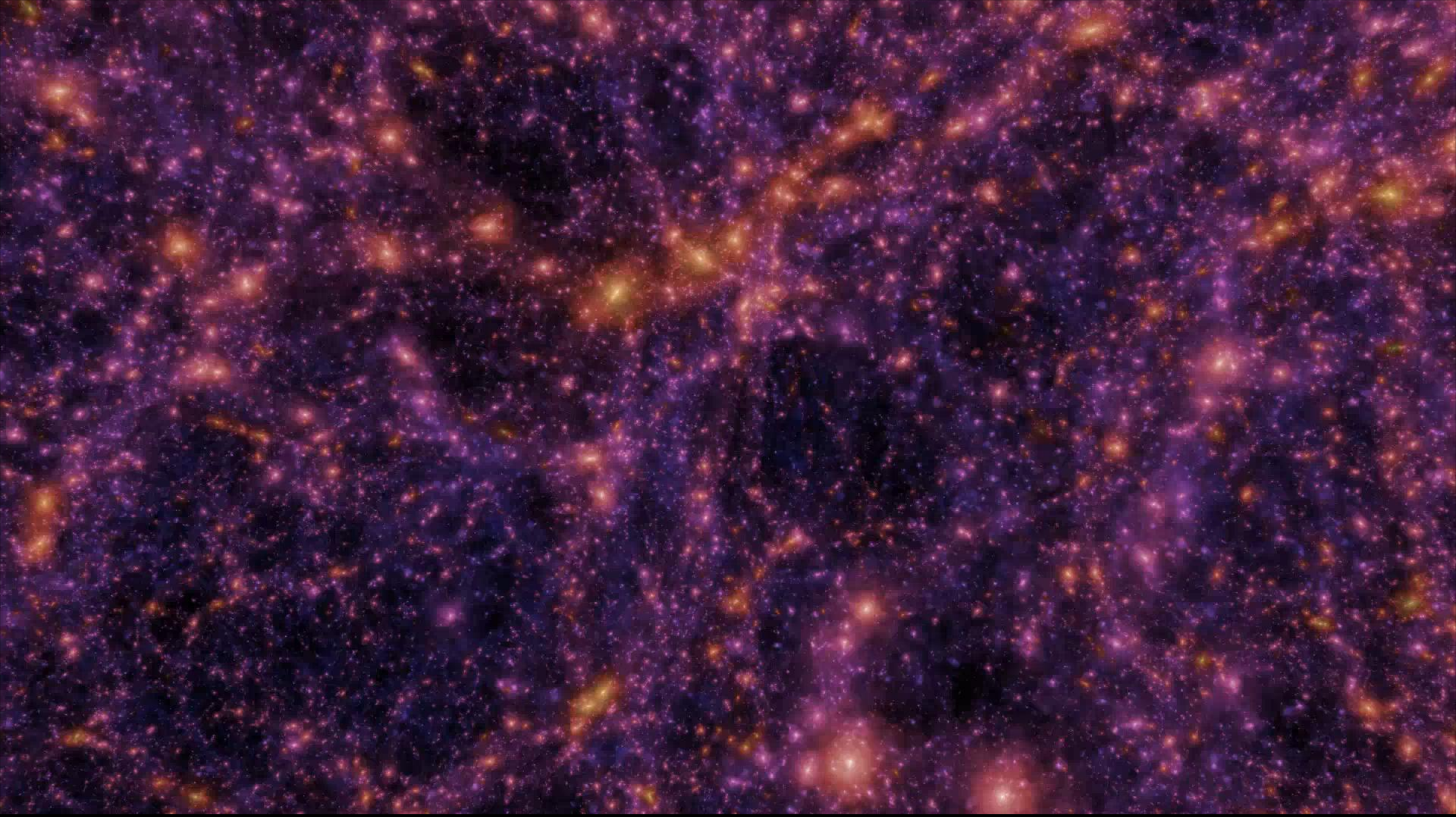


A cosmic web imager is used to visualize simulations of dark matter, showing how the large scale structure of the universe grows and the nests in which galaxies are hatched.

Full video can be found here

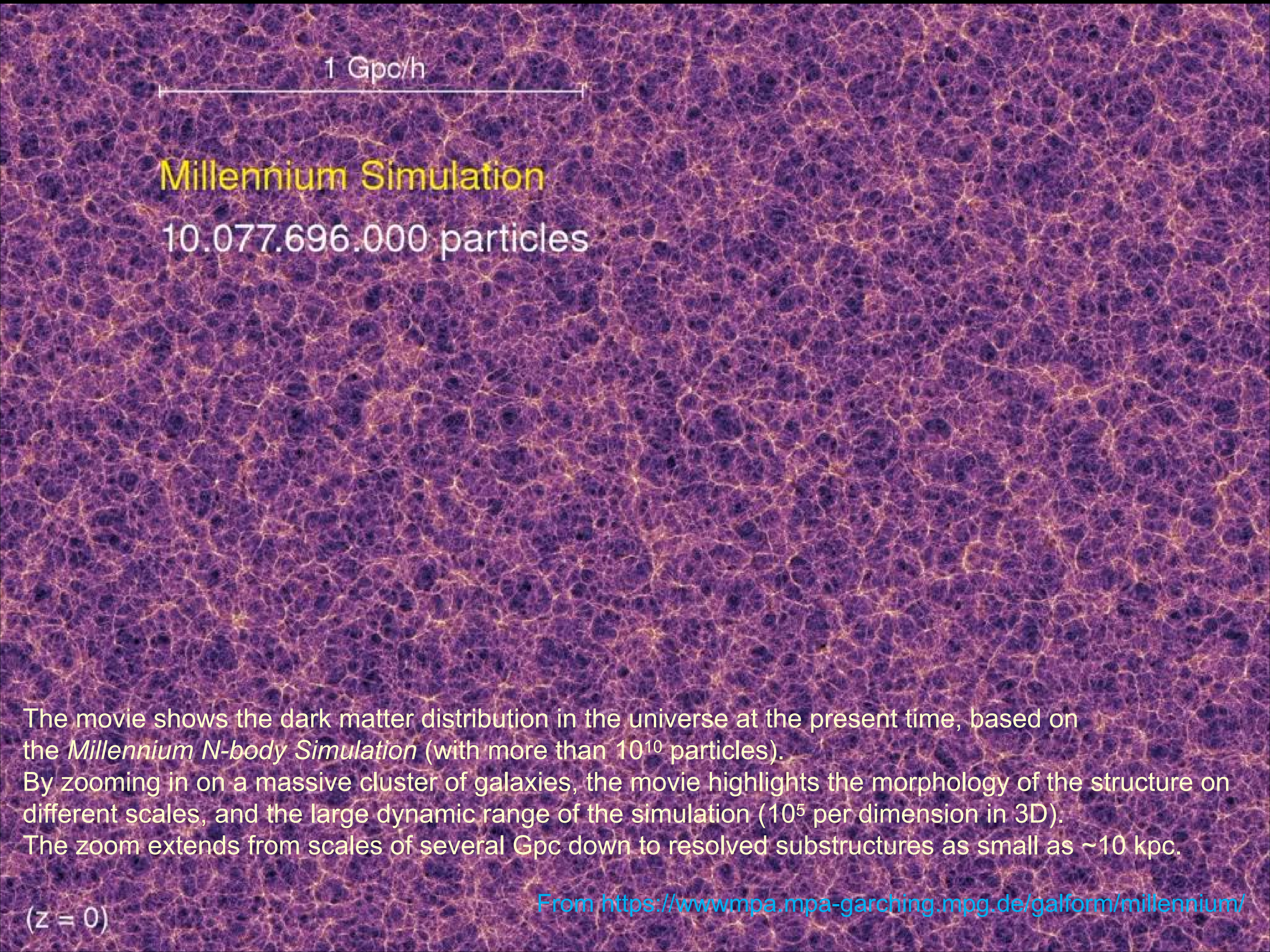
https://archive.nytimes.com/www.nytimes.com/indexes/2014/07/16/video/timesvideo-email/index.html?emc=edit_fs_20140716&nl=video


DARK MATTER
VISIBLE UNIVERSE
8.0 BILLION YEARS SINCE THE BIG BANG



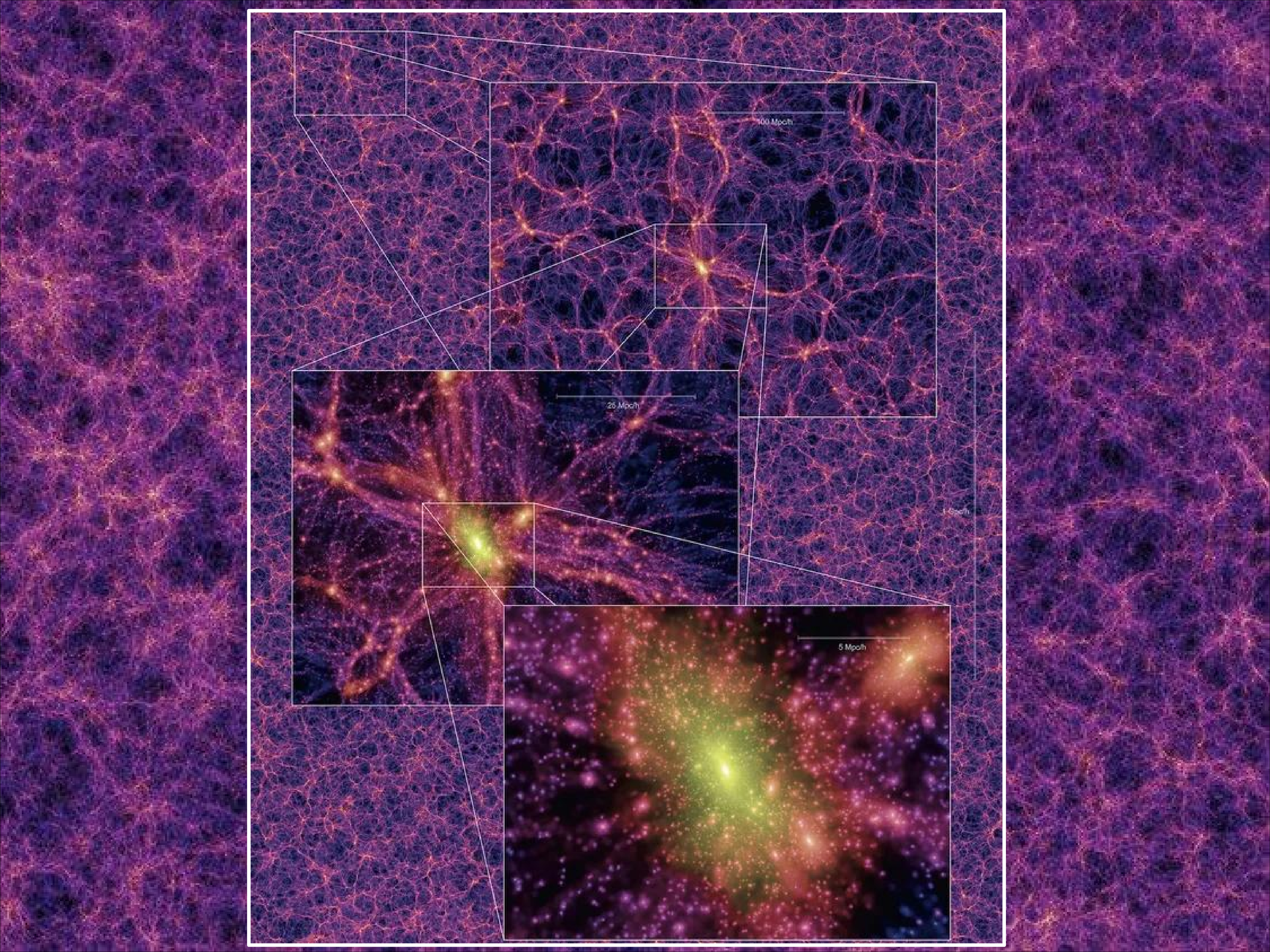
A 3-dimensional visualization of the *Millennium Simulation*. The movie shows a journey through the simulated universe. On the way, we visit a rich cluster of galaxies and fly around it. During the two minutes of the movie, we travel a distance for which light would need more than 2.4 billion years. See details V. Springel et al., "Simulating the joint evolution of quasars, galaxies and their large-scale distribution," Nature **435** (2005) 629-636; astro-ph/0504097.

From https://wwwmpa.mpa-garching.mpg.de/galform/millennium/



The movie shows the dark matter distribution in the universe at the present time, based on the *Millennium N-body Simulation* (with more than 10^{10} particles).
By zooming in on a massive cluster of galaxies, the movie highlights the morphology of the structure on different scales, and the large dynamic range of the simulation (10^5 per dimension in 3D).
The zoom extends from scales of several Gpc down to resolved substructures as small as ~10 kpc.

From https://wwwmpa.mpa-garching.mpg.de/galform/millennium/


100 Mpc/h
25 Mpc/h
5 Mpc/h
1 Gpc/h

STARS

in the Hertzsprung–Russell diagram

The Hertzsprung-Russell diagram is most famous diagram in astronomy.

It is a plot of luminosity (absolute magnitude) against the colour of the stars ranging from the high-temperature blue-white stars on the left side of the diagram to the low temperature red stars on the right side.

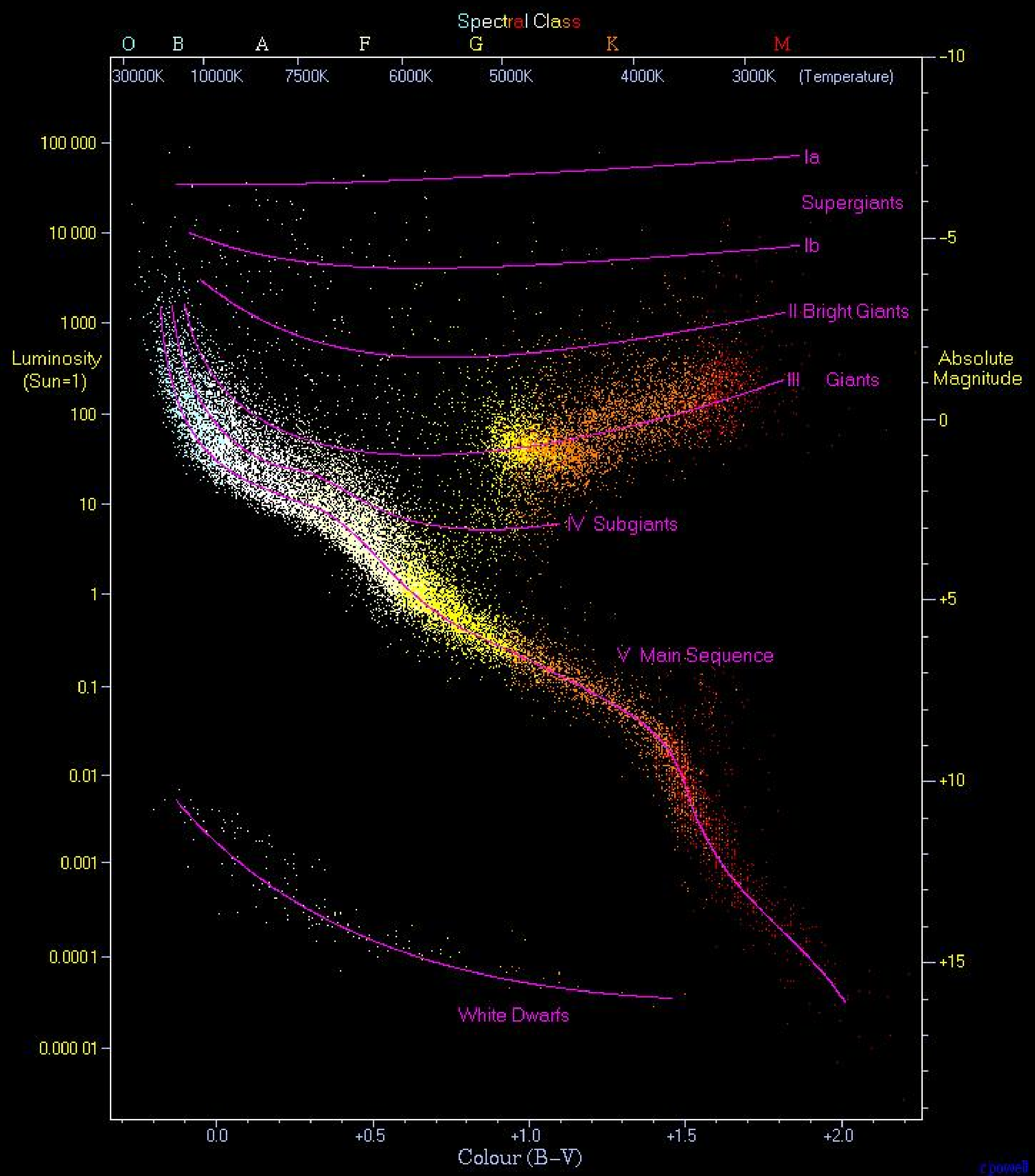
The diagram shown in next slide is a plot of 22000 stars from the Hipparcos Catalogue together with 1000 low-luminosity stars (red and white dwarfs) from the Gliese Catalogue of Nearby Stars.

The ordinary hydrogen-burning dwarf stars like the Sun are found in a band running from top-left to bottom-right called the Main Sequence.

Giant stars form their own clump on the upper-right side of the diagram.

Above them lie the much rarer bright giants and supergiants.

At the lower-left is the band of white dwarfs – these are the dead cores of old stars which have no internal energy source and over billions of years slowly cool down towards the bottom-right of the diagram.



Hertzsprung-Russell diagram by Richard Powell.

Stars are classified into five main luminosity classes:

I Supergiants

Very massive and luminous stars near the end of their lives. They are subclassified as **Ia** or Ib, with **Ia** representing the brightest of these stars. These stars are very rare - 1 in a million stars is a supergiant. The nearest supergiant star is **Canopus** (**F0Ib**) 310 light years away. Some other examples are **Betelgeuse** (**M2Ib**), **Antares** (**M1Ib**), and **Rigel** (**B8Ia**).

II Bright Giants

Stars which have a luminosity between the giant and supergiant stars. Some examples are **Sargas** (**F1II**) and **Alphard** (**K3II**).

III Normal Giants

These are mainly low-mass stars at the end of their lives that have swelled to become a giant star. This category also includes some high mass stars evolving on their way to supergiant status. Some examples are **Arcturus** (**K2III**), **Hadar** (**B1III**), and **Aldebaran** (**K5III**).

IV Subgiants

Stars which have begun evolving to giant or supergiant status. Some examples are **Alnair** (**B7IV**) and **Muphrid** (**G0IV**). Note also **Procyon** which is entering this category and therefore is **F5IV-V**

V Dwarfs

All normal hydrogen-burning stars. Stars spend most of their lives in this category before evolving up the scale. Class **O** and **B** star in this category are actually very bright and luminous and generally brighter than most Giant stars. Some examples are the **Sun** (**G2V**), **Sirius** (**A1V**), and **Vega** (**A0V**).

Oh

Be

A

Fine

Girl/Guy,

Kiss

Me

Stellar Class	Radius	Mass	Luminosity	Temperature
	$R/R_\odot$	$M/M_\odot$	$L/L_\odot$	K
O2	16	158	2,000,000	54,000
O5	14	58	800,000	46,000
B0	5.7	16	16,000	29,000
B5	3.7	5.4	750	15,200
A0	2.3	2.6	63	9,600
A5	1.8	1.9	24	8,700
F0	1.5	1.6	9.0	7,200
F5	1.2	1.35	4.0	6,400
G0	1.05	1.08	1.45	6,000
G2	1.0	1.0	1.0	5,700
G5	0.98	0.95	0.70	5,500
K0	0.89	0.83	0.36	5,150
K5	0.75	0.62	0.18	4,450
M0	0.64	0.47	0.075	3,850
M5	0.36	0.25	0.013	3,200
M8	0.15	0.10	0.0008	2,500
M9.5	0.10	0.08	0.0001	1,900

The table shows typical values for stars along the main sequence.

The values of
radius (R),
mass (M), and
luminosity (L),
are relative to the Sun.

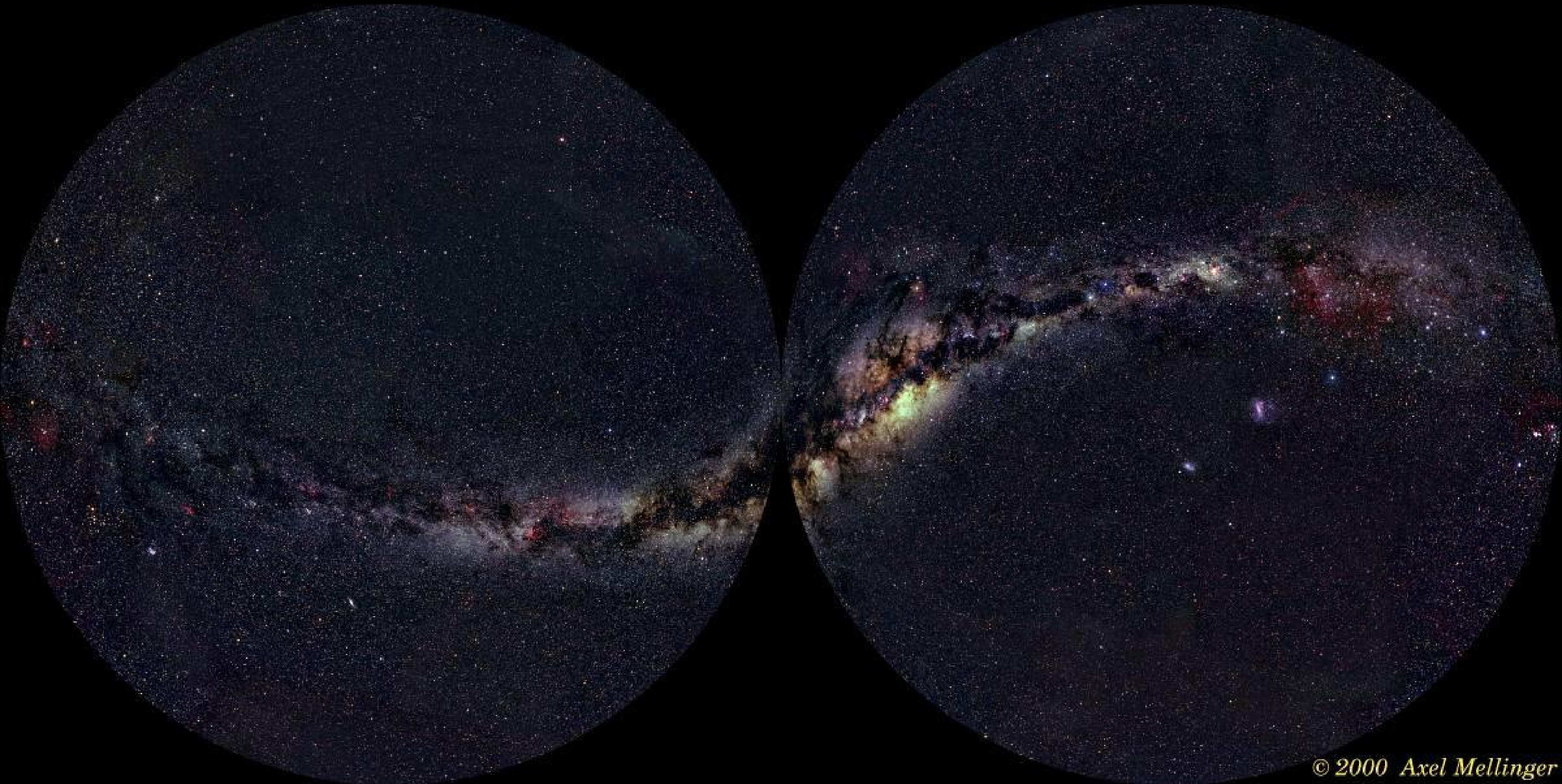
The actual values for a star may vary by as much as 20-30%.

The coloration of the stellar class column gives an approximate representation of the star's photographic color.

[From Wikipedia]

The Deep Sky: 360-degree All-Sky Panorama

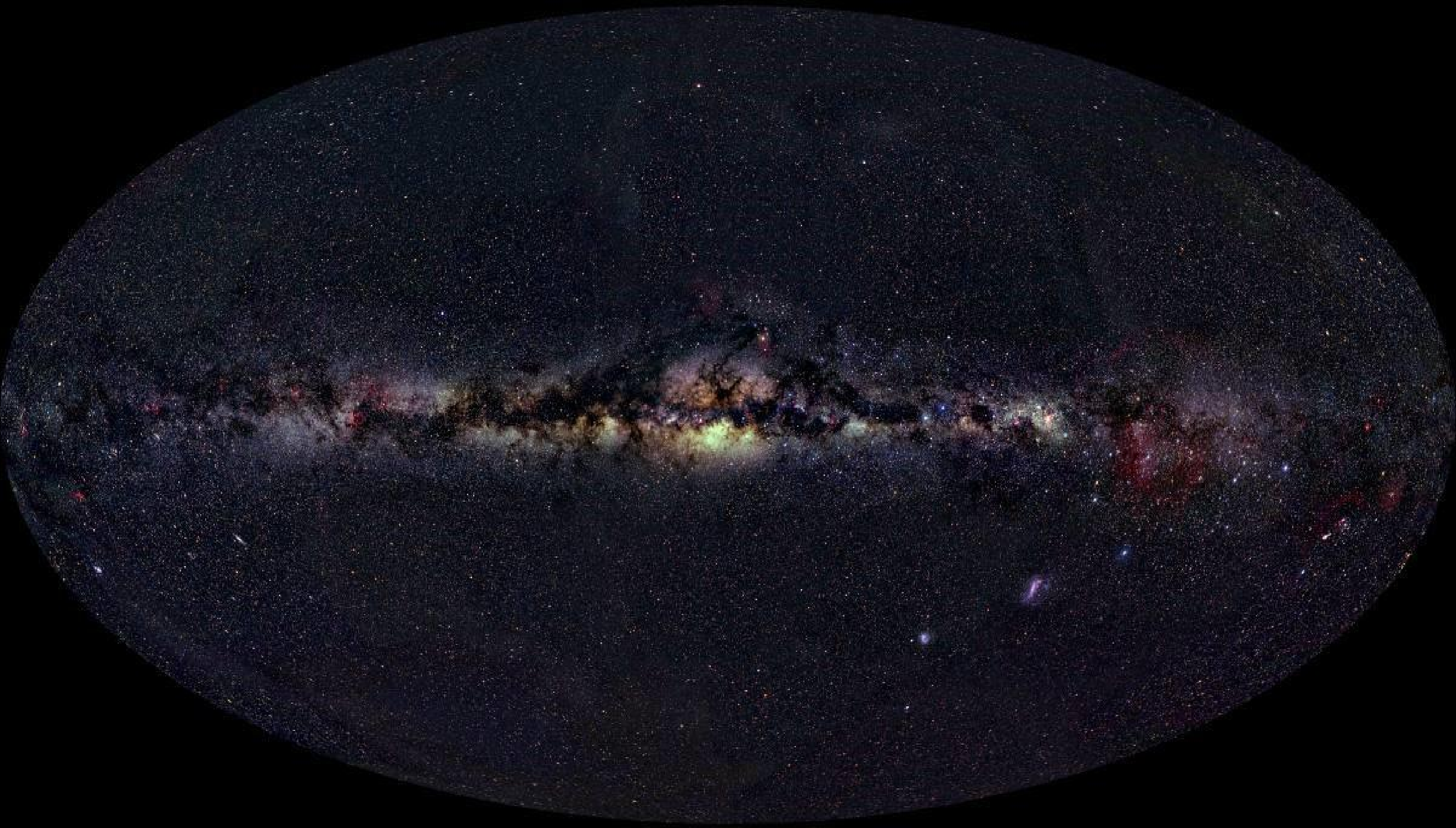
(equidistant azimuthal projection)



This panoramic view of the entire sky has been assembled from 51 wide-angle photographhcs. The individual images were transformed to a cartesian frame based on galactic coordinates prior to assembly, thus eliminating the distortions introduced by the wide-angle lens. The final image was then tranformed using an equidistant azimuthal (polar) projection.

[From Alex Mellinger's All-Sky Milky Way Panorama, URL: http://home.arcor-online.de/axel.mellinger/allsky.html].

The Deep Sky: 360-degree All-Sky Panorama
(Aitoff projection)



The same as in the previous slide but tranformed using an Aitoff projection.

List of the largest discovered cosmic structures

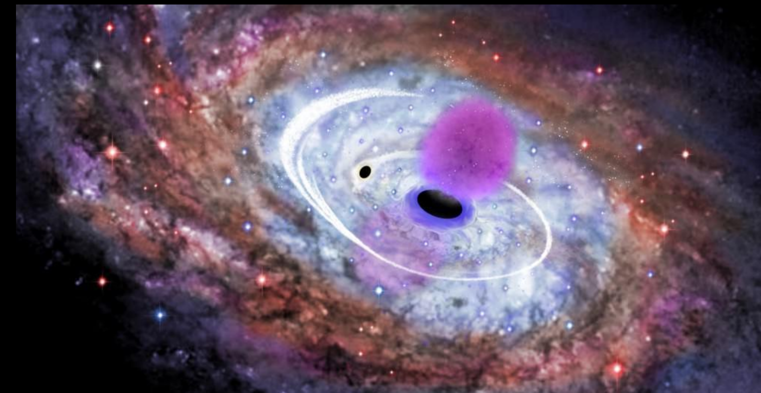
Structure name	year disc.	Maximum dimension (ly)	Structure name	year disc.	Maximum dimension (ly)
Hercules–Corona Borealis Great Wall	2014	$(9.7-10)\times 10^9$	BOSS Great Wall (BGW)	2016	10^9
Giant GRB Ring	2015	5.6×10^9	Perseus–Pegasus Filament	1985	10^9
Huge-LQG	2012–2013	4.0×10^9	Pisces–Cetus Supercluster Complex	1987	10^9
"The Giant Arc"	2021	3.3×10^9	CfA2 Great Wall	1989	7.5×10^8
U1.11 LQG	2011	2.5×10^9	Saraswati Supercluster		6.52×10^8
Clowes–Campusano LQG	1991	5.6×10^9	Boötes Supercluster (MSCC-414)	2015	6.2×10^8
Sloan Great Wall	2003	2.0×10^9	Horologium-Reticulum Supercluster	2005	5.5×10^8
South Pole Wall	2020	1.38×10^9	Laniakea Supercluster	2014	5.2×10^8
King Ghidorah Supercluster	2022	1.37×10^9	Komberg–Kravtsov–Lukash LQG 11	1996	5.0×10^8
Theoretical limit		1.2×10^9			

Hercules-Corona Borealis Great Wall or (more correct name) **Great GRB Wall**

is the largest known structure in the observable Universe, measuring ~10 billion light years in length. This massive superstructure is a region of the sky seen in the data set mapping of GRB that has been found to have an unusually higher concentration of similarly distanced GRBs than expected average distribution. Most likely Great GRB Wall is a supercluster.

It lies in the Northen Hemisphere, centered on the border id the constellation Draco and Hercules. The entire clustering consists of around 19 GRBs with the redshift ranges between 1.6 and 2.1.

Fermi Bubbles



In 2010, astronomers using NASA's Hubble Space Telescope observed giant balloon-like features emanating from the Milky Way core. The balloon-like featured are termed "Fermi Bubbles" and consist of clouds of gas towering about 30,000 ly above and below the plane of the Milky Way Galaxy. The Fermi Bubbles are made up of super-high-energy gamma-ray and X-ray emissions, which are invisible to the naked eye.

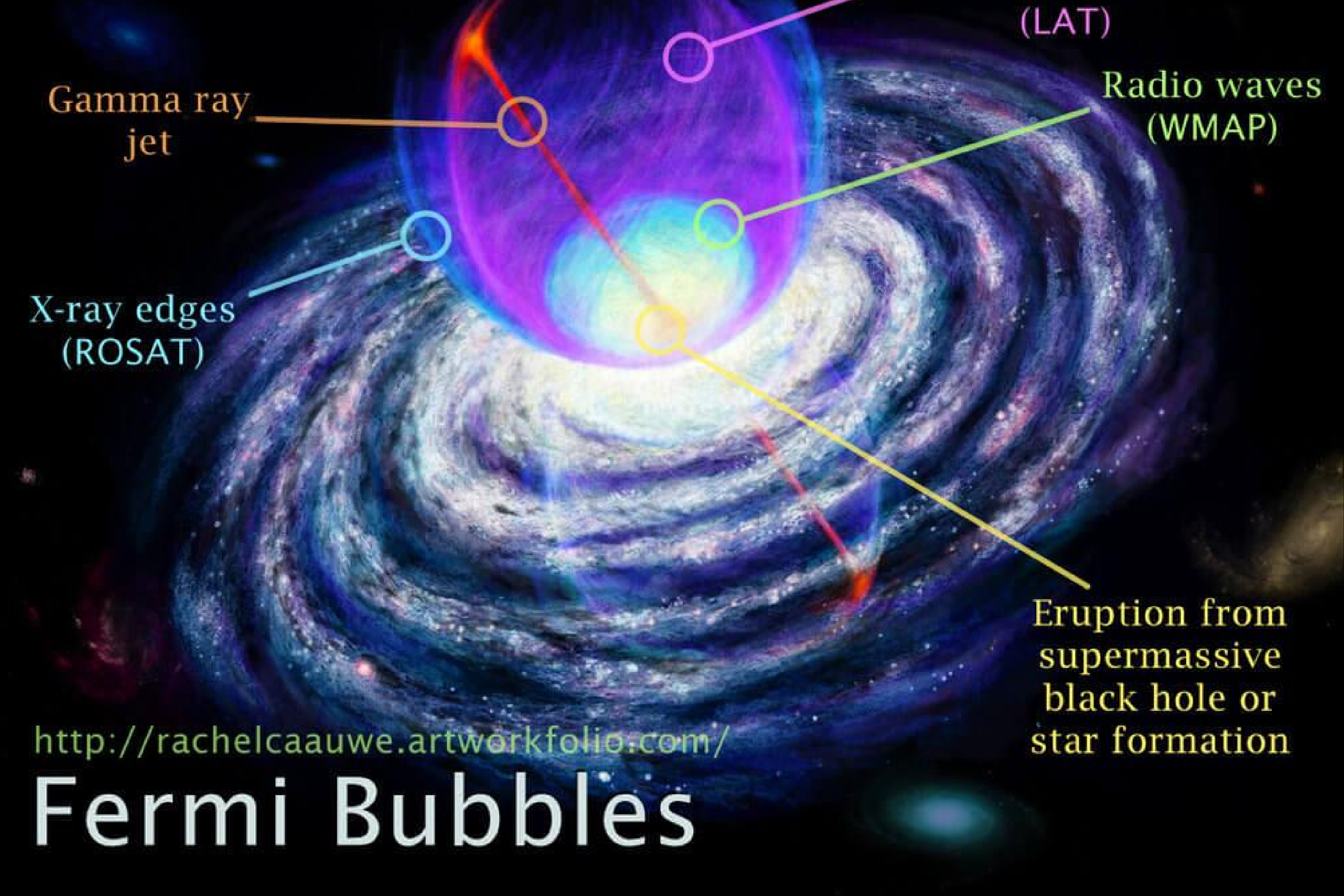
What is causing the Fermi Bubbles is a mystery.
Some scientists have hypothesized that the gamma rays might be shock waves from stars being consumed by the massive black hole at the center of the galaxy.
Others suggest it may be due to a firestorm of star birth at the galactic center.

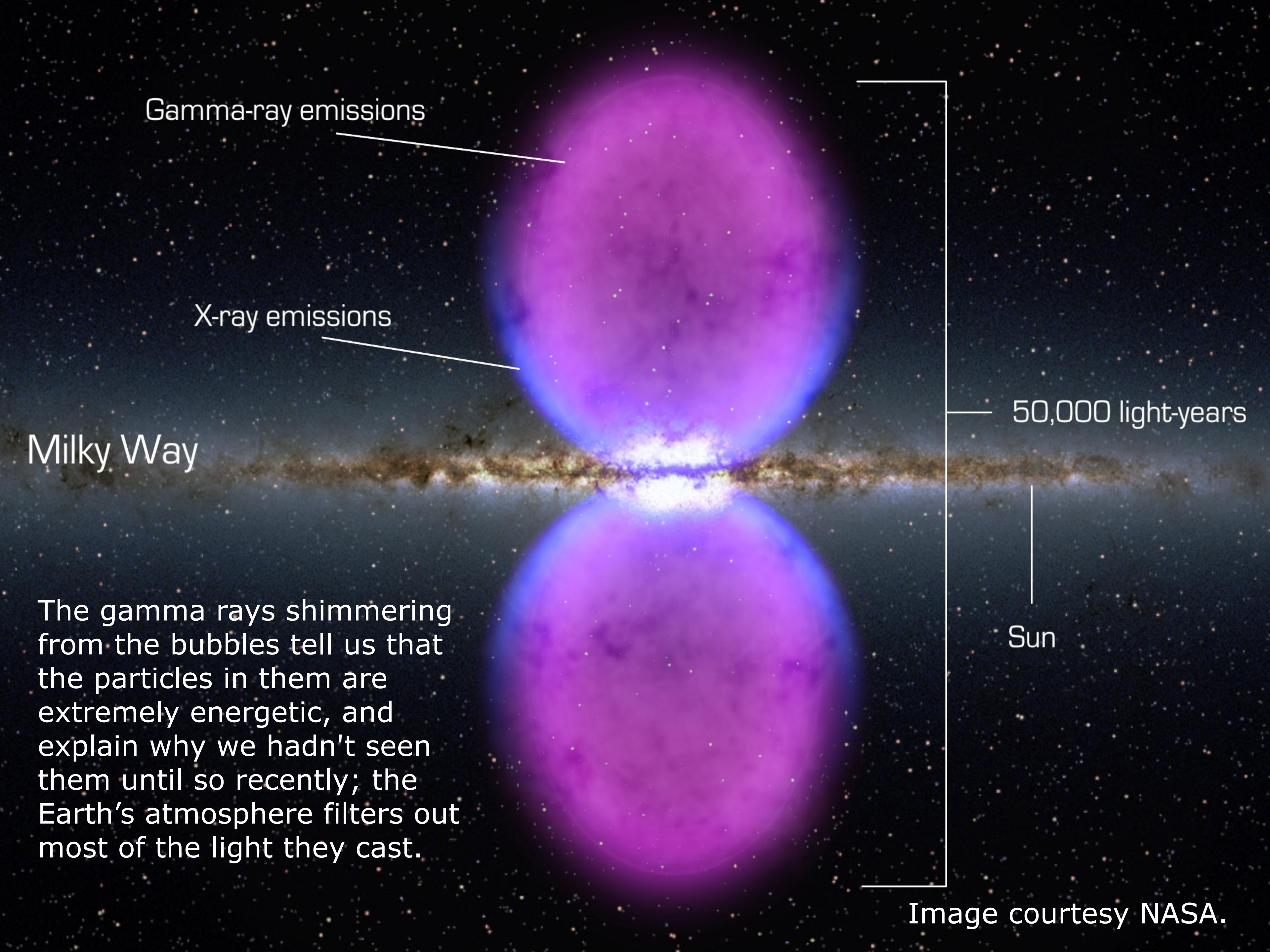
Although, we have seen similar structures emanating from the core of other galaxies, the 2010 discovery was the first time we observed the phenomena in our own galaxy, which gives us a rare close up view of the phenomena.

"When you look at the centers of other galaxies, the outflows appear much smaller because the galaxies are farther away. The outflowing clouds we're seeing are only 25,000 light-years away in our galaxy. We have a front-row seat. We can study the details of these structures. We can look at how big the bubbles are and can measure how much of the sky they are covering."

Andrew Fox of the Space Telescope Science Institute in Baltimore, Maryland (Jan. 5, 2015).

A few more details
(radio, X-ray, gammas)




Gamma-ray emissions
X-ray emissions
Milky Way
50,000 light-years
Sun
The gamma rays shimmering from the bubbles tell us that the particles in them are extremely energetic, and explain why we hadn't seen them until so recently; the Earth's atmosphere filters out most of the light they cast.
Image courtesy NASA.

In addition to being really large and scattered, the bubbles have well-defined edges. The shape of the bubbles and the light they emit indicate that they are created as a result of the rapid release of energy. But with what? And when?

One possible explanation is that they could be leftovers from the last big meal eaten by the supermassive black hole at the center of our galaxy. This monster is more than 4 million times the mass of our own Sun. It may have slurped up a big cloud of hydrogen between 6 and 9 million years ago and then burped jets of hot gas that we see in gamma rays and X-rays.

[From https://nasa.tumblr.com/post/179690202529/blowing-bubbles-in-the-gamma-ray-sky]

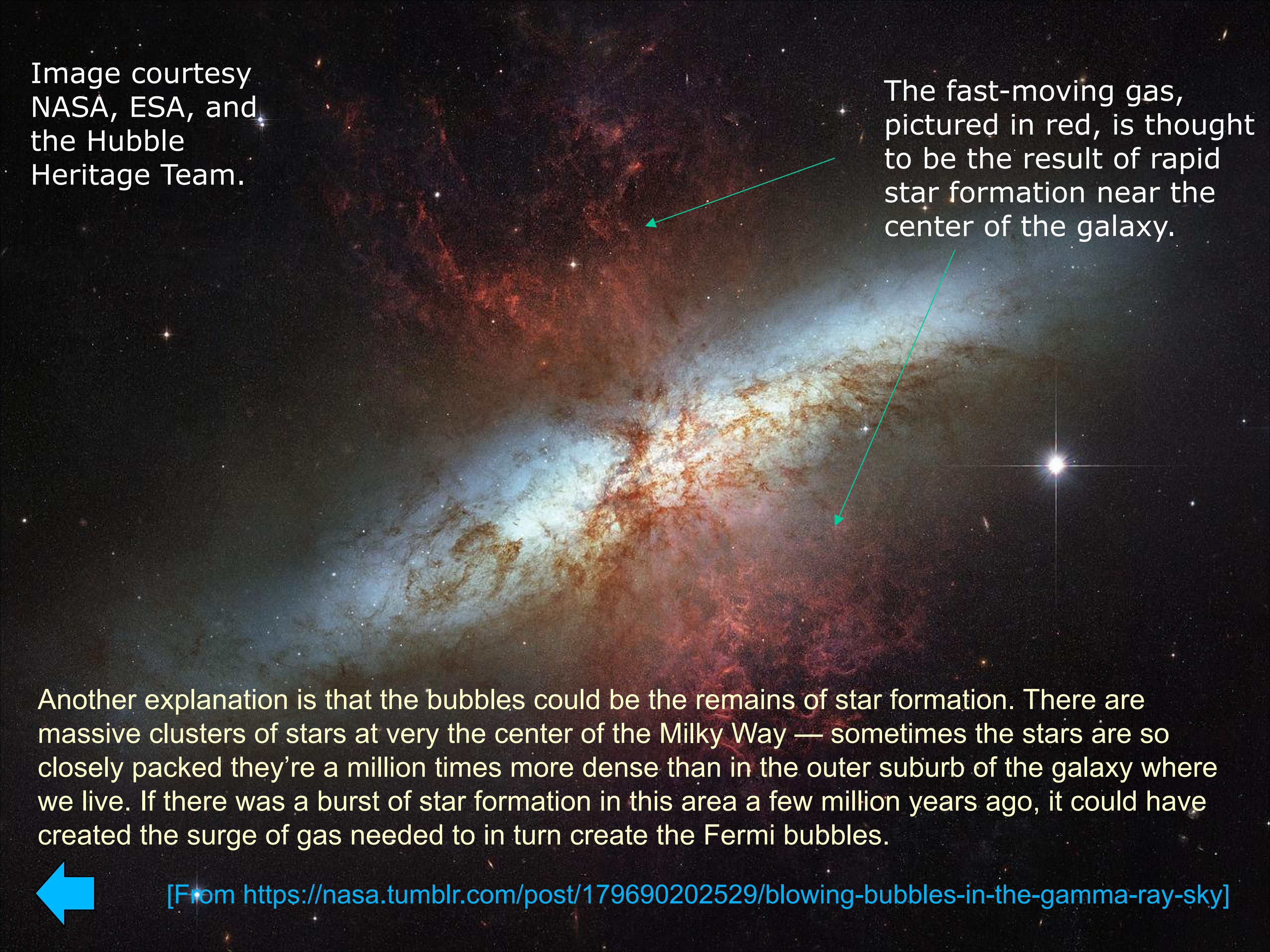


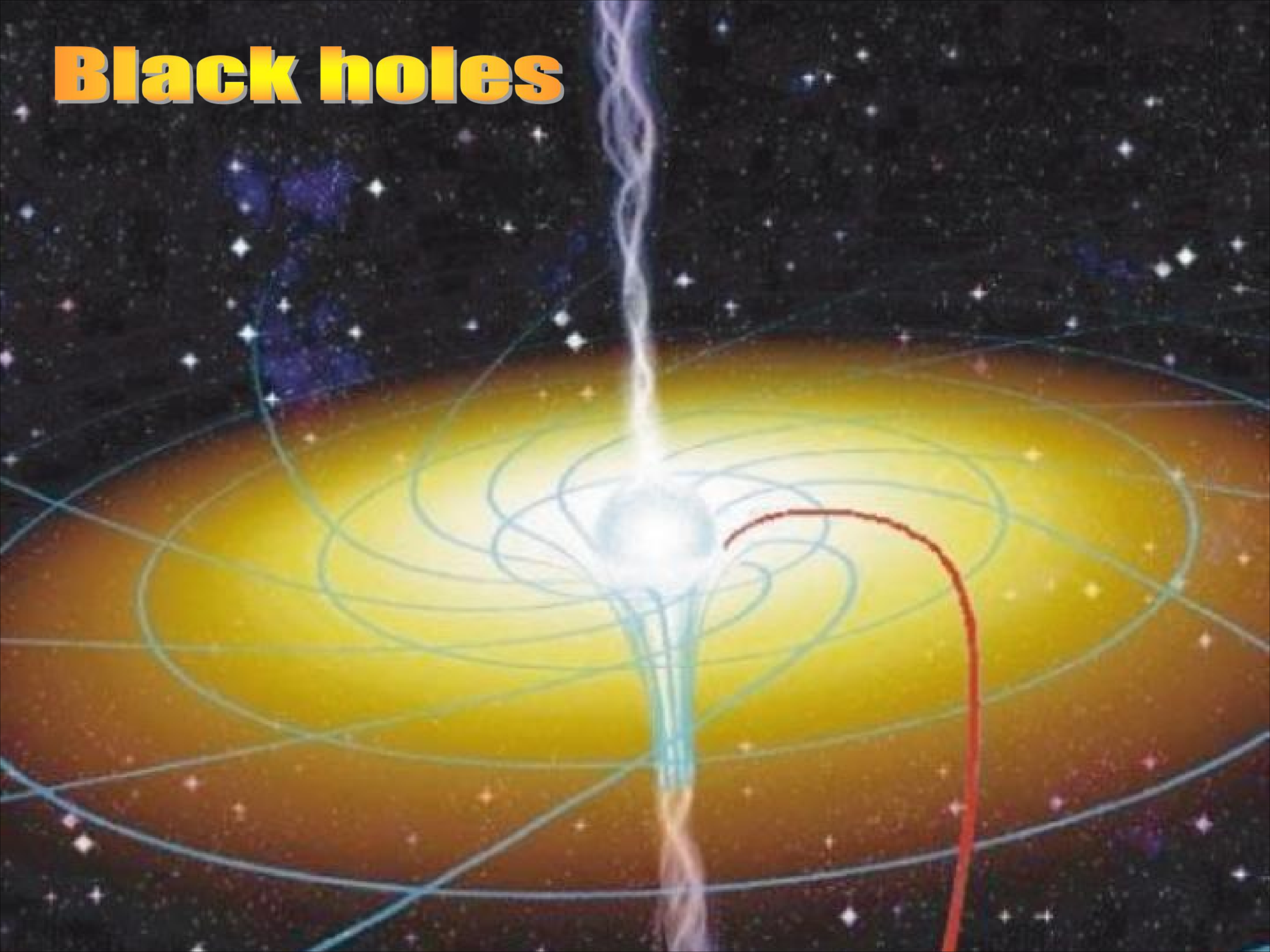
Image courtesy NASA, ESA, and the Hubble Heritage Team.

The fast-moving gas, pictured in red, is thought to be the result of rapid star formation near the center of the galaxy.

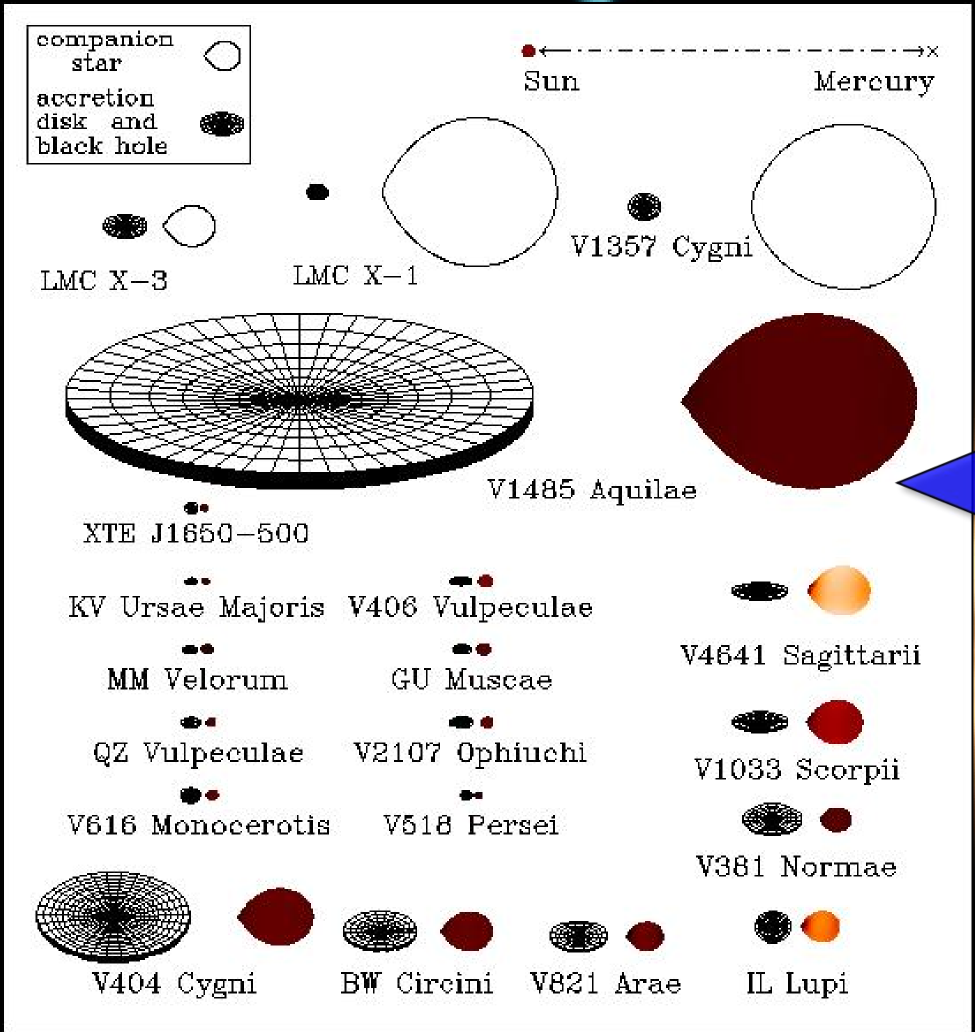
Another explanation is that the bubbles could be the remains of star formation. There are massive clusters of stars at very the center of the Milky Way — sometimes the stars are so closely packed they're a million times more dense than in the outer suburb of the galaxy where we live. If there was a burst of star formation in this area a few million years ago, it could have created the surge of gas needed to in turn create the Fermi bubbles.

[From https://nasa.tumblr.com/post/179690202529/blowing-bubbles-in-the-gamma-ray-sky]

Black holes



How many black holes are known to man that are in the Universe?



Dynamically confirmed black holes:

When the mass of a compact object in an X-ray binary system is shown to be more than about $3M_{Sun}$, then it is a black hole beyond reasonable doubt.

The diagram shows 20 DCBH binaries

17 DBCHs have low mass companions (i.e. stars with $M<3M_{Sun}$);
3 on the top have high mass companions.

The color scale for the 17 objects with low-mass companions represents the temperature of the star.

[Credit: Jerome Arthur Orosz, San Diego State University. < https://jorosz.sdsu.edu/ >]

Massive Black Holes Dwell in Most Galaxies (according to Hubble Census)

News Release Number: STScI-1997-01 **January 13, 1997 09:30 AM (EST)**

Announcing the discovery of three black holes in three normal galaxies, astronomers suggest that nearly all galaxies may harbor super-massive black holes that once powered quasars (extremely luminous objects in the centers of galaxies), but are now quiescent.

This conclusion is based on a census of 27 nearby galaxies carried out by NASA's Hubble Space Telescope and ground-based telescopes in Hawaii, which are being used to conduct a spectroscopic and photometric survey of galaxies to find black holes which have consumed the mass of millions of Sun-like stars.

The key results are:

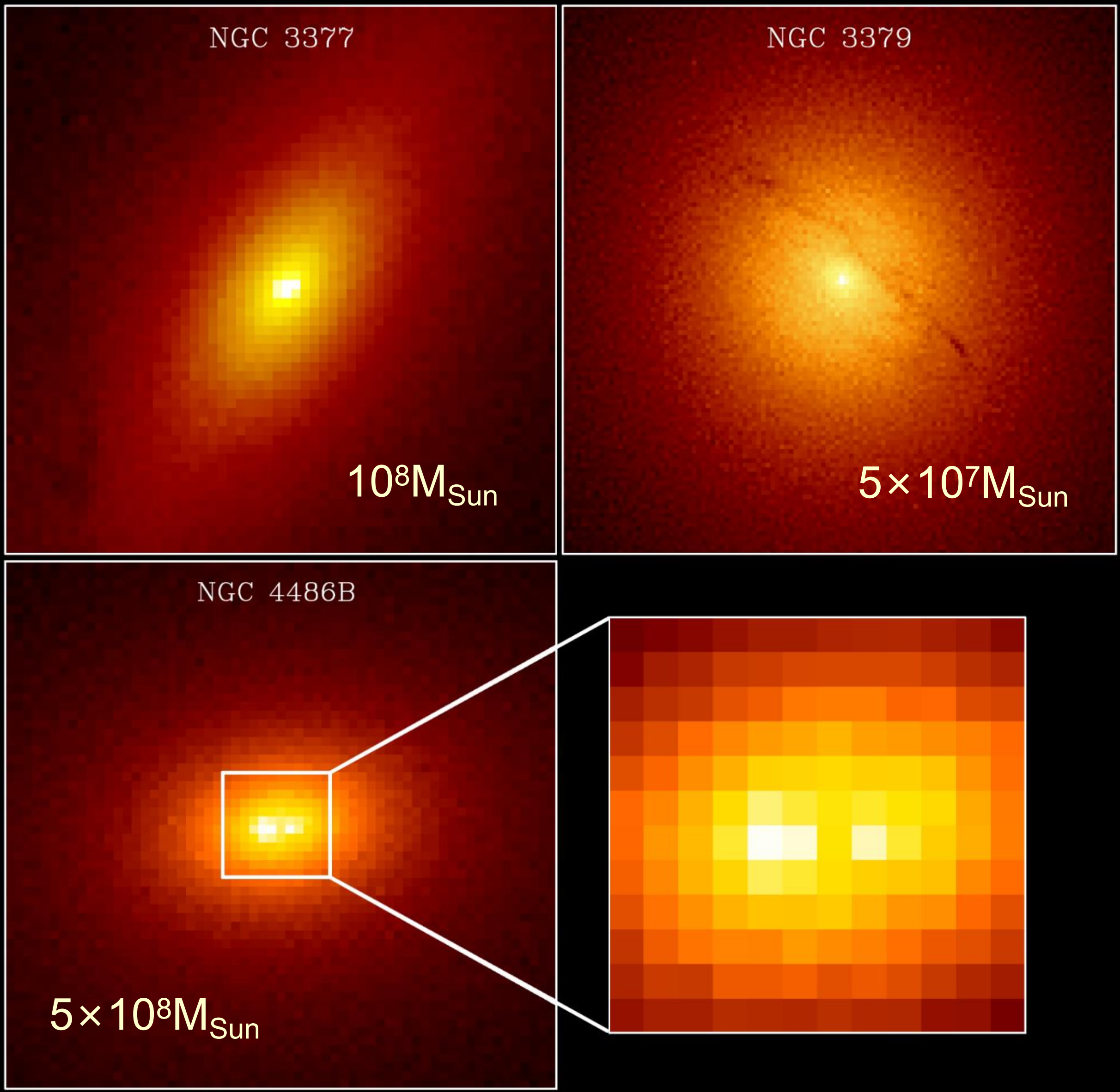
✓Supermassive black holes are so common, nearly every large galaxy has one.

✓A black hole's mass is proportional to the mass of the host galaxy, so that, for example, a galaxy twice as massive as another would have a black hole that is also twice as massive. This discovery suggests that the growth of the black hole is linked to the formation of the galaxy in which it is located.

✓The number and masses of the black holes found are consistent with what would have been required to power the quasars.

[**Credit:** Don Savage, Tammy Jones, & Ray Villard. http://hubblesite.org/newscenter/archive/releases/1997/01/text/]

Supermassive Black Holes in Galaxies NGC 3377, NGC 3379 and NGC 4486b



The three galaxies are believed to contain central, supermassive black holes.

The galaxy **NGC 4486B** (lower-left) shows a double nucleus (lower-right).

The images of **NGC 3377** and NGC 4486B are 2.7 arcsec on a side.

For **NGC 3379** (also known as **M105**) the size is 5.4 arcsec.

The lower-right is a blow-up of the central 0.5 arcsec of **NGC 4486B**.

[**Credit**: Karl Gebhardt, University of Michigan. http://hubblesite.org/newscenter/archive/releases/1997/01/image/a/]

ADOPTED MASSIVE BLACK HOLE DETECTIONS

	Comment	Constellation	Type	Distance[1]	Luminosity[2]	Mass[3]
Milky Way			Sbc	28,000	1.9	2 Million
NGC 224 = M31	Andromeda Nebula	Andromeda	Sb	2.3 Million	5.2	30 Million
NGC 221 = M32	Satellite of M31	Andromeda	E2	2.3 Million	0.25	3 Million
NGC 3115		Sextans	SO	27 Million	14.2	2 Million
NGC 4258	Maser Detection	Canes Venacti	Sbc	24 Million	1.3	40 Million
NGC 4261		Virgo	E2	90 Million	33	400 Million
NGC 4486 = M87		Virgo	E0	50 Million	56	3 Billion
NGC 4594 = M104	The Sombrero	Virgo	Sa	30 Million	47	1 Billion
New objects discovered with the Hubble Space Telescope						
NGC 3377		Leo	E5	32 Million	5.2	100 Million
NGC 3379		Leo	E1	32 Million	13	50 Million
NGC 4486b	Satellite of M87	Virgo	E0	50 Million	0.82	500 Million

[1]In units of Light Years
[2]In units of one billion solar luminosities. For spirals, the bulge luminosities are quoted.
[3]In units of one solar mass.

Rutgers' black hole discovery: The first galaxy without one or the smallest black hole yet?

Rutgers astronomers have made a provocative discovery — the first galaxy without a SBH at its center or the smallest black hole ever detected in the center of a galaxy. They used the Hubble Space Telescope to observe the galaxy M33, one of the nearest neighbors to the Milky Way galaxy at a relatively short distance of 3×10^{6} ly. By using Hubble's high-resolution instruments, the investigators were able to see details at a scale that is at least 10 times finer than was ever possible in the past from the ground.

Based on their observations and calculations, the team concluded that only a BH smaller than $3{,}000 M_{Sun}$ could be present at the center of M33. If M33 contains a SBH, it would be roughly a 1000 times smaller than the SBH in the Milky Way and by far the smallest SBH known

[Credit: Robert W. Provin & Brad D. Wallis. http://www.eurekalert.org/pub_releases/2001-07/rtsu-rbh071601.php]

Galaxy blasts neighbor with deadly jet

'Death star galaxy' could obliterate the atmospheres of planets

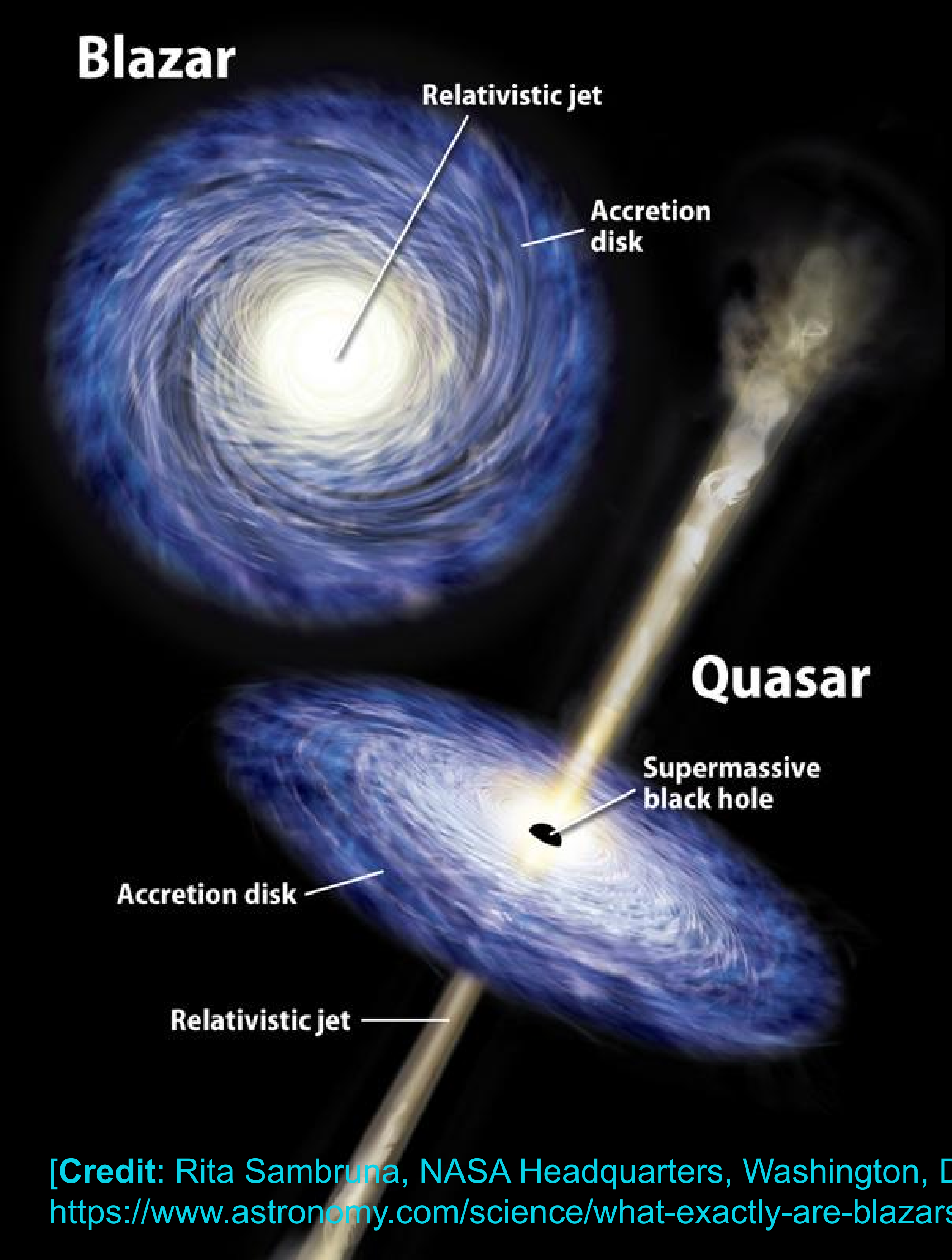
For the first time astronomers have witnessed a supermassive black hole blasting its galactic neighbor with a deadly beam of energy. The "***death star galaxy***," as NASA astronomers called it, could obliterate the atmospheres of planets but also trigger the birth of stars in its wake of its destructive beam. Fortunately, the cosmic violence is a safe distance from our own neck of the cosmos ($\sim 1.4 \times 10^9$ ly).

"***We've seen many jets produced by black holes, but this is the first time we've seen one punch into another galaxy like we're seeing here. This jet could be causing all sorts of problems for the smaller galaxy it is pummeling.***"

Dan Evans, Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass.

Jets from supermassive black holes produce tremendous radiation in the form of X-rays, gamma rays and electrons traveling close to the speed of light. The X-ray and gamma-ray photons would ultimately do the most damage to planets.

The offending galaxy probably began hosing its companion about 10^6 years ago, which is relatively recent on a cosmic time scale.



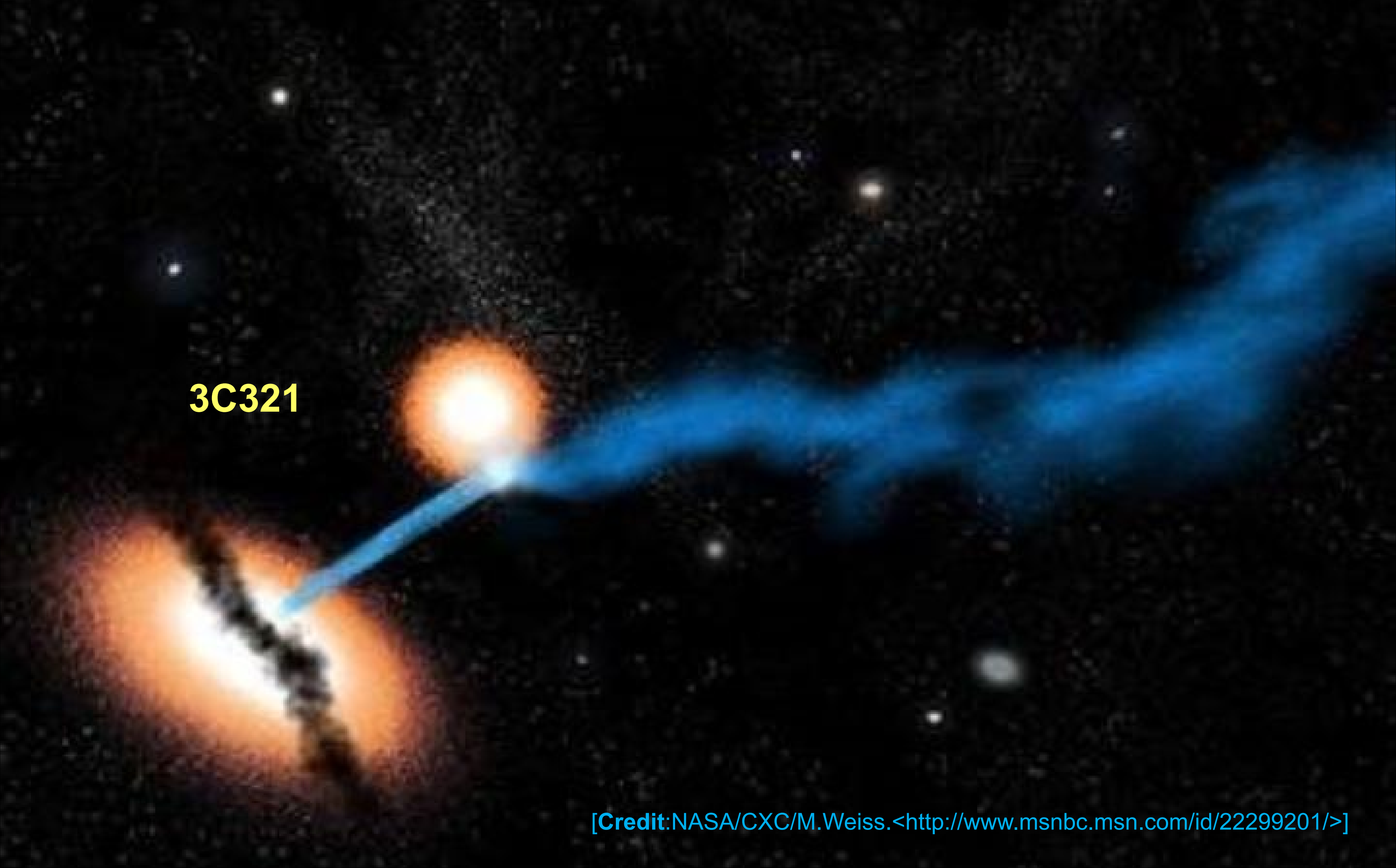
Blazars and quasars are both subclasses of active galactic nuclei (AGN). All AGNs are intrinsically the same object — a supermassive black SMBH) with a surrounding accretion disk, producing a jet — but seen at different orientation angles with respect to the jet's axis.

In blazars, we observe the jet almost end-on, while in quasars the jet is oriented at larger angles to us and we can peek inside the central engine.

In quasars, we see broad optical lines, but also "thermal spectra" (energy at all wavelengths, like a rainbow), and X-ray emission features due to processes occurring near the black hole; these are consistent with an angled view of the accretion disk.

[**Credit**: Rita Sambruna, NASA Headquarters, Washington, D. C., URL: https://www.astronomy.com/science/what-exactly-are-blazars-and-quasars-how-are-they-different/]

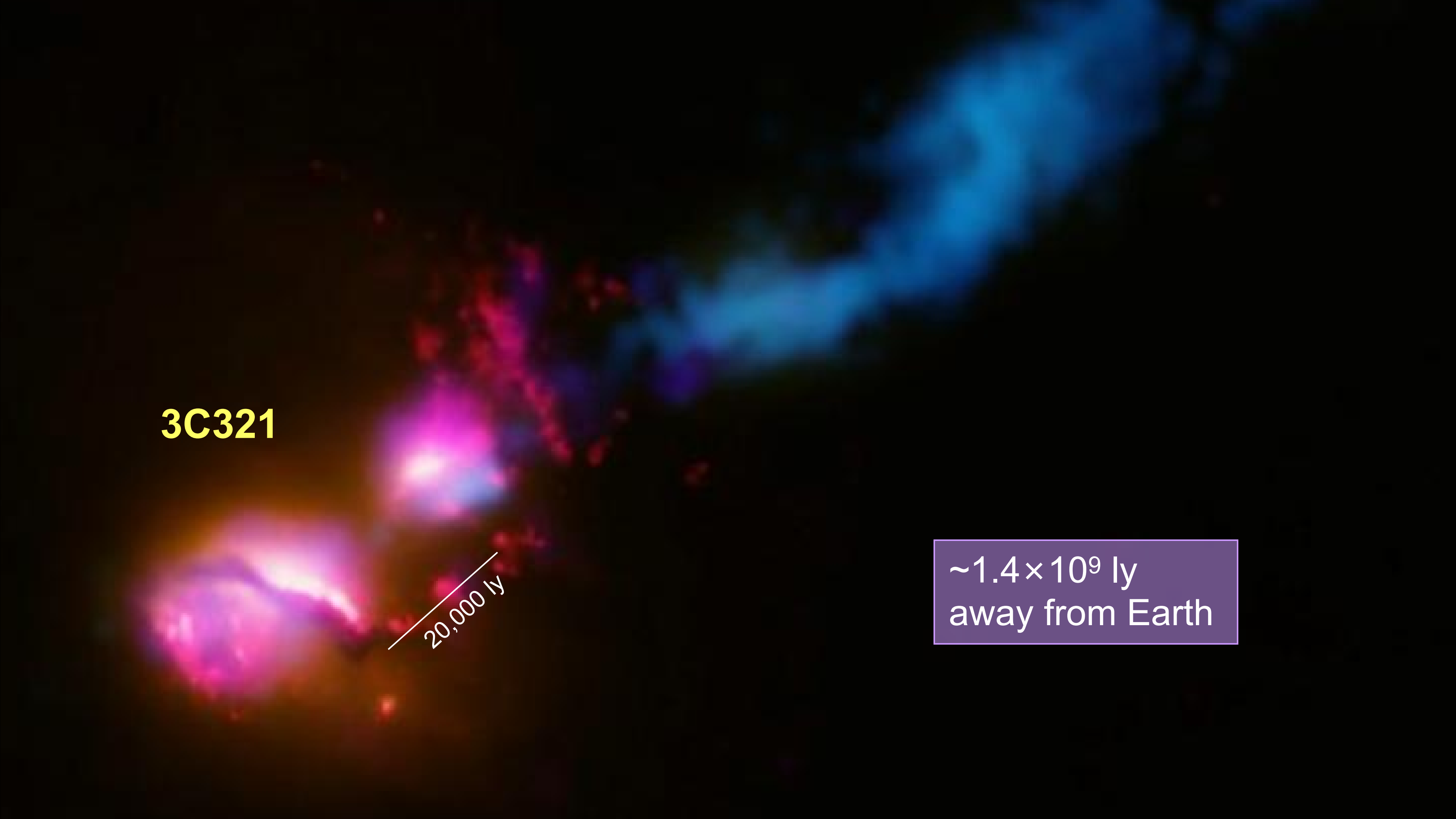
This artist's impression of 3C321 shows the main galaxy and the companion galaxy. A jet of particles generated by a supermassive black hole at the center of the main galaxy is striking the companion galaxy. The jet is disrupted and deflected by this impact.



[**Credit**:NASA/CXC/M.Weiss.<http://www.msnbc.msn.com/id/22299201/>]

This composite image shows the jet from a black hole at the center of a galaxy, at left, striking the edge of another galaxy. The image combines

- X-ray emissions seen by the Chandra X-Ray Observatory (purple),
- optical and ultraviolet data from the Hubble Space Telescope (red & orange),
- radio emissions from the Very Large Array and MERLIN radio telescope (blue).



[Credit: NASA/CXC/CfA/STScI/NSF/STFC. http://www.msnbc.msn.com/id/22299201/]

This artist's conception begins with the Chandra X-ray Observatory as it passes in front of the Moon.

Chandra, one of NASA's "Great Observatories," does not orbit closely around the Earth. Instead, its highly elliptical orbit takes as far as one-third the distance to the Moon.

Operating in space since 1999, Chandra detects and images X-ray sources that lie within our Solar System to those billions of light years away. The results from Chandra help explore high-energy phenomena and provide insights into the Universe's structure and evolution.

[From URL:<http://chandra.harvard.edu/>]

We start with an optical and infrared image that shows the crowded area around the object known as GRS 1915+105, or GRS 1915 for short. Next is a close-up of the Chandra image of GRS 1915, which is located near the plane of the Milky Way. GRS 1915 is a so-called micro-quasar that contains a black hole about fourteen times the mass of the sun, which in turn is pulling material off a nearby companion star.

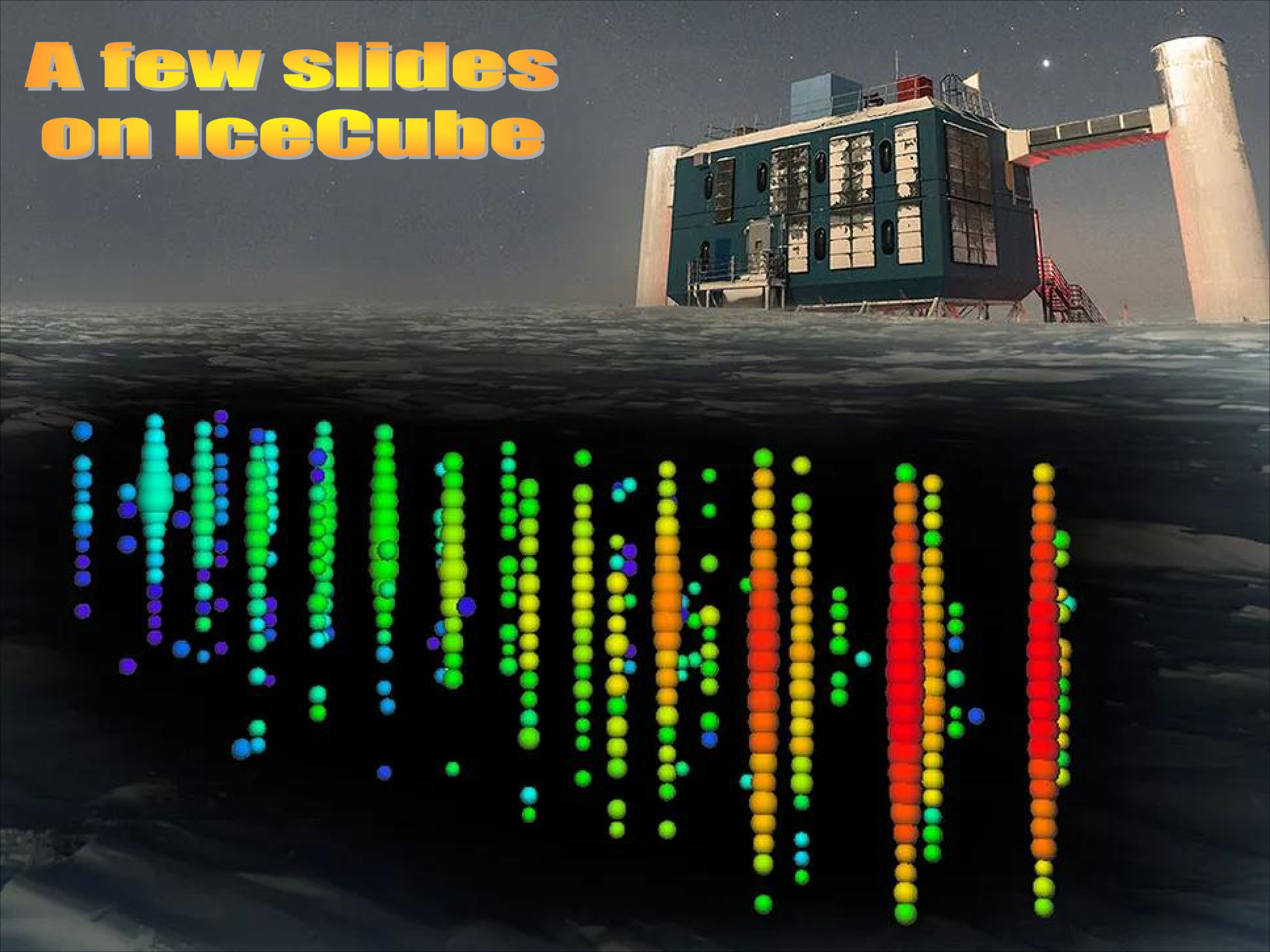
With its high-energy transmission grating, Chandra has observed GRS 1915 eleven times since 1999. These studies reveal that a jet from the black hole in GRS 1915 may be periodically choked off when a hot wind is driven off the disk surrounding the black hole. Conversely, once the wind dies down, the jet can re-emerge. These results suggest that this type of black hole may have a mechanism for regulating the rate at which it grows.

This image of the mammoth spiral galaxy M81, located about 12 million light years away, contains data from four different NASA satellites.

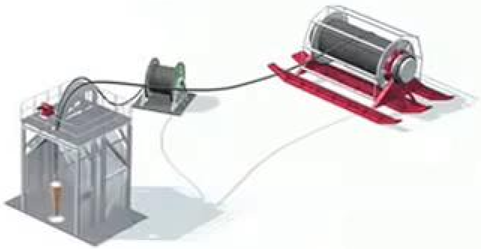
First we see infrared data from the Spitzer Space Telescope, followed by optical data from the Hubble Space Telescope.

The Galex Satellite shows us what M81 looks like in ultraviolet emission. And finally, x-ray data from the Chandra X-ray Observatory reveals what is going on at higher energies. At the center of M81, there is a supermassive black hole that is about 70 million times more massive than the sun. A new study involving Chandra and other telescopes helps astronomers better understand how this black hole is growing.

A few slides on IceCube

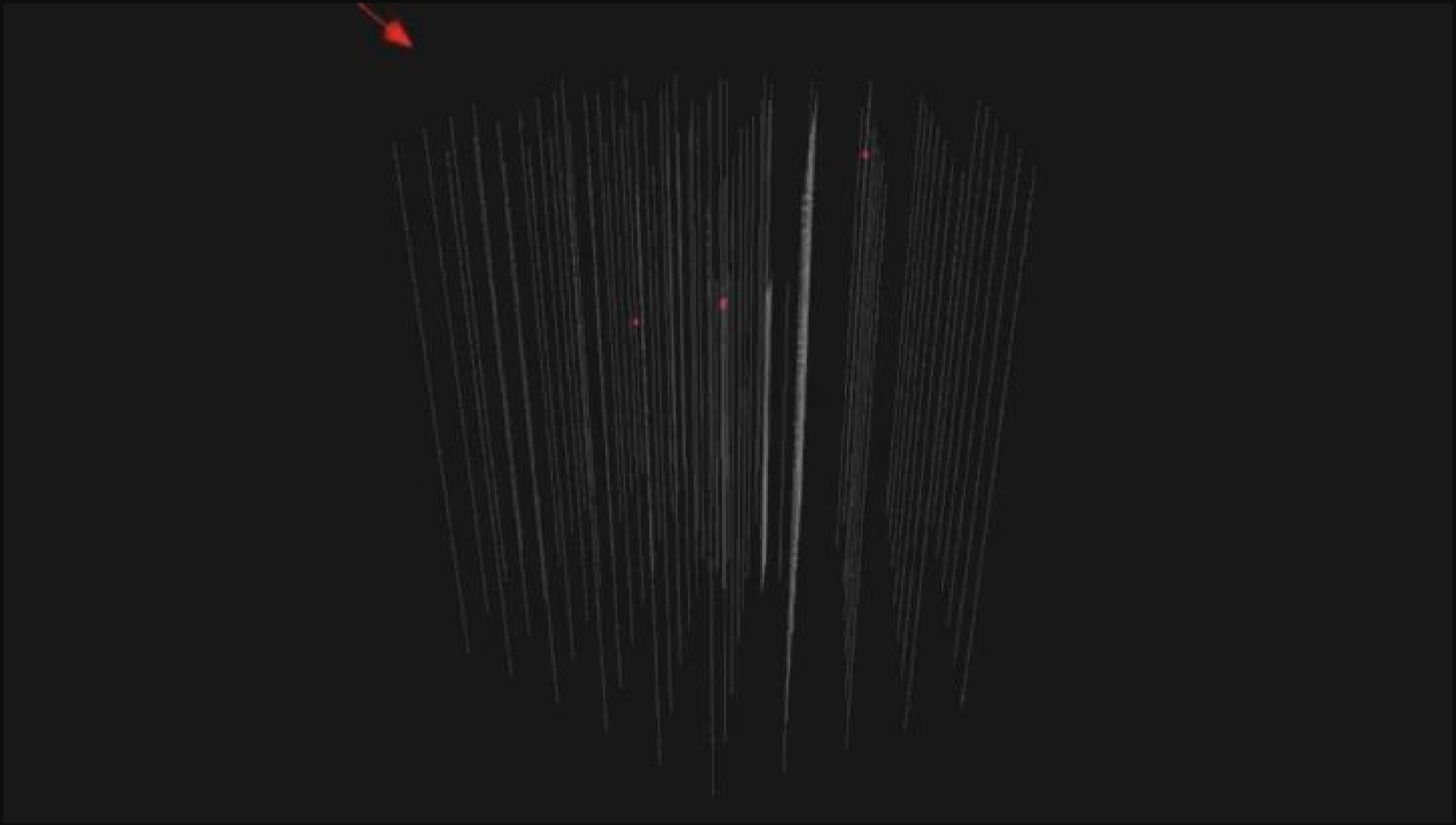


IceCube drilling process



The firn drill was used to drill through the upper layer of compacted snow, or firn, down to where ice actually begins, which is about 50 meters below the surface. The solid ice was melted using a straight, high-pressure stream of hot water from the specially designed enhanced hot water drill.

[URL: https://youtu.be/2I_01ELFeVE. For more videos see URL https://www.youtube.com/c/IceCubeNeutrino/.]



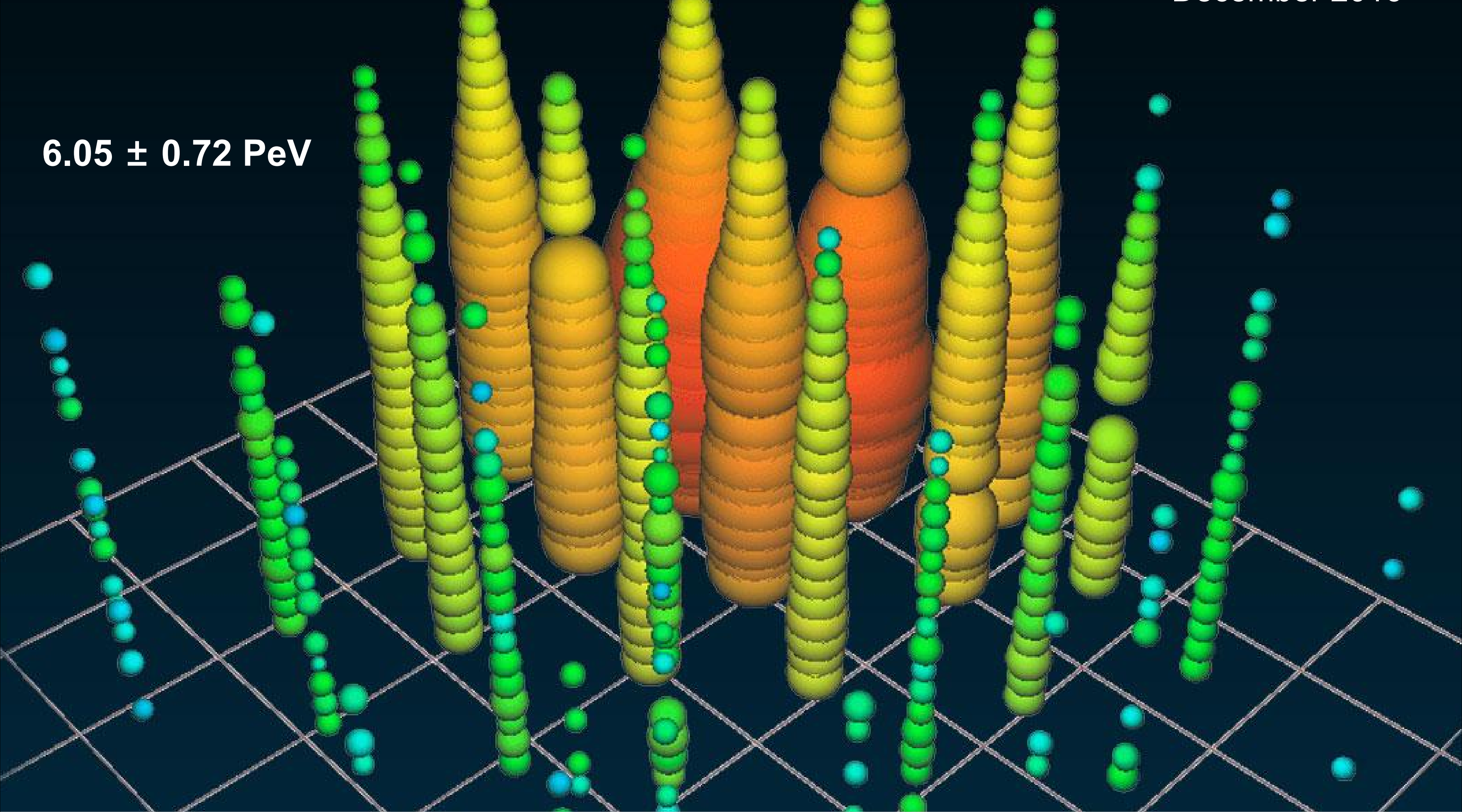
Animation of the IceCube neutrino’s trace of blue light.

[From URL: <https://www.sciencefriday.com/segments/following-a-neutrinos-four-billion-light-year-journey/>]

IceCube Detected the Glashow resonance

December 2016

6.05 ± 0.72 PeV



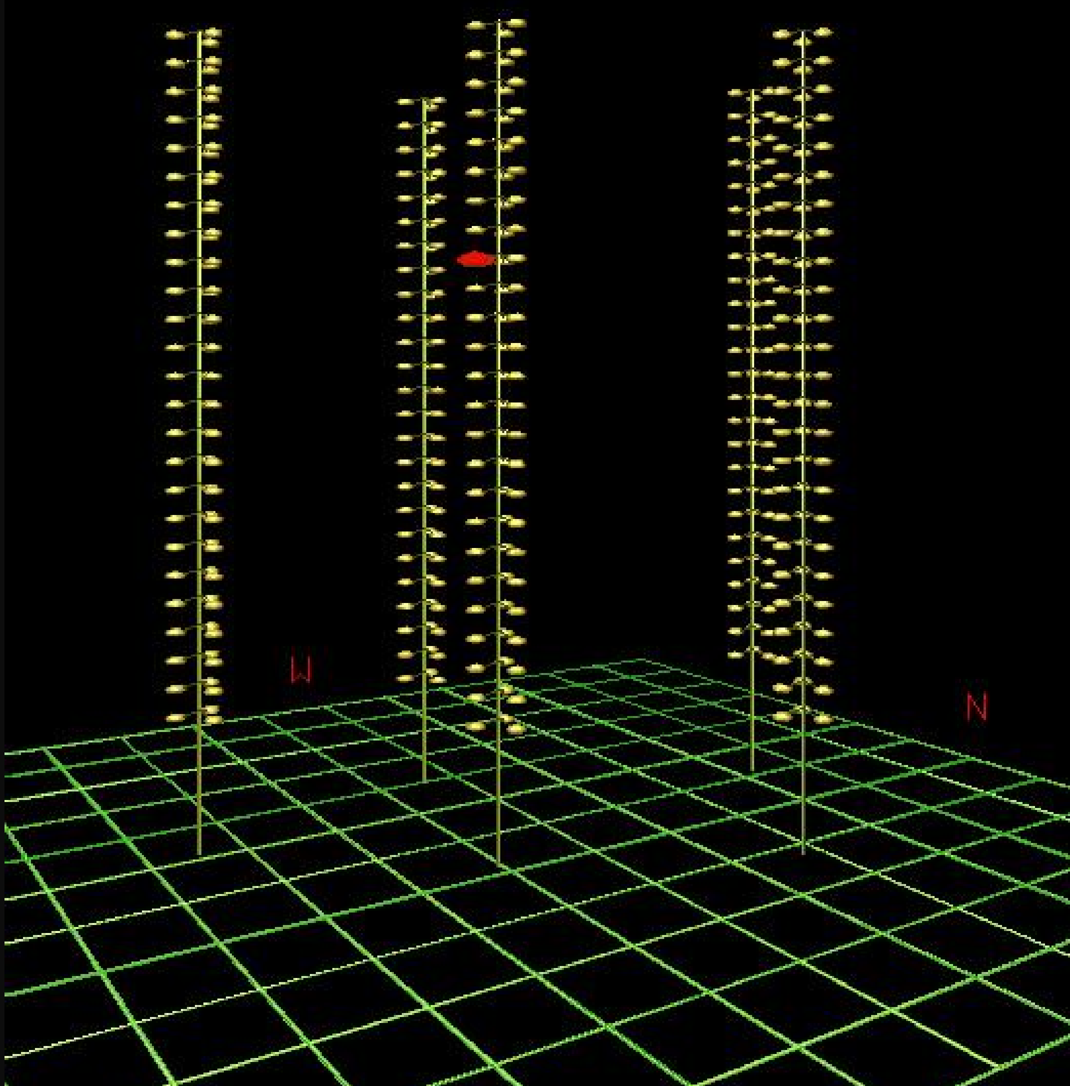
A visualization of the Glashow event recorded by the IceCube detector. Each colored circle shows an IceCube sensor that was triggered by the event; red circles indicate sensors triggered earlier in time, and green-blue circles indicate ones triggered later. This event was nicknamed "**Hydrangea**." Credit: IceCube Collaboration.

From https://ucsdnews.ucsd.edu/pressrelease/icecube-neutrino-observatory-detects-new-high-energy-particle

To simulate this detection, the IceCube collaborators used millions of hours on multiple supercomputers at San Diego Supercomputer Center to sort through the data, understand the detector response and calculate the direction of origin for this particular antineutrino.

From https://ucsdnews.ucsd.edu/pressrelease/icecube-neutrino-observatory-detects-new-high-energy-particle

Antares



A downward going muon seen in the first stage of the **Antares** detector data taking (spring 2007, 5 lines in operation). This muon was produced from the interaction of cosmic rays in the atmosphere above the detector. Its trajectory is obtained from the signals on the photodetectors.

[From http://irfu.cea.fr/dap/en/Phocea/Vie_des_labos/Ast/ast_technique.php?id_ast=2230]

More nice animations can be found on the website of the Nikhef: <https://www.nikhef.nl/~t61/a3d/animation/>