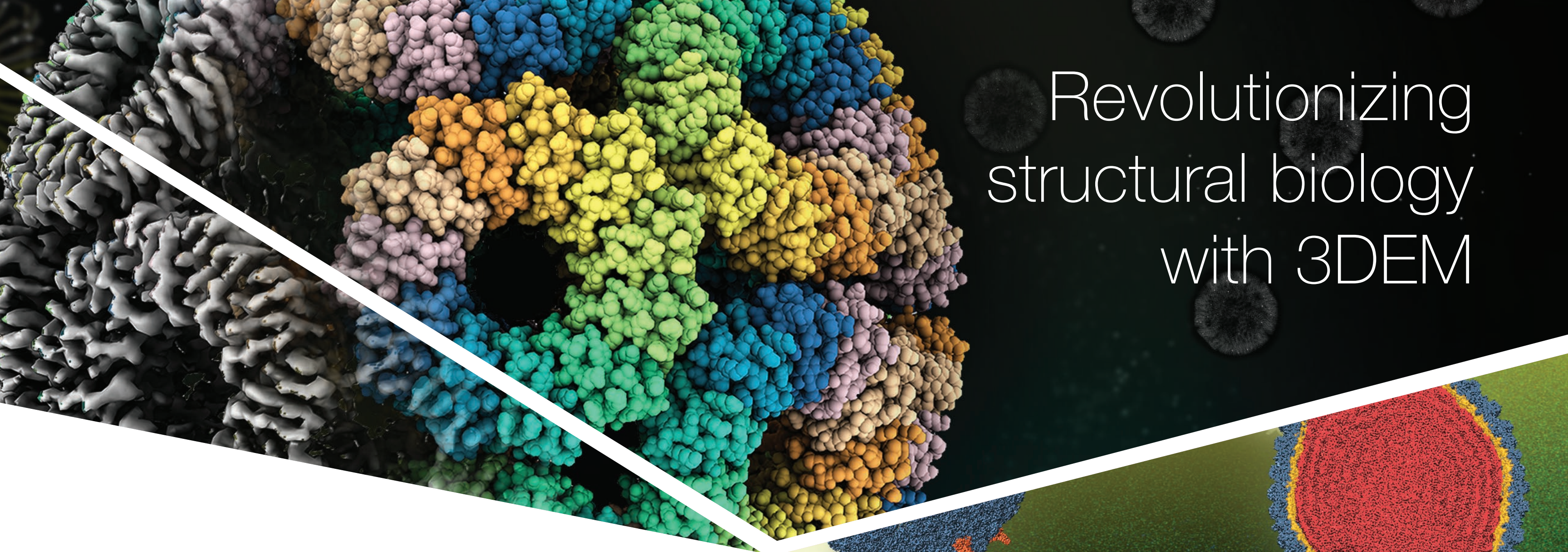
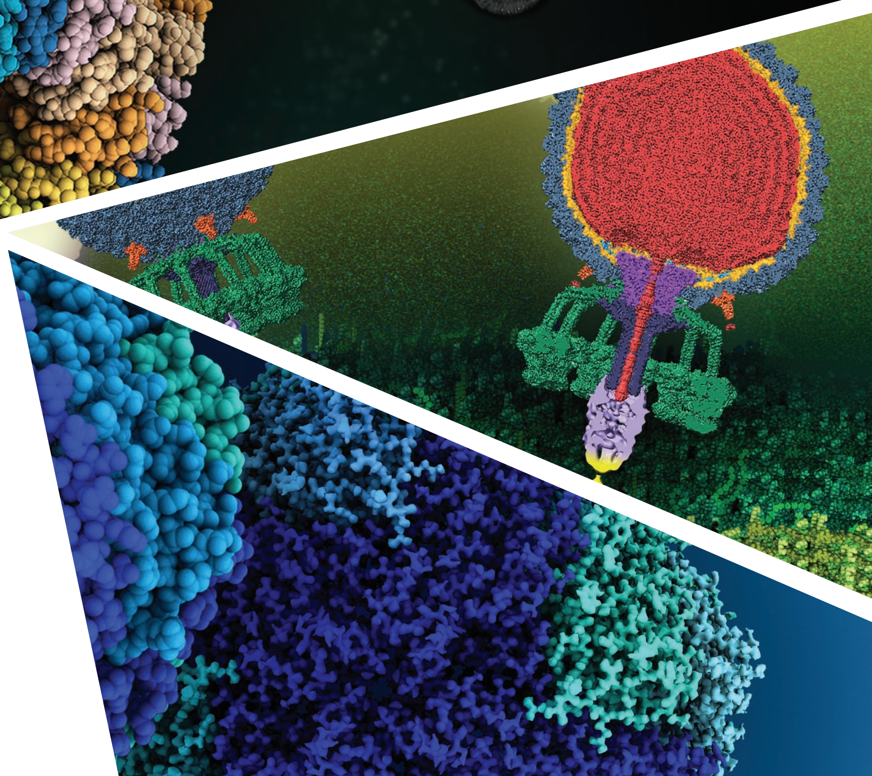


# Revolutionizing structural biology with 3DEM

# 2022 Calendar



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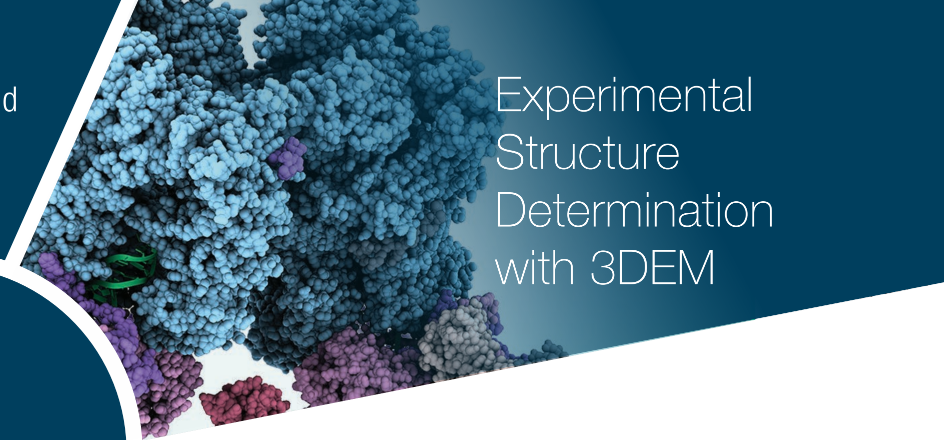
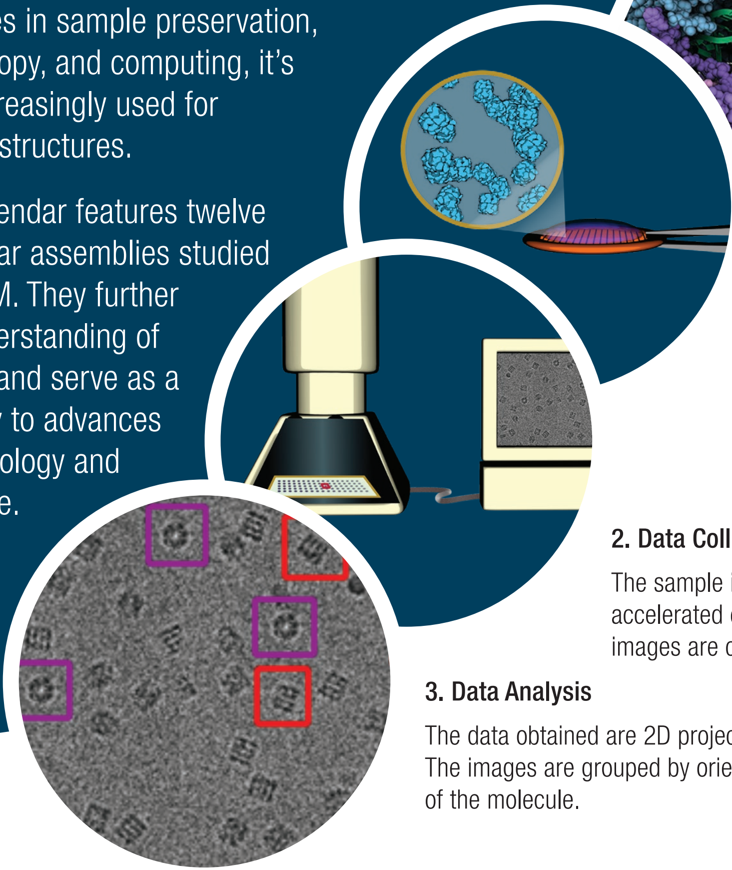


# Experimental Structure Determination with 3DEM

3D electron microscopy (3DEM) is revolutionizing the field of structural biology. This technique has become the method of choice for determining structures of large macromolecular complexes. Thanks to recent advances in sample preservation, microscopy, and computing, it's also increasingly used for smaller structures.

This calendar features twelve molecular assemblies studied by 3DEM. They further our understanding of biology and serve as a gateway to advances in technology and medicine.



### 1. Sample Preparation

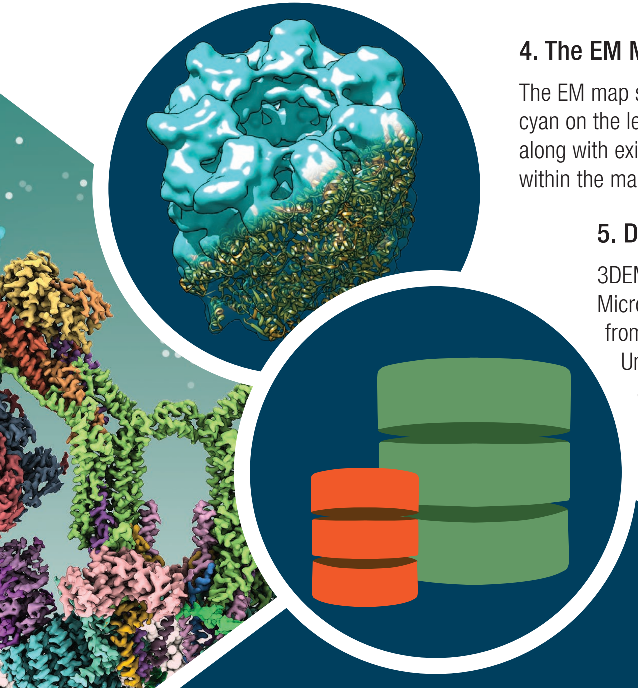
Sample preparation starts with isolating the protein of interest from cells or organisms. To stabilize and ensure that proteins are in a native-like conformation for the experiment, some molecular modifications can be applied, like placing the proteins in nanodiscs or adding stabilizing nanobodies (see illustrations for February, March, and August). A tiny amount of the sample is placed on a small grid and spread in a single layer. Then the sample is frozen in liquid ethane.

### 2. Data Collection

The sample is placed inside an electron microscope and is exposed to a beam of accelerated electrons. The electrons scatter as they hit the sample and thousands of images are captured.

### 3. Data Analysis

The data obtained are 2D projection images showing the macromolecules in many different orientations. The images are grouped by orientation and then combined computationally to reconstruct a 3DEM map of the molecule.



## 4. The EM Map and Atomic Model

The EM map shows the overall shape of the protein structure (shown in cyan on the left). Using the map and advanced computing techniques along with existing sequence and experimental data, atoms are positioned within the map to create an atomic structure model (shown in gold).

## 5. Data Access

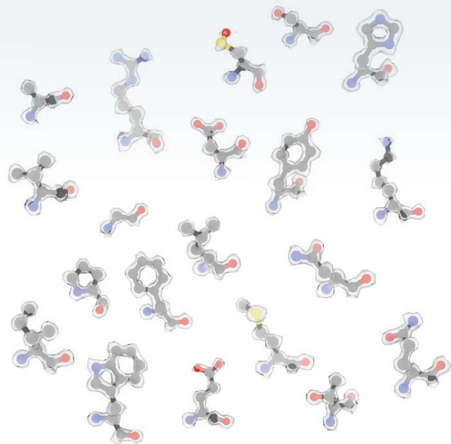
3DEM maps are freely available in a public repository, the Electron Microscopy Data Bank (EMDB). Atomic structure models obtained from 3DEM data are stored in the Protein Data Bank (PDB). Unique IDs are assigned to these maps (e.g., EMD-11657) and models (e.g., PDB ID 2rte).

To explore in 3D, vist ebi.ac.uk/emdb (maps) and RCSB.org (atomic models).

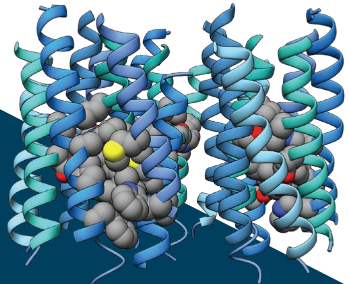
## The 3DEM Resolution: Small numbers are better than big

When we talk about resolution in atomic structure, we use the Ångstrom unit. One Ångstrom is approximately the width of one hydrogen atom. In both X-ray crystallography and 3DEM, a resolution of 1 Ångstrom is highly desirable. A protein structure at this resolution has hydrogen atoms visible and all other atoms mapped accurately. 3DEM maps at greater Ångstrom resolution are typically not as detailed.

The 3DEM structure determined at the highest resolution is currently Apoferritin solved at ~1.2 Å (see January illustration). Shown below are examples of the 3DEM map-to-atomic model fit for each type of amino acid at this resolution.

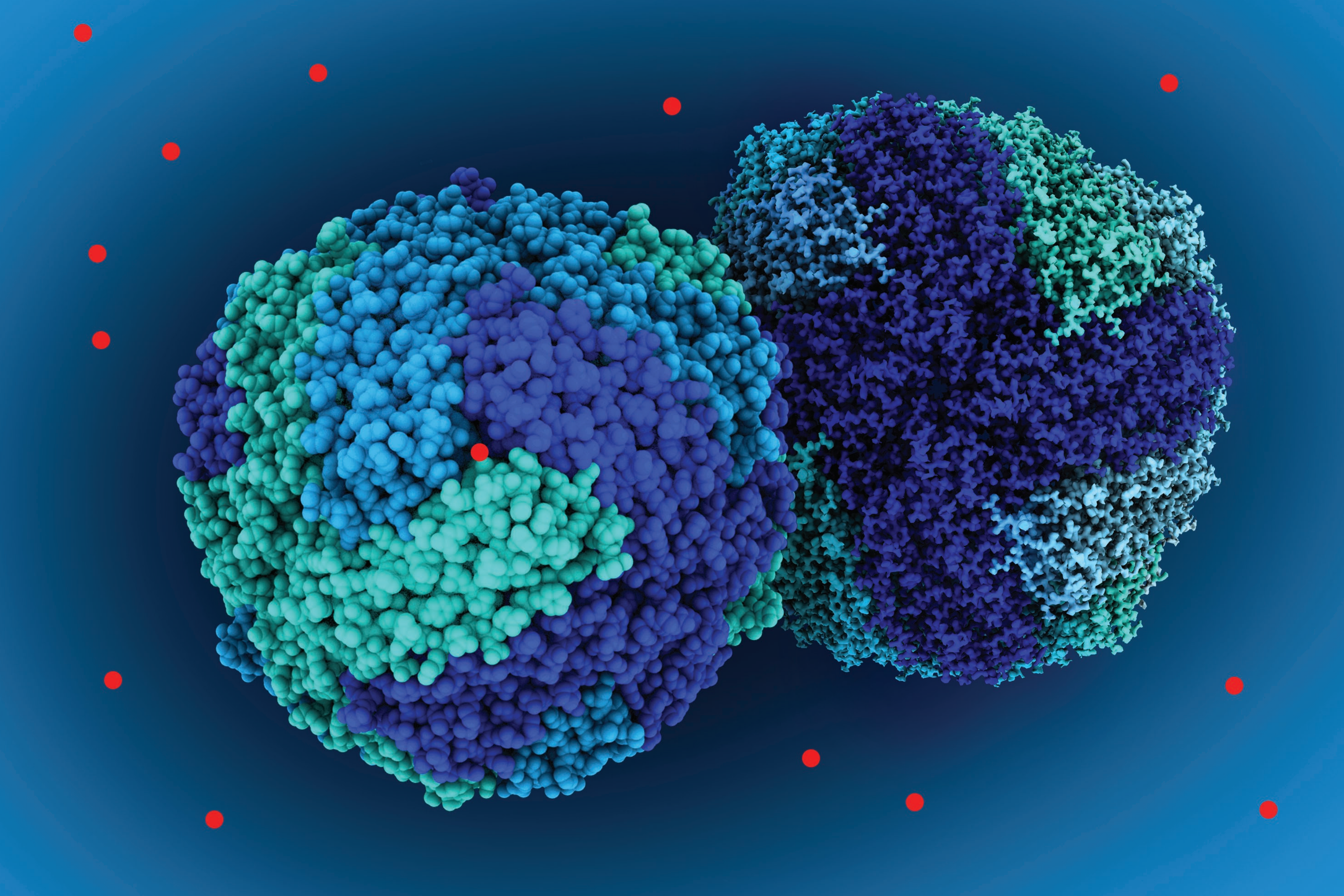


The PDB released its first 3DEM entry, the ground-breaking structure of bacteriorhodopsin, in 1991 (shown right). Since then, more than 9,000 3DEM structures have been made available in the PDB archive, most of them in the last few years.



PDB Structure 1BRD
R. Henderson *et al.* (1990) Model for the structure of bacteriorhodopsin based on high-resolution electron cryo-microscopy. *J Mol Biol* 213: 899–929.

In 2017, Jacques Dubochet, Joachim Frank, and Richard Henderson were recognized with the Nobel Prize in Chemistry for their contributions to experimental determination of atomic structures using single-particle cryo-electron microscopy.



# JANUARY 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 26 | 27 | 28 | 29 | 30 | 31 | 1<br>New Year's Day |
| 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17<br>Martin Luther King Jr. Day | 18 | 19 | 20 | 21 | 22 |
| 23 | 24 | 25 | 26 | 27 | 28 | 29 |
| 30 | 31 | 1 | 2 | 3 | 4 | 5 |

## Ferritin

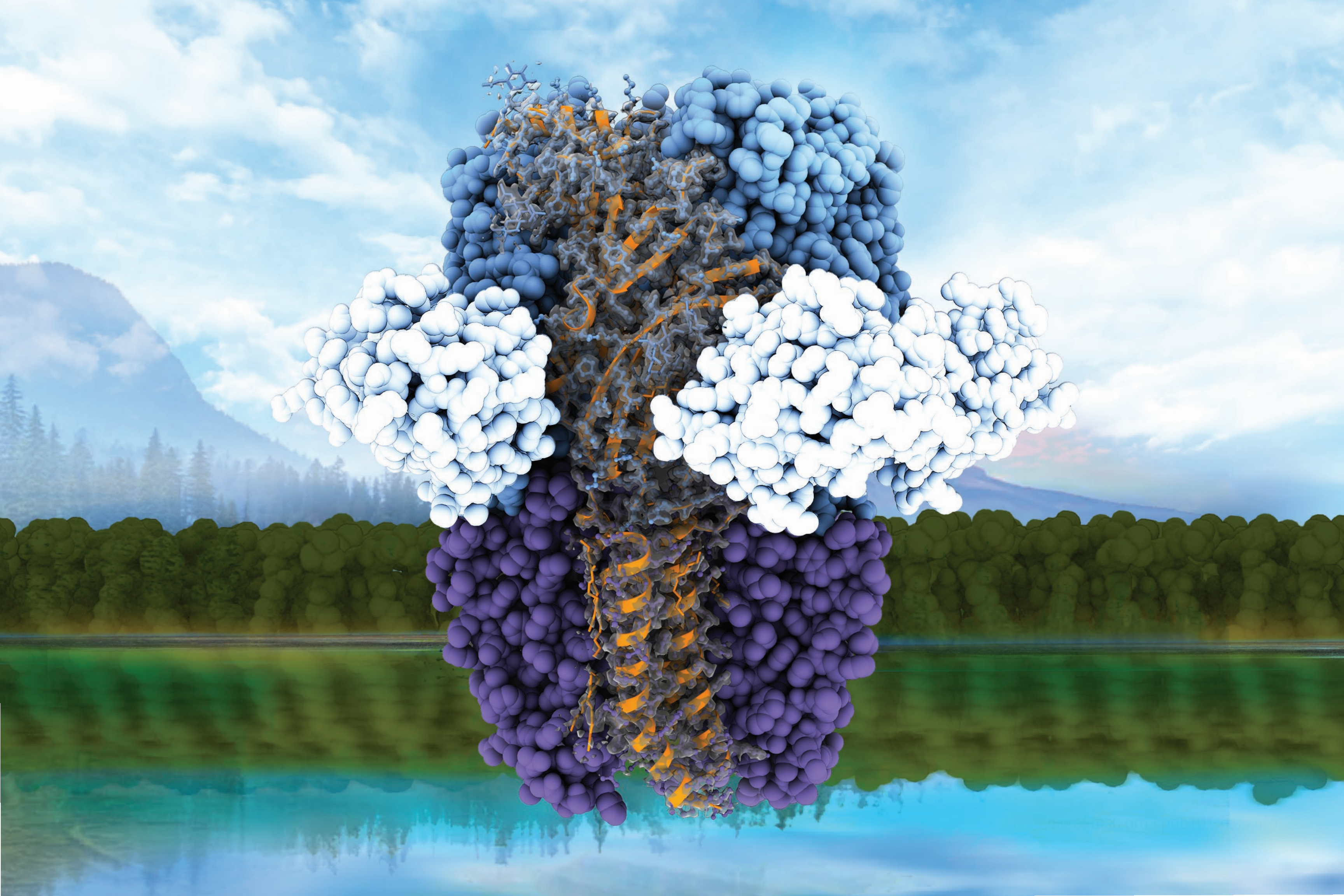
Ferritin helps balance iron levels within living organisms. It forms a spherical shell composed of 24 subunits (shown in shades of blue). Reactive and potentially toxic iron atoms (red) enter the shell through the 3-fold pores (shown on the right) where they form non-reactive small crystallites. The iron mineral is released as needed. Ferritin that is not combined with iron is called apoferritin.

As a structure of extreme stability, ferritin is one of the most widely used test samples in 3DEM. The map of apoferritin at approximately 1.2 Å (shown on the right) is currently the EM structure with the highest resolution. It is precise enough to unambiguously identify the position of individual atoms in the protein.

PDB Structure **6Z6U**
3DEM Map **EMD-11103**

K.M. Yip *et al.* (2020) Atomic-resolution protein structure determination by cryo-EM. *Nature* **587**: 157–161.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# FEBRUARY 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 30 | 31 | 1<br>Lunar New Year | 2 | 3 | 4 | 5 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 13 | 14<br>Valentine's Day | 15 | 16 | 17 | 18 | 19 |
| 20 | 21<br>Presidents' Day | 22 | 23 | 24 | 25 | 26 |
| 27 | 28 | 1 | 2 | 3 | 4 | 5 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |

## $GABA_A$ receptor

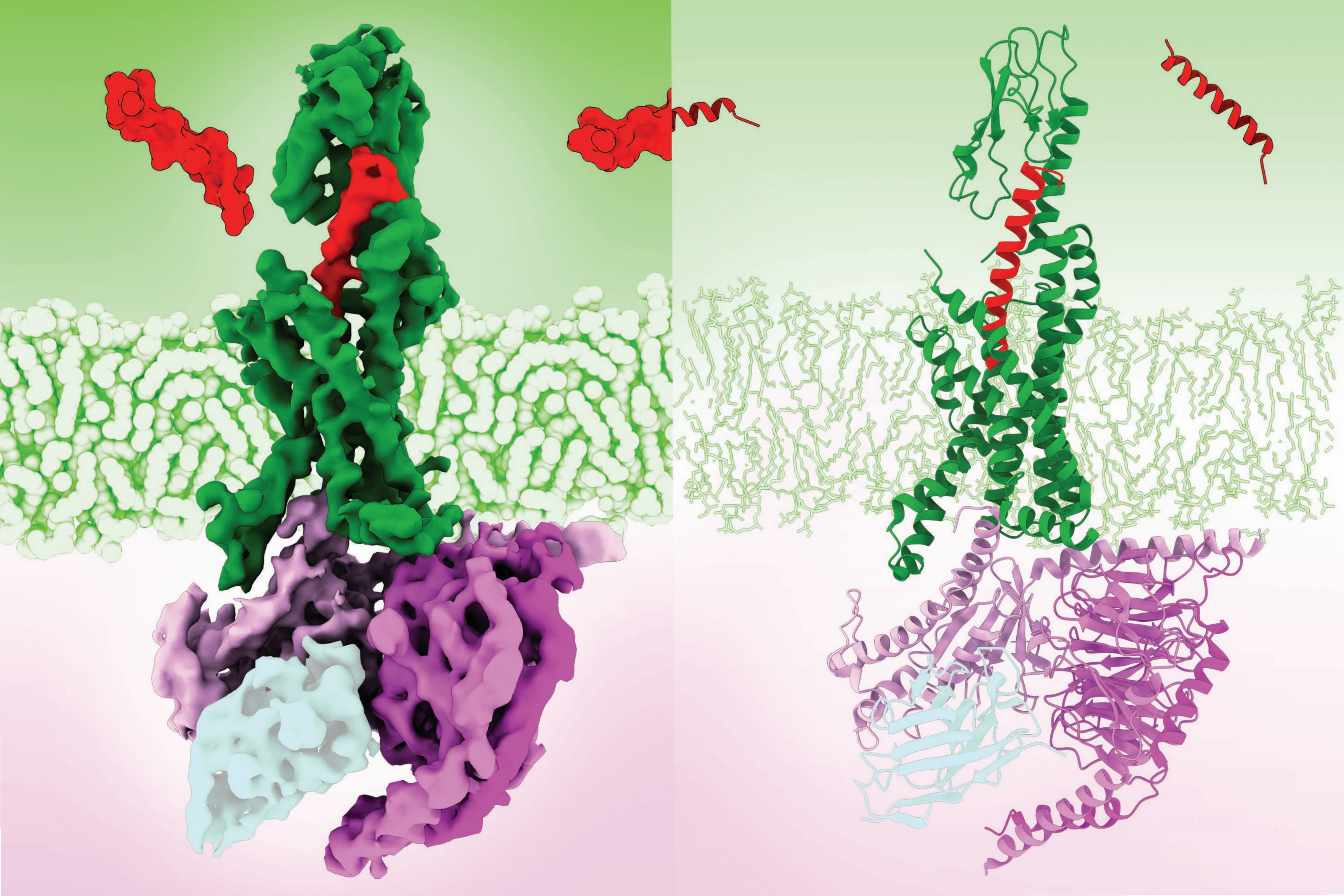
$GABA_A$ receptors reside in neurons in the cell membrane. One protein chain (shown in orange with EM map overlay) is repeated five times radially to form the pentameric channel. Upon binding of the GABA neurotransmitter, the channel opens and allows negatively charged ions to enter the neuron, offsetting the positive charges of the ions driving the neuronal signal. This activity marks the channel as an important drug target for many anti-stimulatory agents.

The structure shown here has a nanobody (light blue, encircling the receptor) bound at the GABA binding site. This helps to stabilize and orient the channel during the experiment. At 1.7 Å resolution, this structure is the most detailed portrait of a $GABA_A$ receptor to date and serves as an invaluable aid for current and future structure-based drug discovery efforts.

PDB Structure **7A5V**
3DEM Map **EMD-11657**

T. Nakane *et al.* (2020) Single-particle cryo-EM at atomic resolution. *Nature* **587**: 152–156.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# MARCH 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 27 | 28 | 1 | 2 | 3 | 4 | 5 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 13 Daylight Saving Time starts (North America) | 14 Pi Day | 15 | 16 | 17 | 18 | 19 |
| 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| 27 | 28 | 29 | 30 | 31 | 1 | 2 |
| 3 | 4 | 5 | 6 | 7 | 8 | 9 |

## GLP-1 Receptor

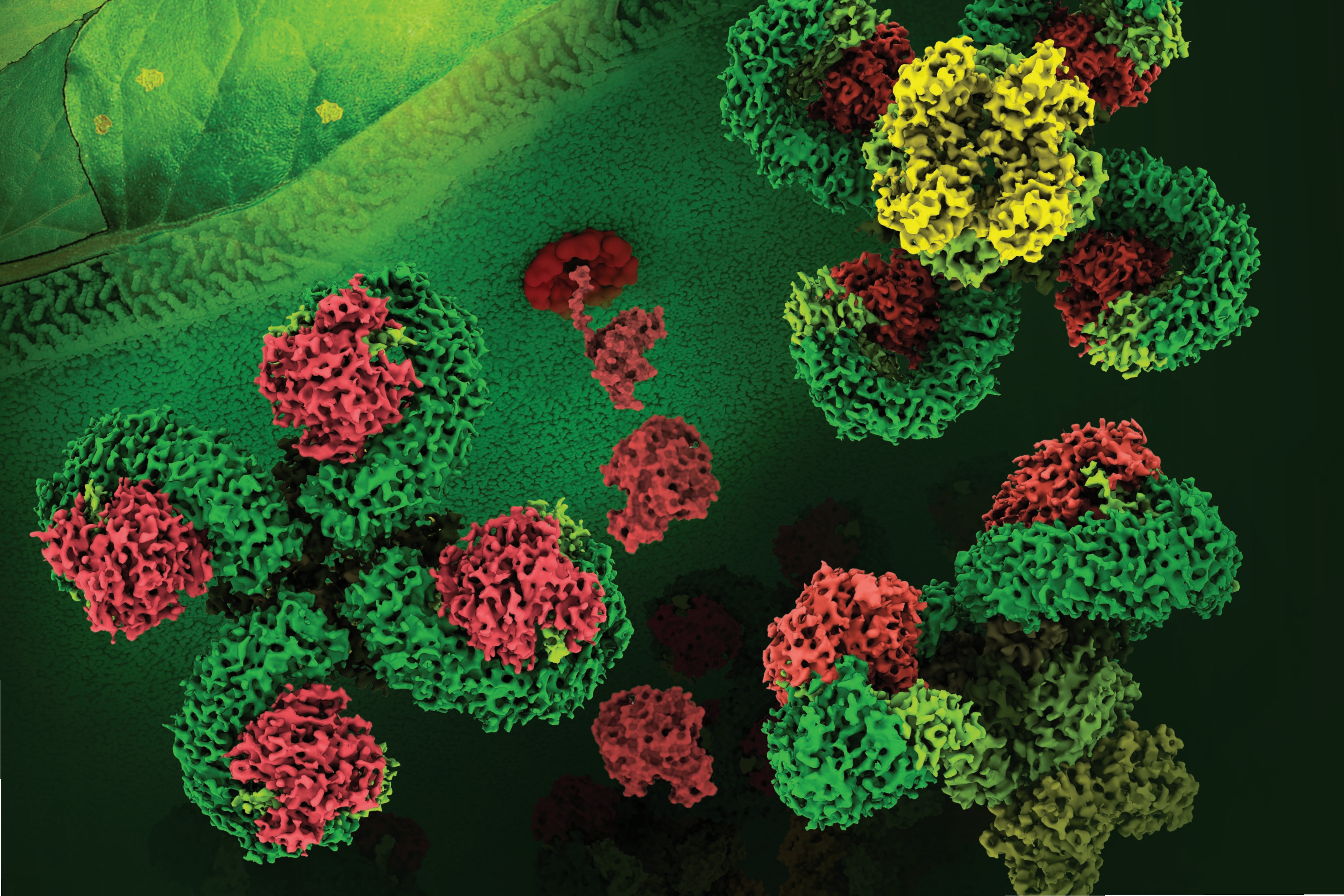
Glucagon-like peptide 1 (GLP-1, red) is a hormone regulating insulin secretion, carbohydrate metabolism, and appetite. When GLP-1 binds to its receptor (green), it activates the G protein (purple) inside the cell, starting a cascade of responses in the insulin-regulating pathway. The receptor is a target for many type 2 diabetes drugs.

3DEM has provided the first clear picture of the full-length activated receptor in complex with G protein, highlighting key interactions not visible in the X-ray structures of the individual components, and revealing how the different domains cooperate to transmit signals upon binding to the GLP-1 hormone. The structure has a nanobody bound to the G protein (shown in light blue) that helped the researchers to capture the active conformation of the receptor.

PDB Structure **5VAI**
3DEM Map **EMD-8653**

Y. Zhang *et al.* (2017) Cryo-EM structure of the activated GLP-1 receptor in complex with a G protein. *Nature* **546**: 248–253.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# APRIL 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 27 | 28 | 29 | 30 | 31 | 1 | 2 |
| 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 17 Easter | 18 | 19 | 20 | 21 | 22 Earth Day | 23 |
| 24 | 25 DNA Day | 26 | 27 | 28 | 29 | 30 |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

## ROQ1 Resistosome

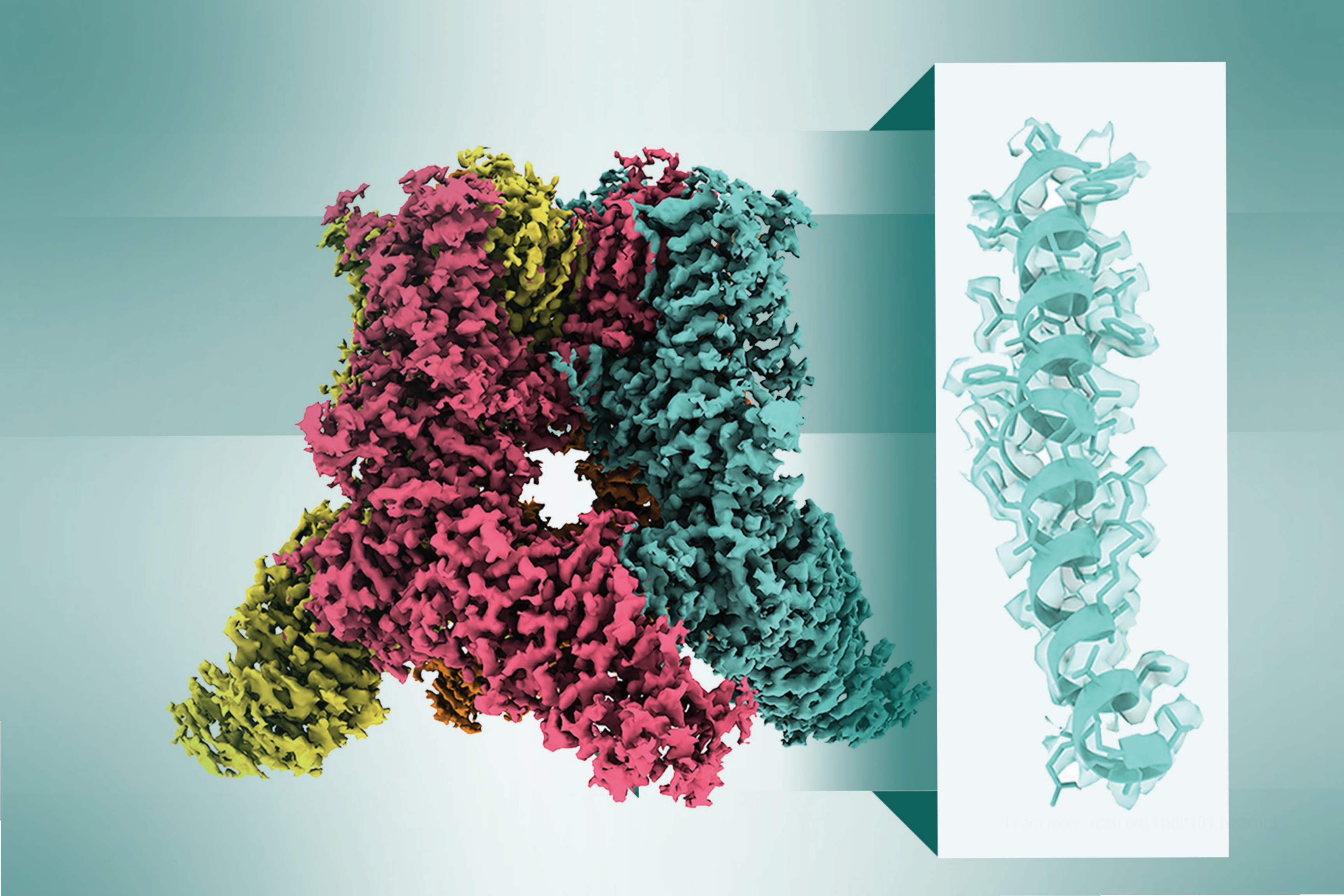
Pathogenic bacteria inject plant cells with effector proteins XopQ (red), which alters plant physiology. The immune system of plants includes the ROQ1 resistosome (green and yellow). The components assemble around foreign proteins and start an orderly process leading to death of the infected cell.

First discovered in 1994, it wasn't until 26 years later that a structure of activated ROQ1 would be determined using state-of-the-art 3DEM, providing mechanistic insights into how detection of the XopQ substrate leads to localized cell death and disease resistance.

PDB Structures **7JLV, 7JLU, 7JLX**
3DEM Map **EMD-22381**

R. Martin *et al.* (2020) Structure of the activated ROQ1 resistosome directly recognizing the pathogen effector XopQ. *Science* **370**: eabd9993.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# MAY 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| 1 | 2 Eid al-Fitr begins | 3 | 4 | 5 | 6 | 7 |
| 8 Mother's Day | 9 | 10 | 11 | 12 | 13 | 14 |
| 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| 29 | 30 Memorial Day | 31 | 1 | 2 | 3 | 4 |

## Transient Receptor Potential (TRP) Ion Channel

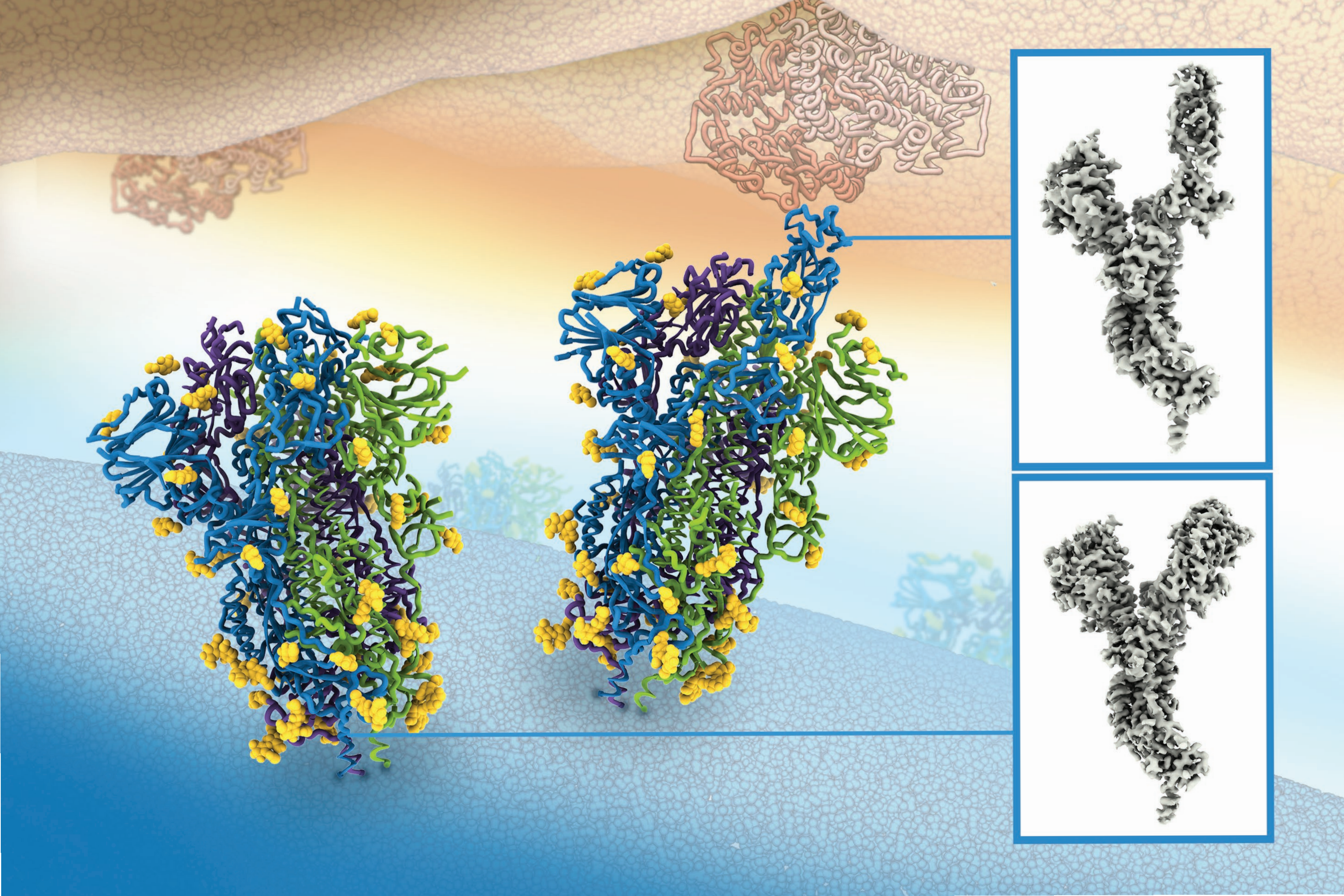
TRP ion channels are used by many different types of organisms to sense pain, temperature, and some natural toxins.

This tetramer is notoriously difficult to crystallize owing to its intrinsic flexibility and low expression level in cells. 3DEM has been the preferred method for producing over 70 structures in the past 8 years, including a 1.8 Å resolution structure of the wild-type mouse temperature-sensitive TRPV3 (atomic detail and map overlay shown in right panel).

PDB Structure **7MIJ**
3DEM Map **EMD-23853**

K.D. Nadezhdin *et al.* (2021) Structural mechanism of heat-induced opening of a temperature-sensitive TRP channel. *Nature Structural & Molecular Biology* **28**: 564–572.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# JUNE 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 29 | 30 | 31 | 1 | 2 | 3 | 4 |
| 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| 19 Father's Day Juneteenth | 20 | 21 | 22 | 23 | 24 | 25 |
| 26 | 27 | 28 | 29 | 30 | 1 | 2 |
| 3 | 4 | 5 | 6 | 7 | 8 | 9 |

## SARS-CoV-2 Spike Protein

The genome sequence of SARS-CoV-2 was first made publicly available on January 10th 2020, and by March 2020 researchers had already produced 3DEM structures of the envelope spike protein. The protein comprises three chains (shown in blue, green and purple). The protein uses a shield of sugars or glycans (some of them highlighted in yellow) to protect itself from the host immune proteins. During the initial steps of the viral infection, the receptor binding domain changes its shape (as shown in the insets) to bind to the angiotensin-converting enzyme (ACE2 receptor, sandy brown) on the host cells.

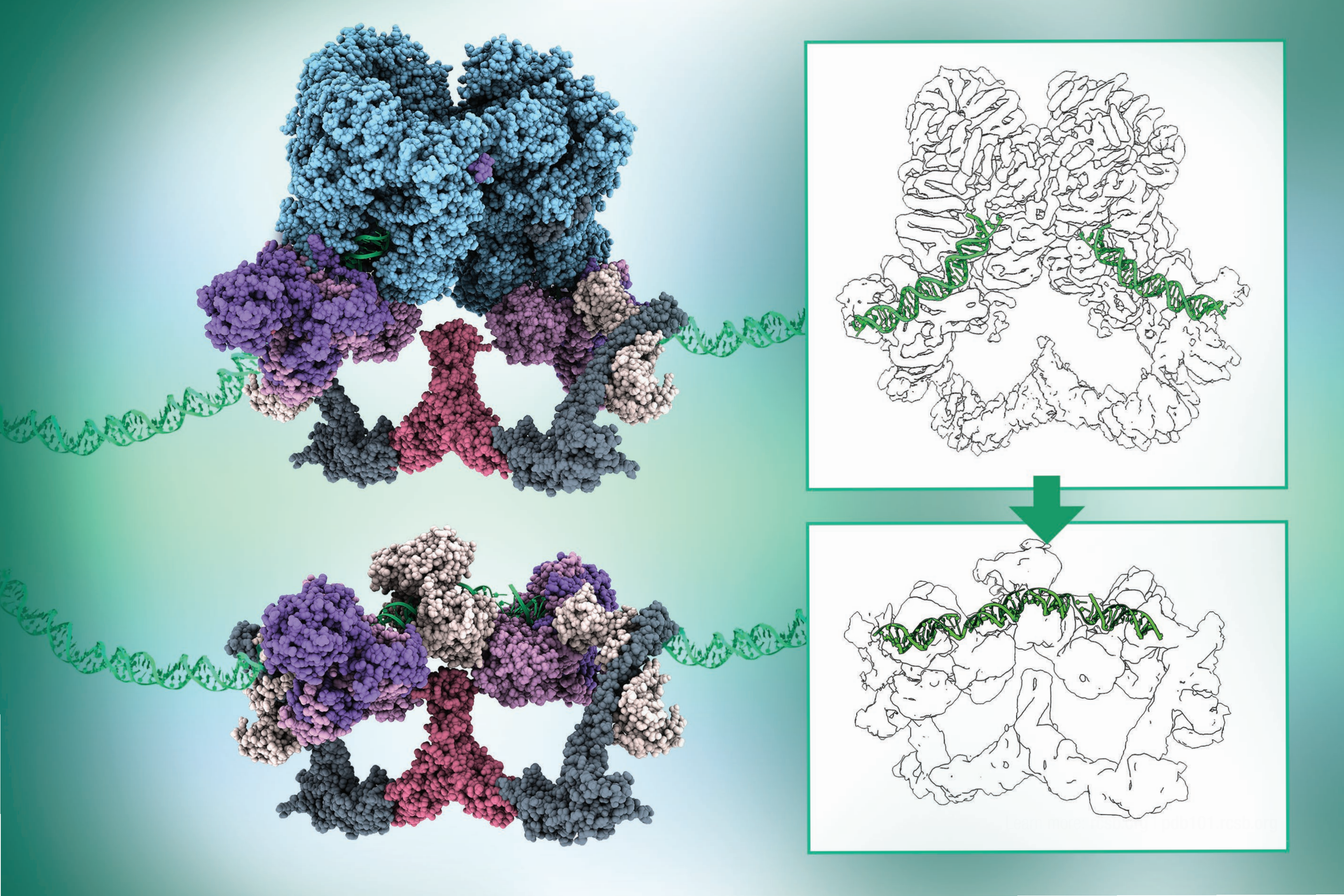
Hundreds of 3DEM spike-related structures are available in the PDB, providing insights on the structural mechanisms of SARS-CoV-2 infection, vaccination, and design of therapeutics.

PDB Structures **6VXX, 6VYB**
3DEM Maps **EMD-21452, EMD-21457**

A.C. Walls *et al.* (2020) Structure, Function, and Antigenicity of the SARS-CoV-2 Spike Glycoprotein. *Cell* **181**: 281–292.

ACE2 Receptor: PDB Structure **6M18**
R. Yan *et al.* (2020) Structural basis for the recognition of SARS-CoV-2 by full-length human ACE2. *Science* **367**: 1444–1448.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# JULY 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 26 | 27 | 28 | 29 | 30 | 1 | 2 |
| 3 | 4 Independence Day (USA) | 5 | 6 | 7 | 8 | 9 |
| 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| 31 | 1 | 2 | 3 | 4 | 5 | 6 |

## NHEJ Complexes

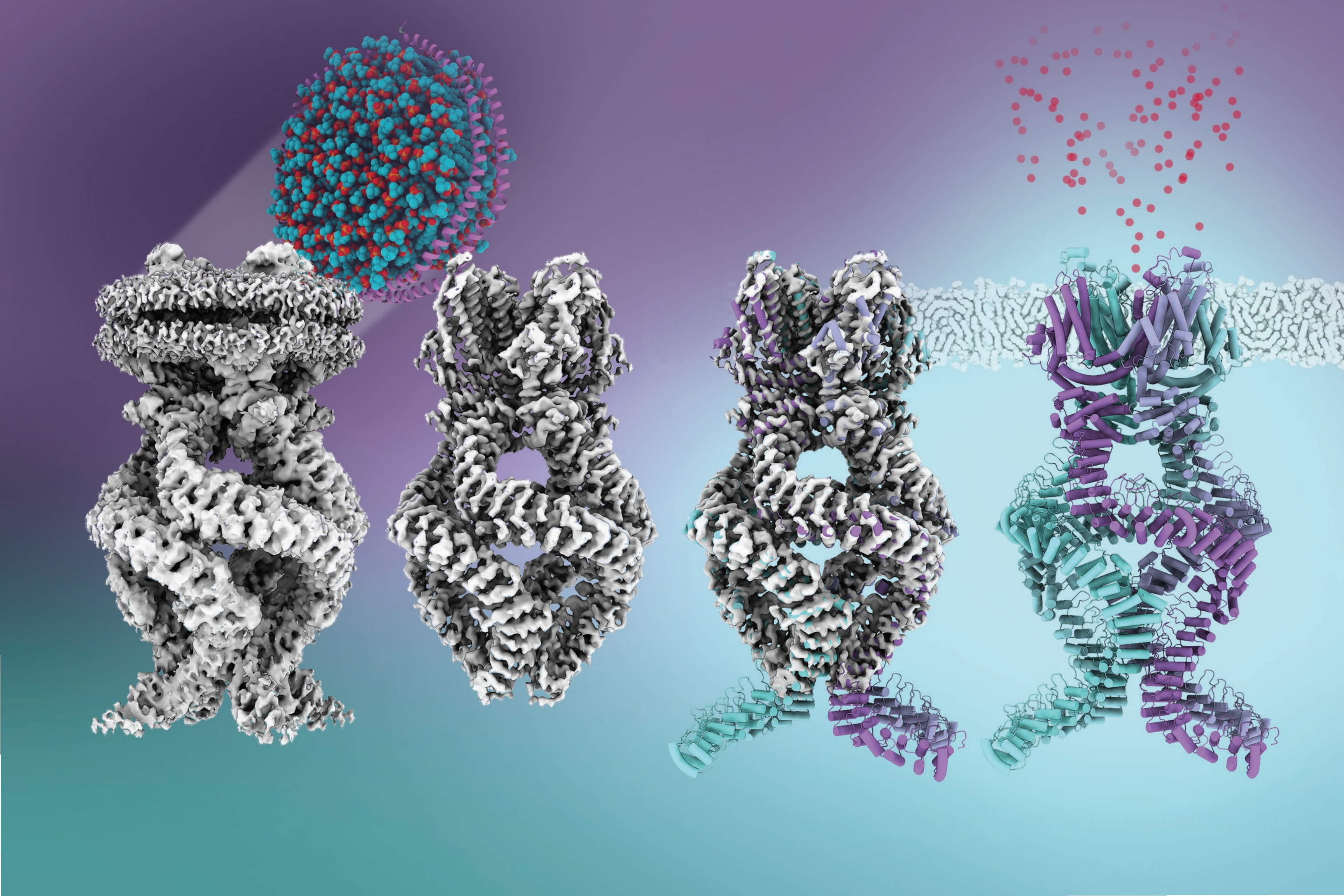
Non-homologous end joining (NHEJ) is the primary pathway by which eukaryotic cells repair DNA double-strand breaks.

3DEM can provide direct views of the essential assembly states during NHEJ, allowing researchers to elucidate the complete reaction cycle for how broken DNA ends are stitched together. This illustration shows a long-range complex (top) which grabs the broken DNA fragments when they are far apart and a short-range complex (bottom), which ultimately joins the DNA ends when they are close together.

PDB Structures **7LT3, 7LSY**
3DEM Maps **EMD-23510, EMD-23509**

S. Chen *et al.* (2021) Structural basis of long-range to short-range synaptic transition in NHEJ. *Nature* **593**: 294–298.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# AUGUST 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 31 | 1 | 2 | 3 | 4 | 5 | 6 |
| 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 28 | 29 | 30 | 31 | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |

## NompC

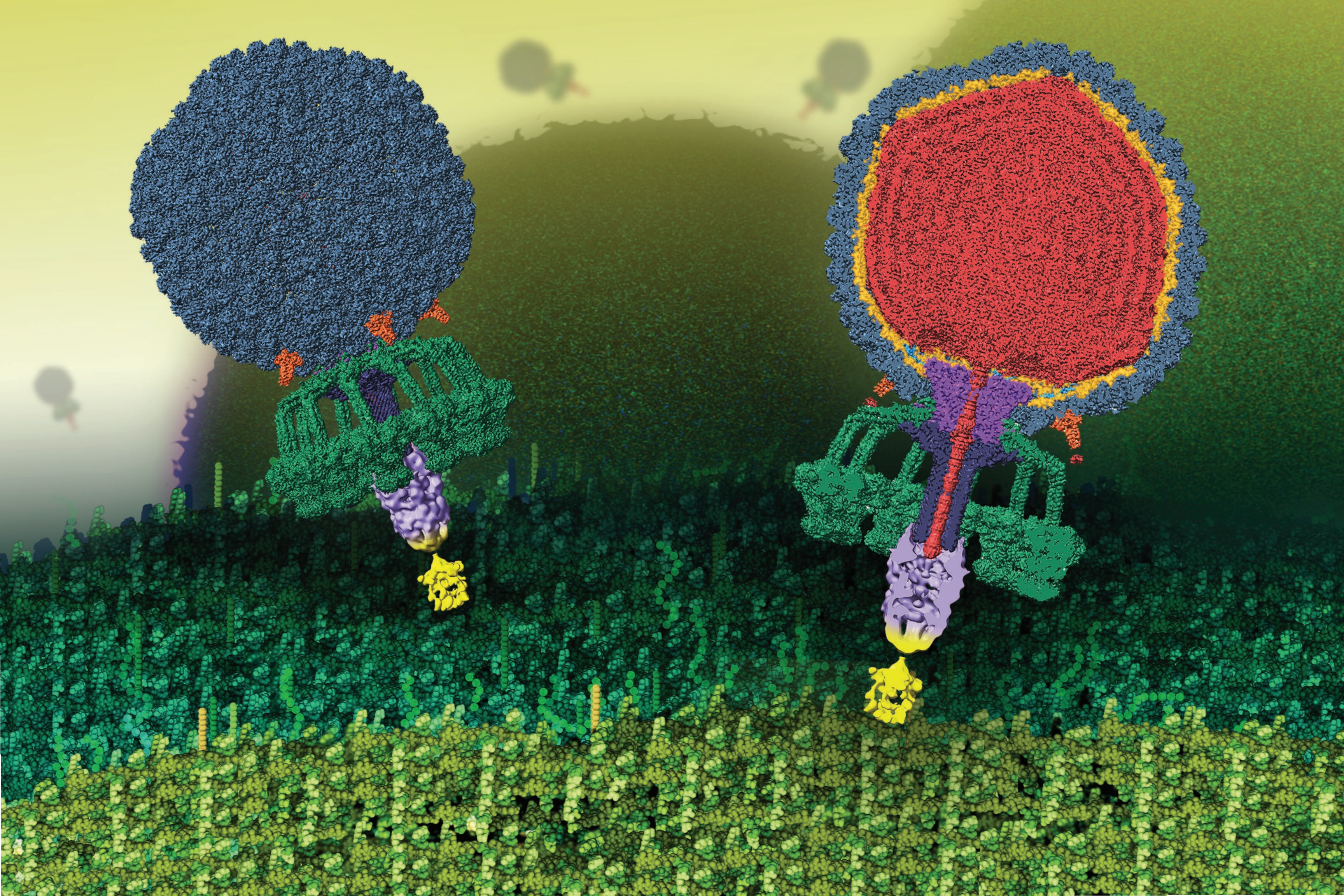
Specialized mechanoreceptive organelles in fruit flies contain thousands of force-sensitive NompC ion channels that are responsible for the sensations of touch and balance. The channel contains a bundle of ~15-nm-long supercoiled helices that act like springs and open in response to mechanical force on the membrane allowing the ion entry.

The illustration shows the 3DEM density map on the left and 3D atomic model on the right. The sample was reconstituted in a lipid nanodisc. Nanodiscs (shown top left) are often used in EM experiments when determining membrane-bound structures. They are composed of a disc of lipids just big enough to hold one copy of a protein surrounded by a stabilizing belt of proteins.

PDB Structure **5VKQ**
3DEM Map **EMD-8702**

P. Jin *et al.* (2017) Electron cryo-microscopy structure of the mechanotransduction channel NOMPC. *Nature* **547**: 118–122.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# SEPTEMBER 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 28 | 29 | 30 | 31 | 1 | 2 | 3 |
| 4 | 5<br>Labor Day | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 25<br>Rosh Hashanah begins | 26 | 27 | 28 | 29 | 30 | 1 |
| 2 | 3 | 4 | 5 | 6 | 7 | 8 |

## Phage P68

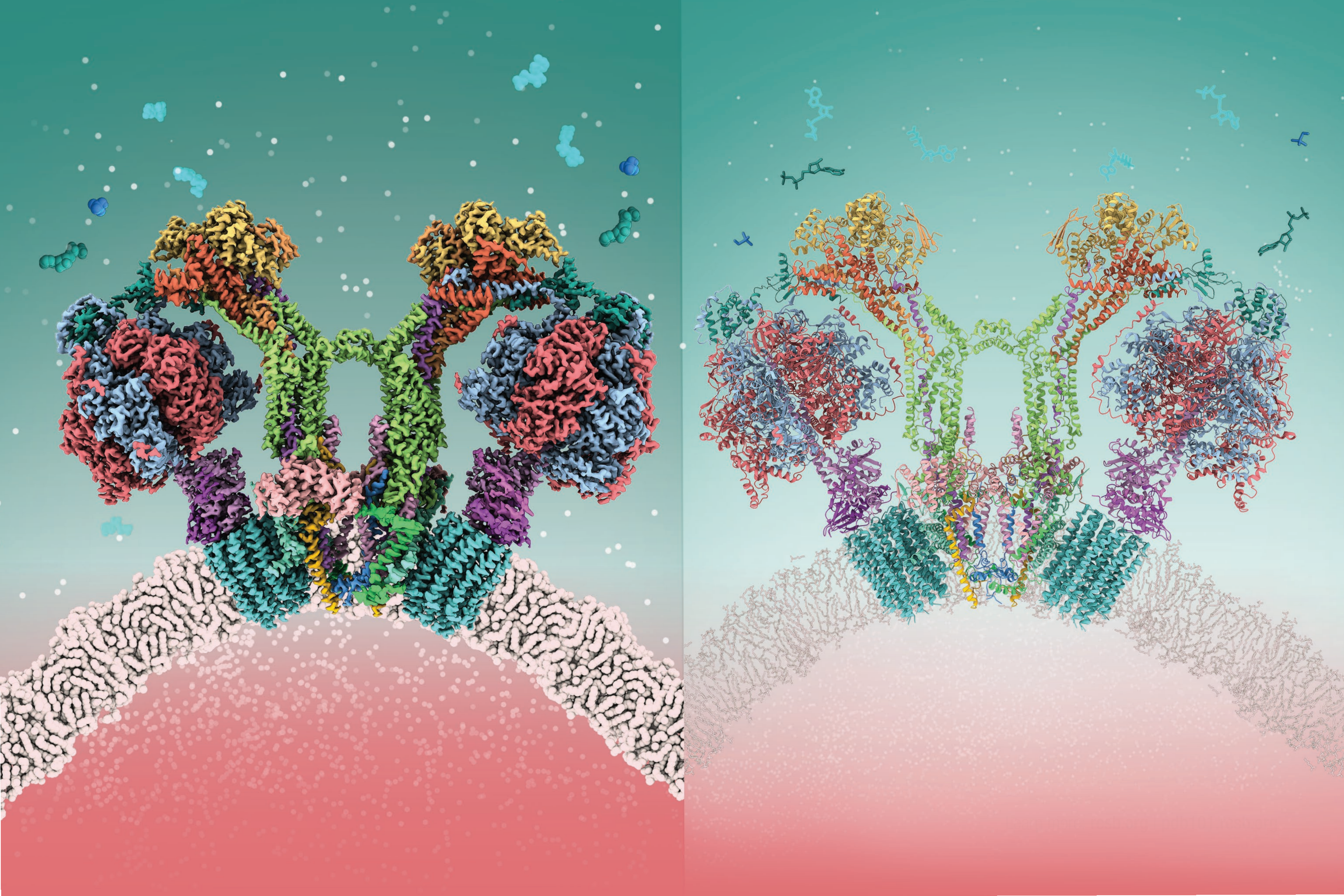
Many bacteriophages (viruses that attack bacteria) have icosahedral capsids (dark blue) to store and protect their genomes (red) from the harsh extracellular environment. These viruses use tail fibers (green) to attach to molecules on the surface of bacterial cell walls. Thereafter, the tail spike (yellow) penetrates the thick layer of bacterial peptidoglycan and the lipid bilayer membrane to inject DNA into the bacterial cytoplasm. This illustration shows Phage P68 in its native form prior to interaction with the cell wall. The same study also reported a genome ejection intermediate and empty particle.

The first electron micrographs of raw unstained phages were published in Germany in 1940. Less than one hundred years later–thanks to remarkable developments in 3DEM–researchers are able to visualize elegant 3D structures of phages releasing their genomes.

PDB Structure **6Q3G**
3DEM Map **EMD-4459**

D. Hrebík *et al.* (2019) Structure and genome ejection mechanism of *Staphylococcus aureus* phage P68. *Science Advances* **5**: eaaw7414.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# OCTOBER 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 25 | 26 | 27 | 28 | 29 | 30 | 1 |
| 2 | 3 | 4<br>Yom Kippur begins | 5 | 6 | 7 | 8 |
| 9 | 10<br>Indigenous Peoples' Day | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20<br>PDB announced in 1971 | 21 | 22 |
| 23 | 24<br>Diwali | 25 | 26 | 27 | 28 | 29 |
| 30 | 31<br>Halloween | 1 | 2 | 3 | 4 | 5 |

## ATP Synthase Dimer

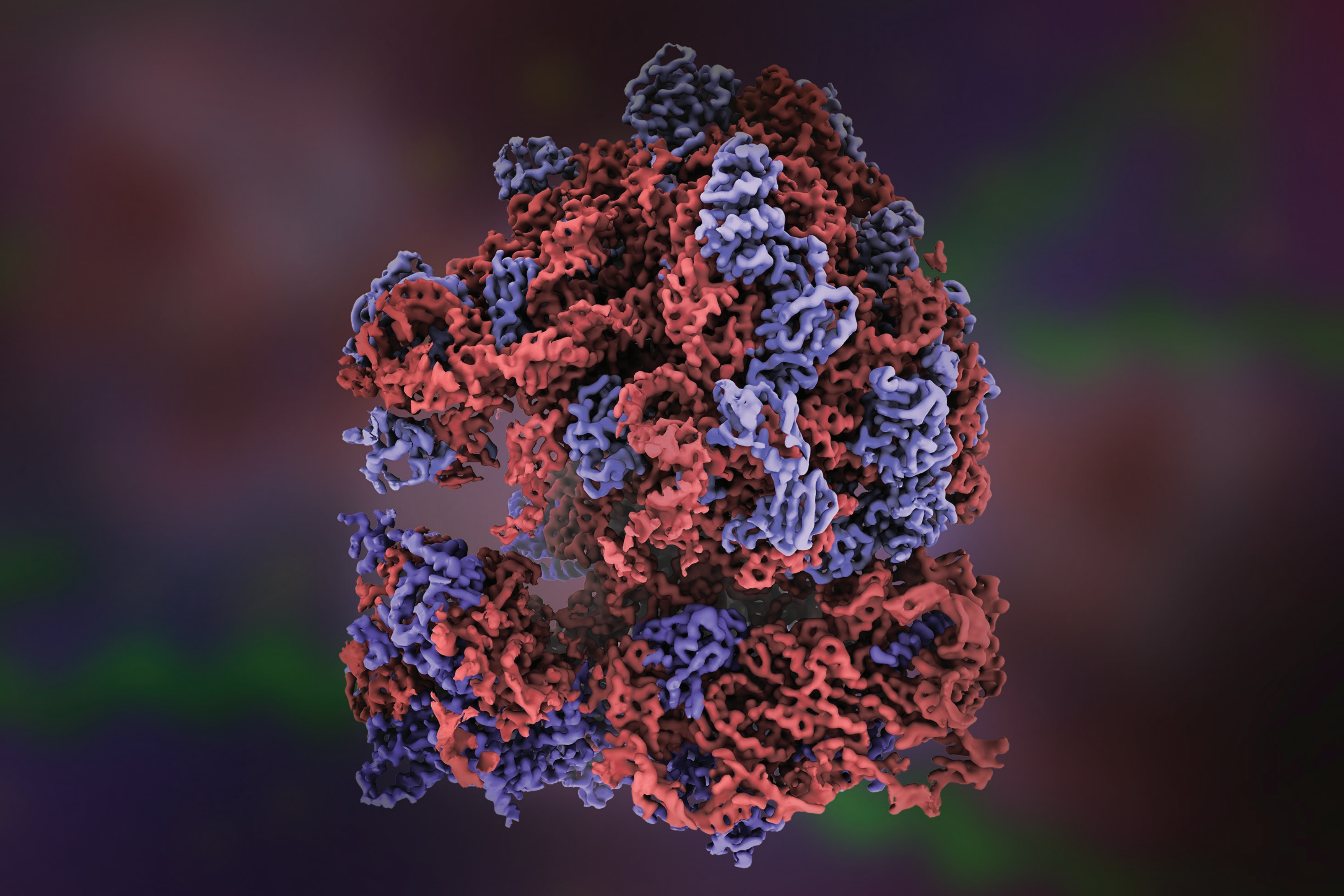
Mitochondrial ATP synthases form dimers and occupy the folds on the inner membranes of the mitochondria. This molecular machine links two rotary motors termed F1 and F0. The F0 motor (cyan) is nested in the membrane where rotations are powered by the difference in the proton gradient across the membrane. A central stalk connects both motors powering the F1 motor, which then uses the power of rotational motion to build ATP from ADP and inorganic phosphate.

F-type ATP synthases have been studied extensively over the past 50 years, but only recently has it become possible to fully understand their molecular mechanisms owing to the determination of complete complexes by 3DEM.

PDB Structure **6RD4**
3DEM Map **EMD-4805**

B.J. Murphy *et al.* (2019) Rotary substates of mitochondrial ATP synthase reveal the basis of flexible F1-Fo coupling. *Science* **364**: eaaw9128.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# NOVEMBER 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 30 | 31 | 1 | 2 | 3 | 4 | 5 |
| 6 Daylight Saving Time ends (North America) | 7 | 8 | 9 | 10 | 11 Veterans Day | 12 |
| 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 20 | 21 | 22 | 23 | 24 Thanksgiving | 25 | 26 |
| 27 | 28 | 29 | 30 | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |

## Ribosome

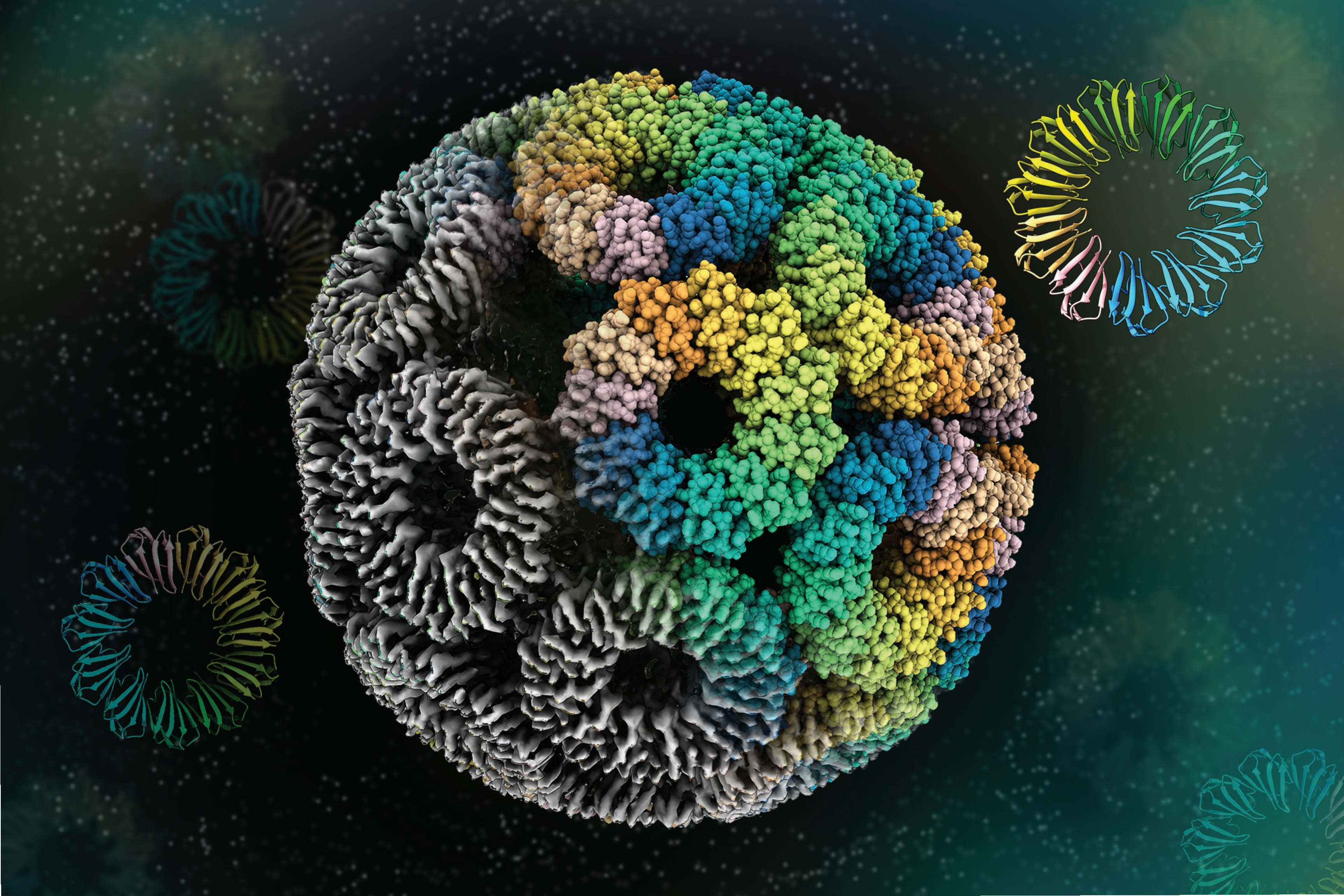
Ribosomes are molecular machines built of proteins (purple) and RNA (red). Ribosomes are found within all living organisms where they synthesize new proteins using mRNA templates. Differences between human and bacterial ribosomes make them an excellent target for many antibiotics.

3DEM enables macromolecular structure determination *in vitro* and *in situ*, which bridges the gap between structural biology and cell biology. This structure shows a snapshot of a ribosome from *Mycoplasma pneumoniae* caught inside its native cellular environment at residue-level resolution. The structure includes a bound antibiotic (chloramphenicol).

3DEM Maps **EMD-11650, EMD-11998, EMD-11999**

D. Tegunov *et al.* (2021) Multi-particle cryo-EM refinement with M visualizes ribosome-antibiotic complex at 3.5Å in cells. *Nature Methods* **18**: 186–193.

Learn more: **rcsb.org** | **pdb101.rcsb.org**



# DECEMBER 2022

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 27 | 28 | 29 | 30 | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 Hanukkah begins | 19 | 20 | 21 | 22 | 23 | 24 |
| 25 Christmas Day | 26 Kwanzaa | 27 | 28 | 29 | 30 | 31 New Year's Eve |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

## Nanocage

Tailor-made protein cages are being engineered in the laboratory for diverse applications in materials science, medicine, and synthetic biology. Several nanocages have been characterized at near-atomic resolution by 3DEM, including the gold-laced TRAP cage that possesses an unusual snub cube geometry long thought to be impossible.

PDB Structure **6RVV**
3DEM Map **EMD-4444**

A.D. Malay *et al.* (2019) An ultra-stable gold-coordinated protein cage displaying reversible assembly. *Nature* **569**: 438–442.

Learn more: **rcsb.org** | **pdb101.rcsb.org**

## ABOUT THIS CALENDAR

This calendar highlights structures studied by 3D electron microscopy (3DEM) that further our understanding of biology and serve as a gateway to advances in technology and medicine.

Corresponding atomic data are freely available in the Protein Data Bank (PDB; structures) and Electron Microscopy Data Bank (EMDB; maps) archives. Access these data at RCSB.org by entering the PDB or EMDB ID listed each month.

## REFERENCES


wwPDB: *Nature Structural Biology* **10**: 980 (2003) doi: 10.1038/nsb1203-980

PDB archive: *Nucleic Acids Research* **47**: D520–D528 (2019) doi: 10.1093/nar/gky949

EMDB: *Nucleic Acids Research* **44**: D396–D403 (2016) doi: 10.1093/nar/gkv1126

RCSB PDB:
*Nucleic Acids Research* **28**: 235–242 (2000) doi: 10.1093/nar/28.1.235

*Nucleic Acids Research* **49**: D437–D451 (2021) doi: 10.1093/nar/gkaa1038


Molecular images were created using UCSF ChimeraX (E. F. Pettersen *et al.* (2021) UCSF ChimeraX: Structure visualization for researchers, educators, and developers. *Protein Sci.* **30**: 70–82.)

RCSB PDB PROTEIN DATA BANK

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*A Living Digital Data Resource that Enables Scientific Breakthroughs*

Cells rely on many large molecular machines that carry out the complex biological and chemical tasks responsible for sustaining life. 3D structures of these machines are freely available at the Protein Data Bank (PDB), the global storehouse of biomolecular structures central to research and education.

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- Inform basic and applied research across the sciences
- Are central to understanding human, animal, and plant health and disease
- Are critical for drug discovery/development and biotechnology
- Enable education across biology and medicine

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## PDB101.RCSB.ORG

*Molecular Explorations through Biology and Medicine*

PDB-101 is the educational portal of the RCSB PDB developed for teachers, students, and the general public to promote exploration in the 3D world of proteins and nucleic acids.

Learning about the diverse shapes and functions of these biological macromolecules helps us understand all aspects of biomedicine and agriculture, from protein synthesis to human health and disease to biological energy.

All resources are freely available, including curricular materials, paper molecular models, videos/animations, and more.

Visit the *Guide to Understanding PDB Data* (accessible from the *Learn* menu) to learn more about 3DEM and other techniques for structure determination.


RCSB PDB is funded by the National Science Foundation (DBI-1832184), the US Department of Energy (DE-SC0019749), and the National Cancer Institute, National Institute of Allergy and Infectious Diseases, and National Institute of General Medical Sciences of the National Institutes of Health under grant R01GM133198.