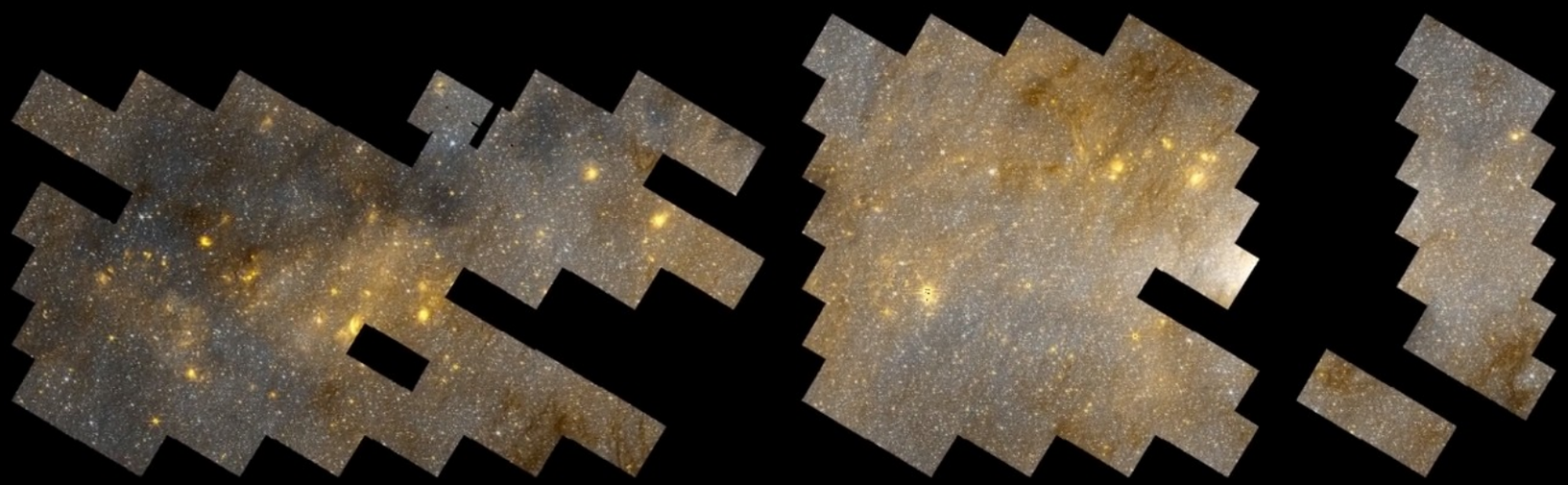
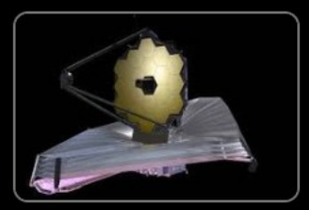
ALMA · radio light from cold dust

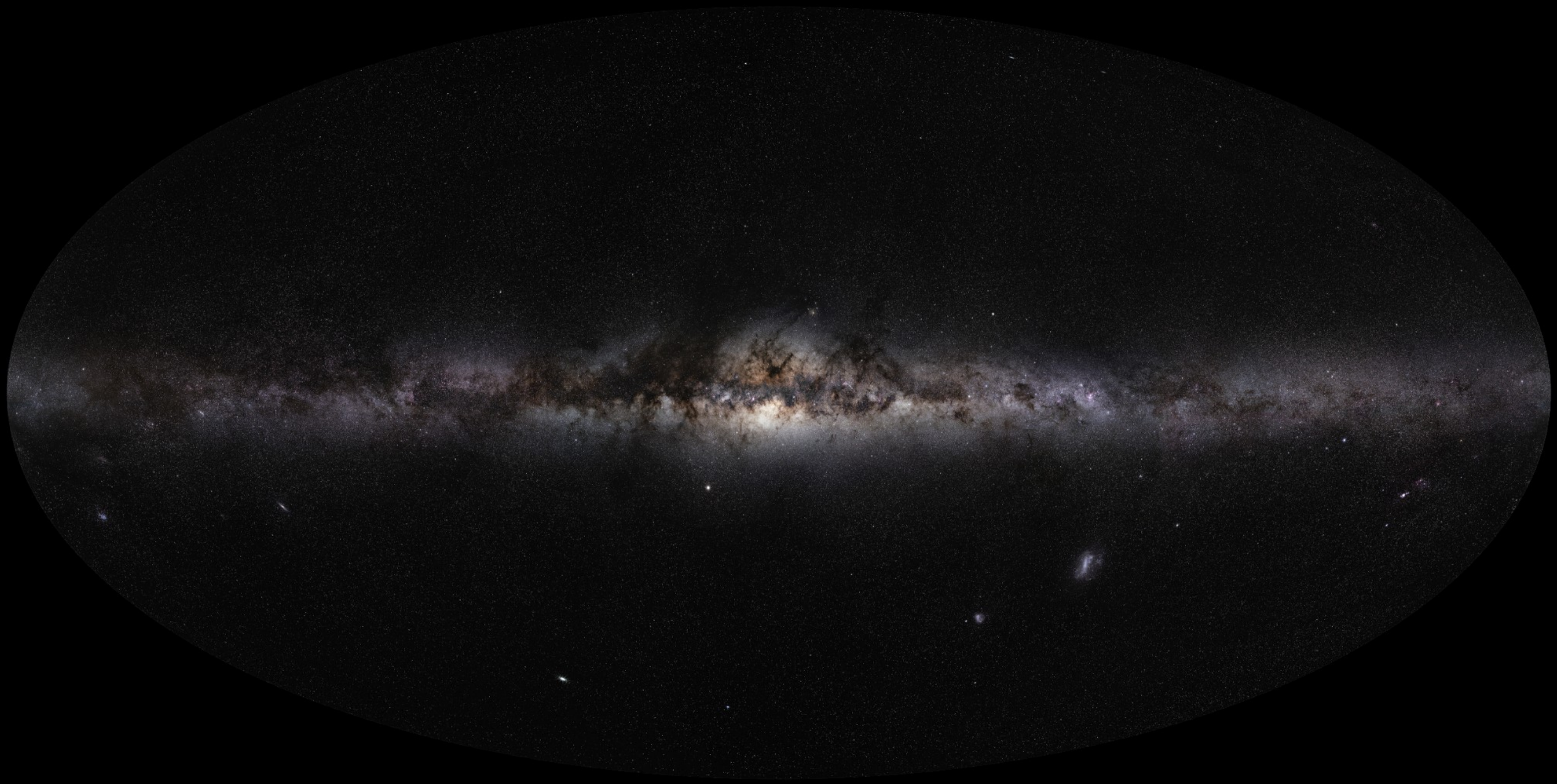


JWST · infrared light from stars



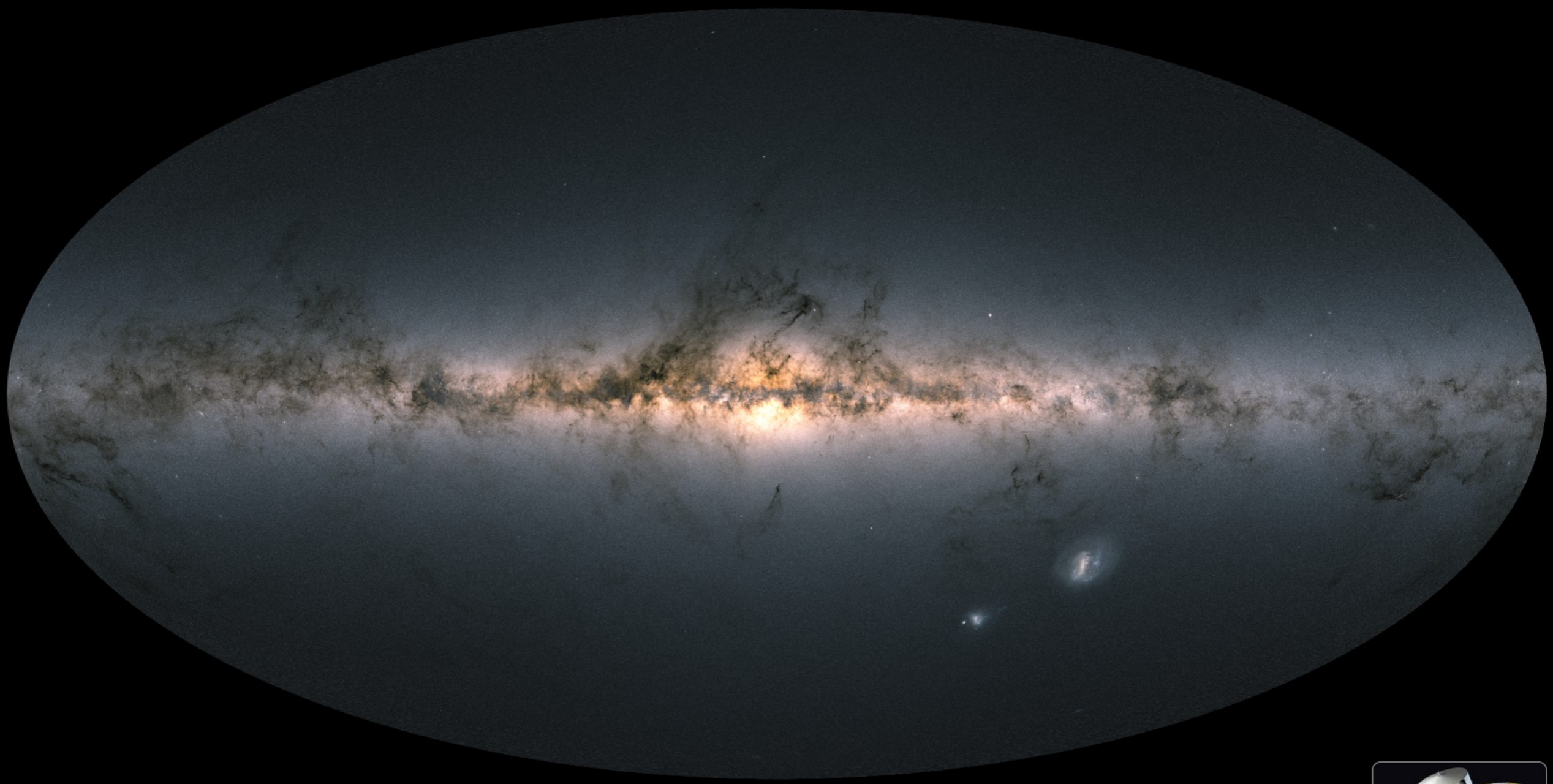


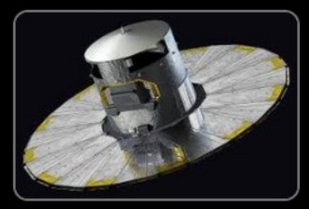
The Milky Way, as your eye sees it



ESO/S. Brunier

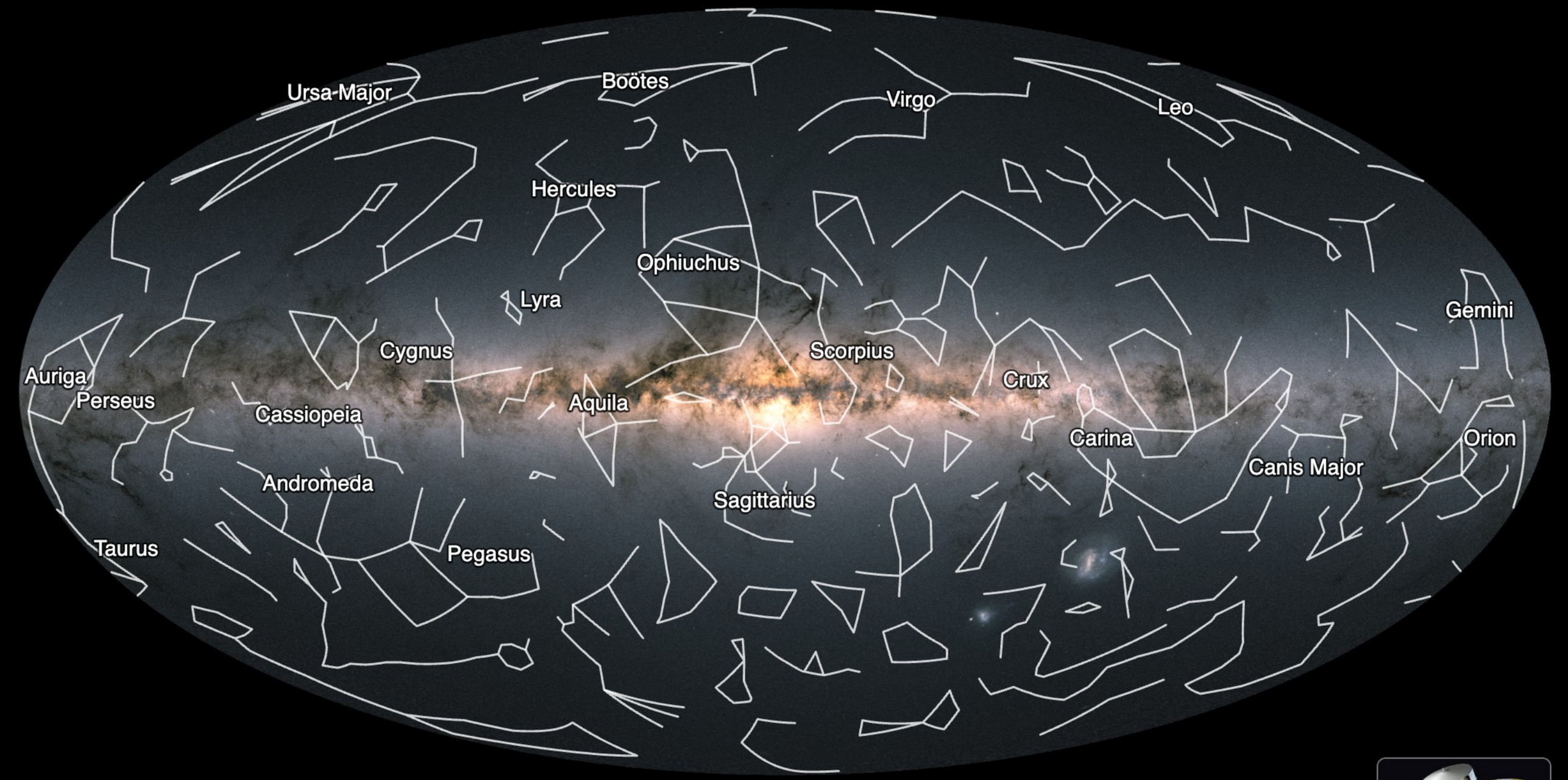
The same sky, star by star: Gaia

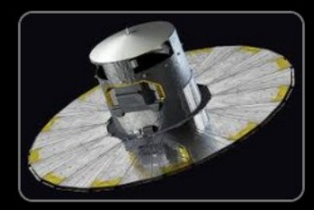




Gaia star colors via ESA

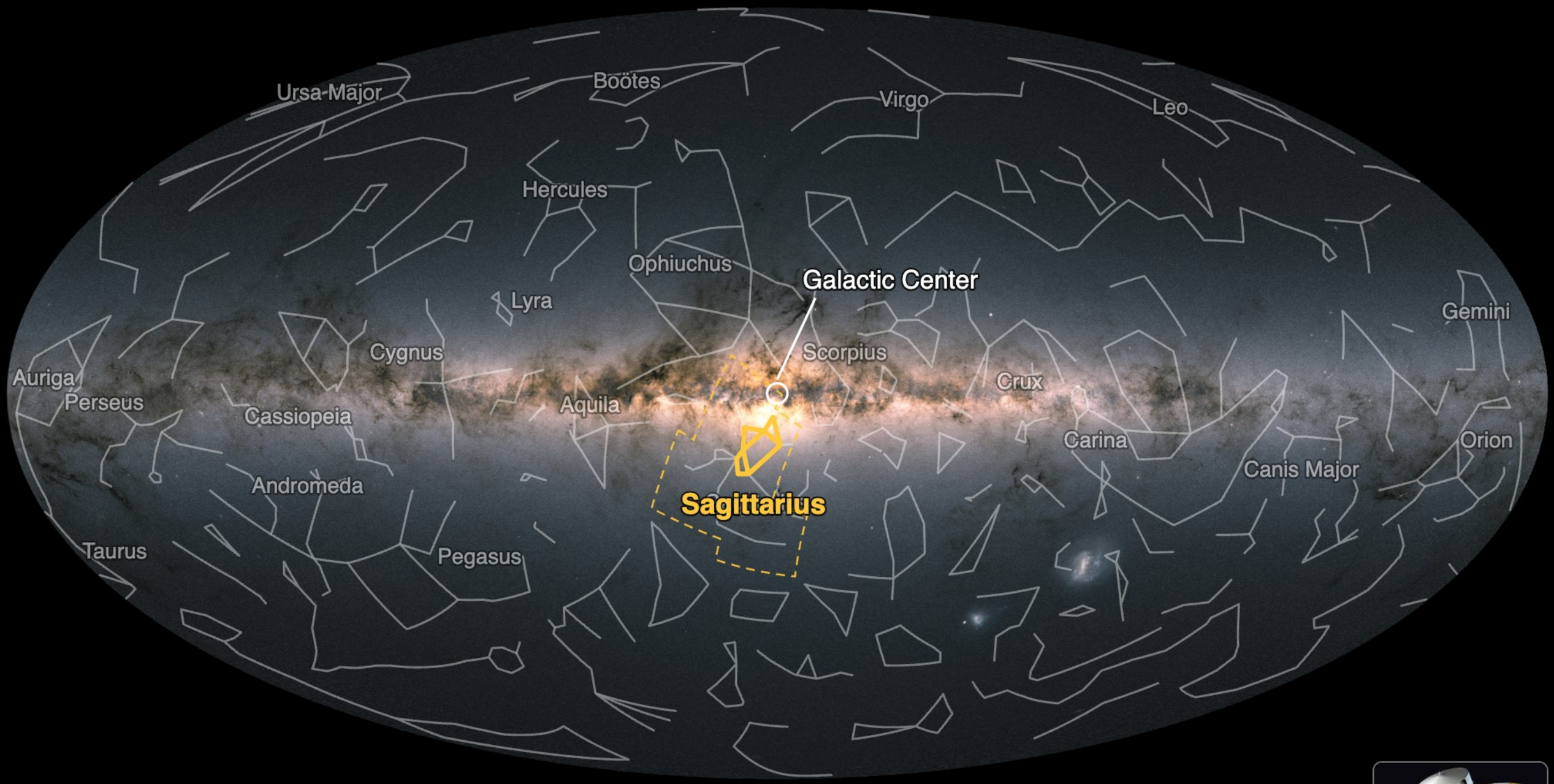
The constellations

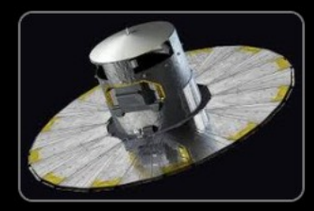




Gaia star colors via ESA · constellation lines: d3-celestial (O. Frohn)

Toward the Galactic Center: Sagittarius

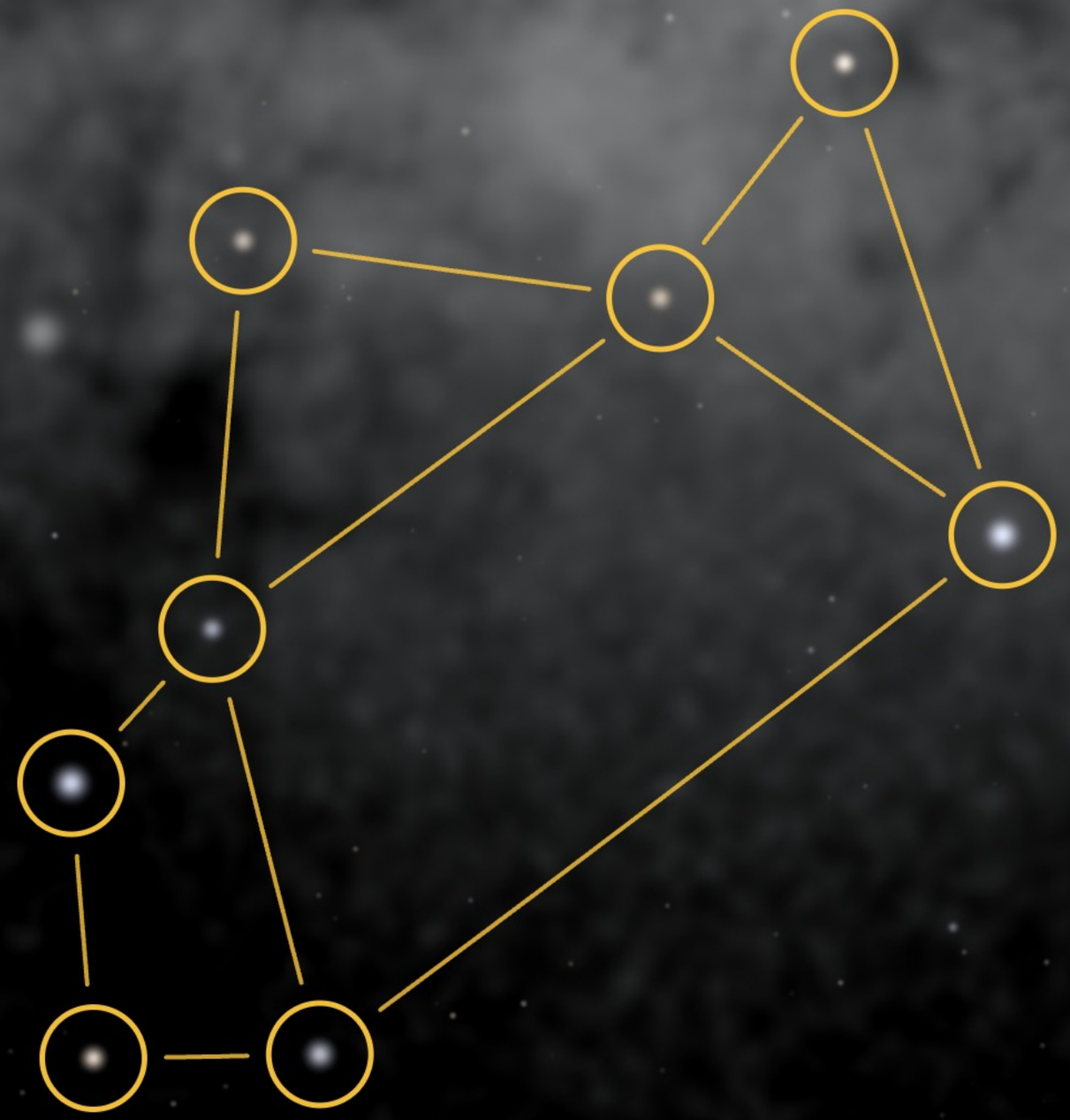


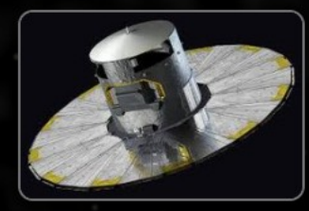


Tonight: low in the southwest, right after dark

Gaia star colors via ESA · constellation lines: d3-celestial (O. Frohn)

The Teapot

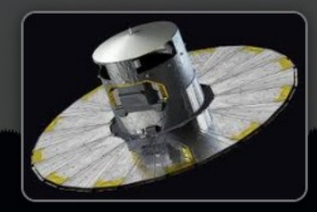




Simulated sky: Gaia DR3 + Hipparcos (ESA)

Tonight at 7 pm, looking southwest

Galactic Center



S SW W

Simulated sky: Gaia DR3 + Hipparcos (ESA)

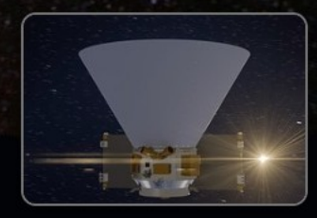
In infrared light

Galactic Center

S

SW

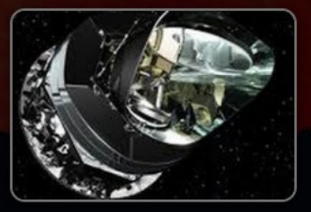
W



SPHEREx via NASA/JPL-Caltech

In millimeter and radio light

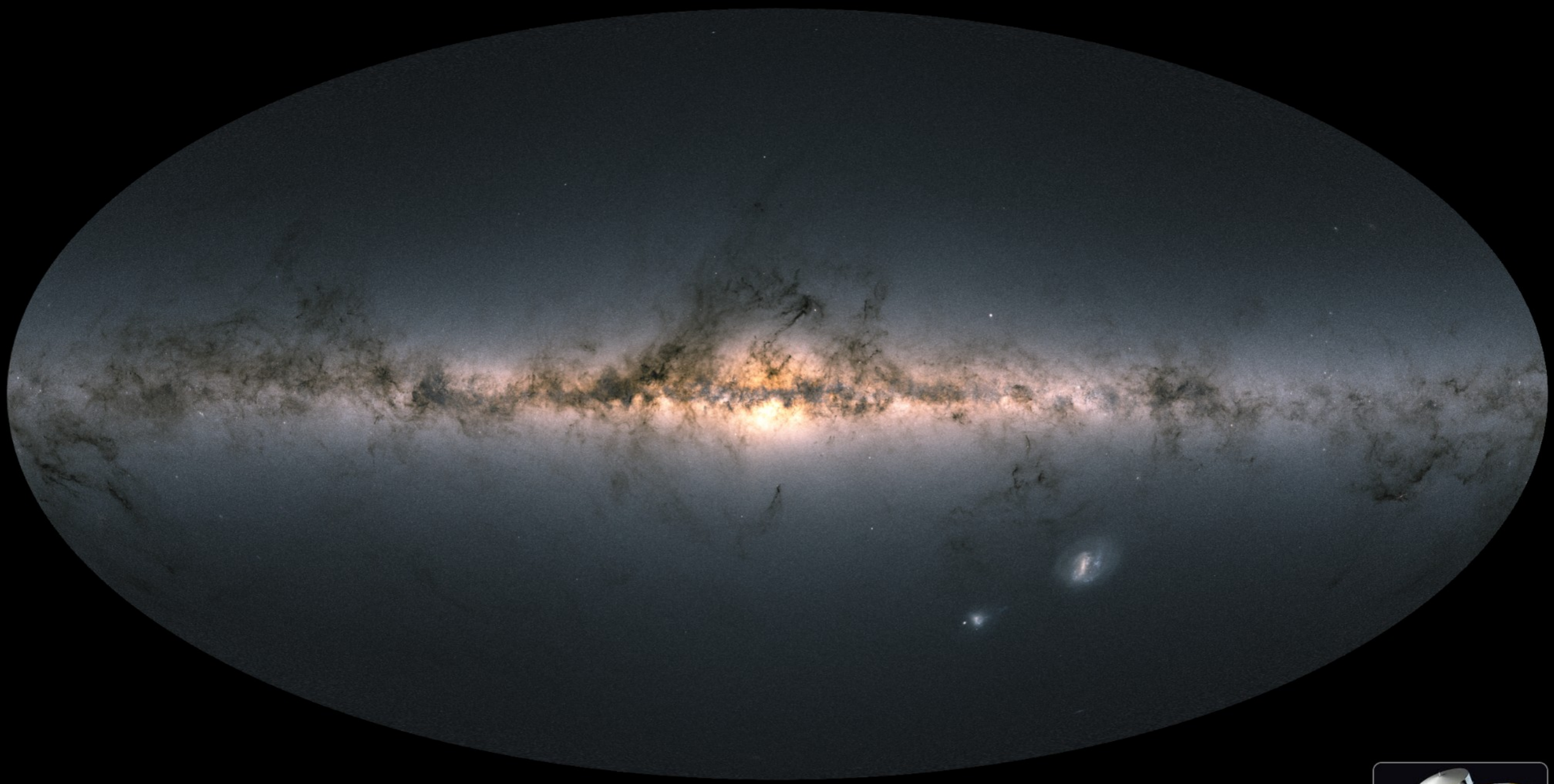
Galactic Center

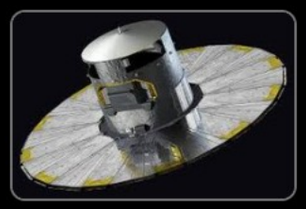


S SW W

Planck + HI4PI via lambda.gsfc.nasa.gov

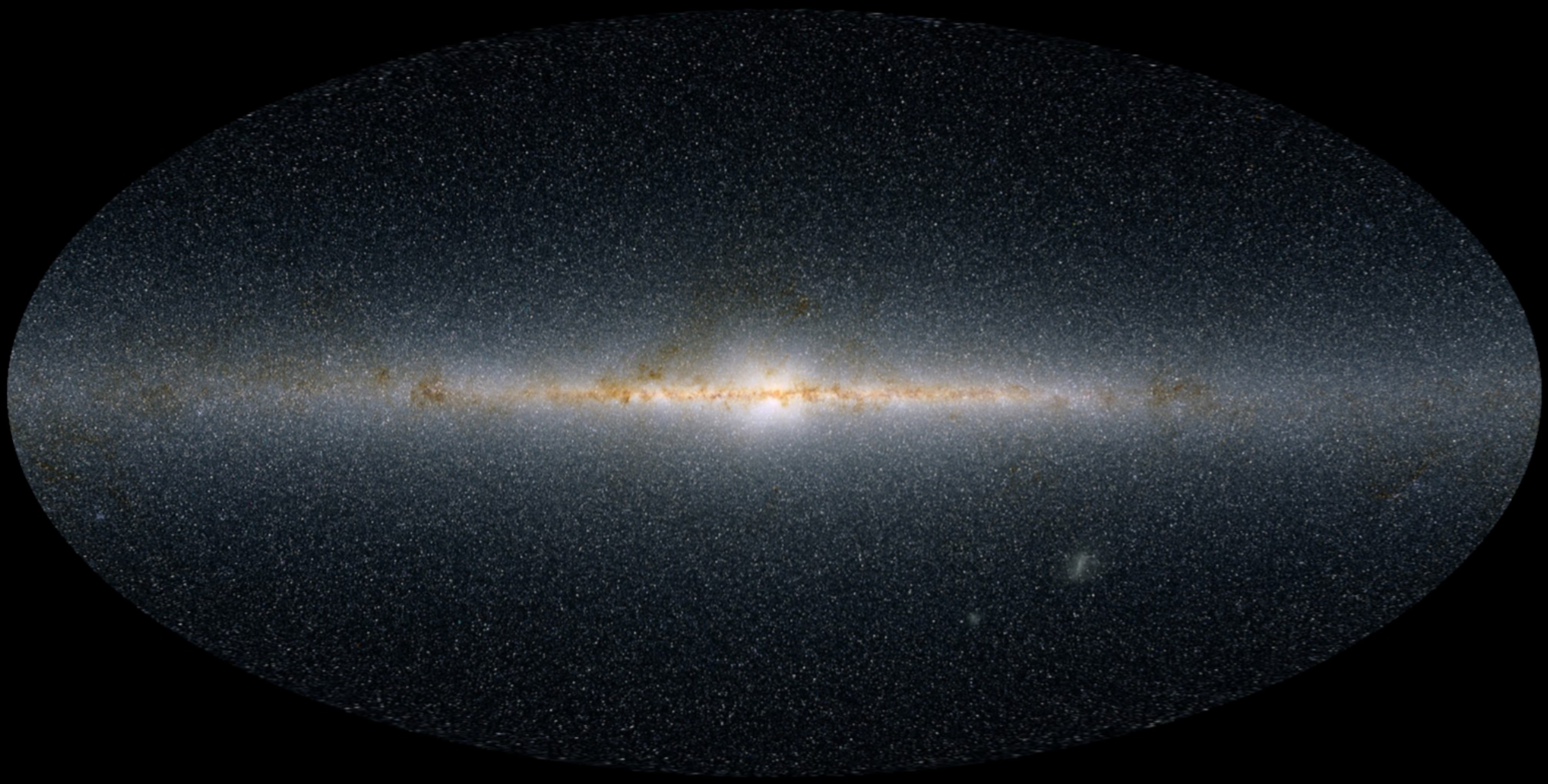
Back to the whole sky



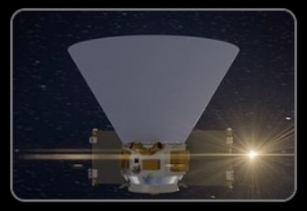


Gaia star colors via ESA

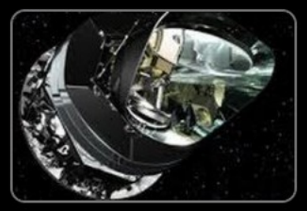




2MASS via IPAC



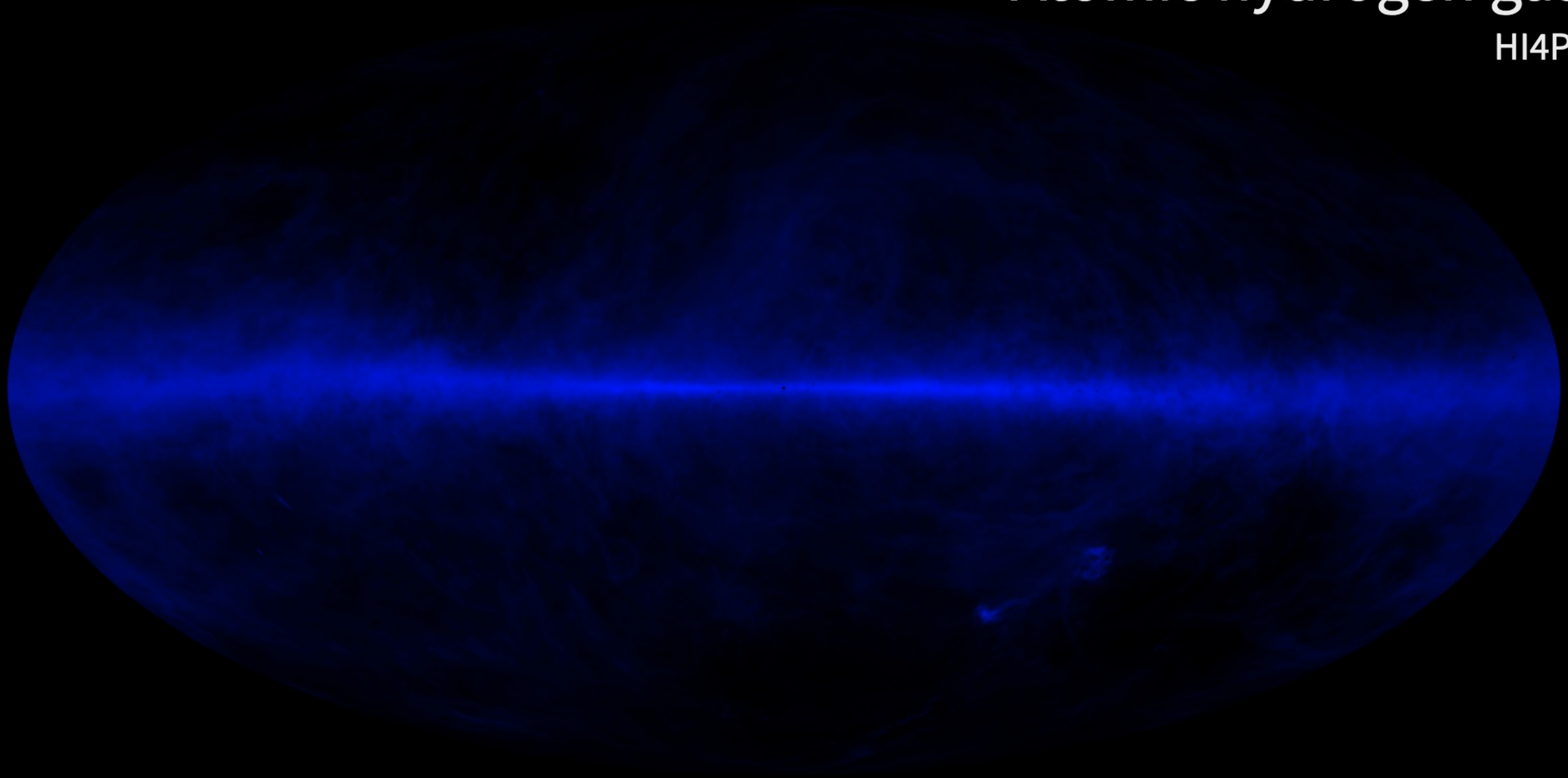
SPHEREx via NASA/JPL-Caltech

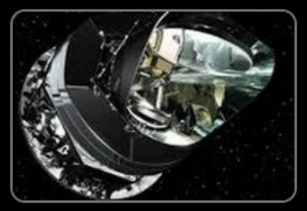


Planck + HI4PI via lambda.gsfc.nasa.gov

Atomic hydrogen gas

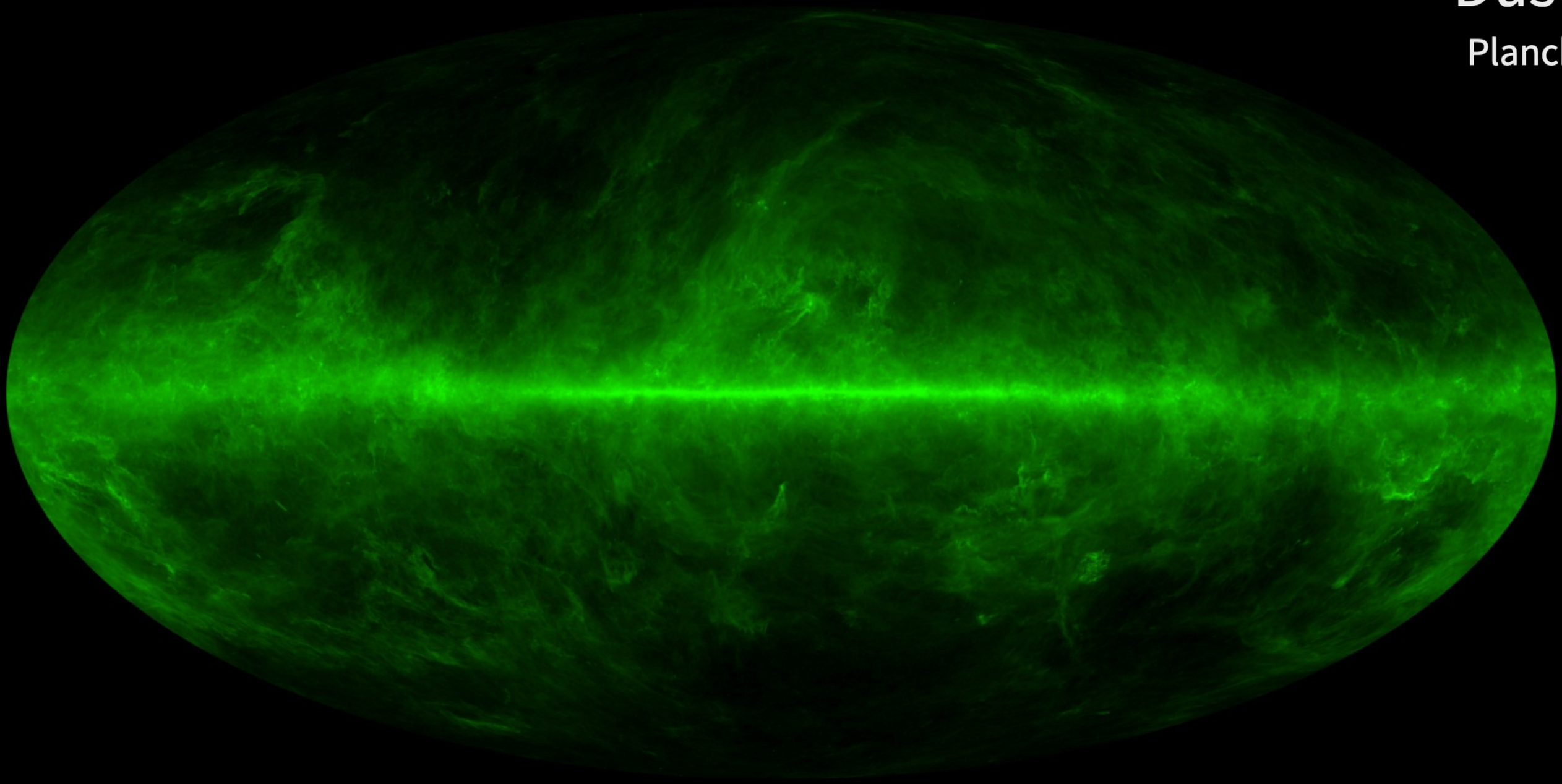
HI4PI

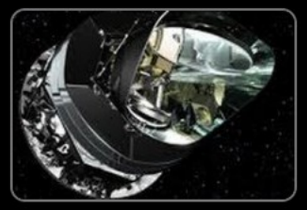




Dust

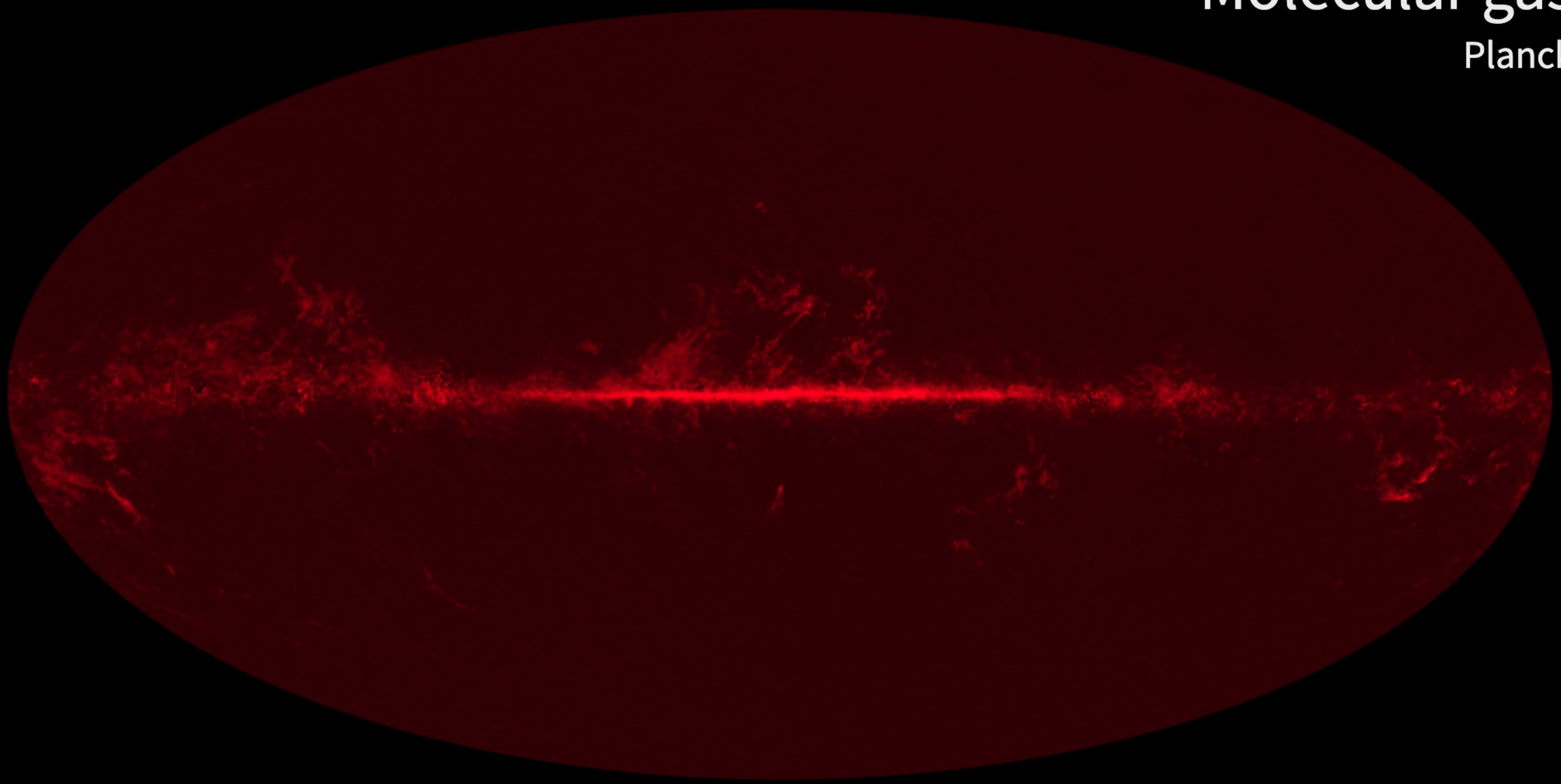
Planck

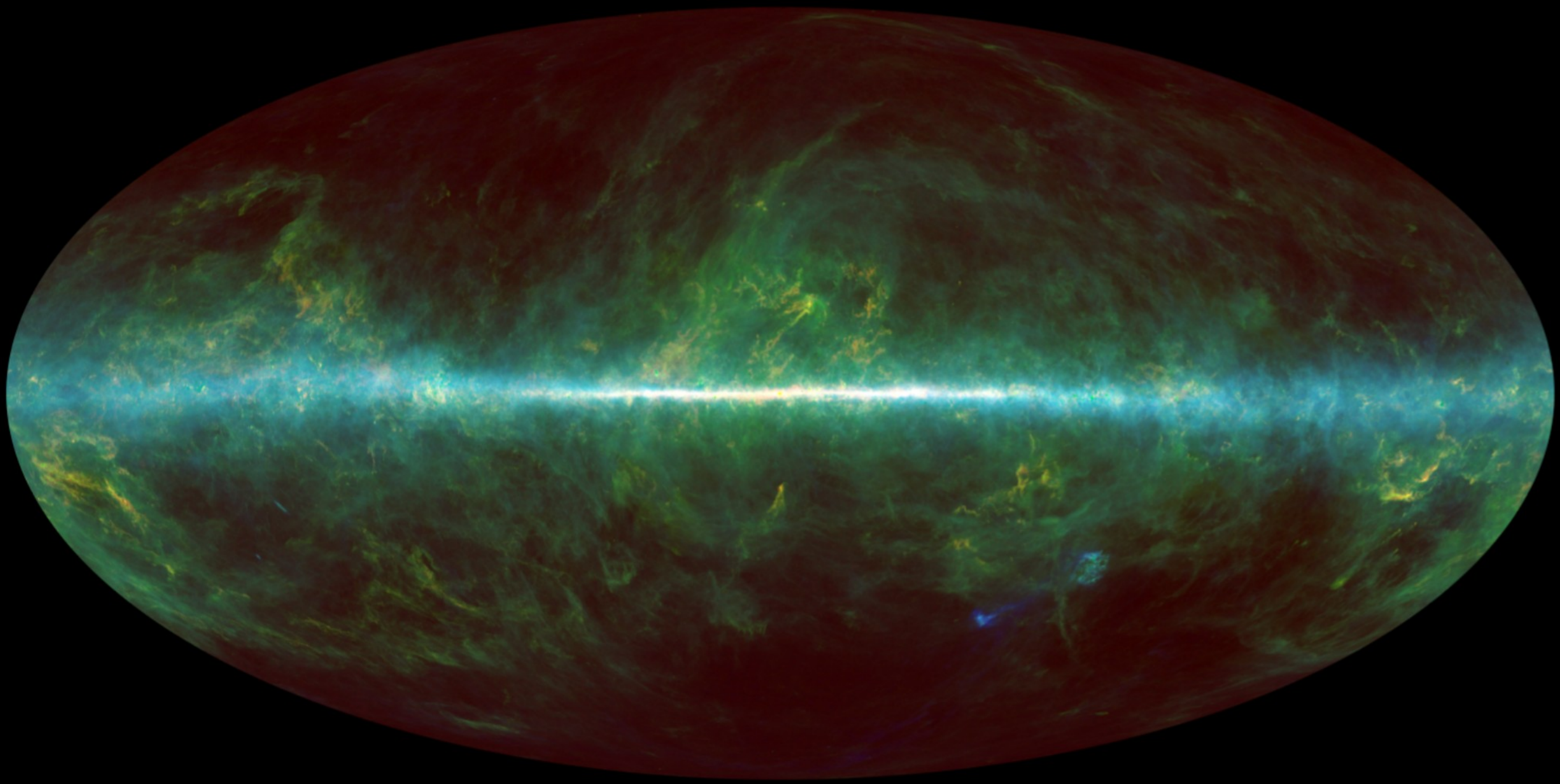




Molecular gas

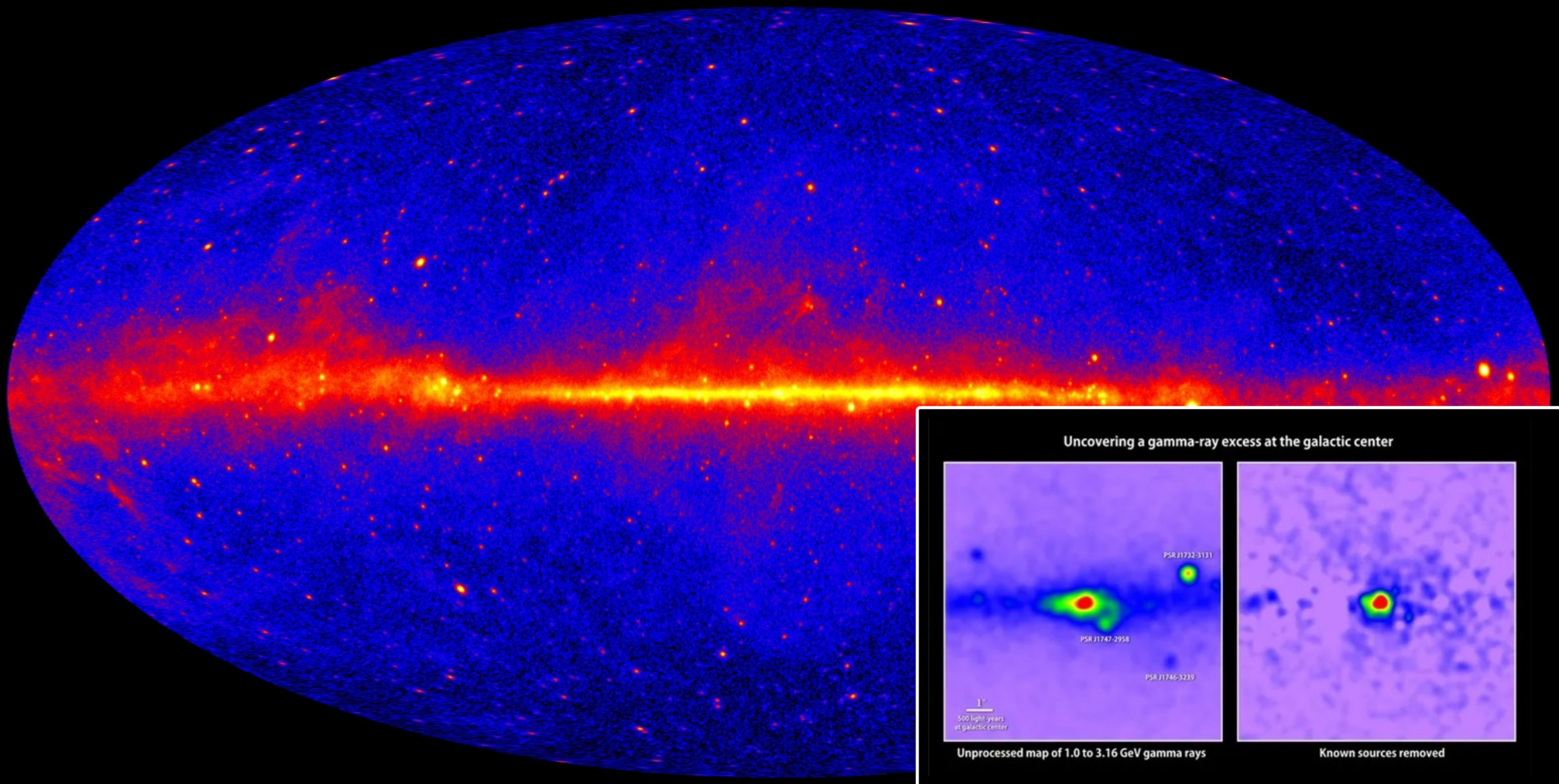
Planck





Gamma rays: the highest-energy light (Fermi)



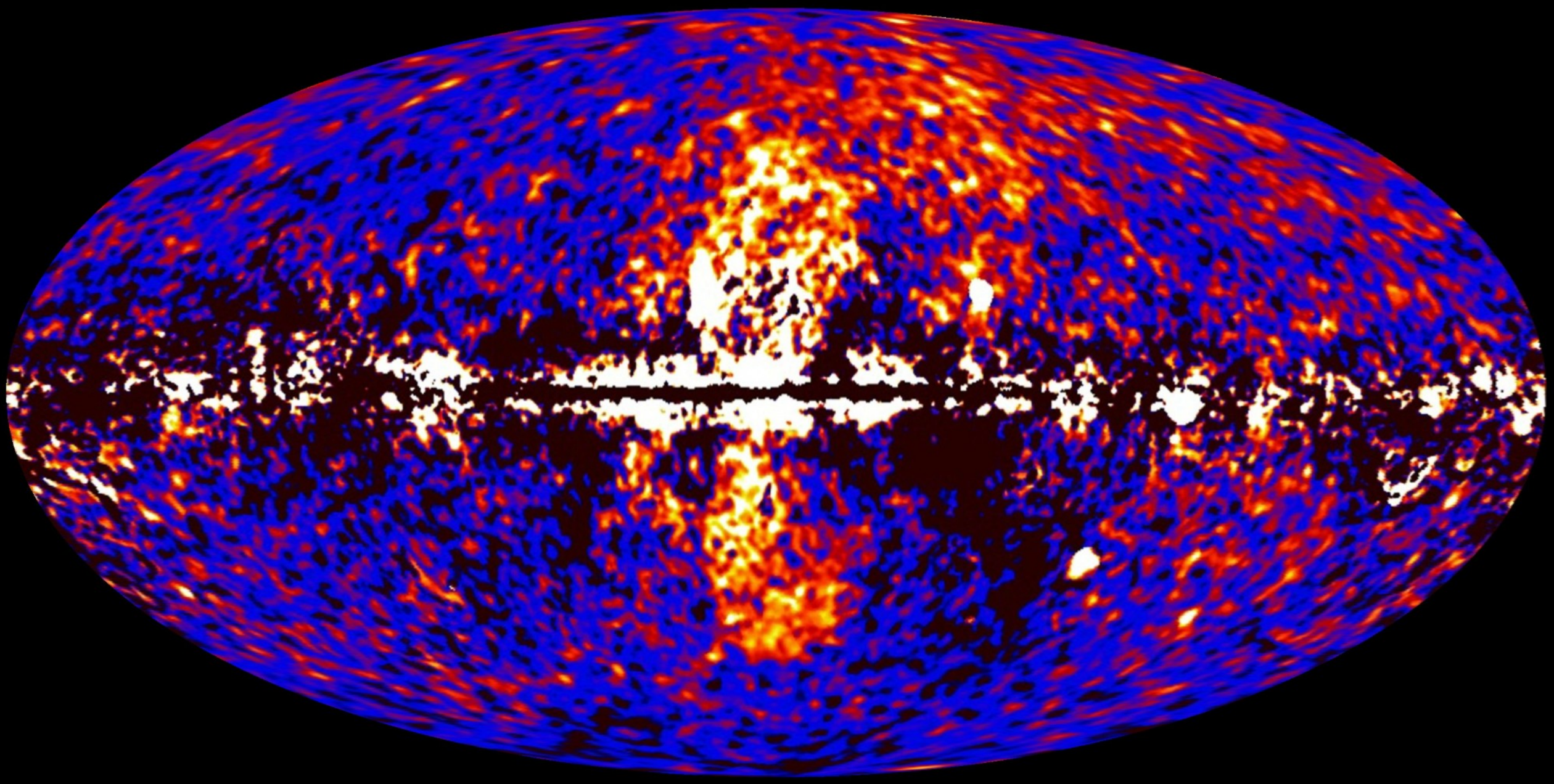


An unexplained glow right at the center (2009). Dark matter? Pulsars? More later…

NASA/DOE/Fermi LAT Collaboration · inset: T. Linden (U. Chicago), NASA

Gamma rays again: the “Fermi bubbles”



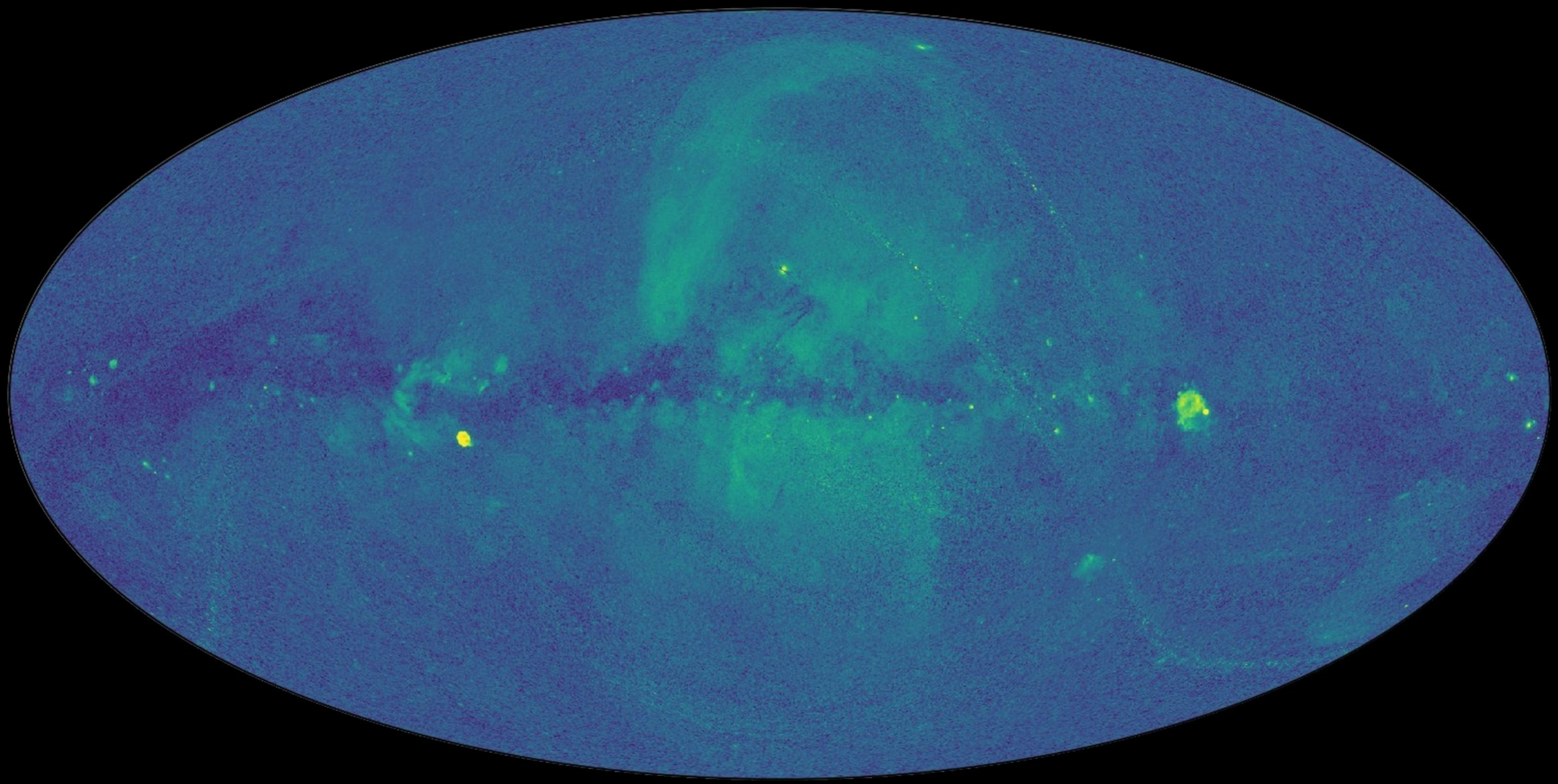


Two giant gamma-ray bubbles above and below the center (2010), each ~8,000 parsecs tall.

NASA/DOE/Fermi LAT/D. Finkbeiner+ · Su+ 2010

X-rays: gas at millions of degrees (ROSAT, 1990s)

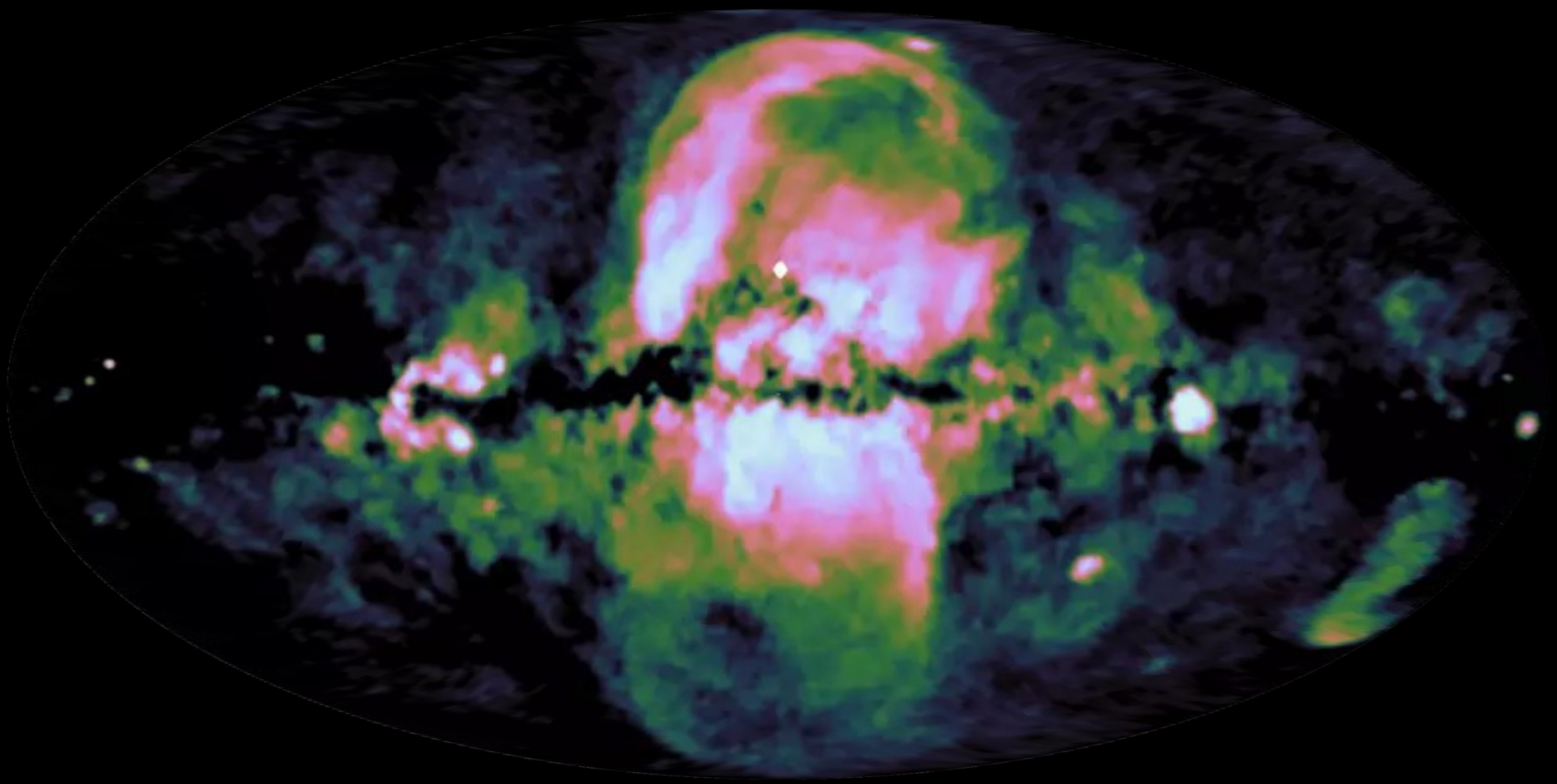




A faint loop arcs high above the center…

ROSAT all-sky survey (MPE)

eROSITA (2020): two giant X-ray bubbles

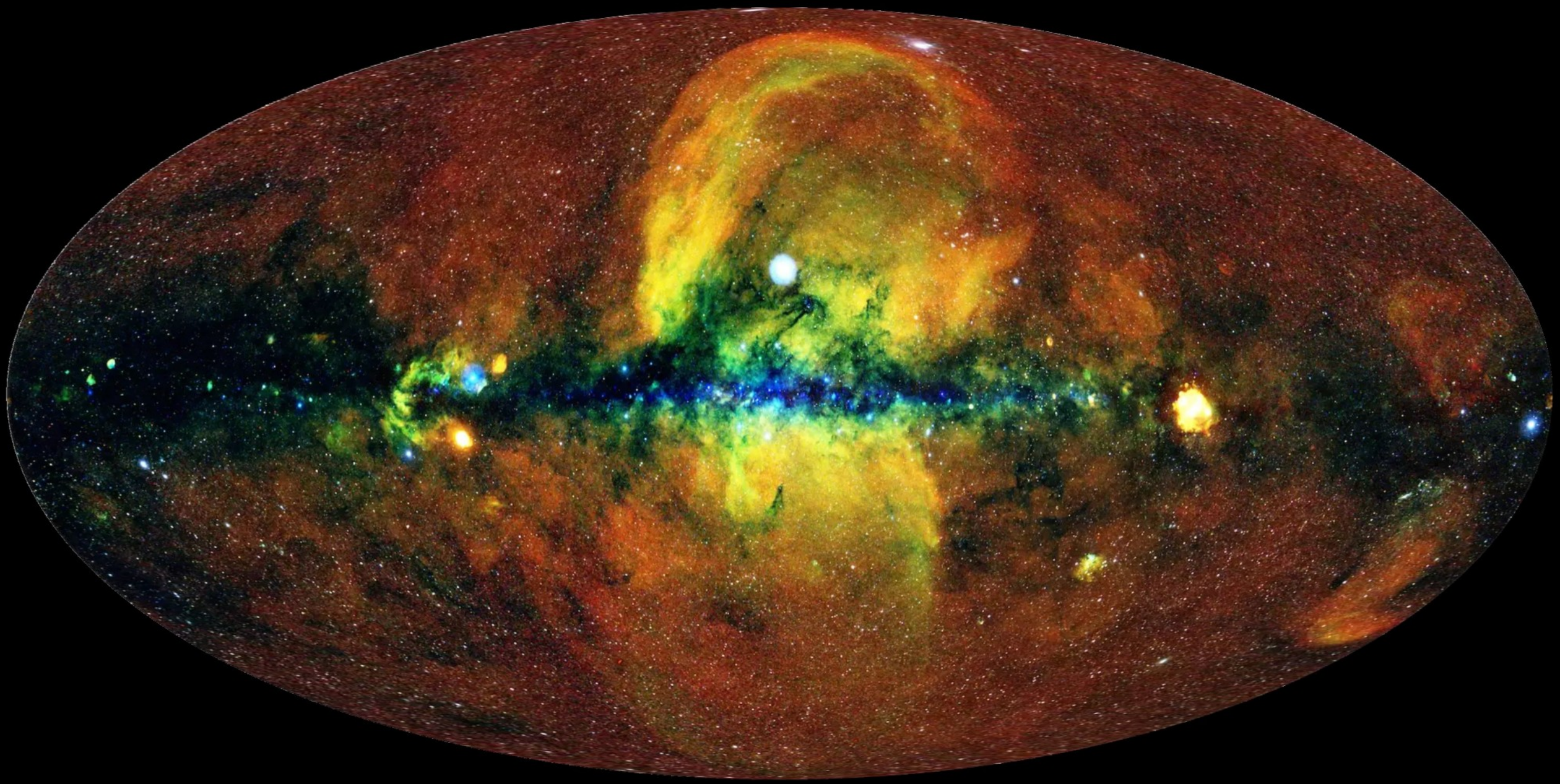


Each reaches ~14,000 parsecs from the plane. Energy: ~100,000 supernovae.



Predehl+ 2020 (eROSITA, MPE/IKI)

eROSITA (2020): two giant X-ray bubbles

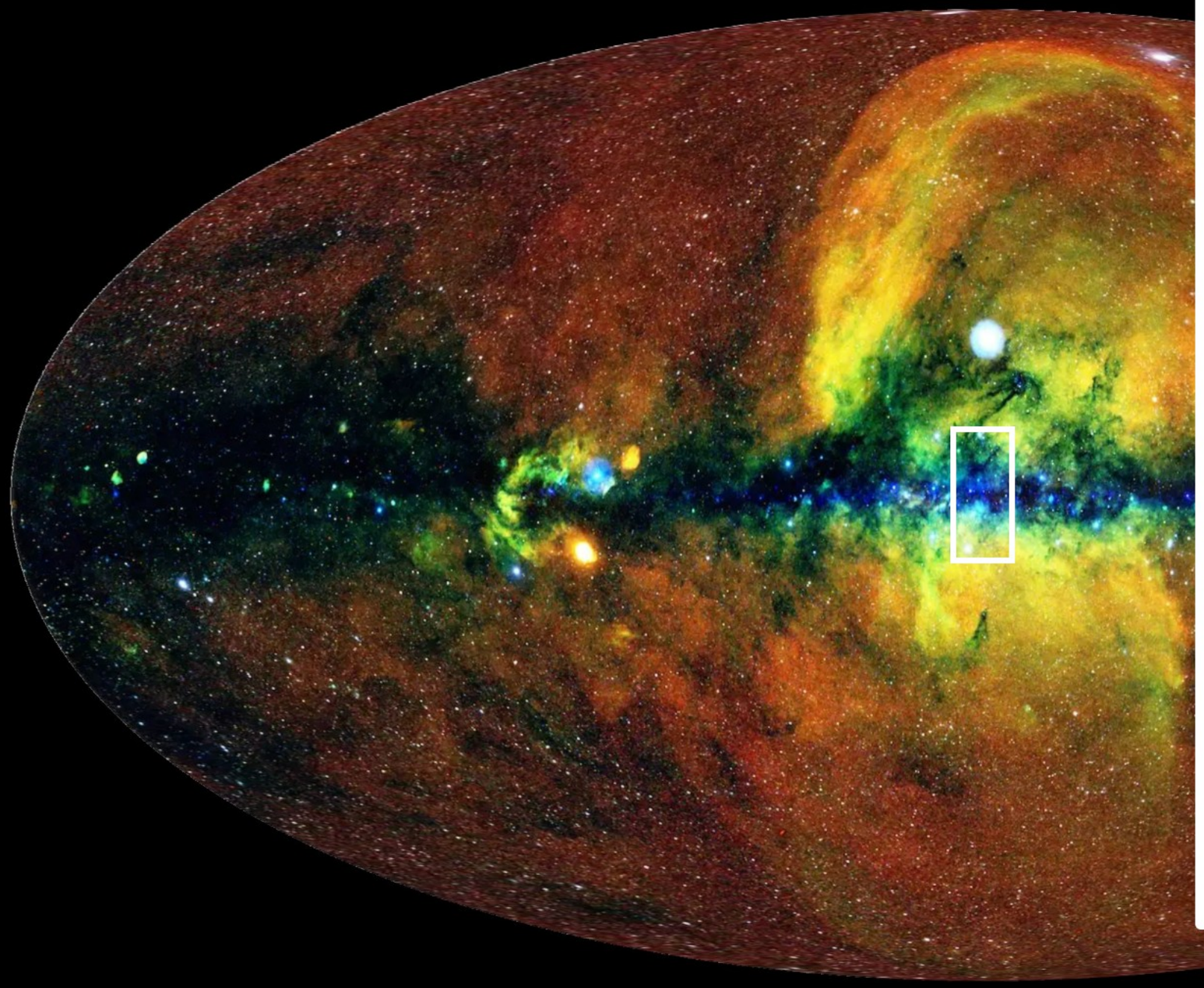


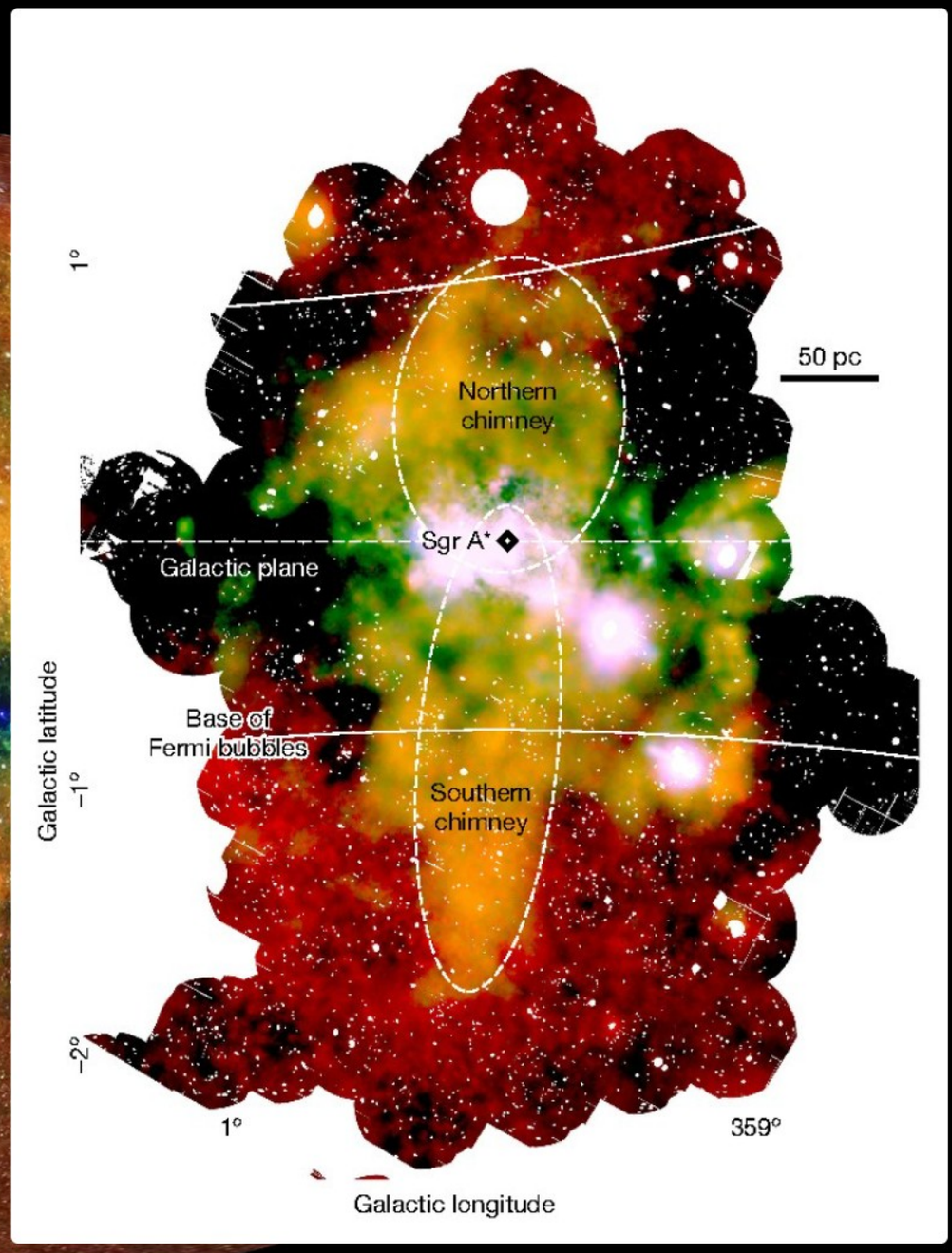
Each reaches ~14,000 parsecs from the plane. Energy: ~100,000 supernovae.



Predehl+ 2020 (eROSITA, MPE/IKI)

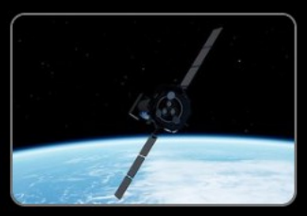
Where do the bubbles start?





X-ray “chimneys” rise from the central ~15 parsecs. The black hole, or many exploding stars? Still debated.

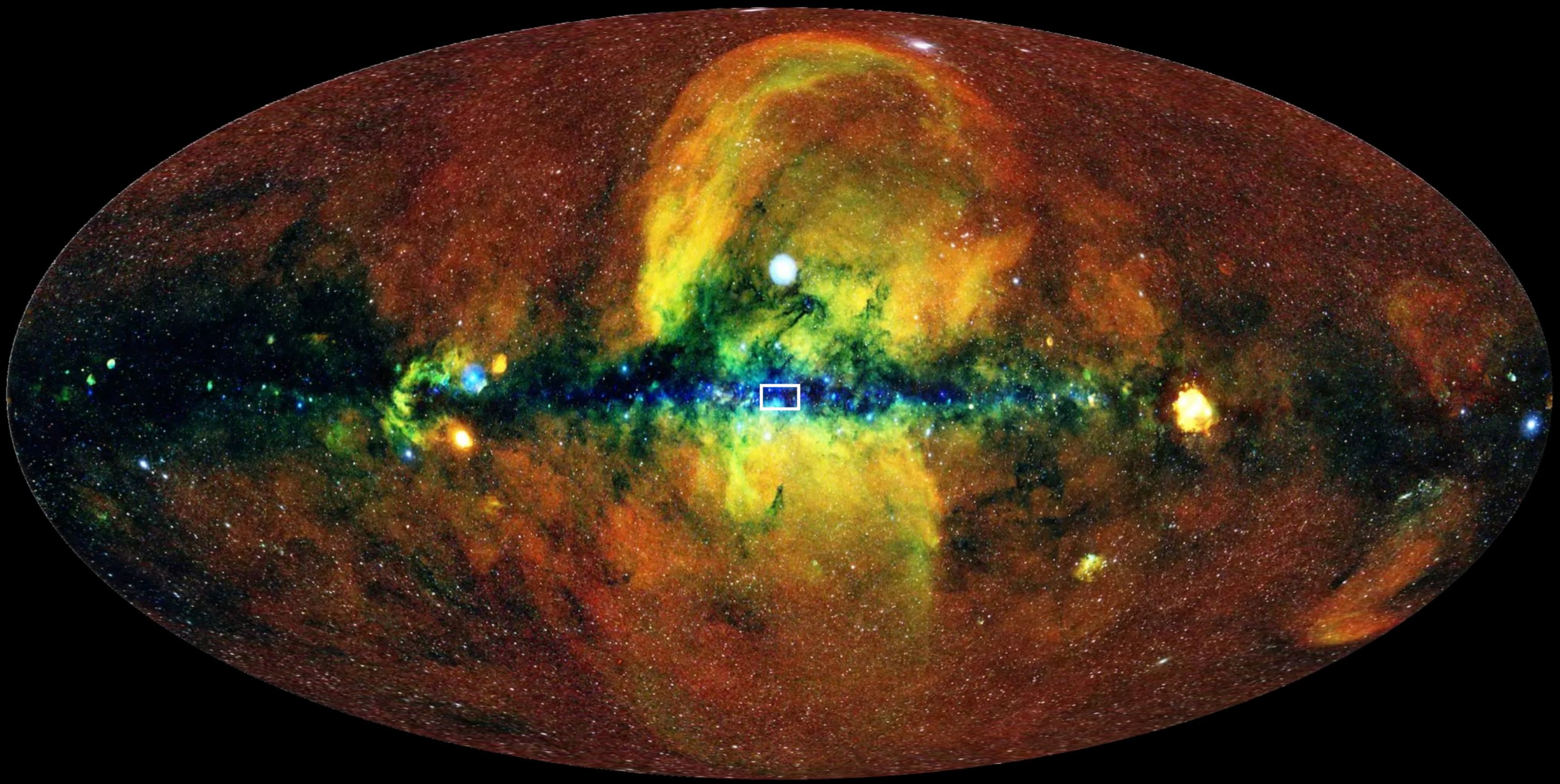






Ponti+ 2019 (XMM-Newton, Chandra) · Predehl+ 2020

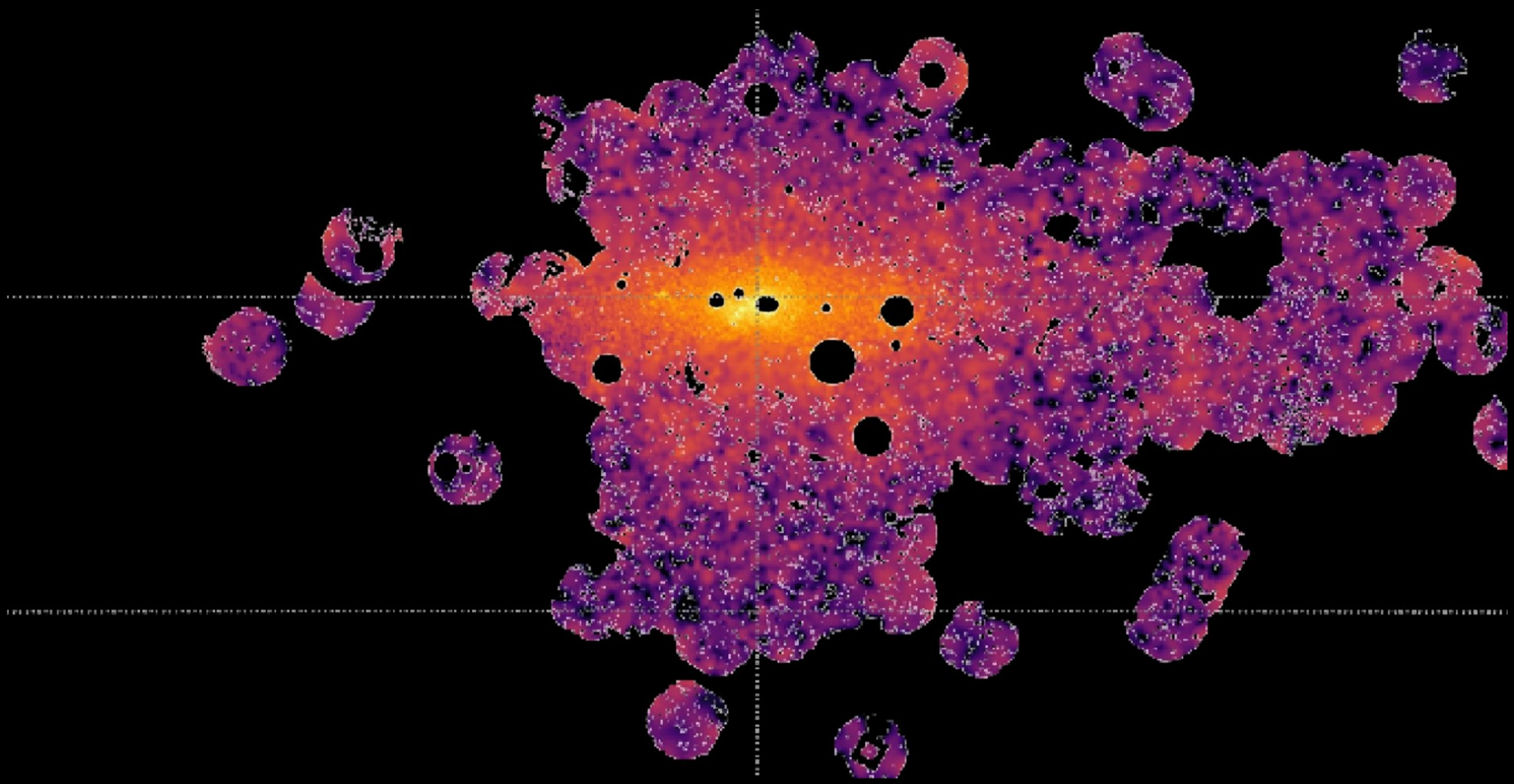
Zoom in on the center

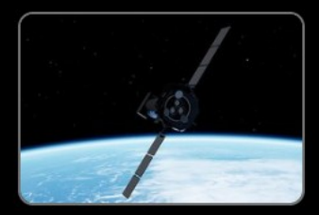




Predehl+ 2020 (eROSITA, MPE/IKI)

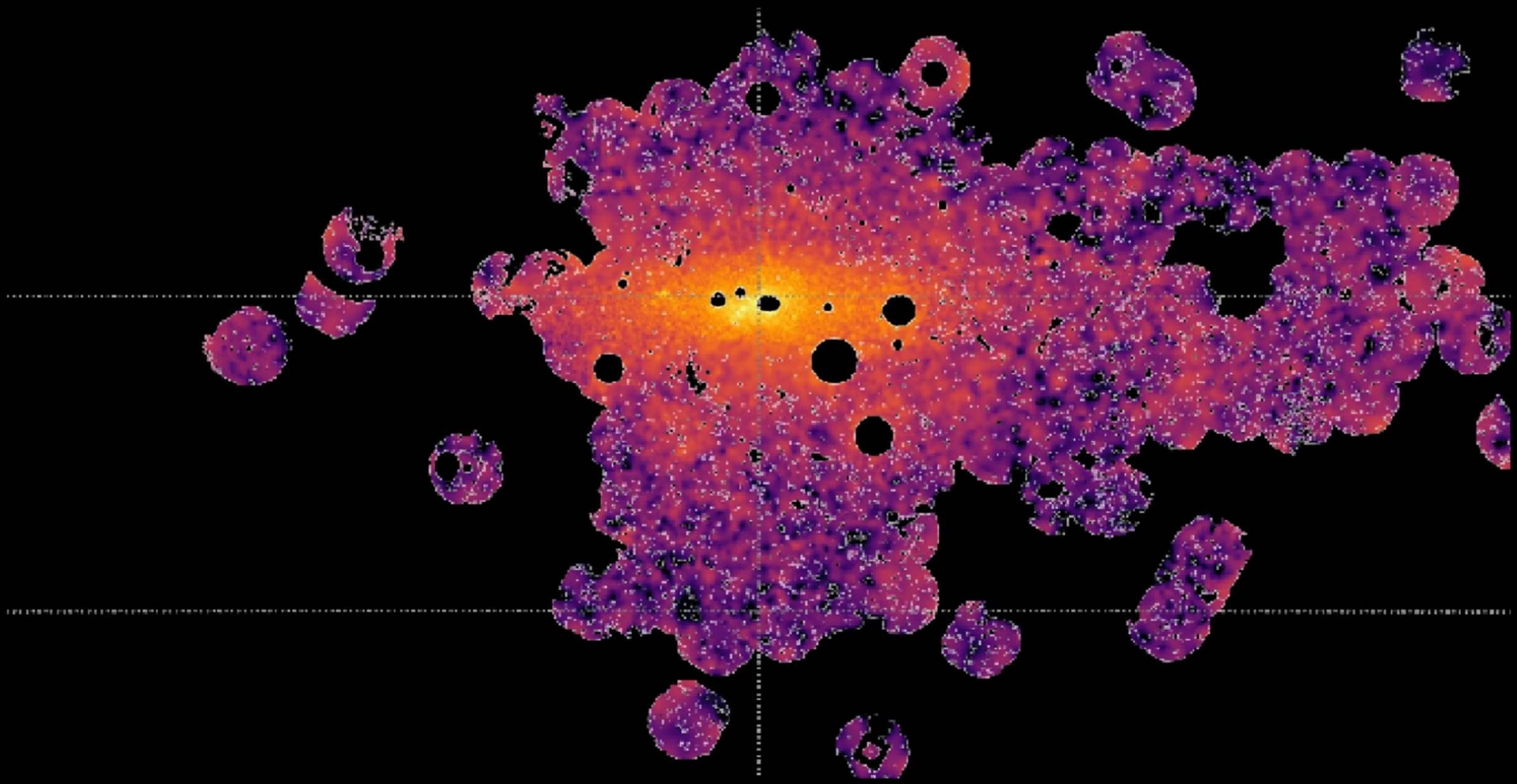
The X-ray hot gas goes all the way to the center, tracing where the stars are

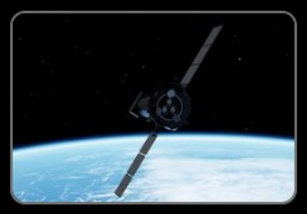




Anastasopoulou+ 2023 (XMM-Newton)

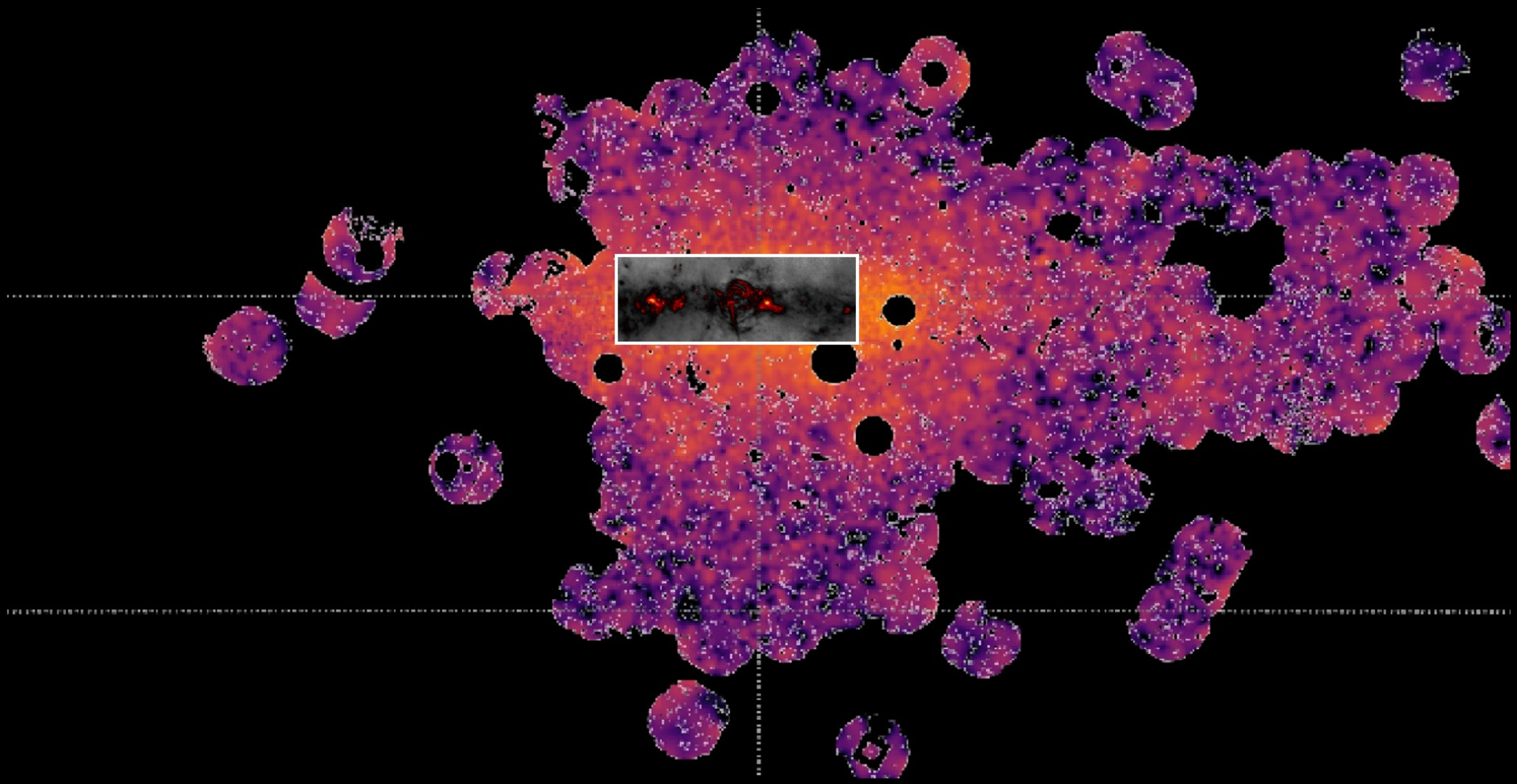
The hot gas at the center is rich in heavy elements





Anastasopoulou+ 2023 (XMM-Newton)

ALMA + Green Bank: the central ring of gas (ACES + MUSTANG)

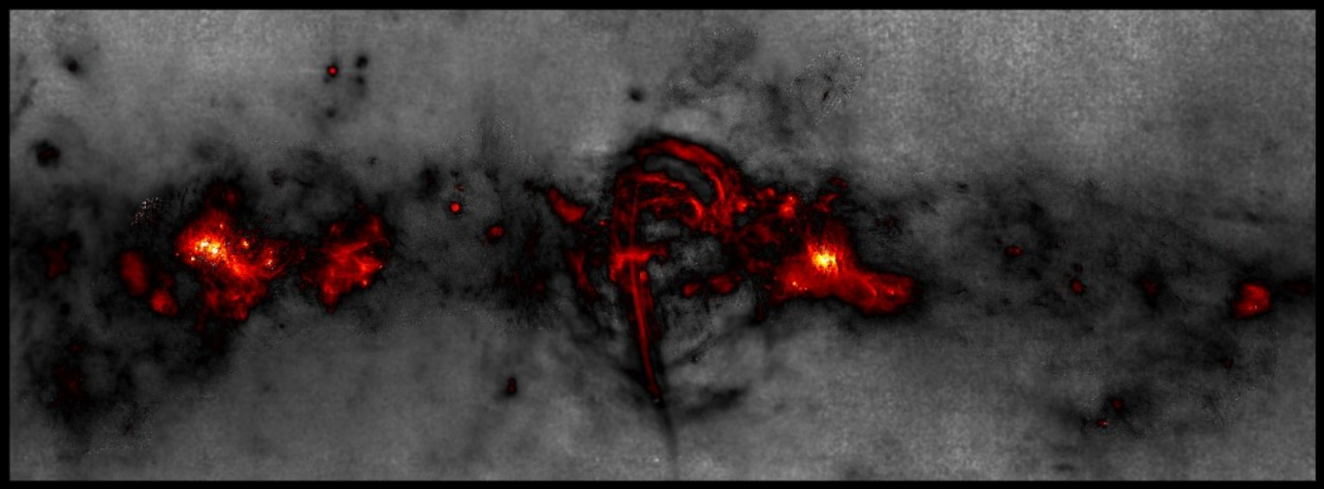






ACES: the ALMA CMZ Exploration Survey (Longmore, Ginsburg+) · MUSTANG-2 (Green Bank Telescope)

ALMA + Green Bank: the central ring of gas (ACES + MUSTANG)



Cold dust glowing at 3 mm across the whole Central Molecular Zone, ~200 parsecs end to end.





ACES: the ALMA CMZ Exploration Survey (Longmore, Ginsburg+) · MUSTANG-2 (Green Bank Telescope)

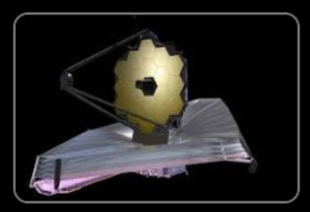
The Galactic Center has the most *stuff*, in the Galaxy and on the sky



MeerKAT radio: Heywood+ 2022 (SARAO) · combined with Spitzer by Judy Schmidt

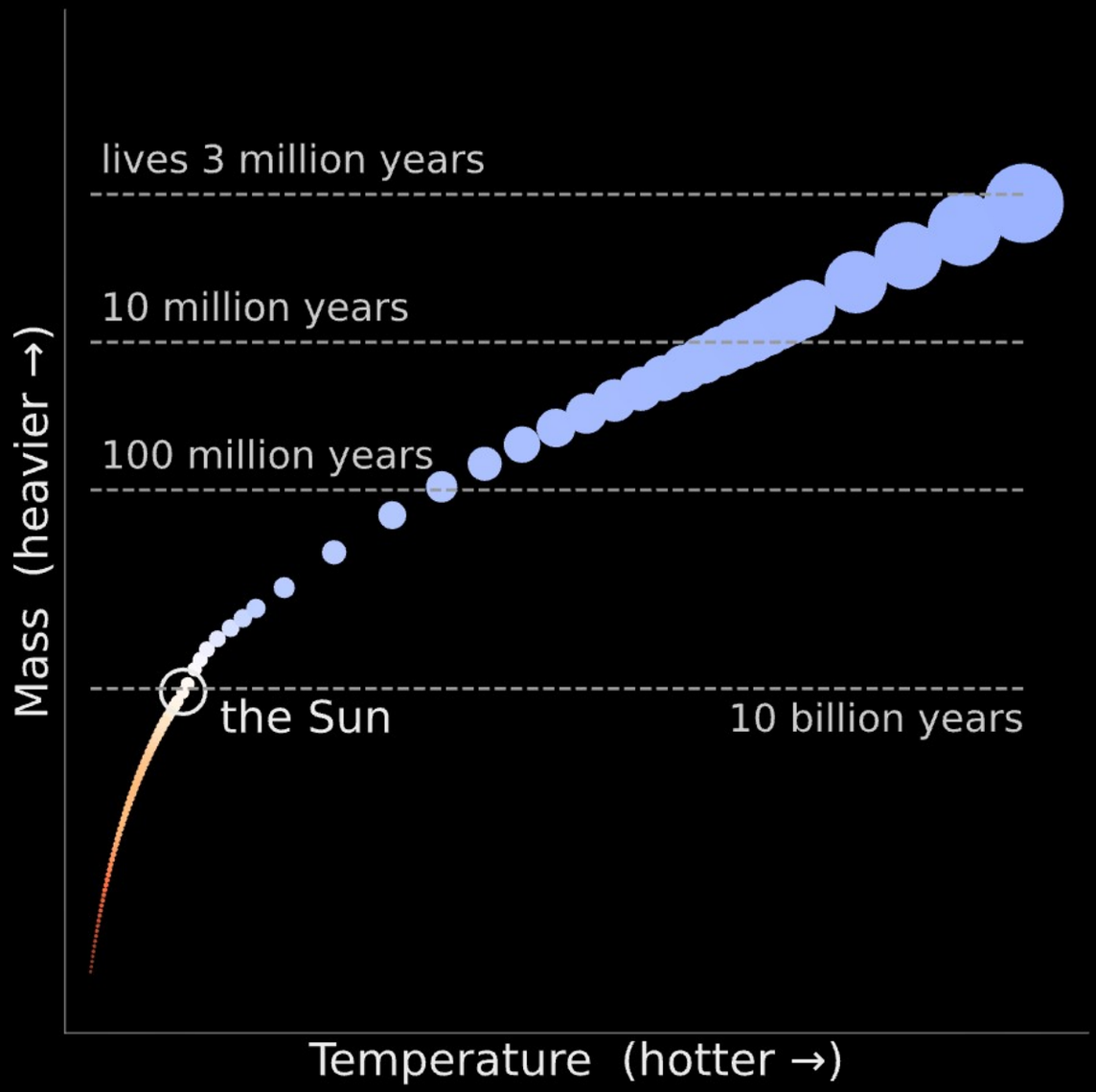
More questions, more answers

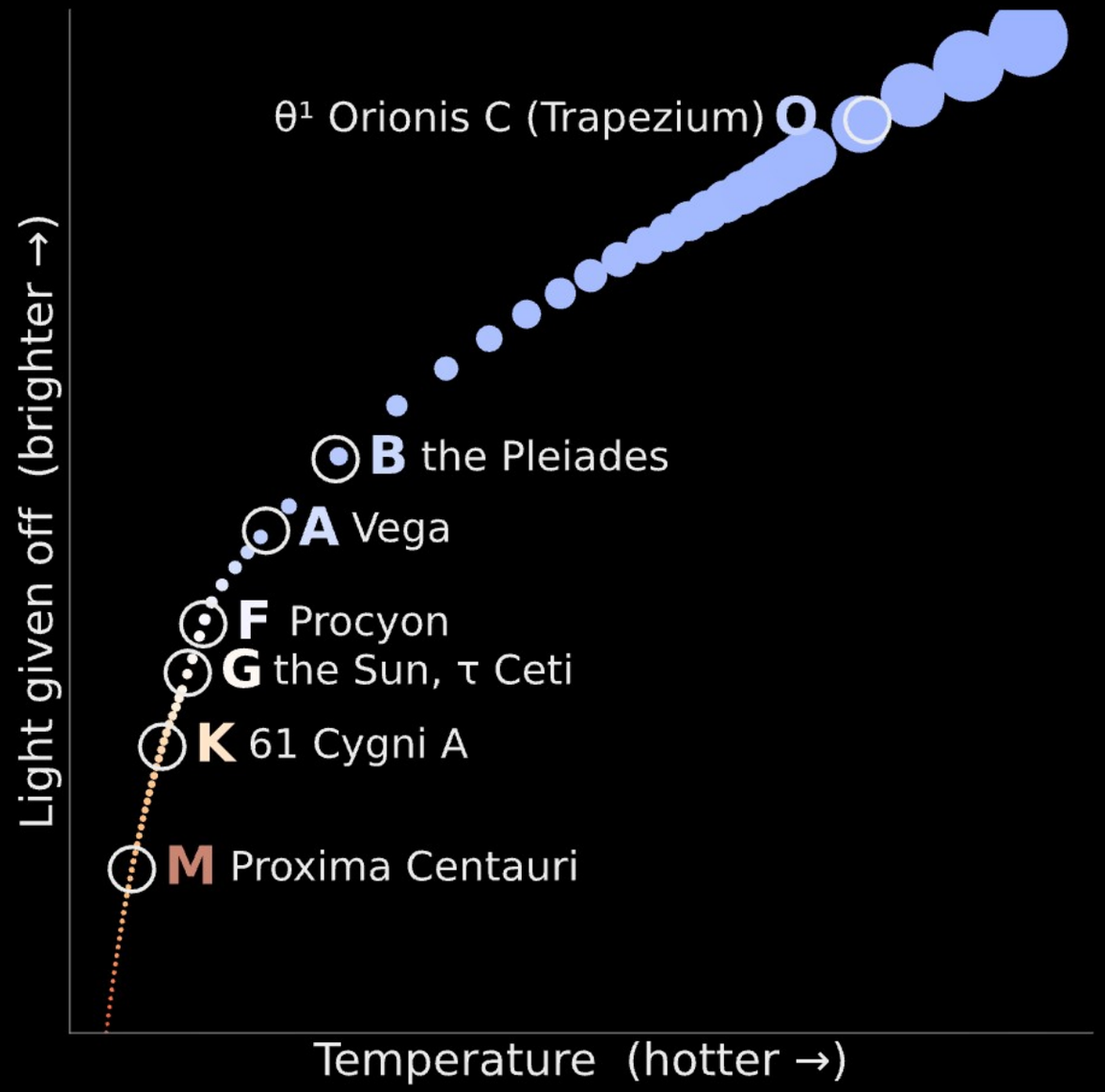
- How far away is the stuff - what does it look like in 3D?
- What's there, and how much? Stars, planets, gas, ...
- We're learning new things all the time with new telescopes: ALMA, JWST, and soon Roman


MASSIVE STARS: BRIGHT, HOT, SHORT-LIVED

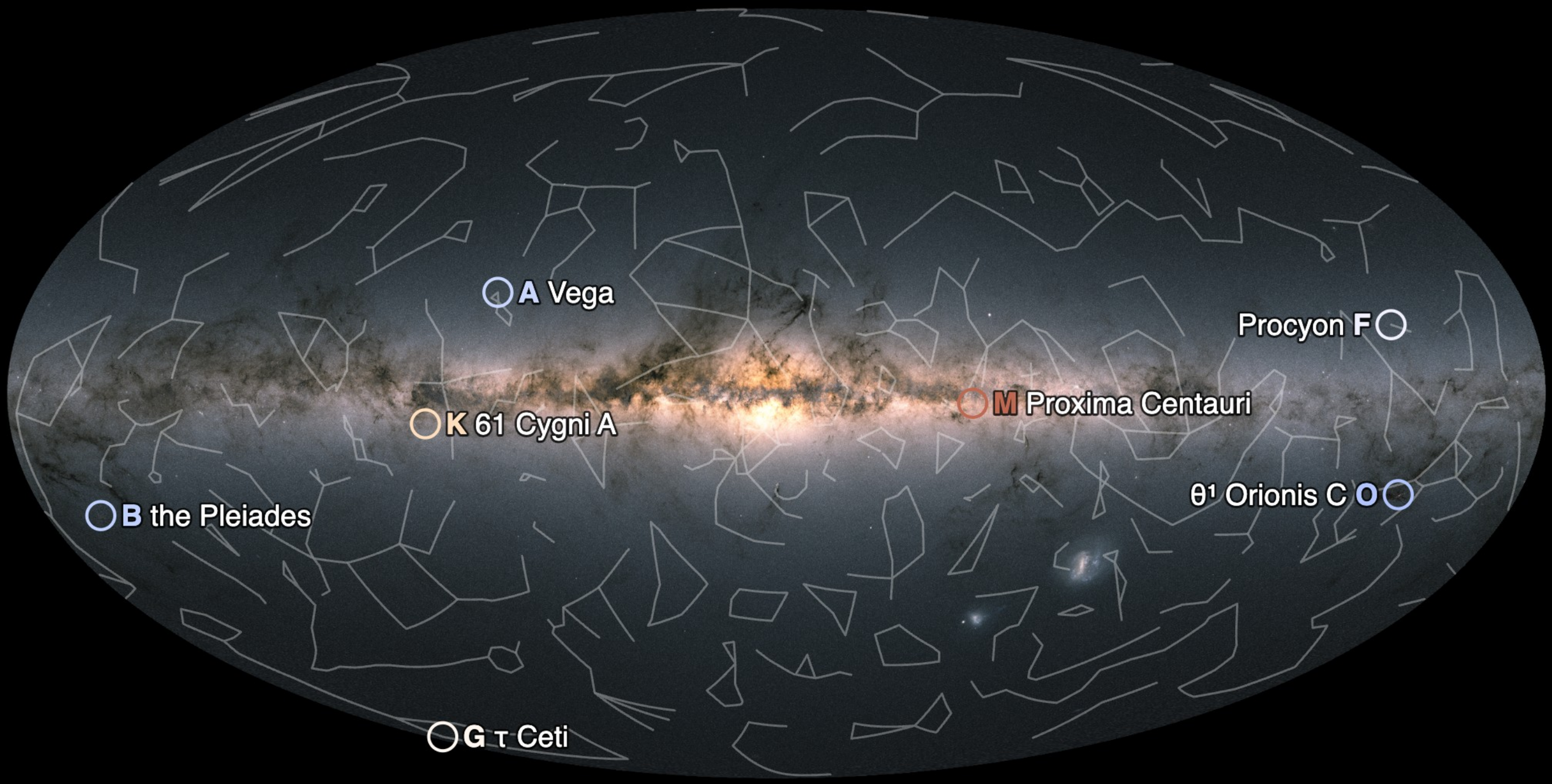
SMALL STARS: DIM, COOL, LIVE PRACTICALLY FOREVER

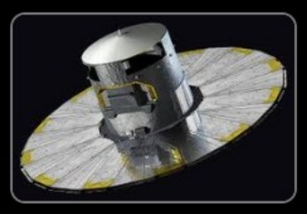




Ekström+ 2012 models, vendian.org colors, www.tinyurl.com/HR-figure

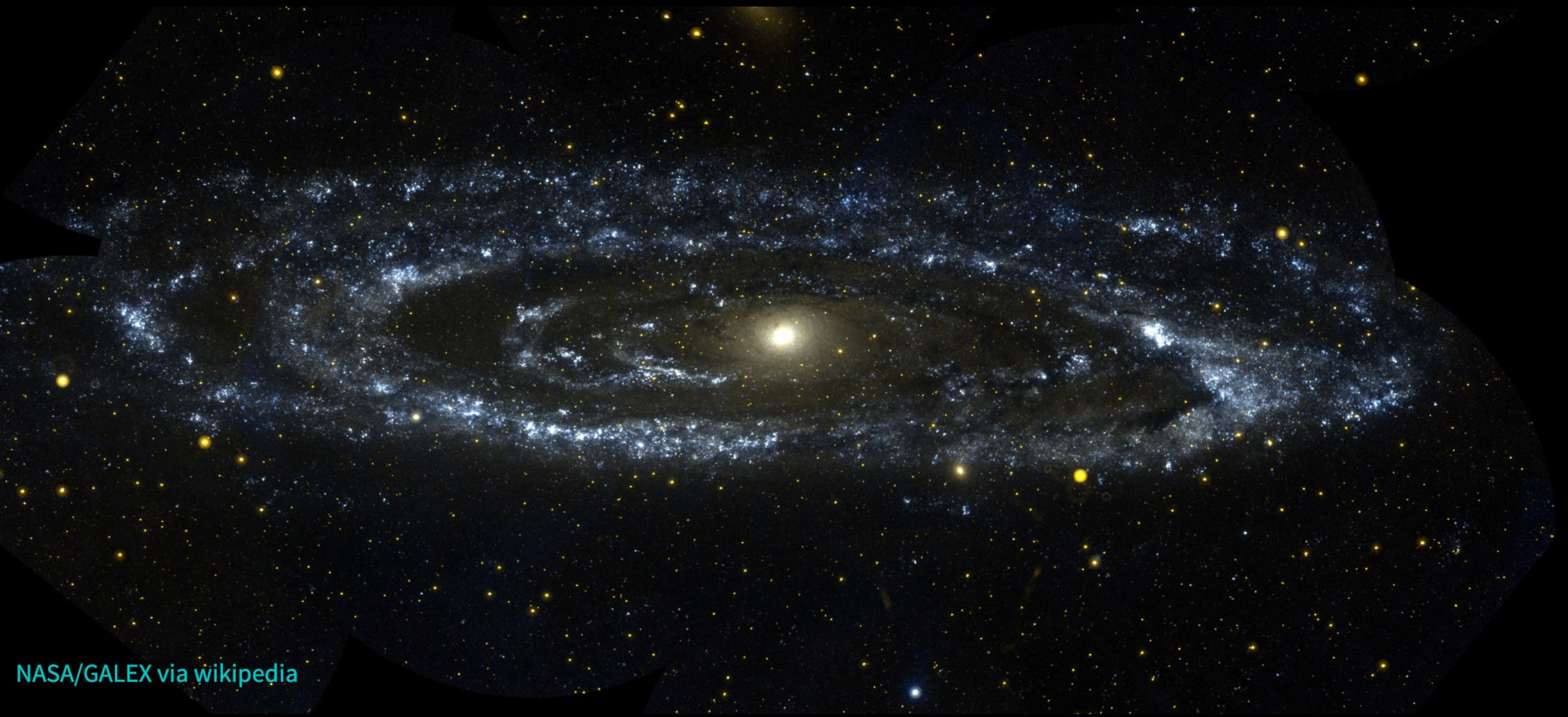
One example of each type of star, on the sky





Gaia star colors via ESA · constellation lines: d3-celestial (O. Frohn)

Almost all of the light in star-forming galaxies comes from massive stars



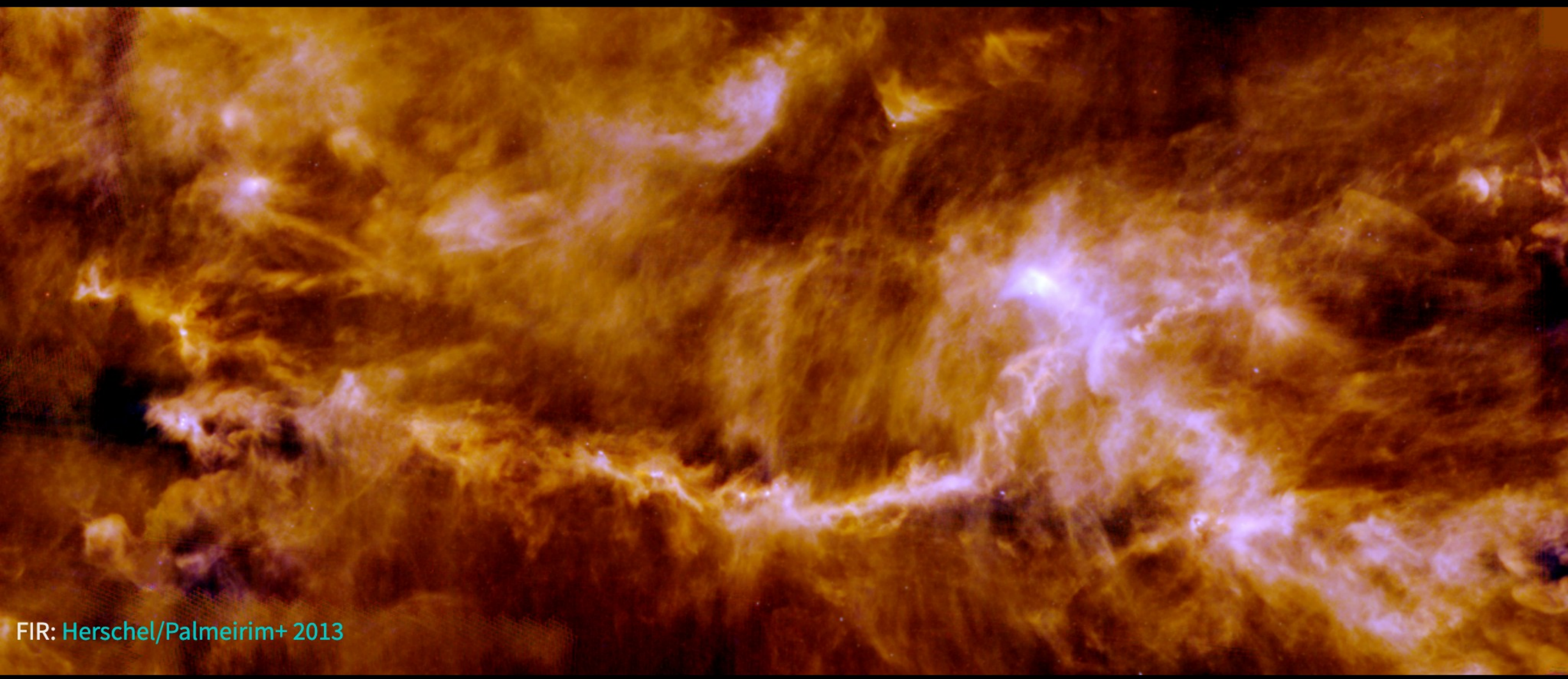
NASA/GALEX via wikipedia

STARS FORM FROM GAS (SEEN HERE VIA ITS DUST)



Herschel

Most of what we know about how stars form comes from small, nearby clouds

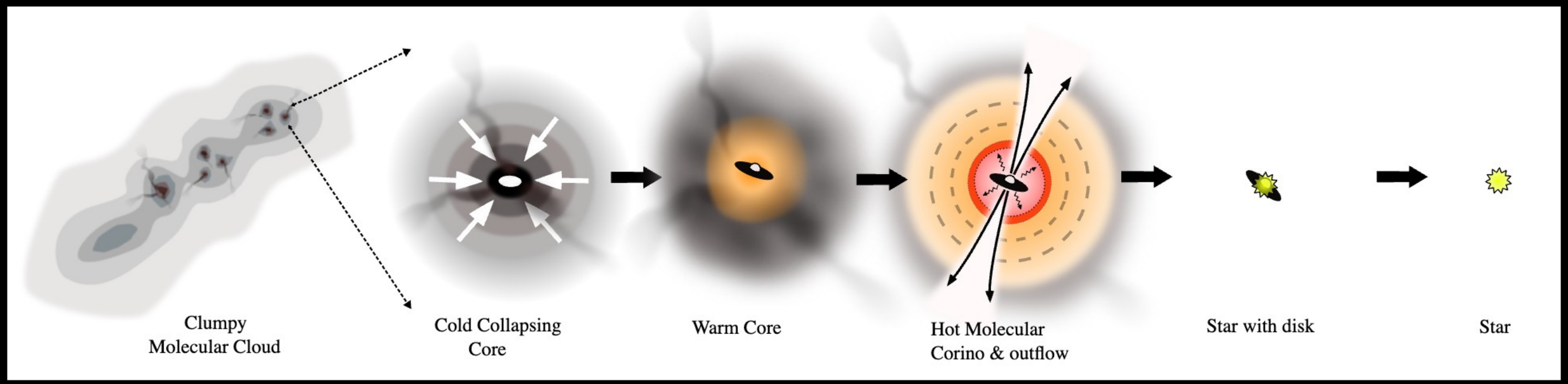




Most of what we know about how stars form comes from small, nearby clouds



How a star like the Sun forms (a cartoon)

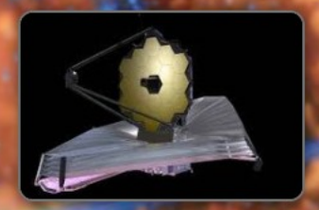


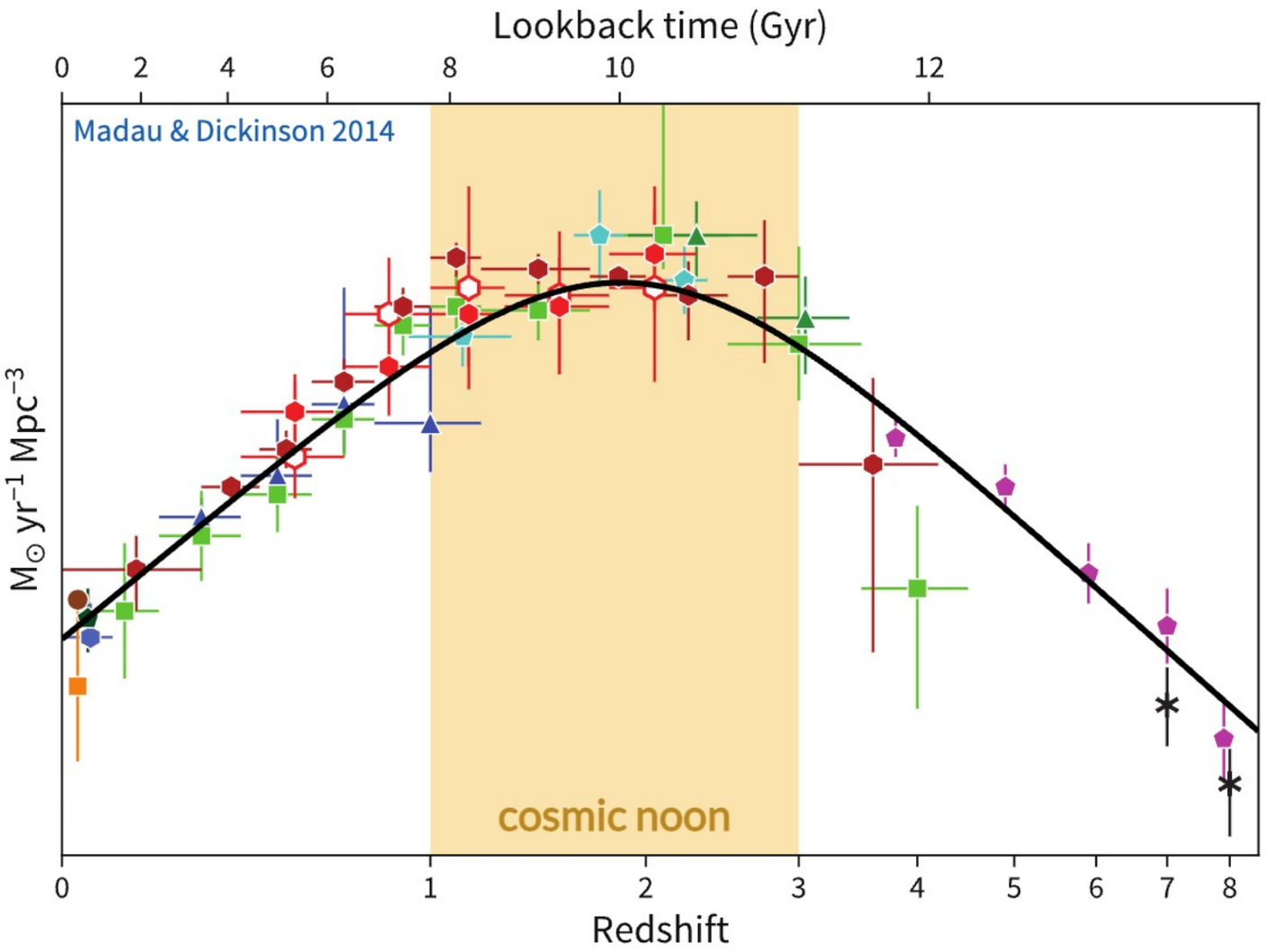
original cartoon by Cormac Purcell, modified by AG

Missing: neighbors and environment

The cartoon is not universal
Most stars form in crowds, near massive stars.

Guarcello+ 2025: JWST EWOCS Wd1





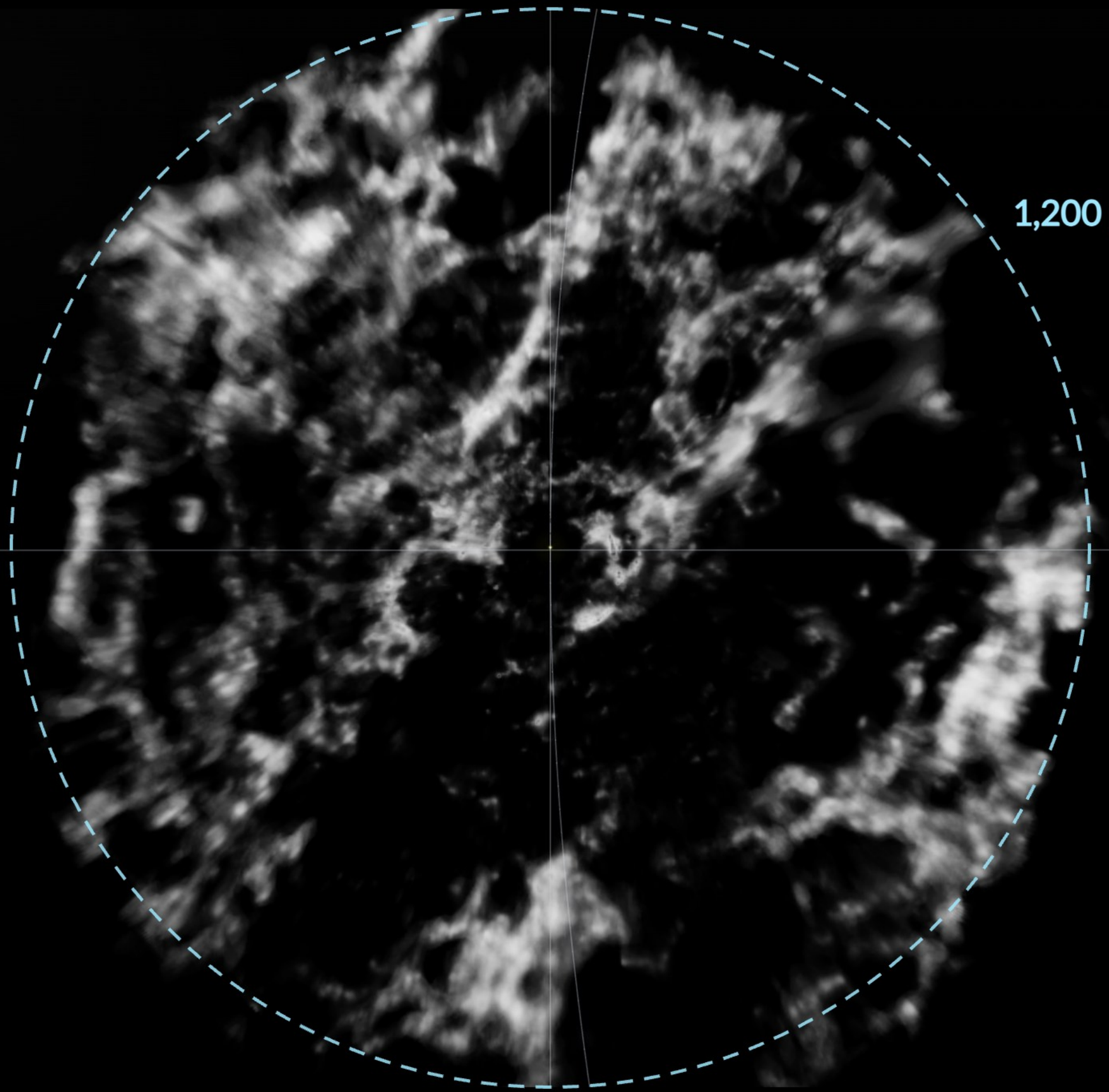
Star formation peaked ~10 billion years ago

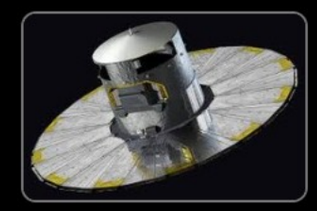
Back then, stars formed in denser, more turbulent clouds

Kruijssen & Longmore 2013

The Galactic Center is our nearest look at those conditions

THE SOLAR NEIGHBORHOOD IS NOT CROWDED





dust: Edenhofer+ 2024 · clusters: Hunt & Reffert 2023 (Gaia DR3), Sco-Cen: Ratzenböck+ 2023 · viz: C. Swiggum (live 3D)

THE SOLAR NEIGHBORHOOD IS NOT CROWDED

young star clusters: **under 15** · **under 60** million years

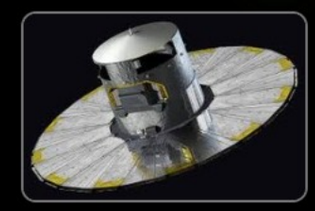
massive O stars

massive stars forming now

1,200 parsecs

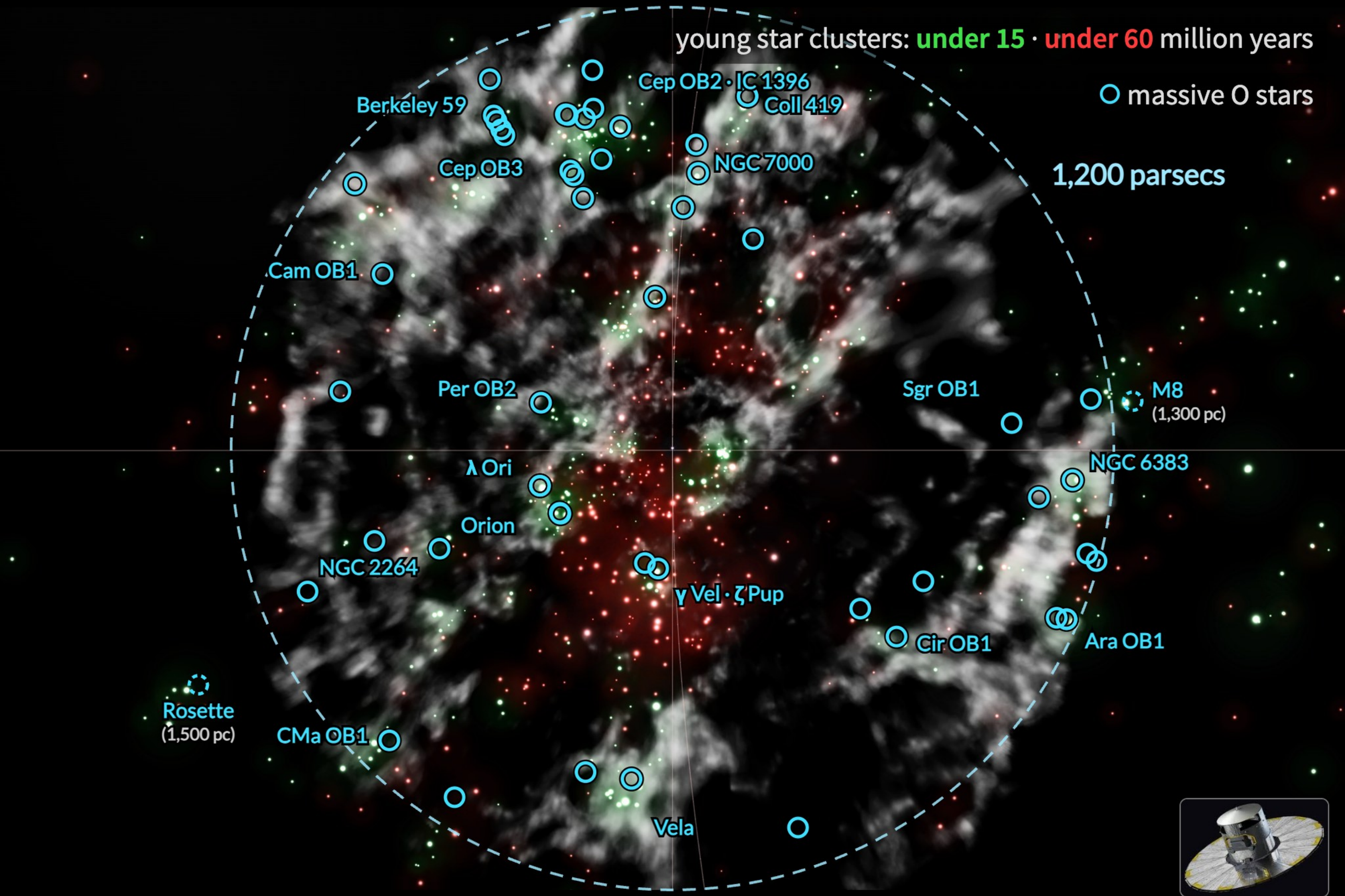
Cepheus A

Orion



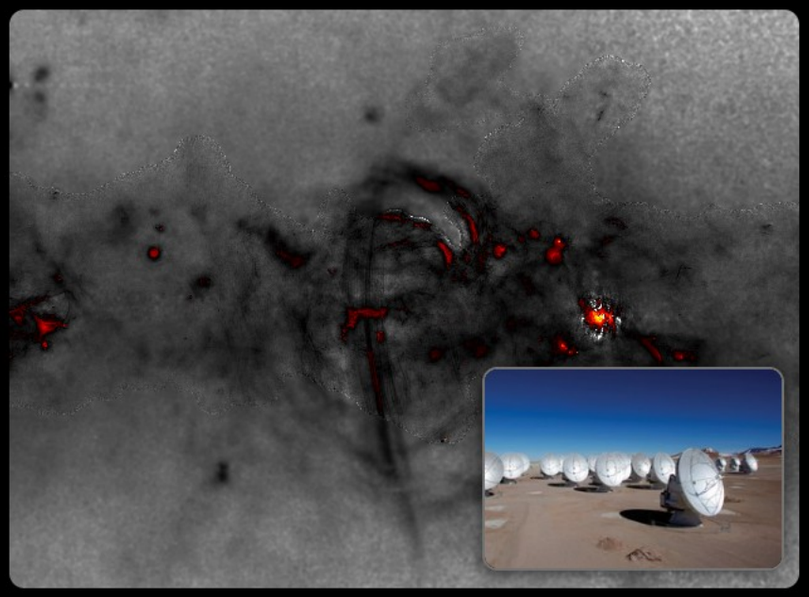
dust: Edenhofer+ 2024 · clusters: Hunt & Reffert 2023 (Gaia DR3), Sco-Cen: Ratzenböck+ 2023 · viz: C. Swiggum (live 3D)

Seen from above: dust and young star clusters near the Sun



dust: Edenhofer+ 2024 · clusters: Hunt & Reffert 2023 (Gaia DR3), Sco-Cen: Ratzenböck+ 2023 · viz: C. Swiggum (live 3D)

Three major surveys change our perspective

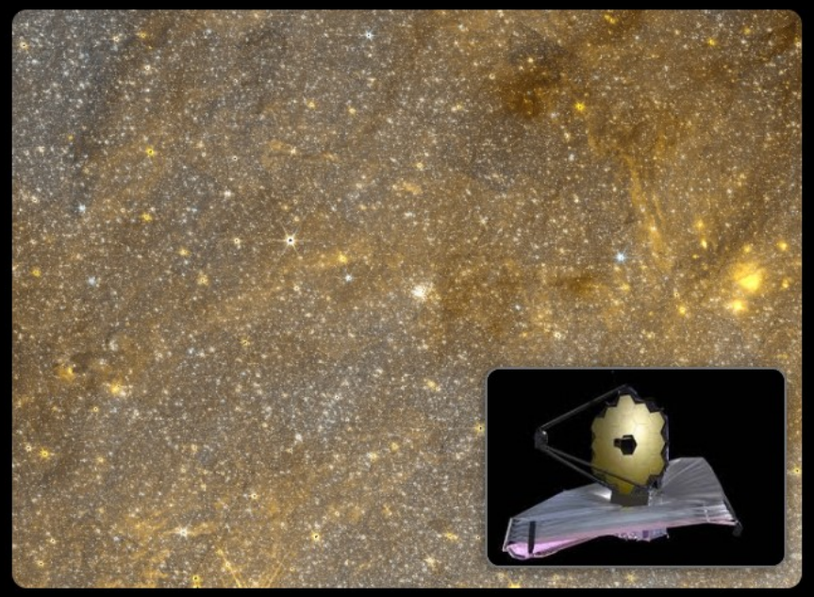


ALMA · ACES

8 papers so far (2025–26)

The whole central ring at 3 mm wavelength: dust and dozens of molecules.

sites.google.com/view/aces-cmz



JWST survey

half done (Sep 2026); the rest in 2027

Infrared images of millions of stars: ~4 million so far.

sites.google.com/view/jwst-gc

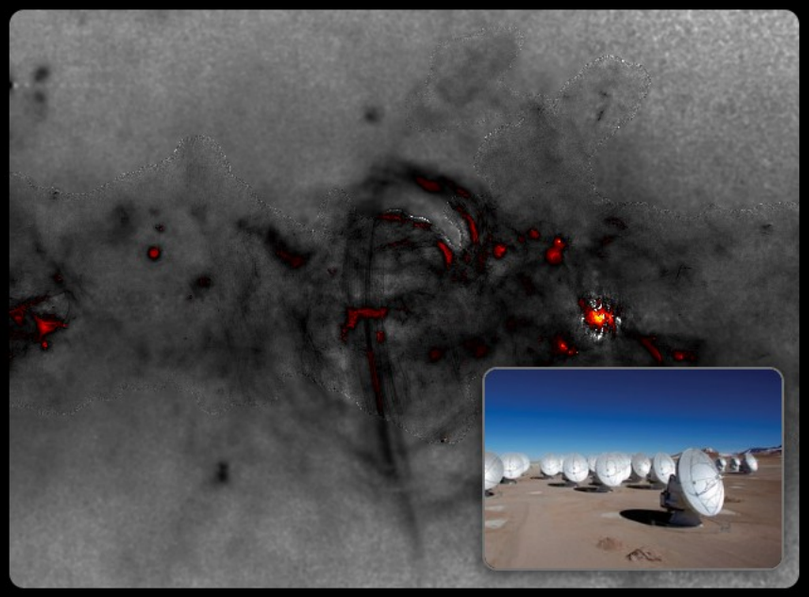


Roman surveys

coming

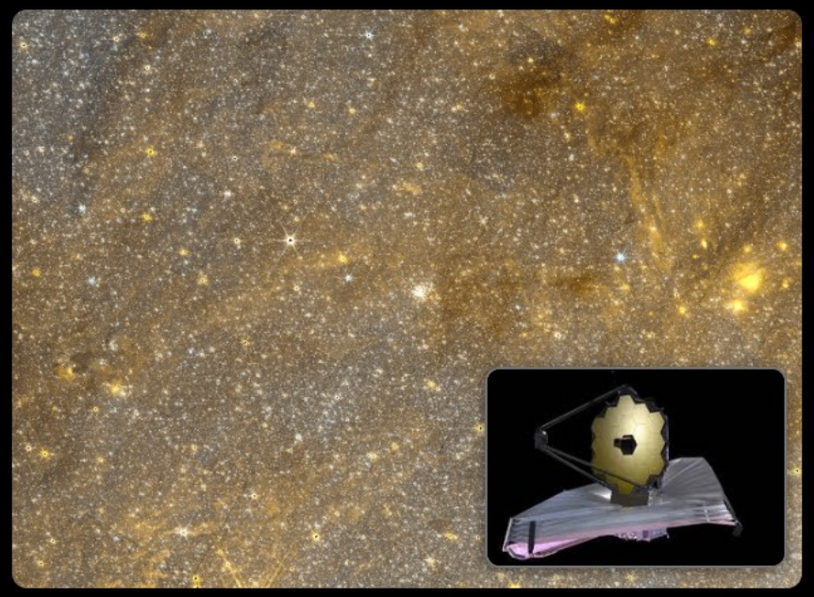
Repeated images of the inner Galaxy: star motions, variable stars, and planets.

Three major surveys change our perspective



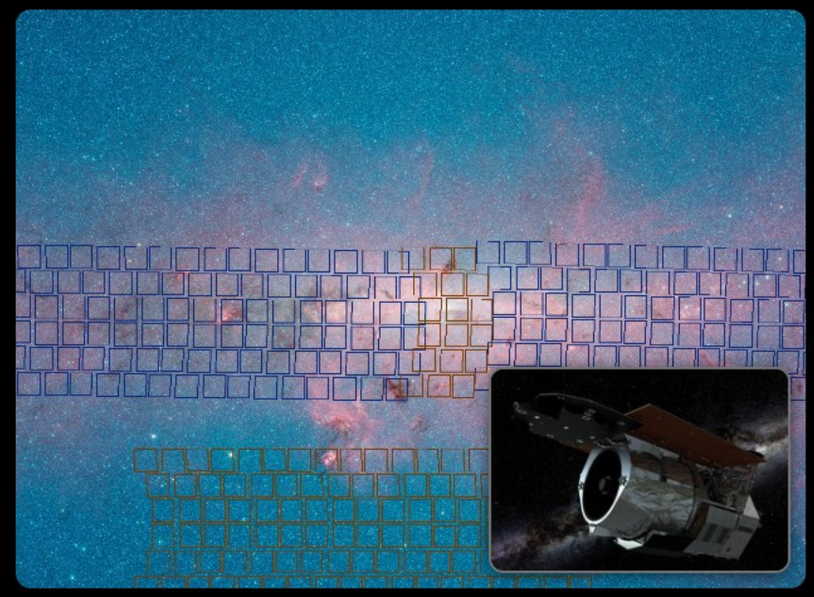
ALMA · ACES

Steve Longmore · **John Bally** · **Cara Battersby** · **Adam Ginsburg** · **Jonathan Henshaw** · **Paul Ho** · **Izaskun Jiménez-Serra** · **Betsy Mills** · **Daniel Walker** · **Ashley Barnes** · **Mattia Sormani** · **Robin Tress** · **Jennifer Wallace** · **Laura Colzi** · **Maya Petkova** · Danya Alboslani · Emad Alkhuja · Jairo Armijos-Abendaño · Lucia Armillotta · N. Bijas · Nazar Budaiev · Rojita Buddhacharya · Alyssa Bulatek · Michael Burton · Laura Busch · Natalie Butterfield · Paola Caselli · Mélanie Chevance · Claire Cook · Samuel Crowe · Ana Karla Díaz-Rodríguez · Simon Dicker · Katarzyna Dutkowska · Adam Fairley · Christoph Federrath · Rubén Fedriani · Zi-Xuan Feng · Karl Fiteni · Gary Fuller · Pablo García · Philipp Girichidis · Simon Glover · Javier Goicoechea · Mark Gorski · Savannah Gramze · Qi-Lao Gu · Perry Hatchfield · Christian Henkel · Rebecca Houghton · Pei-Ying Hsieh · Yue Hu · Katharina Immer · Namitha Issac · Desmond Jeff · Janik Karoly · Jens Kauffmann · Ralf Klessen · Diederik Kruijssen · Mark Krumholz · Cornelia Lang · Alex Lazarian · Rachel Lee · Emily Levesque · Fu-Heng Liang · Dani Lipman · Xunchuan Liu · Xing Lu · Qiu-yi Luo · Alessandro Lupi · Sera Markoff · Sergio Martín · Brian Mason · Farideh Mazoochi · Laura McCafferty · Emily Moravec · Mark Morris · Francisco Nogueras-Lara · Marie Nonhebel · Tomoharu Oka · John Orlowski-Scherer · Jürgen Ott · Marco Padovani · Xing Pan · Dylan Paré · Thushara Pillai · Jaime Pineda · Marc Pound · Denise Riquelme-Vásquez · Víctor Rivilla · Charles Romero · Galaxy Salo · Álvaro Sánchez-Monge · Miriam Santa-Maria · Anika Schmiedeke · Rainer Schödel · Matthias Schultheis · Howard Smith · Yoshiaki Sofue · Jack Sullivan · Enrico Di Teodoro · Leonardo Testi · Volker Tolls · Miguel Requena Torres · Grant Tremblay · Arianna Vasini · Gijs Vermariën · Alexey Vikhlinin · Serena Viti · Q. Daniel Wang · Gwenllian Williams · Fengwei Xu · Qizhou Zhang · Suinan Zhang



JWST survey

Rainer Schödel · **Steve Longmore** · **Adam Ginsburg** · Konstantina Anastasopoulou · Jay Anderson · John Bally · Ashley Barnes · Cara Battersby · Alessandra Mastrobuono Battisti · Giuseppe Bono · Aaron Bryant · Santi Cassisi · Mélanie Chevance · Anna Ciurlo · Angela Cotera · Samuel Crowe · Tuan Do · Rubén Fedriani · Anja Feldmeier-Krause · Sebastiano von Fellenberg · Lucia Bravo Ferres · Dimitri Gadotti · Carme Gallart · Teresa Gallego-Calvente · Eulalia Gallego-Cano · Pablo García · Angela Gardini · Abhimat Gautam · Andrea Ghez · Stefan Gillessen · Miguel Cano González · Alessia Gualandris · Robert Gutermuth · Daryl Haggard · Matthew Hankins · Jonathan Henshaw · Matthew Hosek · Rebecca Houghton · Yue Hu · Tracy Huard · Ralf Klessen · Diederik Kruijssen · Ryan Lau · Alex Lazarian · Rebecca Levy · Mattia Libralato · Anan Lu · Jessica Lu · Xing Lu · Nora Luetzgendorf · John Magorrian · Shifra Mandel · Roeland van der Marel · Macarena García Marín · Sera Markoff · Alvaro Martinez · Maria Melamed · Betsy Mills · Kaya Mori · Mark Morris · Elena Murchikova · Paco Najarro · David Nataf · Nadine Neumayer · Shogo Nishiyama · Francisco Nogueras-Lara · Dylan Paré · Florian Peissker · Maya Petkova · Thushara Pillai · Gabriele Ponti · Rodrigo Contreras Ramos · R. Michael Rich · Carlos Román-Zúñiga · Michael Rugel · Nils Ryde · Nadeen Sabha · Joel Sánchez-Bermúdez · Álvaro Sánchez-Monge · Matthias Schultheis · Stephen Serjeant · Lijing Shao · Janet Simpson · Mattia Sormani · Christopher Sorrell · Jonathan Tan · Enrico Di Teodoro · Brian Thorsbro · Pablo Torne · Robin Tress · Elena Valenti · Sill Verberne · Pierre Vermot · Eduardo Vitral · Gunther Witzel · Siyao Xu · Farhad Yusef-Zadeh · Michal Zajacek · Qizhou Zhang · Manuela Zoccali



Roman surveys

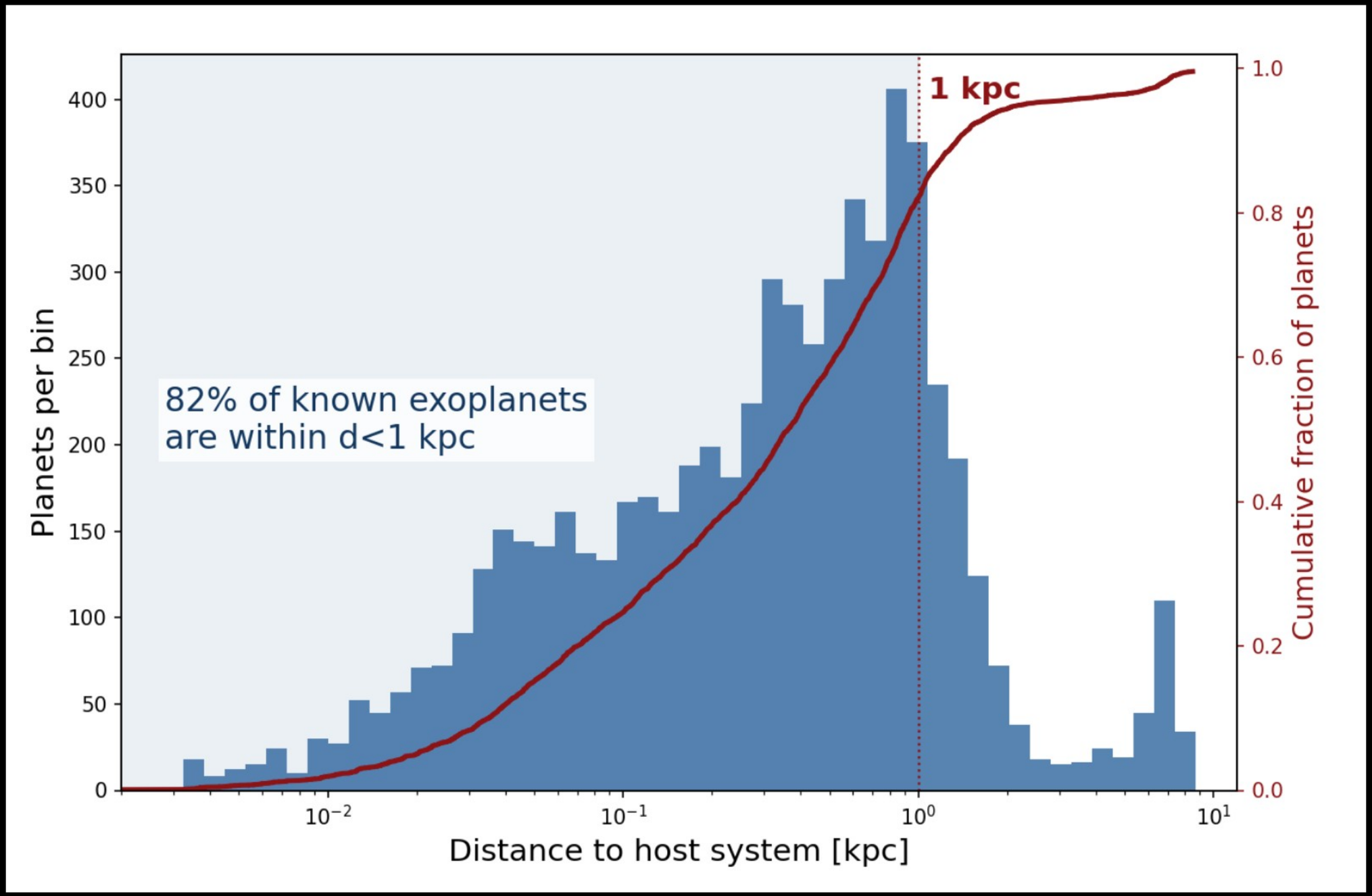
et al.

The Galactic Center: open questions (a partial list)

	question	open since
	What makes the giant radio filaments?	1984
Q2	How does gas flow into the center?	1991
Q4	What shape is the central ring of gas?	1995
Q3	(How) does gas reach the black hole, Sgr A*?	1996
	Was the black hole brighter in the recent past?	1996
	What are the fast-moving compact clouds?	1998
Q7	Is the mix of star masses different here?	1999
Q6	Where do the center's young stars go?	2002
	How did the central disk of stars form?	2002
	Why are there so many cosmic rays?	2005
Q8	Is the chemistry different?	2009
	How does dust dim and redden the light?	2009
	Is the extra gamma-ray glow dark matter, or pulsars?	2009
	Where are the massive stars, and how many are there?	2010
	Where do the lone massive stars come from?	2010
Q5	Why does the center form so few stars?	2013
	Does star formation come in bursts?	2015
	What accelerates the most energetic cosmic rays?	2016
Q1	What planets form there?	2016

Q1	**What planets form there?**	**2016**	←
Q2	How does gas flow into the center?	1991	
Q3	(How) does gas reach the black hole, Sgr A*?	1996	
Q4	What shape is the central ring of gas?	1995	
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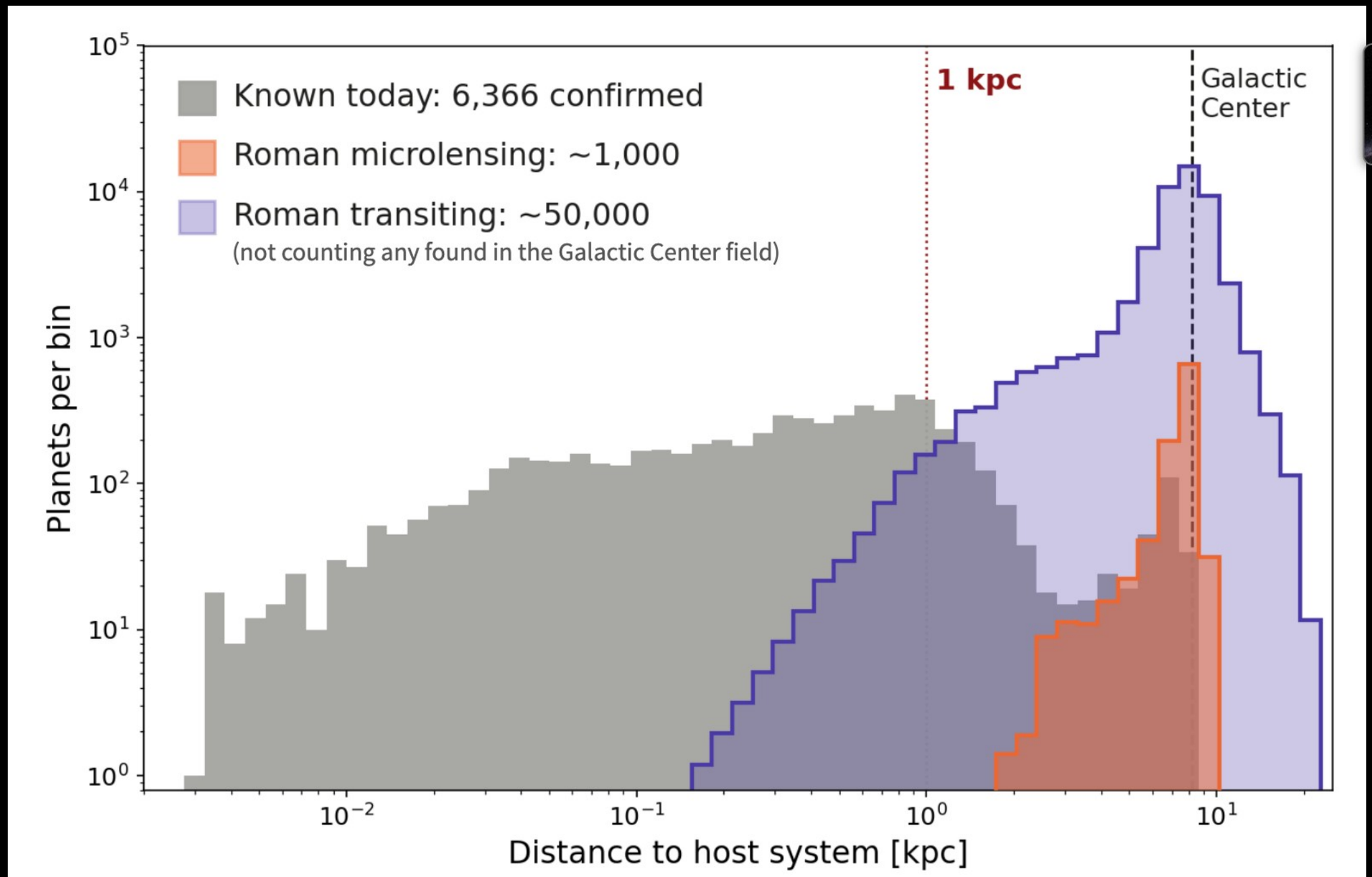
Almost every planet we know is within ~1,000 parsecs of the Sun



NASA Exoplanet Archive, Sept 2026

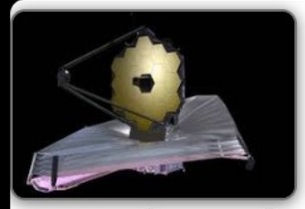
ROMAN WILL FIND TENS OF THOUSANDS OF PLANETS ~8,000 PARSECS AWAY

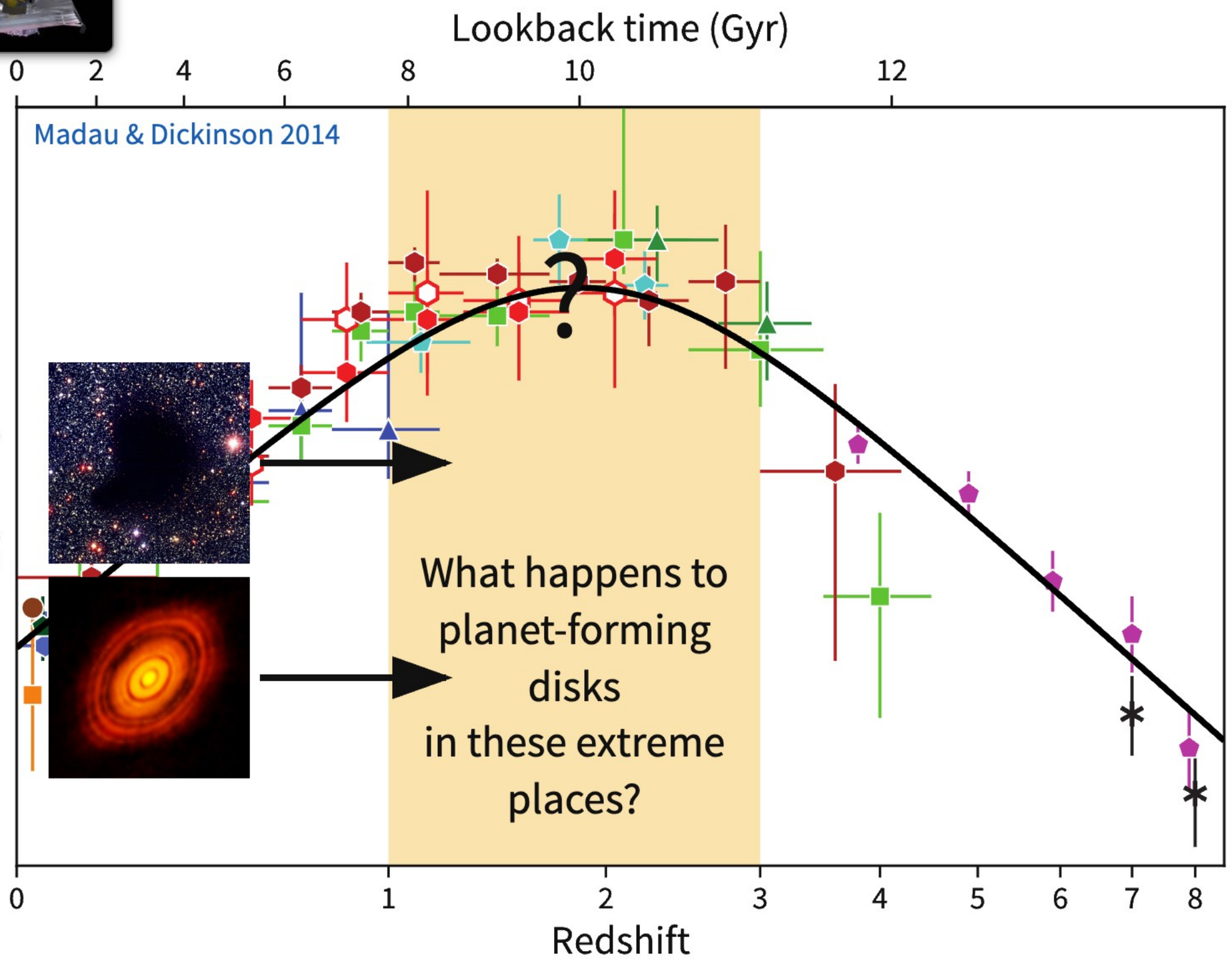




Planets within ~1,000 parsecs: **82%** of those known today → **~10%** after Roman

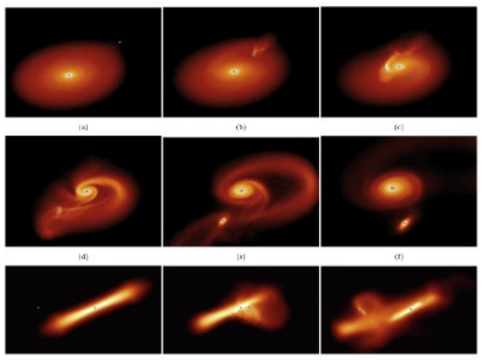
NASA Exoplanet Archive, Sept 2026 · microlensing: Penny+ 2019, ROTAC 2025, Terry+ 2026 · transits: Wilson+ 2023





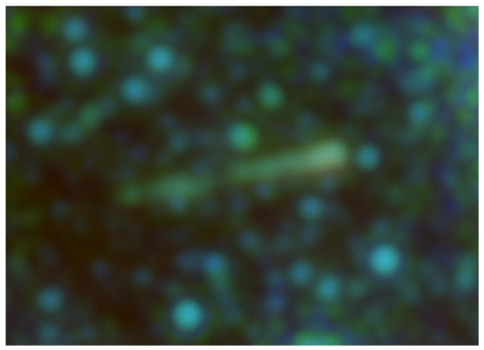


Proplyds: disks boiled away by nearby massive stars



Disks trimmed by surrounding gas

Wijnen+ 2017; Otter+ 2021



Disks with tails in the Arches cluster

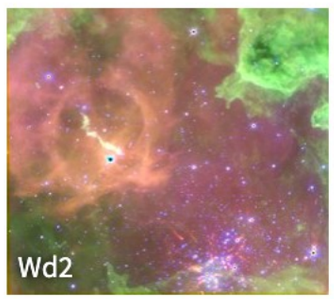
Hosek+ in prep

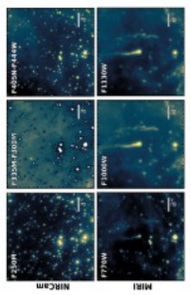
EWOCS: JWST in Westerlund 1 & 2

Monsch et al., incl. **Lovell, Galarza**

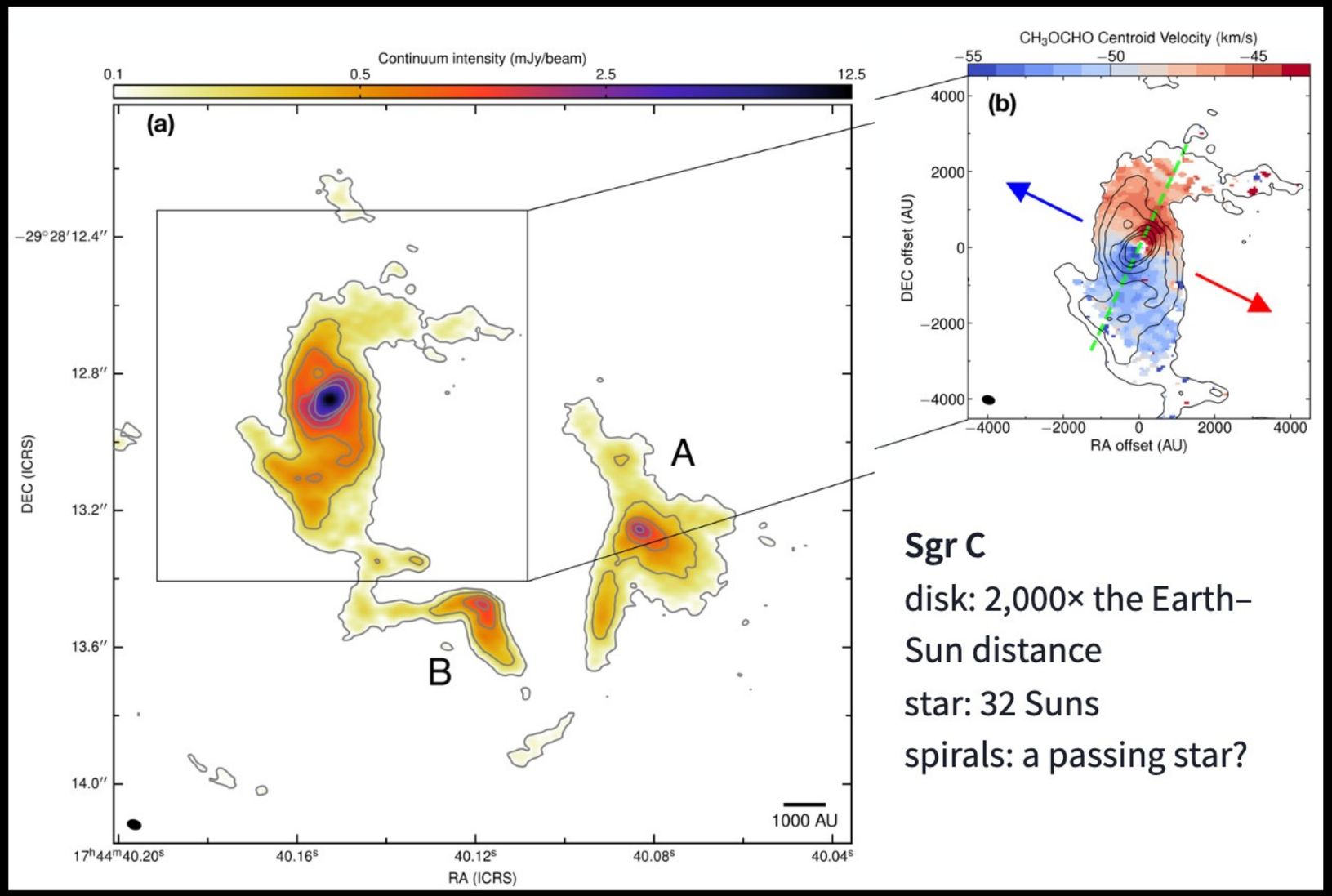
Guarcello+ 2024, 2025







Planet-forming disks exist in the center



Sgr C

disk: 2,000× the Earth–Sun distance

star: 32 Suns

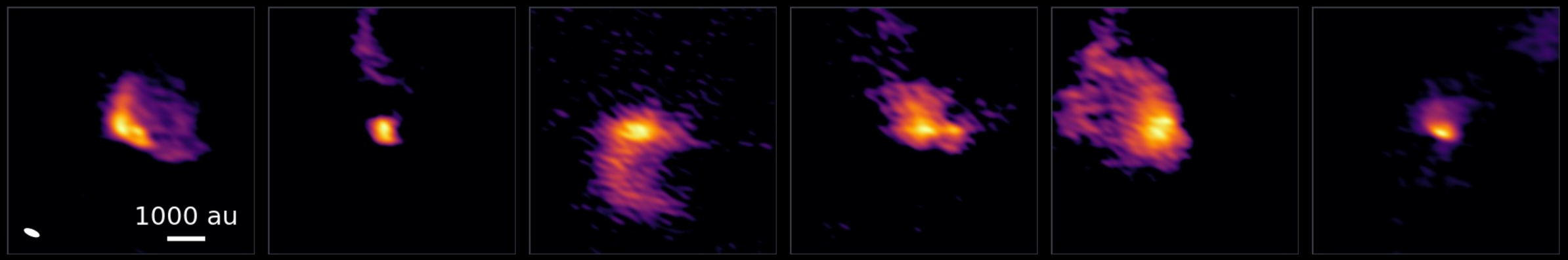
spirals: a passing star?

Hundreds detected, a few resolved

We can study planet formation in this environment.

Early days: so far we can only see the biggest disks.

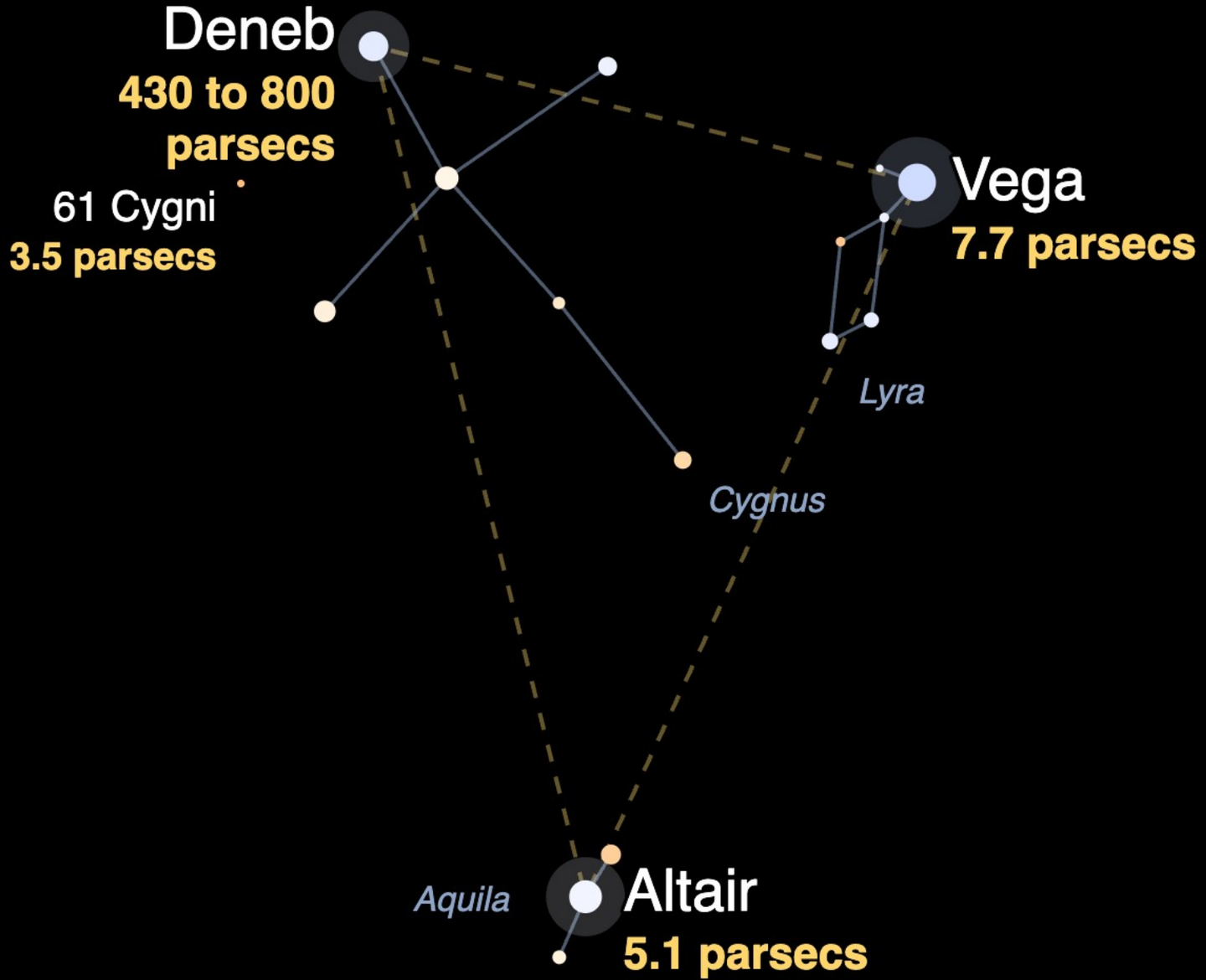
Soon: how many young stars have disks?



Lu+ 2022 (top figure) · Weng+ 2026 · Zhang+ 2025 · Budaiev+ 2024 · Daley+ in prep

Q1	What planets form there?	2016	future!
Q2	How does gas flow into the center?	1991	progress
Q3	(How) does gas reach the black hole, Sgr A*?	1996	future
Q4	**What shape is the central ring of gas?**	**1995**	←
Q5	Why does the center form so few stars?	2013	
Q6	Where do the center's young stars go?	2002	
Q7	Is the mix of star masses different here?	1999	
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Distance: astronomy's most fundamental question

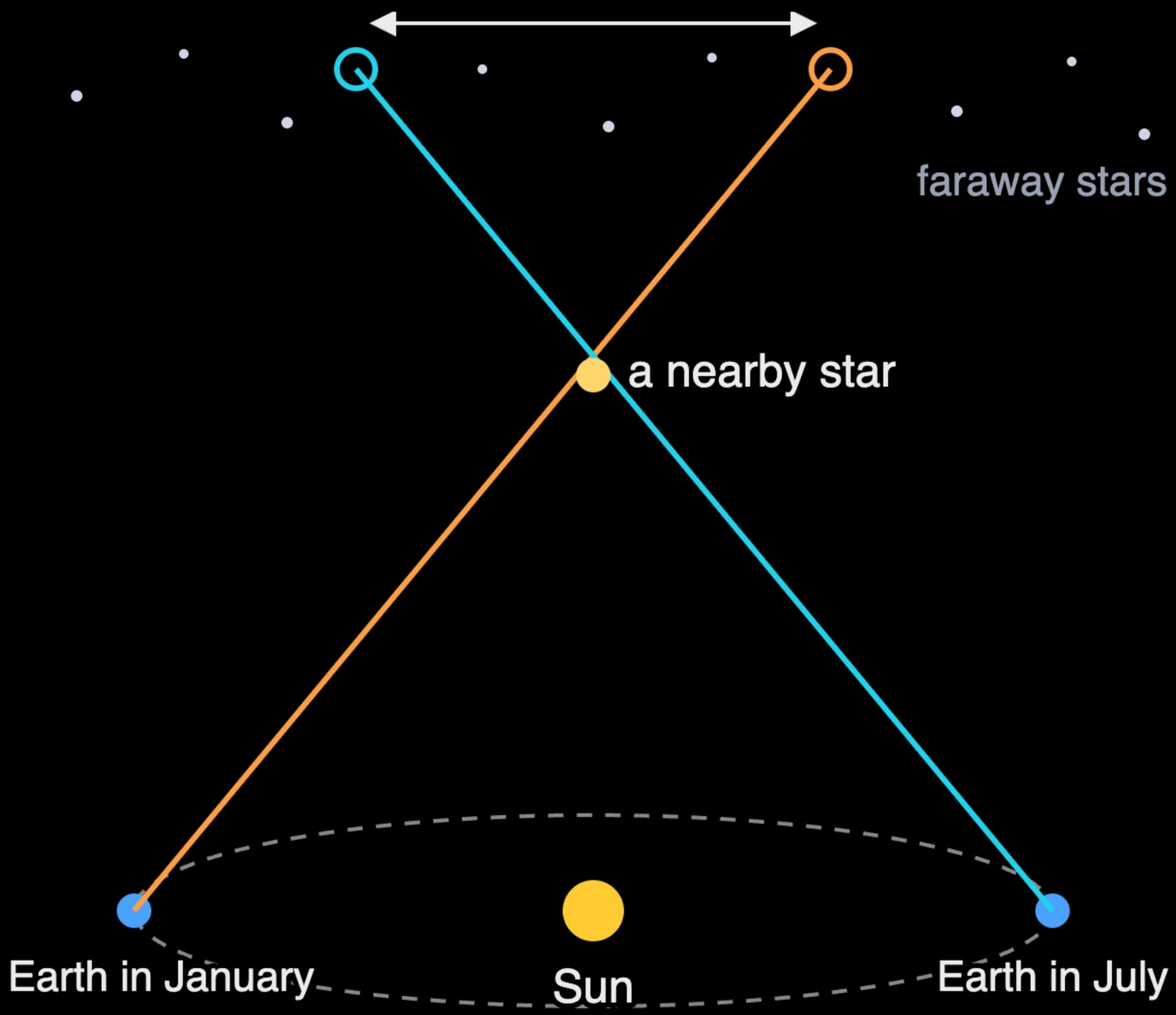


Overhead tonight: the Summer Triangle

Vega and Deneb look similar, but Deneb is 50 to 100 times farther away

→ Deneb gives off more than 1,000× as much light as Vega

Measuring distance: parallax



Blink one eye, then the other: your thumb jumps against the background

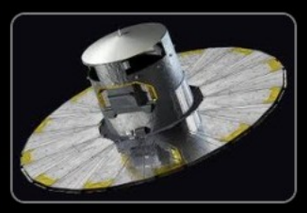
Earth's orbit gives us two “eyes” 300 million km apart

Gaia (2013–2025): distances to 1.5 billion stars

best: a dime seen from 160,000 km (4 laps around the earth) away

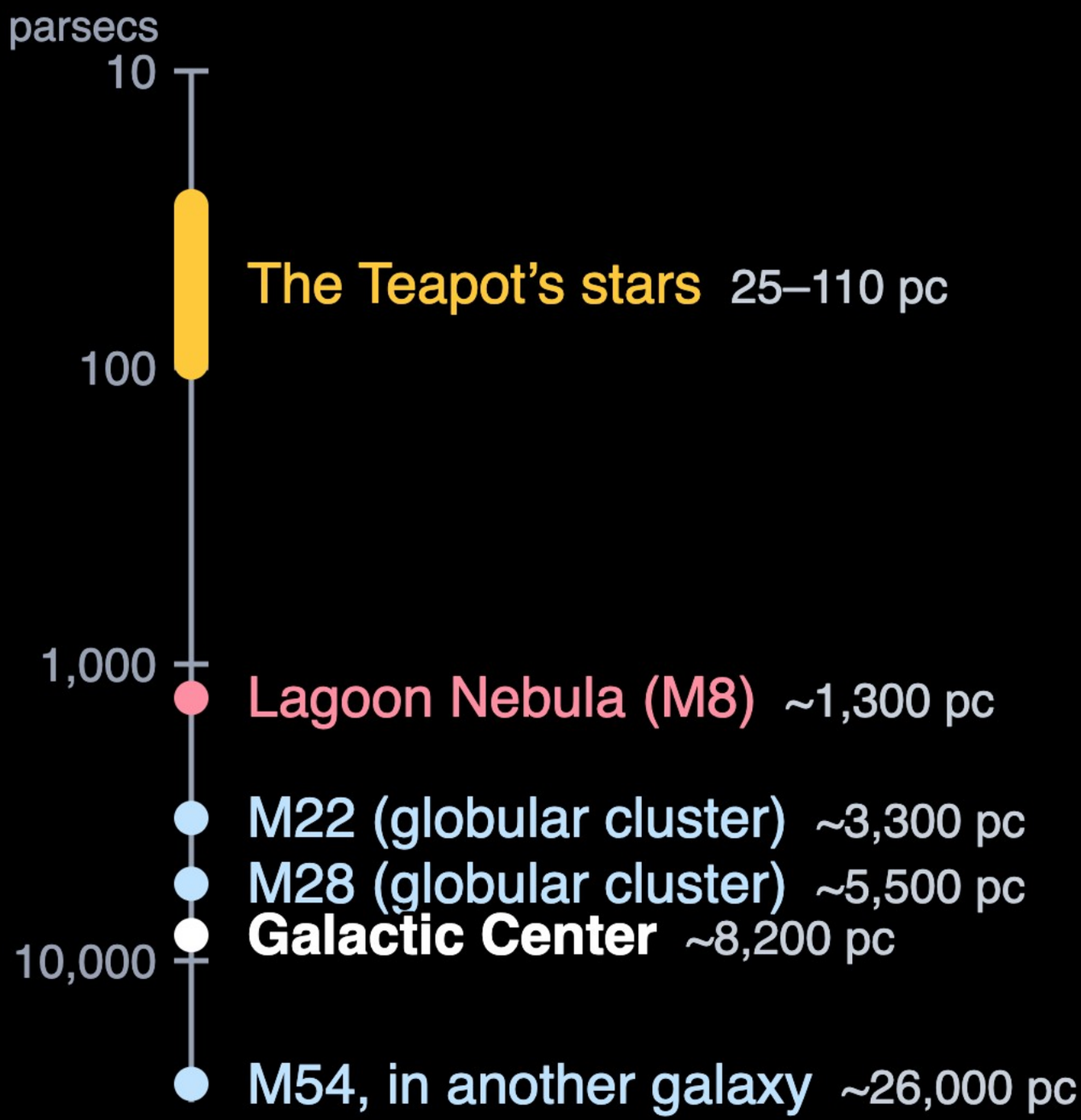


But dust dims the Galactic Center's visible light a trillion times

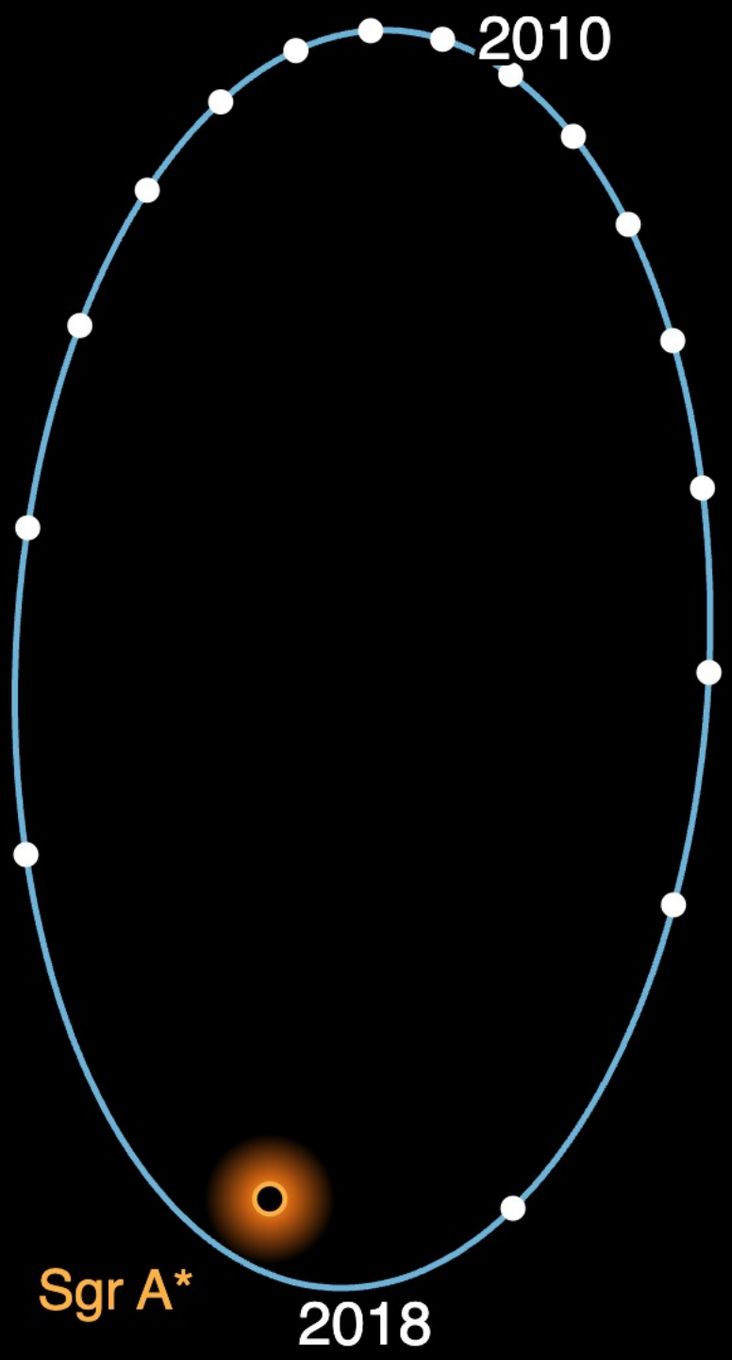


Gaia star colors via ESA

What you can see toward Sagittarius, by distance



The best distance to the center: a star orbiting the black hole



The star S2 orbits the center every 16 years

→ a black hole of 4 million Suns

Nobel Prize 2020: Reinhard Genzel & Andrea Ghez

Orbit size in angle + orbit size in kilometers (from its speed) → 8,200 parsecs, within a few percent

We measure velocity through Doppler shift and sky motion by watching the orbit, giving distance.

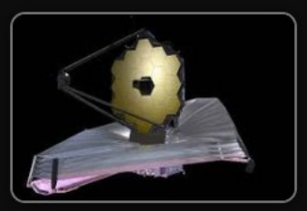


orbit: GRAVITY Collaboration 2020

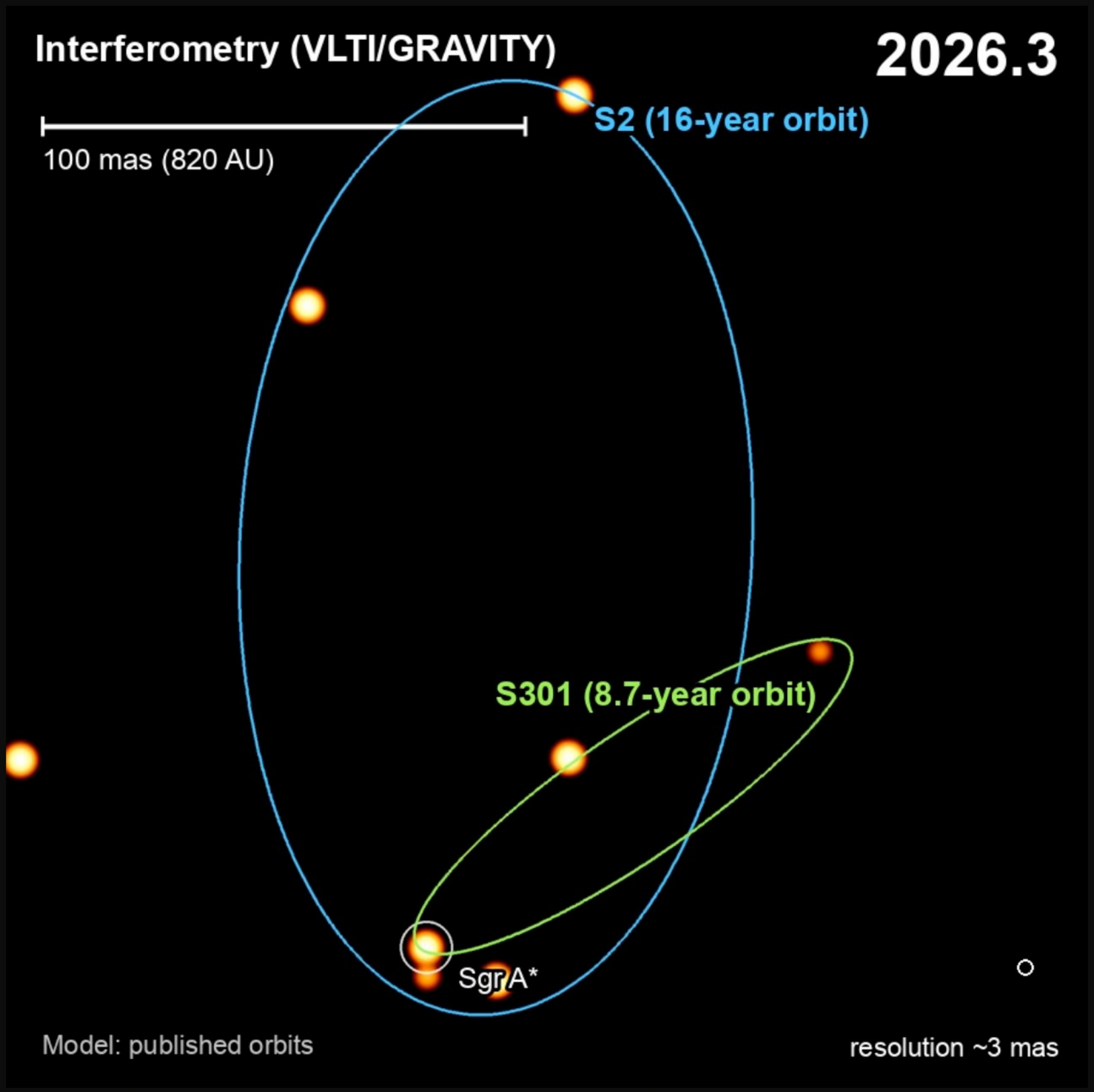
Stars around the black hole, 1995–2026







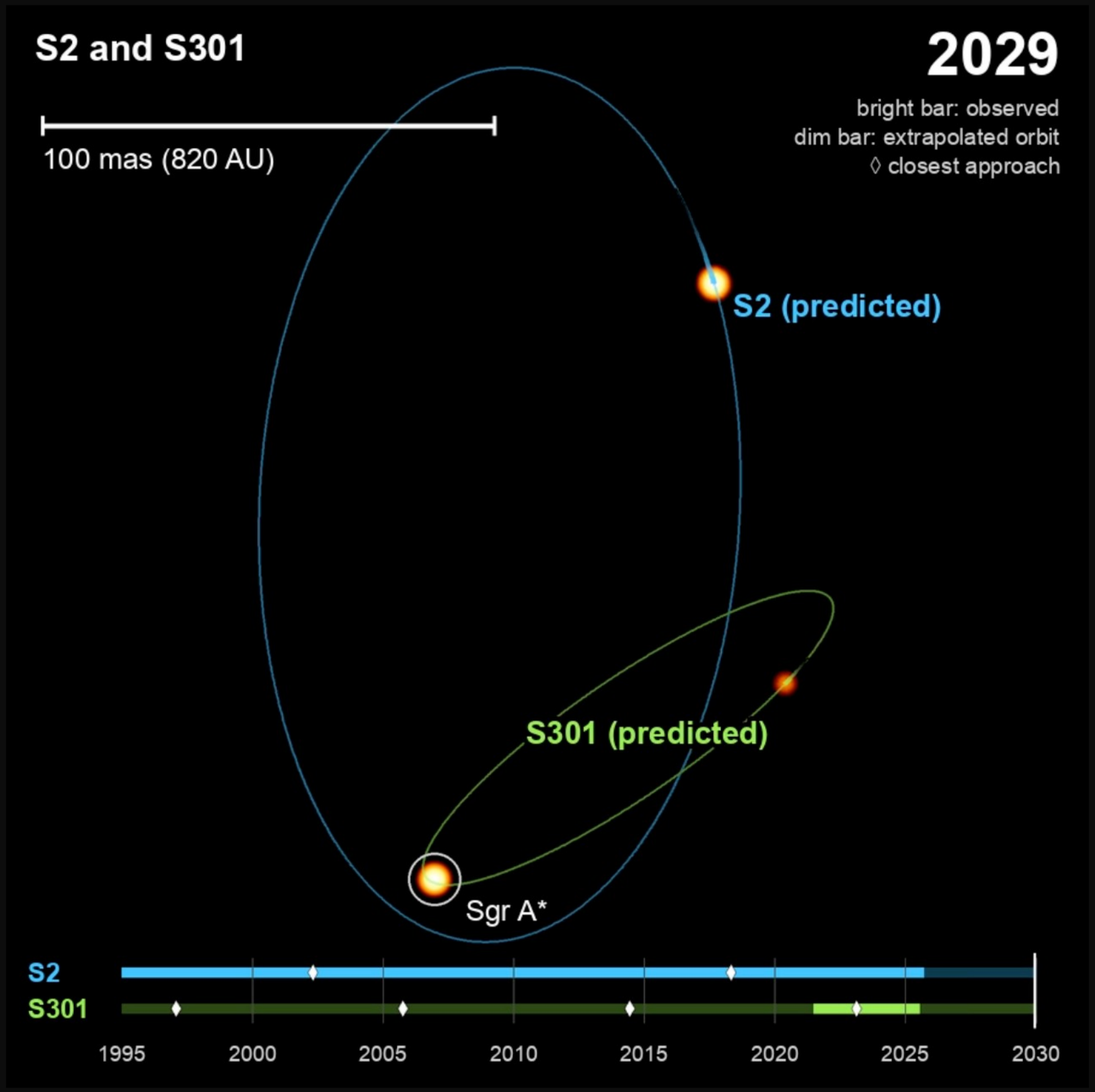




Observed (green label): Keck/NIRC2 (Keck Observatory Archive), VLT/NACO (ESO archive), JWST/NIRCam (MAST) images, aligned for this talk; GRAVITY images from Abd El Dayem et al. 2026. In between: the nearest real image with stars moved along published orbits and motions (Gillessen et al. 2017; GRAVITY Collaboration 2021; Abd El Dayem et al. 2026), blurred as that instrument measured. Before 2002: model at the 1998 Keck speckle resolution.

S2 and S301, 1995–2030

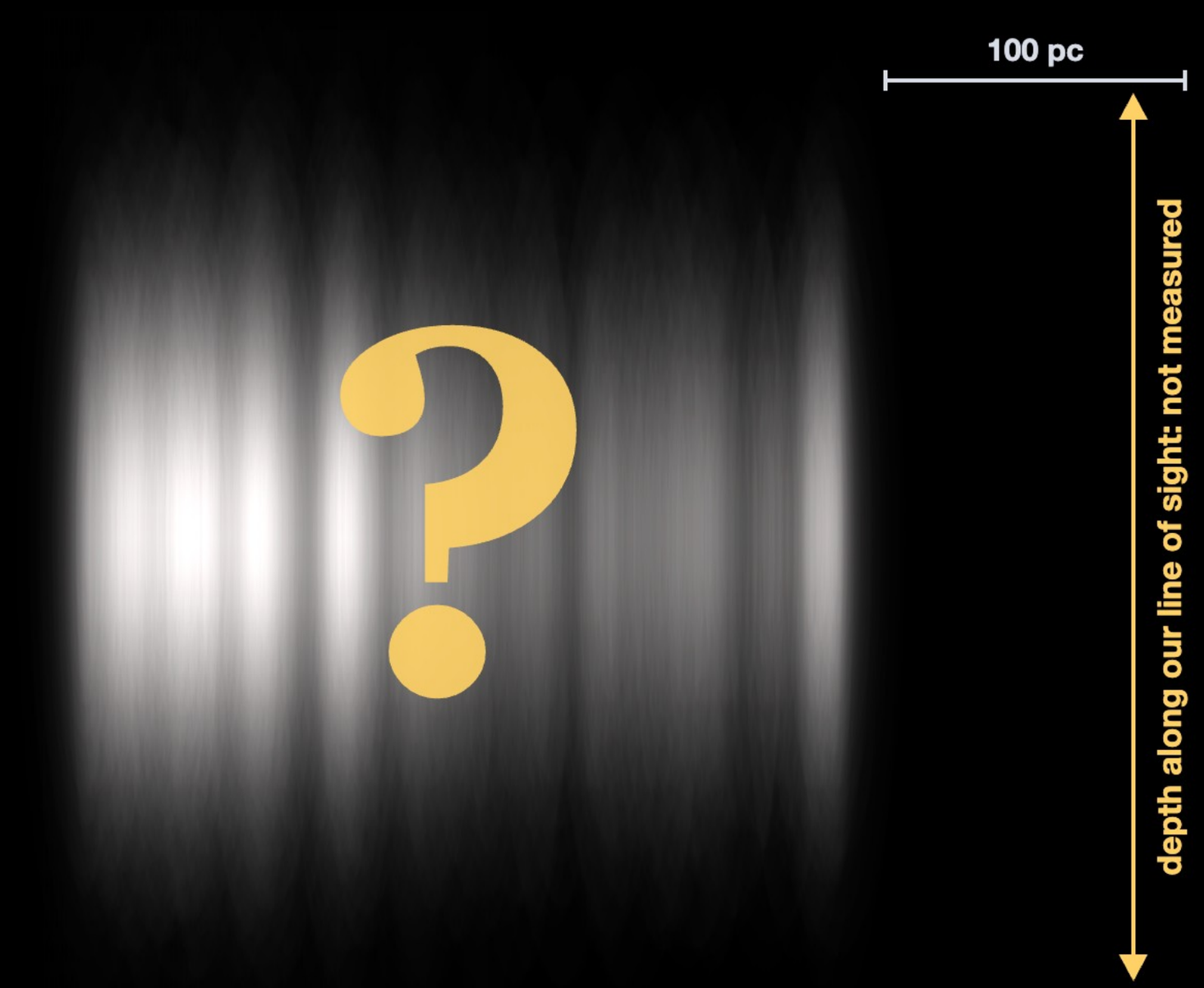




Positions from published orbits (Gillessen et al. 2017; GRAVITY Collaboration 2021; Abd El Dayem et al. 2026), drawn at GRAVITY resolution. Bright bar: years with observations; dim bar: orbit extrapolated backward or forward in time.

We know our neighborhood in 3D, but not the Galactic Center

At the Galactic Center we have excellent 2D maps but poor 3D

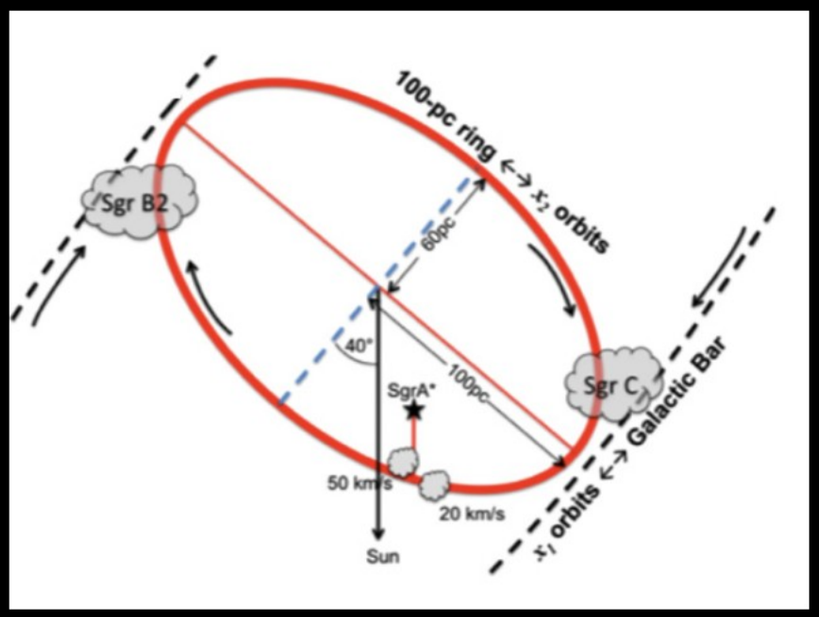


what we see from the Sun: positions on the sky

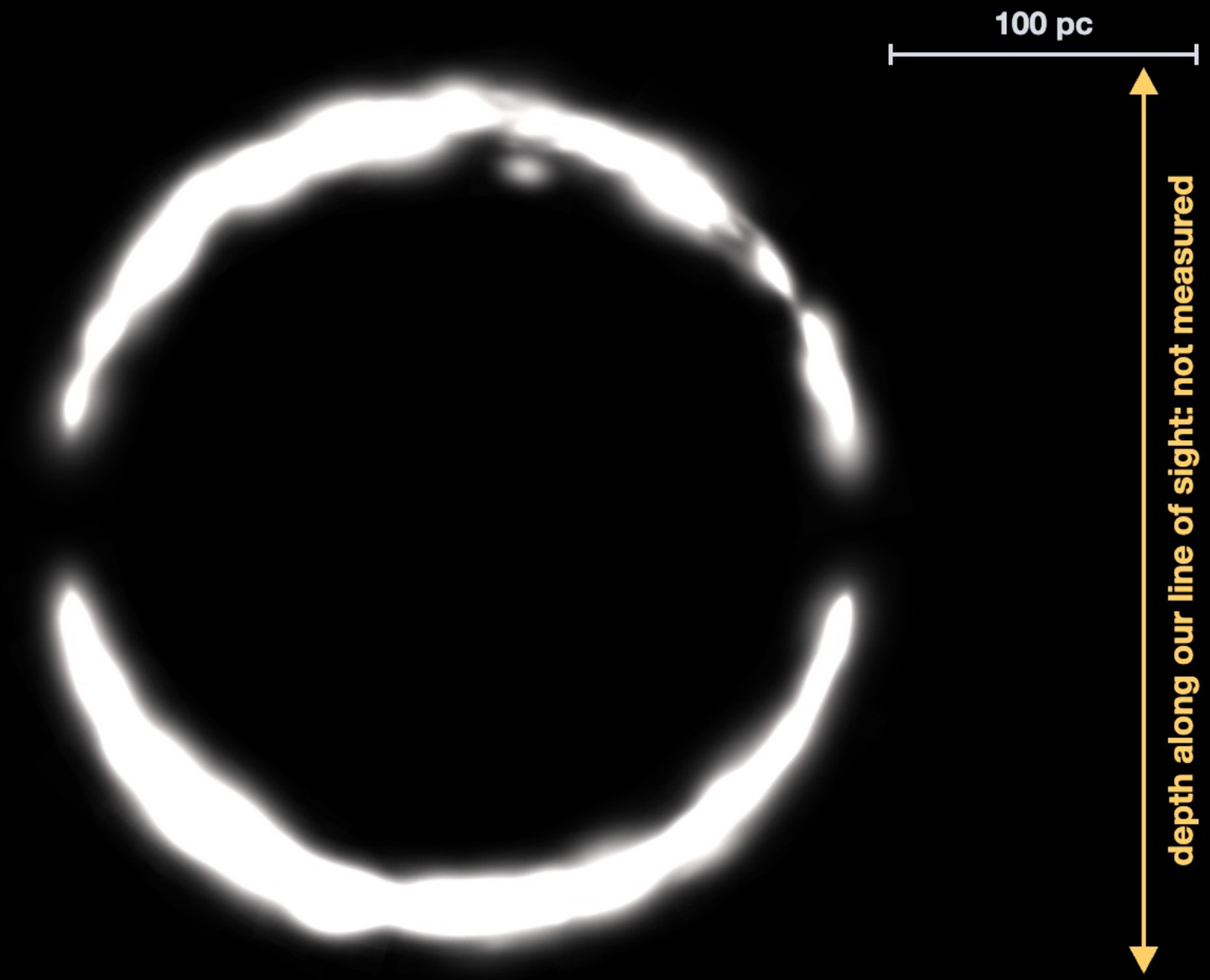


We know our neighborhood in 3D, but not the Galactic Center

Hypotheses include:
A ring?



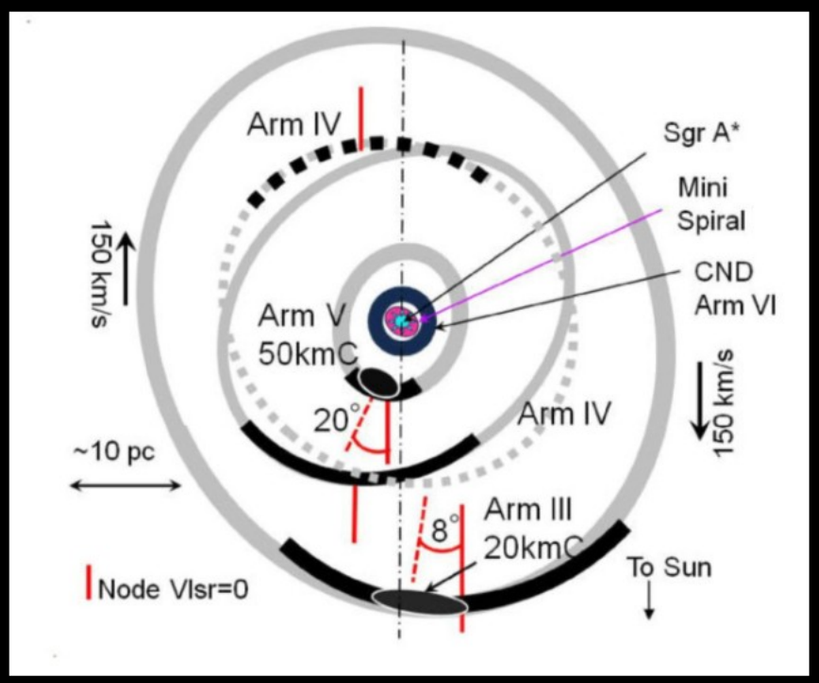
Molinari+ 2011: a twisted ring, seen from above





We know our neighborhood in 3D, but not the Galactic Center

Hypotheses include:
Spiral arms?



Sofue+ 2025: spiral arms in the center, from ALMA



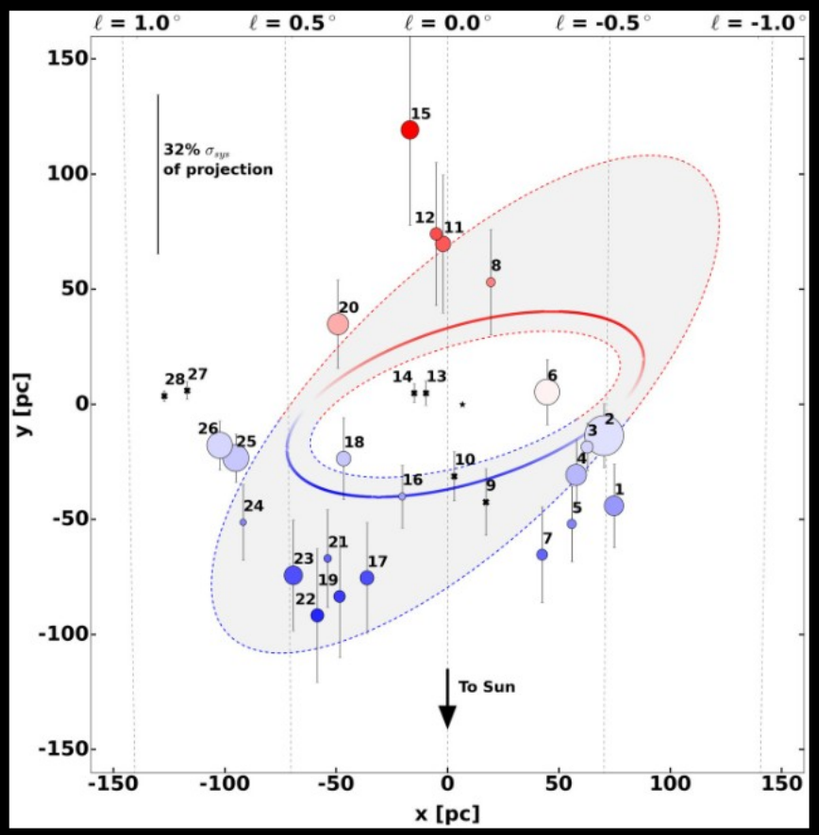




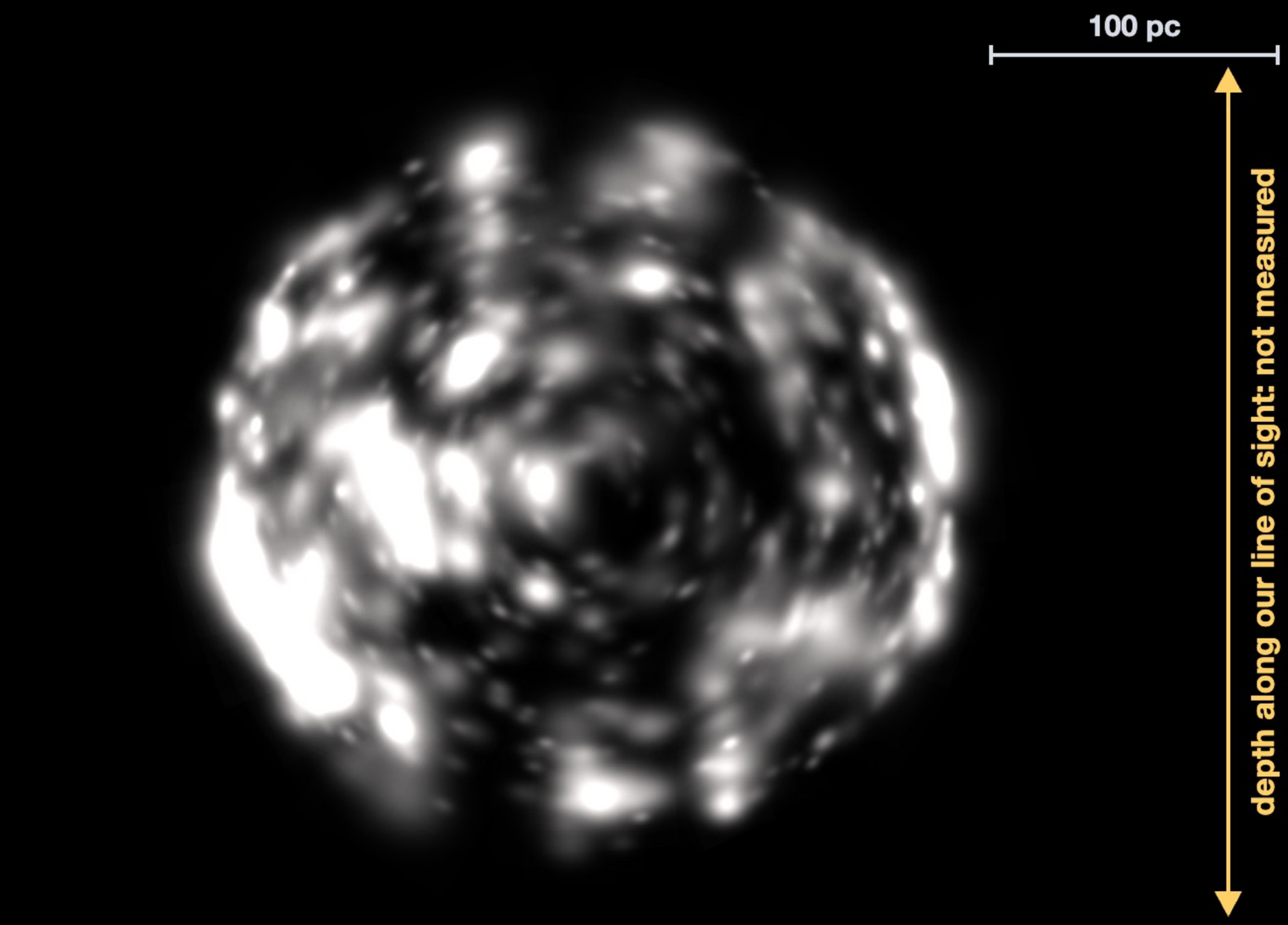
We know our neighborhood in 3D, but not the Galactic Center

Hypotheses include:
A filled disk?

same sky positions in every shape:
only the depth changes



Lipman+ 2026: nested orbits

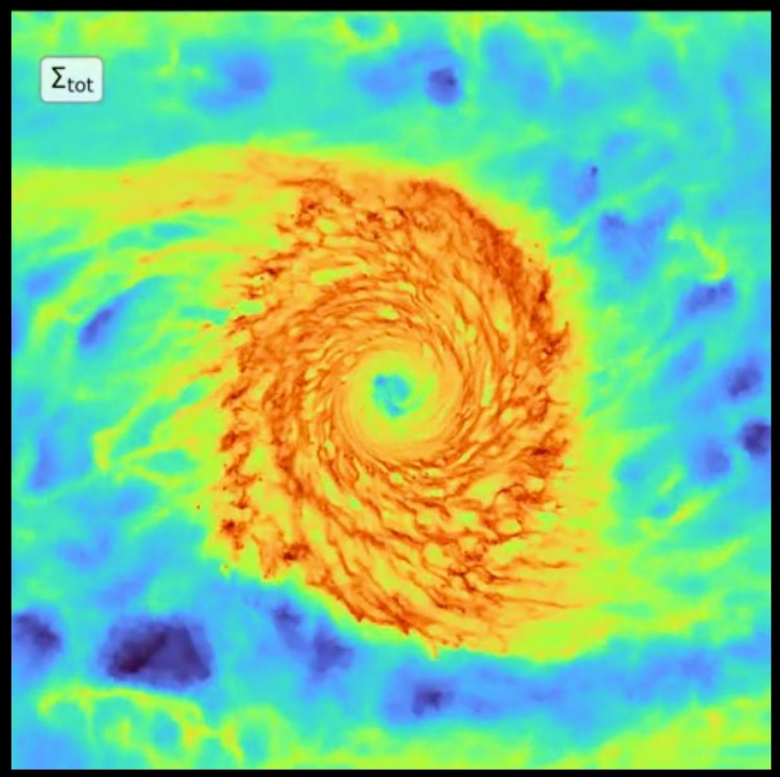


what we see from the Sun: positions on the sky



We know our neighborhood in 3D, but not the Galactic Center

Hypotheses include:
A mix of all?



Tress+ 2026: a simulation seen from above,
~1,000 parsecs across, over 125 million years



We know our neighborhood in 3D, but not the Galactic Center

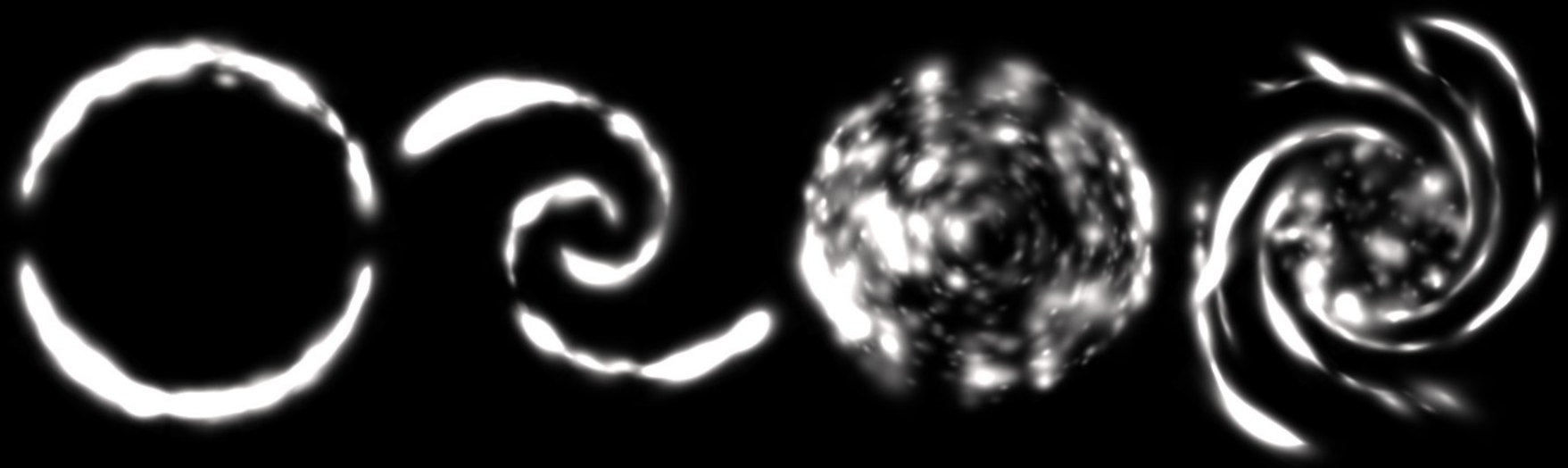
We need to measure depth.

ring

spiral arms

disk

as in simulations



↓ seen from the Sun



↓ seen from the Sun



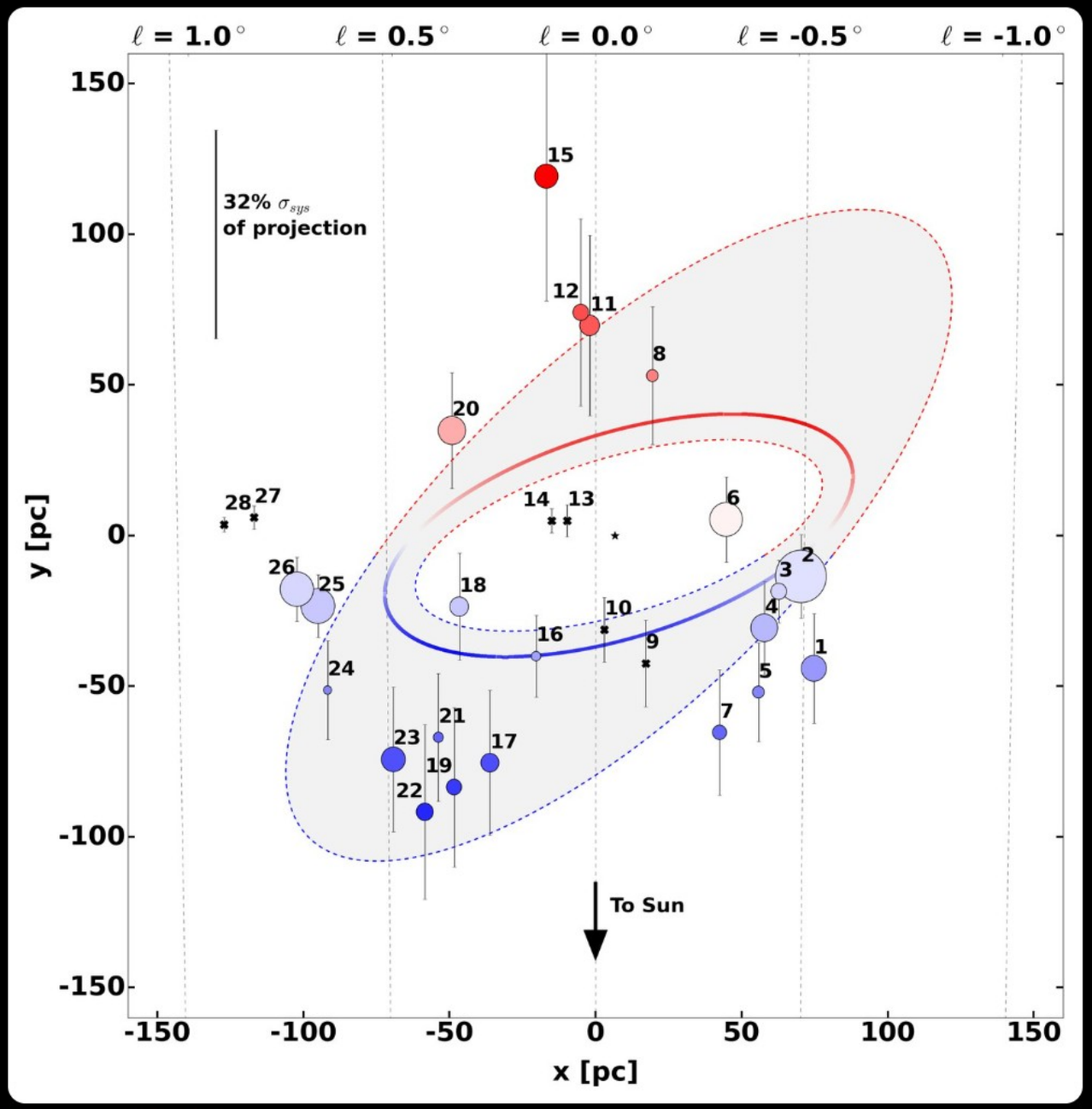
↓ seen from the Sun



↓ seen from the Sun



Progress: a 3D map of the central ring, 2025–26



Lipman+ 2026, 3D-CMZ V Fig. 6

- ~3/4 of known clouds are **in front** of the black hole

  Walker+ 2025; Lipman+ 2026; Nogueras-Lara+ 2026; Mills+ 2026

- For most clouds, the best we can say is "in front"
- Most of the gas isn't in clouds, so we can't place it yet

Roman will track the motions of tens of millions of stars: a new way to map the gas in 3D



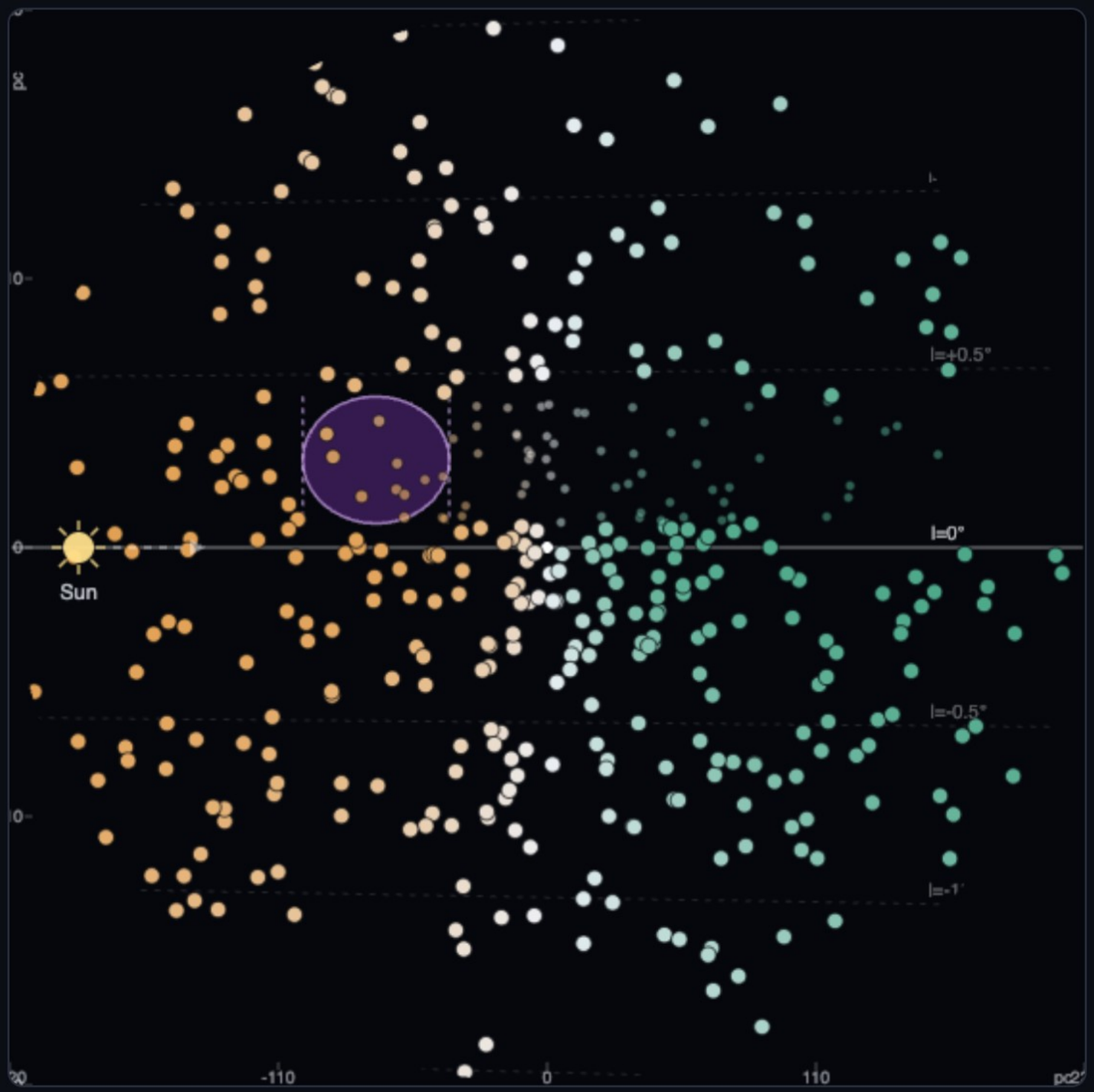
Roman Galactic Center survey Roman bulge survey

Roman will track the motions of tens of millions of stars: a new way to map the gas in 3D



Roman Galactic Center survey
Roman bulge survey

Mapping the gas in 3D with moving stars



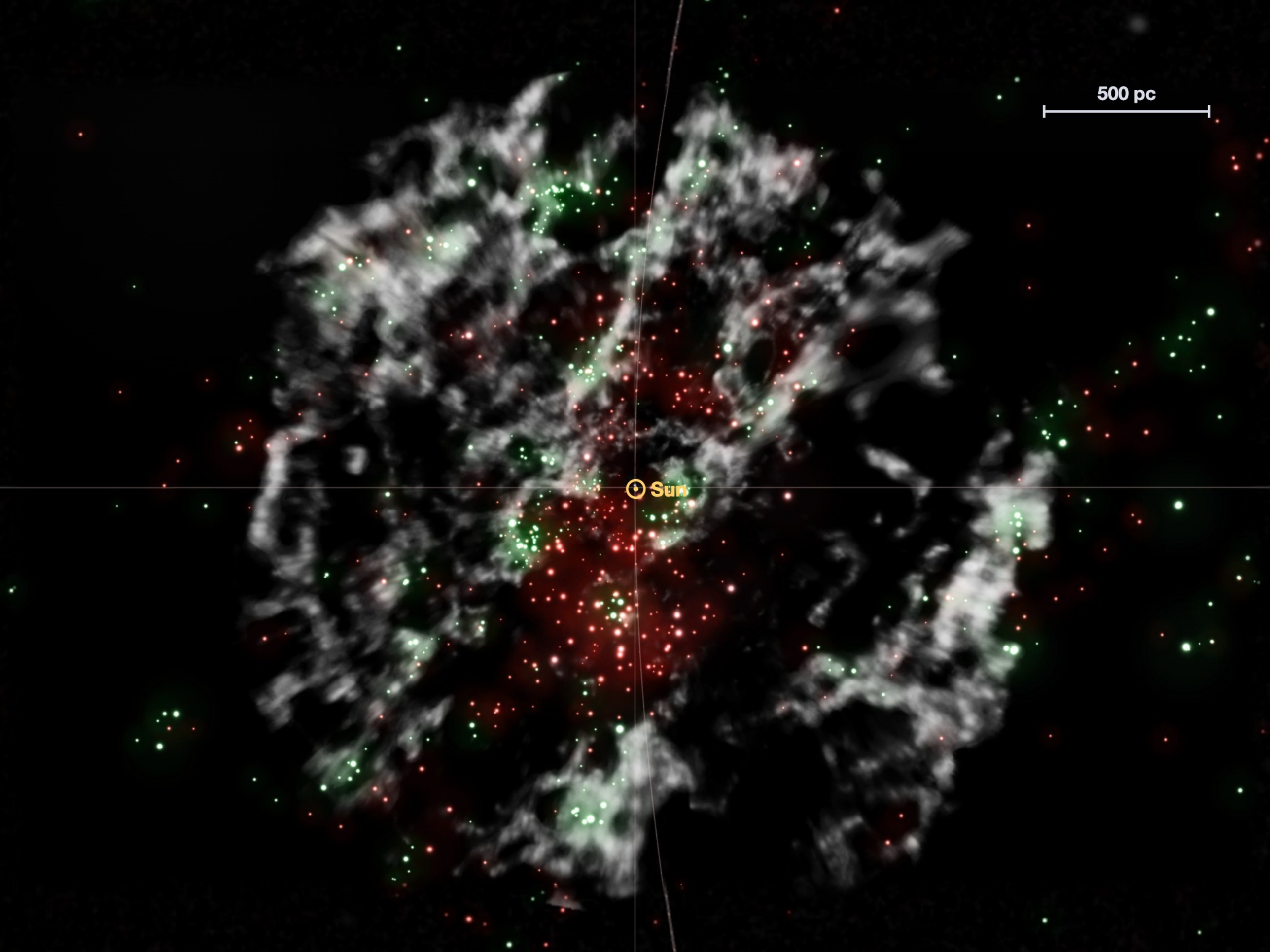
Stars circle the center: on the near side they drift one way across the sky, on the far side the other way

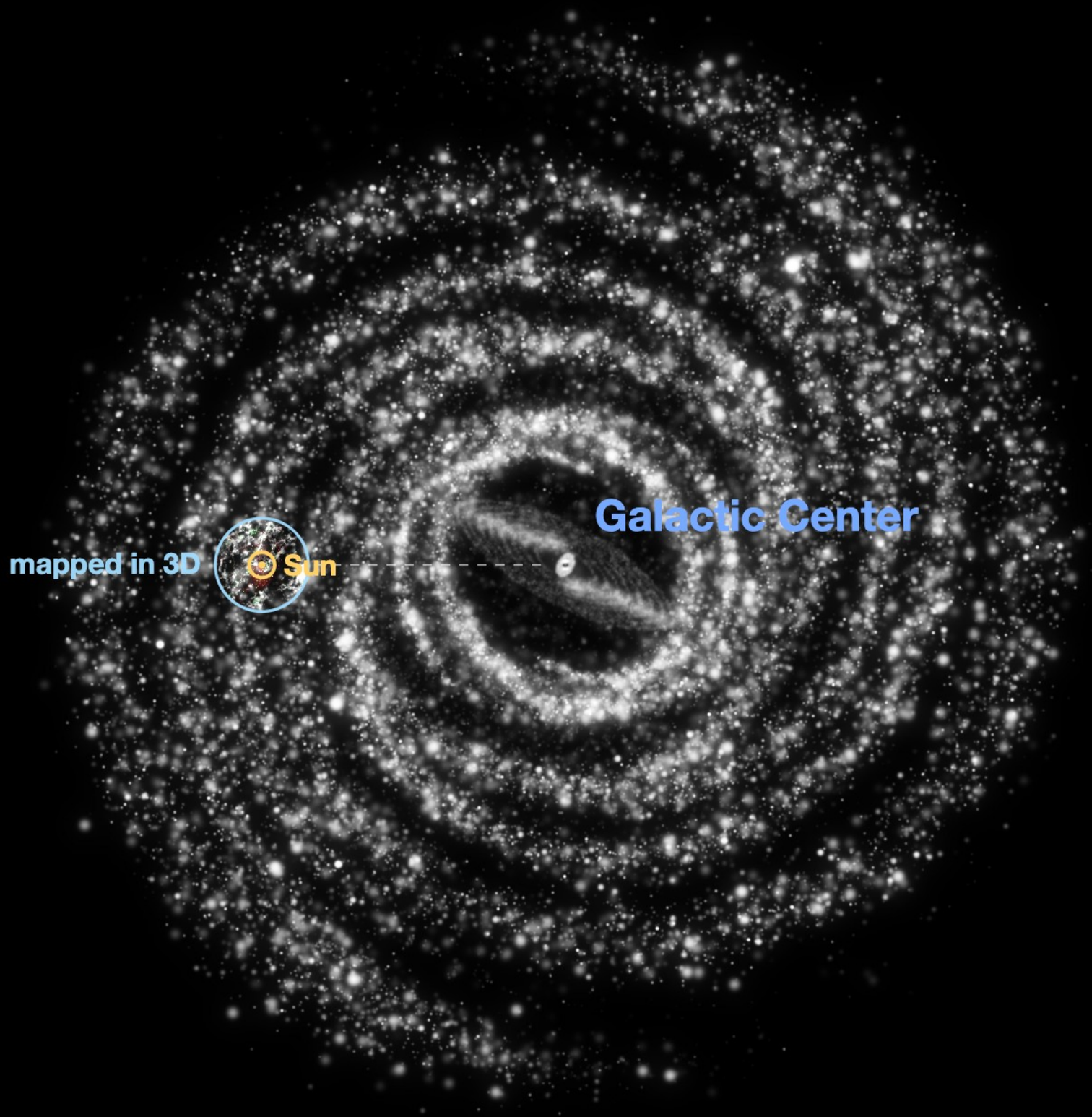
A cloud of gas dims and reddens the stars behind it

Which stars are dimmed tells us where the cloud sits, to within ~10 parsecs

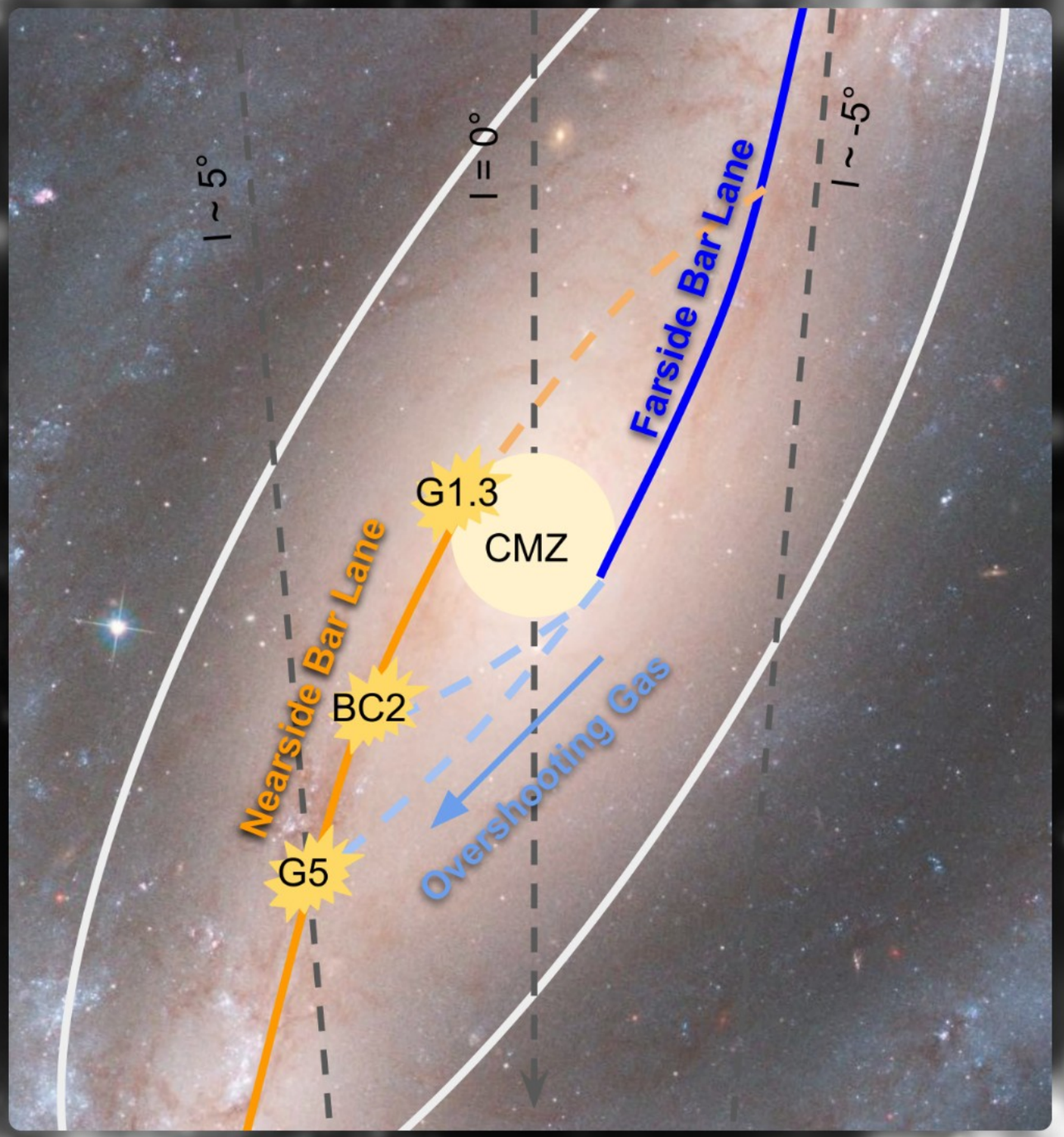
Orbits: Nieuwmunster+ 2024; method: Vasini+ 2026

Q1	What planets form there?	2016	future!
Q2	**How does gas flow into the center?**	**1991**	←
Q3	(How) does gas reach the black hole, Sgr A*?	1996	
Q4	What shape is the central ring of gas?	1995	
Q5	Why does the center form so few stars?	2013	
Q6	Where do the center’s young stars go?	2002	
Q7	Is the mix of star masses different here?	1999	
Q8	Is the chemistry different?	2009	

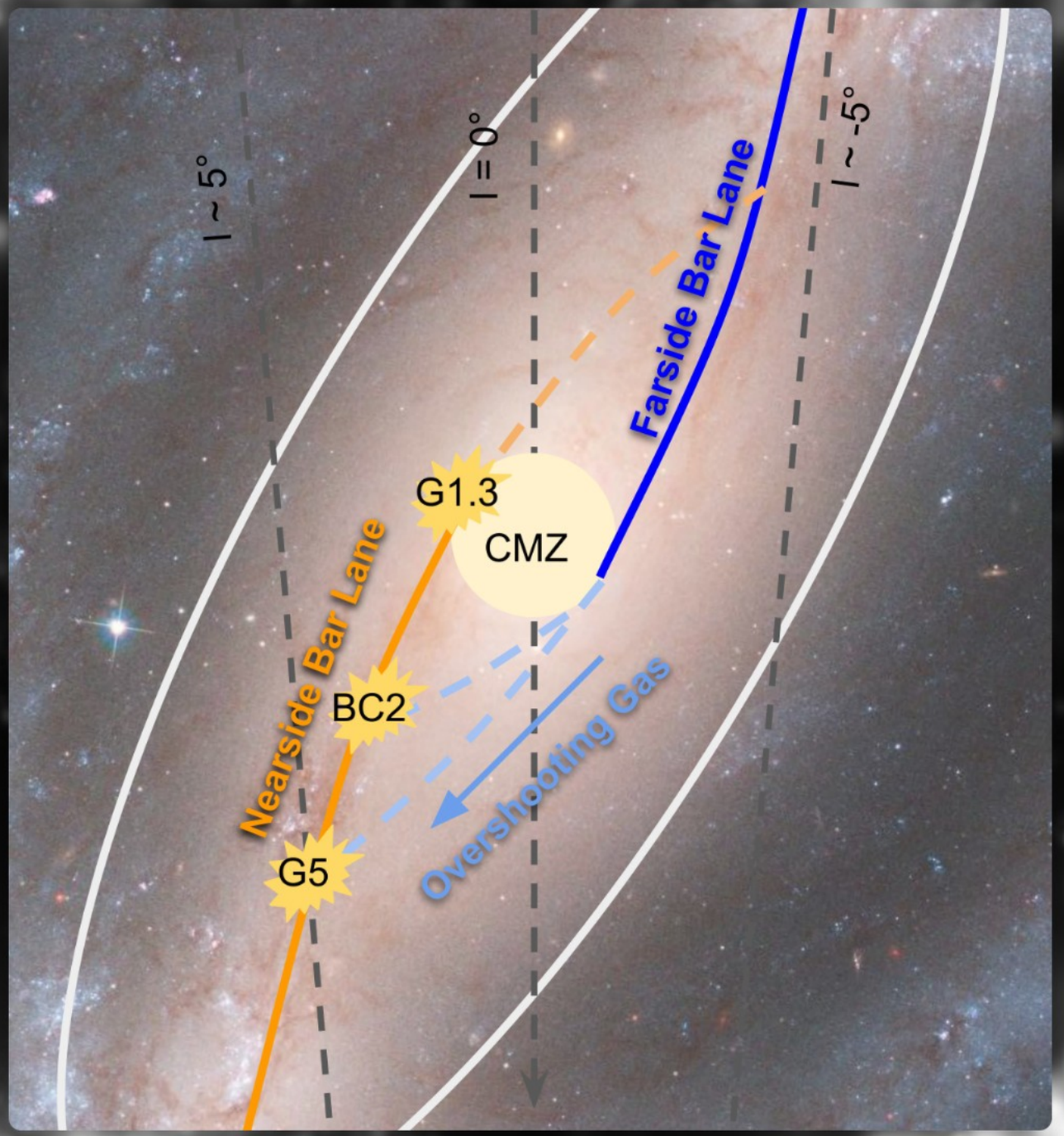

500 pc
Sun


Galactic Center
mapped in 3D
Sun

THE BAR FEEDS THE CENTER



THE BAR FEEDS THE CENTRAL RING

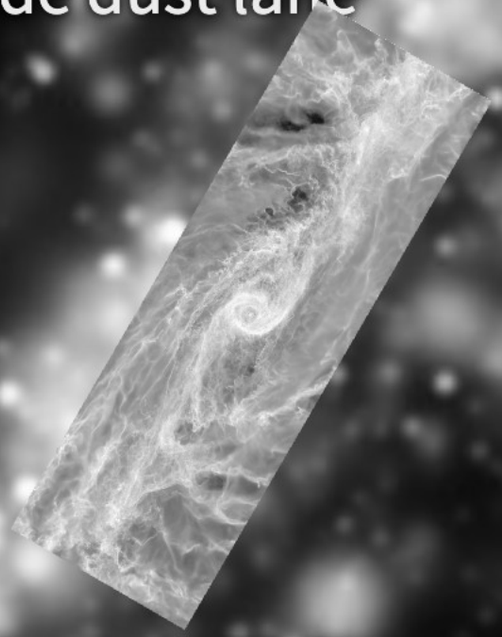


Gas falls along the bar's dust lanes: about one Sun's worth per year

About a third lands on the ring on its first pass; the rest overshoots

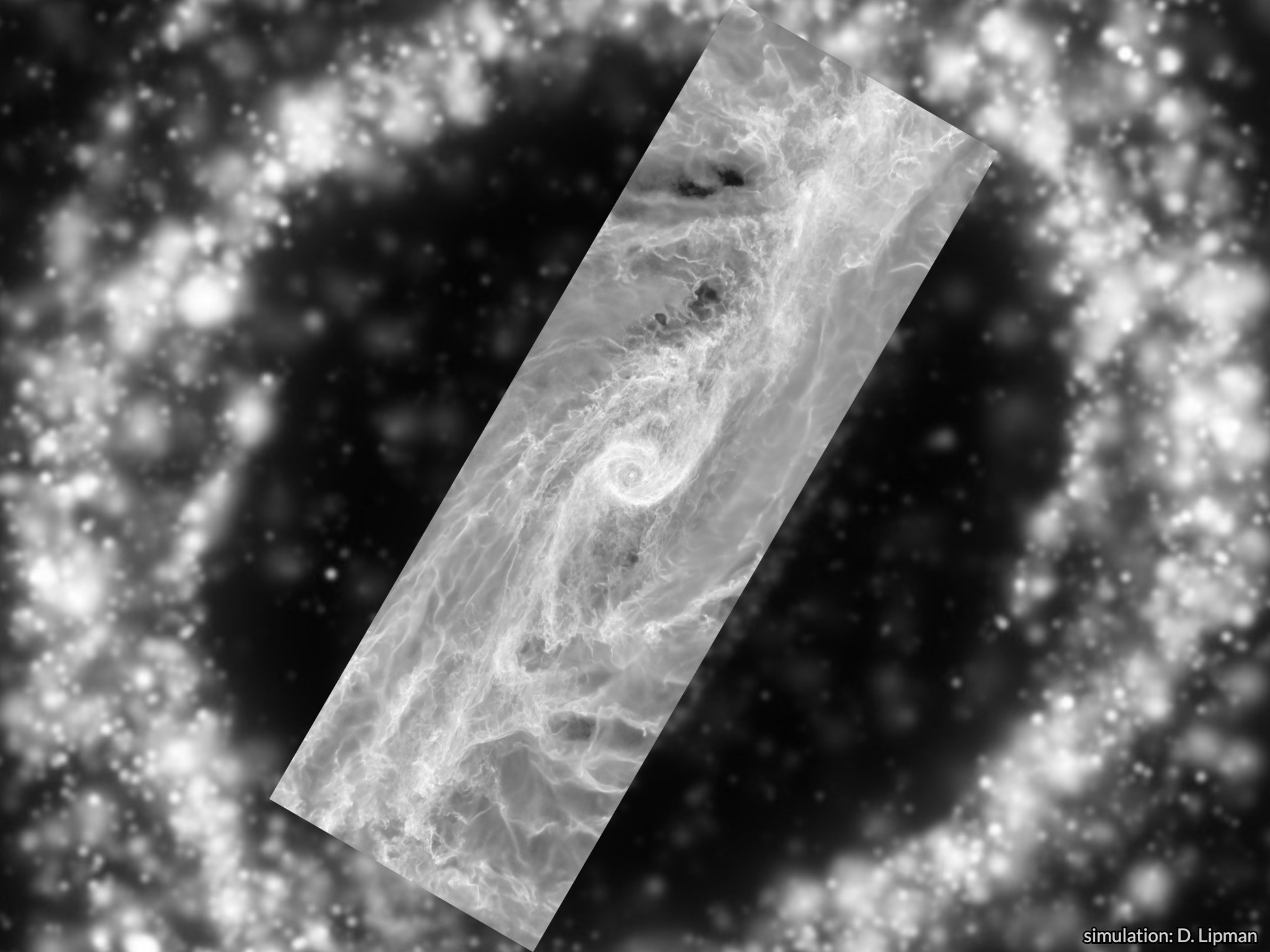
Hatchfield+ 2021

...and hits the far side dust lane



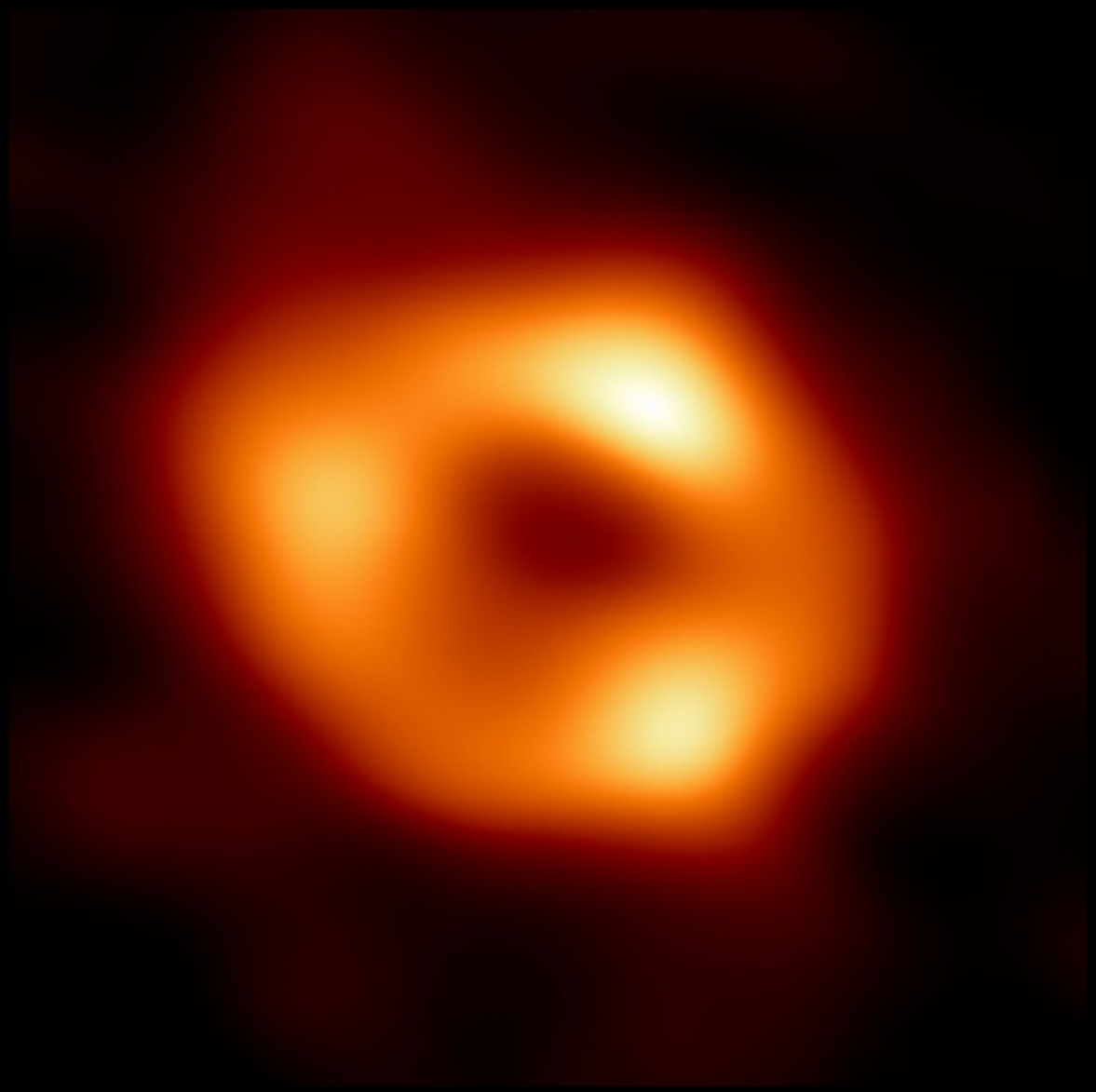
simulation: D. Lipman

cartoon: S. Gramze (Gramze+ 2023)


simulation: D. Lipman

Q1	What planets form there?	2016	future!
Q2	How does gas flow into the center?	1991	progress
Q3	**(How) does gas reach the black hole, Sgr A*?**	**1996**	←
Q4	What shape is the central ring of gas?	1995	
Q5	Why does the center form so few stars?	2013	
Q6	Where do the center’s young stars go?	2002	
Q7	Is the mix of star masses different here?	1999	
Q8	Is the chemistry different?	2009	

The central black hole barely eats



EHT Collaboration / ESO, CC BY 4.0

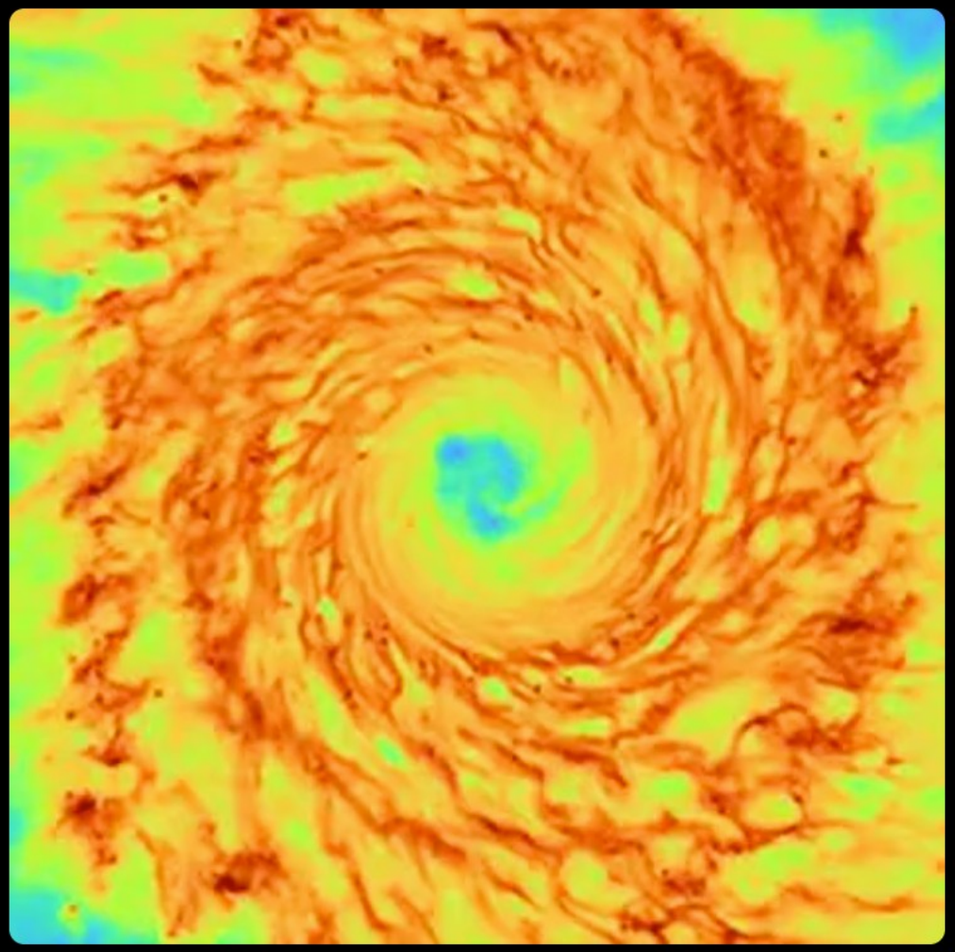
Sgr A*: 4 million Suns

Gas flowing into the center along the bar: ~1 Sun's worth per year

The black hole swallows less than a millionth of that

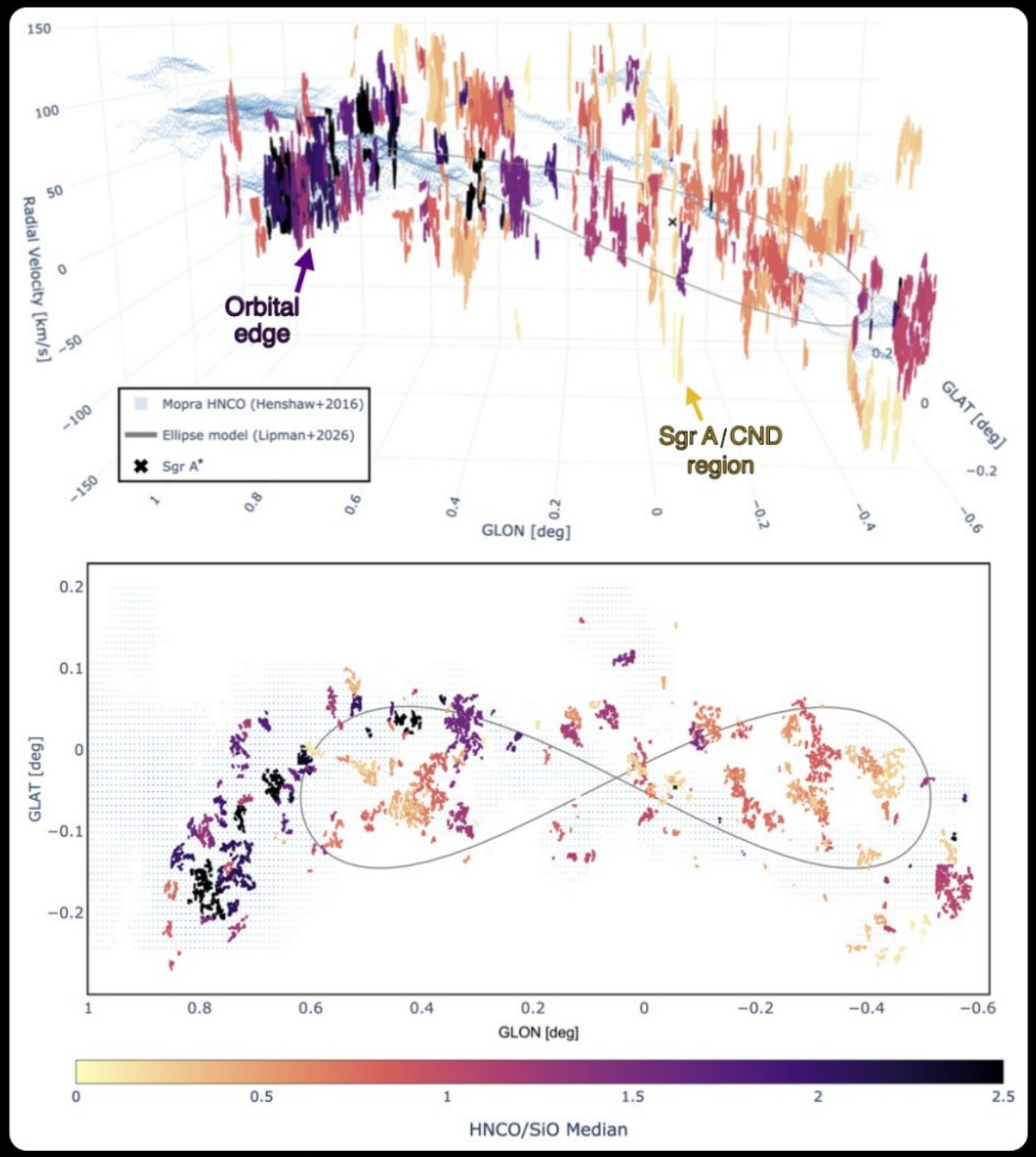
What happens to the rest?

Is gas flowing in toward the black hole?



Tress+ 2026 (Rhea-RT)

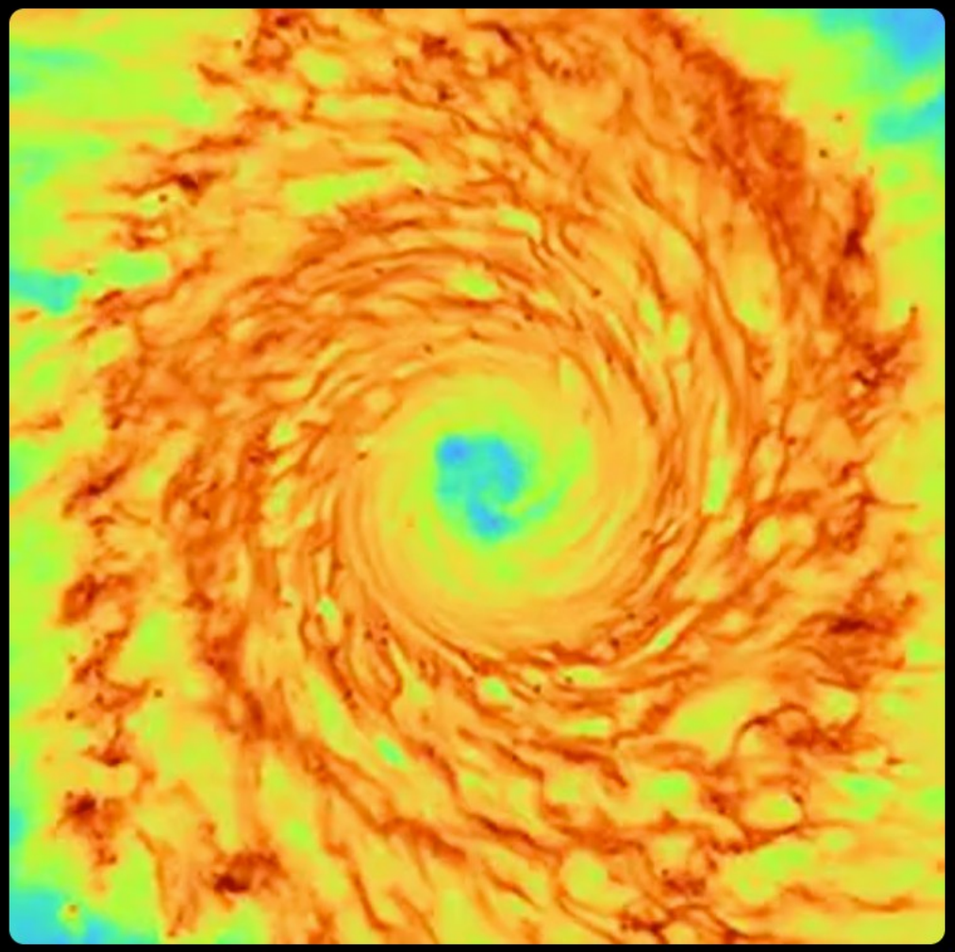
- Some fast-moving gas features are **shocks**: gas crashing into gas — Lipman+ 2026



Lipman+ 2026 ACES VIII, Fig. 8



Is gas flowing in toward the black hole?

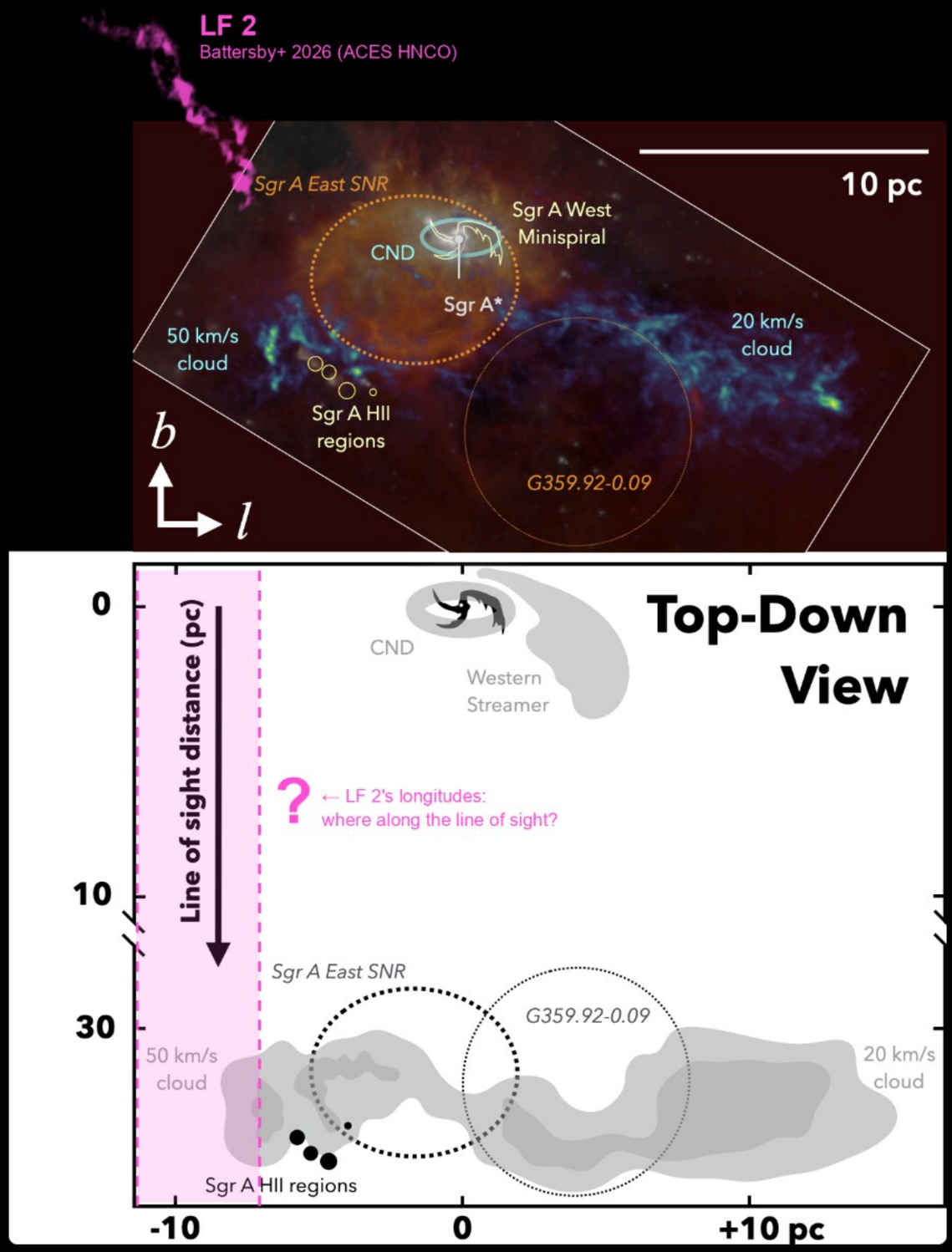


Tress+ 2026 (Rhea-RT)

- Some fast-moving gas features are **shocks**: gas crashing into gas — Lipman+ 2026
- Hints of gas **flowing inward** — Battersby+ 2026

Future: Roman 3D maps; detailed simulations

Is this inflow?



LF 2: Battersby+ 2026 · figure: Mills+ 2026

The Galactic Center: open questions (a partial list)

	question	open since
	What makes the giant radio filaments?	1984
Q2	How does gas flow into the center?	1991
Q4	What shape is the central ring of gas?	1995
Q3	(How) does gas reach the black hole, Sgr A*?	1996
	Was the black hole brighter in the recent past?	1996
	What are the fast-moving compact clouds?	1998
Q7	Is the mix of star masses different here?	1999
Q6	Where do the center's young stars go?	2002
	How did the central disk of stars form?	2002
	Why are there so many cosmic rays?	2005
Q8	Is the chemistry different?	2009
	How does dust dim and redden the light?	2009
	Is the extra gamma-ray glow dark matter, or pulsars?	2009
	Where are the massive stars, and how many are there?	2010
	Where do the lone massive stars come from?	2010
Q5	Why does the center form so few stars?	2013
	Does star formation come in bursts?	2015
	What accelerates the most energetic cosmic rays?	2016
Q1	What planets form there?	2016

Mystery: giant radio filaments



Sgr C



~1,000 thin, straight threads, some ~30 parsecs long
Radio glow from electrons spiraling around magnetic fields
Found in 1984. What makes them is still unknown.

MeerKAT: Heywood+ 2022, Yusef-Zadeh+ 2022 · image: Judy Schmidt

Mystery: giant radio filaments



Sgr C



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MeerKAT: Heywood+ 2022, Yusef-Zadeh+ 2022 · image: Judy Schmidt

Mystery: hot gas bubbles shaped by magnetic fields?





Sgr C: NASA, ESA, CSA, STScI, S. Crowe (UVA), J. Bally (CU), R. Fedriani (IAA-CSIC)

Mystery: where are the neutron stars?



10^8–10^9 neutron stars predicted in the Milky Way: one for each massive star that has died

thousands found, almost all as pulsars

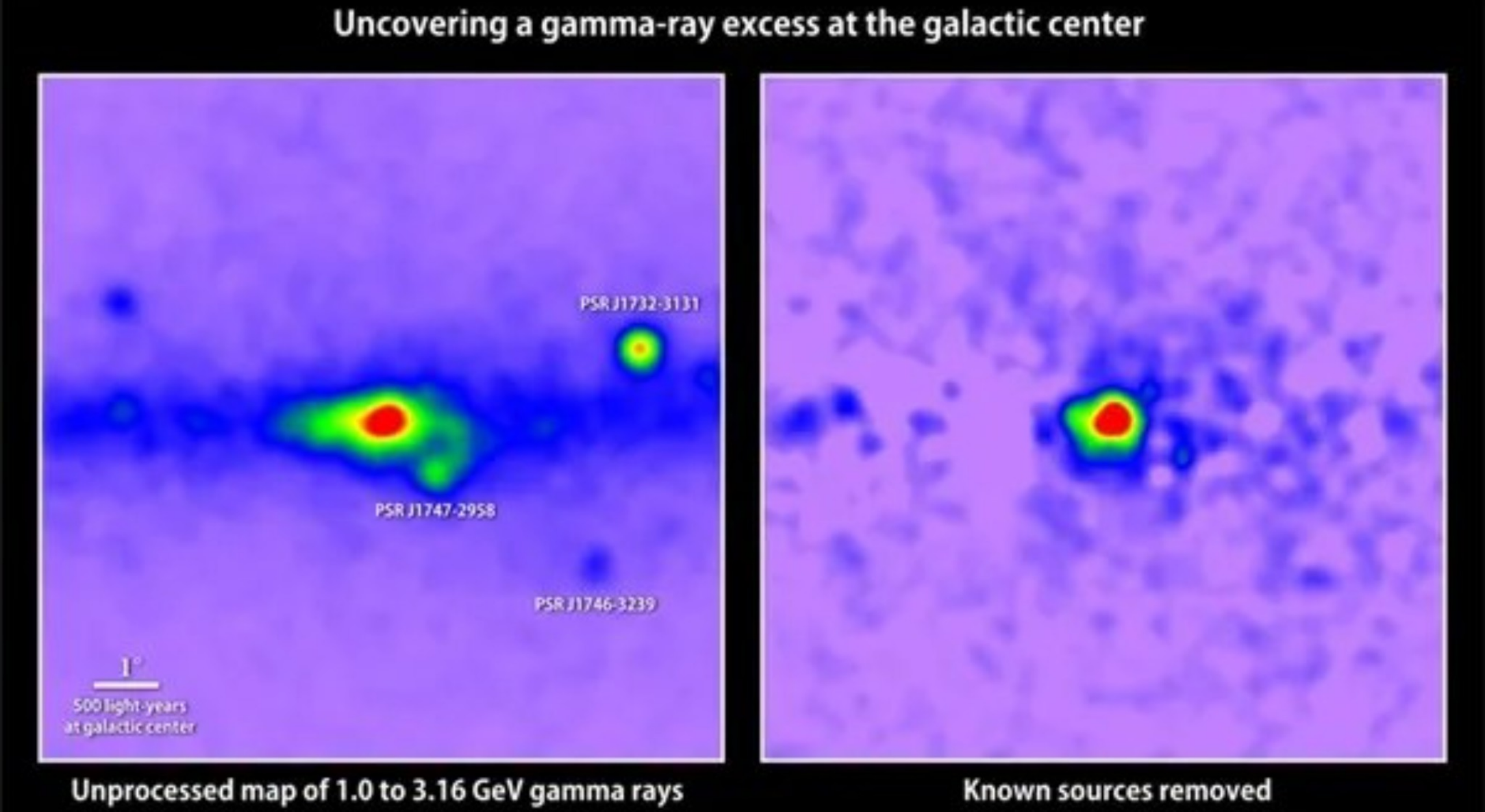
~6 known within ~30 parsecs of the center. The closest, a magnetar found in 2013, is 0.1 parsecs from Sgr A*.

Theory expects hundreds or more near the black hole. **Hidden behind blurring gas, or really missing?**



Known pulsars: ATNF Pulsar Catalogue (Manchester+ 2005), Johnston+ 2006, Deneva+ 2009 · magnetar: Mori+ 2013, Eatough+ 2013 · MeerKAT: Heywood+ 2022 · image: Judy Schmidt

Mystery: is the gamma-ray glow dark matter?



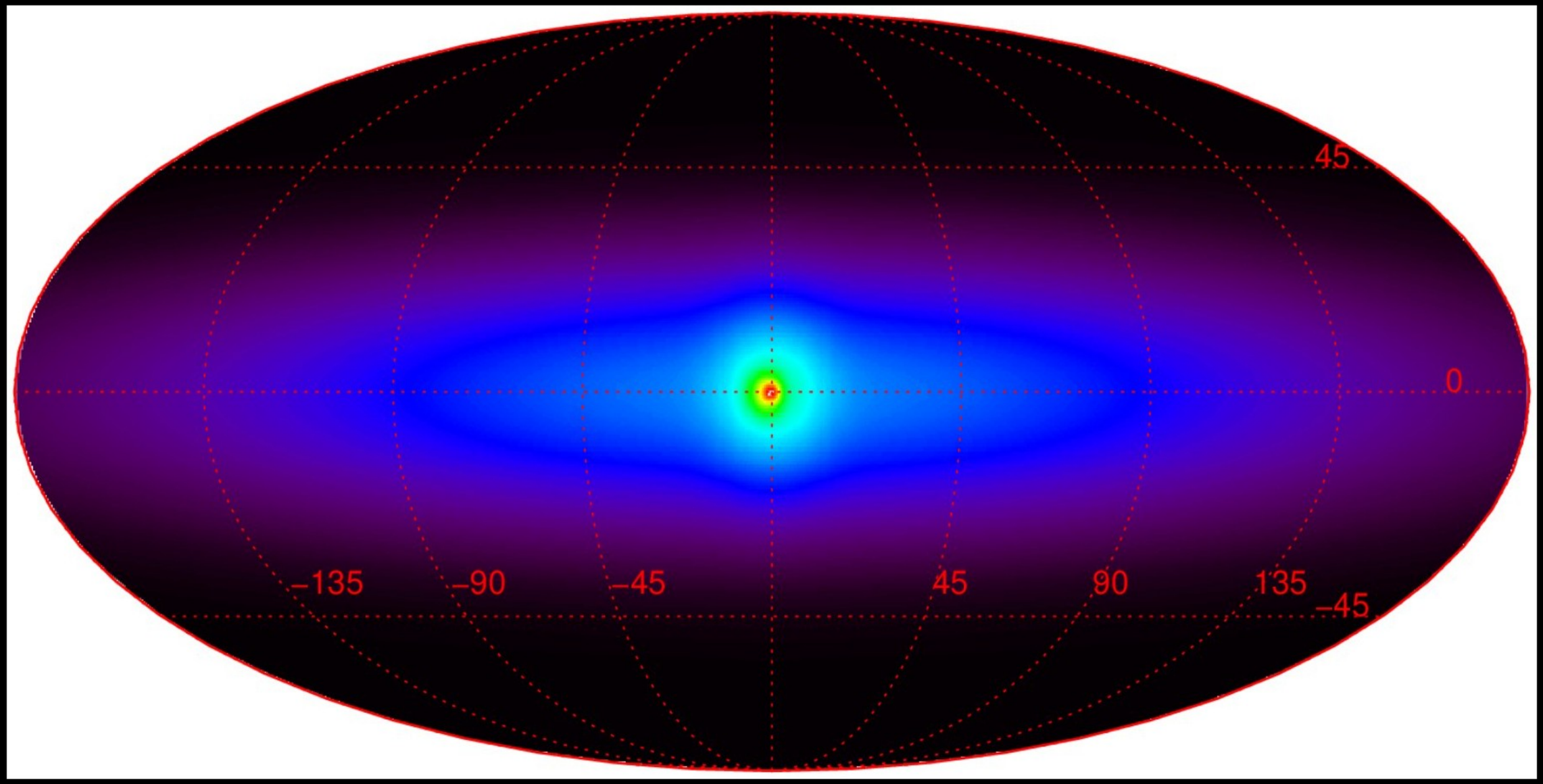
Dark-matter particles that collide and annihilate would make gamma rays, brightest where dark matter is densest: the center.

Since 2009: an extra glow at about the right brightness and shape.

T. Linden (U. Chicago), NASA · Goodenough & Hooper 2009; Daylan+ 2016

Mystery: antimatter at the center

When an electron meets its antimatter twin, a **positron**, both vanish into gamma rays of exactly **511 keV**.



511 keV sky model, INTEGRAL/SPI (Siegert+ 2016)

Possible sources

- Radioactive atoms from exploding stars
- Past outbursts of Sgr A*
- Black holes & neutron stars feeding on companions
- Dark matter

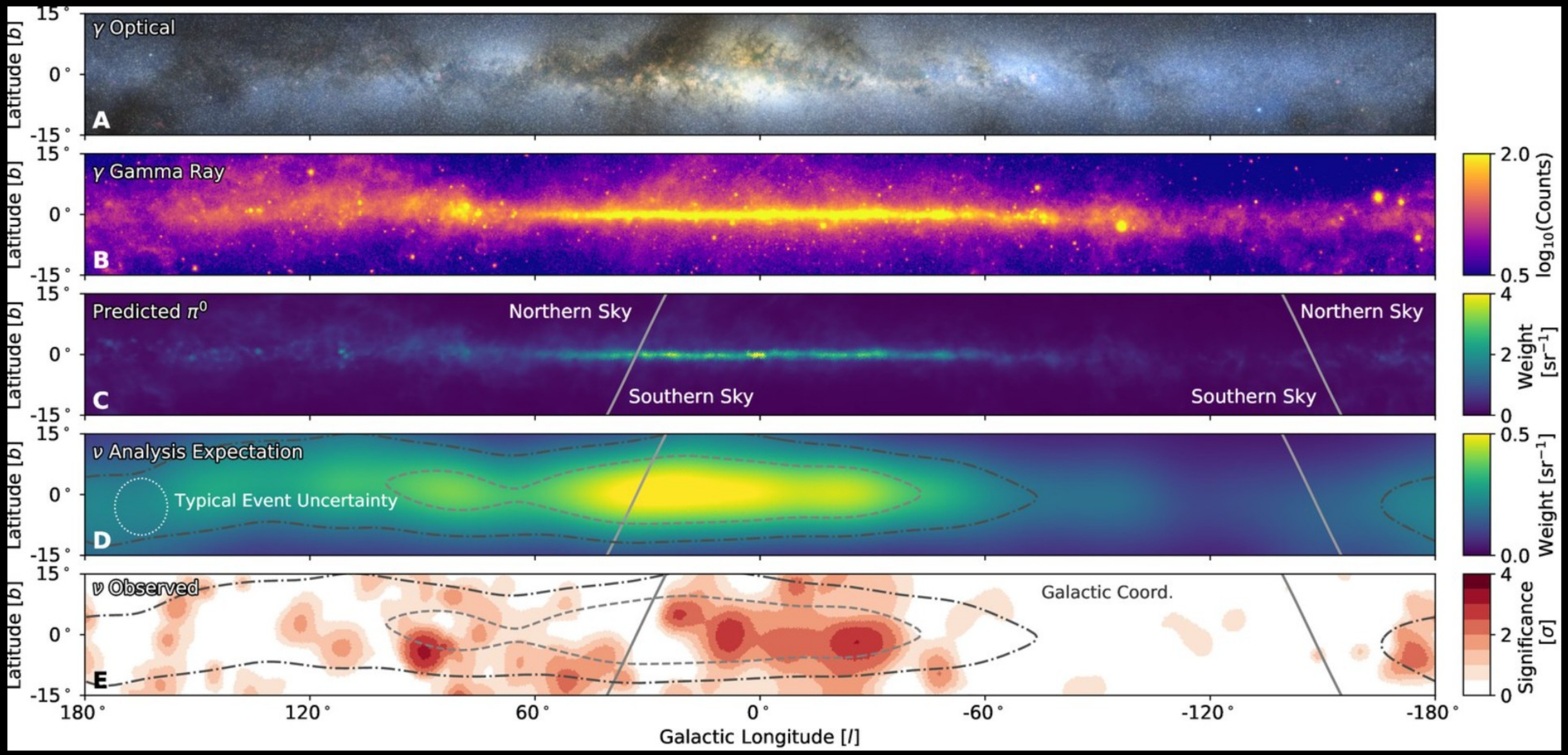


Siegert+ 2016 (INTEGRAL/SPI)

Mystery: neutrinos from the Galactic plane



Neutrinos pass through almost everything, so they point back to where they were made. **IceCube**, a cubic kilometer of Antarctic ice, sees them from the Galaxy.



Top to bottom: starlight · gamma rays · predicted neutrinos · prediction as IceCube blurs it · observed neutrinos

- **4.5σ**: 10 years of IceCube data show neutrinos from the plane
- A smooth glow of cosmic rays hitting gas, or a crowd of sources too faint to resolve?
- At the center IceCube blurs by up to ~10°; the whole central zone is ~3° long

IceCube Collaboration 2023, Science 380, 1338 · telescope photo: J. Hardin (CC BY 4.0)

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The central ring of gas

Gas: 50 million Suns' worth · new stars: ~1 Sun's worth per decade



>1/3 of its stars are born in clusters that stay together (3–8× the local rate)

About half of its star formation happens in one cloud: Sgr B2

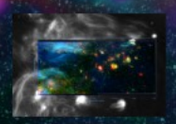
Barnes+ 2017, Hatchfield+ 2024, Ginsburg+ 2018b, Budaiev+ 2024

Image: NRAO, Ginsburg Ginsburg+ 2018a

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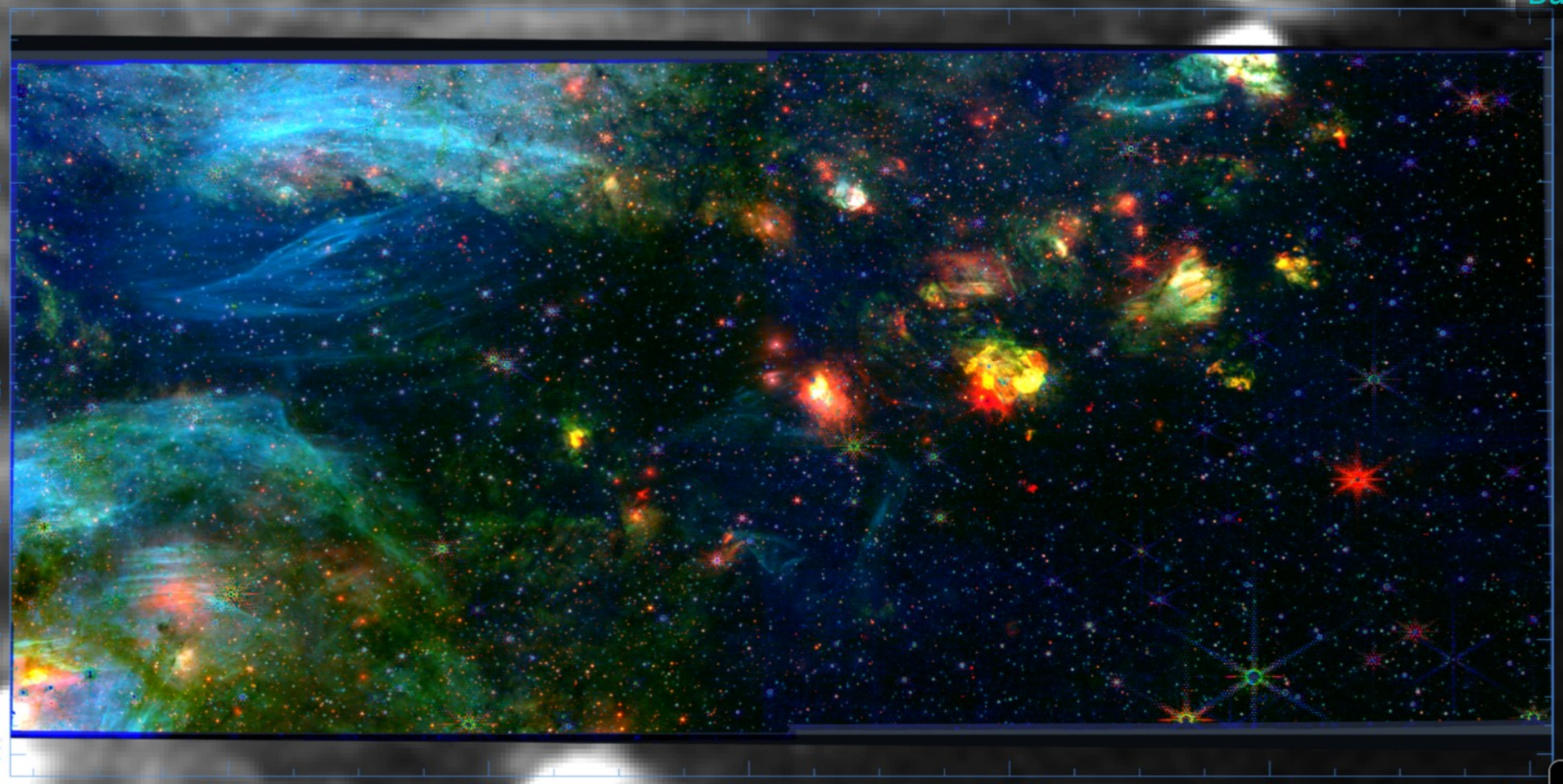
Image: NRAO, Ginsburg Ginsburg+ 2018a

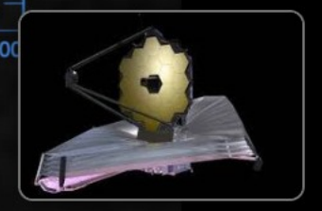
We're going to zoom in ~300× to count young stars.

Sgr B2 with JWST/NIRCam on MeerKAT radio: glowing gas around massive stars



Budaiev+ 2026







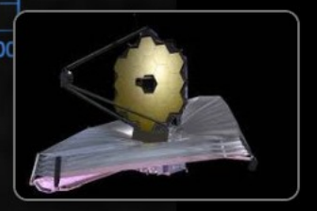
1 pc

Sgr B2 with JWST/ MIRI on MeerKAT radio: glowing gas around massive stars



Budaiev+ 2026





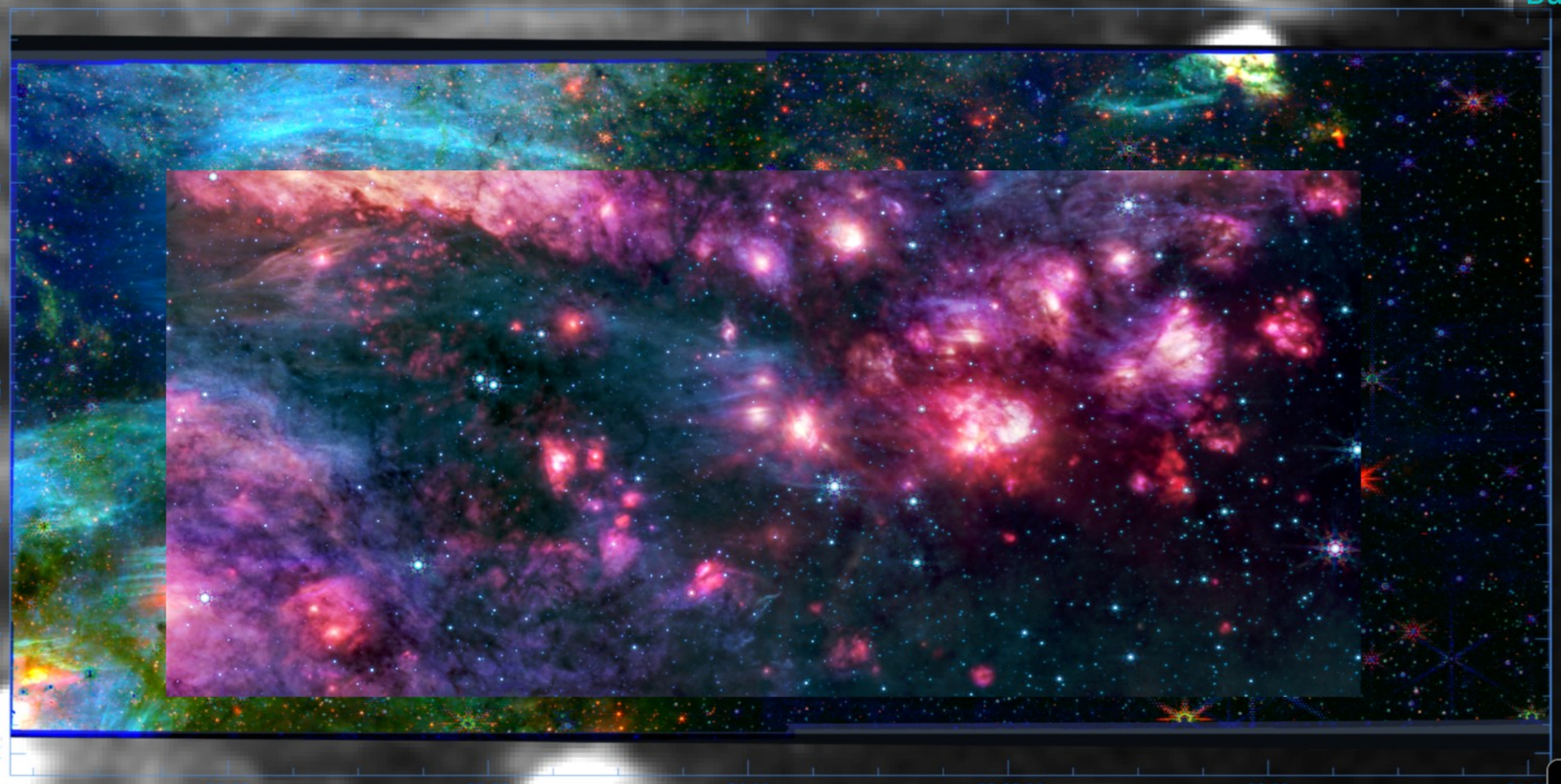


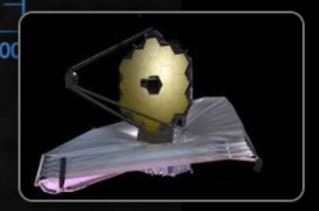
1 pc

Sgr B2 with JWST/ MIRI on MeerKAT radio: glowing gas around massive stars



Budaiev+ 2026







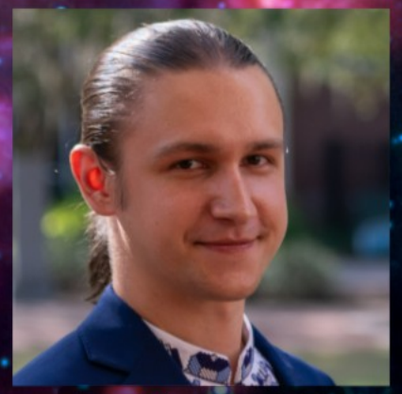
1 pc

Right ascension (

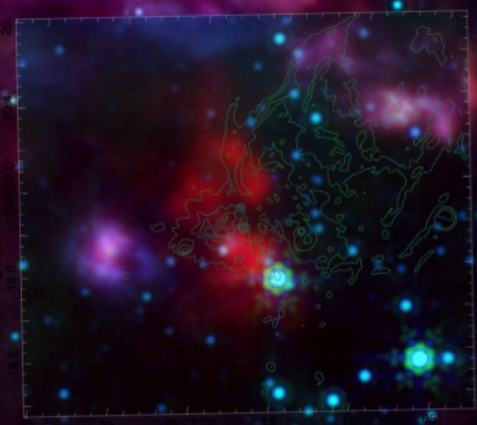
18 17:47:20





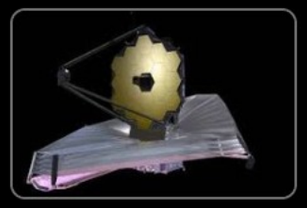


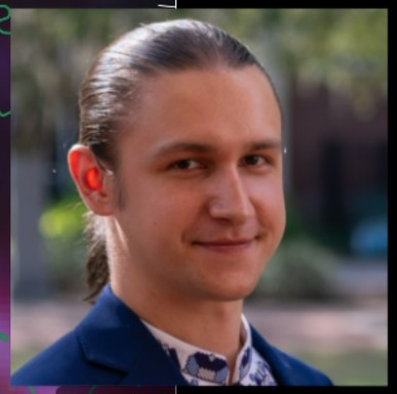
Budaiev+ 2026



1 pc

MIRI sees massive young stars still buried in dust





Budaiev+ 2026

5"

0.2 pc

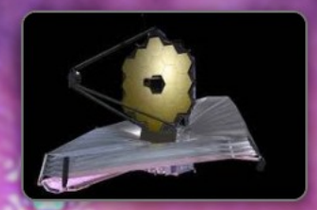
JWST sees an outflow:

the first infrared light from deep inside Sgr B2 North

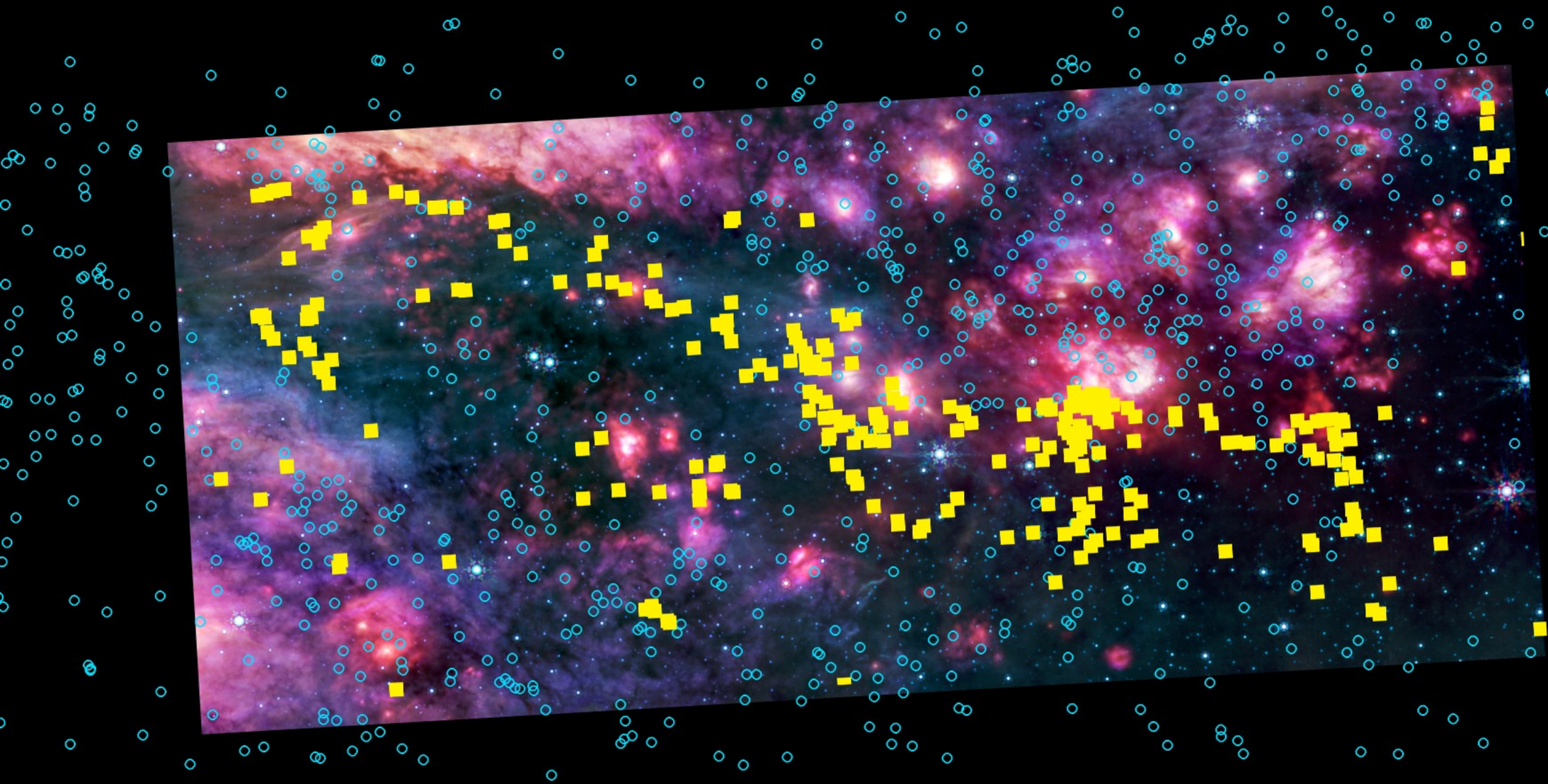
a cluster of ~3,000 Suns, still gaining ~1 Sun's worth of gas every 10 years

The puffy red stuff, only at 25µm, is still a mystery

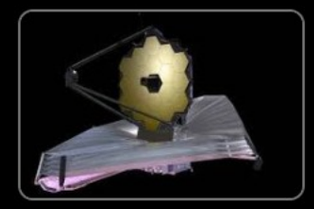




JWST: slightly older young stars, spread out
ALMA: stars forming right now, still buried



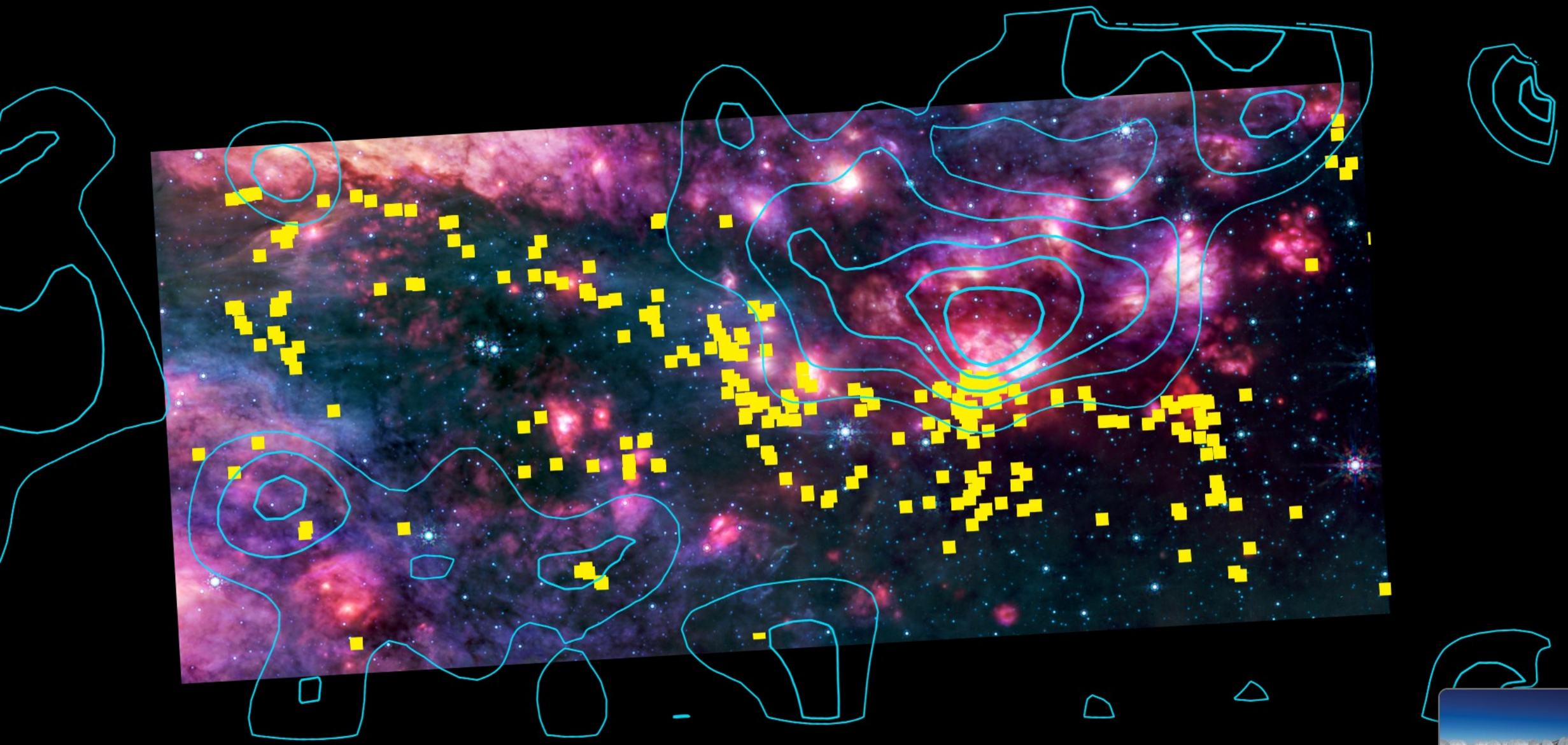




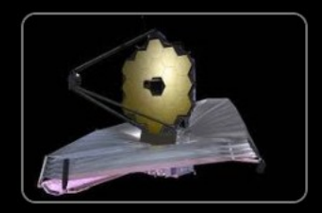
◯ JWST: young stars with warm dust (Budaiev+ 2026)

▪ ALMA: forming stars (Ginsburg+ 2018, Budaiev+ 2024, Daley+ in prep)

JWST: slightly older young stars, spread out
ALMA: stars forming right now, still buried







— JWST: where young stars are most crowded

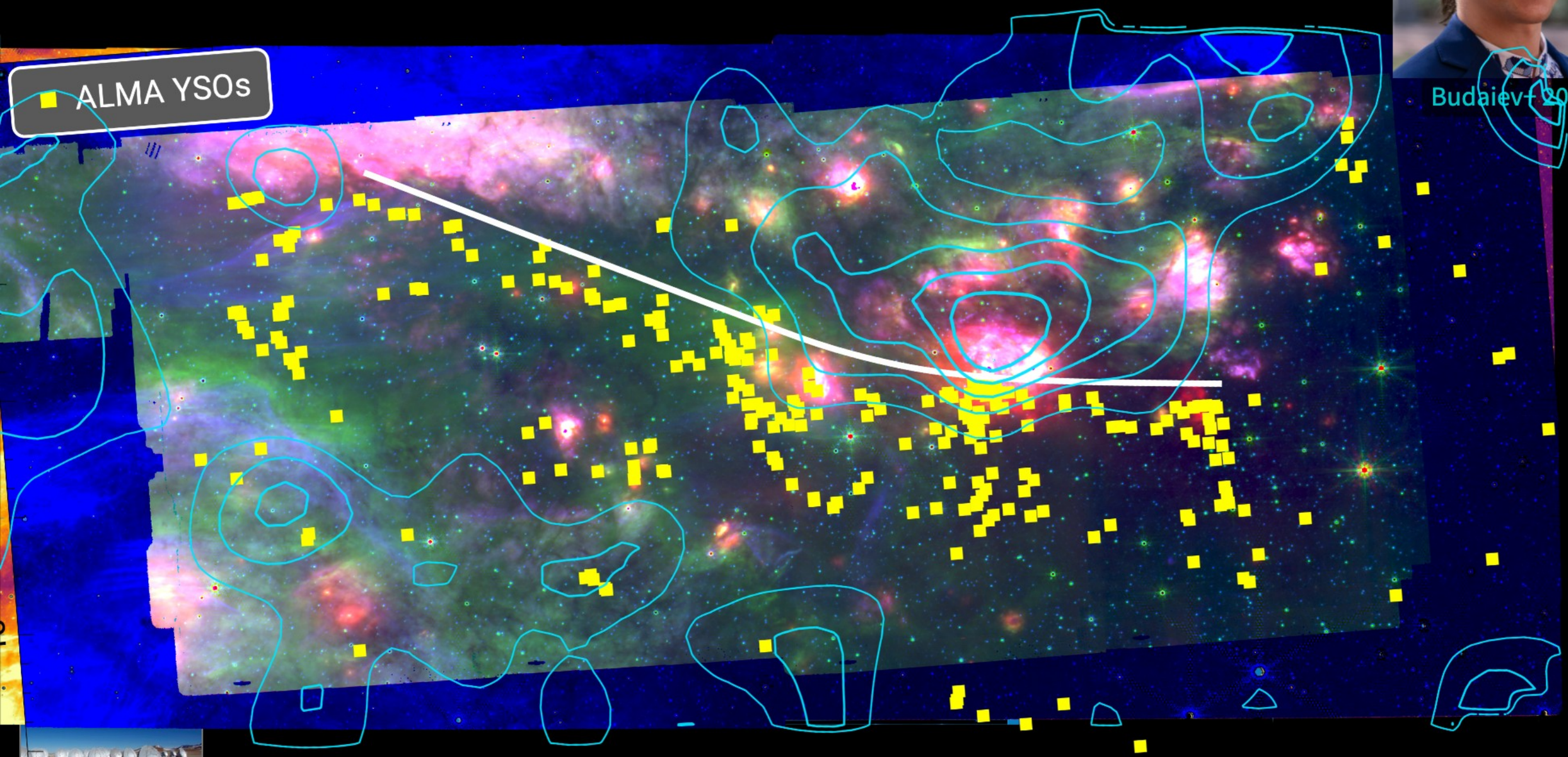
▪ ALMA: forming stars (Ginsburg+ 2018, Budaiev+ 2024, Daley+ in prep)

Star formation in Sgr B2 is lopsided: JWST and ALMA see different sides

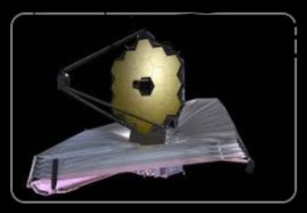
The transition is sharp



Budaiev+ 2026





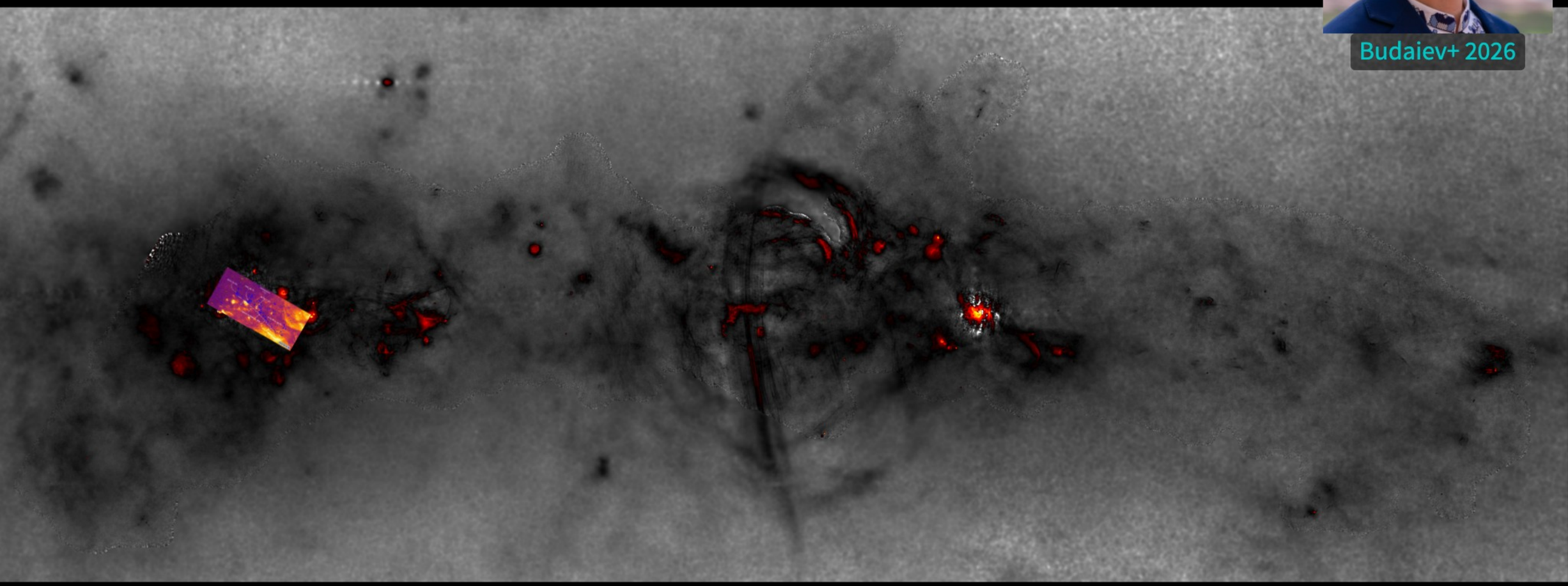


Star formation in Sgr B2 is lopsided: JWST and ALMA see different sides

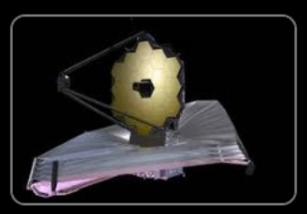
The transition is sharp



Budaiev+ 2026

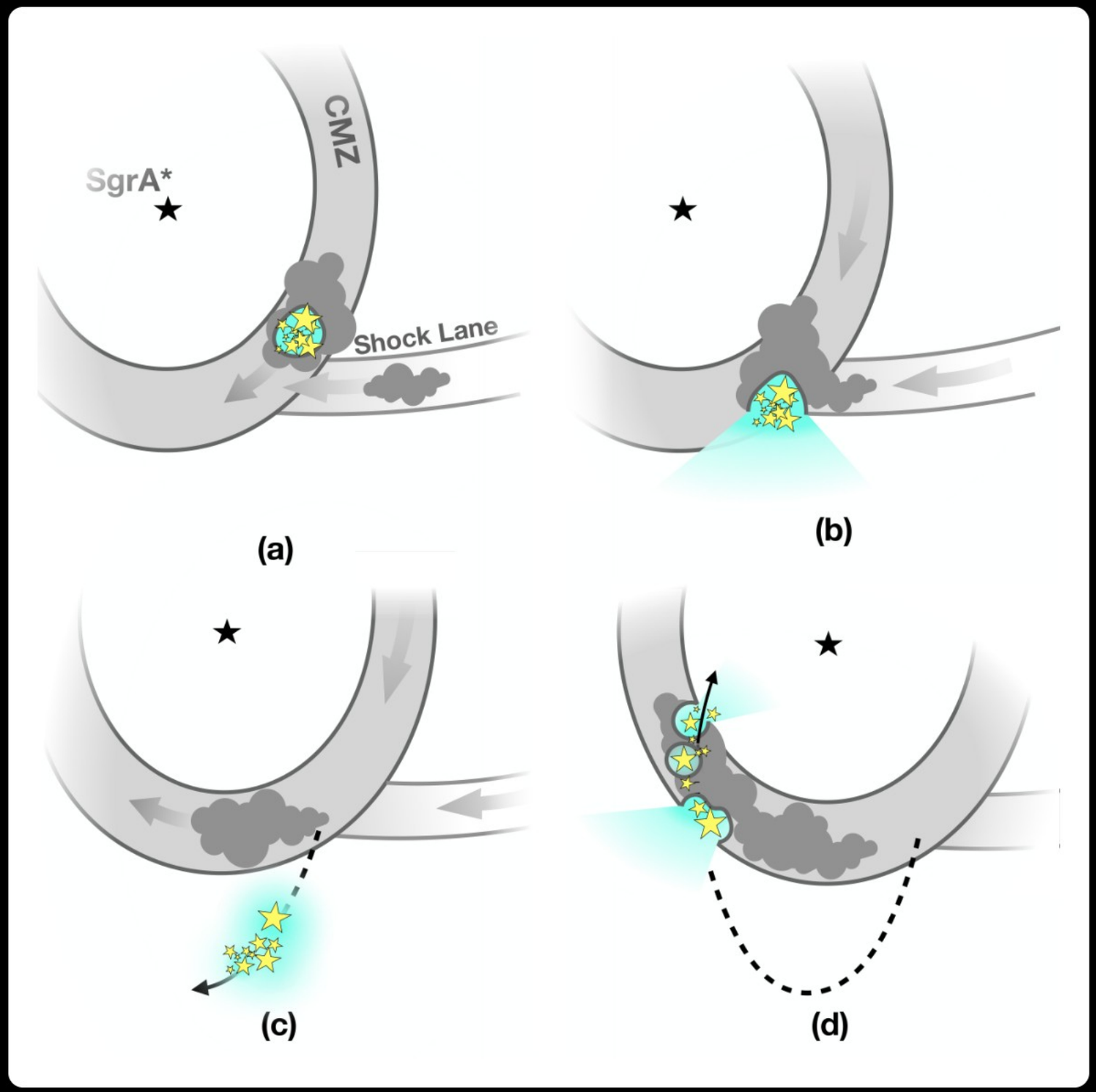






- Star formation is ongoing
- Lopsided because the cloud is being squeezed or hit
- Still open: why does a collision make stars?

Gas and young stars can go separate ways



(a) A cluster forms, perhaps where the bar's gas hits the ring

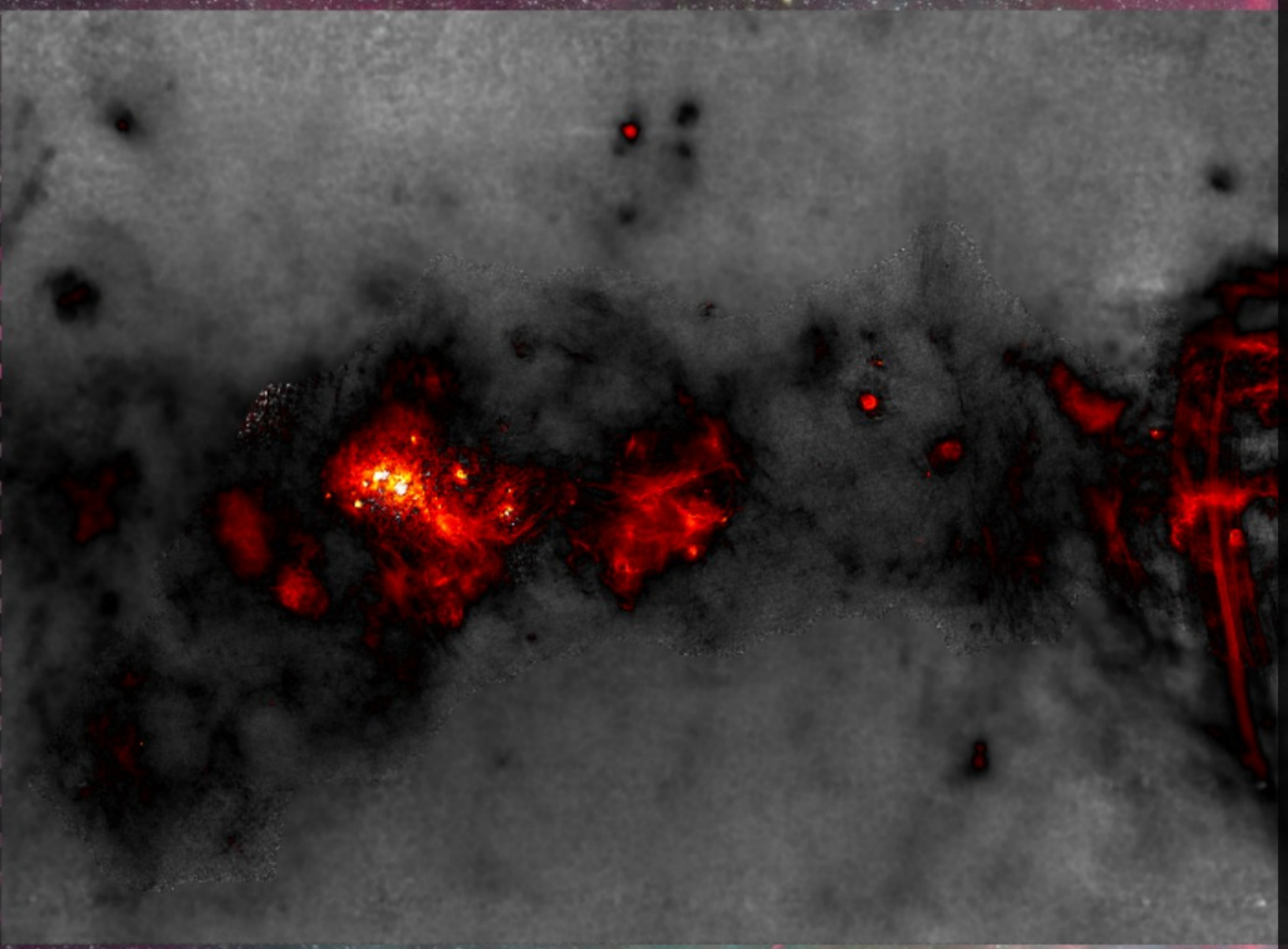
(b) The new stars blow a hole in the cloud, but don't destroy it

(c) The gas is pushed around and stays on circular orbits; the stars drift off

(d) stars *may* drift back and affect a different cloud

Tress+ 2026 (Rhea-RT), Fig. 22

Sgr B2 is forming stars — is the rest of the center?



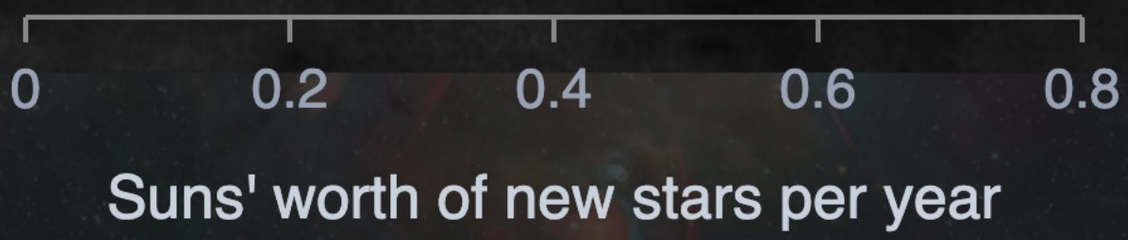
6–11× fewer than expected

stars the gas should make

0.4–0.8

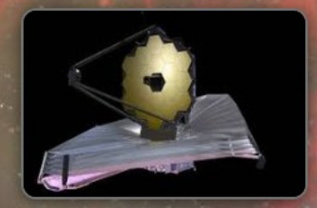
stars we count

~0.07



Henshaw+ 2023; Longmore+ 2013

JWST looked at a few of the center's clouds before 2026



Sgr B2: >500 young stars forming (ALMA)

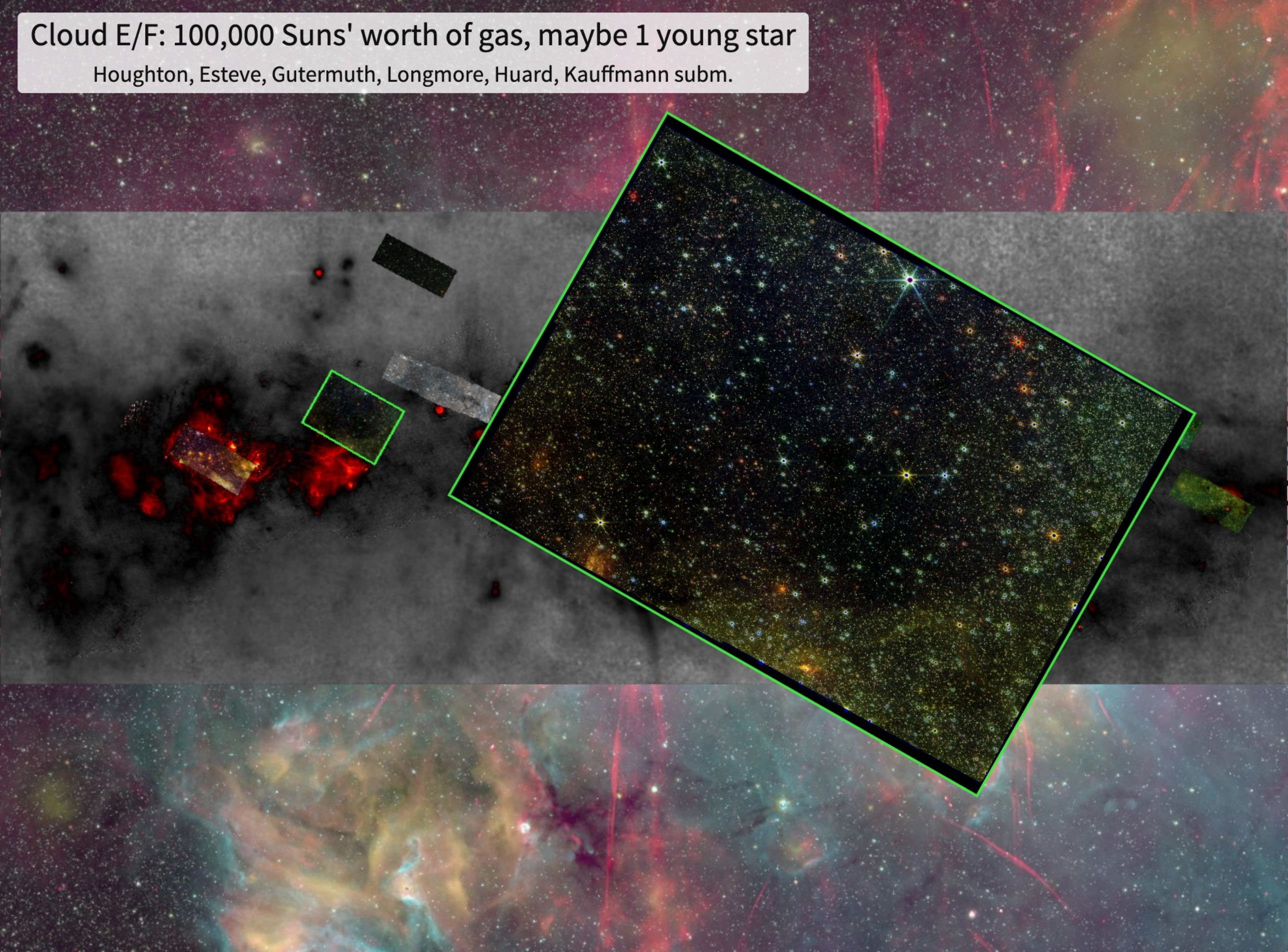
~100 bubbles of glowing gas around new massive stars

Ginsburg+ 2018, Jeff+ 2024, Budaiev+ 2024, 2025, 2026, Daley+ in prep



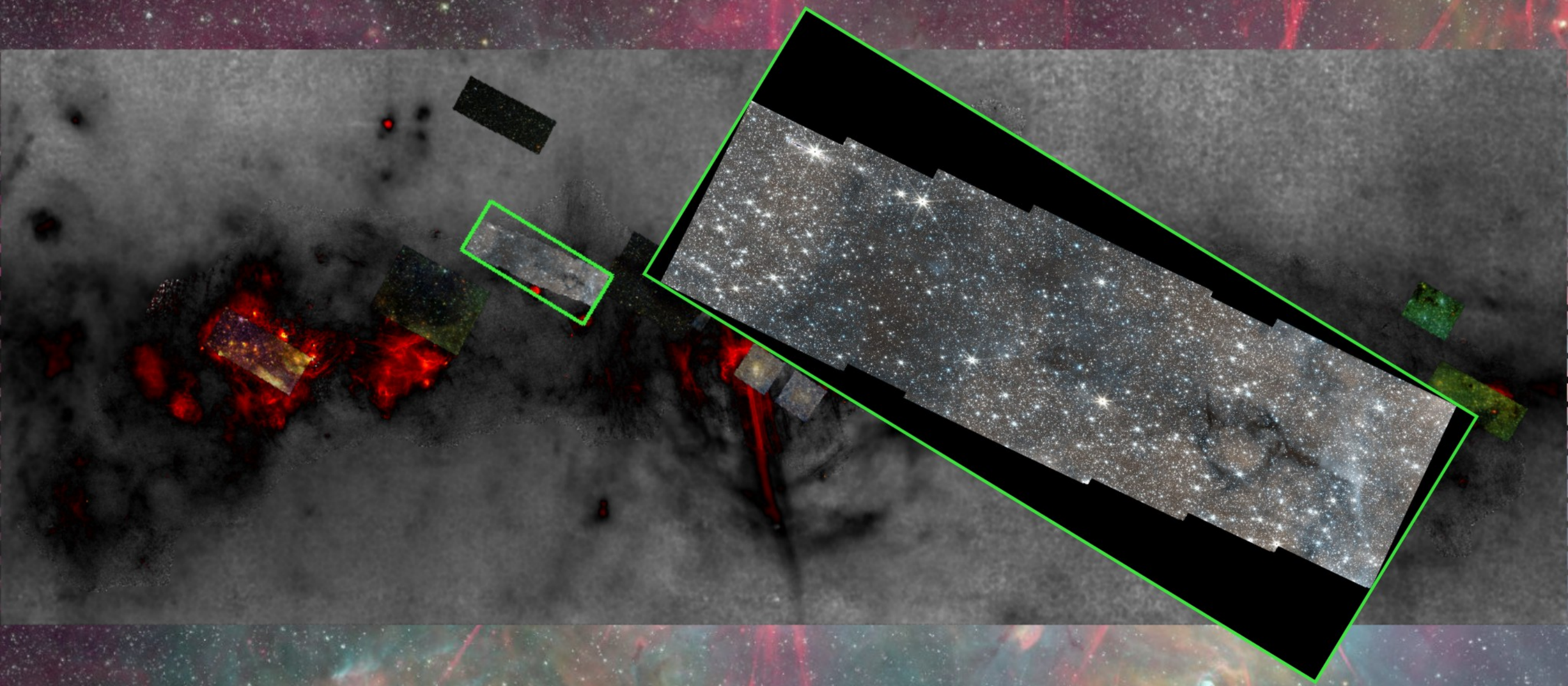
Cloud E/F: 100,000 Suns' worth of gas, maybe 1 young star

Houghton, Esteve, Gutermuth, Longmore, Huard, Kauffmann subm.



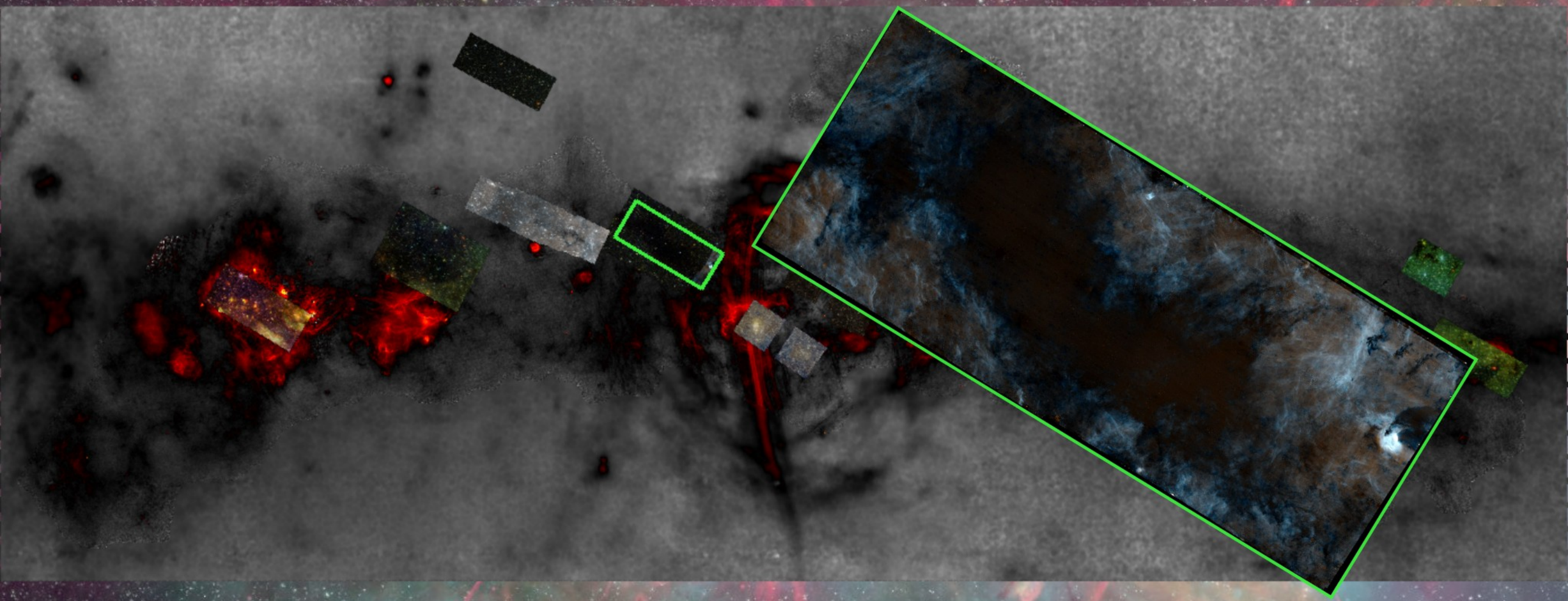
Clouds C & D: 100,000 Suns' worth of gas, one small cluster

Gramze+ in prep



The Brick: 100,000 Suns' worth of gas, about 10 young stars

Walker+ 2021

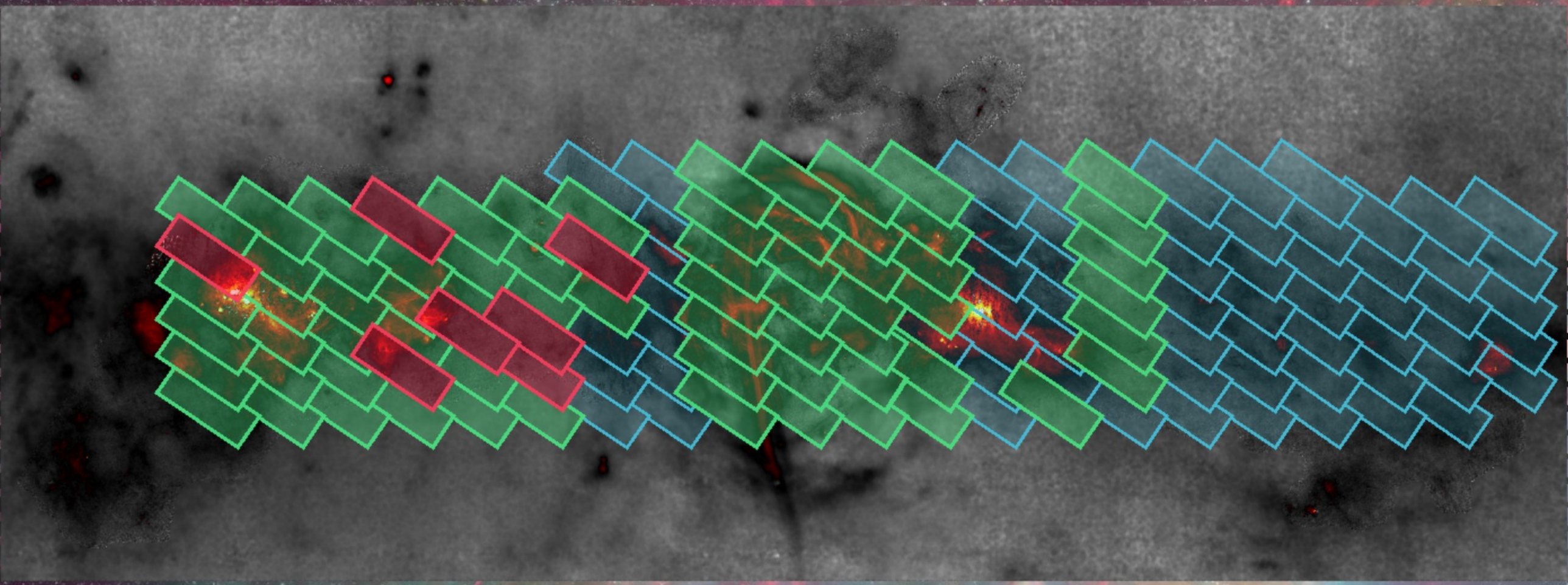


Stars are forming in the center, but we've only checked a small part of it

The JWST Galactic Center Treasury Survey (GO 10678) — NIRCam: **half observed**

- When did the stars form?
- Where are the dust and gas?
- Finding young stars

starformation.astro.ufl.edu/avm_images/jwst_gc_aladin.html
starformation.astro.ufl.edu/jwst-gc



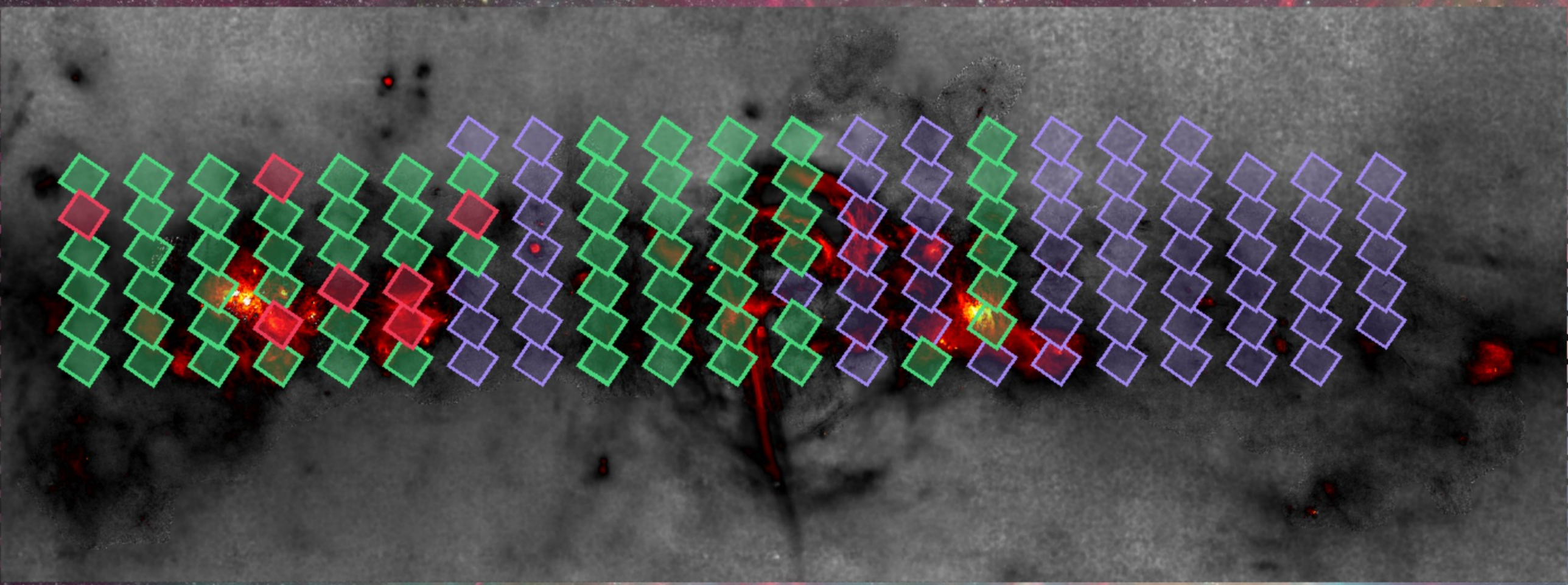


▪ observed Sep 2026 (68) ▪ planned Aug–Sep 2027 (64) ▪ skipped, to be rescheduled (7) status 2026-10-15

…and the same survey with MIRI

- Finding young stars
- How new stars heat their surroundings

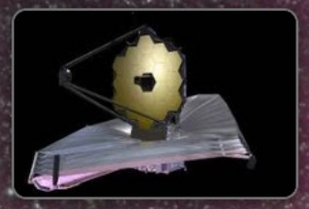
starformation.astro.ufl.edu/avm_images/jwst_gc_aladin.html
starformation.astro.ufl.edu/jwst-gc



▪ observed Sep 2026 (68) ▪ planned Aug–Sep 2027 (64) ▪ skipped, to be rescheduled (7) status 2026-10-15

Progress:

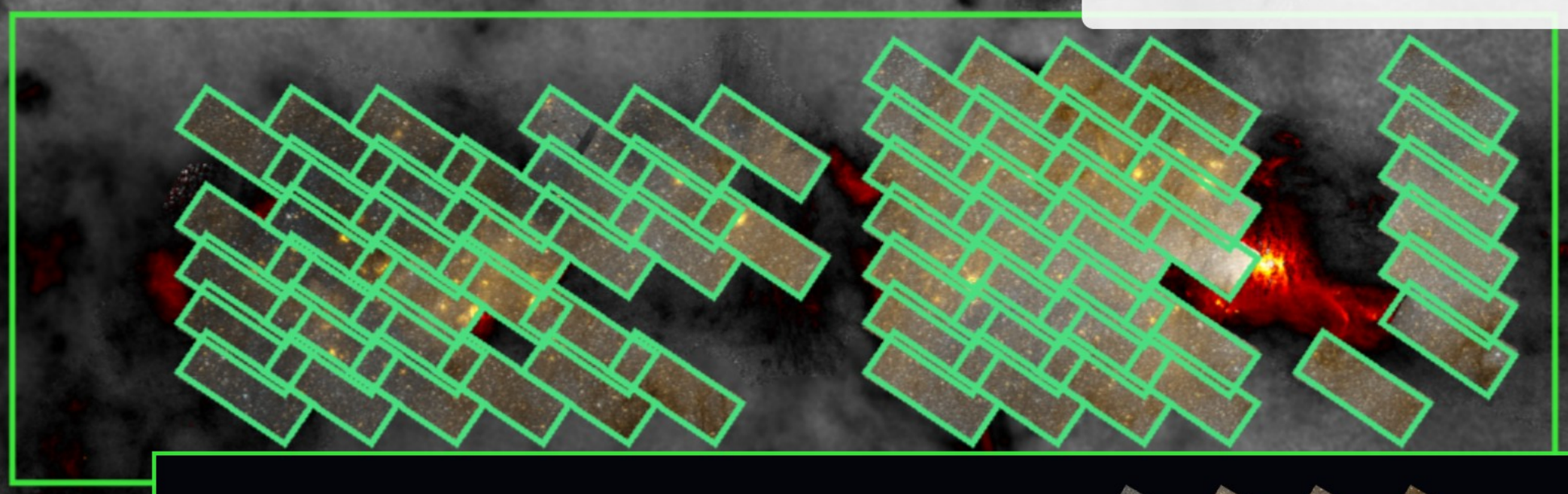
- Half observed, Sep 2026
- two infrared colors
- the rest: Aug–Sep 2027

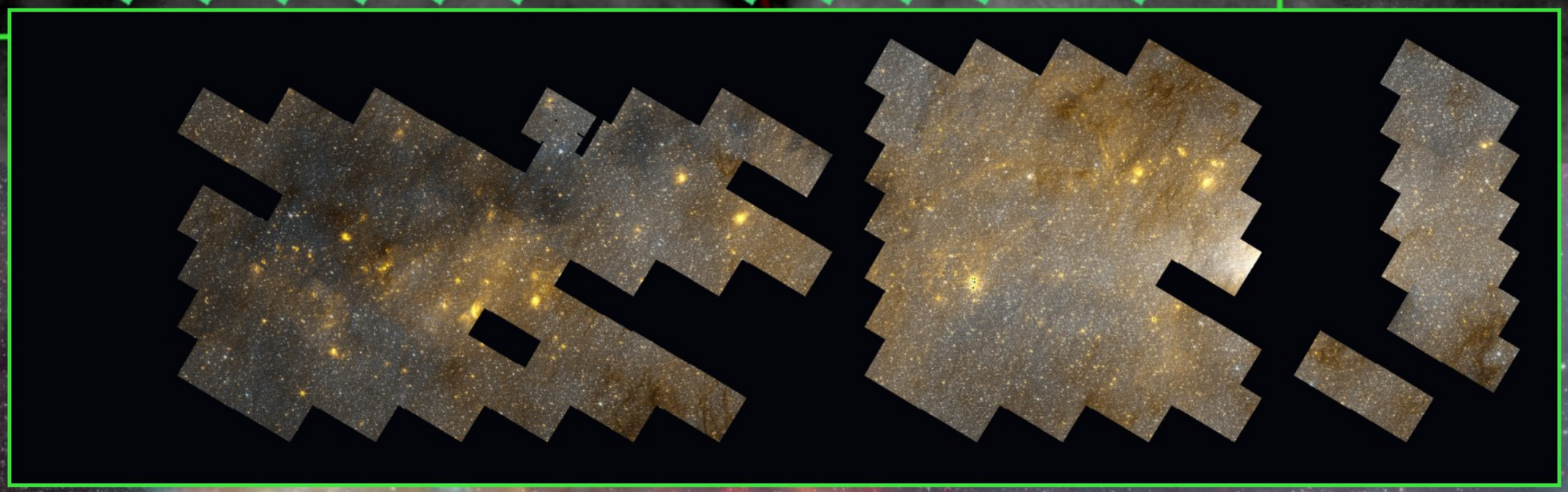


starformation.astro.ufl.edu/avm_images/jwst_gc_aladin.html
starformation.astro.ufl.edu/jwst-gc

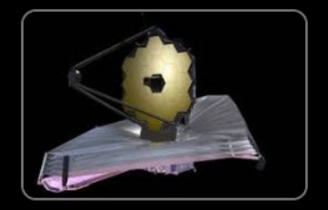
Early highlights

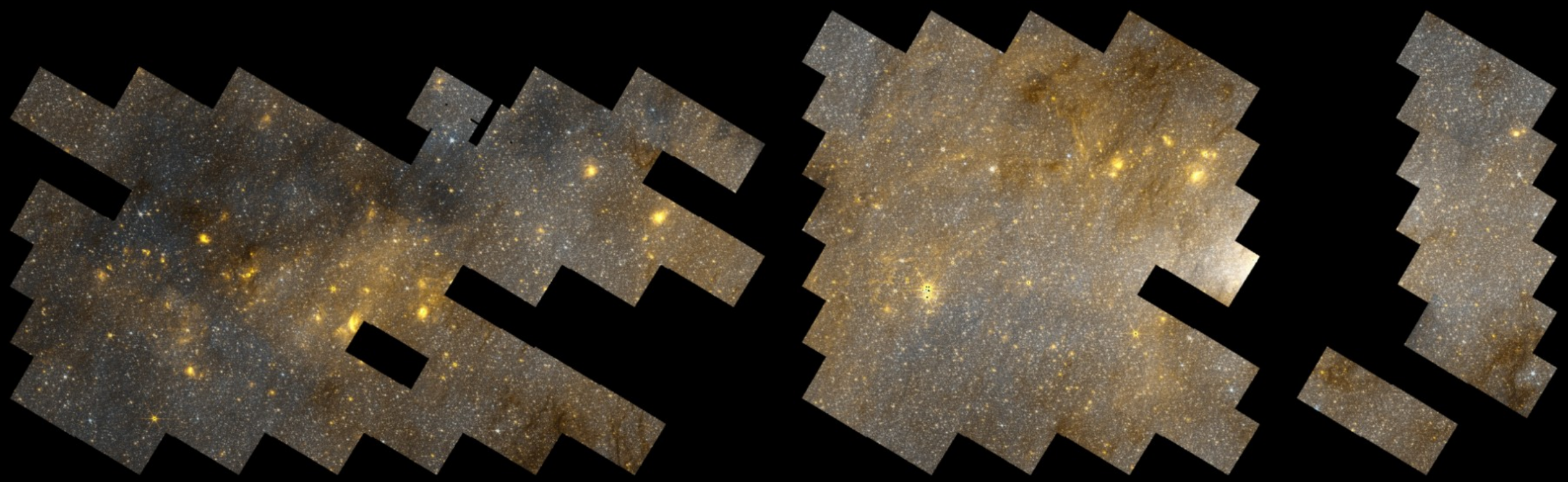
- ~4 million stars so far
- positions precise to a dime seen from 3,200 km
- star motions, by comparing with earlier JWST images



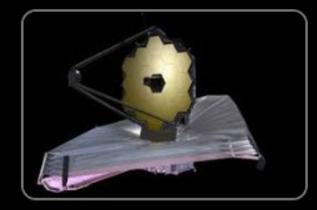


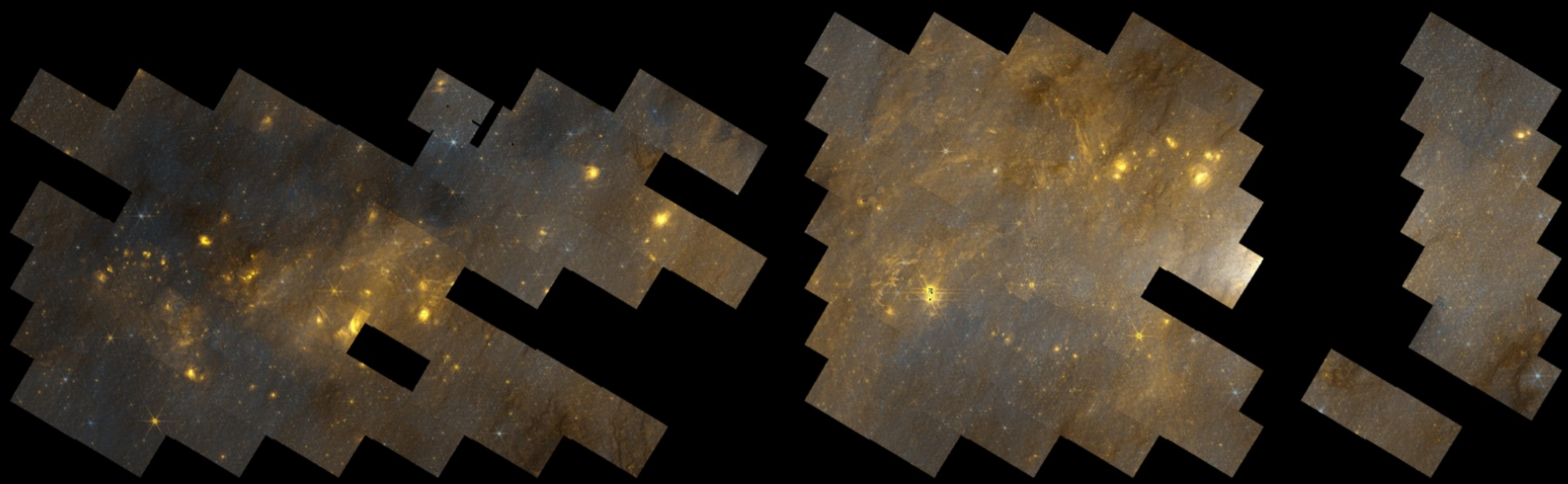
▫ observed mosaic of 2026-10-15



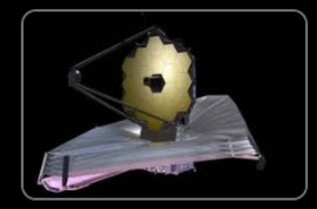


JWST Galactic Center survey

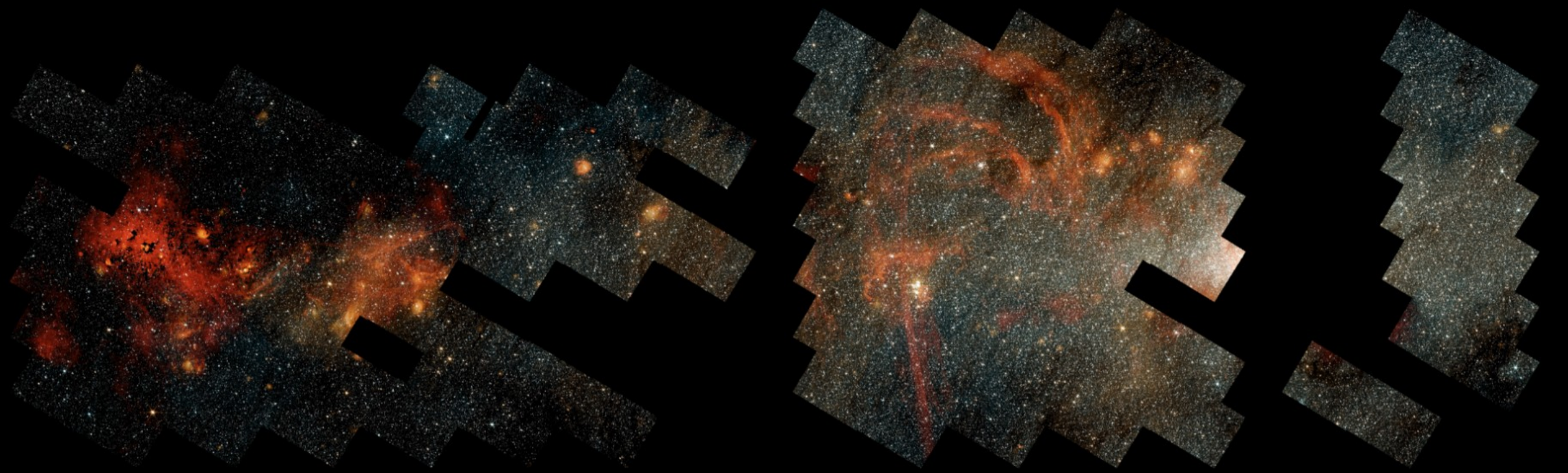




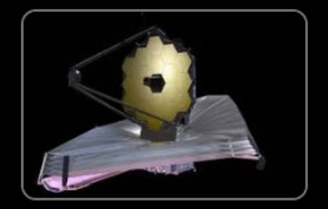
stars removed: now you see the gas and dust







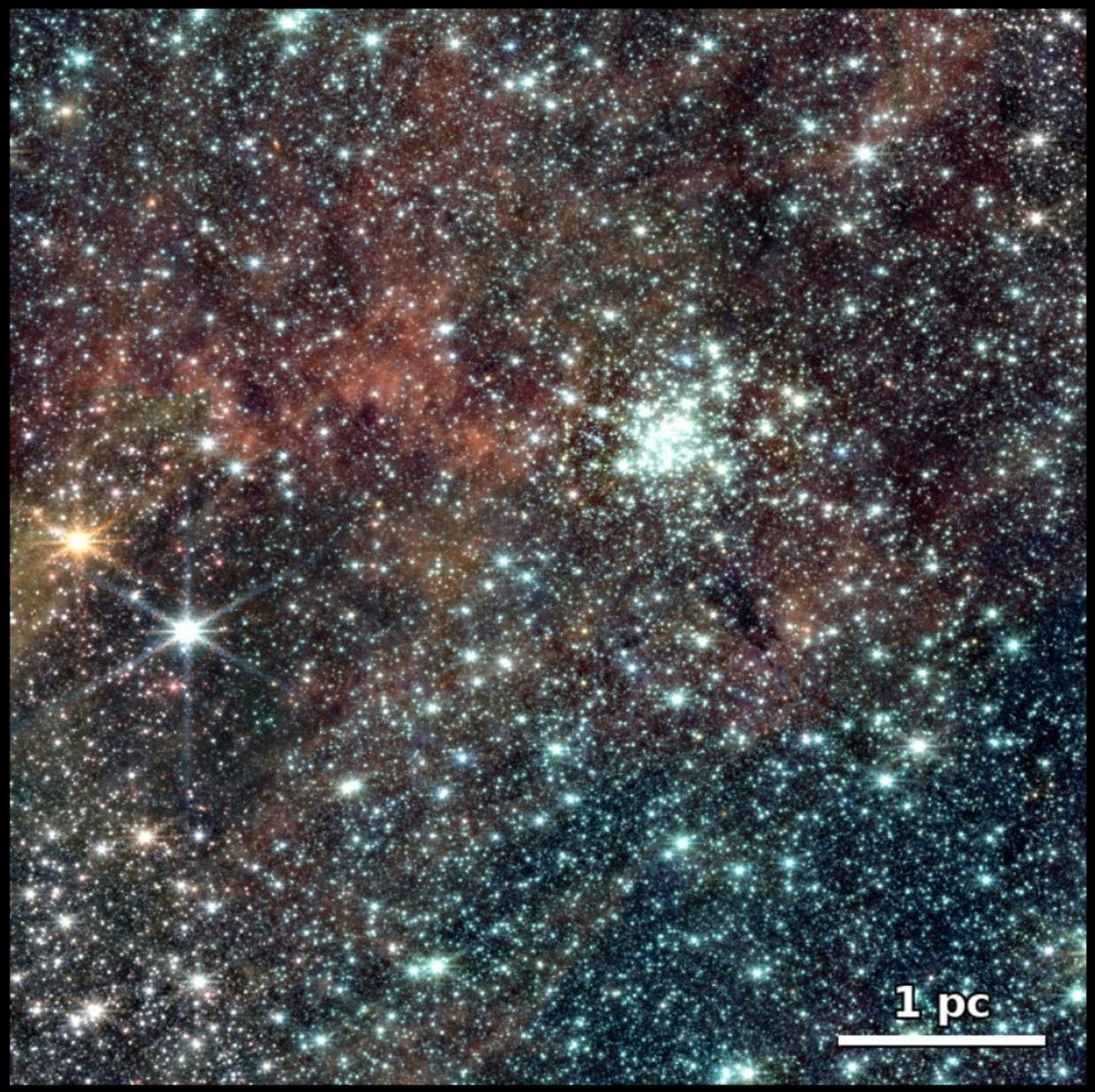
JWST + ALMA (red: cold dust)



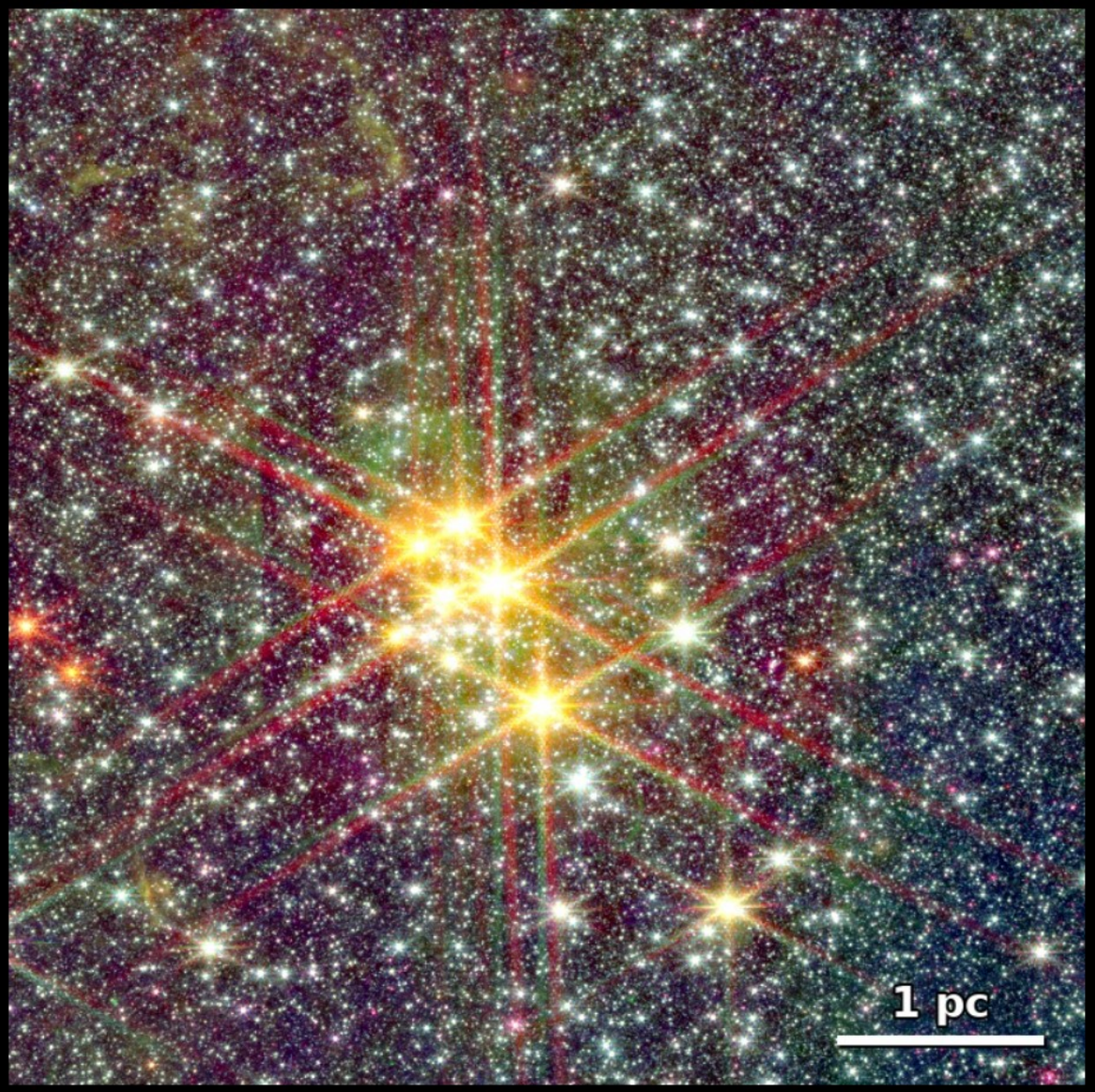
JWST MIRI: longer-wavelength infrared (Budaiev+ in prep)

Q1	What planets form there?	2016	future!
Q2	How does gas flow into the center?	1991	progress
Q3	(How) does gas reach the black hole, Sgr A*?	1996	future
Q4	What shape is the central ring of gas?	1995	progress
Q5	Why does the center form so few stars?	2013	progress
Q6	**Where do the center's young stars go?**	**2002**	←
Q7	**Is the mix of star masses different here?**	**1999**	←
Q8	Is the chemistry different?	2009	

Where do the center's star clusters go?



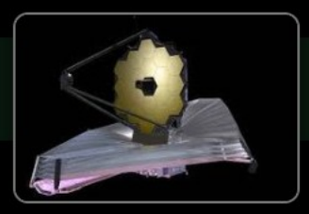
Arches



Quintuplet

- Expected to dissolve within a few tens of millions of years, and blend in even sooner — Portegies Zwart+ 2002

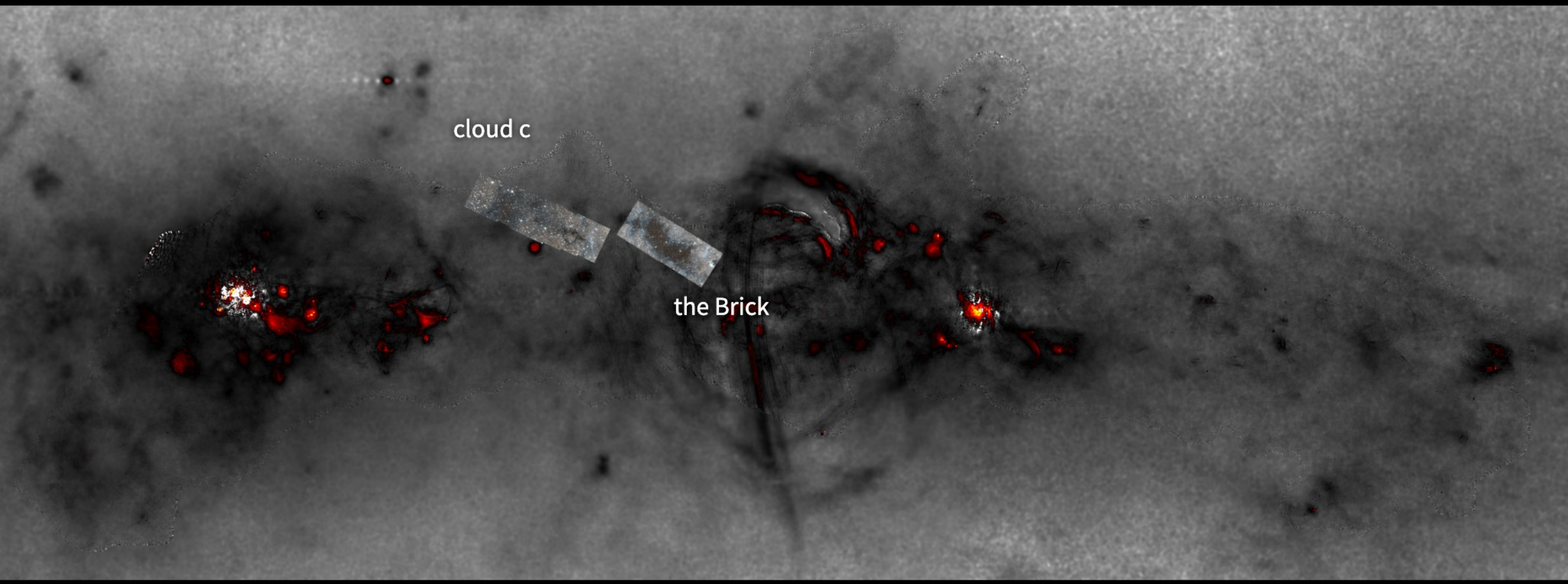




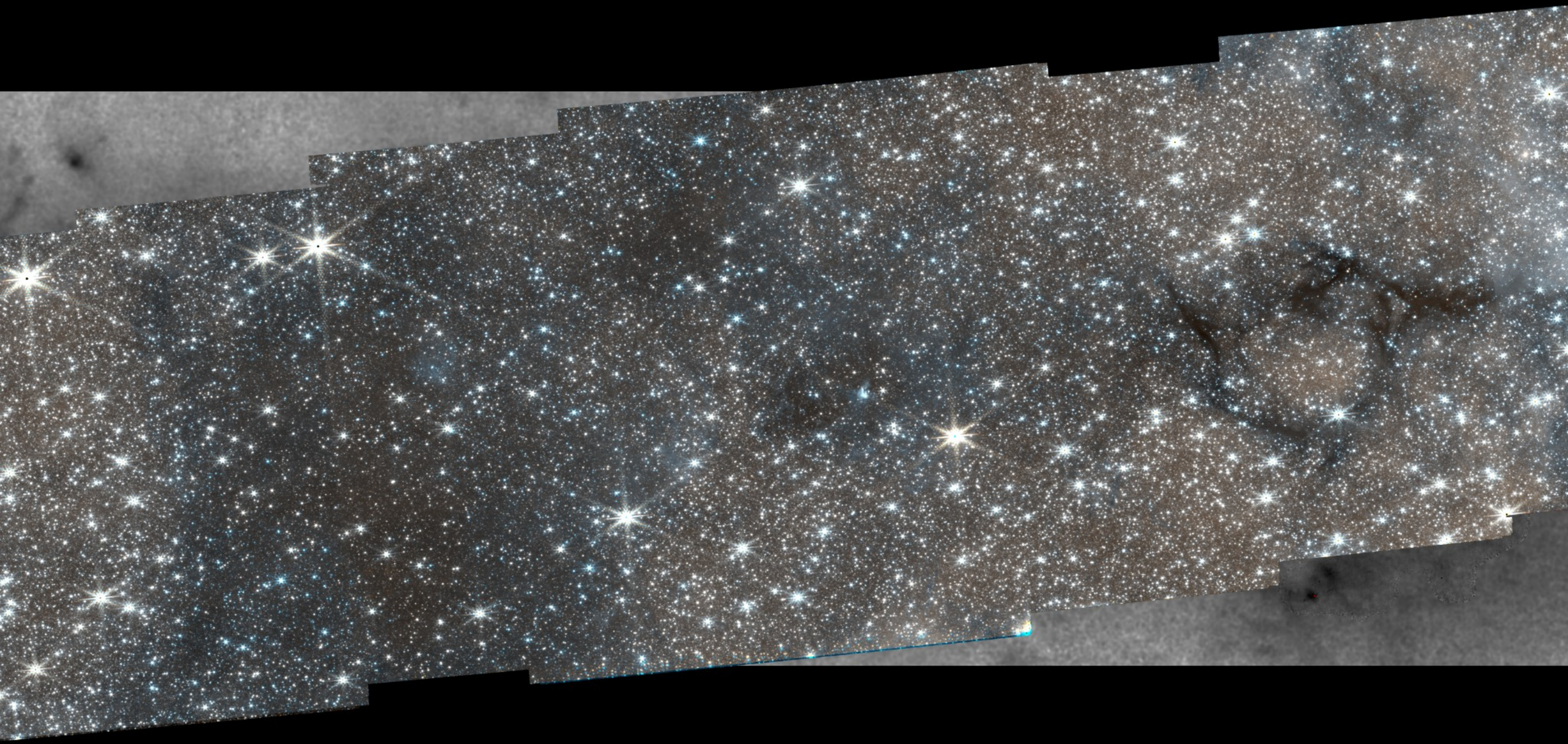
Future: look for **trails of stars** behind the Arches and Quintuplet with JWST + Roman

Q1	What planets form there?	2016	future!
Q2	How does gas flow into the center?	1991	progress
Q3	(How) does gas reach the black hole, Sgr A*?	1996	future
Q4	What shape is the central ring of gas?	1995	progress
Q5	Why does the center form so few stars?	2013	progress
Q6	Where do the center's young stars go?	2002	future
Q7	Is the mix of star masses different here?	1999	future
Q8	**Is the chemistry different?**	**2009**	←

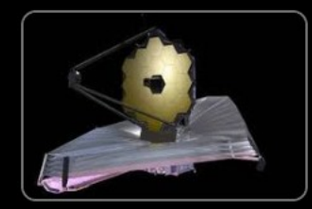
Ice hints that the center has more heavy elements

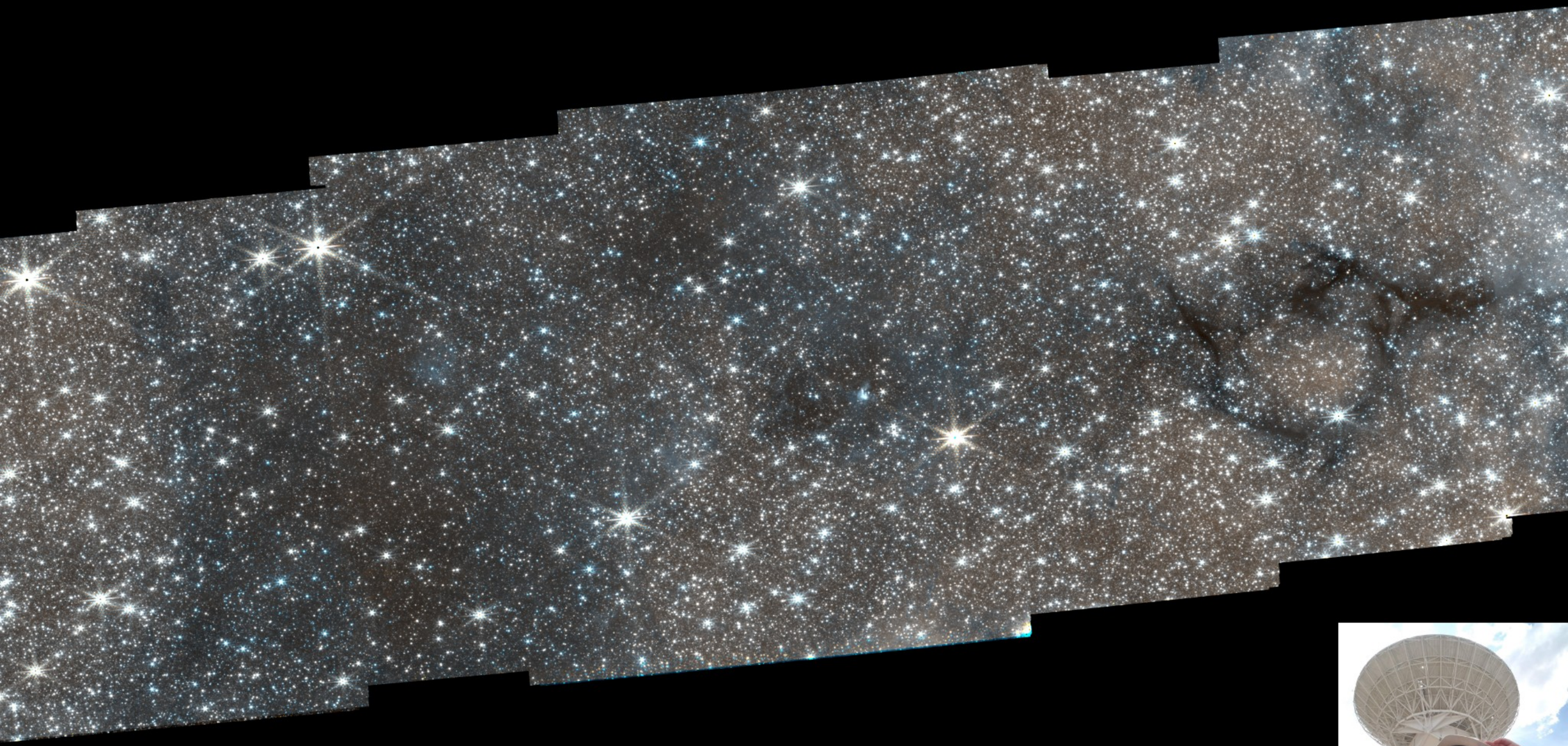


Ice hints that the center has more heavy elements



JWST's colors show ice

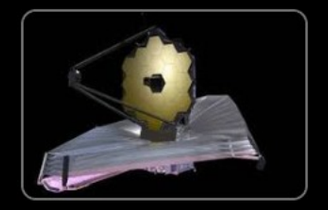




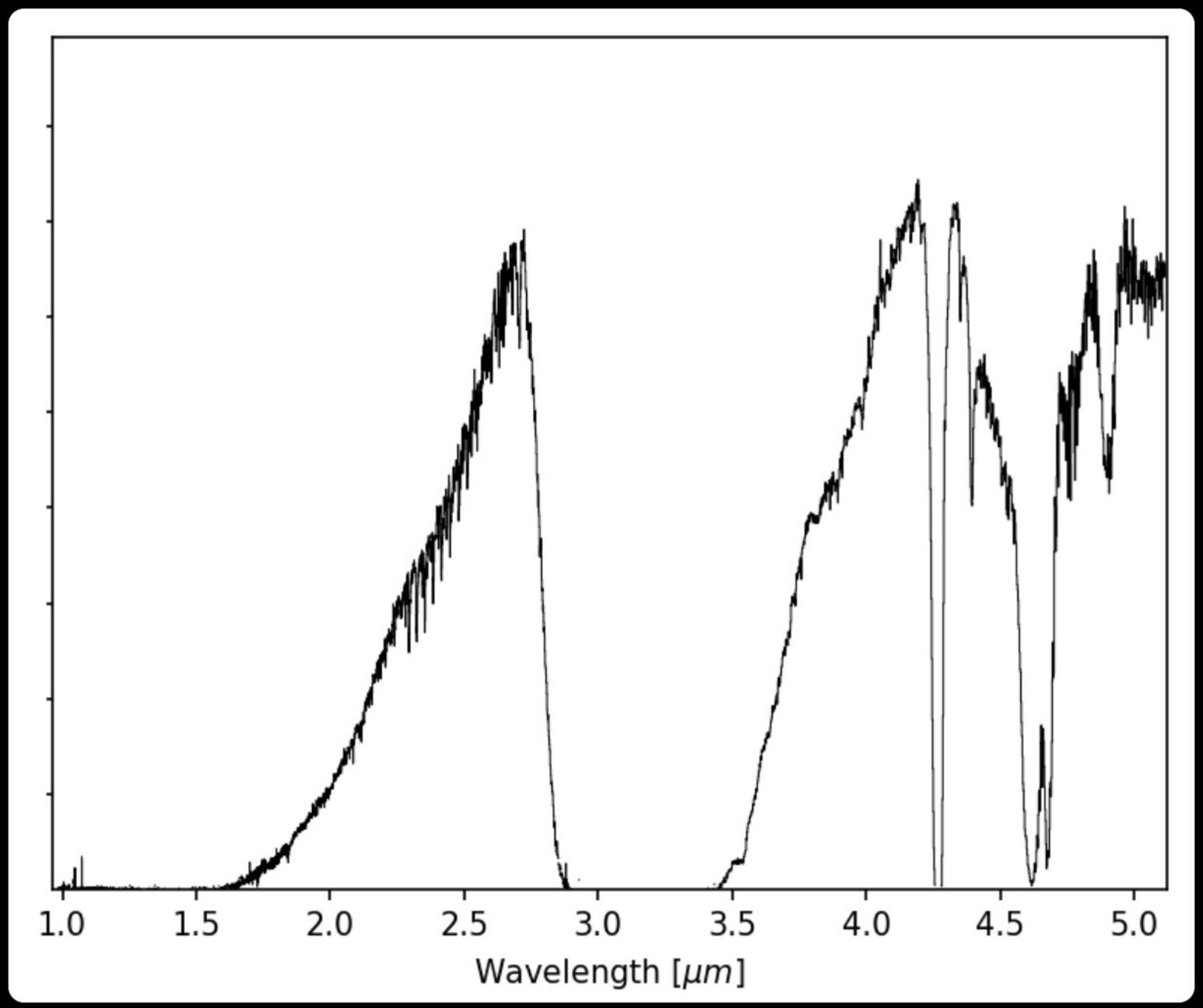


Gramze+ 2026, OJAP

NEXT: MEASURING THE ICE WITH JWST SPECTRA

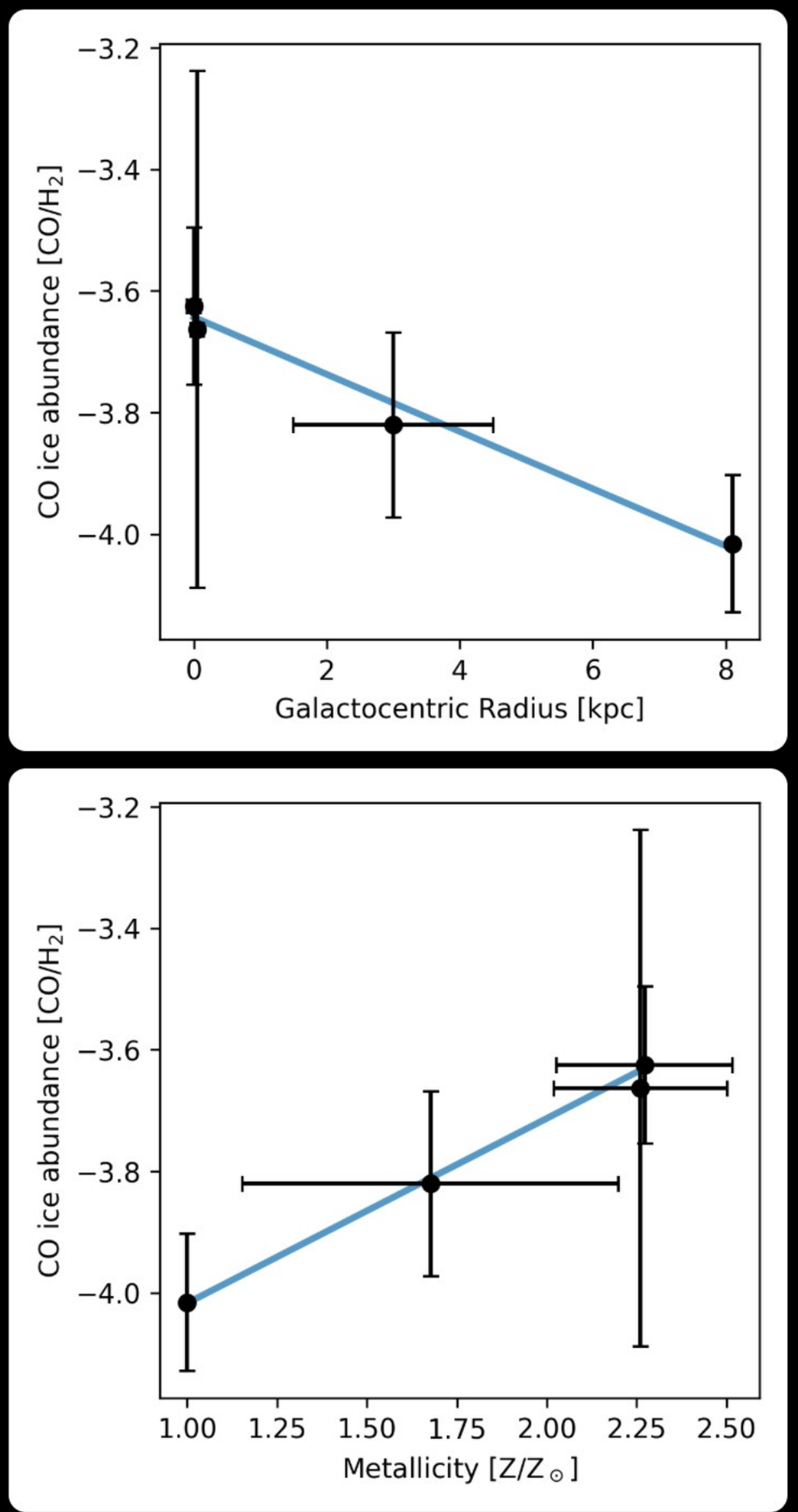


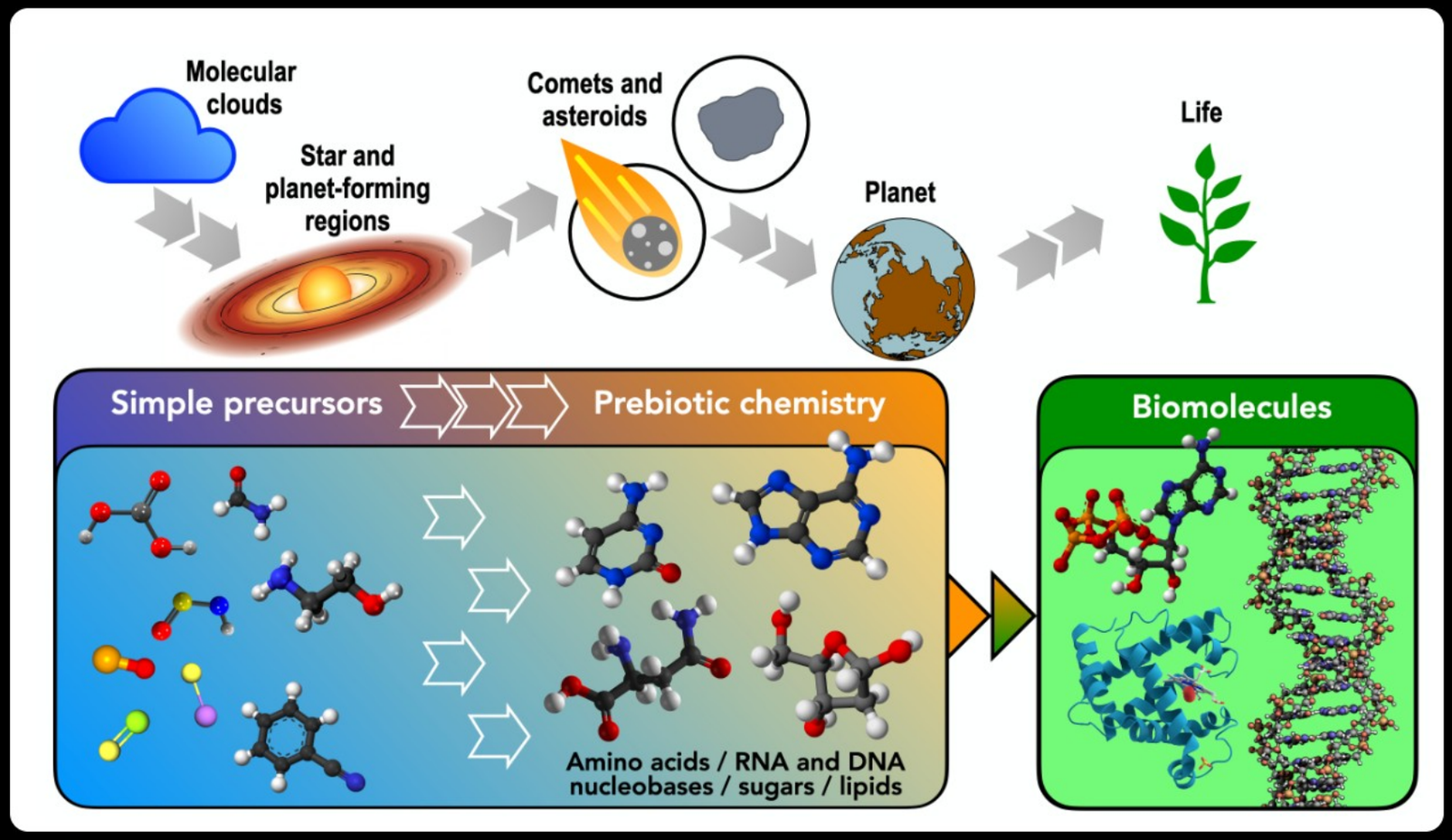
JWST spectra, observed Sep 2026



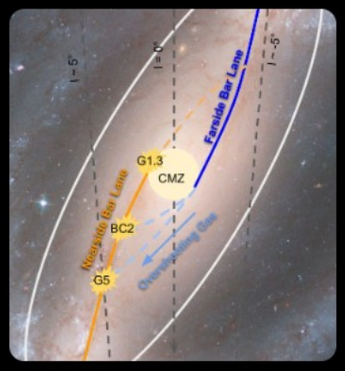
PI **Matt Ashby** (SAO) · **Cargile**, Ginsburg, **Hora**, Lisse, **Melnick**, Paladini, **Tolls**, Werner, Young, **Zucker**, Kim

Heavy elements matter for forming stars; chemistry matters for planets





Rivilla+ 2026, Fig. 1





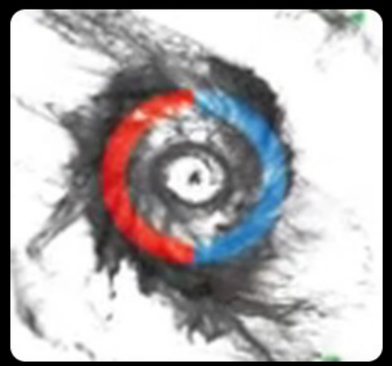
Gas pours in along the bar

Stars are forming, but too few

Icy, with rich chemistry

3D maps coming!



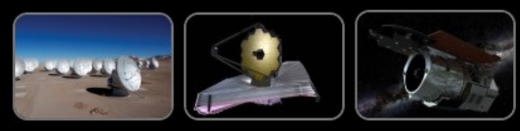


	question	now	future
Q1	What planets form there?	disks seen; no planets yet	Roman planet hunt, ALMA disks
Q2	How does gas flow into the center?	measured: ~1 Sun per year	ALMA maps + simulations
Q3	(How) does gas reach the black hole?	hints of inflow	Roman + simulations
Q4	What shape is the central ring?	~3/4 of known clouds in front	Roman 3D maps
Q5	Why so few stars?	6–11× too few	JWST young-star census
Q6	Where do the young stars go?	no tails found yet	JWST star motions
Q7	Is the mix of star masses different?	Arches: extra heavy stars	deeper JWST, more clusters
Q8	Is the chemistry different?	ices: more heavy elements?	JWST spectra

Answered: Why is the gas so warm? (Ginsburg+ 2016)

Partly: how dust dims the light (Bravo Ferres+ 2025)

Still open: radio filaments · the black hole's past · fast compact clouds · cosmic rays · lone massive stars · bursts of star formation



Thank you! Questions?

