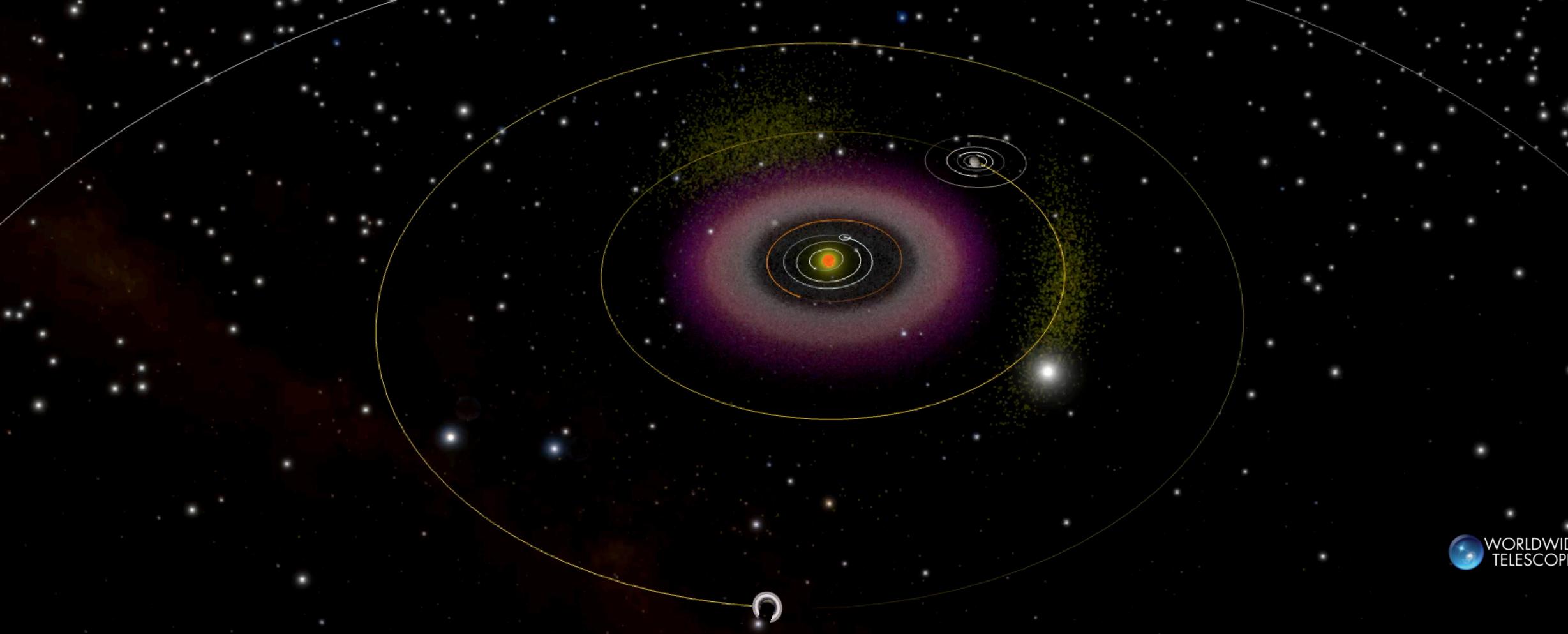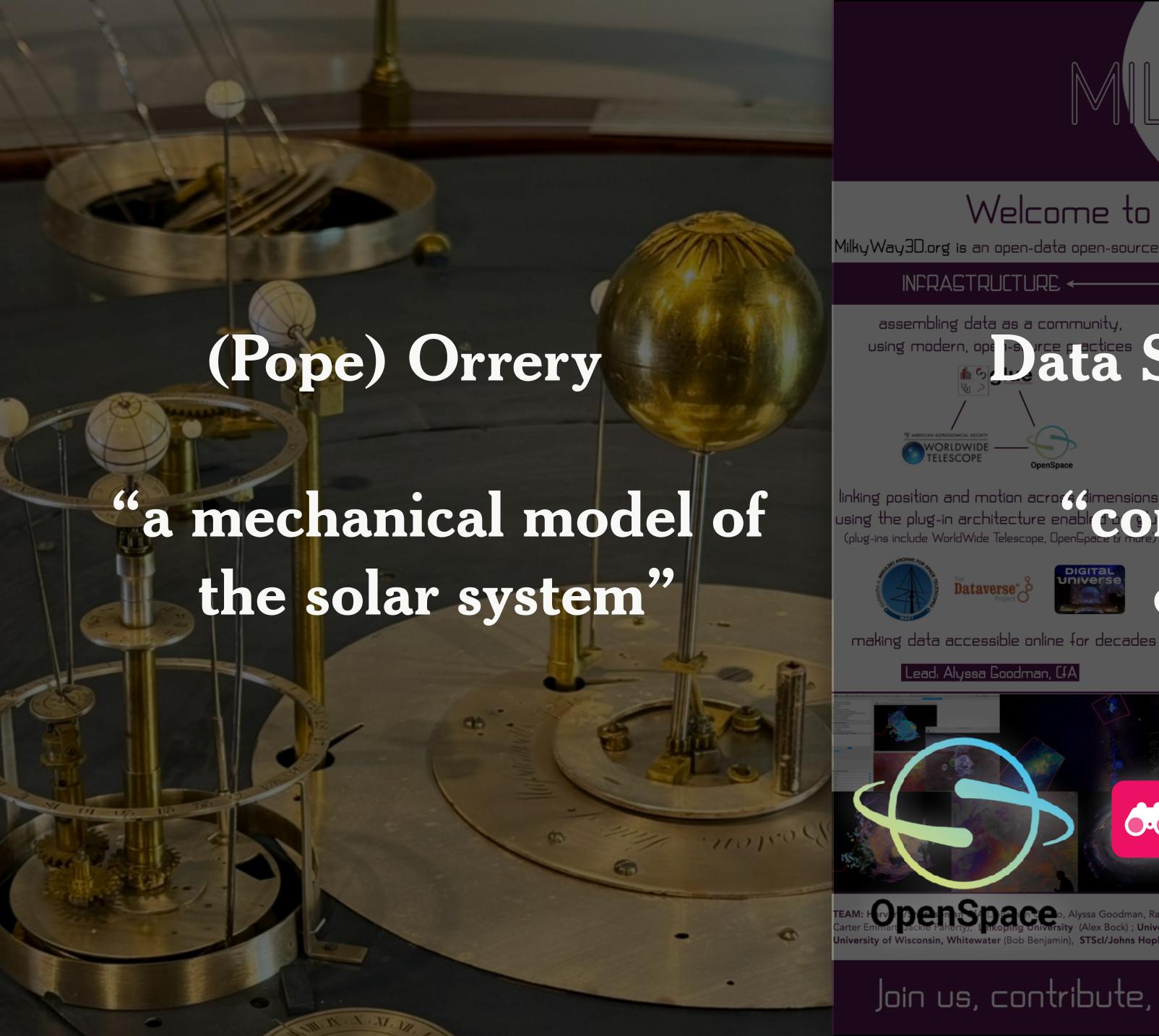# From Orreries to WorldWide Telescope:
Making 2D Paths on the Sky into Motions in a 3D Universe

Alyssa A. Goodman, Center for Astrophysics | Harvard & Smithsonian

WORLDWIDE TELESCOPE

From Orreries to WorldWide Telescope:
Making 2D Paths on the Sky into Motions in a 3D Universe

(Pope) Orrery

"a mechanical model of the solar system"

Data Science Views today

"computational models of the Universe"

Data Collection

Data

- Edenhofer2023_mean_and_std_xyz[MEAN]
- Hunt2023_arXiv_2303.13424_MW3D[HDU1]
- ONeill2023_LocalBubble
- Sun_MW3D[HDU1]
- Marchal2023_ApJ_942_70_MW3D[HDU1]
- Foley2022_arXiv_2212.01405_OrionShell_MW3D[HDU1]
- Dharmawardena2023_MNRAS_519_228_CepheusFlareShell_MW3D[HDU1]
- Zucker2021_ApJ_919_35_spines_MW3D[HDU1]
- Alves2020_Nat_578_237_MW3D[HDU1]
- Bialy2021_ApJL_919_L5_MW3D[HDU1]
- Palmeirim2020_A.A_636_A17_Imax10_MW3D[HDU1]

Plot Layers - Earth/Planet/Sky Viewer (WWT)

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Alves Radwave, Zucker spines, O'Neill Bubble (Edenhofer Map)

X Alves-Bialy-Foley-O'Neill-Zucker   X 3D views

Size | Color

Fixed

Plot Options - Earth/Planet/Sky Viewer (WWT)

Mode:	Milky Way
Frame:	Galactic
Longitude:	GLON
Latitude:	GLAT
Distance	Distance
	pc

Earth/Planet/Sky Viewer (WWT)

glue
multidimensional data exploration

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MILKYWAY3D.org

Welcome to a new view of the Milky Way… in 3D!

MilkyWay3D.org is an open-data open-source discovery hub, providing data, visualization, and research tools for studying the MilkyWay in 3D.

INFRASTRUCTURE ←——————→ SCIENCE ←——————→ EDUCATION & OUTREACH

assembling data as a community, using modern, open-source practices

glue

AMERICAN ASTRONOMICAL SOCIETY
WORLDWIDE TELESCOPE
OpenSpace

linking position and motion across dimensions, using the plug-in architecture enabled by glue (plug-ins include WorldWide Telescope, OpenSpace & more)

The Dataverse Project   DIGITAL universe

making data accessible online for decades

Lead: Alyssa Goodman, CfA

enabling studies of how galaxies turn gas into stars, using…

stellar positions, clusters, motions

topology, positions & motions of (long) features

tracers of feedback & magnetic fields

details on star-forming regions…and more!

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real-time data exploration anywhere, including in planetaria

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"Cosmic Data Stories" teach data science using astronomical data & tools

Lead: Jackie Faherty, AMNH

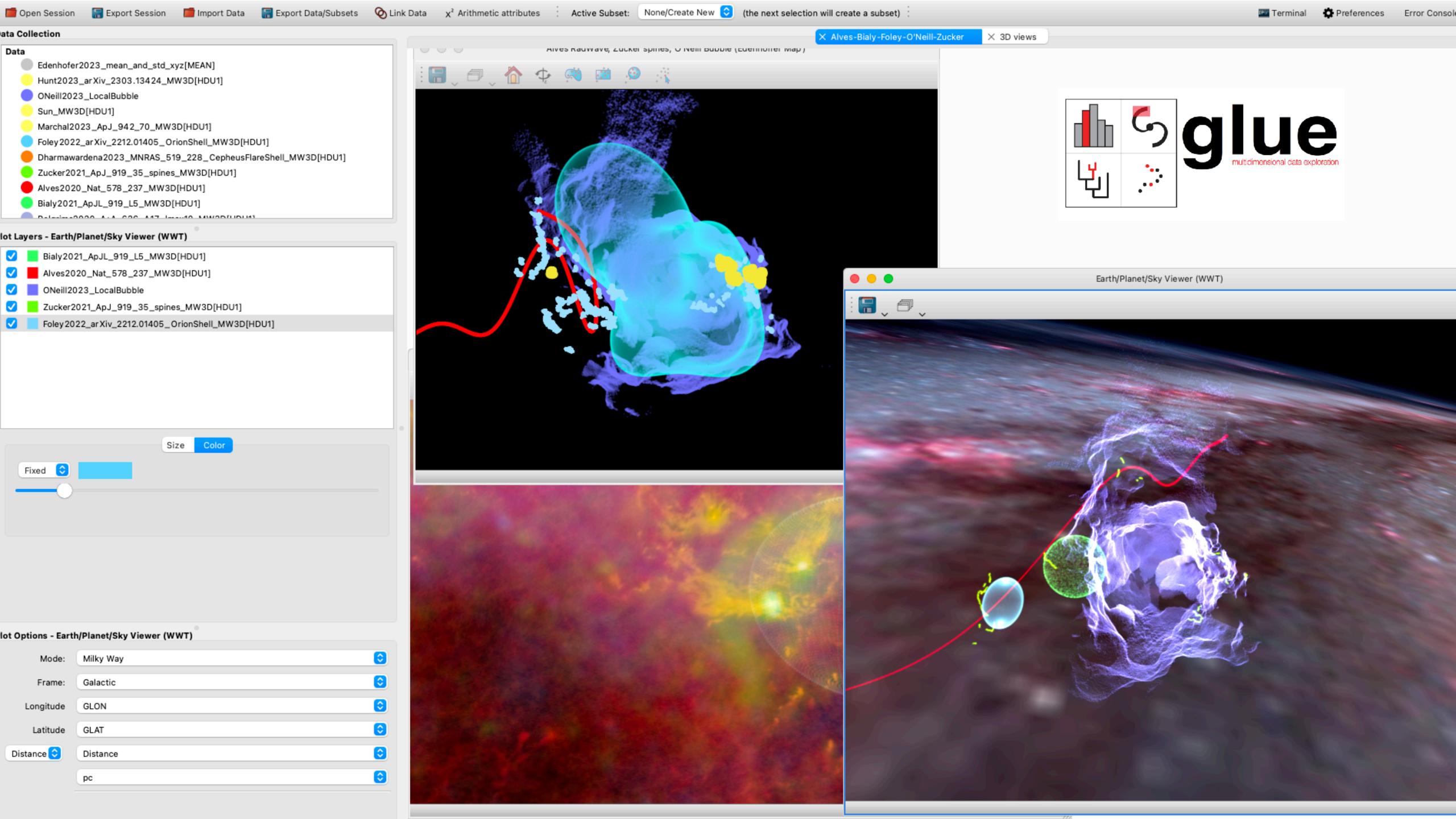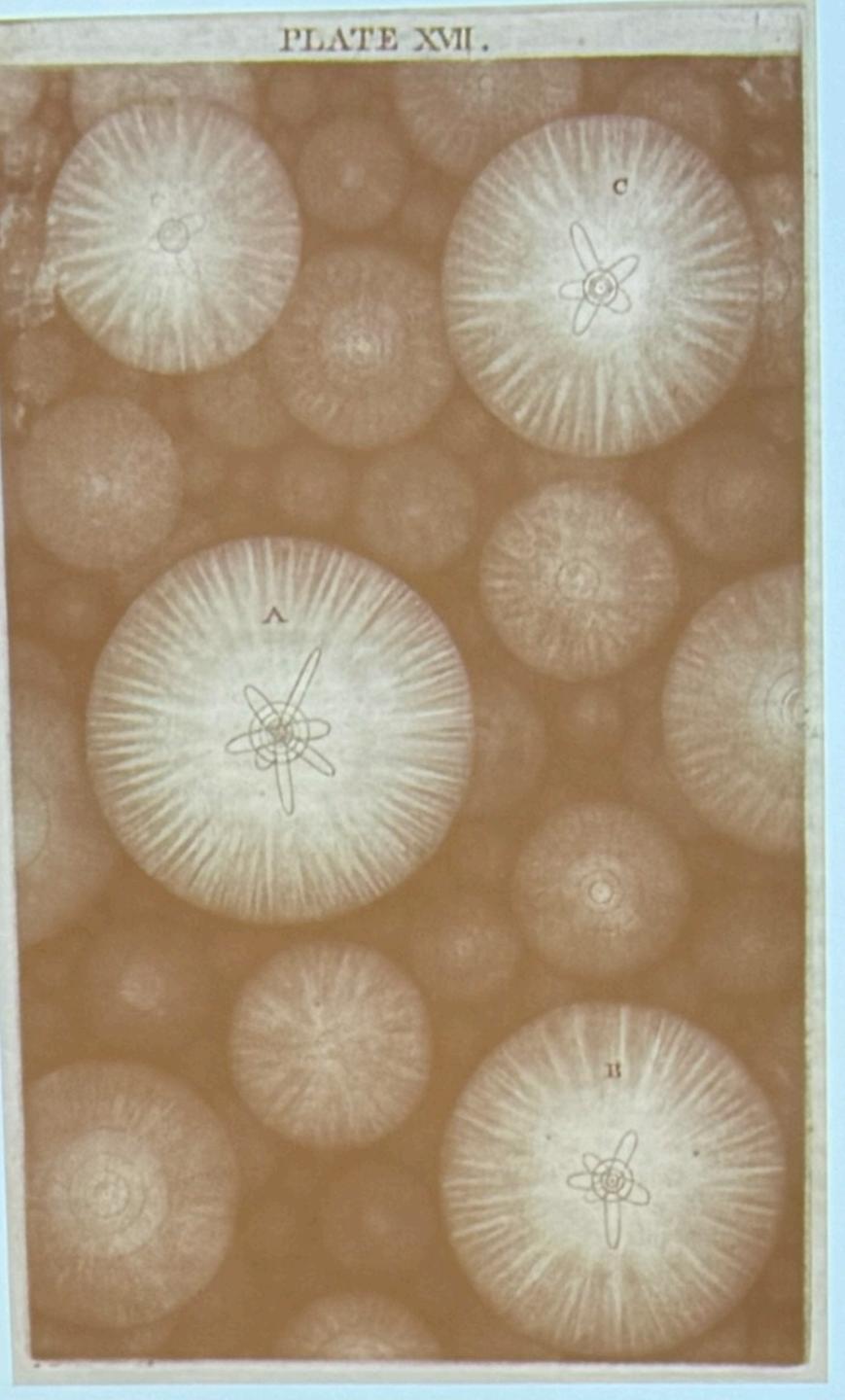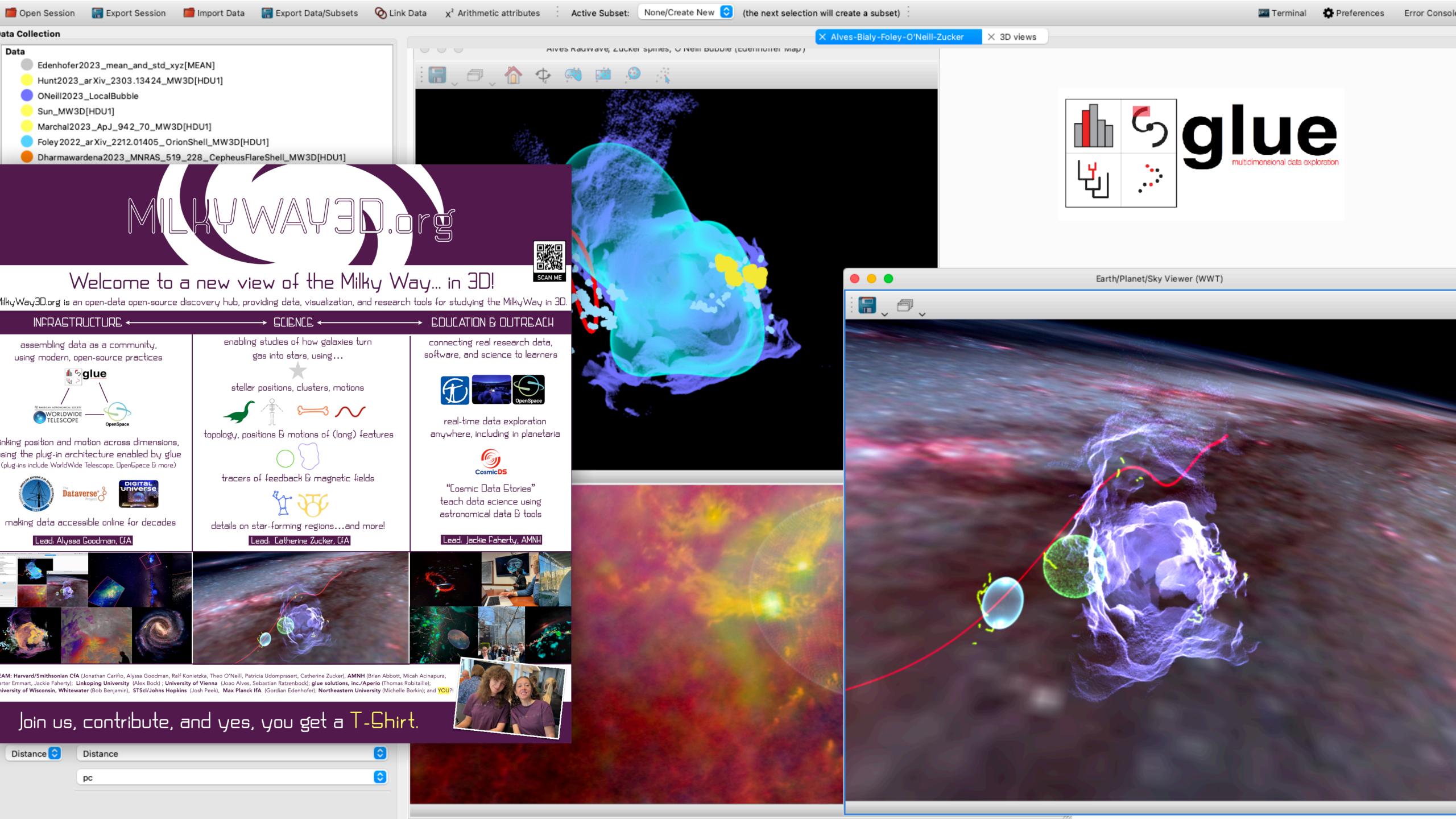TEAM: Harvard/Smithsonian CfA (Jonathan Carifio, Alyssa Goodman, Ralf Konietzka, Theo O'Neill, Patricia Udomprasert, Catherine Zucker), AMNH (Brian Abbott, Micah Acinapura, Carter Emmart, Jackie Faherty), Linkoping University (Alex Bock) ; University of Vienna (Joao Alves, Sebastian Ratzenbock); glue solutions, inc./Aperio (Thomas Robitaille); University of Wisconsin, Whitewater (Bob Benjamin), STScI/Johns Hopkins (Josh Peek), Max Planck IfA (Gordian Edenhofer); Northeastern University (Michelle Borkin); and YOU?!

Join us, contribute, and yes, you get a T-Shirt.

SCAN ME

Distance   Distance

pc

glue
multidimensional data exploration
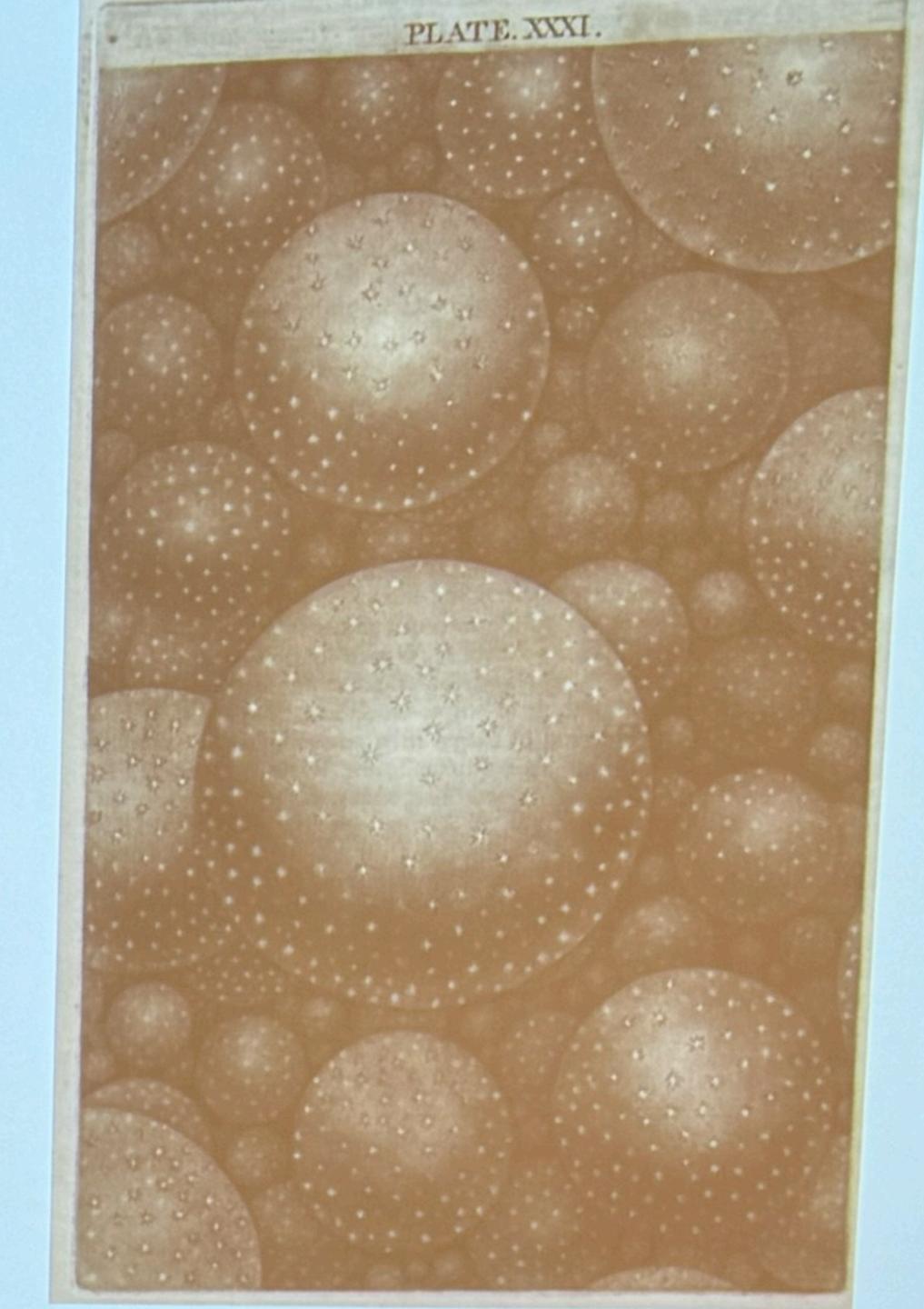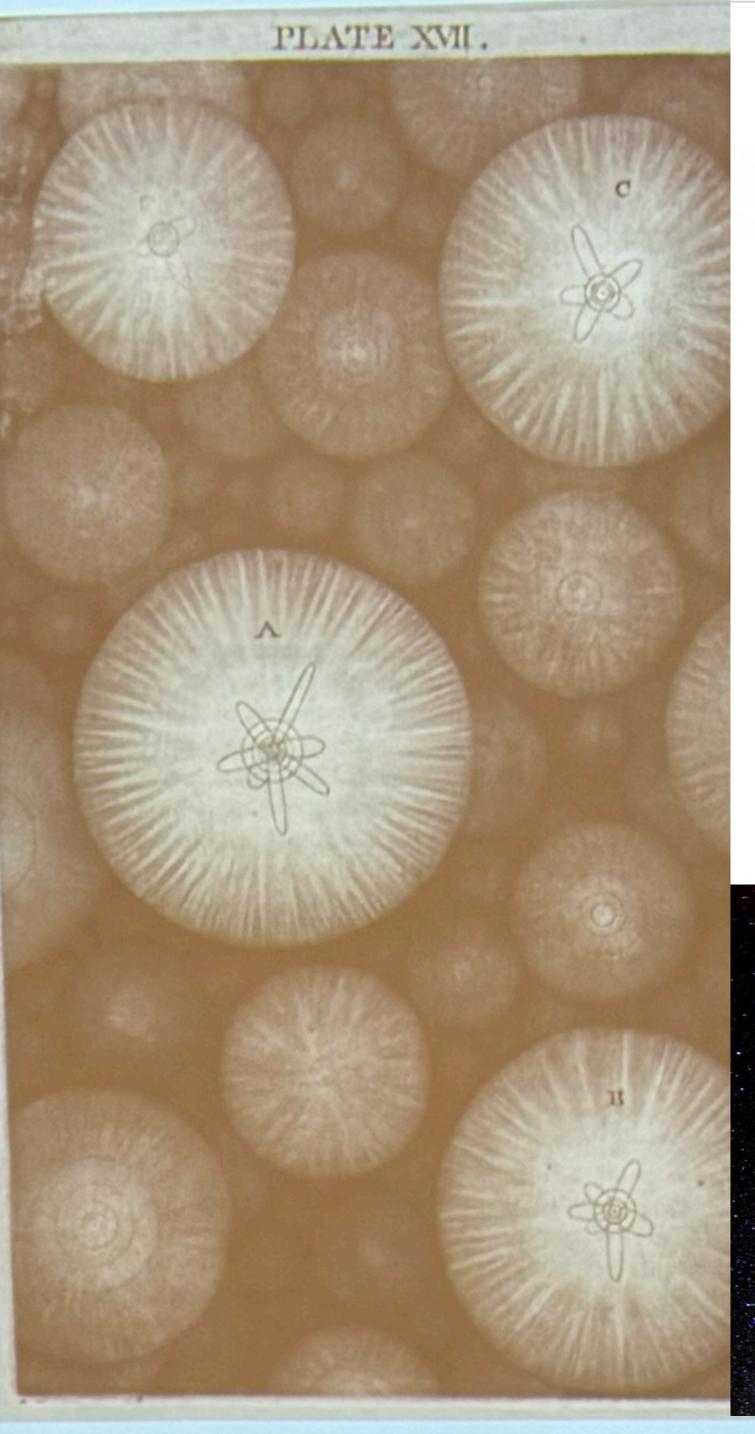
Earth/Planet/Sky Viewer (WWT)

Thomas Wright, *An Original Theory or New Hypothesis of the Universe Founded upon the Laws of Nature* (1750)

Jessica Riskin's slide from earlier...

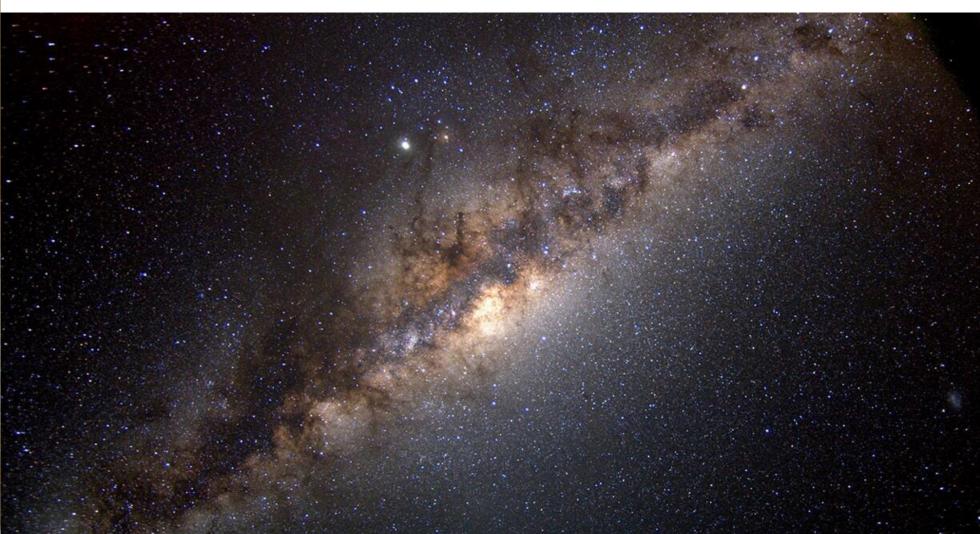**American Museum**
of **Natural History**

Astronomy Live: Mapping the Milky Way in 3D
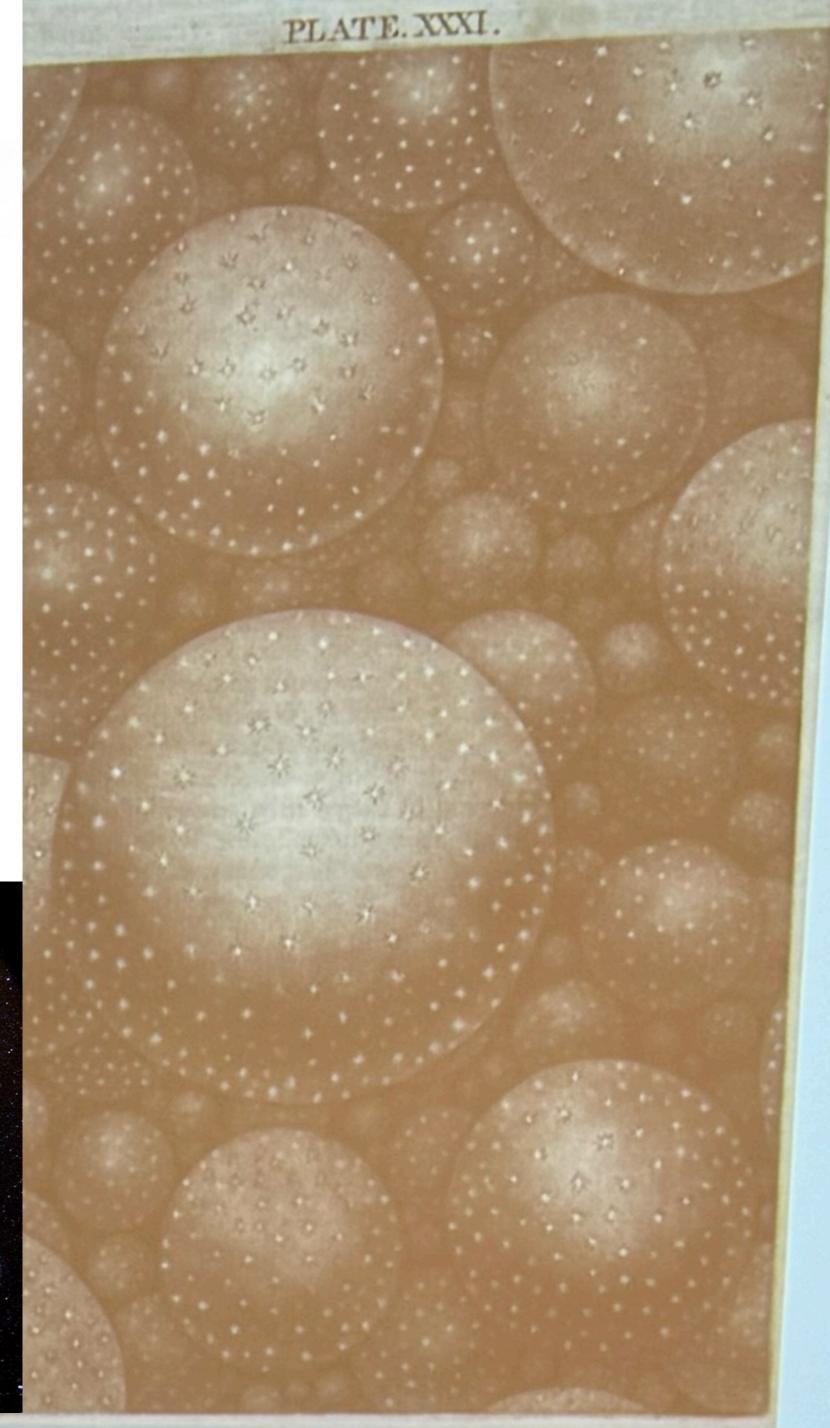
Part of Astronomy Live

Tuesday, December 12, 2023

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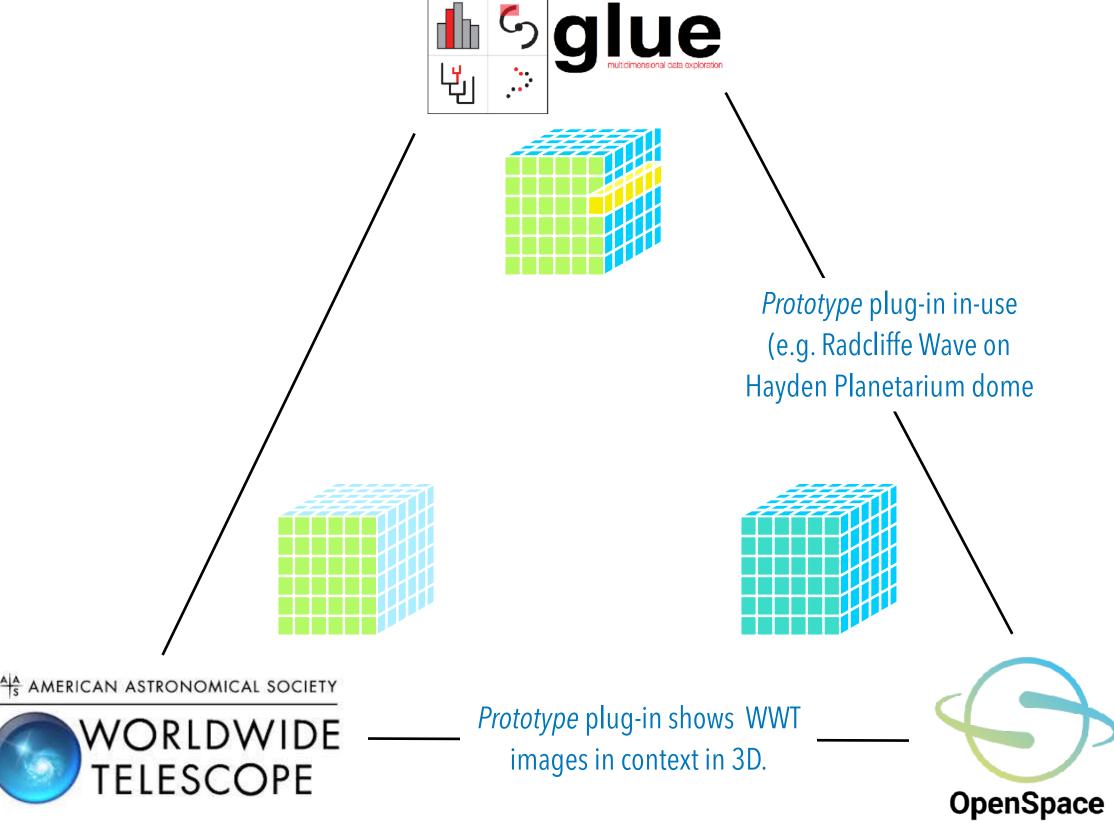
pc ◊

great **1D**, **2D** and **3D** data manipulation, flexible architecture facilitating plug-ins, data transfer, and interactive data exploration; "glupyter" flavor runs in web pages

glue
multidimensional data exploration

Prototype plug-in in-use (e.g. Radcliffe Wave on Hayden Planetarium dome

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WORLDWIDE TELESCOPE

Prototype plug-in shows WWT images in context in 3D.

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great 2D object and all-sky images
limited 3D functionality

limited 2D all-sky images
great 3D functionality

The "Perseus-Taurus Superbubble"
a demo of the need for 2D-3D contextualization functionality

TAURUS

PERSEUS

This video was composited using the WWT and OpenSpace, making some use of prototype plug-ins, but 2D and 3D imagery was aligned manually by experts. As a generalizable STEM concept, it explains the deceptive "forced perspective" made possible in when objects at very different distances, in 3D, appear to touch in 2D.
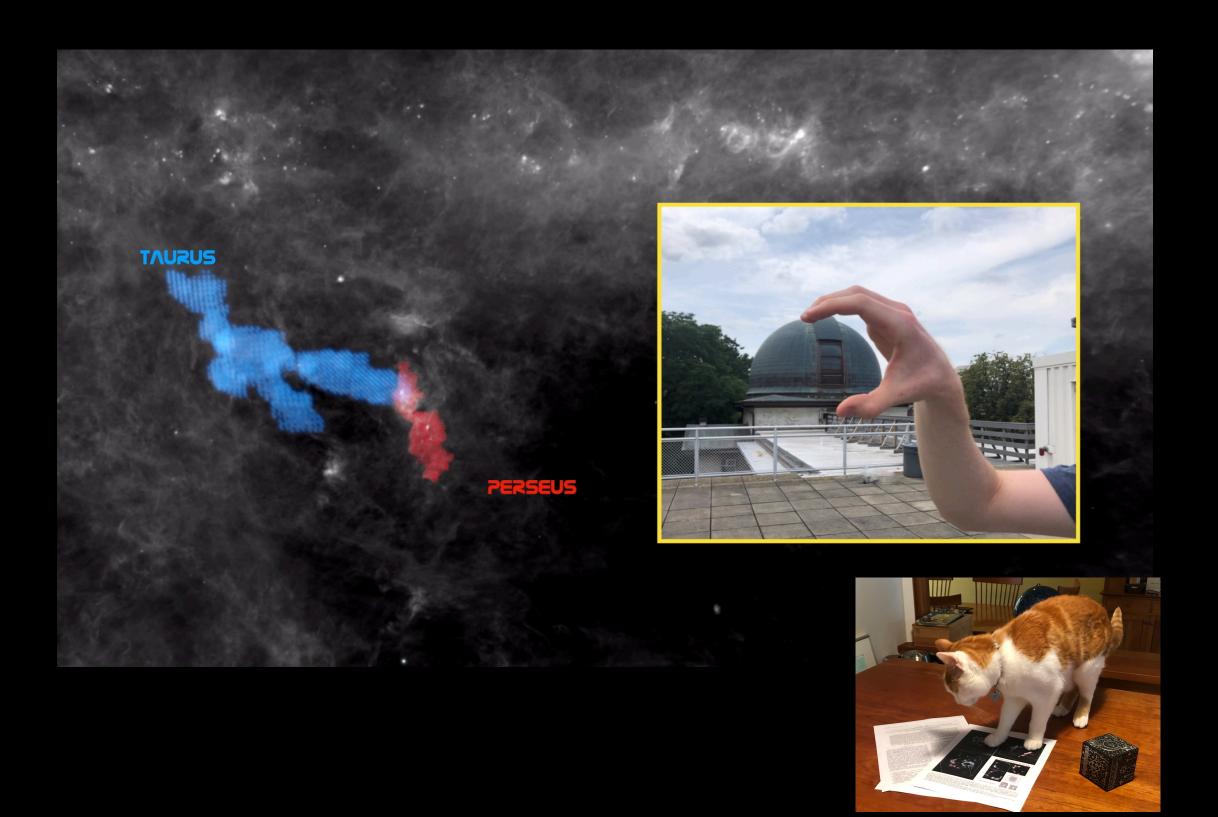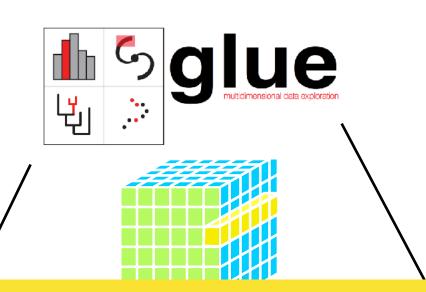
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a demo of the need for 2D-3D contextualization functionality

This is a sample slide from a recent astronomy/visualization research talk.
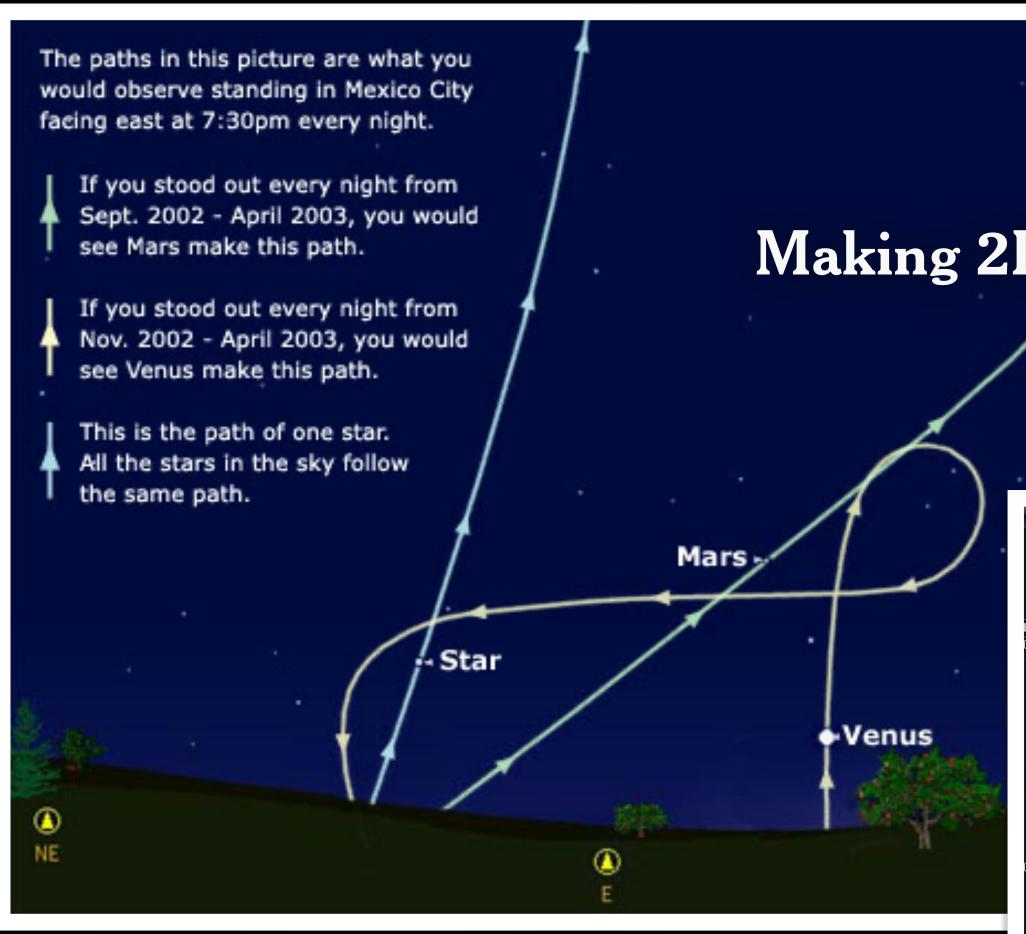
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WORLDWIDE TELESCOPE

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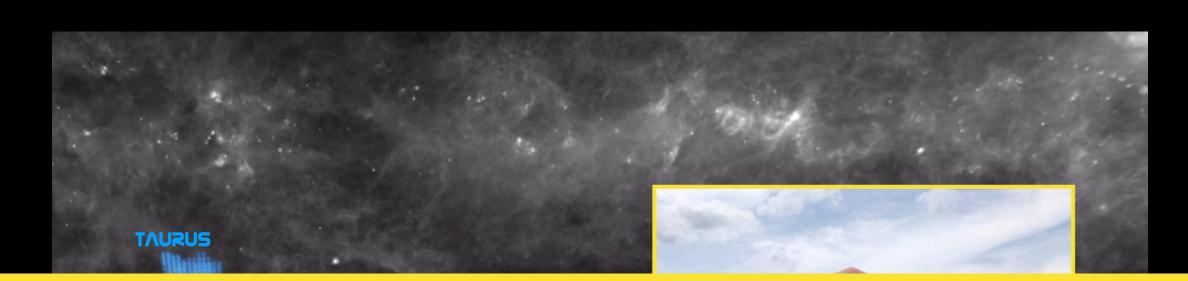*great* 3D functionality

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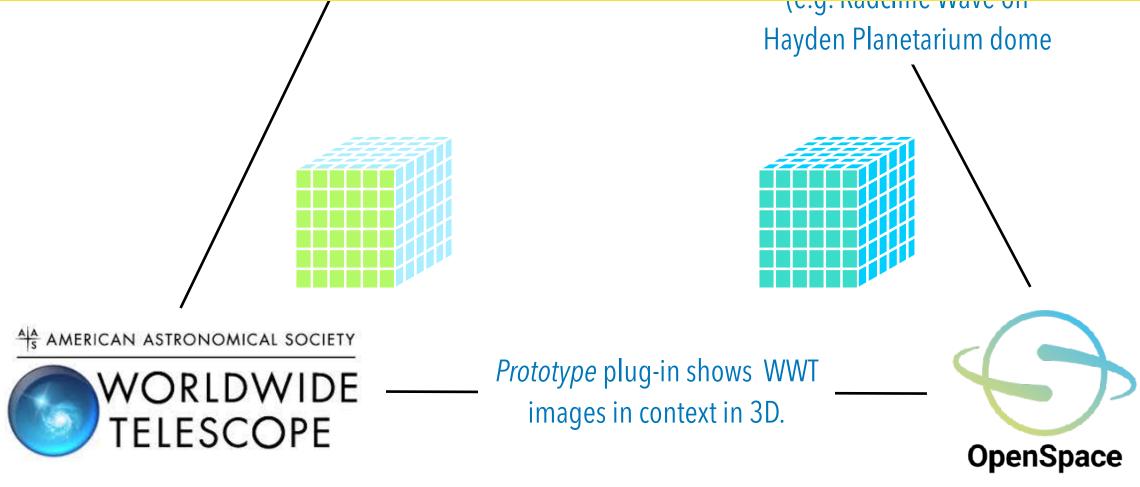
"From Orreries to WorldWide Telescope: Making 2D Paths on the Sky into Motions in a 3D Universe"

The paths in this picture are what you would observe standing in Mexico City facing east at 7:30pm every night.

If you stood out every night from Sept. 2002 - April 2003, you would see Mars make this path.

If you stood out every night from Nov. 2002 - April 2003, you would see Venus make this path.

This is the path of one star. All the stars in the sky follow the same path.

Mars

Star

Venus

NE

E
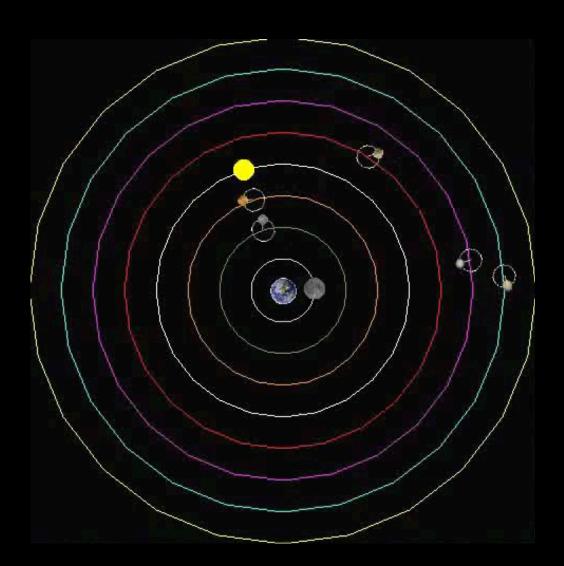
https://ecuip.lib.uchicago.edu/diglib/science/cultural_astronomy/phenom_planets_images-1c.html

[demo]

Ptolemaic

Geocentric,
with Epicycles

Copernican

Heliocentric
(correct)

Tychonic

Geoheliocentric
hybrid

150 A.D.

1543

1587

The Path to Newton

PredictionX
prediction.org

demo: path-to.org   or   LabXchange™
Science and learning–connected.

The Path to Newton

| PREVAILING BELIEF | CONCERNED WITH PHENOMENA | EARTH AT CENTER | (☉ BELIEVED SUN AT CENTER) |

TOOLS AVAILABLE
GNOMON
GNOMON
ASTROLABE

MATH AVAILABLE
ARITHMETIC & ACCOUNTING — ARITHMETIC — ARITHMETIC — ARITHMETIC
ZERO AS PLACE HOLDER — ZERO AS PLACE HOLDER — ZERO AS PLACE HOLDER — ZERO AS PLACE HOLDER — ZERO AS NUMERAL
PLANAR GEOMETRY — PLANAR GEOMETRY — PLANAR GEOMETRY — PLANAR GEOMETRY
SPHERICAL GEOMETRY — SPHERICAL GEOMETRY — SPHERICAL GEOMETRY
SPHERICAL GEOMETRY — TRIGONOMETRY — TRIGONOMETRY
TRIGONOMETRY — SPRERICAL TRIGONOMETRY — SPHERICAL TRIGONOMETRY
ALGEBRA

2000 B.C.

BIG IDEAS

Correct

Partial credit

Wrong

CONNECTIONS BETWEEN IDEAS

Teacher-Pupil or Senior-Junior Researcher

Travel between cultures

Published works

BABYLONIANS
c. 2000–300 BCE

Hey, the cycles in the sky repeat. Let's track them.

THALES
624–546 BCE
Greek

Natural, not supernatural.

Nature can be explained

Motion and change are illusions

ANAXIMANDER
610–546 BCE
Greek

The universe is WAY bigger than you might think.

Earth generated by boundless eternity

Some "stars" move more than others

If circles are perfect, spheres are sublime.

PYTHAGORAS
570–495 BCE
Greek

Universe is spherical

PARMENIDES
515–450 BCE
Greek

Question all you "see."

ANAXAGOROS
510–428 BCE
Greek

Motion needs a little push.

Motion must have a cause

The air moves objects through it

SOCRATES
470–399 BCE
Greek

PLATO
427–347 BCE
Greek

Symmetry rules.

Rearranging "atoms" allows motion

STUFF on Earth and in the Heavens is all the same... just atoms.

DEMOCRITUS
460–370 BCE
Greek

💕 Circles spheres, beauty, eternity...

ARISTOTLE
383–322 BCE
Greek

...oh, and you're so wrong about motion, Plato.

All things move to their natural place

EUDOXUS
390–337 BCE
Greek

It's spheres all the way down.

Planets, Moon, Sun, move on spheres

Earth is stationary center of the universe

ARISTARCHUS
310–230 BCE
Greek ☉

Hello? Is this thing on?

Sun at center

EUCLID
300? BCE
Greek

I can prove it!

A single framework for all geometry

Circles ARE the best! We just need more!

PTOLEMY
100–170
Greek living in Roman Egypt

Epicycles, equants, eccentrics

Celestial and terrestrial phenomena similar

Motion caused by self-exhausting force

JOHN PHILOPONUS
490–570
Greek living in Roman Egypt

Aristotle is wrong about space, time, and matter.

It just keeps going, and going, but not really

Motion is indefinite without external forces

VĀRĀHAMIHIRA
505–587
Indian

I must gather more information for better astrology, and I shall share what I learn!

With one little function, I'll give you the Moon!

ARYABHATA
476–550
Indian

Sines improve accuracy

HIPPARCHUS
190–120 BCE
Greek living in Rome

I'm not sure Earth is exactly in the center?

Math can model the universe

AL-BATTANI
858–929
Arab

Years from now, Copernicus will love me.

Who knew nothing could be so useful?

BRAHMAGUPTA
598–668
Indian

Accuracy is key (e.g., 365.24 days in a year)

Zero is a numeral unto itself

| **On the Heavens** Aristotle c. 350 BCE | **Physics** Aristotle c. 320 BCE | **Elements** Euclid c. 300 BCE | **The Almagest** Ptolemy c. 150 | **Aryabhatiya** Aryabhata c. 499 | **On Aristotle's Physics 3** Philoponus c. 520 | **Pañca-siddhāntikā** Vārāhamihira c. 575 | **Brahmasphuta-siddhanta** Brahmagupta c. 628 | **TRANSLATION MOVEMENT WORKS** | **Kitāb az-Zīj** al-Battani c. 900 | **Kitāb a** Ibn |

Astronomical Diaries

GNOMON
ASTROLABE
PRINTING PRESS

GNOMON
ASTROLABE
PRINTING PRESS

ARITHMETIC
ZERO AS PLACE HOLDER
PLANAR GEOMETRY
SPHERICAL GEOMETRY
TRIGONOMETRY
SPRERICAL TRIGONOMETRY

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ALGEBRA

ZERO AS NUMERAL

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TUSI COUPLE AND OTHER SPECIAL FORMS

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Persian

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1126–1198
Arab

Come on! You can't "give" an object motion.

Objects are "set into" motion

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1320–1382
French

With giant spendy instruments, I can get GREAT data.

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Metaphysics? Hooey! Give me evidence and math.

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Bigger observatories, better observations.

AL-TUSI
1201–1274
Persian

This is math, not philosophy.

JEAN BURIDAN
1295–1358
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Motion explained with "impetus theory"

Math first, philosophy later.

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Polish

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If I use a teeny unit of time...

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Simple circular orbits work with better math

Sun at center of Earth's & planets' orbits

The Earth might actually rotate

Jupiter has moons, which orbit like our Moon

I have Tycho's fancy data!

Hmm... circles are a problem.

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German

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Sines improve accuracy

Zero is a numeral unto itself

Much of what we today call calculus

Earth need not be at rest, Ptolemy!

ALI QUSHJI
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Turkic

I can improve Ptolemy! To the printing press!

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Orbits are ellipses, not circles

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TRANSLATION MOVEMENT WORKS

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al-Battani
c. 900

Kitāb al-Shifa'
Ibn Sīnā
c. 1020

Al-Shukūk 'alā Batlamyūs
Ibn al-Haytham
c. 1025

Siddhānta Shiromani
Bhāskara II
c. 1150

Commentaries on Aristotle
Ibn Rushd
c. 1150-1200

Alfonsine Tables
1252

Al-Tadhkirah fi'ilm al-hay'ah
al-Tusi
1261

Epitome of the Almagest
Regiomontanus
1496

De Revolutionibus
Copernicus
1543

Astronomia Nova
Johannes Kepler
1609

Siderius Nuncius
Galileo
1610

SUN AT CENTER (⊕ BELIEVED EARTH AT CENTER)
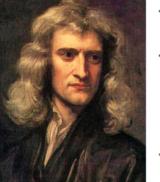
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1546–1601
Danish

Oooh, I like this Dutch spyglass!

GALILEO GALILEI
1564–1642
Italian

Sorry, Aristotle, you're just wrong.

Aristotle, mon ami, above and below, it's all matter in motion.

RENÉ DESCARTES
1596–1650
French

We're gonna need better math.

This apple. That moon. Could they feel the same pull?

ISAAC NEWTON
1642–1726
British

father more ...tion for ...trology, ...ll share ...arn!

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Jupiter has moons, which orbit like our Moon

All bodies on Earth have (circular) inertia

Sun is the center

Sun is the center

All bodies have inertia

GRAVITY GOVERNS ALL

I must make Newton publish!

EDMOND HALLEY
1656–1742
British

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Much of what we today call calculus

Orbits are ellipses, not circles

Some comets return, predictably

Brahmasphuta-siddhanta
Brahmagupta
c. 628

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Ibn al-Haytham
c. 1025

Siddhānta Shiromani
Bhāskara II
c. 1150

Commentaries on Aristotle
Ibn Rushd
c. 1150-1200

Alfonsine Tables
1252

Al-Tadhkirah fi'ilm al-hay'ah
al-Tusi
1261

Epitome of the Almagest
Regiomontanus
1496

De Revolutionibus
Copernicus
1543

Astronomia Nova
Johannes Kepler
1609

Siderius Nuncius
Galileo
1610

Dialogue on the Two Chief Systems of the World
Galileo
1632

Two New Sciences
Galileo
1638

Principles of Philosophy
Descartes
1644

Principia
Isaac Newton
1687

Synopsis Astronomia Cometicae
Edmond Halley
1705

Ptolemaic

Geocentric,
with Epicycles

Copernican

Heliocentric
(correct)

Tychonic

Geoheliocentric
hybrid

150 A.D.

1543

1587

18th Century

21st Century

HARVARD UNIVERSITY
WorldWide Telescope
Ambassadors Program

CosmicDS

SUN
(lamp)

EARTH
(your head)

MOON
(foam moon)

Watch and Compare

WATCH the October 14
ANNULAR ECLIPSE

Explore the view
Choose any location
Identify the path
New! Video guide

This Mini Data Story is brought to you by
Cosmic Data Stories and WorldWide
Telescope.

Time rate: Paused

The Prediction Project

The Past and Present of the Future
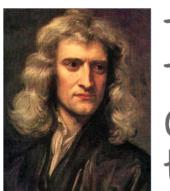
MILKYWAY3D.org

WORLDWIDE
TELESCOPE   glue   OpenSpace

GNOMON
ASTROLABE
PRINTING PRESS
TELESCOPE

ARITHMETIC
ZERO AS NUMERAL
PLANAR GEOMETRY
SPHERICAL GEOMETRY
TRIGONOMETRY
SPHRERICAL TRIGONOMETRY
ALGEBRA
SPECIAL FORMS
LOGARITHMS
CALCULUS

ELECTRONIC COMPUTERS

NUMERICAL SIMULATION
BAYESIAN STATISTICS
INTERACTIVE DATA VISUALIZATION
AI/MACHINE LEARNING

I like
Dutch
glass!

Sorry,
Aristotle,
you're just
wrong.

GALILEI

Aristotle,
mon ami,
above and
below, it's
all matter

We're gonna
need better
math.

This apple.
That moon.
Could they feel
the same pull?

Bialy et al., 2021

"ARE COMPUTERS THE NEW TELESCOPES?"

ELECTRONIC COMPUTERS

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Bialy et al., 2021

from the Sun

Sun

White: n=5 cm⁻³ iso-surface
Color: n=25 cm⁻³ iso-surface

"side-on" view of Per-Tau Shell, Sun at left

Sun

Taurus

Perseus

Per-Tau
Shell Model

"side-on," highlighting Taurus ring

Tau Ring
Model

Orthogonal Slices through Per-Tau Shell center

xz plane at $y=65$ pc

yz plane at $x=-190$ pc

xy plane at $z=-84$ pc

Scan codes for AR views

Merge cube required   no cube required
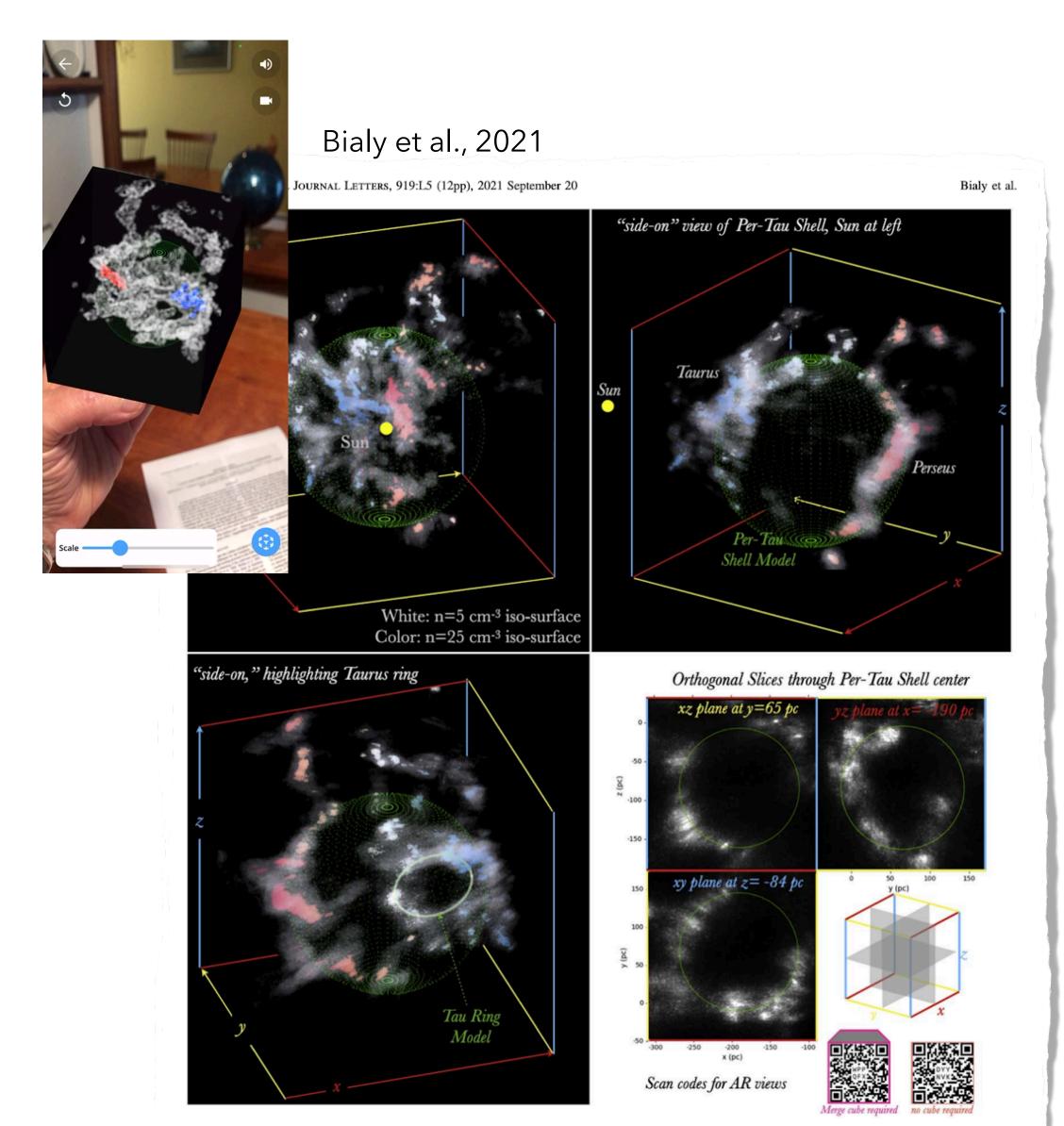
Figure 2. 3D views of the Per-Tau shell (for an interactive version[8] of this figure click here[9]; see Figure 5 for more static visualizations). Plotted are density surfaces at levels $n = 5$ cm⁻³ (gray) and $n = 25$ cm⁻³ (color), overlaid with our spherical-shell model, radius $R_s = 78$ pc, distance from the Sun $d = 218$ pc. $n = 25$ cm⁻³ surfaces are colored by distance from the Sun (blue-to-red). Top-left panel: view from the Sun (compare with Figure 1). Top-right panel: a side view of the region. Perseus and Taurus and their diffuse envelopes are arranged on two opposing sides of the Per-Tau shell. Bottom-left panel: another side view emphasizing the Tau Ring. The ellipse is the Tau Ring model (Appendix B). Bottom-right panel: 2D density slices along the xy, xz, yz planes. All planes intersect at shell's In all panels xyz are the Heliocentric Cartesian Galactic Coordinates.

2. *Tau Ring:* in a sky projection the Tau Ring is seen almost edge-on. The near side of the Tau Ring connects with the main body of Taurus at $d \approx 150$ pc, whereas the farthest

3. *The Fictitious Connection:* A filament seems to co Taurus to Perseus. This connection is only a coinci projection effect, where in actuality the filament is lo

Scale

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