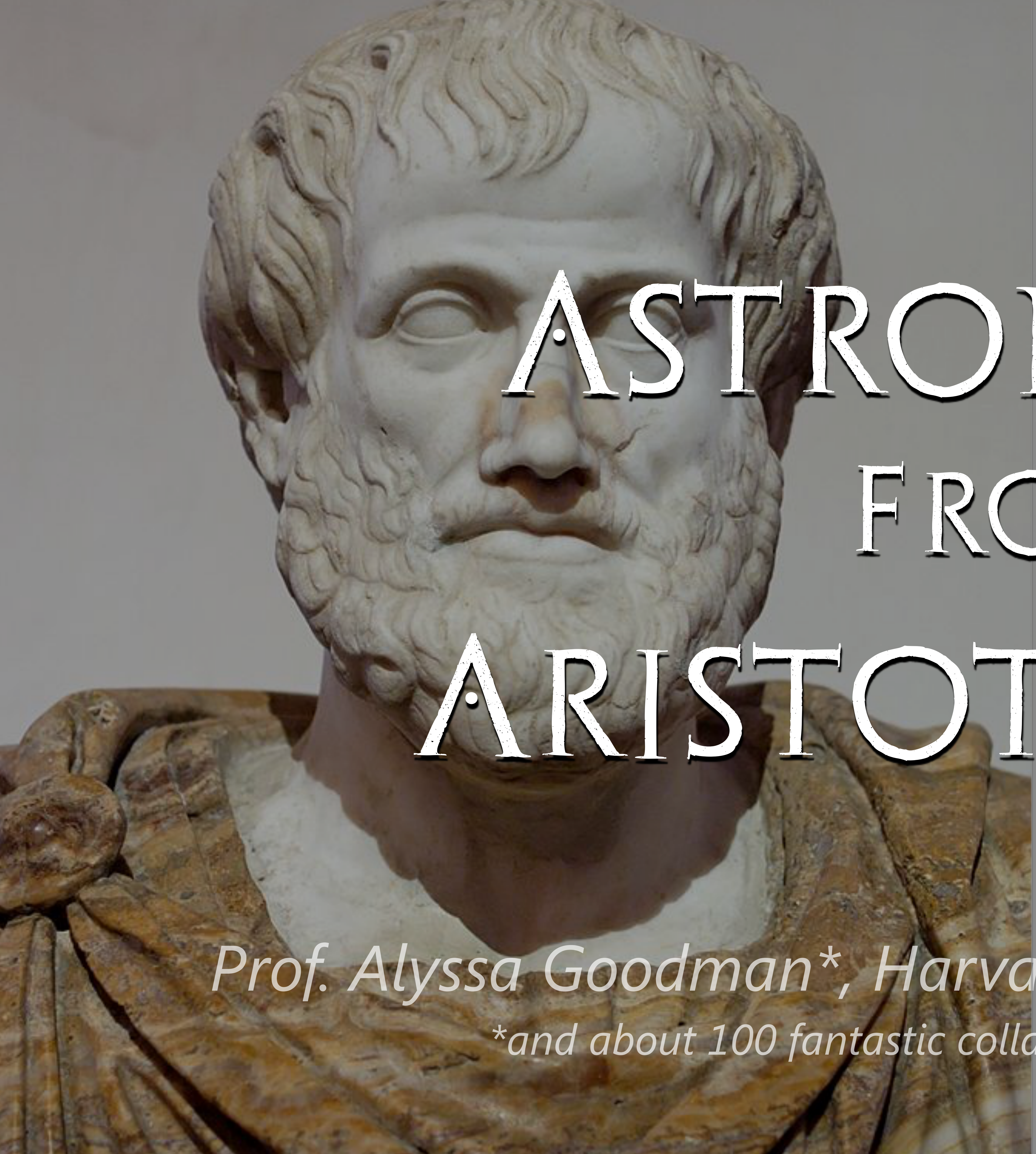
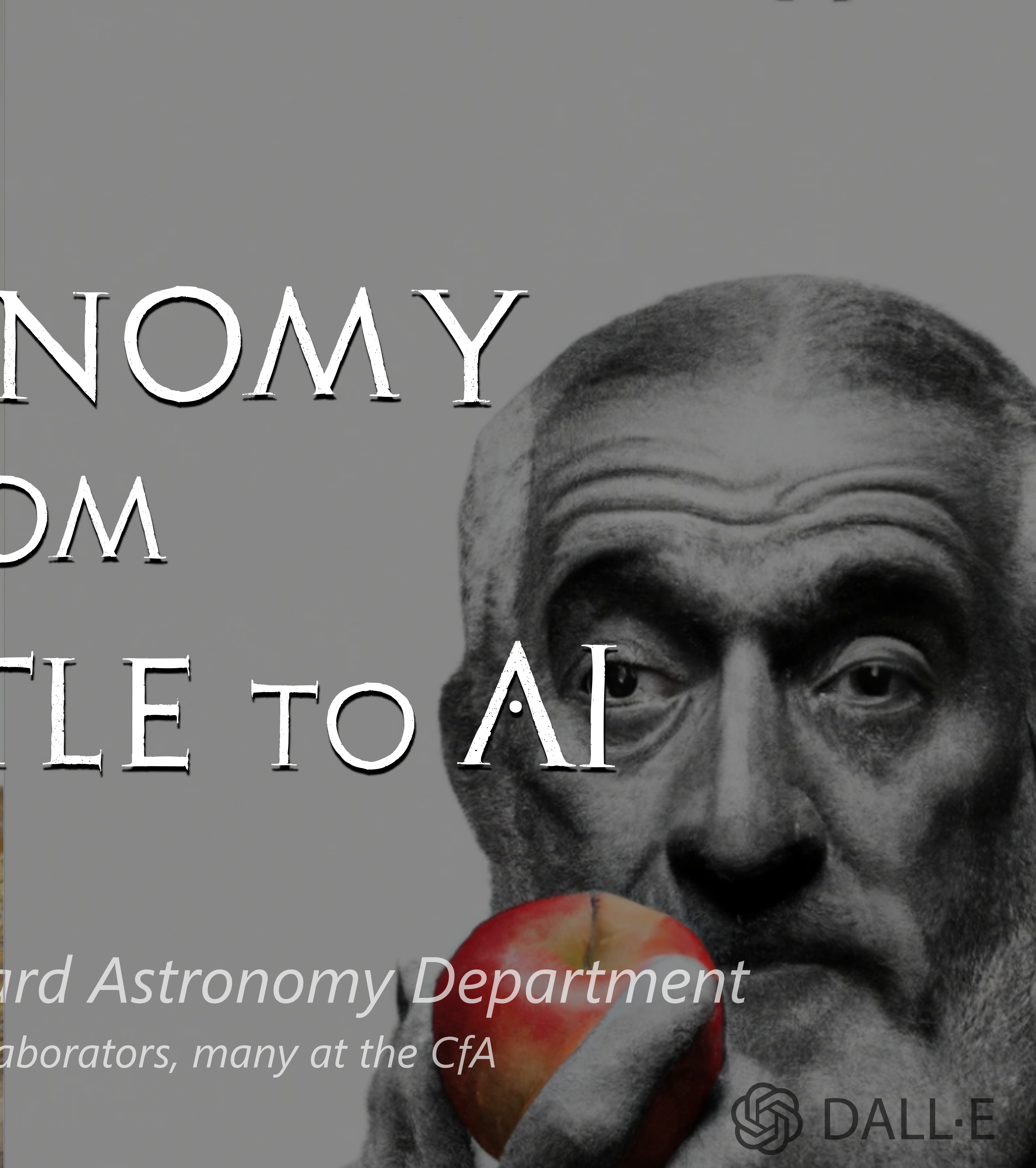


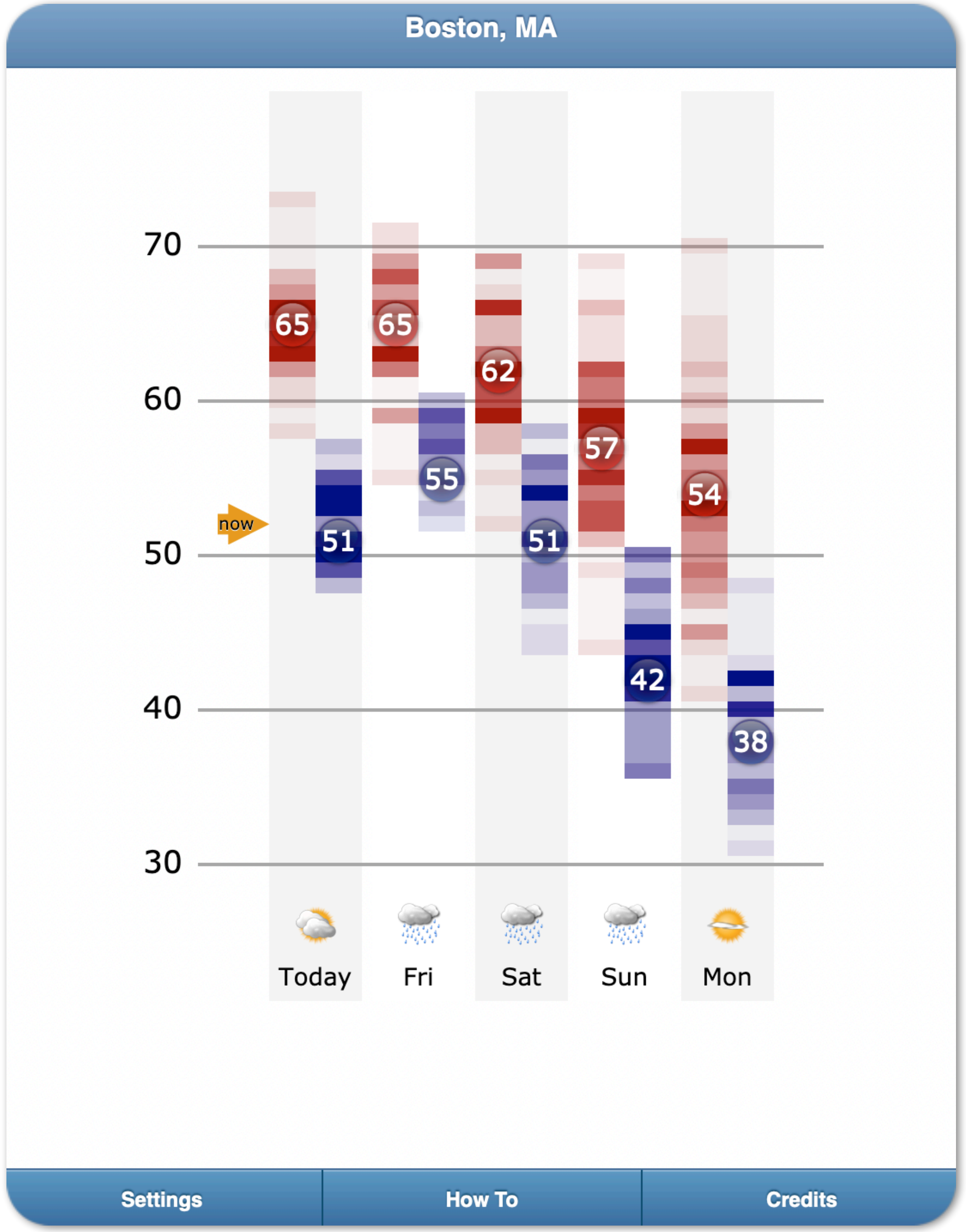


Astronomy
From
Aristotle to AI

Prof. Alyssa Goodman, Harvard Astronomy Department*

**and about 100 fantastic collaborators, many at the CfA*

How are weather forecasts made?


Boston, MA
70
60
50
40
30
now
65
51
65
55
62
51
57
42
54
38
Today
Fri
Sat
Sun
Mon
Settings
How To
Credits

today's forecast from "takeasweater.com," part of The Prediction Project (predictionx.org).

How are stars made?

ASTRONOMY

Open Session
Export Session
Import Data
Export Data/Subsets
Link Data
x^2 Arithmetic attributes
Terminal
Preferences
Alves-Bialy-Foley-O'Neill-Zucker
3D views
Alves Radwave, Zucker spines, O'Neill Bubble (Edenhofer Map)
Earth/Planet/Sky Viewer (WWT)
Size
Color

Active Subset: None/Create New (the next selection will create a subset)

ata 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]

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

- ☑ 🟩 Bialy2021_ApJL_919_L5_MW3D[HDU1]
- ☑ 🟥 Alves2020_Nat_578_237_MW3D[HDU1]
- ☑ 🟦 ONeill2023_LocalBubble
- ☑ 🟩 Zucker2021_ApJ_919_35_spines_MW3D[HDU1]
- ☑ 🟦 Foley2022_arXiv_2212.01405_OrionShell_MW3D[HDU1]

Fixed

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

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

How are stars made?

ASTRONOMY

“STARFORGE” simulations

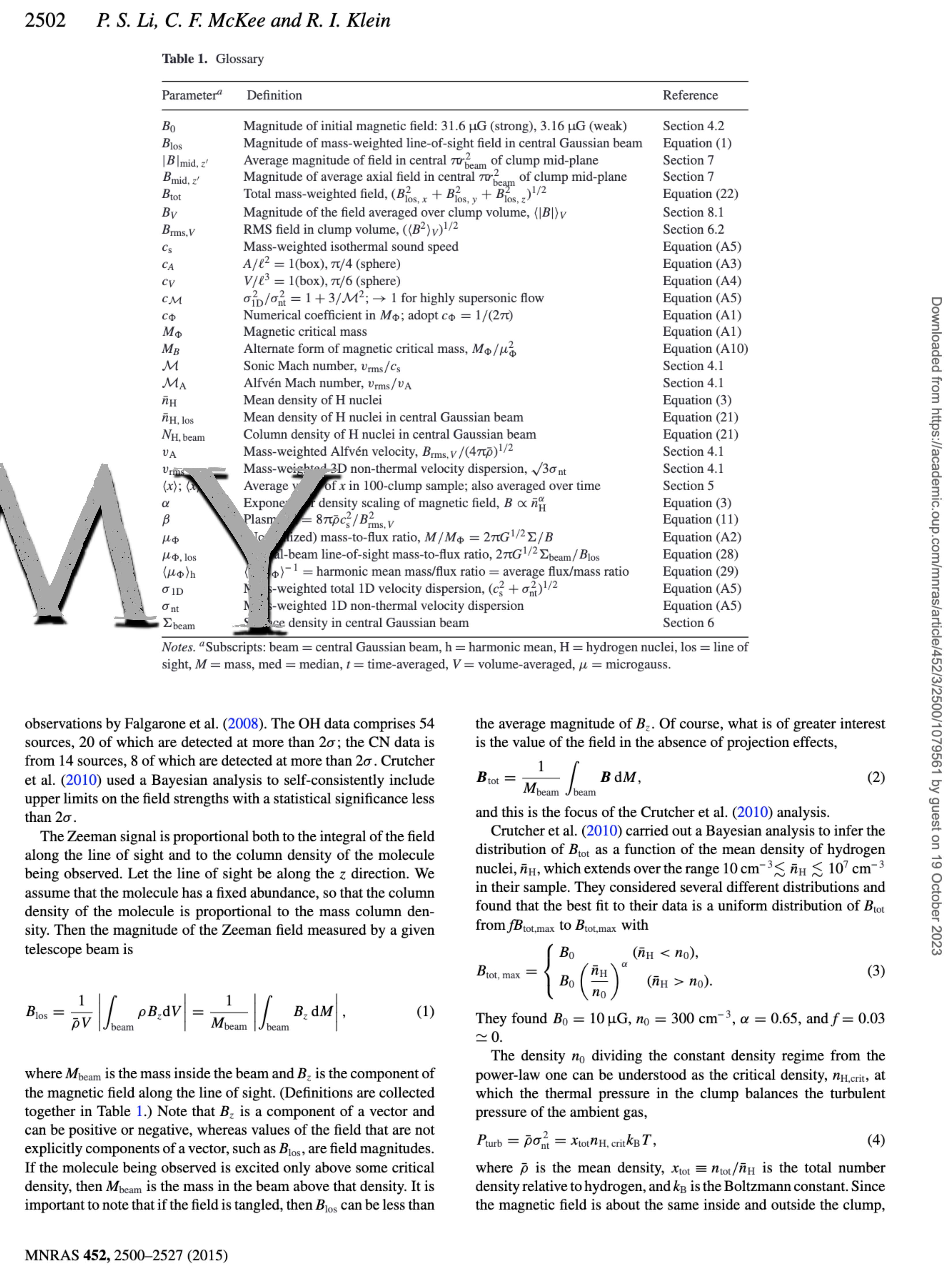


Table 1. Glossary

Parameter[a]	Definition	Reference
B_0	Magnitude of initial magnetic field: 31.6 μG (strong), 3.16 μG (weak)	Section 4.2
$B_{\rm los}$	Magnitude of mass-weighted line-of-sight field in central Gaussian beam	Equation (1)
$\lvert B\rvert_{{\rm mid},\,z'}$	Average magnitude of field in central $\pi r^2_{\rm beam}$ of clump mid-plane	Section 7
$B_{{\rm mid},\,z'}$	Magnitude of average axial field in central $\pi r^2_{\rm beam}$ of clump mid-plane	Section 7
$B_{\rm tot}$	Total mass-weighted field, $(B^2_{{\rm los},\,x} + B^2_{{\rm los},\,y} + B^2_{{\rm los},\,z})^{1/2}$	Equation (22)
B_V	Magnitude of the field averaged over clump volume, $\langle\lvert B\rvert\rangle_V$	Section 8.1
$B_{{\rm rms},V}$	RMS field in clump volume, $(\langle B^2\rangle_V)^{1/2}$	Section 6.2
$c_{\rm s}$	Mass-weighted isothermal sound speed	Equation (A5)
c_A	$A/\ell^2 = 1$(box), $\pi/4$ (sphere)	Equation (A3)
c_V	$V/\ell^3 = 1$(box), $\pi/6$ (sphere)	Equation (A4)
$c_{\mathcal{M}}$	$\sigma^2_{\rm 1D}/\sigma^2_{\rm nt} = 1 + 3/\mathcal{M}^2; \to 1$ for highly supersonic flow	Equation (A5)
c_Φ	Numerical coefficient in M_Φ; adopt $c_\Phi = 1/(2\pi)$	Equation (A1)
M_Φ	Magnetic critical mass	Equation (A1)
M_B	Alternate form of magnetic critical mass, M_Φ/μ^2_Φ	Equation (A10)
$\mathcal{M}$	Sonic Mach number, $v_{\rm rms}/c_{\rm s}$	Section 4.1
$\mathcal{M}_{\rm A}$	Alfvén Mach number, $v_{\rm rms}/v_{\rm A}$	Section 4.1
$\bar{n}_{\rm H}$	Mean density of H nuclei	Equation (3)
$\bar{n}_{{\rm H},\,{\rm los}}$	Mean density of H nuclei in central Gaussian beam	Equation (21)
$N_{{\rm H},\,{\rm beam}}$	Column density of H nuclei in central Gaussian beam	Equation (21)
$v_{\rm A}$	Mass-weighted Alfvén velocity, $B_{{\rm rms},\,V}/(4\pi\bar{\rho})^{1/2}$	Section 4.1
$v_{\rm rms}$	Mass-weighted 3D non-thermal velocity dispersion, $\sqrt{3}\sigma_{\rm nt}$	Section 4.1
$\langle x\rangle$; $\langle x$	Average v of x in 100-clump sample; also averaged over time	Section 5
α	Expone r density scaling of magnetic field, $B \propto \bar{n}^\alpha_{\rm H}$	Equation (3)
β	Plasm $= 8\pi\bar{\rho}c^2_{\rm s}/B^2_{{\rm rms},\,V}$	Equation (11)
μ_Φ	lized) mass-to-flux ratio, $M/M_\Phi = 2\pi G^{1/2}\Sigma/B$	Equation (A2)
$\mu_{\Phi,\,{\rm los}}$	al-beam line-of-sight mass-to-flux ratio, $2\pi G^{1/2}\Sigma_{\rm beam}/B_{\rm los}$	Equation (28)
$\langle\mu_\Phi\rangle_{\rm h}$	$\langle \quad _\Phi\rangle^{-1}$ = harmonic mean mass/flux ratio = average flux/mass ratio	Equation (29)
$\sigma_{\rm 1D}$	M s-weighted total 1D velocity dispersion, $(c^2_{\rm s} + \sigma^2_{\rm nt})^{1/2}$	Equation (A5)
$\sigma_{\rm nt}$	M s-weighted 1D non-thermal velocity dispersion	Equation (A5)
$\Sigma_{\rm beam}$	S ce density in central Gaussian beam	Section 6

Notes. [a]Subscripts: beam = central Gaussian beam, h = harmonic mean, H = hydrogen nuclei, los = line of sight, M = mass, med = median, t = time-averaged, V = volume-averaged, μ = microgauss.

observations by Falgarone et al. (2008). The OH data comprises 54 sources, 20 of which are detected at more than 2σ; the CN data is from 14 sources, 8 of which are detected at more than 2σ. Crutcher et al. (2010) used a Bayesian analysis to self-consistently include upper limits on the field strengths with a statistical significance less than 2σ.

The Zeeman signal is proportional both to the integral of the field along the line of sight and to the column density of the molecule being observed. Let the line of sight be along the z direction. We assume that the molecule has a fixed abundance, so that the column density of the molecule is proportional to the mass column density. Then the magnitude of the Zeeman field measured by a given telescope beam is

$$B_{\rm los} = \frac{1}{\bar{\rho}V}\left|\int_{\rm beam}\rho B_z {\rm d}V\right| = \frac{1}{M_{\rm beam}}\left|\int_{\rm beam} B_z\,{\rm d}M\right|, \tag{1}$$

where $M_{\rm beam}$ is the mass inside the beam and B_z is the component of the magnetic field along the line of sight. (Definitions are collected together in Table 1.) Note that B_z is a component of a vector and can be positive or negative, whereas values of the field that are not explicitly components of a vector, such as $B_{\rm los}$, are field magnitudes. If the molecule being observed is excited only above some critical density, then $M_{\rm beam}$ is the mass in the beam above that density. It is important to note that if the field is tangled, then $B_{\rm los}$ can be less than the average magnitude of B_z. Of course, what is of greater interest is the value of the field in the absence of projection effects,

$$\boldsymbol{B}_{\rm tot} = \frac{1}{M_{\rm beam}}\int_{\rm beam}\boldsymbol{B}\,{\rm d}M, \tag{2}$$

and this is the focus of the Crutcher et al. (2010) analysis.

Crutcher et al. (2010) carried out a Bayesian analysis to infer the distribution of $B_{\rm tot}$ as a function of the mean density of hydrogen nuclei, $\bar{n}_{\rm H}$, which extends over the range $10\,{\rm cm}^{-3} \lesssim \bar{n}_{\rm H} \lesssim 10^7\,{\rm cm}^{-3}$ in their sample. They considered several different distributions and found that the best fit to their data is a uniform distribution of $B_{\rm tot}$ from $fB_{\rm tot,max}$ to $B_{\rm tot,max}$ with

$$B_{\rm tot,\,max} = \begin{cases} B_0 & (\bar{n}_{\rm H} < n_0), \\ B_0\left(\dfrac{\bar{n}_{\rm H}}{n_0}\right)^\alpha & (\bar{n}_{\rm H} > n_0). \end{cases} \tag{3}$$

They found $B_0 = 10\,\mu{\rm G}$, $n_0 = 300\ {\rm cm}^{-3}$, $\alpha = 0.65$, and $f = 0.03 \simeq 0$.

The density n_0 dividing the constant density regime from the power-law one can be understood as the critical density, $n_{\rm H,crit}$, at which the thermal pressure in the clump balances the turbulent pressure of the ambient gas,

$$P_{\rm turb} = \bar{\rho}\sigma^2_{\rm nt} = x_{\rm tot}n_{\rm H,\,crit}k_{\rm B}T, \tag{4}$$

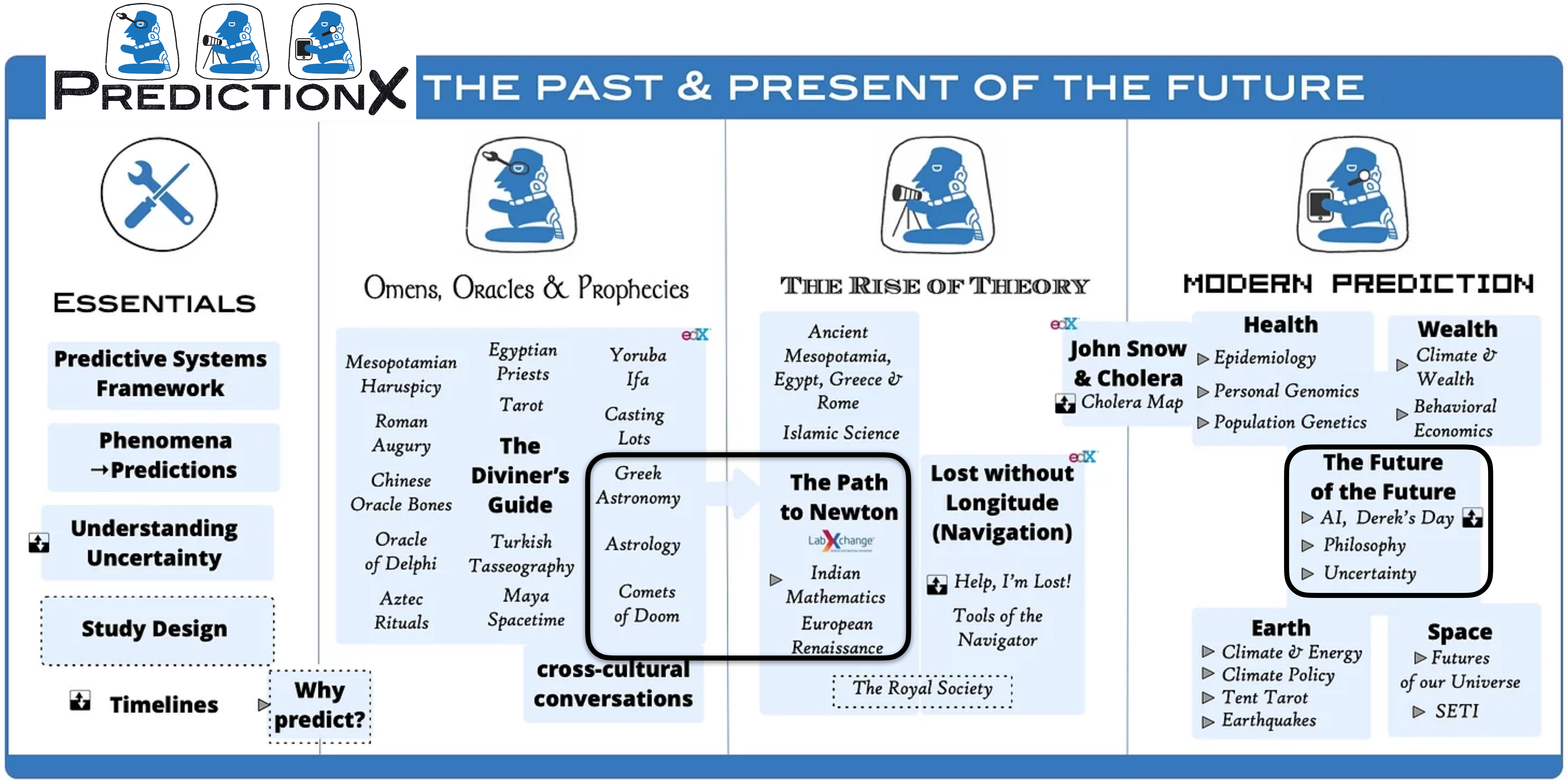
where $\bar{\rho}$ is the mean density, $x_{\rm tot} \equiv n_{\rm tot}/\bar{n}_{\rm H}$ is the total number density relative to hydrogen, and $k_{\rm B}$ is the Boltzmann constant. Since the magnetic field is about the same inside and outside the clump,

Downloaded from https://academic.oup.com/mnras/article/452/3/2500/1079561 by guest on 19 October 2023

Documentation of the MHD functionality of the “Orion” simulation code, from: Li, Pak Shing, Christopher F. McKee, and Richard I. Klein. 2015. “Magnetized Interstellar Molecular Clouds – I. Comparison between Simulations and Zeeman Observations.” Monthly Notices of the Royal Astronomical Society 452 (3): 2500–2527. https://doi.org/10.1093/mnras/stv1437.

The Prediction Project

The Past and Present of the Future



PREDICTIONX

THE PAST & PRESENT OF THE FUTURE

ESSENTIALS

Predictive Systems Framework

Phenomena →Predictions

Understanding Uncertainty

Study Design

Timelines

Why predict?

Omens, Oracles & Prophecies

Mesopotamian Haruspicy
Roman Augury
Chinese Oracle Bones
Oracle of Delphi
Aztec Rituals

Egyptian Priests
Tarot
The Diviner's Guide
Turkish Tasseography
Maya Spacetime

Yoruba Ifa
Casting Lots
Greek Astronomy
Astrology
Comets of Doom

cross-cultural conversations

THE RISE OF THEORY

Ancient Mesopotamia, Egypt, Greece & Rome
Islamic Science

The Path to Newton
LabXchange
▷ *Indian Mathematics*
European Renaissance

Lost without Longitude (Navigation)
Help, I'm Lost!
Tools of the Navigator

The Royal Society

John Snow & Cholera
Cholera Map

MODERN PREDICTION

Health
▷ *Epidemiology*
▷ *Personal Genomics*
▷ *Population Genetics*

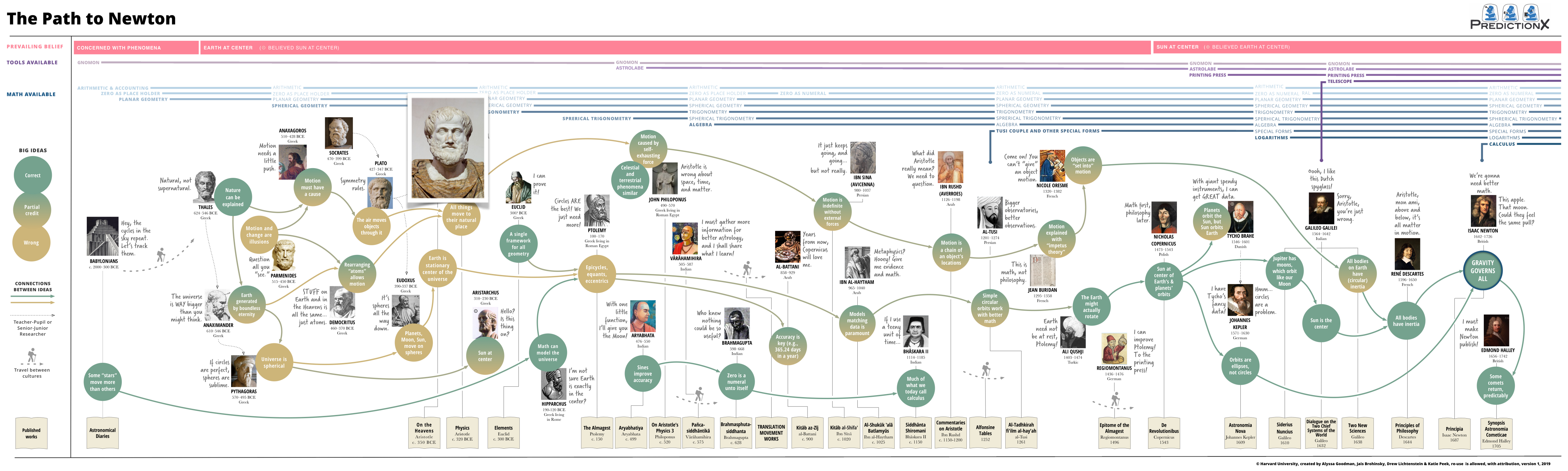
Wealth
▷ *Climate & Wealth*
▷ *Behavioral Economics*

The Future of the Future
▷ *AI, Derek's Day*
▷ *Philosophy*
▷ *Uncertainty*

Earth
▷ *Climate & Energy*
▷ *Climate Policy*
▷ *Tent Tarot*
▷ *Earthquakes*

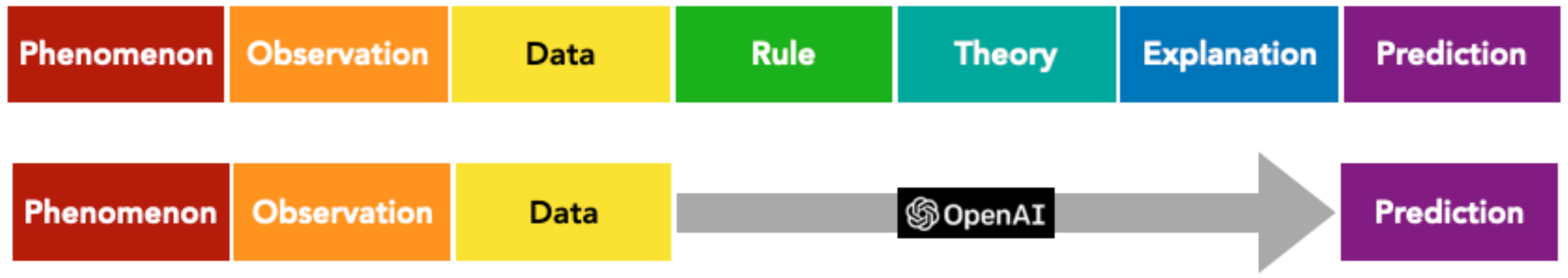
Space
▷ *Futures of our Universe*
▷ *SETI*

FROM ARISTOTLE



The Path to Newton

TO AI



Phenomenon → Observation → Data → Rule → Theory → Explanation → Prediction

Phenomenon → Observation → Data → OpenAI → Prediction

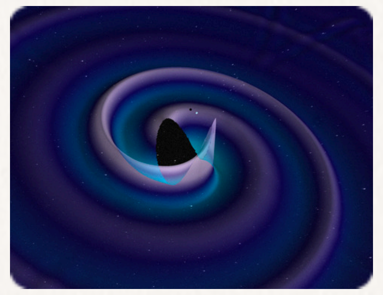
Opinion

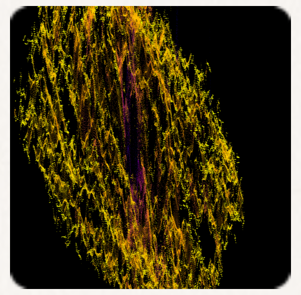
The New Universe

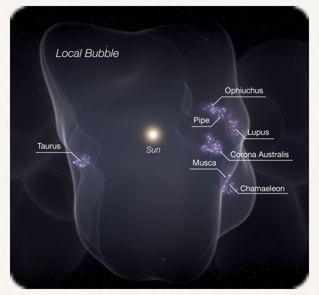
MEMPHIS, SUNDAY OCTOBER 23, 2022

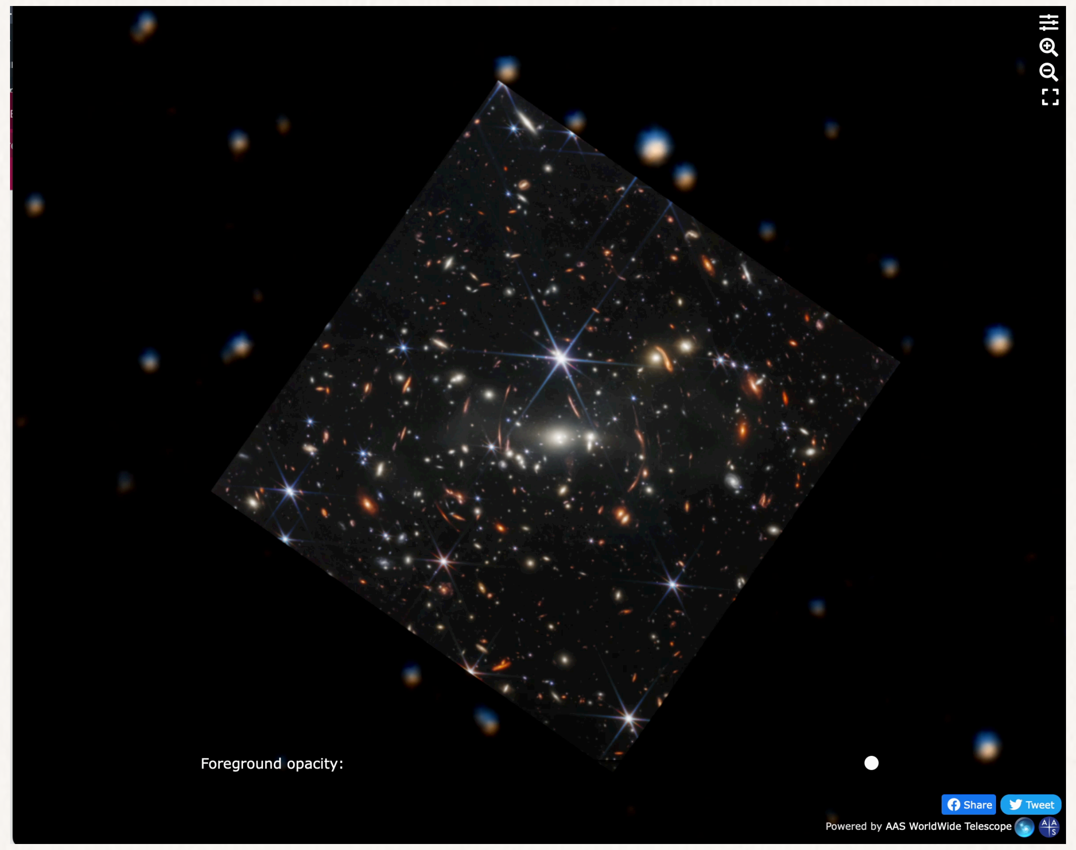
WHAT DO EXPENSIVE NEW TELESCOPES DO FOR HUMANITY TODAY?

Are mega-projects like ALMA, LIGO, JWST, and Gaia worth the billions?



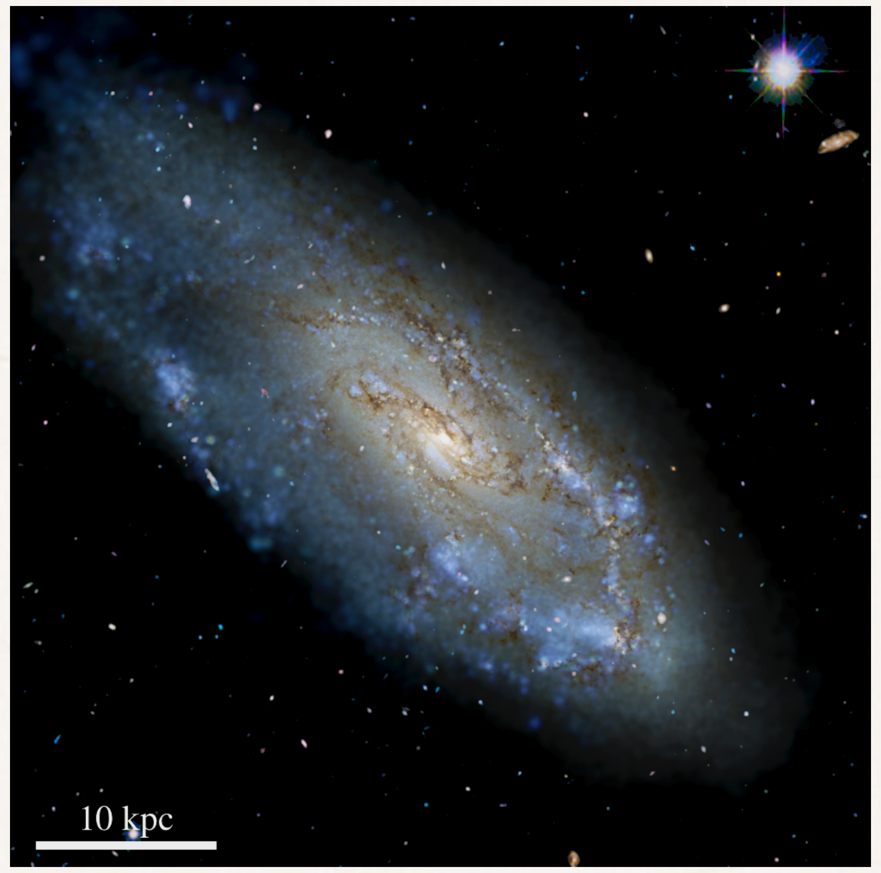


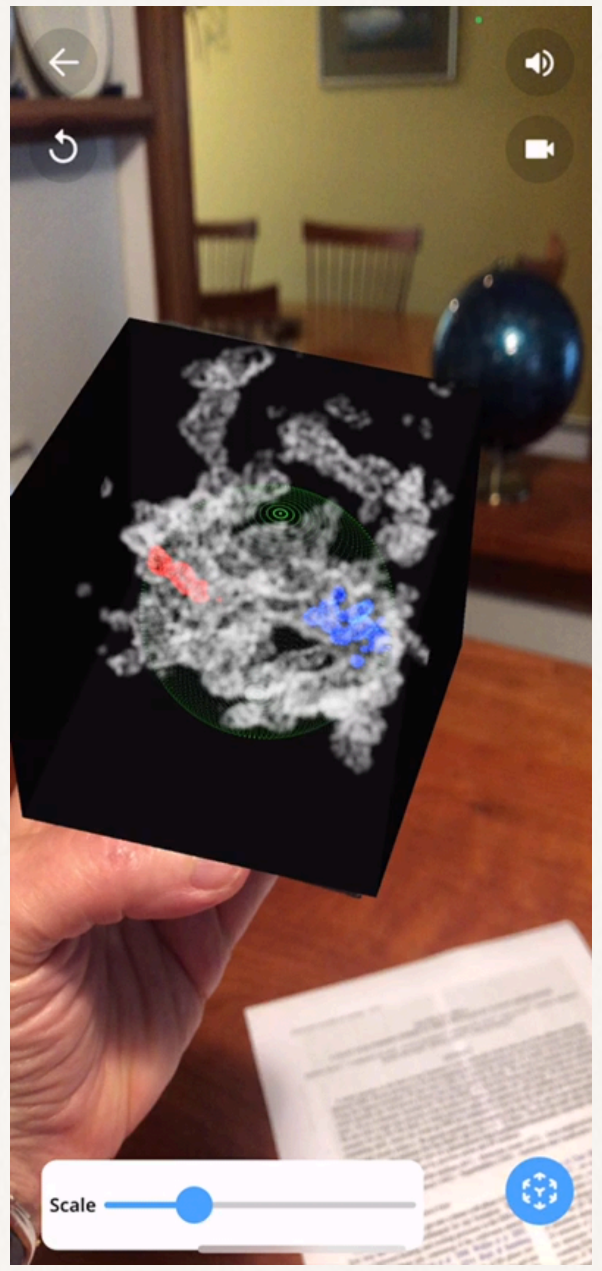

Local Bubble
Ophiuchus
Pipe
Lupus
Sun
Taurus
Corona Australis
Musca
Chamaeleon


Foreground opacity:
Share
Tweet
Powered by AAS WorldWide Telescope

ARE COMPUTERS THE NEW TELESCOPES?

New galaxies in-silico, the early Universe without physics, and new stars forming in your hand.

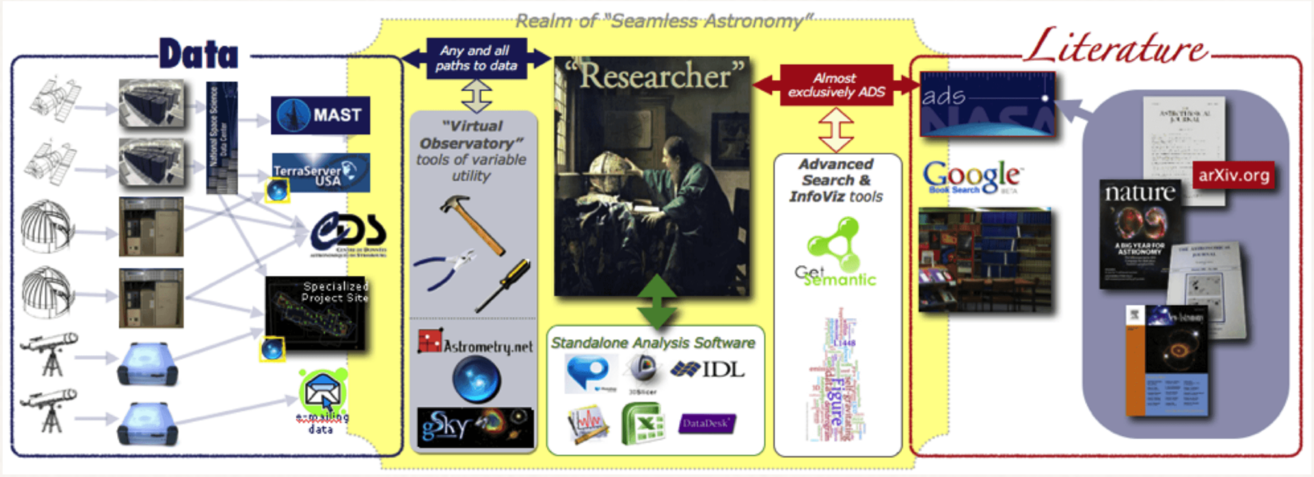




IS ASTROPHYSICS BEING (RE)ORGANIZED?

Lone stargazers are a rarer and rarer breed in professional astronomy. Teams and data scientists seem the way of the future, and tools that talk to each other are essential.

SEAMLESS ASTRONOMY
Linking scientific data, publications, and communities


Realm of "Seamless Astronomy"
Data
Literature
Any and all paths to data
"Researcher"
Almost exclusively ADS
"Virtual Observatory" tools of variable utility
Advanced Search & InfoViz tools
Standalone Analysis Software
MAST
TerraServer USA
CDS
Specialized Project Site
emailing data
National Space Science Data Center
Astrometry.net
gSky
IDL
DataDesk
GetSemantic
ads
Google Book Search
nature
arXiv.org

Editor: Alyssa Goodman, Center for Astrophysics | Harvard & Smithsonian, @AlyssaAGoodman

ARE COMPUTERS THE NEW TELESCOPES?

The Path to Newton

PREDICTIONX
predictionx.org

The Path to Newton

PREDICTIONX

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

TOOLS AVAILABLE
GNOMON
ASTROLABE
PRINTING PRESS
TELESCOPE

MATH AVAILABLE
ARITHMETIC & ACCOUNTING
ZERO AS PLACE HOLDER
PLANAR GEOMETRY
SPHERICAL GEOMETRY
ARITHMETIC
TRIGONOMETRY
SPRERICAL TRIGONOMETRY
SPHERICAL TRIGONOMETRY
ALGEBRA
ZERO AS NUMERAL
SPRERICAL TRIGONOMETRY
TUSI COUPLE AND OTHER SPECIAL FORMS
SPERHICAL TRIGONOMETRY
SPECIAL FORMS
LOGARITHMS
SPHRERICAL TRIGONOMETRY
CALCULUS

BIG IDEAS
Correct
Partial credit
Wrong

CONNECTIONS BETWEEN IDEAS
Teacher-Pupil or Senior-Junior Researcher
Travel between cultures
Published works

Hey, the cycles in the sky repeat. Let's track them.
BABYLONIANS
c. 2000–300 BCE
Some "stars" move more than others
Astronomical Diaries

Natural, not supernatural.
THALES
624–546 BCE
Greek
Nature can be explained

The universe is WAY bigger than you might think.
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Earth generated by boundless eternity

If circles are perfect, spheres are sublime.
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570–495 BCE
Greek
Universe is spherical

Motion needs a little push.
ANAXAGOROS
510–428 BCE
Greek
Motion must have a cause

Motion and change are illusions
Question all you "see."
PARMENIDES
515–450 BCE
Greek

SOCRATES
470–399 BCE
Greek

Symmetry rules.
PLATO
427–347 BCE
Greek
The air moves objects through it

STUFF on Earth and in the Heavens is all the same… just atoms.
DEMOCRITUS
460–370 BCE
Greek
Rearranging "atoms" allows motion

It's spheres all the way down.
EUDOXUS
390-337 BCE
Greek
Planets, Moon, Sun, move on spheres

💕Circles spheres, beauty, eternity…
…oh, and you're So wrong about motion, Plato.
ARISTOTLE
383–322 BCE
Greek
All things move to their natural place
Earth is stationary center of the universe
On the Heavens
Aristotle
c. 350 BCE
Physics
Aristotle
c. 320 BCE

☉ Hello? Is this thing on?
ARISTARCHUS
310–230 BCE
Greek
Sun at center

I can prove it!
EUCLID
300? BCE
Greek
A single framework for all geometry
Elements
Euclid
c. 300 BCE

I'm not sure Earth is exactly in the center?
HIPPARCHUS
190-120 BCE
Greek living in Rome
Math can model the universe

Circles ARE the best! We just need more!
PTOLEMY
100–170
Greek living in Roman Egypt
Epicycles, equants, eccentrics
The Almagest
Ptolemy
c. 150

With one little function, I'll give you the Moon!
ARYABHATA
476–550
Indian
Sines improve accuracy
Aryabhatiya
Aryabhata
c. 499

Aristotle is wrong about space, time, and matter.
JOHN PHILOPONUS
490–570
Greek living in Roman Egypt
Motion caused by self-exhausting force
Celestial and terrestrial phenomena similar
On Aristotle's Physics 3
Philoponus
c. 520

I must gather more information for better astrology, and I shall share what I learn!
VĀRĀHAMIHIRA
505–587
Indian
Pañca-siddhāntikā
Vārāhamihira
c. 575

Who knew nothing could be so useful?
BRAHMAGUPTA
598–668
Indian
Zero is a numeral unto itself
Brahmasphuta-siddhanta
Brahmagupta
c. 628

TRANSLATION MOVEMENT WORKS

Years from now, Copernicus will love me.
AL-BATTANI
858–929
Arab
Accuracy is key (e.g., 365.24 days in a year)
Kitāb az-Zīj
al-Battani
c. 900

It just keeps going, and going… but not really.
IBN SINA (AVICENNA)
980–1037
Persian
Motion is indefinite without external forces
Kitāb al-Shifa'
Ibn Sīnā
c. 1020

Metaphysics? Hooey! Give me evidence and math.
IBN AL-HAYTHAM
965–1040
Arab
Models matching data is paramount
Al-Shukūk 'alā Batlamyūs
Ibn al-Haytham
c. 1025

If I use a teeny unit of time…
BHĀSKARA II
1114–1185
Indian
Much of what we today call calculus
Siddhānta Shiromani
Bhāskara II
c. 1150

What did Aristotle really mean? We need to question.
IBN RUSHD (AVERROES)
1126–1198
Arab
Motion is a chain of an object's locations
Commentaries on Aristotle
Ibn Rushd
c. 1150-1200

Alfonsine Tables
1252

Bigger observatories, better observations.
AL-TUSI
1201–1274
Persian
Simple circular orbits work with better math
Al-Tadhkirah fi'ilm al-hay'ah
al-Tusi
1261

This is math, not philosophy.
JEAN BURIDAN
1295–1358
French
Motion explained with "impetus theory"

Come on! You can't "give" an object motion.
NICOLE ORESME
1320–1382
French
Objects are "set into" motion

Earth need not be at rest, Ptolemy!
ALI QUSHJI
1403–1474
Turkic
The Earth might actually rotate

I can improve Ptolemy! To the printing press!
REGIOMONTANUS
1436–1476
German
Epitome of the Almagest
Regiomontanus
1496

Math first, philosophy later.
NICHOLAS COPERNICUS
1473–1543
Polish
Sun at center of Earth's & planets' orbits
De Revolutionibus
Copernicus
1543

With giant spendy instruments, I can get GREAT data.
⊕
TYCHO BRAHE
1546–1601
Danish
Planets orbit the Sun, but Sun orbits Earth

I have Tycho's fancy data!
Hmm… circles are a problem.
JOHANNES KEPLER
1571–1630
German
Orbits are ellipses, not circles
Astronomia Nova
Johannes Kepler
1609

Oooh, I like this Dutch spyglass!
Sorry, Aristotle, you're just wrong.
GALILEO GALILEI
1564–1642
Italian
Jupiter has moons, which orbit like our Moon
Sun is the center
All bodies on Earth have (circular) inertia
Siderius Nuncius
Galileo
1610
Dialogue on the Two Chief Systems of the World
Galileo
1632
Two New Sciences
Galileo
1638

Aristotle, mon ami, above and below, it's all matter in motion.
RENÉ DESCARTES
1596–1650
French
All bodies have inertia
Principles of Philosophy
Descartes
1644

We're gonna need better math.
This apple. That moon. Could they feel the same pull?
ISAAC NEWTON
1642–1726
British
GRAVITY GOVERNS ALL
Principia
Isaac Newton
1687

I must make Newton publish!
EDMOND HALLEY
1656–1742
British
Some comets return, predictably
Synopsis Astronomia Cometicae
Edmond Halley
1705

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

The Path to Newton

2000 B.C.

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

TOOLS AVAILABLE
GNOMON
GNOMON
ASTROLABE

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

BIG IDEAS
Correct
Partial credit
Wrong

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Teacher-Pupil or Senior-Junior Researcher

Travel between cultures

Published works

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460–370 BCE
Greek
STUFF on Earth and in the Heavens is all the same… just atoms.

Rearranging "atoms" allows motion

PLATO
427–347 BCE
Greek
Symmetry rules.

The air moves objects through it

EUDOXUS
390-337 BCE
Greek
It's spheres all the way down.

Planets, Moon, Sun, move on spheres

ARISTOTLE
383–322 BCE
Greek
Circles, spheres, beauty, eternity…
…oh, and you're So wrong about motion, Plato.

All things move to their natural place

Earth is stationary center of the universe

On the Heavens
Aristotle
c. 350 BCE

Physics
Aristotle
c. 320 BCE

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

Elements
Euclid
c. 300 BCE

HIPPARCHUS
190-120 BCE
Greek living in Rome
I'm not sure Earth is exactly in the center?

Math can model the universe

PTOLEMY
100–170
Greek living in Roman Egypt
Circles ARE the best! We just need more!

Epicycles, equants, eccentrics

The Almagest
Ptolemy
c. 150

ARYABHATA
476–550
Indian
With one little function, I'll give you the Moon!

Sines improve accuracy

Aryabhatiya
Aryabhata
c. 499

Motion caused by self-exhausting force

Celestial and terrestrial phenomena similar

JOHN PHILOPONUS
490–570
Greek living in Roman Egypt
Aristotle is wrong about space, time, and matter.

On Aristotle's Physics 3
Philoponus
c. 520

VĀRĀHAMIHIRA
505–587
Indian
I must gather more information for better astrology, and I shall share what I learn!

Pañca-siddhāntikā
Vārāhamihira
c. 575

BRAHMAGUPTA
598–668
Indian
Who knew nothing could be so useful?

Zero is a numeral unto itself

Brahmasphuta-siddhanta
Brahmagupta
c. 628

TRANSLATION MOVEMENT WORKS

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

AL-BATTANI
858–929
Arab
Years from now, Copernicus will love me.

Kitāb az-Zīj
al-Battani
c. 900

It just kee
going, a
going
but not reall

Motion is indefinite without external forces

IB

Kitāb a
Ibn
c.

SUN AT CENTER (⊕ BELIEVED EARTH AT CENTER)

GNOMON
ASTROLABE

GNOMON
ASTROLABE
PRINTING PRESS

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

ARITHMETIC
ZERO AS PLACE HOLDER
ZERO AS NUMERAL
PLANAR GEOMETRY
SPHERICAL GEOMETRY
TRIGONOMETRY
SPHERICAL TRIGONOMETRY
ALGEBRA

ARITHMETIC
ZERO AS NUMERAL
PLANAR GEOMETRY
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TRIGONOMETRY
SPRERICAL TRIGONOMETRY
ALGEBRA
TUSI COUPLE AND OTHER SPECIAL FORMS

ARITHMETIC
ZERO AS NUMERA
PLANAR GEOMETR
SPHERICAL GEOM
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SPERHICAL TRIGO
ALGEBRA
SPECIAL FORMS
LOGARITHMS

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3–322 BCE
Greek

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IBN SINA (AVICENNA)
980–1037
Persian

Motion is indefinite without external forces

IBN AL-HAYTHAM
965–1040
Arab

Metaphysics? Hooey! Give me evidence and math.

Models matching data is paramount

What did Aristotle really mean? We need to question.

IBN RUSHD (AVERROES)
1126–1198
Arab

Motion is a chain of an object's locations

If I use a teeny unit of time...

BHĀSKARA II
1114–1185
Indian

Much of what we today call calculus

AL-TUSI
1201–1274
Persian

Bigger observatories, better observations.

Simple circular orbits work with better math

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

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1320–1382
French

Objects are "set into" motion

Motion explained with "impetus theory"

This is math, not philosophy.

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French

Earth need not be at rest, Ptolemy!

ALI QUSHJI
1403–1474
Turkic

The Earth might actually rotate

REGIOMONTANUS
1436–1476
German

I can improve Ptolemy! To the printing press!

Math first, philosophy later.

NICHOLAS COPERNICUS
1473–1543
Polish

Sun at center of Earth's & planets' orbits

With giant spendy instruments, I can get GREAT data.

Planets orbit the Sun, but Sun orbits Earth

⊕ **TYCHO BRAHE**
1546–1601
Danish

I have Tycho's fancy data!

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Hmm... circles are a problem.

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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

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Regiomontanus
1496

De Revolutionibus
Copernicus
1543

Astronomia Nova
Johannes Kepler
1609

Siderius Nuncius
Galileo
1610

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PREDICTIONX

SUN AT CENTER (⊕ BELIEVED EARTH AT CENTER)

GNOMON
ASTROLABE
PRINTING PRESS
TELESCOPE

E HOLDER
ZERO AS NUMERAL
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RY
IGONOMETRY

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LOGARITHMS
CALCULUS

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Hmm… circles are a problem.

JOHANNES KEPLER
1571–1630
German

Orbits are ellipses, not circles

Oooh, I like this Dutch spyglass!

Sorry, Aristotle, you're just wrong.

GALILEO GALILEI
1564–1642
Italian

Jupiter has moons, which orbit like our Moon

Sun is the center

All bodies on Earth have (circular) inertia

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

RENÉ DESCARTES
1596–1650
French

All bodies have inertia

We're gonna need better math.

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

ISAAC NEWTON
1642–1726
British

GRAVITY GOVERNS ALL

1700

I must make Newton publish!

EDMOND HALLEY
1656–1742
British

Some comets return, predictably

rahmasphuta-siddhanta
Brahmagupta
c. 628

TRANSLATION MOVEMENT WORKS

Kitāb az-Zīj
al-Battani
c. 900

Kitāb al-Shifa'
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Siderius Nuncius
Galileo
1610

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Galileo
1632

Two New Sciences
Galileo
1638

Principles of Philosophy
Descartes
1644

Principia
Isaac Newton
1687

Synopsis Astronomia Cometicae
Edmond Halley
1705

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“ARE COMPUTERS THE NEW TELESCOPES?”

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

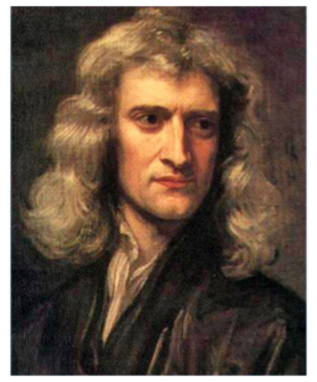
I like
Dutch
lass!

Sorry,
Aristotle,
you’re just
wrong.

GALILEI

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

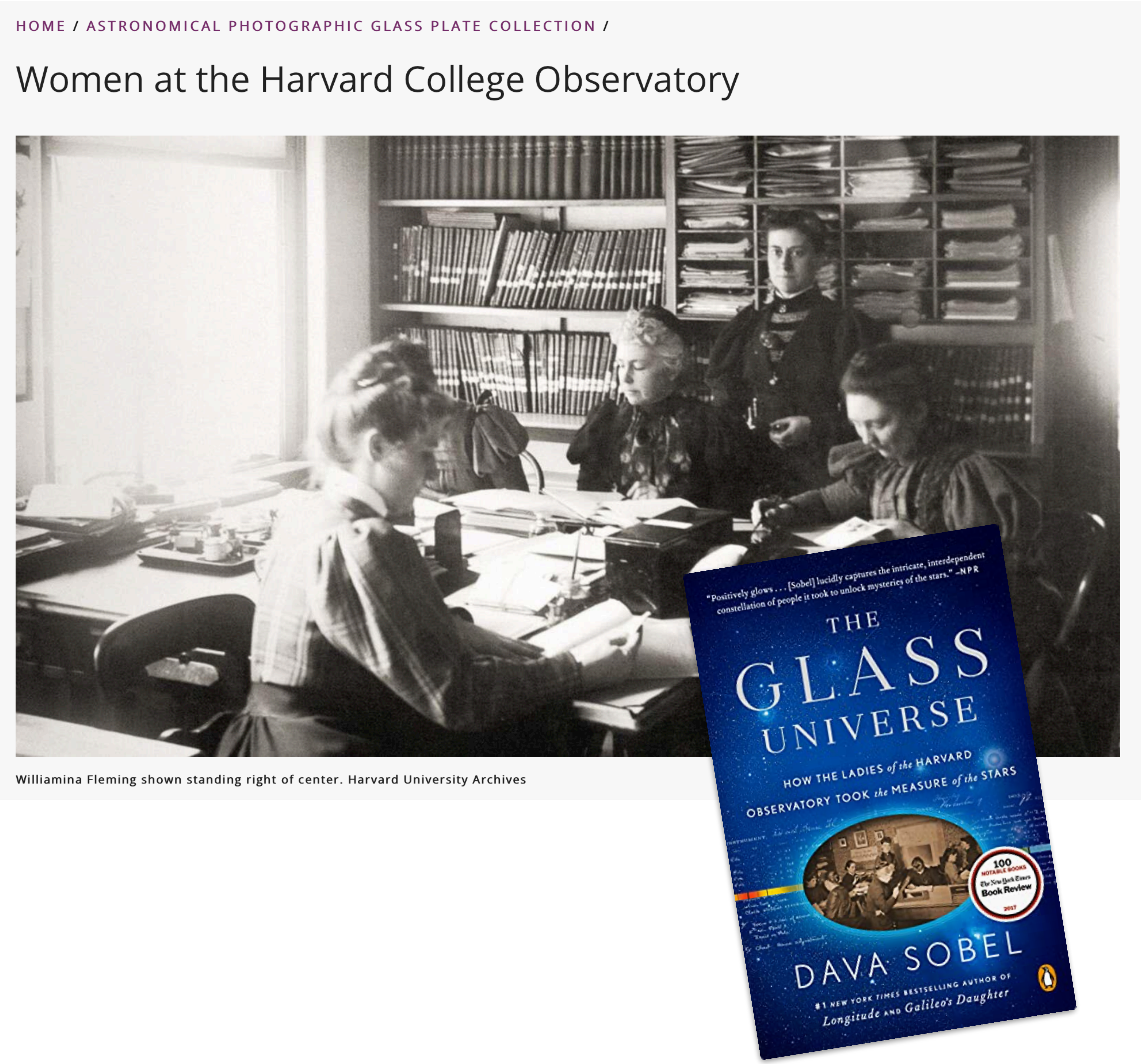
We’re gonna
need better
math.



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

DATA SCIENCE IN ASTRONOMY BEGAN AT HARVARD

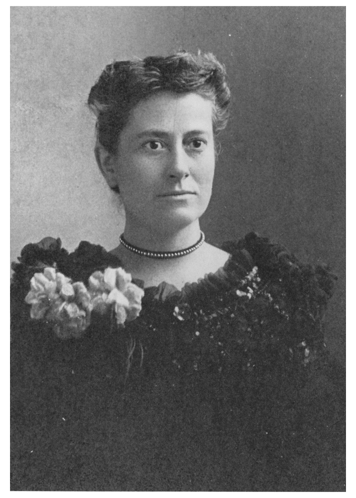
With HUMAN COMPUTERS


HOME / ASTRONOMICAL PHOTOGRAPHIC GLASS PLATE COLLECTION /

Women at the Harvard College Observatory

Williamina Fleming shown standing right of center. Harvard University Archives

"Positively glows . . . [Sobel] lucidly captures the intricate, interdependent constellation of people it took to unlock mysteries of the stars." -NPR
THE GLASS UNIVERSE
HOW THE LADIES of the HARVARD OBSERVATORY TOOK the MEASURE of the STARS
100 NOTABLE BOOKS The New York Times Book Review 2017
DAVA SOBEL
#1 NEW YORK TIMES BESTSELLING AUTHOR OF Longitude AND Galileo's Daughter



Williamina Fleming

Discovered Horsehead Nebula in 1888 and the first white dwarf in 1910. She became the first woman with an officially appointed job at Harvard as Curator of Astronomical Photographs in 1898.

Antonia Maury

First to detect and calculate the orbit of a spectroscopic binary, which was published in 1933. She worked intermittently with Harvard College Observatory before returning in 1918 as an adjunct professor until her retirement in 1948.

Henrietta Swan Leavitt

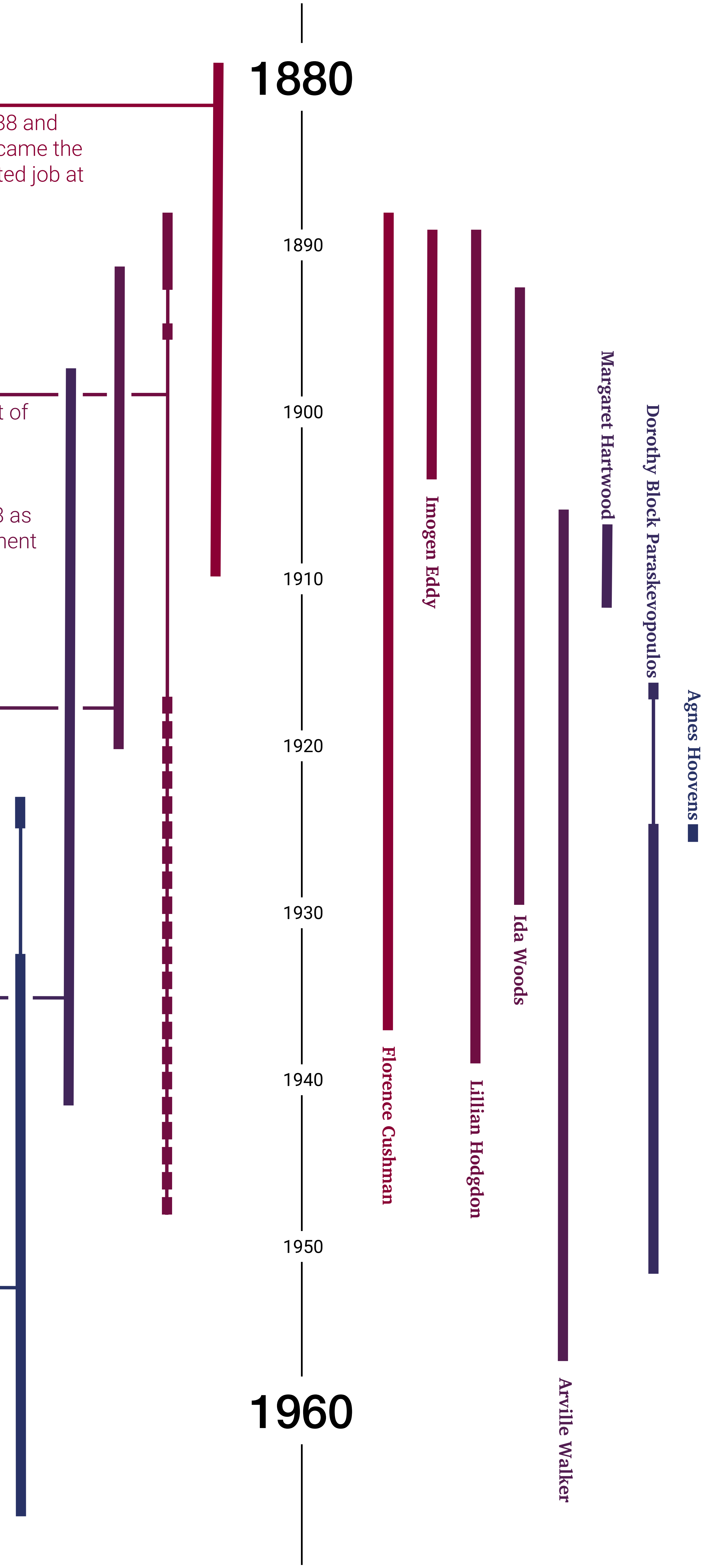
Found period-luminosity relation for Cepheid variable stars in 1912, providing astronomers with the first "standard candle" with which to measure the distance to faraway galaxies.

Annie Jump Cannon

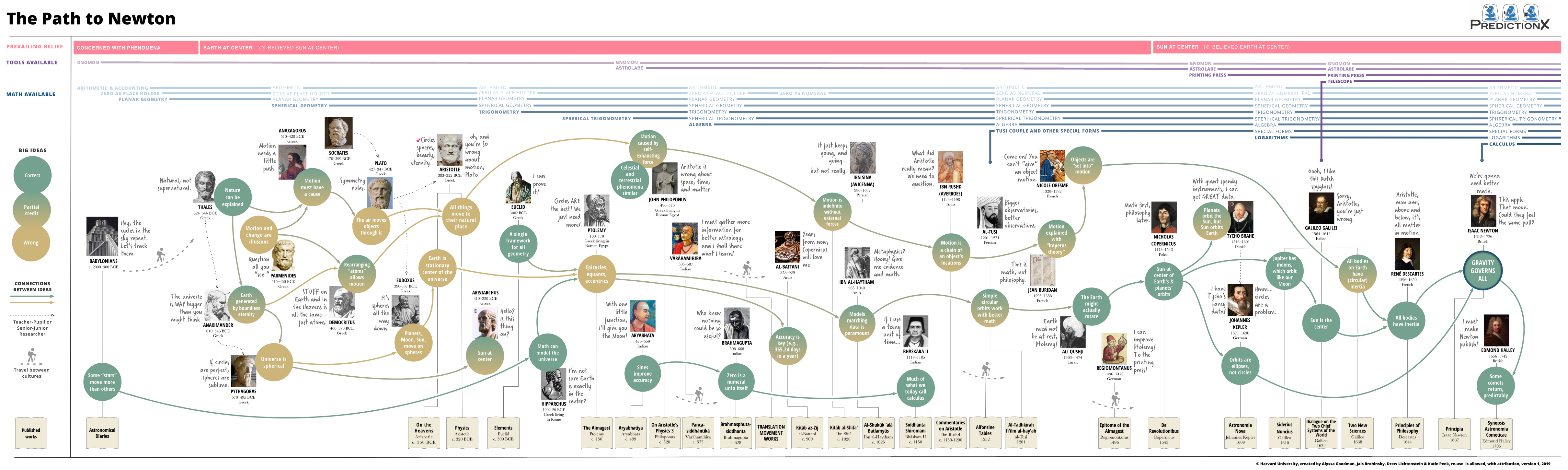
Developed the Harvard Classification Scheme in 1922, the stellar classification system still in use today. In 1938, two years before retirement, she finally obtained a regular appointment from Harvard as William C. Bond Astronomer.

Cecilia Payne-Gaposchkin

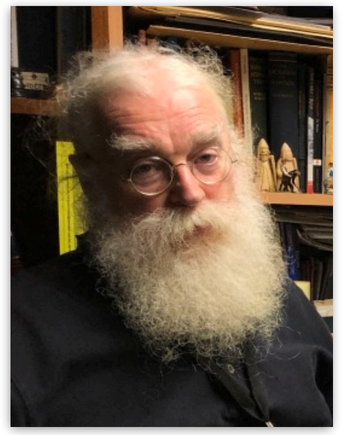
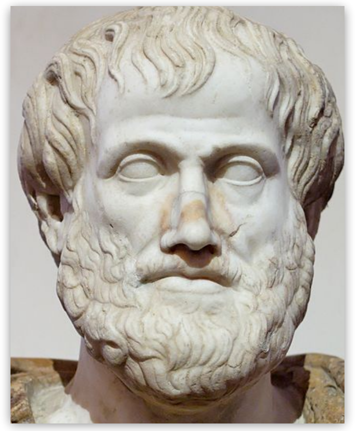
Determined the chemical composition of stars, particularly that hydrogen and helium are the most abundant elements.
She was the first person awarded a PhD in Astronomy at Harvard, and in 1956 she became Harvard's first regularly appointed female professor and the first female department chair.

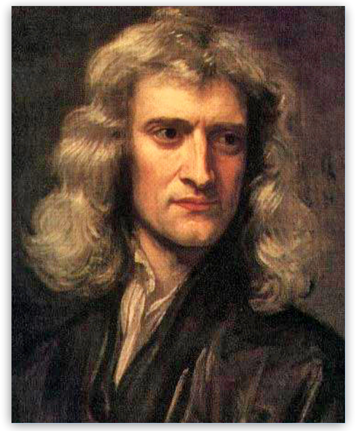


The “Padua Rainbow”


The Path to Newton
PredictionX
© Harvard University, created by Alyssa Goodman, Jais Brohinsky, Drew Lichtenstein & Katie Peek, re-use is allowed, with attribution, version 1, 2019

path-to.org



Babylonians	Phenomenon	Observation	Data	Rule			
Aristotle	Phenomenon	Observation			Theory	Explanation	Predict
Kepler 1609	Phenomenon	Observation	Data	Rule			Prediction
Newton 1687	Phenomenon	Observation	Data	Rule	Theory	Explanation	Prediction

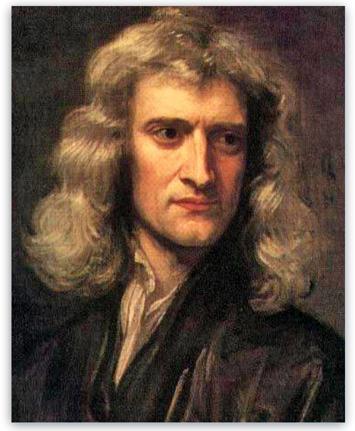
Path To Newton – brought to you by PredictionX

All things move to their natural place

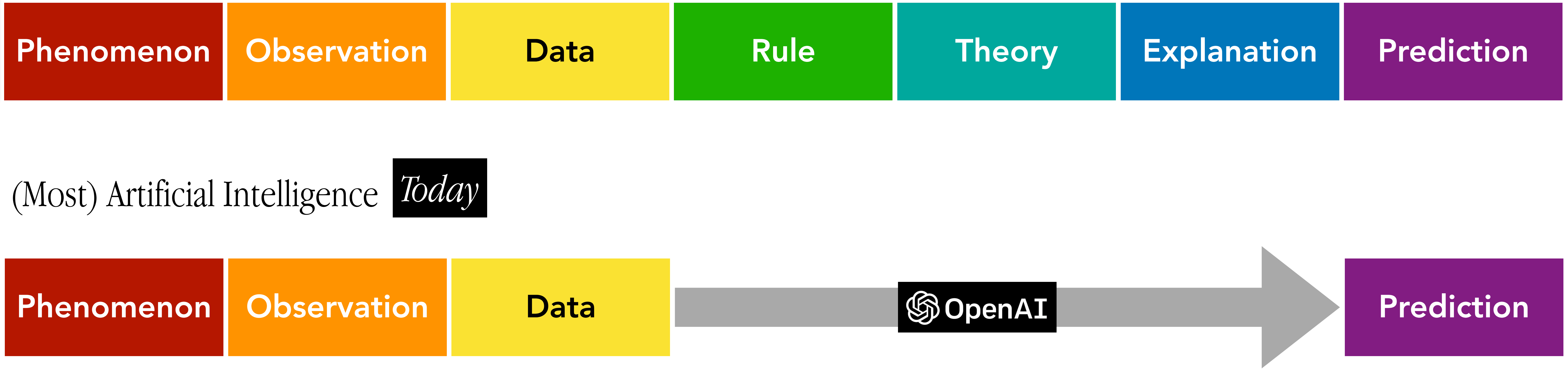
Aristotle (384 - 322 BCE) - [hearts] Circles, spheres, beauty, eternity

Aristotle had a grand theory of motion, based on the concept that different types of matter had each their “natural place.” He subscribed to the prevailing theory of matter which held that all *Earthly* substance was comprised of the four elements: earth, air, fire, and water.

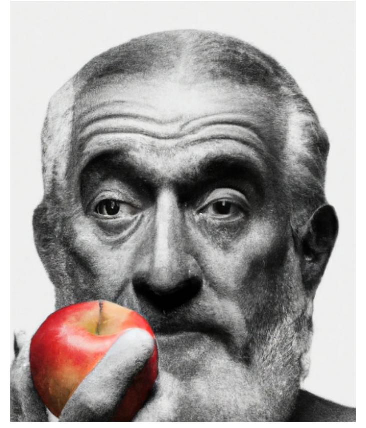
Schema huius præmiſſæ diuiſionis Sphærarum.



Newton *1687*



Phenomenon | Observation | Data | Rule | Theory | Explanation | Prediction



(Most) Artificial Intelligence *Today*

Phenomenon | Observation | Data → OpenAI → Prediction

We will come back to this later…

How do stars form?

Open Session
Export Session
Import Data
Export Data/Subsets
Link Data
Arithmetic attributes
Active Subset:
None/Create New
(the next selection will create a subset)
Terminal
Preferences
Alves-Bialy-Foley-O'Neill-Zucker
3D views
Earth/Planet/Sky Viewer (WWT)

Data Collection

Data
- Edenhofer2023_mean_and_std_xyz[MEAN]
- Hunt2023_
- ONeill2023_
- 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]

Plot Layers - Earth/Planet/Sky Viewer (WWT)
- ☑ Bialy2021_ApJL_919_L5_MW3D[HDU1]
- ☑ Alves2020_Nat_578_237_MW3D[HDU1]
- ☑ ONeill2023_LocalBubble
- ☑ Zucker2021_ApJ_919_35_spines_MW3D[HDU1]
- ☑ Foley2022_arXiv_2212.01405_OrionShell_MW3D[HDU1]

Fixed

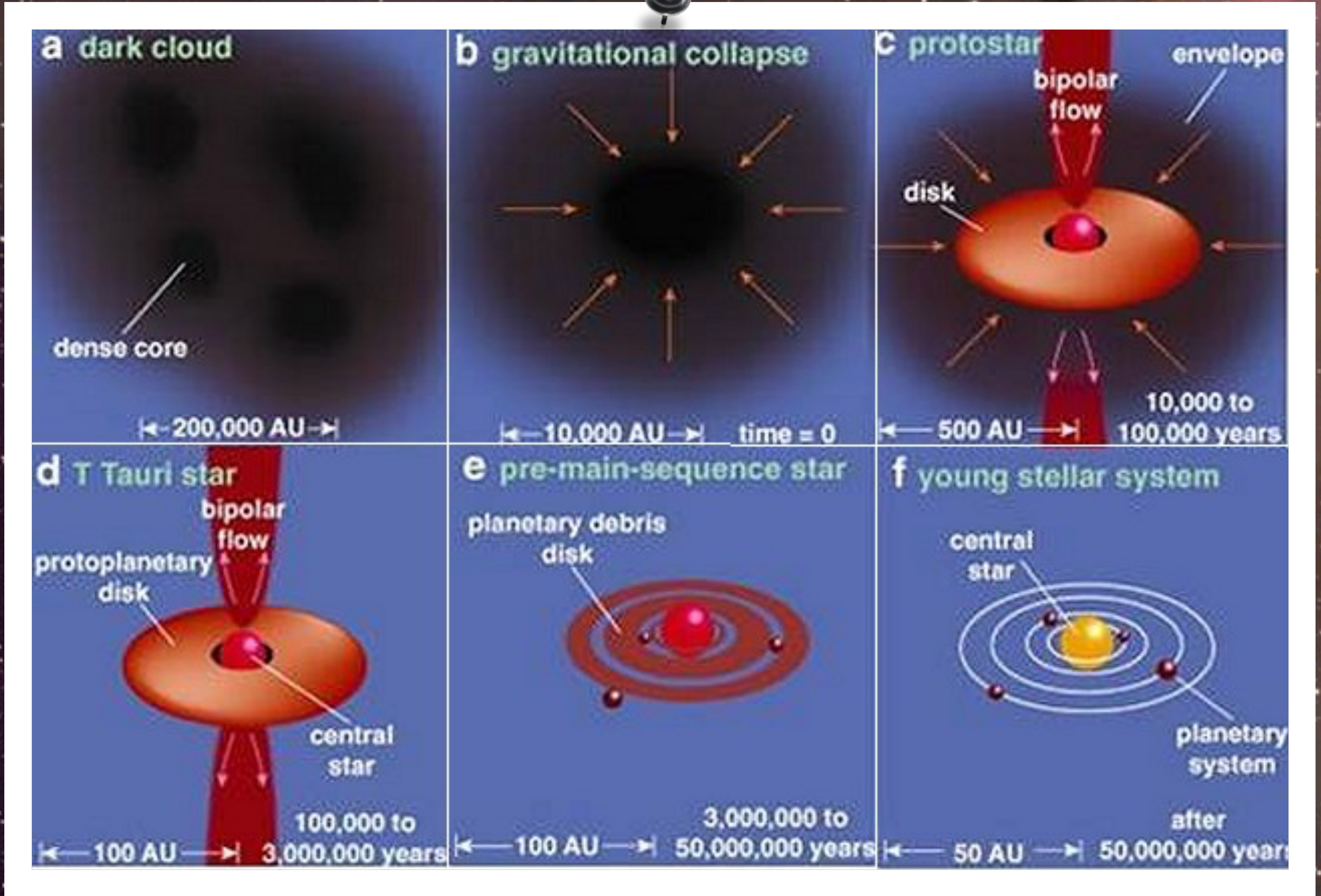
Plot Options - Earth/Planet/Sky Viewer (WWT)

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

Phenomenon | **Observation** | **Data** | **Rule** | **Theory** | **Explanation** | **Prediction**

The image in the background shows how I study this question today… but first, let's look back 20 years first…

How do stars form?


a dark cloud
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
bipolar flow
envelope
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years

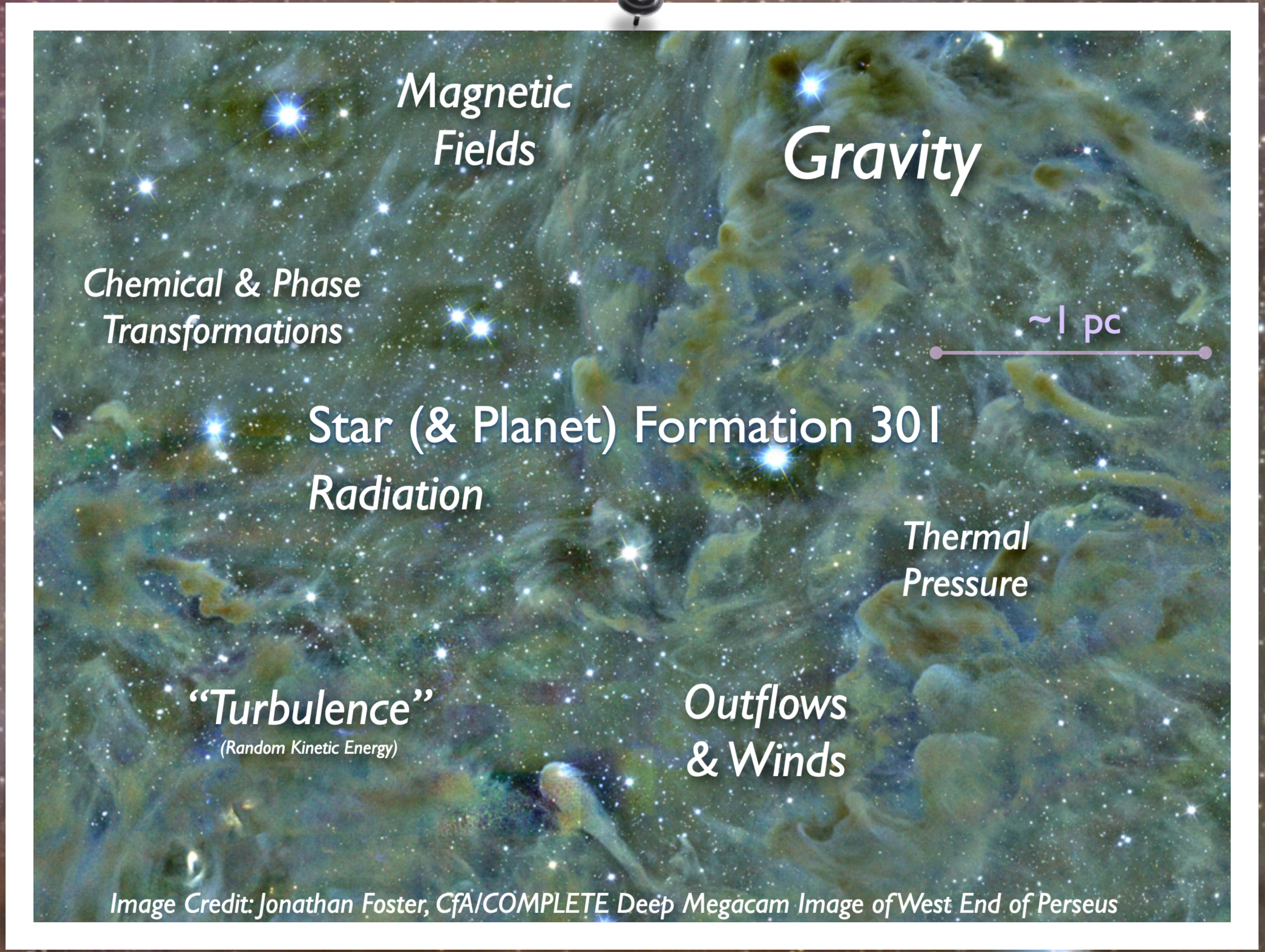

Magnetic Fields
Gravity
Chemical & Phase Transformations
~1 pc
Star (& Planet) Formation 301
Radiation
Thermal Pressure
"Turbulence"
(Random Kinetic Energy)
Outflows & Winds

Image Credit: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus

Perseus

www.flickr.com/photos/66496709@N00/6791649829/in/photostream

© Adam Block/Science Photo Library

How do stars form?

Phenomenon

Observation

Data

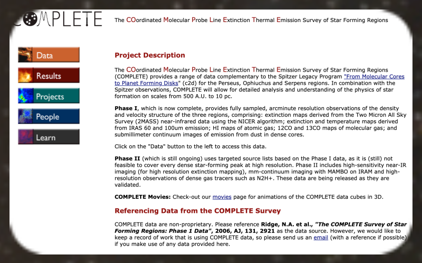
Rule

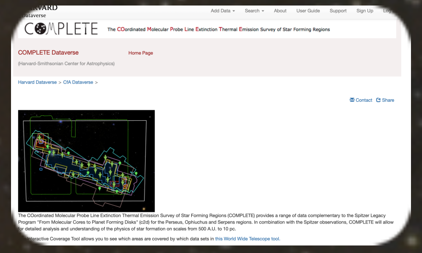
Theory

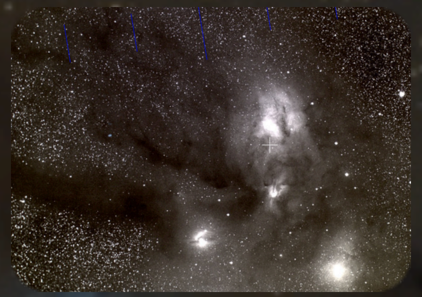
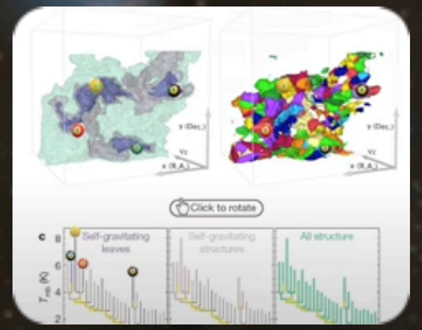
Explanation

Prediction

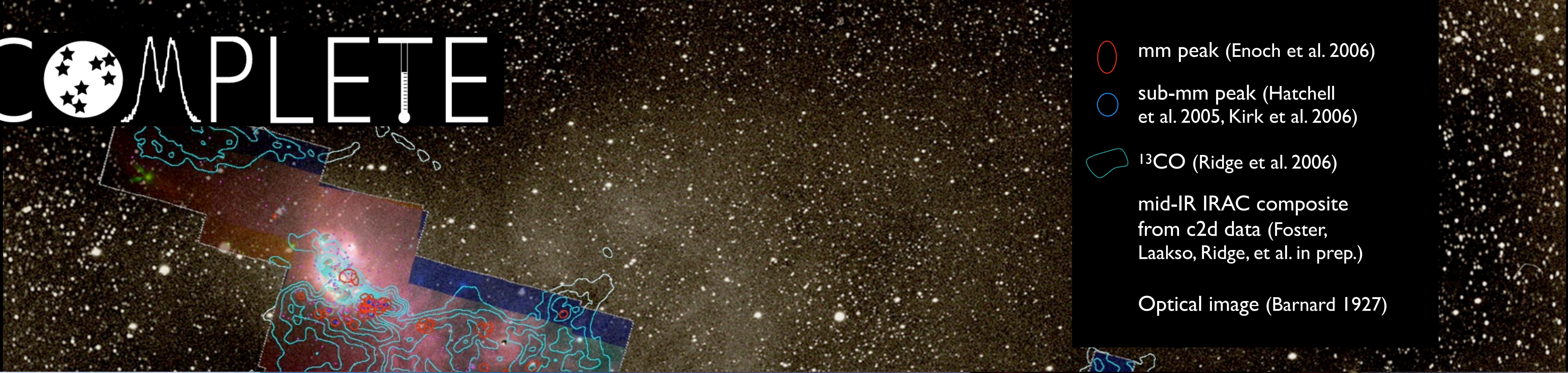
Phenomenon	*Looks like* there are stars and clouds of darkness in the Sky.
Observation	Let’s *observe* them every way we know how.
Data	And *keep track* of everything we find.
Rule	Bright nebulae are often *near* dark cloudy patches.
Theory	Stars *form* from *collapsing* gas in the clouds.
Explanation	Bright nebulae are *caused* by new stars lighting up clouds.
Prediction	Dark clouds form new stars, *even if we can’t see them*.





COMPLETE



○ mm peak (Enoch et al. 2006)

○ sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)

〰 ^{13}CO (Ridge et al. 2006)

mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al. in prep.)

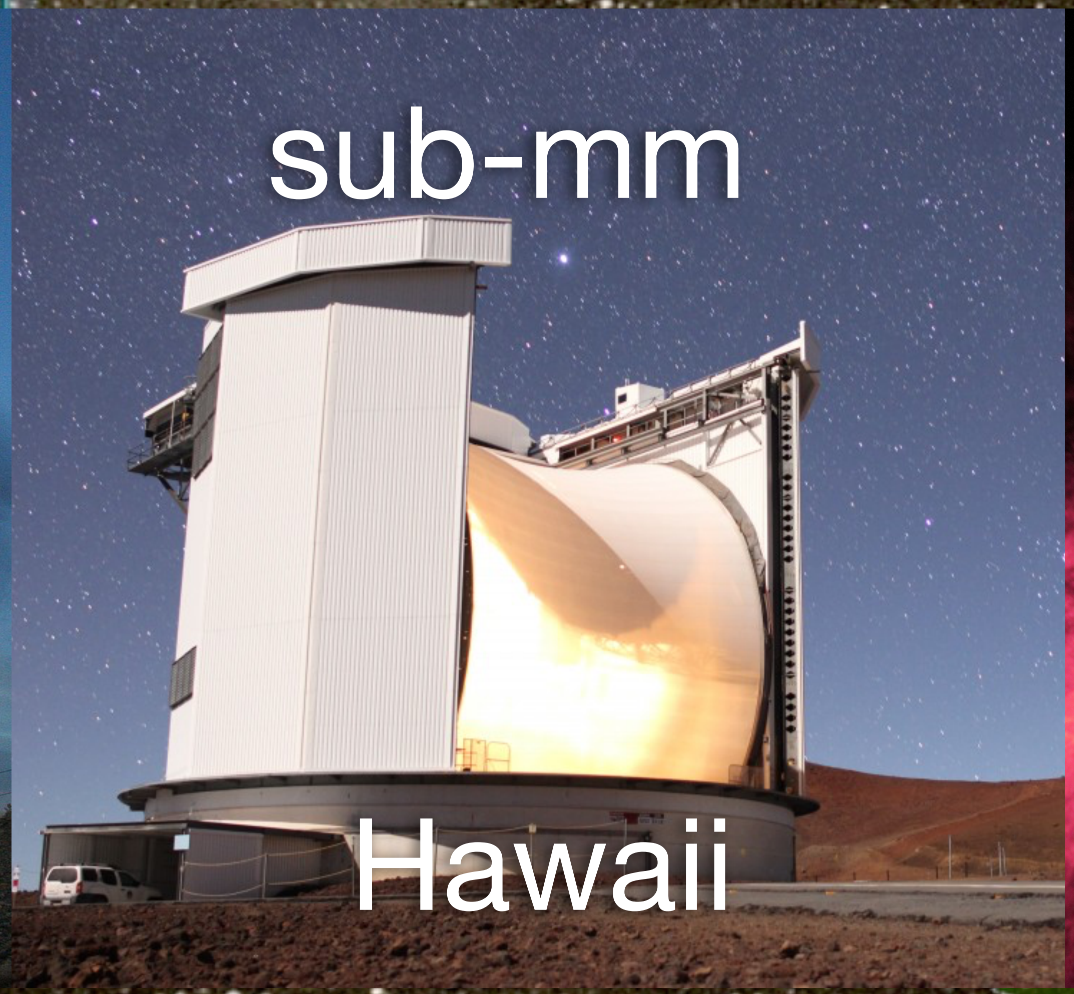
Optical image (Barnard 1927)

mm-wave

Massachusetts

mm/sub-mm

Spain

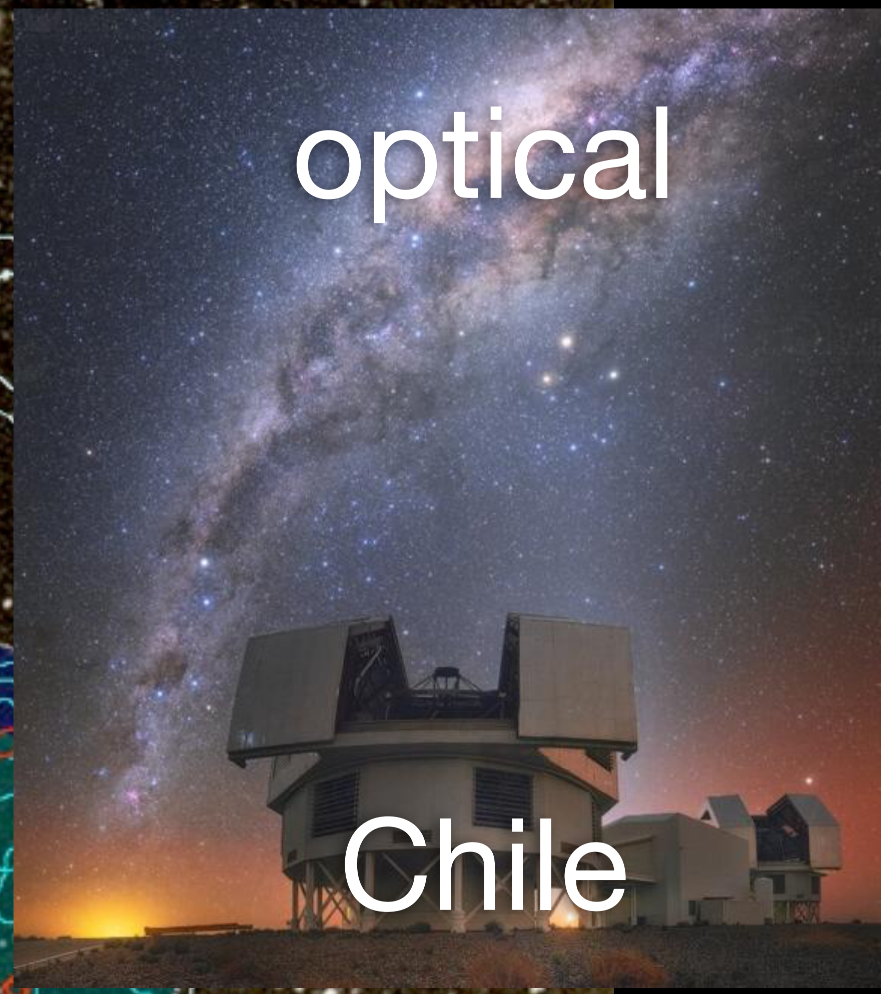


sub-mm

Hawaii

infrared

Space



optical

Chile

2002-11

WEBB
SPACE TELESCOPE

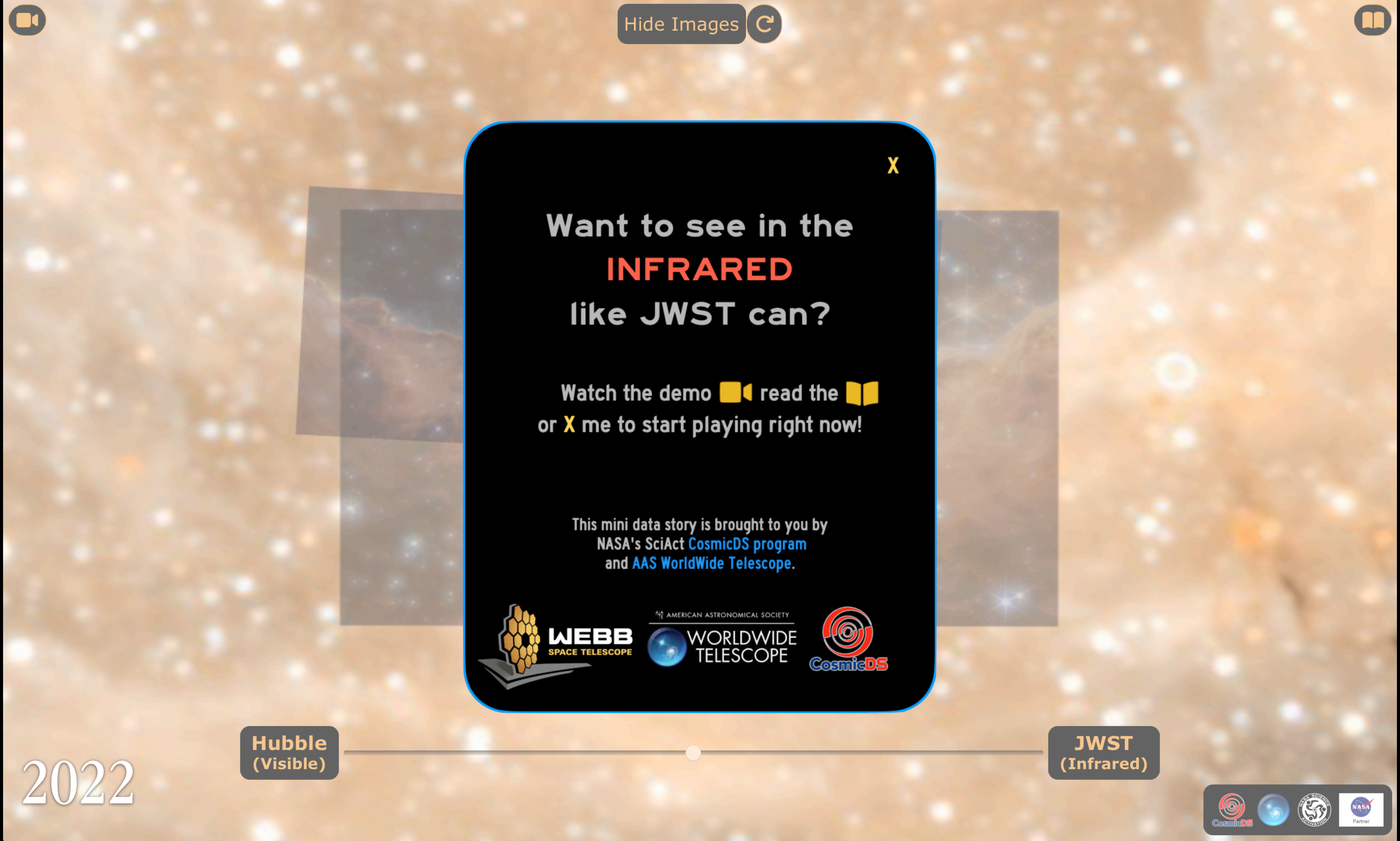
Portion of electromagnetic spectrum that humans are capable of seeing

Gamma
X-ray
Ultraviolet
Infrared
Microwave
Radio
Hubble
Spitzer

Portion of spectrum that JWST is capable of detecting

2022

Spectrum image credit: Jen Christiansen, Scientific American


Hide Images
Hubble (Visible)
JWST (Infrared)
2022
X

Want to see in the **INFRARED** like JWST can?

Watch the demo, read the, or X me to start playing right now!

This mini data story is brought to you by NASA's SciAct CosmicDS program and AAS WorldWide Telescope.

WorldWide Telescope
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Collections > JWST >
1 of 6
Up Level
A FEAST for the ...
M51 (NIRCam im...
M51 (MIRI image)
Westerlund 2
Webb captures d...
Webb captures d...
Galaxy cluster W...
The life and times...
Webb spotlights ...
Webb identifies t...
Clash of the Titans
rbig-Haro 46/4...
Look At
Sky
Imagery
Digitized Sky Survey (Color)
Image Crossfade
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Carina Nebula Je...
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HR4169
IC2599
HR4179
Tracking
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Carina
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RA: 10h37m11.3s
Dec: -58:37:010

WorldWide
Telescope

Is that arc part of
a bubble in ***3D****??*

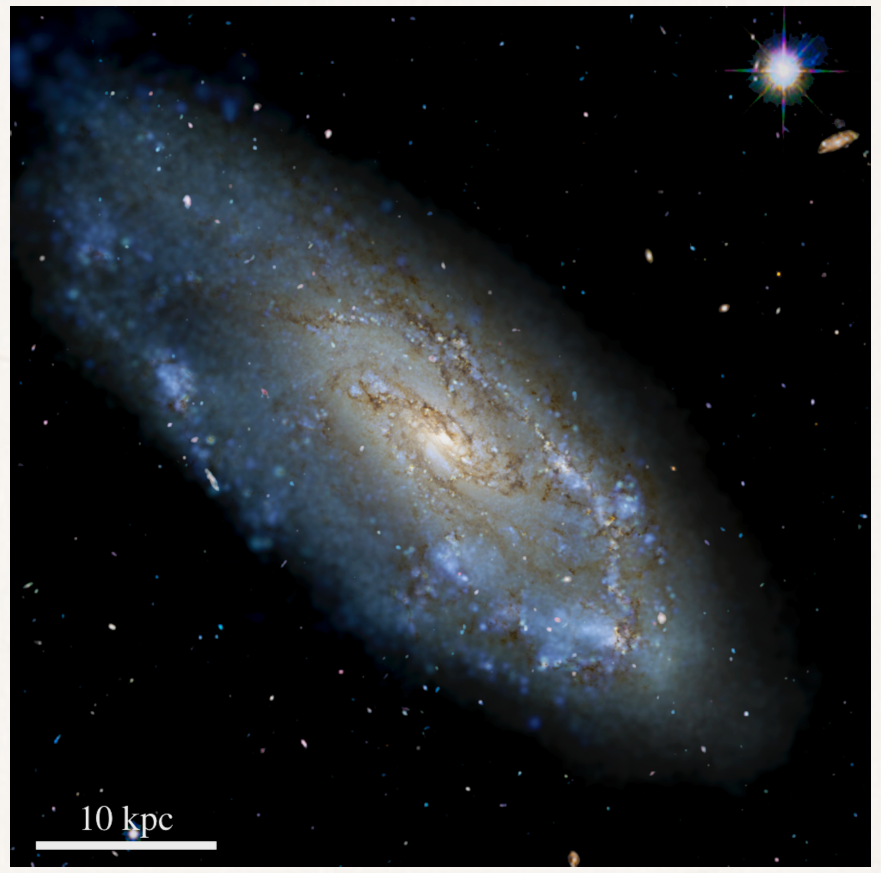
Opinion

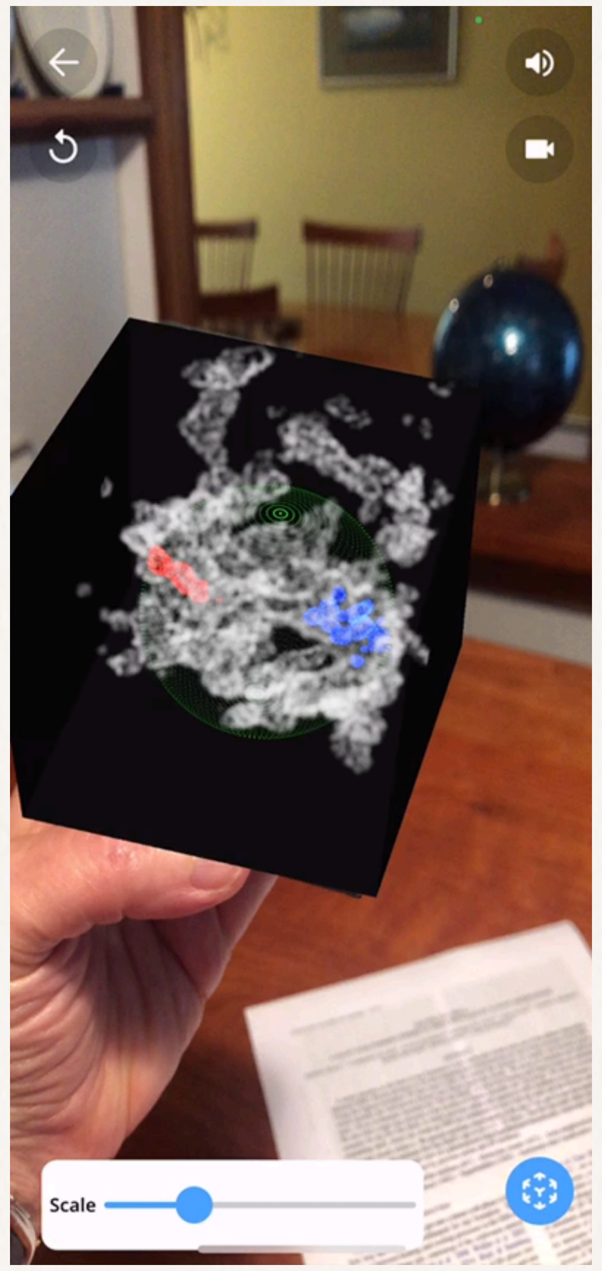
The New Universe

MEMPHIS, SUNDAY OCTOBER 23, 2022

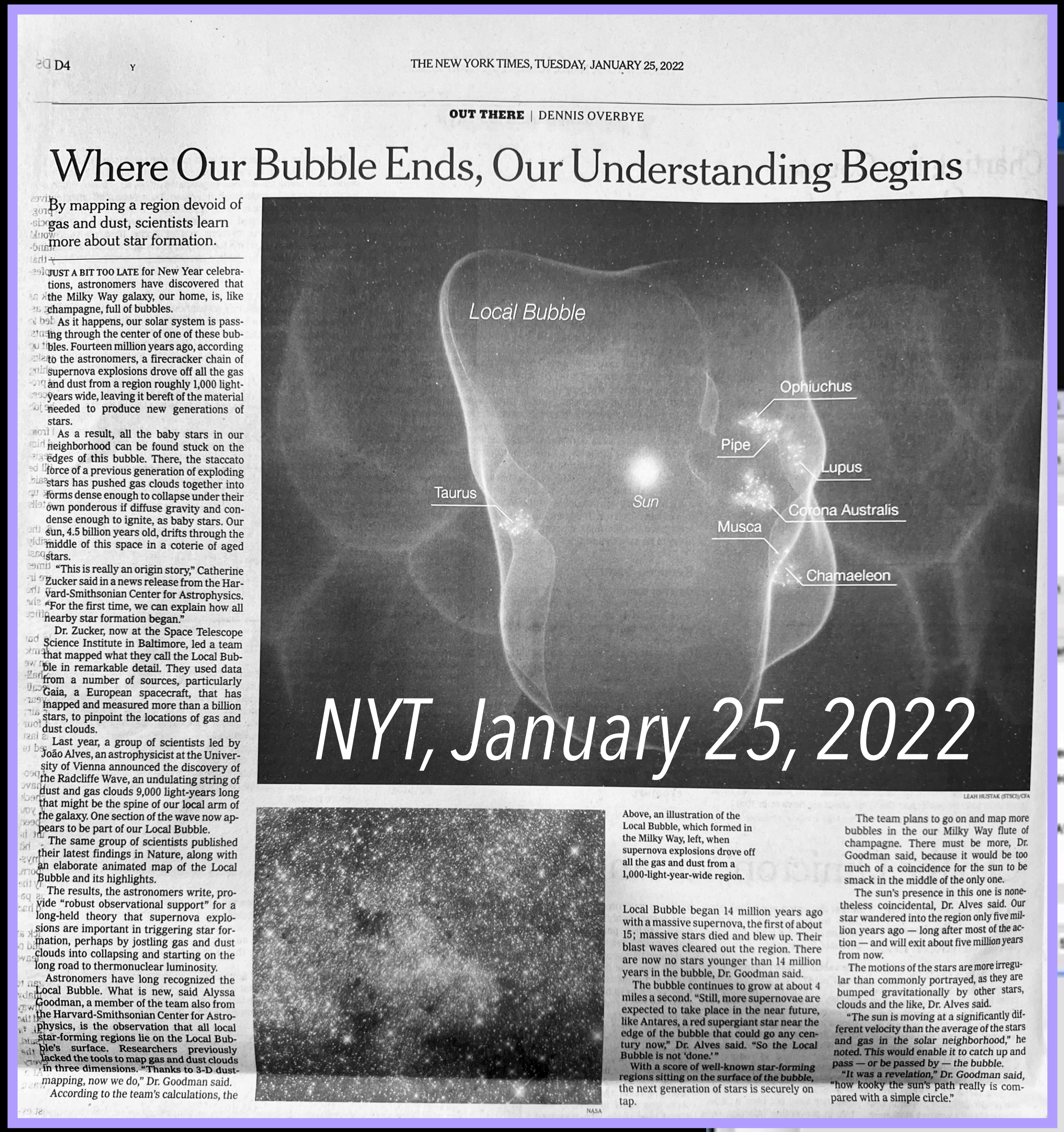
ARE COMPUTERS THE NEW TELESCOPES?

New galaxies in-silico, the early Universe without physics, and new stars forming in your hand.





Editor: Alyssa Goodman, Center for Astrophysics | Harvard & Smithsonian, @AlyssaAGoodman


Local Bubble
Ophiuchus
Pipe
Lupus
Taurus
Sun
Musca
Corona Australis
Chamaeleon

D4 THE NEW YORK TIMES, TUESDAY, JANUARY 25, 2022

OUT THERE | DENNIS OVERBYE

Where Our Bubble Ends, Our Understanding Begins

By mapping a region devoid of gas and dust, scientists learn more about star formation.

JUST A BIT TOO LATE for New Year celebrations, astronomers have discovered that the Milky Way galaxy, our home, is, like champagne, full of bubbles.

As it happens, our solar system is passing through the center of one of these bubbles. Fourteen million years ago, according to the astronomers, a firecracker chain of supernova explosions drove off all the gas and dust from a region roughly 1,000 light-years wide, leaving it bereft of the material needed to produce new generations of stars.

As a result, all the baby stars in our neighborhood can be found stuck on the edges of this bubble. There, the staccato force of a previous generation of exploding stars has pushed gas clouds together into forms dense enough to collapse under their own ponderous if diffuse gravity and condense enough to ignite, as baby stars. Our sun, 4.5 billion years old, drifts through the middle of this space in a coterie of aged stars.

"This is really an origin story," Catherine Zucker said in a news release from the Harvard-Smithsonian Center for Astrophysics. "For the first time, we can explain how all nearby star formation began."

Dr. Zucker, now at the Space Telescope Science Institute in Baltimore, led a team that mapped what they call the Local Bubble in remarkable detail. They used data from a number of sources, particularly Gaia, a European spacecraft, that has mapped and measured more than a billion stars, to pinpoint the locations of gas and dust clouds.

Last year, a group of scientists led by João Alves, an astrophysicist at the University of Vienna announced the discovery of the Radcliffe Wave, an undulating string of dust and gas clouds 9,000 light-years long that might be the spine of our local arm of the galaxy. One section of the wave now appears to be part of our Local Bubble.

The same group of scientists published their latest findings in Nature, along with an elaborate animated map of the Local Bubble and its highlights.

The results, the astronomers write, provide "robust observational support" for a long-held theory that supernova explosions are important in triggering star formation, perhaps by jostling gas and dust clouds into collapsing and starting on the long road to thermonuclear luminosity.

Astronomers have long recognized the Local Bubble. What is new, said Alyssa Goodman, a member of the team also from the Harvard-Smithsonian Center for Astrophysics, is the observation that all local star-forming regions lie on the Local Bubble's surface. Researchers previously lacked the tools to map gas and dust clouds in three dimensions. "Thanks to 3-D dust-mapping, now we do," Dr. Goodman said.

According to the team's calculations, the Local Bubble began 14 million years ago with a massive supernova, the first of about 15; massive stars died and blew up. Their blast waves cleared out the region. There are now no stars younger than 14 million years in the bubble, Dr. Goodman said.

The bubble continues to grow at about 4 miles a second. "Still, more supernovae are expected to take place in the near future, like Antares, a red supergiant star near the edge of the bubble that could go any century now," Dr. Alves said. "So the Local Bubble is not 'done.'"

With a score of well-known star-forming regions sitting on the surface of the bubble, the next generation of stars is securely on tap.

The team plans to go on and map more bubbles in the our Milky Way flute of champagne. There must be more, Dr. Goodman said, because it would be too much of a coincidence for the sun to be smack in the middle of the only one.

The sun's presence in this one is nonetheless coincidental, Dr. Alves said. Our star wandered into the region only five million years ago — long after most of the action — and will exit about five million years from now.

The motions of the stars are more irregular than commonly portrayed, as they are bumped gravitationally by other stars, clouds and the like, Dr. Alves said.

"The sun is moving at a significantly different velocity than the average of the stars and gas in the solar neighborhood," he noted. This would enable it to catch up and pass — or be passed by — the bubble.

"It was a revelation," Dr. Goodman said, "how kooky the sun's path really is compared with a simple circle."

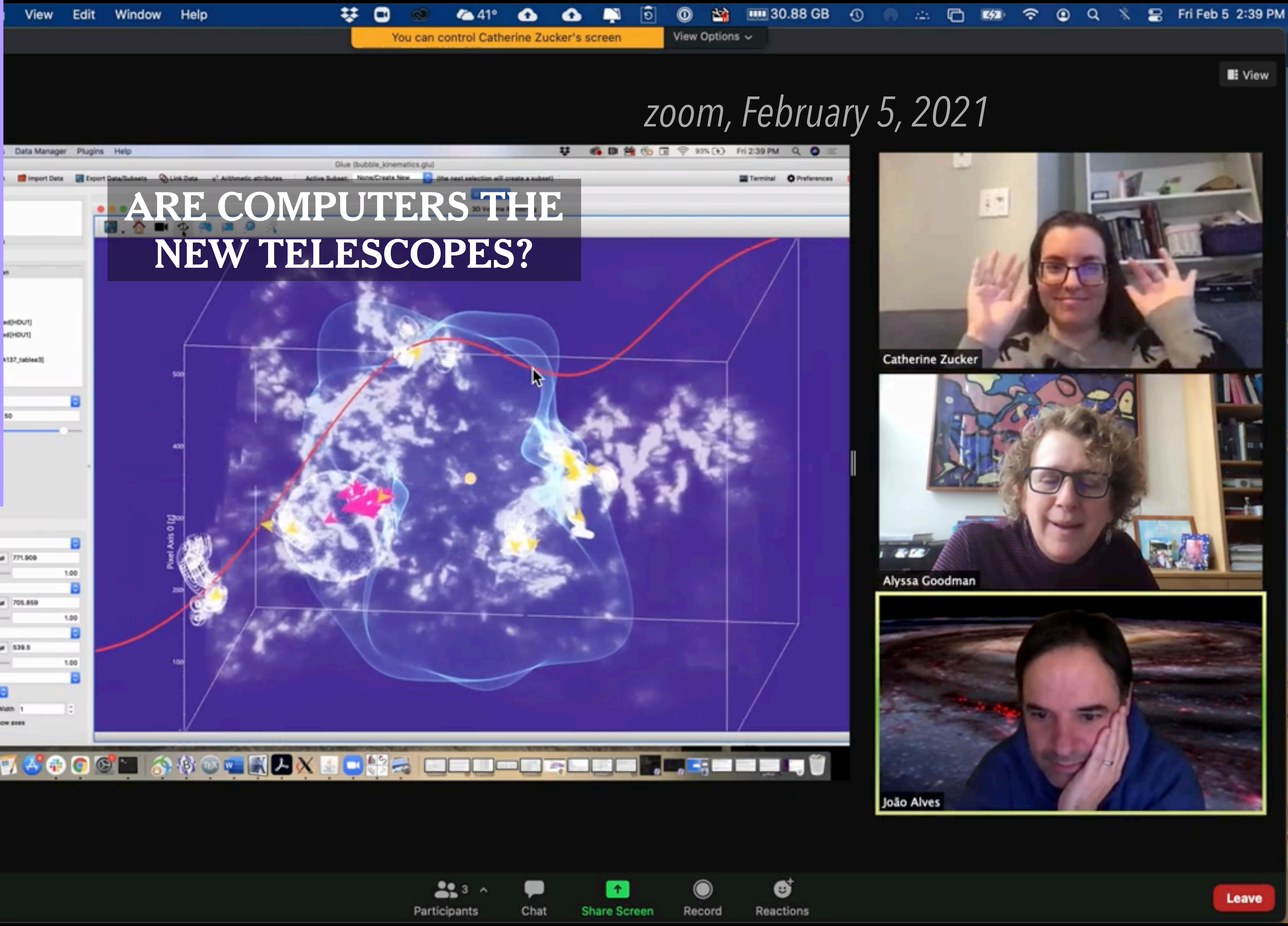
Above, an illustration of the Local Bubble, which formed in the Milky Way, left, when supernova explosions drove off all the gas and dust from a 1,000-light-year-wide region.

LEAH HUSTAK (STSCI)/CFA

NASA

NYT, January 25, 2022

"…a bubble in **3D**??"



ARE COMPUTERS THE NEW TELESCOPES?

zoom, February 5, 2021

A Bubbly Origin

for Stars Around the Sun

Narrator & Project Lead: Dr. Catherine Zucker (CfA)

EARLIER *TODAY*…

HHSF2023
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Participants
Venue & Travel
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Code of Conduct
Contact
Resources (Private)
PHILLIPS AUDITORIUM
D

October 16-20, 2023

Harvard-Heidelberg Star Formation Workshop 2023

The Impact of Feedback on Star and Planet Formation

at Center for Astrophysics | Harvard & Smithsonian

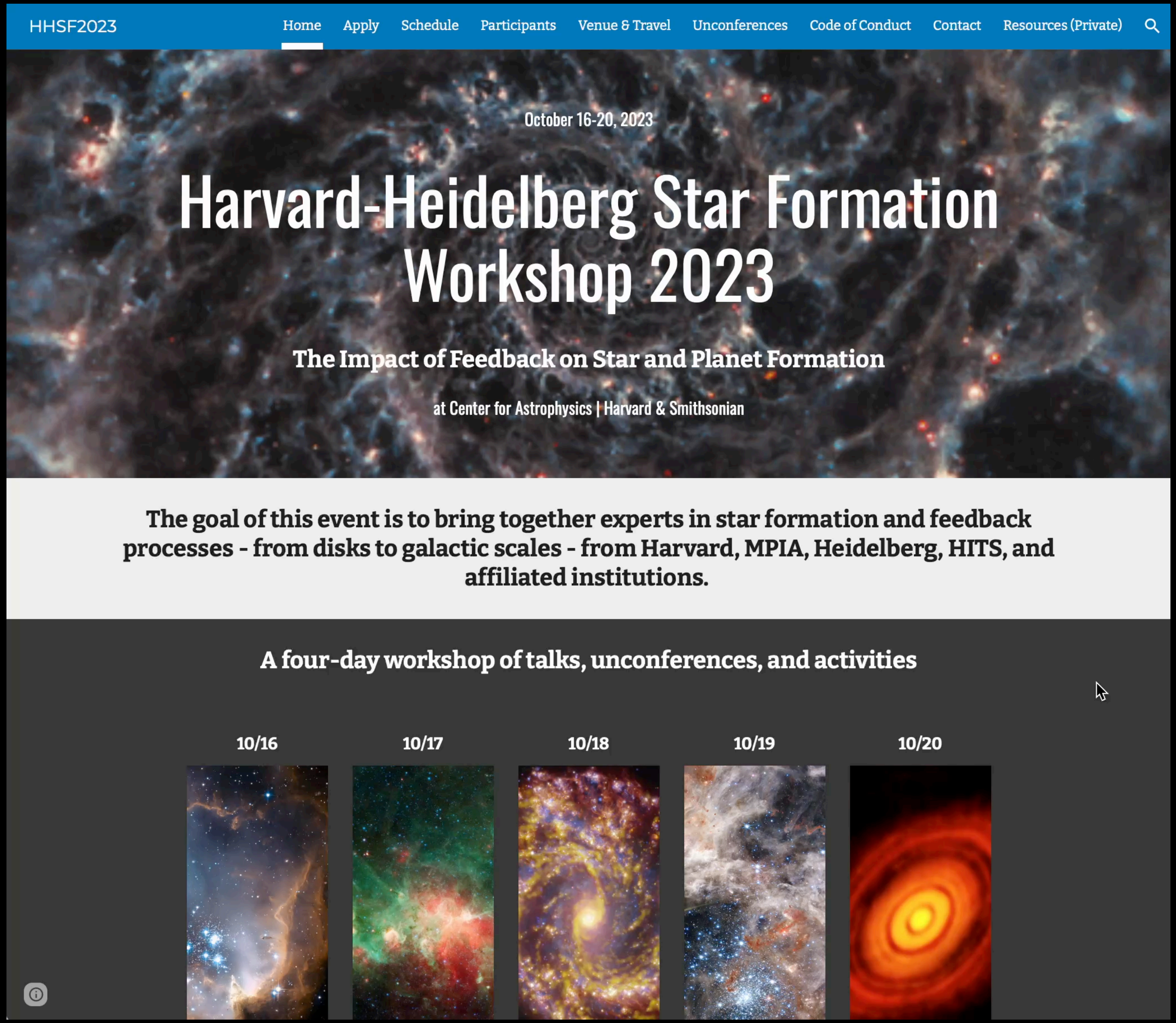
The goal of this event is to bring together experts in star formation and feedback processes - from disks to galactic scales - from Harvard, MPIA, Heidelberg, HITS, and affiliated institutions.

A four-day workshop of talks, unconferences, and activities

10/16 10/17 10/18 10/19 10/20

2023

EARLIER *TODAY*…



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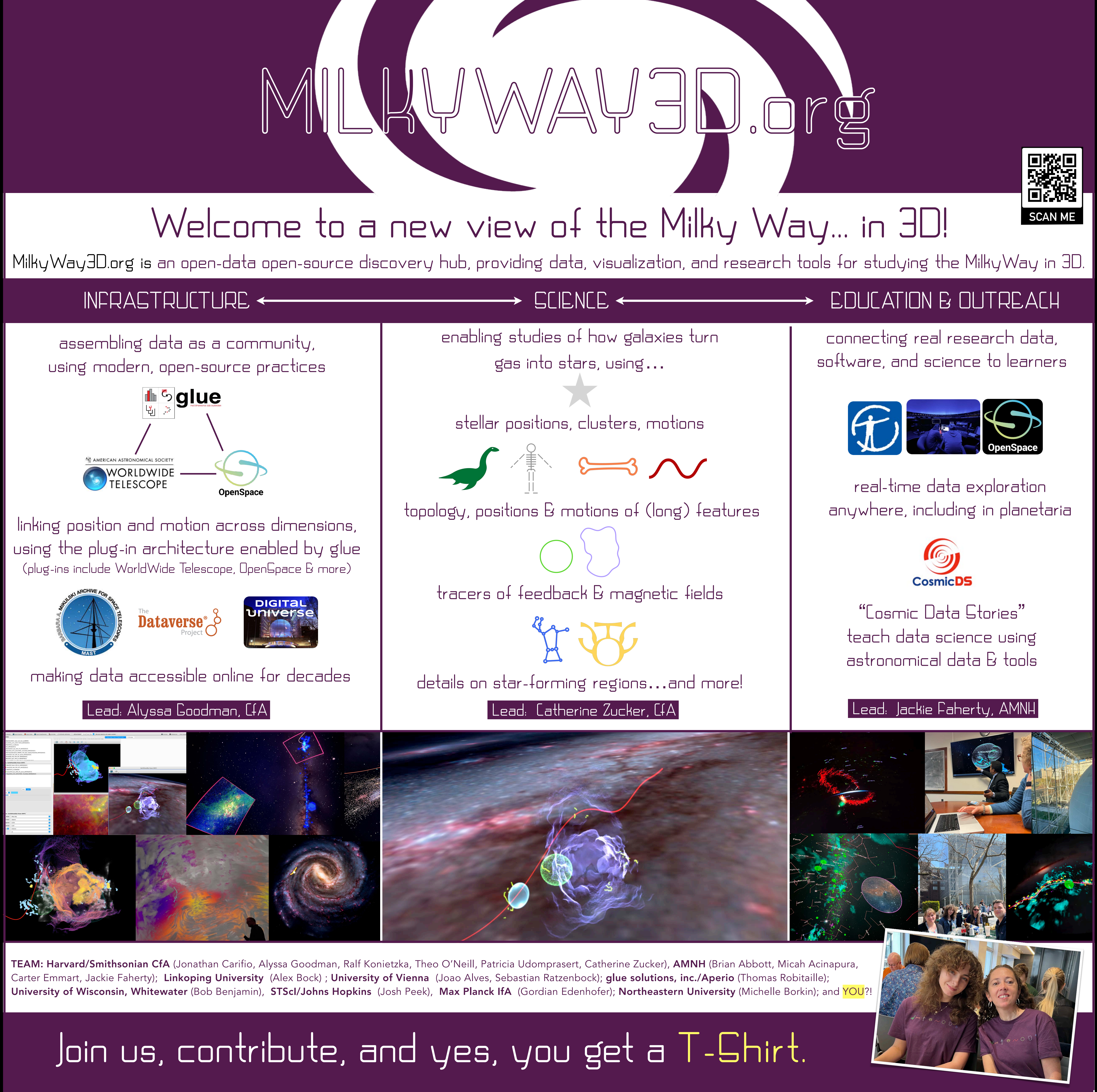


MILKYWAY3D.org

SCAN ME

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

INFRASTRUCTURE

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)

making data accessible online for decades

Lead: Alyssa Goodman, CfA

SCIENCE

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!

Lead: Catherine Zucker, CfA

EDUCATION & OUTREACH

connecting real research data, software, and science to learners

real-time data exploration anywhere, including in planetaria

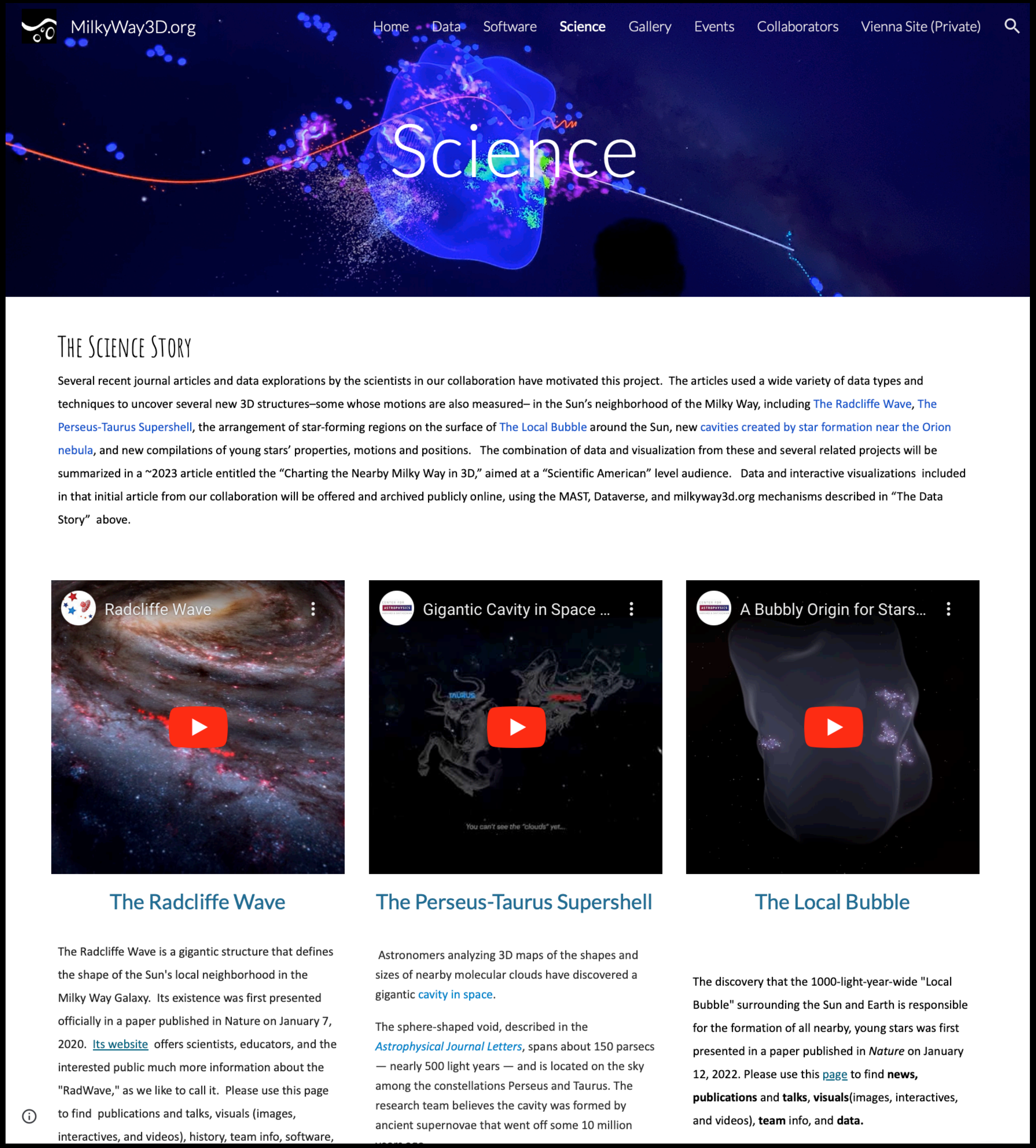
"Cosmic Data Stories" teach data science using astronomical data & tools

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.

EARLIER *TODAY*…



THE SCIENCE STORY

Several recent journal articles and data explorations by the scientists in our collaboration have motivated this project. The articles used a wide variety of data types and techniques to uncover several new 3D structures–some whose motions are also measured– in the Sun's neighborhood of the Milky Way, including The Radcliffe Wave, The Perseus-Taurus Supershell, the arrangement of star-forming regions on the surface of The Local Bubble around the Sun, new cavities created by star formation near the Orion nebula, and new compilations of young stars' properties, motions and positions. The combination of data and visualization from these and several related projects will be summarized in a ~2023 article entitled the "Charting the Nearby Milky Way in 3D," aimed at a "Scientific American" level audience. Data and interactive visualizations included in that initial article from our collaboration will be offered and archived publicly online, using the MAST, Dataverse, and milkyway3d.org mechanisms described in "The Data Story" above.

Radcliffe Wave
Gigantic Cavity in Space ...
A Bubbly Origin for Stars...
You can't see the "clouds" yet...

The Radcliffe Wave

The Radcliffe Wave is a gigantic structure that defines the shape of the Sun's local neighborhood in the Milky Way Galaxy. Its existence was first presented officially in a paper published in Nature on January 7, 2020. Its website offers scientists, educators, and the interested public much more information about the "RadWave," as we like to call it. Please use this page to find publications and talks, visuals (images, interactives, and videos), history, team info, software,

The Perseus-Taurus Supershell

Astronomers analyzing 3D maps of the shapes and sizes of nearby molecular clouds have discovered a gigantic cavity in space.

The sphere-shaped void, described in the *Astrophysical Journal Letters*, spans about 150 parsecs — nearly 500 light years — and is located on the sky among the constellations Perseus and Taurus. The research team believes the cavity was formed by ancient supernovae that went off some 10 million

The Local Bubble

The discovery that the 1000-light-year-wide "Local Bubble" surrounding the Sun and Earth is responsible for the formation of all nearby, young stars was first presented in a paper published in *Nature* on January 12, 2022. Please use this page to find **news, publications** and **talks**, **visuals**(images, interactives, and videos), **team** info, and **data.**

MilkyWay3D.org "Science"

MILKYWAY3D.org

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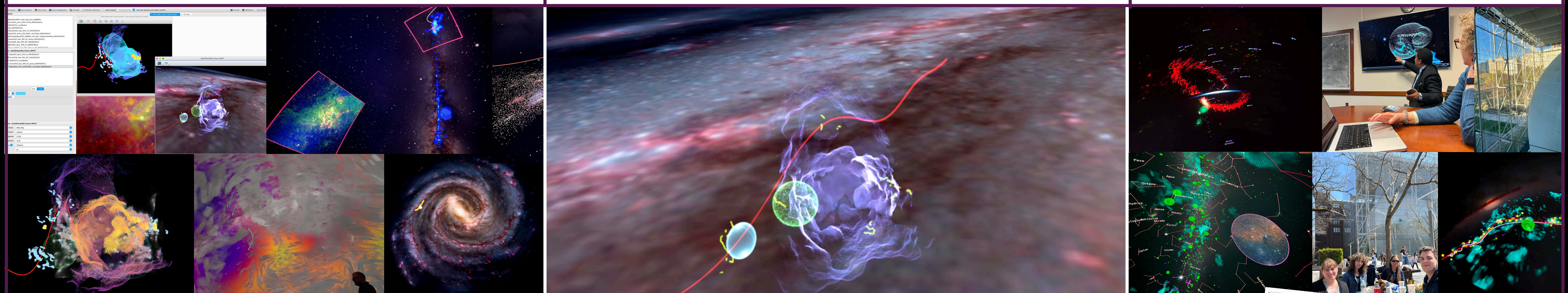

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Join us, contribute, and yes, you get a T-Shirt.

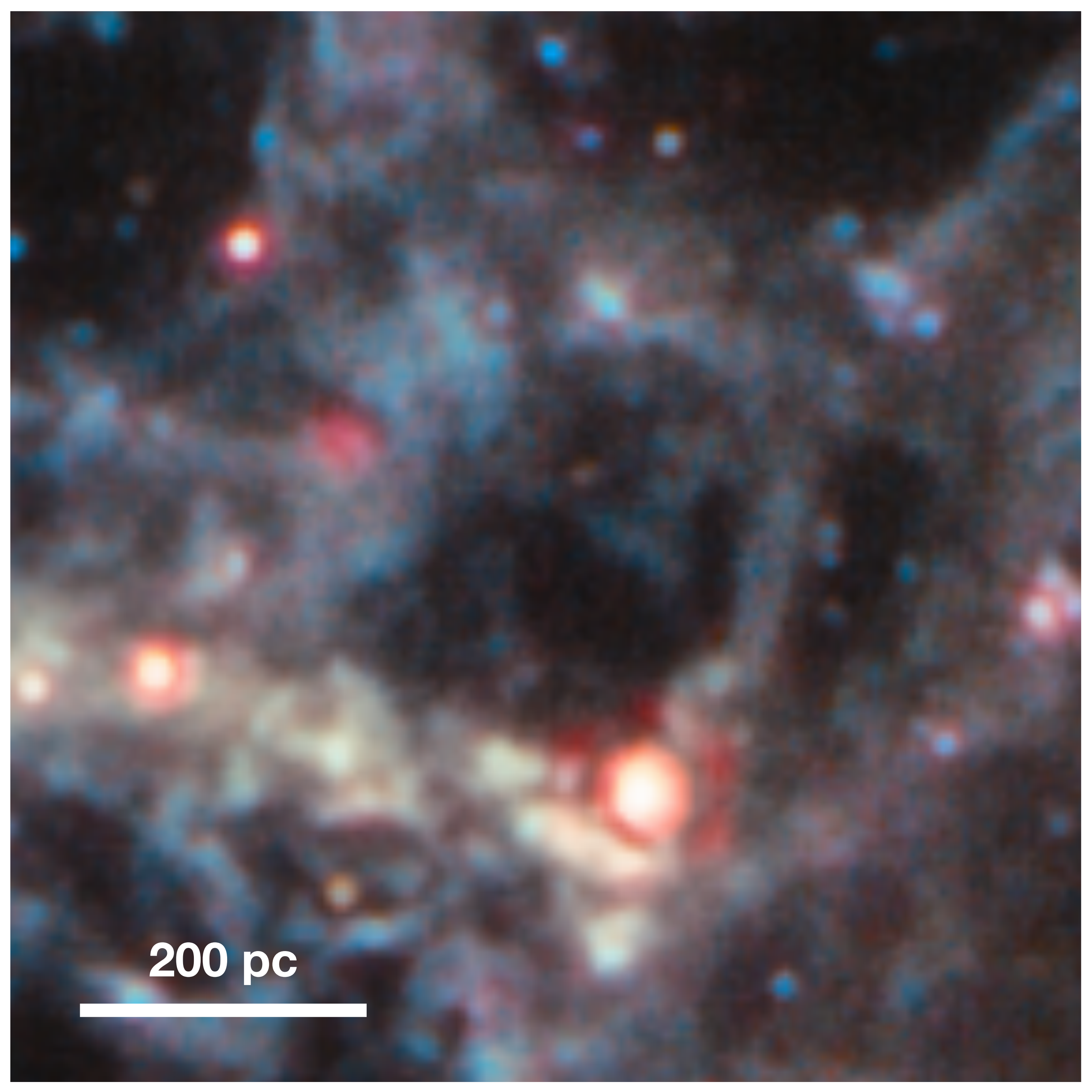
EARLIER TODAY...

NGC 628 (PHANGS-JWST)

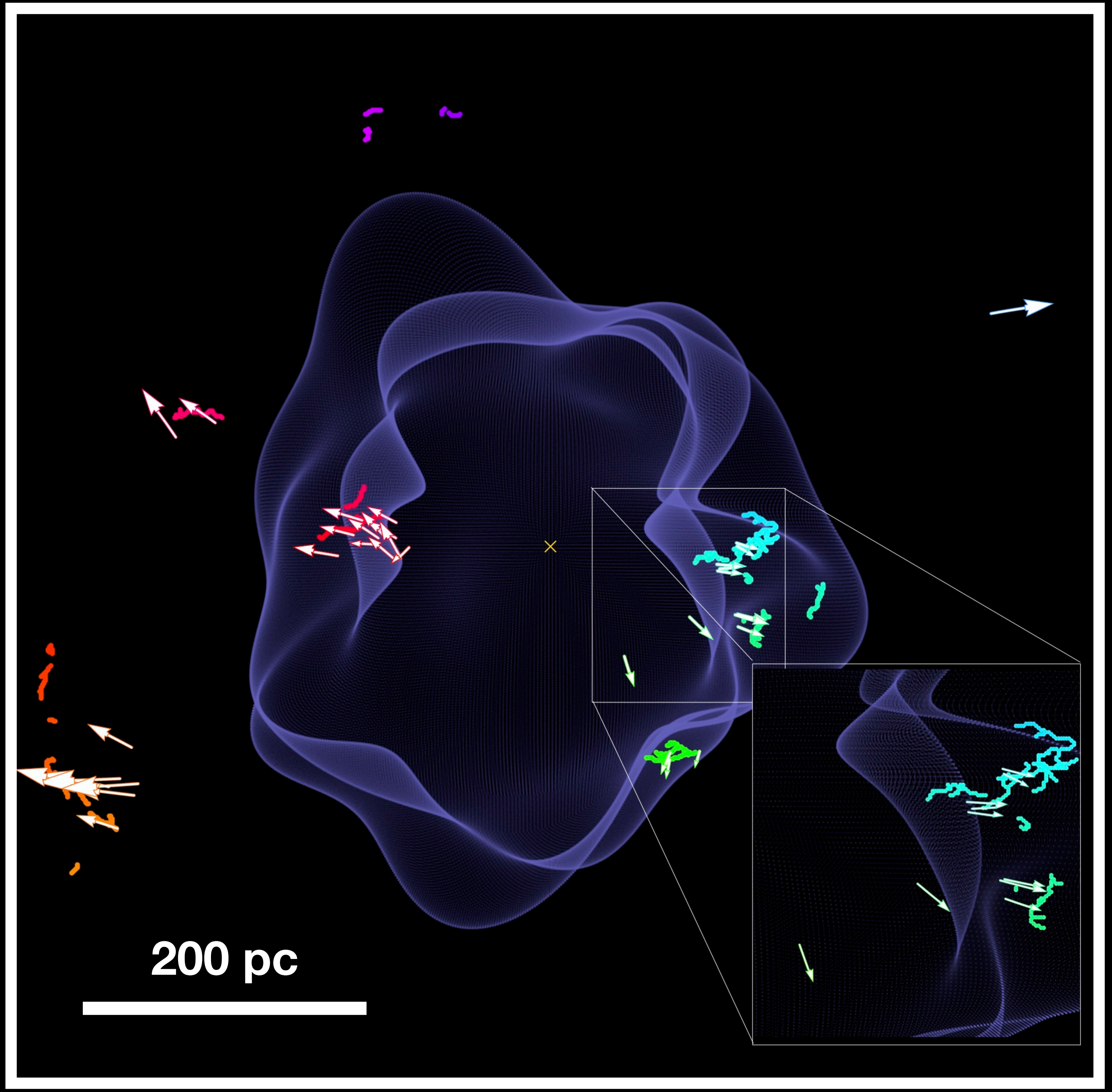
Credit: Judy Schmidt. Slide courtesy Catherine Zucker.

EARLIER TODAY…

Local Bubble Analog (NGC 628)



Local Bubble



Slide courtesy Catherine Zucker.

See e.g. Watkins+2023, Barnes+2023 for analysis of bubbles in NGC628

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4 of 6
Webb Finds Star ...
VV191
Webb Explores a ...
Galactic Get-Tog...
Pillars of Creation...
Southern Ring N...
Southern Ring N...
Protostar L1527
Pillars of Creation...
Webb Takes a St...
Tarantula Nebula ...
Tarantula Nebula ...
Webb Inspects th...
The Phantom Gal...
WEBB
SPACE TELESCOPE
Image Crossfade
1 of 2
Messier 74
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The "Perfect Spir...
PESSTO snaps S...
Perfect Spiral M74
Webb Inspects th...
The Phantom Gal...
M74, NGC 628
M74, NGC 628
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Messier 74
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Look At: Sky

Imagery: Digitized Sky Survey (Color)

Tracking: Webb Inspects the Heart ...

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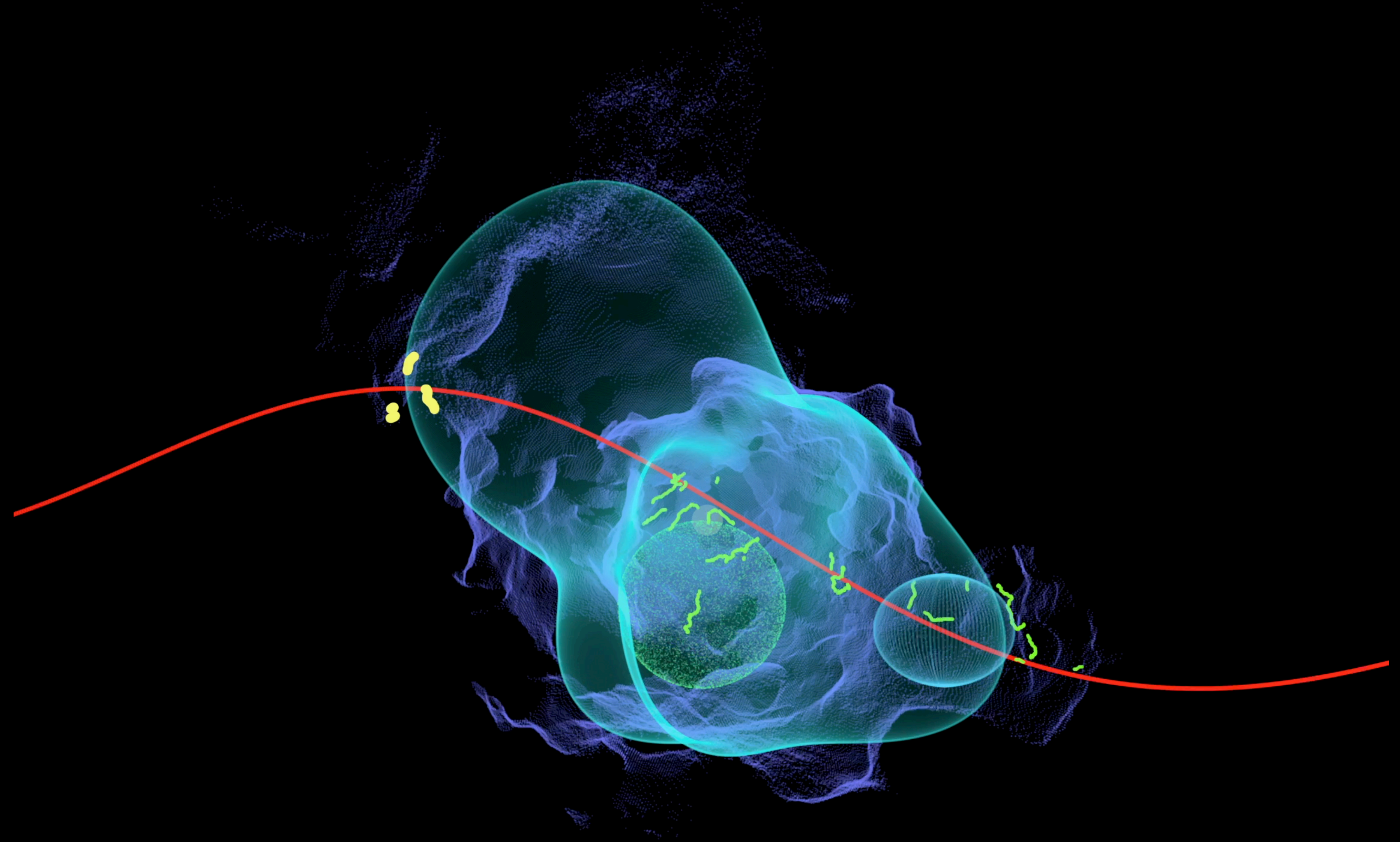
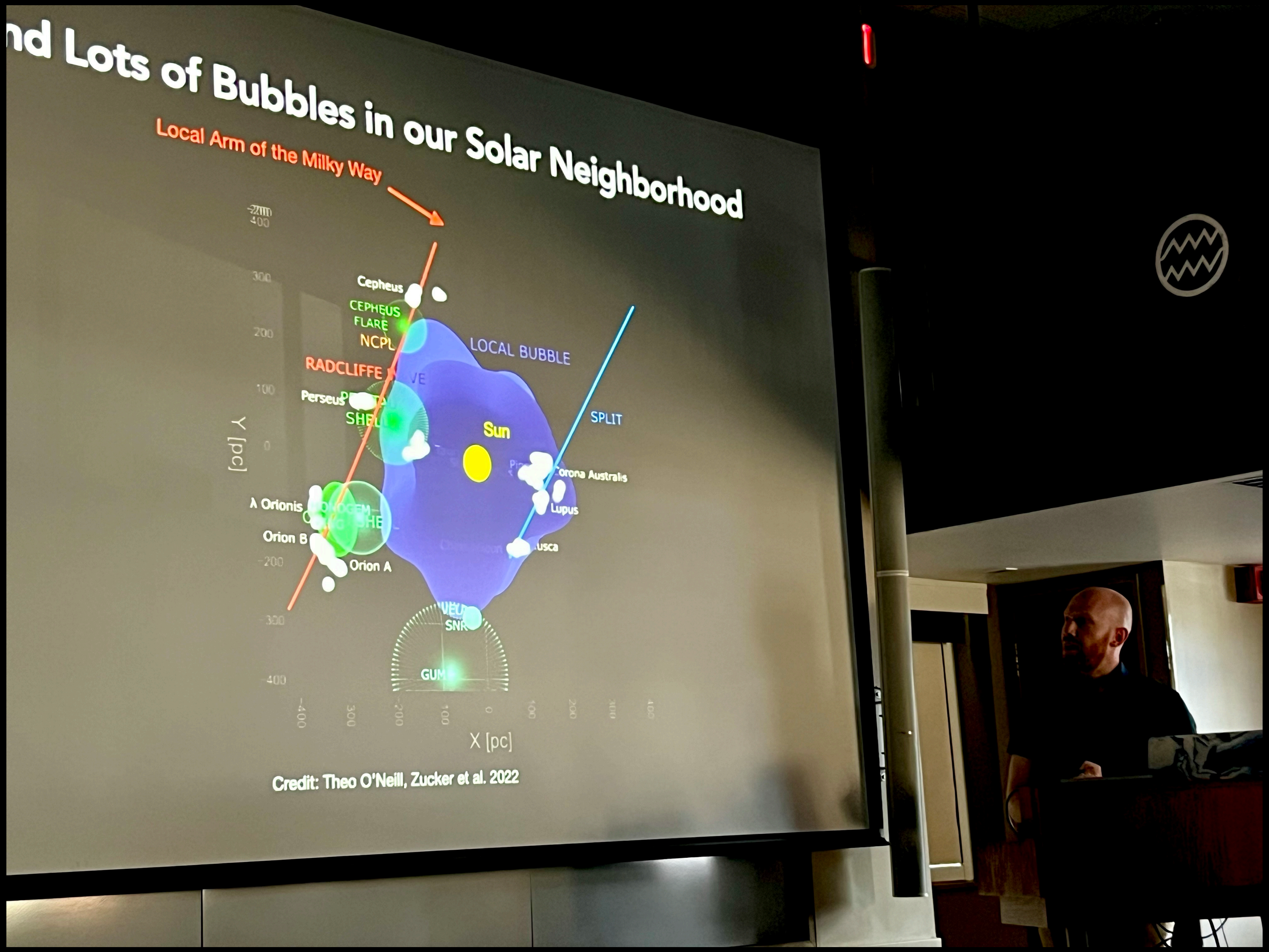
EARLIER *TODAY*…



Bubbles & the Radcliffe Wave in "glue"



nd Lots of Bubbles in our Solar Neighborhood

Local Arm of the Milky Way
Cepheus
CEPHEUS FLARE
NCPL
LOCAL BUBBLE
RADCLIFFE
Perseus
Sun
SPLIT
Corona Australis
Lupus
λ Orionis
Orion B
Orion A
GUM
Y [pc]
X [pc]

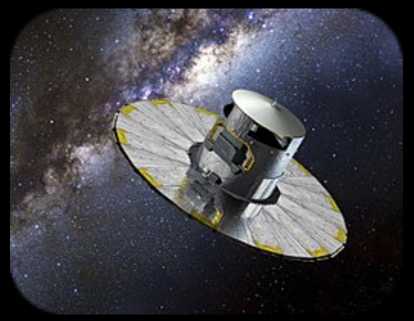
Credit: Theo O'Neill, Zucker et al. 2022

Talk by CfA graduate student Michael Foley

“ARE COMPUTERS THE NEW TELESCOPES?”

HOW= 3D dust mapping*

+ Gaia*

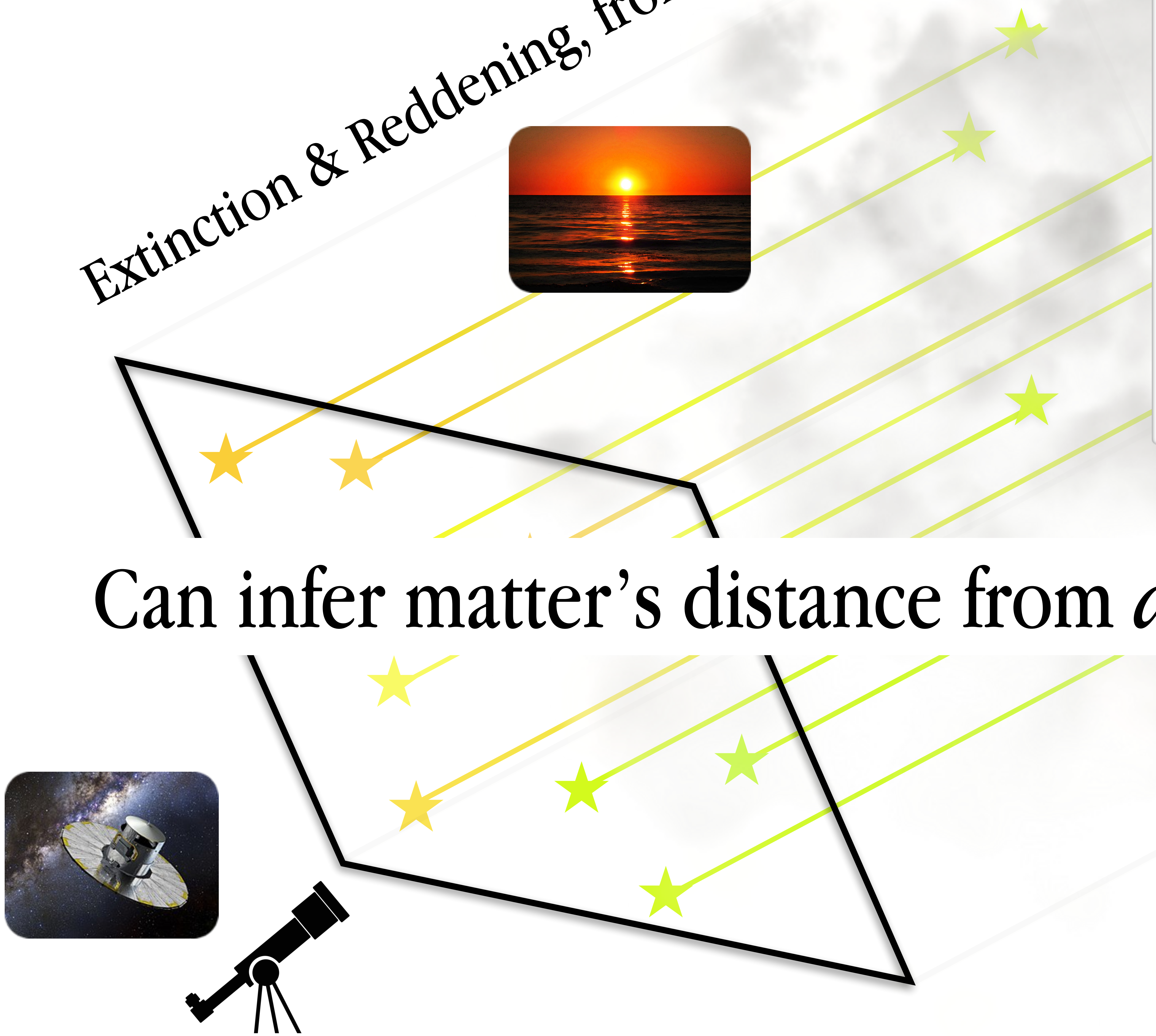


+ glue*

+ WorldWide Telescope

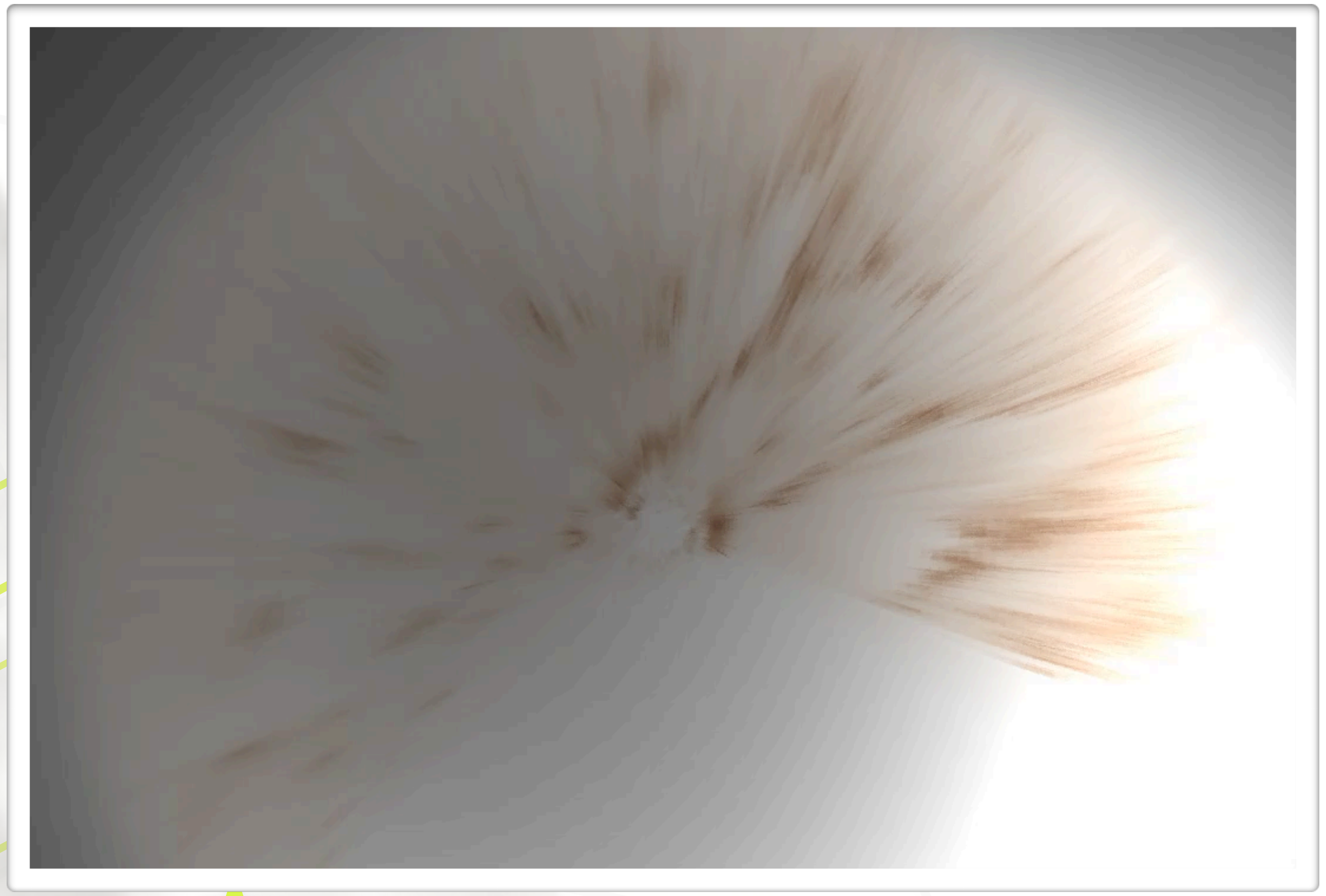
*2 million CPU hours, Harvard   *800 million stars, ESA   *NASA/JWST, NSF   *Microsoft Research, NSF, AAS

3D dust mapping



Extinction & Reddening, from Color Imaging

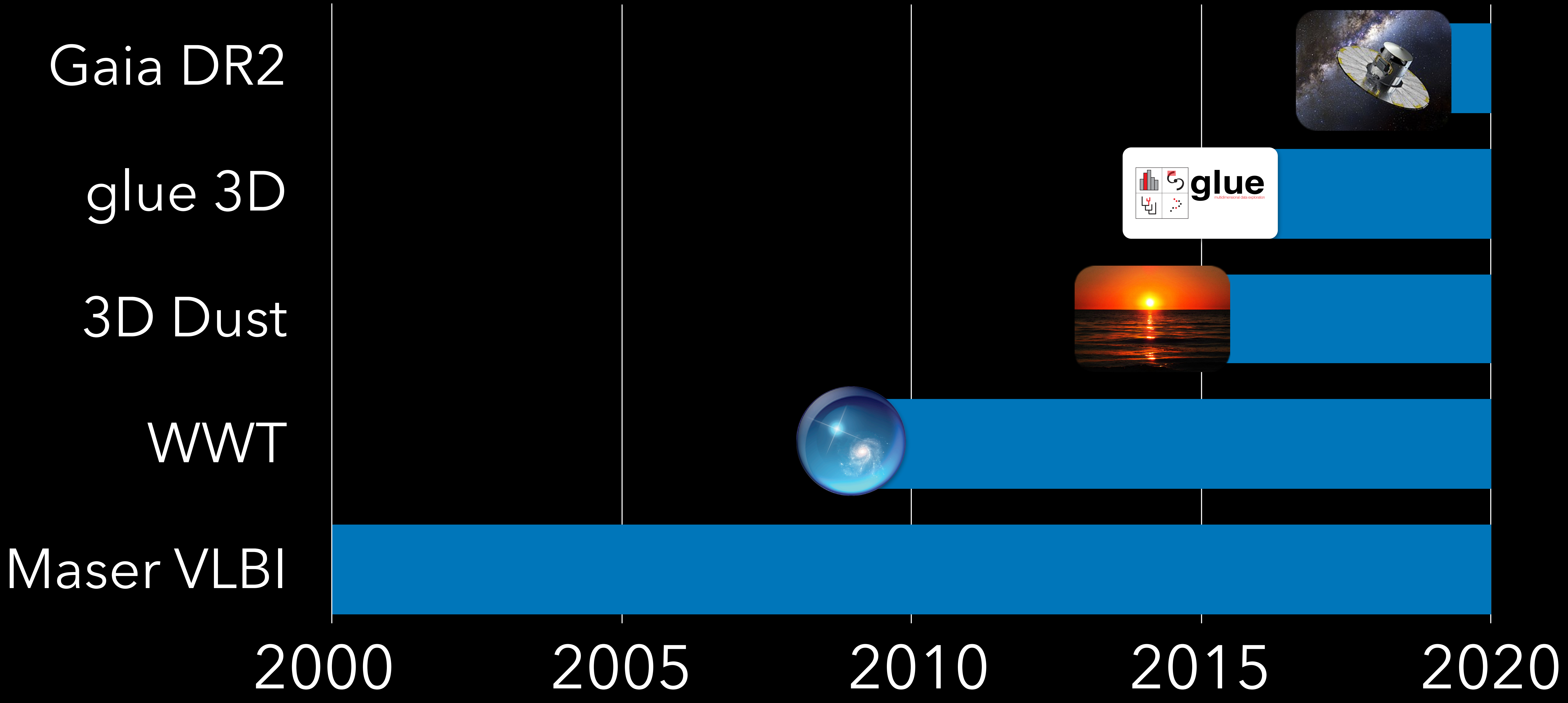
Can infer matter's distance from *dust's* effects on stars.



Green et al. 2019

WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

WHY COULDN'T WE DO THIS ALL A LONG TIME AGO?



“ARE COMPUTERS THE NEW TELESCOPES?”

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

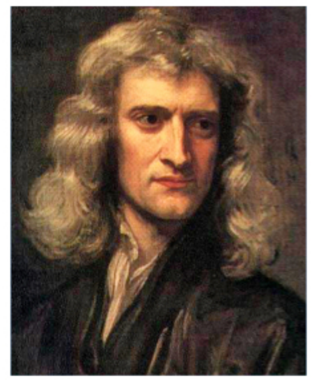
I like
Dutch
glass!

Sorry,
Aristotle,
you’re just
wrong.

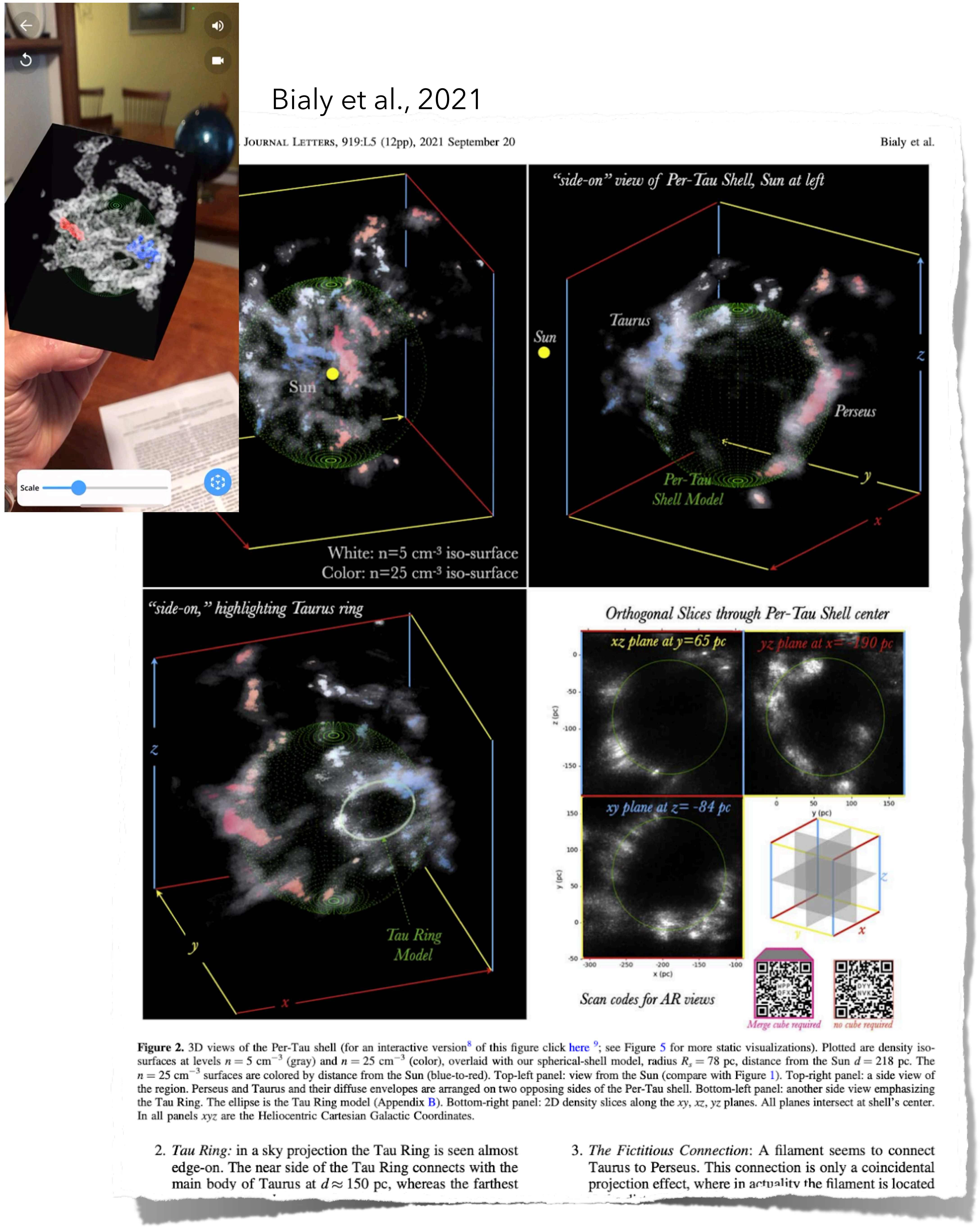
GALILEI

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?


Scale
"side-on" view of Per-Tau Shell, Sun at left
Sun
Taurus
Perseus
Per-Tau Shell Model
White: n=5 cm-3 iso-surface
Color: n=25 cm-3 iso-surface
"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
z (pc)
y (pc)
x (pc)
x
y
z
Scan codes for AR views
Merge cube required
no cube required

Biały et al., 2021

JOURNAL LETTERS, 919:L5 (12pp), 2021 September 20 Bialy et al.

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 isosurfaces at levels $n = 5\ \mathrm{cm}^{-3}$ (gray) and $n = 25\ \mathrm{cm}^{-3}$ (color), overlaid with our spherical-shell model, radius $R_s = 78$ pc, distance from the Sun $d = 218$ pc. The $n = 25\ \mathrm{cm}^{-3}$ 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 center. 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 connect Taurus to Perseus. This connection is only a coincidental projection effect, where in actuality the filament is located

"ARE COMPUTERS THE NEW TELESCOPES?"

ELECTRONIC COMPUTERS

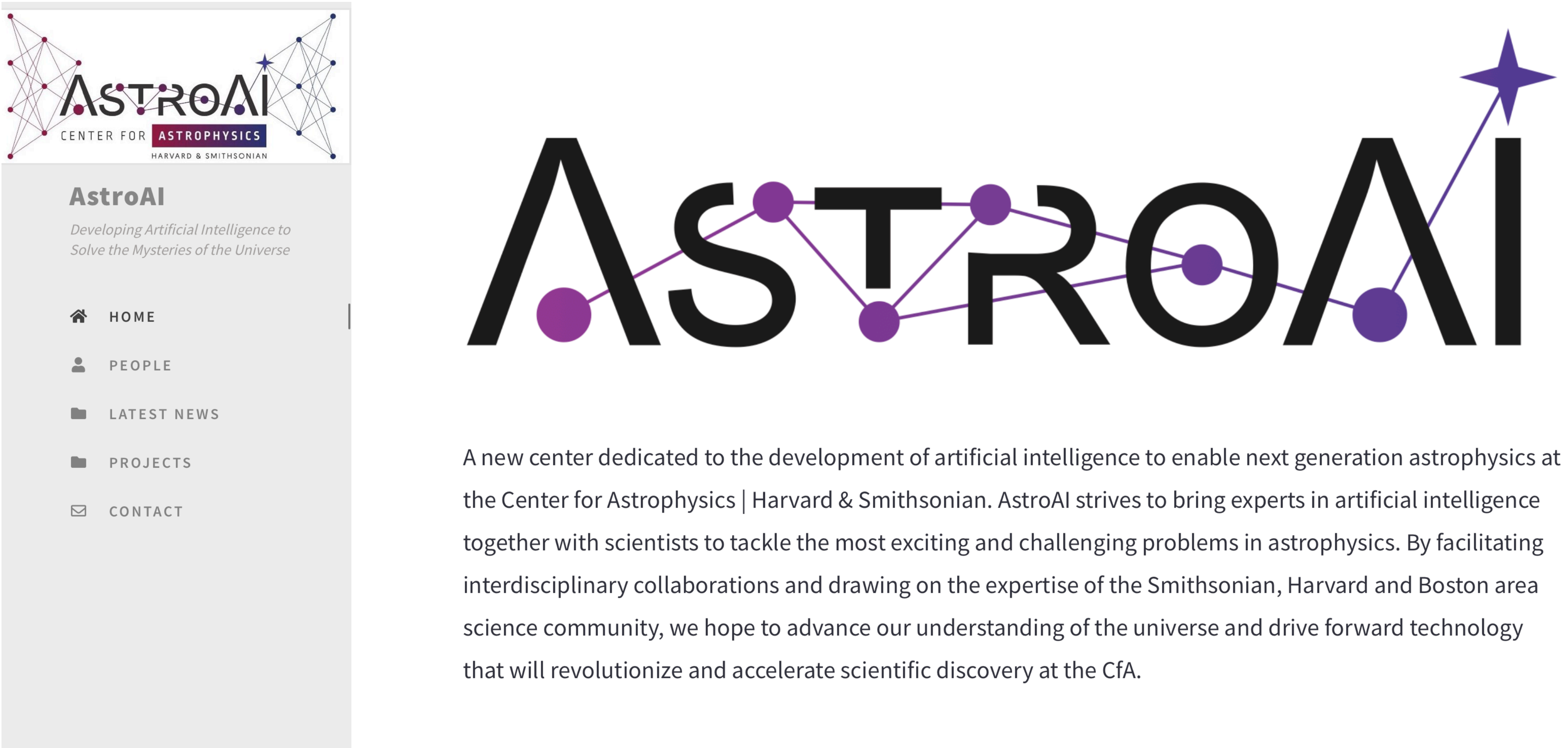
NUMERICAL SIMULATION

BAYESIAN STATISTICS

INTERACTIVE DATA VISUALIZATION

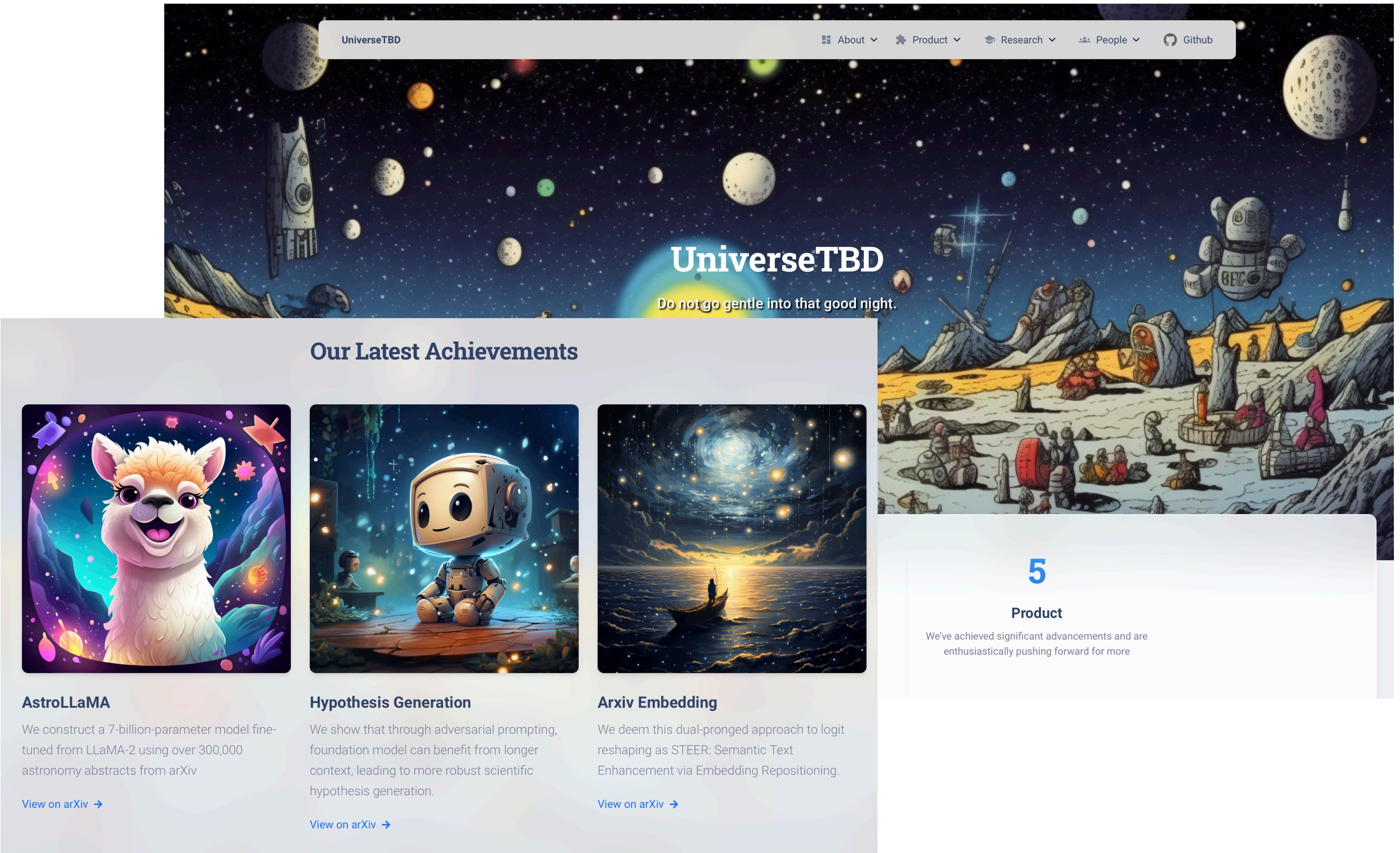
AI/MACHINE LEARNING

“ARE COMPUTERS THE NEW TELESCOPES?”



Developing Artificial Intelligence to Solve the Mysteries of the Universe

A new center dedicated to the development of artificial intelligence to enable next generation astrophysics at the Center for Astrophysics | Harvard & Smithsonian. AstroAI strives to bring experts in artificial intelligence together with scientists to tackle the most exciting and challenging problems in astrophysics. By facilitating interdisciplinary collaborations and drawing on the expertise of the Smithsonian, Harvard and Boston area science community, we hope to advance our understanding of the universe and drive forward technology that will revolutionize and accelerate scientific discovery at the CfA.



UniverseTBD

Do not go gentle into that good night.

Our Latest Achievements

AstroLLaMA

We construct a 7-billion-parameter model fine-tuned from LLaMA-2 using over 300,000 astronomy abstracts from arXiv

View on arXiv →

Hypothesis Generation

We show that through adversarial prompting, foundation model can benefit from longer context, leading to more robust scientific hypothesis generation.

View on arXiv →

Arxiv Embedding

We deem this dual-pronged approach to logit reshaping as STEER: Semantic Text Enhancement via Embedding Repositioning.

View on arXiv →

5

Product

We've achieved significant advancements and are enthusiastically pushing forward for more

ELECTRONIC COMPUTERS

NUMERICAL SIMULATION

BAYESIAN STATISTICS

INTERACTIVE DATA VISUALIZATION

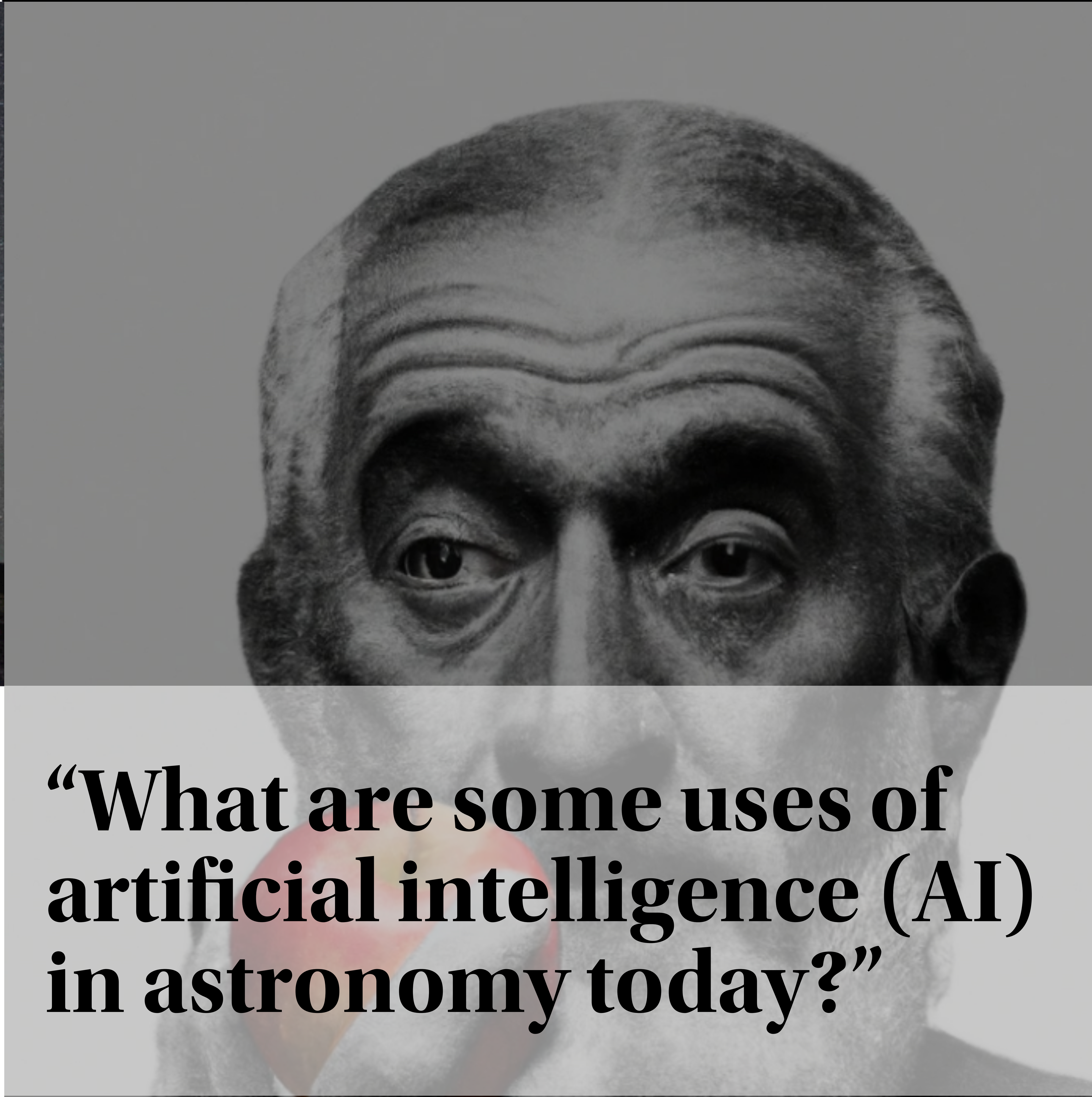
AI/MACHINE LEARNING

PBS NEWSHOUR

Analysis: How AI is helping astronomers study the universe

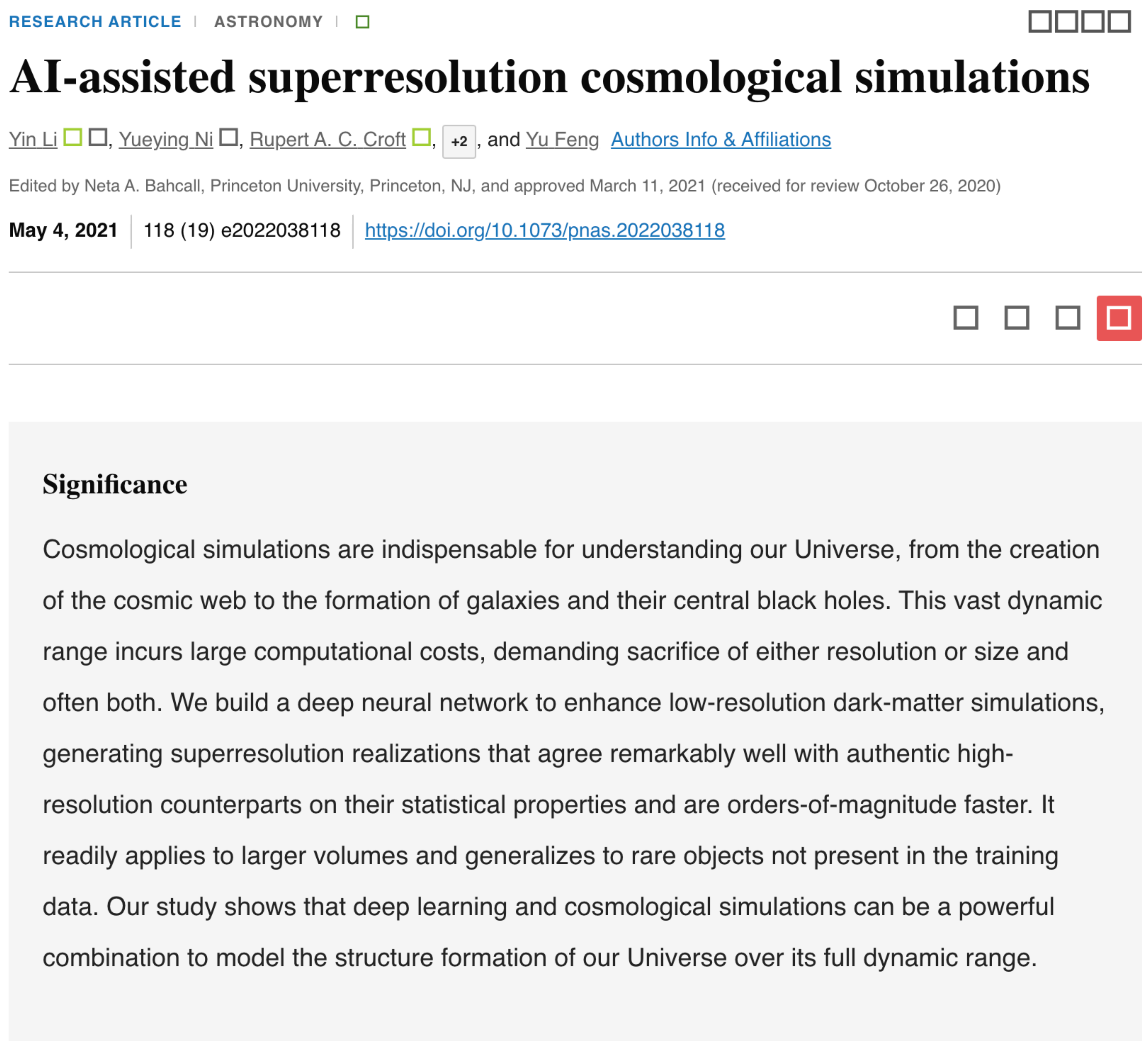
Science May 8, 2023 1:31 PM EDT

OpenAI



“What are some uses of artificial intelligence (AI) in astronomy today?”

LEARNED UNIVERSES



RESEARCH ARTICLE | ASTRONOMY

AI-assisted superresolution cosmological simulations

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Significance

Cosmological simulations are indispensable for understanding our Universe, from the creation of the cosmic web to the formation of galaxies and their central black holes. This vast dynamic range incurs large computational costs, demanding sacrifice of either resolution or size and often both. We build a deep neural network to enhance low-resolution dark-matter simulations, generating superresolution realizations that agree remarkably well with authentic high-resolution counterparts on their statistical properties and are orders-of-magnitude faster. It readily applies to larger volumes and generalizes to rare objects not present in the training data. Our study shows that deep learning and cosmological simulations can be a powerful combination to model the structure formation of our Universe over its full dynamic range.

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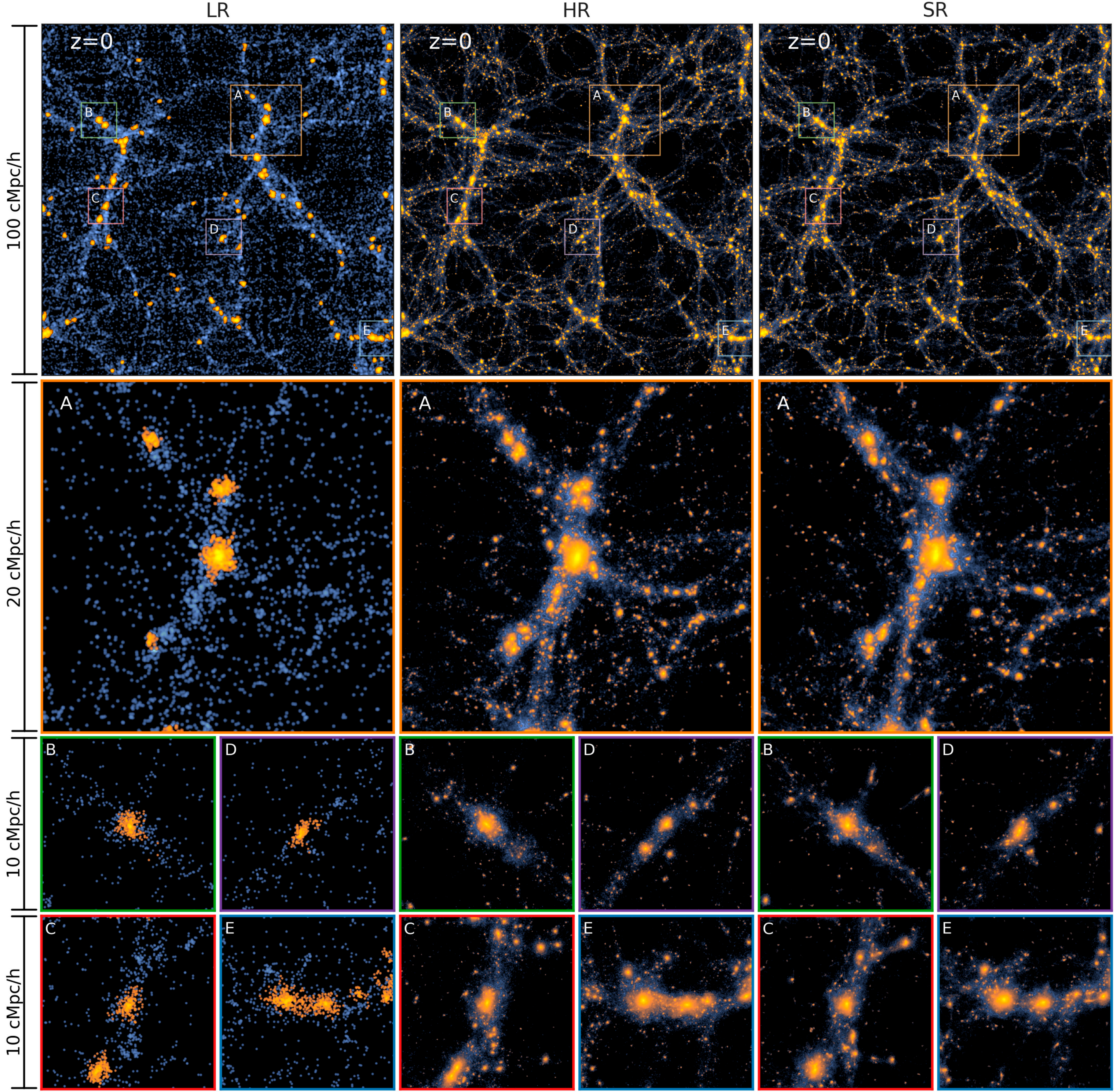

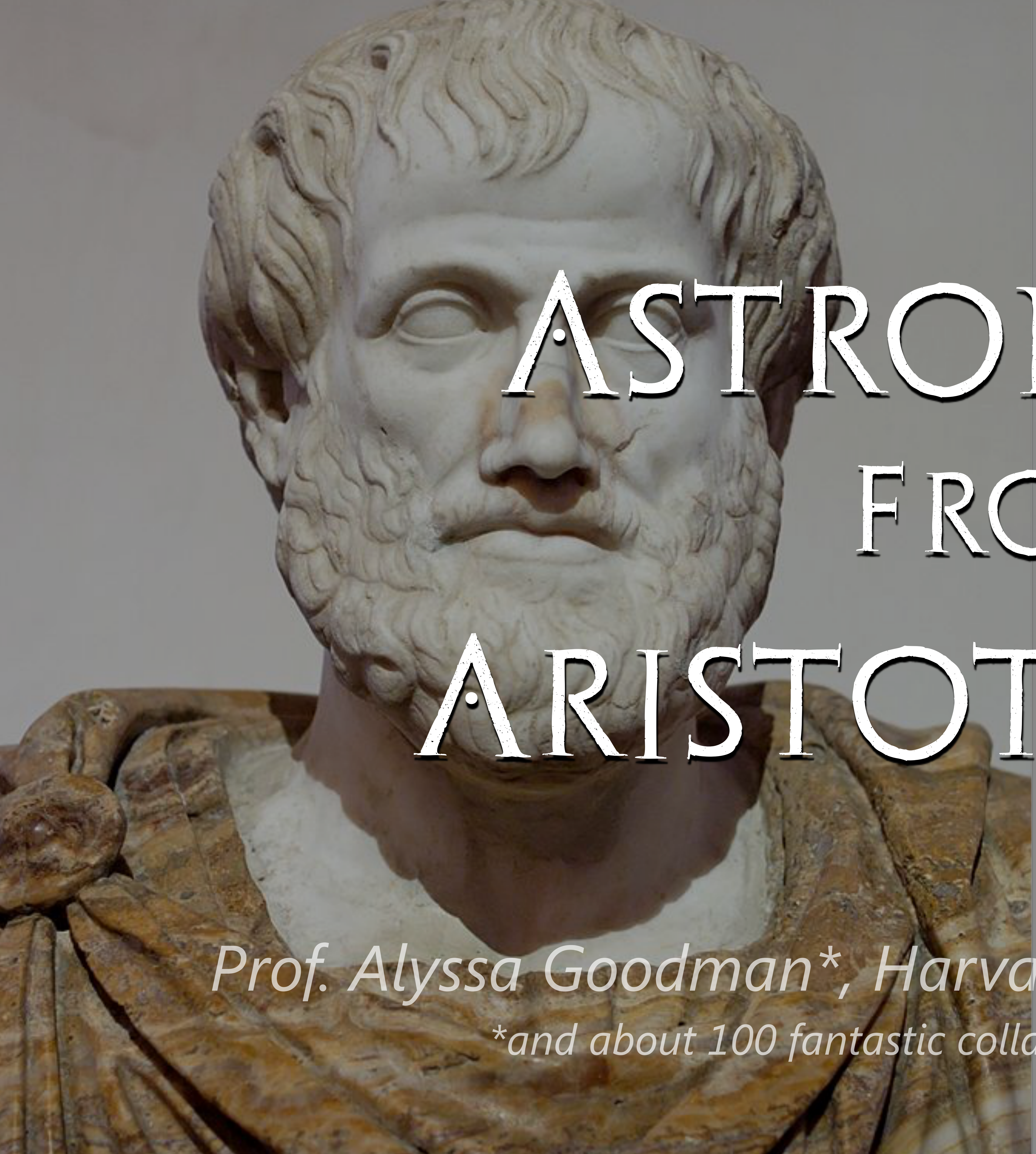

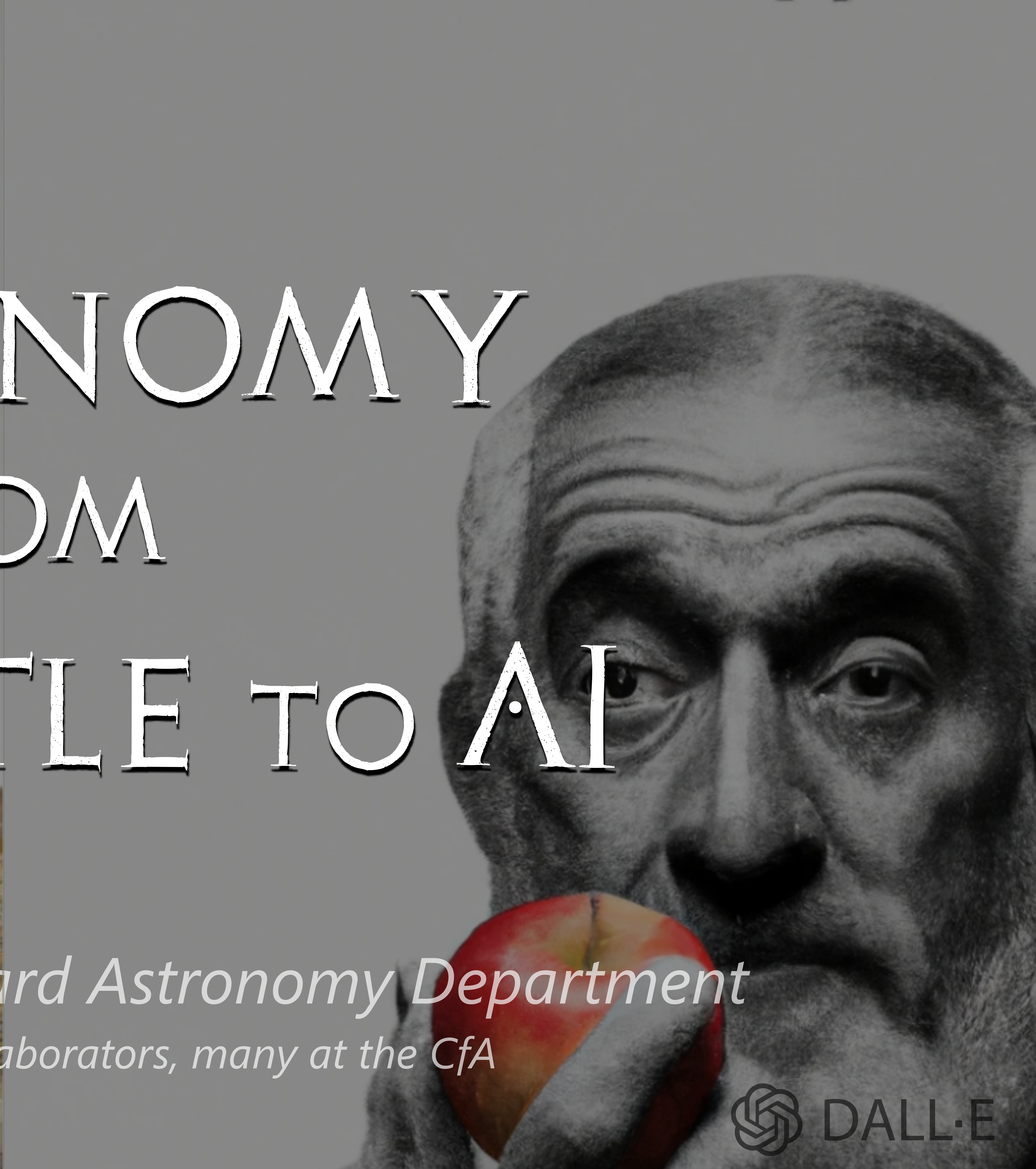

Astronomy From Aristotle to AI

Prof. Alyssa Goodman, Harvard Astronomy Department*

**and about 100 fantastic collaborators, many at the CfA*

CODY JOHNSON
HUMAN
THE DOUBLE ALBUM

"If you got a dream, chase it,
‘cause a dream won’t chase you back.”