These slides are online at: tinyurl.com/NESF-Goodman

New Perspectives on Star Formation, The Milky Way, and Isaac Newton*

Alyssa Goodman
Center for Astrophysics | Harvard & Smithsonian, Radcliffe Institute for Advanced Study

**an unusual collection of topics requested by our organizers, Cara Battersby & Mark Heyer*

RESOLUTION + SENSITIVITY	*Cores*	Haystack NH_3, IRAS	GAS, Herschel	B5, DYNAMICS/DROPLETS
	Disks	Beckwith & Sargent, HST	ALMA, SPHERE	RINGS, PLANETS
SURVEYS	*Stars*	Hipparcos	Gaia	3D ORION 📖
SIMULATIONS	*MHD++*	Gammie-Stone-Ostriker📖	Moving mesh, Arepo	SERPENS 📖
SIMULATIONS	*Photons, chem*	SPH, Bate et al. 📖	Krumholz 📖, Rosen 📖	"FRAGMENTATION?"
COMPARISONS	*Synthetic Obs*	Falgarone 📖	Beaumont 📖	*P-P-V* DISASTER
STATISTICS	*Fitting*	Least squares	Bayes	*EXTINCTION/DISTANCES*
ANALYSIS	*Learning*	Human	Human+Machine	BUBBLES 📖,FLOWS 📖
SHARING	*Data*	NVO	*WWT, ESA Sky*	ADSASS
SHARING	*Code*	email	GitHub	ASTROPY
VISUALIZATION	*3D plots*	*DataDesk*	*glue*	RADCLIFFE WAVE
IDEAS	*Connections*	Triggered Star Formation	Radcliffe Wave 📖	ISOLATIONISM BAD
GEOGRAPHY	*Meetings*	Protostars & Planets	*Zoom*, HHSF	BIG(!) COLLABORATIONS
PEOPLE	*Diversity*	few women, POC	look around	MORE PERSPECTIVES

Evolution:
B5, DYNAMICS/DROPLETS

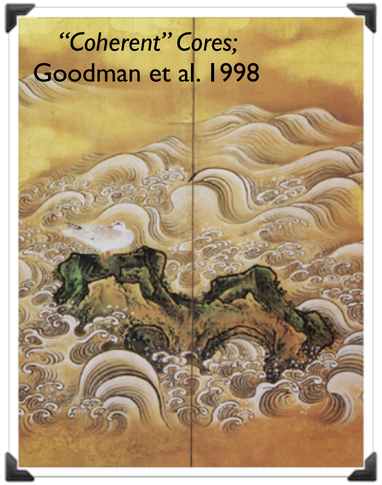
Revelation:
RADCLIFFE WAVE

B5, DYNAMICS/DROPLETS

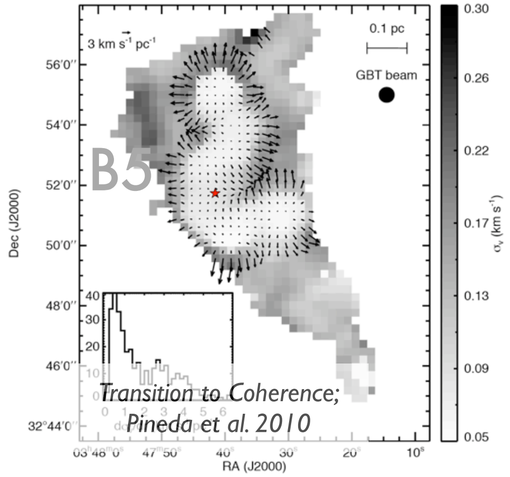
1989

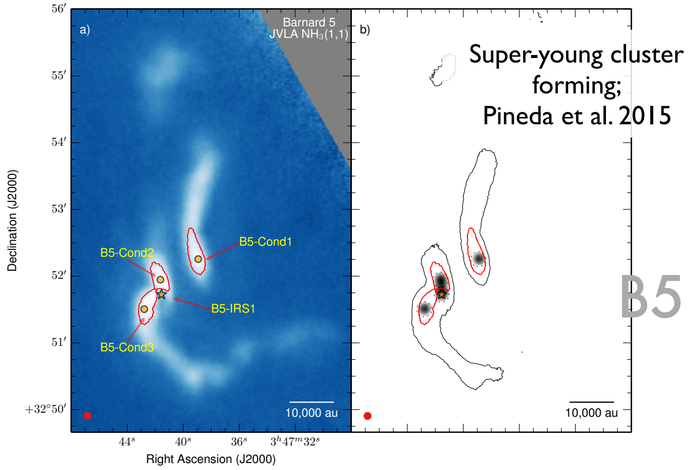
NH_3 *Benson & Myers 1989*

1998

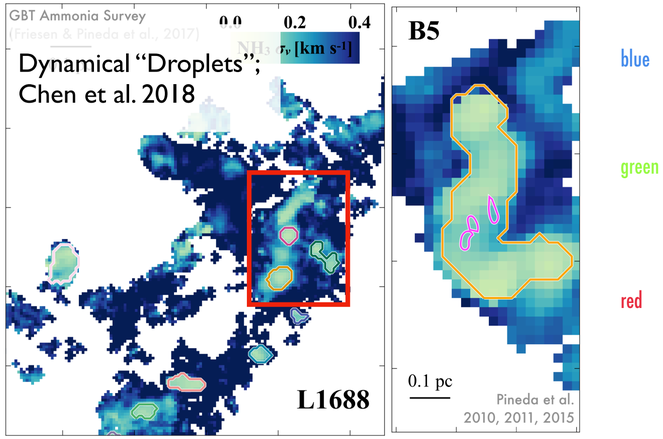


2010

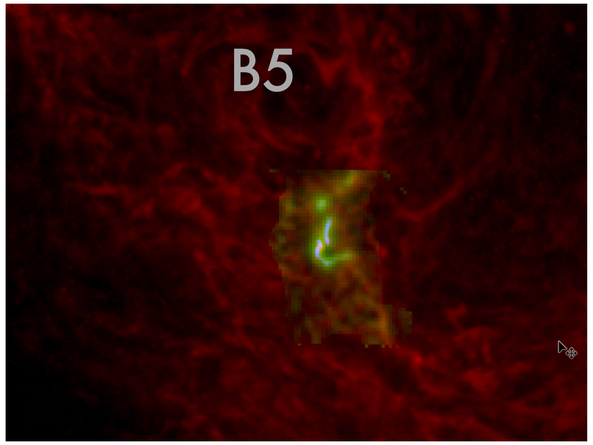




2015



2018



"SOON"

B5, DYNAMICS/DROPLETS

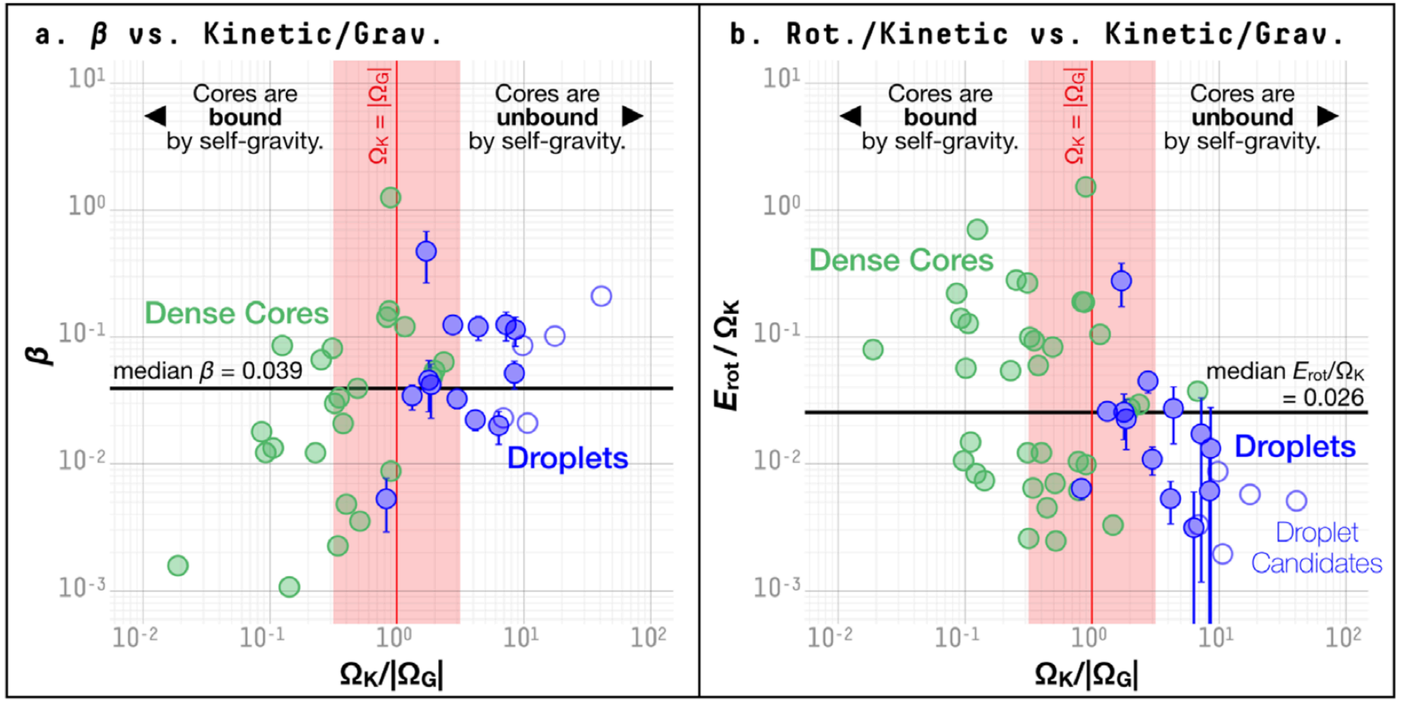
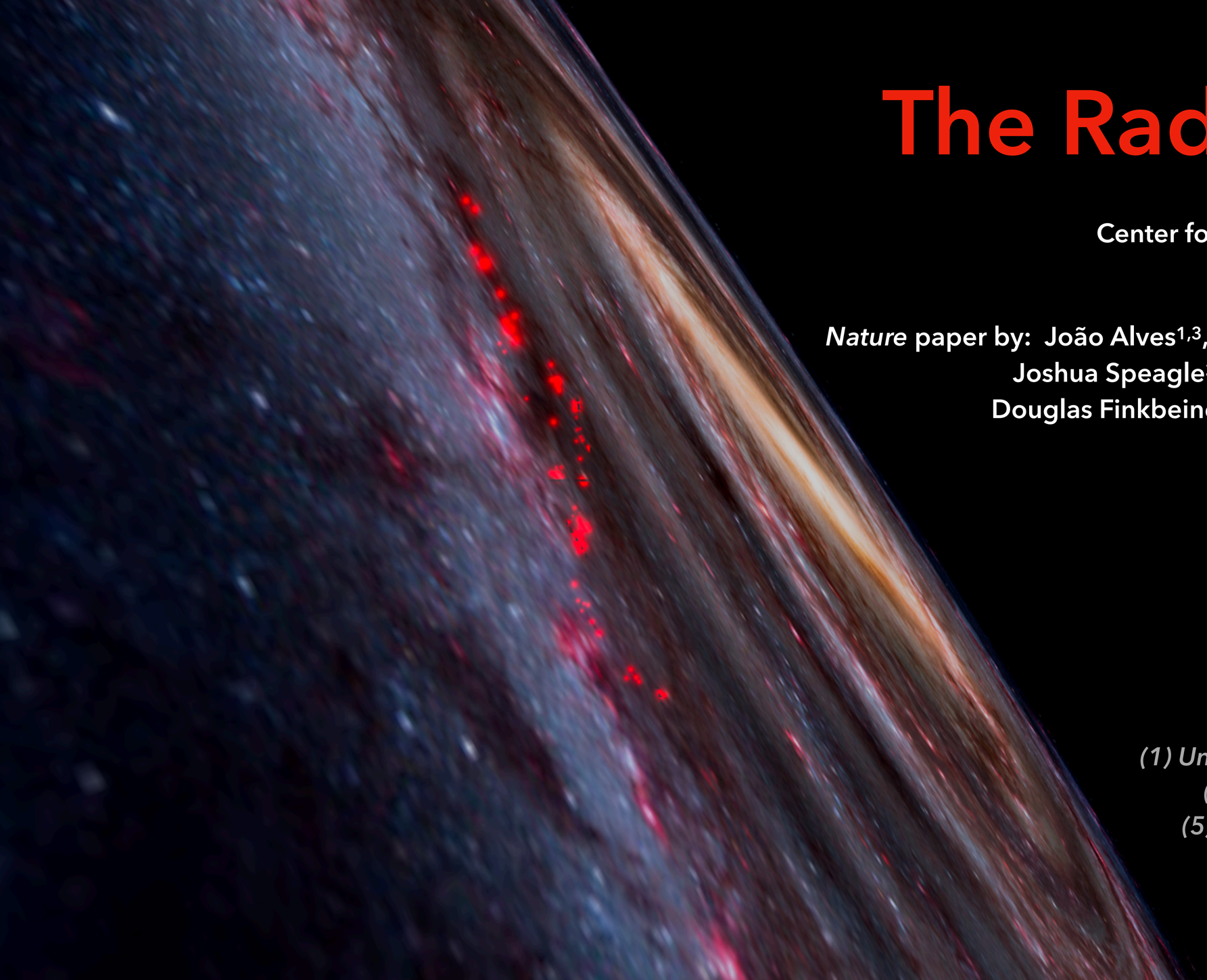


Figure 9. (a) Ratio between rotational and gravitational energies, β, plotted against the ratio between the kinetic and gravitational energies, $\Omega_K/|\Omega_G|$, for larger-scale dense cores (green dots), droplets (blue filled dots), and droplet candidates (blue empty dots). The red line corresponds to the relation, $E_{rot} = |\Omega_G|$, and the red band marks the parameter space within an order of magnitude from this relation. The parameter space to the right of the red line corresponds to $|\Omega_G| < \Omega_K$, and the left corresponds to $|\Omega_G| > \Omega_K$. The horizontal black line marks the median value of β for all cores shown in the figure (both dense cores and droplets; excluding droplet candidates). (b) Ratio between rotational and total kinetic energies, E_{rot}/Ω_K, plotted against the ratio between the kinetic and gravitational energies, $\Omega_K/|\Omega_G|$, for larger-scale dense cores (green dots), droplets (blue filled dots), and droplet candidates (blue empty dots). Same as in (a), the red line corresponds to the relation, $E_{rot} = |\Omega_G|$ and separates the parameter space into one corresponding to objects being bound by self-gravity (left) and another corresponding to objects not being bound by self-gravity (right). The horizontal black line marks the median value of $E_{rot} = |\Omega_G|$ for all cores shown in the figure, excluding droplet candidates.

Droplets are essentially pressure-bound cores in a dynamical flow, and their rotation comes from that..
Chen et al. 2019 (cf. Burkert & Bodenheimer 2000).



The Radcliffe Wave

presented by Alyssa Goodman,
Center for Astrophysics | Harvard & Smithsonian,
Radcliffe Institute for Advanced Study

Nature paper by: João Alves[1,3], Catherine Zucker[2], Alyssa Goodman[2,3], Joshua Speagle[2], Stefan Meingast[1], Thomas Robitaille[4], Douglas Finkbeiner[3], Edward Schlafly[5] & Gregory Green[6]

representing
(1) University of Vienna; (2) Harvard University; (3) Radcliffe Insitute; (4) Aperio Software; (5) Lawrence Berkeley National Laboratory; (6) Kavli Insitute for Particle Physics and Cosmology

The Radcliffe Wave

CARTOON*

DATA

*drawn by Dr. Robert Hurt, in collaboration with Milky Way experts based on data; as shown in screenshot from AAS WorldWide Telescope

The Radcliffe Wave

Each **red** dot marks a star-forming blob of gas whose distance from us has been accurately measured.

The Radcliffe Wave is **2.7 kpc**, and ~**120 pc wide**, with crest and trough reaching **160 pc** out of the Galactic Plane.
Its gas mass is **more than three million** Solar masses.

video created by the authors using AAS WorldWide Telescope
(includes cartoon Milky Way by Robert Hurt)

The Radcliffe Wave

ACTUALLY 2 IMPORTANT DEVELOPMENTS

DISTANCES!!

We can now measure distances to gas clouds in our own Milky Way galaxy to ~5% accuracy.

Zucker et al. 2019; 2020

RADWAVE

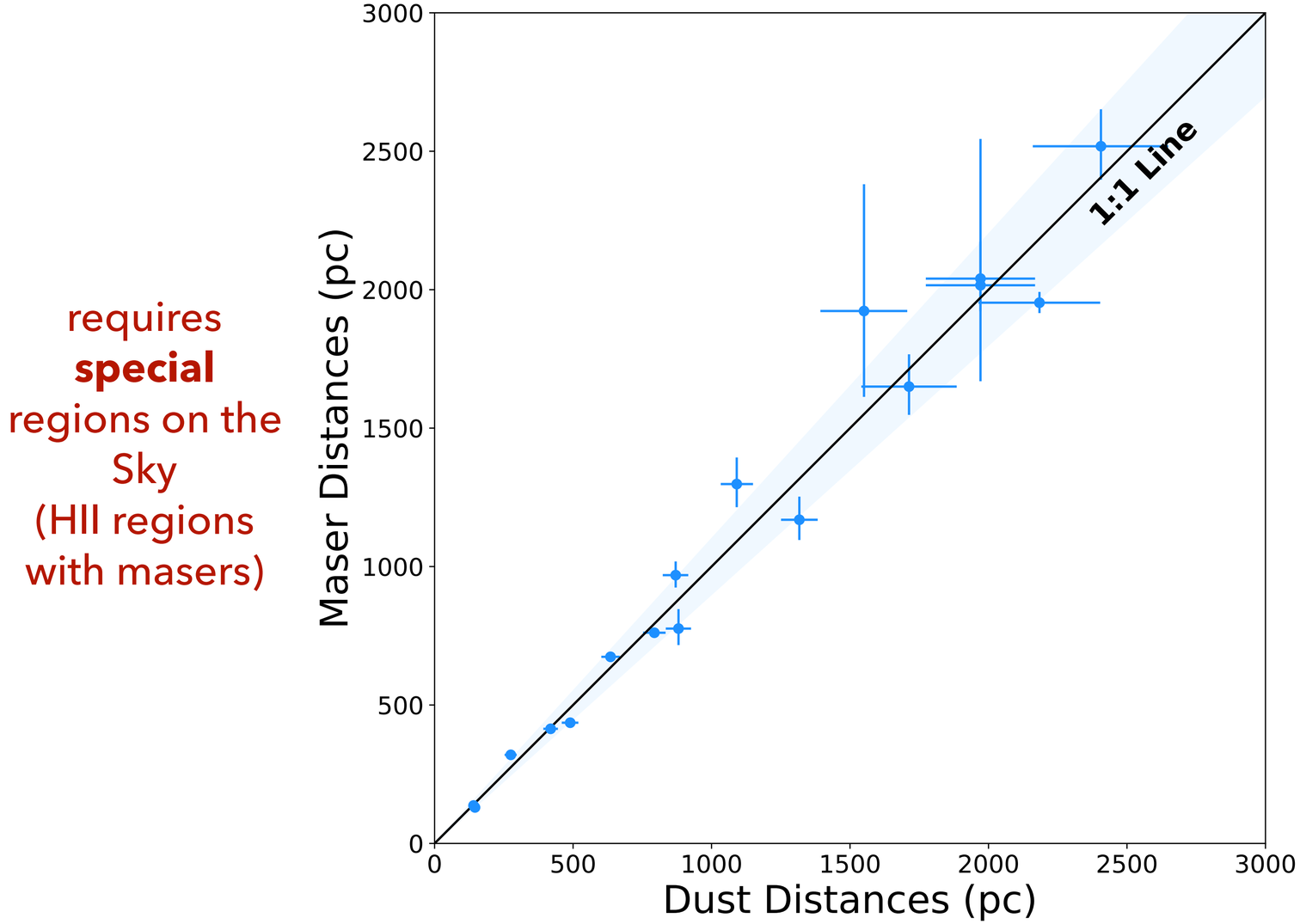
Surprising wave-like arrangement of star-forming gas *is* the "Local Arm" of the Milky Way.

Alves et al. 2020

DISTANCES!!

We can now measure distances to gas clouds in our own Milky Way galaxy to ~5% accuracy.

requires **special** regions on the Sky (HII regions with masers)



can be used **anywhere** there's dust & measurable stellar properties

Zucker et al. 2019

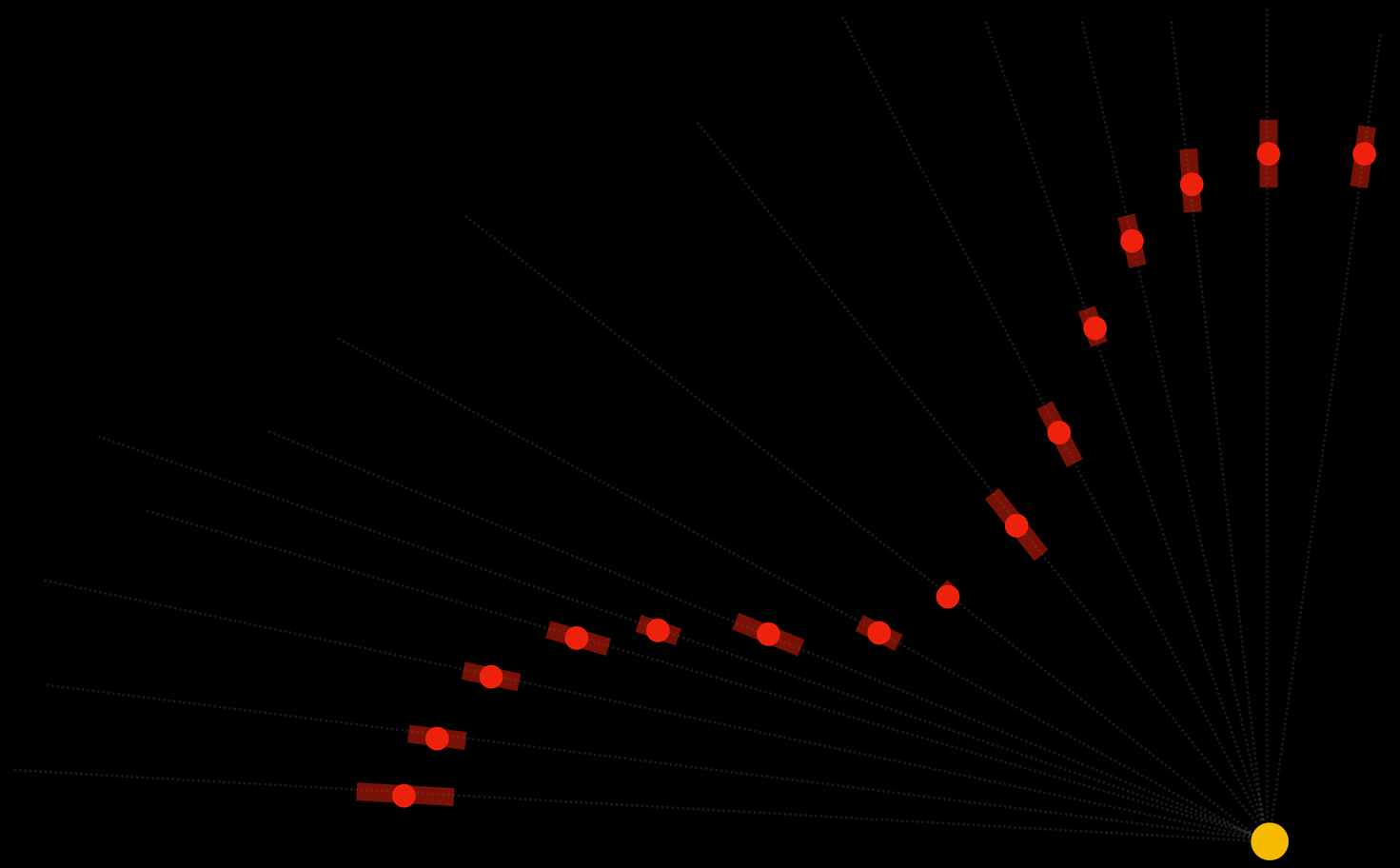
DISTANCES!!

We can now measure distances to gas clouds in our own Milky Way galaxy to ~5% accuracy.

Uncertain Distances

SCHEMATIC CARTOON(!)

Distances estimates **BEFORE** 3D dust mapping & Gaia (~30%)



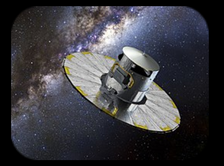
"The Radcliffe Wave"

SCHEMATIC CARTOON(!)

Distances estimates **AFTER** 3D dust mapping & Gaia (~5%)

HOW= 3D dust mapping*

+ Gaia*

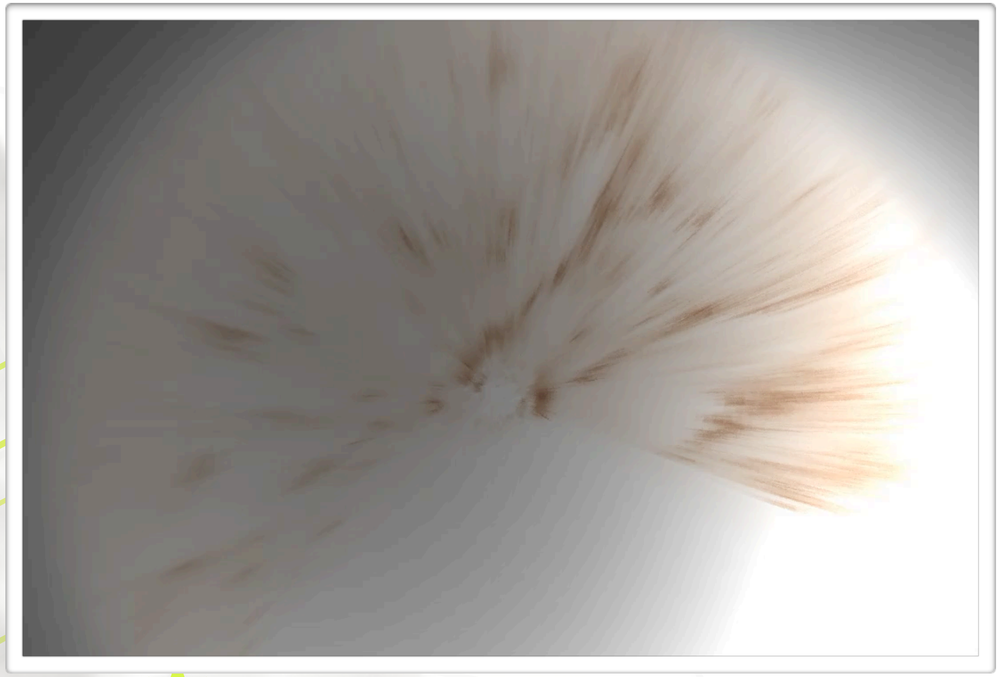


+ glue*

+ WorldWide Telescope

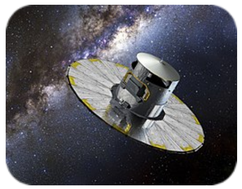
*2 million CPU hours, Harvard *800 million stars, ESA *NASA/JWST, NSF *Microsoft Research, NSF, AAS

Extinction & Reddening, from Color Imaging



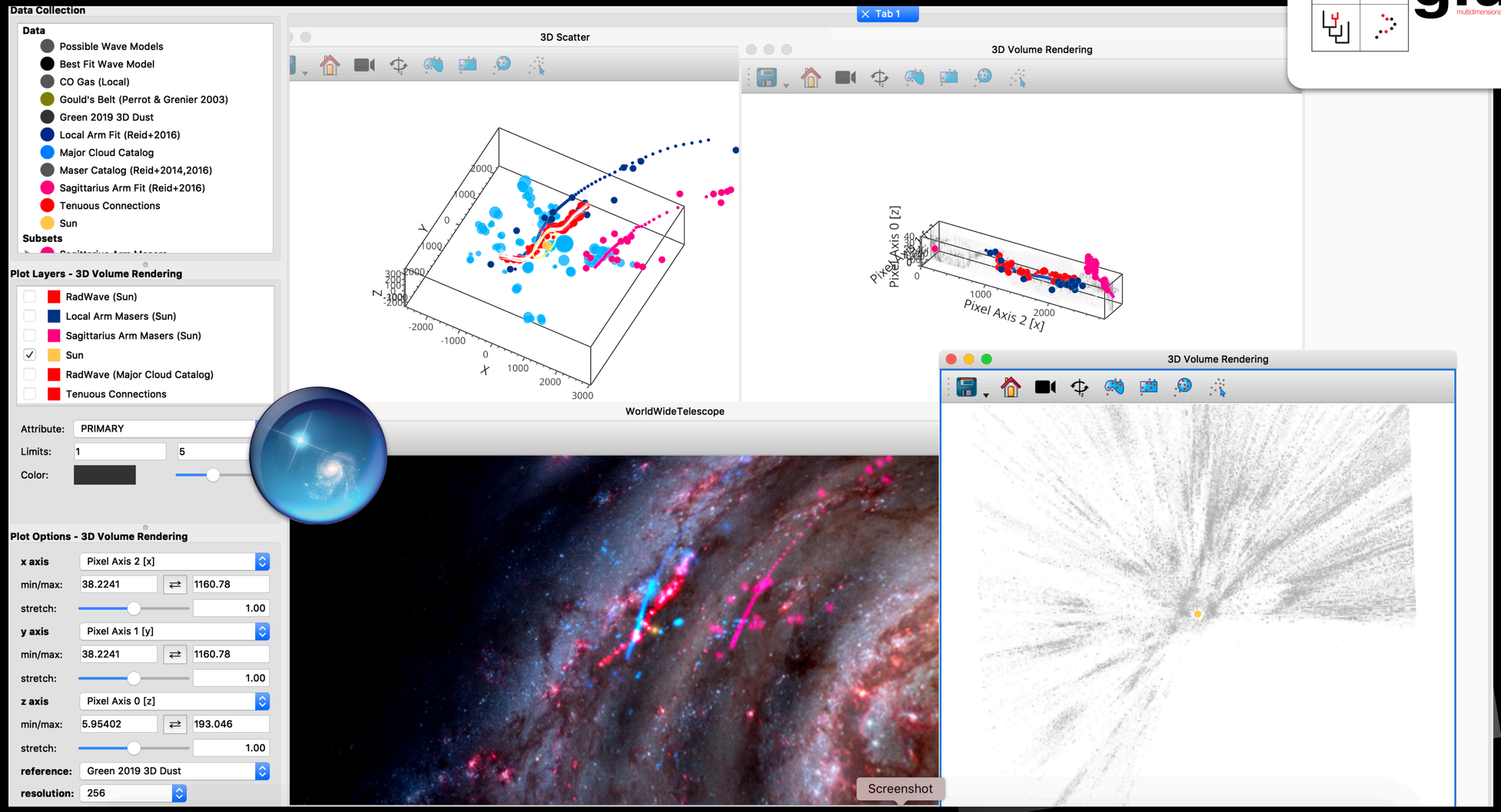
Green et al. 2019

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



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

“Seeing” The Radcliffe Wave, in 3D

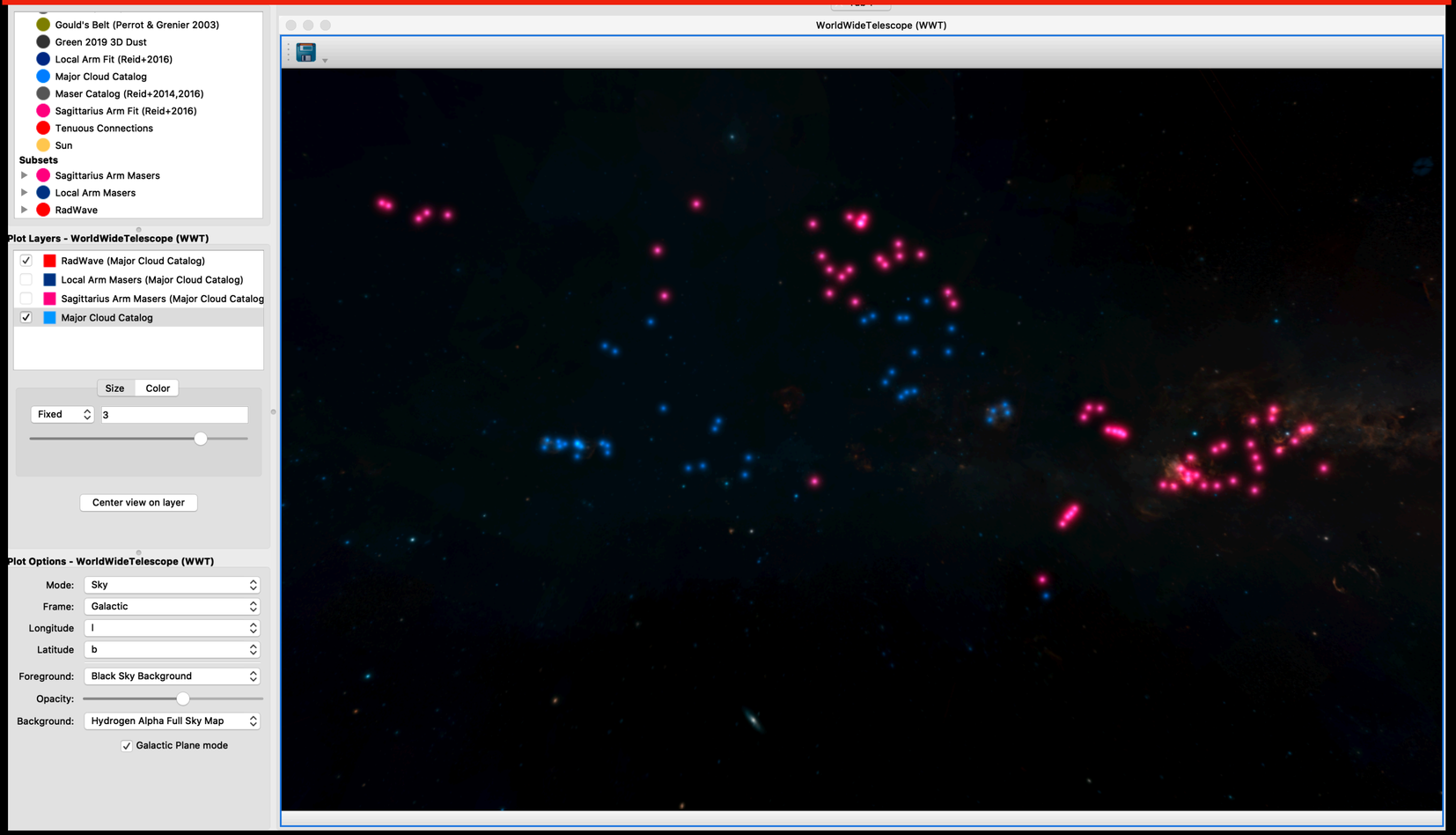


AAS WorldWide Telescope: worldwidetelescope.org

glue: glueviz.org

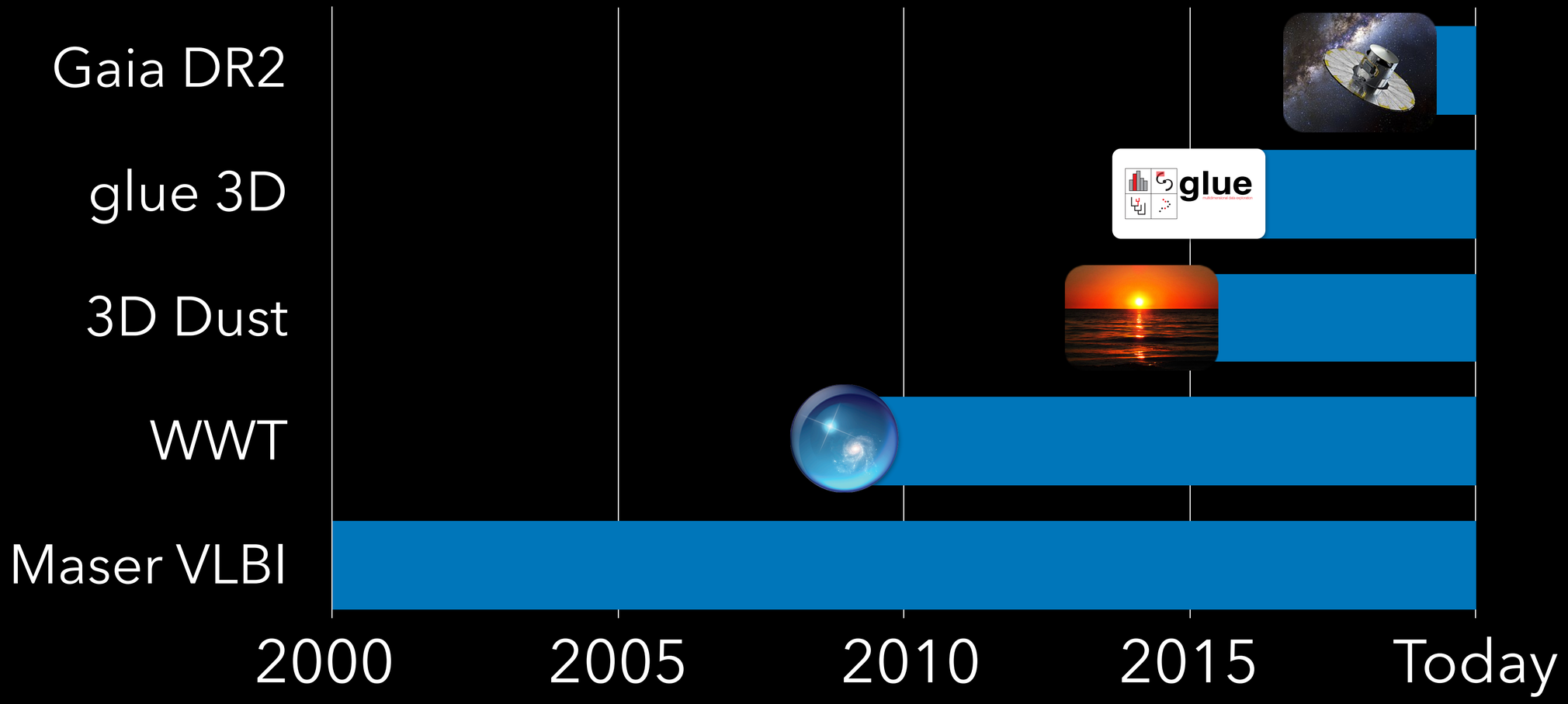
WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?

It's not apparent in 2D on the Sky.



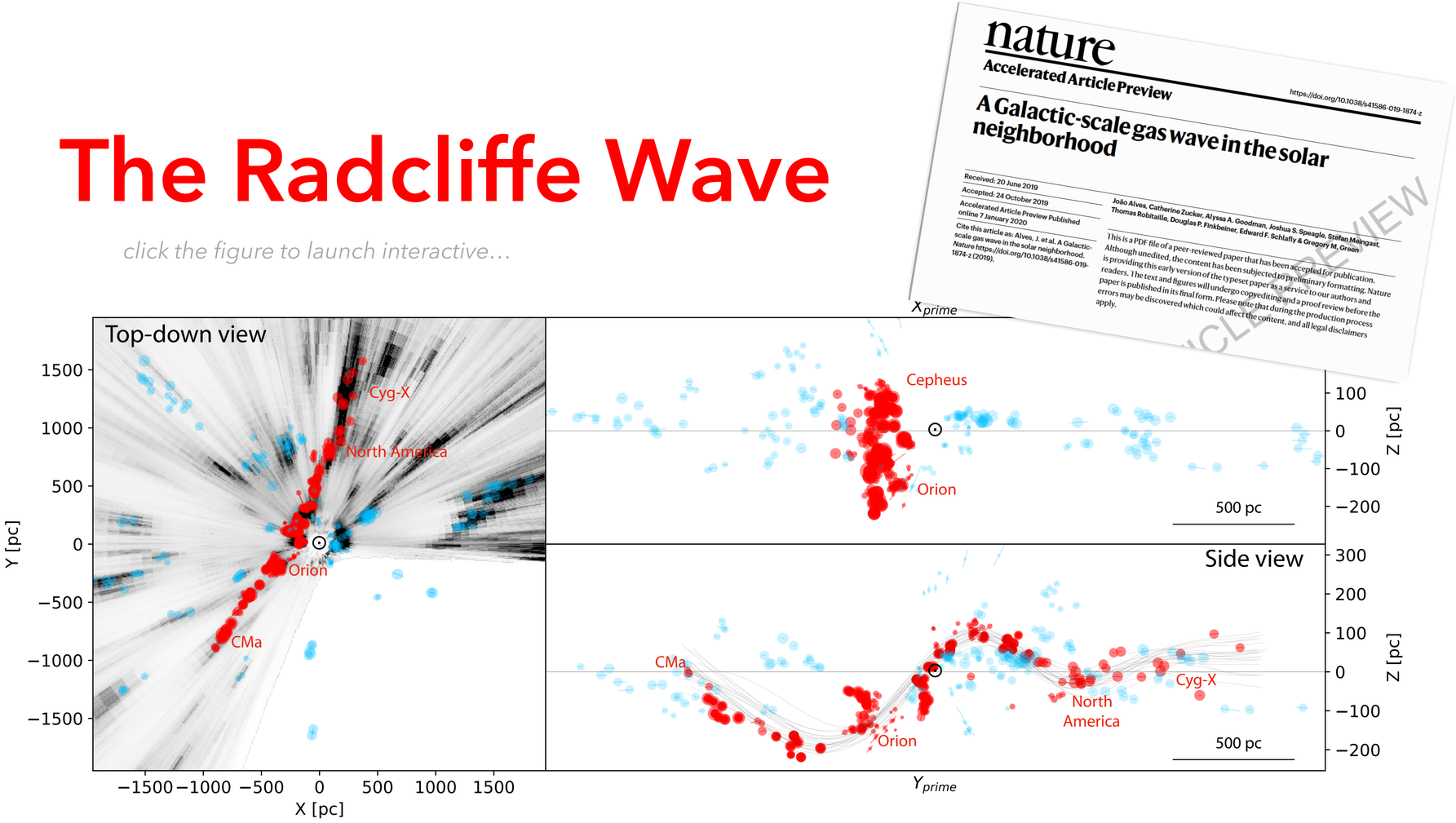
AAS WorldWide Telescope: worldwidetelescope.org glue: glueviz.org

WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?



The Radcliffe Wave

click the figure to launch interactive…



RADWAVE

Surprising wave-like arrangement of star-forming gas *is* the "Local Arm" of the Milky Way.

João Alves, Catherine Zucker, Alyssa Goodman, Joshua Speagle, Stefan Meingast, Thomas Robitaille, Douglas Finkbeiner, Edward F. Schlafly, and Gregory Green 2020, *Nature* (today)

Alves et al. *Nature* paper & two distance catalog papers by Zucker et al. (2019, 2020) include several interactive figures (via plot.ly & bokeh), and deep links to data (on Dataverse) and code (on GitHub) inspired by AAS "Paper of the Future" (Goodman et al. 2015)

RADWAVE
Surprising wave-like arrangement of star-forming gas *is* the “Local Arm” of the Milky Way.

“So What,” for Astronomers?

demise of “Gould's Belt”

end to 100-year-old paradigm

“Local Arm" not shaped as we thought it was, locally

arm is “straight" from top-down

big wave in “arm” never previously observed

wave’s origin unknown (collision? dark matter? accretion?)

Open Questions

What is the ORIGIN of the Radcliffe Wave? Collision?

Do other parts of the Milky Way show this wavy structure? How about other galaxies? How can we SEARCH?

What do “waves “ mean for the STAR-FORMING HISTORIES of galaxies?

SURF the Radcliffe Wave

It appears that the Sun, on its galactic orbit, crossed the Radcliffe Wave 13 million years ago, and may cross it again in the future.

video created by the authors using AAS WorldWide Telescope (includes cartoon Milky Way by Robert Hurt)

Find these slides, the papers, videos, WWT Tours, and much more at: tinyurl.com/RadWave

The Path to Newton

A Lunch Appetizer/Bonus “ordered” by Mark

What would a “Path-To” look like for Star Formation (so far)?

The Path to Newton

PREVAILING BELIEF

TOOLS AVAILABLE

MATH AVAILABLE

CONCERNED WITH PHENOMENA

EARTH AT CENTER (⊙ BELIEVED SUN AT CENTER)

GNOMON

GNOMON
ASTROLABE

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

ARITHMETIC
ZERO AS PLACE HOLD
PLANAR GEOMETRY
SPHERICAL GEOMETR
TRIGONOMETRY
SPHERICAL TRIGONO
SPRERICAL TRIGONOMETRY
ALGEBRA

BIG IDEAS

Correct

Partial credit

Wrong

CONNECTIONS BETWEEN IDEAS

Teacher-Pupil or Senior-Junior Researcher

Travel between cultures

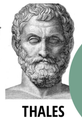
Published works

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

Motion and change are illusions

Motion needs a little push.

ANAXAGOROS
510–428 BCE
Greek

Motion must have a cause

Question all you "see."

PARMENIDES
515–450 BCE
Greek

The universe is WAY bigger than you might think.

ANAXIMANDER
610–546 BCE
Greek

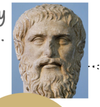
Earth generated by boundless eternity

If circles are perfect, spheres are sublime.

PYTHAGORAS
570–495 BCE
Greek

Universe is spherical

SOCRATES
470–399 BCE
Greek



Symmetry rules.

PLATO
427–347 BCE
Greek

The air moves objects through it

Rearranging "atoms" allows motion

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

DEMOCRITUS
460–370 BCE
Greek

It's spheres all the way down.

EUDOXUS
390-337 BCE
Greek

Planets, Moon, Sun, move on spheres

Earth is stationary center of the universe

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

Hello? Is this thing on?

ARISTARCHUS
310–230 BCE
Greek

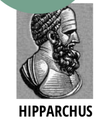
Sun at center

Math can model the universe

I can prove it!

EUCLID
300? BCE
Greek

A single framework for all geometry



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

HIPPARCHUS
190-120 BCE
Greek living in Rome

Epicycles, equants, eccentrics

Circles ARE the best! We just need more!

PTOLEMY
100–170
Greek living in Roman Egypt

Motion caused by self-exhausting force

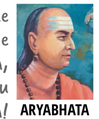
Celestial and terrestrial phenomena similar

Aristotle is wrong about space, time, and matter.

JOHN PHILOPONUS
490–570
Greek living in Roman Egypt

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

VĀRĀHAMIHIRA
505–587
Indian



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

ARYABHATA
476–550
Indian

Sines improve accuracy

Who knew nothing could be so useful?

BRAHMA
598–
Indi

Zero
nume
unto i

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

Brahmas siddha
Brahma
c. 62

SUN AT CENTER (⊕ BELIEVED EARTH AT CENTER)

GNOMON
ASTROLABE
PRINTING PRESS

ARITHMETIC
ZERO AS PLACE HOLDER
ZERO AS NUMERAL
PLANAR GEOMETRY
SPHERICAL GEOMETRY
TRIGONOMETRY
SPRERICAL TRIGONOMETRY
ALGEBRA
TUSI COUPLE AND OTHER SPECIAL FORMS
LOGARITHMS

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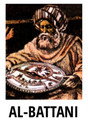


Years from now, Copernicus will love me.

AL-BATTANI
858–929
Arab

Metaphysics? Hooey! Give me evidence and math.

IBN AL-HAYTHAM
965–1040
Arab

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

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

ARYABHATA
476–550
Indian

Who knew nothing could be so useful?

BRAHMAGUPTA
598–668
Indian

Zero is a numeral unto itself

If I use a teeny unit of time...

BHĀSKARA II
1114–1185
Indian

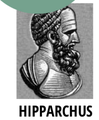
Much of what we today call calculus

Hello? Is this thing on?

ARISTARCHUS
310–230 BCE
Greek

Sun at center

Math can model the universe



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

HIPPARCHUS
190-120 BCE
Greek living in Rome

Sines improve accuracy

It just keeps going, and going... but not really.

IBN SINA (AVICENNA)
980–1037
Persian

Motion is indefinite without external forces

What did Aristotle really mean? We need to question.

IBN RUSHD (AVERROES)
1126–1198
Arab

Motion is a chain of an object's locations

Bigger observatories, better observations.

AL-TUSI
1201–1274
Persian

Simple circular orbits work with better math

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

Sun at center of Earth's & planets' orbits

Math first, philosophy later.

NICHOLAS COPERNICUS
1473–1543
Polish

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!

Hmm... circles are a problem.

JOHANNES KEPLER
1571–1630
German

Orbits are ellipses, not circles

Jupiter has moons, which orbit like our Moon

Physics
Aristotle
c. 320 BCE

Elements
Euclid
c. 300 BCE

The Almagest
Ptolemy
c. 150

Aryabhatiya
Aryabhata
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Pañca-siddhāntikā
Vārāhamihira
c. 575

Brahmasphuta-siddhanta
Brahmagupta
c. 628

TRANSLATION MOVEMENT WORKS

Kitāb az-Zīj
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

© Harvard University

PREDICTIONX

SUN AT CENTER (⊕ BELIEVED EARTH AT CENTER)

GNOMON
ASTROLABE
PRINTING PRESS
TELESCOPE
ARITHMETIC
ZERO AS NUMERAL
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1201–1274
Persian

Motion explained with "impetus theory"

Motion is a chain of an object's locations

Metaphysics? Hooey! Give me evidence and math.

IBN AL-HAYTHAM
965–1040
Arab

This is math, not philosophy.

JEAN BURIDAN
1295–1358
French

Math first, philosophy later.

NICHOLAS COPERNICUS
1473–1543
Polish

With giant spendy instruments, I can get GREAT data.

Planets orbit the Sun, but Sun orbits Earth

TYCHO BRAHE
1546–1601
Danish

Ooooh, I like this Dutch spyglass!

Sorry, Aristotle, you're just wrong.

GALILEO GALILEI
1564–1642
Italian

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

Simple circular orbits work with better math

The Earth might actually rotate

Sun at center of Earth's & planets' orbits

Jupiter has moons, which orbit like our

All bodies on Earth have (circular) inertia

GRAVITY GOVERNS ALL

Models matching data is paramount

If I use a teeny unit of time...

BHĀSKARA II
1114–1185
Indian

Much of what we today call calculus

Earth need not be at rest, Ptolemy!

ALI QUSHJI
1403–1474
Turkic

REGIOMONTANUS
1436–1476
German

I can improve Ptolemy! To the printing press!

JOHANNES KEPLER
1571–1630
German

Orbits are ellipses, not circles

Sun is the center

All bodies have inertia

I must make Newton publish!

EDMOND HALLEY
1656–1742
British

Some comets return, predictably

Kitāb al-Shifā' 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

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

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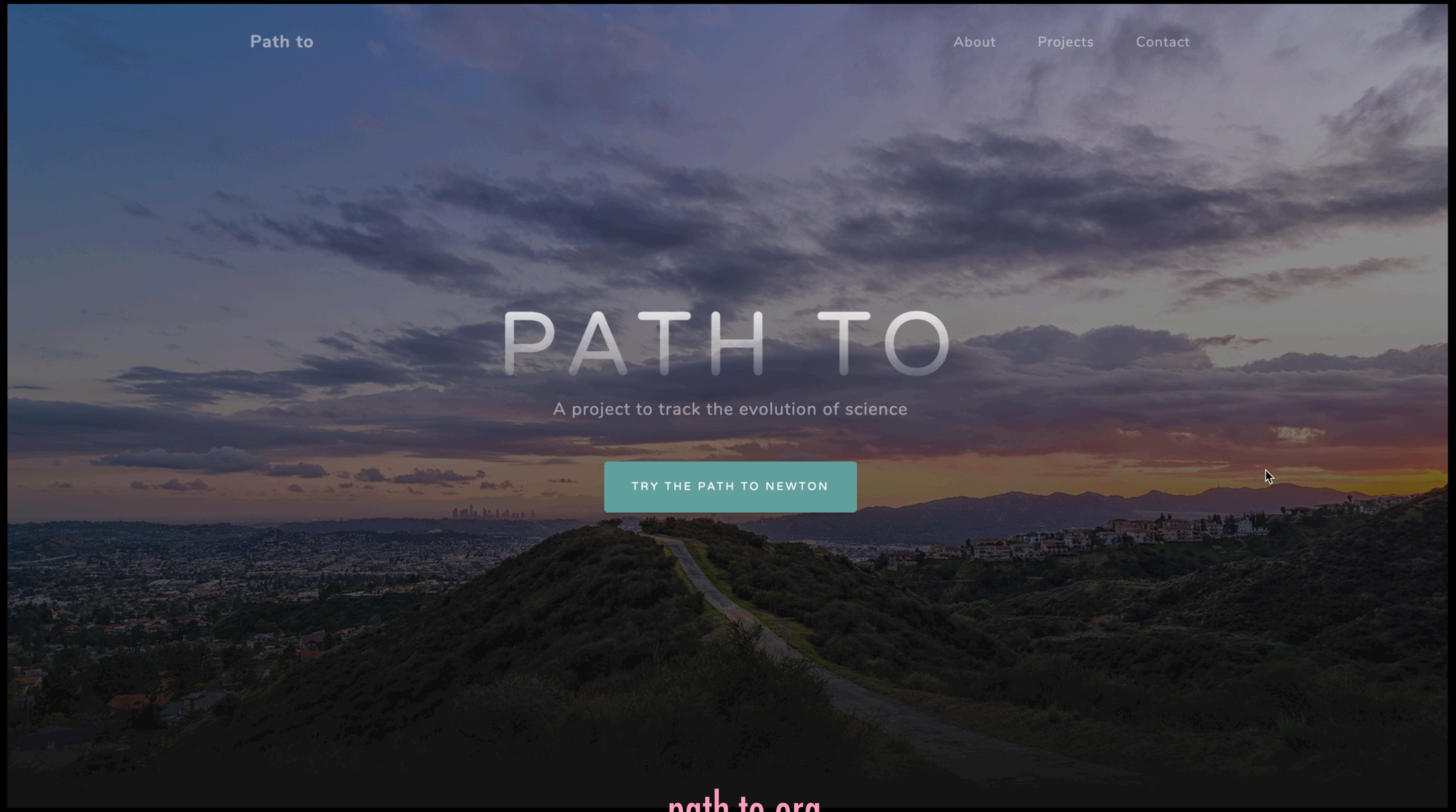

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