HOW ASTRONOMERS MEASURE THE UNIVERSE

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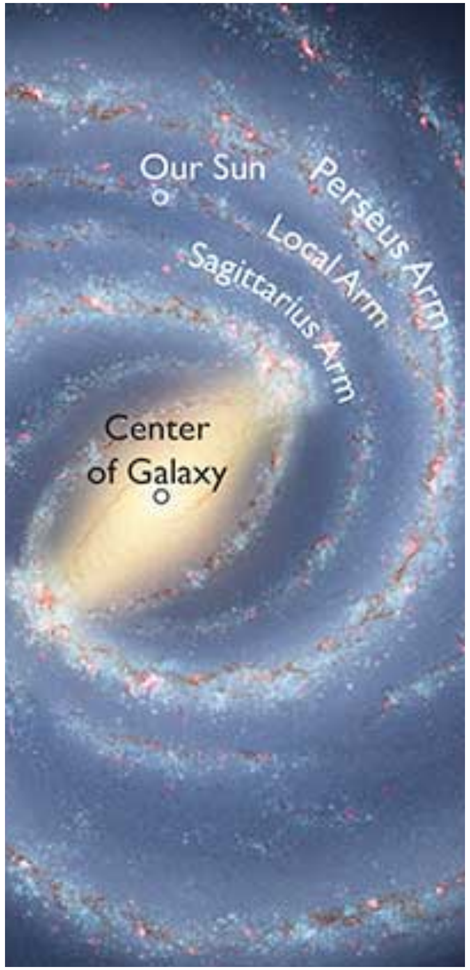

Congreso Nacional de Física 2018
Puebla
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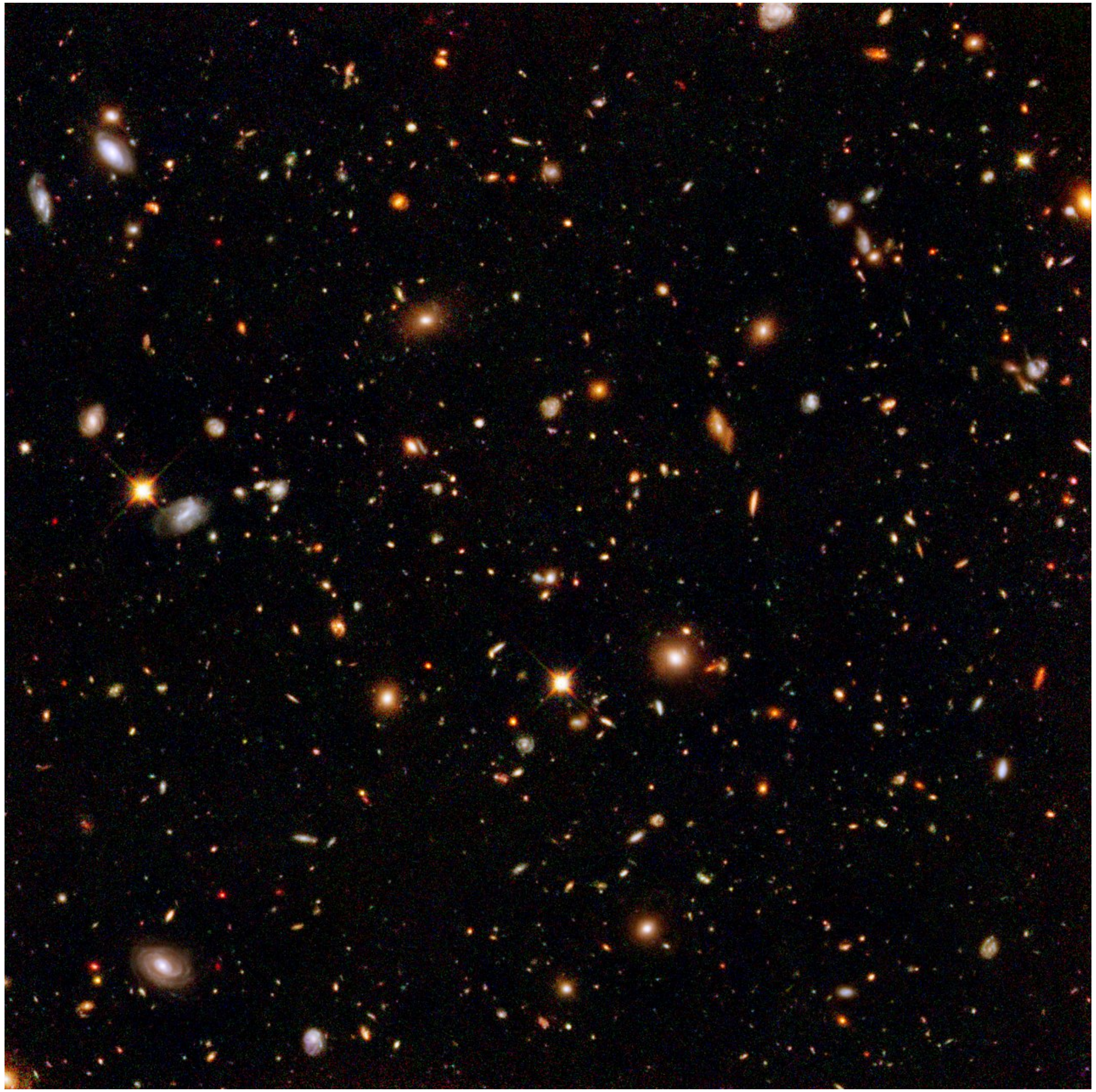
Galaxies are the building blocks of our Universe

The Milky Way (top) and the Andromeda galaxy (bottom)



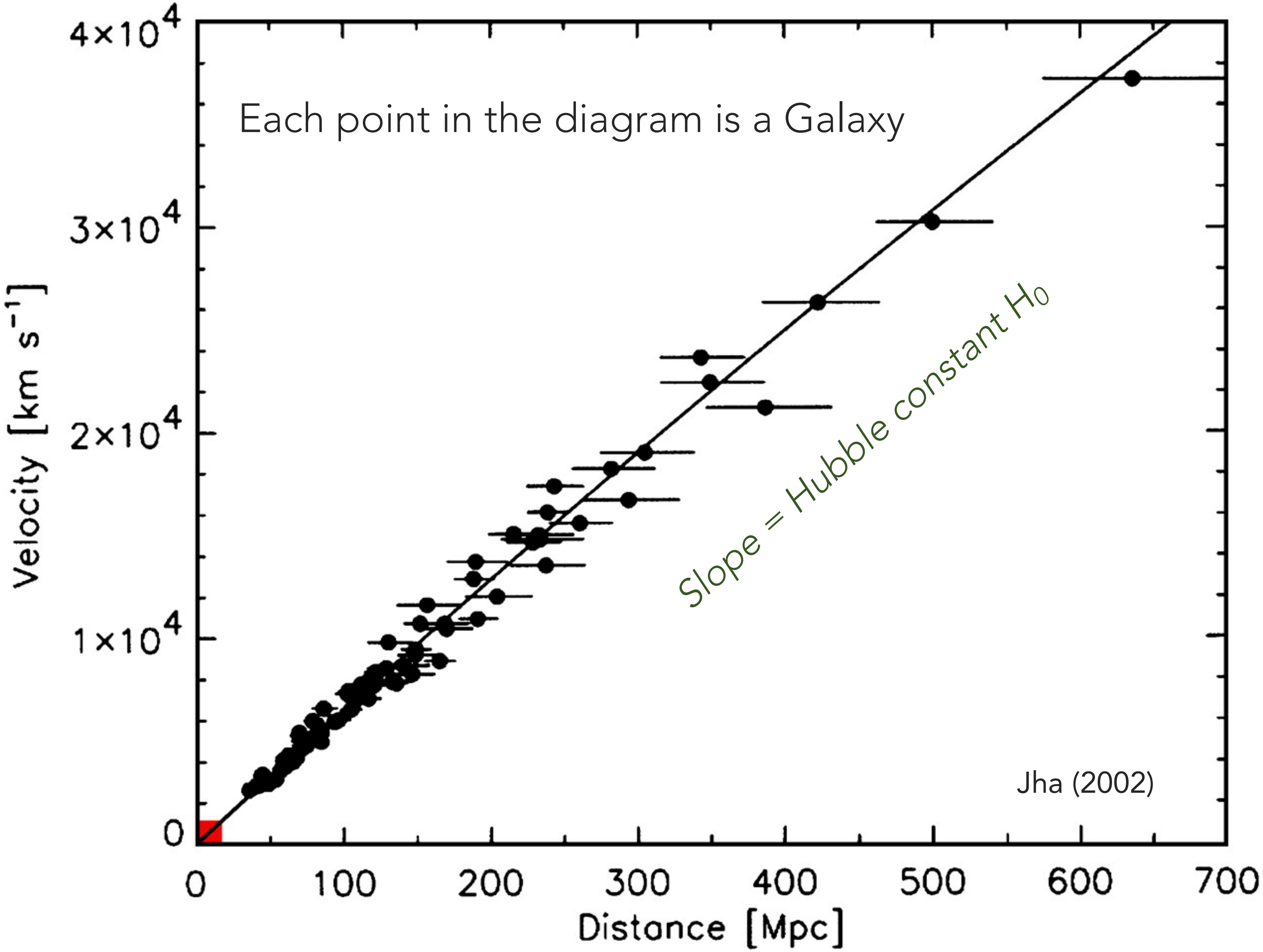
The “Hubble Deep Fields” © NASA

The Hubble-Lemaître law – expansion of the Universe

$$v = H_0\, d$$

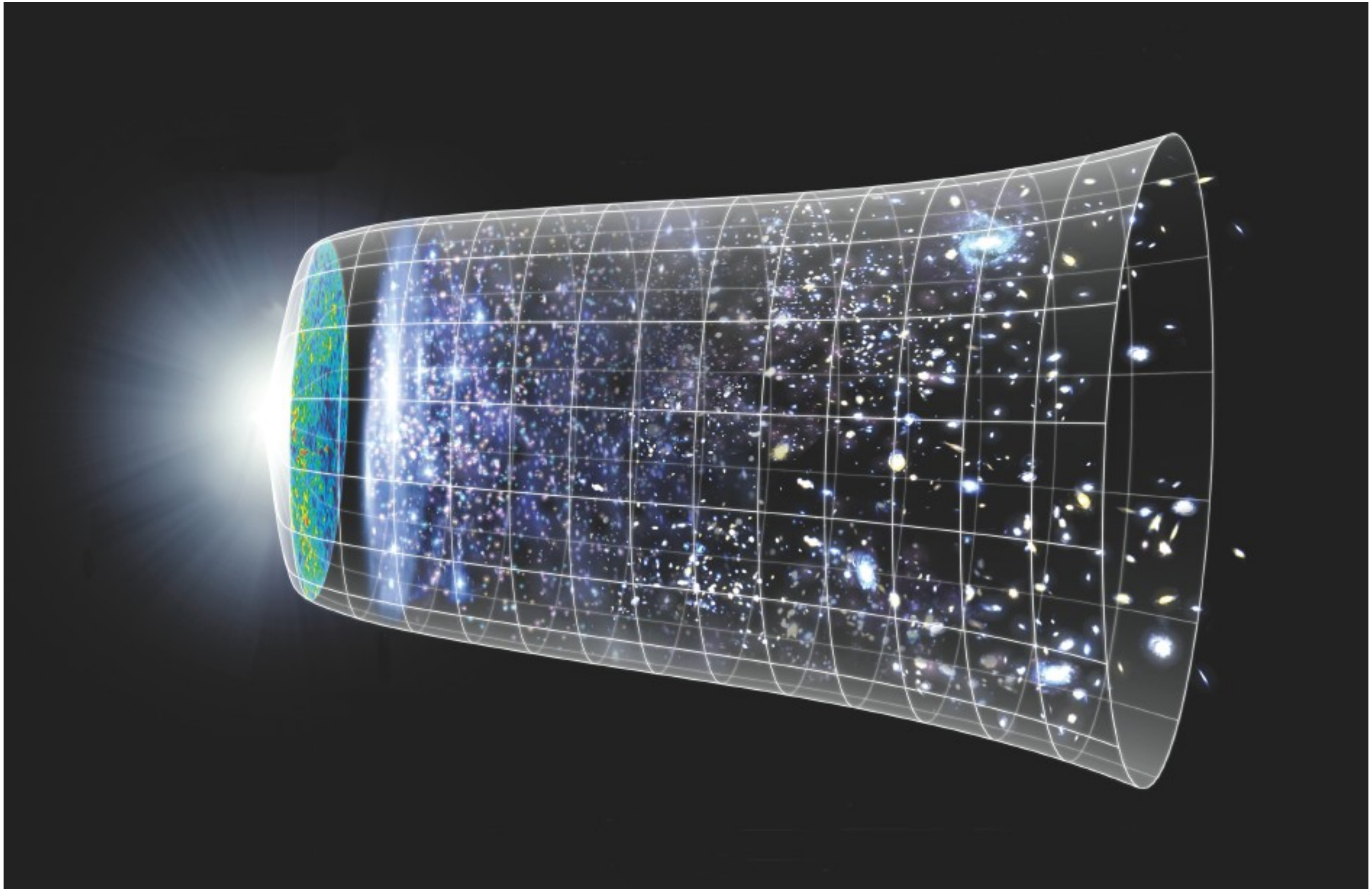

Edwin Hubble


George Lemaître



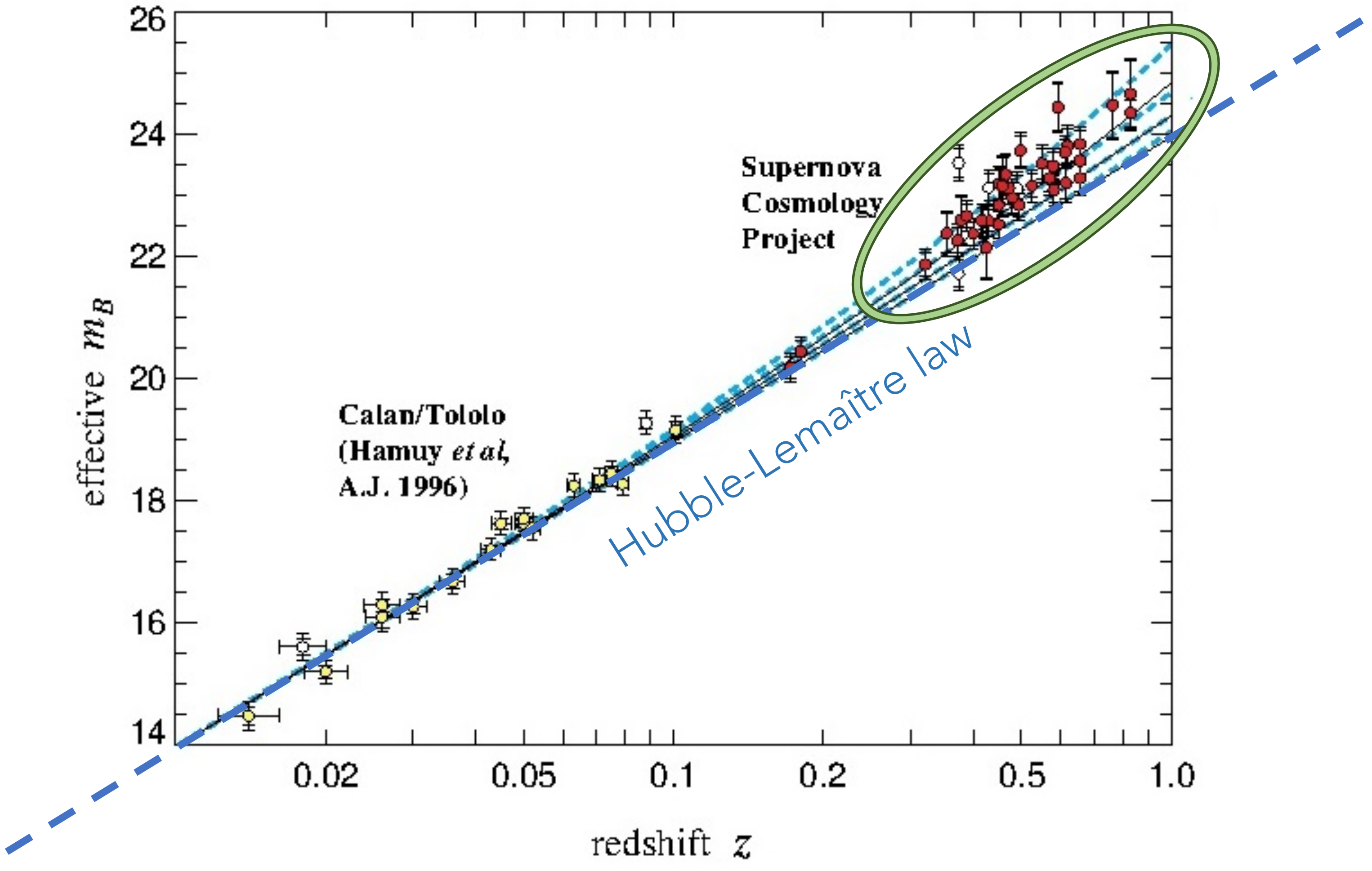
Jha (2002)

The Hubble-Lemaître law is one of the fundamental empirical evidences for a Big-Bang

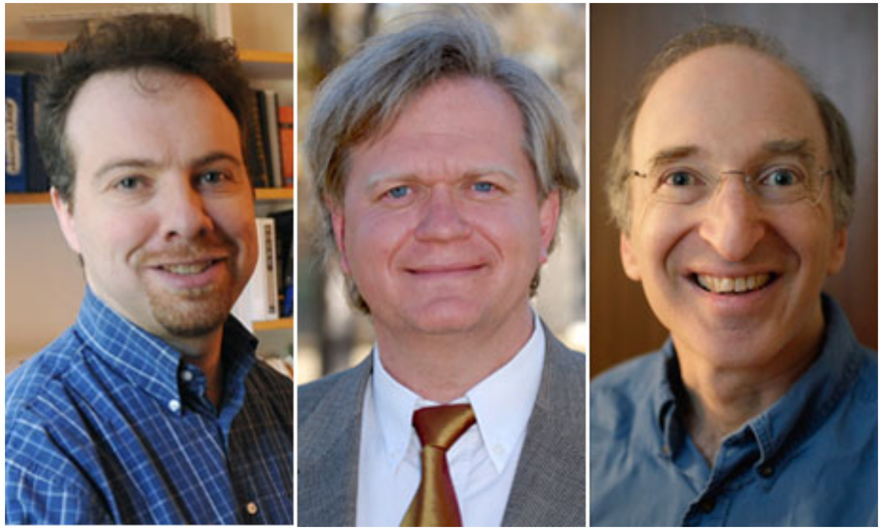


The accelerated expansion of the Universe

Departure from simple Hubble-law at large distances (i.e. in the past)



"distance"



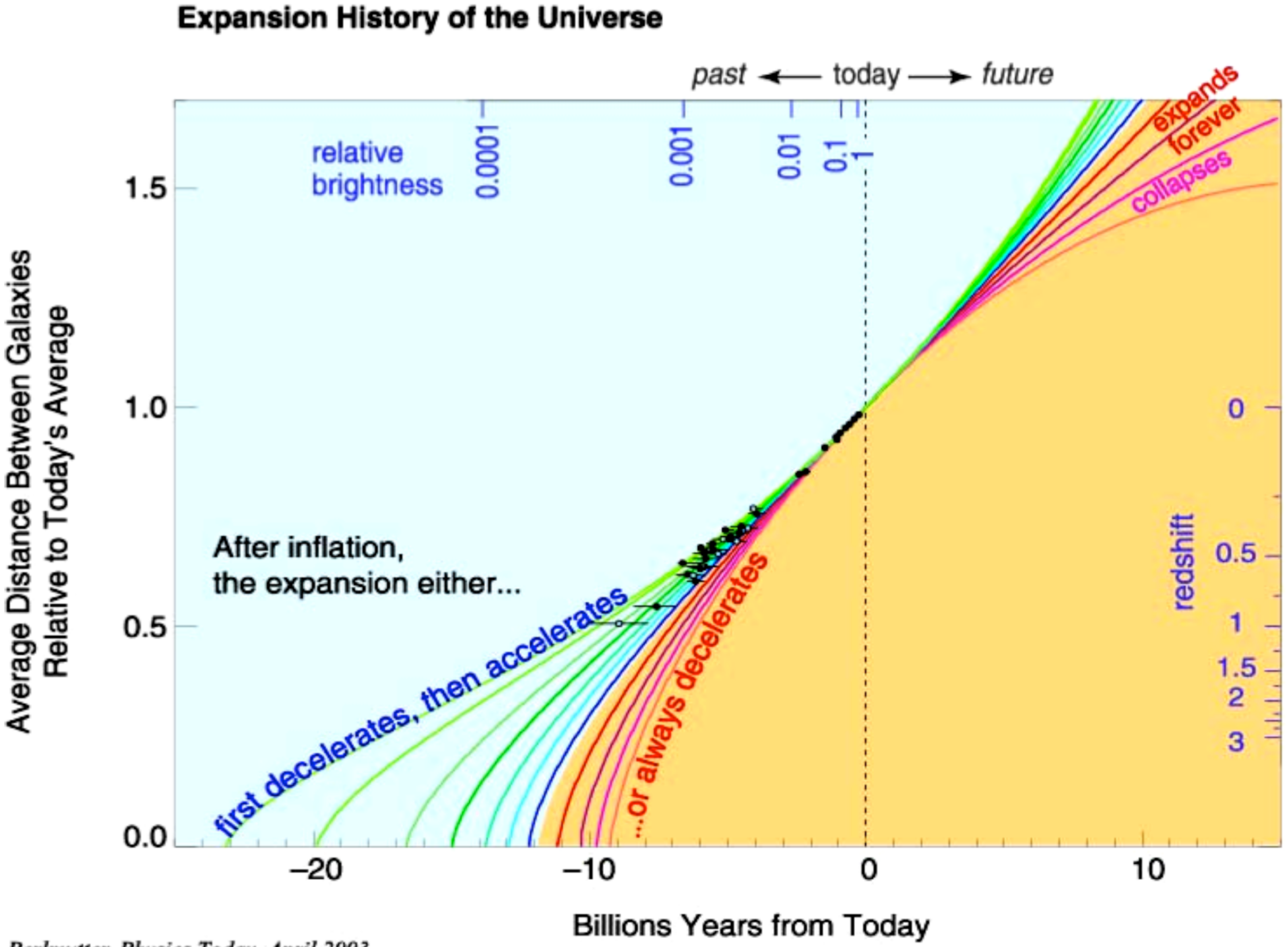
Adam Riess Brian Schmidt Saul Perlmutter

Existence of "dark energy" in the Universe


Adam Riess

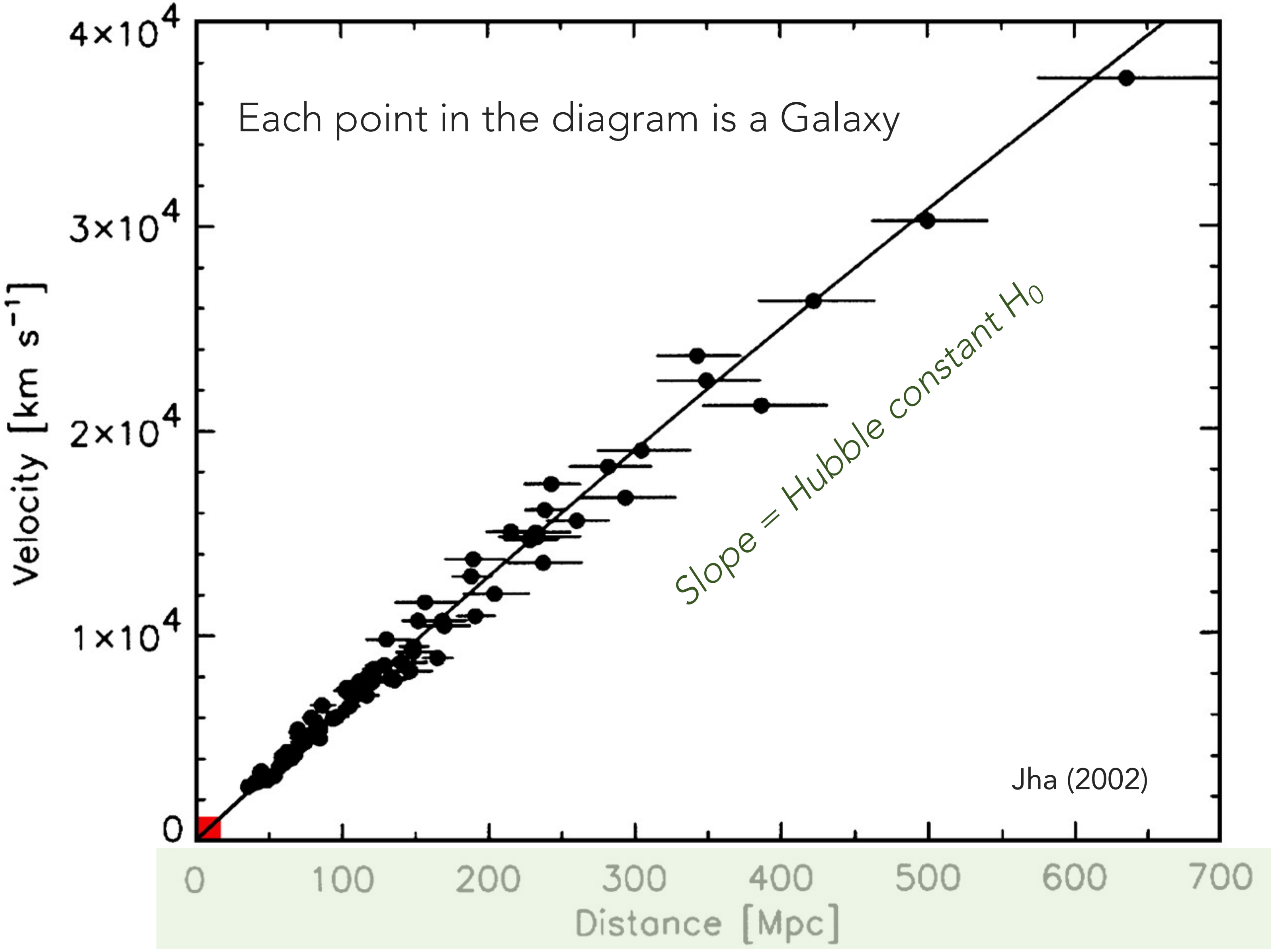

Brian Schmidt


Saul Perlmutter



Perlmutter, Physics Today, April 2003

It all depends on distance determinations…

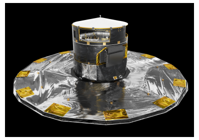


Each point in the diagram is a Galaxy

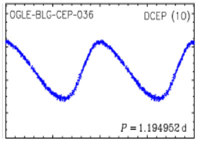
Slope = Hubble constant H_0

Jha (2002)

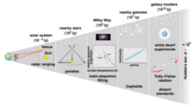
Laser/radar ranging



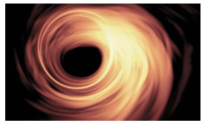
Trigonometric parallax – Hipparcos, Gaia, VLBI



Indirect methods – Cepheids and Supernovae Ib



The "cosmic distance ladder"



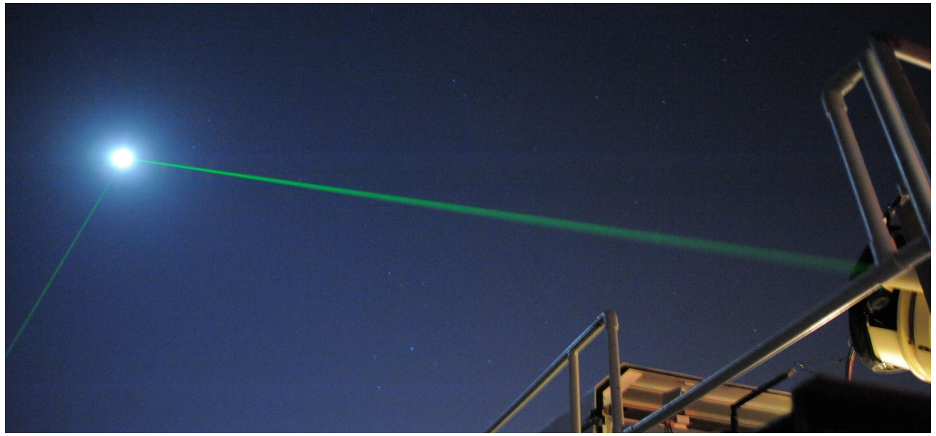
Other applications of VLBI – The Event Horizon Telescope

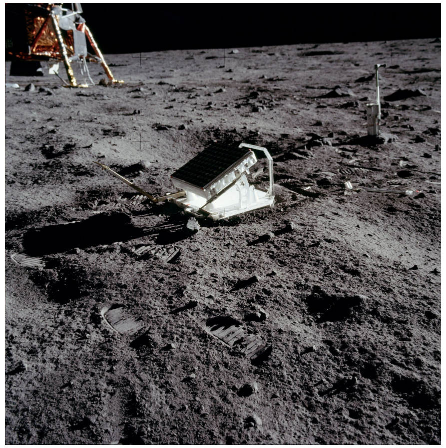
How do astronomers measure distances to celestial objects?

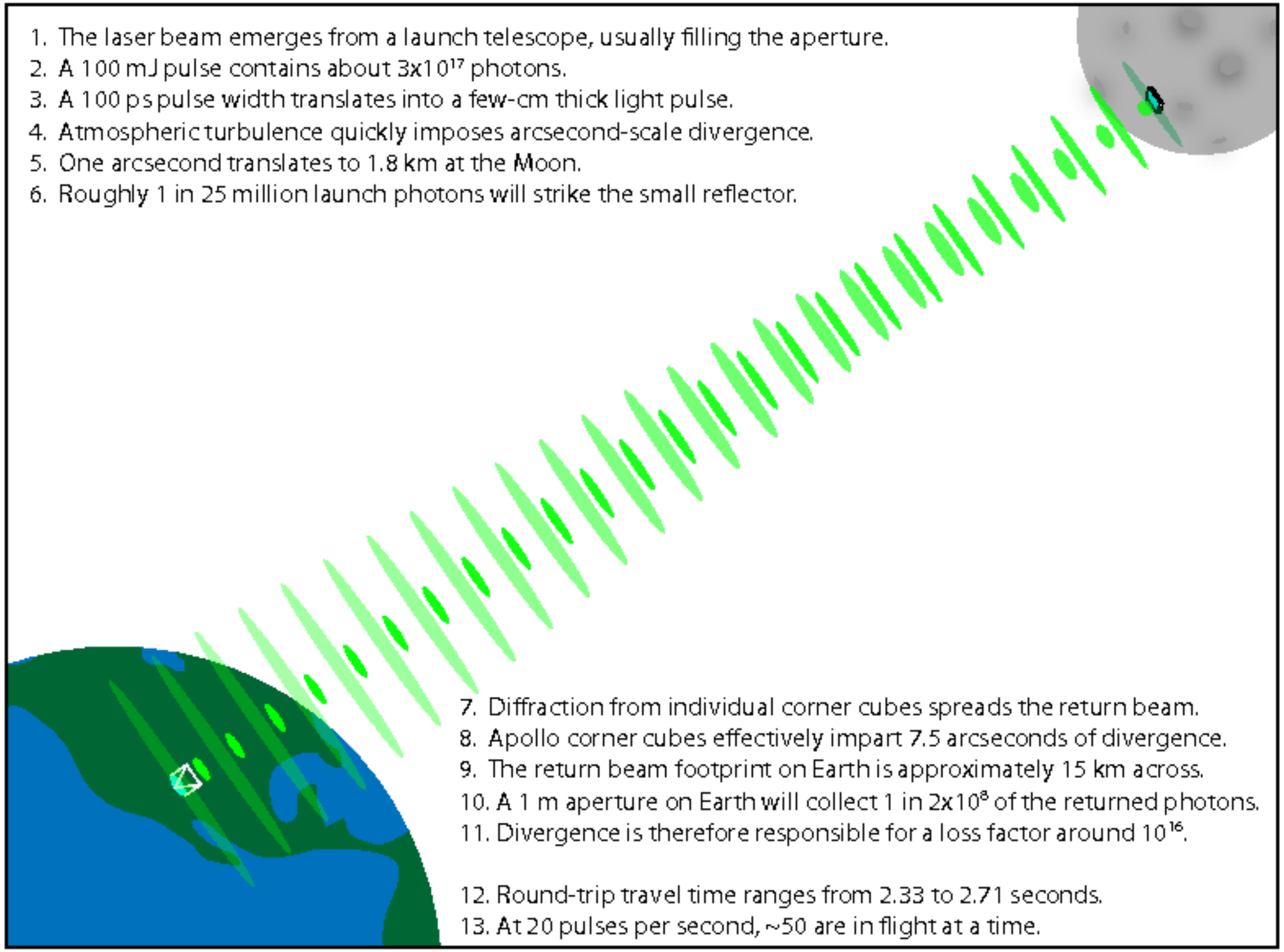
"The only good distance indicator… is a ~~tape measure.~~"
Jeremy Mould (2014)

laser distance measurer

But that’s only possible for objects in the Solar System



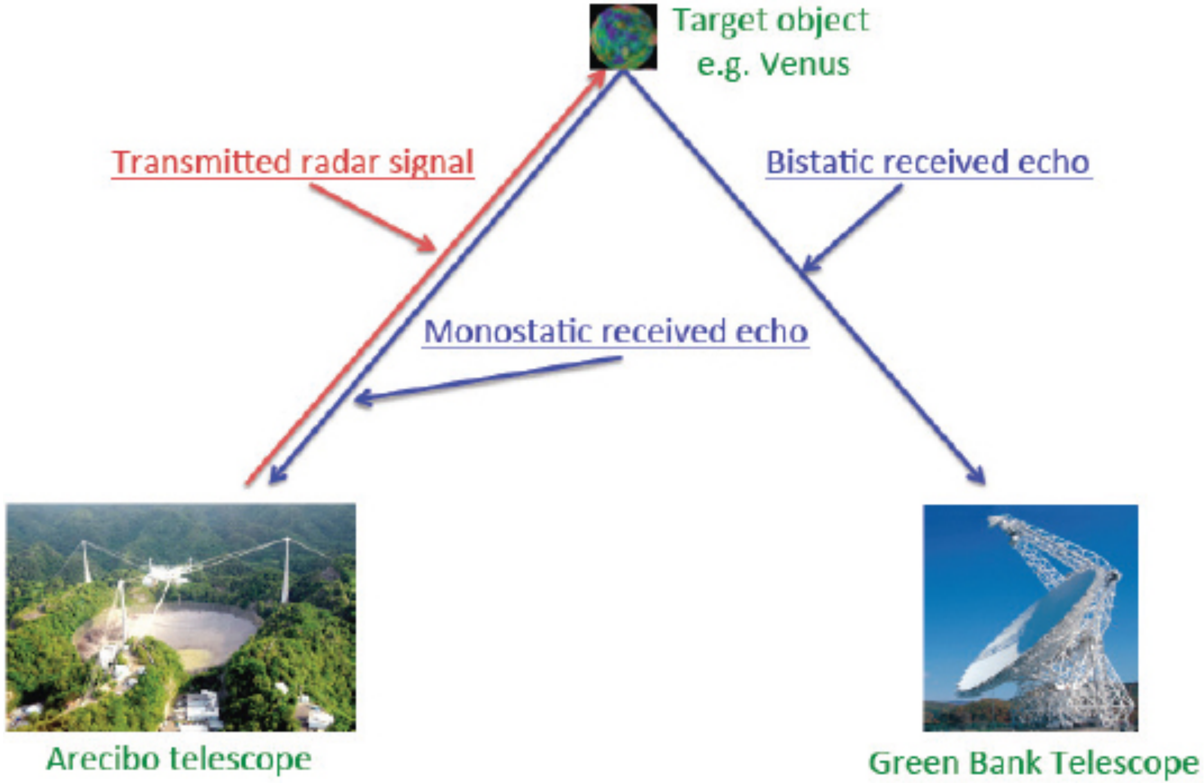




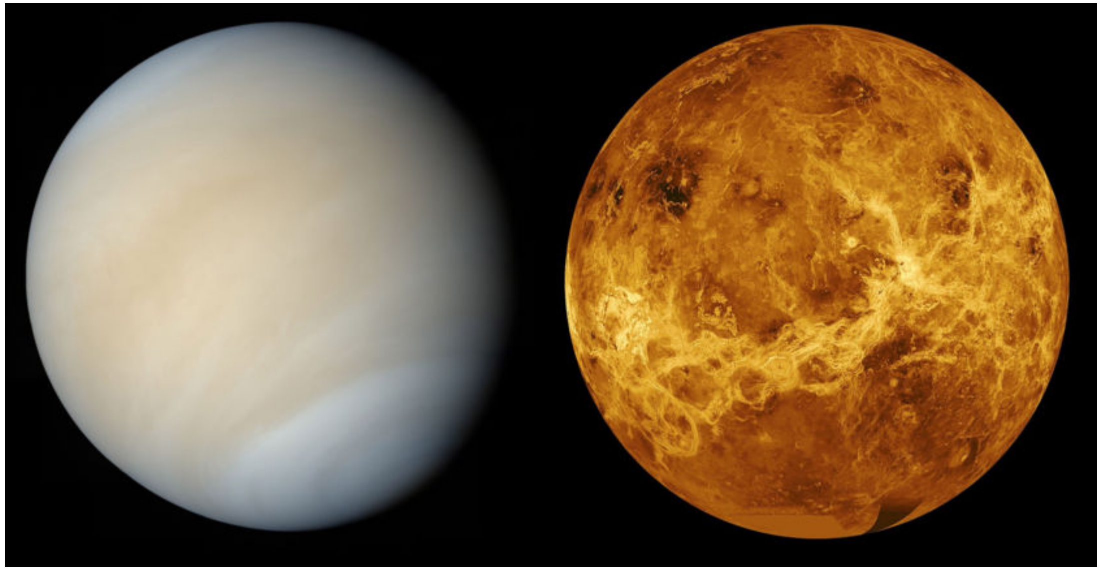
1. The laser beam emerges from a launch telescope, usually filling the aperture.
2. A 100 mJ pulse contains about $3\text{x}10^{17}$ photons.
3. A 100 ps pulse width translates into a few-cm thick light pulse.
4. Atmospheric turbulence quickly imposes arcsecond-scale divergence.
5. One arcsecond translates to 1.8 km at the Moon.
6. Roughly 1 in 25 million launch photons will strike the small reflector.
7. Diffraction from individual corner cubes spreads the return beam.
8. Apollo corner cubes effectively impart 7.5 arcseconds of divergence.
9. The return beam footprint on Earth is approximately 15 km across.
10. A 1 m aperture on Earth will collect 1 in $2\text{x}10^{8}$ of the returned photons.
11. Divergence is therefore responsible for a loss factor around 10^{16}.

12. Round-trip travel time ranges from 2.33 to 2.71 seconds.
13. At 20 pulses per second, ~50 are in flight at a time.

But that's only possible for objects in the Solar System

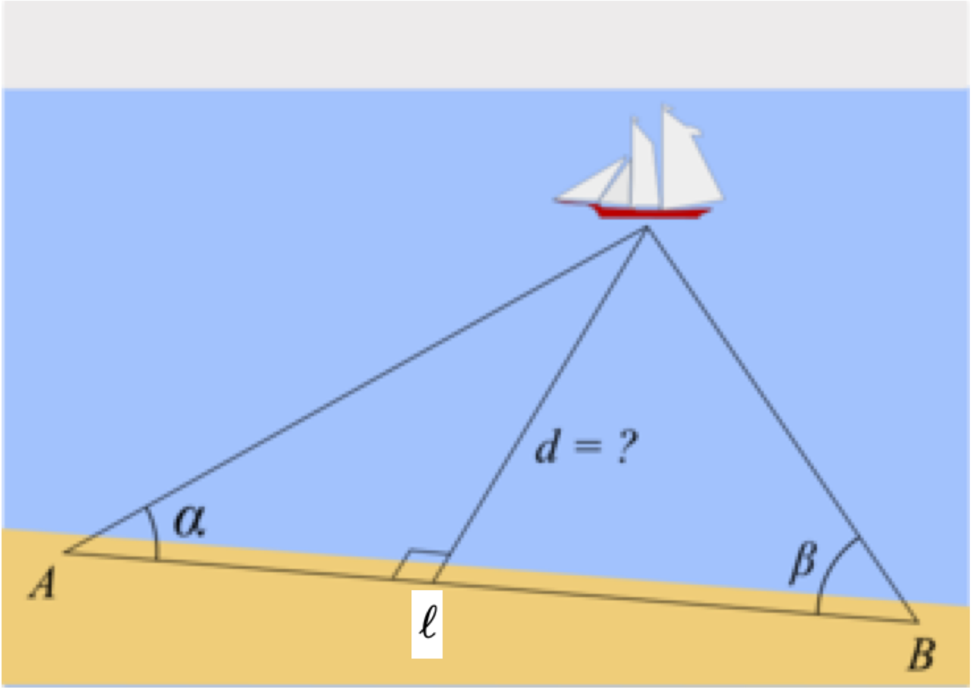


Added bonus: actually seeing the surface of Venus.



What do we do (on Earth) when we can't use a tape measure?

We use **triangulation**!!



$$d = \ell \, \frac{\sin\alpha \sin\beta}{\sin(\alpha+\beta)}$$

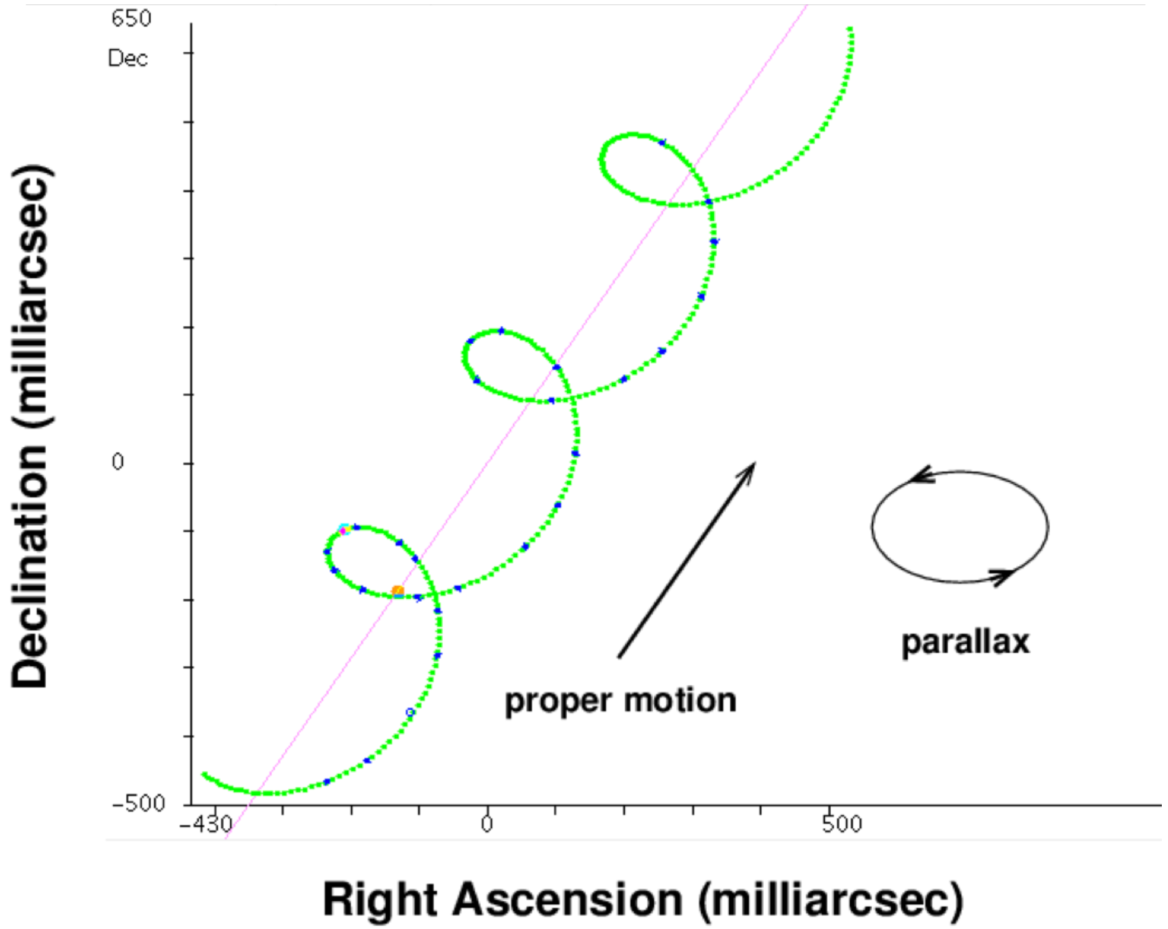
What baseline do we use? The motion of the Earth about the Sun!

The motion of the Earth about the Sun causes “nearby” stars to exhibit an apparent motion on the plane of the sky, called *trigonometric parallax*.

It is an *apparent* motion because it occurs even if the star does not actually move relative to the Sun.

To determine the trigonometric parallax of a star, one must measure its position at mutiple times and follow the trajectory of the star on the plane of the sky. Thus, it implies doing ***astrometry***.

Astrometry also delivers the actual motion between the Sun and the stars (6D).



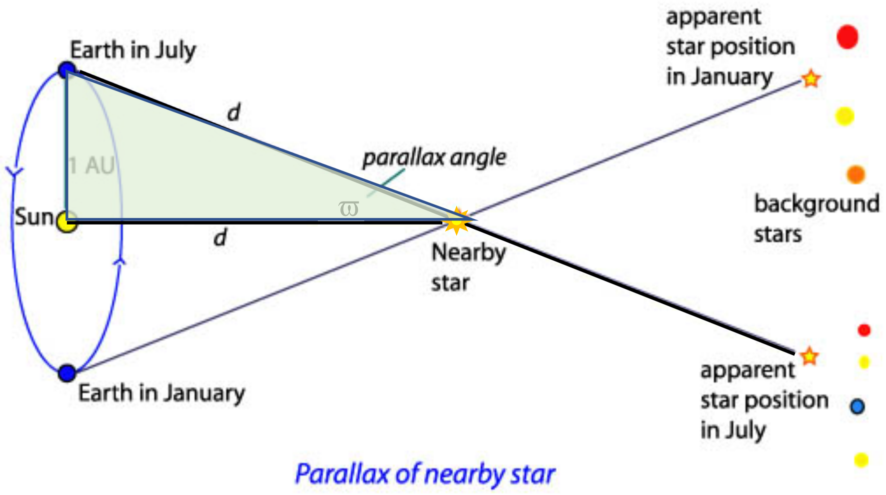
How do we relate trigonometric parallax and distance?

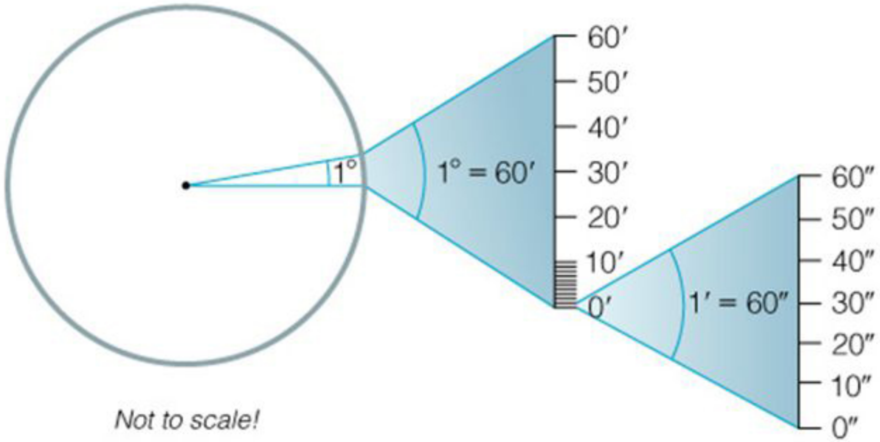
$$\tan \varpi \approx \varpi = \frac{1AU}{d}$$

This leads to the definition of the unit of distance used in astronomy:

A star whose parallax is 1 arcsecond is located at 1 ***parsec*** (= 3.26 light-year).

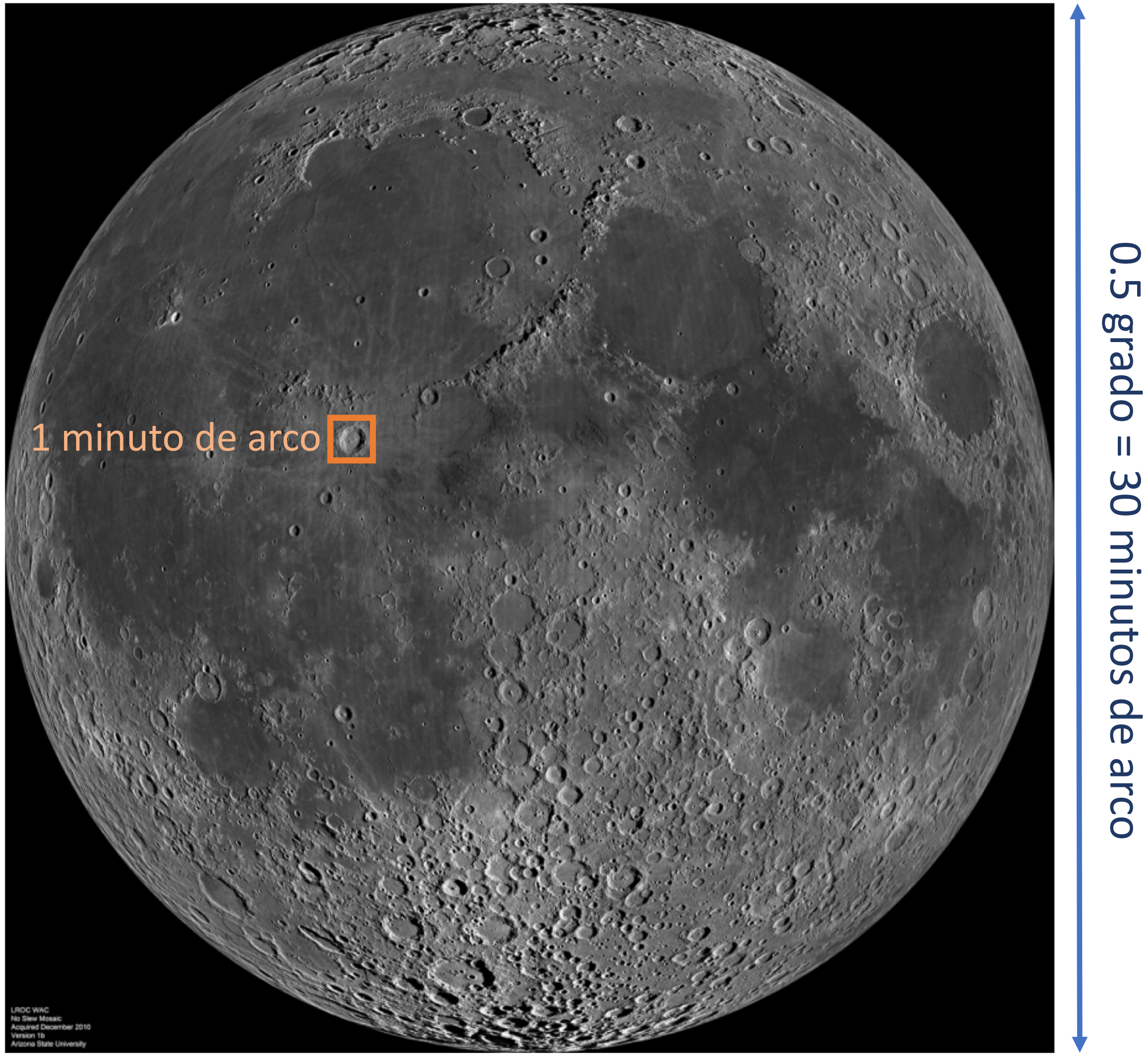
(parsec is "per arcsec")





So it’s easy to measure distances in the Universe, right?

The nearest stars are farther than 1 pc – their parallax is smaller than 1arcsec.



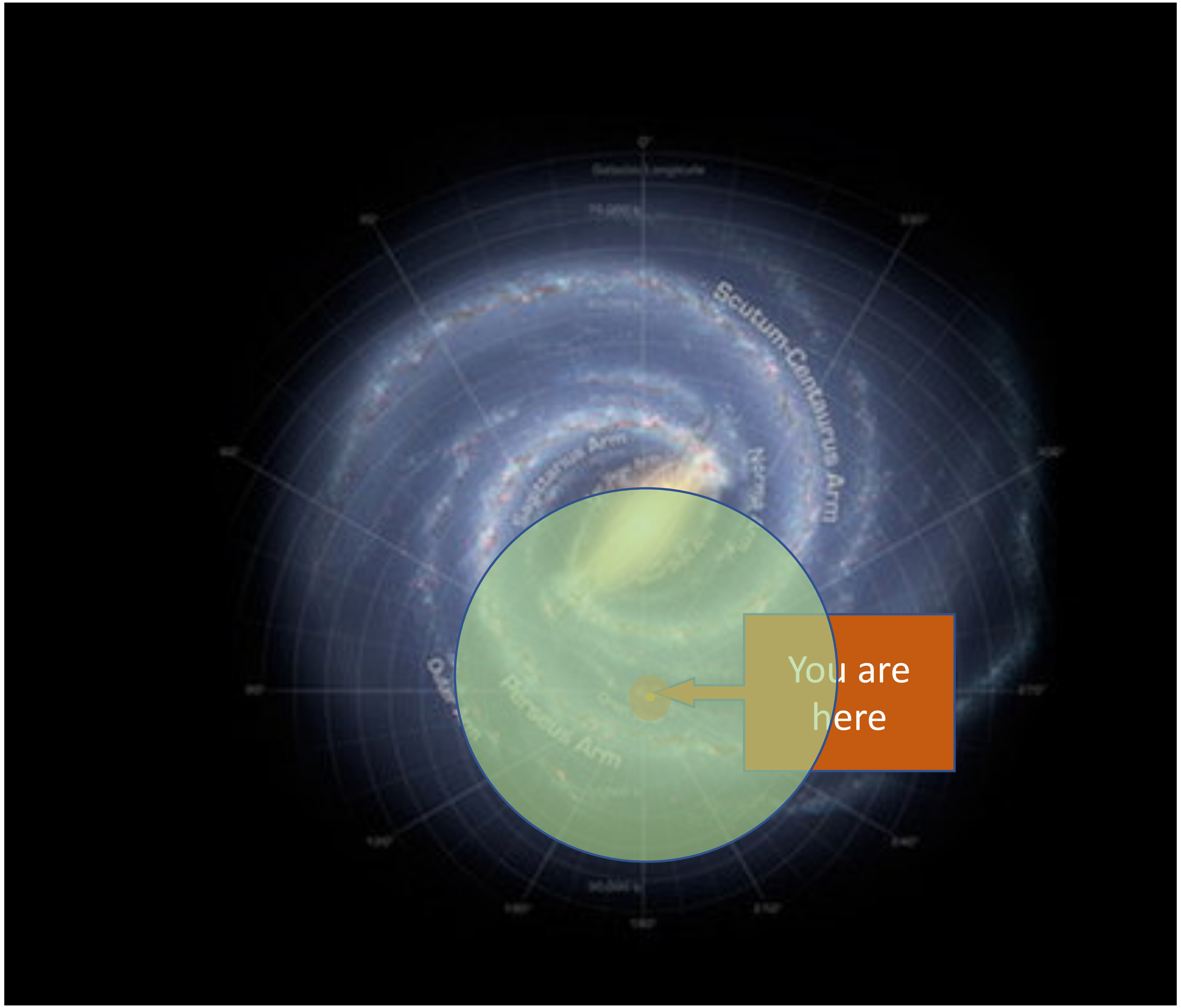
So it's easy to measure distances in the Universe, right?

There are about 10^{11} stars in the Milky Way.

Only about 400 within 10 pc of the Sun.

To reach a large fraction of the stars in the Milky Way, we need to probe out to about 10 kpc. The corresponding parallax is 100 micro-arcseconds.

1 micro-arcsecond is a **very small** angle…

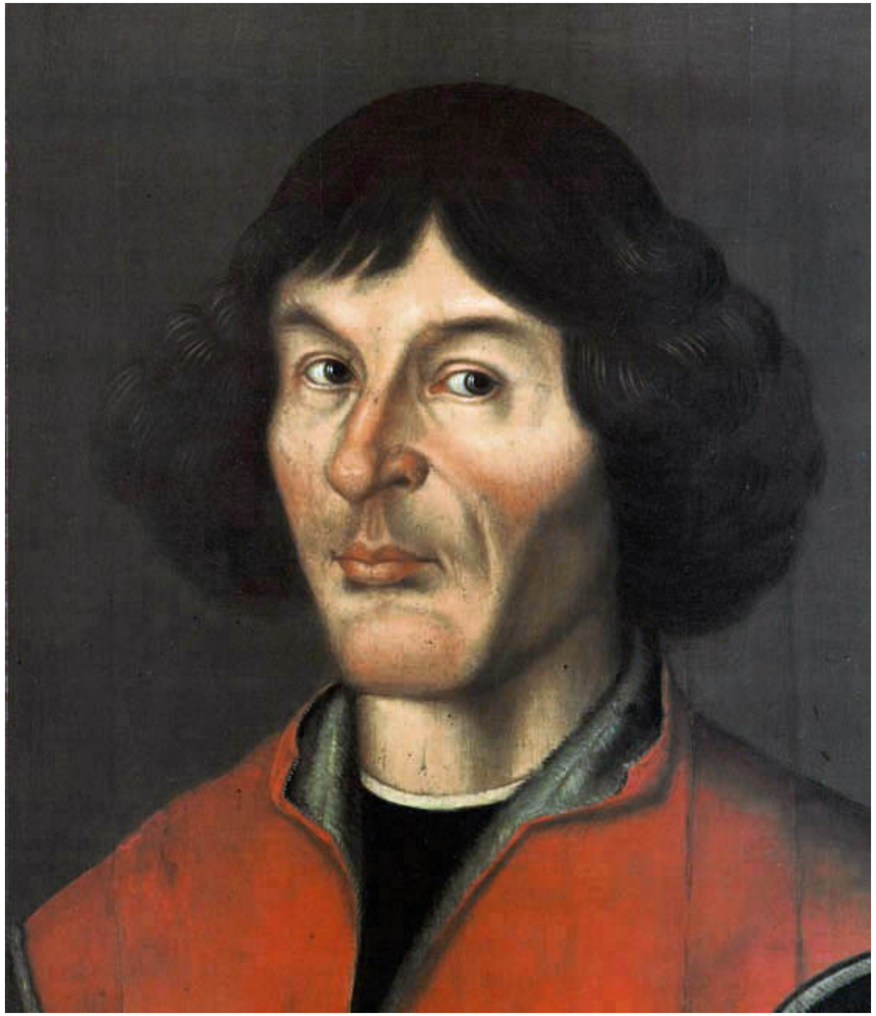


A brief historical interlude…

During more than 13 centuries, the most accepted model of the Universe was the model proposed by Ptolemeo (150 AD). In that model, the Earth was at the center of the Universe, and all other bodies revolved around it.

In 1514, Nicolaus Copernicus, a Polish astronomer of the Renaissance, proposed an alternative model where the Sun is at the center and the Earth revolved arount it.

Since the trigonometric parallax is a consequence of the rotation of the Earth around the Sun, detecting the parallax would prove Copernicus' model. Many of the famous early astronomers (Galileo, Tycho, etc.) tried



A brief historical interlude…

Finally, three astronomers independently did it during the 1830's (Bessel, Stuve and Henderson) for three different stars (61 Cygni, alpha Centauri, y Vega).

Only a few hundred stars had measured parallaxes by 1990.

ASTRONOMISCHE NACHRICHTEN.

№. 365. 366.

Bestimmung der Entfernung des 61sten Sterns des Schwans.

Von Herrn Geheimen-Rath und Ritter *Bessel.*

Als es *Bradley* gelungen war, seine Beobachtungen in *Kew* und *Wansted*, welche die Entdeckungen der Aberration und Nutation herbeiführten, durch diese allein genügend zu erklären, ohne dazu der Annahme einer jährlichen Parallaxe der beobachteten Fixsterne zu bedürfen, lieſs er nicht unbemerkt, daſs ein über eine Secunde betragender Werth derselben, den Beobachtungen der Sterne γ *Draconis* und η *Ursæ majoris* nicht entgangen sein würde. Indem er hinzusetzt, daſs diese Sterne mehr als 400000 Mal so weit als die Sonne von uns entfernt seien *), geht hervor, daſs er unter jährlicher Parallaxe den Winkel versteht, welchen die *ganze* Erdbahn an den Sternen einschlieſst.

Hierauf beruhet die später gewöhnlich gewordene Annahme, daſs die jährliche Parallaxe der Fixsterne im Allgemeinen *sehr klein* sei. Wenn diese Annahme aber auch für die groſse Mehrheit der zahllosen Sterne dieser Art unbezweifelbar ist, so ist doch eben so wenig zu bezweifeln, daſs einige darunter weit näher sind, als die groſse Menge der übrigen; bis zu welcher Grenze die jährliche Parallaxe dieser näheren Sterne steigen kann, kann aus der von *Bradley* erkannten Kleinheit derselben für die beiden angeführten Sterne (denen man noch mehrere andere, bei derselben Gelegenheit beobachtete hinzusetzen kann), offenbar nicht gefolgert werden. Wenn man also auch des Mittels entbehrte, durch fortgehende Verbesserung der Apparate und Beobachtungsmethoden, Gröſsen bestimmbar zu machen, welche die von *Bradley* angegebene Grenze der jährlichen Parallaxen jener Sterne nicht überschreiten, so würde man dennoch die Hoffnung nicht verlieren, das Maaſs der Entfernungen *anderer* Sterne aus den Beobachtungen hervorgehen zu sehen.

Bei dem jetzigen Zustande unserer Kenntnisse des Weltgebäudes können wir nur zwei, in der That nicht sichere Gründe der Vermuthung, daſs ein Fixstern verhältniſsmäſsig nahe sei, anführen; nämlich den *optischen* Grund, seine ausgezeichnete Helligkeit, und den *geometrischen*, seine ausgezeichnet starke eigene Bewegung. Daſs beide täuschen können, ist nicht zu bezweifeln; allein wenn eine Untersuchung über die jährliche Parallaxe eines Fixsterns unternommen werden soll, so sind sie dennoch die einzigen, welche seine Wahl leiten können.

Bekanntlich ist die jährliche Parallaxe einiger Sterne der *ersten Gröſse* der Gegenstand mehrerer neueren Untersuchungen gewesen. *Piazzi* fand im Jahr 1805 beträchtliche, von 2″ bis 10″ gehende Werthe dieser Parallaxen für α *Tauri*, α *Canis maj.*, α *Canis min.* und α *Lyræ*, dagegen verschwindende für α *Arigæ*, α *Bootis* und α *Aquilæ*; er selbst war mit der Sicherheit, mit welcher seine Beobachtungen diese Resultate ergaben, zwar nicht zufrieden, hielt aber einen Werth der jährlichen Parallaxe von α *Canis maj.* von 4″ für wahrscheinlich. Sein Resultat für α *Lyræ* (2″) wurde von dem von *Calandrelli*, aus Zenithsector-Beobachtungen in Rom gezogenen (4″4) noch übertroffen. Obgleich diesen Bemühungen zur Kenntniſs der jährlichen Parallaxen einiger Fixsterne zu gelangen, genügende Sicherheit nicht beigelegt werden kann, indem *Piazzi* die seinigen selbst verdächtig macht, und das von *Calandrelli* angewandte Instrument nicht geeignet ist, groſses Zutrauen zu seinen Leistungen zu erwecken, so standen sie doch *ohne Widerspruch*, und man konnte wirklich den Beobachtungen, welche zu ihnen geführt hatten, nichts auſser ihnen selbst liegendes entgegensetzen. Indessen hatten die Beobachtungen der Unterschiede der Geradenaufsteigungen der Sterne, seit *Bradley*, nicht nur eine groſse Vollkommenheit erreicht, sondern es war auch eine so groſse Zahl von ihnen, durch *Bradley* und *Maskelyne* bekannt geworden, daſs man darauf eine Untersuchung gründen konnte, deren Resultat wenigstens so viele Sicherheit versprach, daſs sich auch beträchtlich kleinere jährliche Parallaxen, als die neuerlich angegebenen, dadurch bestätigt oder widerlegt finden muſsten. Ich suchte daher alle von *Bradley*, in dem Laufe von 12 Jahren, auf der Greenwicher Sternwarte beobachteten Geradenaufsteigungsunterschiede von α *Canis maj.* und α *Lyræ* auf, indem sich, wegen ihrer Annäherung an 180°, in ihnen die *Summe* der Parallaxen beider Sterne verrathen muſste; es fanden sich 207 Beobachtungen dieser Art und sie ergaben die Summe der Parallaxe von α *Canis maj.* und der mit 1,227 multiplicirten von α *Lyrae* = 0″044 und den wahrscheinlichen

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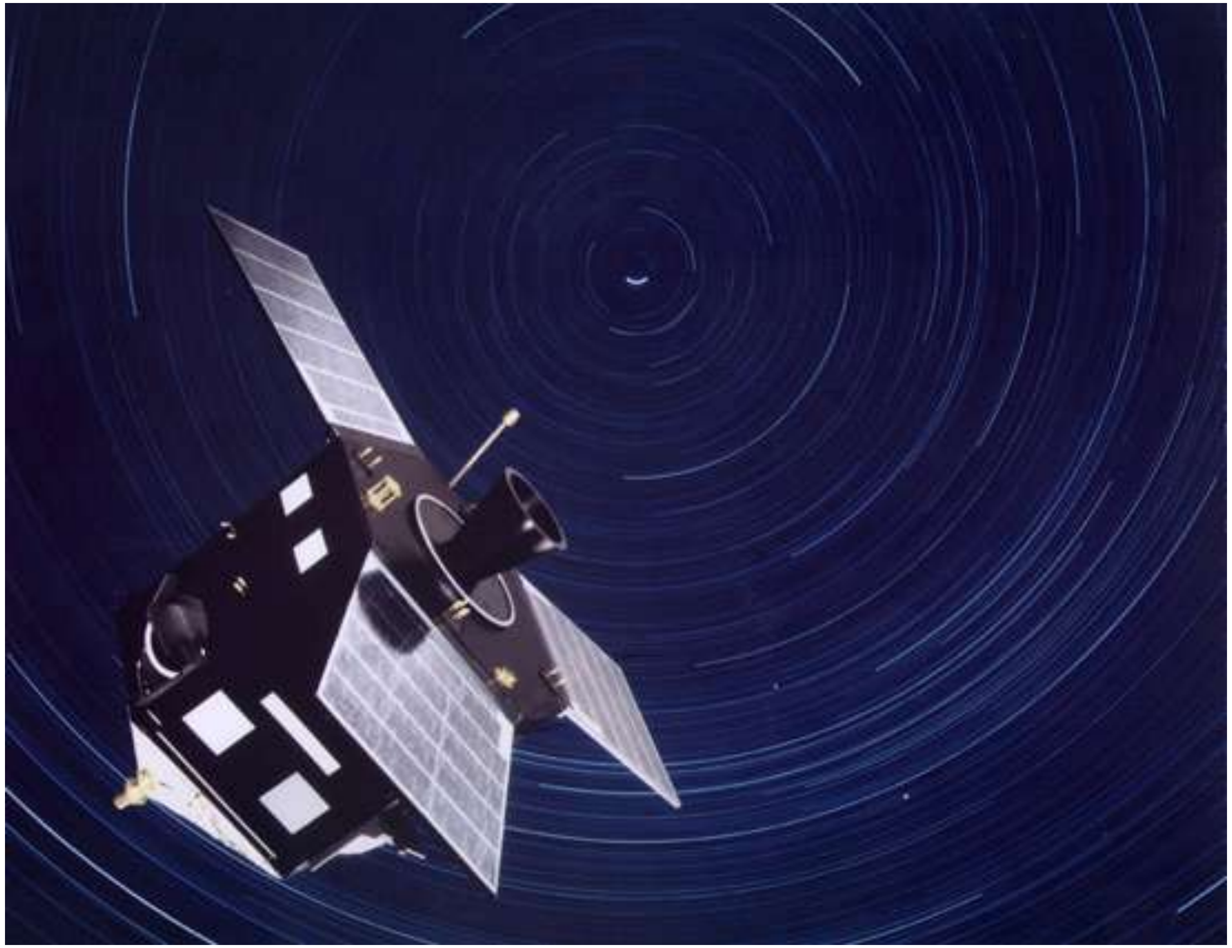
*) *Rigaud* Miscellaneous works and Correspondence of James Bradley. Oxford 1832. p. 15.

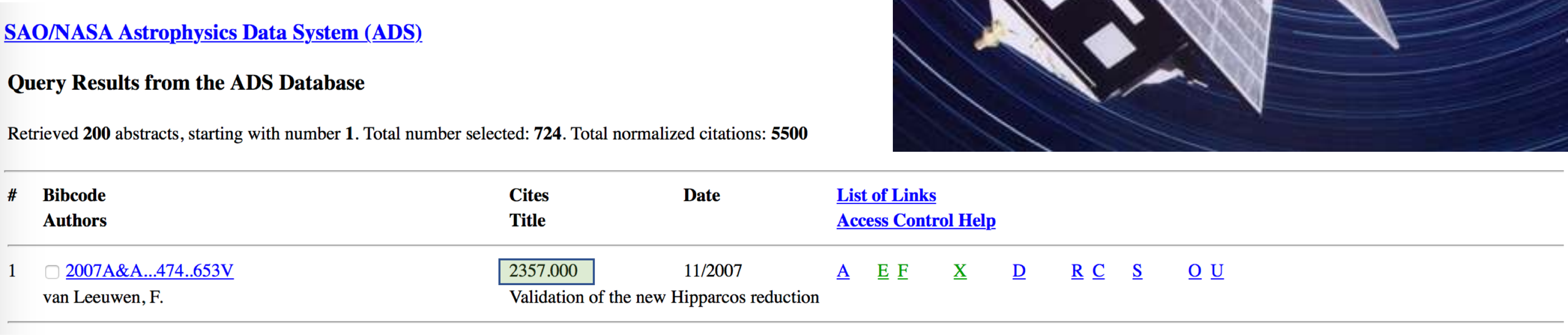
Then came Hipparcos…



In 1989, the European Space Agency (ESA) launched a satellite called Hipparcos (The High Precision Parallax Collecting Satellite) fully dedicated to parallax measurements.

It measured about 100,000 parallaxes, with a typical accuracy of 1 milli-arcsecond.

It changed all fields of astronomy.



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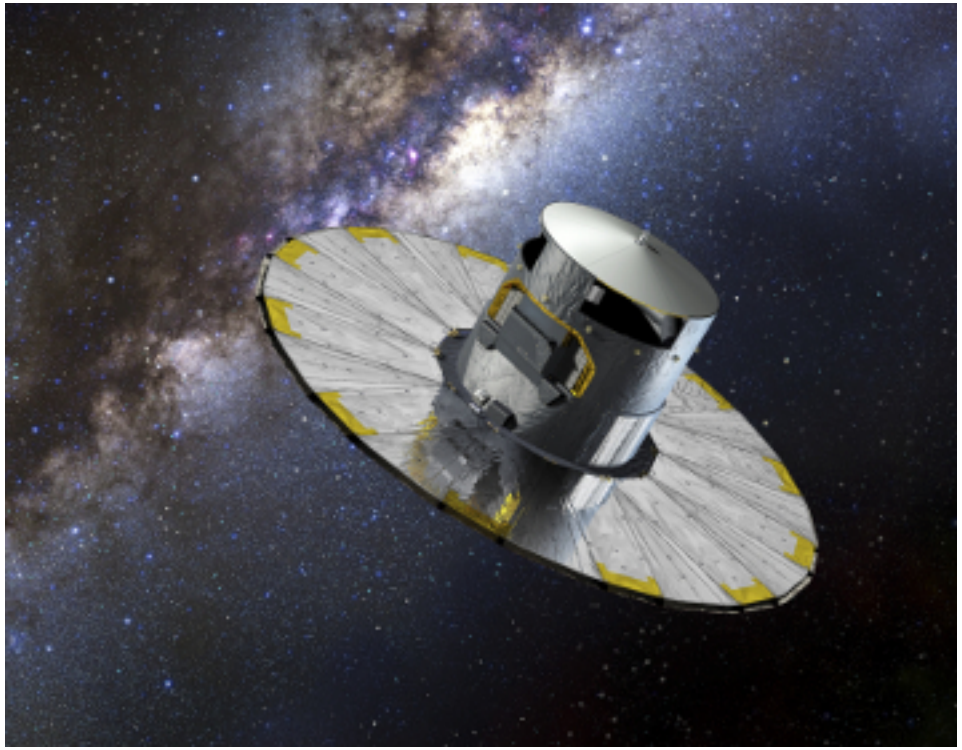
…and now Gaia

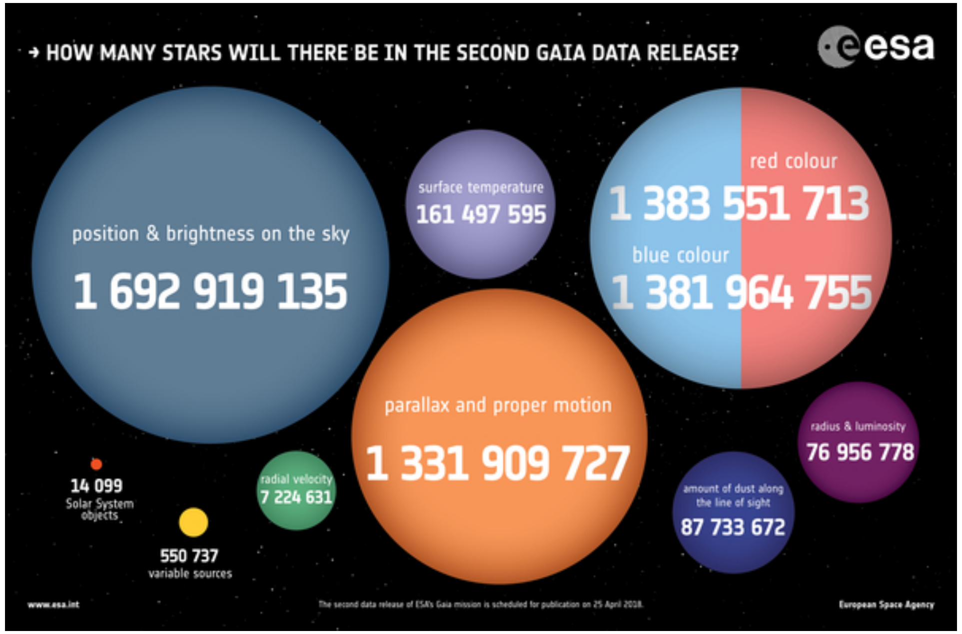
In 2013, the European Space Agency (ESA) launched a second astrometric satellite called Gaia. Its expected accuracy is 10 – 100 microarcseconds.

It will measure distances to more that 10^9 stars.

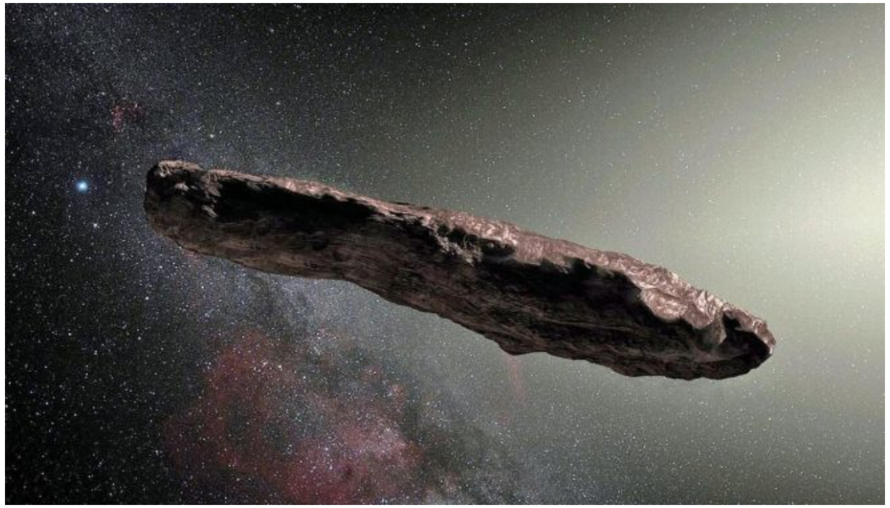
It will revolutionize all fields of astronomy.

Second data release (DR2) came out about 6 months ago. Final results will be published in 2021.

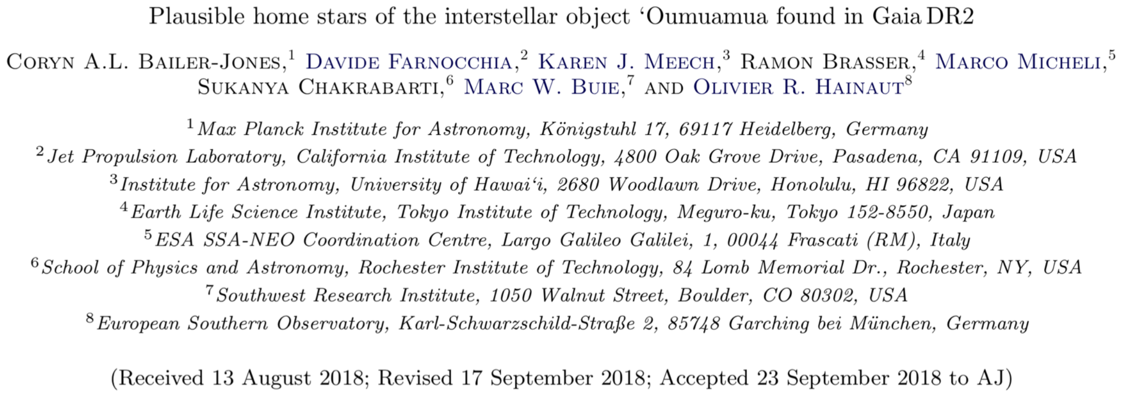




Examples of Gaia results.



El asteroide Oumouamoua.



Plausible home stars of the interstellar object ‘Oumuamua found in Gaia DR2

Coryn A.L. Bailer-Jones,[1] Davide Farnocchia,[2] Karen J. Meech,[3] Ramon Brasser,[4] Marco Micheli,[5]
Sukanya Chakrabarti,[6] Marc W. Buie,[7] and Olivier R. Hainaut[8]

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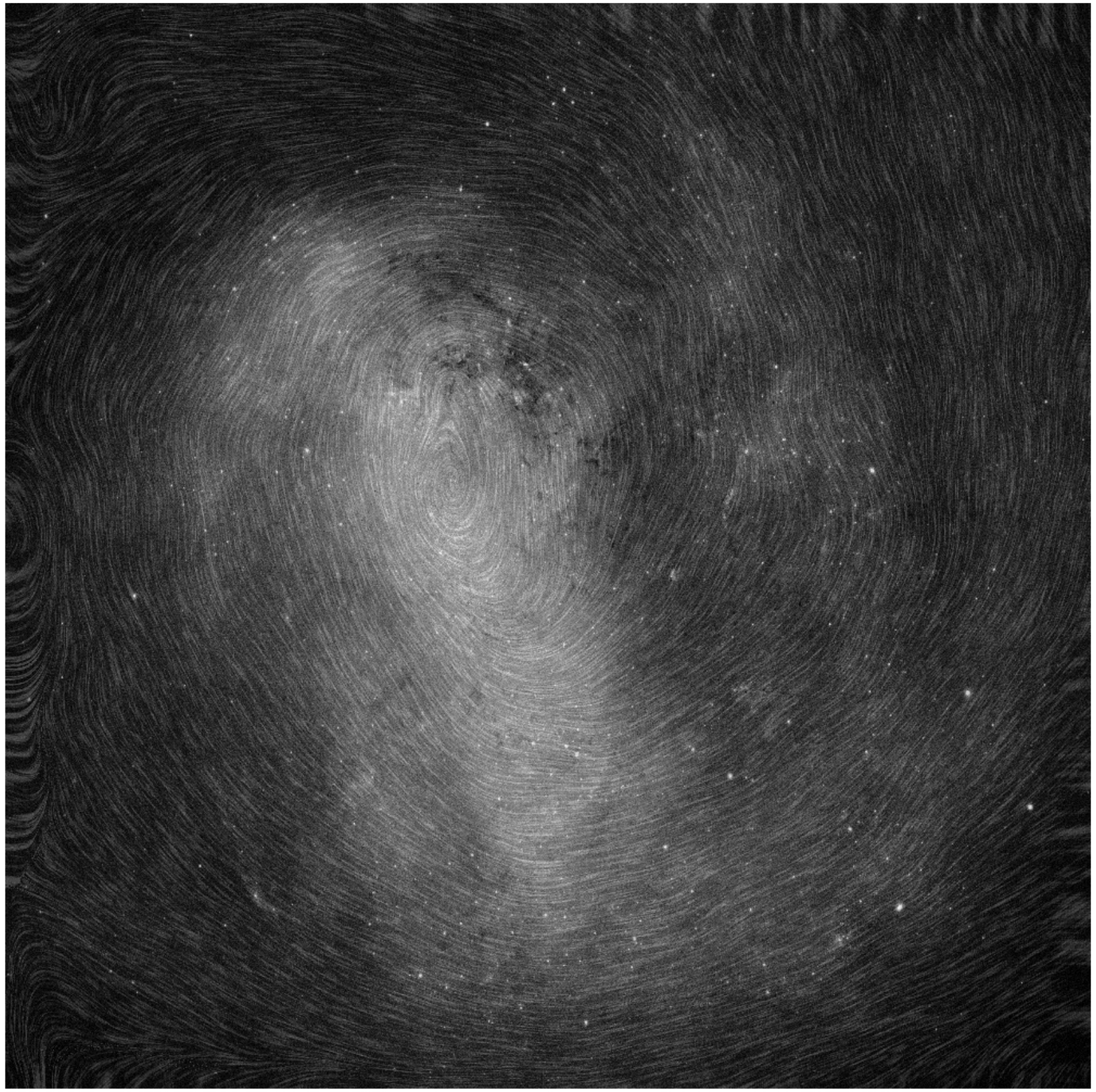


Rotation of the Magellanic Cloud.

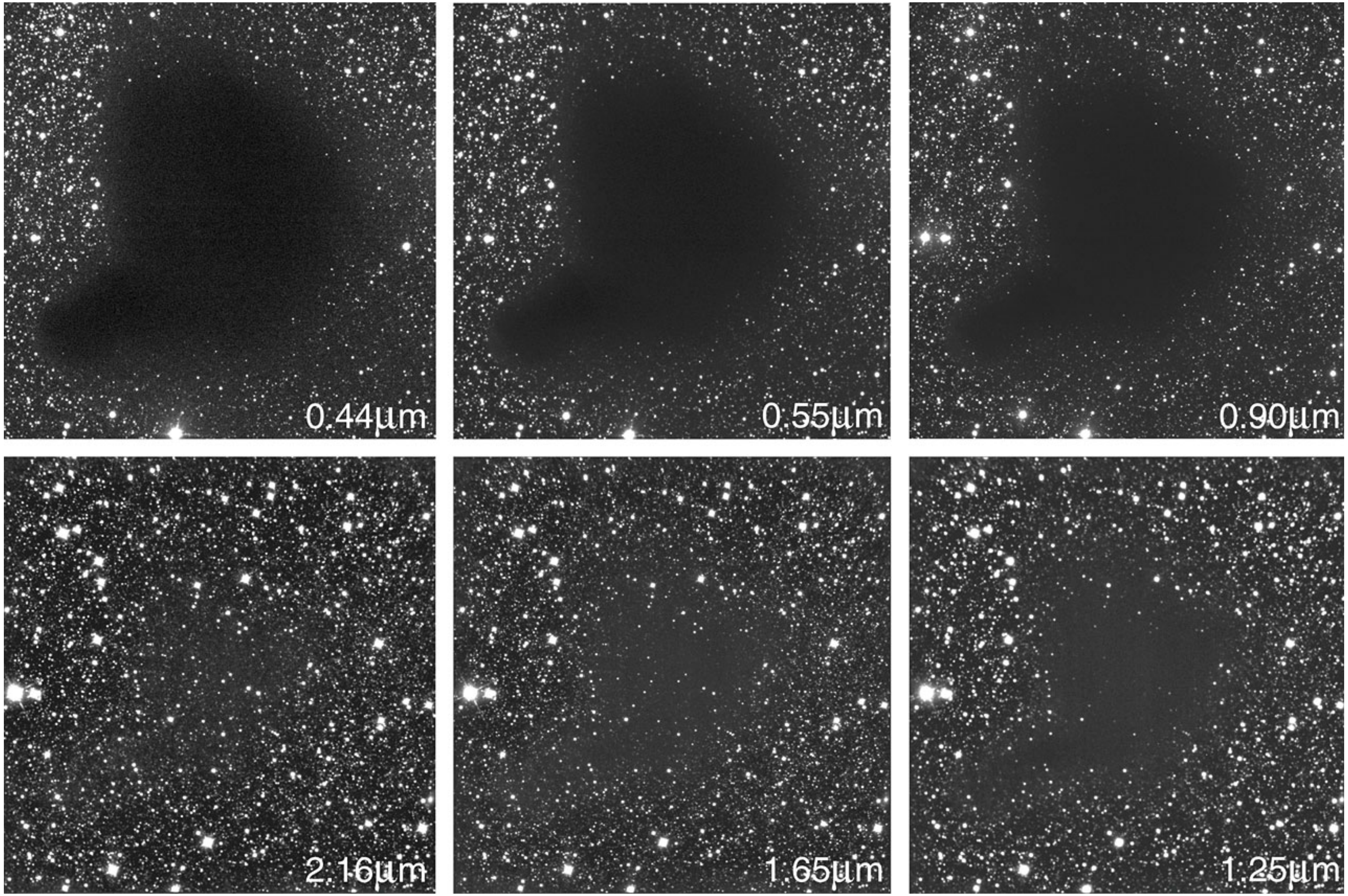
Not all objects are detectable by Gaia: star-forming regions.

Stars form in dusty interstellar clouds which are opaque to optical radiation.

Gaia can't see forming stars.

Dust clouds

Dust opacity is strongly chromatic.

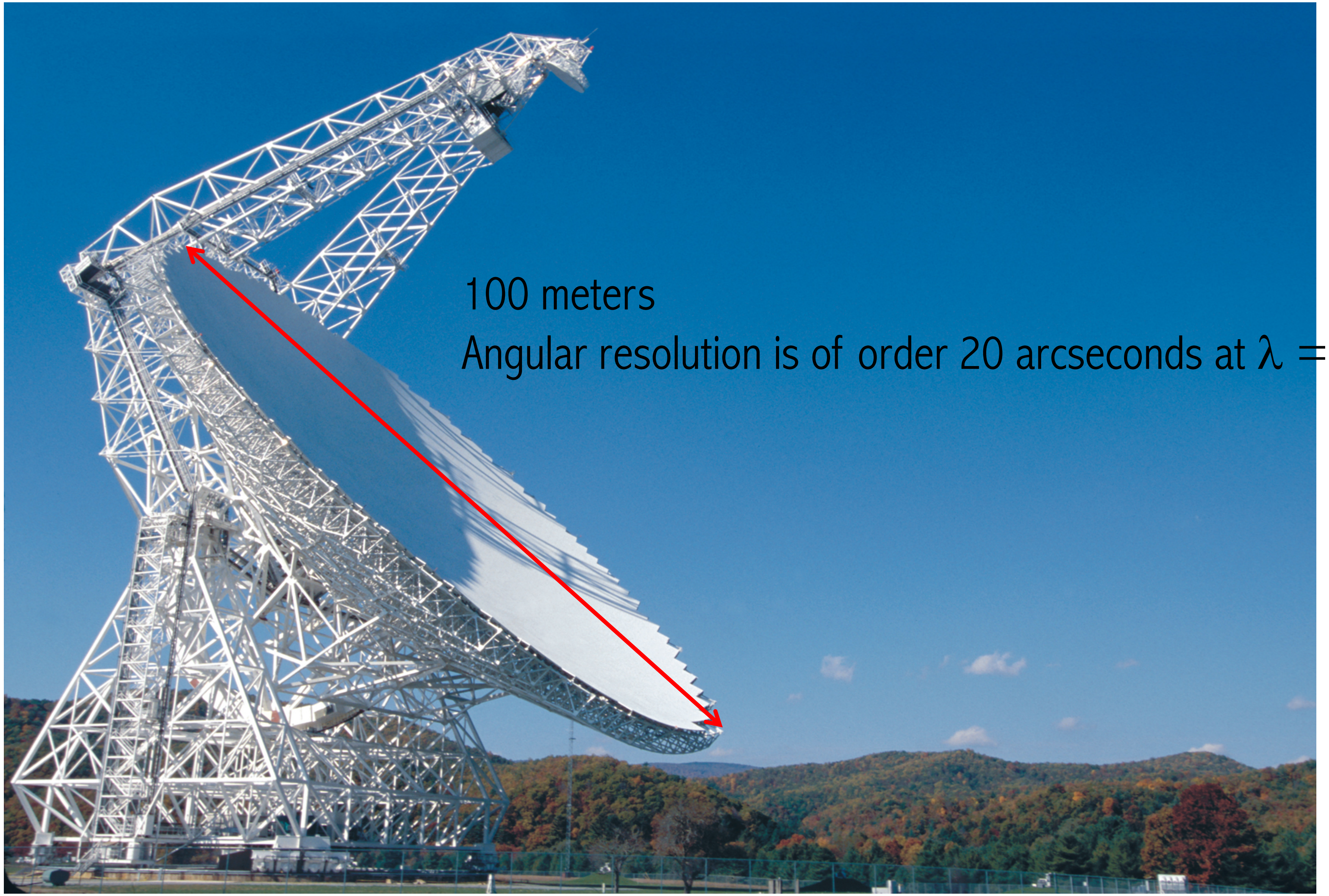


At radio wavelengths, dust is completely transparent.

Can we use radio observations to complement Gaia?

It’s all about angular resolution.

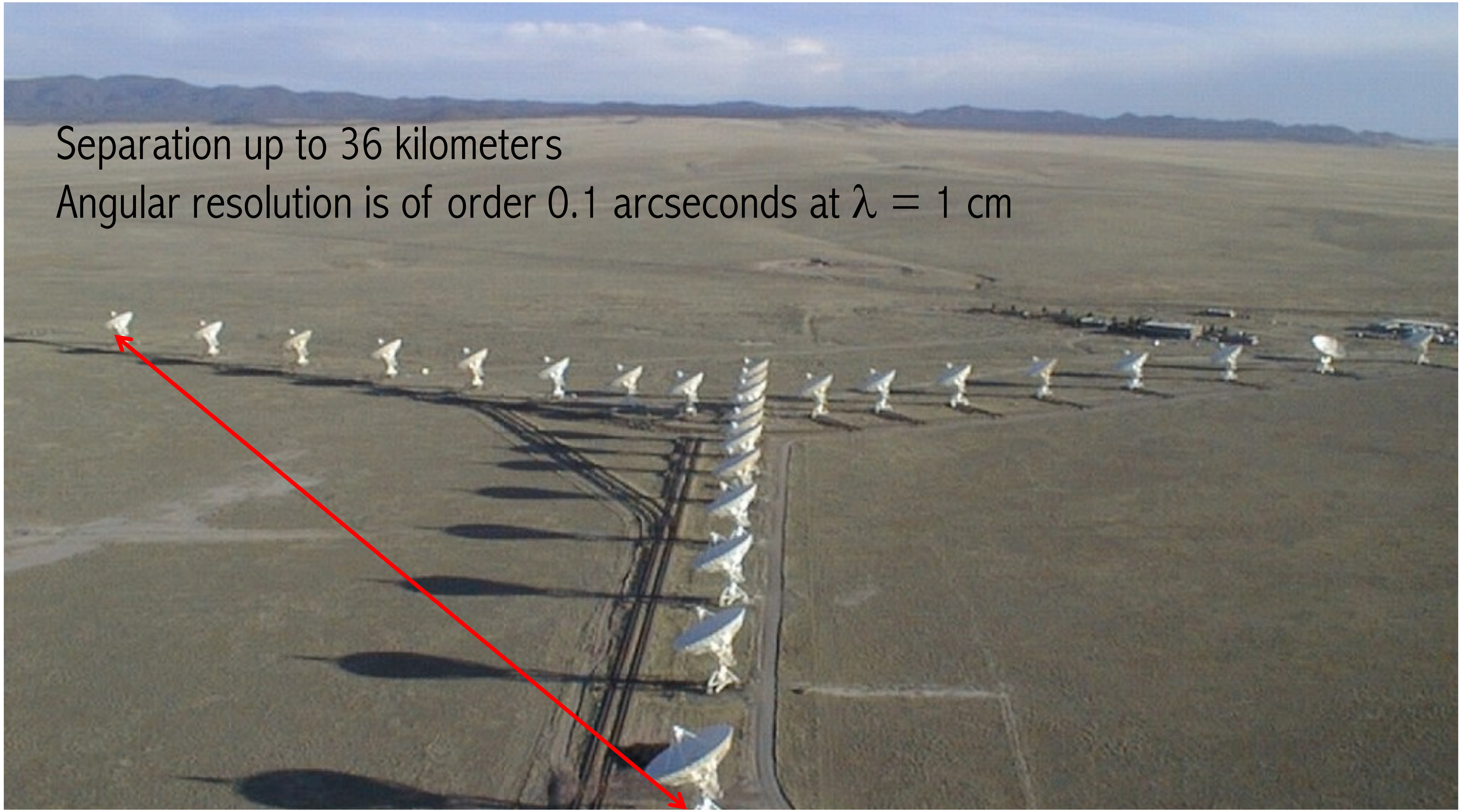
If the aperture of an optical instrument is D, then the angular resolution is λ/D, where λ is the wavelength.



100 meters

Angular resolution is of order 20 arcseconds at λ = 1 cm

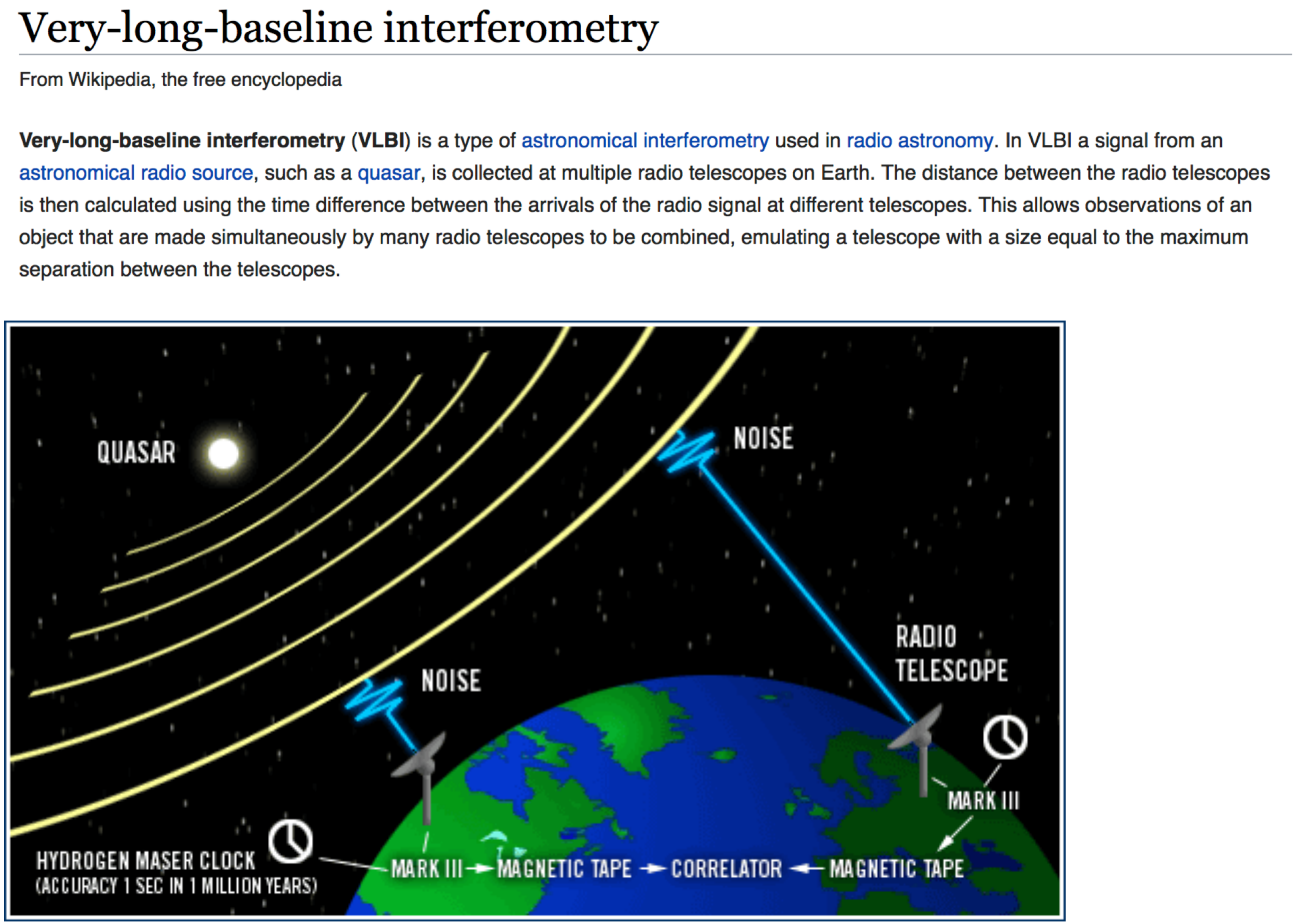
Interferometers



Separation up to 36 kilometers

Angular resolution is of order 0.1 arcseconds at $\lambda = 1$ cm

WIKIPEDIA
The Free Encyclopedia



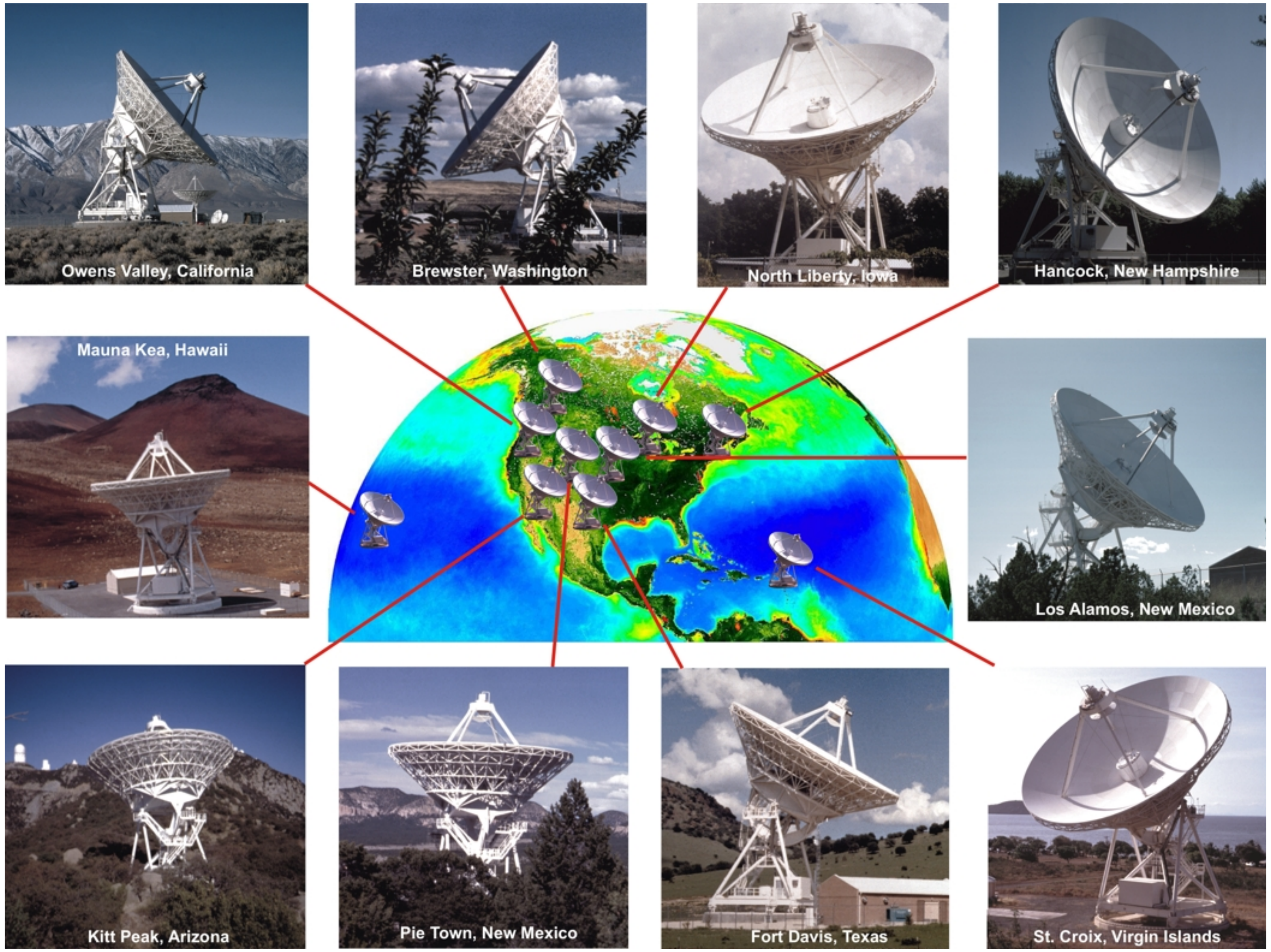
Very-long-baseline interferometry

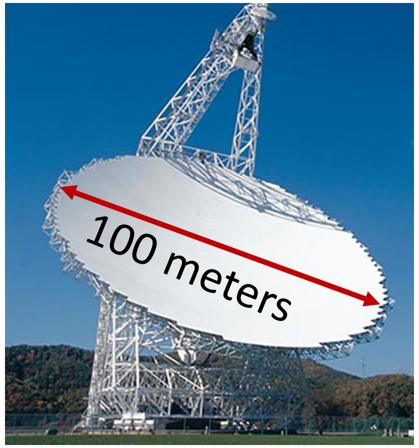
From Wikipedia, the free encyclopedia

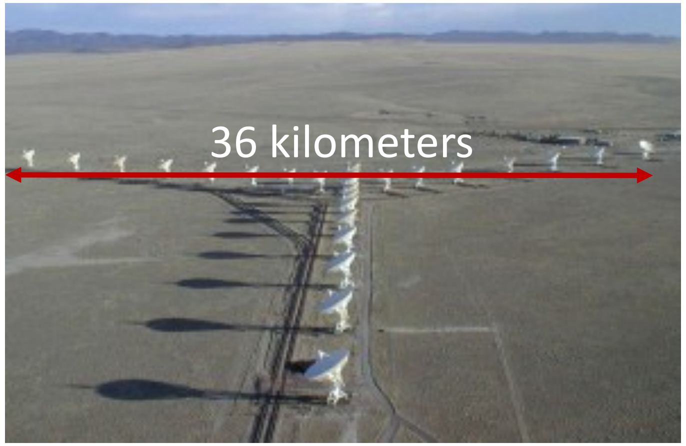
Very-long-baseline interferometry (**VLBI**) is a type of astronomical interferometry used in radio astronomy. In VLBI a signal from an astronomical radio source, such as a quasar, is collected at multiple radio telescopes on Earth. The distance between the radio telescopes is then calculated using the time difference between the arrivals of the radio signal at different telescopes. This allows observations of an object that are made simultaneously by many radio telescopes to be combined, emulating a telescope with a size equal to the maximum separation between the telescopes.

Separation of 8,000 kilometers

Angular resolution is of order 0.3 milli-arcseconds at $\lambda = 1$ cm







“Single-dish” telescope
Green-Bank Telescope
$D = 100$ m
$\theta = \lambda/D = 20''$ @ 1 cm

“Conventional” interferometer
Very Large Array
$B = 36$ km
$\theta = \lambda/B = 0.1''$ @ 1 cm

“VLBI” interferometer
Very Long Baseline Array
$B = 8{,}000$ km
$\theta = \lambda/B = 0.3$ mas @ 1 cm

The GOBELINS Project (2,500 hours on the VLBA)

Rosy Torres (UNAM PhD. 2009
U. Guadalajara)

Sergio Dzib (UNAM PhD. 2013
MPIfR)

Gerardo Pech
(UNAM PhD. 2015
U. TecMilenio)

Gisela Ortiz
(UNAM, PhD. 2016
MPIfR)

Juana Leticia Rivera
(UNAM, PhD. 2017)

Marina Kounkel
(U. Michigan, PhD. 2017
Western Washington)

"Gely" Duran
(U. Guadalajara, B.S.)

GOBELINS

THE GOULD'S BELT DISTANCES SURVEY

Andy Boden
(CalTech)

Cesar Briceño
(NOAO, Chile)

Neal Evans
(Texas)

Phillip Galli
(USP, Brazil)

Lee Hartmann
(Michigan)

Laurent Loinard – PI
(UNAM)

Amy Mioduszewski – co-PI
(NRAO)

Luis F. Rodríguez
(UNAM)

Rama Teixeira
(USP, Brazil)

John Tobin
(NRAO)

IAU PhD Prize 2017 for Gisela Ortiz

7 May 2018

IAU PhD Prize winners 2017 announced

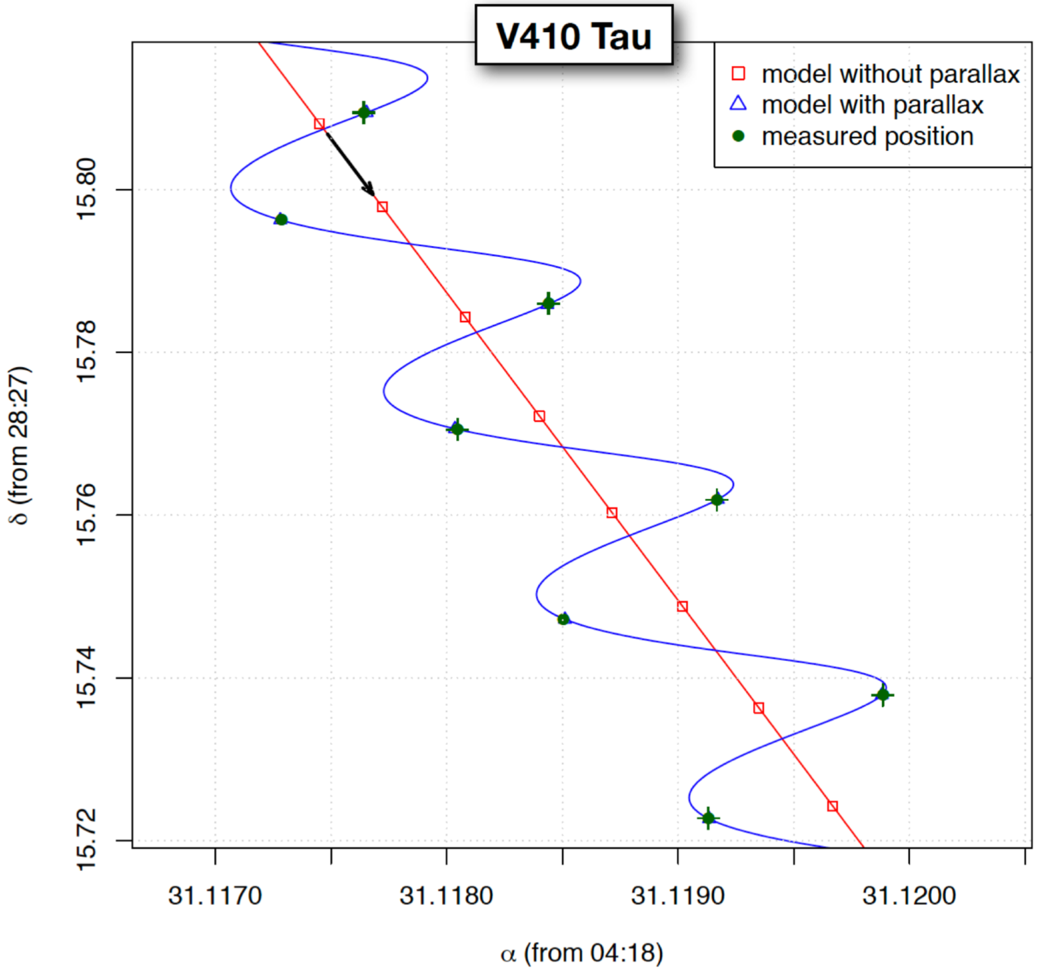
Click to Enlarge

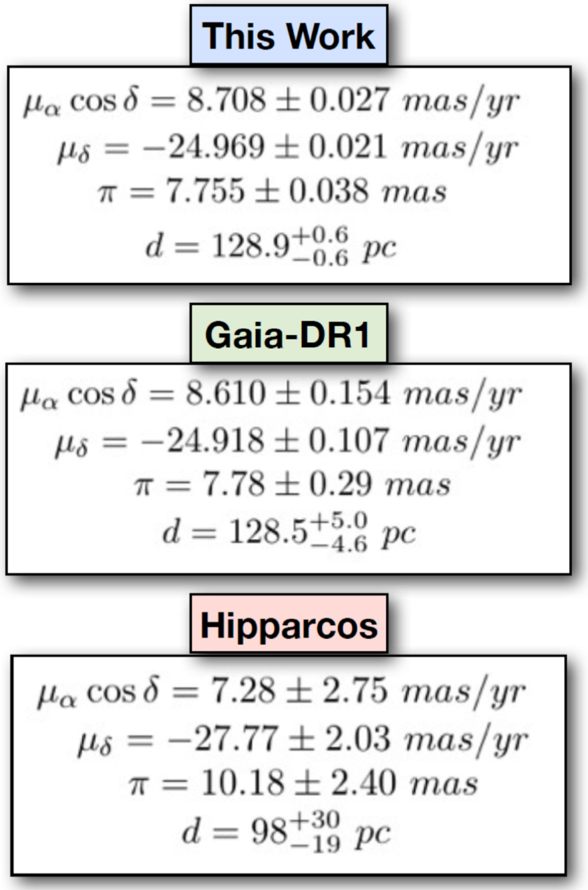
The IAU PhD Prize recognises the outstanding scientific achievement in astronomy by PhD students around the world. There are a series of awards, one for each of the IAU's nine Divisions, with each division selecting a winner in its own field of astronomy.

The IAU Executive Committee is pleased to announce the winners of the IAU PhD Prize for 2017 which are as follows:

- **Division A Fundamental Astronomy**: Gisela Ortiz Leon, Instituto de Radioastronomía y Astrofísica, Mexico, Ultra-high precision astrometry with centimeter and millimeter very long baseline interferometry.
- **Division B Facilities, Technologies and Data Science**: Barak Zackay, Weizmann Institute of Science, Rehovot, Israel, Statistical and algorithmic techniques in observational astronomy.
- **Division C Education, Outreach and Heritage**: None (No candidates)
- **Division D High Energy Phenomena and Fundamental Physics**: Guillaume Voisin, Observatoire de Paris, PSL Research University, Simulation of pulsar magnetospheres: detailed study of some radiative mechanisms.
- **Division E Sun and Heliosphere**: Christopher Moore, University of Colorado, Boulder, The Solar Corona viewed through the MinXSS (Miniature X-ray Solar Spectrometer) CubeSats.
- **Division F Planetary Systems and Bioastronomy**: Megan Ansdell, University of Hawaii, Protoplanetary disk demographics with ALMA.
- **Division G Stars and Stellar Physics**: Gaël Buldgen, University of Liège, Belgium, Development of inversion techniques in Asteroseismology.
- **Division H Interstellar Matter and Local Universe**: Georgia Virginia Panopoulou, University of Crete, Structure and evolution of magnetic molecular clouds, observational consequences and tests.
- **Division J Galaxies and Cosmology**: Max Gronke, Institute of Theoretical Astrophysics, Oslo, Lyman alpha observables of the high-redshift Universe.

Example of radio distance measurement




This Work

$$\mu_\alpha \cos\delta = 8.708 \pm 0.027\ mas/yr$$
$$\mu_\delta = -24.969 \pm 0.021\ mas/yr$$
$$\pi = 7.755 \pm 0.038\ mas$$
$$d = 128.9^{+0.6}_{-0.6}\ pc$$

Gaia-DR1

$$\mu_\alpha \cos\delta = 8.610 \pm 0.154\ mas/yr$$
$$\mu_\delta = -24.918 \pm 0.107\ mas/yr$$
$$\pi = 7.78 \pm 0.29\ mas$$
$$d = 128.5^{+5.0}_{-4.6}\ pc$$

Hipparcos

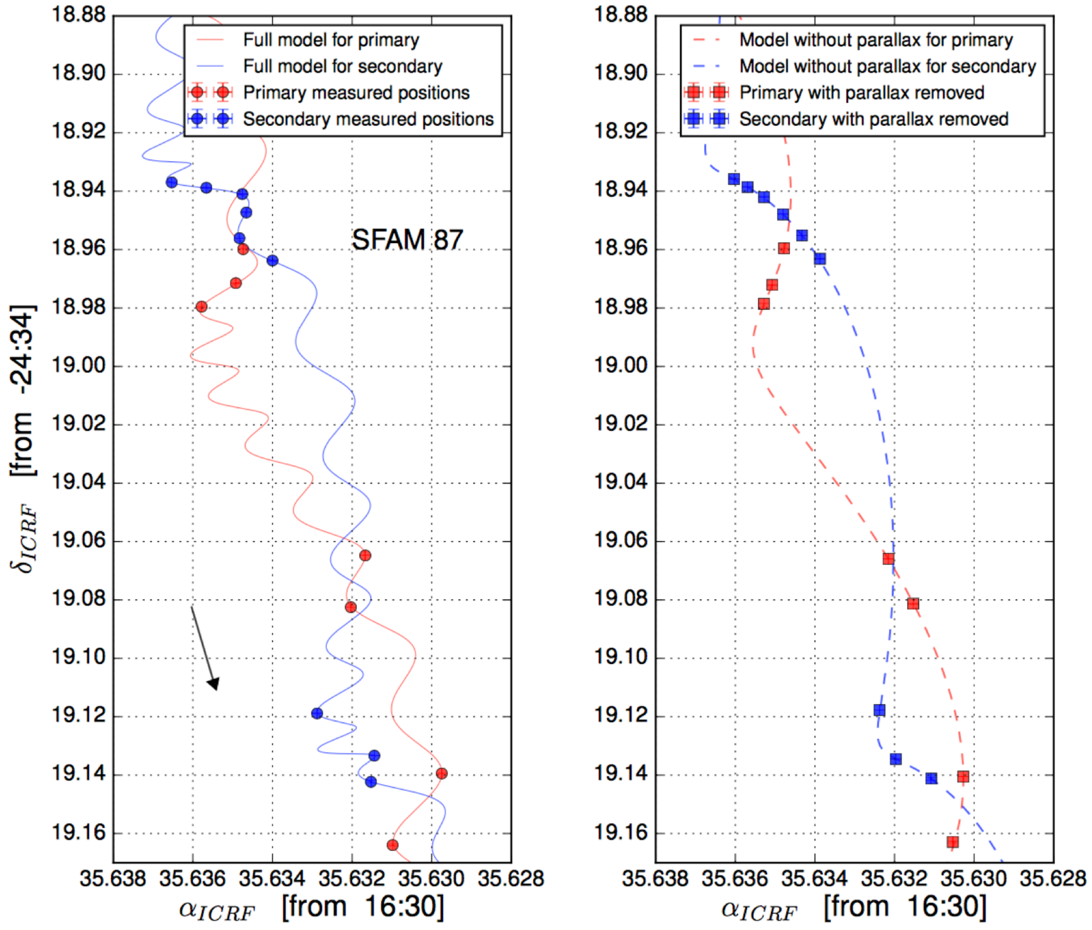
$$\mu_\alpha \cos\delta = 7.28 \pm 2.75\ mas/yr$$
$$\mu_\delta = -27.77 \pm 2.03\ mas/yr$$
$$\pi = 10.18 \pm 2.40\ mas$$
$$d = 98^{+30}_{-19}\ pc$$

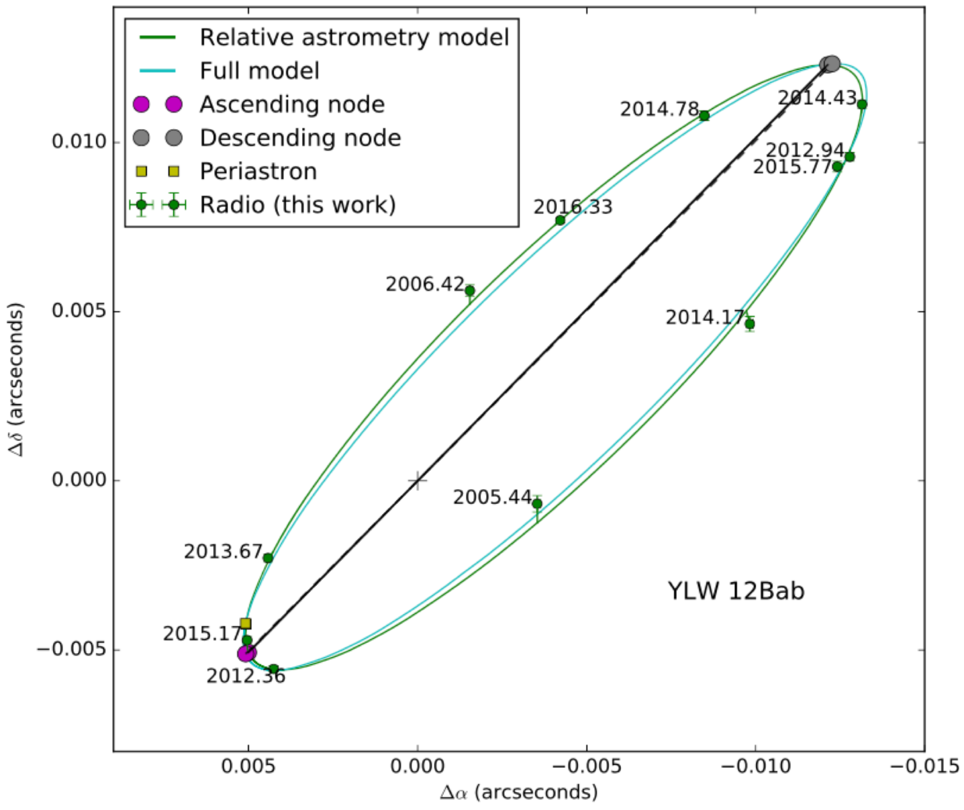
Galli et al. (2018)

Binary systems: individual masses

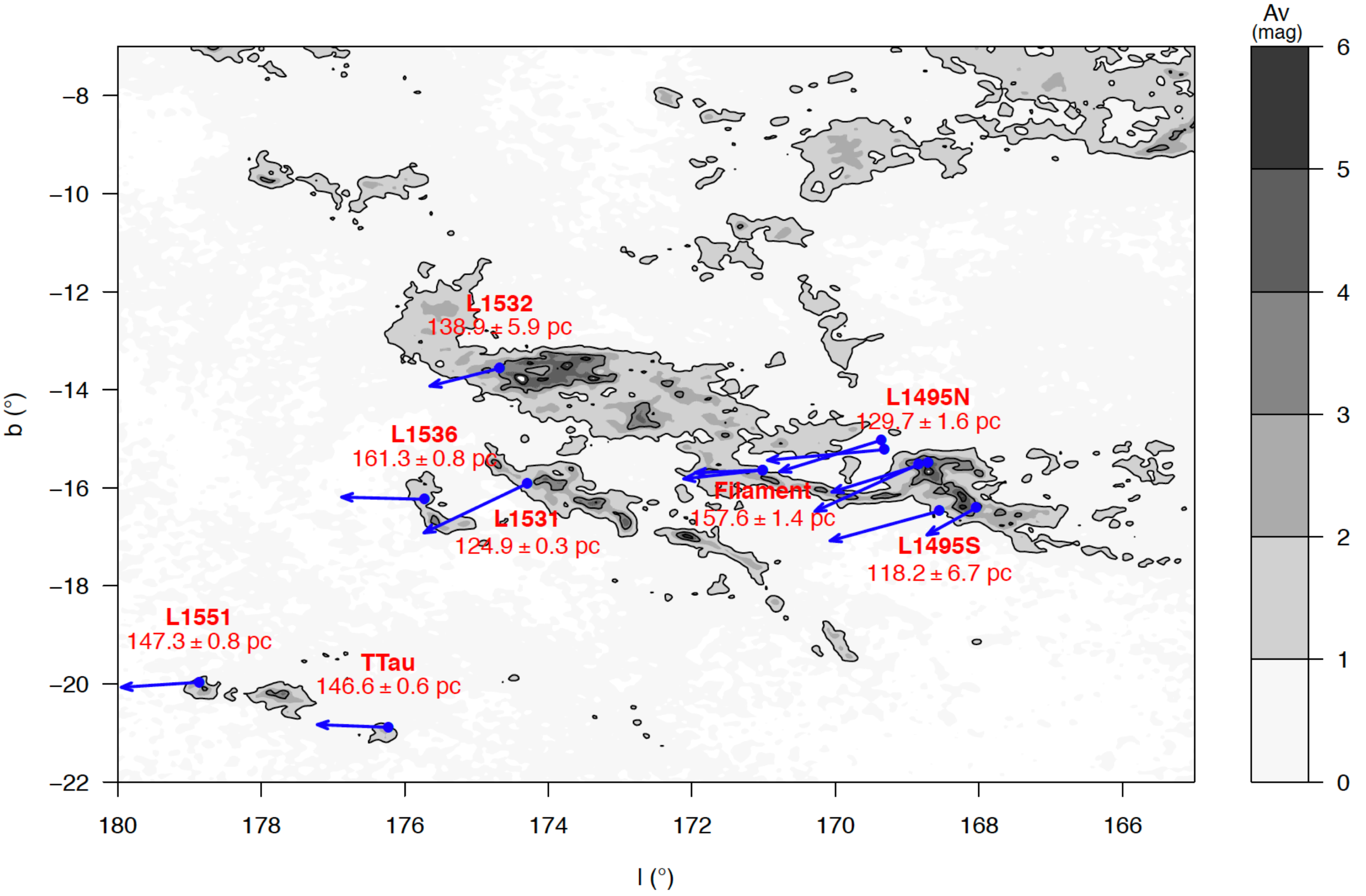
$M_{primary}$ = 1.3969±0.00194 Msun
$M_{secondary}$ = 1.25 ± 0.006 Msun

YLW12B
Ortiz-León et al. 2017

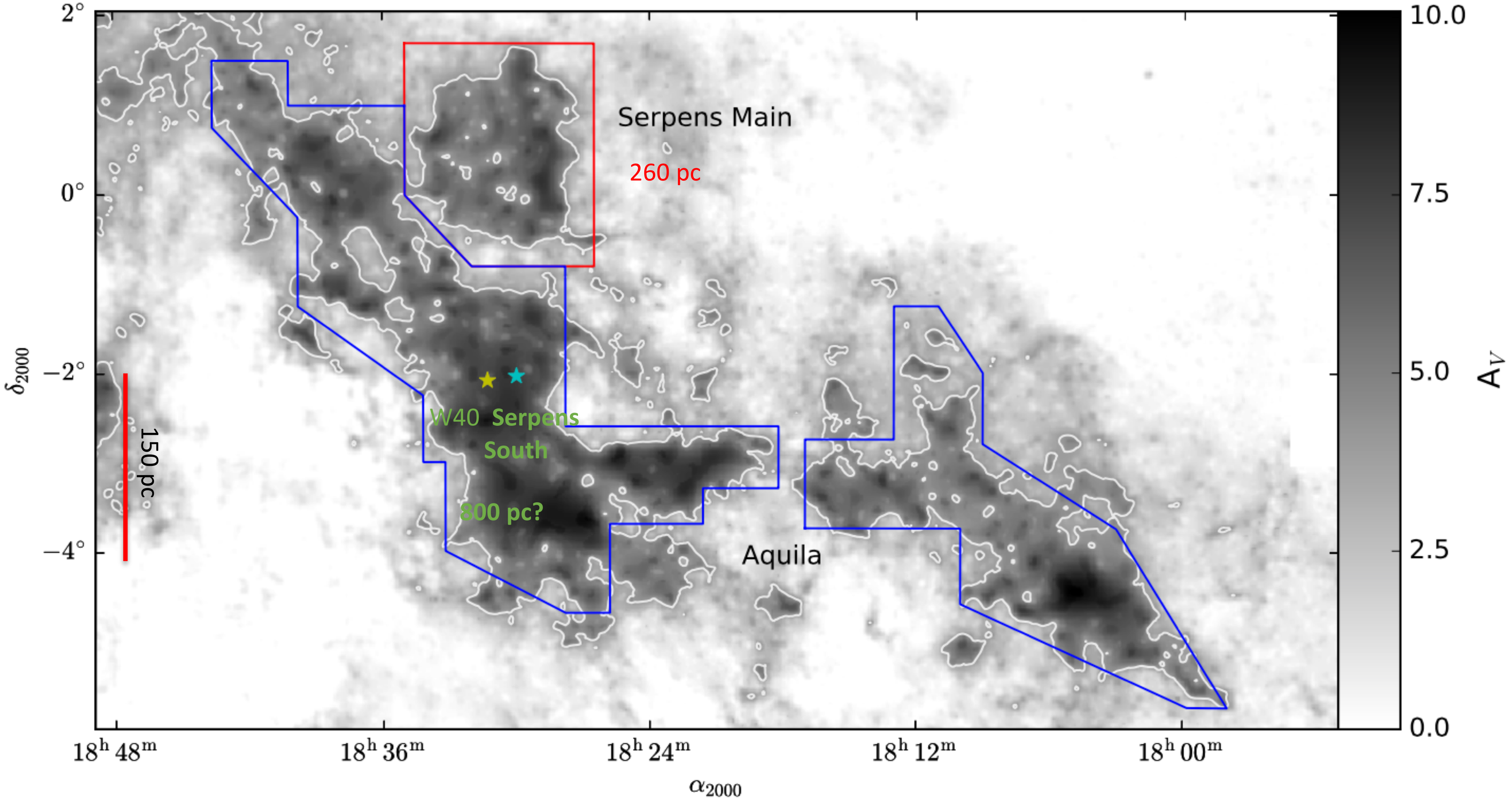




6D Tomographic view!



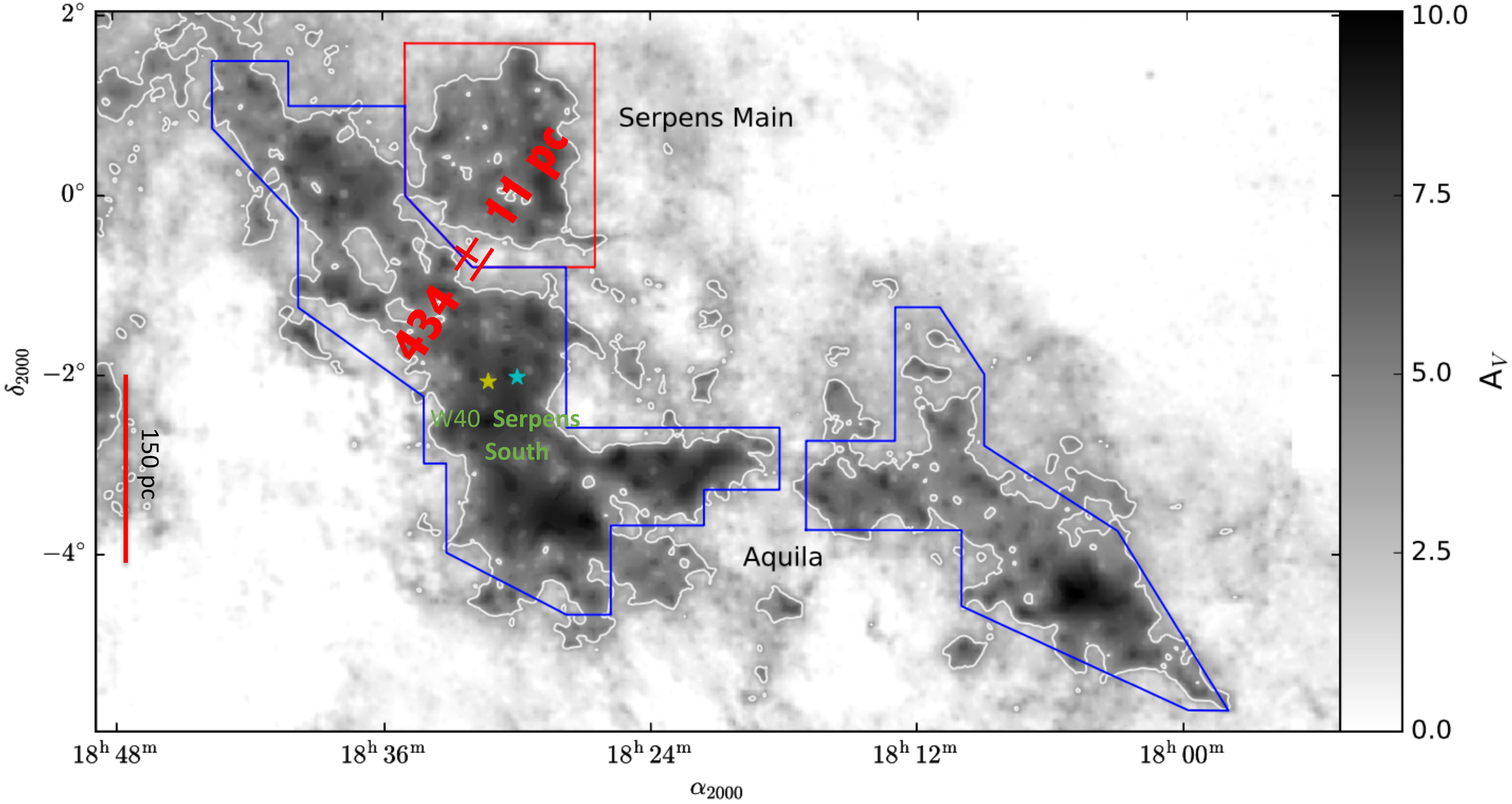
The distance to Serpens



HOW ASTRONOMERS MEASURE THE UNIVERSE

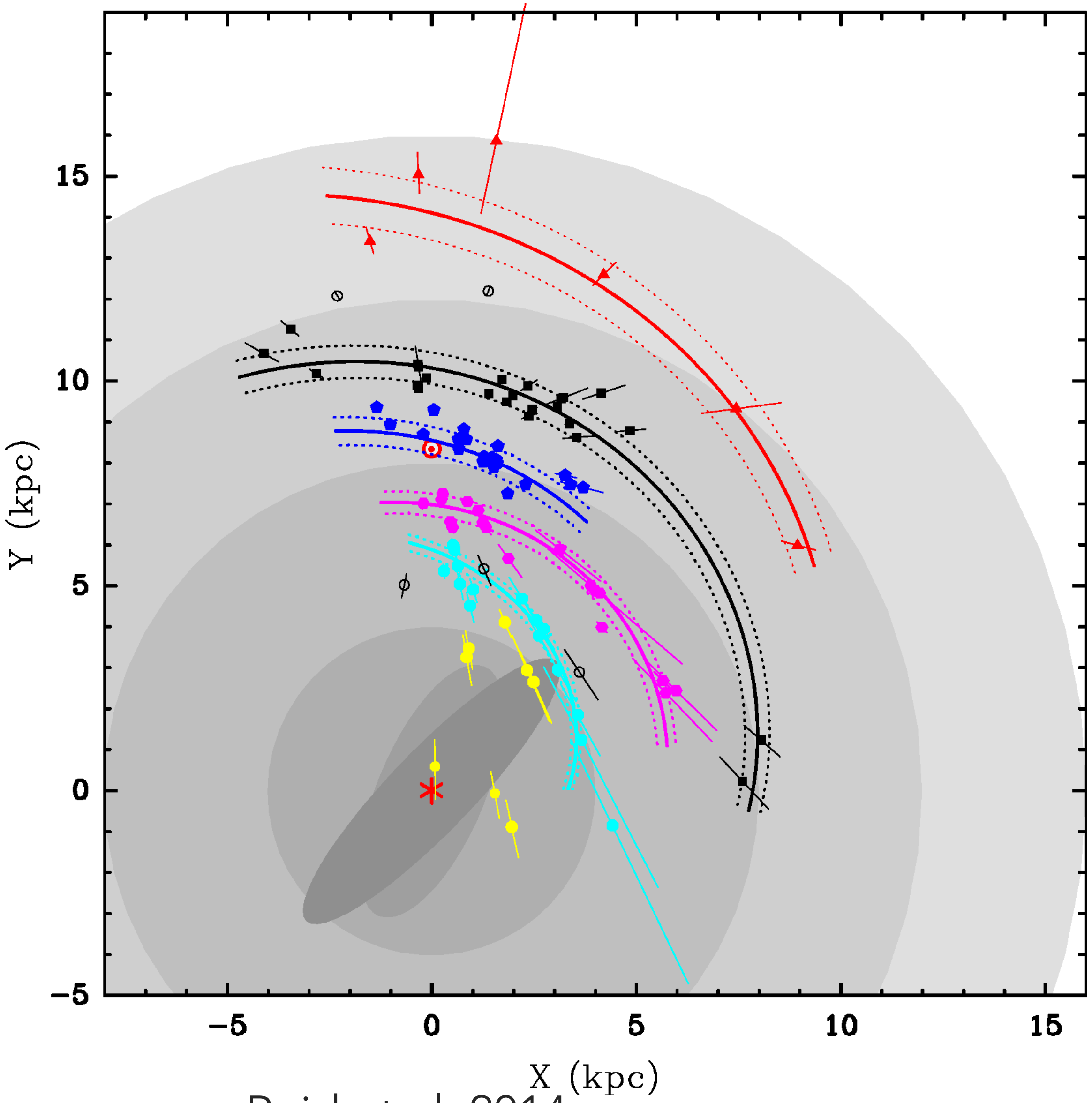
CNF 2018

The distance to Serpens



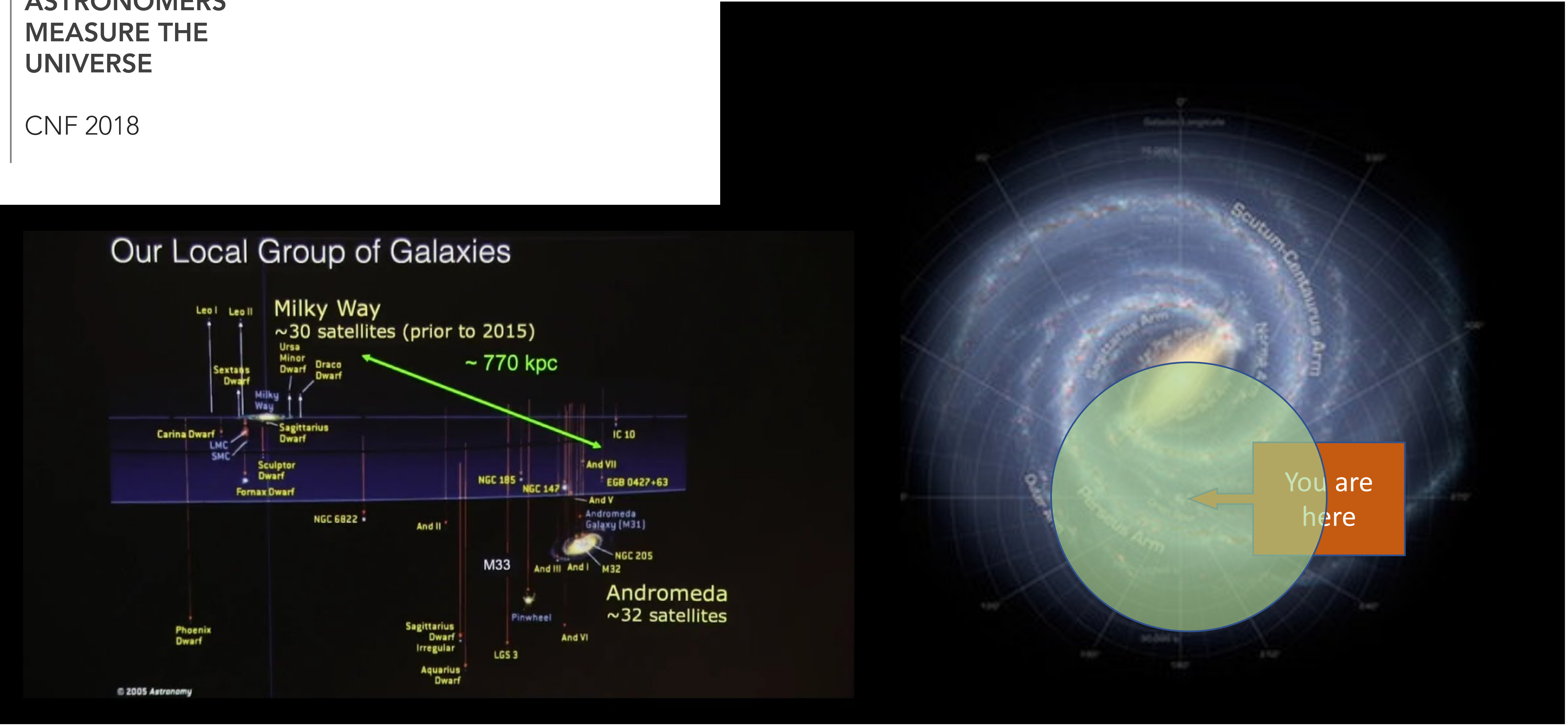
The structure of the Milky Way

Messier 51



Reid et al. 2014

It is still only a small portion of the Universe…



HOW ASTRONOMERS MEASURE THE UNIVERSE

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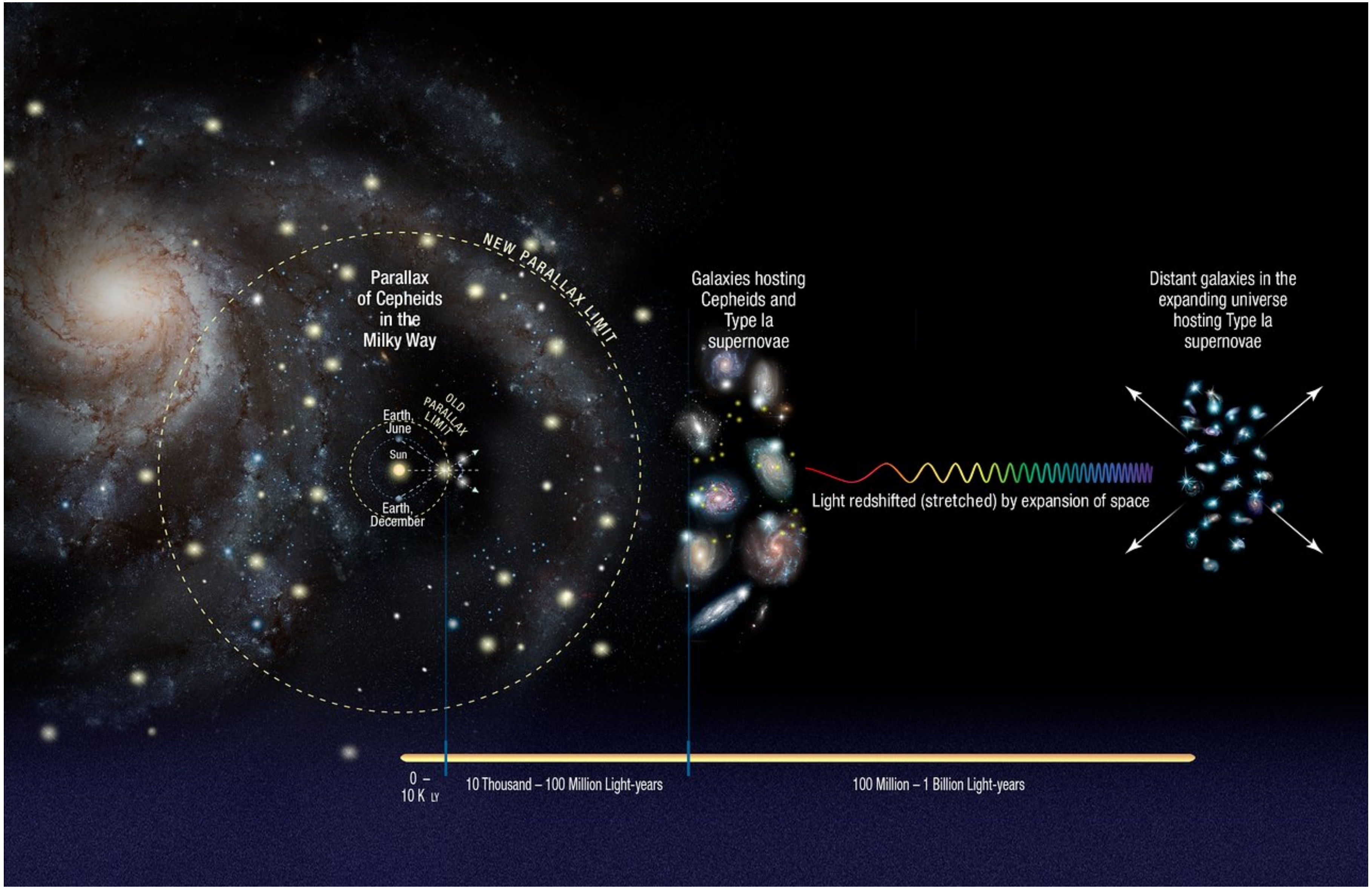
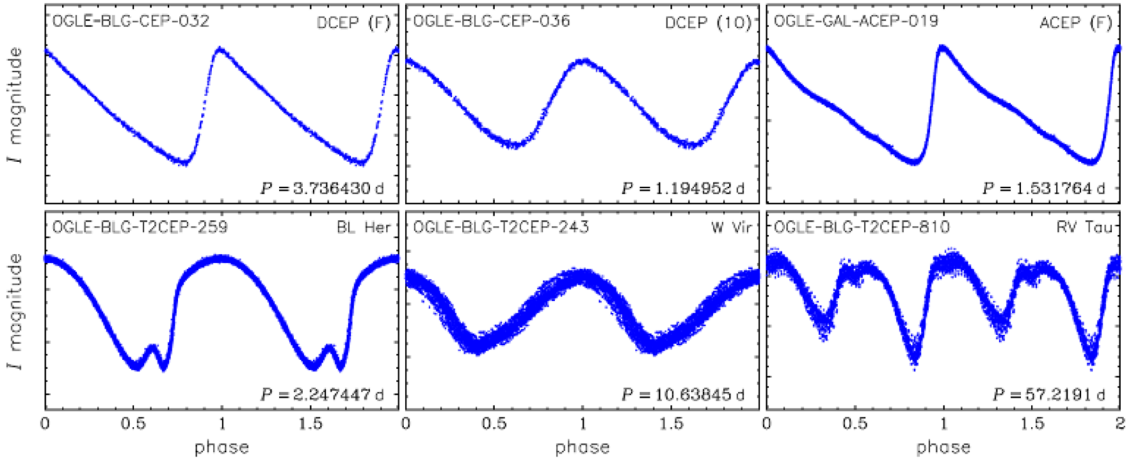


Cepheid stars



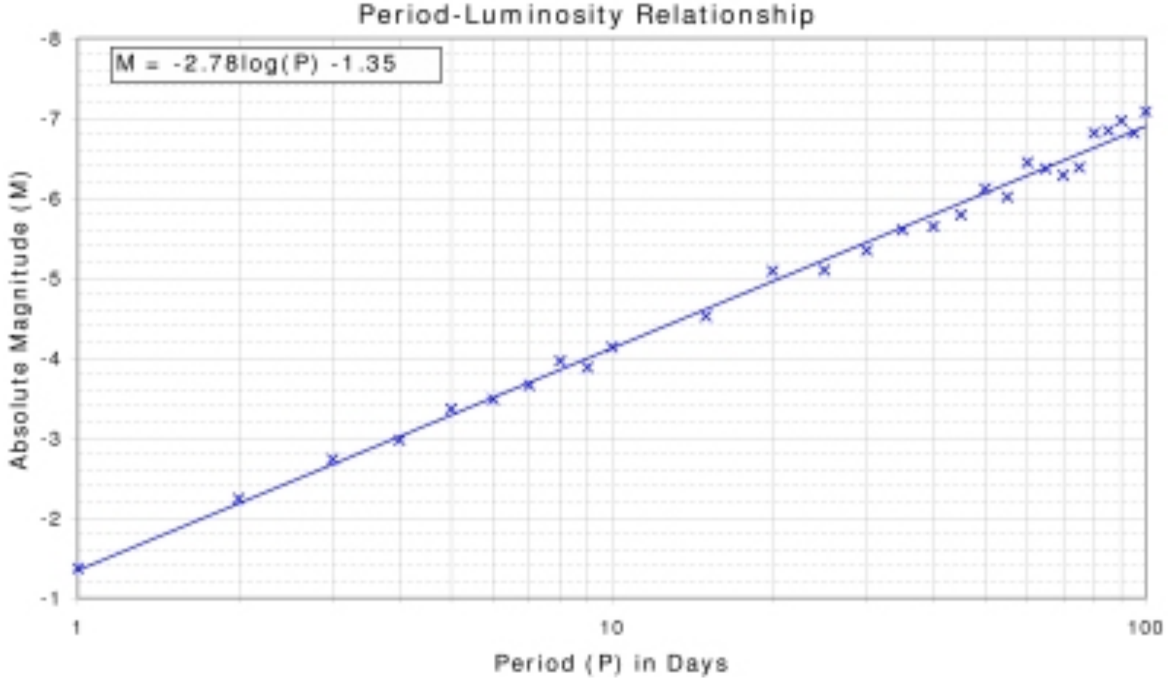
Rotation period

Intrinsic luminosity

+

Apparent brightness

Distance



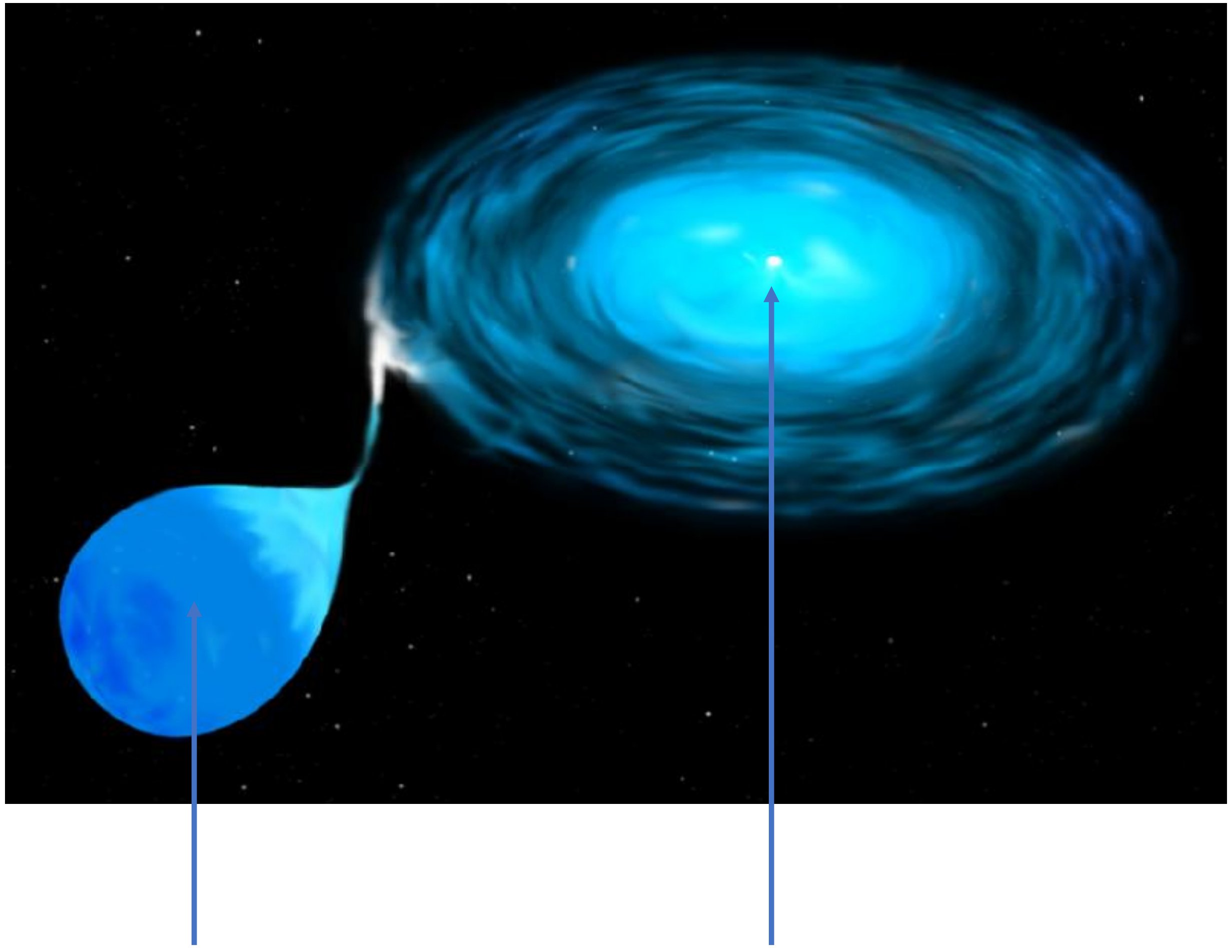
Cepheid stars are fairly bright so they can be detected in external galaxies

Type Ia supernovae

If/when the mass of the White dwarf exceeds 1.4 Msun, the electron degeneracy can no longer counteract gravity.

It explodes as a so-called type Ia supernova. Type Ia supernovae all have very similar intrinsic brightnesses (because the energy released comes from gravitational energy, and they all have the same mass when they explode).

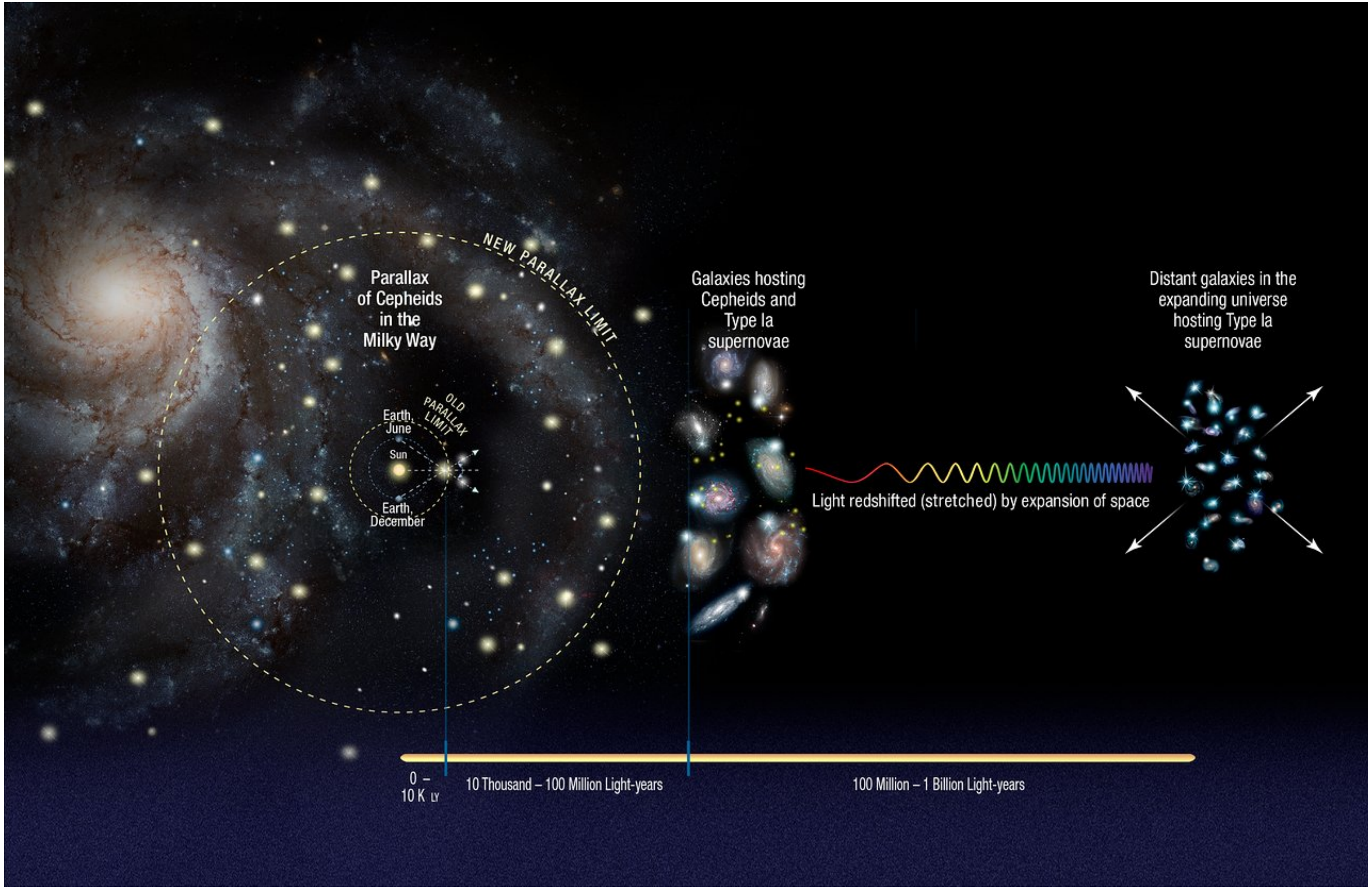
Comparing apparent brightness to intrinsic luminosity gives the distance.



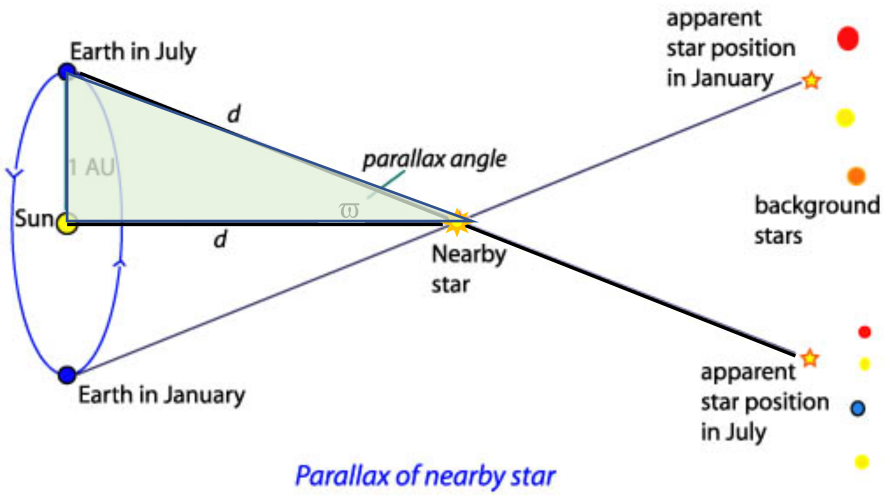
Companion star loosing mass to the white dwarf.

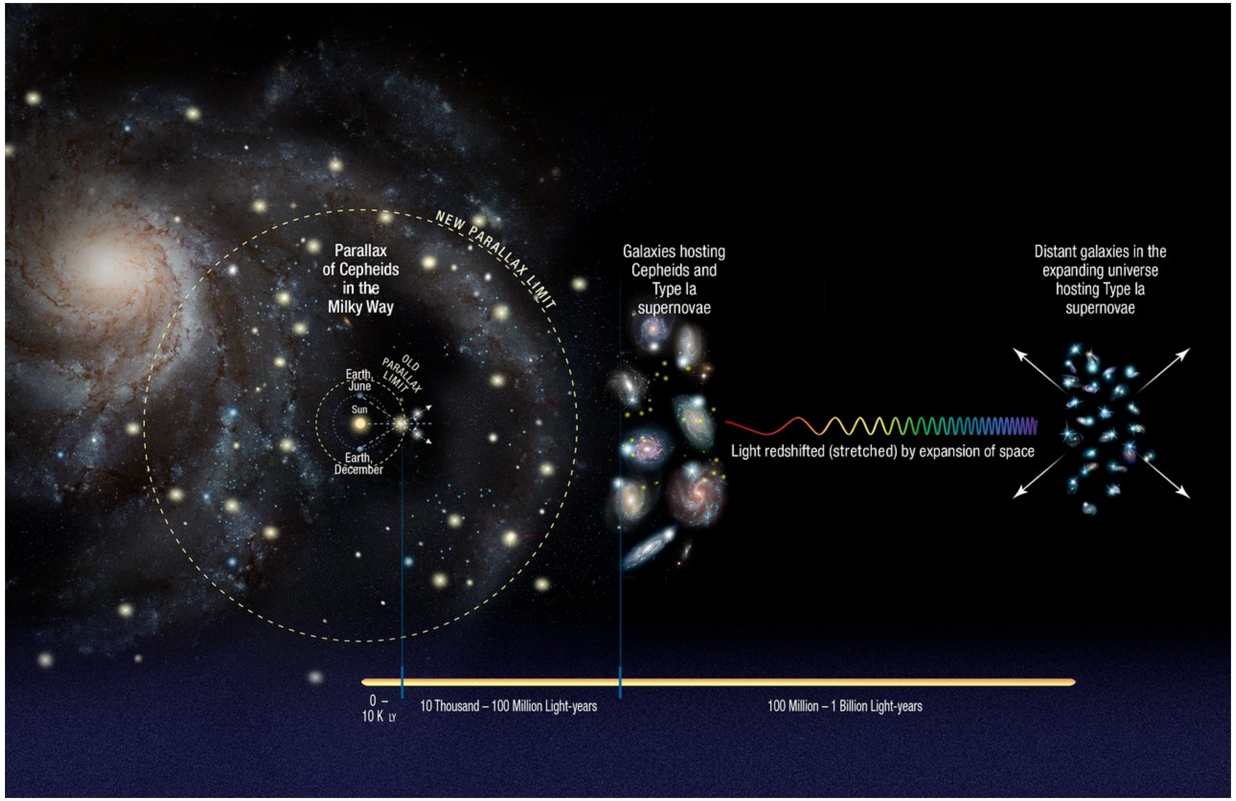
White dwarf (gravitation balanced by degeneracy of electrons)

All this needs to be calibrated



The cosmic distance scale ladder





Supernovae Ia in distant galaxies

Cepheids in external (“nearby”) galaxies (incl. SN Ia)

Trigonometric parallax measurements (incl. Cepheids)

Solar System Measurements

HOW ASTRONOMERS MEASURE THE UNIVERSE

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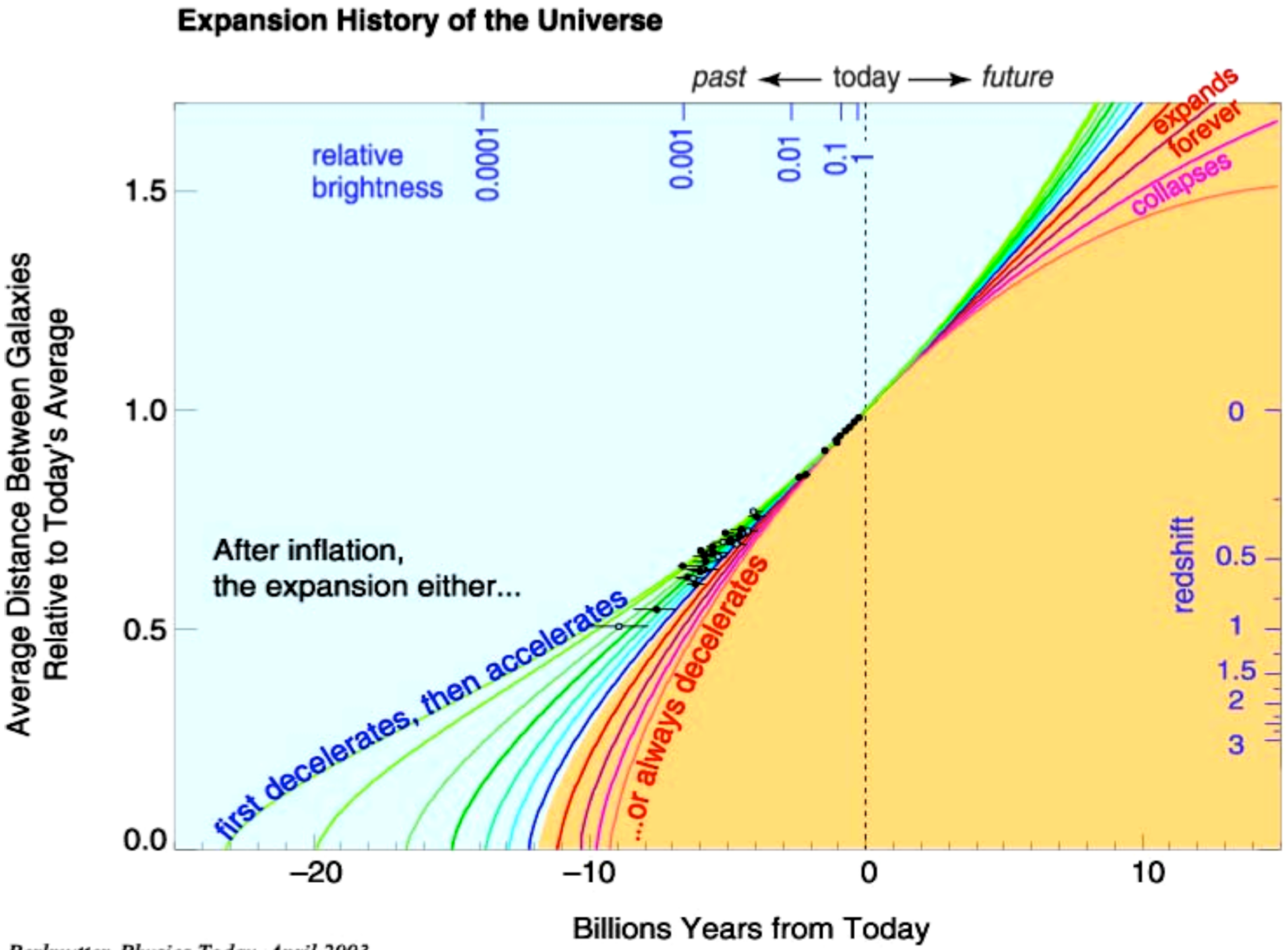
Existence of “dark energy” in the Universe

Adam Riess

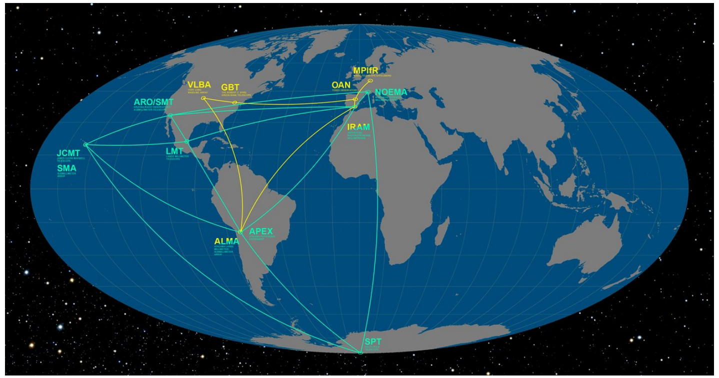
Brian Schmidt

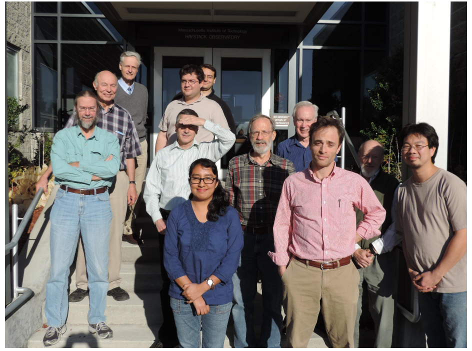
Saul Perlmutter



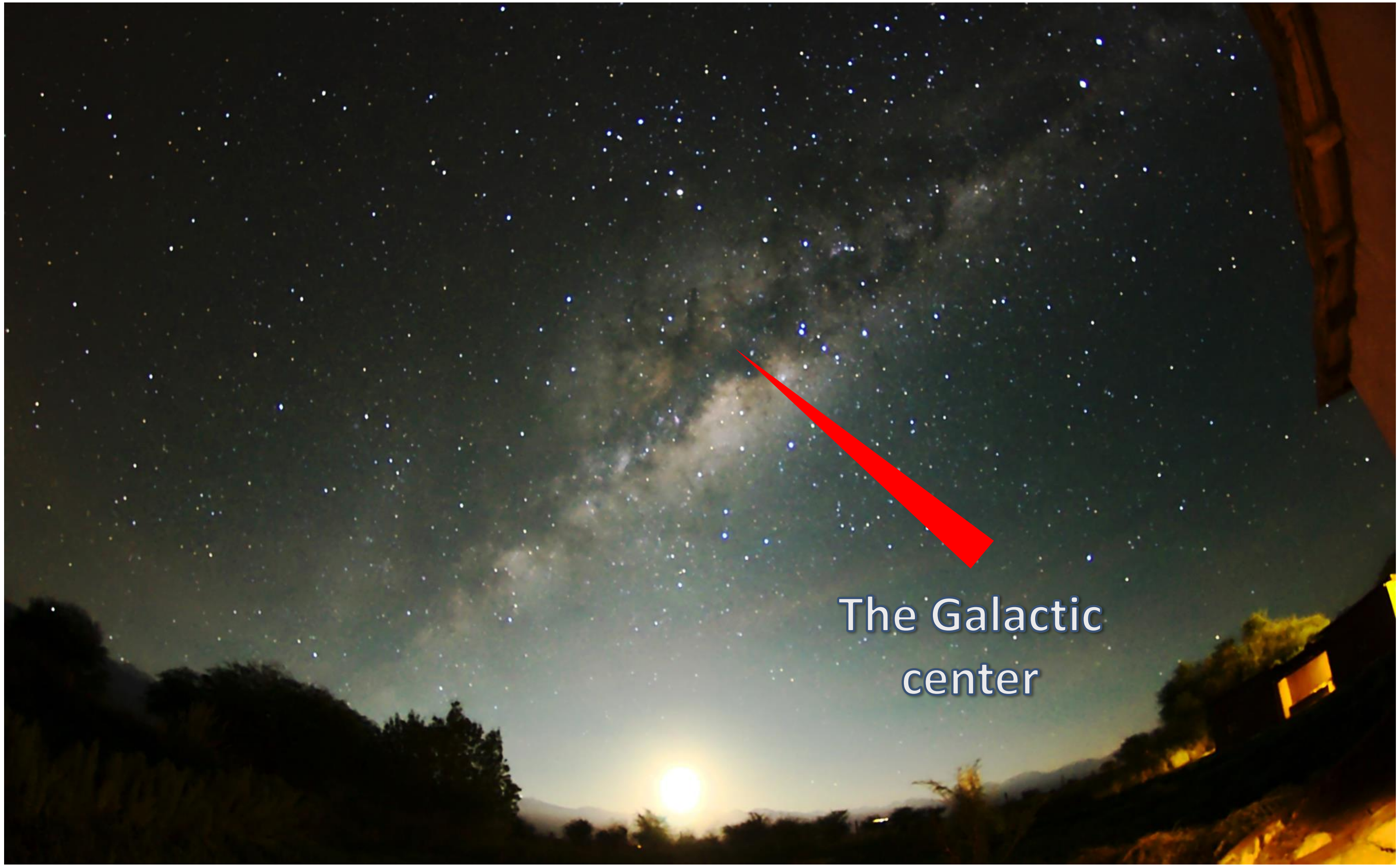
Perlmutter, Physics Today, April 2003

The LMT in Puebla as a VLBI element.

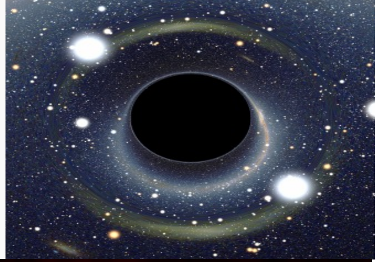




The Galactic center



A zoom toward the Galactic center



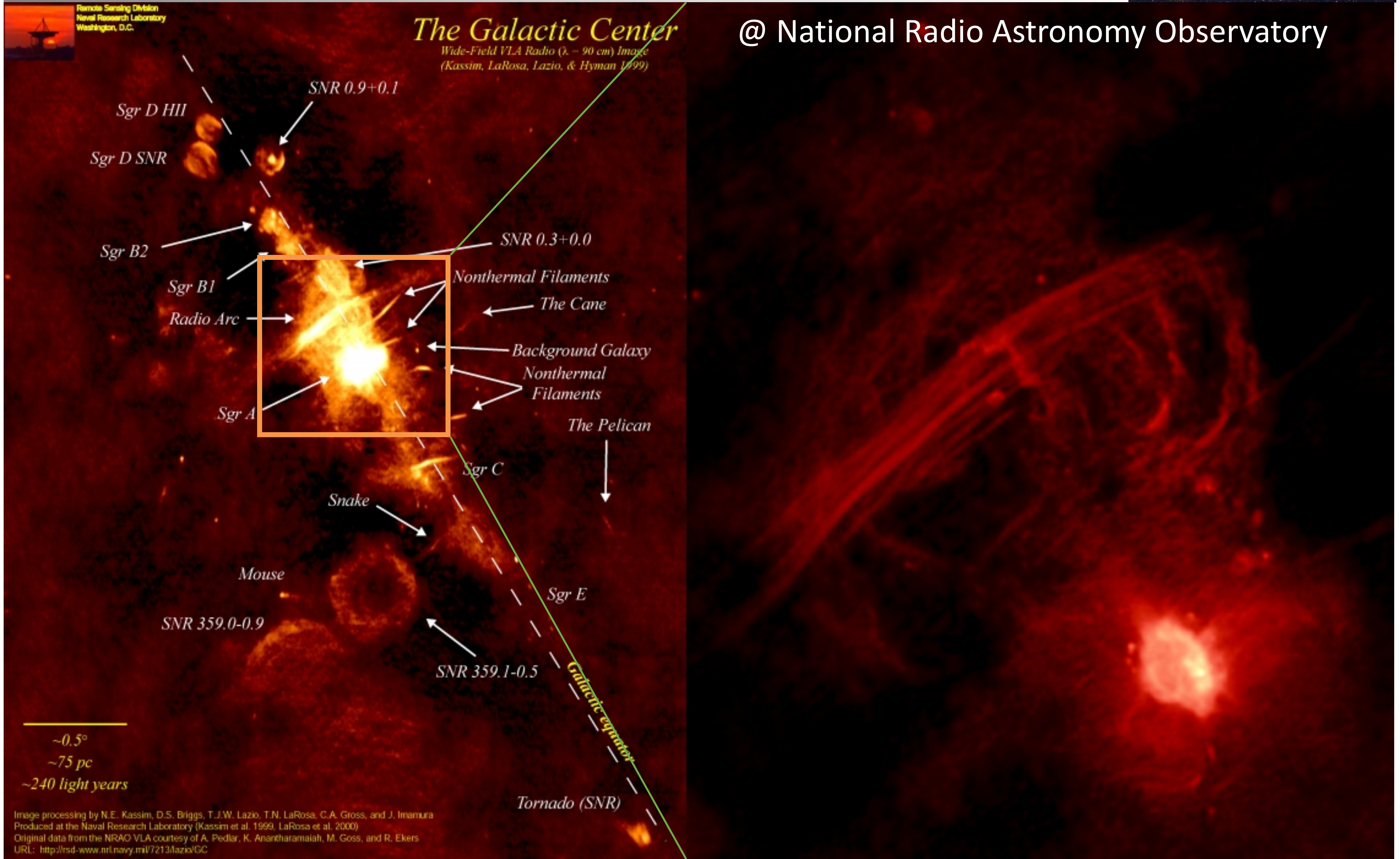
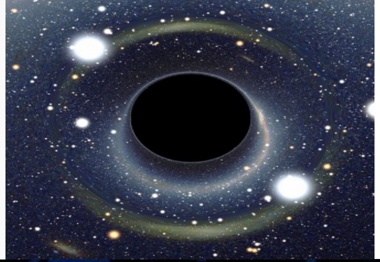
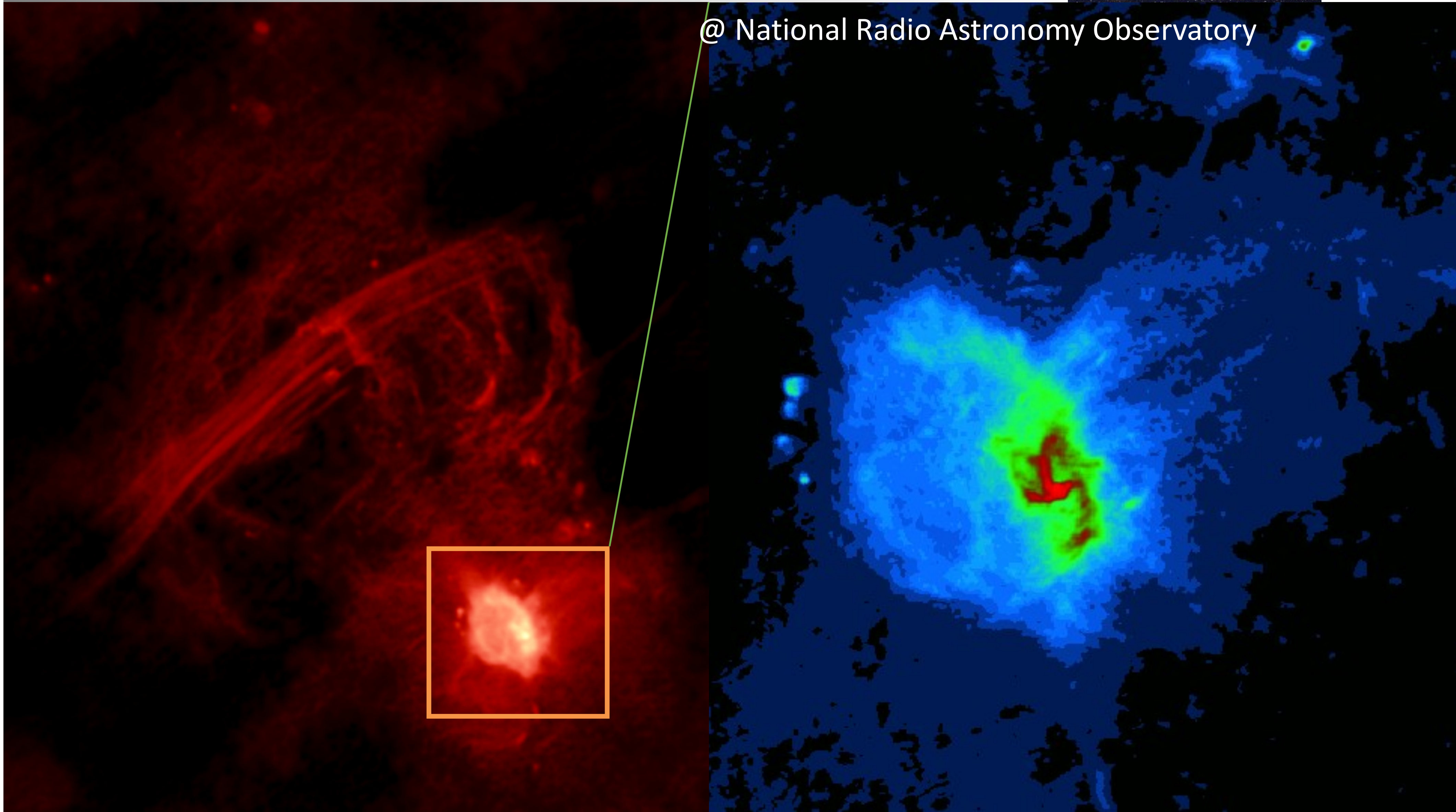


Image processing by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, C.A. Gross, and J. Imamura
Produced at the Naval Research Laboratory (Kassim et al. 1999, LaRosa et al. 2000)
Original data from the NRAO VLA courtesy of A. Pedlar, K. Anantharamaiah, M. Goss, and R. Ekers
URL: http://rsd-www.nrl.navy.mil/7213/lazio/GC

@ National Radio Astronomy Observatory

A zoom toward the Galactic center





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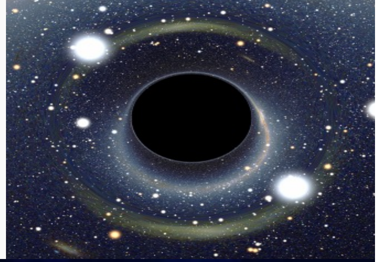
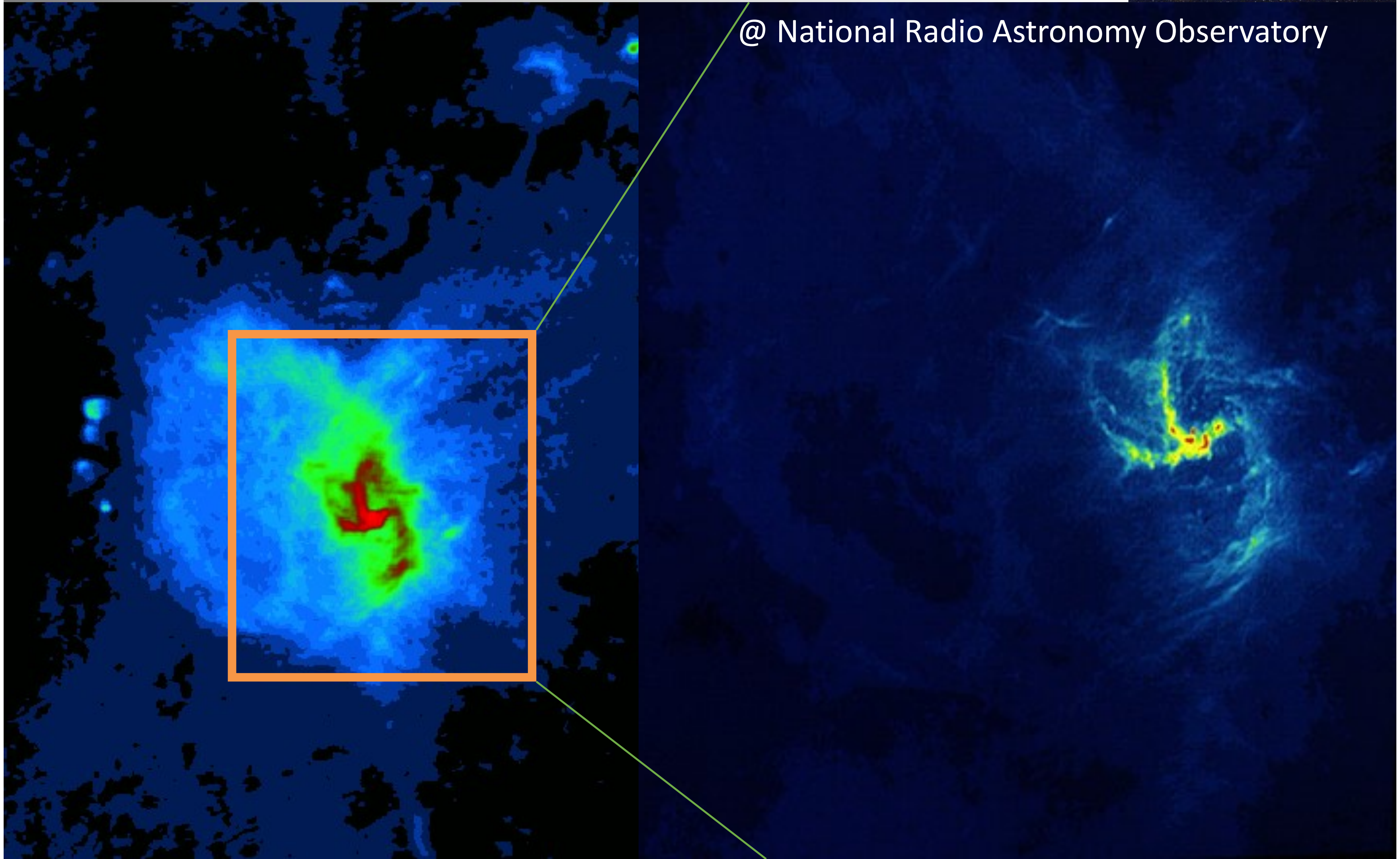
A zoom toward the Galactic center





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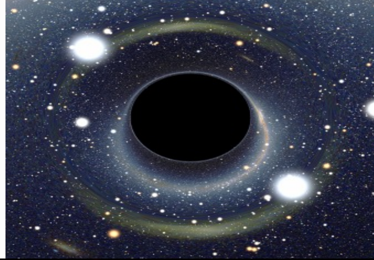
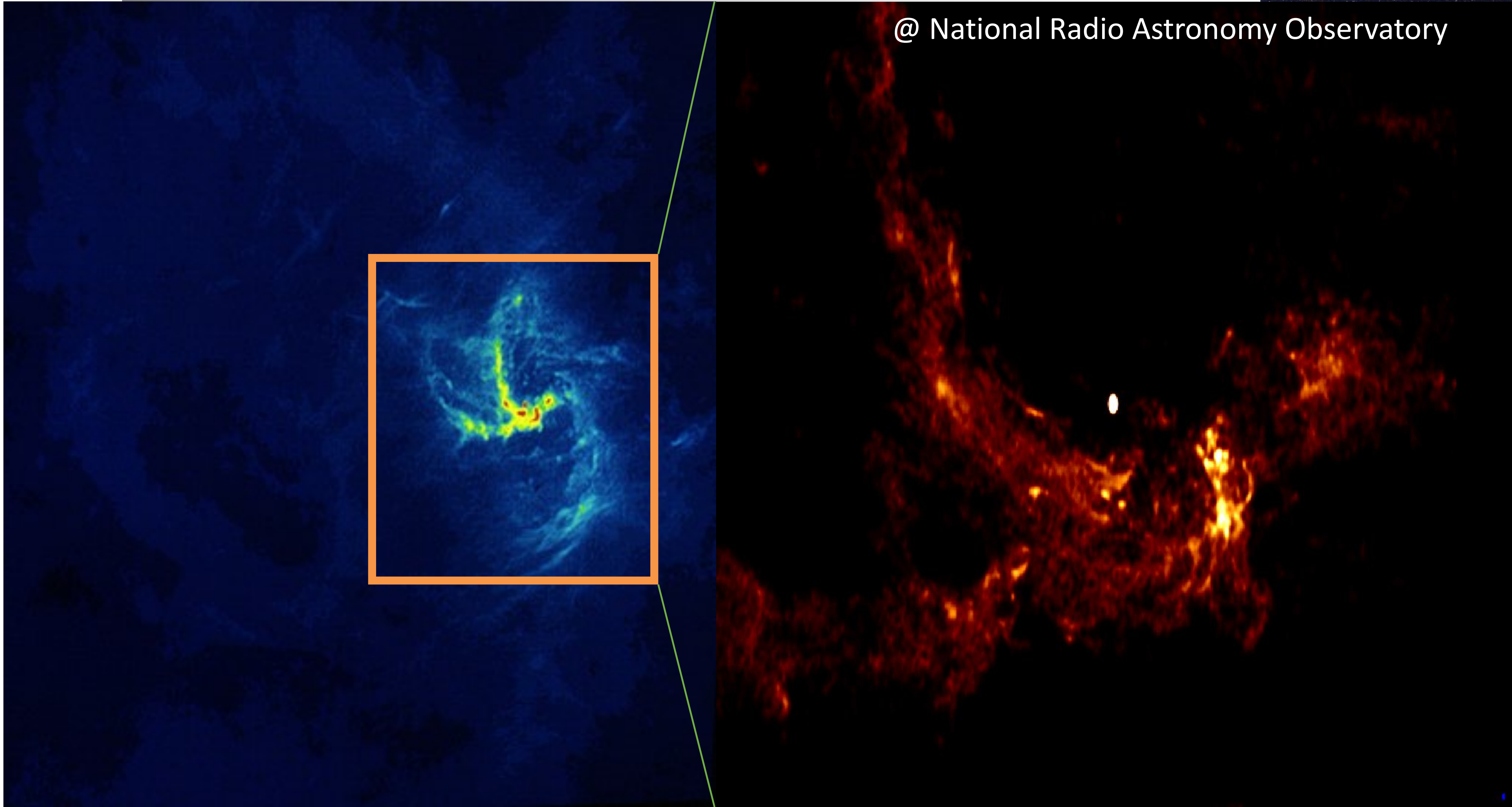
A zoom toward the Galactic center





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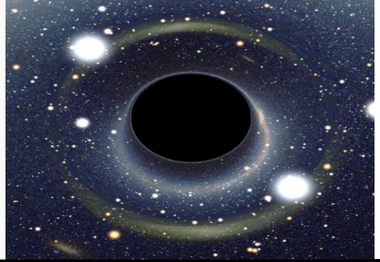
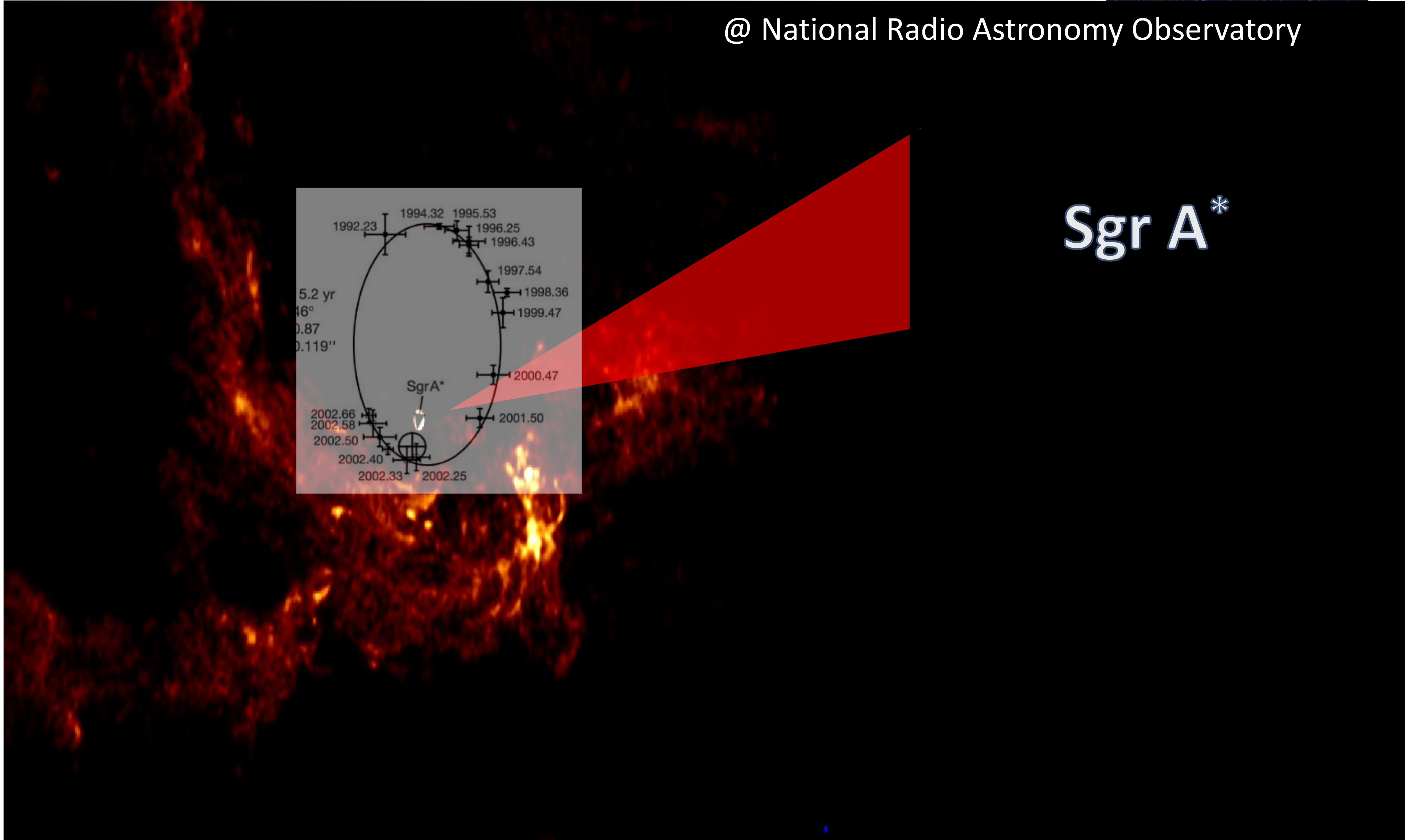
A zoom toward the Galactic center



Ghez et al.
Genzel et al.

Mass = 4.1 10^6 Msun (in a radius of 6 light-hours -more or less the size of the Solar system)

The Schwarzschild diameter is about 40 microarcseconds.



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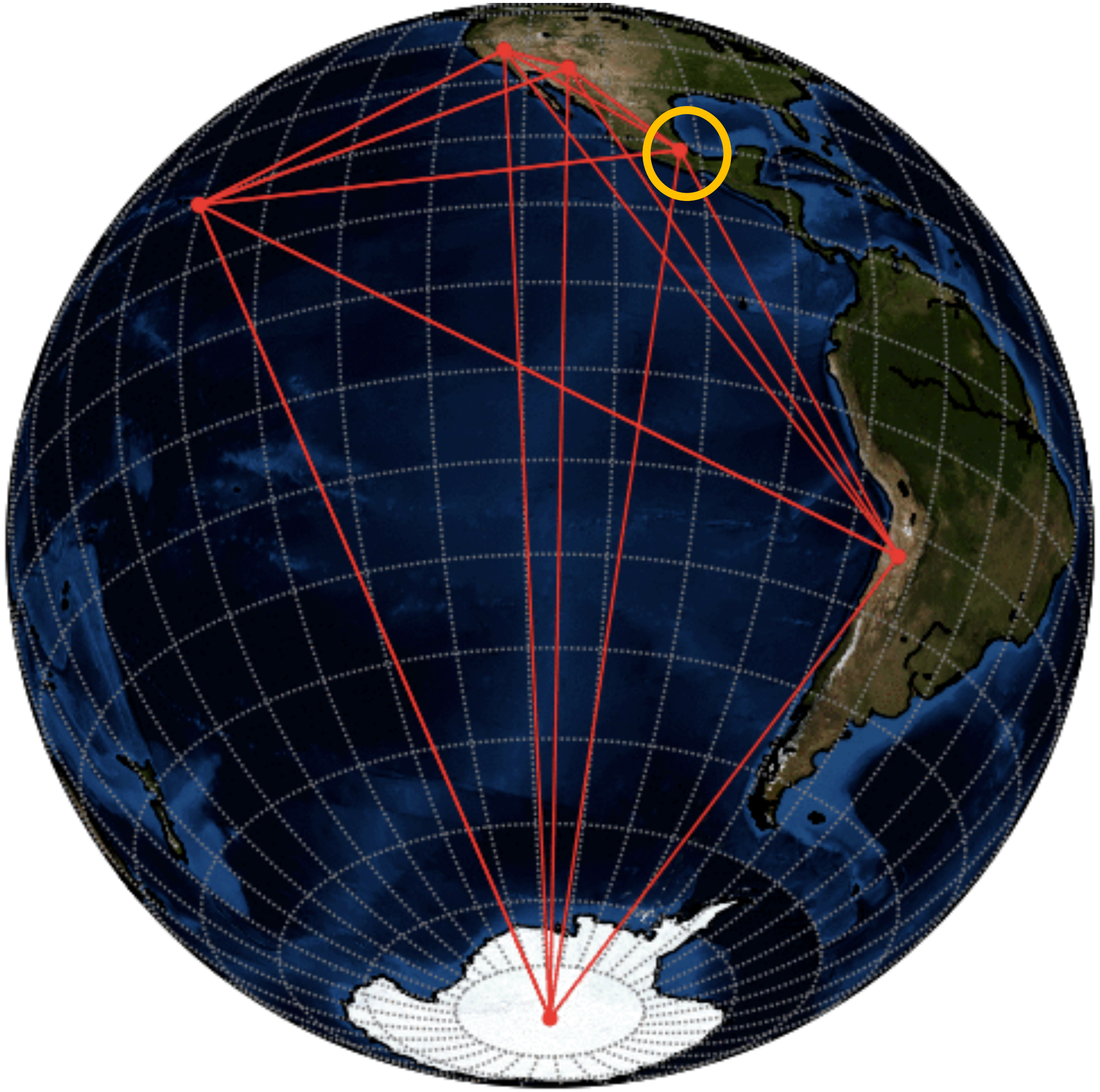
Sgr A*

The “event horizon telescope”

Angular resolution in about 20 microarcseconds (at a wavelength of 1.3 mm)

Can resolve Sgr A* at scales of the Schwarzschild radius.



First VLBI results with the LMT

THE ASTROPHYSICAL JOURNAL, 824:40 (10pp), 2016 June 10
doi:10.3847/0004-637X/824/1/40

THE INTRINSIC SHAPE OF SAGITTARIUS A* AT 3.5 mm WAVELENGTH

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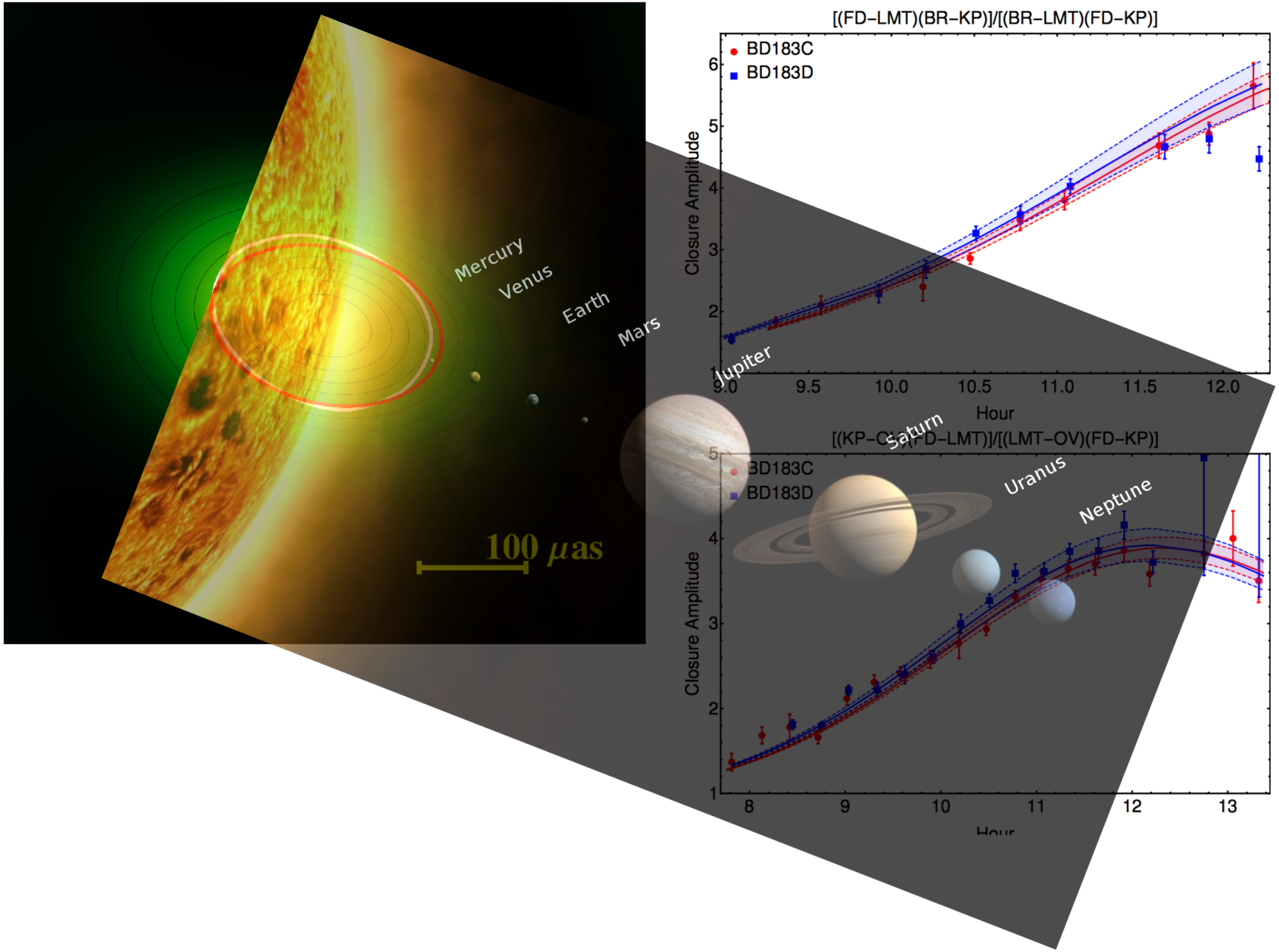
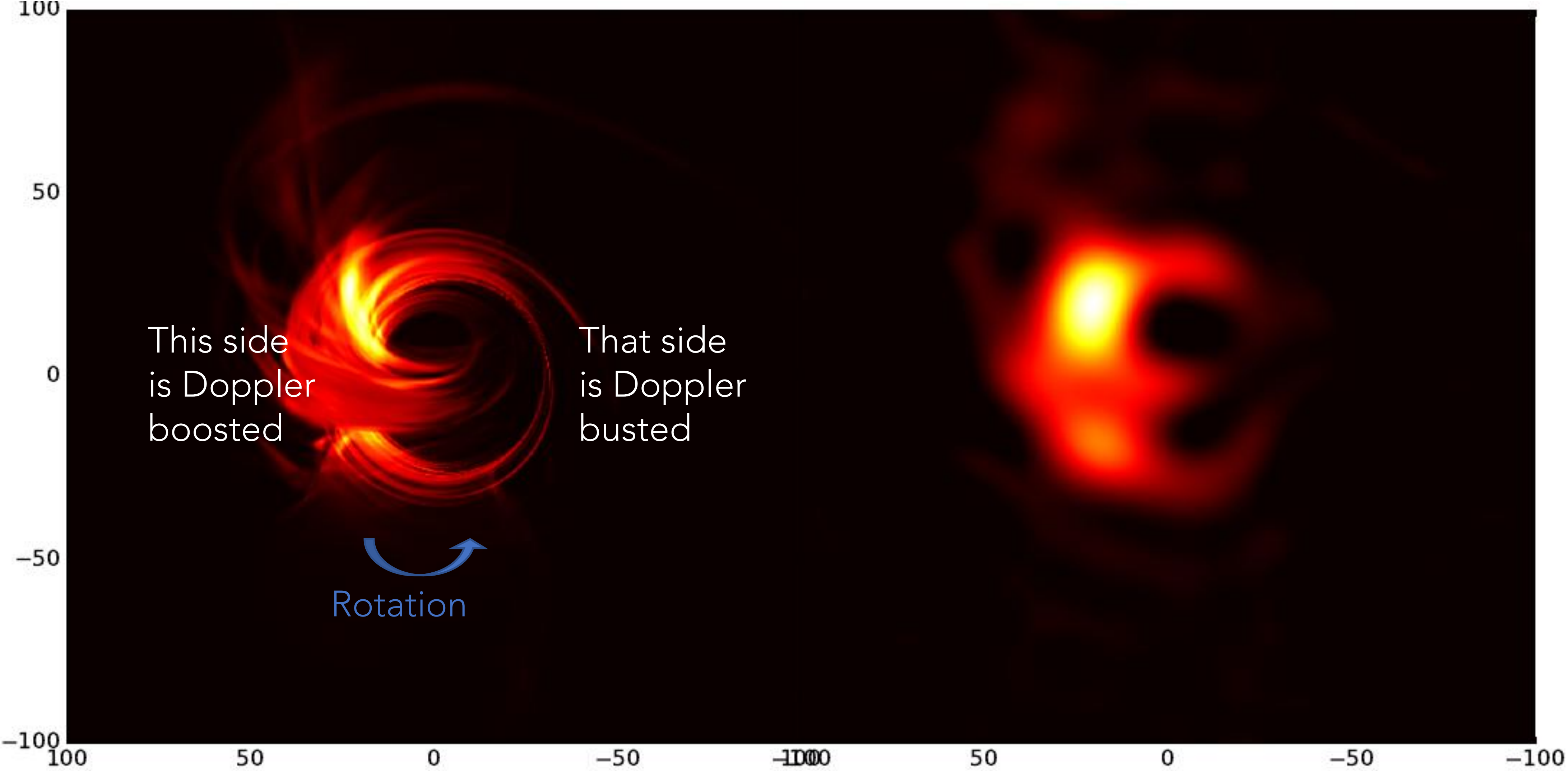
ABSTRACT

The radio emission from Sgr A* is thought to be powered by accretion onto a supermassive black hole of $\sim 4 \times 10^6\,M_\odot$ at the Galactic Center. At millimeter wavelengths, Very Long Baseline Interferometry (VLBI) observations can directly resolve the bright innermost accretion region of Sgr A*. Motivated by the addition of many sensitive long baselines in the north–south direction, we developed a full VLBI capability at the Large Millimeter Telescope Alfonso Serrano (LMT). We successfully detected Sgr A* at 3.5 mm with an array consisting of six Very Long Baseline Array telescopes and the LMT. We model the source as an elliptical Gaussian brightness distribution and estimate the scattered size and orientation of the source from closure amplitude and self-calibration analysis, obtaining consistent results between methods and epochs. We then use the known scattering kernel to determine the intrinsic two-dimensional source size at 3.5 mm: $(147 \pm 7\ \mu\mathrm{as}) \times (120 \pm 12\ \mu\mathrm{as})$, at position angle $88° \pm 7°$ east of north. Finally, we detect non-zero closure phases on some baseline triangles, but we show that these are consistent with being introduced by refractive scattering in the interstellar medium and do not require intrinsic source asymmetry to explain.

Key words: accretion, accretion disks – galaxies: active – galaxies: individual (Sgr A*) – Galaxy: center – techniques: interferometric


Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
100 μas
[(FD–LMT)(BR–KP)]/[(BR–LMT)(FD–KP)]
BD183C
BD183D
Closure Amplitude
1
2
3
4
5
6
9.0
9.5
10.0
10.5
11.0
11.5
12.0
Hour
[(KP–OV)(FD–LMT)]/[(LMT–OV)(FD–KP)]
BD183C
BD183D
Closure Amplitude
1
2
3
4
5
8
9
10
11
12
13
Hour



This side
is Doppler
boosted

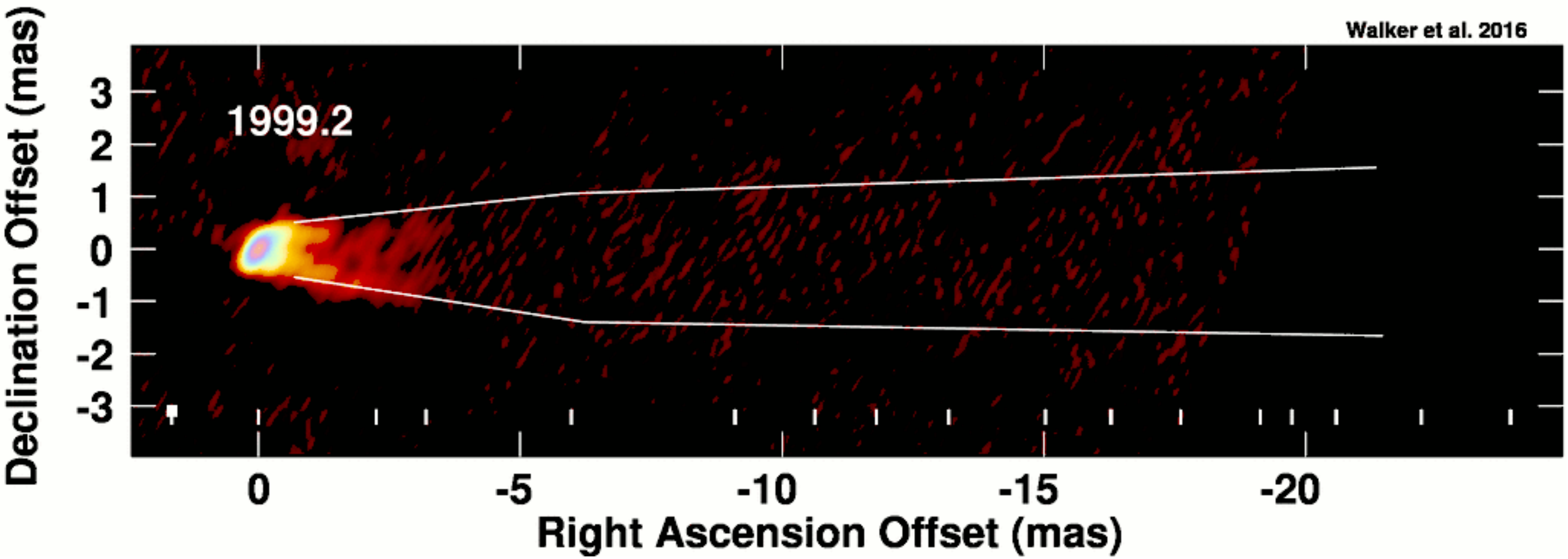
That side
is Doppler
busted

Rotation

Theoretical simulation

How that image would look like to the EHT

Second target: Messier 87



About 2,000 farther, but about 1,000 times more massive.
The angular size of the Schwarzschild radius is similar as Sgr A*.

The first images of a black hole (from 2017 observations)
February 15, mark your calendars…

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CNF 2018

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