Trigonometric Parallax

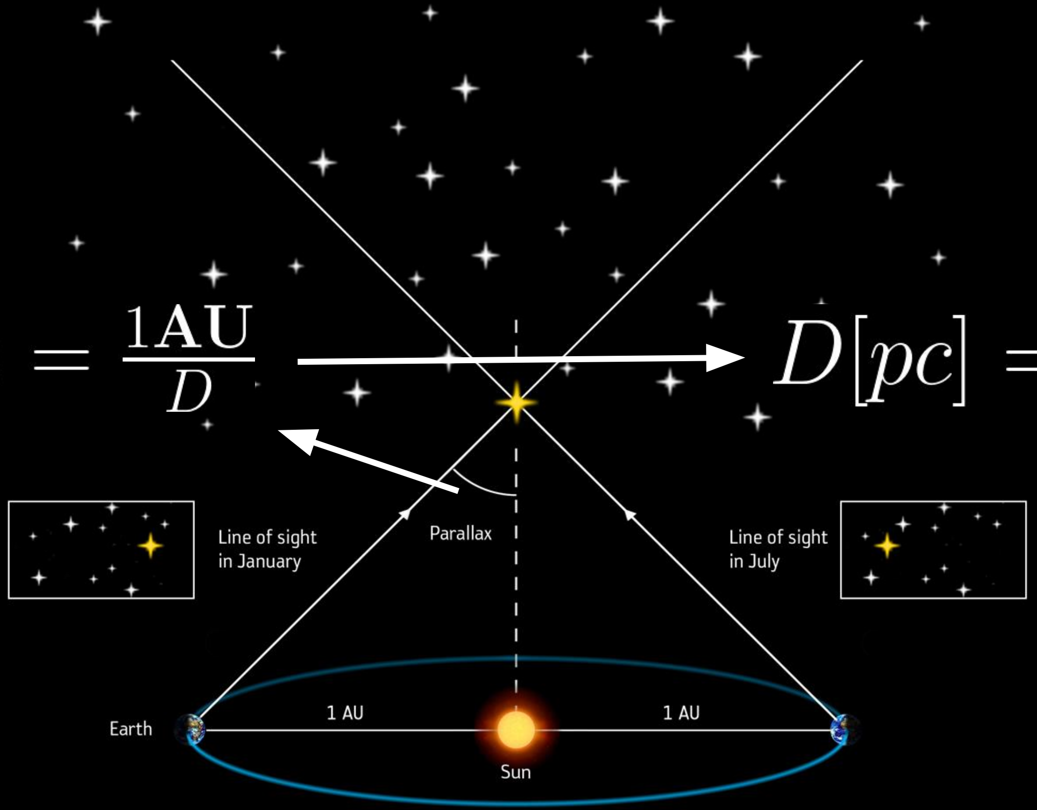
Jacob Tutterow

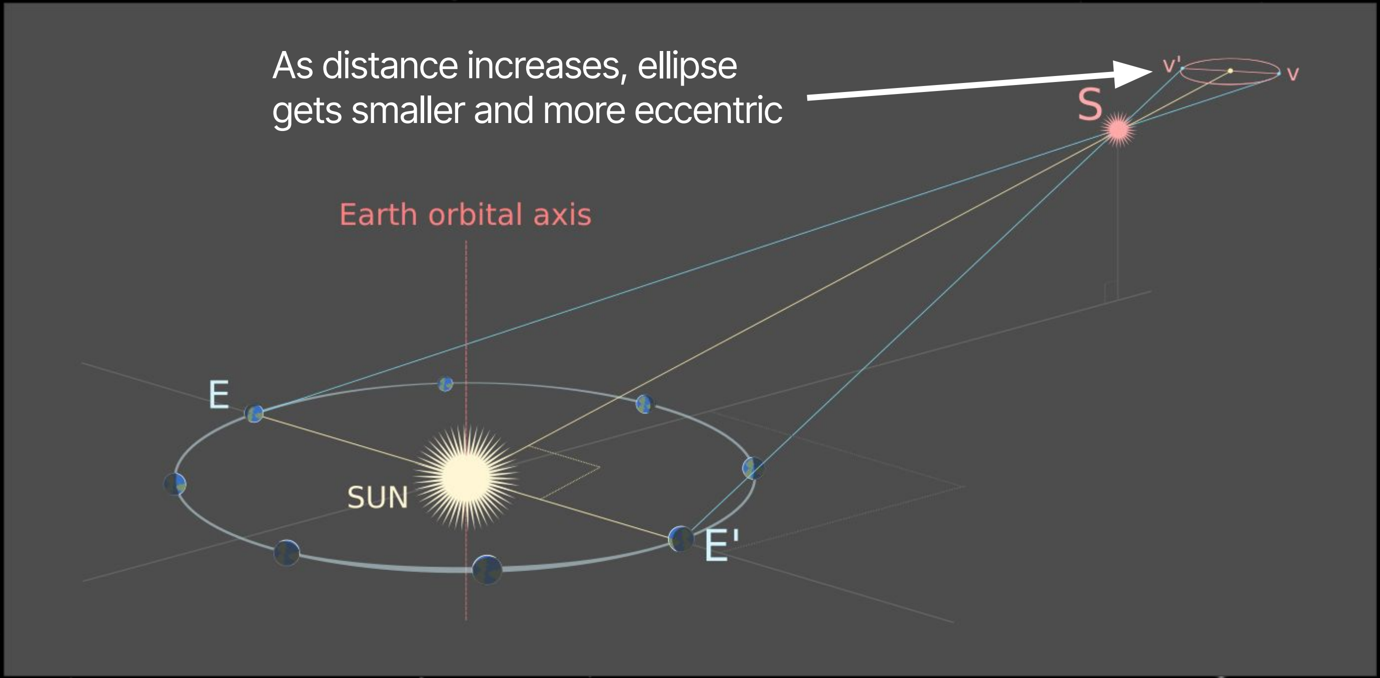
The first rung

- Main astronomical measurements:
    - Photometry
        - Measure light
    - Spectroscopy
        - Measure wavelength
    - Astrometry
        - Measure position
        - ...to get parallax!

$$tan(\theta) = \frac{1\mathbf{AU}}{D}$$

$$D[pc] = \frac{1}{\pi[arcsec]}$$





Direct distance measurement!

Parallax – the drawbacks

- Need accurate astrometry
- Have to wait 6 months for biggest angle
- Only reliable for relatively close objects
  - 1000 parsecs gives ~10% error with Gaia
- Errors come from:
  - Atmospheric effects
  - Instrumental errors

Parallax is difficult

- Closest star (Proxima Centauri) has parallax <1″
- Atmospheric turbulence/seeing typically limits observations to 1″
- Need proper motions of background stars
- Even for close stars, parallax errors can be high
- Even more difficult for binary stars
- Theorized for hundreds of years before actually measured
- Your fingertip at arm’s length is ~1 degree on the sky
    - Nearest star’s parallax is less than 1/3600th of that!

Parallax is difficult

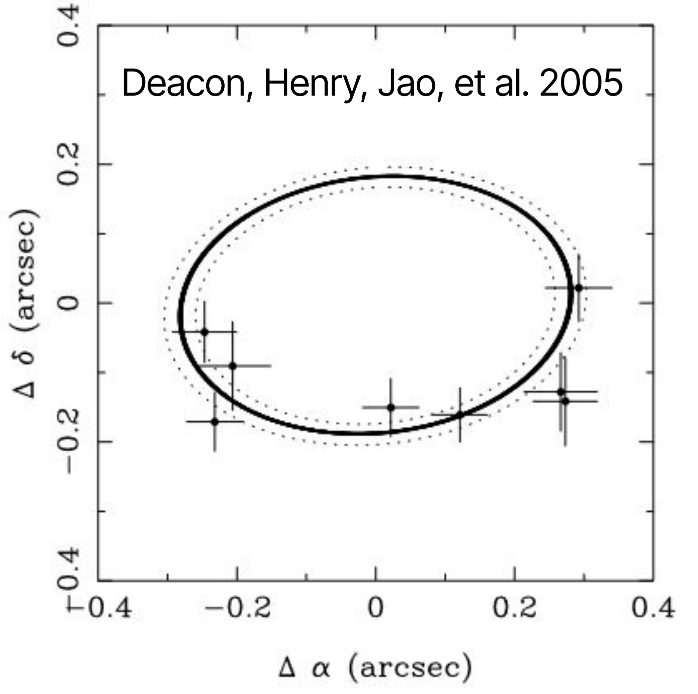


FIG. 2.—Parallax ellipse traced out by the target. The dotted lines represent 1 σ upper and lower limits on the parallax.

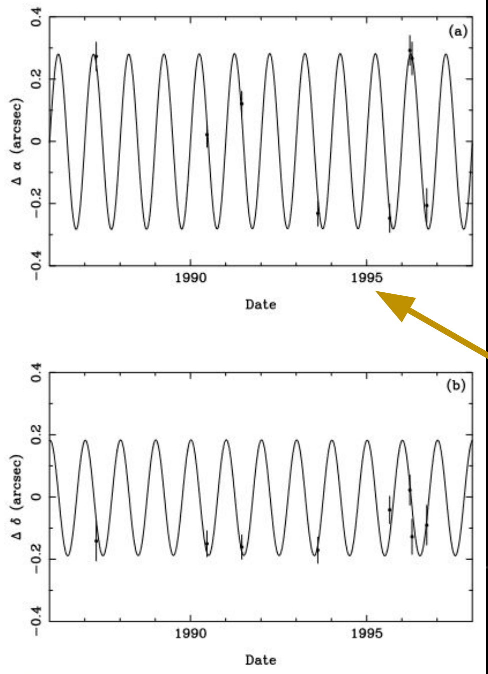
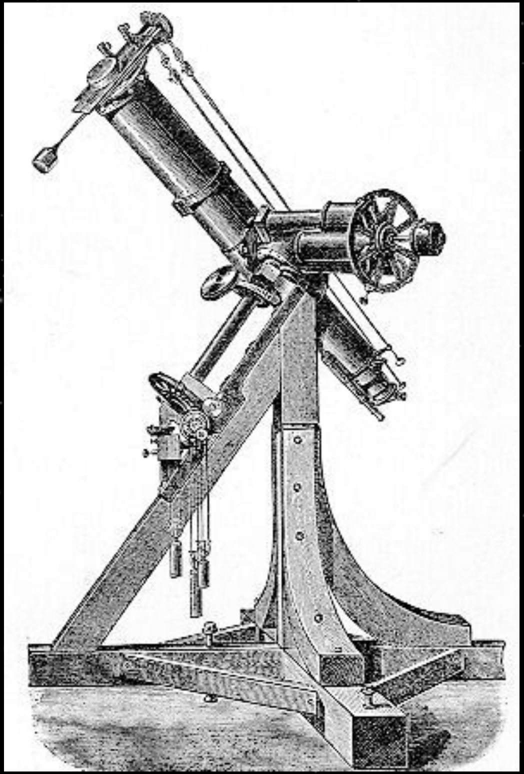


FIG. 1.—Deviation from the proper motion in (*a*) right ascension and (*b*) declination vs. time. The line shown is the path of parallax motion predicted by the astrometric solution.

Years!

1800s first measurements

- Henderson, Struve, and Bessel were first to measure parallax (mostly Bessel)
  - **Alpha Centauri** -- Measured 0.912″, actual 0.747″
  - **61 Cygni** -- Measured 0.314″, actual 0.285″
  - **Vega** -- Measured 0.125″, actual 0.130″
    - Struve revised his measurement to 0.314″ after Bessel released his 61 Cygni parallax



Bessel's 1830s heliometer

Modern ground-based astrometry

- By 1910, **only ~100 parallaxes known**
- "It is now possible to measure parallaxes out to 200 parsec" - Binney & Merrifield, 1981
- 60's -- photographic plates, speckle
- 80's -- CCDs significantly reduced uncertainties
  - Catalogues of 100,000s of stars!
- 90's - Adaptive Optics

Automated Plate Measuring machine at Cambridge

Manually set x/y grid, then did 2mm strip laser scans

“**In an average year** the facility is available for scanning roughly 90% of the time and typically **over 1000 plates are measured**.”

“The scanning and processing time for a complete UK or Palomar Schmidt plate at 1/2 arcsec resolution is **just over 4 hours**.”

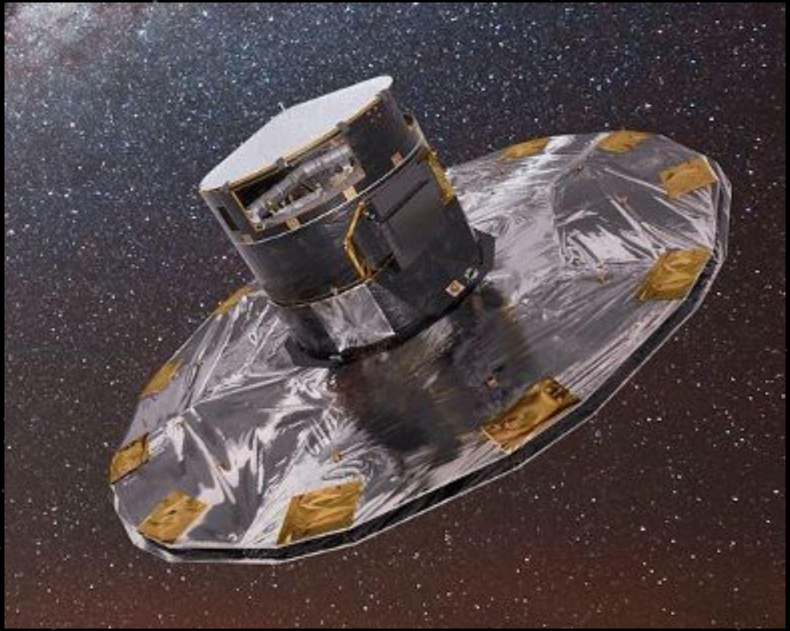
From the APM Facility historical website

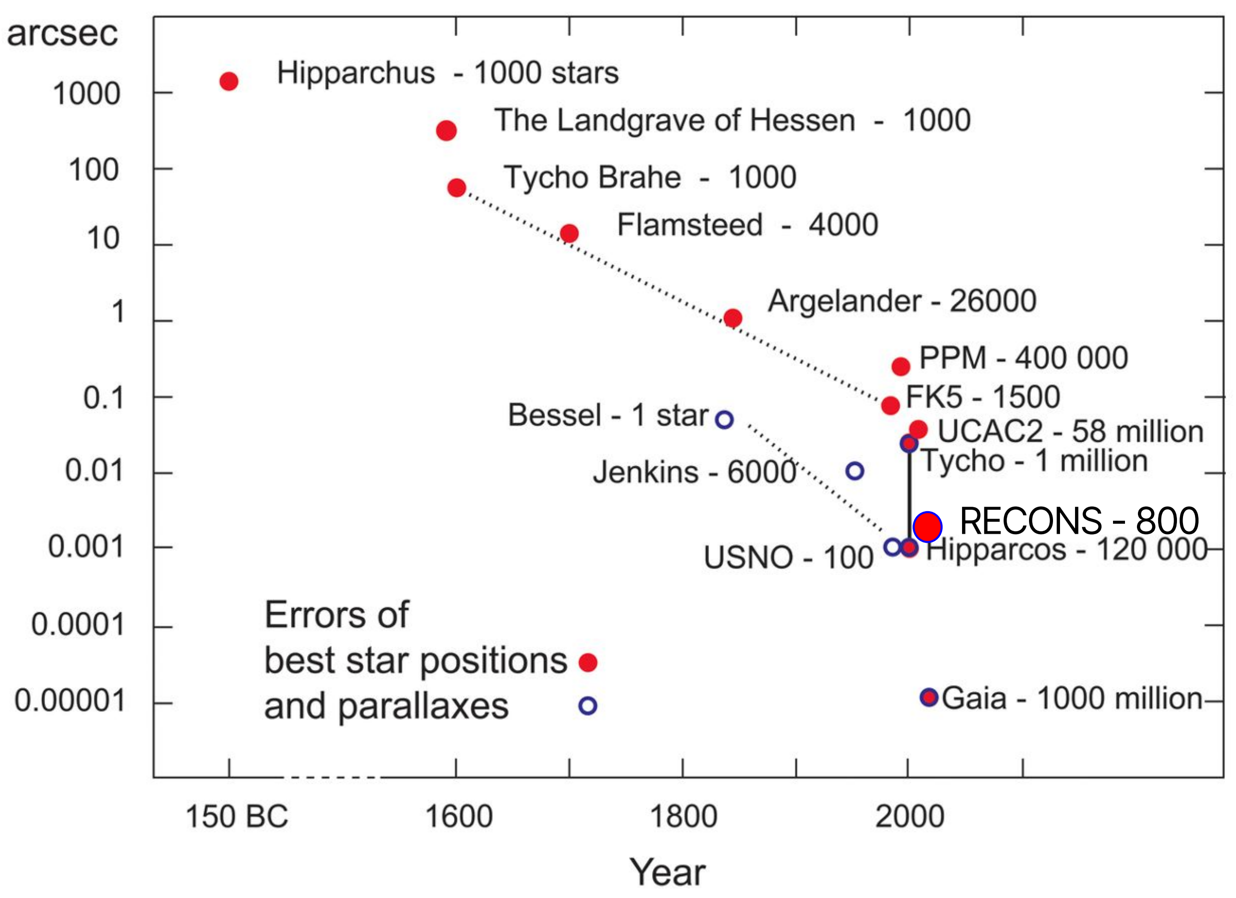
Going to space!

- Hipparcos! “**H**igh **P**recision **PAR**allax **CO**llecting **S**atellite”
  - Launched 1989
  - Measured parallax for >1,000,000 stars, accuracy of ~0.002 arcsec
- Hubble Space Telescope
  - Launched 1990
  - Precision of ~20-40 micro arcsec

Gaia

- 0.1 milli arcsec error at 1000 pc!!
- Over 1 billion objects!!
- Can see down to ~20 G mag!!



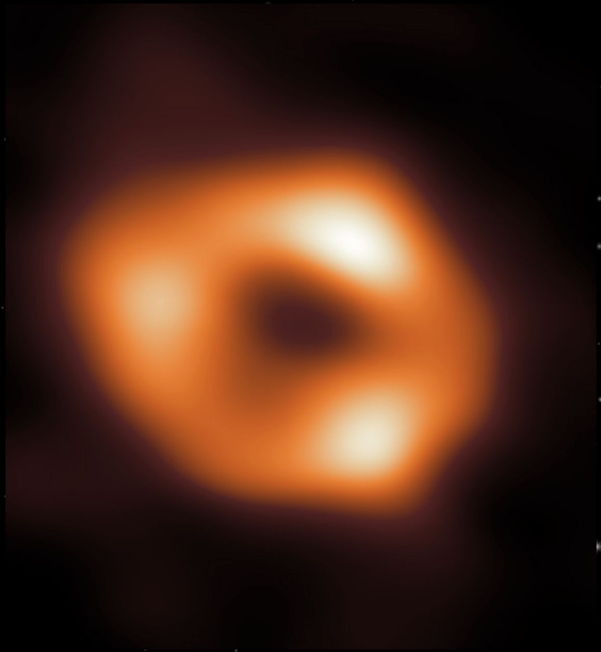


arcsec
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
Hipparchus - 1000 stars
The Landgrave of Hessen - 1000
Tycho Brahe - 1000
Flamsteed - 4000
Argelander - 26000
PPM - 400 000
FK5 - 1500
Bessel - 1 star
UCAC2 - 58 million
Tycho - 1 million
Jenkins - 6000
RECONS - 800
USNO - 100
Hipparcos - 120 000
Errors of
best star positions
and parallaxes
Gaia - 1000 million
150 BC
1600
1800
2000
Year

The future?

- Telescopes can get very high angular resolution
    - CHARA resolves ~200 micro arcsec
- But what has the highest angular resolution?

Very Long Baseline Interferometry



Event Horizon Telescope -- ~20 micro arcsec resolution

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Techniques for Measuring Parallax and Proper Motion with VLBI

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Abstract

Astrometry at centimeter wavelengths using Very Long Baseline Interferometry is approaching accuracies of $\sim$1 μas for the angle between a target and a calibrator source separated by $\lesssim 1^\circ$ on the sky. The BeSSeL Survey and the Japanese VERA project are using this to map the spiral structure of the Milky Way by measuring trigonometric parallaxes of hundreds of maser sources associated with massive, young stars. This paper outlines how μas astrometry is done, including details regarding the scheduling of observations, calibration of data, and measuring positions.

Unified Astronomy Thesaurus concepts: Astrophysical masers (103); Annual parallax (42); Astronomical techniques (1684); Radio astrometry (1337); Very long baseline interferometry (1769)

Online material: color figures

1. Introduction

This paper focuses on the techniques of differential astrometry using Very Long Baseline Interferometry (VLBI)

which requires significant bandwidth to measure. Thus, group delay is the peak of the broadband response, often called a delay or bandwidth pattern (see, e.g., Thompson et al. 2017). In

If we could measure 1μas…

- D[pc] = 1/π[arcsec]
  - D = 1,000,000 pc = **1 Mpc**!!!
- LMC -- ~50 kpc
- SMC -- ~60 kpc
- Andromeda -- ~765 kpc
- If we could measure ~0.2μas…
  - Could get parallaxes to Centaurus A, the closest AGN!!
- Of course, only in the radio
  - Masers, AGN, pulsars, etc

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Microarcsecond VLBI Pulsar Astrometry with PSRπ II. Parallax Distances for 57 Pulsars

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Abstract

We present the results of PSRπ, a large astrometric project targeting radio pulsars using the Very Long Baseline Array (VLBA). From our astrometric database of 60 pulsars, we have obtained parallax-based distance measurements for all but 3, with a parallax precision that is typically $\sim$45 μas and approaches 10 μas in the best cases. Our full sample doubles the number of radio pulsars with a reliable ($\gtrsim 5\sigma$) model-independent distance constraint. Importantly, many of the newly measured pulsars are well outside the solar neighborhood, and so PSRπ brings a near-tenfold increase in the number of pulsars with a reliable model-independent distance at $d > 2$ kpc. Our results show that both widely used Galactic electron density distribution models contain significant shortcomings, particularly at high Galactic latitudes. When comparing our results to pulsar timing, two of the four millisecond pulsars in our sample exhibit significant discrepancies in their proper motion estimates. With additional VLBI observations that extend our sample and improve the absolute positional accuracy of our reference sources, we will be able to additionally compare pulsar absolute reference positions between VLBI and timing, which will provide a much more sensitive test of the correctness of the solar system ephemerides used for pulsar timing. Finally, we use our large sample to estimate the typical accuracy attainable for differential VLBA astrometry of pulsars, showing that for sufficiently bright targets observed eight times over 18 months, a parallax uncertainty of 4 μas per arcminute of separation between the pulsar and calibrator can be expected.

Key words: astrometry – galaxies: ISM – pulsars: general – stars: neutron – techniques: high angular resolution

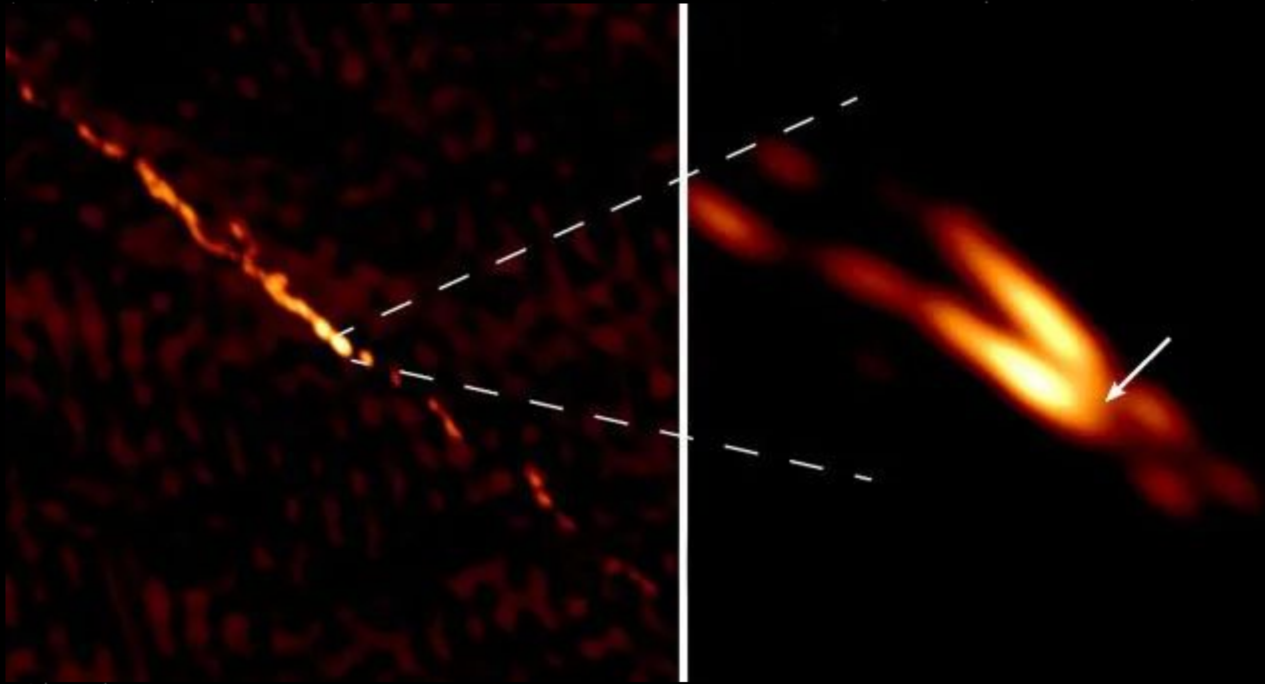
1. Introduction

With magnetic field strengths exceeding 10^{14} G, rotation rates approaching 1000 Hz, central densities exceeding 10^{14} g cm^3, and surface gravitational field potentials of order 40% of that of a

reliability of DM-based distance estimates for individual pulsars is generally quite low, and errors of a factor of several are not rare (Chatterjee et al. 2009; Deller et al. 2009). While some pulsar science use cases are relatively unaffected by such

Parallax precision of **~45 µas,** approaches **10 µas!**

Questions?



EHT image of Centaurus A's radio jets

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M. J. Reid. *Techniques for Measuring Parallax and Proper Motion with VLBI*. arXiv e-prints, page arXiv:2301.04756, Jan. 2023.