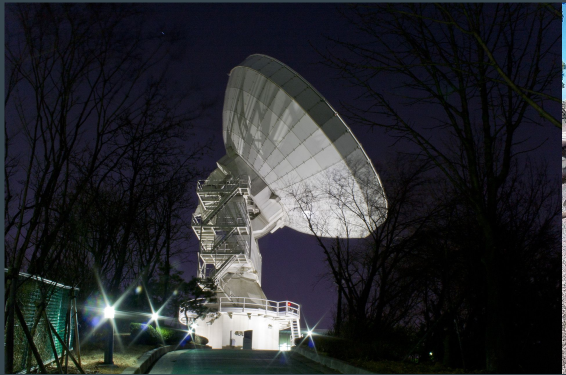

Cosmological QUOKKAS

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Measuring distances

Sounds boring, but actually very interesting

Distances are one of the most difficult things to get in astronomy

Redshift

What is it?

Redshift

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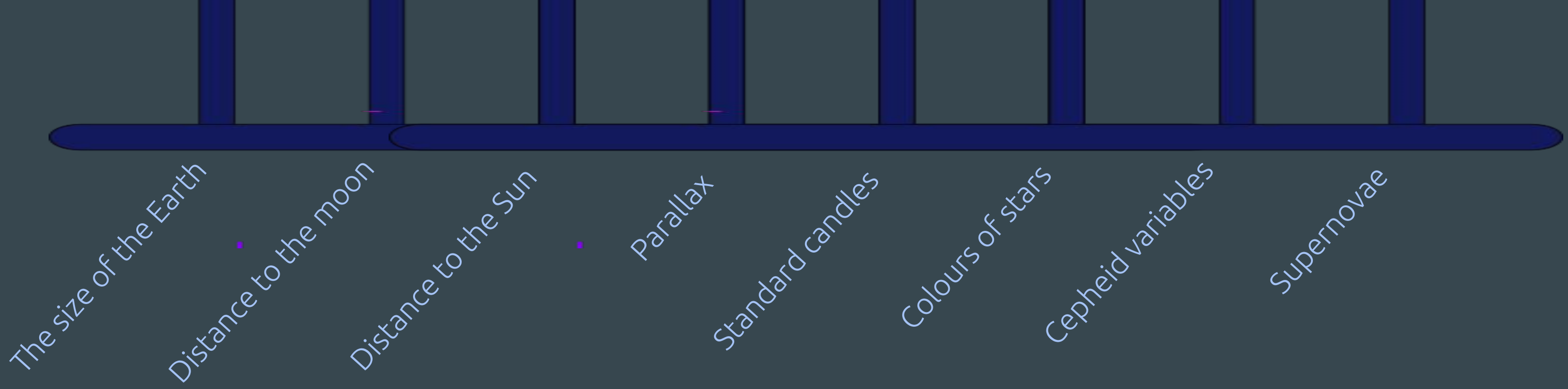
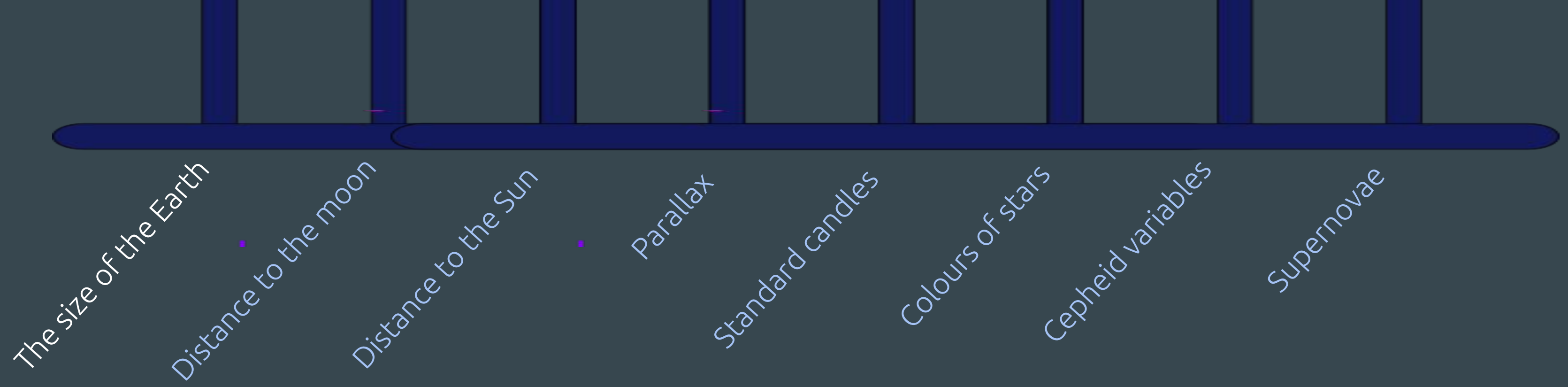
The same as that, except with light.
Moving **towards** you = more blue
Moving **away** = more red
What does this have to do with distance??!



The ladder

Each rung of the ladder builds on the previous rung

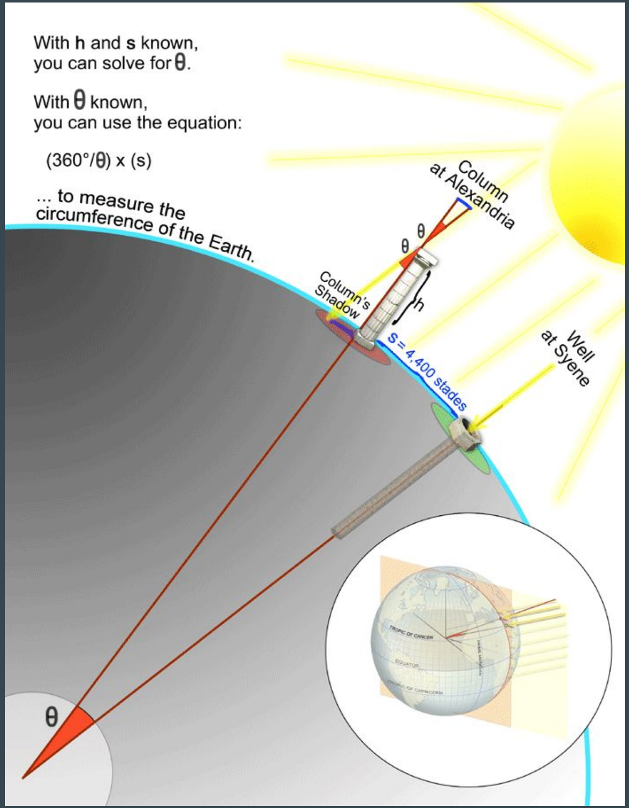


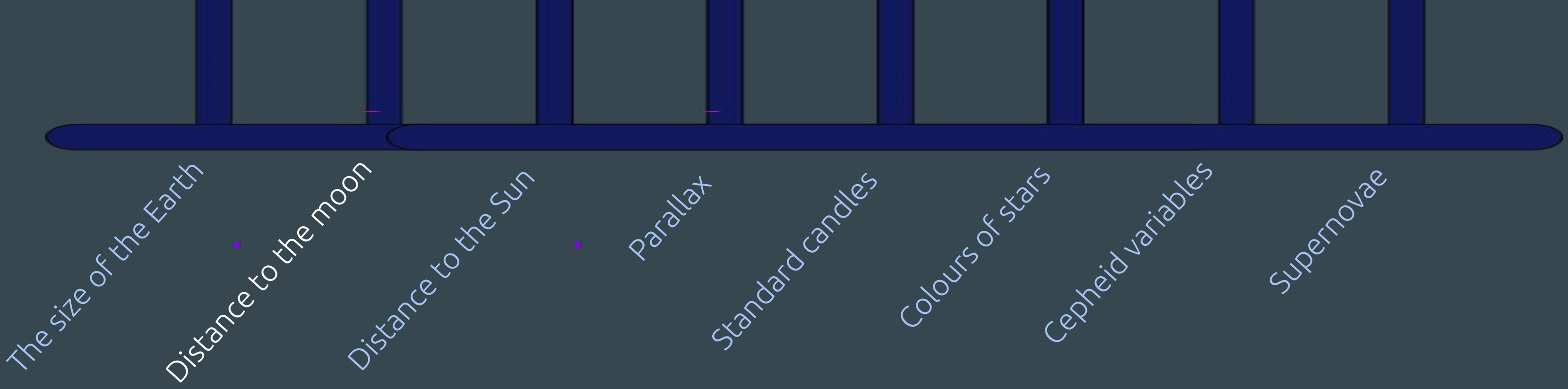
The size of the Earth …

Even the ancient Greeks knew it accurately

The size of the Earth: How did the Greeks do it?

- They knew the Earth was spherical.
  - They saw that ships would go “down” over the horizon
  - The boundary of the Earth’s shadow during a lunar eclipse was always circular (a disk would make elliptical shadows) - Aristotle
- Eratosthenes (~200 BCE) used the difference in shadows and the distance between two locations to determine the size of the Earth
  - 6800 km - compared with 6377 km !
  - Didn’t even know Pi back then!



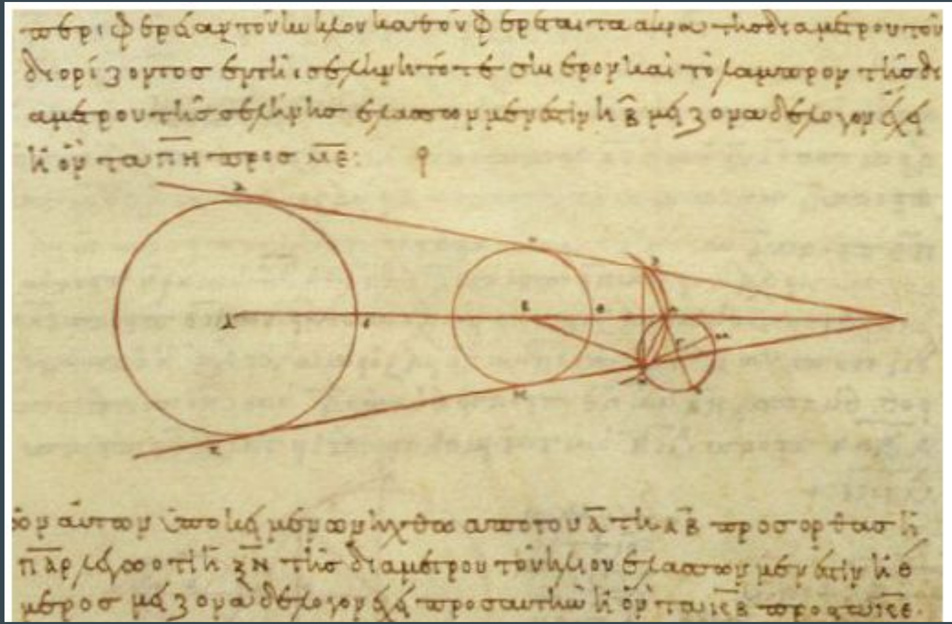


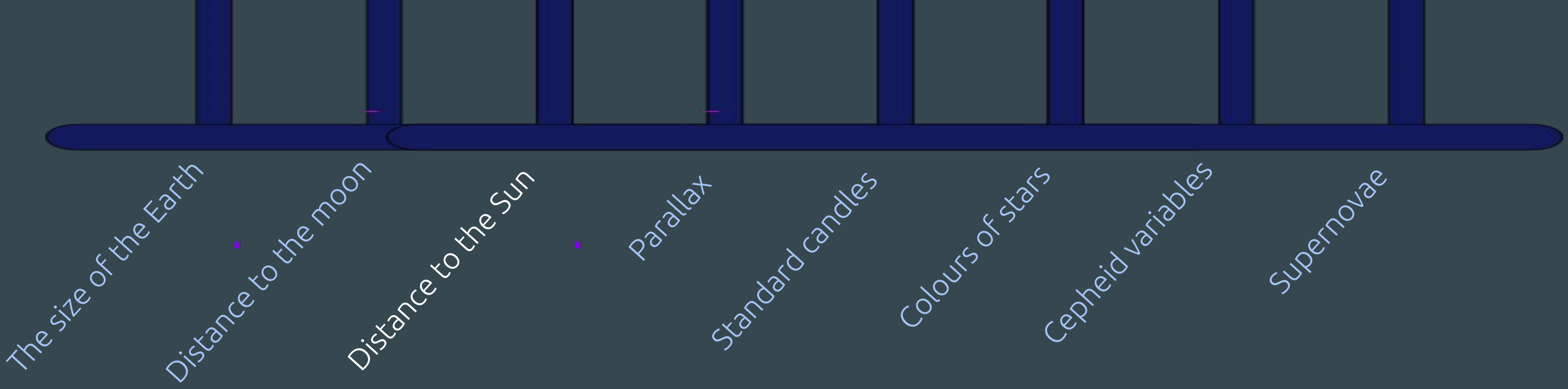
Distance to the Moon

Knowing the size of the Earth allows us to measure the distance to the Moon!

Distance to the Moon - Aristarchus

- Lunar eclipses due to shadow of the Earth on the moon (roughly an Earth diameter in size)
- Lunar eclipses takes 3 hours
- Moon takes 28 days to orbit the Earth
- Worked out that the moon must be about 60 Earth radii away
- 60 x 6800 = 408 000 km
  - 384 000 km is the real value
  - Accurate to 6% 2000+ years ago!





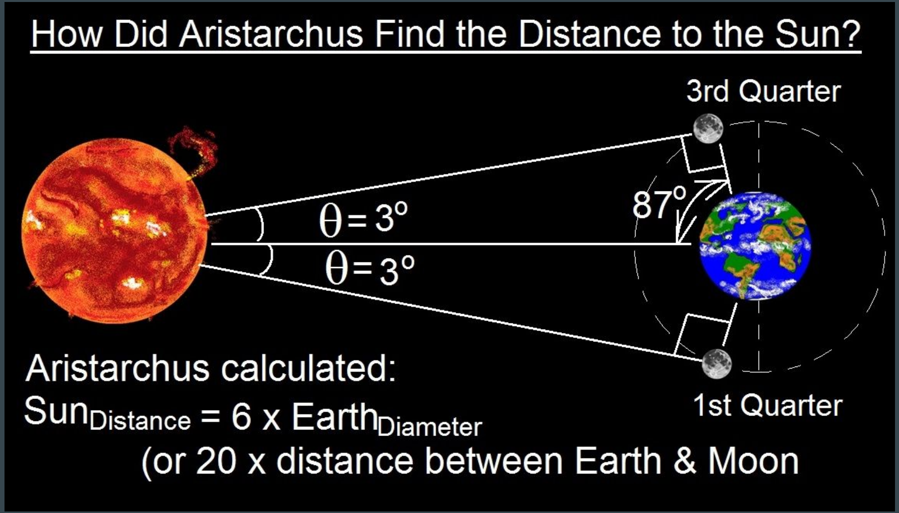
Distance to the Sun …

Probably the most important measurement in all of astronomy

So important that we call it *The Astronomical Unit*

Distance to the Sun

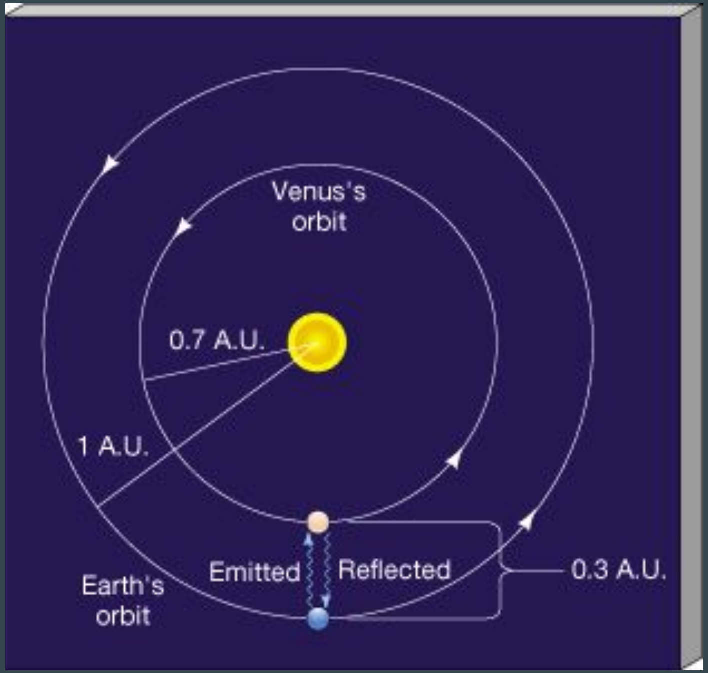
- Aristarchus also estimated a distance to the Sun
- Measure the angle between the Sun and the Moon at 1st and last quarters
- Because we know the distance to the Moon, could solve for the distance to the Sun
- Inadequate data meant he thought ~20 times Earth-Moon distance (400x is closer)
- Heliocentric model of the solar system 1700 years before Copernicus!

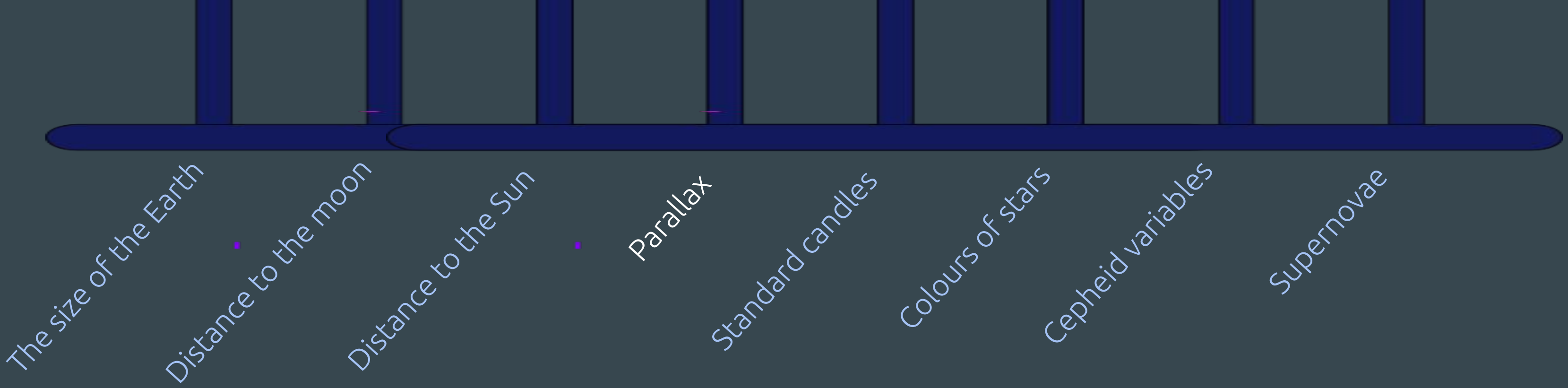


Distance to the Sun

1 AU: 149 597 870.7 km

- Estimates were greatly improved in the 17th century by Copernicus, and then Brahe and Kepler
- Kepler got the distance to Mars (very cleverly!) and then used it to get the distances to all of the planets and Sun
- These days we use radar and Kepler's laws to get the distance extremely accurately
  - Bounce radio waves off Venus (and other planets) to get the distance to it
  - Use Kepler's laws to solve for the distances



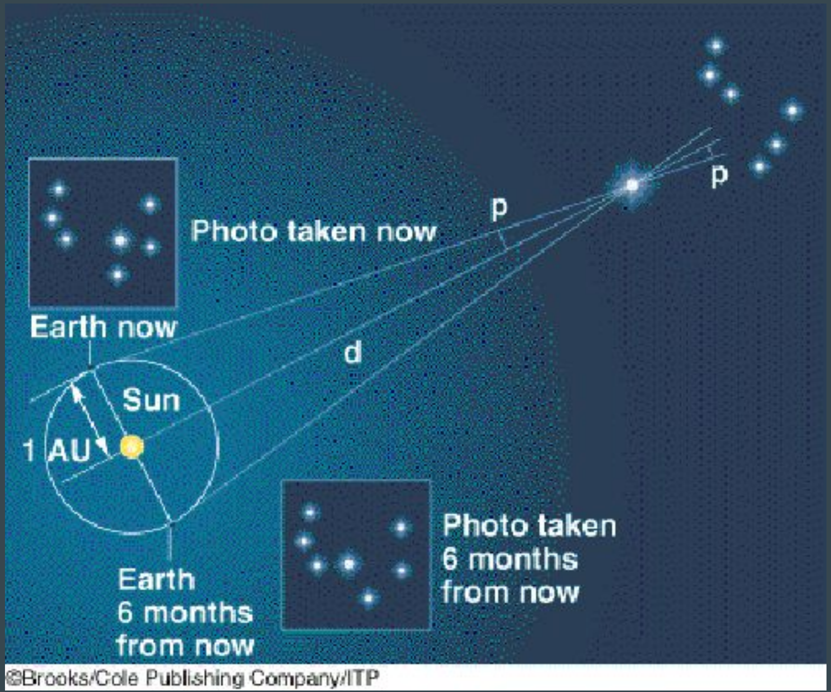


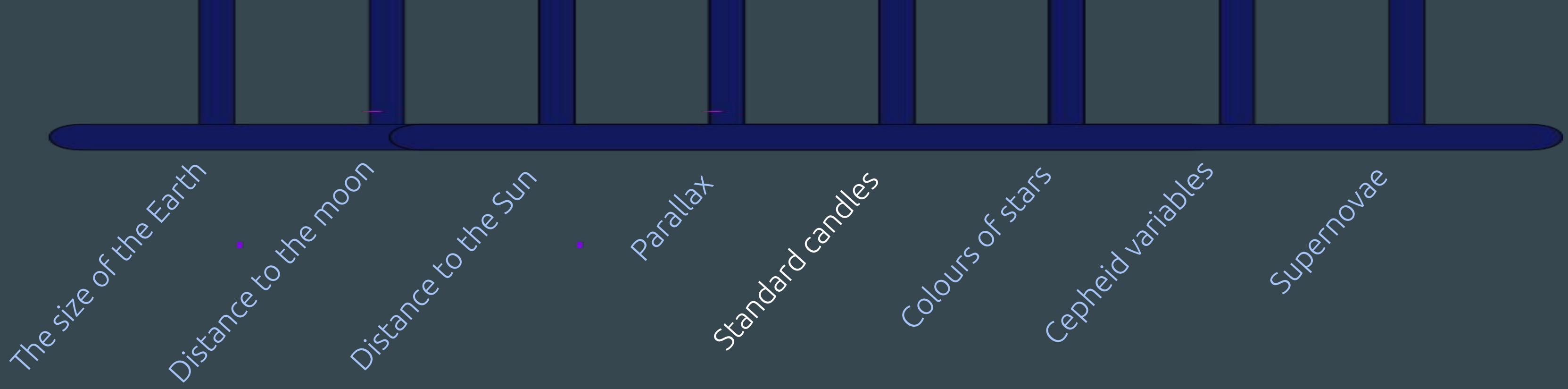
Parallax

Starting to measure distance to objects outside of our solar system

Parallax

- Very simple, basically the same concept as how our eyes do depth perception
- Observing a nearby star (compared to distant stars) at 6 month intervals will appear to shift position
- Measuring that shift and combining with the Astronomical Unit gives the distance!
- That the Ancient Greeks *didn't* see parallax was interpreted as the stars being impossibly far away, thus leading to Earth centered solar system models!

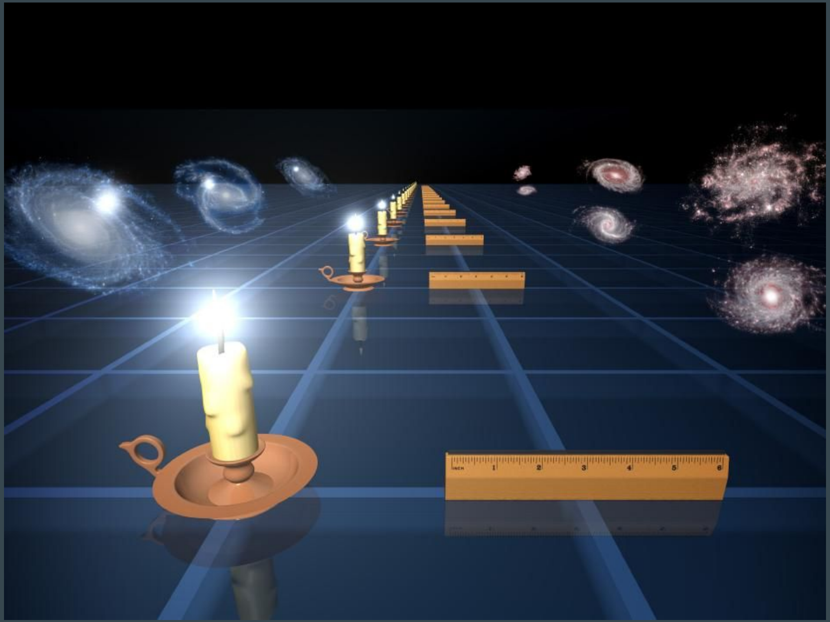


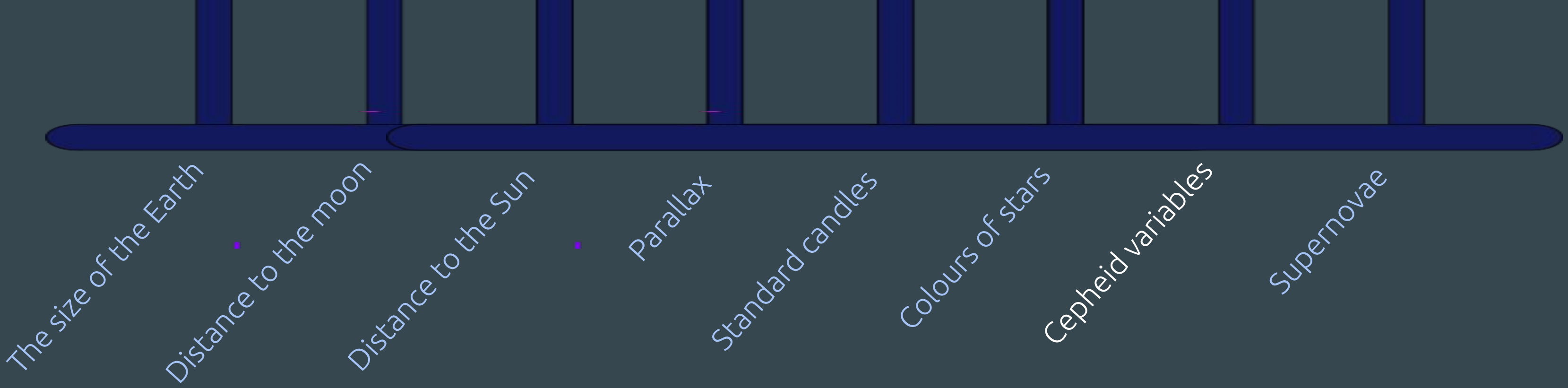


Standard Candles
...

Standard Candles

- At some point, we can't resolve the the motion of the stars
- If we know how bright something actually and we measure how bright it *appears* to be, we can find out how far away it is: **Standard candles**
- Similarly, if we know how big something is, we can determine how far away it is by measuring how big it appears to be: **Standard rulers**



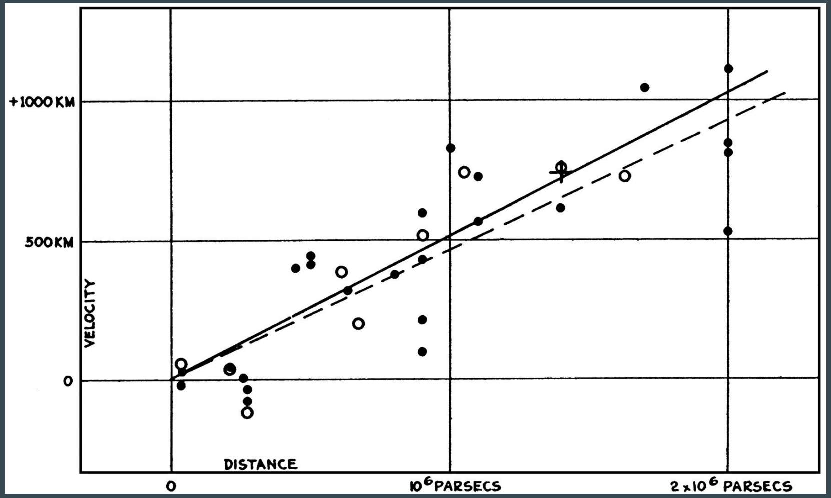


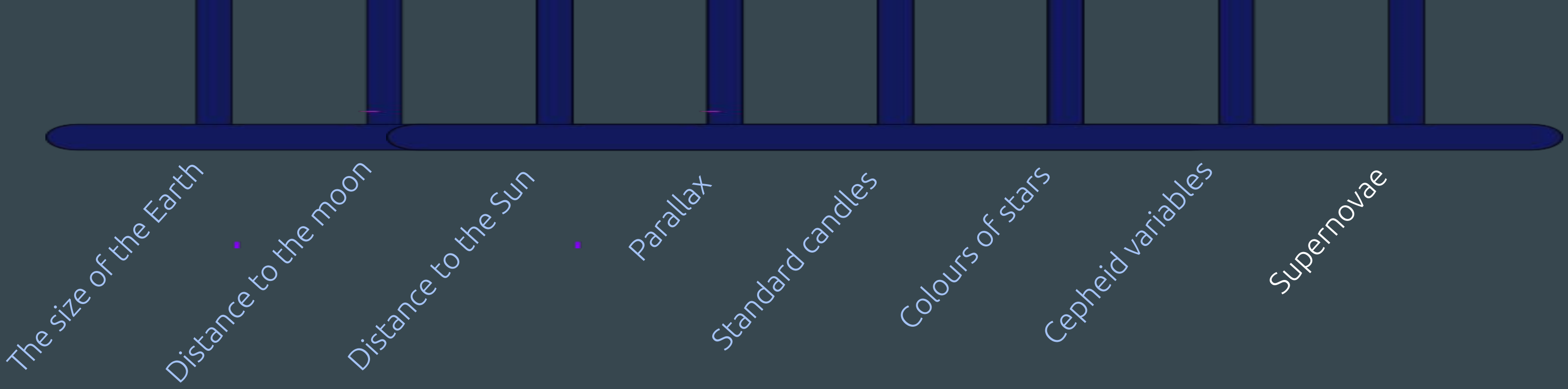
Cepheid variables…

What made Hubble famous

Cepheid Variables

- Very bright stars that pulsate in a predictable way
- We measured their distance with parallax!
- Hubble measured the distance to them
- They found that galaxies further away appeared to be redder than they should be: **redshift**
- **Had discovered that the universe was getting bigger!**





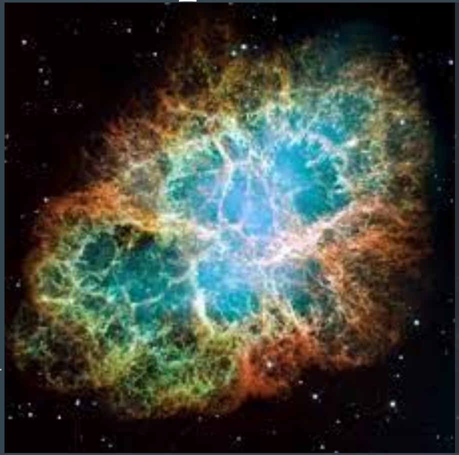
Supernovae…

And Dark Energy

Supernovae

- Supernovae are amongst the brightest objects in the universe
- Special kind of supernova (Type 1a) explode in a unique way
  - “Standard explosion?”
  - Relationship calibrated on galaxies where distances via Cepheids has been measured
- Distant Supernovae are fainter than they should be!
  - Universe is not only expanding, but getting bigger even faster!
- “Dark Energy” - We don’t know what it is

Expected



Observed

¯_(ツ)_/¯

The Future!

- Even larger distances (using quasars etc)
- The Hubble constant is still a source of controversy!
- While we know the universe is accelerating in its expansion, we have no idea why or what causes it!
- **But we know all of this, effectively, because we know the distance between the Earth and the Sun**

Cosmological QUOKKAS

“Single-rung” distance measure (or maybe 1.5 rung)

Low redshift to high redshift (z>5)

Even if our results are noisier (initially), we should be sensitive to changes from the distance-redshift relationship at high-z

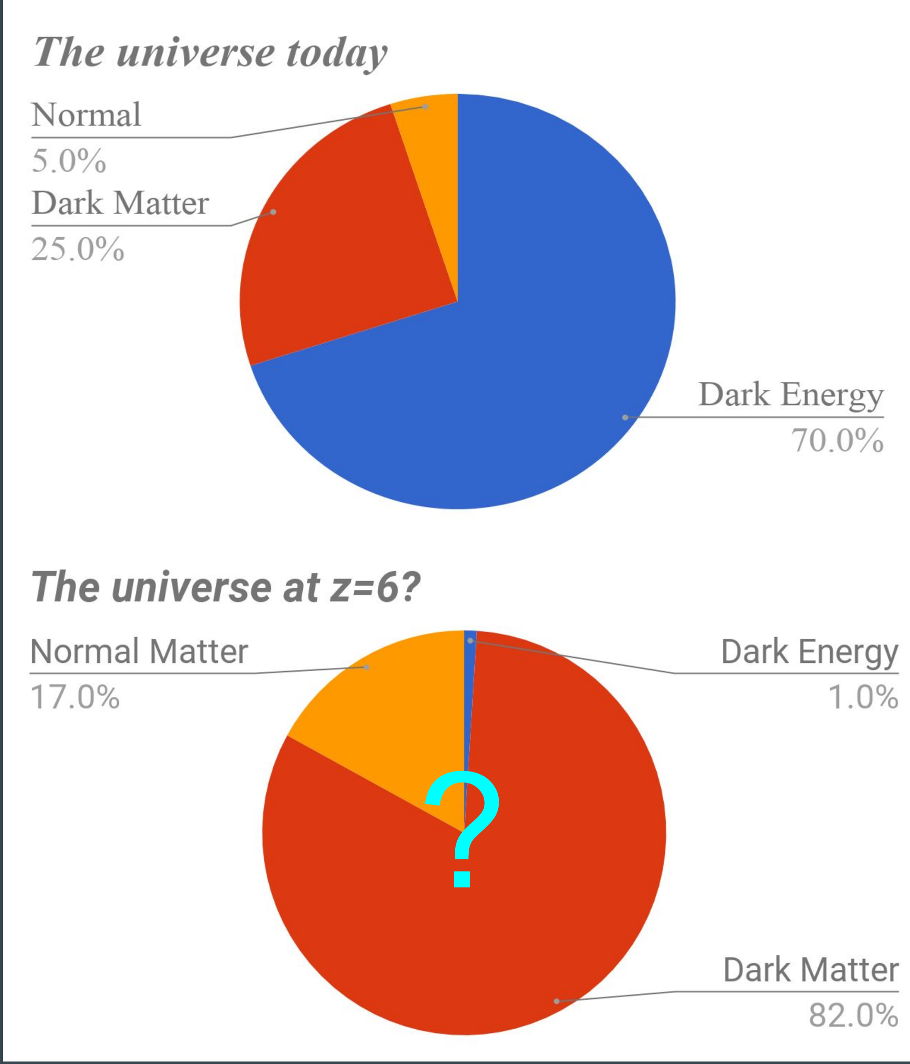
Need cross-checks for Supernovae/BAOs

Method has its systematics, but different kind of systematics to Distance Ladder etc.

Open questions..

- Hubble Constant tension (low-z)
- **We don't know what ~95% of the Universe is**
- What is the nature of Dark Energy?
- Was there **really** so little Dark Energy in the early universe?

Any variations from the concordance cosmology would be expected to be seen at high-z



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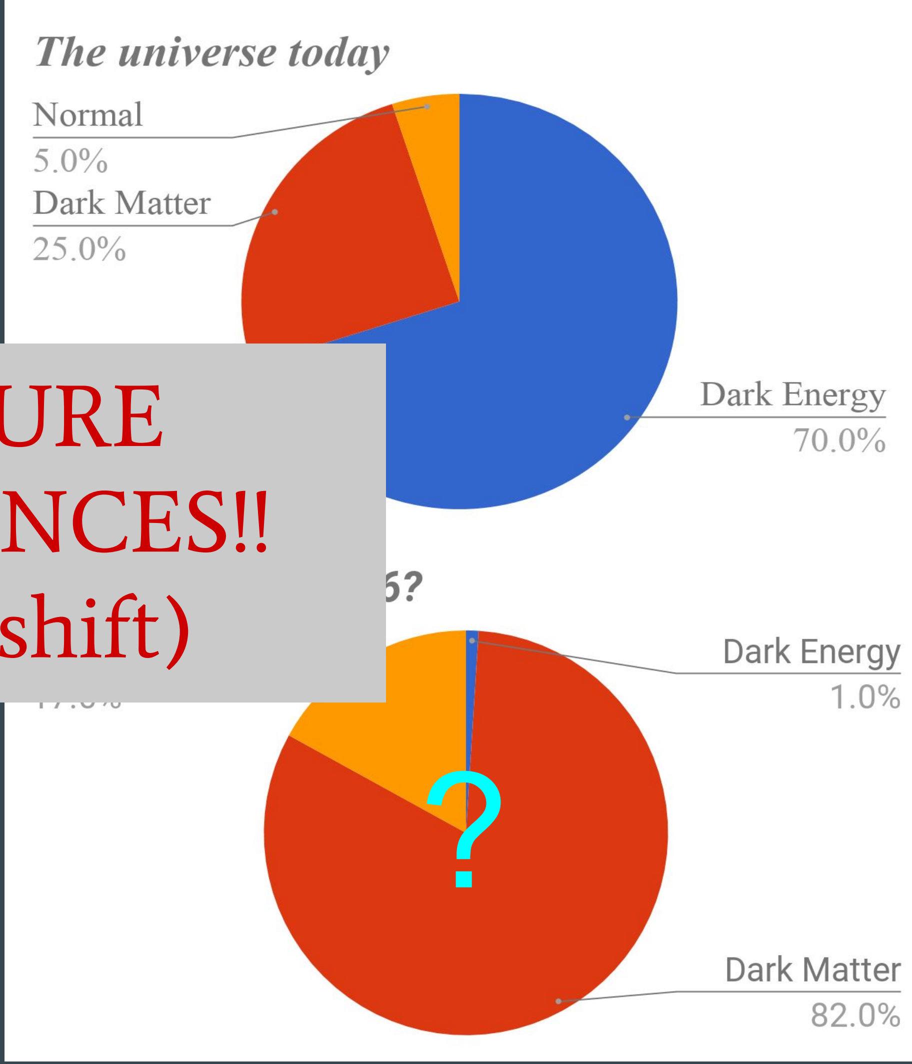
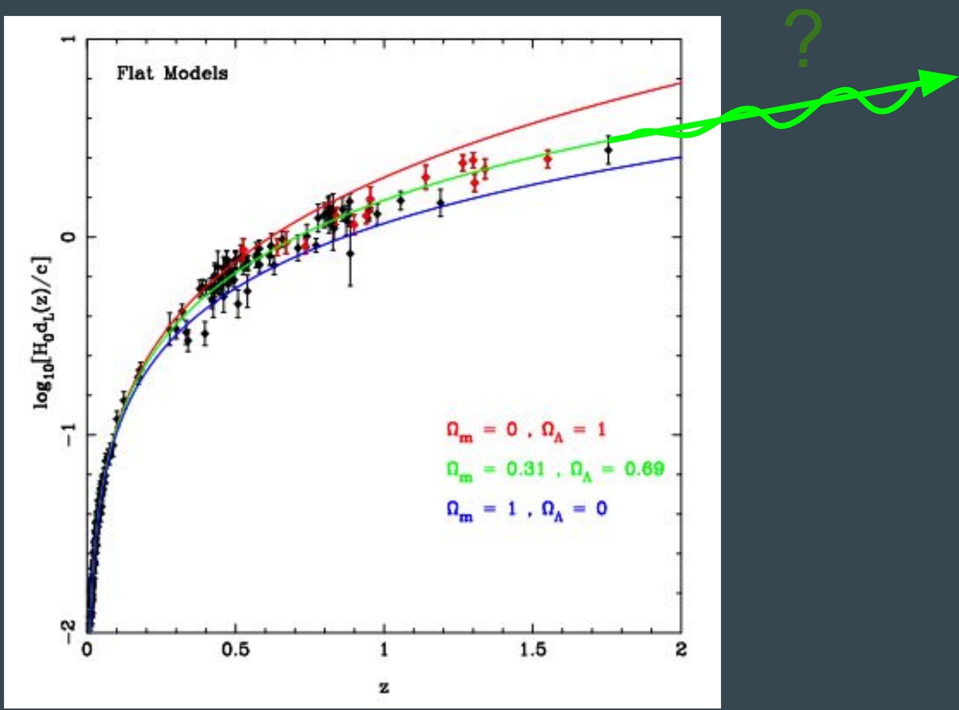
MEASURE DISTANCES!!
(vs redshift)



Any variations from the concordance cosmology would be expected to be seen at high-z

Current cutting-edge

- Type Ia Supernovae (SN Ia)
  - Very bright "standard explosion"
  - Dark Energy discovery (Nobel 2011)
  - Distances up to z~2
- Baryonic Acoustic Oscillations
  - Imprint of early universe physics on large scale galaxy distribution
  - Distances up to z~2.5
- Cosmic Microwave Background
  - Fit cosmological model parameters to the observed CMB power spectrum
  - Model dependent
- **Does the distance-z trend continue as expected past z~2?**

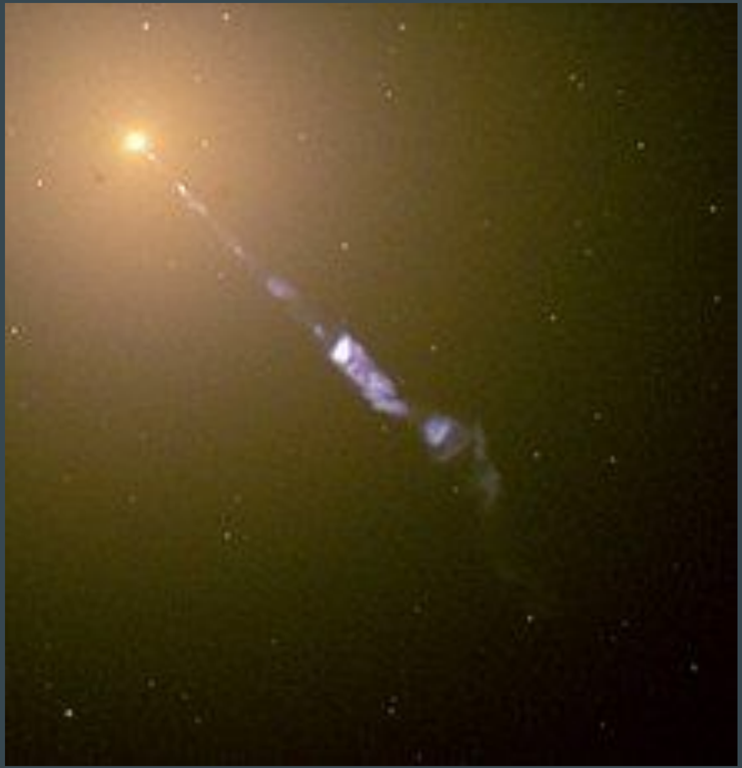


Roy Choudhury & Padmanabhan 2008

Active Galactic Nuclei as standard candles

- AGN are supermassive black-holes (SMBH) at the center of massive galaxies producing jets that move at near the speed of light
- When jet is pointing at us: quasars and blazars
- Most continuously bright objects in the Universe
- Long desired as a standard candle

- **Need better methods**



M87 jet, Image: NASA

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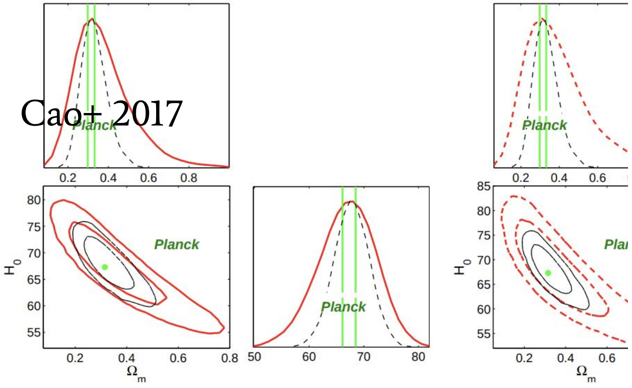
- When jet is pointing at us: quasars and blazars
- Most continuously bright objects in the Universe
- Long desired as a standard candle
    - Reverberation mapping
        - Accurate, but difficult and need BH mass
    - Size scales (Gurvits+ 1995)
        - Complicated, has other dependencies
    - Parsec scale structures
        - Not possible (Wilkinson+ 1998)
- Many have proposed, none succeeded
- **Need better methods**

M87 jet, Image: NASA

Active Galactic Nuclei as standard candles

Cosmological models	Cosmological parameters	Cosmological parameters (sys)
Flat cosmological constant	$\Omega_m = 0.322^{+0.244}_{-0.141}$, $H_0 = 67.6^{+7.8}_{-7.4} km/s/Mpc$	$\Omega_m = 0.312^{+0.295}_{-0.154}$, $H_0 = 67.0^{+11.2}_{-8.6}\ km/s/Mpc$
Constant w	$\Omega_m = 0.309^{+0.215}_{-0.151}$, $w = -0.97^{+0.50}_{-1.73}$	$\Omega_m = 0.295^{+0.213}_{-0.157}$, $w = -1.13^{+0.63}_{-2.12}$
Ricci dark energy	$\Omega_m = 0.229^{+0.184}_{-0.184}$, $\beta = 0.550^{+0.265}_{-0.265}$	$\Omega_m = 0.240^{+0.210}_{-0.210}$, $\beta = 0.520^{+0.365}_{-0.275}$
Dvali-Gabadadze-Porrati	$\Omega_m = 0.285^{+0.255}_{-0.155}$, $H_0 = 66.2^{+7.4}_{-8.2} km/s/Mpc$	$\Omega_m = 0.248^{+0.335}_{-0.130}$, $H_0 = 64.3^{+11.8}_{-7.6} km/s/Mpc$

Cao+ 2017



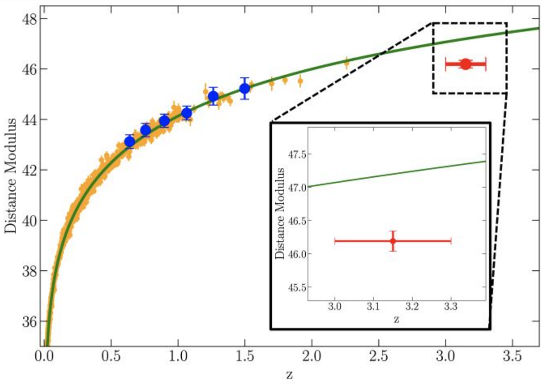
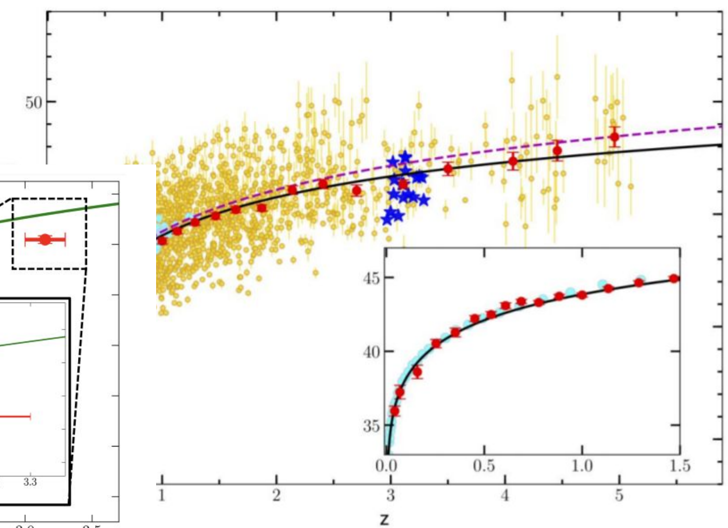


Fig. 4. Hubble Diagram of *Pantheon* supernovae (orange points, Scolnic et al. 2018), quasars at redshifts $z = 0.7$–1.3 (blue points), and quasars at redshifts $z = 3.0$–3.3 (red point). The luminosity distances for quasars are calculated using the parameters γ and β as described in the text, i.e. assuming that these parameters do not change with redshift, and adopting the best-fit flat ΛCDM model for supernovae. Each quasar point represents the average for all the quasars in the corresponding redshift interval.

Fig. 8.— Cosmological constraints on the flat ΛCDM model fron (left panel) and with systematical uncertainties (right panel). Fitt measurements (black dashed lines) and Planck observations (green dot represents the best-fist with 1σ errors denoted by green solid lines) are also added for comparison.



gram of supernovae from the JLA survey[2] (cyan points) and quasars (yellow present the mean (and uncertainties on the mean) of the distance modulus in or quasars only. These averages are shown just for visualization and, as such, the statistical analysis. The new sample of $z>3$ quasars with dedicated XMM- is shown with blue stars. The inset is a zoom of quasar and supernovae on redshift range. The dashed magenta line shows a flat ΛCDM model with the $z<1.4$ data and extrapolated to higher redshifts. The black solid line is the third order expansion of $\log(1+z)$.

Risaliti et. al. 2018, Sacchi+ 2022

Introducing Cosmological QUOKKAS

- Stands for:

- **Cosmological Quasar Observations on the KVN from Korea to Australia (and Spain)**

- Project that aims to measure distances to the active nuclei of quasars and blazars
- How do we do it?
- Use the variability of AGN to our advantage

How are we doing it?

Key assumption:

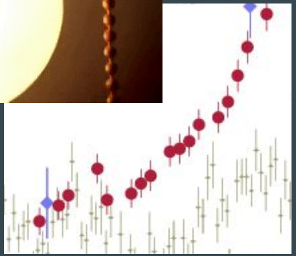
The variability seen in AGN at radio wavelengths is reasonably constrained by the speed of light.

QUOKKA _ A project to measure Dark Energy

"Single-rung" (well, 1.5 rung) method - no need for the distance ladder!

H0, Om in one go

Biggest issue is with Doppler factors (i.e. weird relativistic effects)



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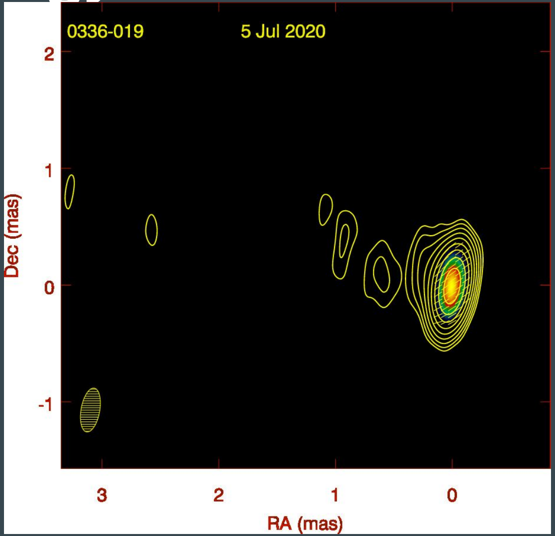
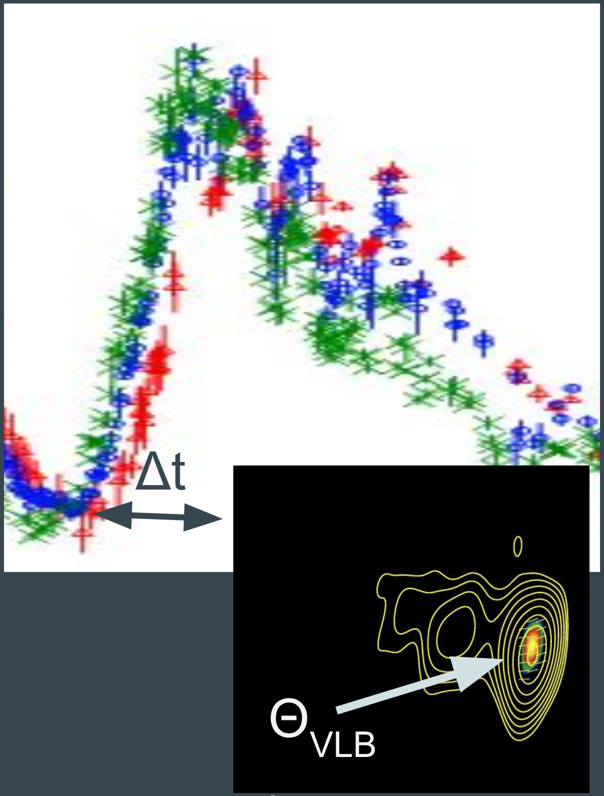


= Distance

$$\text{Distance} = \frac{\text{Time for light to cross the source} \times \text{c}}{\text{Apparent angular size (measured with VLBI)}}$$

How are we doing it?

Causality limited "variability size" $D_{var} \sim c\Delta t$
gives a *linear* size (measured in km)
Compare against the angular size (measured in mas) directly measured by VLBI Θ_{VLBI}



$$D_A = \frac{c\Delta t\delta}{\theta(1+z)}.$$

Distance can be found when the Doppler factor is known!

Looked at decades ago by Wiik+ 2001… but never kept up

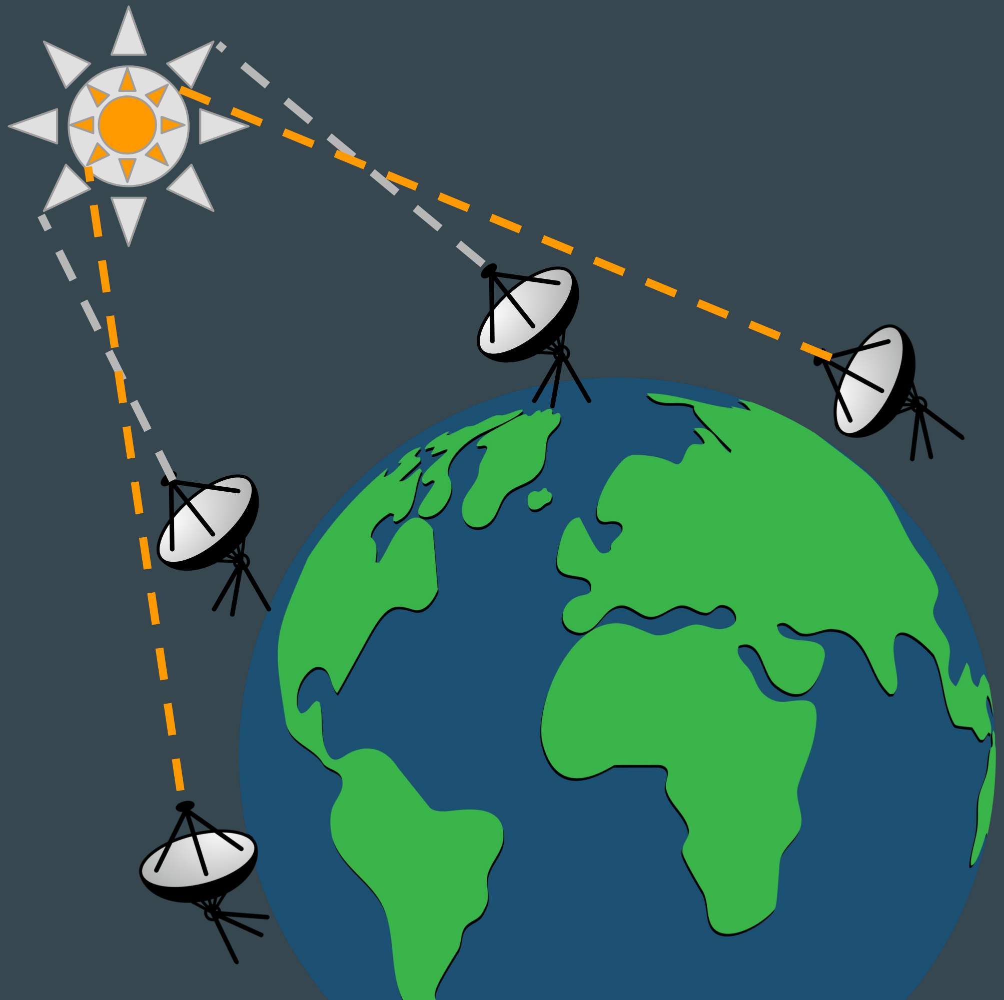
Very Long Baseline Interferometry

In **Astronomical** VLBI, we assume that we know where the stations are **(this becomes important later!!)** and then try to determine where the **radio light** is coming from

The further apart the dishes, more precisely we can determine where on the sky the radio light is coming from

Lots of the 1D slices → Image

(Actually more complicated.. Ignoring phases, but basically the Fourier Transform of the sky image)



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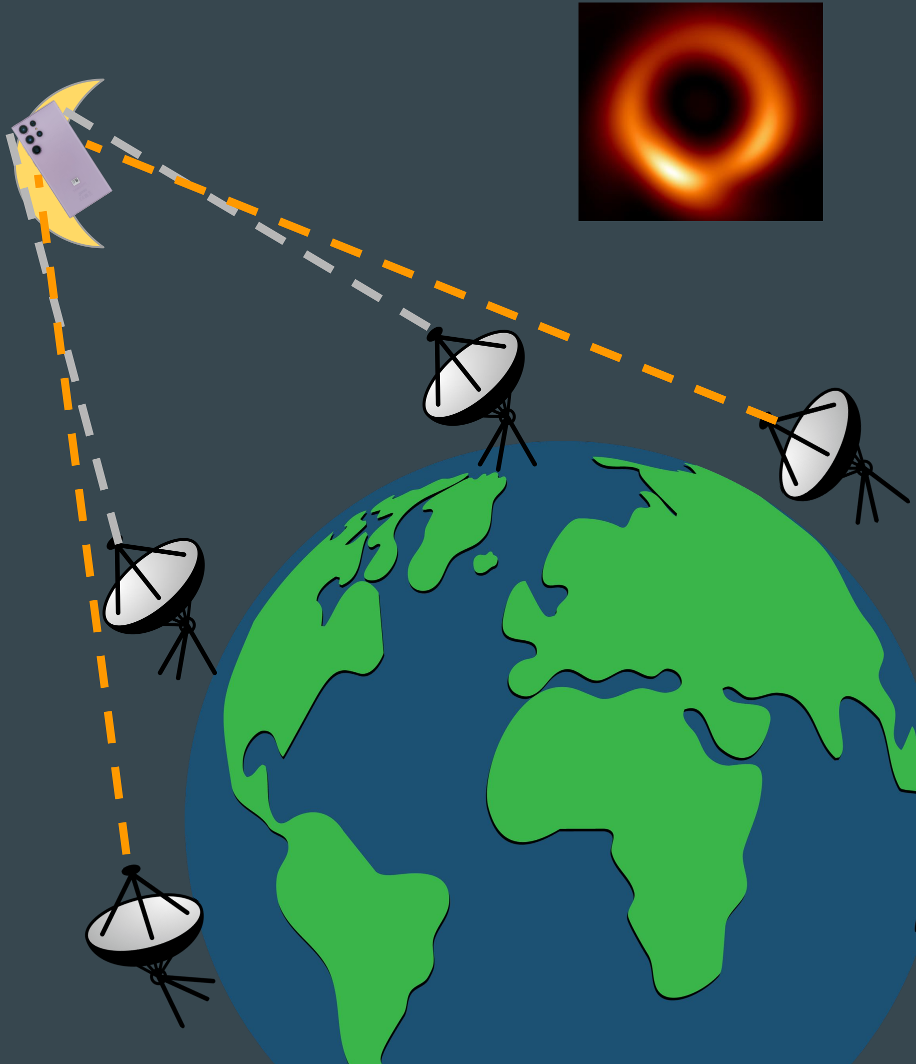
(Actually more complicated.. Ignoring phases, but basically the Fourier Transform of the sky image)

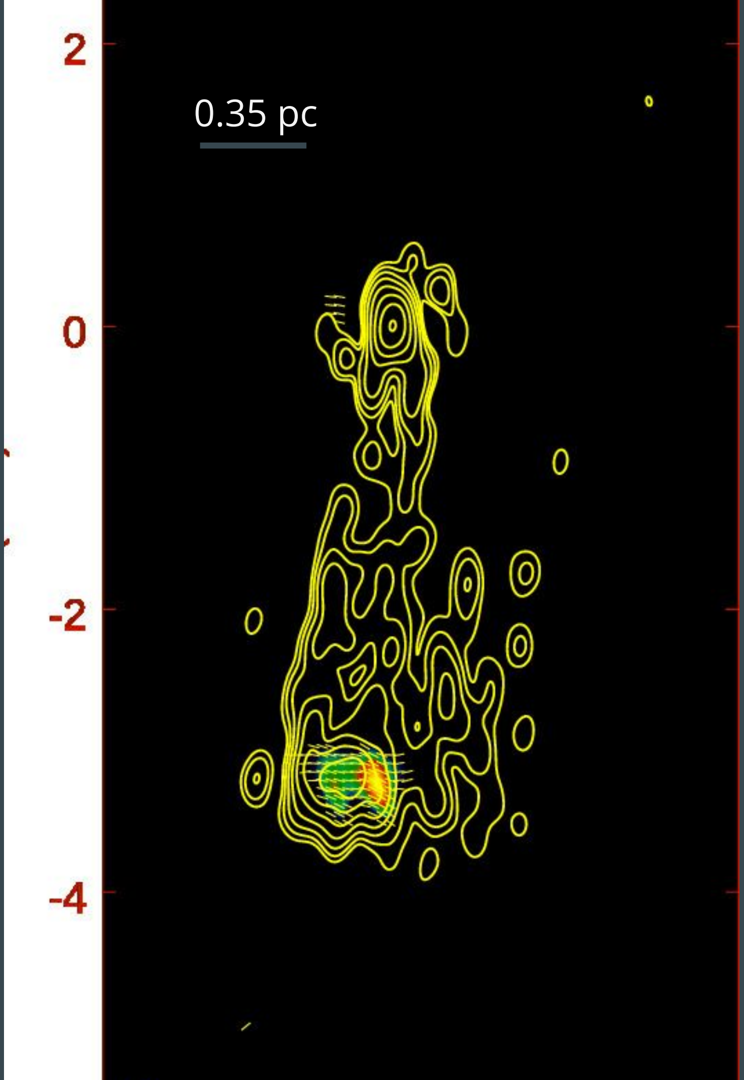
< 50uas - Can resolve a Galaxy on the Moon!

JWST doesn’t even come close

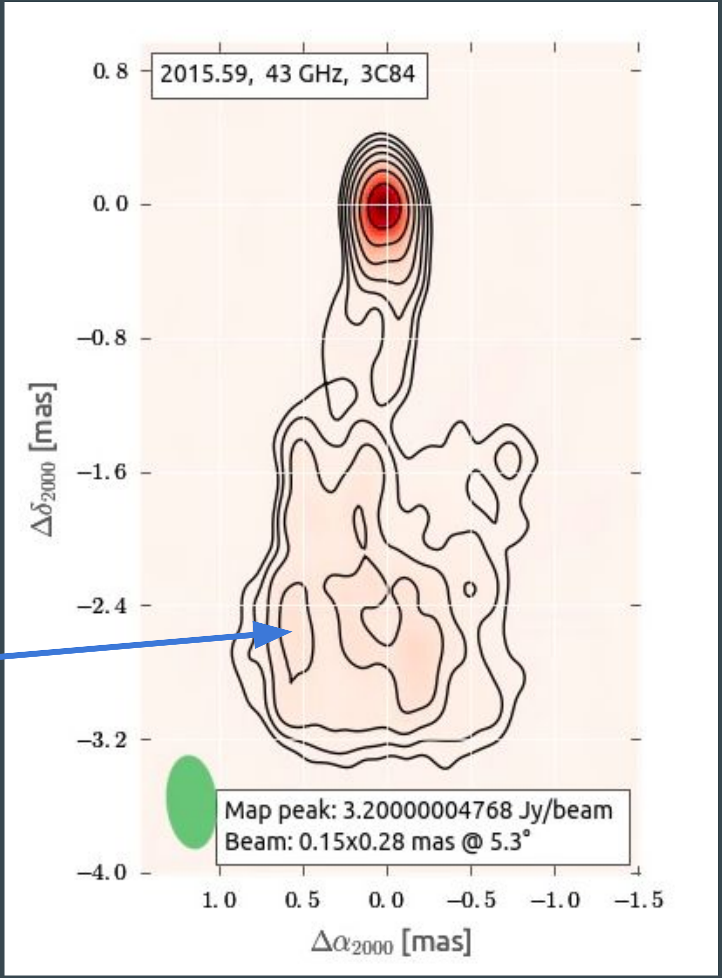


Distance to 3C 84

- Hodgson+ 2020
- z=0.0178
- Often compared with M87
- 3C84: Doppler ~1 is justified
- Big flare with clearly resolved components
- LCDM DL (H0=70,Om=0.3) = 78 Mpc
- SN Ia 64 +/- 6 Mpc (Lennarz et. al. 2012)



A flare in 3C 84



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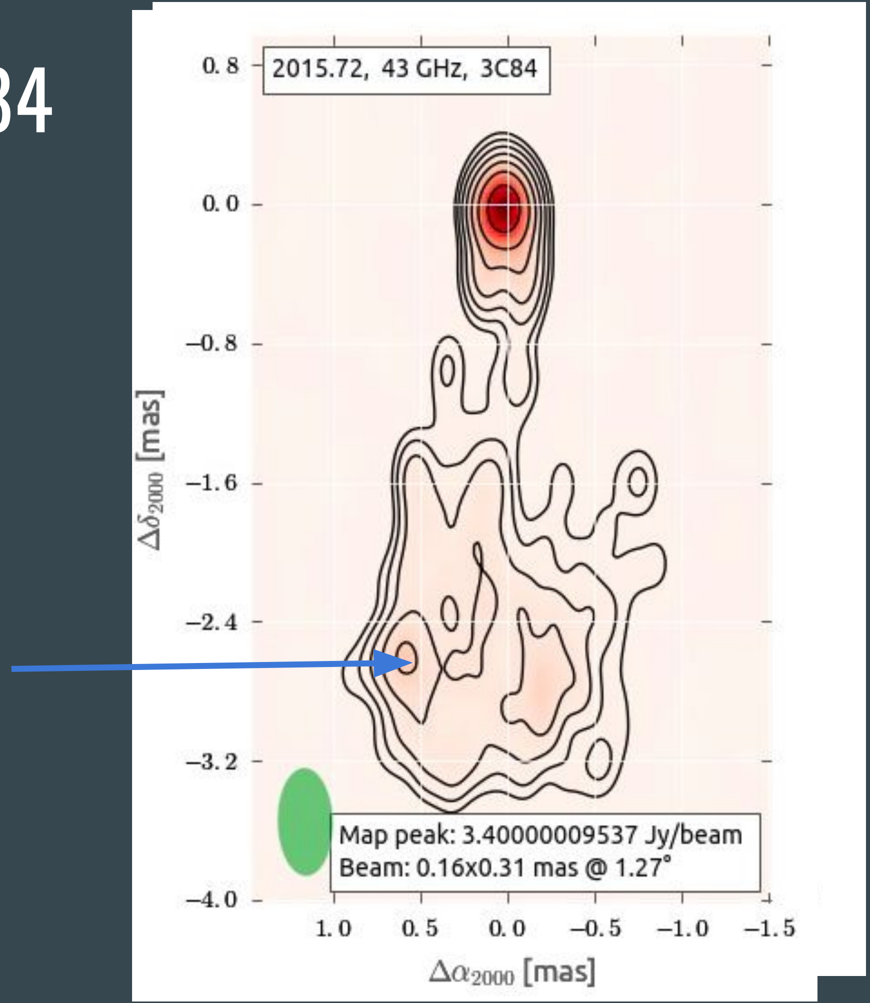

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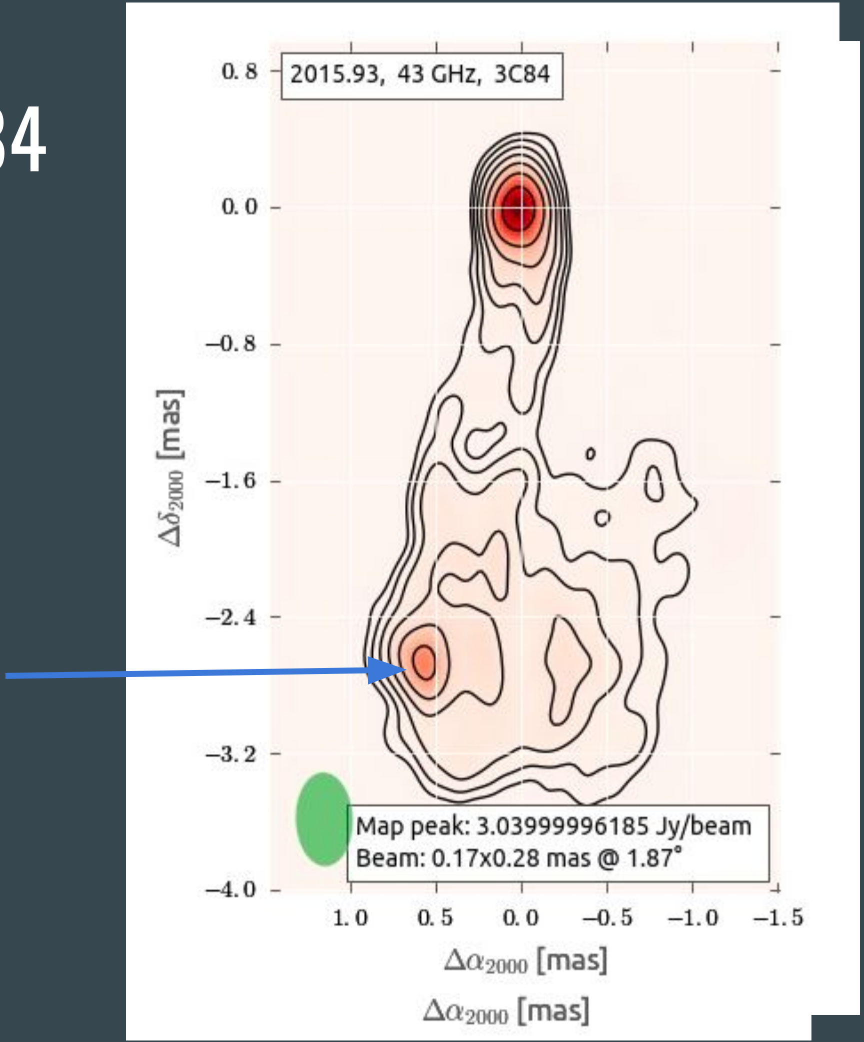

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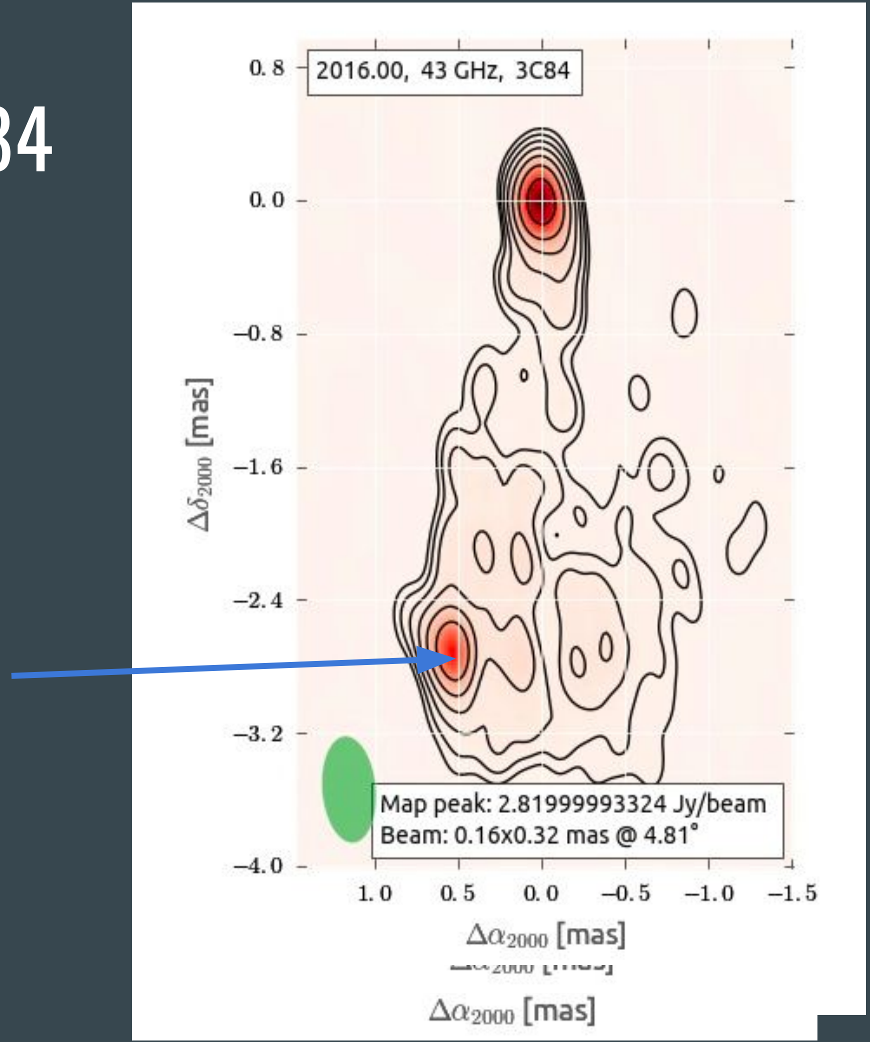

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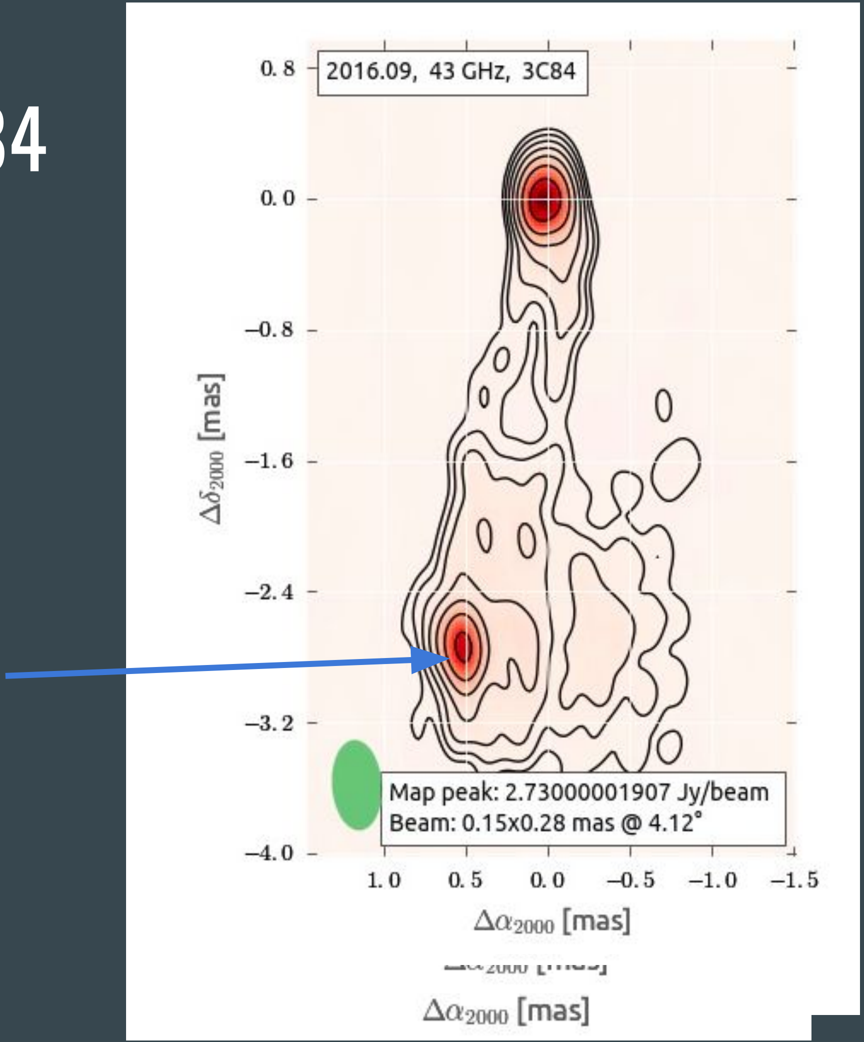

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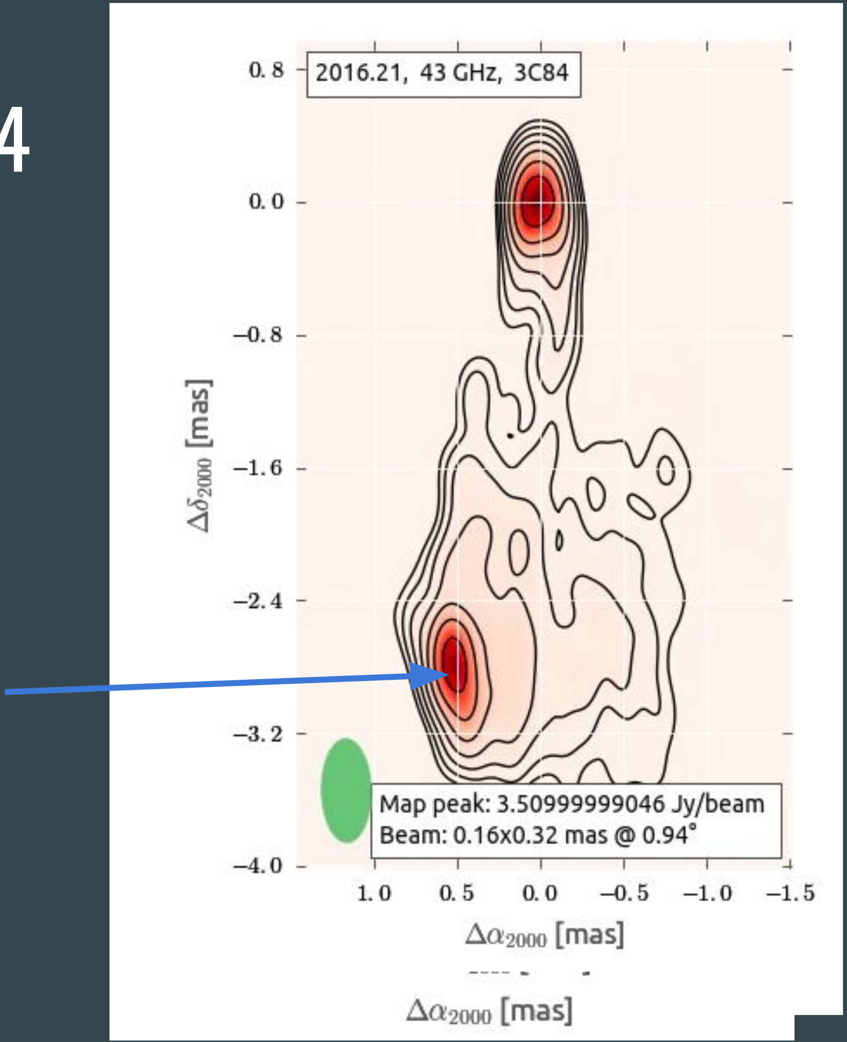

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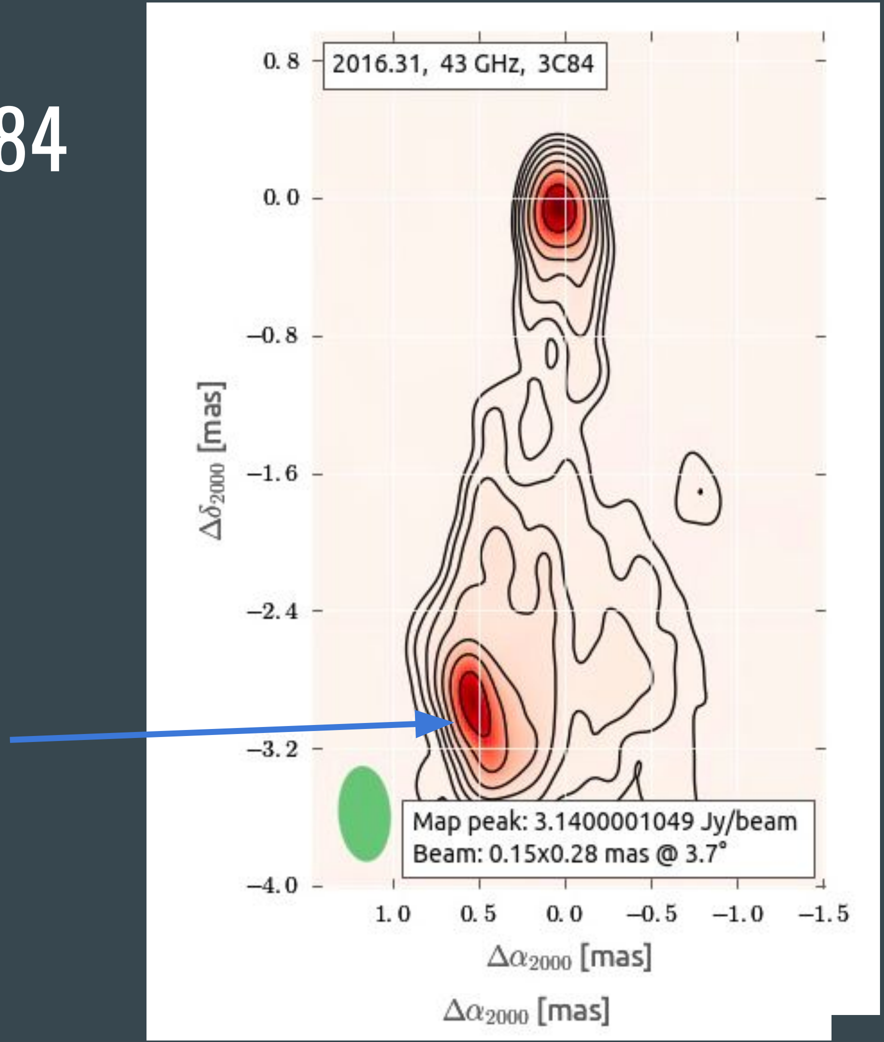

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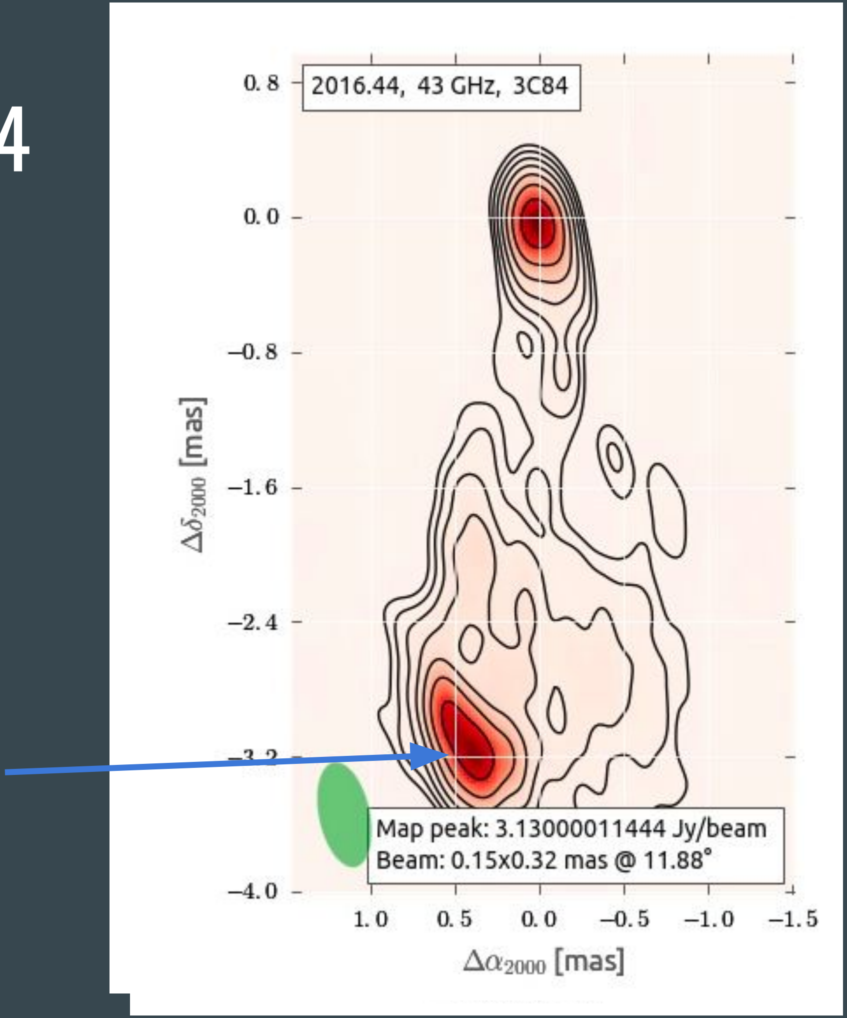

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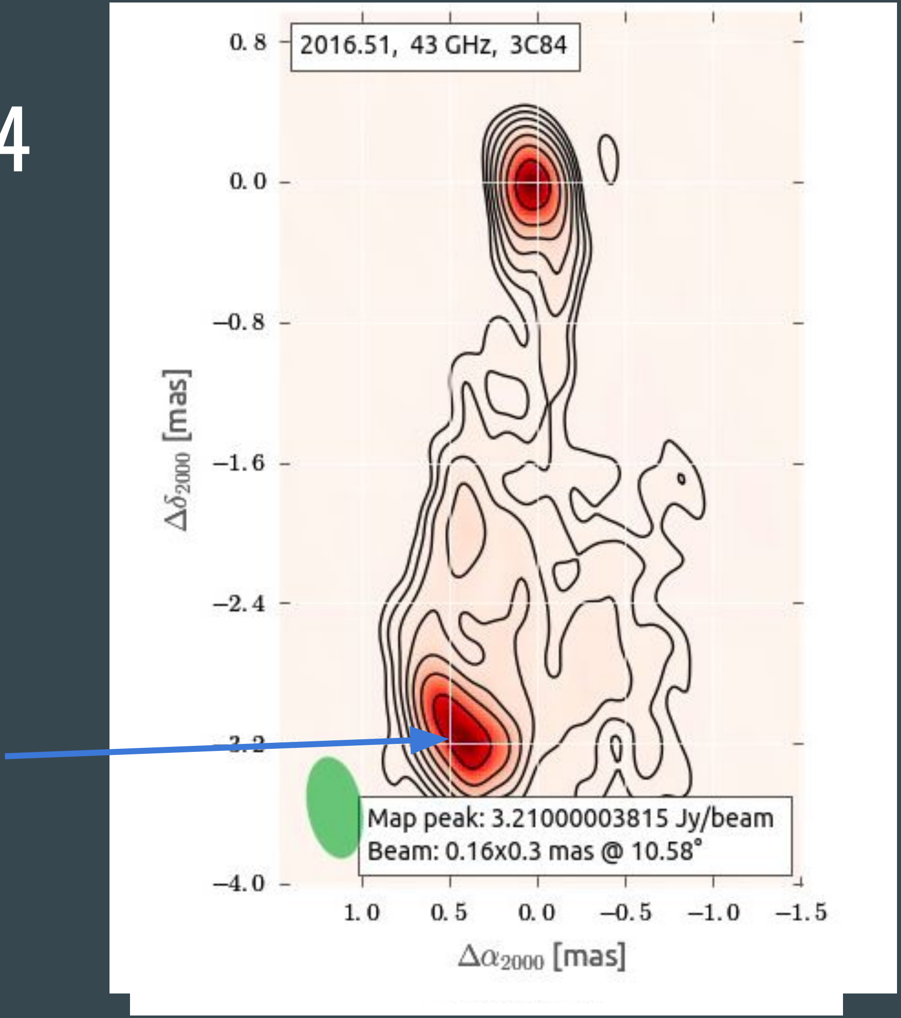

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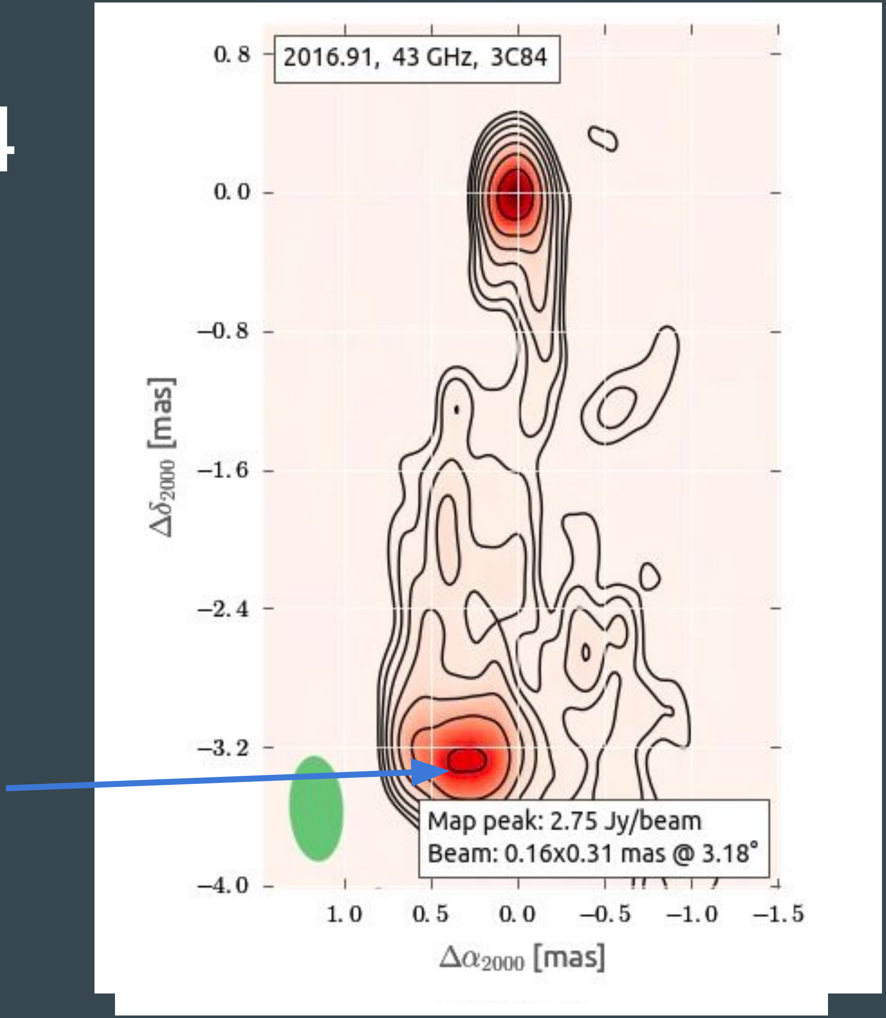

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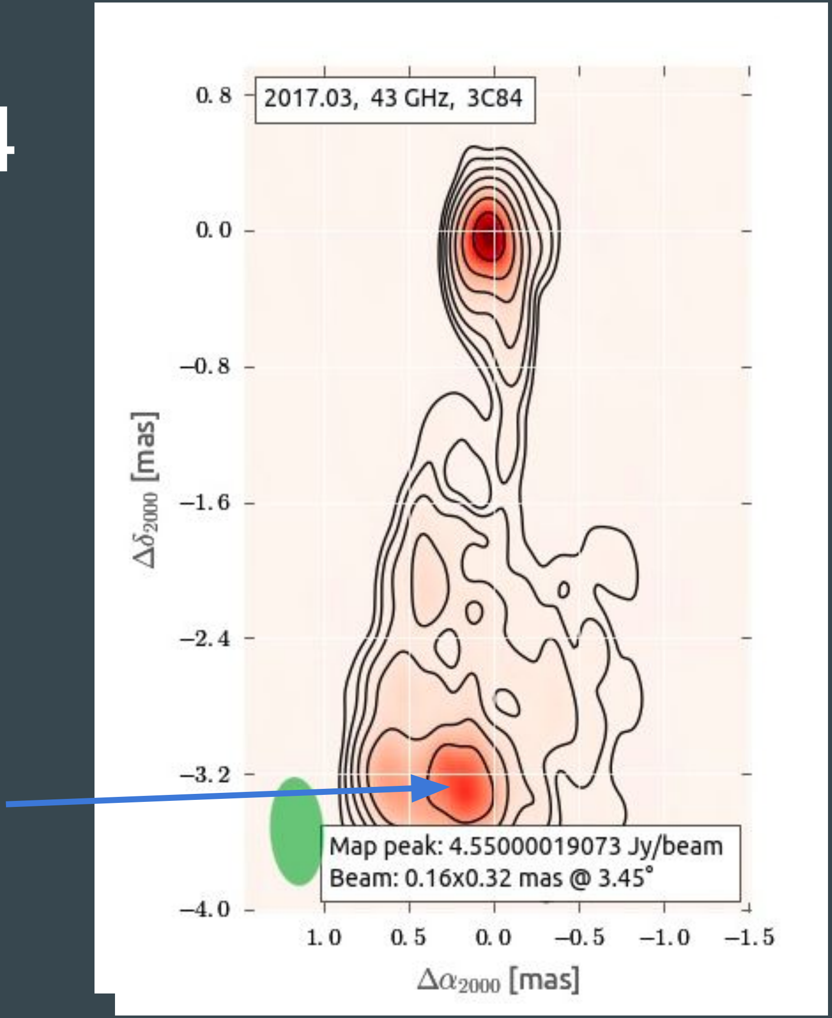
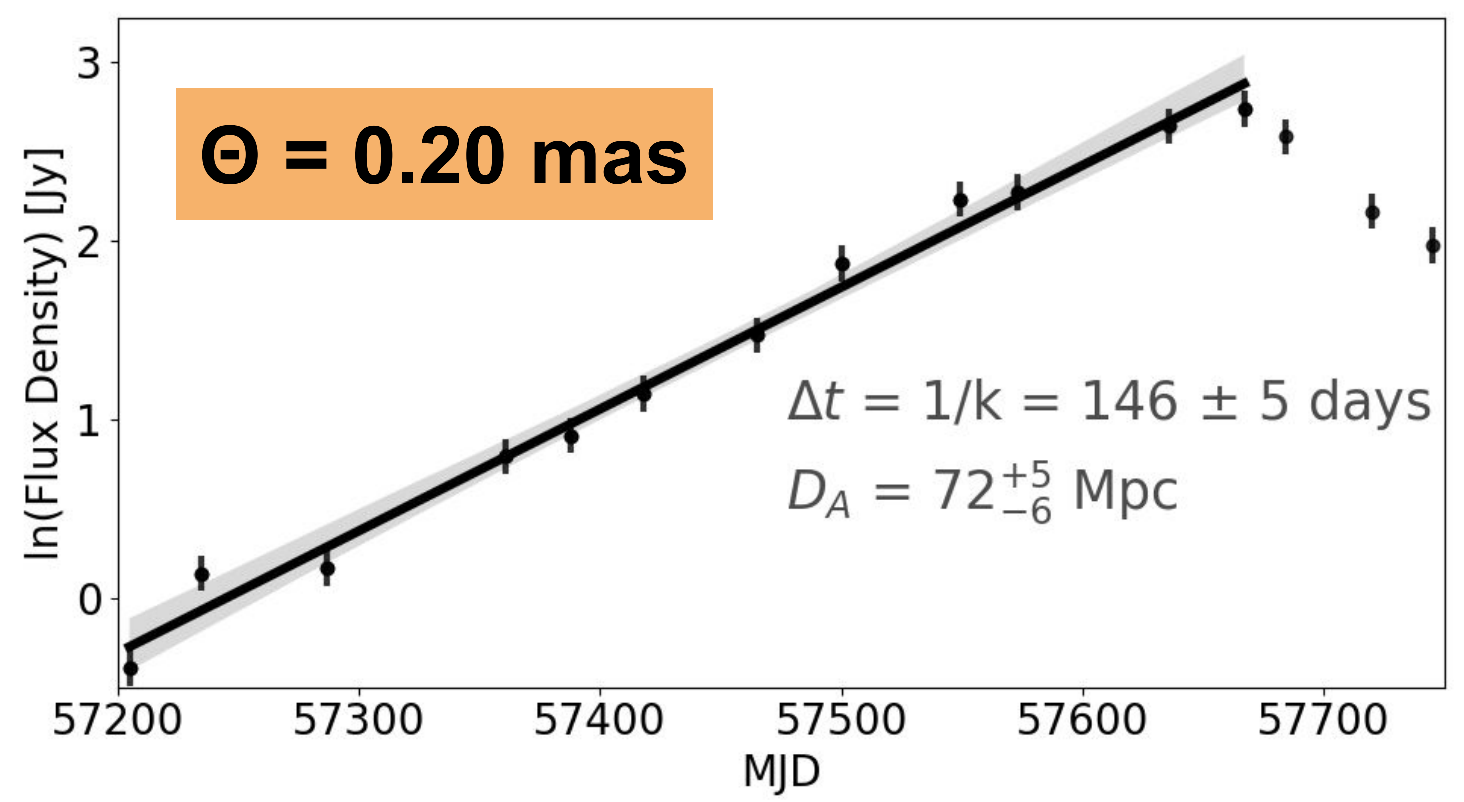
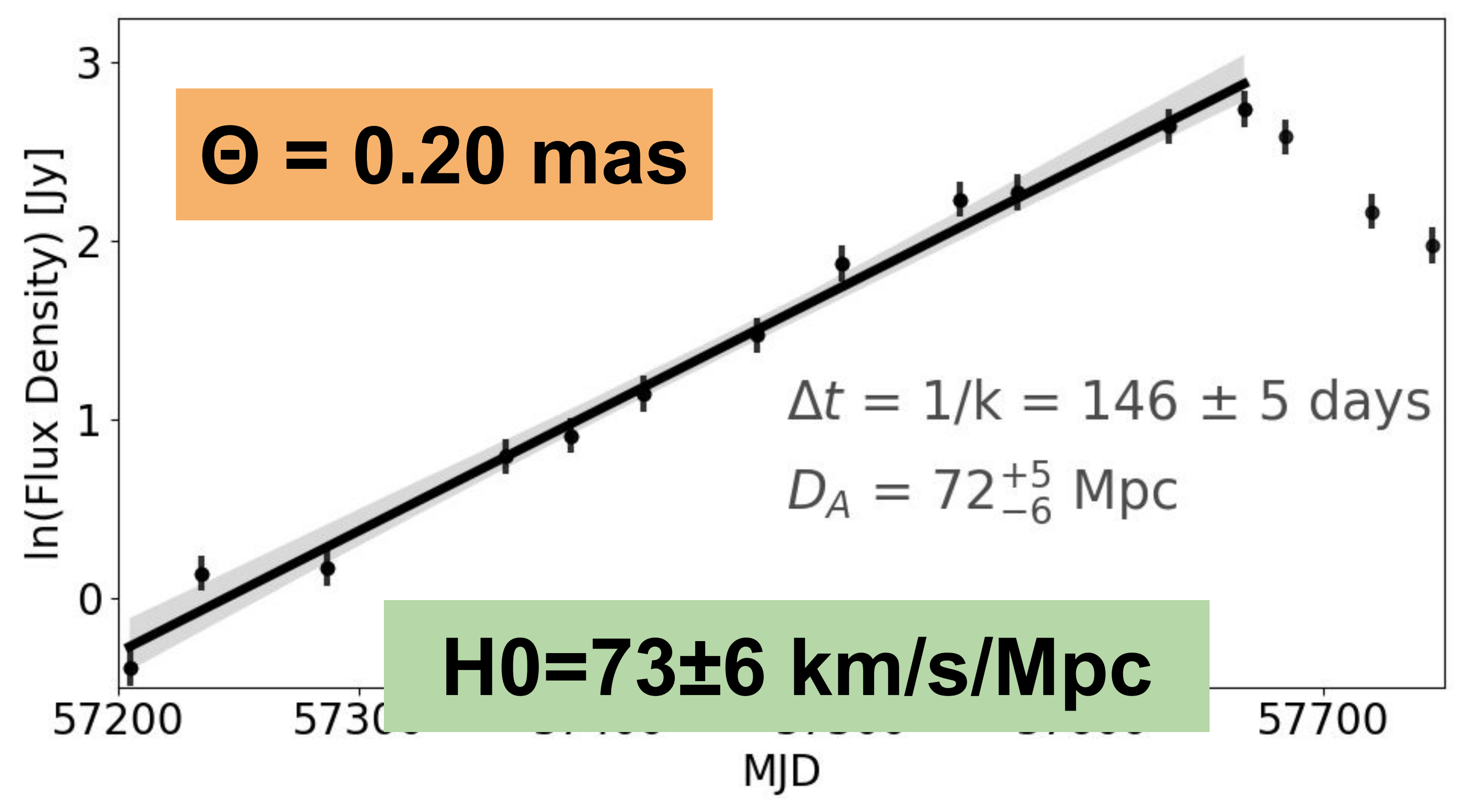


Flare LC



Θ = 0.20 mas
Δt = 1/k = 146 ± 5 days
$D_A = 72^{+5}_{-6}$ Mpc
ln(Flux Density) [Jy]
3
2
1
0
57200
57300
57400
57500
57600
57700
MJD

Flare LC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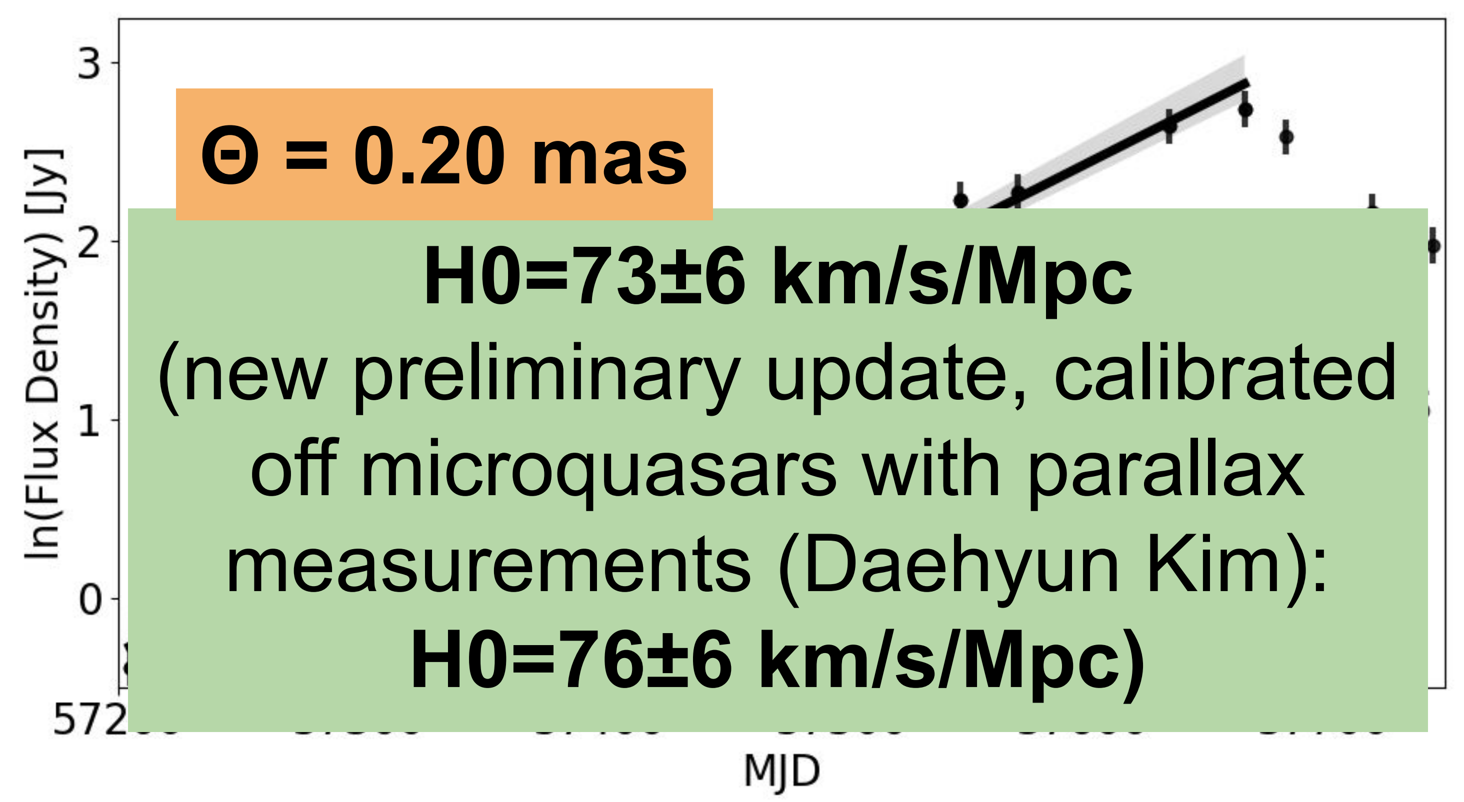
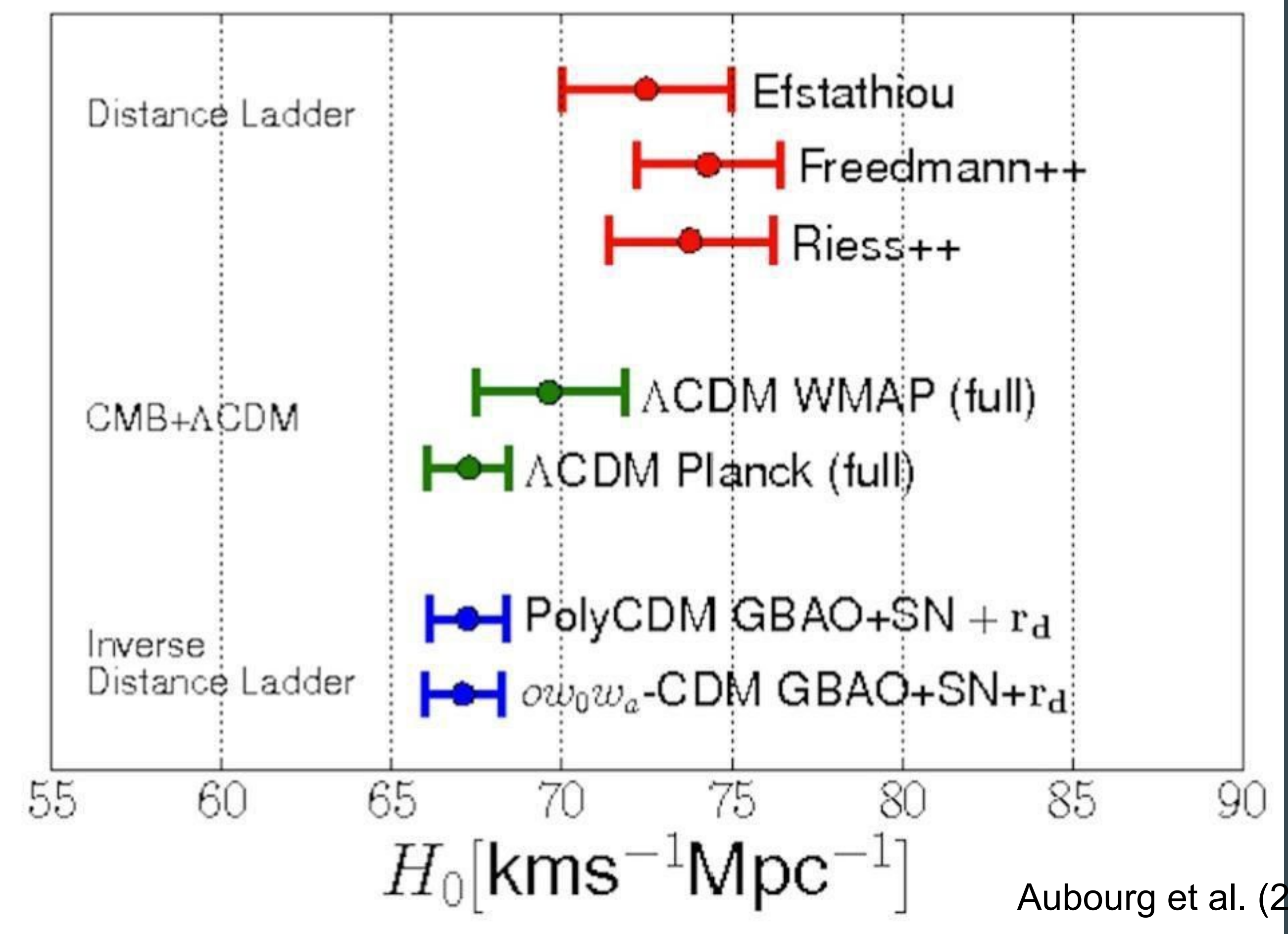
H0=73±6 km/s/Mpc
ln(Flux Density) [Jy]
3
2
1
0
57200
57700
MJD

Flare LC

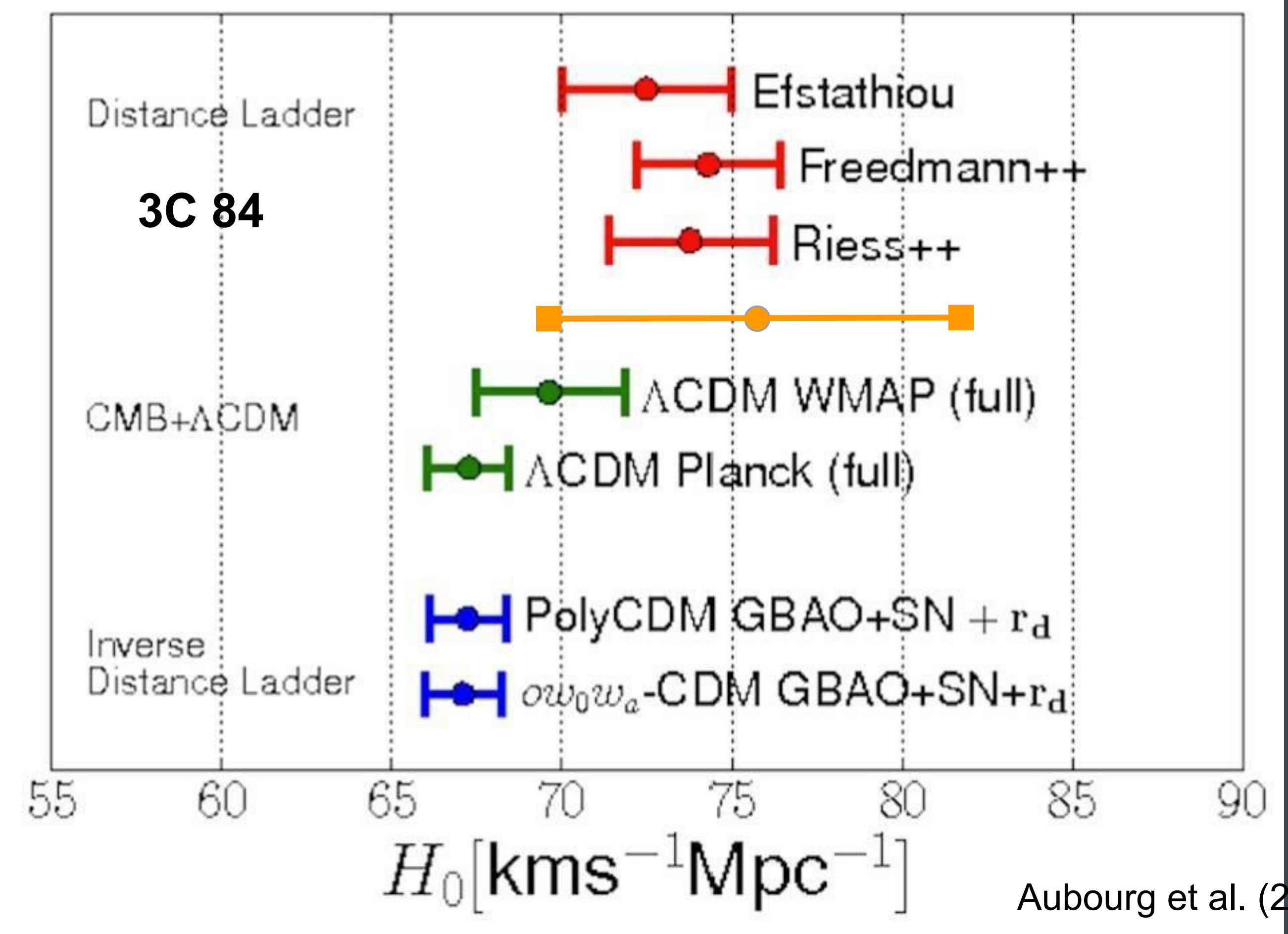


Θ = 0.20 mas

H0=73±6 km/s/Mpc
(new preliminary update, calibrated off microquasars with parallax measurements (Daehyun Kim):
H0=76±6 km/s/Mpc)



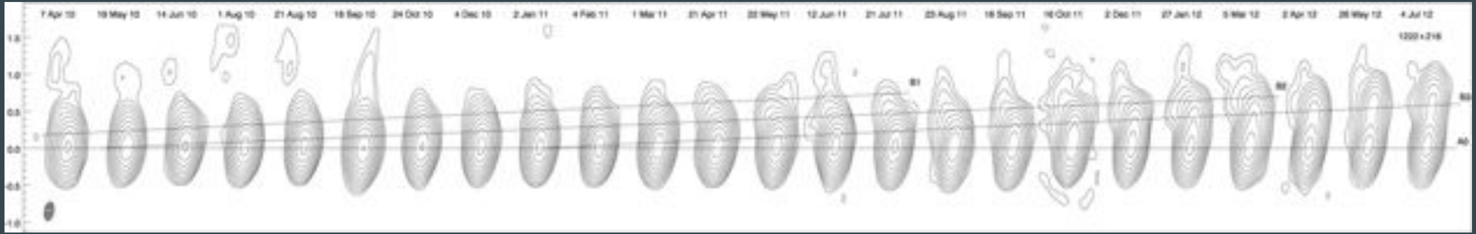
Aubourg et al. (2015)



Aubourg et al. (2015)

Blazars - what we see at high-z

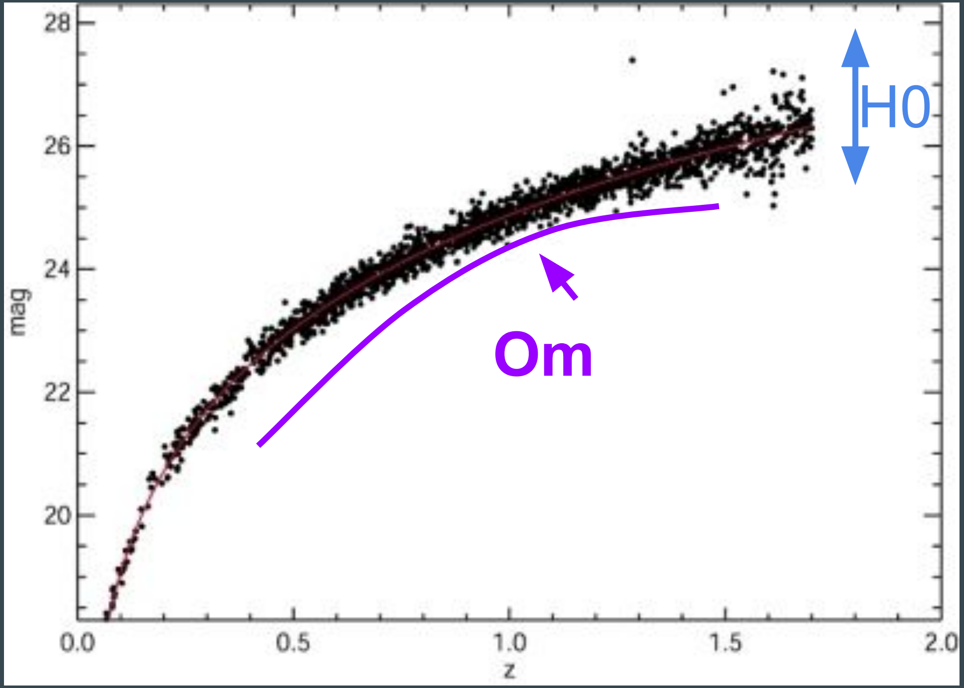
- Blazars often exhibit relativistic effects
  - Superluminal motions, time dilation etc
- Need to get the Doppler factor - a function of the viewing angle to the source and the Lorentz factor
- In blazars, we cannot ignore the Doppler factor, but is notoriously difficult to get
- Need to get the Doppler factor in a non-cosmologically dependent way
- Equipartition Doppler factor, jet-speeds Doppler factor, inverse Compton
- **It's hard to get the Doppler factor… But if we can show that our Doppler factor estimates don't evolve with z, we can measure Om**
- **Or…. find ways to measure the distance that doesn't depend on the Doppler factor**



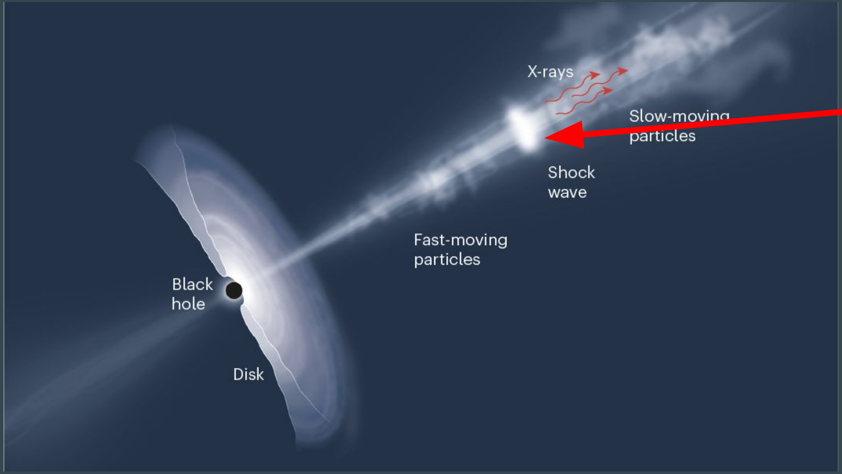
Jorstad+ 2017

Source based or z-dependent systematics

- Two main model parameters we are trying to measure:
  - H0 and Omega_m
- H0 sensitive to *source-based* systematics and z-based systematics
  - C*t_var assumption etc
- Om sensitive to *redshift* dependent systematics
  - Source based systematics will only add scatter



Not supposed to show equations... (Hodgson+ 2023)



Max energy density (brightness temperature) that a source can reach – apparent brightness temperature over this limit is the Doppler factor!

$$D_{\mathrm{A}} = \frac{2 \ln 2 c^3 S \Delta t}{\pi k_{\mathrm{B}} T_{\mathrm{B,int}} \nu^2 \theta^3_{\mathrm{VLBI}}}.$$

3C 84 →

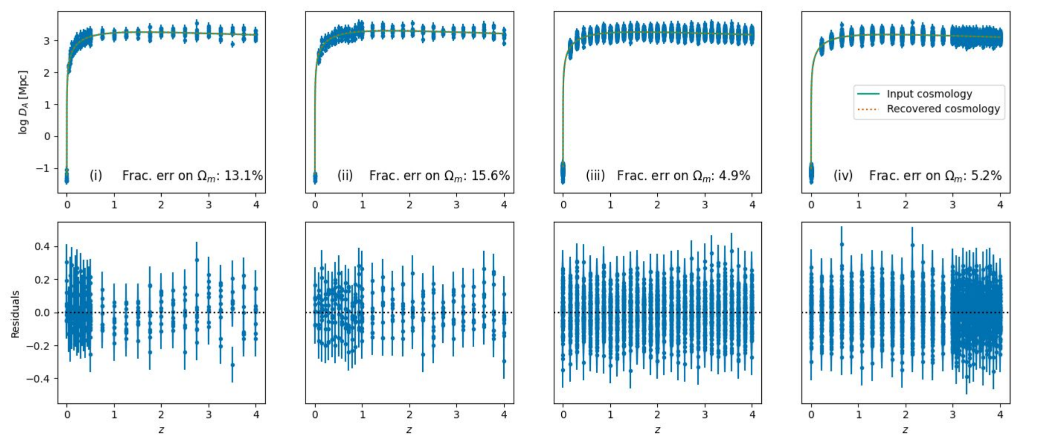
Hubble Constant km s Mpc	Doppler factor -	$T_{\mathrm{B,int}}$ [$\times 10^{11}$ K]
67.40 ± 0.50	$1.07^{0.13}_{0.13}$	$4.06^{1.07}_{1.62}$
73.04 ± 1.04	$0.99^{0.12}_{0.12}$	$4.44^{1.17}_{1.70}$

Can we use these to solve for our systema

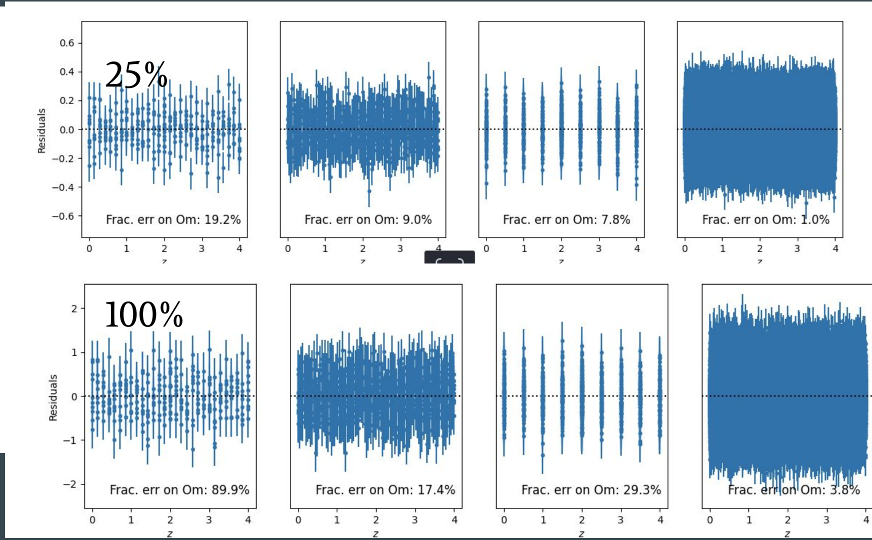
TLDR: we can calibrate relativistic effects with just a number! (Tbint is a sort of maximum energy density)

How well do we need to know TBint? (Hodgson+ 2023)

Does the distribution of sources by redshift affect our measurements? Yes, a bit.
(assuming 25% uncertainty on TBint)



What if we have a 100% uncertainty but a billion dollars?



Can achieve ~4% errors!

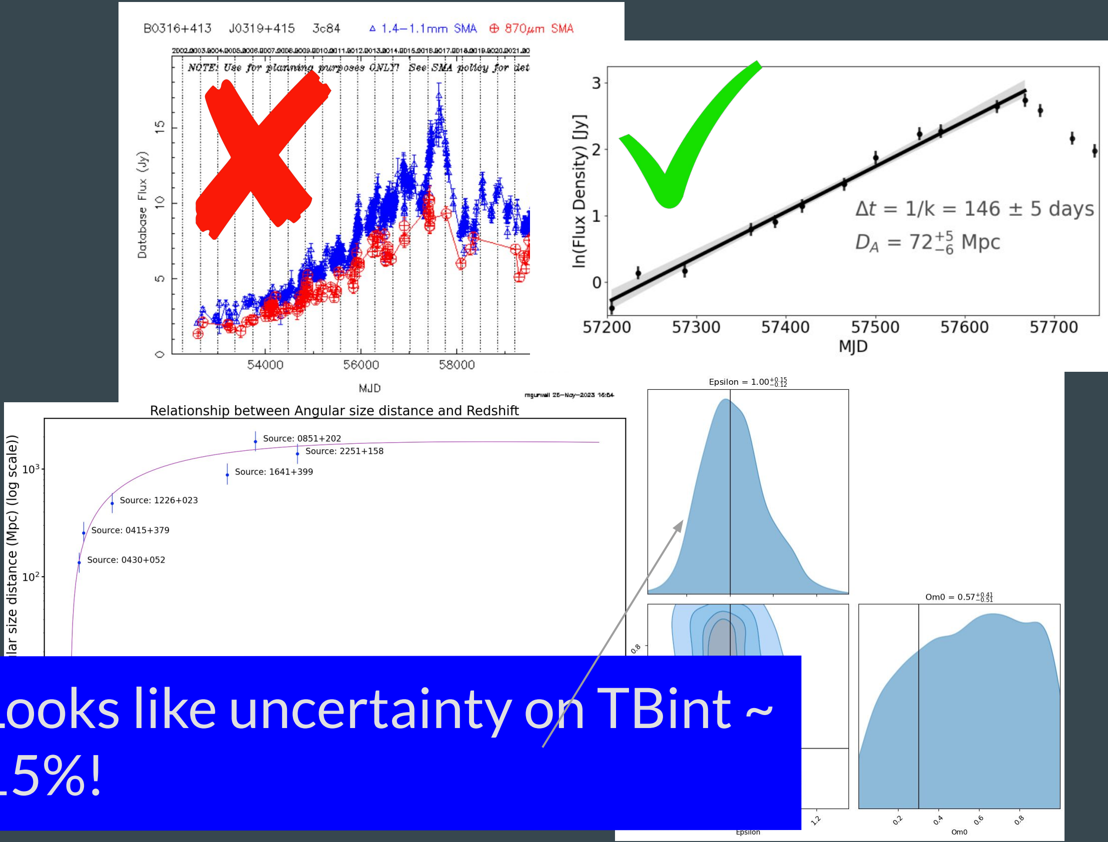
How constrained is TBint? - Lorena

Archival MOJAVE data -> not very good

Seems like apart from resolved and and well-sampled light curves, want “clean” flares that are highly prominent

Fiddling with parameters (relative cadence, relative prominence, relative resolution) → best fit cosmology

So let’s do it properly!

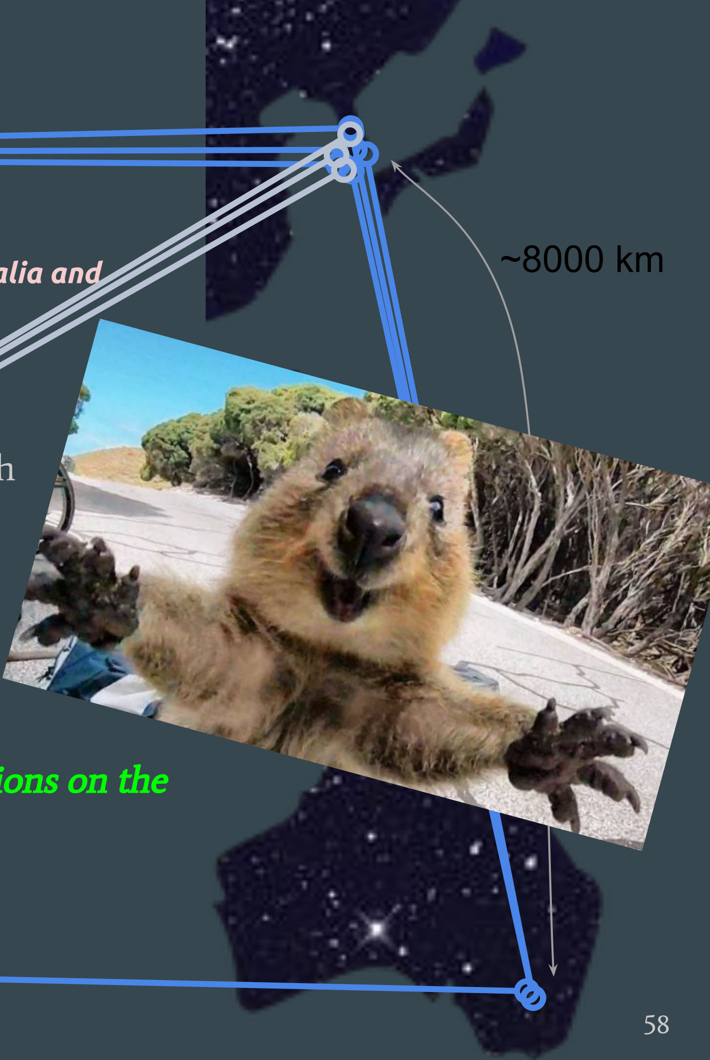


Looks like uncertainty on TBint ~ 15%!

Cosmological QUOKKAS

Quasar observations using the KVN from Korea to Australia and Spain/South Africa

- **We require high cadence and high resolution!**
- **Want to sample the light-curve as well as possible**
- A Quokka is a small marsupial on an island off Perth
- Between KVN and Mopra and South Africa
- ~8000 km baseline
- Initial sample of ~50 sources
- Extremely high resolution (~150 uas at 15 GHz)
- Initially 22 GHz only, 43/86 GHz possible too...
- ***But could we do actually get the "billion $ observations on the cheap?!***



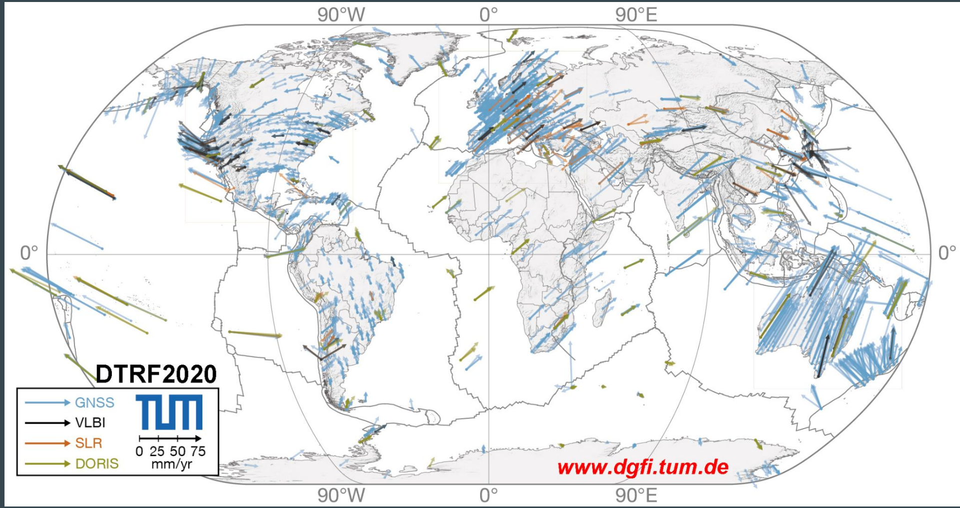
Geodetic VLBI

The most important science you've never heard of

In astronomical VLBI, we assume we know where the stations are and try to work out where on the sky the emission is coming from

Geodetic VLBI flips it: assume quasars are stationary and measure the locations of the stations

BUT we observe many of the same things! blazars



Win-win combined observations

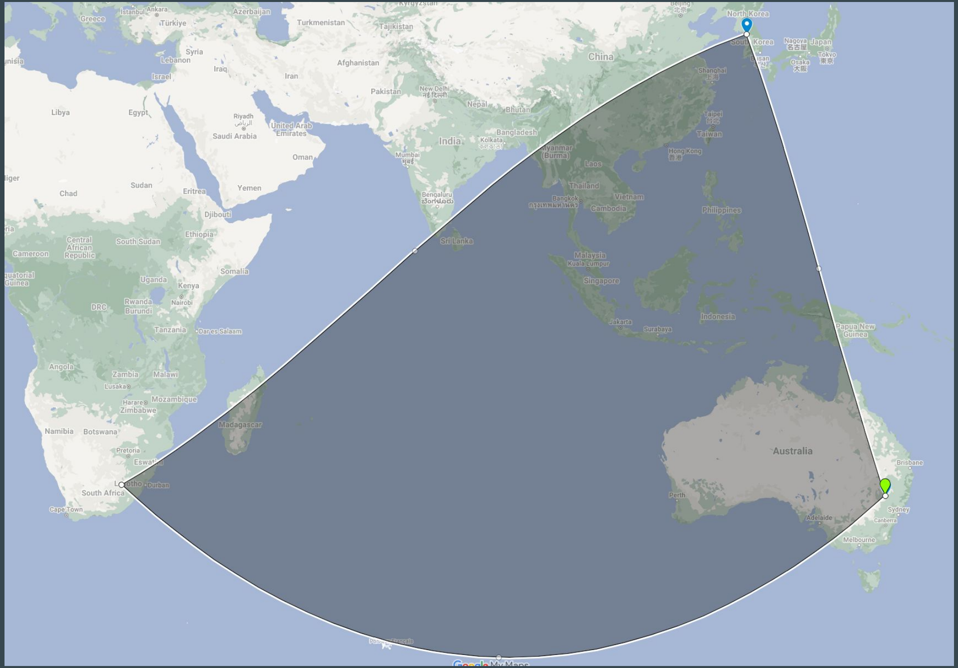
Geodesists want to observe quasars regularly - as do I

By combining, we both get much more observing time and more telescopes

QUOKKArray + Tasmania + Thailand + Spain + USA (USNO)

(Romania would be a great addition for the North)

This will be an amazing dataset! → publicly available !



Combined observations? Proposal accepted

Bi-weekly 24 h session
KVN+Mopra+Hobart+Hart, Yebes, VLBA

Every other week KVN-Mopra-Hart of the ~50 QUOKKAS sources

Much work on automating Mopra (very very hacky...)

7th observation ongoing (literally right now!)

	Total Duration	# Sources	RA range	Dec Range	Antennas	Project
	5 hours	18 Quokkas sources+ 20 K-CRF calibrators	$17h$ to $23h$	$+20^\circ$ to -40°	KVN+Sejong+Hart +Hobart+Mopra	Quokkas Geo-Intensive
	24 hours	18 Quokkas sources+ 150 K-CRF sources	$0h$ to $24h$	$+40^\circ$ to -40°	KVN+Sejong+Hart+ Hobart+Mopra+**Yebes**	Quokkas K-CRF
	24 hours	18 Quokkas sources+ 150 K-CRF sources	$0h$ to $24h$	$+20^\circ$ to -40°	KVN+Sejong+Hart+ Hobart+Mopra	Quokkas K-CRF
	24 hours	18 Quokkas sources+ 150 K-CRF sources	$0h$ to $24h$	$+20^\circ$ to -80°	KVN+Sejong+Hart +Hobart+Mopra	Quokkas K-CRF

Conclusions

- Demonstrated a new method for measuring distances to AGN
- Starting the Cosmological QUOKKA project to do this “properly” and hopefully sort out the systematics
- We can use a single method from low-z to z>6.
- Potentially thousands of sources
- New H0 measure (with caveats): ~76
- Can continuously monitor sources -> averaging down our statistical errors.
- We believe that with a properly designed experiment, we can be competitive or better than other methods
- Observations **now** happening in collaboration with geodetic VLBI
- Data will be made publicly available
- Mountains of data: feel free to get involved!