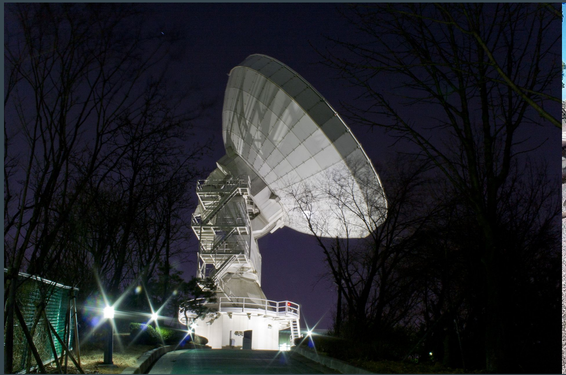

Cosmological QUOKKAS

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NRF National Research Foundation of Korea

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SEJONG UNIVERSITY

Introduction

- A brief history (inspired by a talk I saw many years ago by Terence Tao)
- Introduce the CosQUOKKA(S) project
  - Cosmological Quasar Observations on the KVN from Korea to Australia (and Spain)
- Describe our methods
- Preliminary results
- Introduce the QUOKKA array...

Measuring distances

•••

Sounds boring, but actually very interesting

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

Redshift

•••

“The more redshifted something is, the further away it is”

Redshift

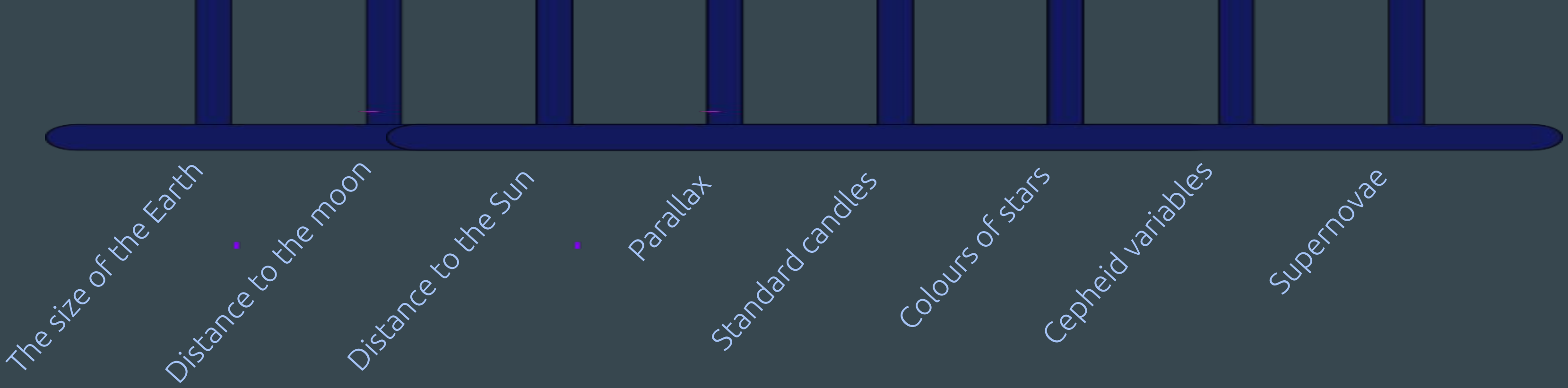
•••

“The more redshifted something is, the further away it is”
This is sort-of true. Only true if you assume there is a relationship between redshift and distance.

Redshift

•••

“The more redshifted something is, the further away it is”
This is sort-of true. Only true if you assume there is a relationship between redshift and distance.
How did we get here?



The size of the Earth

Distance to the moon

Distance to the Sun

Parallax

Standard candles

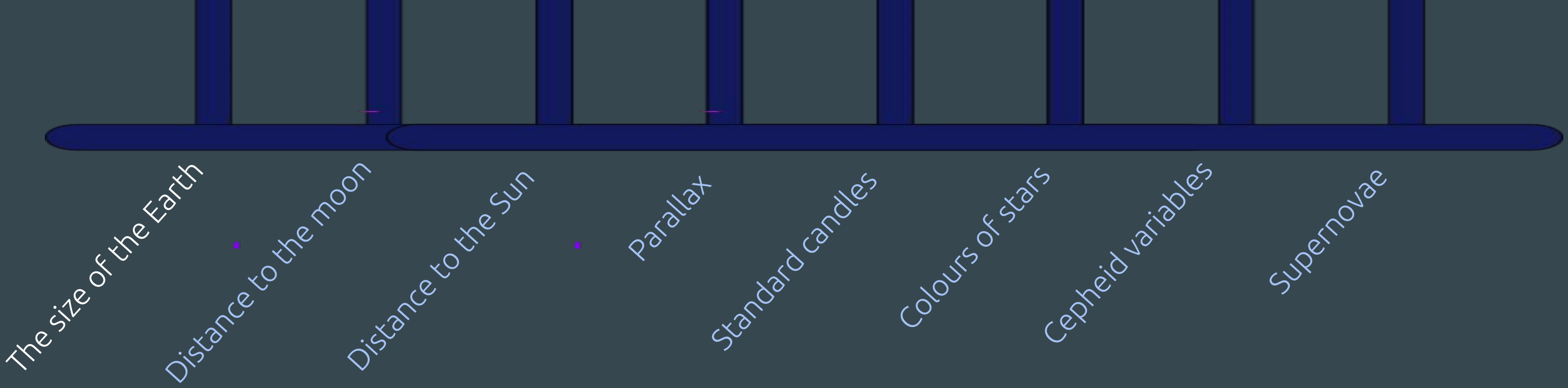
Colours of stars

Cepheid variables

Supernovae

The ladder…

Each rung of the ladder builds on the previous rung



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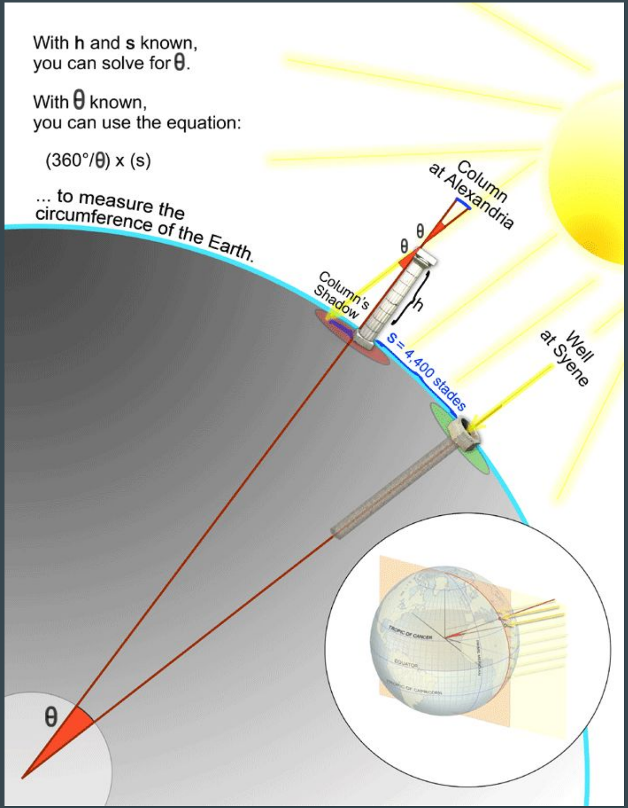
- Colours of stars
- Cepheid variables
- Supernovae

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!

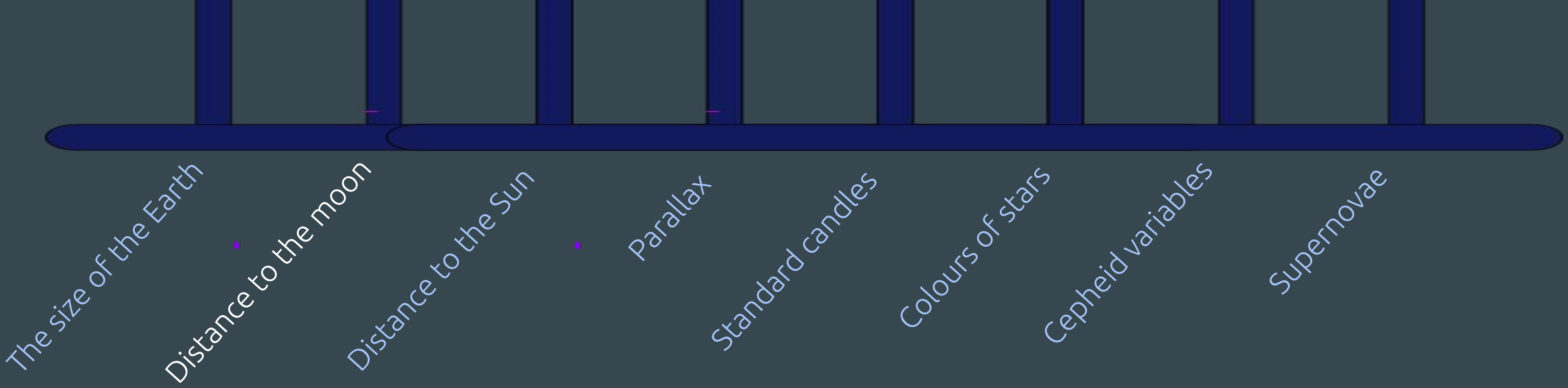


With h and s known, you can solve for θ.

With θ known, you can use the equation:

(360°/θ) x (s)

... to measure the circumference of the Earth.



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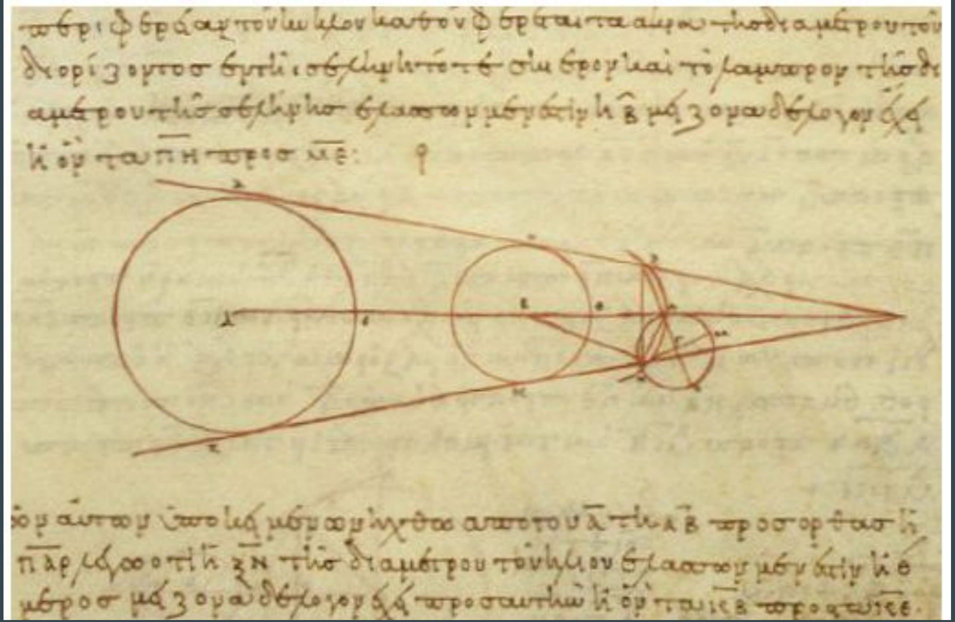
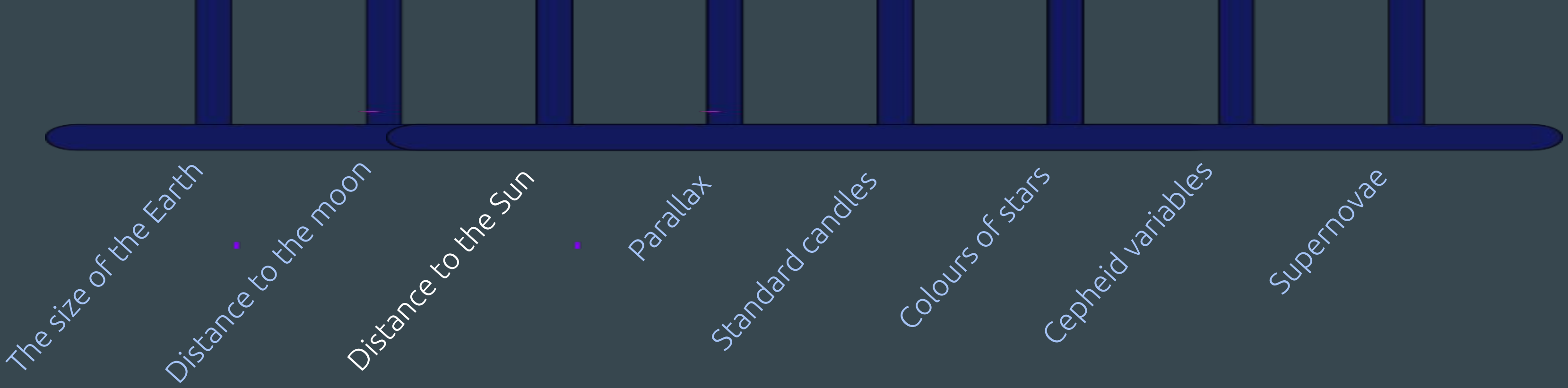
Distance to the Moon

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!





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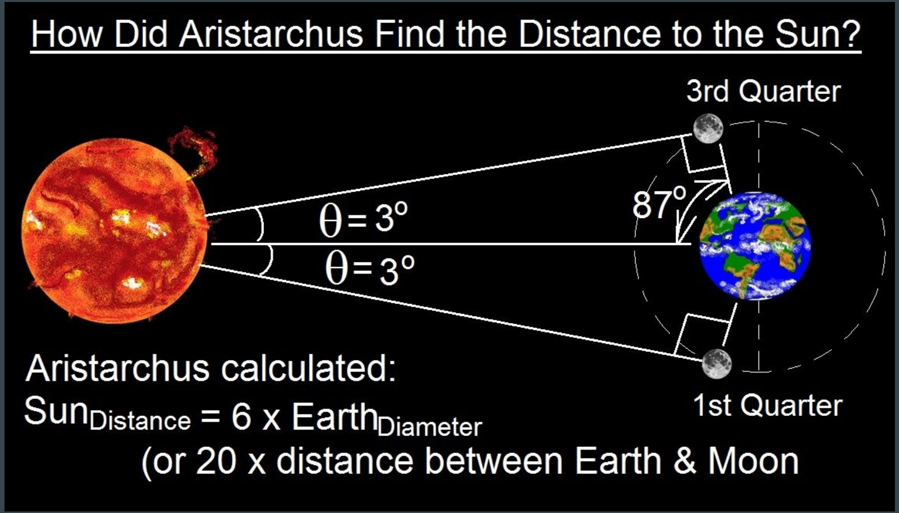
Distance to the Sun

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!



How Did Aristarchus Find the Distance to the Sun?

Aristarchus calculated:

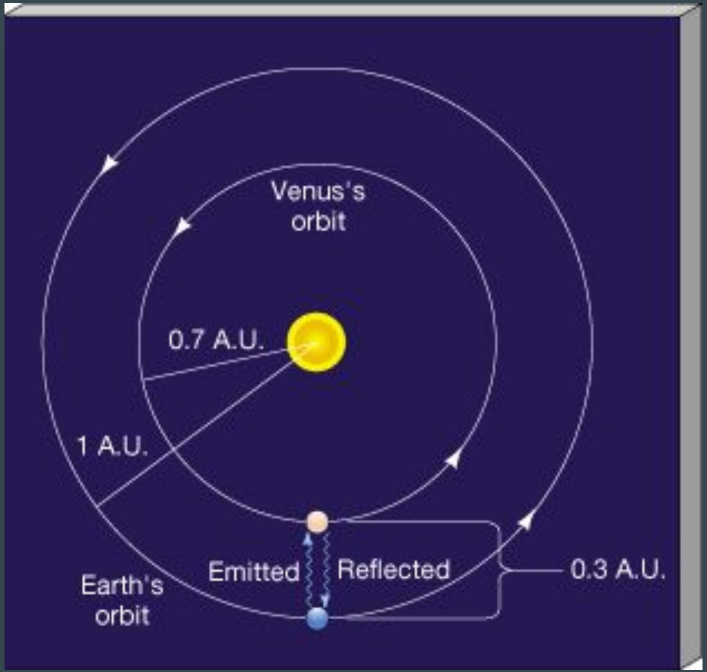
$\text{Sun}_{\text{Distance}} = 6 \times \text{Earth}_{\text{Diameter}}$

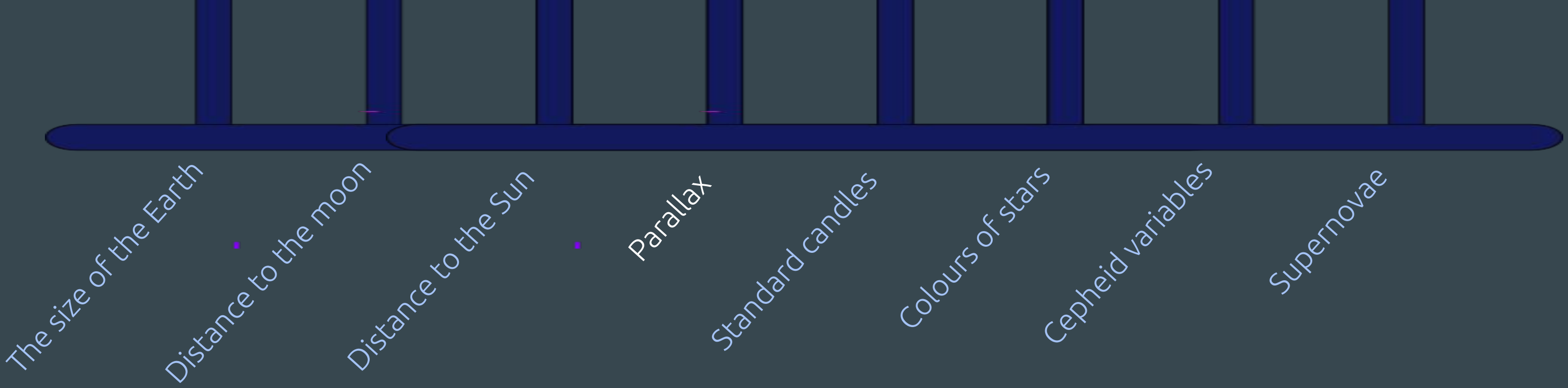
(or 20 x distance between Earth & Moon

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





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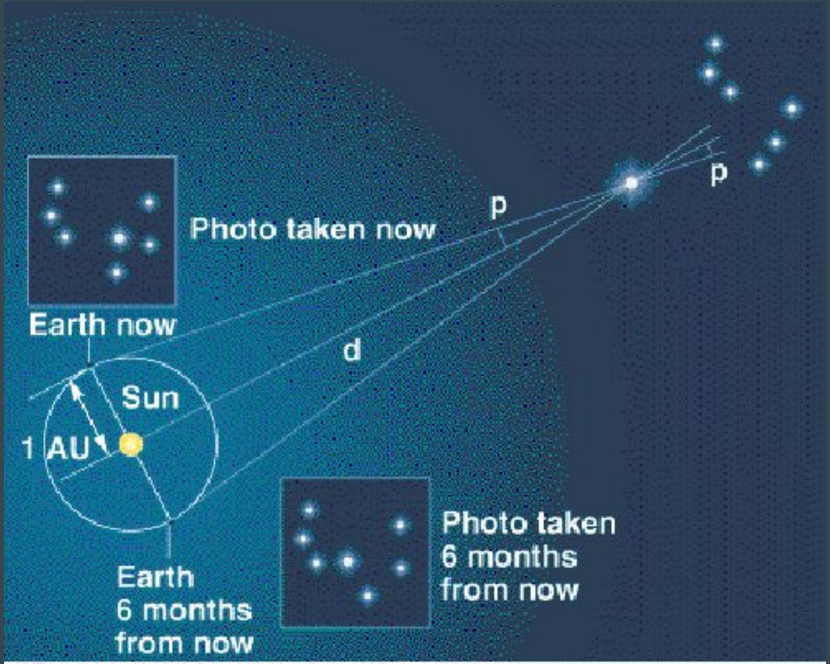
Parallax

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!



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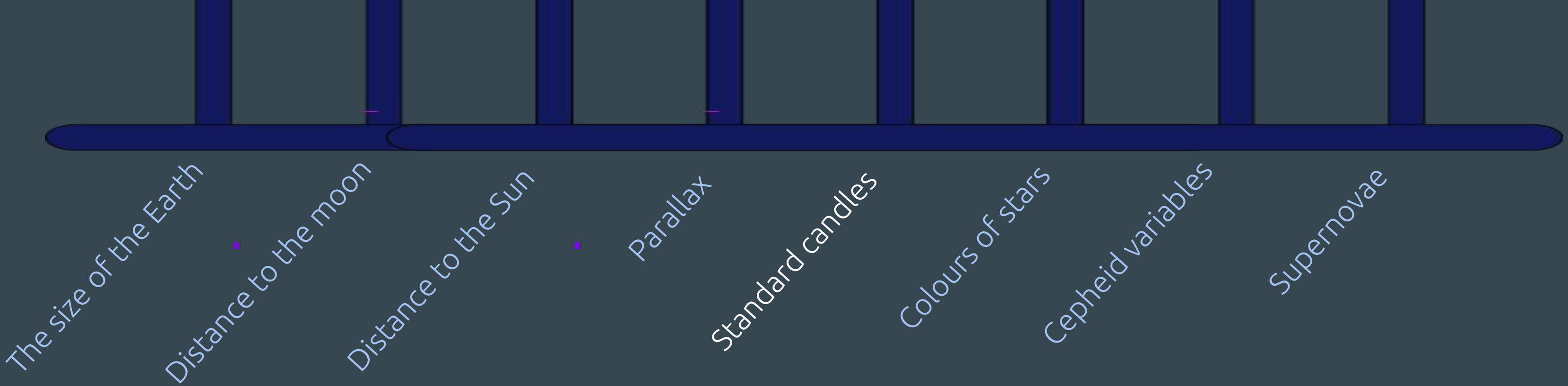
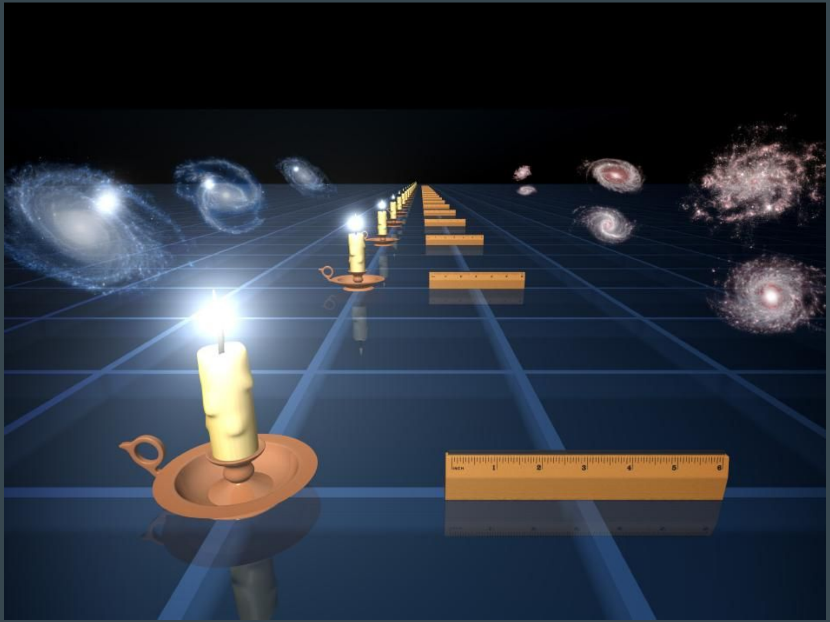
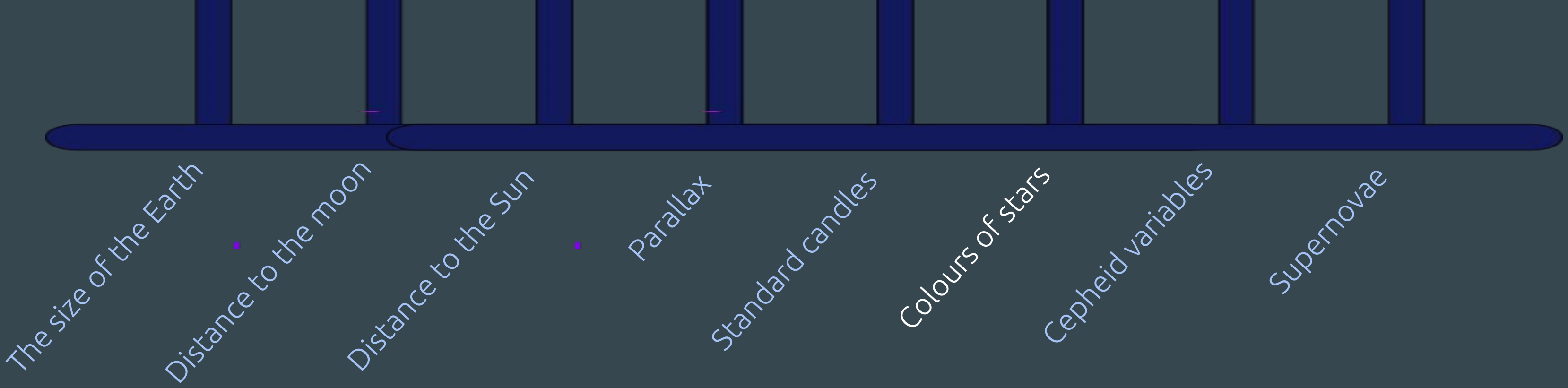


Standard Candles

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**





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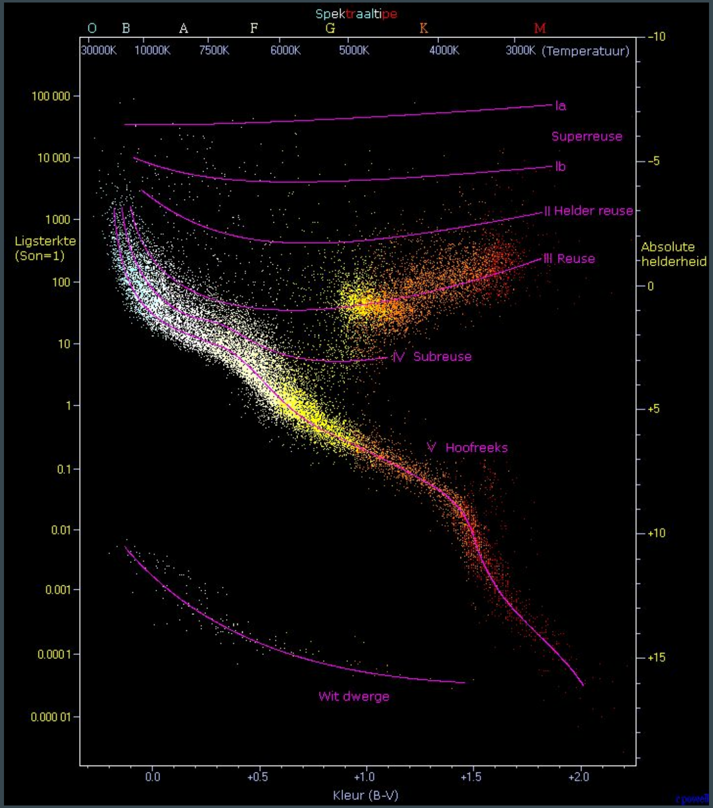
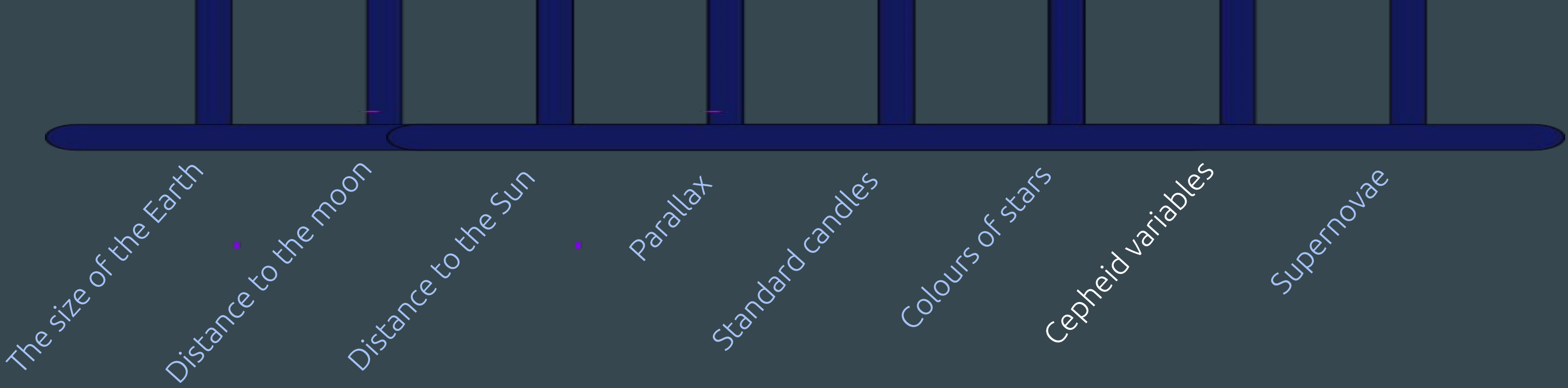
Colours of stars

Mapping the Milky Way

Colours of stars

- Once we had developed telescopes and could measure distances to stars, people would do this for as many stars as possible
- Because we know the distance, we could find out how bright they *actually* are
- When they did this, they found a relationship between the colour of the star and their actual brightness
- Thus, if you measured the colour, you could also get the distance! A standard candle





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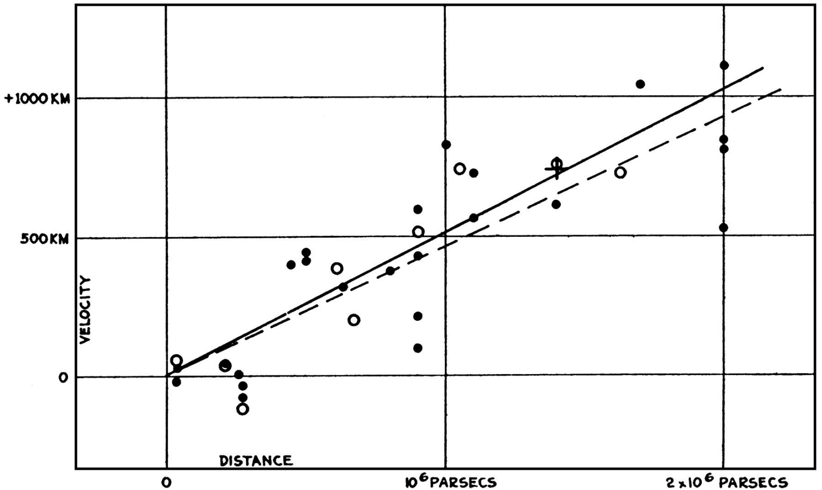
Cepheid variables

What made Hubble famous

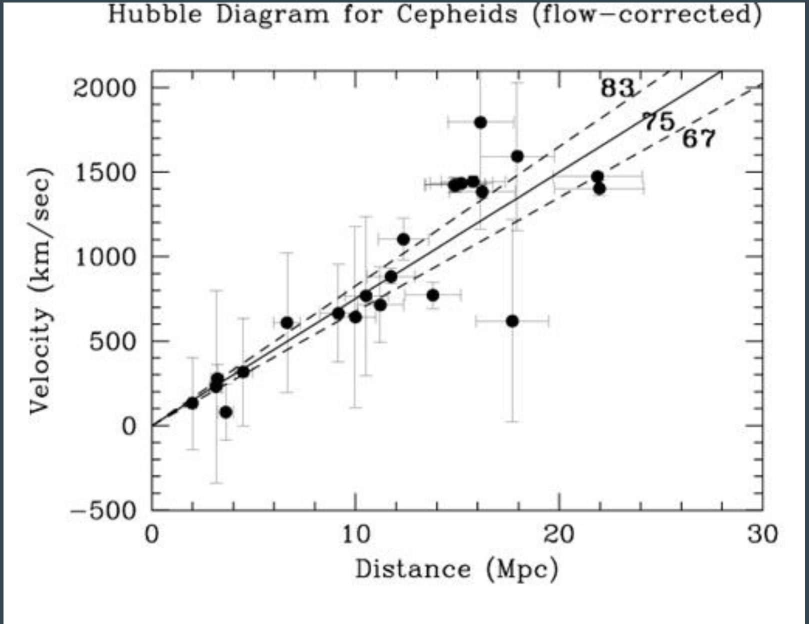
Cepheid Variables

- Very bright stars that pulsate in a predictable way
  - The brighter they are, the longer the pulsations take
  - By measuring their brightness and period, their distances could be determined
  - The relationship is calibrated on Cepheids that are close enough to be measured via parallax
- Hubble (and others) used this to measure distances
  - They found that galaxies further away appeared to be redder than they should be: **redshift**
  - **Had discovered that the universe was expanding!**



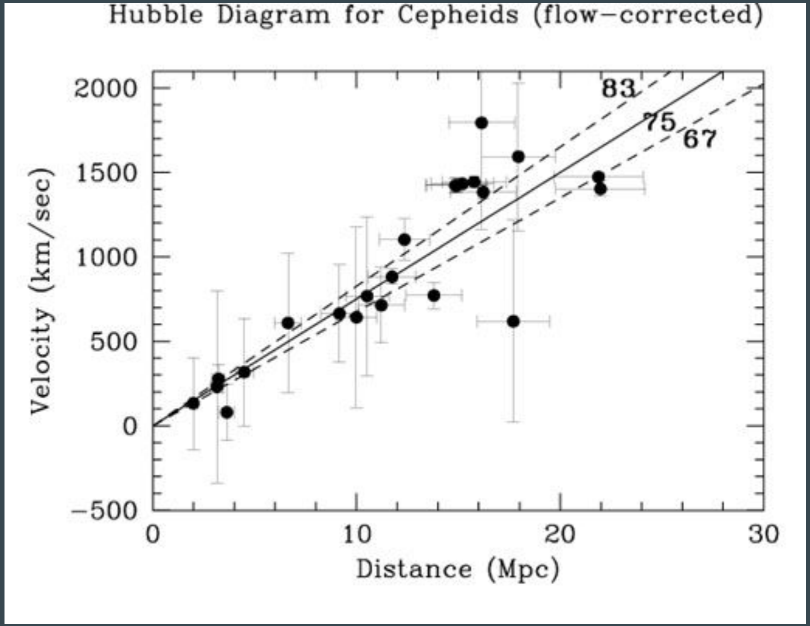
Cepheid Variables

- Calibrating the cepheids is very important!
- Hubble found that the universe was expanding, but he determined the rate of expansion to be very high!
    - ~500 km per sec per mega parsec
- This was due to bad calibration of the Cepheids
- One of the major goals of the Hubble space telescope was to calibrate the Cepheids and measure their distances better



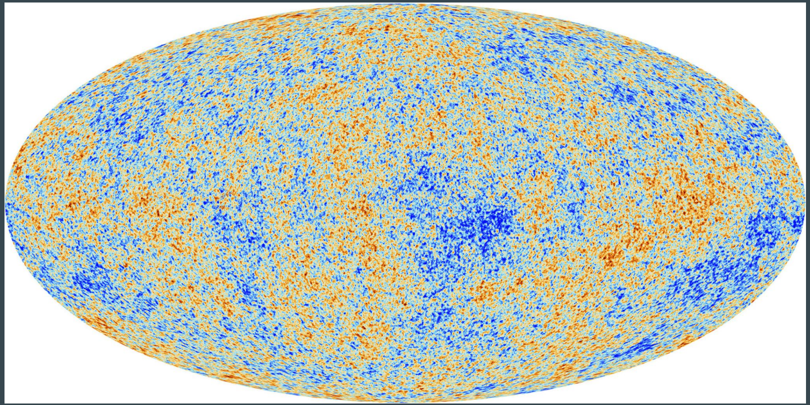
Cepheid Variables

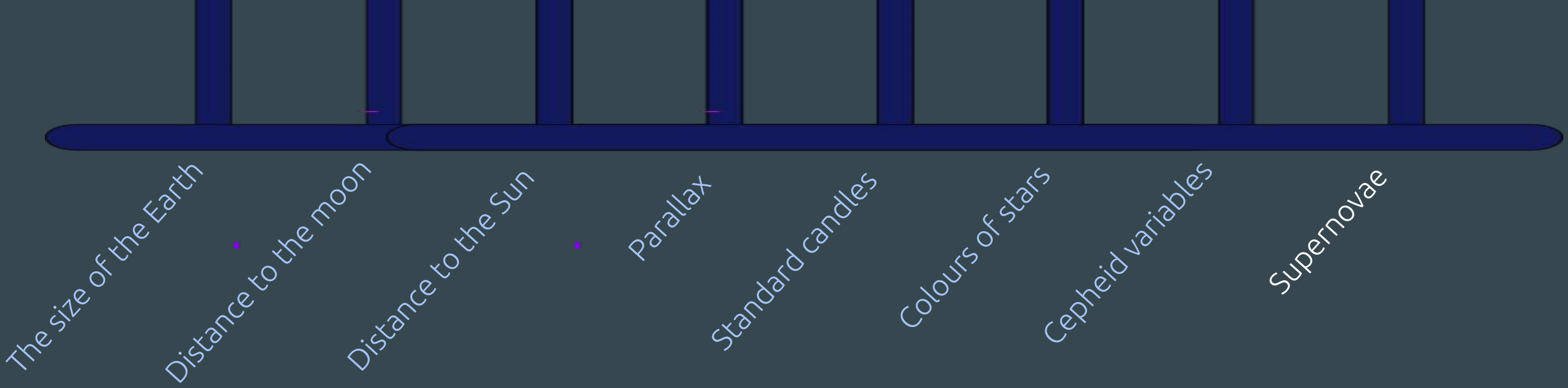
- Hubble found a relationship between **distance** and **redshift**
- This was predicted by Lemaître - the result is known as the **Hubble-Lemaître** law
- The expansion rate of the universe is governed by the **Hubble Constant - H0**
- Interpreted as the expansion of Space itself evidence of the Big Bang
- This itself led to the prediction of the left-over glow of the Big Bang: The **Cosmic Microwave Background**



The Cosmic Microwave Background

- The CMB is a huge science in and of itself
- At a redshift of z~1100
- It's model dependent, but we can measure the Hubble Constant
- If we measure H0 from the CMB: 67.66 ±0.42 km/s/Mpc
- If we measure it from the Distance Ladder: 74.03±1.42 km/s/Mpc
- Is it real or systematics? We will come back to that...
- But for now, on to the next rung!





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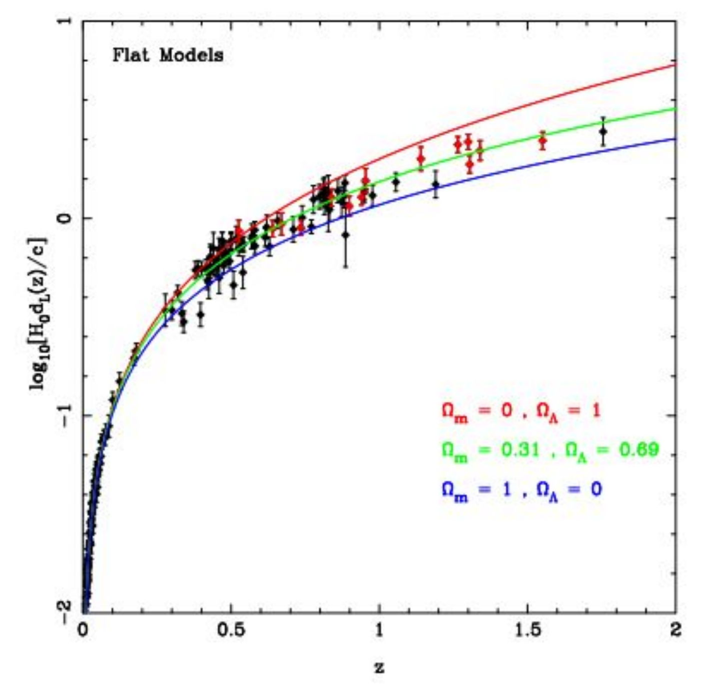
Supernovae …

And Dark Energy

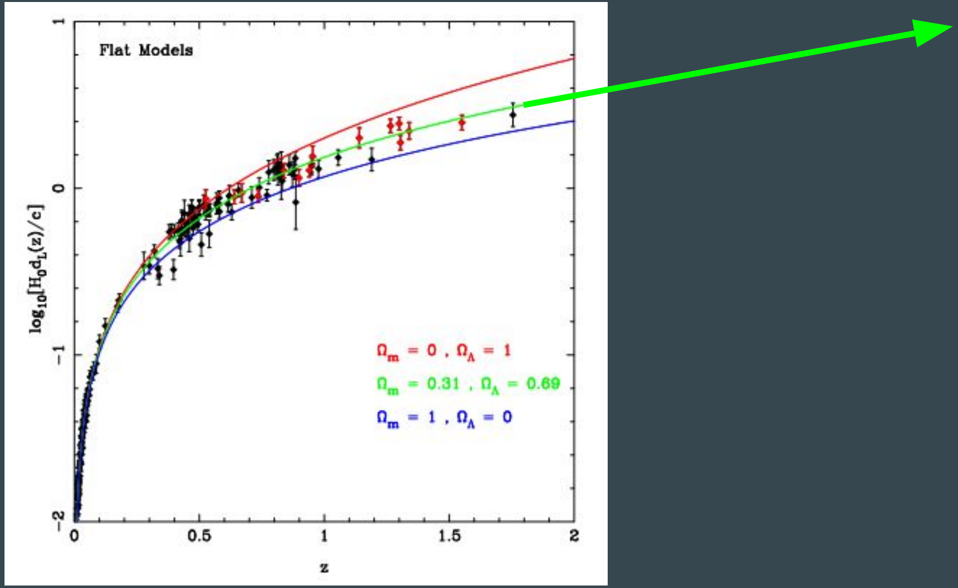
Supernovae

- 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
  - Y Lee at Yonsei casting doubt though...
- Distant Supernovae are fainter than they should be!
  - Universe is not only expanding, but accelerating in its expansion!
- “Dark Energy”



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**

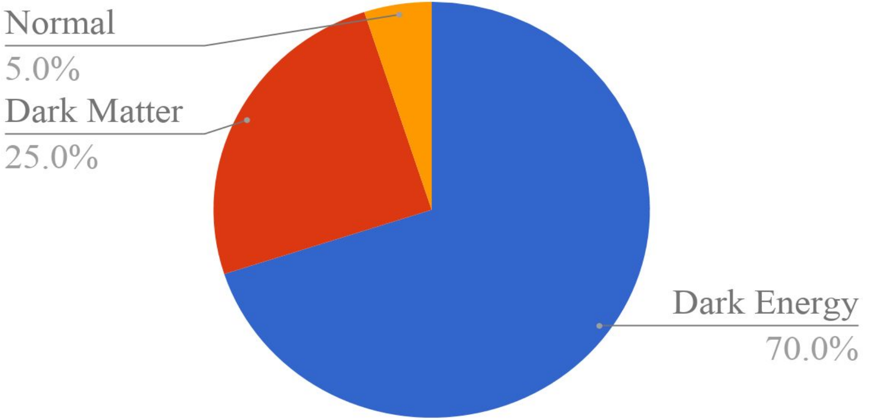


Open questions..

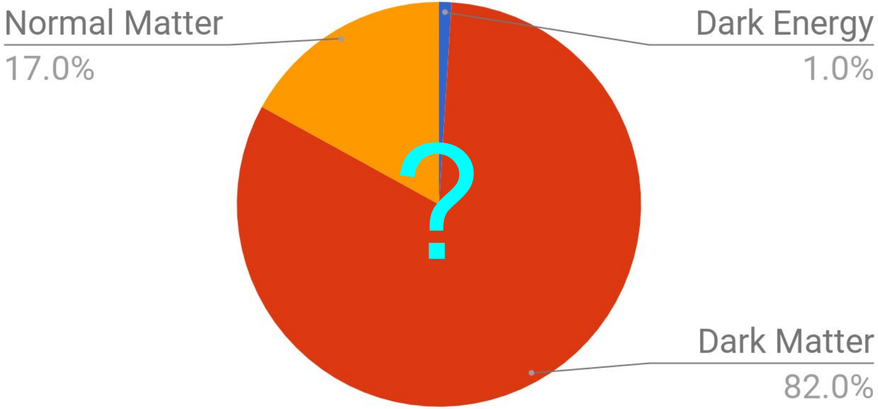
- This leads us onto the need for new distance measures
- **We don't know what ~95% of the Universe is**
- What is the nature of Dark Energy?
- Was there **really** so little Dark Energy in the early universe?
- Does Dark Energy evolve with time?
  - Hints but unproven (Zhao+ 2017, Nature)
  - Deviations at high-z? (Risaliti+ 2018, Nature)

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

The universe today

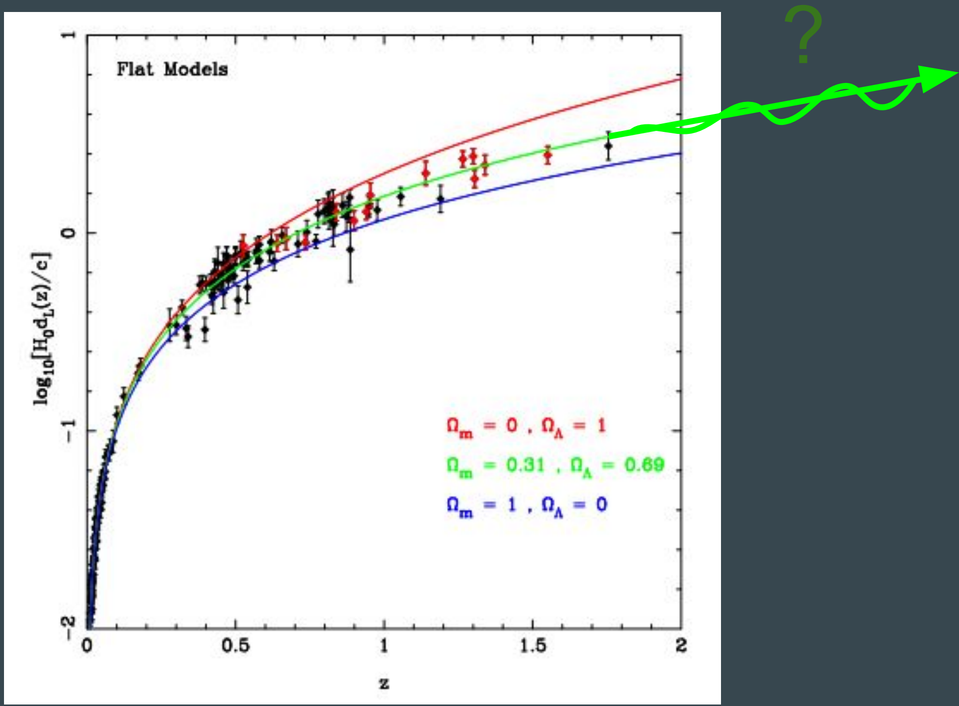


The universe at z=6?



Current cutting-edge

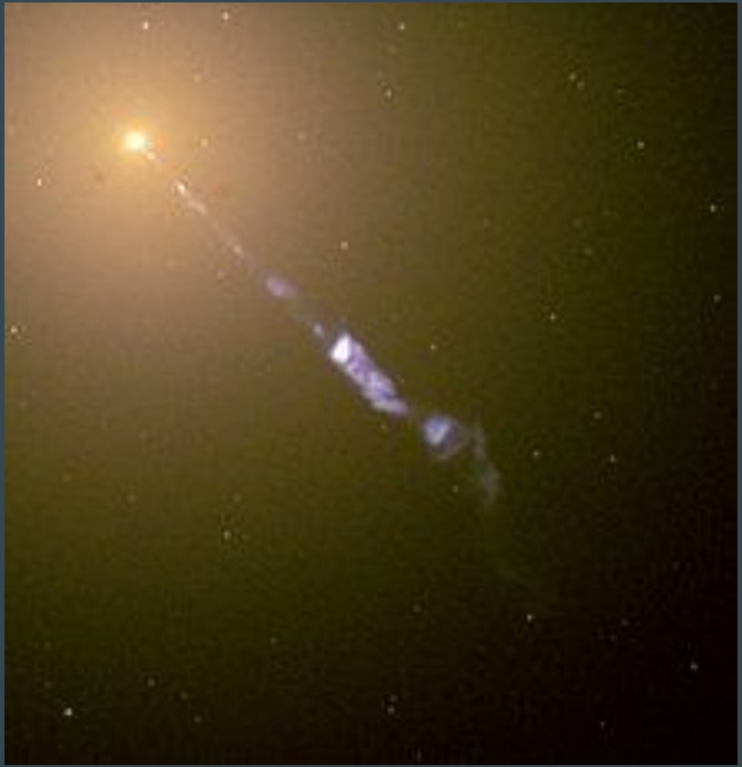
- Type Ia Supernovae (SN Ia)
  - Very bright "standard explosion"
  - Dark Energy discovery (Nobel 2011)
  - Distances up to z~2
- Baryonic Acoustic Oscillations
  - Imprint of early universe physics on large scale galaxy distribution
  - Distances up to z~2.5
- Cosmic Microwave Background
  - Fit cosmological 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
  - 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

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M87 jet, Image: NASA

Active Galactic Nuclei as standard candles

- New paper out in Nature Astron. a few months ago
- Use UV/X-ray luminosity relationship:
    - $\log(L_X)=\gamma\log(L_{UV})+\beta$
    - But beta parameter needs to be fit with the Type 1as
- Claim a 4-sigma deviation from LCDM at high-z
- They interpret the deviation as due to dynamical Dark Energy
- Is it real? Maybe we can find out...

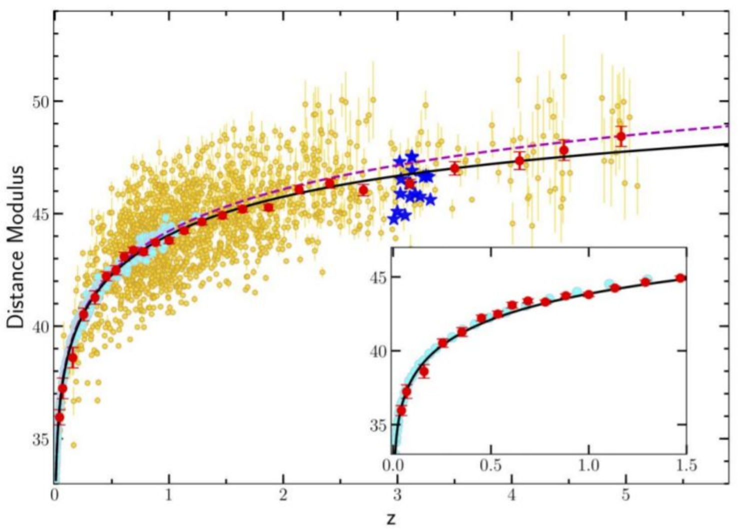

Figure 2: Hubble diagram of supernovae from the JLA survey[2] (cyan points) and quasars (yellow points). Red points represent the mean (and uncertainties on the mean) of the distance modulus in narrow redshift bins for quasars only. These averages are shown just for visualization and, as such, are not considered in the statistical analysis. The new sample of $z>3$ quasars with dedicated XMM-*Newton* observation is shown with blue stars. The inset is a zoom of quasar and supernovae averages in the common redshift range. The dashed magenta line shows a flat ΛCDM model with $\Omega_M=0.31\pm0.05$ fitting the $z<1.4$ data and extrapolated to higher redshifts. The black solid line is the best MCMC fit of the third order expansion of $\log(1+z)$.

Risaliti et. al. 2018

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.

How are we doing it?

Causality limited “variability size” $D_{var} \sim c\tau$

Think of this as a kind of explosion, where the brightness is increasing as fast as possible

This gives a ***linear*** size (ie. measured in km)

Compare against the* angular *size (measured in mas) directly measured by VLBI: Θ_{VLBI}

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

Distance can be found when the Doppler factor is known!

θ - VLBI size [mas]

dt - Variability timescale [dy]

Measuring distances to AGN using archival data

- Arguably better than SNIa*
  - We can constrain Hubble constant *and* Omega_m
  - In principle, can go from very nearby to very far away inc inside the galaxy
- Testing our methods on archival BU 7mm VLBA data
- Methods are “geometric”: so long as we can detect the source, we can (in principle) get the distance
- Case study in 3C 84
- *Disclaimer: Type Ias are awesome

Measuring distances to AGN using archival data

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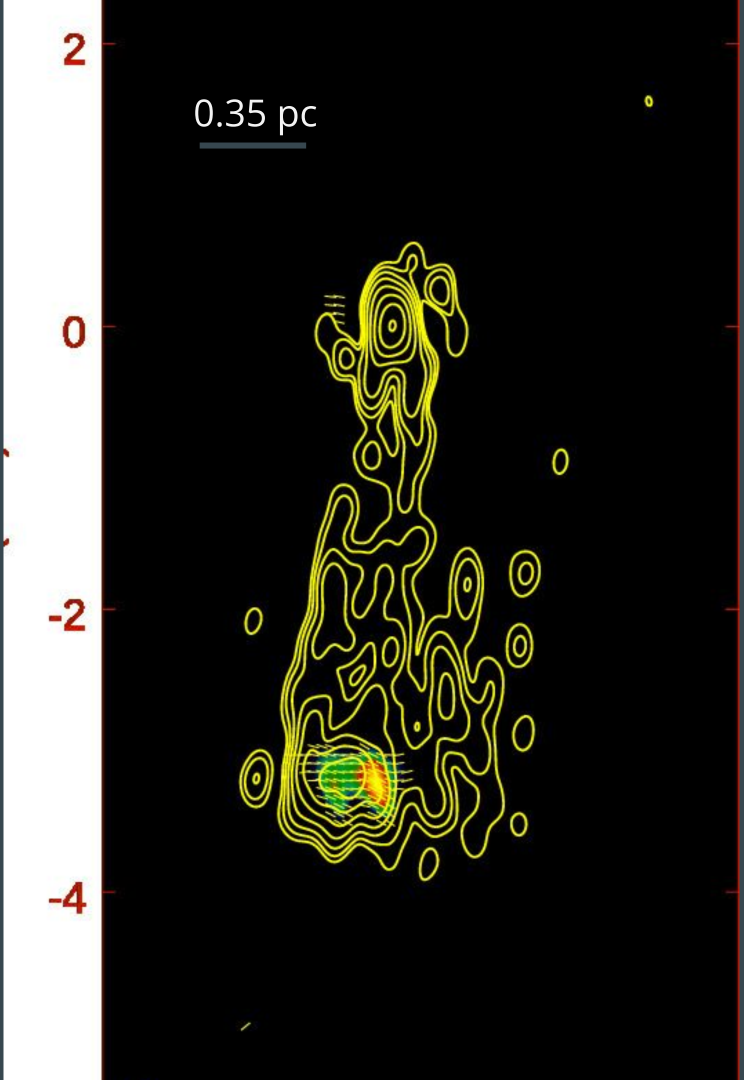
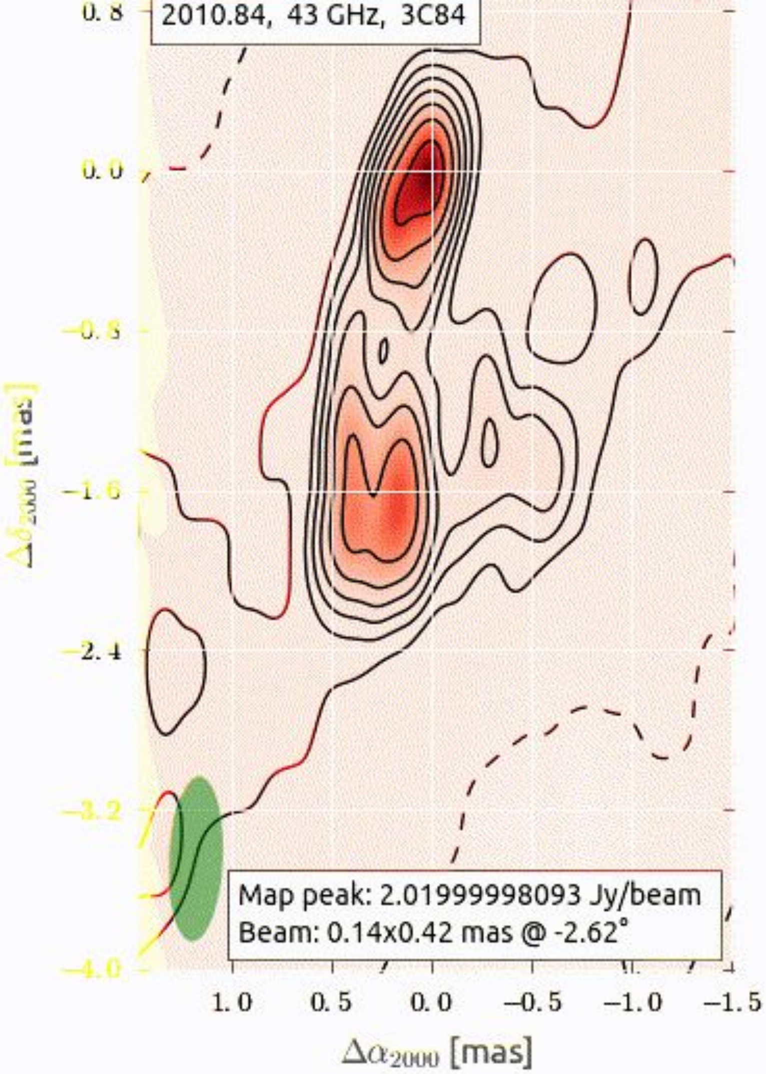
- Methods are “geometric”: so long as we can detect the source, we can (in principle) get the distance
- Case study in 3C 84 - Published in MNRAS (Hodgson+ 2020)
- 2 major assumptions: 1) causality argument
- 2) To convert the measured Gaussian in Difmap to a physical size, multiply by 1.6x (disk-like geometry) or 1.8x (spherical).. We assumed 1.7x

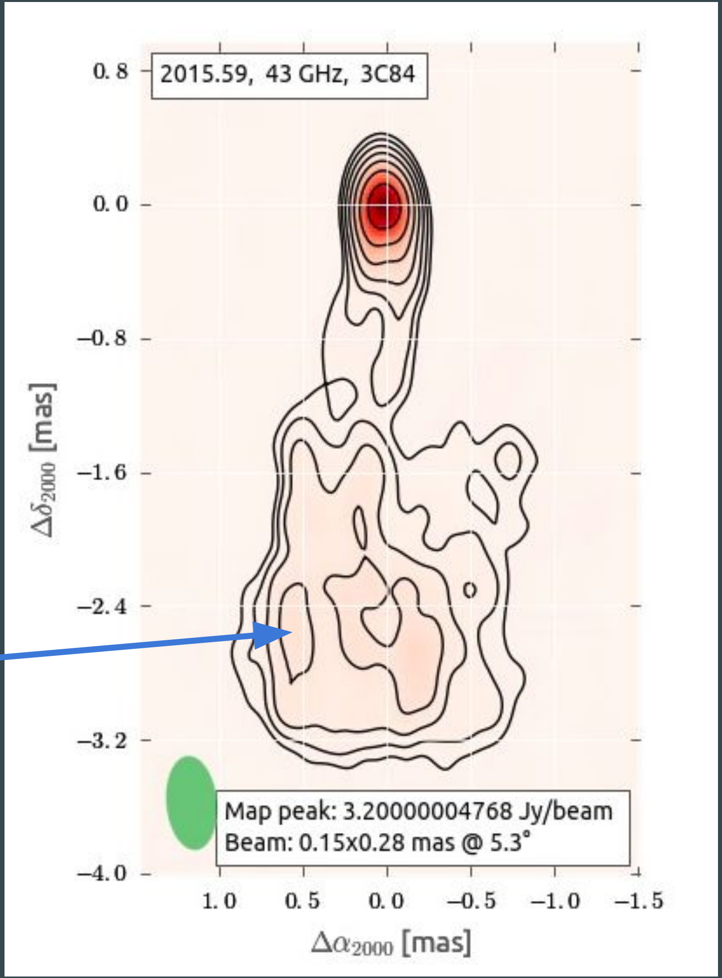
Distance to 3C 84

- 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)




2010.84, 43 GHz, 3C84
Map peak: 2.01999998093 Jy/beam
Beam: 0.14x0.42 mas @ -2.62°
0.8
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
$\Delta\delta_{2000}$ [mas]
1.0
0.5
0.0
−0.5
−1.0
−1.5
$\Delta\alpha_{2000}$ [mas]

A flare in 3C 84



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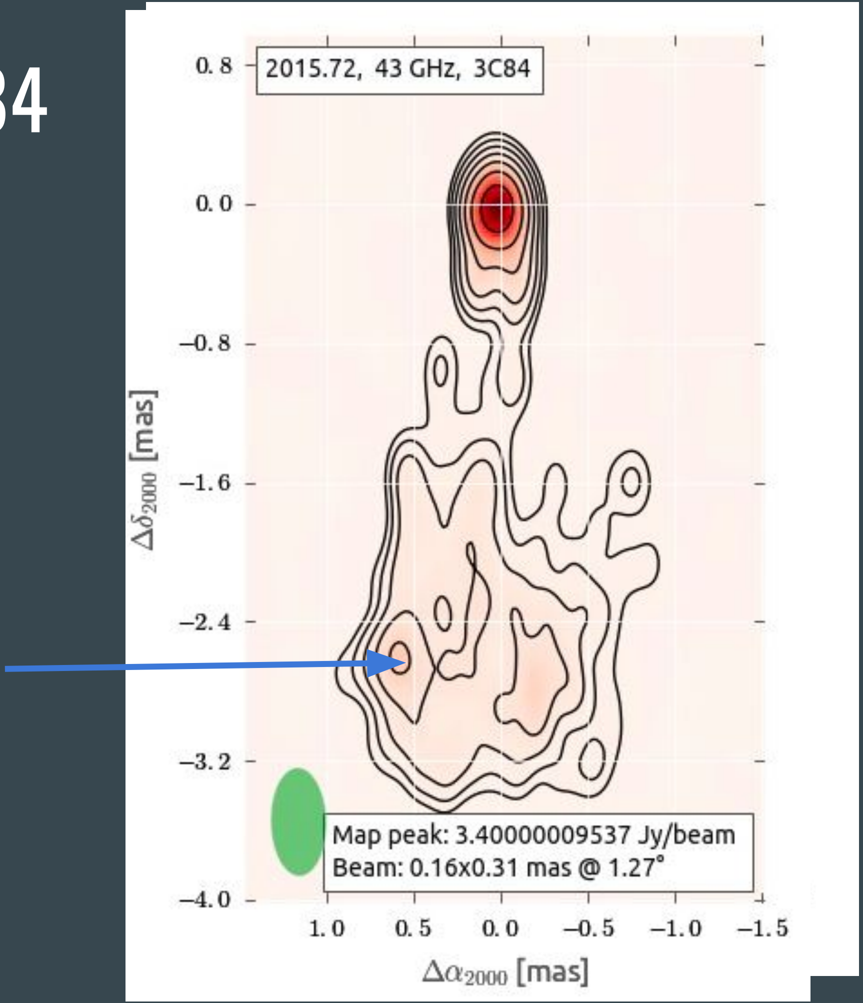

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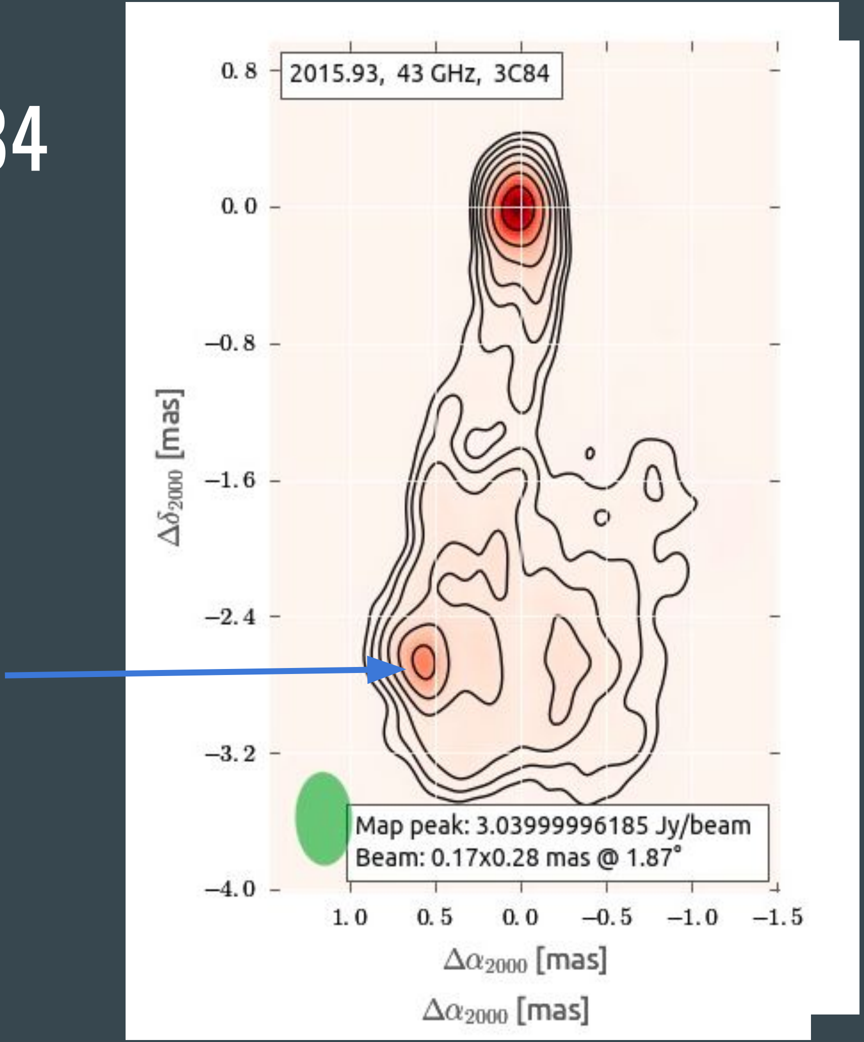

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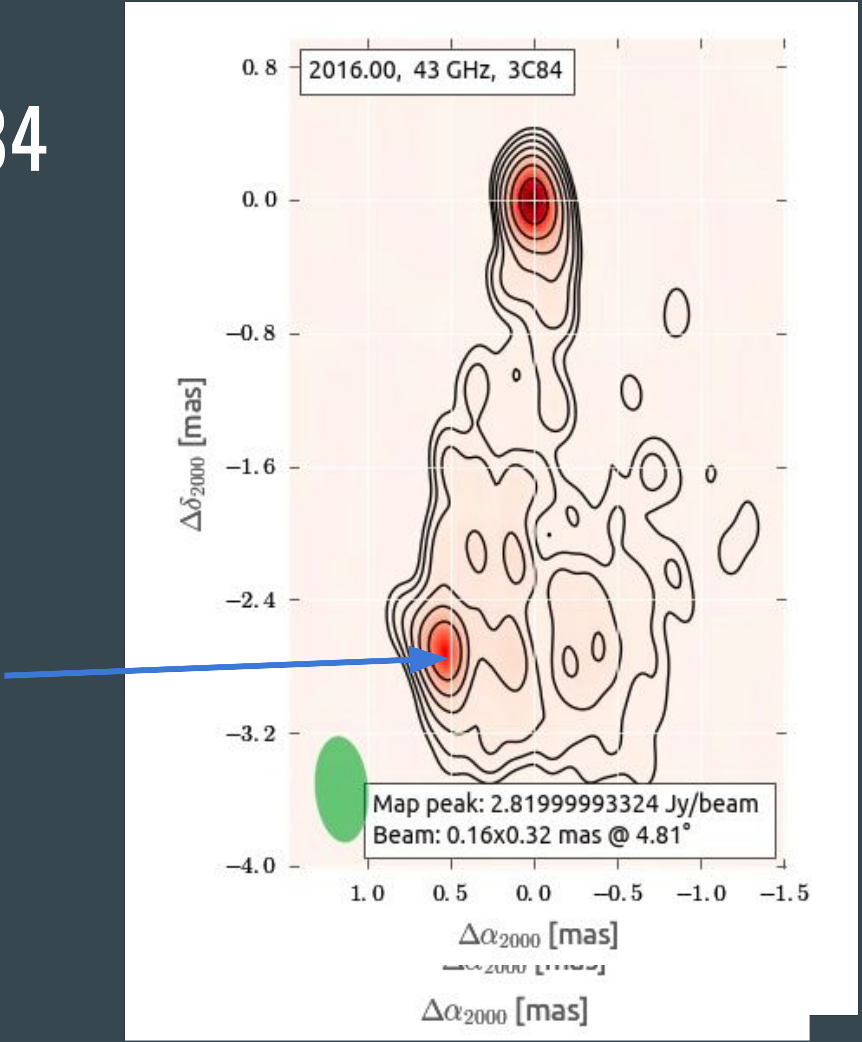

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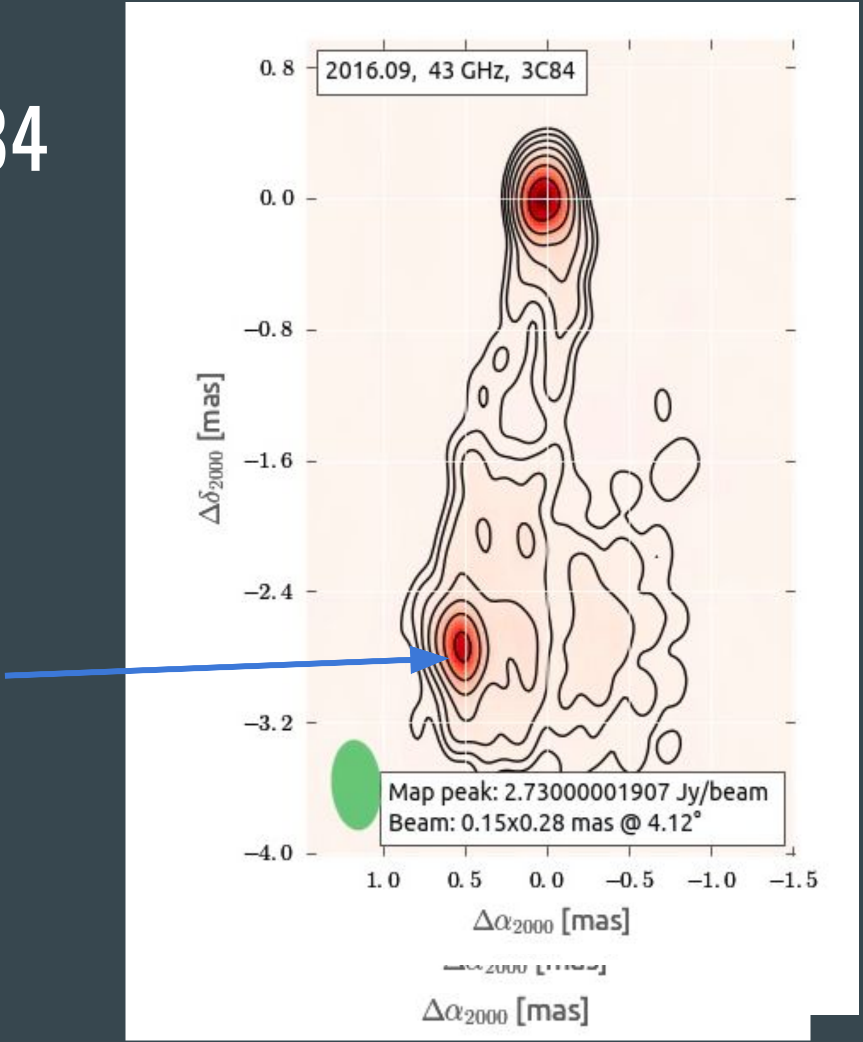

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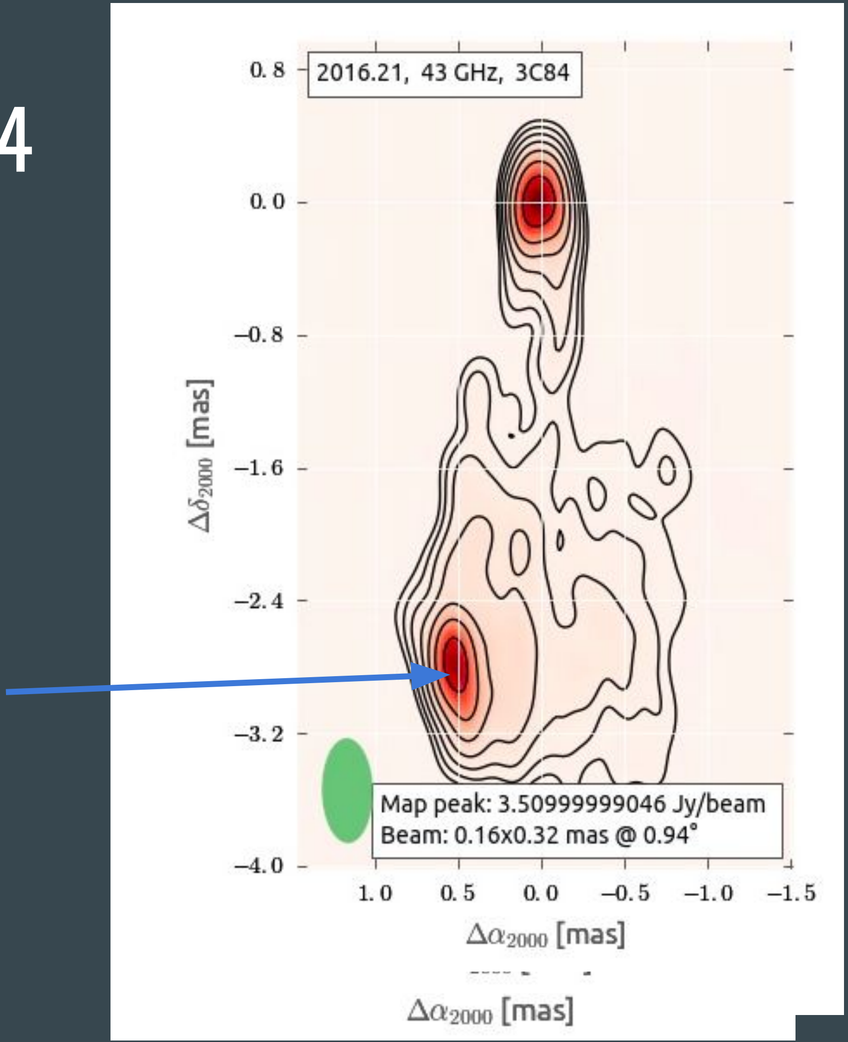

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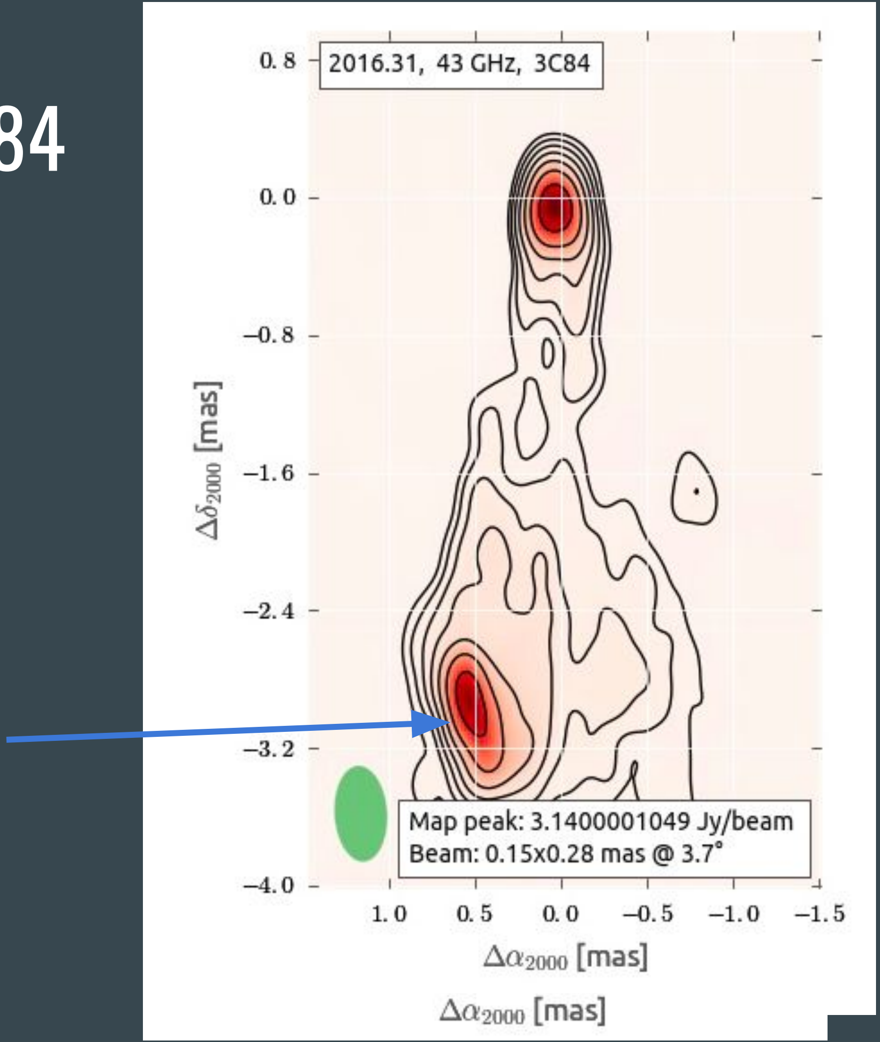
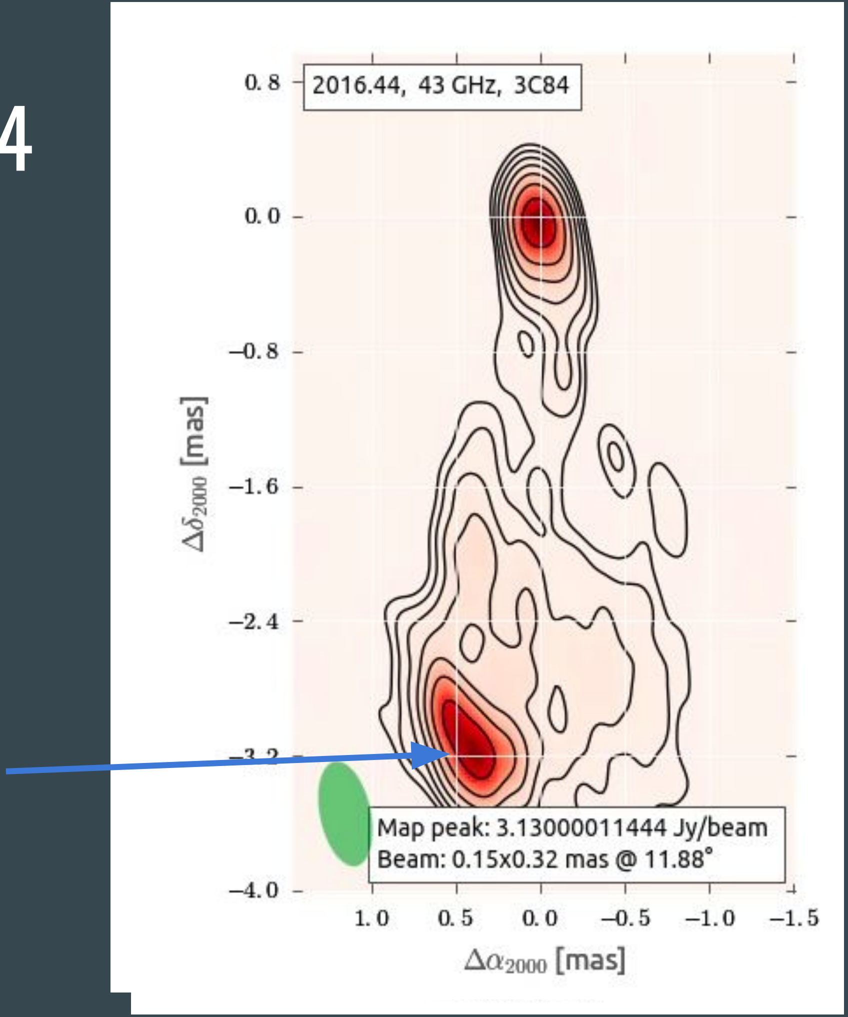
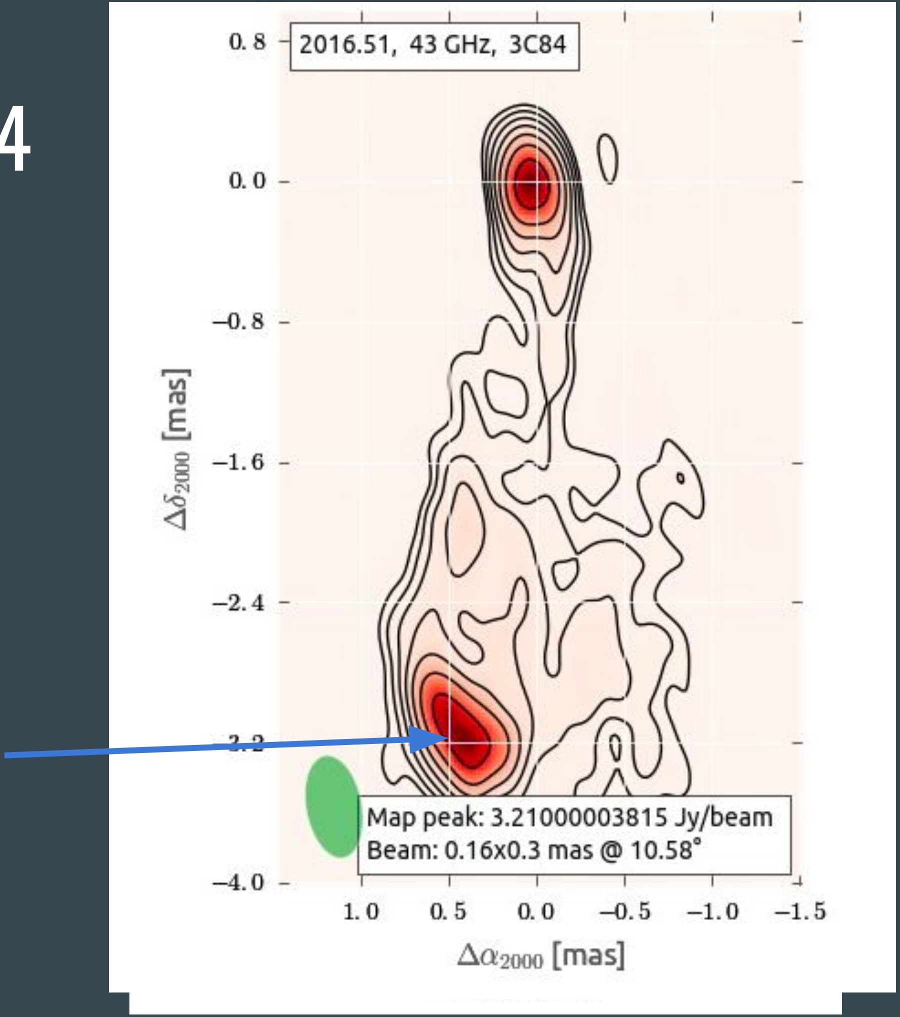


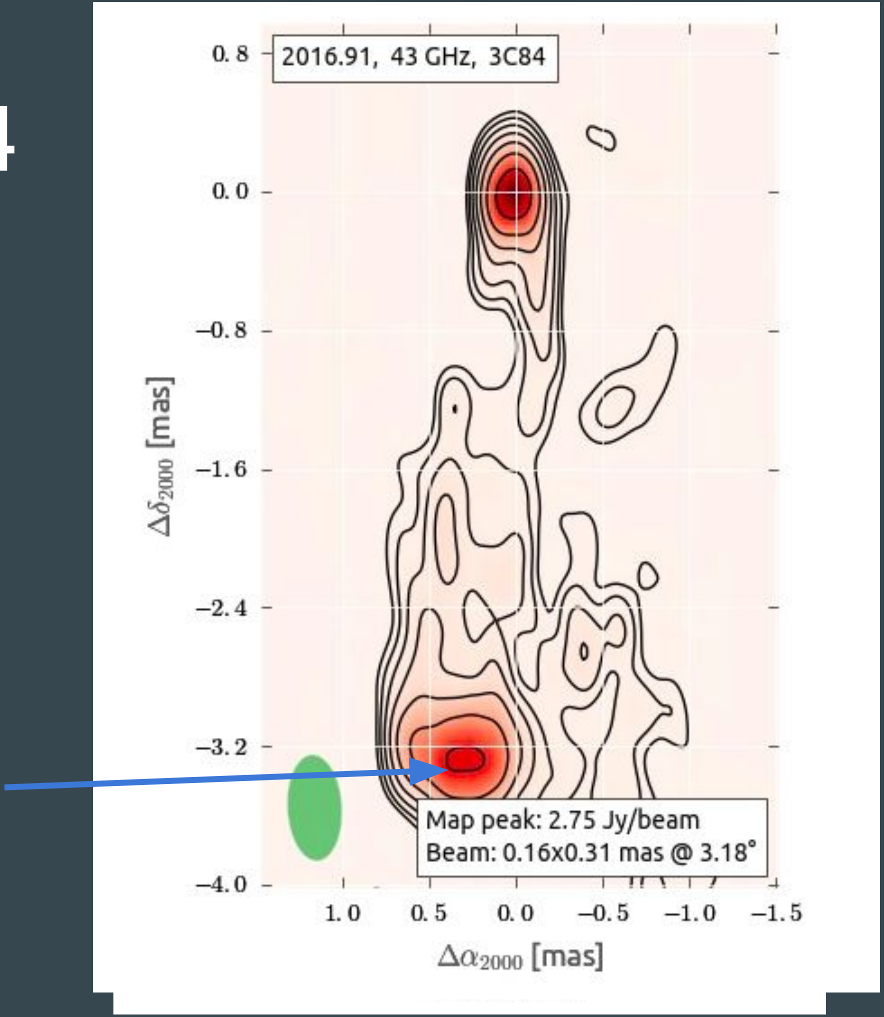
A flare in 3C 84



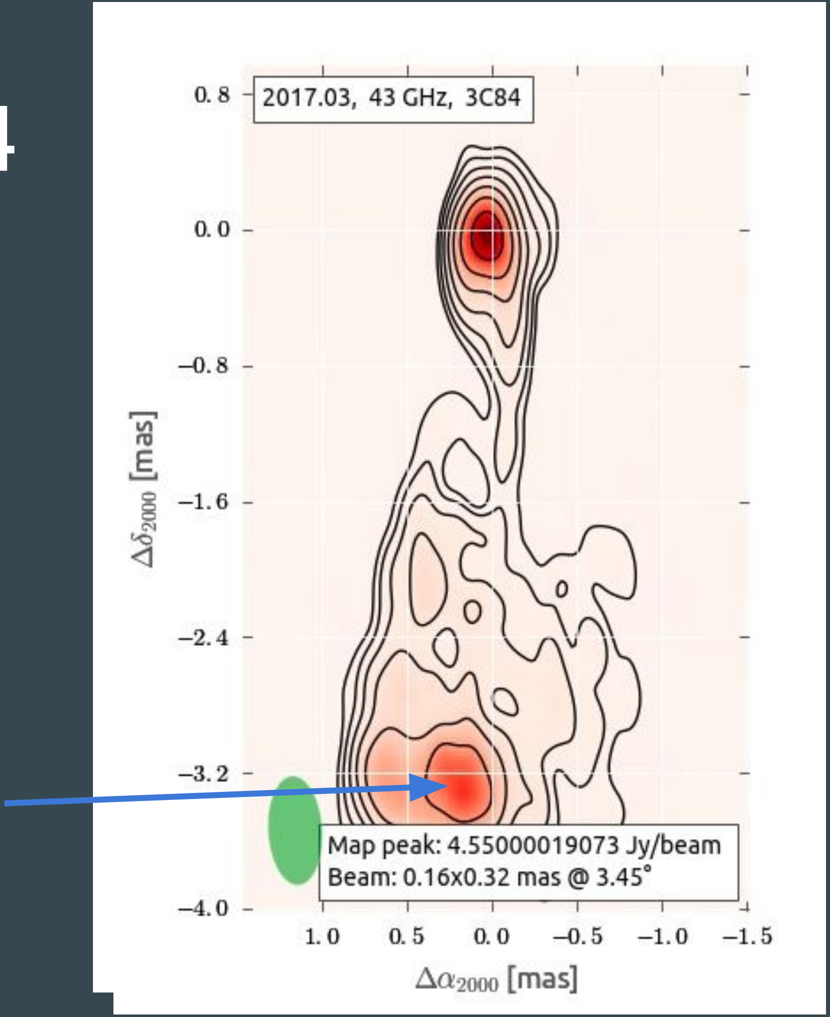
A flare in 3C 84



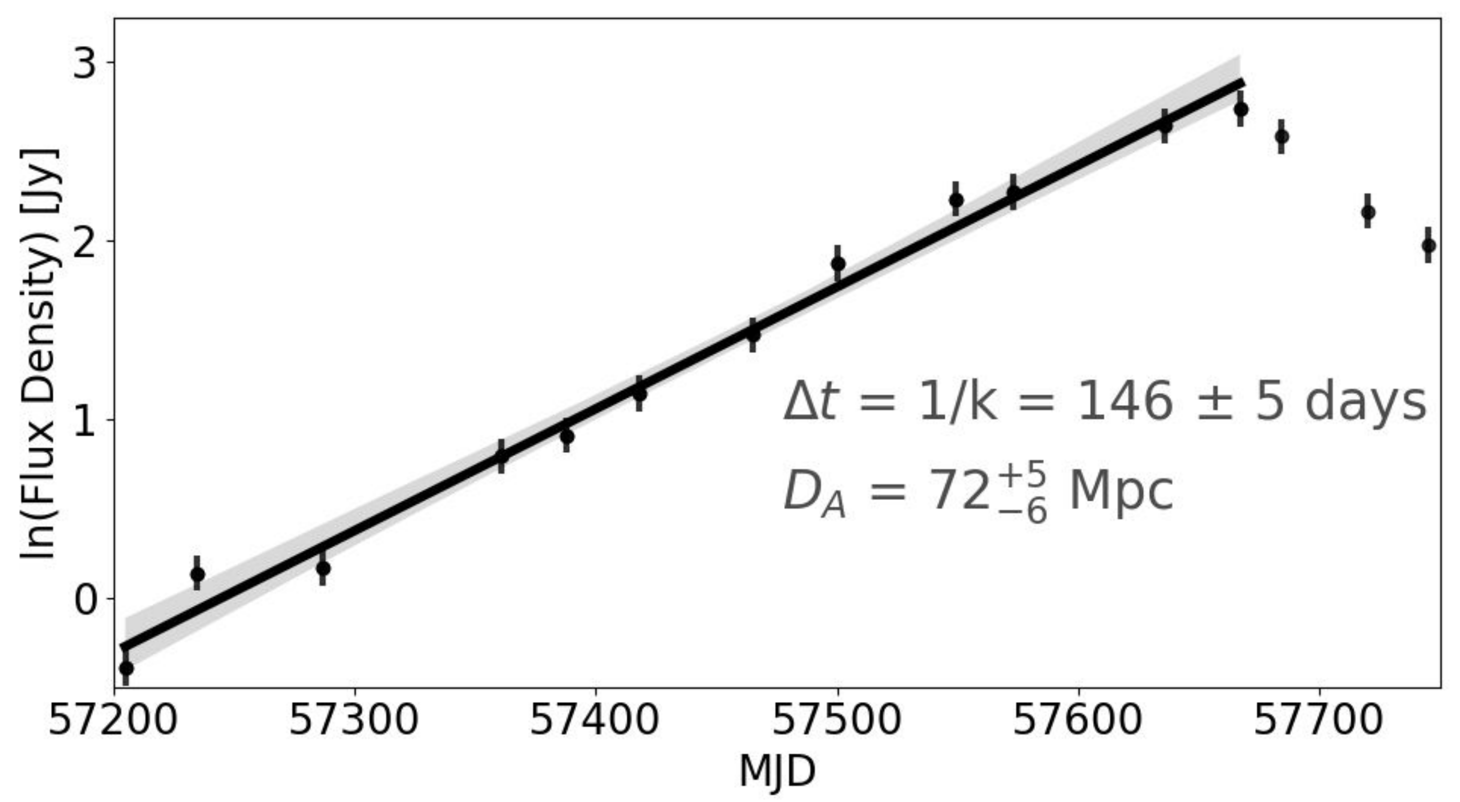
A flare in 3C 84



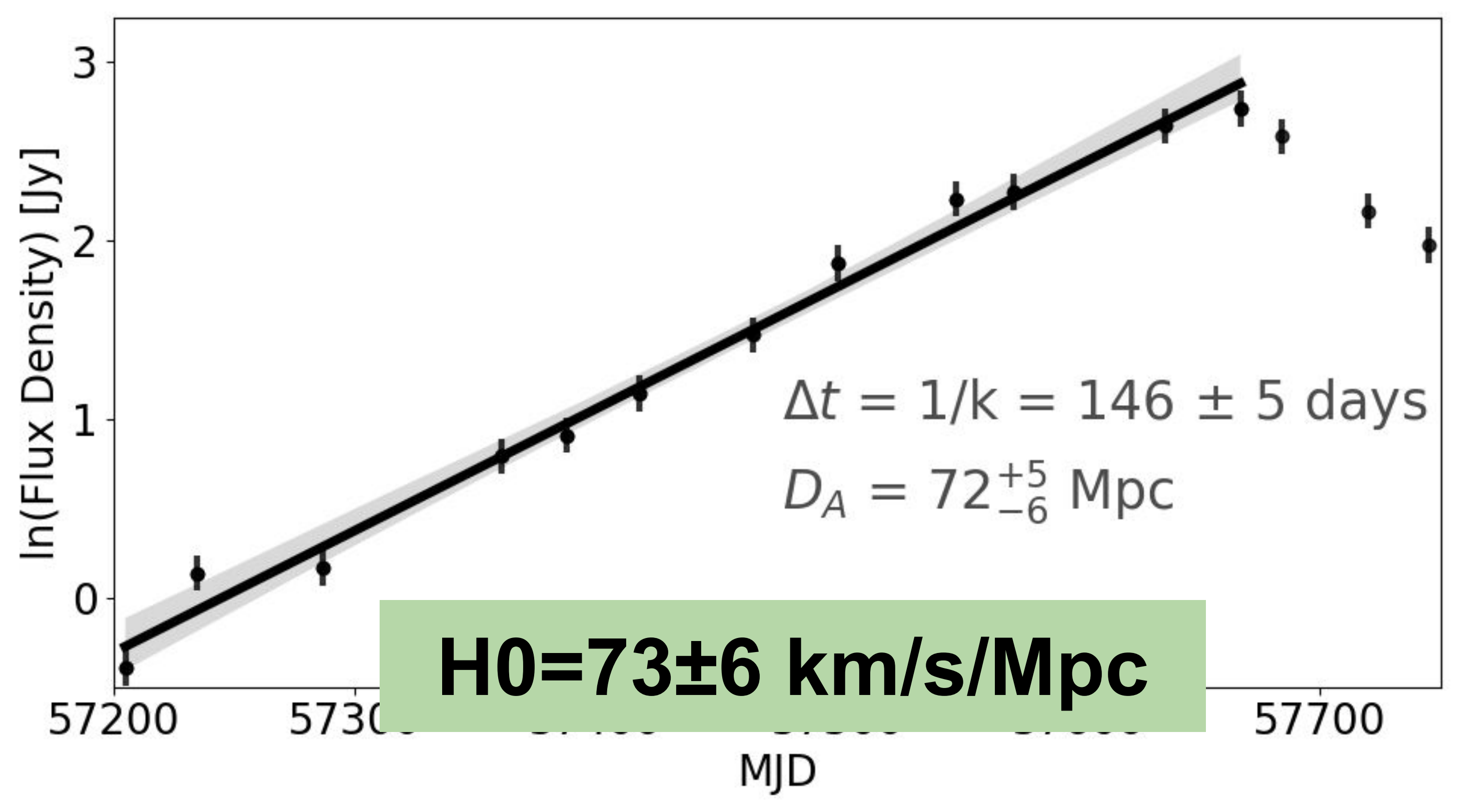
A flare in 3C 84



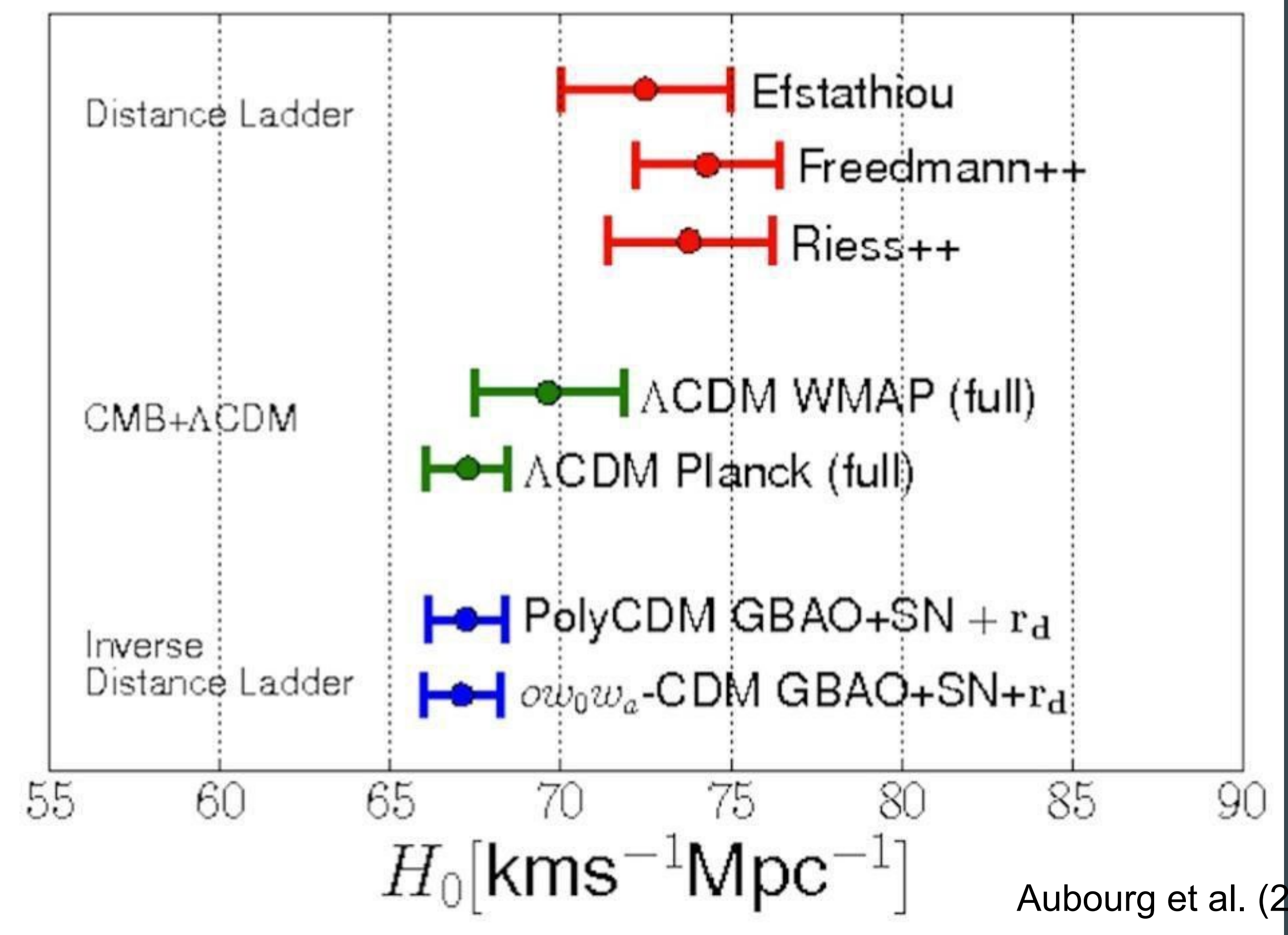
Flare LC


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

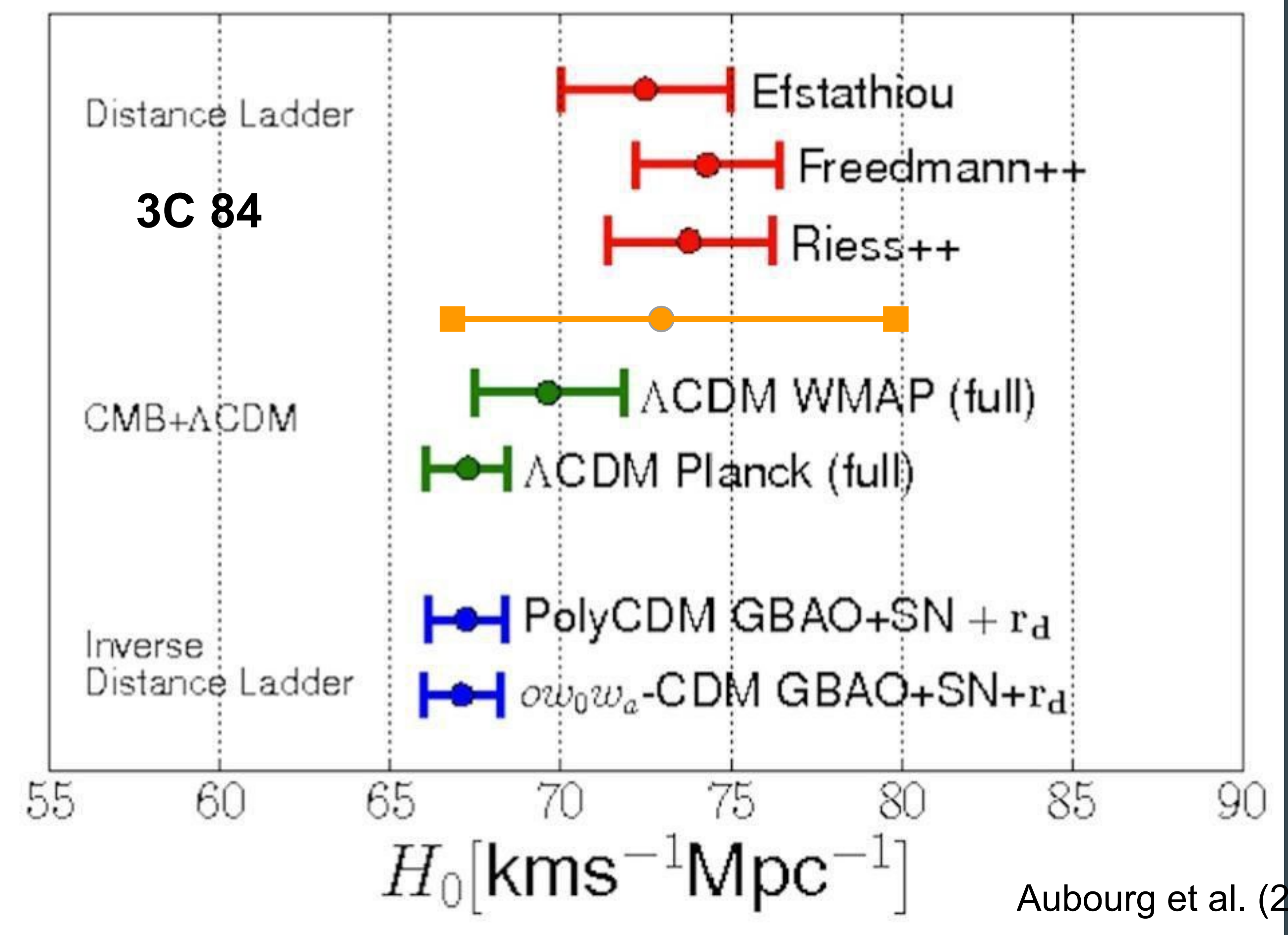
Flare LC



H0=73±6 km/s/Mpc



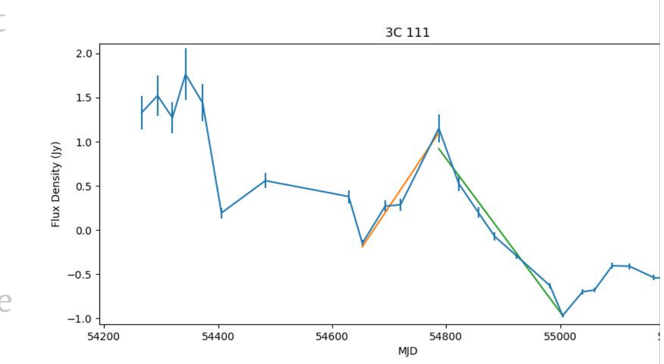
Aubourg et al. (2015)

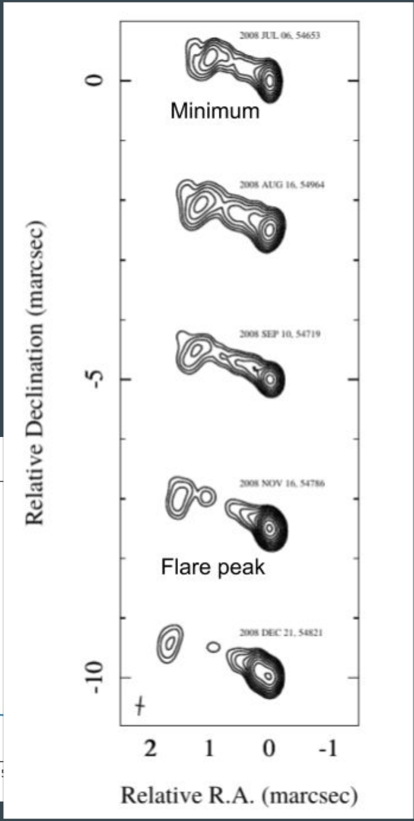


Aubourg et al. (2015)

3C 111 - another radio galaxy

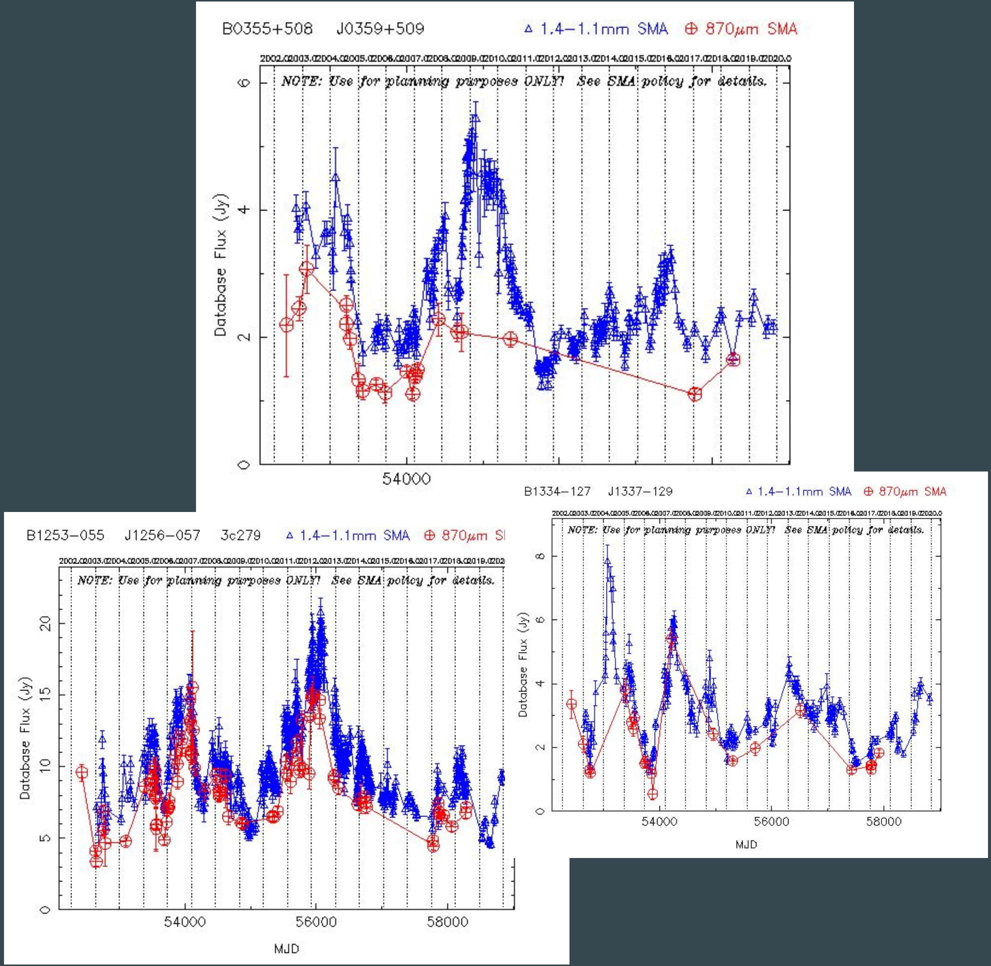
- z=0.048
- More limited data, but we could fit the rise and decay timescales
- Using the “core” rather than a jet component
- Leads to
    - D_A(rise) = 180 ± 30 Mpc
        - ⇒ H_0~76 km/s/Mpc
    - D_A(decay) = 200 ± 22 Mpc
        - ⇒ H_0~70 km/s/Mpc
- If there is a mild Doppler factor, will increase the distance measurement → lower H0





Observational systematics

- Archival data means limited cadence
    - Not accurately determining Δt
    - Source size may be smaller than resolution of the instrument
- Flares can be ‘messy’
    - It can be difficult to determine when a flare starts and ends
    - **Determining the systematics of actually measuring the variability timescale will be critically important**
- Limited uv-coverage of the QUOKKA array will make imaging difficult
- Looked at (indirectly) by Liodakis+2021, it seems we are OK...



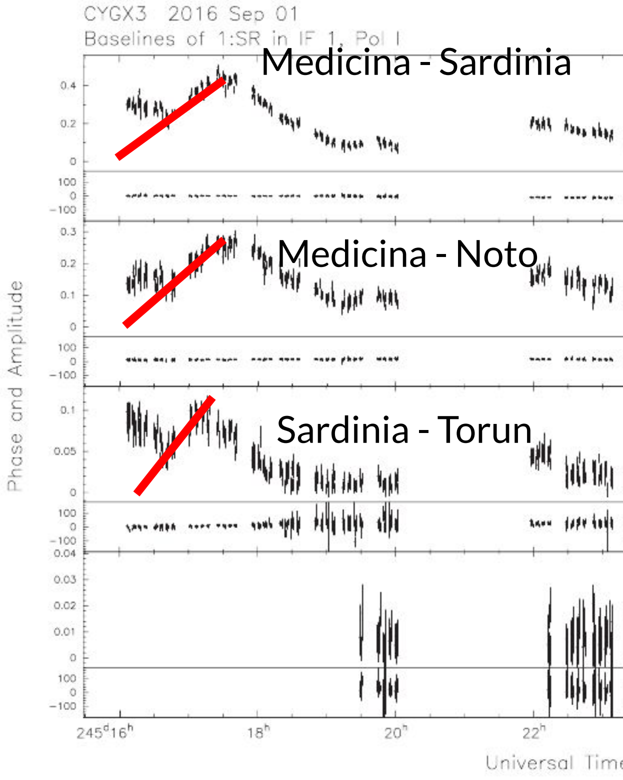
From SMA cal page

Methodological systematics

- How valid is the causality assumption?
  - Can test the method on micro-quasars with known parallax distances.
- What is the exact geometry of the system?
  - Very careful analysis of VLBI visibility data can resolve this
- Are there any redshift dependencies in the critical angle assumption?
  - We would expect that higher-z sources would be more relativistic because they are brighter, because we can see them

VLBI observations of the micro-quasar Cyg-X3 (Egron+ 2017).

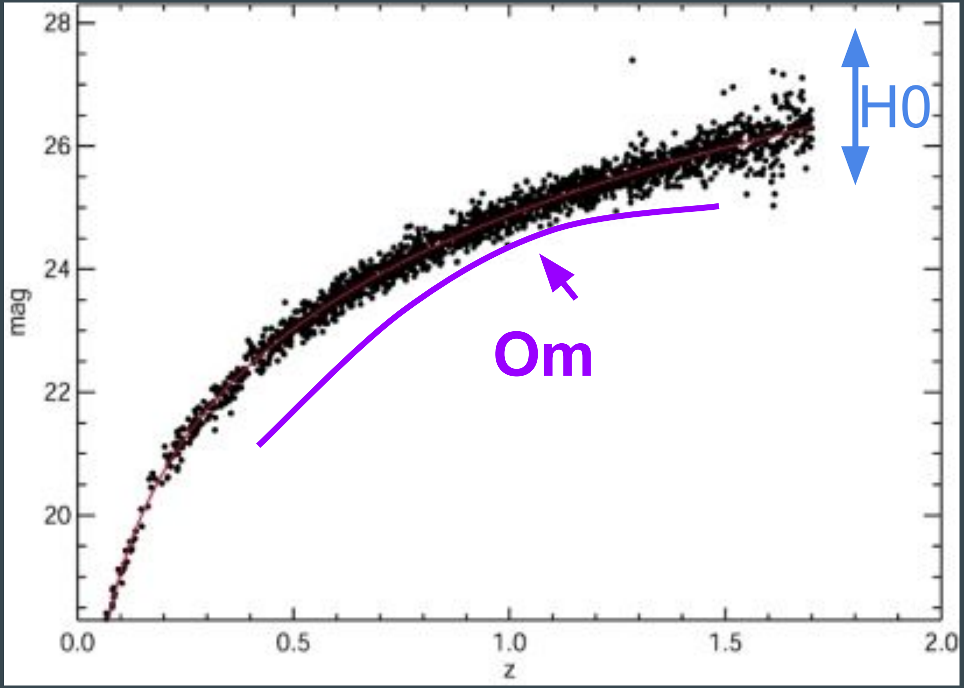
Δt appears to vary as a function of source position angle!



Egron+ 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



Redshift dependent systematics

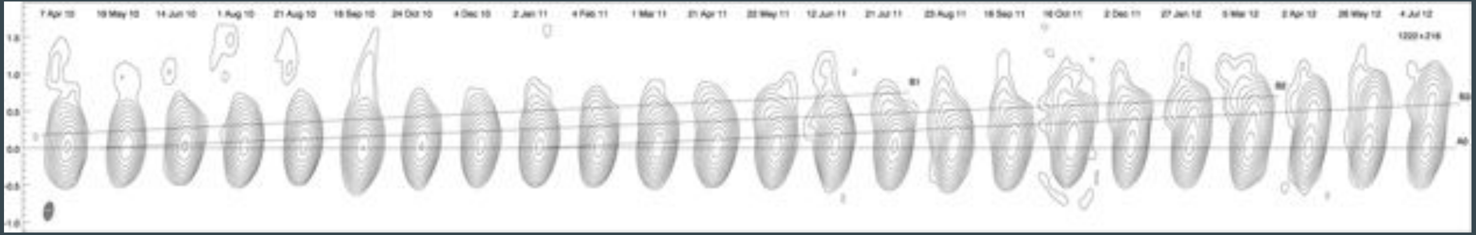
- The ‘core-logic’ of the method may have source-based systematics, but should be free of redshift based systematics*
    - (*assuming no observational systematics)
- The Doppler factor correction can have systematics, but must not have *redshift dependent* systematics

Solution

- Use two or more independent methods of getting the Doppler factor
- The difference *between* the Doppler factor estimates should not evolve with redshift
- If they are not, you should be (within errors) dominated by statistical errors

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**



Jorstad+ 2017

Blazars - Jet speeds Doppler factor

$$D_{\mathrm{A}} = \frac{c\Delta t}{\theta_{\mathrm{VLBI}}(1+z)}$$

$$D_{\mathrm{A}} = \frac{\delta c\Delta t}{\theta_{\mathrm{VLBI}}(1+z)}$$

$$\beta_{\mathrm{app}} = \frac{\mu(1+z)D_{\mathrm{A}}}{c}$$

$$\delta = \sqrt{1+\beta_{\mathrm{app}}^2}$$

$$D_{\mathrm{A}} = \frac{c\Delta t}{\sqrt{\theta^2+\mu^2\Delta t^2}(1+z)}.$$

$$\delta > \frac{\theta}{\sqrt{(\theta^2-\mu^2\Delta t^2)}}$$

Or equivalently the Doppler factor -

But only true if observing the source at a viewing angle that maximises the observed speeds (aka the critical angle).

Blazars - Equipartition Doppler factor

- Assumes that there is a maximum brightness temperature that can be achieved by a source - “TB int” or intrinsic Brightness Temperature
- Equipartition limit ~5e10 K (Readhead 1995)
- Inverse Compton limit ~1e12 K (Kellerman 69)
- Observationally determined limit 2.7e11 +/- 25% K (Liodakis+ 15)
- But - MOJAVE team found it to be lower... ~4e10 K (Homan+ 2021)
- Maybe use it as an upper limit?

$$T_{\mathrm{B,VLBI}} = \delta T_{\mathrm{B,int}}$$

$$T_{\mathrm{B,var}} = \frac{\delta^3 T_{\mathrm{B,int}}}{(1+z)^3}$$

Can we use these to solve for our systematic errors?

Blazars - Inverse-Compton Doppler factor

- assumes that synchrotron self-Compton (SSC) is the dominant emission mechanism at X-ray (and Gamma-ray) frequencies
- Needs knowledge of the turnover frequency/sizes/flux density → KVN style multi-frequency...
- Liodakis+ showed that both IC and variability (equipartition) Doppler factors represent FSRQ populations well
- SED modelling could help

$$\delta_{\mathrm{IC}} = f(\alpha)F_m\left[\frac{\ln(\nu_{\mathrm{b}}/\nu_m)}{F_\chi\theta_{\mathrm{d}}^{6+4\alpha}\nu_\chi^{\alpha}\nu_m^{5+3a}}\right]^{1/(4+2\alpha)}(1+z),$$

$$\delta_{\mathrm{cont}} = \delta_{\mathrm{discr}}^{(4+2\alpha)/(3+2\alpha)}.$$

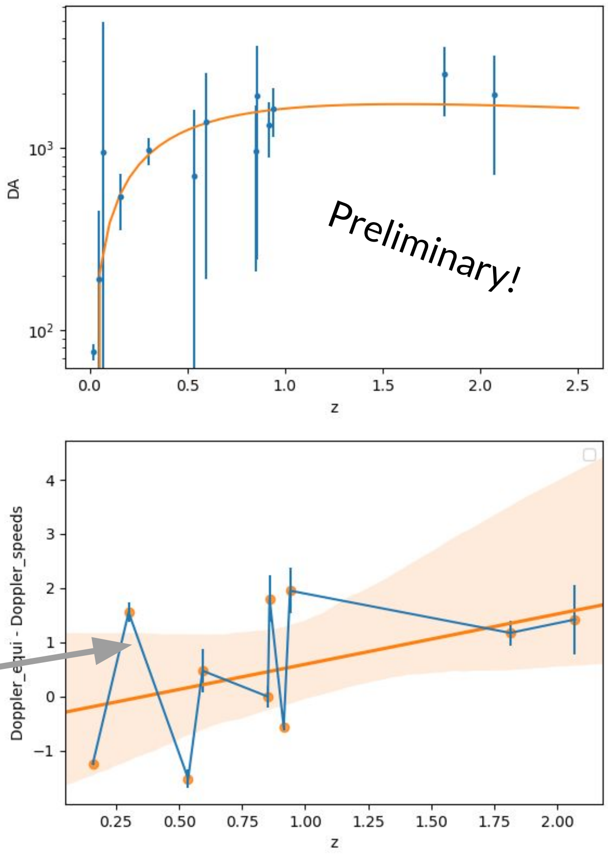
Can we use these to solve for our systematic errors?

Testing using global VLBI data

- Use data of ultra-high resolution VLBI data from the global mm-VLBI array (e.g. Hodgson+ 2017)
- Can achieve >50 micro-arcsecond angular resolution
- Jet proper motions taken from BU monitoring program (Jorstad+ 2017)
- Δt information from single-dish monitoring (Angelakis+2019)
- Doing this “properly”, should reduce the errors

H0 = 71 +/- 2 km/s/Mpc
Omega_m = 0.33 +/- 0.15

- Don’t trust these numbers at this stage!



Probably observational systematics, but this is what a z-dependence would look like

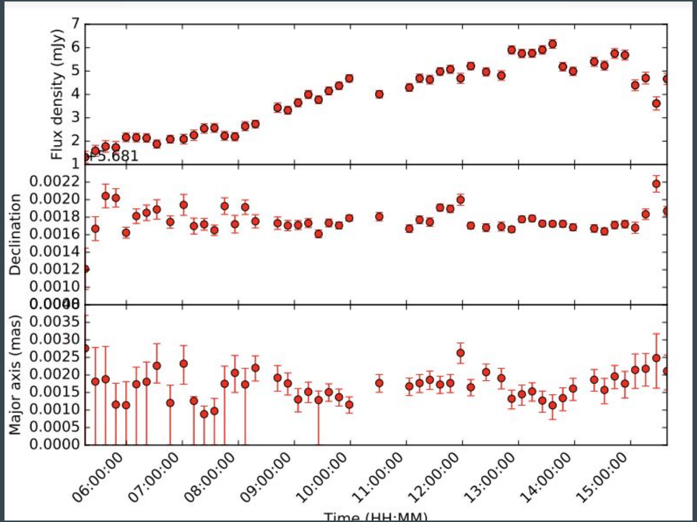
Hodgson+ in prep

Systematics.. Causality assumption

- Indirectly looked at by Liodakis+ 2015
  - Tried to find the best method for finding the Doppler factor in the blazar population
  - Found that the variability Doppler factor best fit the population
  - Since the variability Doppler factor relies on the causality assumption, we think it holds up to within the ~10% errors of the experiment
- On a physical level, the emission from 3C 84 is due to synchrotron radiation by electrons (or other charged particles) being accelerated around magnetic field lines travelling at nearly the speed of light. Given the physics of the radiation, we believe it likely that the emission is tightly constrained by the speed of light, but not exactly.
- Also, for statistical errors, we can “average down” the errors by observing multiple flares within the same source

Calibrating source-based systematics on Microquasars

- If we make the assumption that the causality arguments and the geometry (disk or spherical-like) of a microquasar is similar enough to a “real” quasar, we can calibrate our systematics on microquasars with parallax distances
- We can ‘mix’ these systematic uncertainties into a ‘fudge-factor’ - “K-factor”
- Work done by my student **Daehyun Kim**
- Measured on Cygnus X-1 - parallax distance 2.2 kpc (Miller-Jones+ 2021)
- Used the VLBI measurements from the parallax measurements!

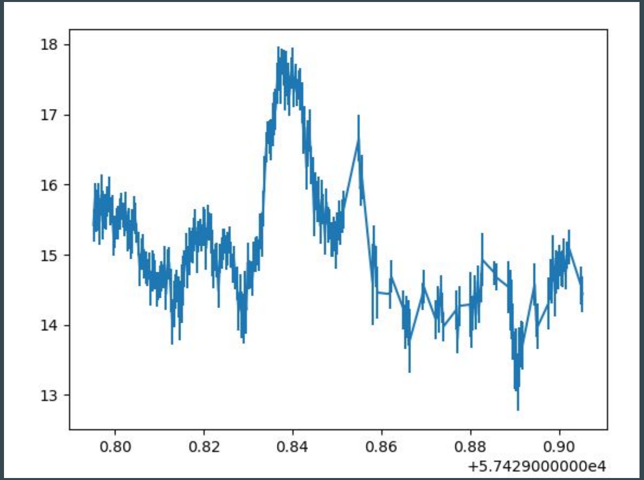


(Cyg X-1 - Courtesy James Miller-Jones)

Calibrating source-based systematics on Microquasars

- We can then calculate the K-factor
- Theta ~ 2 mas
- dt ~ 0.036 days ~ 50 minutes
- Assuming Delta=1, we get a distance of ~2 kpc to Cyg X1 -> Delta=1.1
- K ~ 0.64
- **Very preliminary!!**
- 0.64 * 1.8x scaling (effectively measuring the speed of light) = 1.15 -> 15% above the speed of light -> seems ruled out
- 0.64 * 1.6x scaling = 1.02
- **Seems to suggest disk-like geometry and that the causality argument agrees within errors**
- Error bars being calculated as we speak...

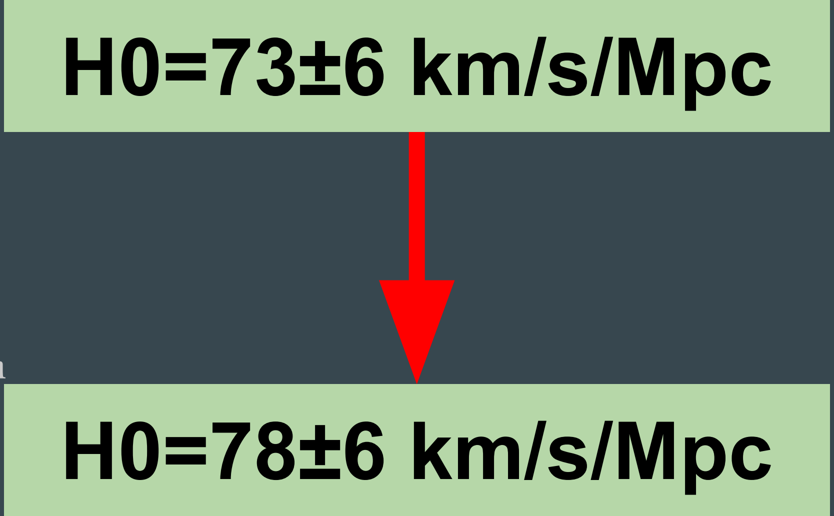
$$K = \frac{D\theta_{\mathrm{VLBI}}}{c\Delta t\delta}$$



VLA LC courtesy of Alex Tatarenko

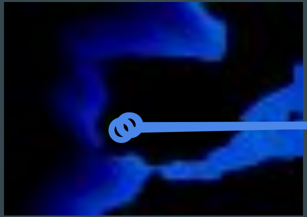
Implications for the Hubble Constant Controversy

- ***If*** these results hold up, we need to revise down the distance to 3C 84 by about ~6%
- This means that our H0 estimate would be revised *up* by about 6%
- Also, remember that we assumed Delta=1
- If there is a mild Doppler factor, it would increase the distance (and therefore lower the H0 measurement)
- Would need a Doppler factor of Delta>1.15 to match the observations with the CMB measurements -> unlikely in this case - but need to be confirmed
- **If Delta<~1.1 with the Distance Ladder and that the tension is *real***
- Very very very preliminary! Waiting on errors and significance calculation.. More sources... etc...



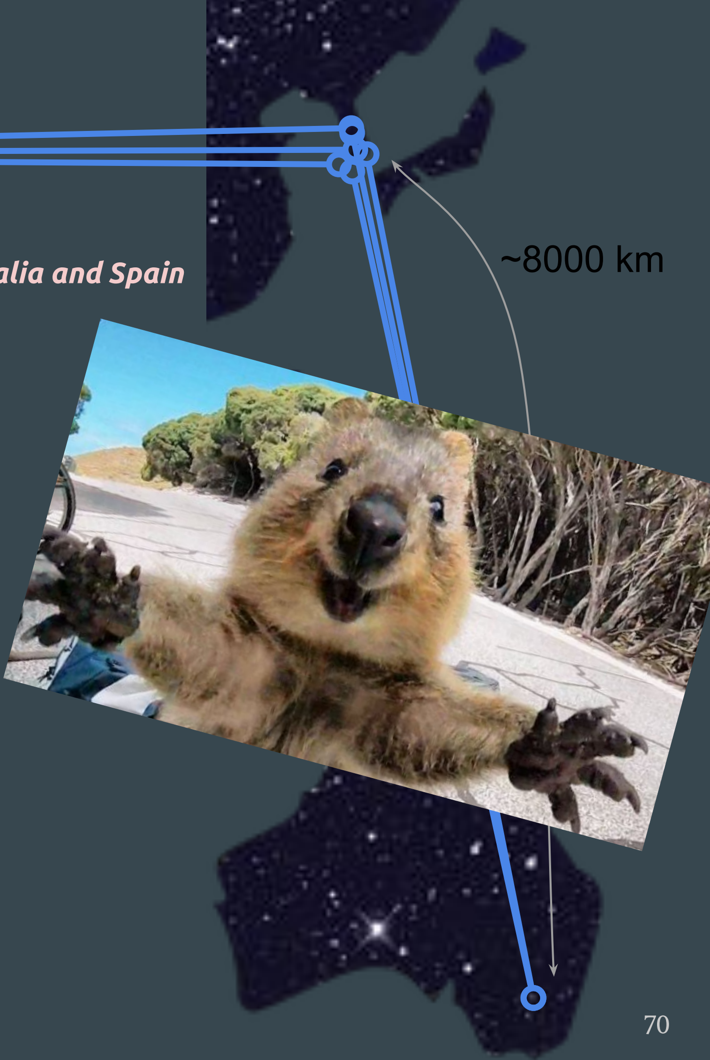
H0=73±6 km/s/Mpc

H0=78±6 km/s/Mpc



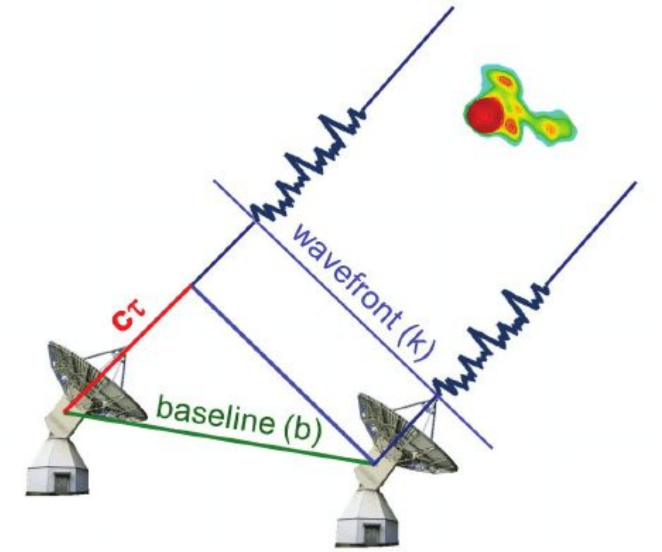
Cosmological QUOKKAS

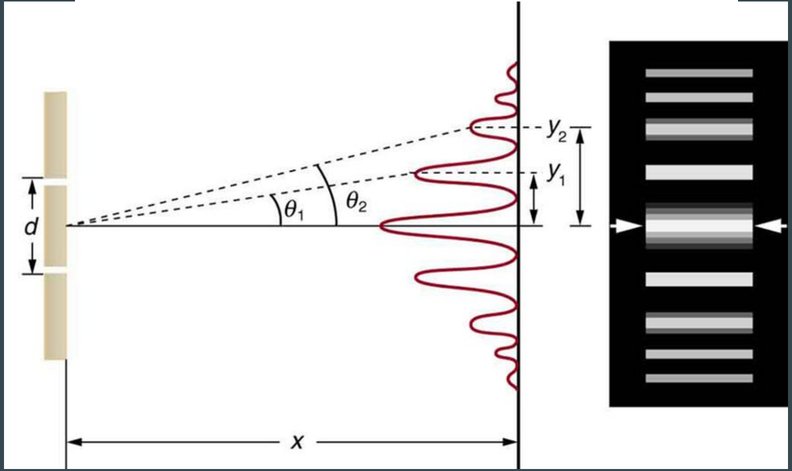
Quasar observations using the KVN from Korea to Australia and Spain



- **We require high cadence and high resolution!**
- A Quokka is a small marsupial on an island off Perth
- Between KVN and Mopra (and potentially Yebes and even Italy)
- ~8000 km baseline, observations every 2-3 weeks
- Initial sample of ~20 sources (need a detection survey first)
- Extremely high resolution (~50 uas at 3mm)
- Unique NS baseline
- Mark6 and OCTAD backend ordered, test observations have been conducted at 22/43/86 GHz - success!
- Full observations starting this year...
- Tried to detect M87 and Cen A - failed.

Very Long Baseline Interferometry





Any pair of telescopes can be thought of as the ‘slits’ in a double-slit experiment.

This (when everything is working properly…) will give fringes

The fringe is in effect sampling the Fourier Transform of the sky brightness distribution

Many telescope pairs = better sampling of the FT

Inverse FT to give you an image

Much more complicated than that, but that’s the basic idea

Why VLBI?

Resolution!

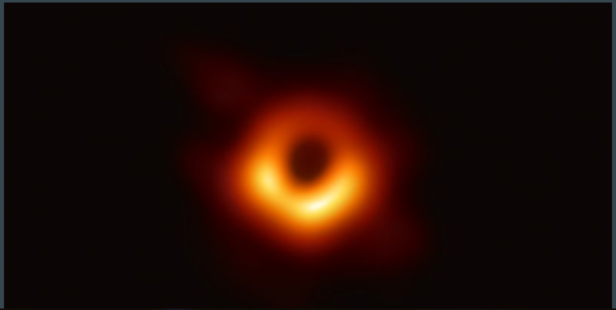
Resolution is wavelength/telescope diameter

VLBI diameter = distance between the most distant radio antennas (but be careful - can resolve out structure... probably the case in black hole image)

Can make an Earth sized (or space!) telescope

Event Horizon Telescope = ~20 uas

Equivalent of resolving your smartphone on the moon



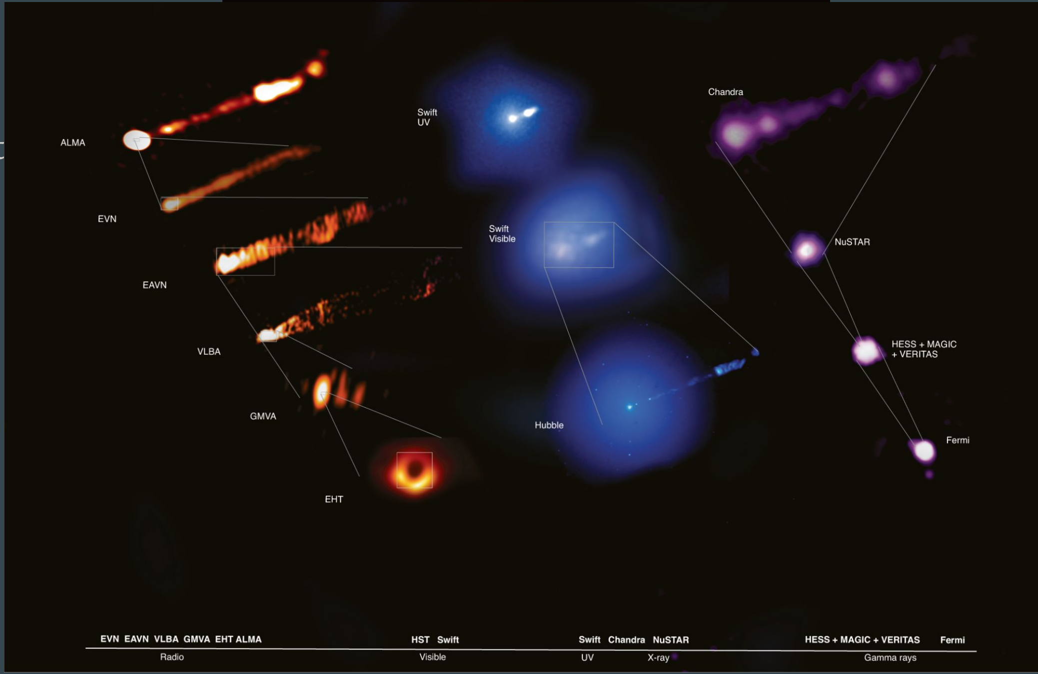
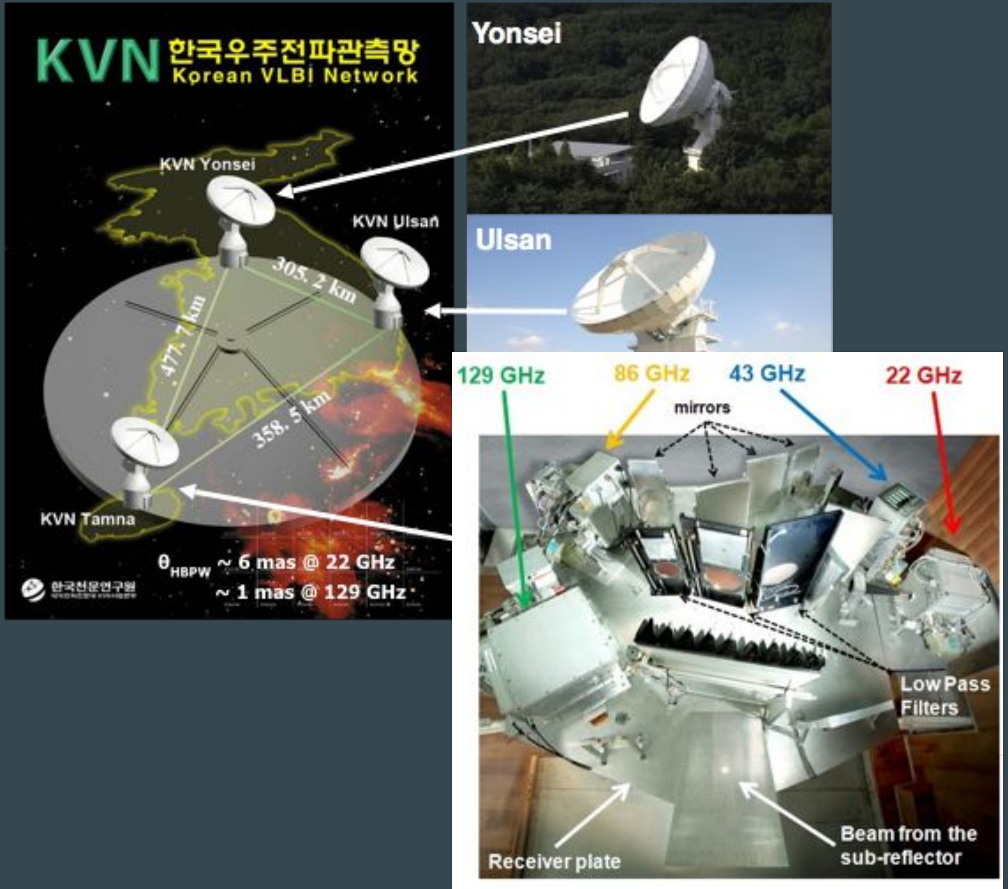


Image by JC Algaba

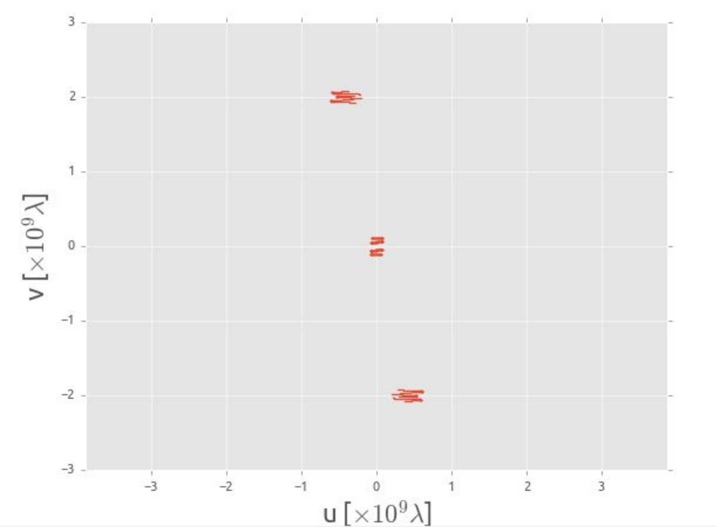
The Korean VLBI Network

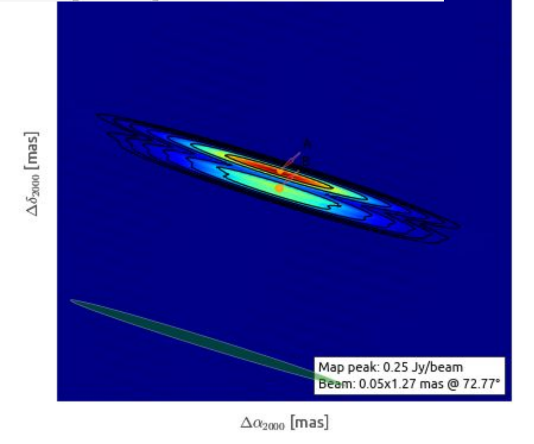
- Three 21m dish located in Seoul, Ulsan, and Jeju island, Korea
- Remotely operated from Daejeon, center of the array
- 22/43/86/129 GHz bands
- 4th dish under construction in Pyeongchang (Not Pyongyang!)
- Multi-frequency quasi-optics
  - First realization in the world
  - Simultaneous multi-frequency observations
  - Frequency Phase Transfer technique



The QUOKKA(S) Array

- High cadence observations
- Mopra for low-dec sources
- Yebes for high-dec sources
- Extremely high resolution (~50 uas at 3mm)
- Unique NS baseline
- Mark6 and OCTAD backend installed
- Not great for imaging... but OK for our purposes
- Mopra maybe coming to EAVN/GMVA soon...



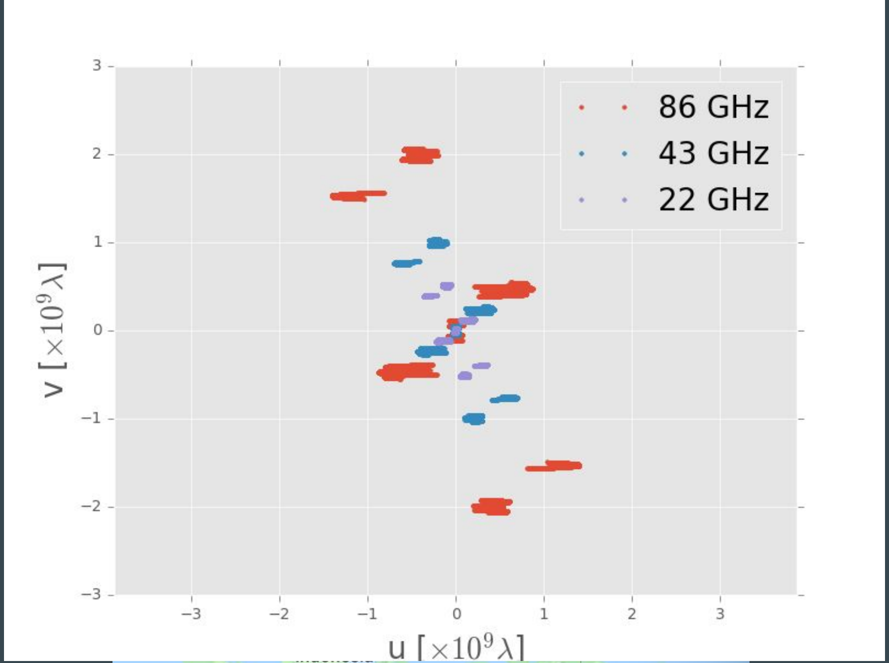


Towards an Asia-Pacific VLBI Network

- Effectively a single-baseline
- Can we do more than just the cosmology project?
- Limited imaging capabilities
- KaVA/EAVN with Mopra?
  - 22/43 single frequency
- Good for mid-dec sources
  - M87
  - Sgr A* (may be resolved out...)
  - Cen A

Towards an Asia-Pacific VLBI

- Thailand will make imaging on the array much better
- Very useful mid-spacing
- NS orientation has implications for common visibility/high cadence obs.
- New Zealand?
- South Africa?
- Mauna Kea?
- Multi-frequency a must...



Can we actually resolve the sources?

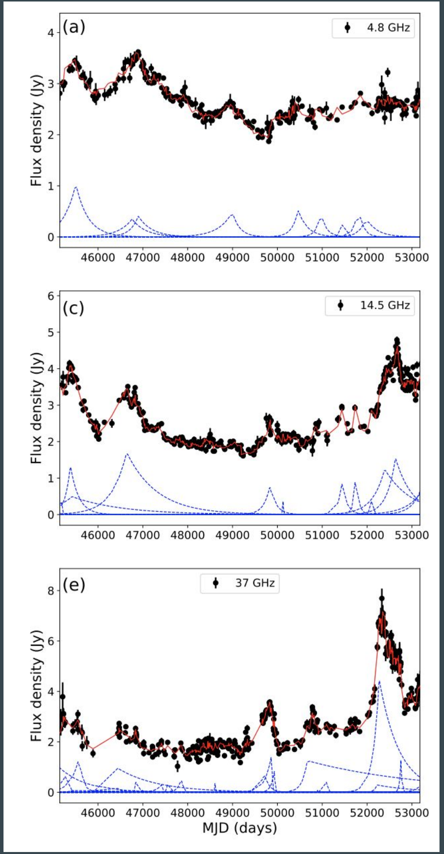
Short answer - yes

Took the ‘raw’ t_var data from Liodakis+ using OVRO 15 GHz data

Many interesting things...

Combined with MOJAVE data (still using variability Doppler factor which assumes a cosmology) and can mostly recover the input cosmology

Giving a feel for observational systematics?

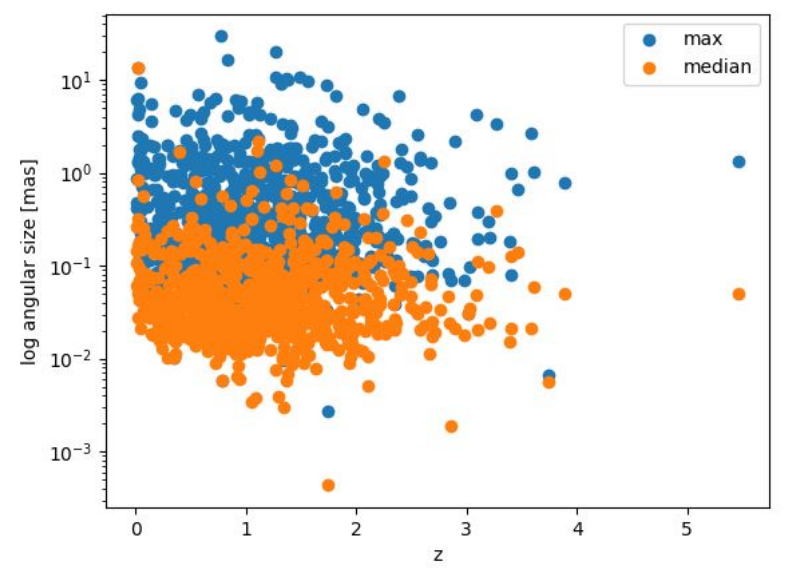


Median vs max variability size

Estimate the 'variability' size by reversing equations showed earlier

The variability sizes of the largest flares are 1-2 orders of magnitude larger than the median

Turns out that these longer flares are what we are sensitive to using VLBI. Often > 1 mas

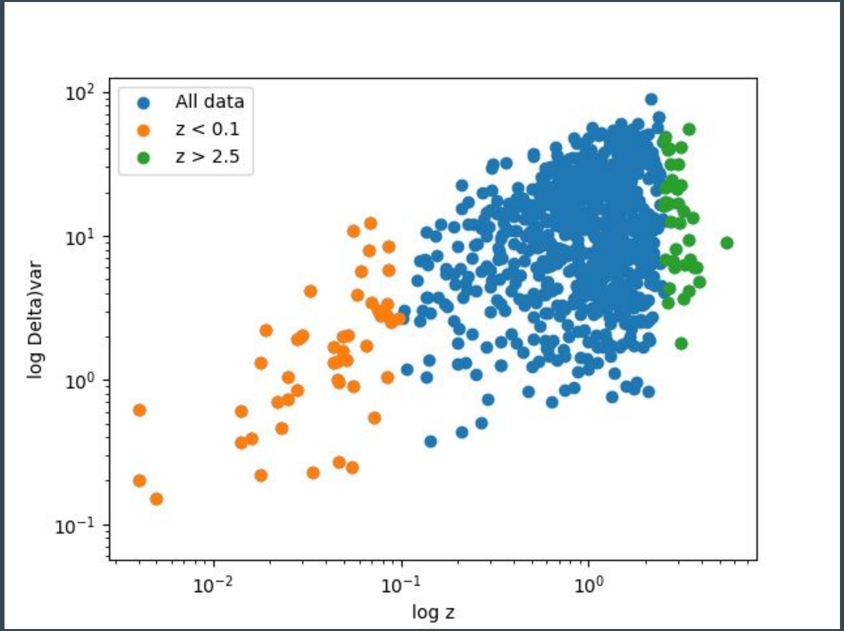


Doppler factor evolution

We would expect that the Doppler factor will increase with redshift, because Doppler boosted sources are brighter and more distant sources are fainter → potential bias

Is seen

Not necessarily a problem - so long as the Doppler factor corrections are made accurately



Combining with MOJAVE data

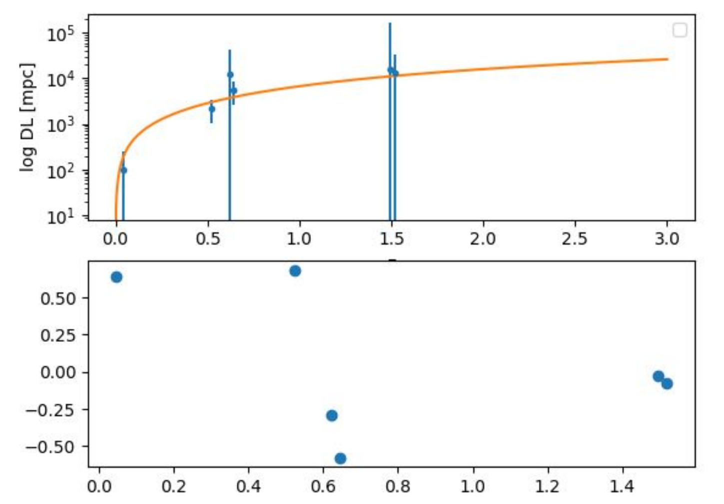
Not too many epochs that fit the criteria...

But we more-or-less recover the input cosmology (included in the Doppler factor)

Sensitive to the major axis of the fitted sizes

Matches with the longest flares

Basically seems to work...



Conclusions

- Demonstrated a new method for measuring distances to AGN
- Tested some famous sources and we find they are consistent with other methods
- Hints that we may be more consistent with the Distance Ladder than the CMB
- 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
- Can continuously monitor sources -> averaging down our statistical errors.
- We believe that we have developed ways of handling systematic uncertainties.
    - Multiple Doppler-factor test allows us to handle redshift dependent systematics (or at least check if they exist)
    - Low redshift sources with Doppler ~1 can be calibrated on microquasars with parallax measurements
- We believe that with a properly designed experiment, we can significantly improve our errors.