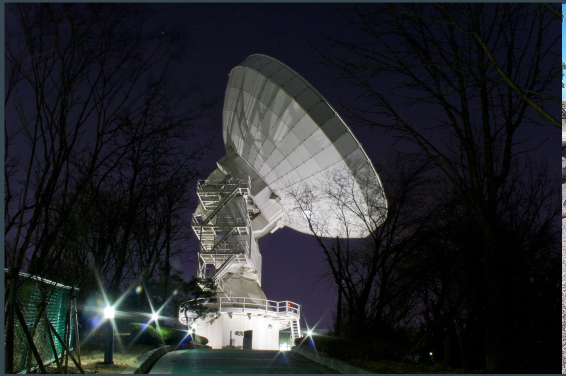

Cosmological QUOKKAS

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National Research Foundation of Korea

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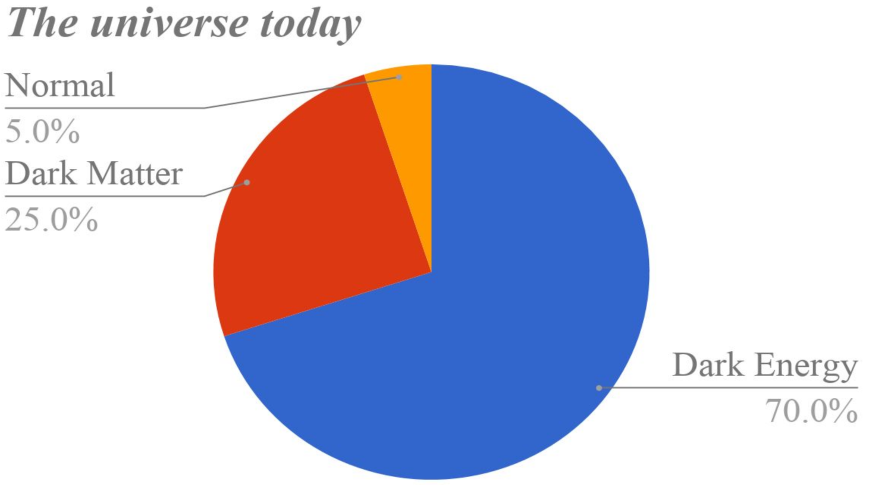
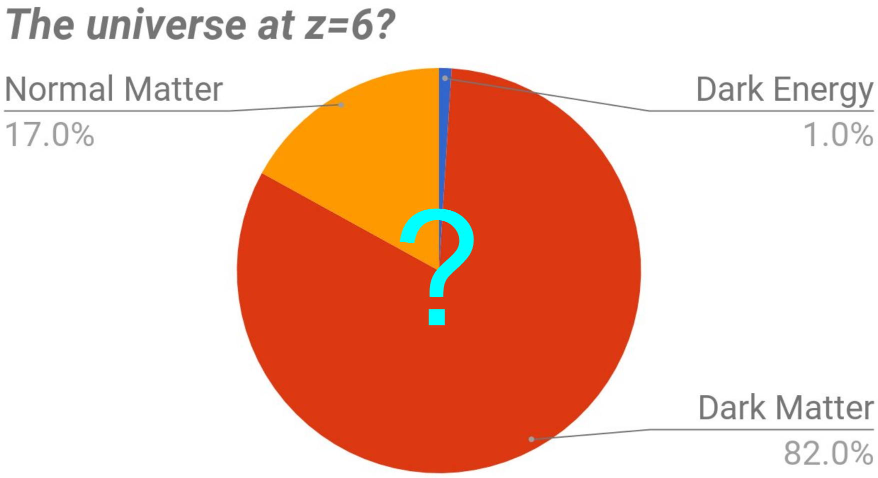
Open questions..

- 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





Open questions..

- Hubble Constant tension (low-z)
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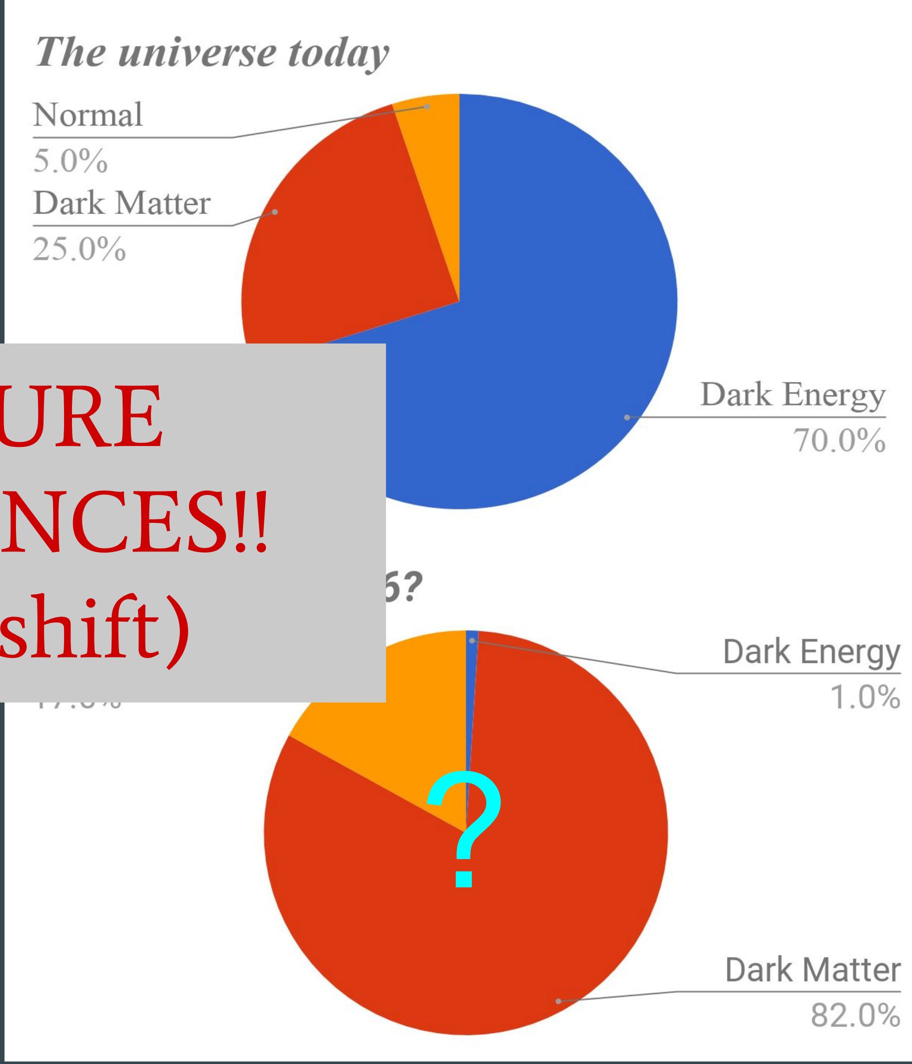
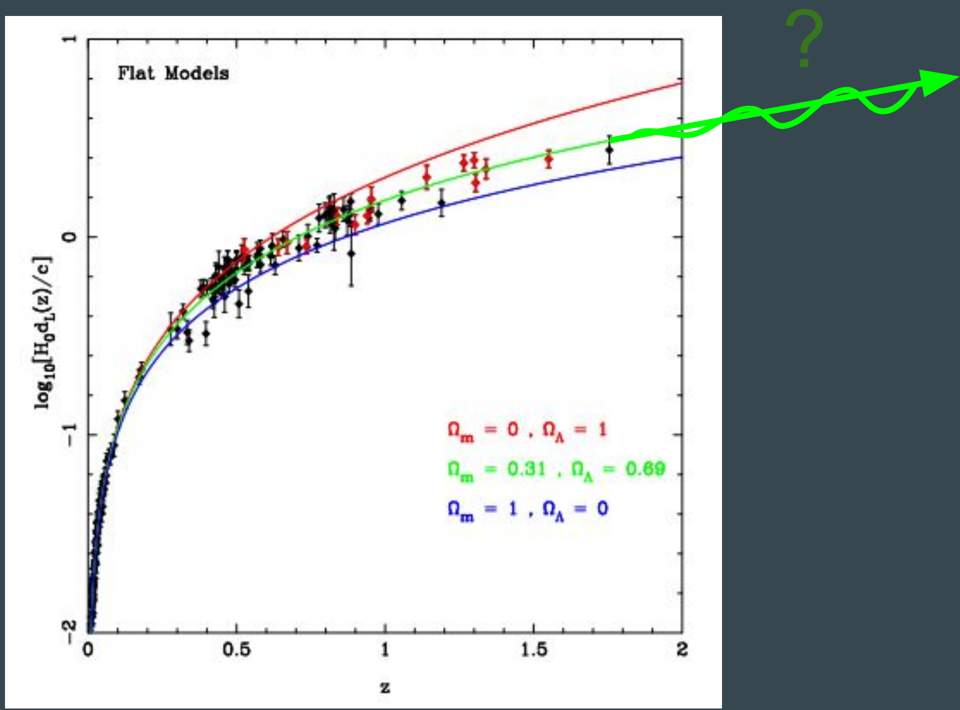
MEASURE DISTANCES!!
(vs redshift)



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

Current cutting-edge

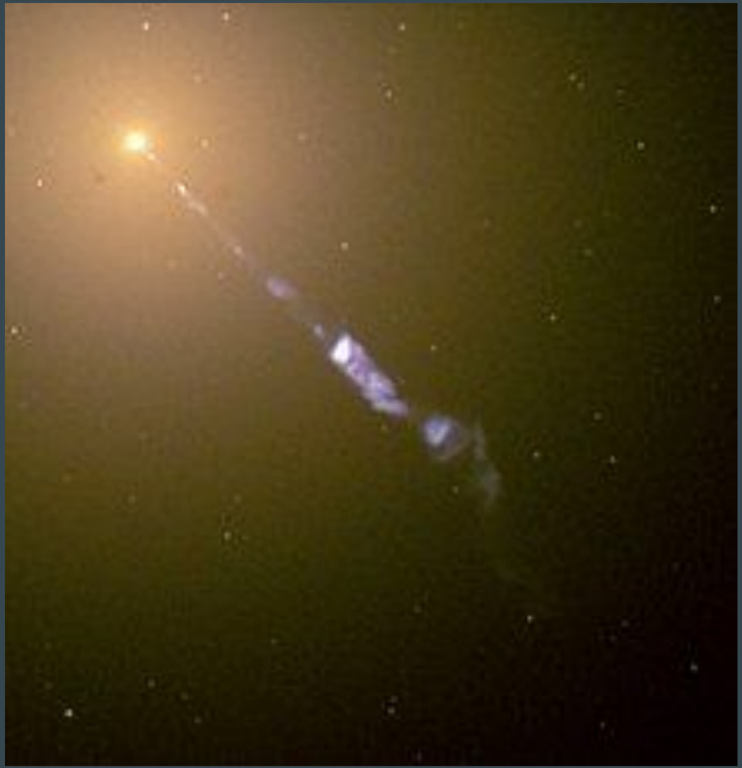
- Type Ia Supernovae (SN Ia)
  - Very bright "standard explosion"
  - Dark Energy discovery (Nobel 2011)
  - Distances up to z~2
- Baryonic Acoustic Oscillations
  - Imprint of early universe physics on large scale galaxy distribution
  - Distances up to z~2.5
- Cosmic Microwave Background
  - Fit cosmological 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
  - 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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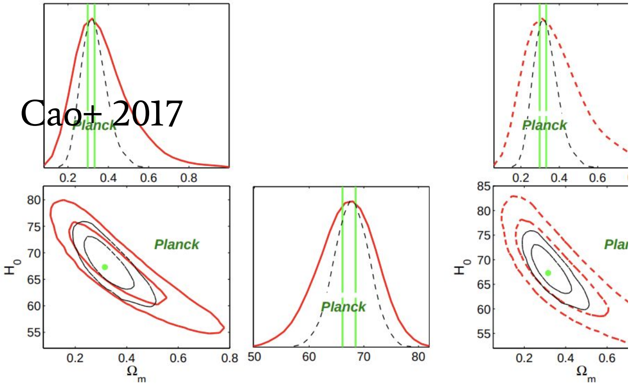
M87 jet, Image: NASA

Active Galactic Nuclei as standard candles

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. 8.— Cosmological constraints on the flat ΛCDM model fror
(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.

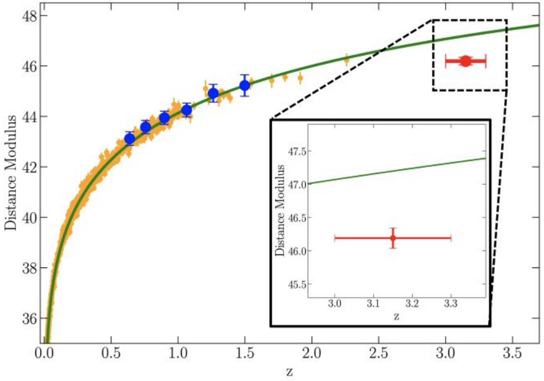
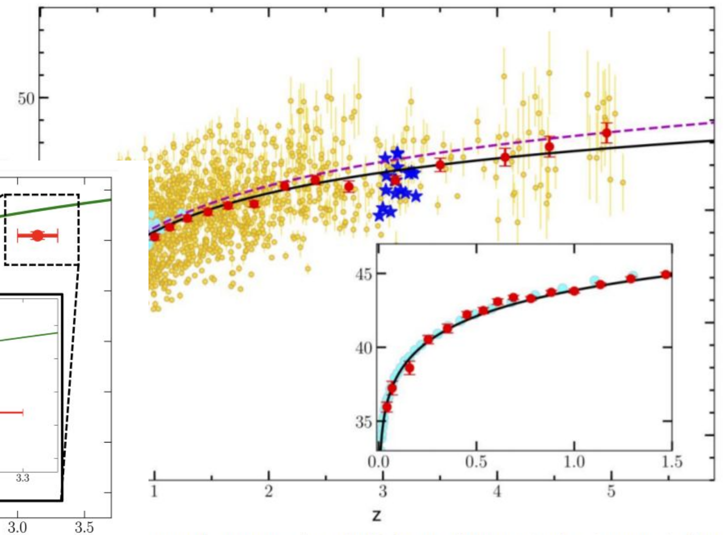


Fig. 4. Hubble Diagram of *Pantheon* supernovae (orange points, Scolnic et al. 2018), quasars at redshifts $z = 0.7$–1.3 (blue points), and quasars at redshifts $z = 3.0$–3.3 (red point). The luminosity distances for quasars are calculated using the parameters γ and β as described in the text, i.e. assuming 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.



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,
he statistical analysis. The new sample of $z>3$ quasars with dedicated XMM-
s 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:

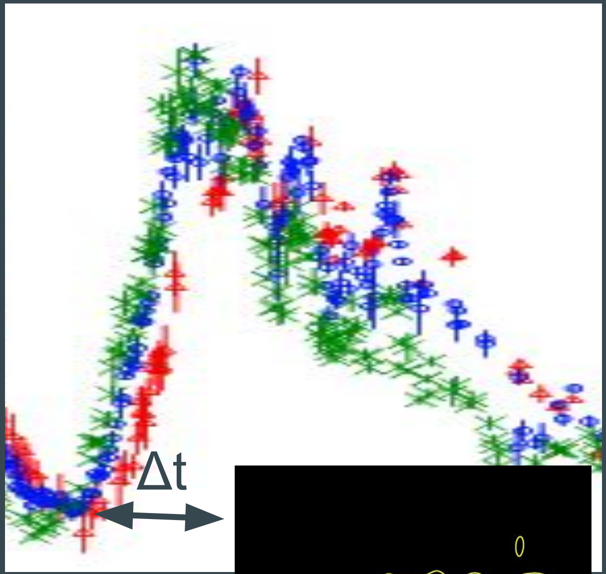
The variability seen in AGN at radio wavelengths is reasonably constrained by the speed of light.

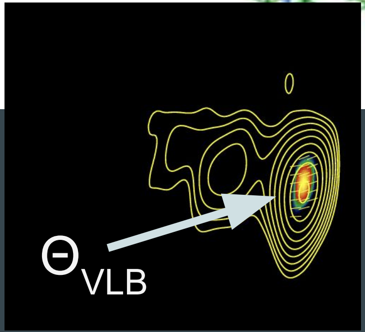
How are we doing it?

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}





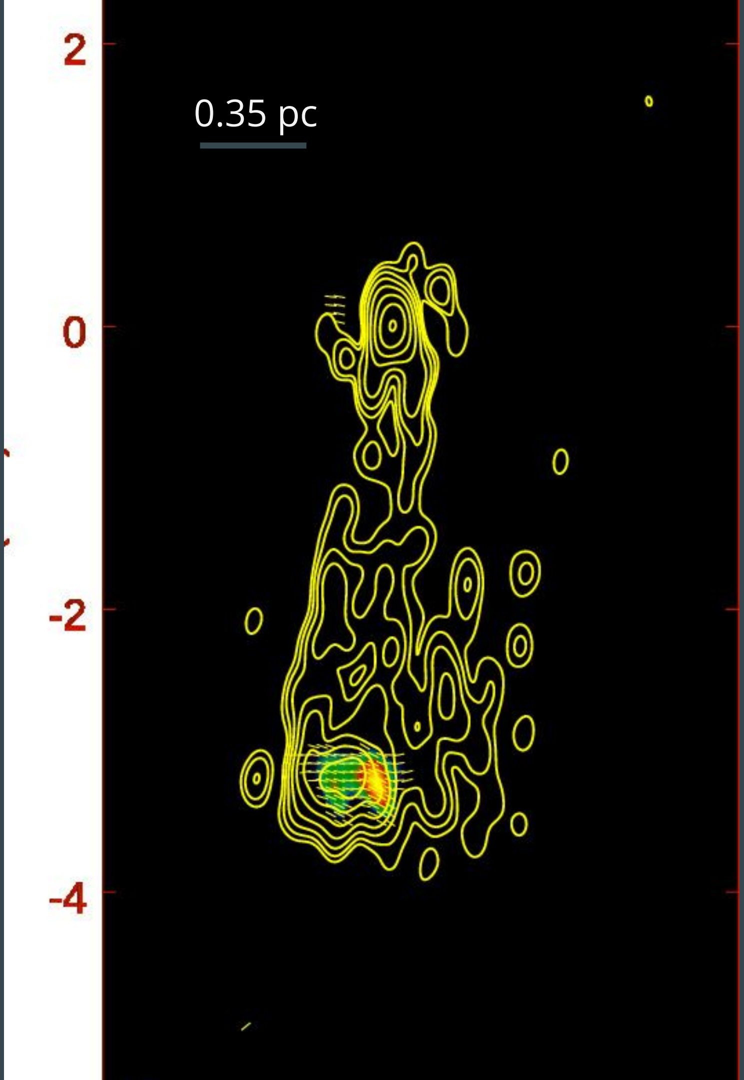
$$D_{\rm A} = \frac{c\Delta t\delta}{\theta(1+z)}.$$

Distance can be found when the Doppler factor is known!

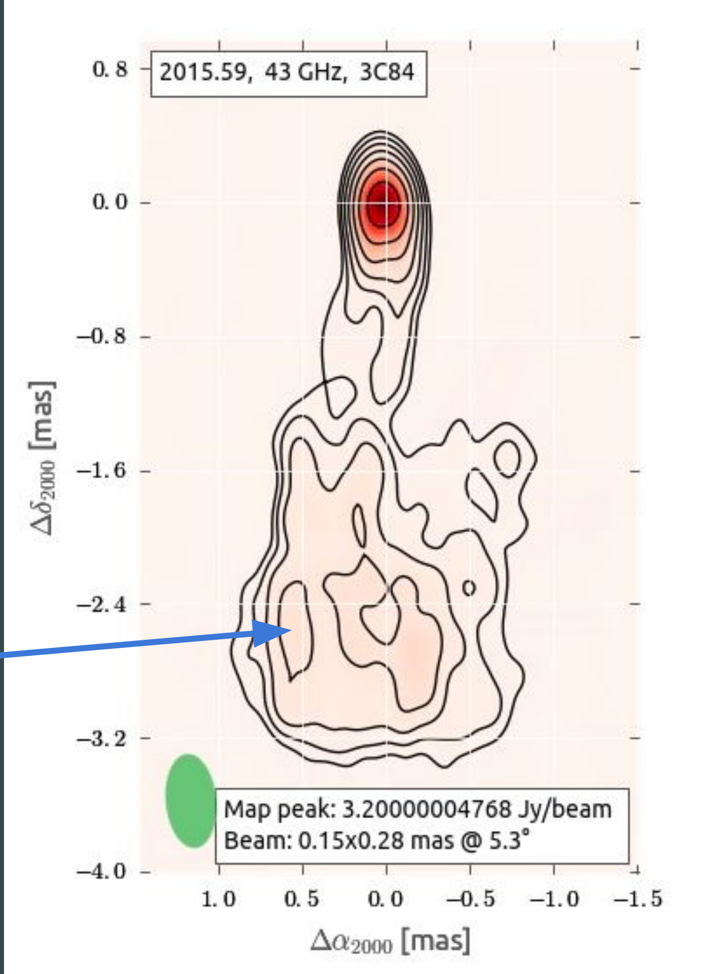
Looked at decades ago by Wiik+ 2001… but never kept up

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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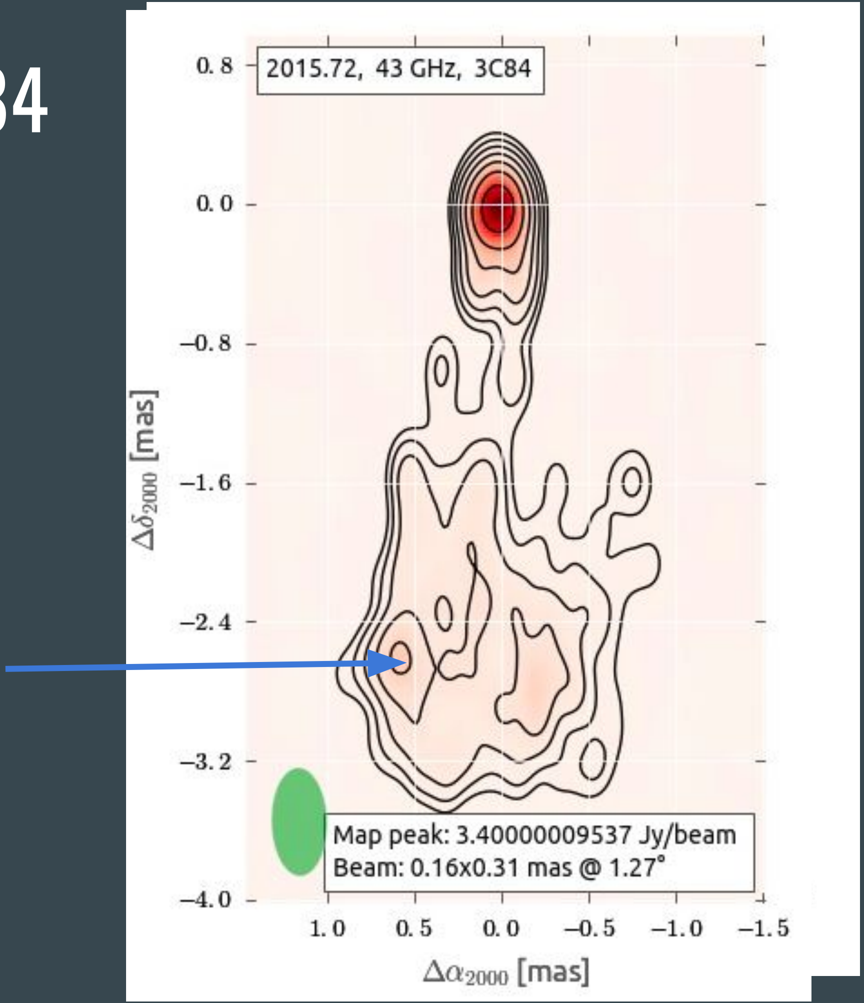

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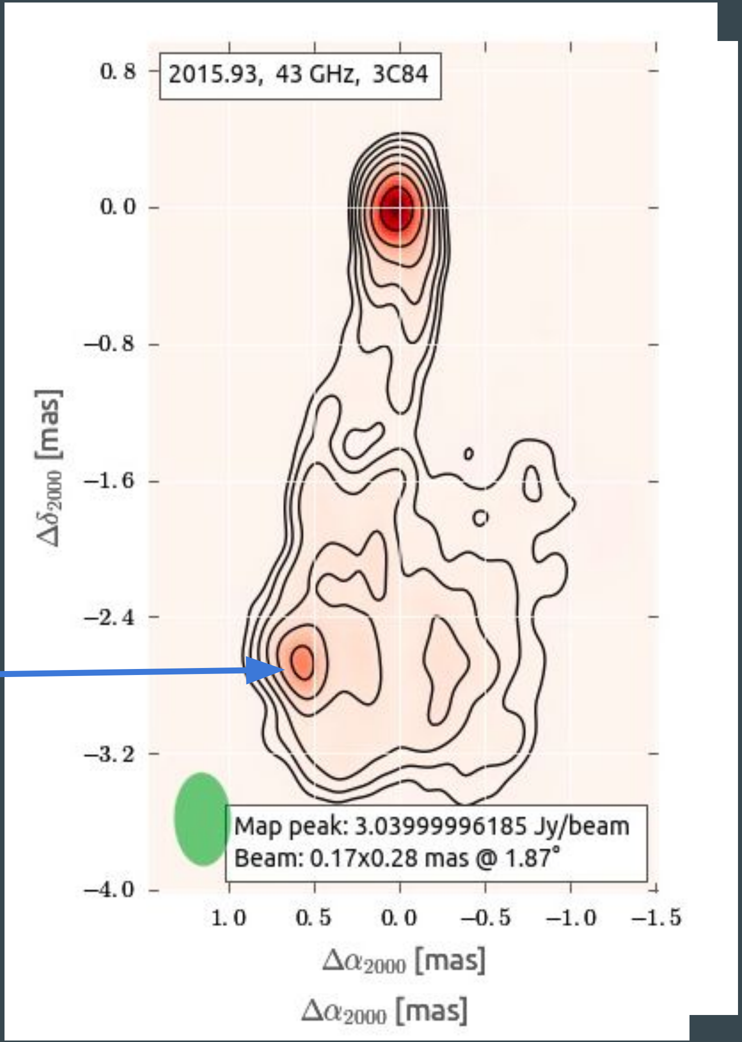

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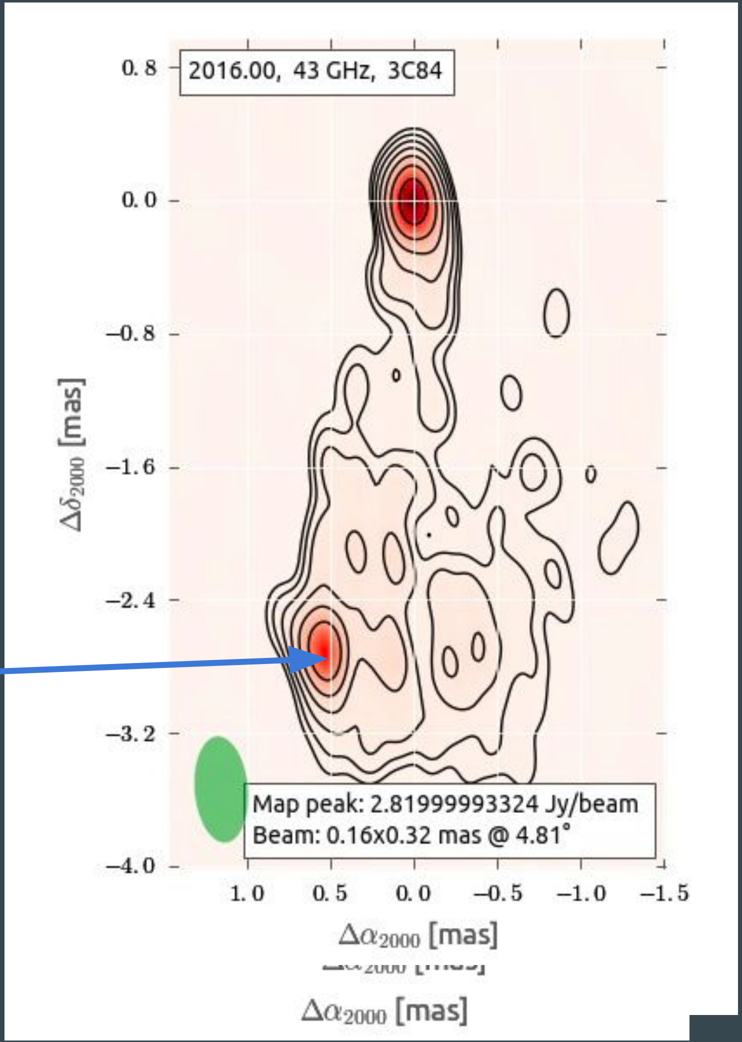

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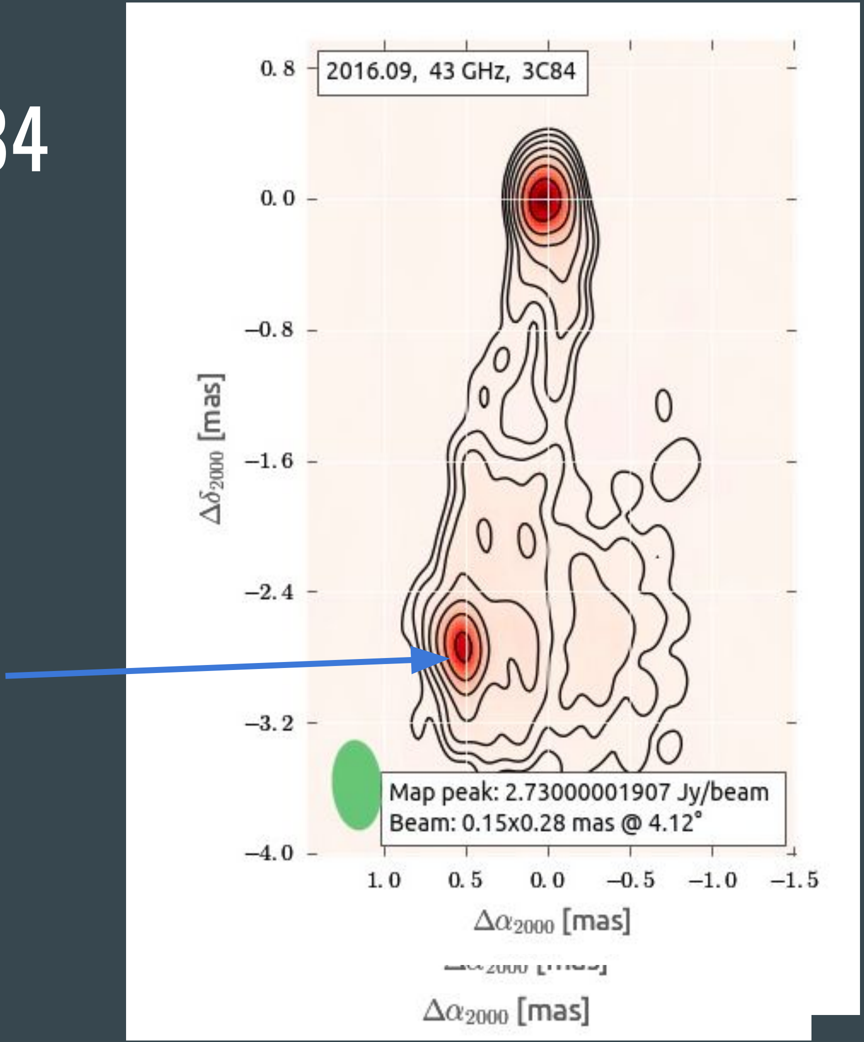

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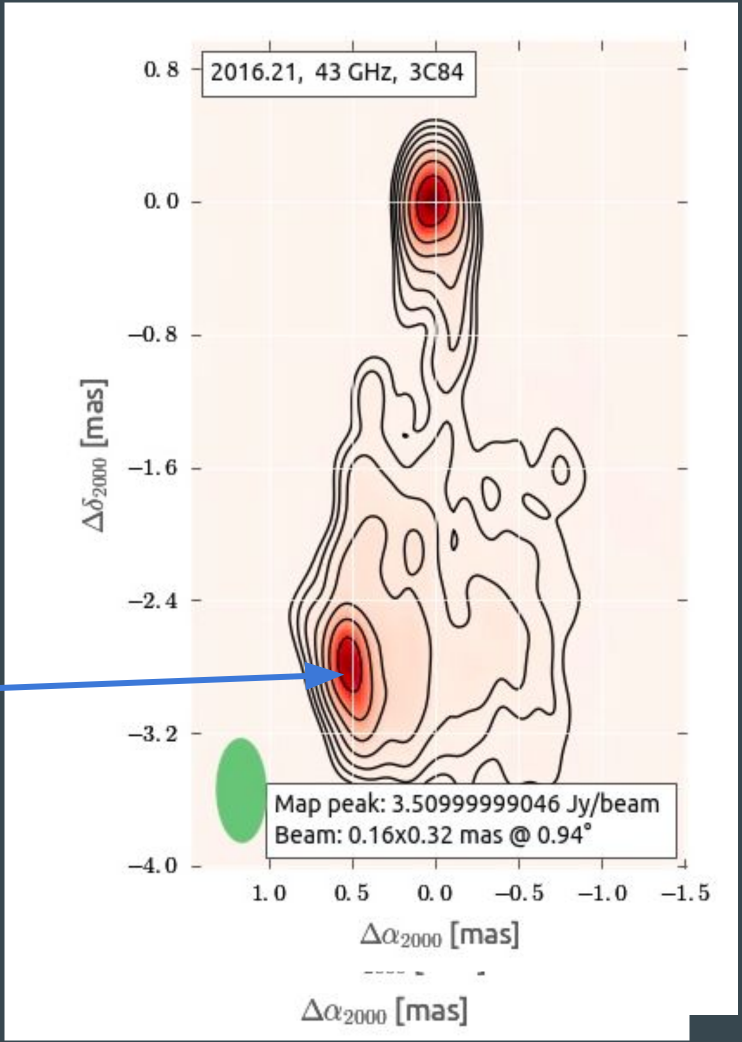
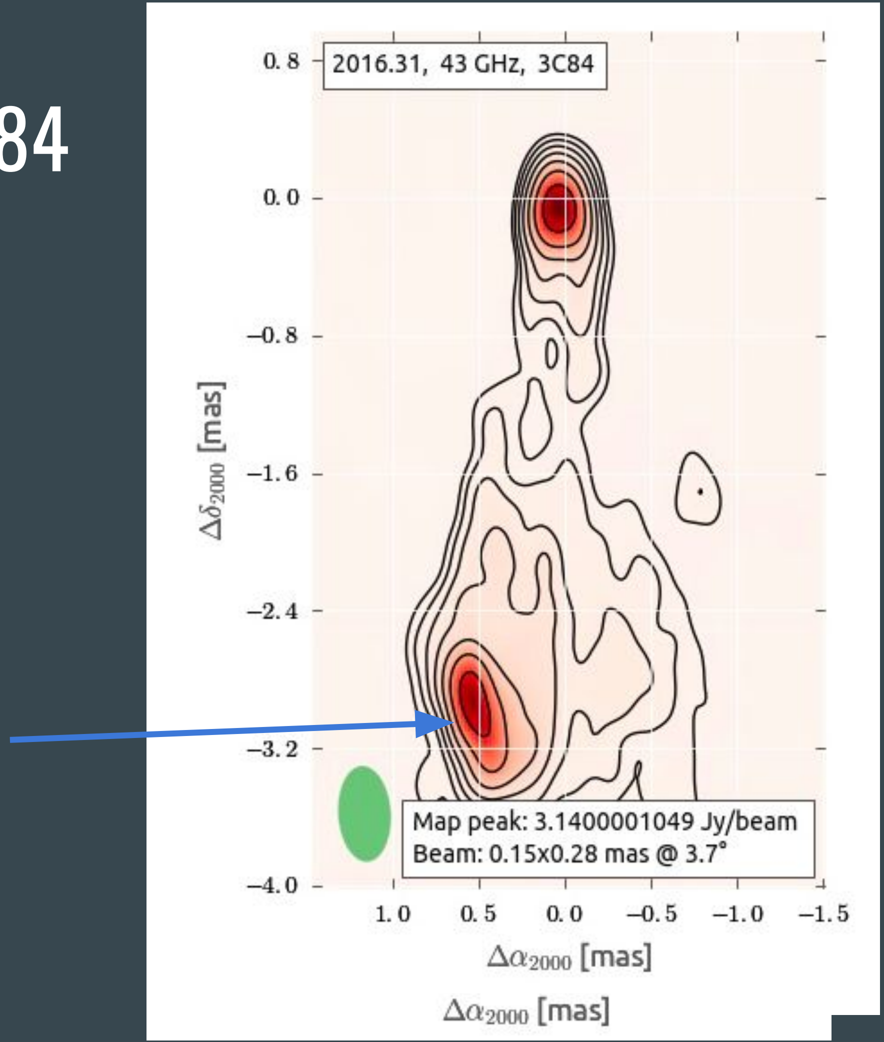
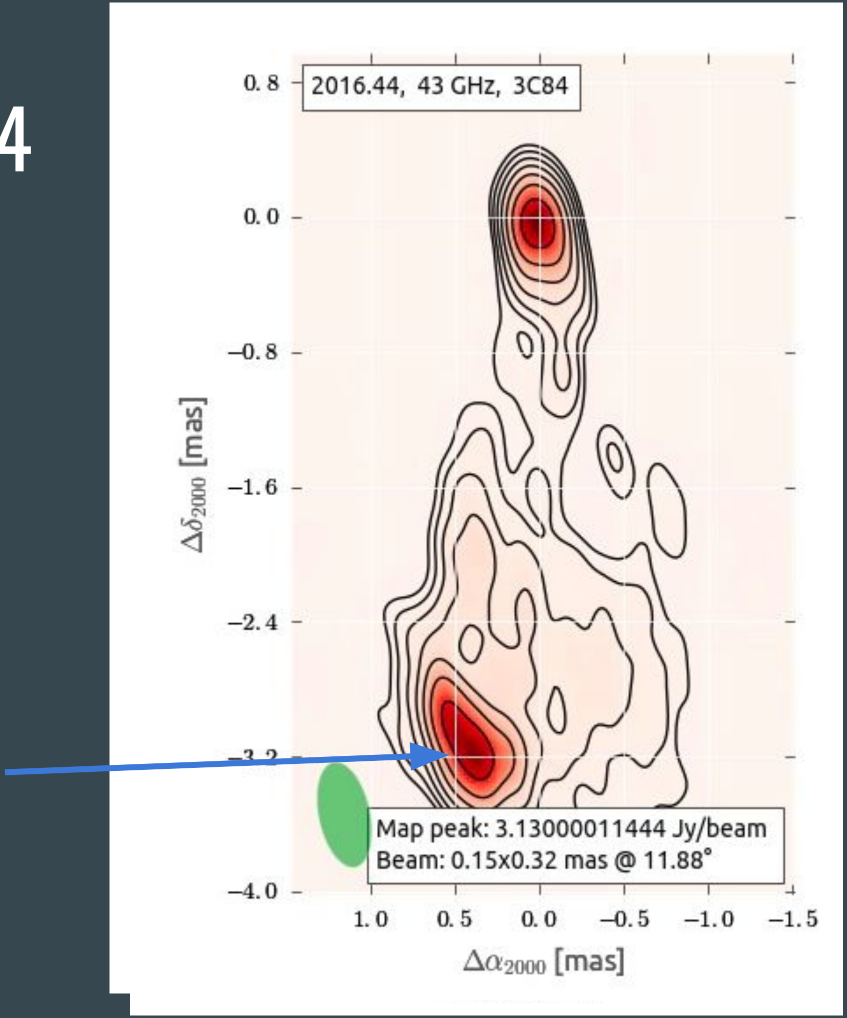


A flare in 3C 84



A flare in 3C 84



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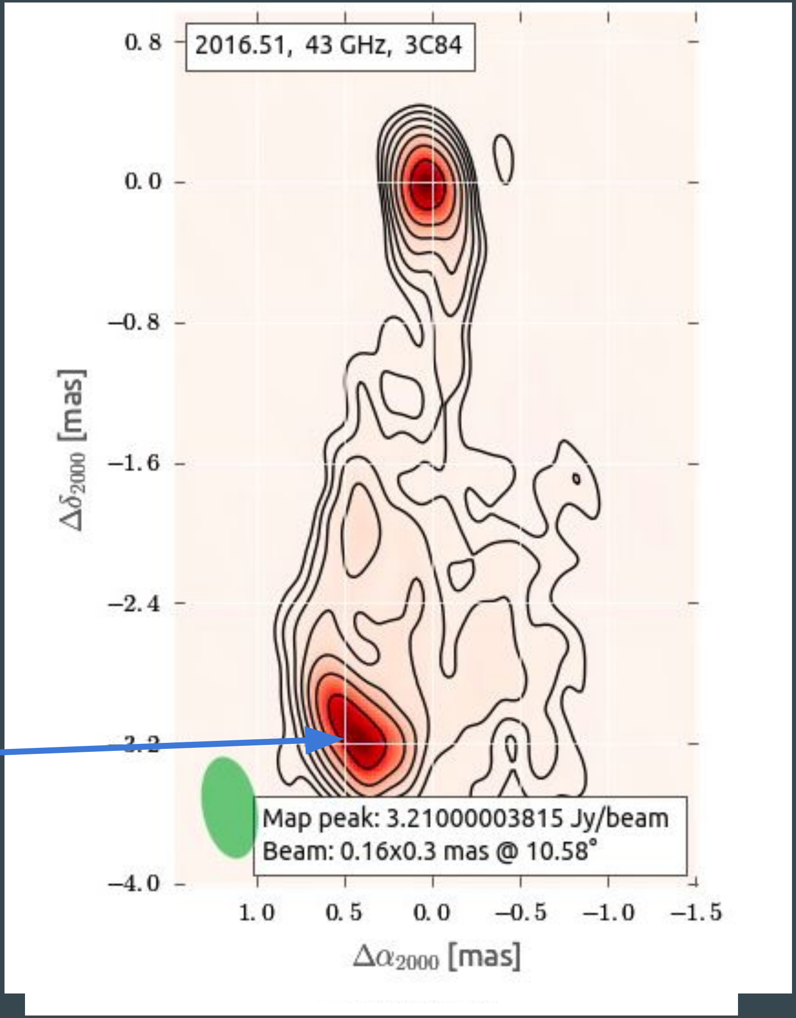

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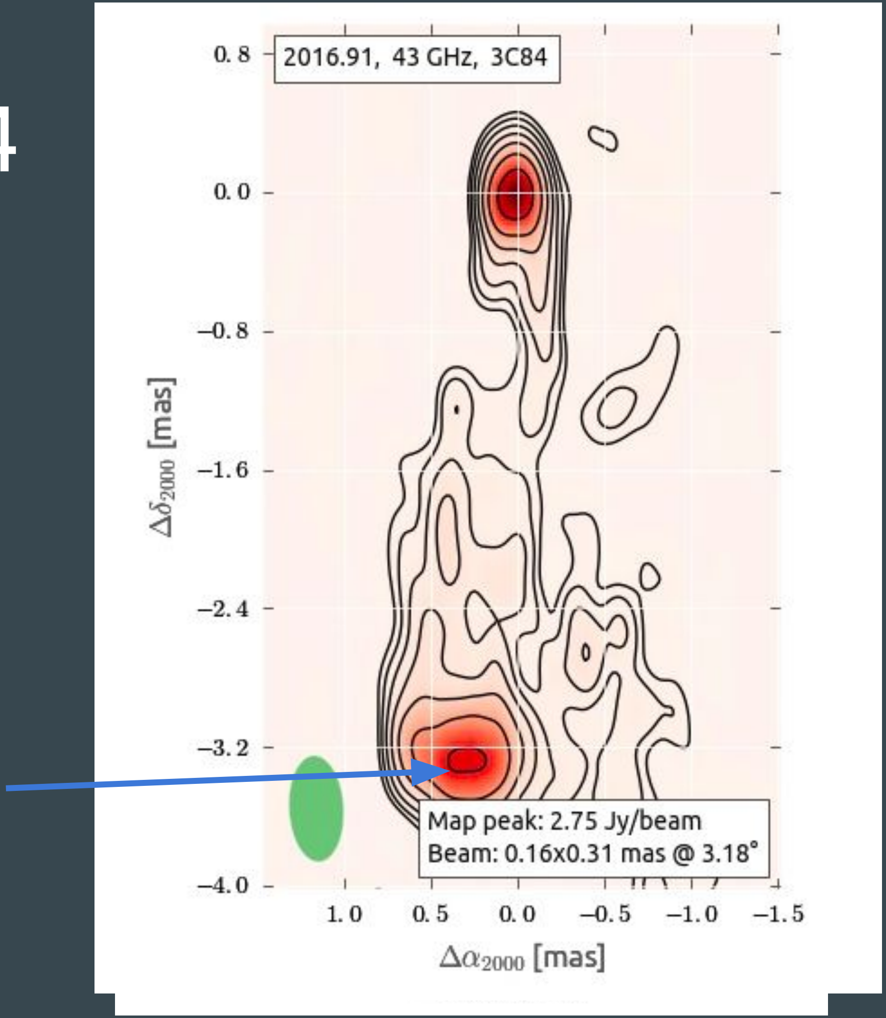

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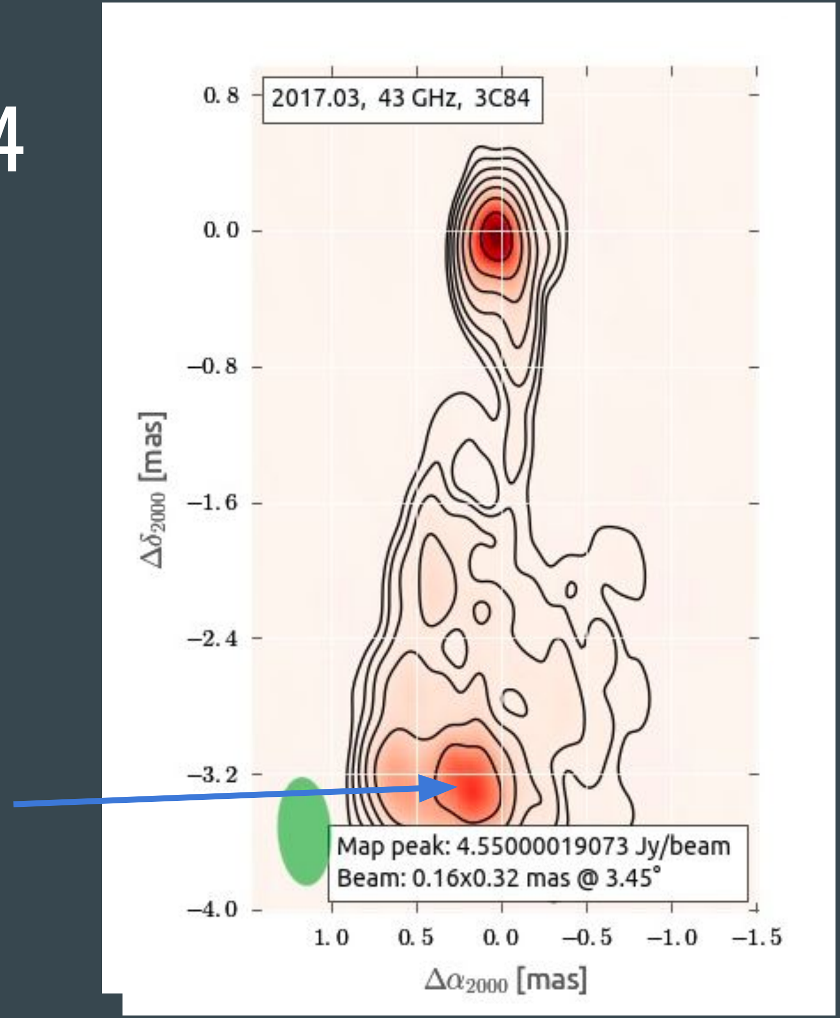
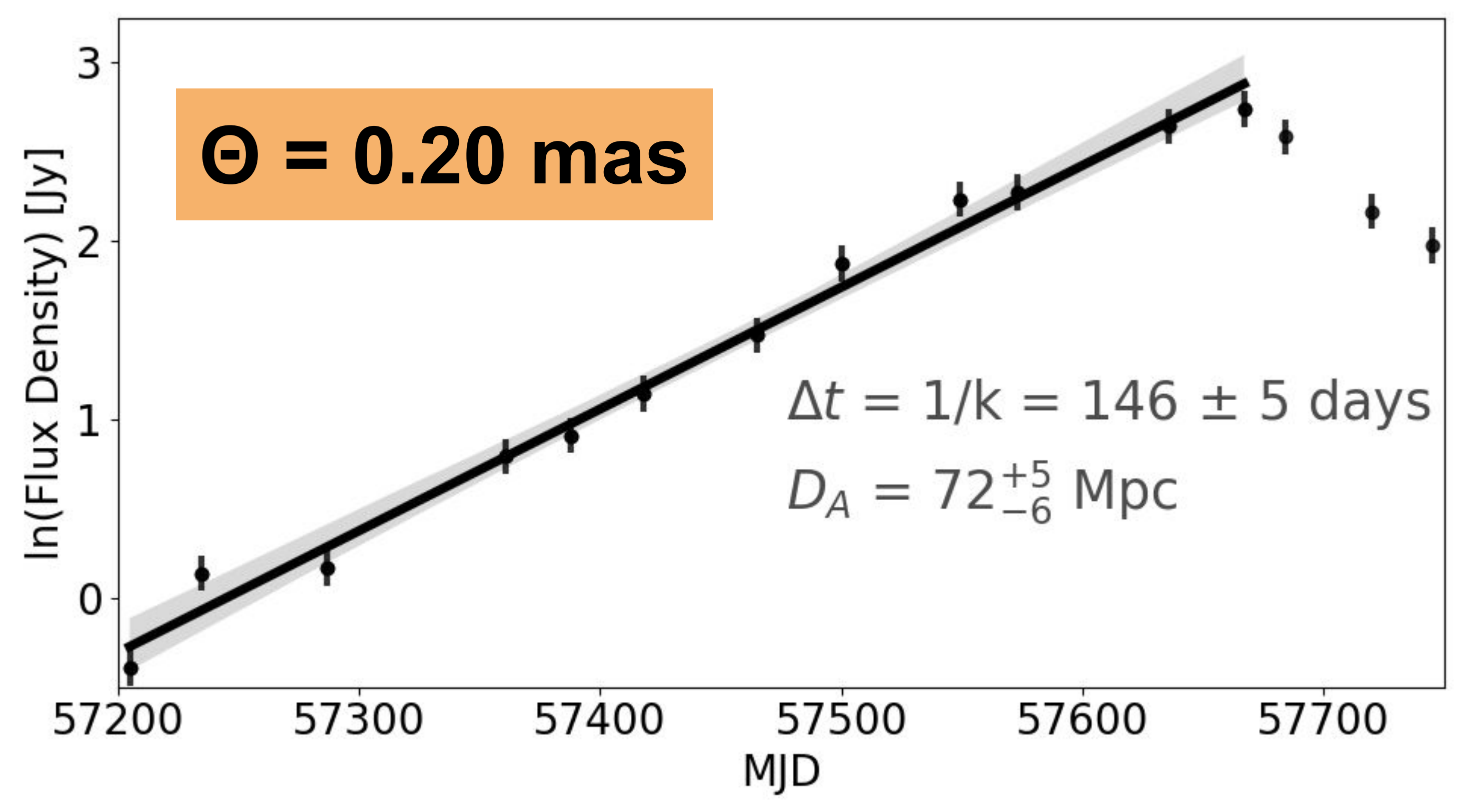
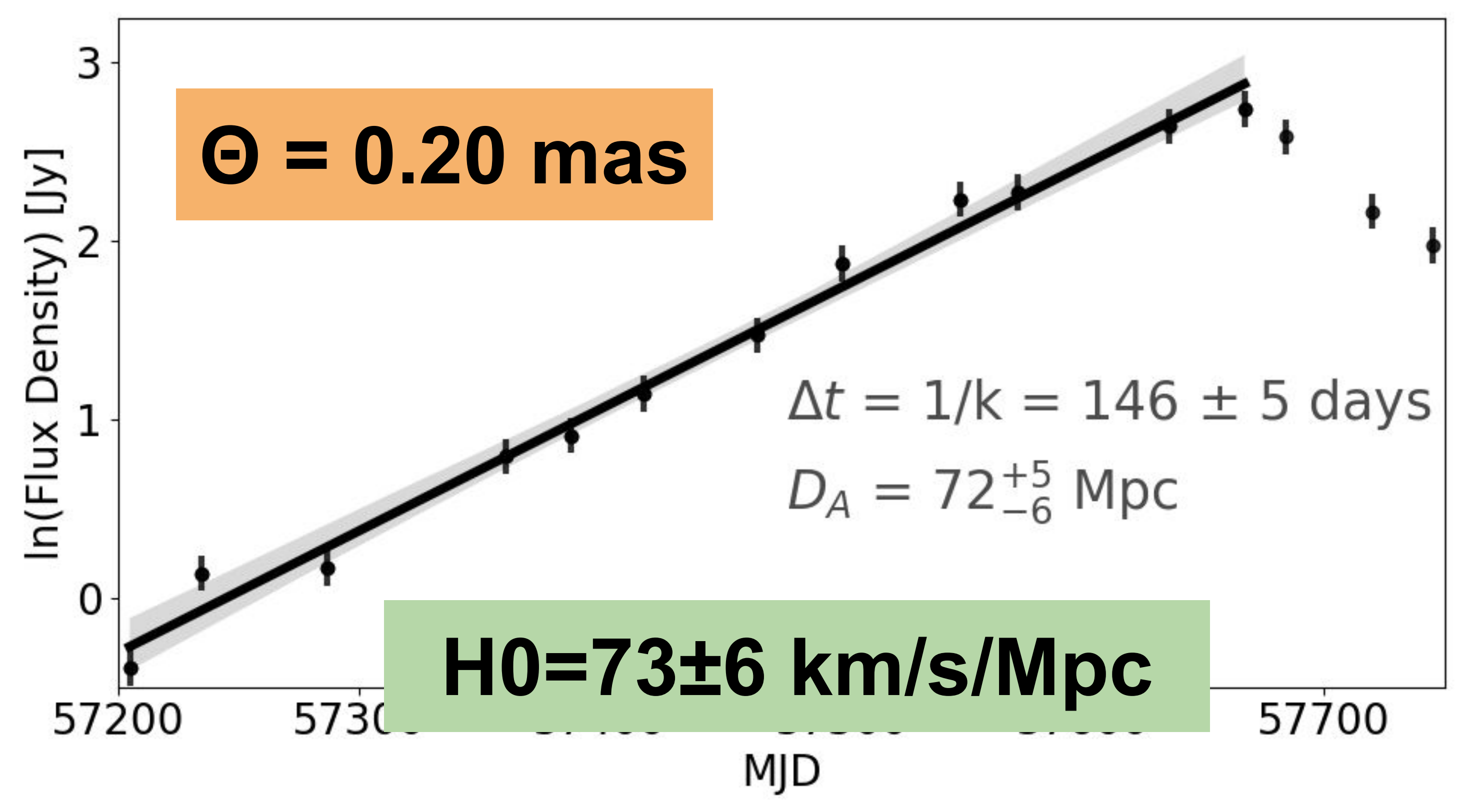


Flare LC

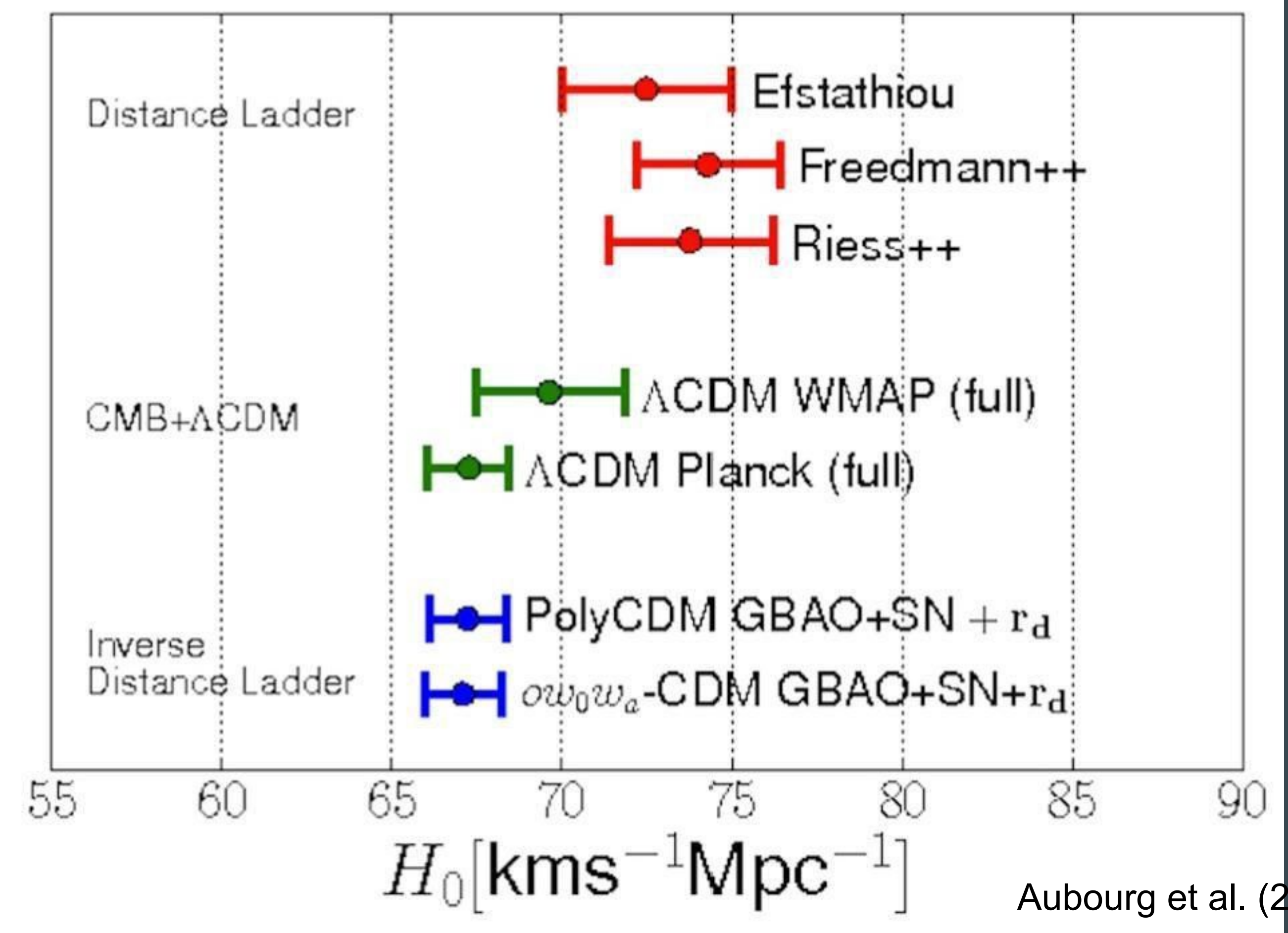

Θ = 0.20 mas
Δt = 1/k = 146 ± 5 days
$D_A = 72^{+5}_{-6}$ Mpc
ln(Flux Density) [Jy]
3
2
1
0
57200
57300
57400
57500
57600
57700
MJD

Flare LC

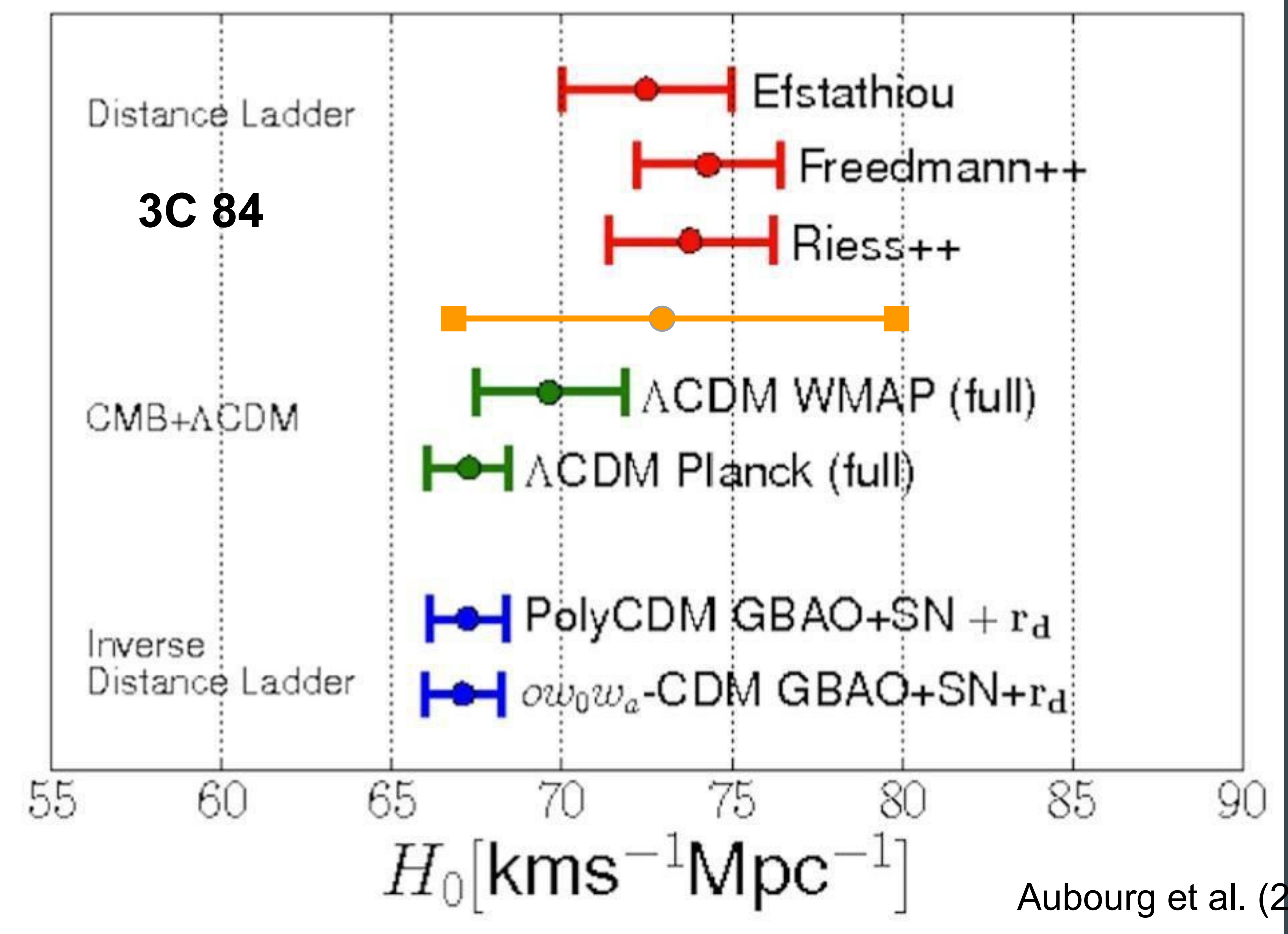


Θ = 0.20 mas

H0=73±6 km/s/Mpc



Aubourg et al. (2015)

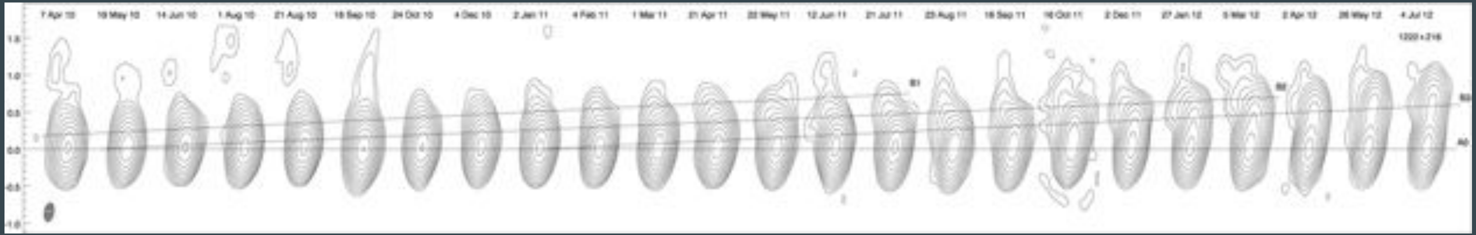


Aubourg et al. (2015)

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

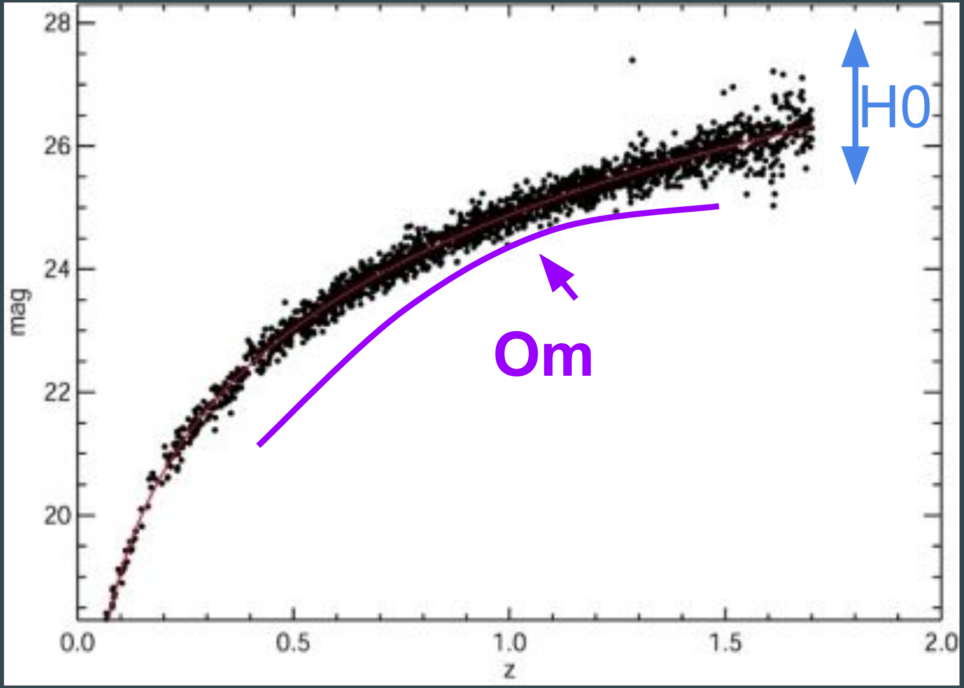
- Need to get the Doppler factor in a non-cosmologically dependent way
- Equipartition Doppler factor, jet-speeds Doppler factor, inverse Compton
- **It's hard to get the Doppler factor… But if we can show that our Doppler factor estimates don't evolve with z, we can measure Om**
- **Or…. find ways to 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+ submitted)

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

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

OR!

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

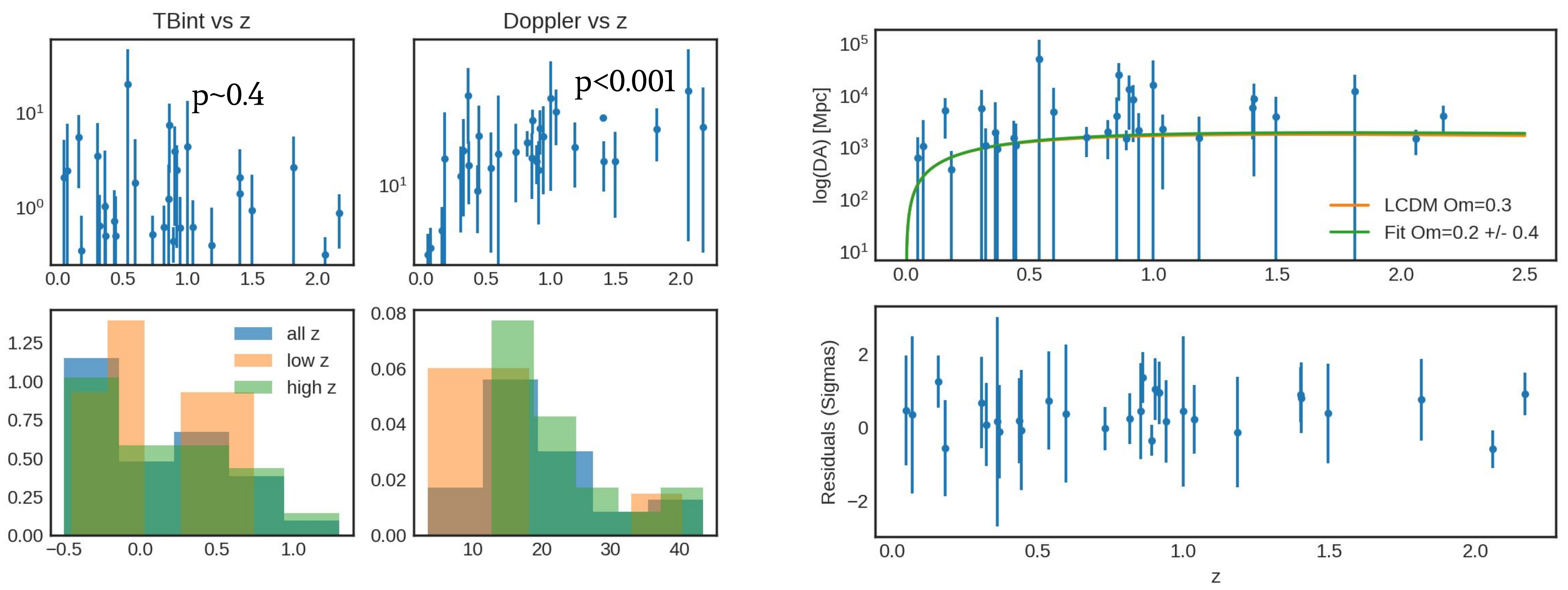
$$D_{\mathrm{A}} = \frac{2\ln 2c^3 S\Delta t}{\pi k_{\mathrm{B}} T_{\mathrm{B,int}}\nu^2\theta^3_{\mathrm{VLBI}}}.$$

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 systematic errors?

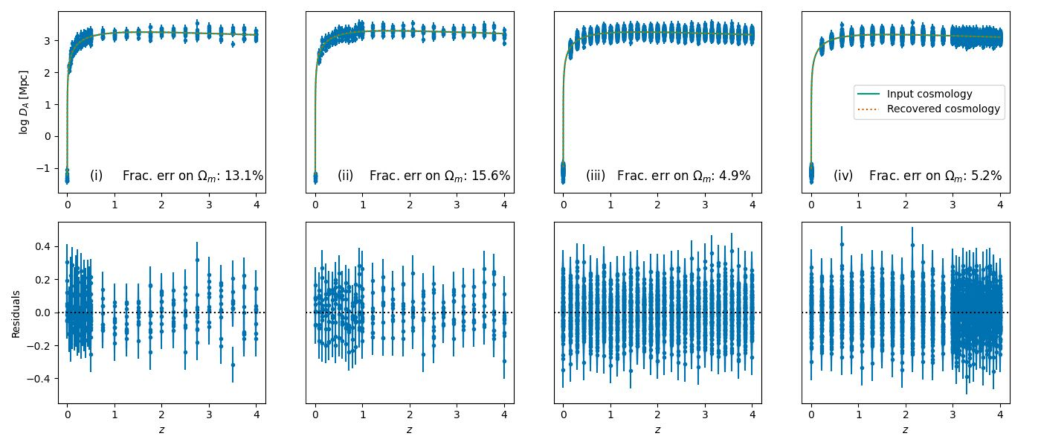
Does TBint evolve with redshift (using BU data)?



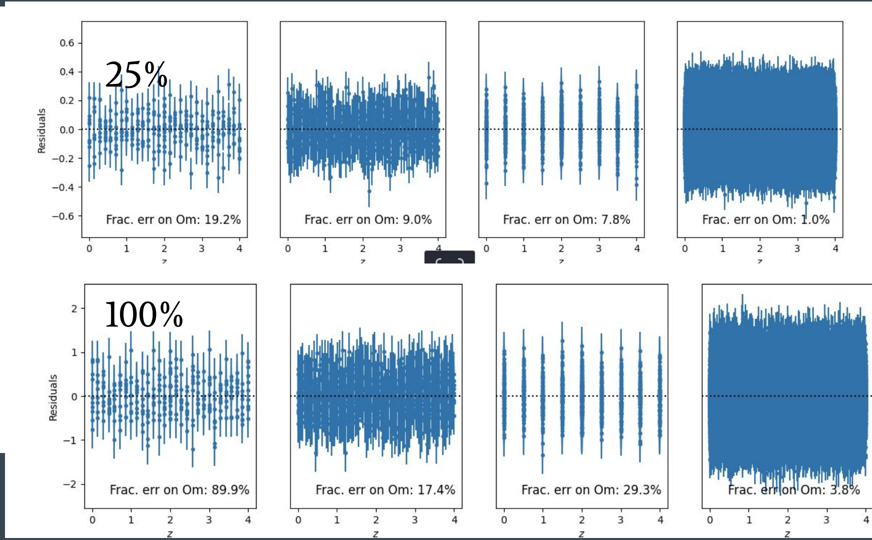
TBint is degenerate with H0 (and source based systematics) →TBint/H0/Systematics left as a free parameter and fit for Om..

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

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



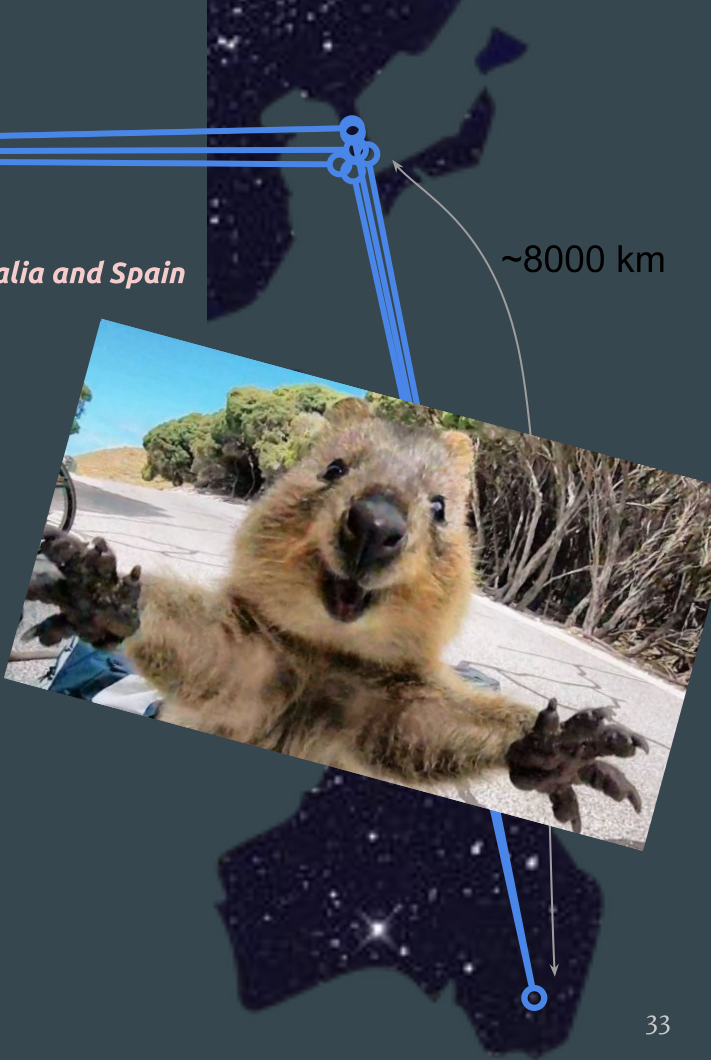
What if we have a 100% uncertainty but a billion dollars?



Can achieve ~4% errors!

Cosmological QUOKKAS

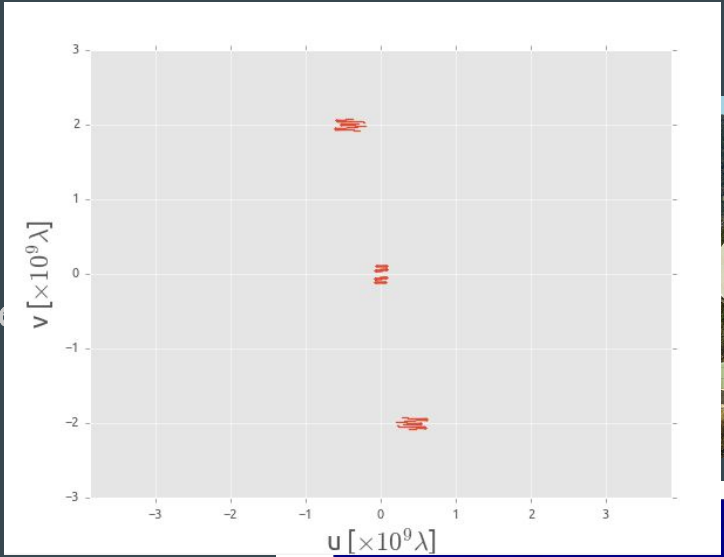
Quasar observations using the KVN from Korea to Australia and Spain

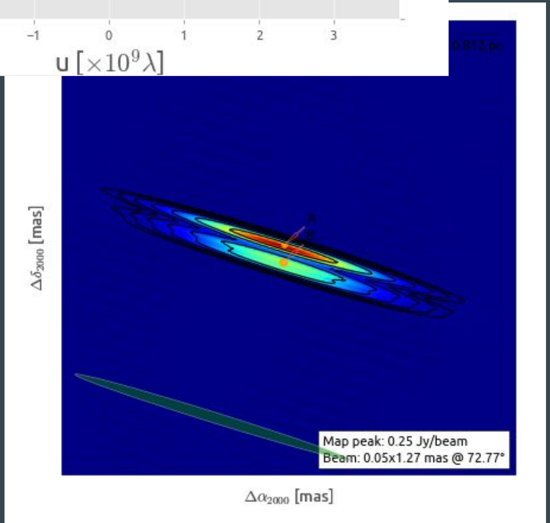


- **We require high cadence and high resolution!**
- A Quokka is a small marsupial on an island off Perth
- Between KVN and Mopra (and potentially Yebes and even Italy)
- ~8000 km baseline, observations every 2-3 weeks
- Initial sample of ~20 sources (need a detection survey first)
- Extremely high resolution (~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 at 3mm...

Observational strategy

- Will observe an initial sample of ~10-20 sources 0 < z < 3 weekly
- Follow-up imaging observations using the East-Asian VLBI Network
- Limited to declination +/- 30
- Initial detection work (and ironing out practical difficulties off piping data from Australia to Korea….) this semester
- Observing program to begin very soon!
- Much practical work to be done (pipelining etc etc)





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
- 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!

A cosmological quokka in Ireland (according to ML Night Cafe)