Real-Time Cosmology with Lensed FRBs

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Lensed FRBs

- We've been talking about measuring H0, or detecting increasing numbers of lensed quasars and supernovae to measure H0 etc.
- Another natural transient which has a few important advantages over typical, optical transients, are Fast Radio Bursts.
- Key point: TD can be measured to great accuracy. There should be many such lensed system. Disadvantage for now: localization.
- So, I should be talking about lensed FRB and how we constrain H0 with them. I won't. We already know how to do that (same as with Quasars, SNe etc.). [In fact, lensed FRBs can also be used to constrain DM properties - see Eichler 2017, Munoz et al. 2016).
- While I won't be talking about this - this needs stressing - it should revolutionise H0 science from lensing.
- Instead, in this talk I concentrate on *Real-Time Cosmology* with lensed FRBs.

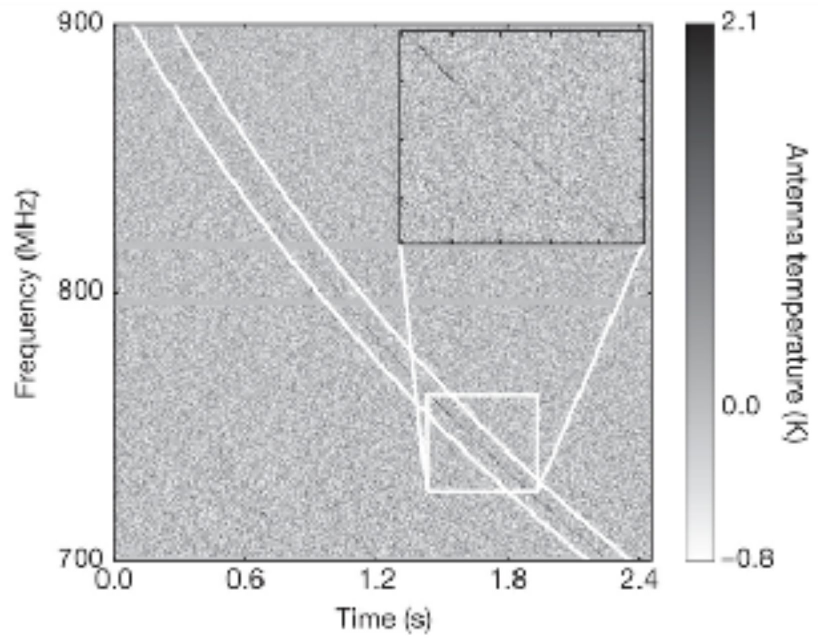
What are FRBs?

- Fast Radio Burst is a transient source of ~ms (to s) duration, quite luminous at the source (10^38-10^46 erg/s at the source)

- First noted about a decade or a bit more ago (2007, in archival data). By now dozens detected (initially by Parkes, Arecibo; recently many more by CHIME and ASKAP)

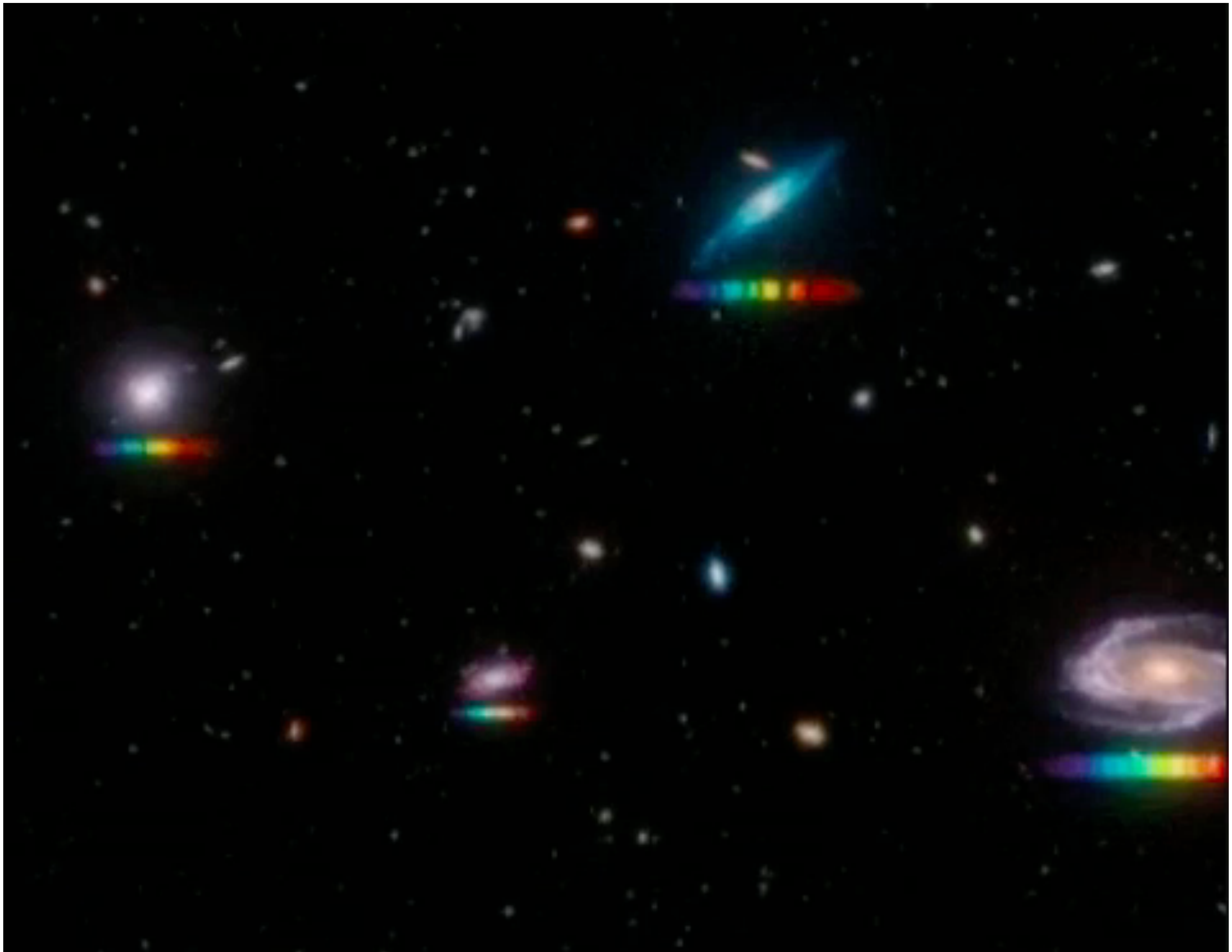
- Mostly extragalactic according to dispersion measures (one galactic recently detected)

- Mechanism unknown. Associated with magnetars it appears.



Estimate of about 1 every second across sky (Fialkov & Loeb 2017)

What is Real-Time Cosmology?



GIPHY from COSMOS

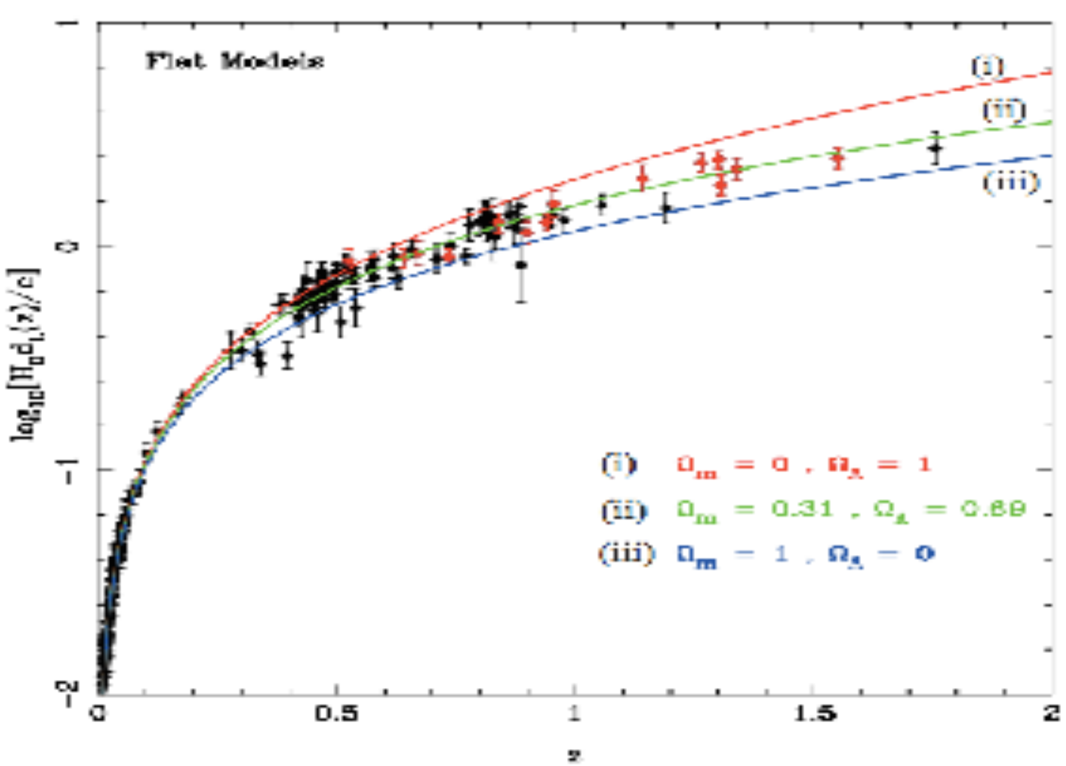
What is Real-Time Cosmology?

- Measuring the temporal change of radial and transverse position of sources in the sky in real time (Quercellini+ 2010; Sandage 1962, Loeb 1998)
- Meaning, for example, delta_z in a certain delta_t, or, **dz/dt**.
- How much did the universe expand/change in that time period
- Radial *redshift drift*
- Transverse position change
- Mass growth

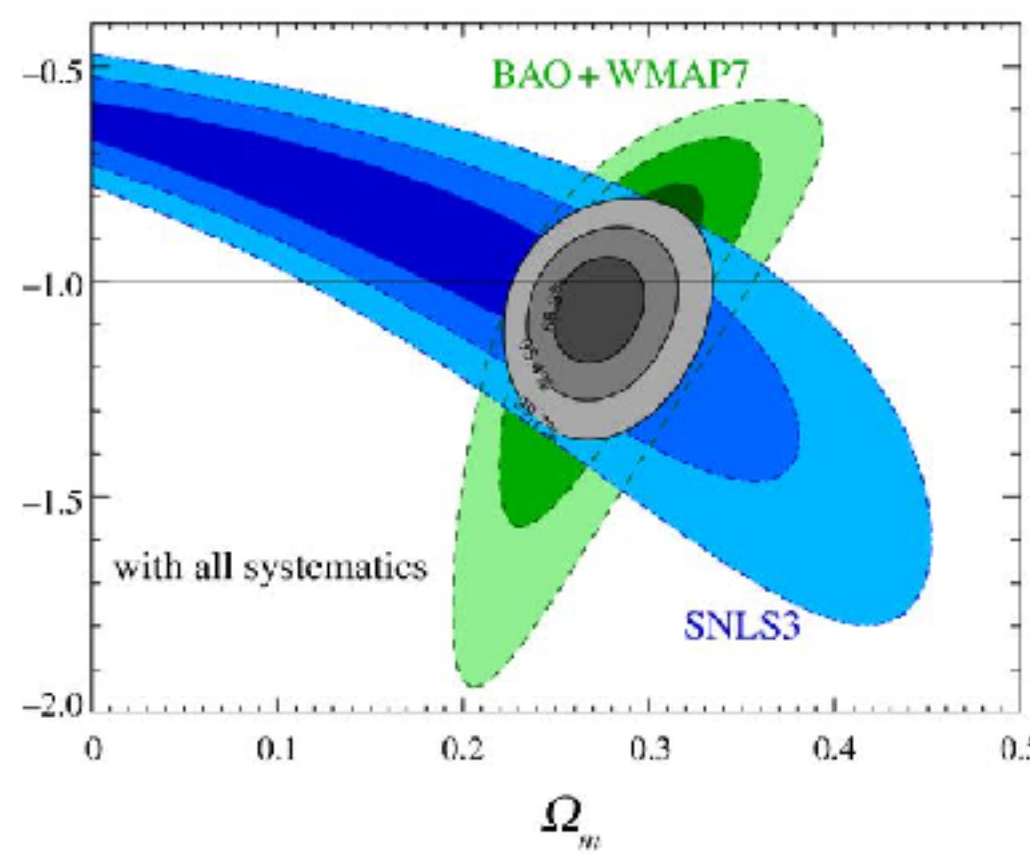
Real-Time Cosmology: Why?

- Let's start with what we know and how: universe expanding and accelerating. How do we know? for example, Type Ia SNe, distance modulus-redshift relation:

(Many seminal works, Nobel prizes; Some random figures)



Choudhury & Padmanabhan 2005

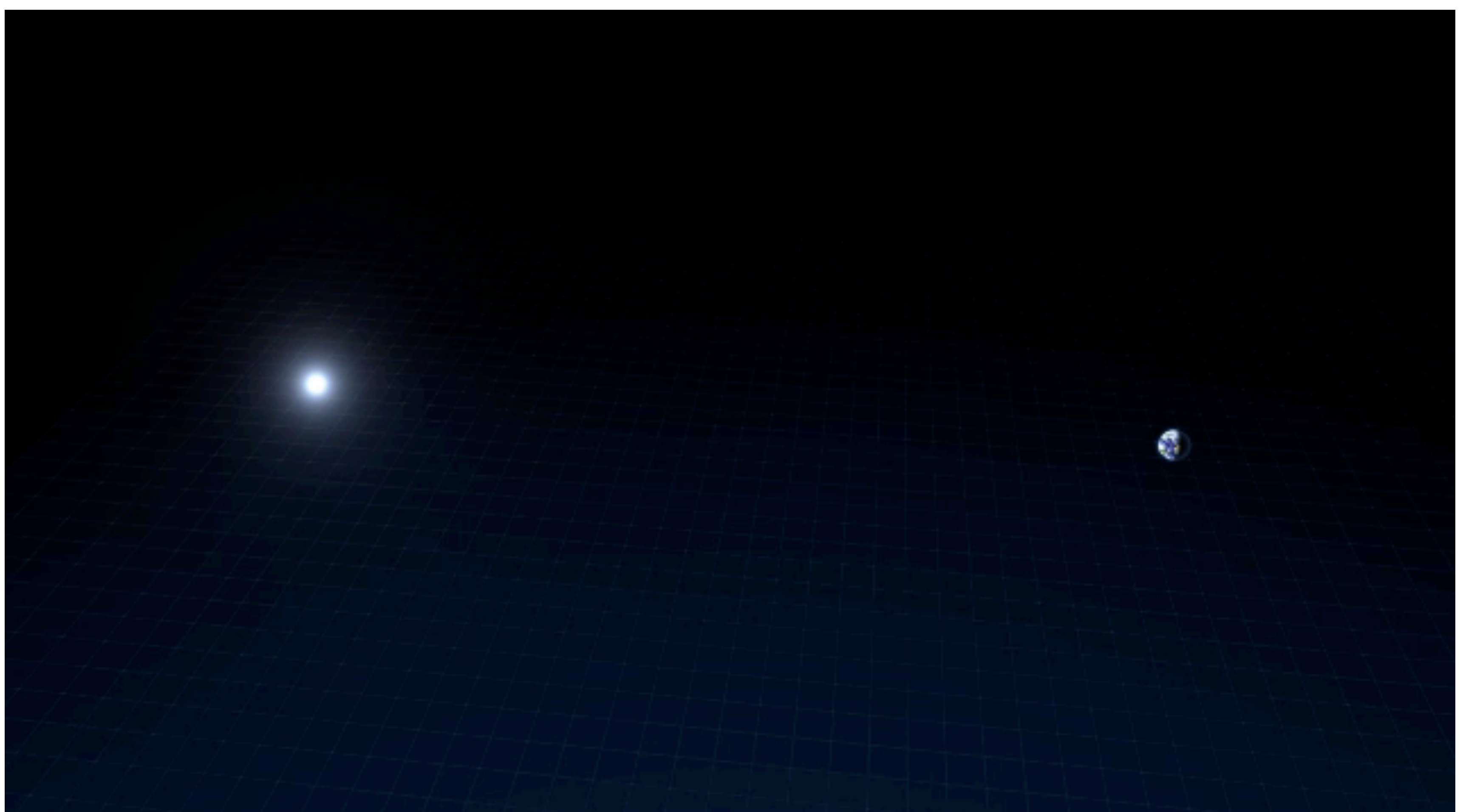


Sullivan M, et al. 2011 SNLS3

Real-Time Cosmology: Why?

- Multiply imaged Quasars, for example, yield H0, through the time delay

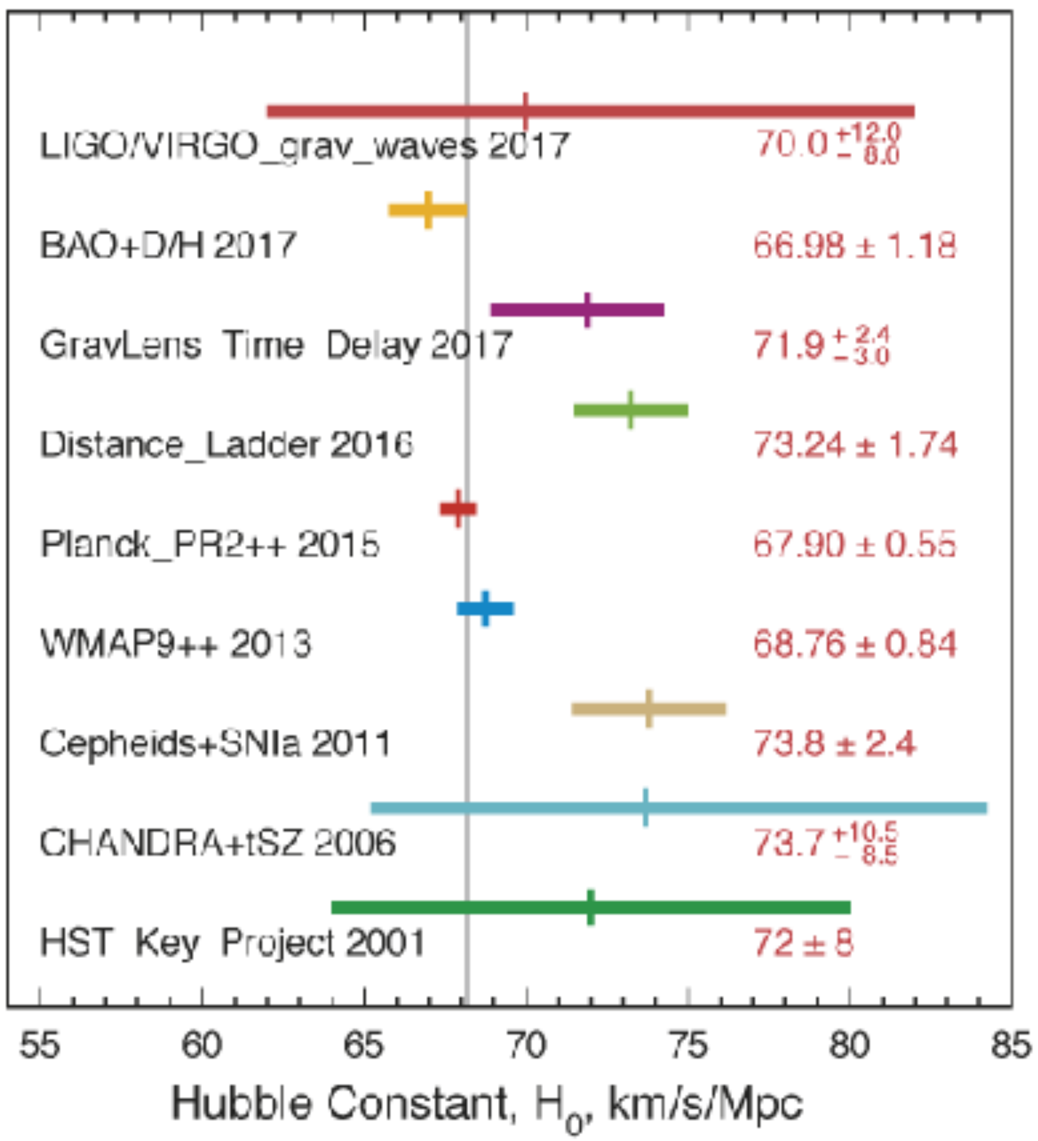
$$t(\vec{\theta}) = \frac{(1+z_d)}{c}\frac{D_d D_s}{D_{ds}}\left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \psi(\vec{\theta})\right]$$ \propto 1/H0

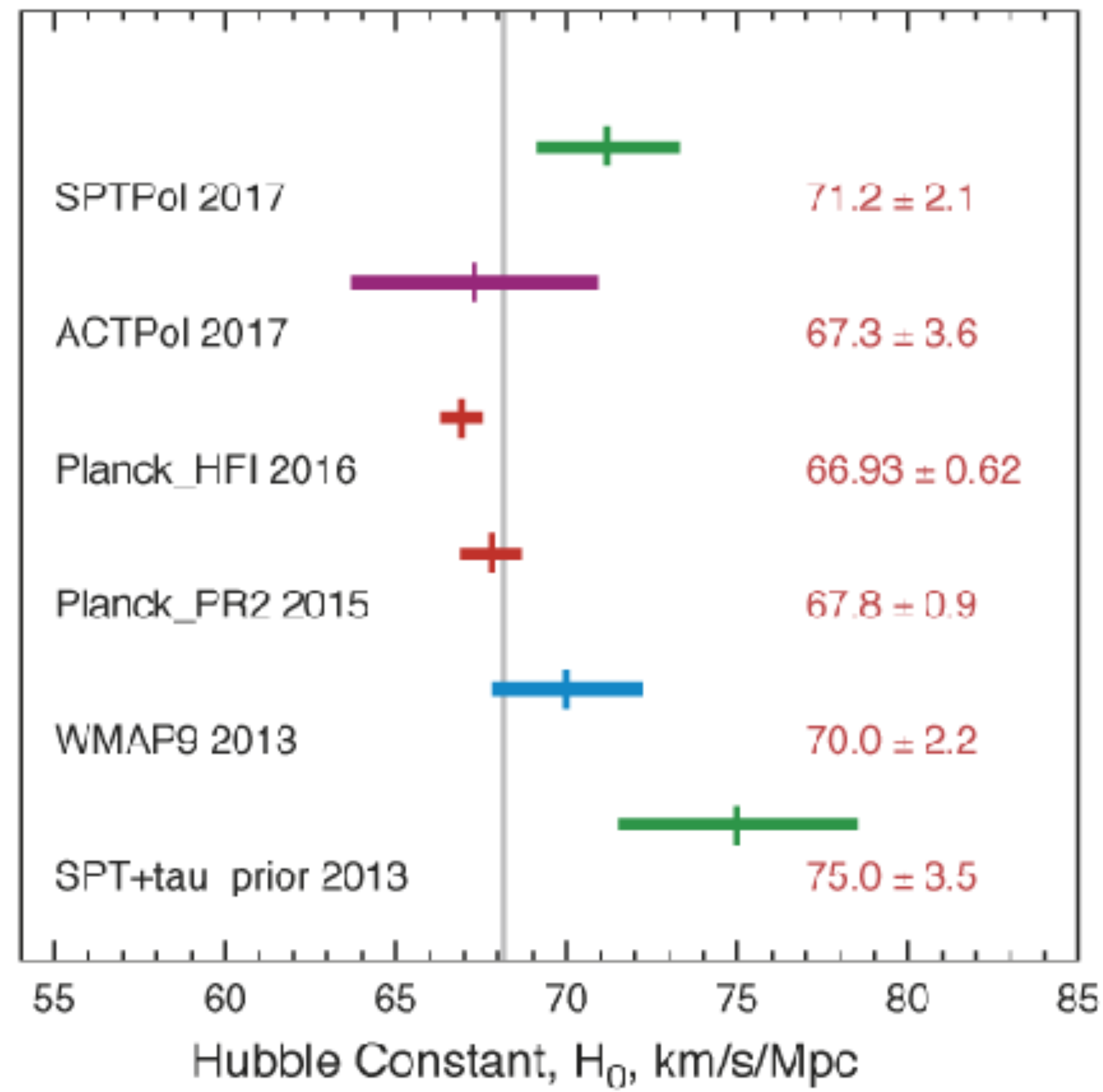


https://lambda.gsfc.nasa.gov/education/graphic_history/hubb_const.cfm

Real-Time Cosmology: Why?

- And many other probes





https://lambda.gsfc.nasa.gov/education/graphic_history/hubb_const.cfm

Real-Time Cosmology: Why?

$$H(z) = \sqrt{H_0^2(\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0})},$$

$$\frac{dz}{dt_0} = (1+z)H_0 - H(z)$$

- As we know, the Hubble (Hubble -Lemaitre) “constant” is a function of z, H(z)
- H0 can be measured from CMB, lensed quasars, SNe — and as mentioned — lensed FRBs!
- We can *characterize* the function H(z) from various probes. So we can *characterize* dz/dt. Real-Time cosmology refers to ***directly measuring*** by how much the universe changes in a certain (earthly) time period, and as a function of redshift.
- In simple words: measure universe (ie redshift) today, measure it tomorrow, see how differs.

Challenge

- Age of universe: 13.8 Gyr, ~10^10 yr
- Human lifetime: close to ~ 10^2 yr
- In a human lifetime we thus witness only a 10^-8 change in universe.
- Since we can't measure nearly anything to that accuracy (redshift, distances, etc.), can’t do real-time cosmology directly.
- If we wanted to observe the universe changing (esp., expanding) in real time, to say, ~1% relative change, need to wait ~10^8 yr.

Challenge

- Example - in one earthly year:
- dz = 1.369110185744580E-11
- 1/R02 = 0.999999999928459
- H02 =69.999999997746471
- OmegaM2 =0.299999999954929
- OmegaL2 =0.700000000045071

Ideas to bypass challenge

- Loeb 1998
- **1.** Two observations, set a few decades apart, of large samples of quasars using sensitive high-resolution spectrographs where cross-correlating the (many) Lyman-alpha absorption lines. For example CODEX experiment.
- Absorption line width of about ~20 km/s or narrower, and hundreds of lines detectable to HI densities of 10^13 cm^-2.
- Cosmic signal in a decade is about 10^-3 of high-res element
- Enough elements are available and enough quasars.

Ideas to bypass challenge

- Loeb 1998
- **2.** Galaxies are fainter than quasars and thus need larger time separation to detect effect with the same signal to noise.
- How much time? about 10^3 years to detect signal in their spectra.
- A way to bypass: “While such time intervals might appear impractical on the scale of a human lifetime, they are accessible through the multiple images of a background galaxy that is gravitationally lensed by a foreground cluster of galaxies.” In addition, SNR aided by magnification if lensed.
- Comparison of the spectra of two multiple images - should be offset by the amount corresponding to how much the universe expanded in the TD.

BUT: so far ideas not feasible

- Quasars so far not realized and haven't supplied the required measurements.
- Multiply imaged galaxies are not point sources - measure integrated spectra so cannot measure z as accurately as required.
- Transverse (random) motion will govern signal

Another idea:

- Time-delay between multiple images of a persistent/repeating source *will change with time* due to the radial and transverse motions of the lens (and source), and due to mass growth (Piattella & Giani 2017, Broadhurst & Oliver 1991). **Cool!**

- **BUT:** change in TD per year due to redshift drift is of order ~10^-2 - 10^-3 s. Can't measure TDs to that accuracy for any source so far.

However, FRBs can be useful

- Zitrin & Eichler 2018:
- Note that FRB time delays can be measured to superb accuracy - because FRBs only last about 10^-3 sec.
- Very crudely estimate number of *lensed* and repeating FRBs
- Reconstruct the time delay equation to full solution (or at least higher orders)
- Characterize the expected observed shift for radial transverse and mass changes, for reasonable lenses over reasonable time scales.

*Estimated number of repeating FRBs

- Input: about 7*10^5 per year above 1 Jy (or fluence of about 2 Jy ms), >1*10^7.5 above 0.8 mJy (Keane & Petroff 2015, Foalkov & Loeb 2017) [as for the SKA array]

- At time of writing 30 FRBs known, discovered mostly over 5 years.

- If all sky rate were 7*10^5 per year, and only ~30 discovered, then “sky-time coverage” or fractional sky coverage (*fraction* of sky observed times observing time) is of order 4.3*10^-5 yr.

- If observing time was say ~ 1year, then fraction of sky observed is about ~10^-5.

- About 1/30 repeats (with ~ 1 Jy), so that **about N_1Jy~10^4-10^5 repeating FRBs with >1 Jy will be eventually detected across sky.**

- **Above 0.8 mJy it will be more like ~10^7** (the relevant volume increases).

- Magnification not taken into account.

*Estimated number of repeating FRBs lensed by clusters/galaxies

- 10^4 massive clusters in sky

- cross section for multiple images about 10 arcsec^2, or 10^-6 sq. deg.

- So in total 10^-2 sq. degrees across sky. With 4*10^4 sq. deg. of sky and ~10^7 repeating FRBs with SKA-like sensitivity, **a few to ~10 repeating FRBs lensed by some rich cluster** (not too many! see quasars).

- But **by galaxies many more, perhaps up to ~10^4**.

Conclusion

- Lensed FRBs should be common; TDs can be measured to great accuracy, allowing for unprecedented constraints on H0, DM.
- Repeaters can be used for *real-time cosmology:*
- TD between multiple images changes with time
- Depending on rate/number of course (need enough lensed repeating ones).
- Transverse component governs effect (change in TD of 0.1-1 s per year), but might be averaged out with many sources. Of course the transverse effect itself is very interesting.
- Radial effect and mass assembly effects are of same order, (10^-2-10^-3 s roughly), to be distinguished statistically or by new means.
- Some hopeful news: some of the degeneracies could be broken with quads (Wucknitz, Spitler & Pen 2020).

Thank you.