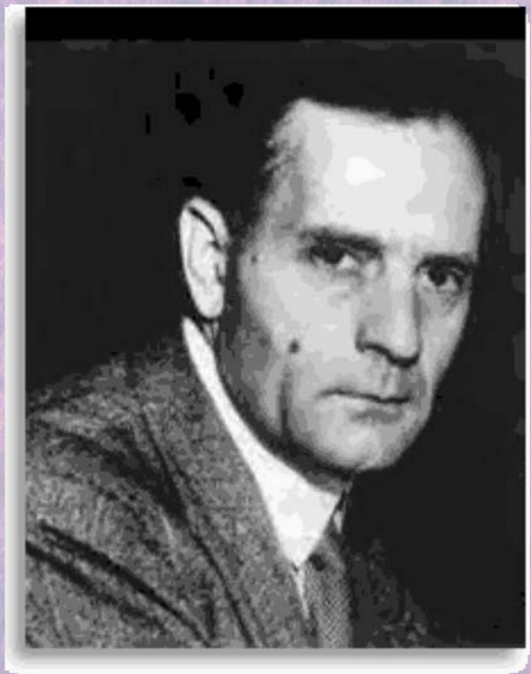
# H0 and Gravitational Lensing

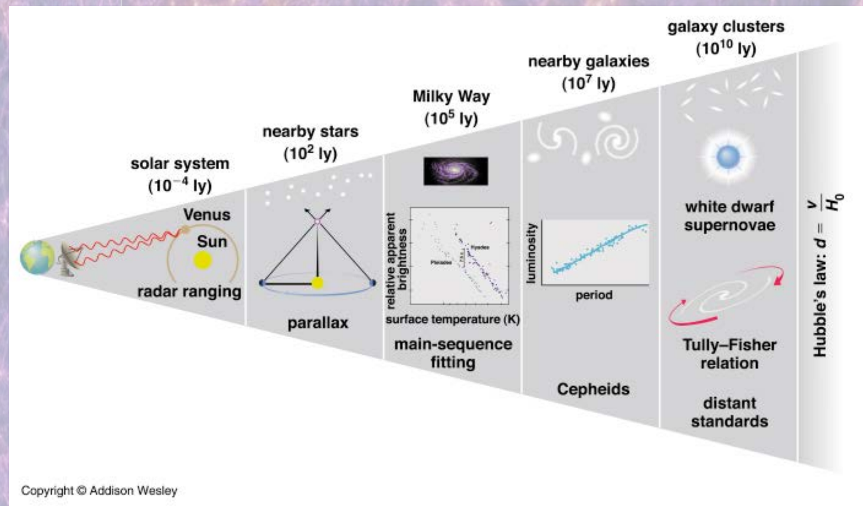
Rachel Webster
University of Melbourne

# Two giants of the evolving universe



Edwin Powell Hubble (1889-1953)

Hubble




Lemaitre

# Sjur Refsdal - Insight

ON THE POSSIBILITY OF DETERMINING HUBBLE'S PARAMETER AND THE MASSES OF GALAXIES FROM THE GRAVITATIONAL LENS EFFECT*

*Sjur Refsdal*

(Communicated by H. Bondi)

(Received 1964 January 27)

*Summary*

The gravitational lens effect is applied to a supernova lying far behind and close to the line of sight through a distant galaxy. The light from the supernova may follow two different paths to the observer, and the difference $\Delta t$ in the time of light travel for these two paths can amount to a couple of months or more, and may be measurable. It is shown that Hubble's parameter and the mass of the galaxy can be expressed by $\Delta t$, the red-shifts of the supernova and the galaxy, the luminosities of the supernova "images" and the angle between them. The possibility of observing the phenomenon is discussed.

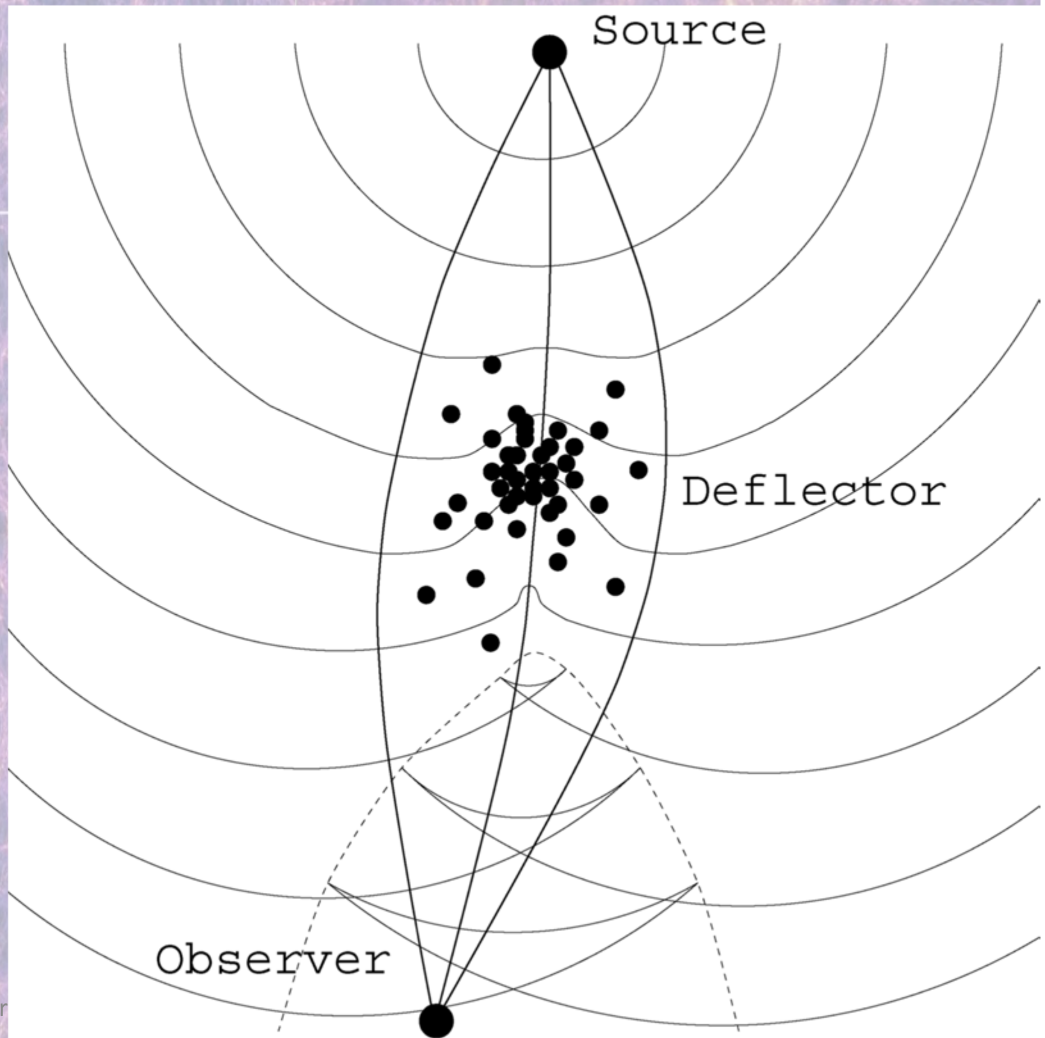
1935-2009

The time delay between two images *i* and *j* is given by

$$\Delta t_{i,j} = \frac{1}{H_0}(1 + z_d)D(z_d, z_s, \Omega_0, \Lambda_0)f$$

$$D = \frac{D_s D_d}{D_{ds}}$$

where the function *f* depends on the different path length to each image taking account of both the geometric path length, due to the image positions, and gravitational timedelay due to the lens potential.



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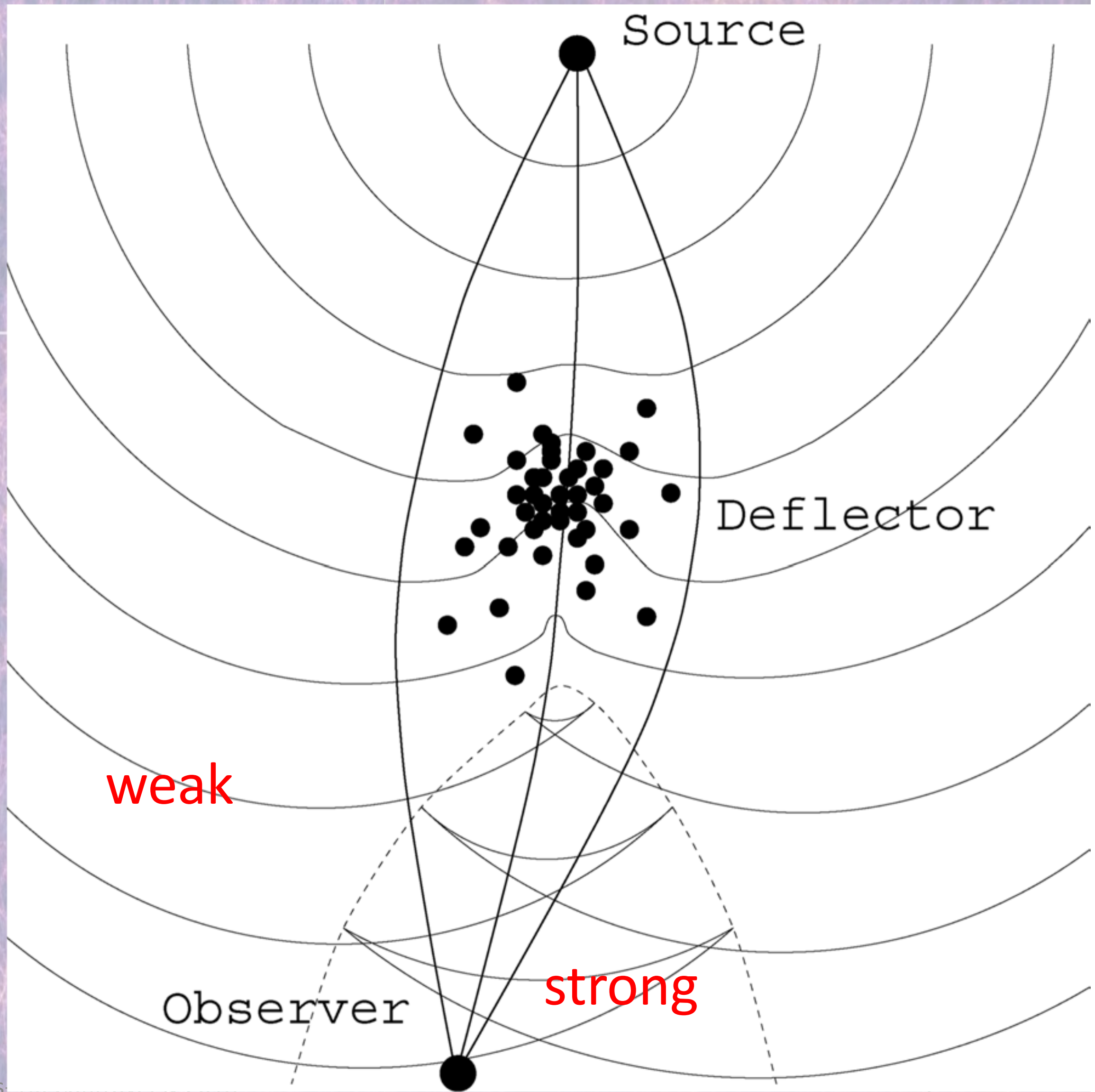


www.eso.org

# Gravitational Lensing

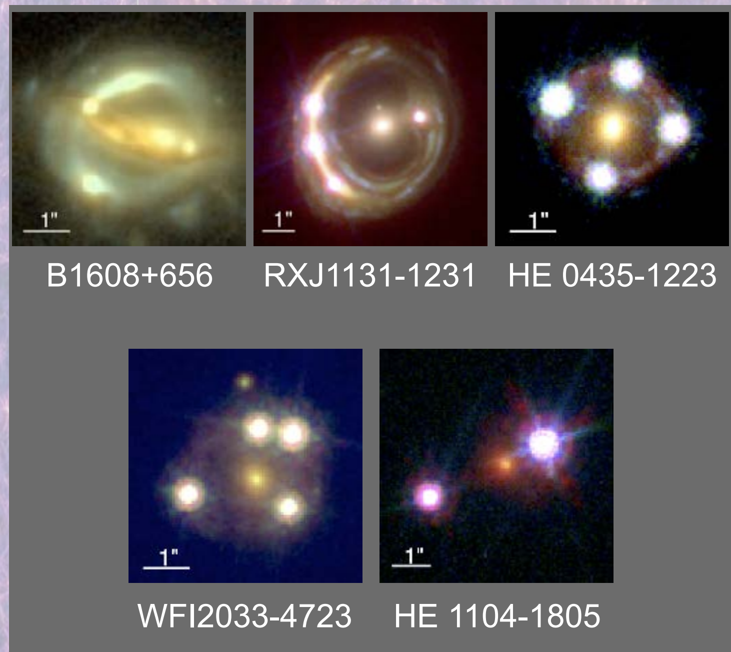
**OPPORTUNITY**

Variable & multiply-imaged sources:

quasars, gravitational waves, SNe

→ the 'Refsdal Experiment'

H0LiCOW multiply-imaged quasars:
Sherry Suyu's talk after lunch



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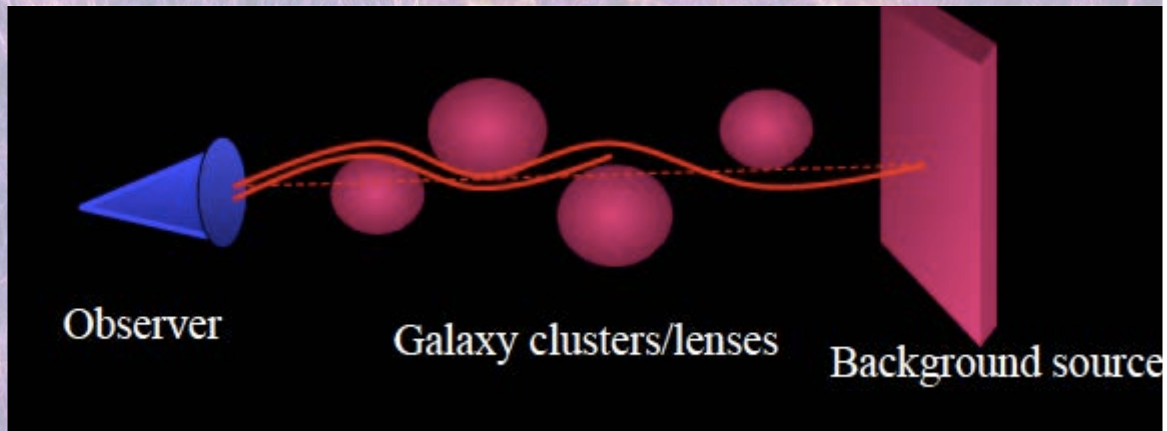
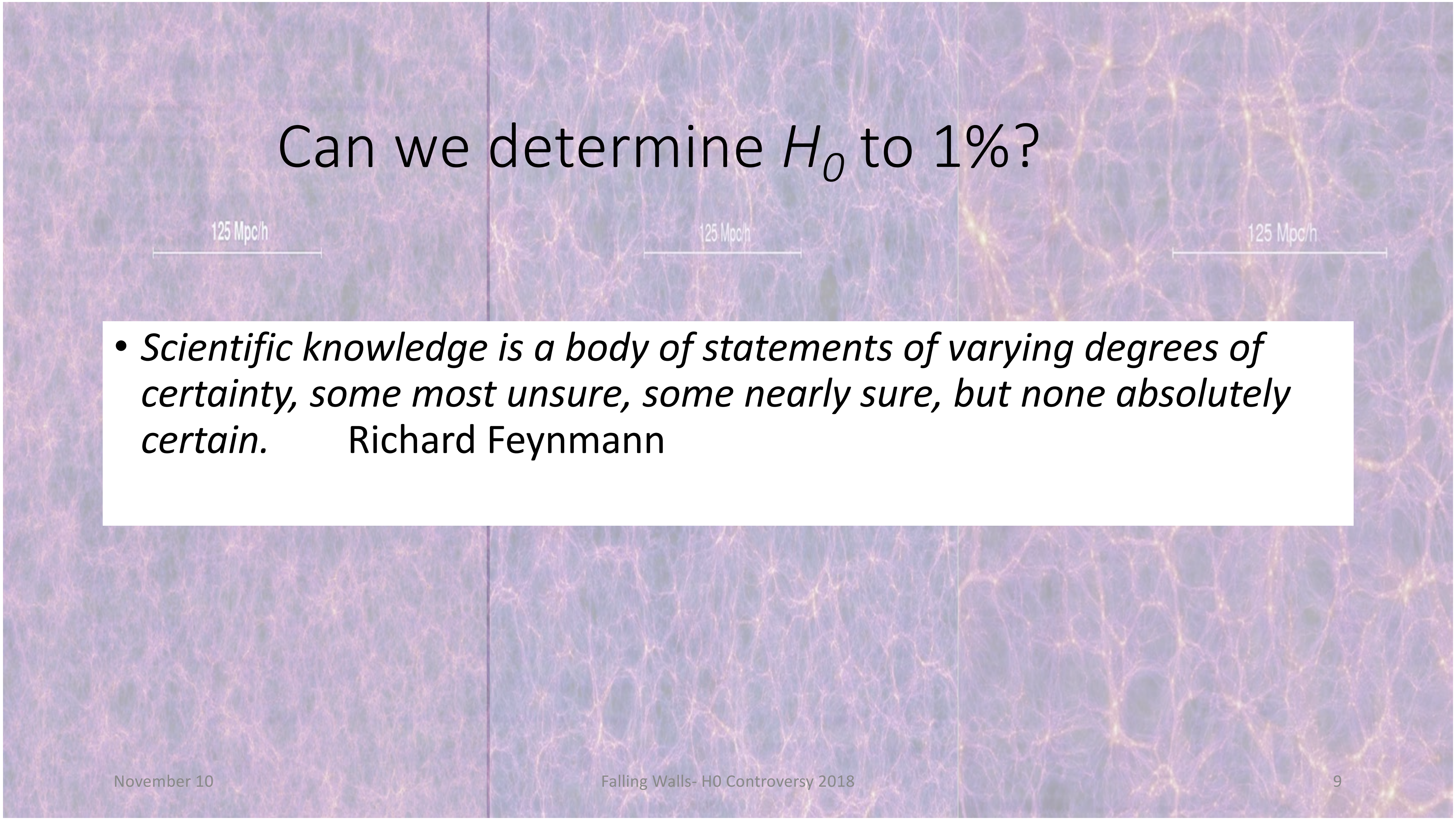



**UNCERTAINTY**

Is there a fundamental limit to the accuracy with which measurements can be made?

# Can we determine $H_0$ to 1%?

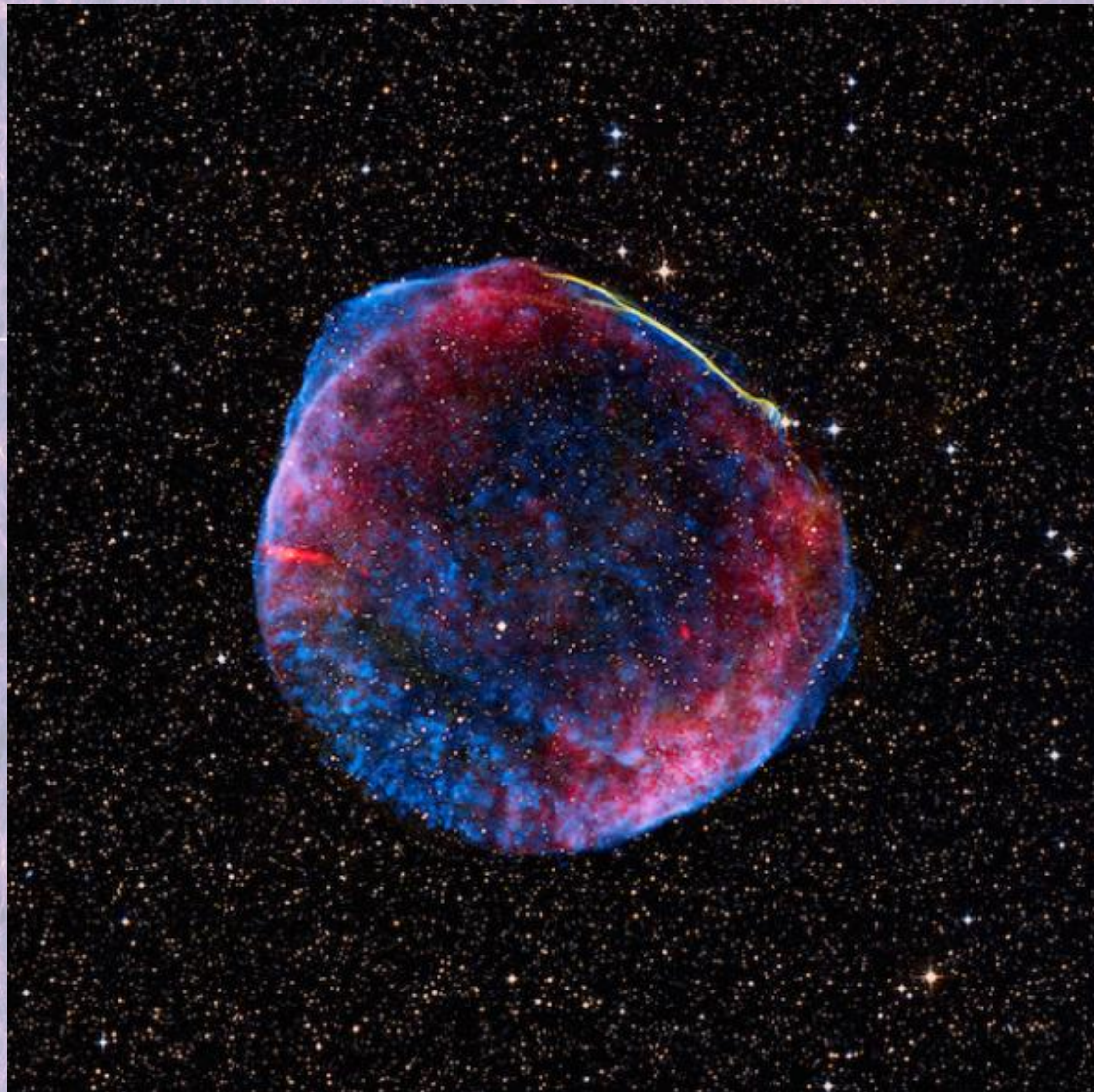



- *Scientific knowledge is a body of statements of varying degrees of certainty, some most unsure, some nearly sure, but none absolutely certain.* Richard Feynmann

# Sources - Supernovae

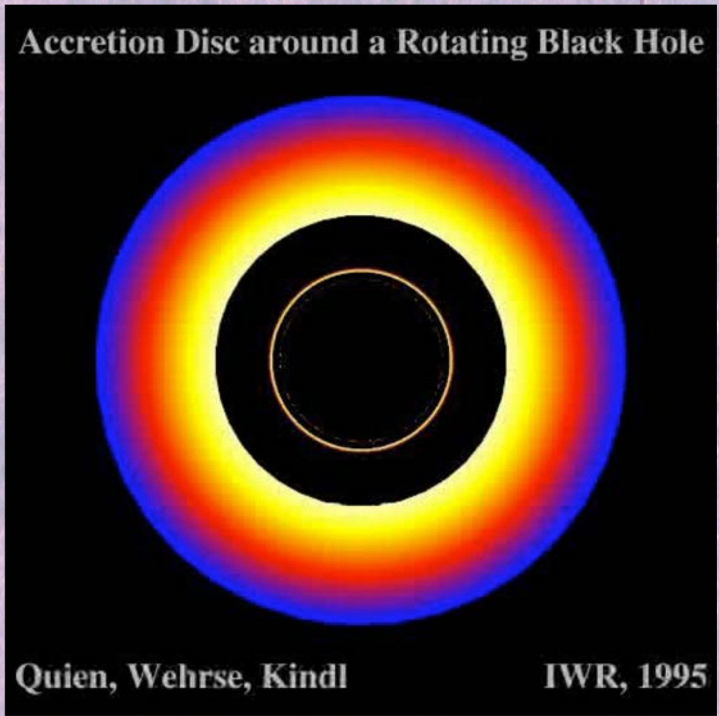
**Angular scale of the source matters**

$$\theta_s \sim \theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{ds}}{D_d D_s}}$$

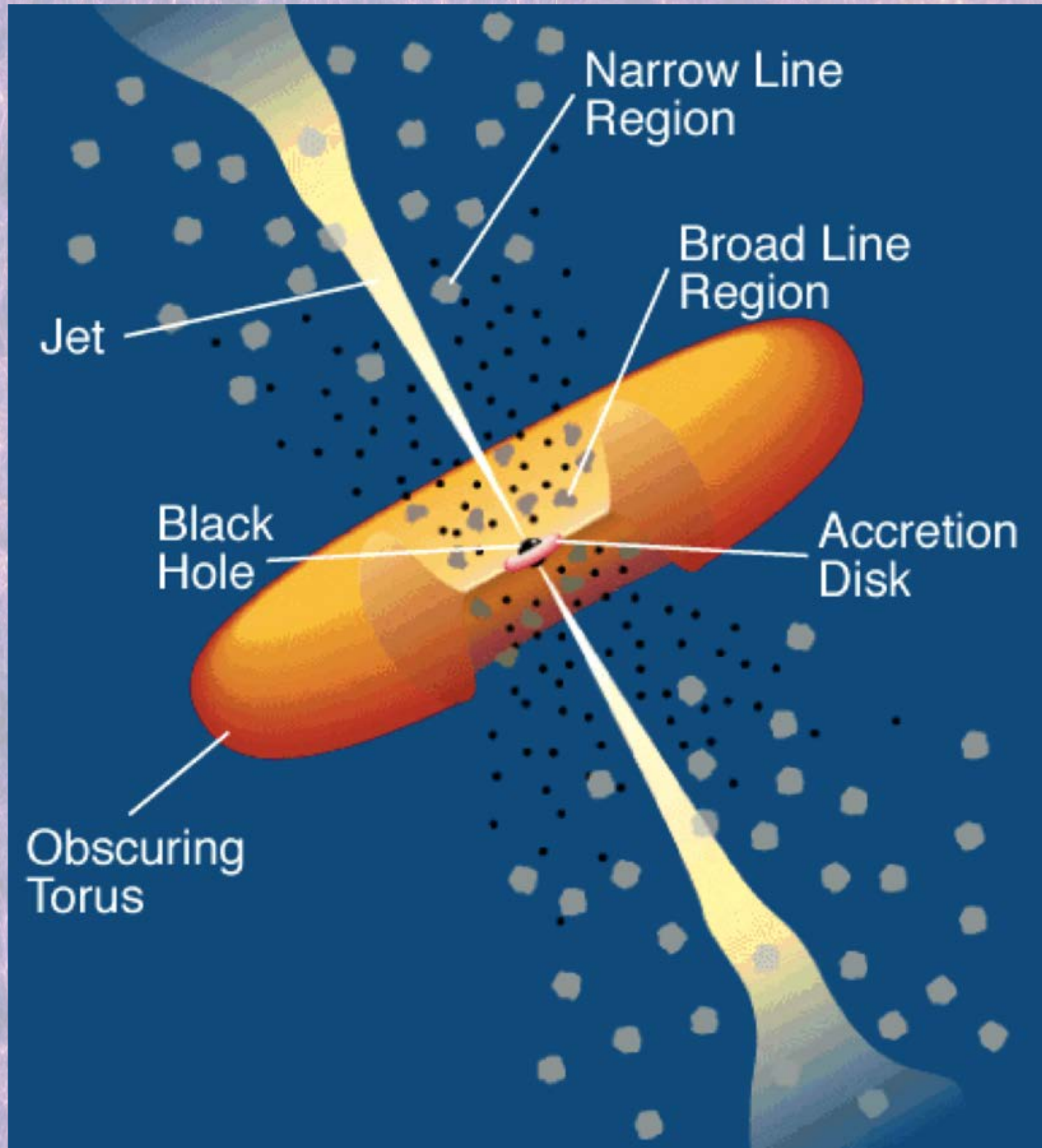


The remnant of a type 1a supernova that exploded in the year 1006. (NASA/CXC/et al)

# Sources - quasars

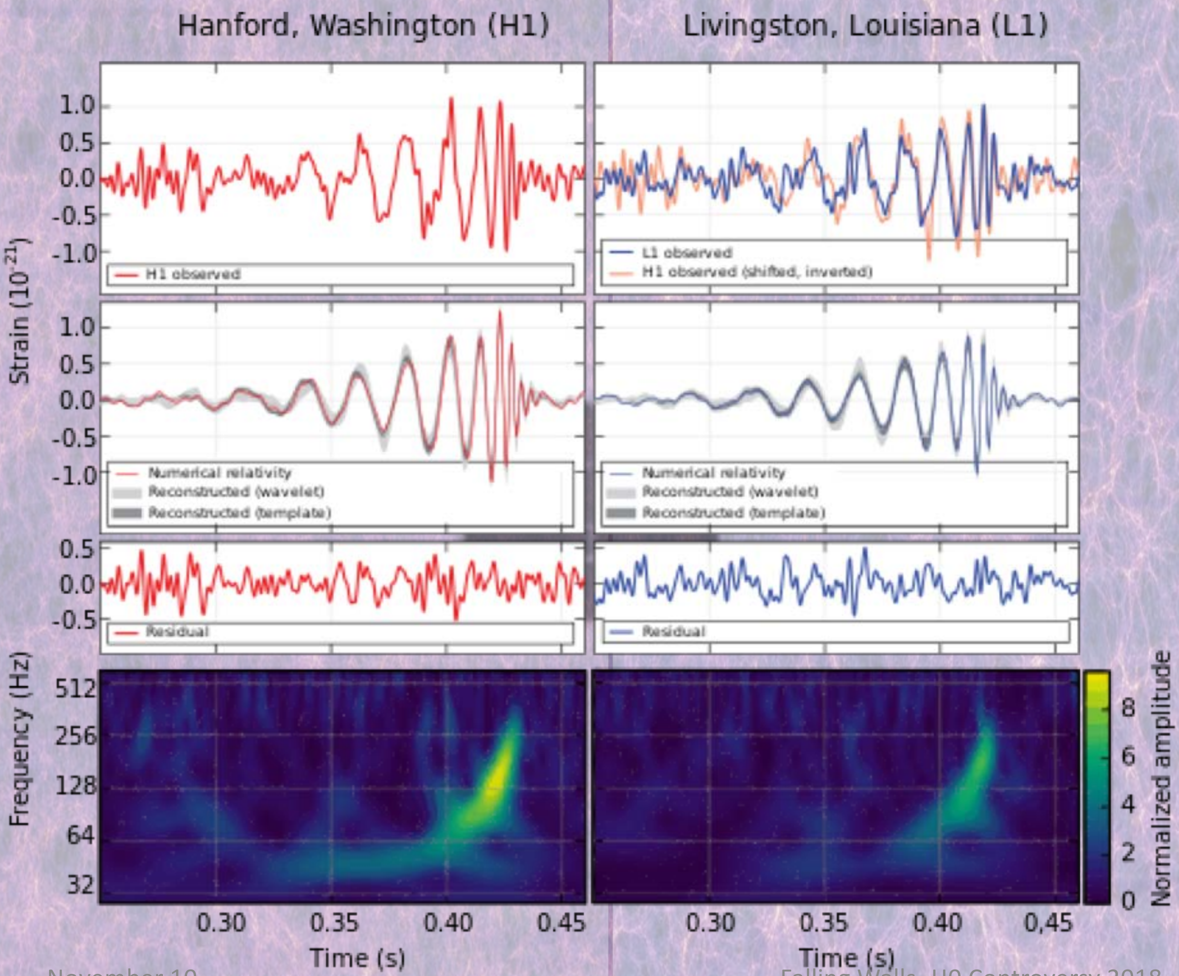



C.Kindl, Diploma Thesis, U Heidelberg (IWR) 1995




Urry& Padovani 2002

# Sources – gravitational waves



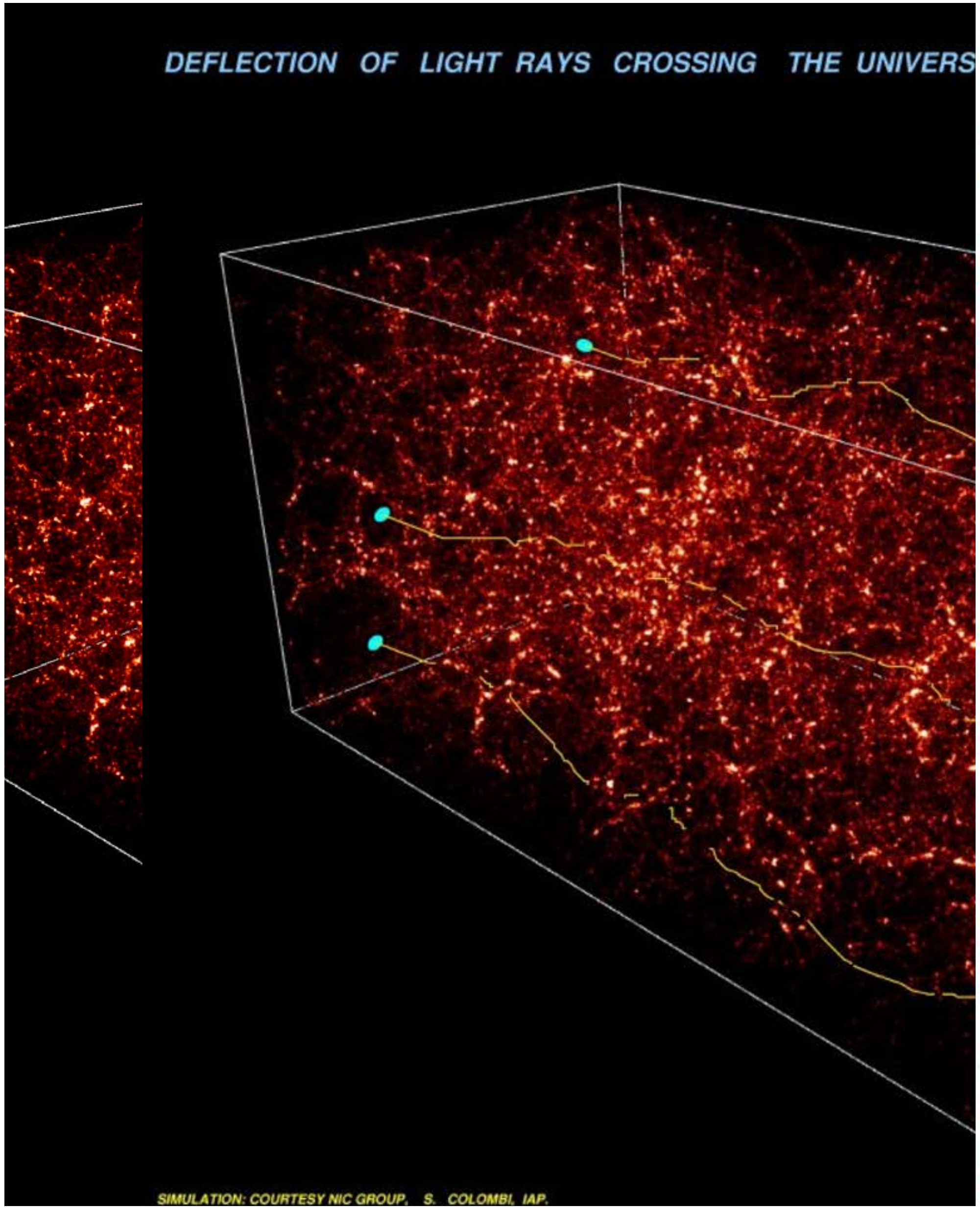

$M_{chirp}$ and $h$ (strain):

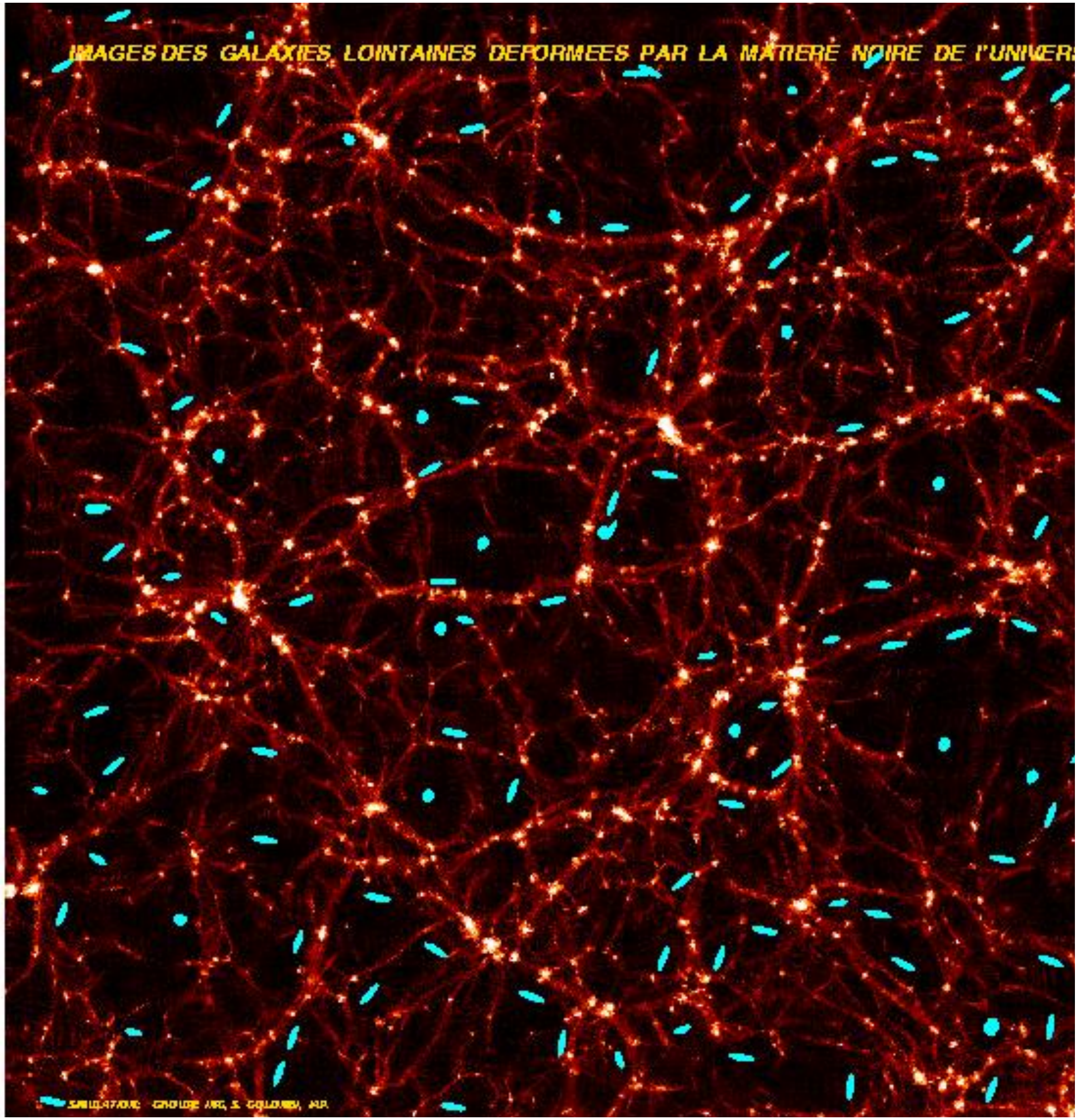
$$D_l = \frac{M_{chirp}^{\frac{5}{6}}(z)}{h(t)} f$$

$$M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

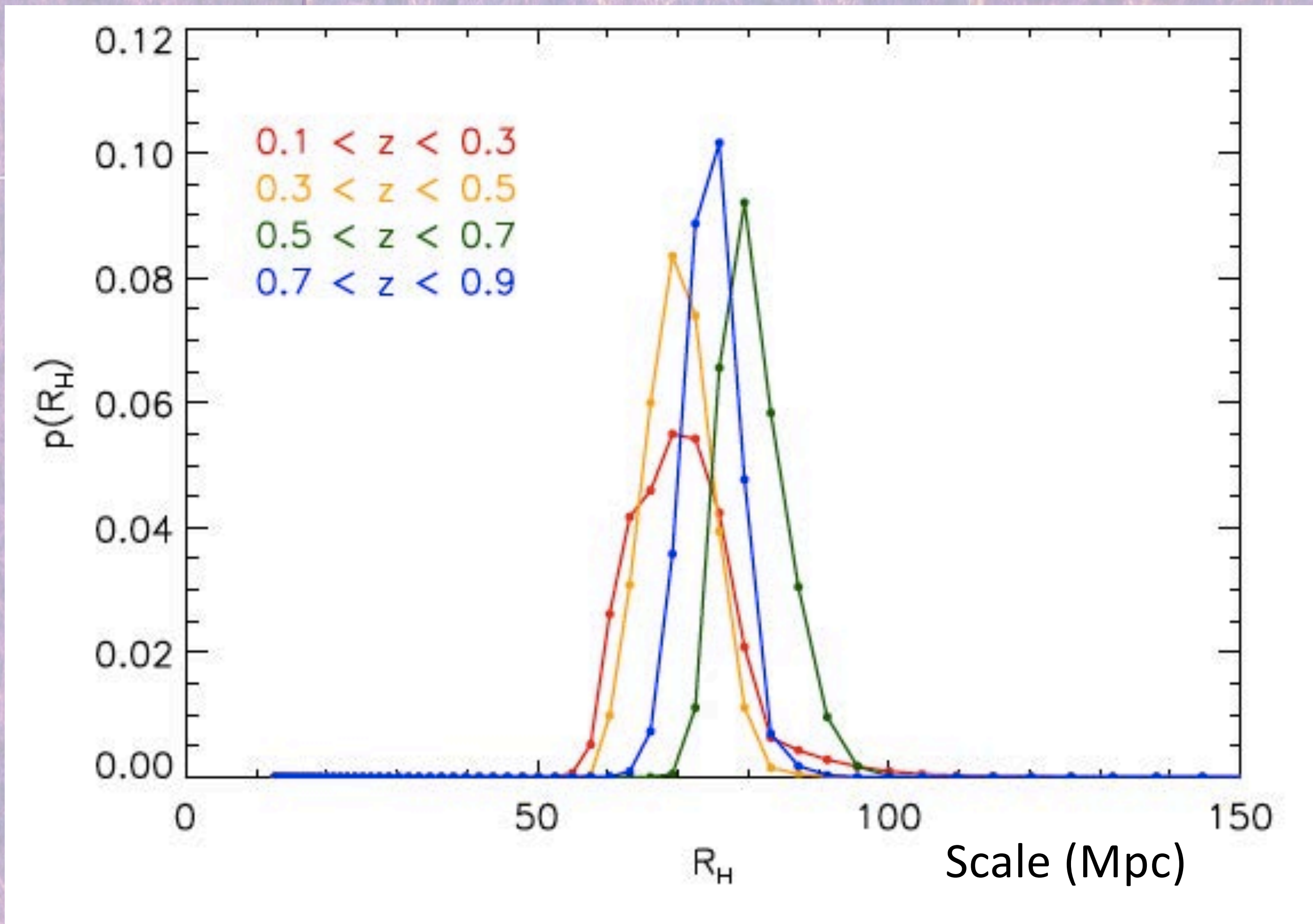
Gravitational lensing

$$h \propto \sqrt{\mu}$$


DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERS
SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

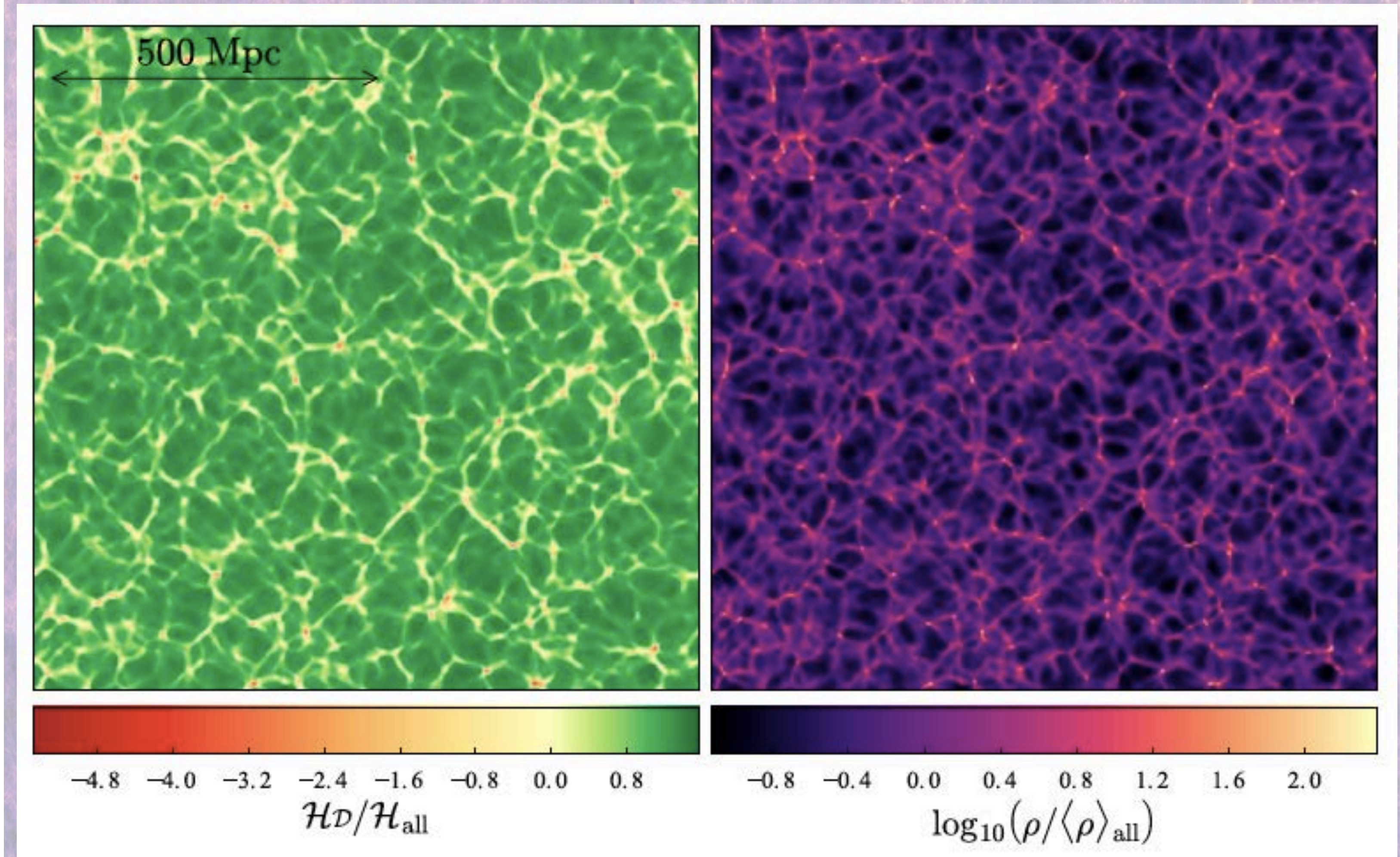

IMAGES DES GALAXIES LOINTAINES DEFORMEES PAR LA MATIERE NOIRE DE l'UNIVER

# Scale of Cosmological Homogeneity?




Scrimgeour+2012

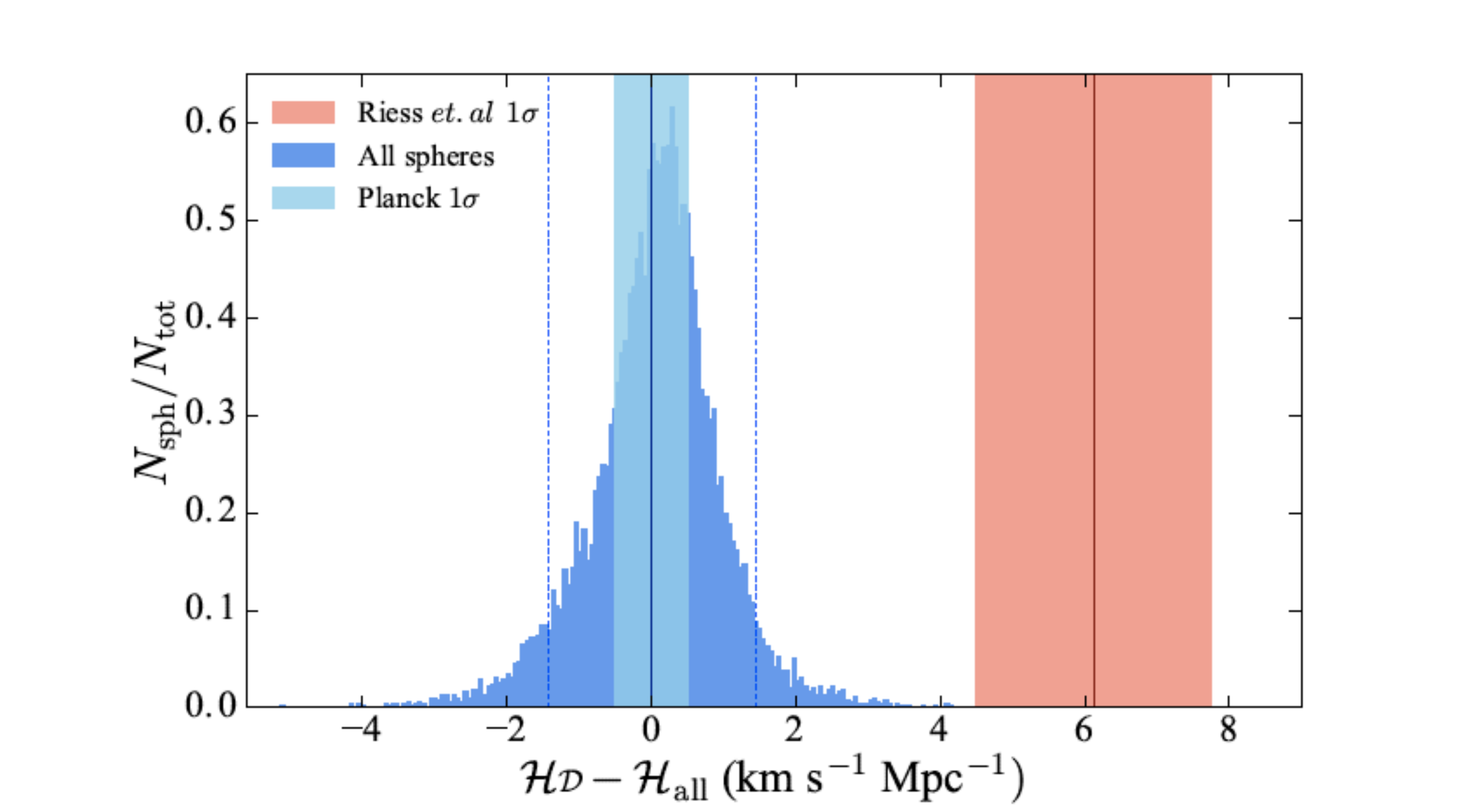
# Background metric – numerically




Deviation of local Hubble parameter (l) and density (r)

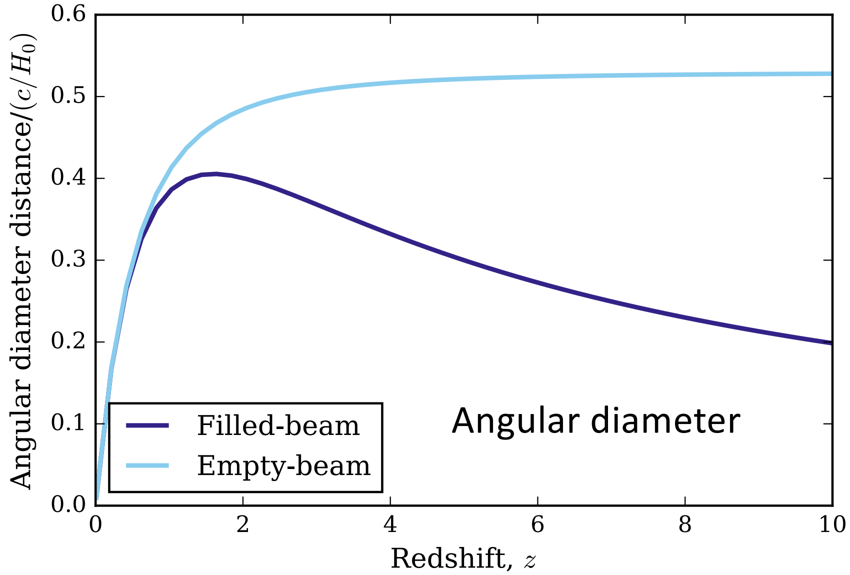
Macpherson+ 2018

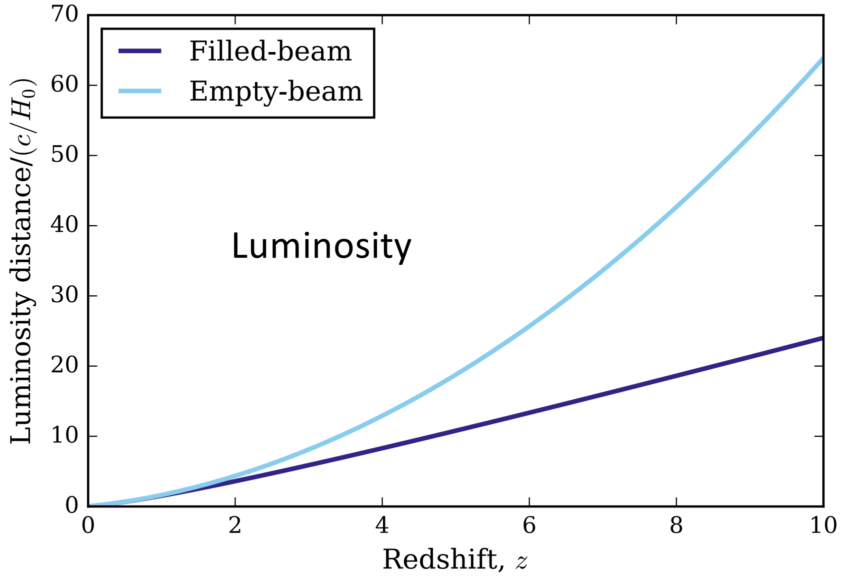
# Measurements of $H_0$ locally

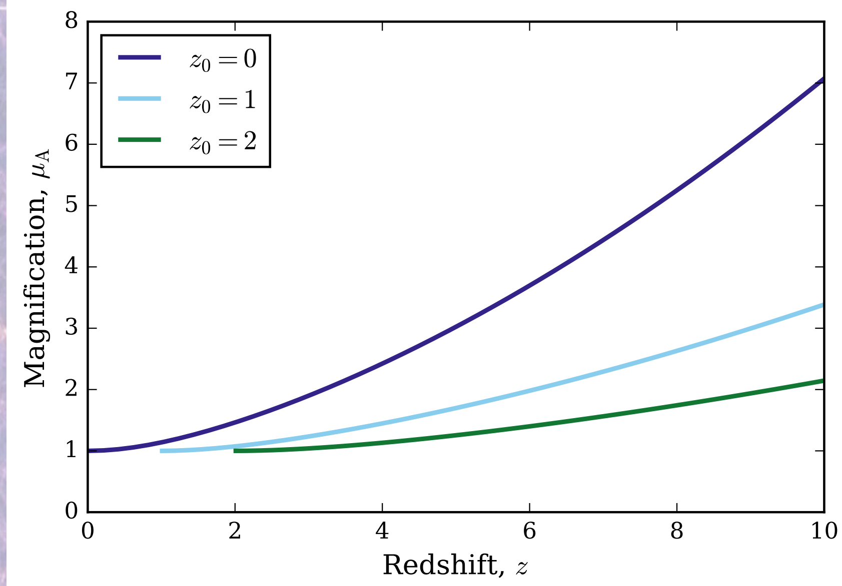



Macpherson+ 2018

# Background metric - distances

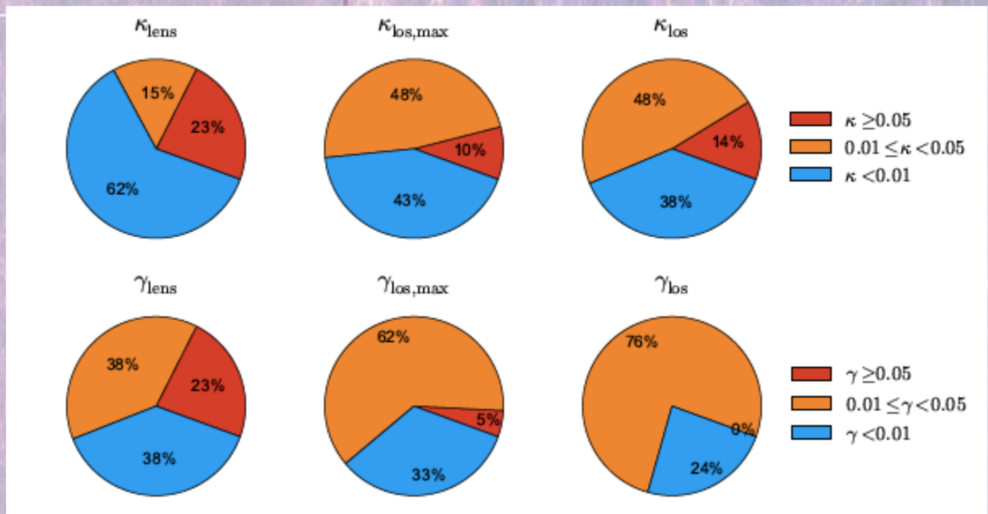


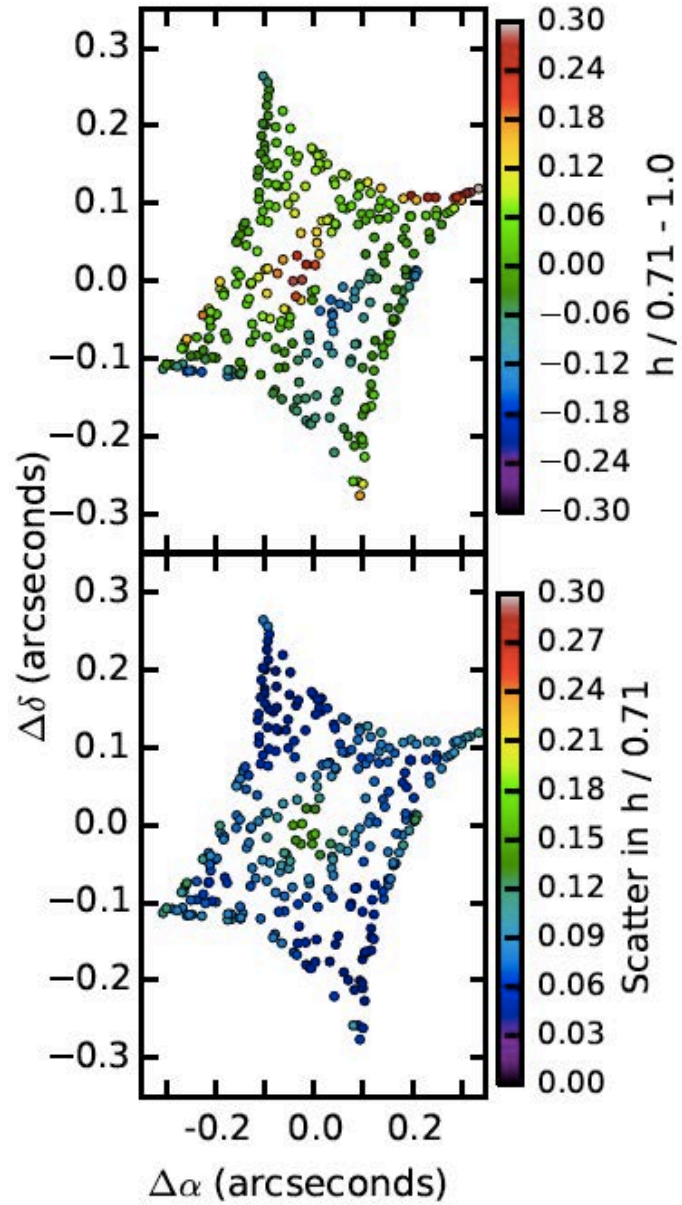




Empty beam demagnification

# Biased lines-of-sight (1)




Wilson+ 2017

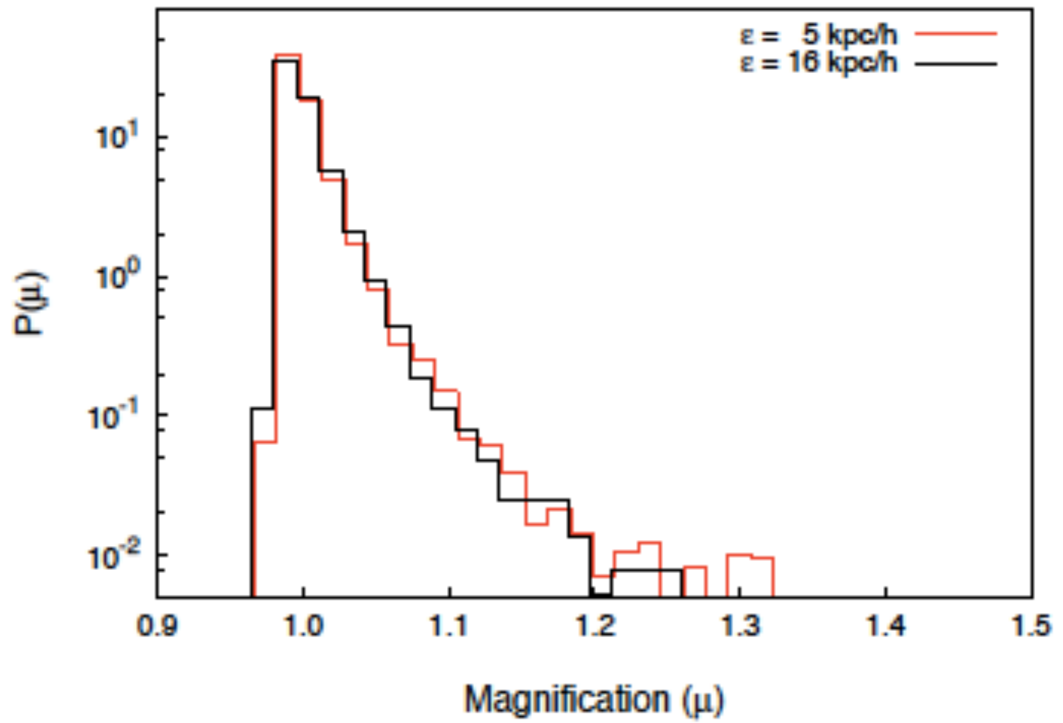



McCully+2016

# Biased lines-of-sight (2)

125 Mpc/h

The magnification PDF for small sources

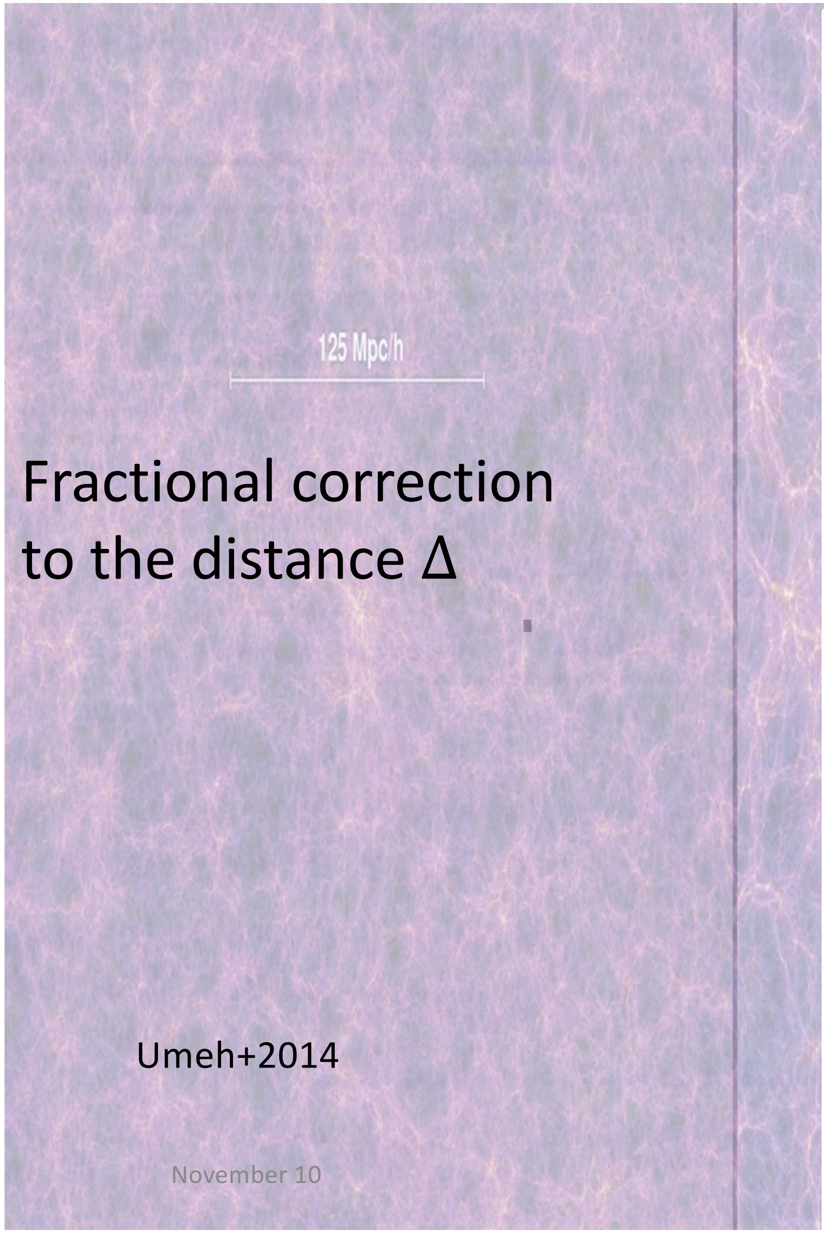



Wilson+ 2017

Killdear+2011

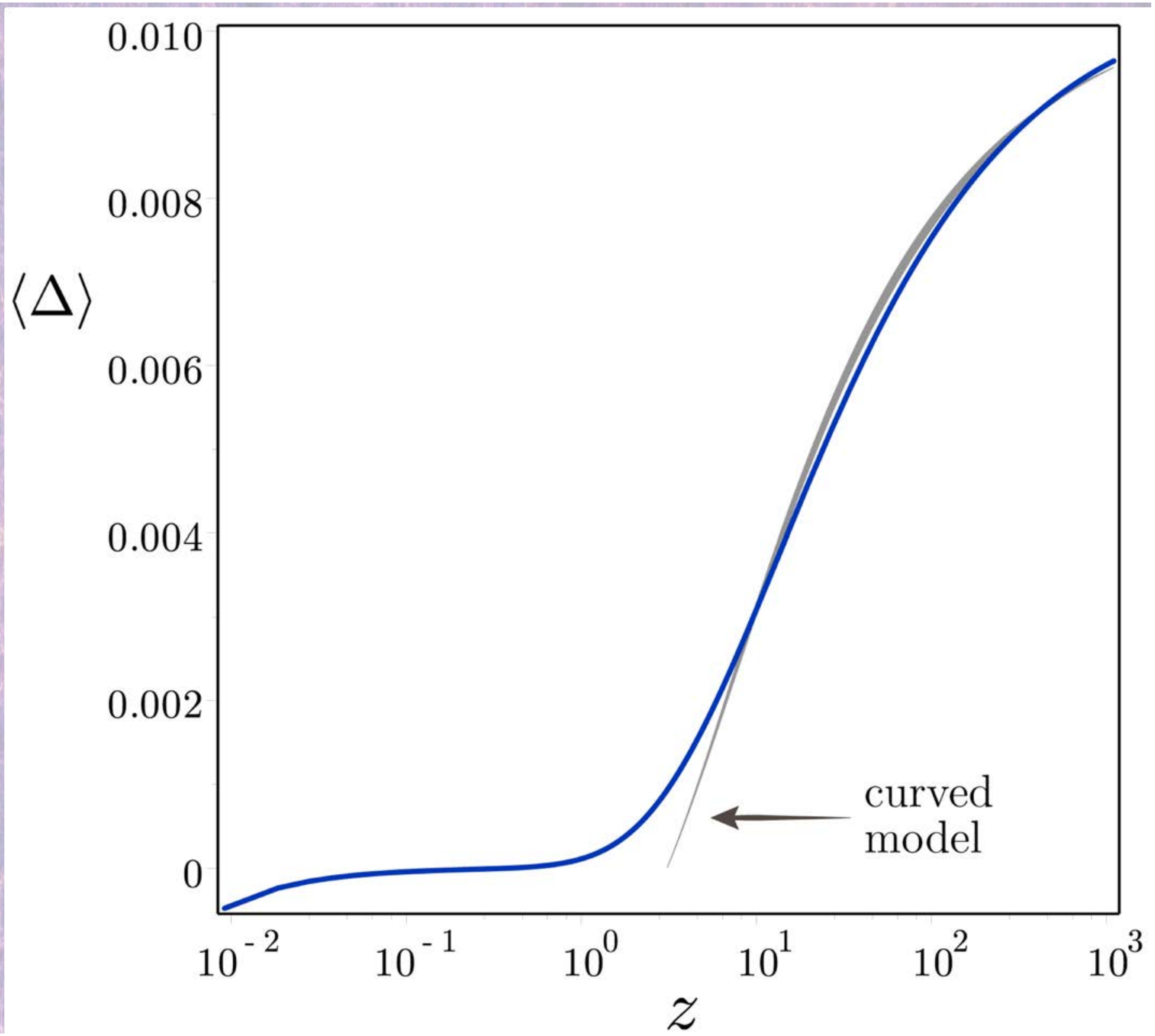
# Cosmological Averaging

- Weinberg (1976): Flux is conserved $\langle\mu\rangle = 1$ averaged over sources
- Seitz, Schneider&Ehlers(1994): Focussing theorem → one image is always brighter with a lens (but 'empty beams' need to be taken into account)
- Kibble&Liu (2005): distinguish between averaging over sources and averaging over directions (relevant for CMB) arguing that $\langle\mu^{-1}\rangle = 1$
- Kaiser&Peacock(2016): support Weinberg and Kibble&Liu, but argue that a nonlinear function of $\mu$ such as $D \propto \mu^{-1}$ will be biased by $\sim\langle\kappa^2\rangle$
- Ellis&Durrer(2018): consider there are still open questions, → not convinced the analysis is yet correct




Fractional correction
to the distance Δ

Umeh+2014



# Redshift drift –or – the Sandage-Loeb Effect

Sandage 1962
Loeb 1998

$$\frac{dz}{dt_{obs}}(t_0) = (1+z)H_0 - H(z)$$

$$c\delta(z) \sim 1\ \frac{cm}{sec}/yr$$

Liske+ 2004

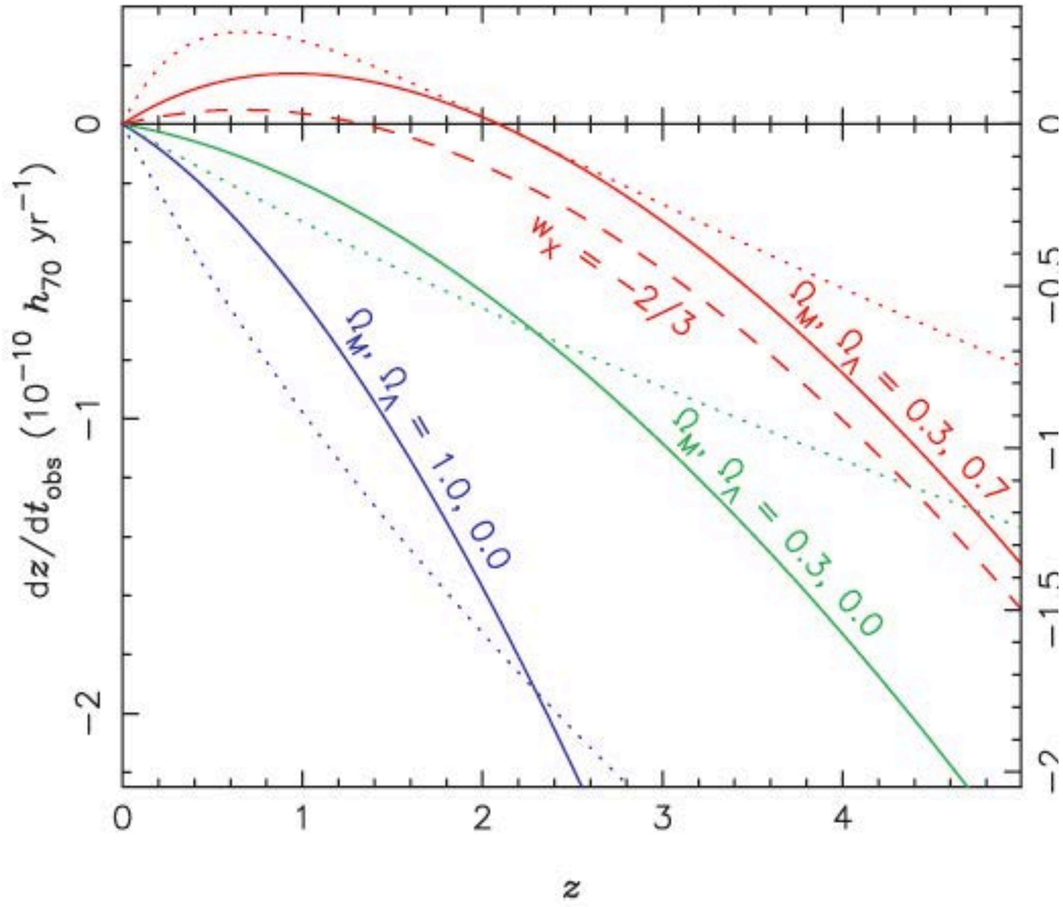
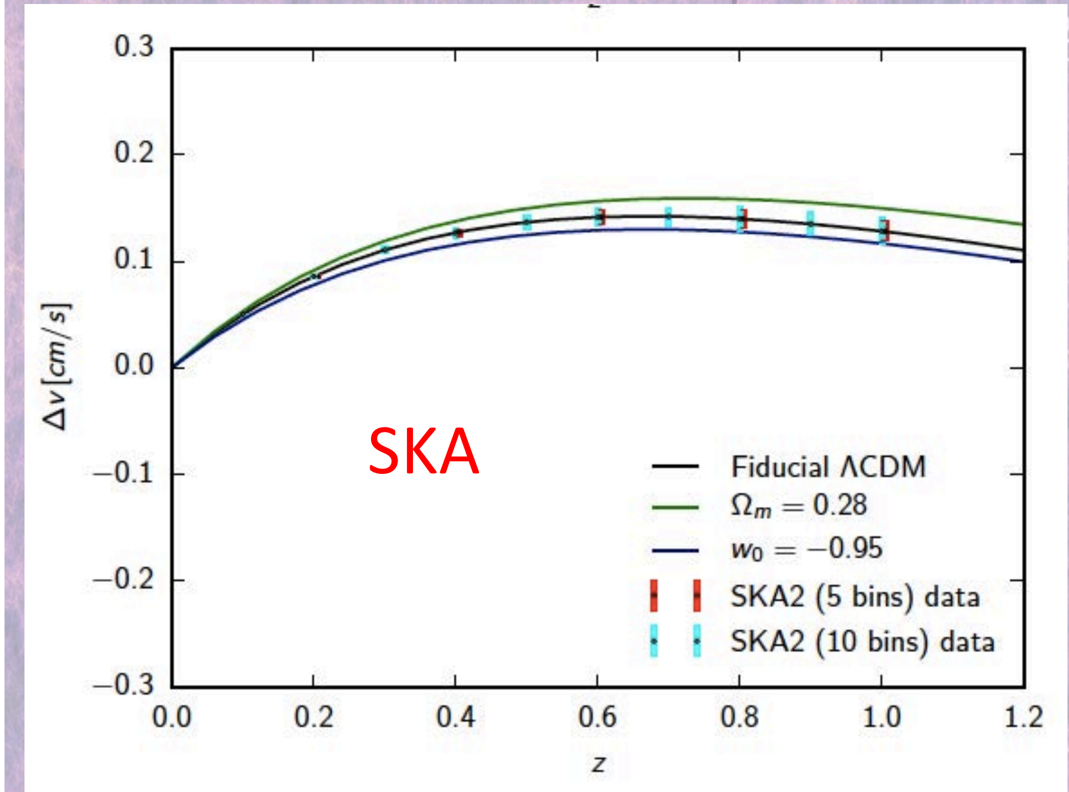
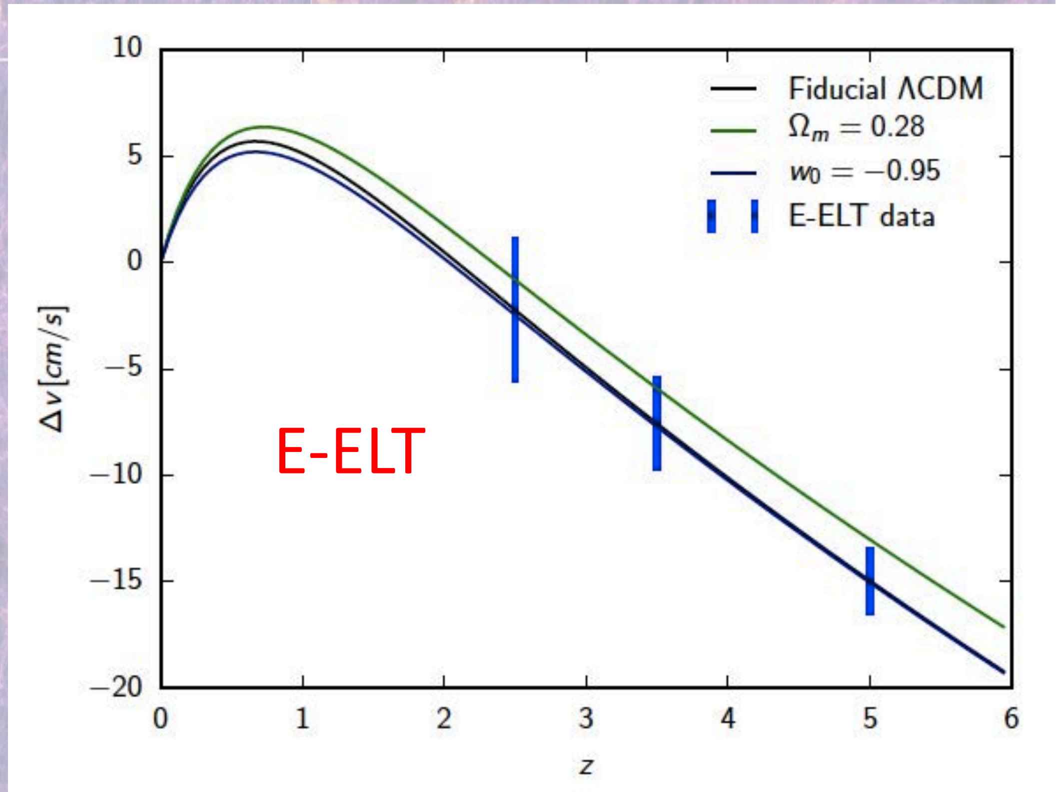



**Figure 2.** The solid (dotted) lines and left-hand axis (right-hand axis) s the redshift drift $\dot{z}$ ($\dot{v}$) as a function of redshift for various combinatio $\Omega_M$ and $\Omega_\Lambda$ as indicated. The dashed line shows $\dot{z}$ for the case of dark en having a constant $w_X = -2/3$ (and $\Omega_M, \Omega_X = 0.3, 0.7$).

# Measuring the SL Effect



# Conclusions

- Measuring $H_0$ – path to the 1% experiment
- Scale of homogeneity is ~100 Mpc
- General relativistic cosmological models with structure formation → framework
- Issues in measuring $H_0$ to better than 1% - theoretical

- SL test – hard but worth it