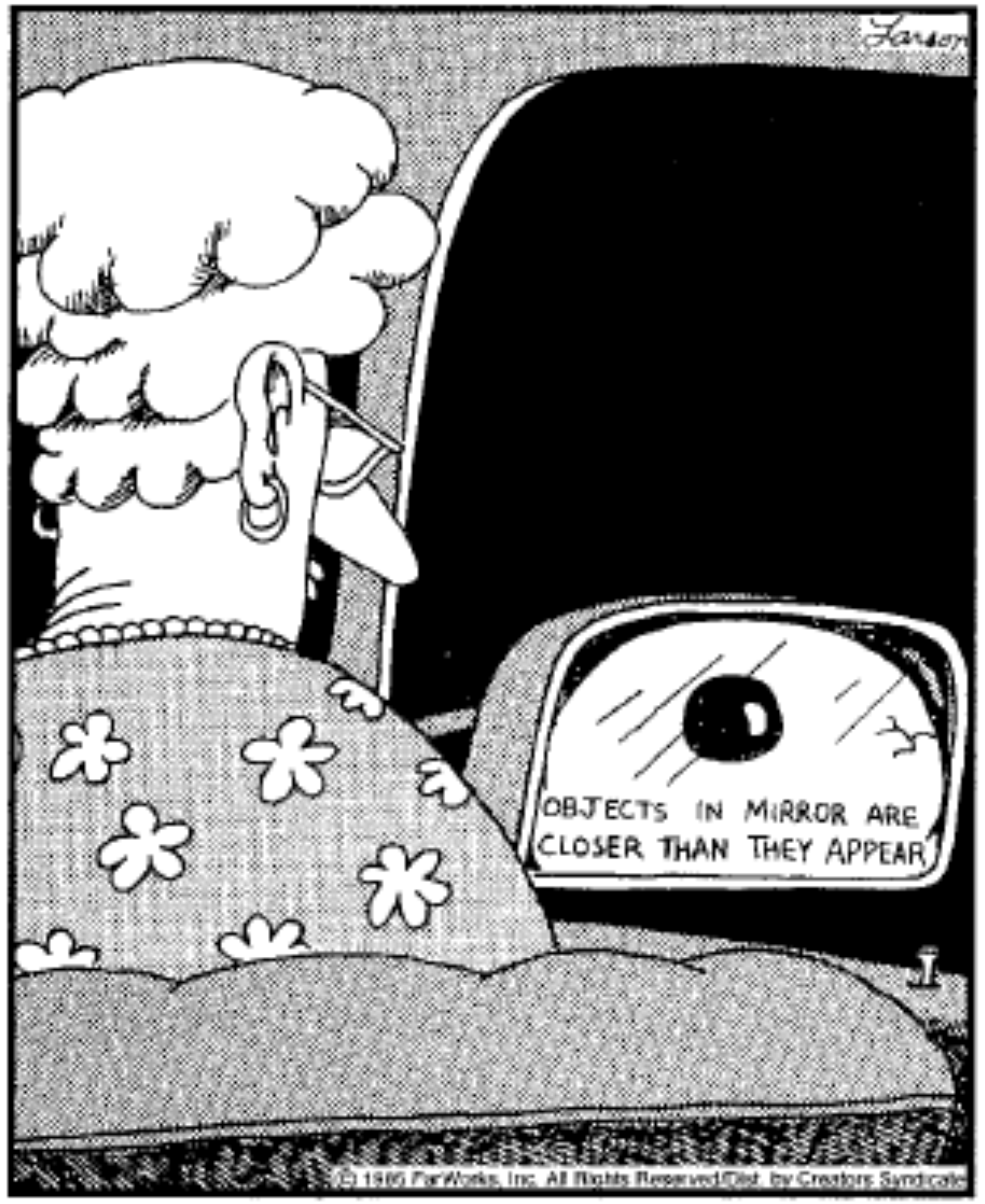
Measuring Distances

ASTR/PHYS 4080: Intro to Cosmology
Week 6



How do you measure distances when you're too lazy to get off the couch?

TV is 6 or 7 years old, new TVs are cheap, so it's a great time to upgrade!

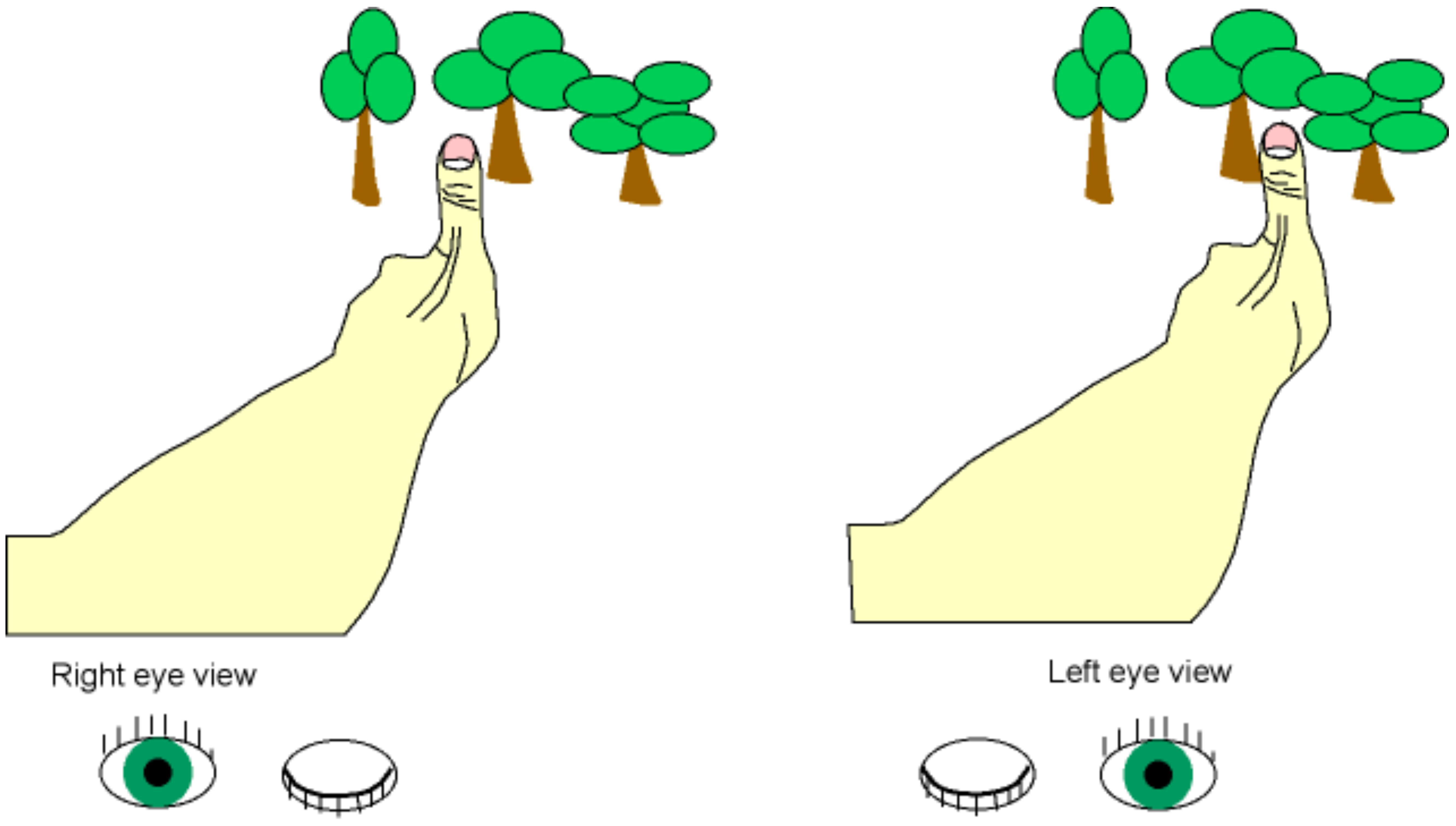
Problem: I know roughly how much bigger I'd like the new TV to be (about or a little less than 2x bigger), but I don't know how big my current TV is.

How do I measure it?

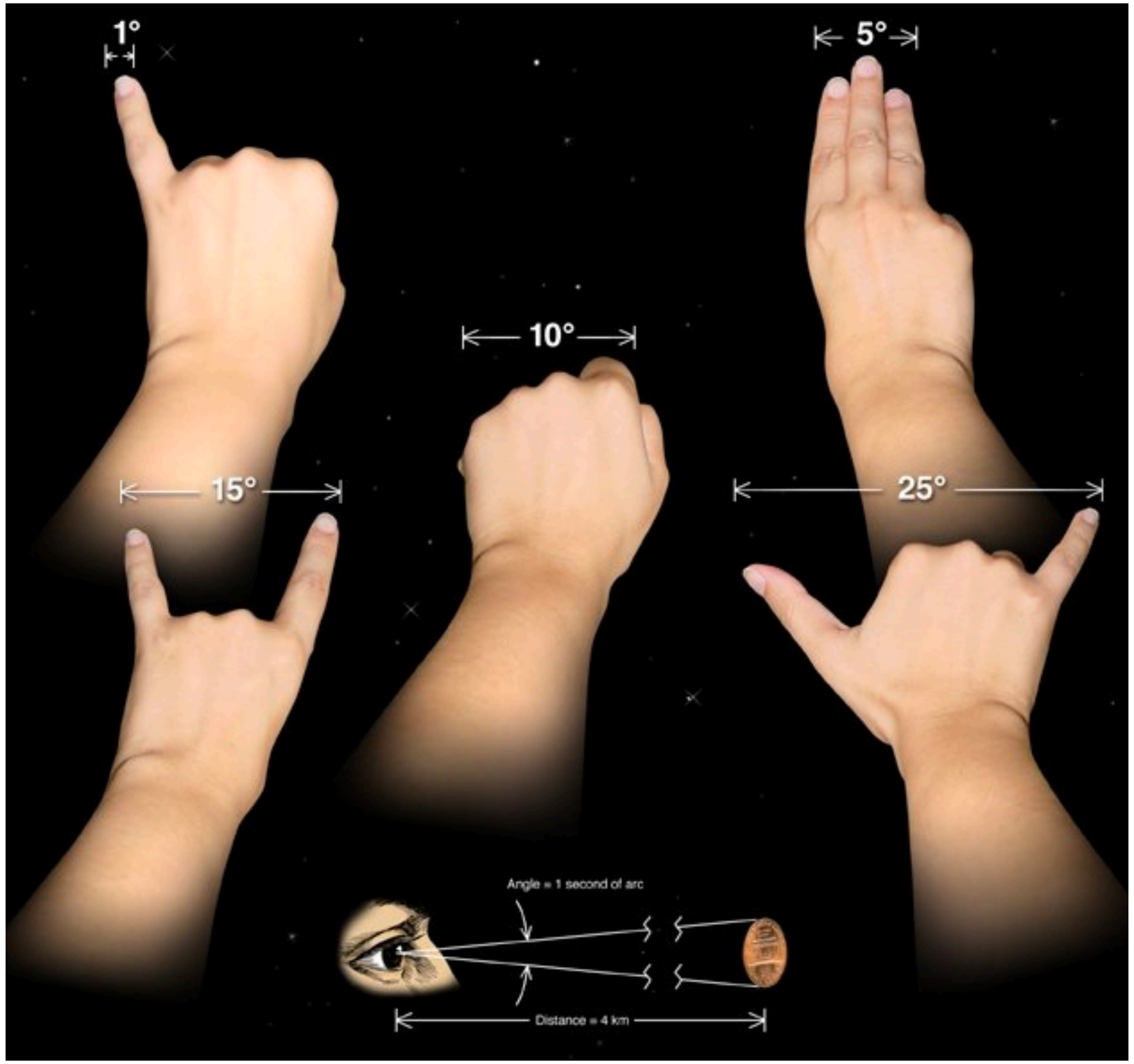
WITHOUT relinquishing my seat to the cat.

Farther away things are fainter

Angular extent depends on distance

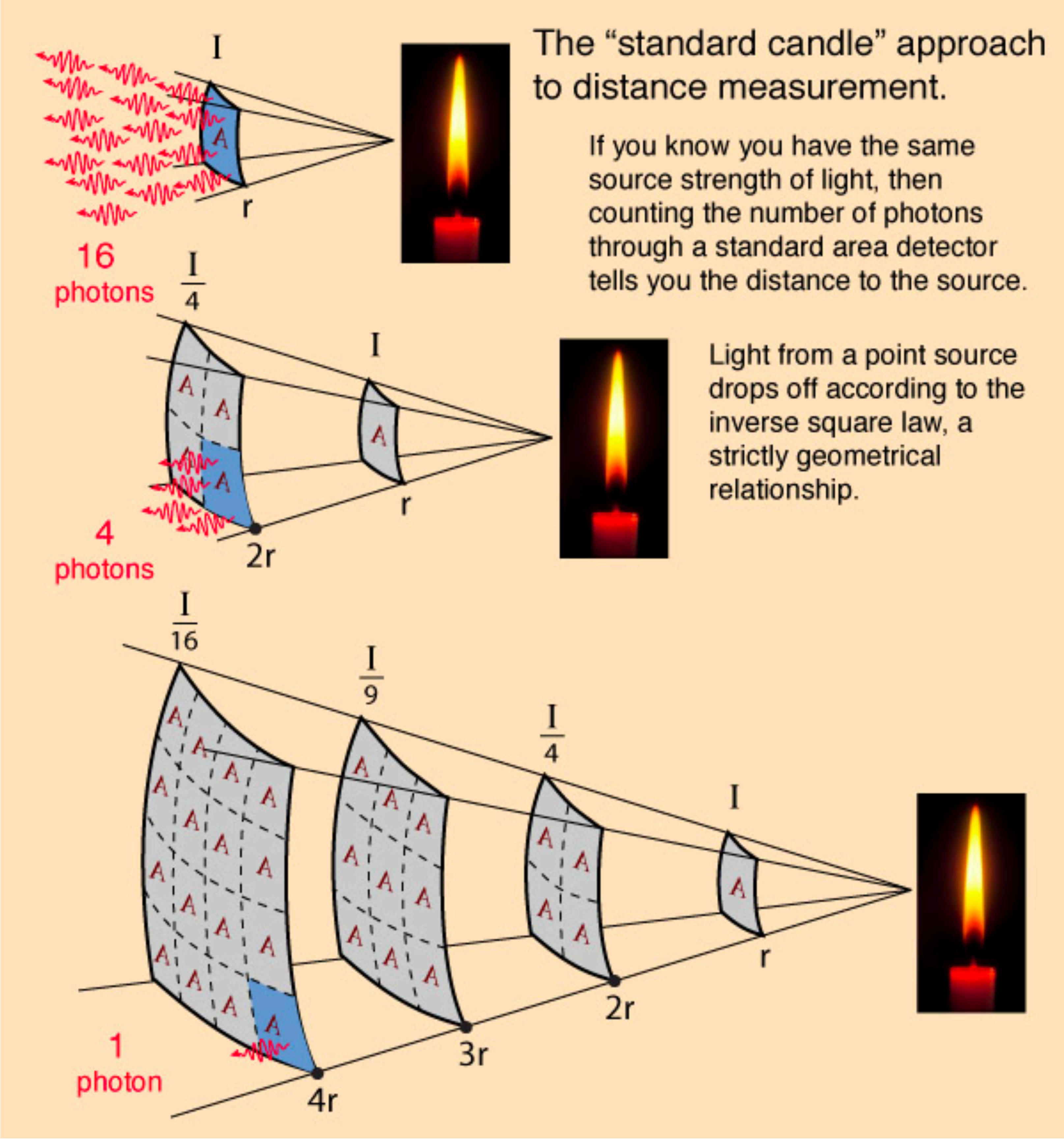


Parallax effect illustrated with your thumb. Notice how your thumb held at arm's length appears to shift with respect to background objects when you look at it with one eye and then the other eye.

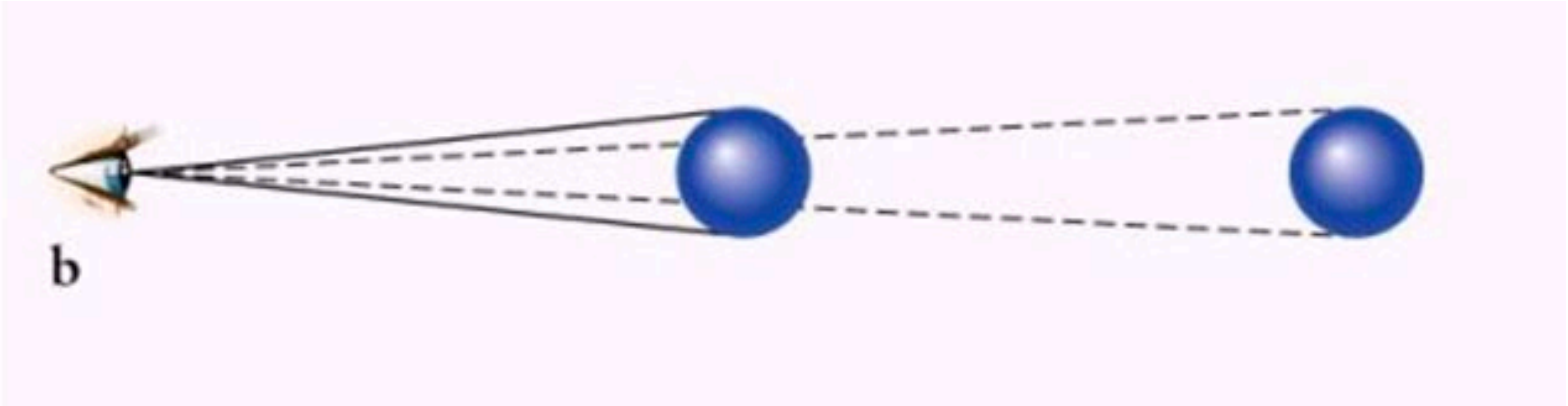


Practical Distance Measures

Luminosity Distance



Angular Diameter Distance



d_L and d_A in a universe with curvature

Robertson-Walker Metric

$$ds^2 = -c^2 dt^2 + a(t)[dr^2 + S_\kappa(r)^2 d\Omega^2]$$

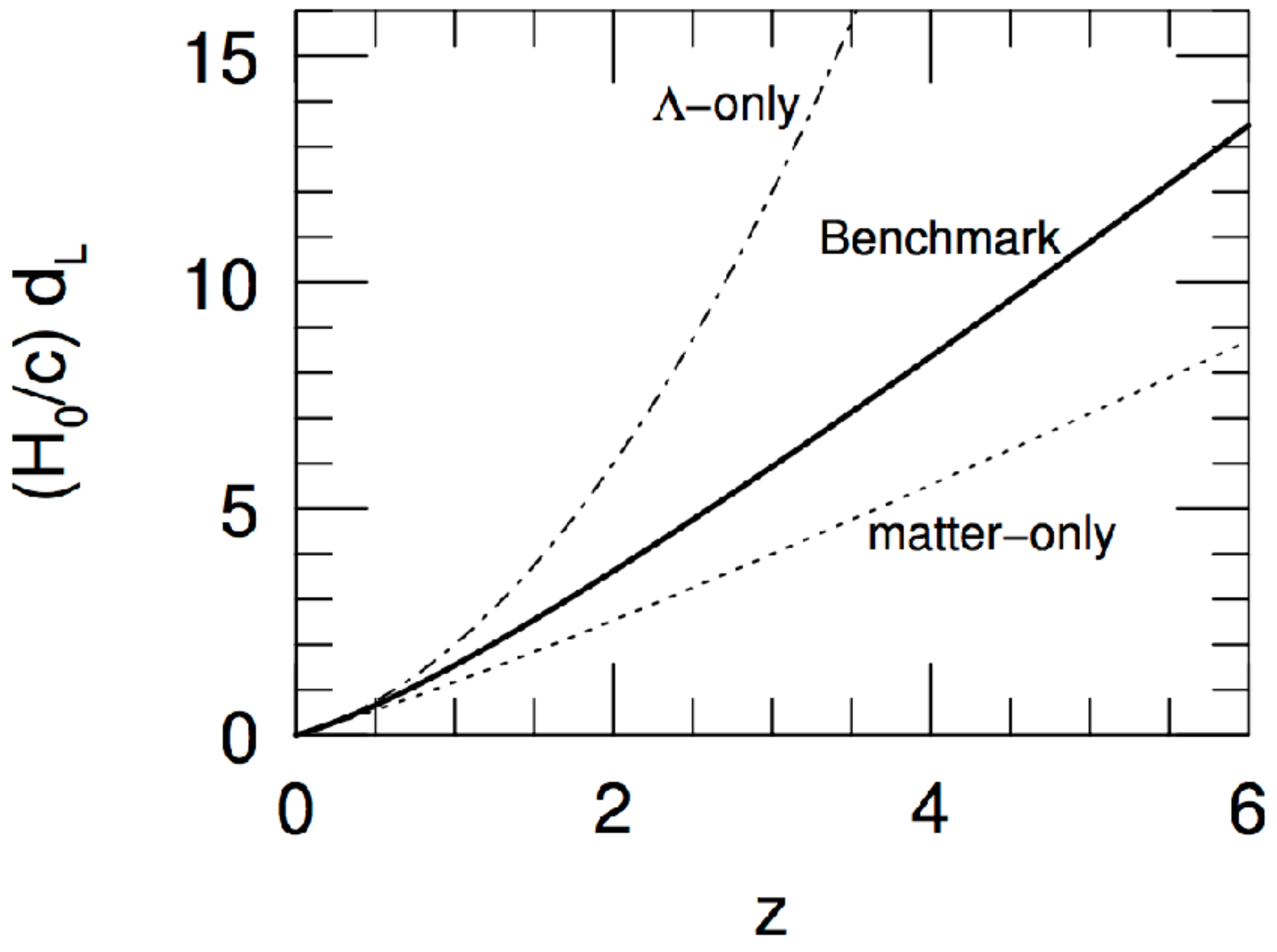
$$S_\kappa(r) = \begin{cases} R \sin \frac{r}{R} & (\kappa = +1) \\ r & (\kappa = 0) \\ R \sinh \frac{r}{R} & (\kappa = -1) \end{cases}$$

flux affected by area of
expanding shell of light

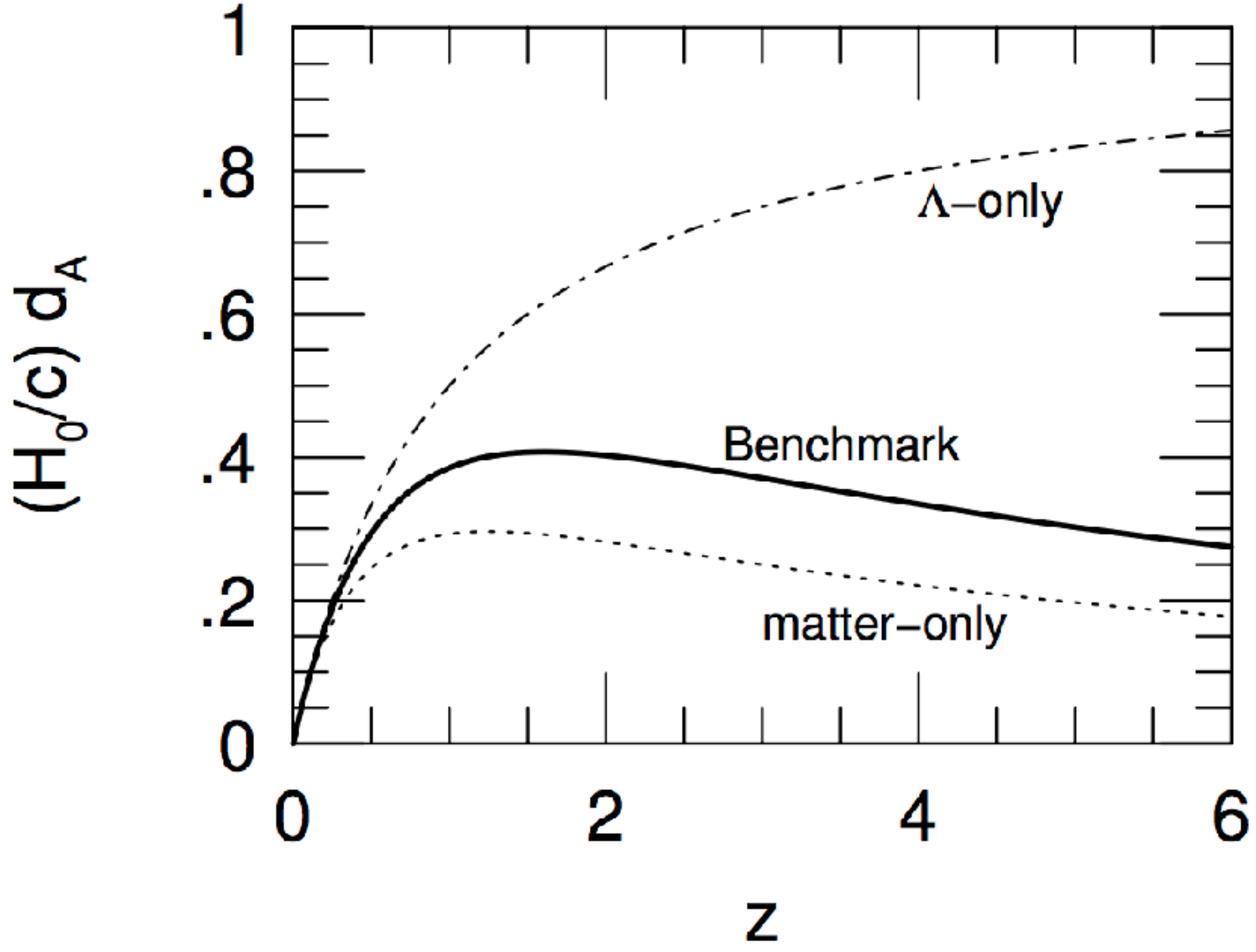
angular extent affected by
curvature of geodesics

How distances are affected by underlying cosmology

Luminosity Distance



Angular Diameter Distance

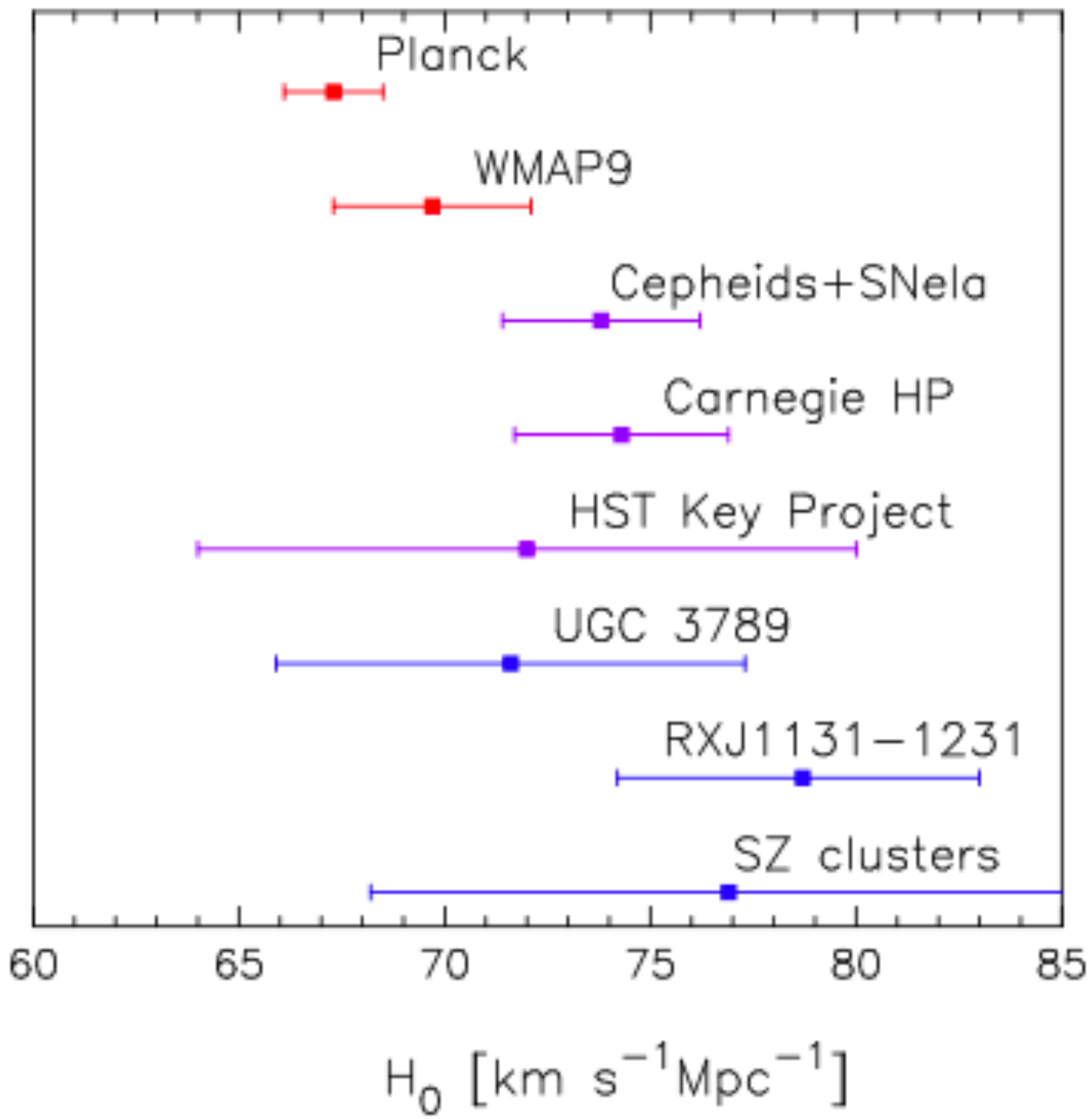


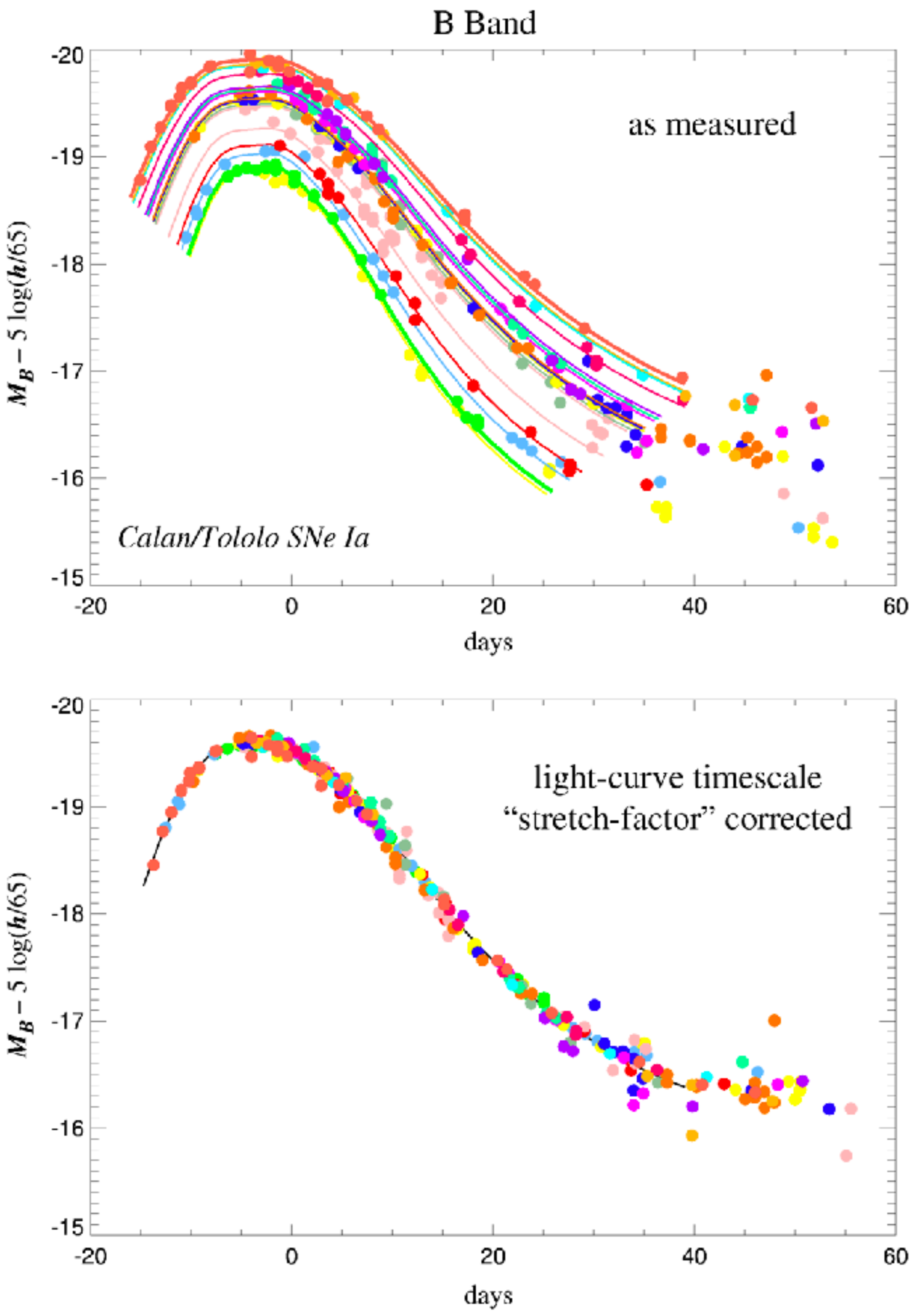
Contemporary Measurements

Supernovae Luminosity Distances

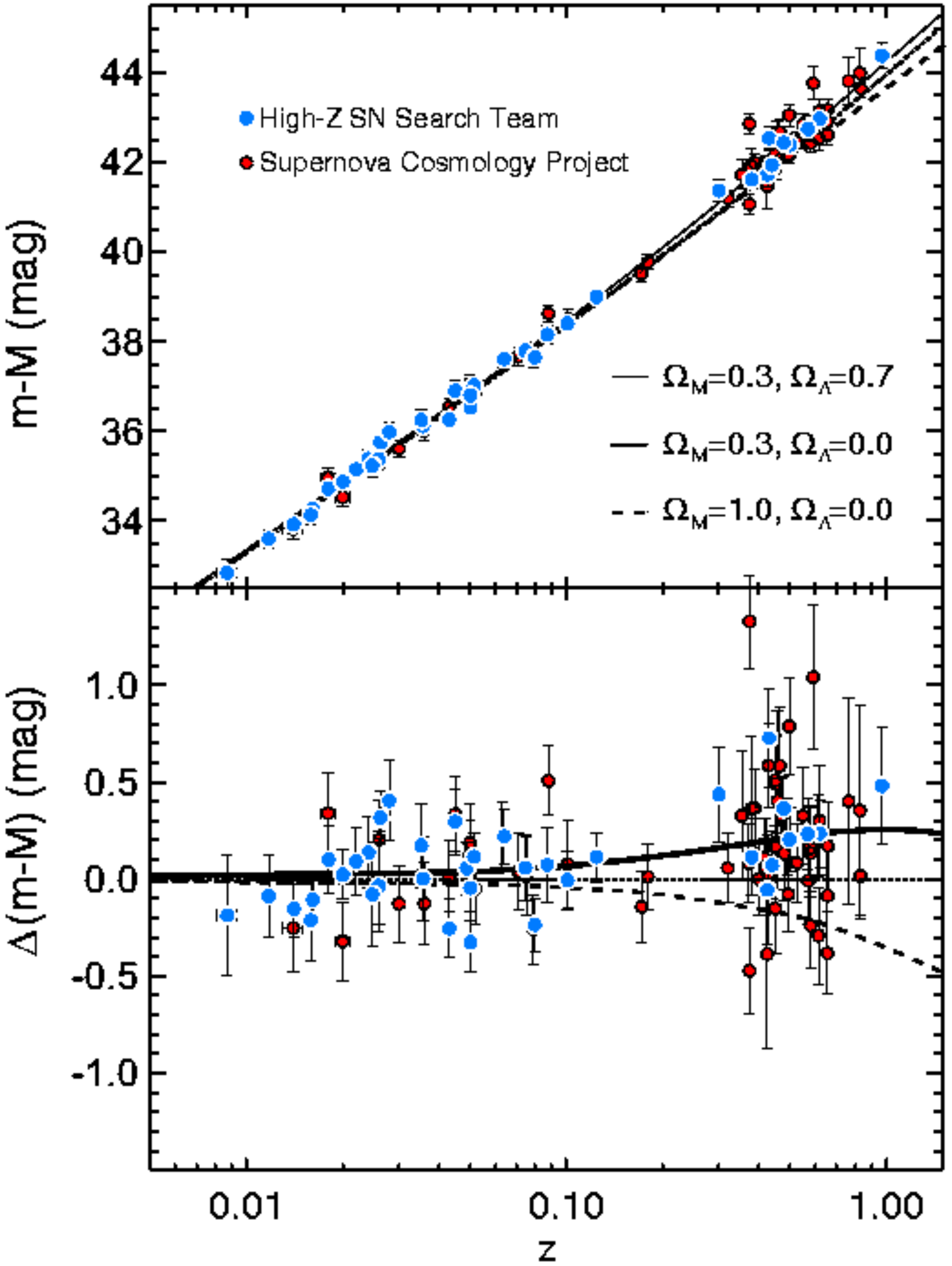
Megamaser Potential

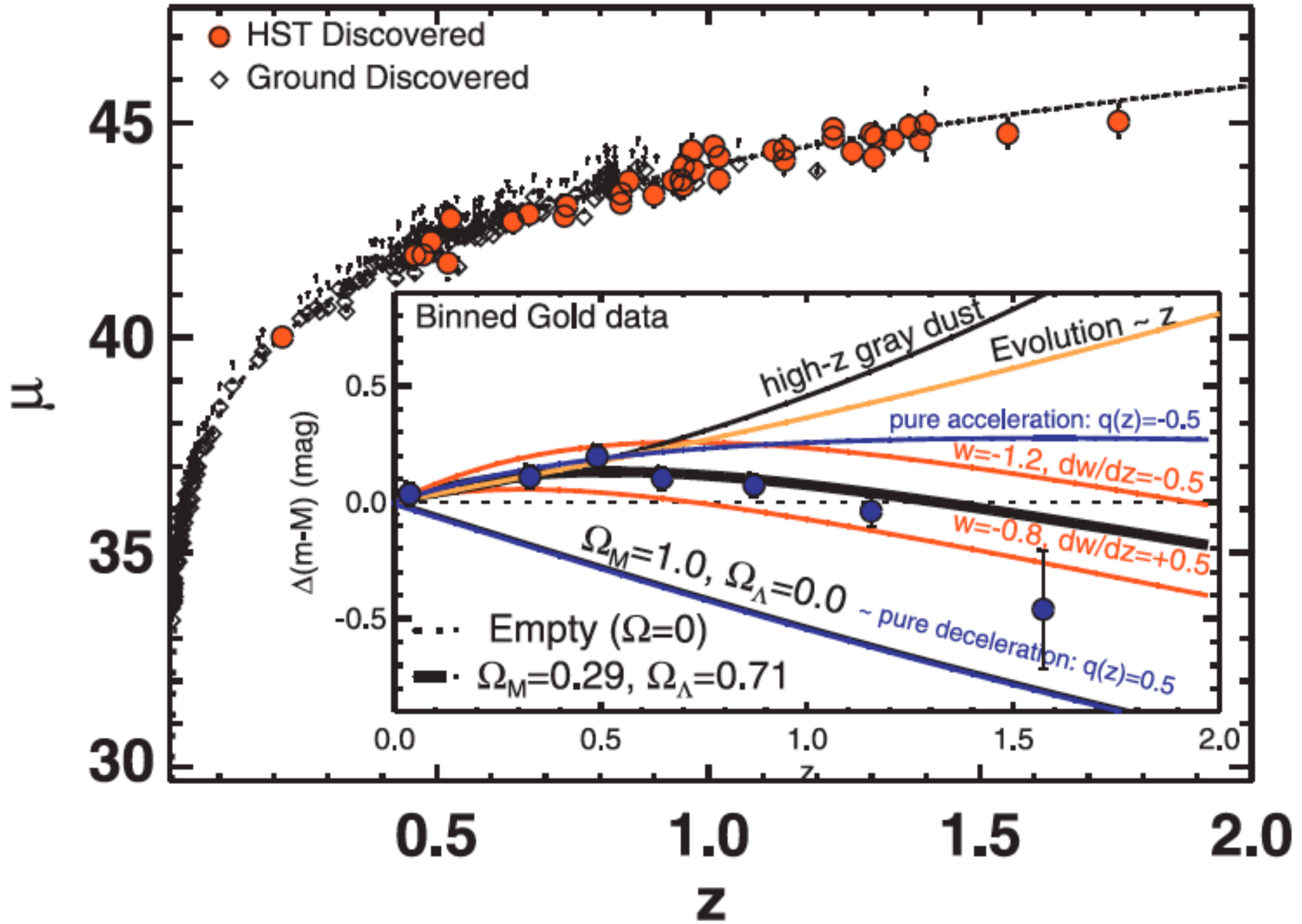
Promise of GW sources as
“standard sirens”

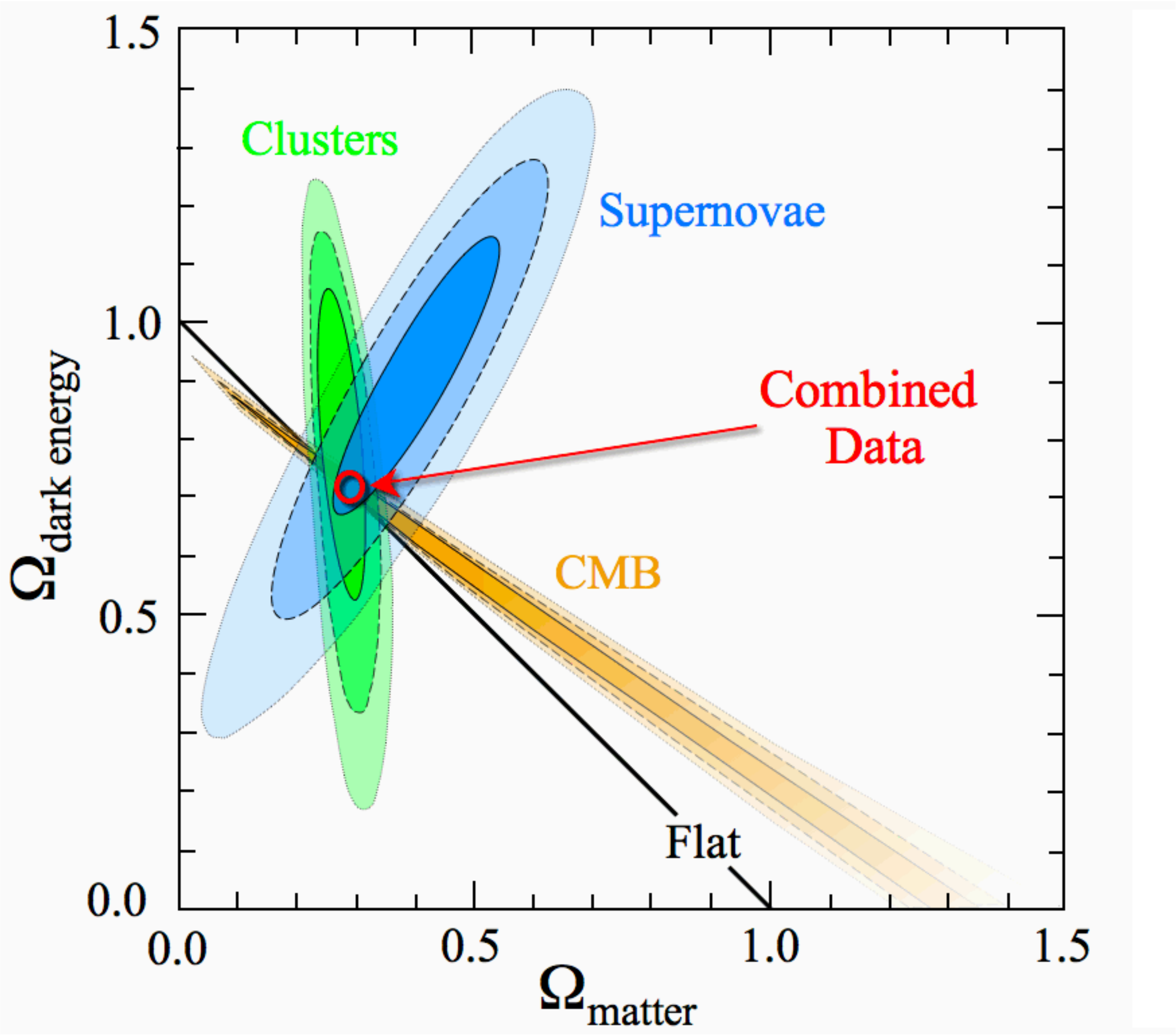


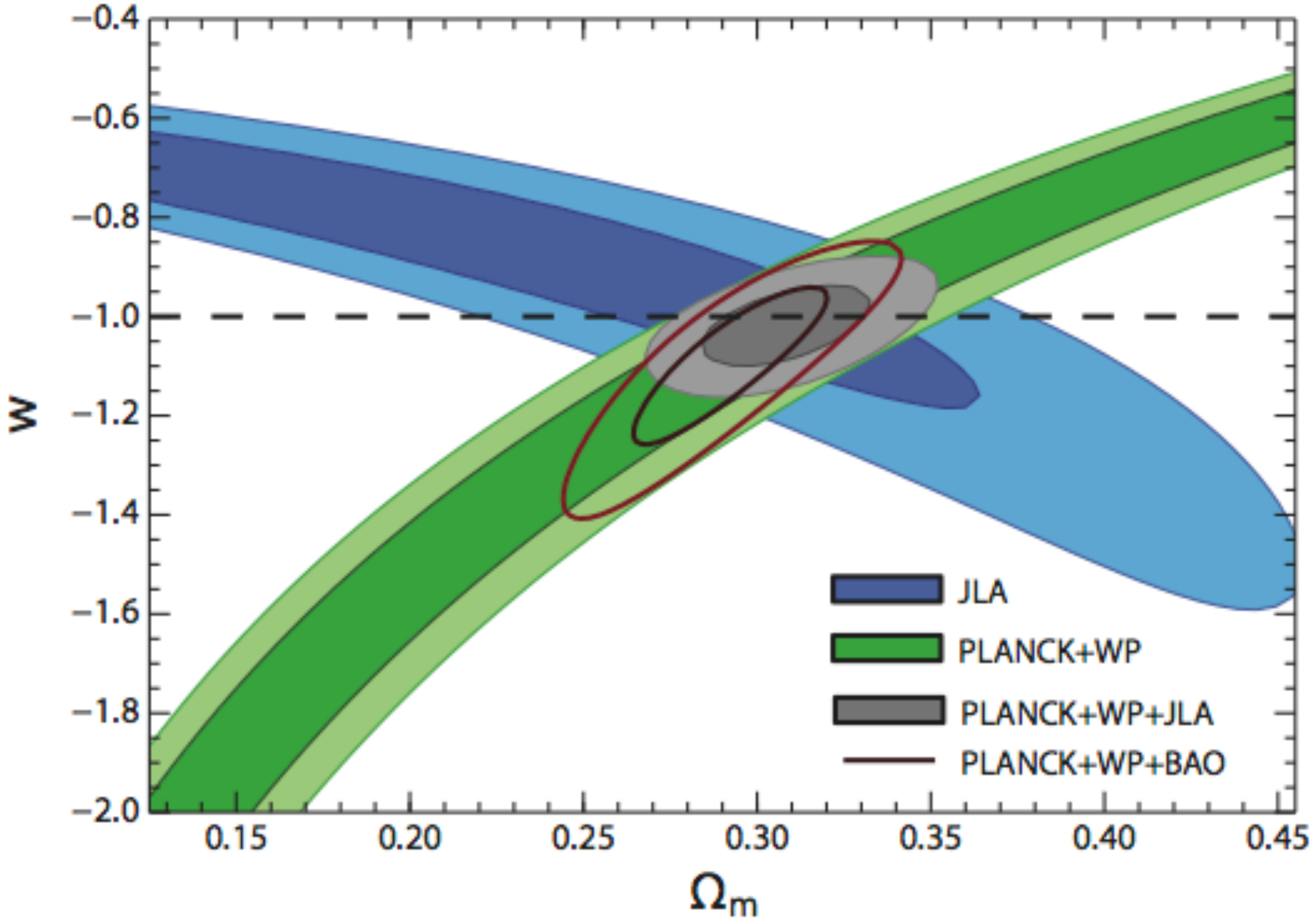


Kim, *et al.* (1997)

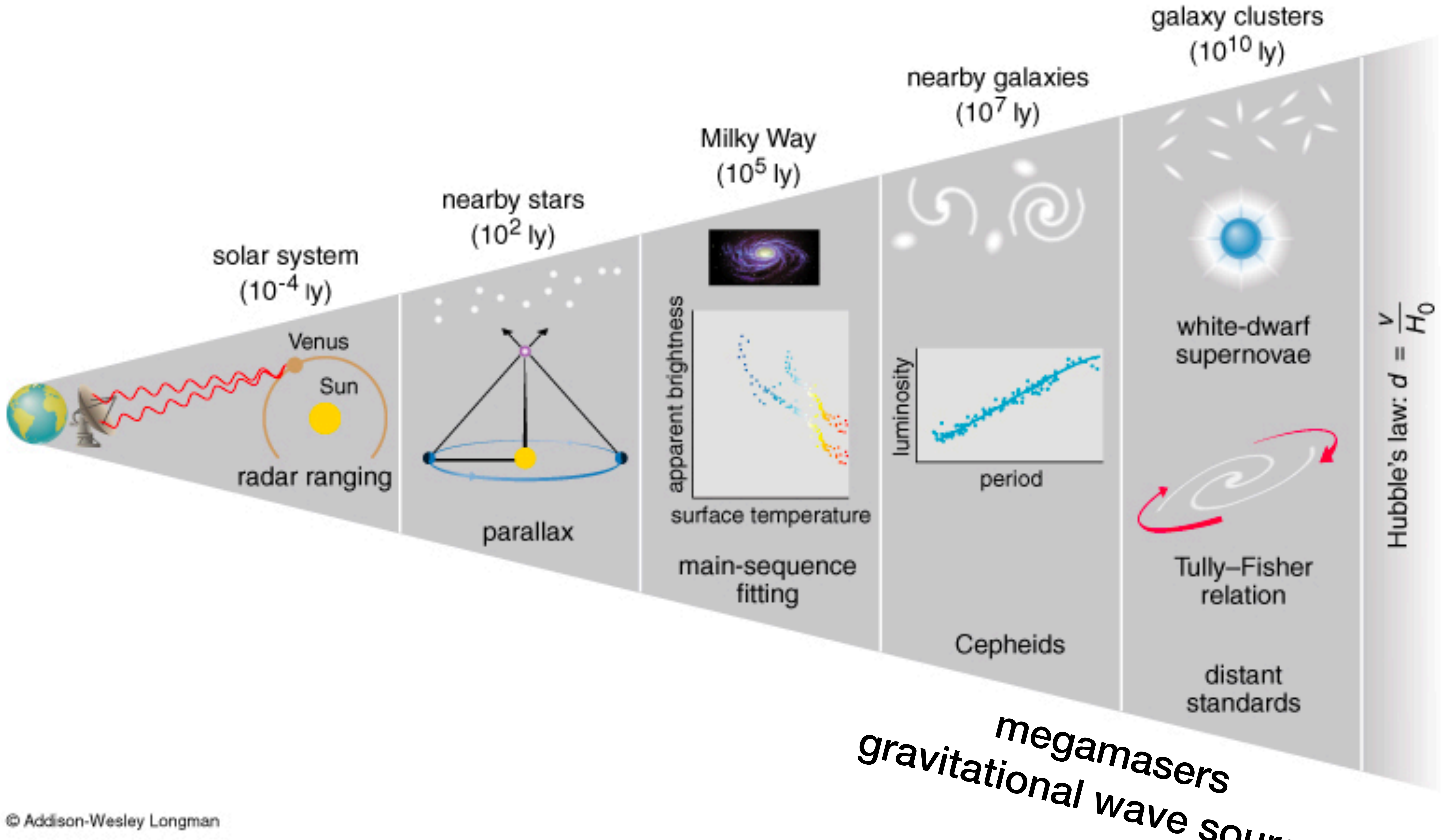



HST Discovered
Ground Discovered
45
40
35
30
μ
0.5
1.0
1.5
2.0
z
Binned Gold data
high-z gray dust
Evolution ~ z
pure acceleration: q(z)=-0.5
w=-1.2, dw/dz=-0.5
w=-0.8, dw/dz=+0.5
Ω_M=1.0, Ω_Λ=0.0
~ pure deceleration: q(z)=0.5
Empty (Ω=0)
Ω_M=0.29, Ω_Λ=0.71
Δ(m-M) (mag)
0.5
0.0
-0.5
0.0
0.5
1.0
1.5
2.0
z


1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
$\Omega_{\text{dark energy}}$
Ω_{matter}
Clusters
Supernovae
Combined Data
CMB
Flat

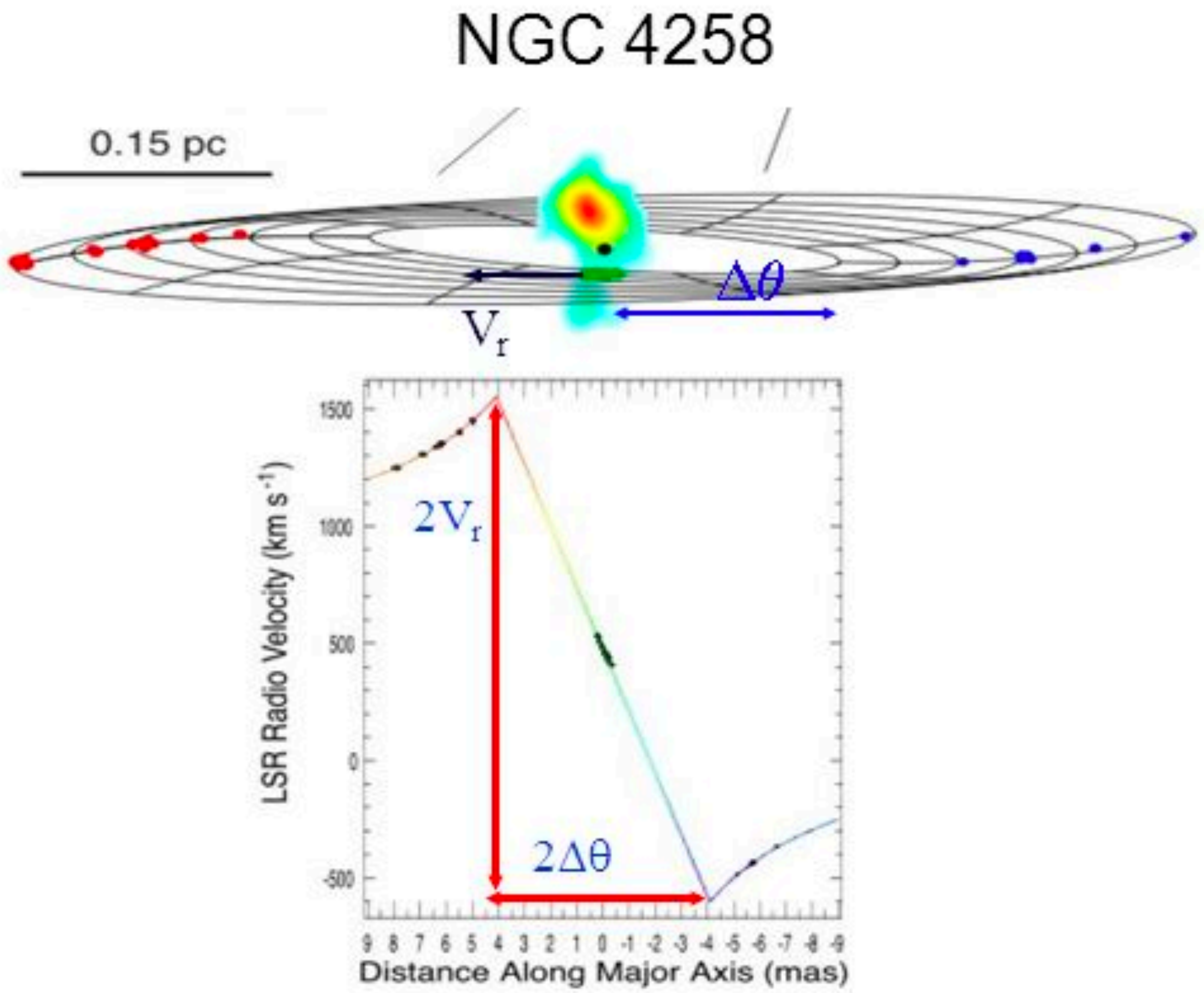

−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
w
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Ω_m
JLA
PLANCK+WP
PLANCK+WP+JLA
PLANCK+WP+BAO

Distance Ladder



megamasers
gravitational wave sources

Measuring Distances to H_2O Megamasers



7.2 ± 0.5 Mpc : Herrnstein et al. (1999))

Thin-ring model:

$$D = a^{-1} k^{2/3} \Omega^{4/3}$$

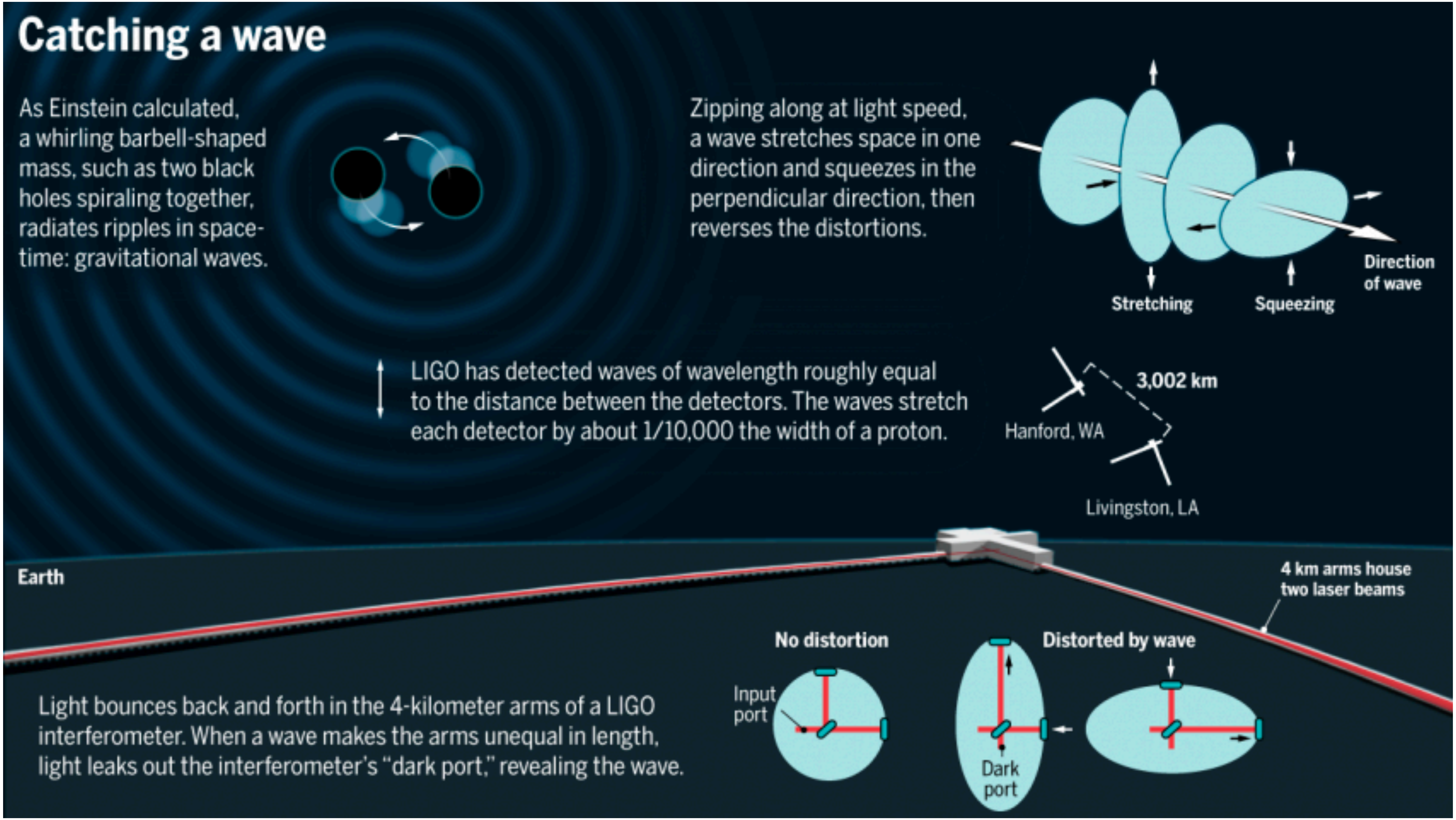
a = acceleration

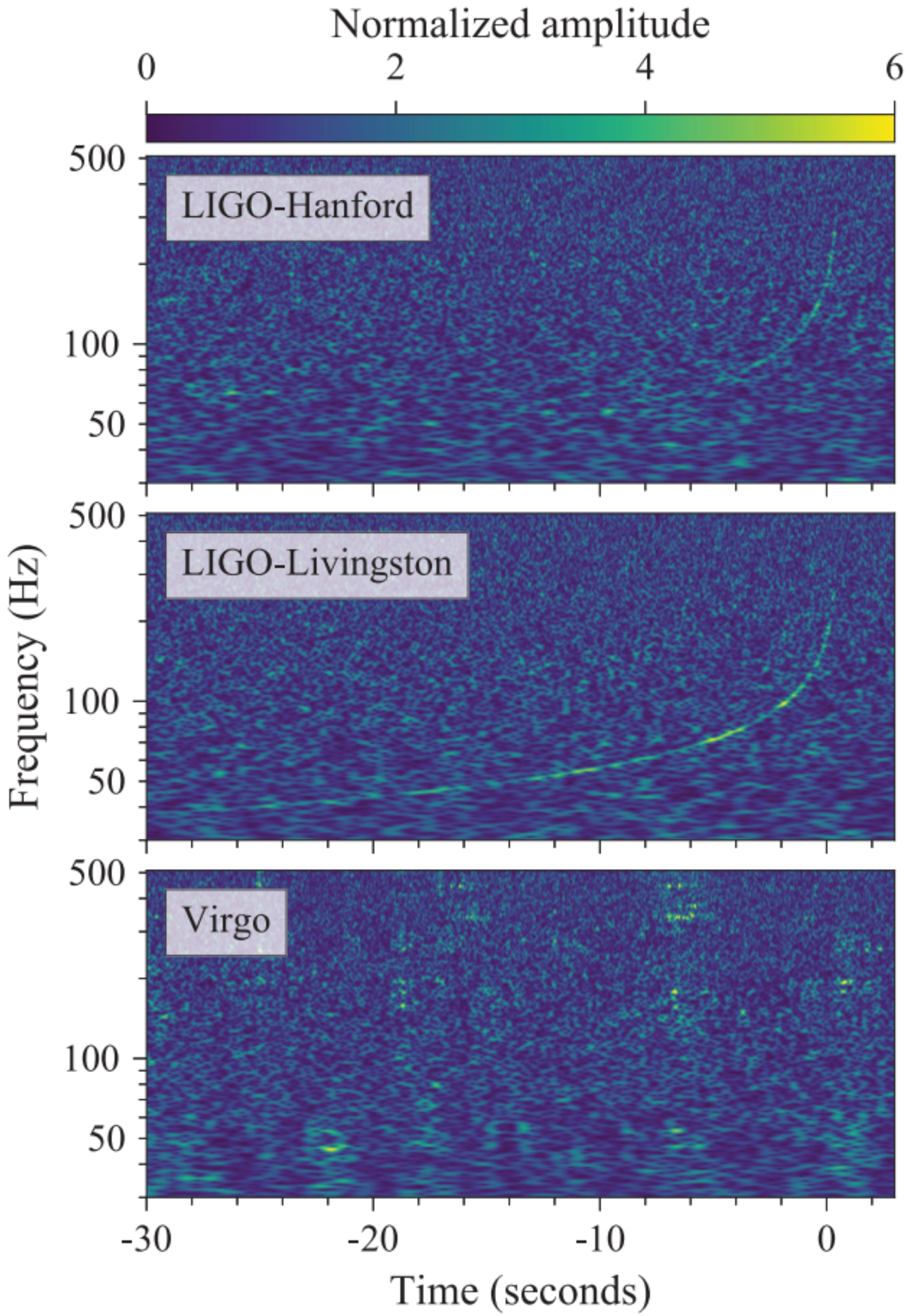
$v = k\, r^{-1/2}$

Ω = slope of sys features

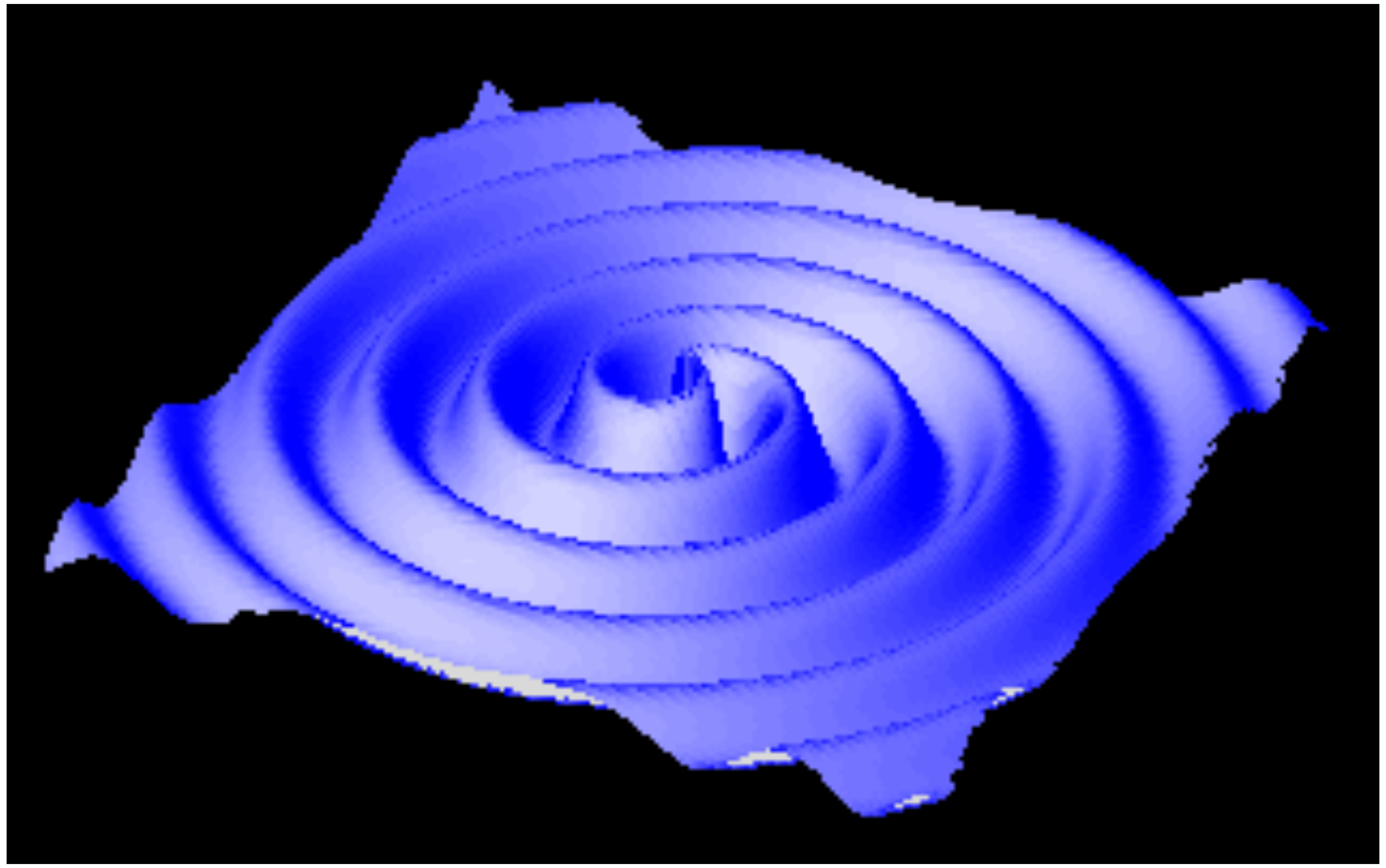
$$\frac{\sigma_{Da}}{D_a} \simeq \sqrt{\left(\frac{\sigma_a}{a}\right)^2 + \frac{4}{9}\left(\frac{\sigma_k}{k}\right)^2 + \frac{16}{9}\left(\frac{\sigma_\Omega}{\Omega}\right)^2}.$$

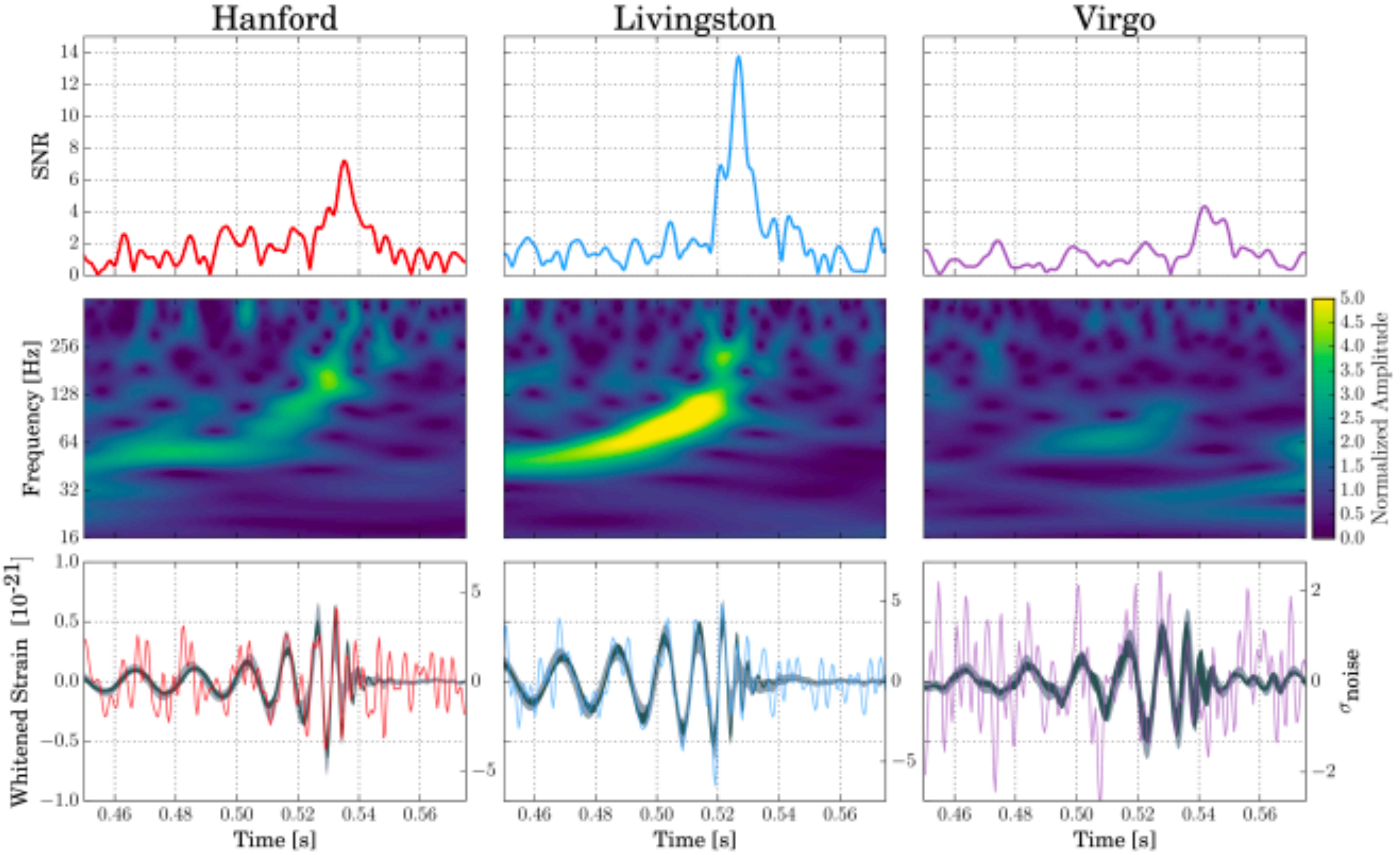
NRAO

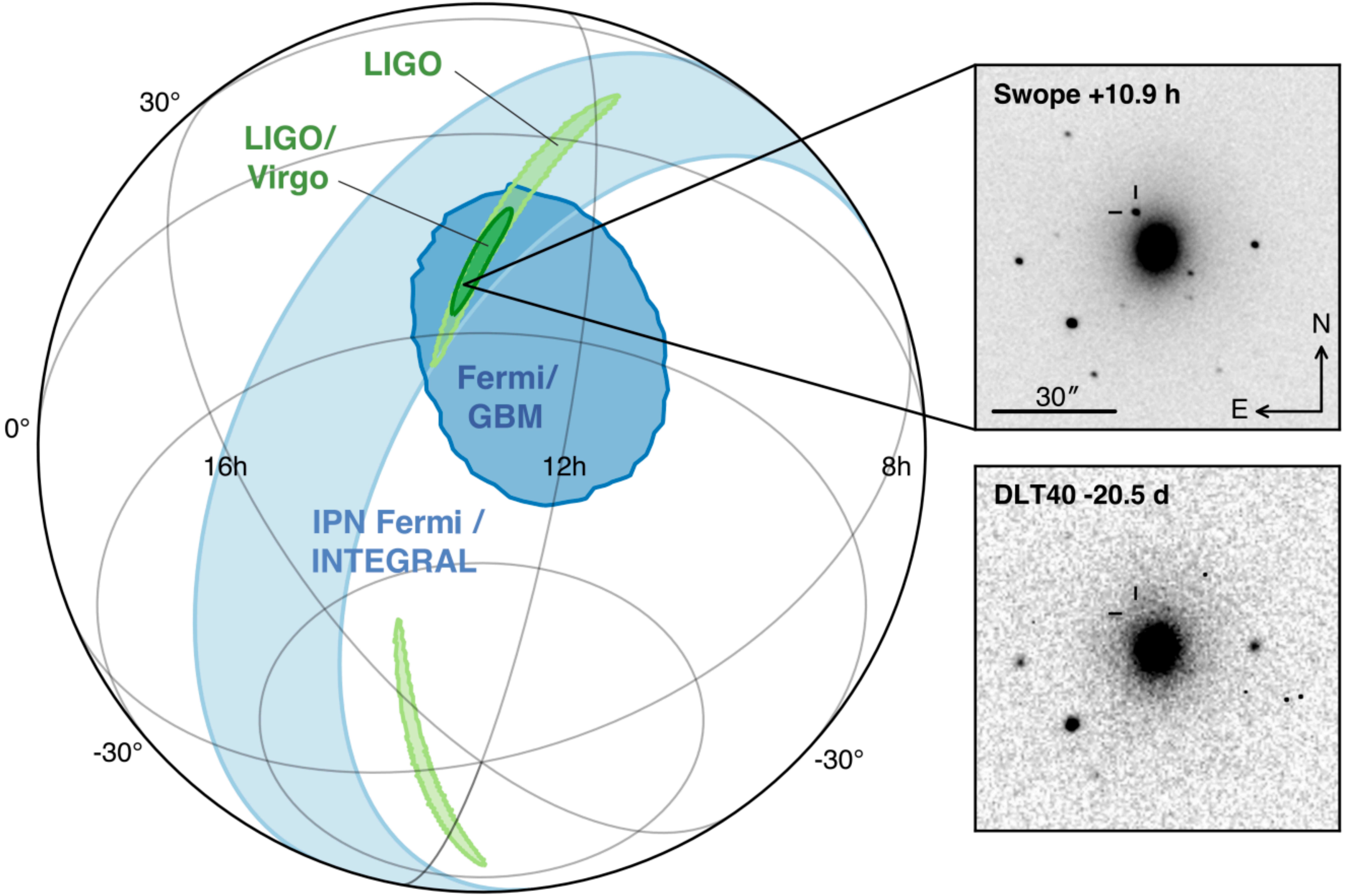

Catching a wave
As Einstein calculated, a whirling barbell-shaped mass, such as two black holes spiraling together, radiates ripples in space-time: gravitational waves.
Zipping along at light speed, a wave stretches space in one direction and squeezes in the perpendicular direction, then reverses the distortions.
Direction of wave
Stretching
Squeezing
LIGO has detected waves of wavelength roughly equal to the distance between the detectors. The waves stretch each detector by about 1/10,000 the width of a proton.
3,002 km
Hanford, WA
Livingston, LA
Earth
4 km arms house two laser beams
No distortion
Distorted by wave
Input port
Dark port
Light bounces back and forth in the 4-kilometer arms of a LIGO interferometer. When a wave makes the arms unequal in length, light leaks out the interferometer's "dark port," revealing the wave.



GW170817
NS-NS Merger




Hanford
Livingston
Virgo
SNR
14
12
10
8
6
4
2
0
Frequency [Hz]
256
128
64
32
16
Normalized Amplitude
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Whitened Strain [10^{-21}]
1.0
0.5
0.0
−0.5
−1.0
5
0
−5
2
−2
σ_{noise}
0.46
0.48
0.50
0.52
0.54
0.56
Time [s]


LIGO
LIGO/
Virgo
30°
0°
16h
12h
8h
Fermi/
GBM
IPN Fermi /
INTEGRAL
-30°
-30°
Swope +10.9 h
N
30″
E
DLT40 -20.5 d

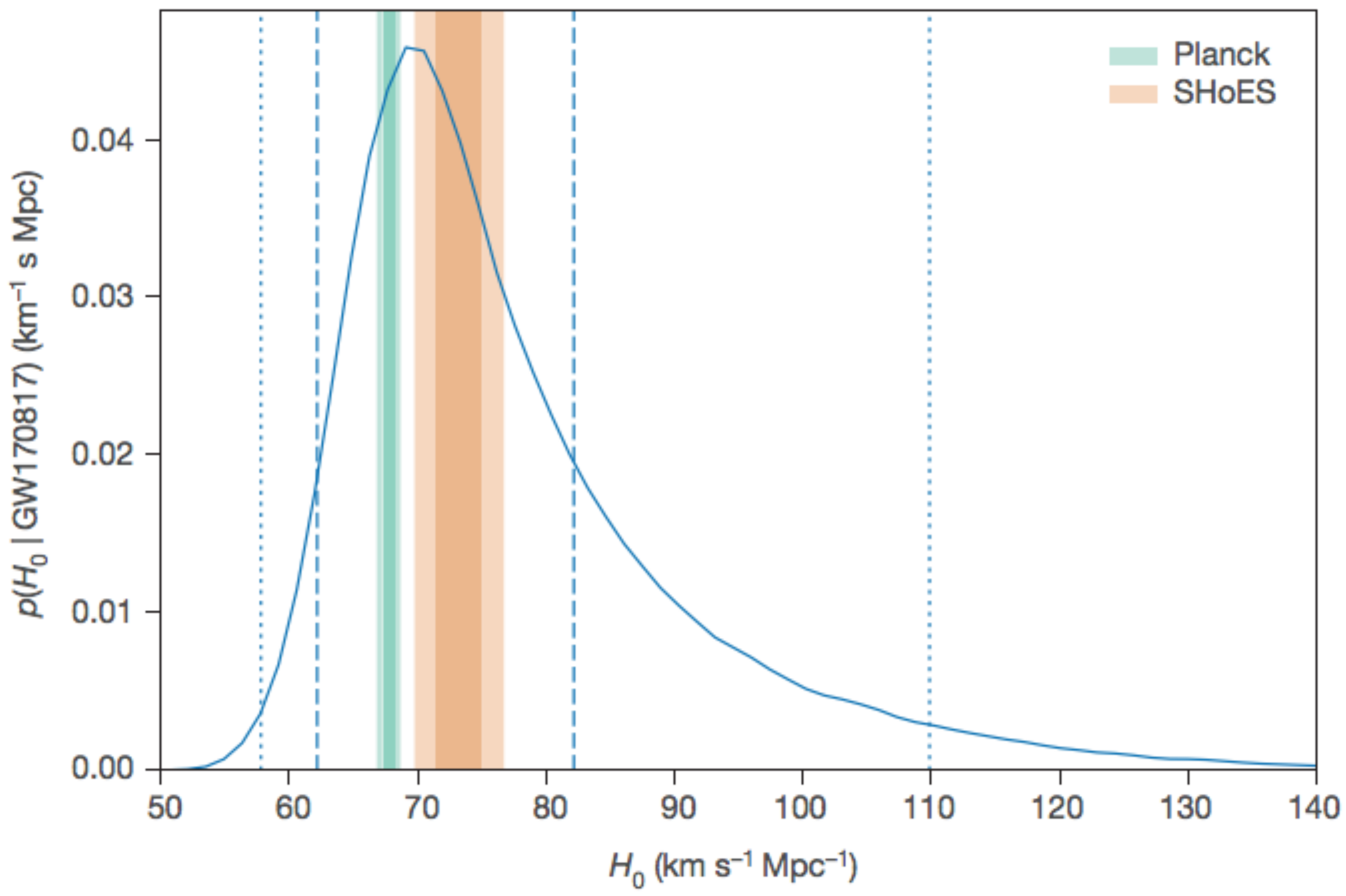


Figure 1 | GW170817 measurement of H_0. The marginalized posterior density for H_0, $p(H_0 \mid \text{GW170817})$, is shown by the blue curve. Constraints at 1σ (darker shading) and 2σ (lighter shading) from Planck[20] and SHoES[21] are shown in green and orange, respectively. The maximum a posteriori value and minimal 68.3% credible interval from this posterior density function is $H_0 = 70.0^{+12.0}_{-8.0}\,\text{km s}^{-1}\text{Mpc}^{-1}$. The 68.3% ($1\sigma$) and 95.4% ($2\sigma$) minimal credible intervals are indicated by dashed and dotted lines, respectively.

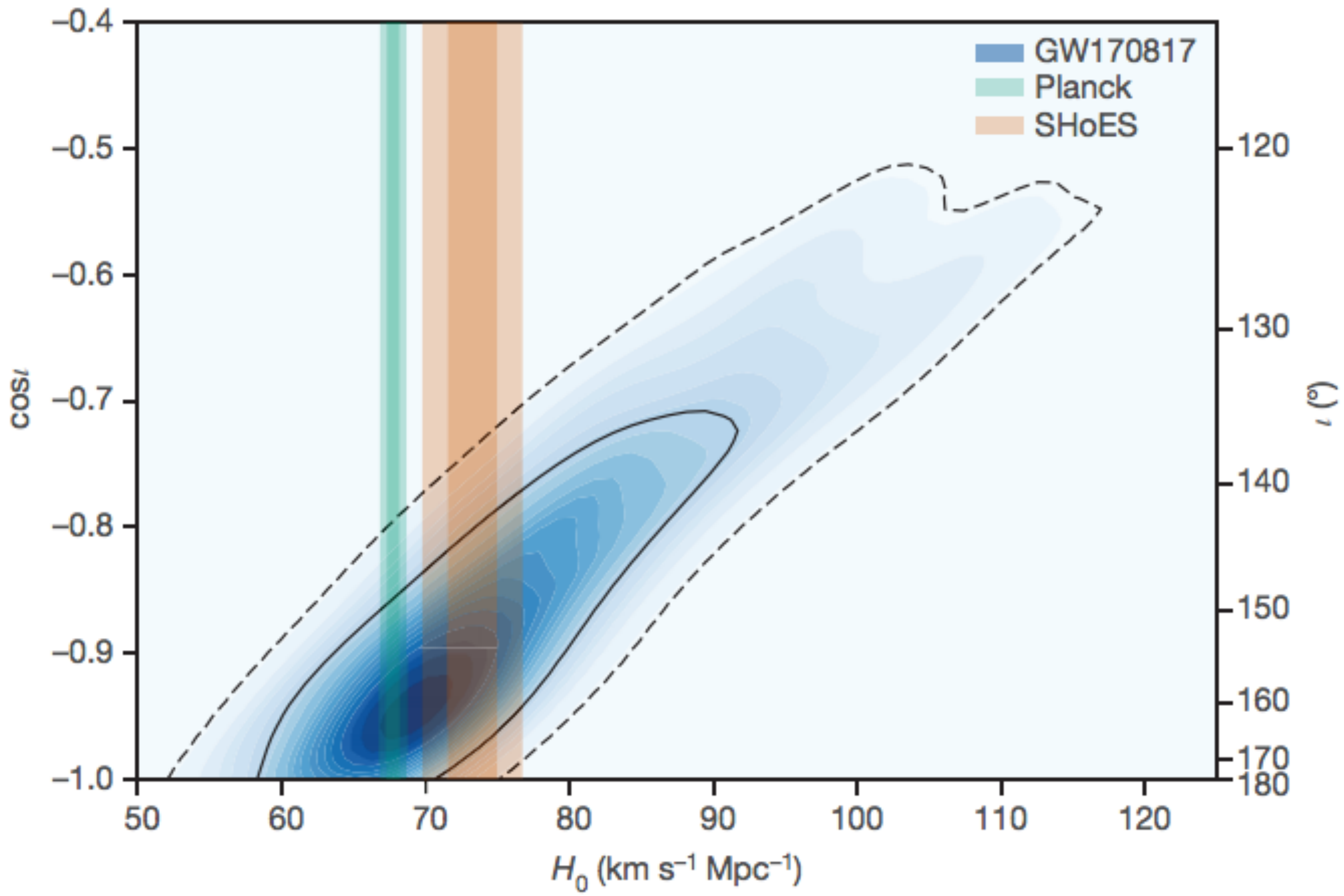


Figure 2 | Inference on H_0 and inclination. The posterior density of H_0 and $\cos\iota$ from the joint gravitational-wave–electromagnetic analysis are shown as blue contours. Shading levels are drawn at every 5% credible level, with the 68.3% (1σ; solid) and 95.4% (2σ; dashed) contours in black. Values of H_0 and 1σ and 2σ error bands are also displayed from Planck[20] and SHoES[21]. Inclination angles near 180° ($\cos\iota = -1$) indicate that the orbital angular momentum is antiparallel to the direction from the source to the detector.