Cosmological probes of gravity

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Cosmological probes of gravity

Lecture 3

Observing the sky

The Hubble constant (H_0)

Big Bang Nucleosynthesis (BBN)

Type-Ia supernovae (SNIa)

Baryon acoustic oscillations (BAO)

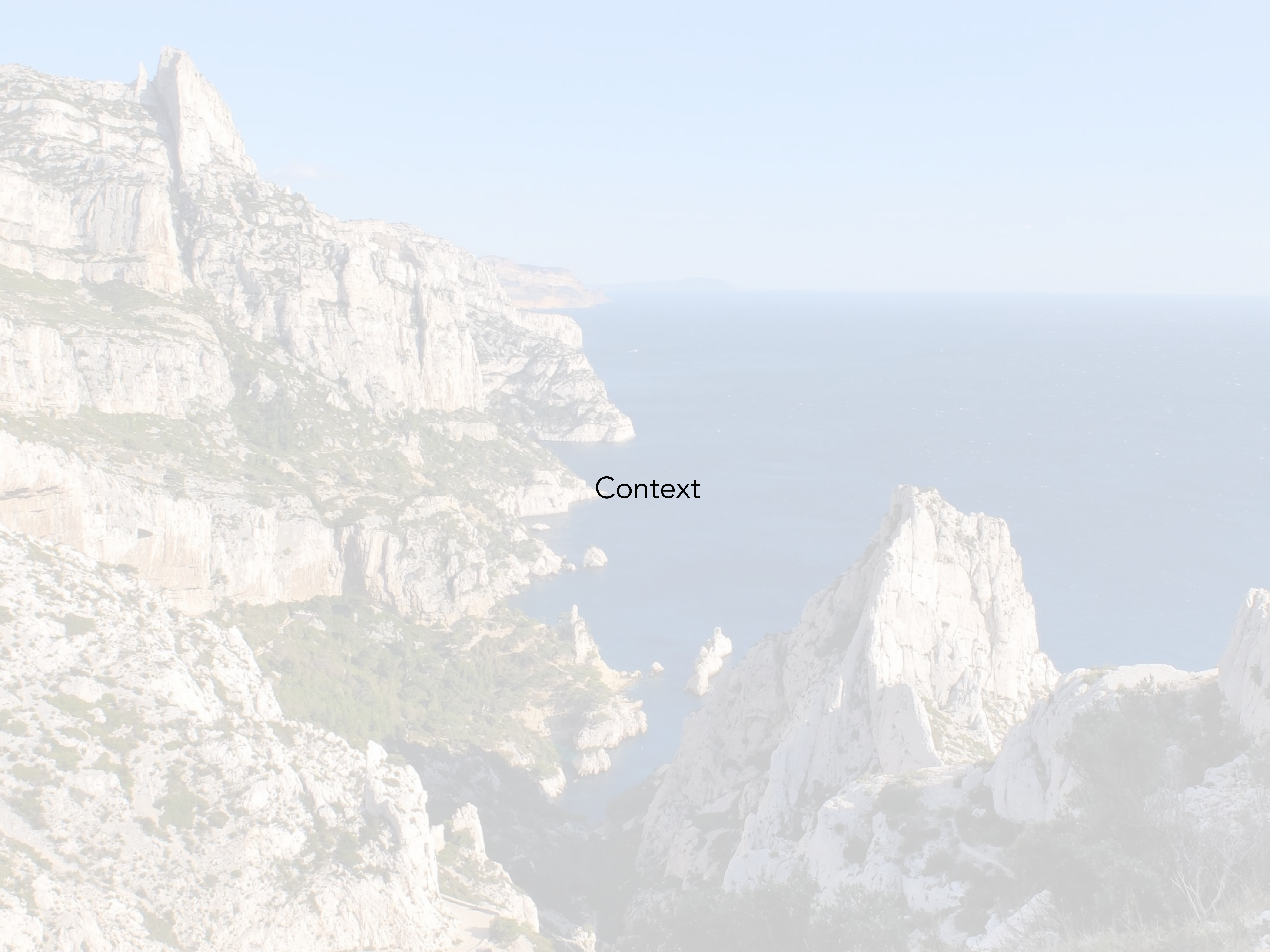
Lecture 4

Cosmic microwave background (CMB)

Redshift-space distortions (RSD)

Weak gravitational lensing (WL)

The future



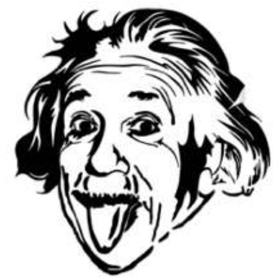
Context

What is dark energy ?

What is causing the observed acceleration of the expansion of the Universe

Spoiler: we don't know yet

Model for the expansion
General Relativity



Space-time properties = **Energy content of the Universe**

+ smooth Universe

$$H(t)^2 \sim \Omega_m[a(t)]^{-3} + \Omega_r[a(t)]^{-4} + \Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)} e^{3w_a[1-a(t)]}$$

Expansion-rate

$\Omega_m[a(t)]^{-3}$	$\Omega_r[a(t)]^{-4}$	$\Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)} e^{3w_a[1-a(t)]}$
p^+, n, e^-, dark matter	photons, neutrinos	dark energy (quintessence, phantom force)
30%	**0.008%**	**70%**

The only one causing acceleration of the expansion!

Model for the expansion
General Relativity

Space-time properties

=

Energy content of the Universe

+ smooth Universe

No fundamental origin for Λ !

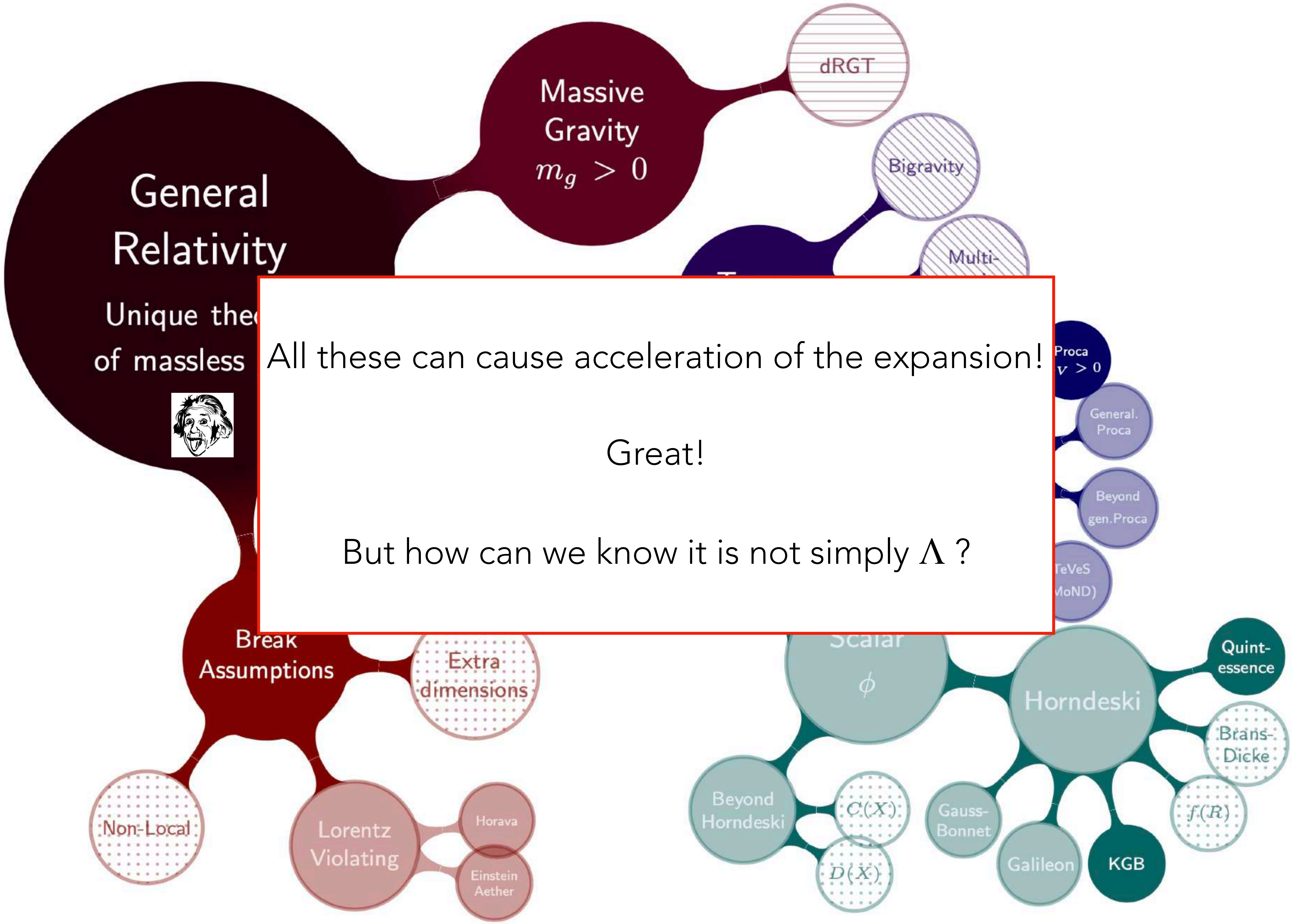
$$\Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)}e^{3w_a[1-a(t)]}$$

dark energy
(quintessence, phantom force)

70%

The only one causing acceleration of the expansion!

Physically motivated theory ? Alternatives or extensions of General Relativity



All these can cause acceleration of the expansion!

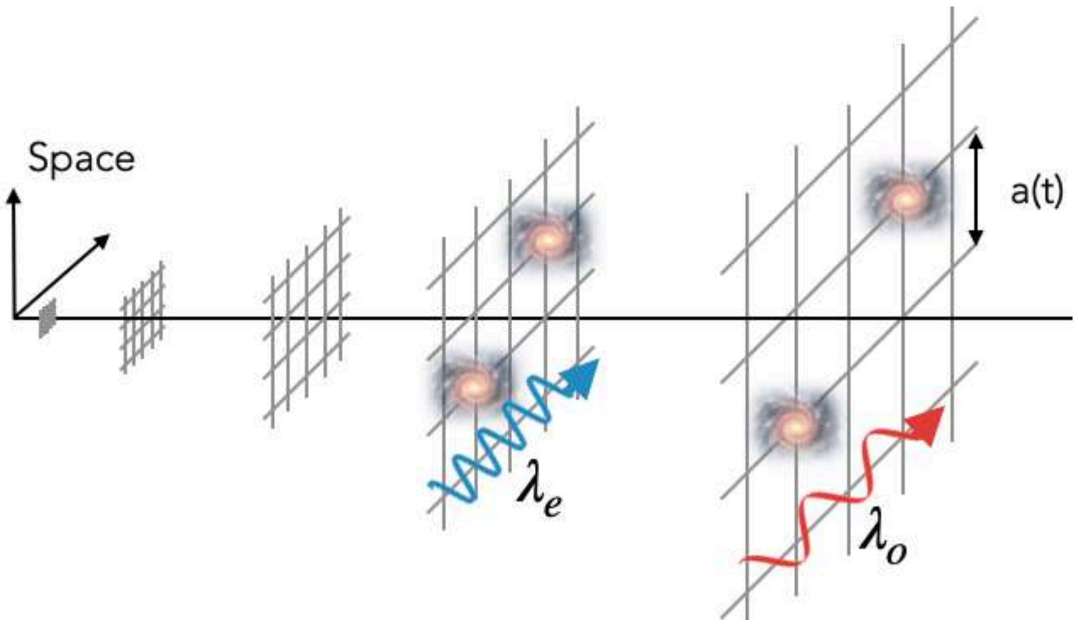
Great!

But how can we know it is not simply Λ ?

Review by Ezquiaga & Zumalacárregui 2018, Heisenberg 2018

What is dark energy ?

The acceleration problem

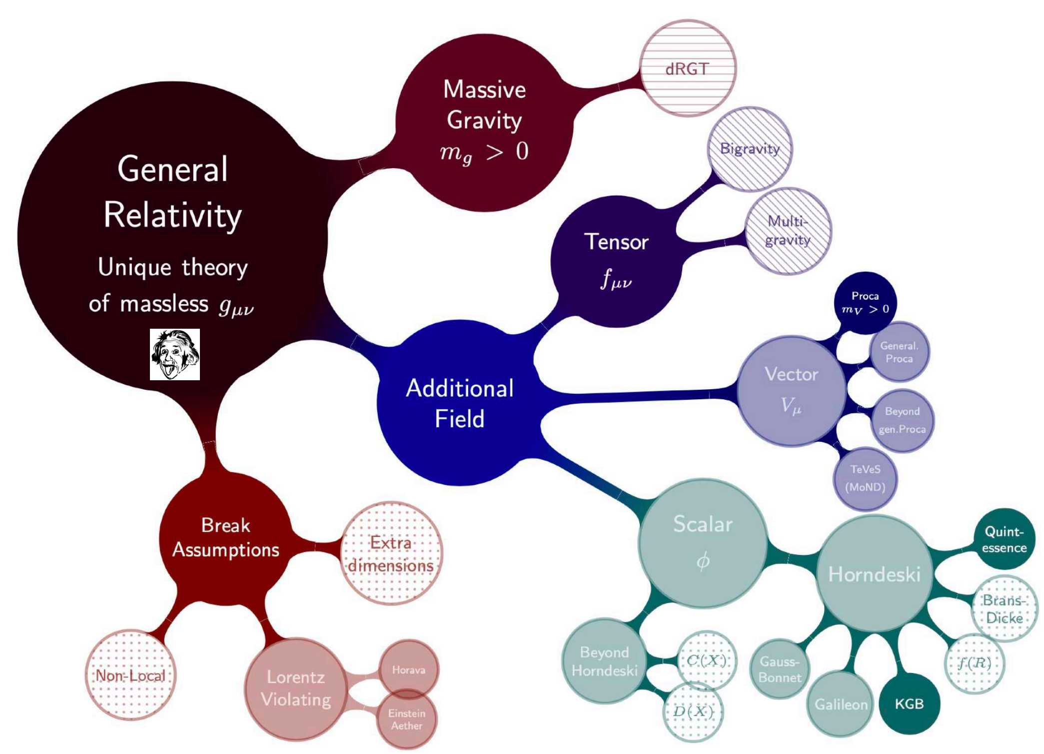


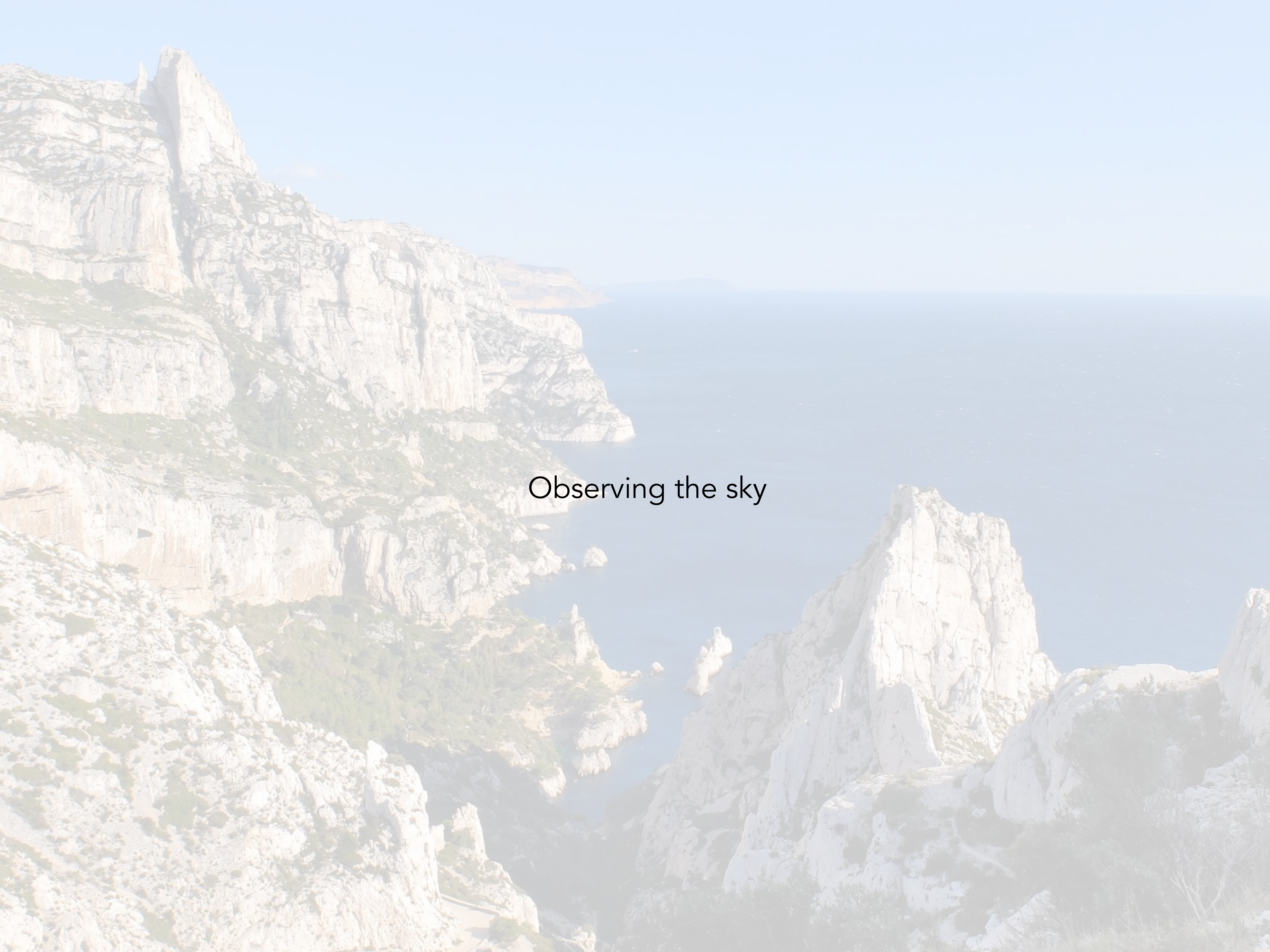
$$\Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)}e^{3w_a[1-a(t)]}$$

dark energy
(quintessence, phantom force)

70%

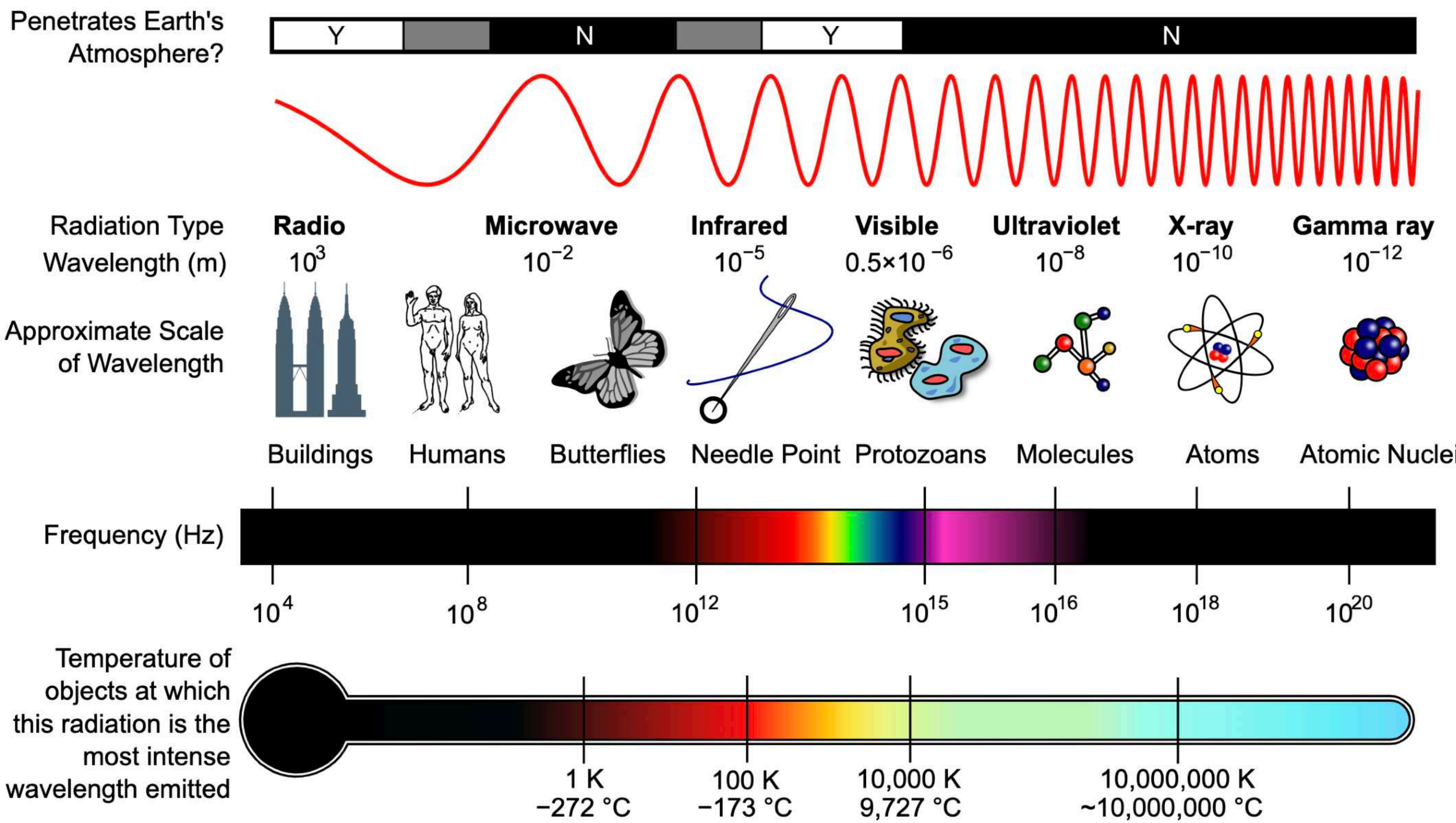
or





Observing the sky

The electromagnetic spectrum



Source: WikiMedia

Astroparticles

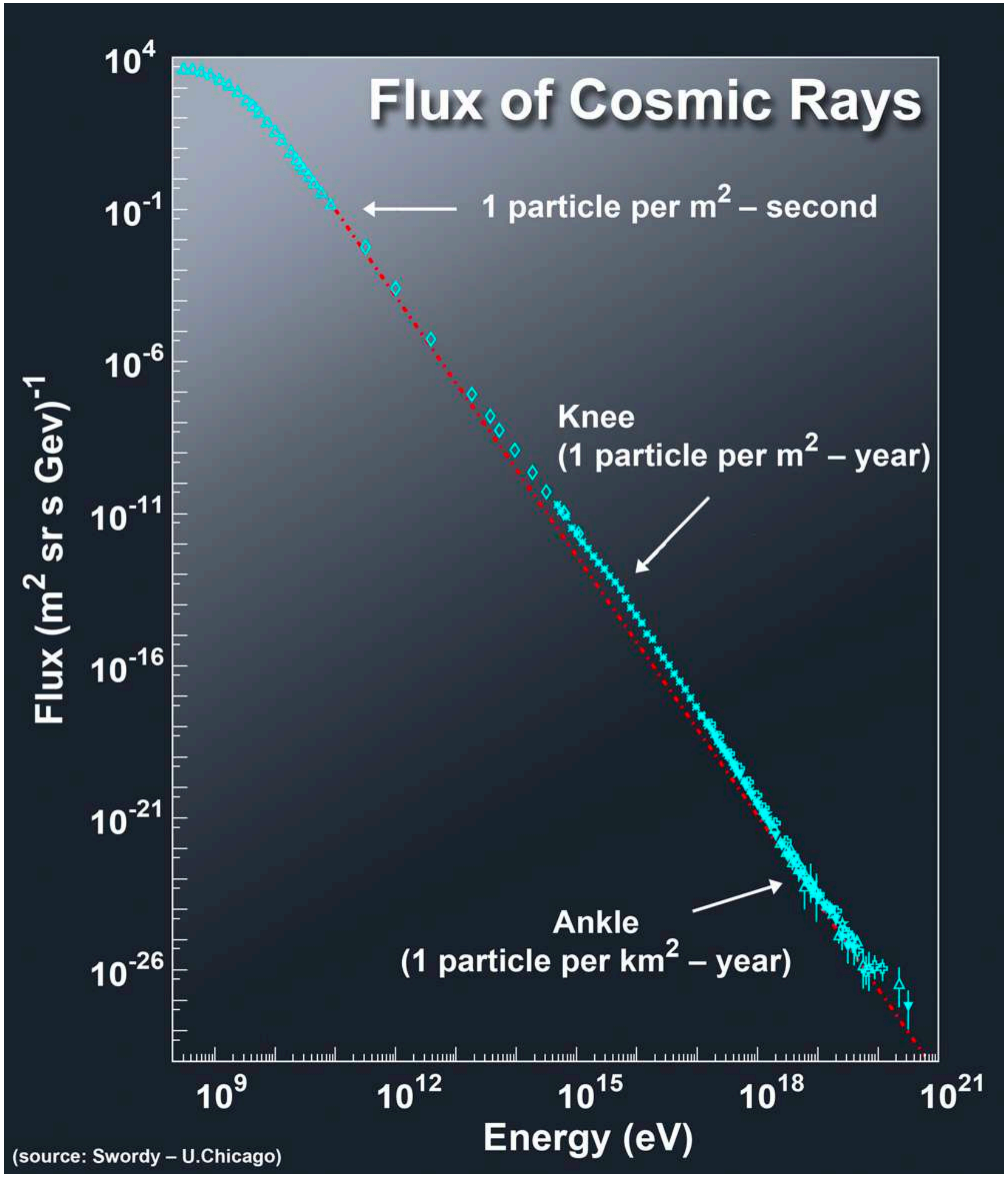
Photons
- gamma rays
- not great for large distances

Protons & co.
- astrophysics of black holes, supernovae, etc
- affected by magnetic fields

Neutrinos
- oscillations -> mass!
- supernovae
- cosmic background ?

Gravitational waves
New since 2016!

- gravity probe
- distance estimator



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Big Bang Nucleosynthesis (BBN)

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Baryon acoustic oscillations (BAO)

Cosmic microwave background (CMB)

Redshift-space distortions (RSD)

Weak gravitational lensing (WL)

Based on observations of visible light (or almost)

Photometry or **Spectroscopy**

Observing (nearly-) visible light with photometry or spectroscopy

Source

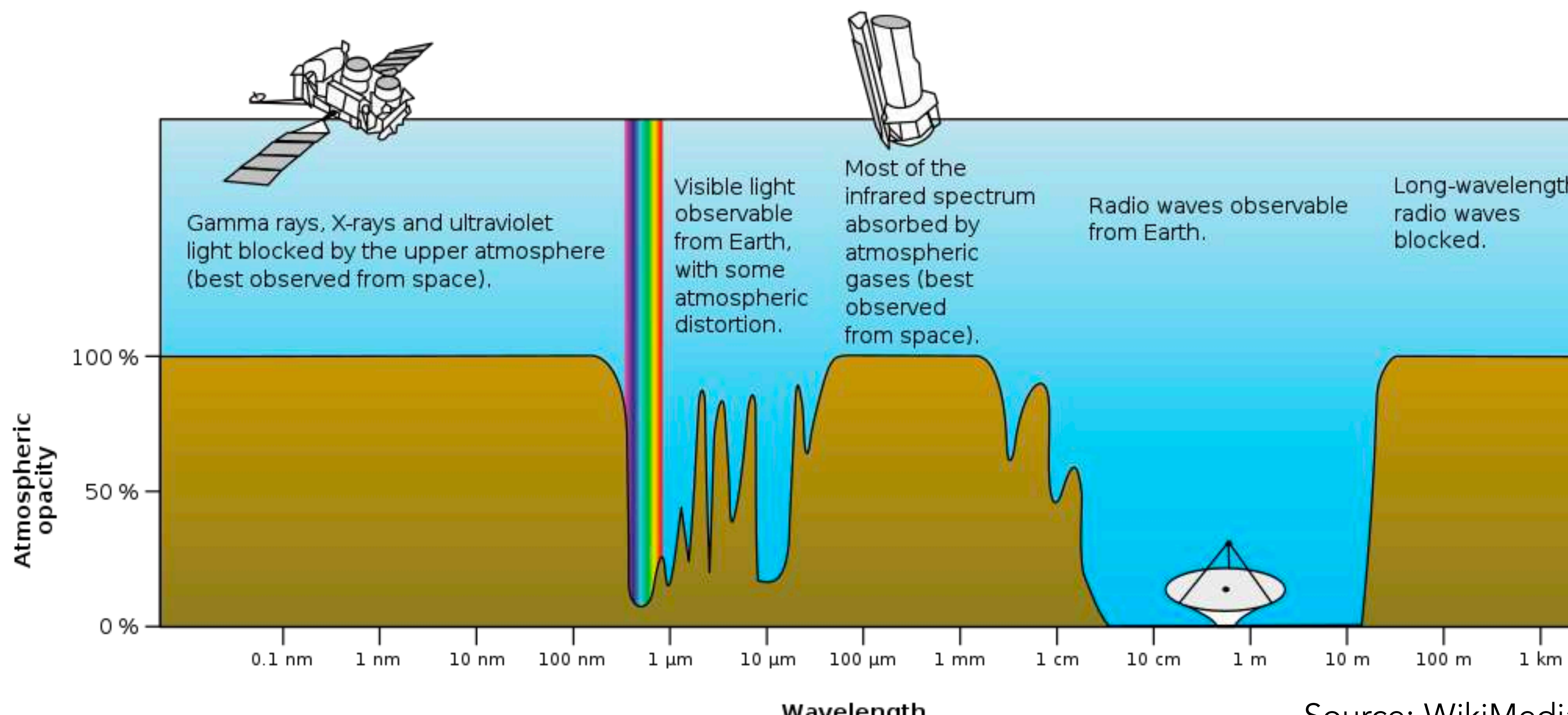
Absorption by surroundings

Absorption by intergalactic medium

Absorption by Milky Way dust

Absorption by atmosphere

Source: flickr.com/photos/andrew_thomas_73



Source: WikiMedia

Observing (nearly-) visible light with photometry or spectroscopy

Source

Absorption by surroundings

Absorption by intergalactic medium

Absorption by Milky Way dust

Absorption by atmosphere

Mirrors

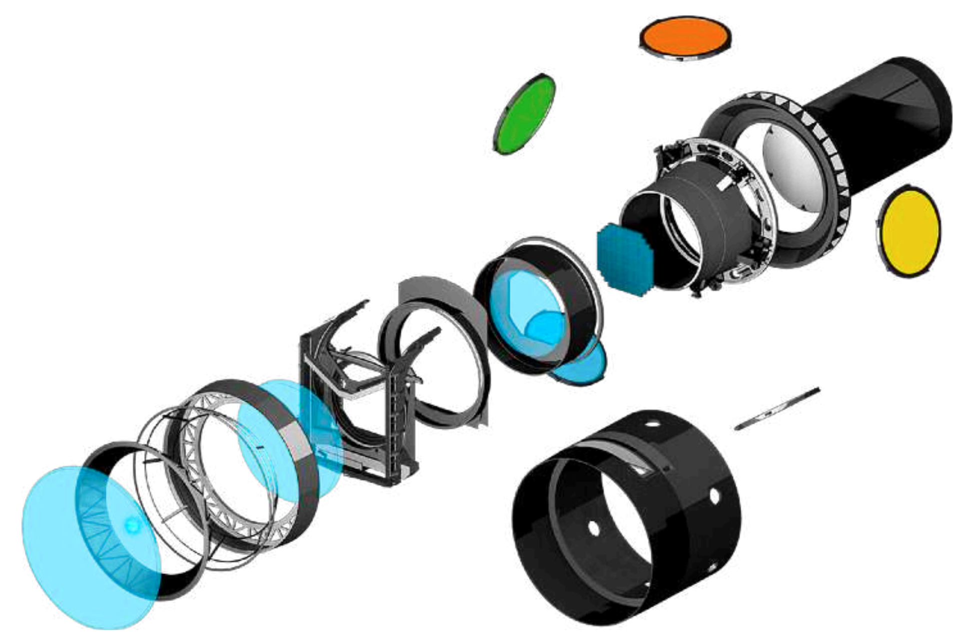
Lenses

Photometry or Spectroscopy

Filters

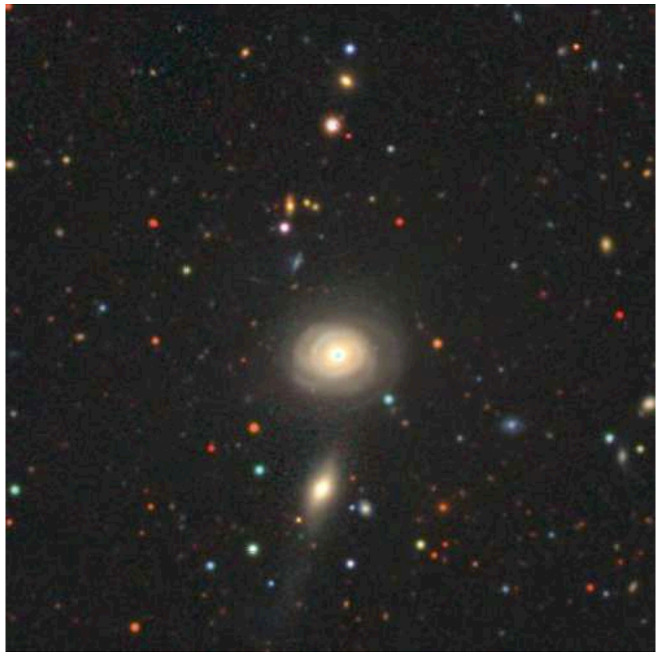
CCD quantum efficiency

Source: lsst.org

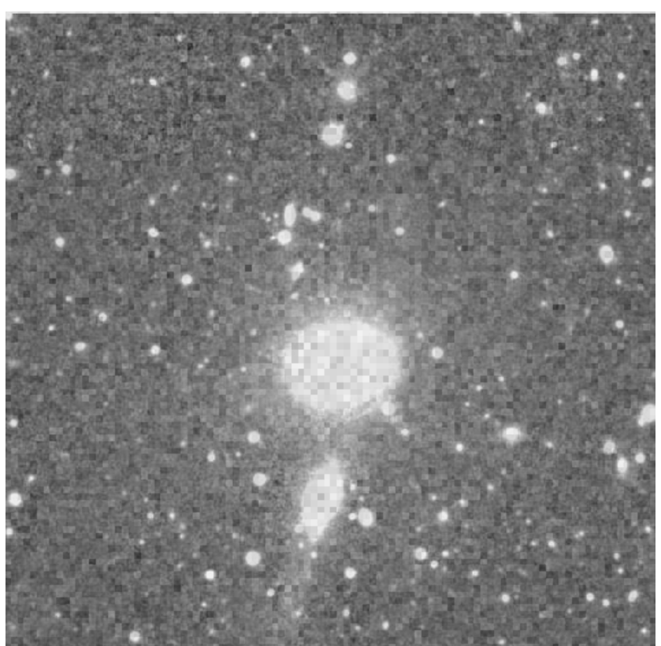


Source: lsst.slac.stanford.edu

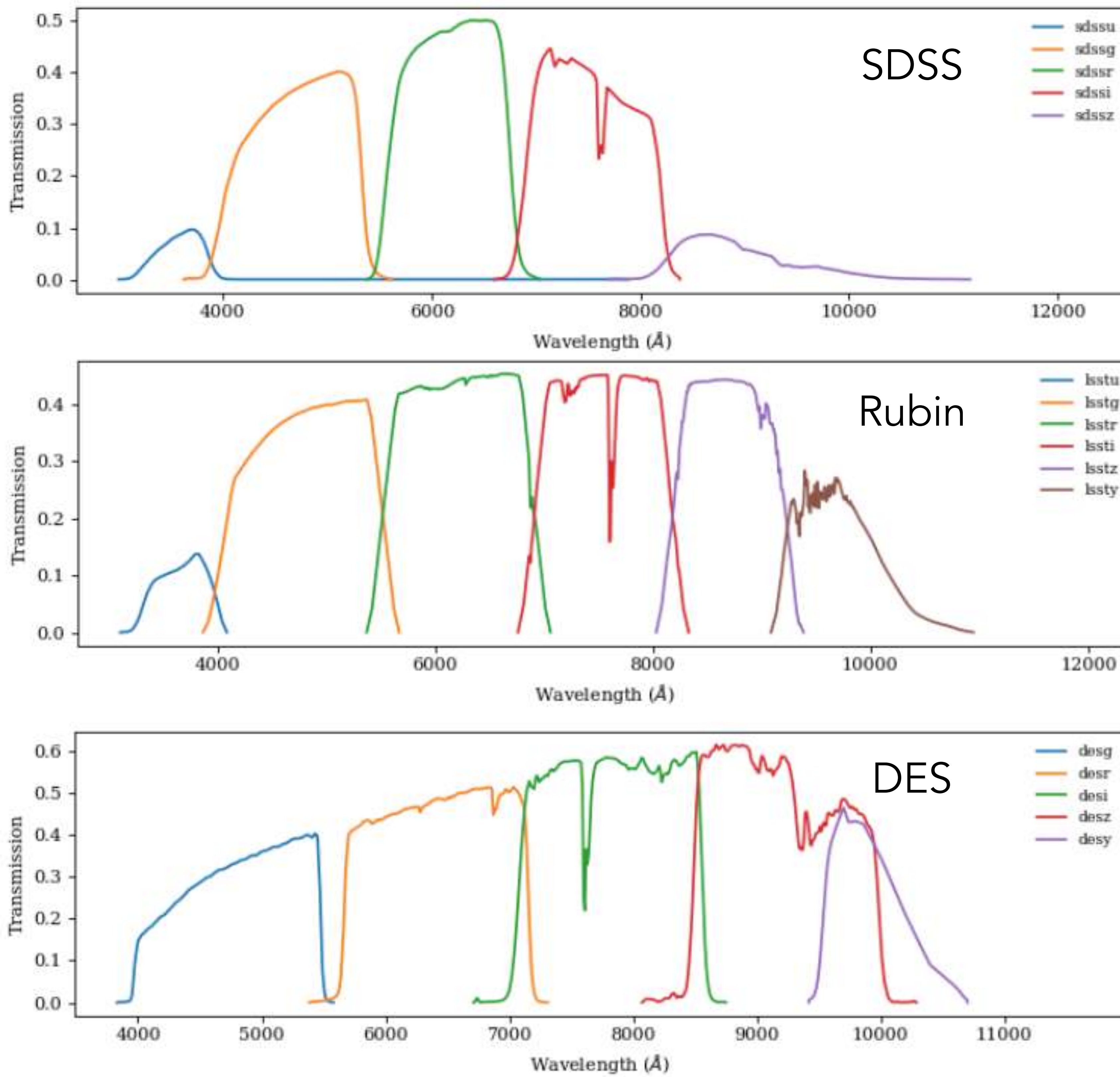
Photometry



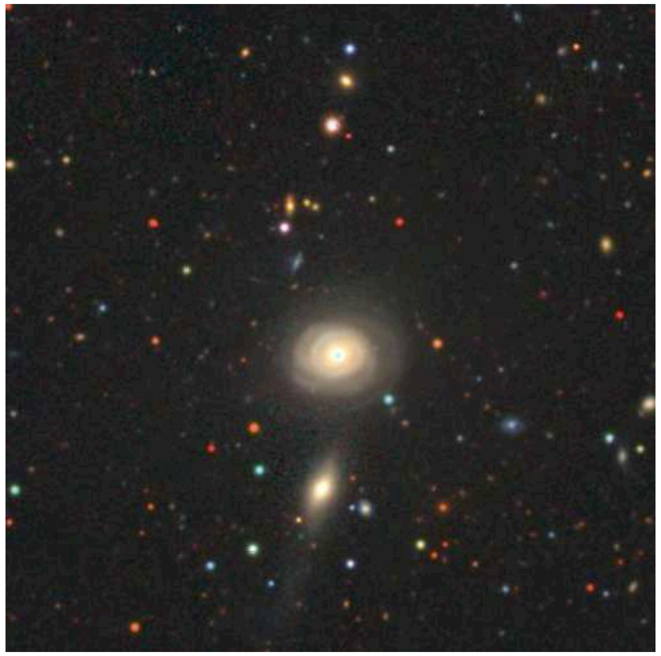
Filter



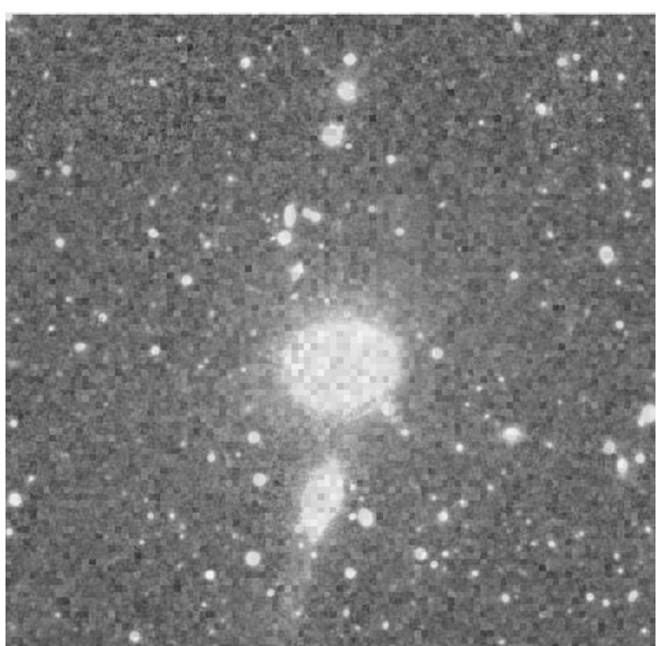
Examples of filters



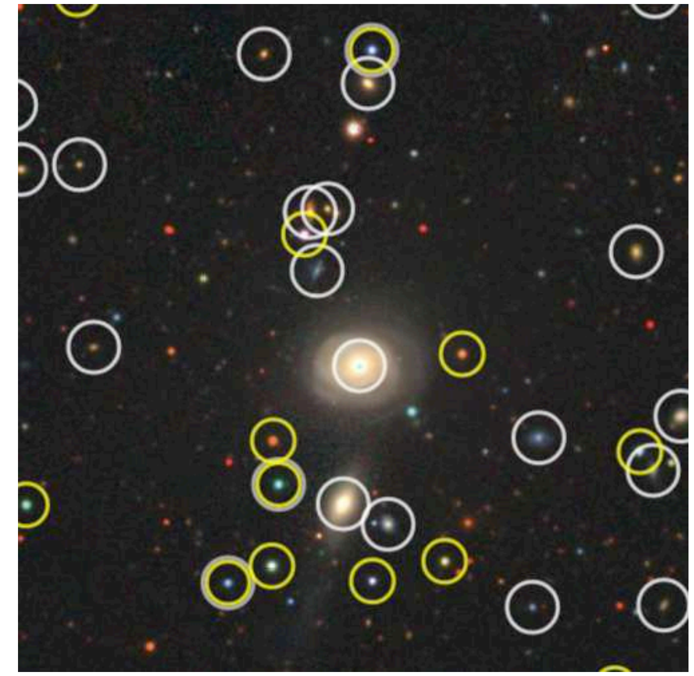
Photometry

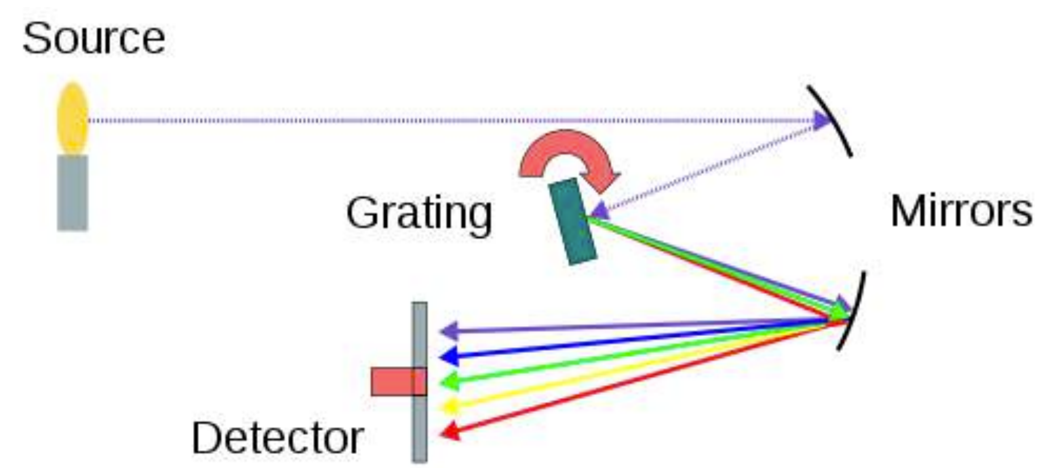


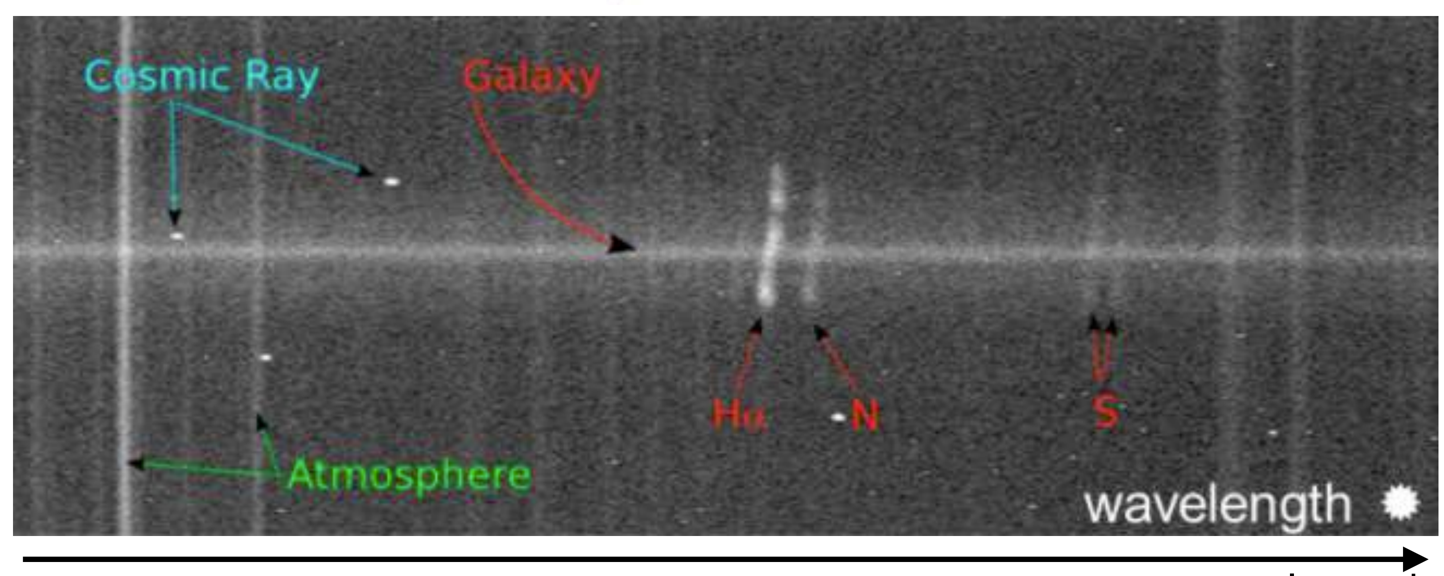
Filter



Spectroscopy







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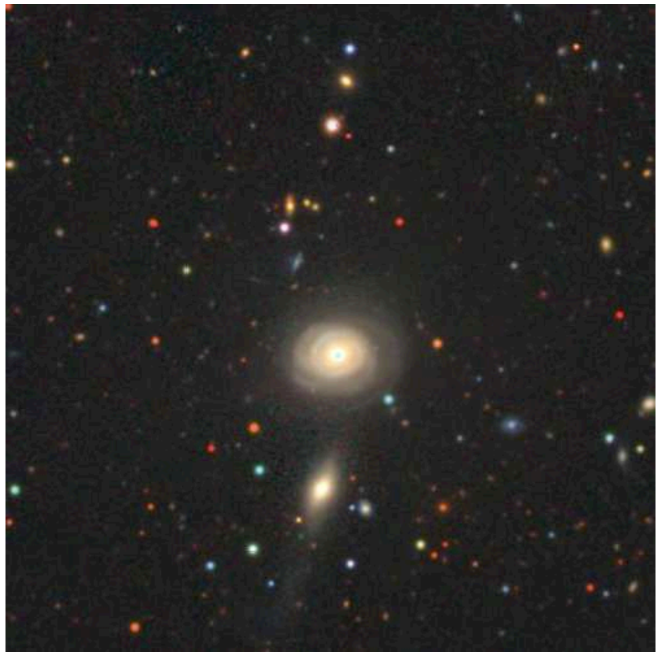

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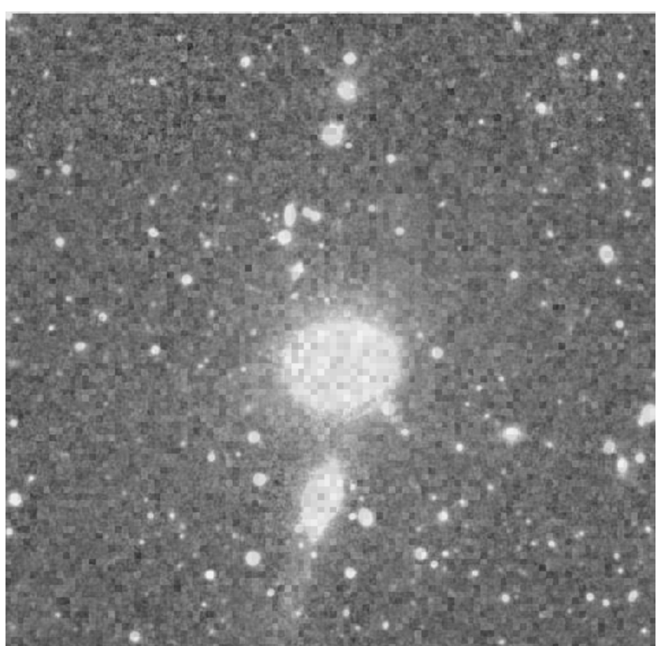
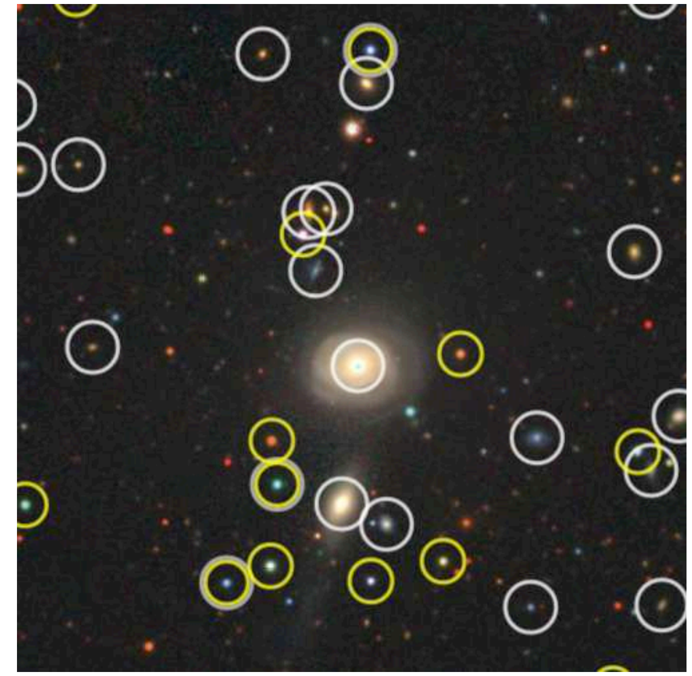
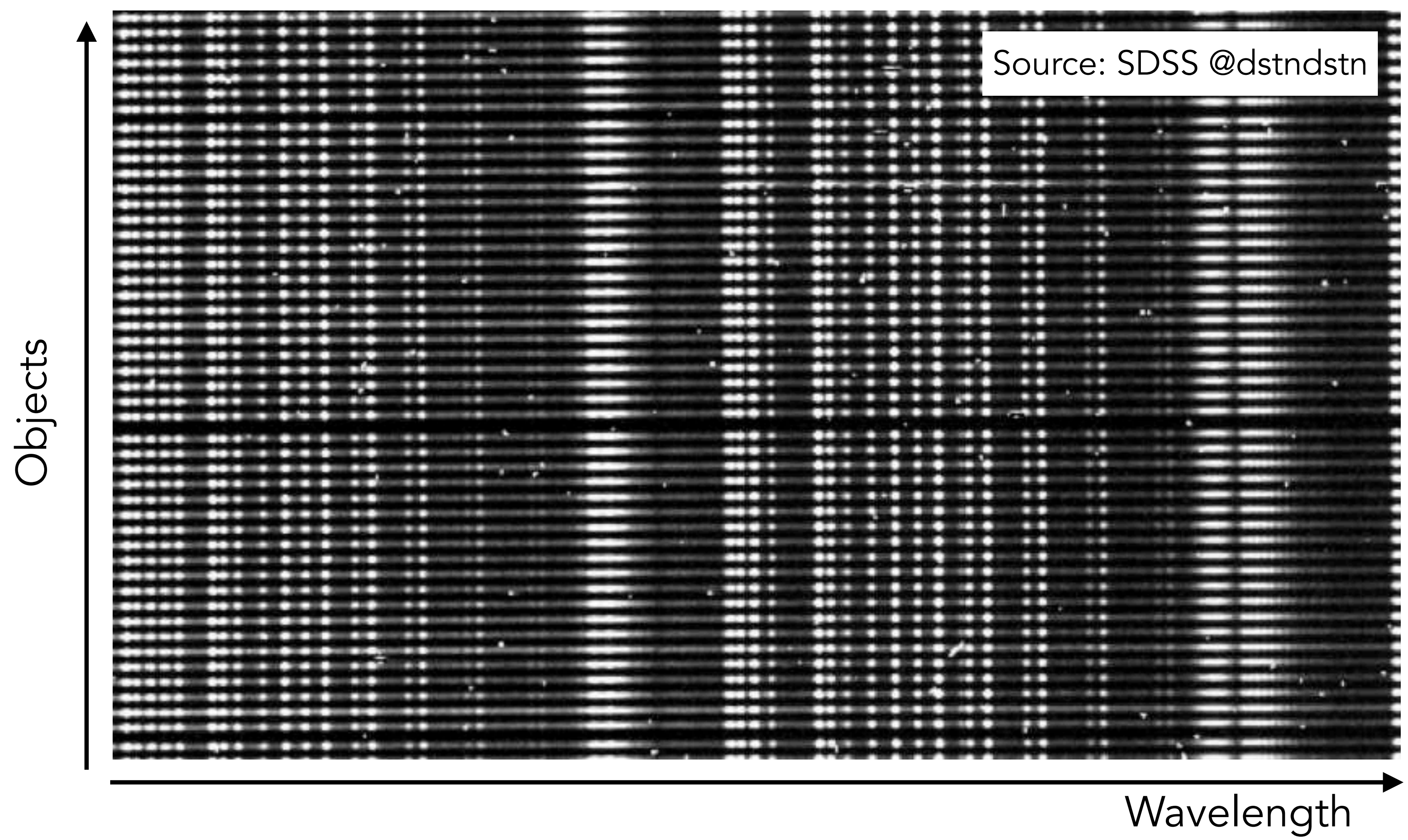


Spectroscopy





Photometry

- 2D image, spatial information
- higher signal-to-noise
- no selection required
- rough spectral information

Less selection effects (SNIa)
Great for galaxy shapes (WL)

Spectroscopy

- 1D information
- requires large exposure times
- selection of targets required
- fine spectral information

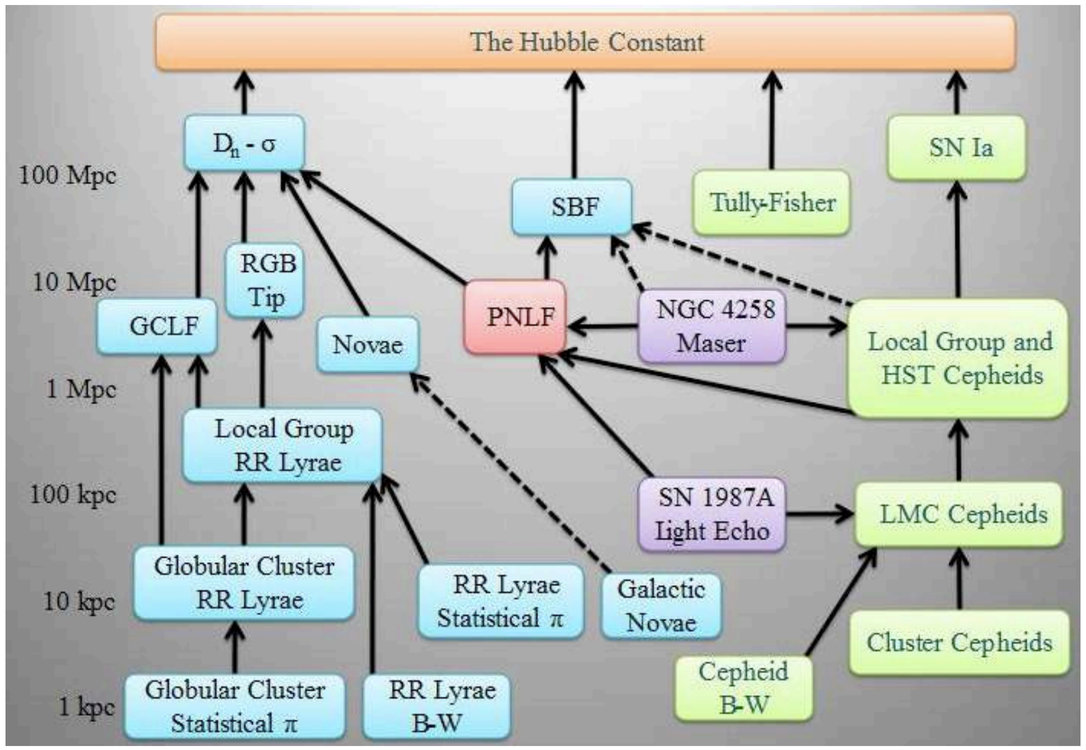
Better redshifts for clustering (BAO, RSD)
Better physical characterisation of galaxies/stars

Both are essential for cosmology

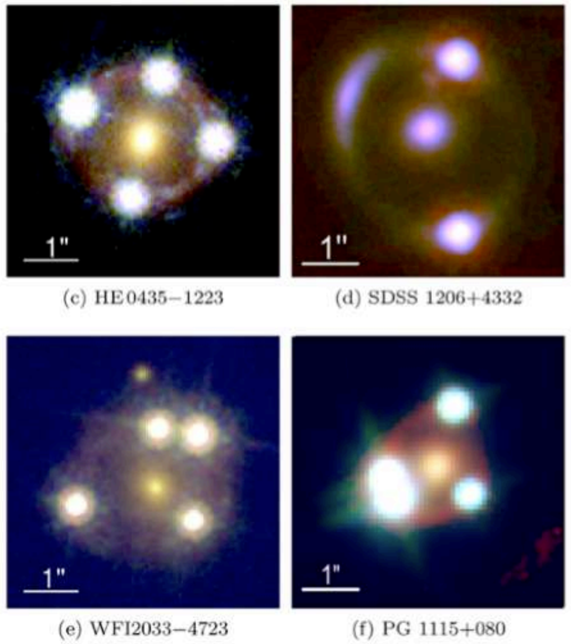
The Hubble Constant H_0

The Hubble Constant H_0

Distance ladder

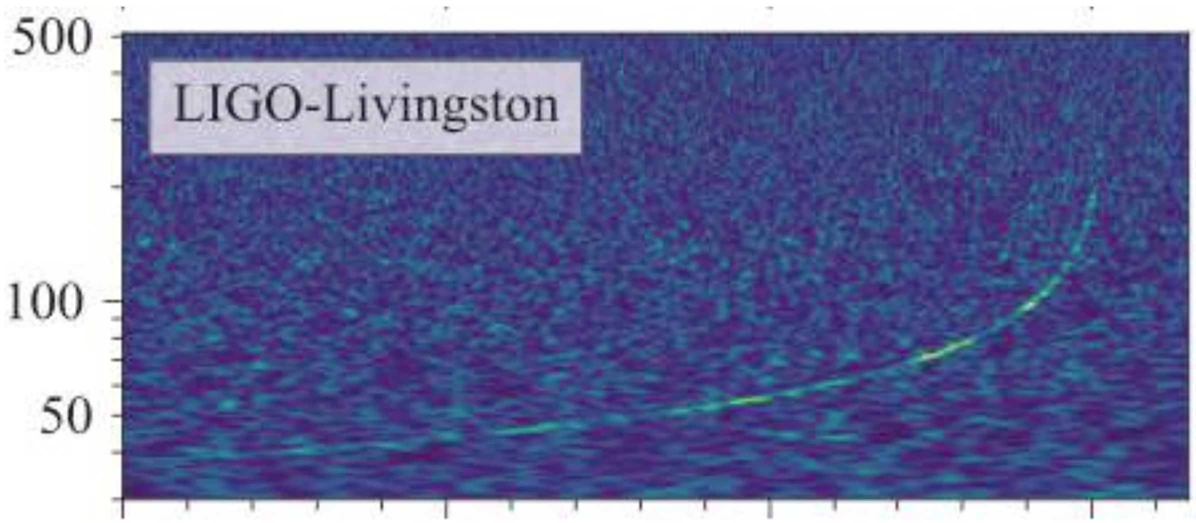


Strong lensing of variable quasars



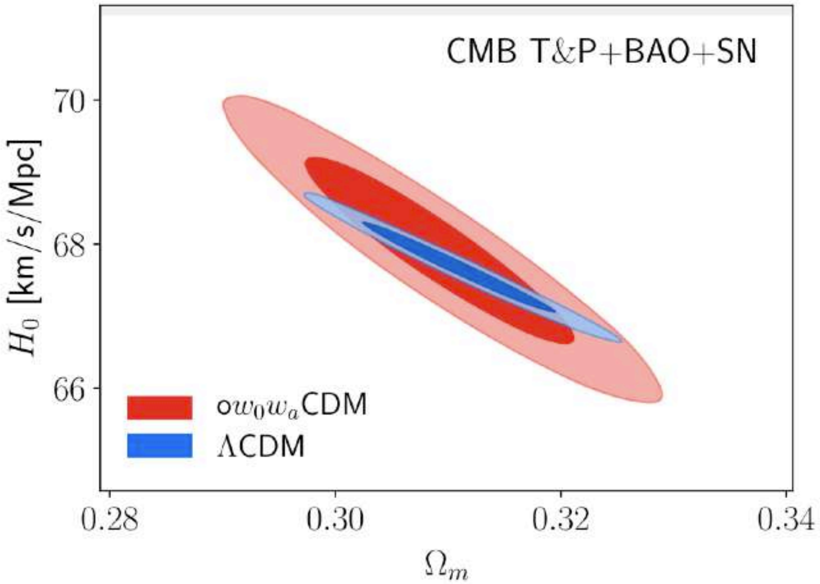
H0LiCOW (Wong et al. 2020)

Standard sirens



LIGO & Virgo 2017

Inverse distance ladder



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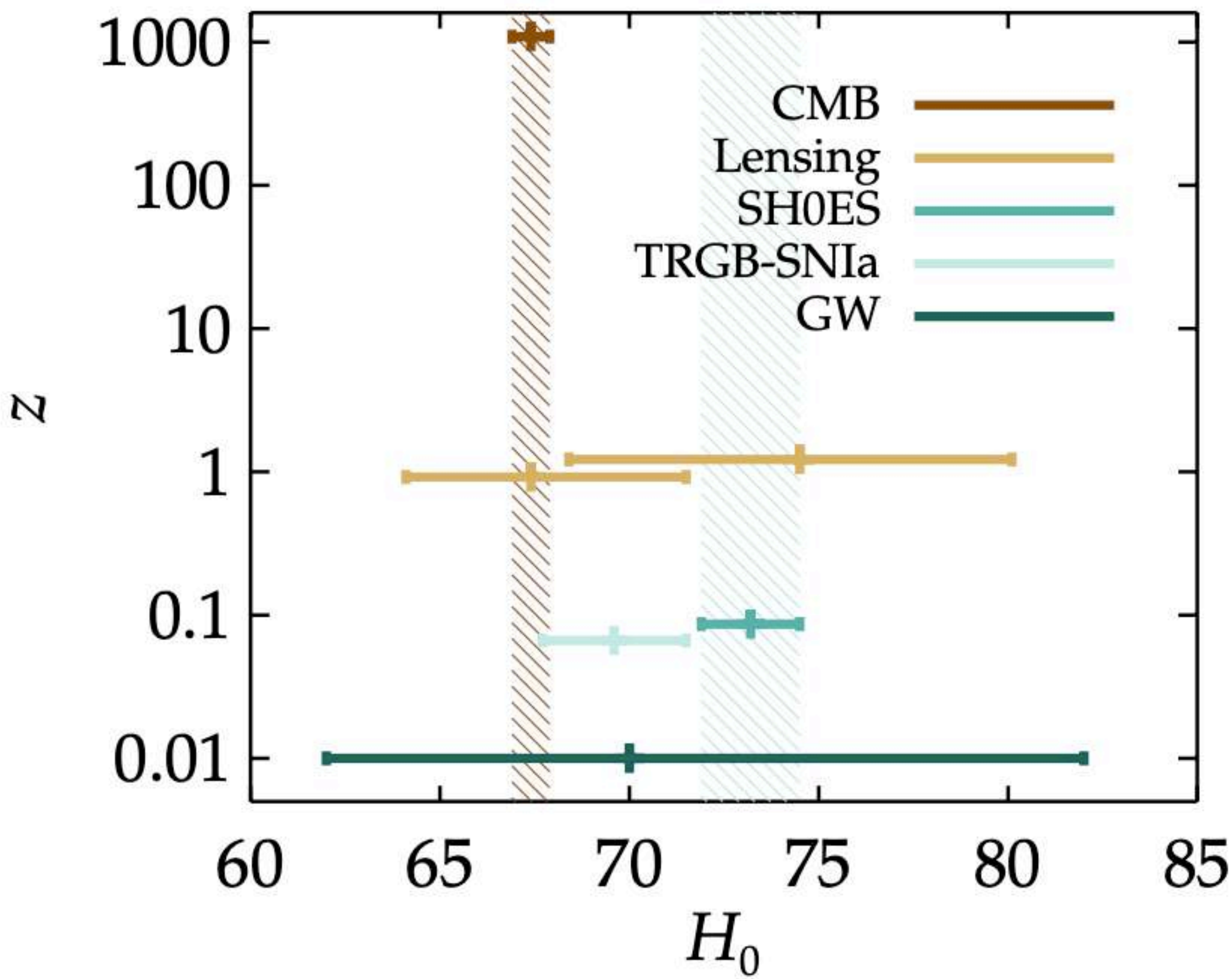
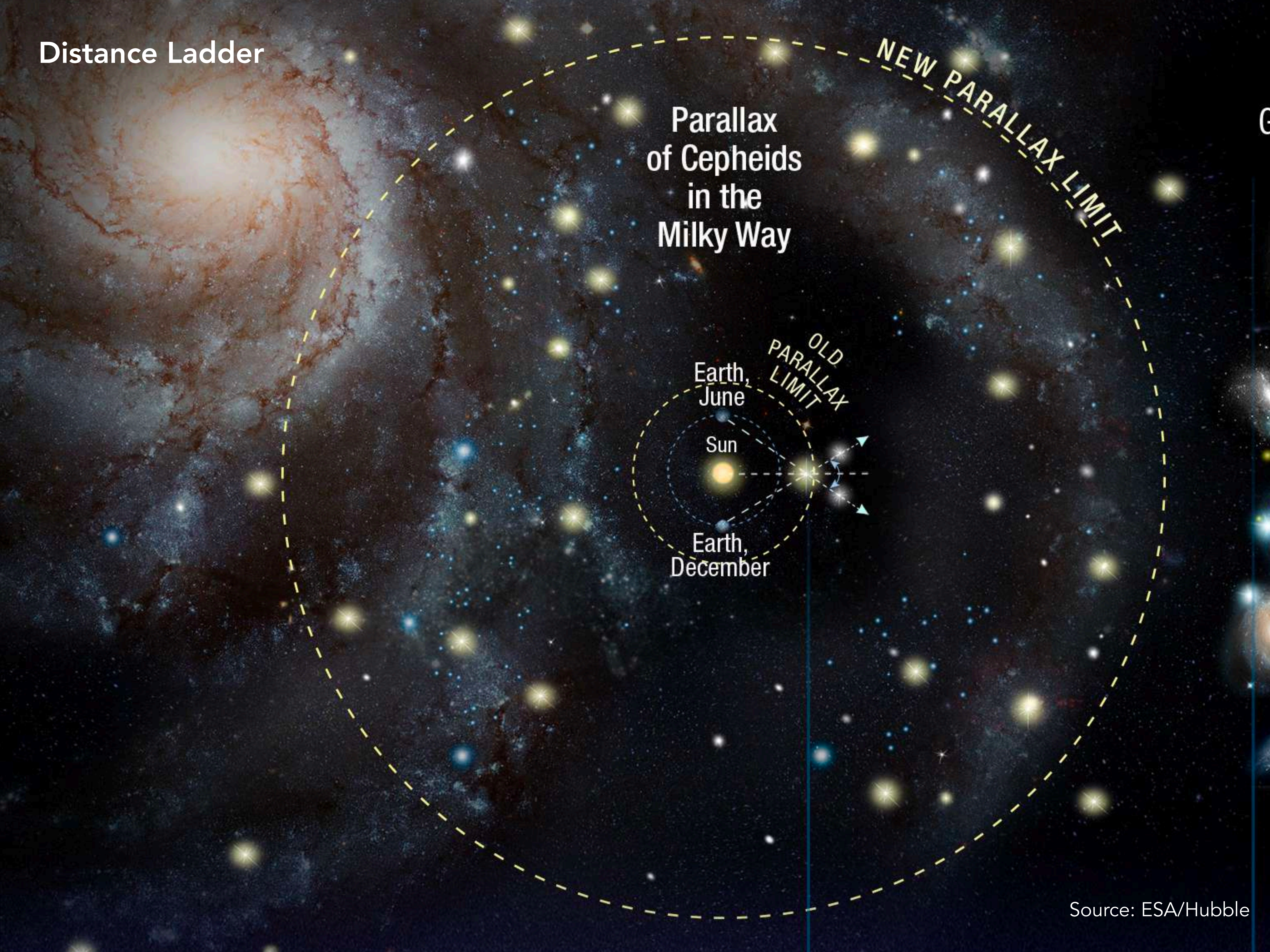
The Hubble Constant H_0

"Redshift" of sources



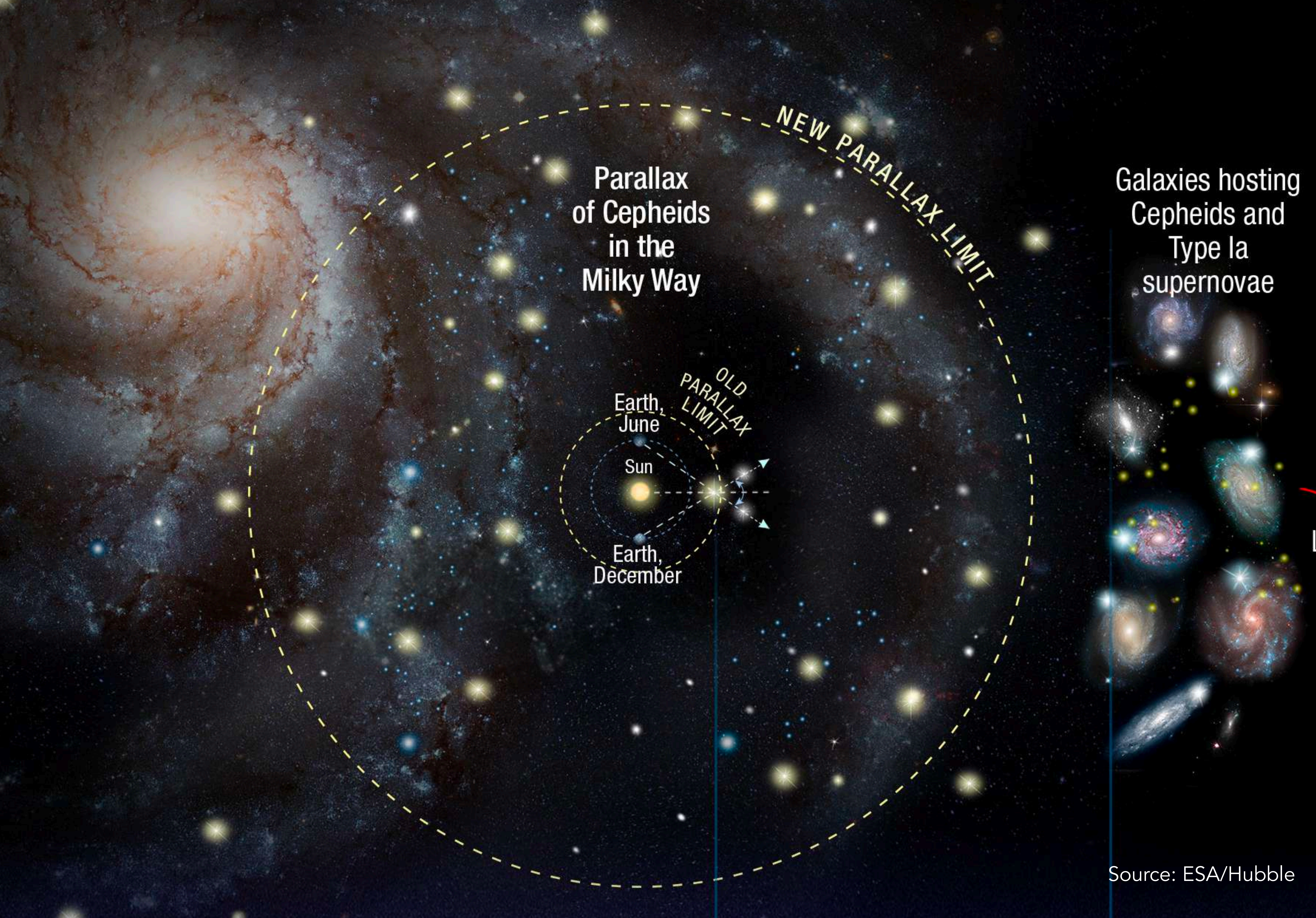
Mörtsell et al. 2021a

Distance Ladder



Source: ESA/Hubble

Distance Ladder



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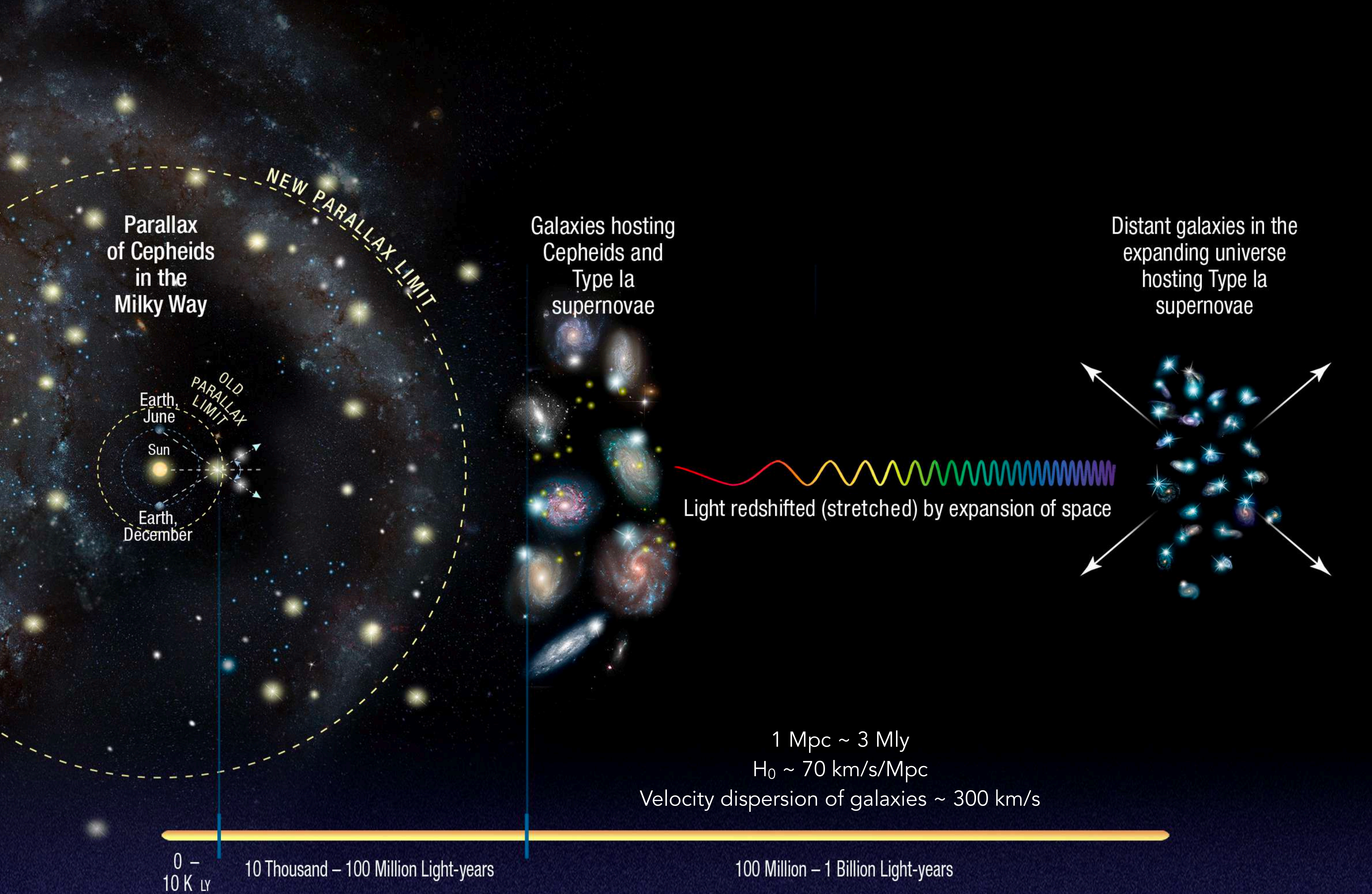
Distance Ladder



1 Mpc ~ 3 Mly

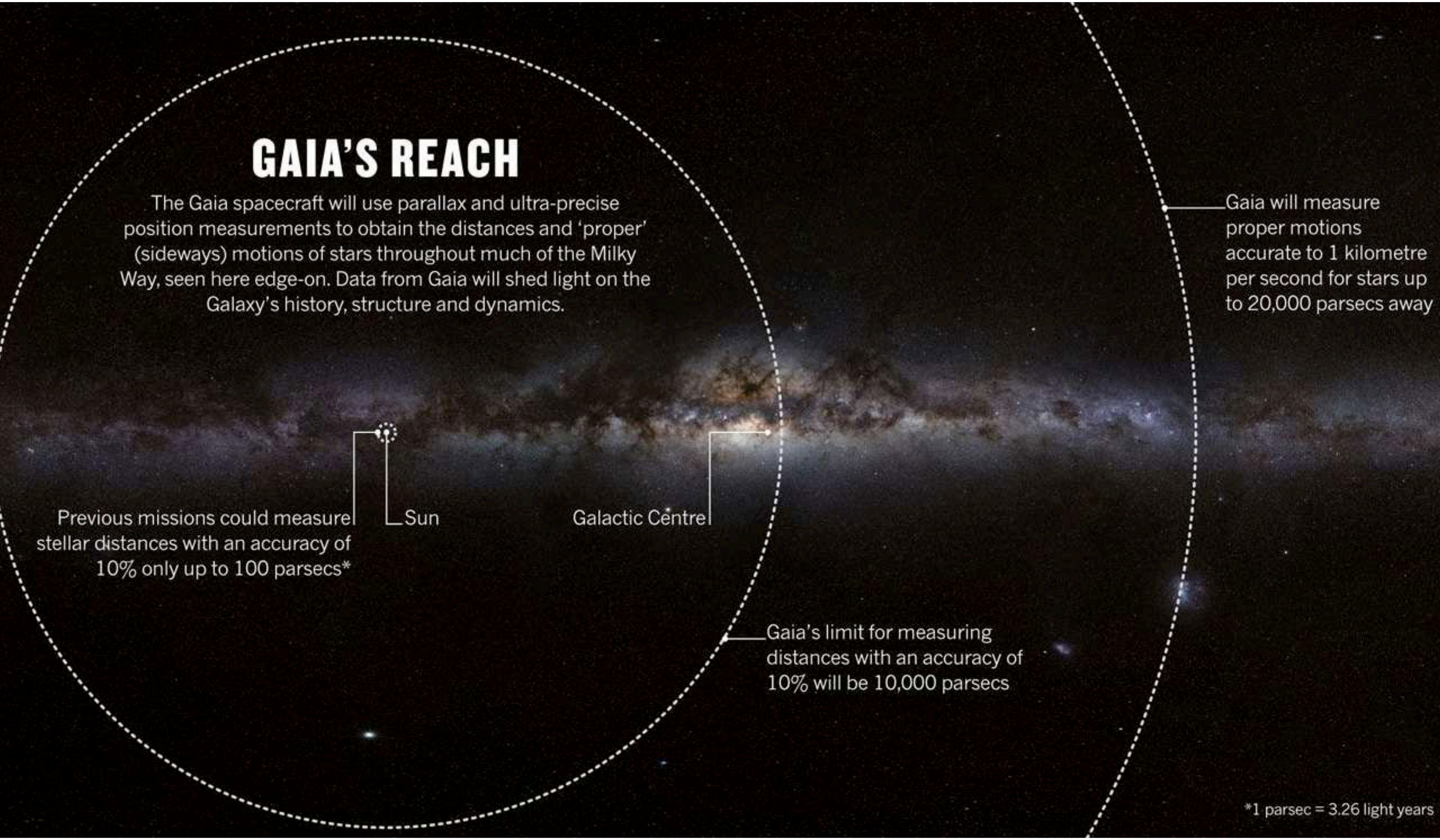
H_0 ~ 70 km/s/Mpc

Velocity dispersion of galaxies ~ 300 km/s

Source: ESA/Hubble

Parallax

A direct or absolute distance measurement

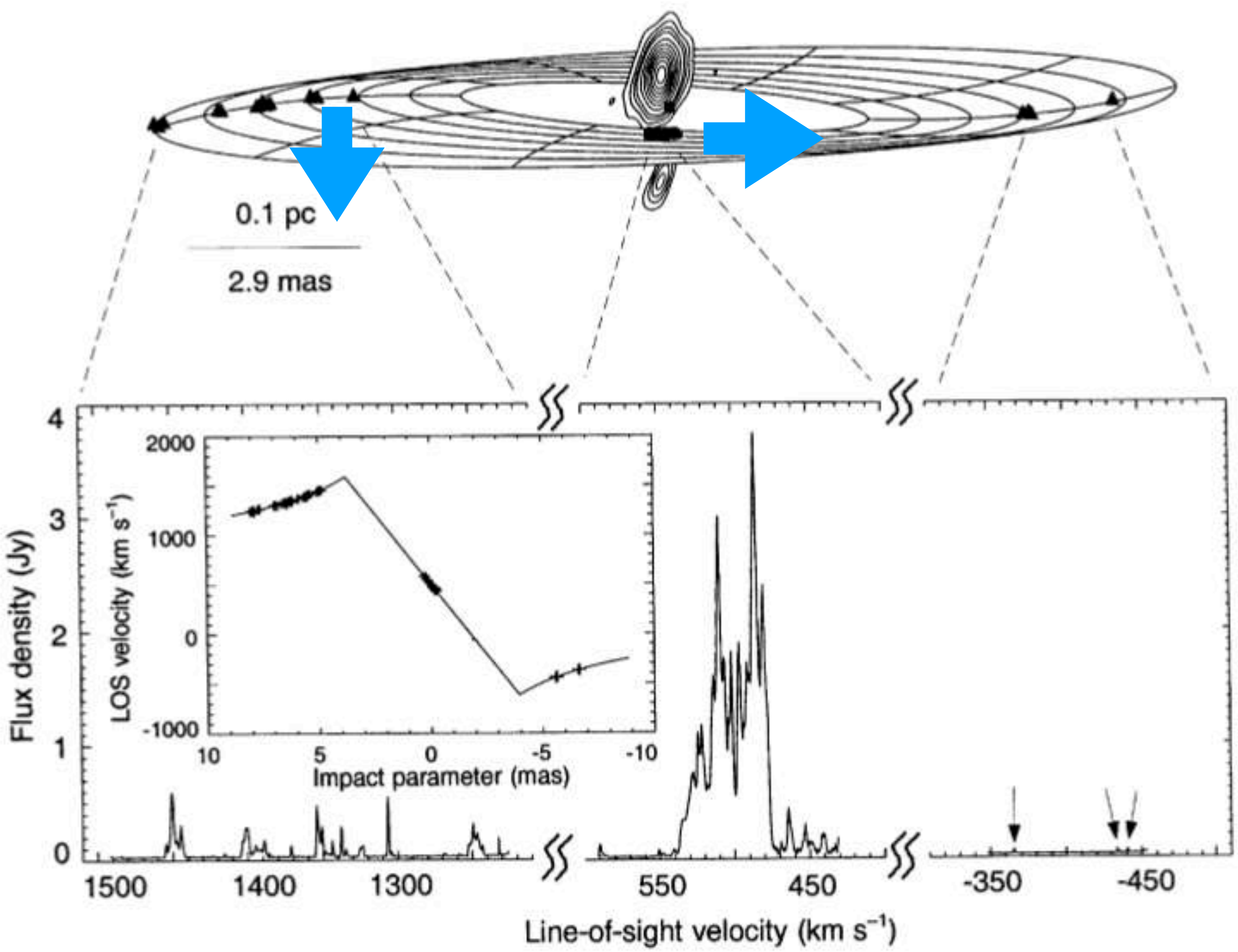


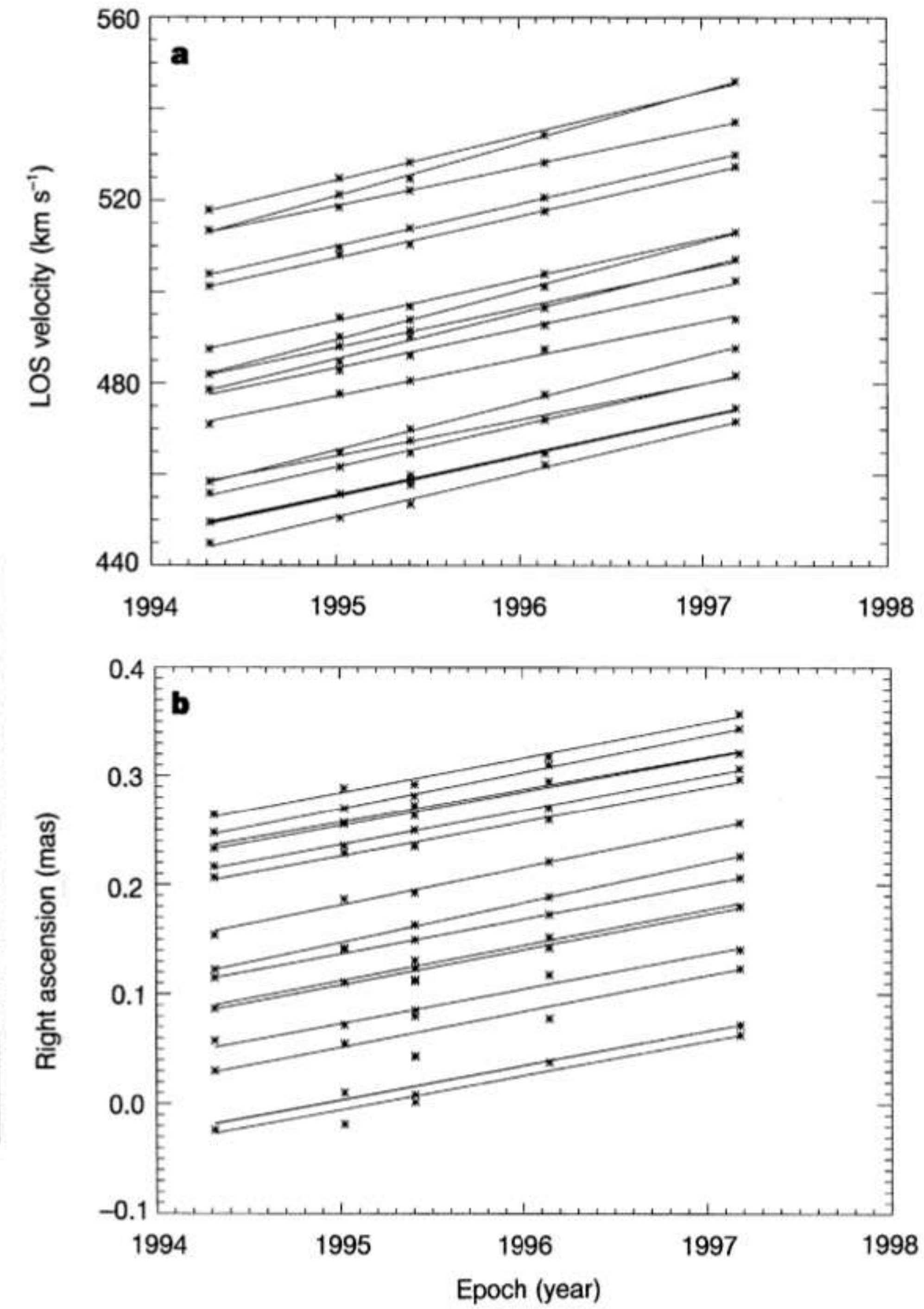
Gaia DR2 Luri et al. 2018

Source: Nature

Direct distance to NGC 4258

Radial and angular proper motions of water masers orbiting central black hole





$$D = 7.576 \pm 0.082\ (\text{stat.}) \pm 0.076(\text{sys.})\ \text{Mpc}$$

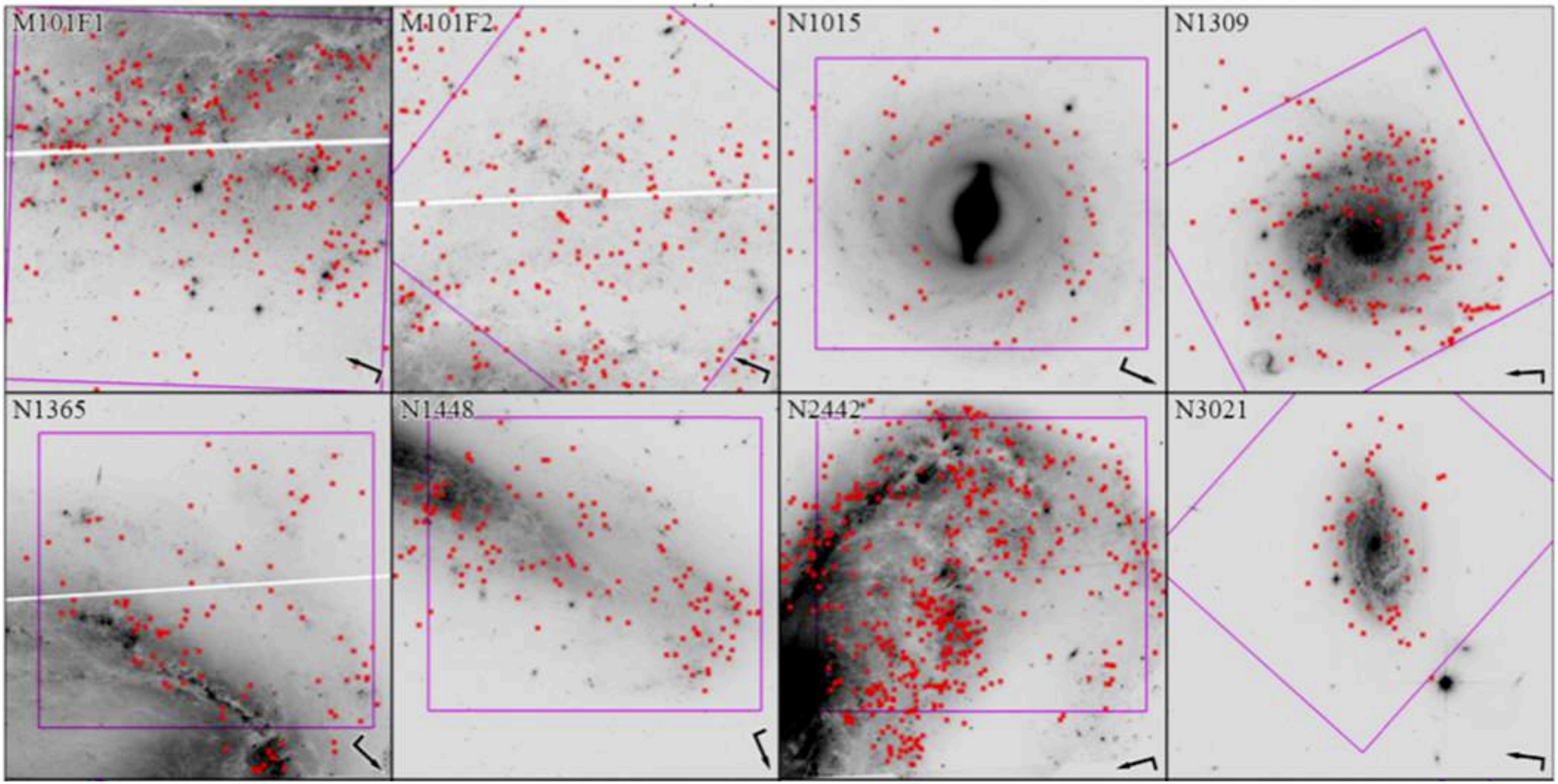
1.5% direct distance measurement !

Herrnstein et al. 1999

Reid et al. 2019

The distance ladder

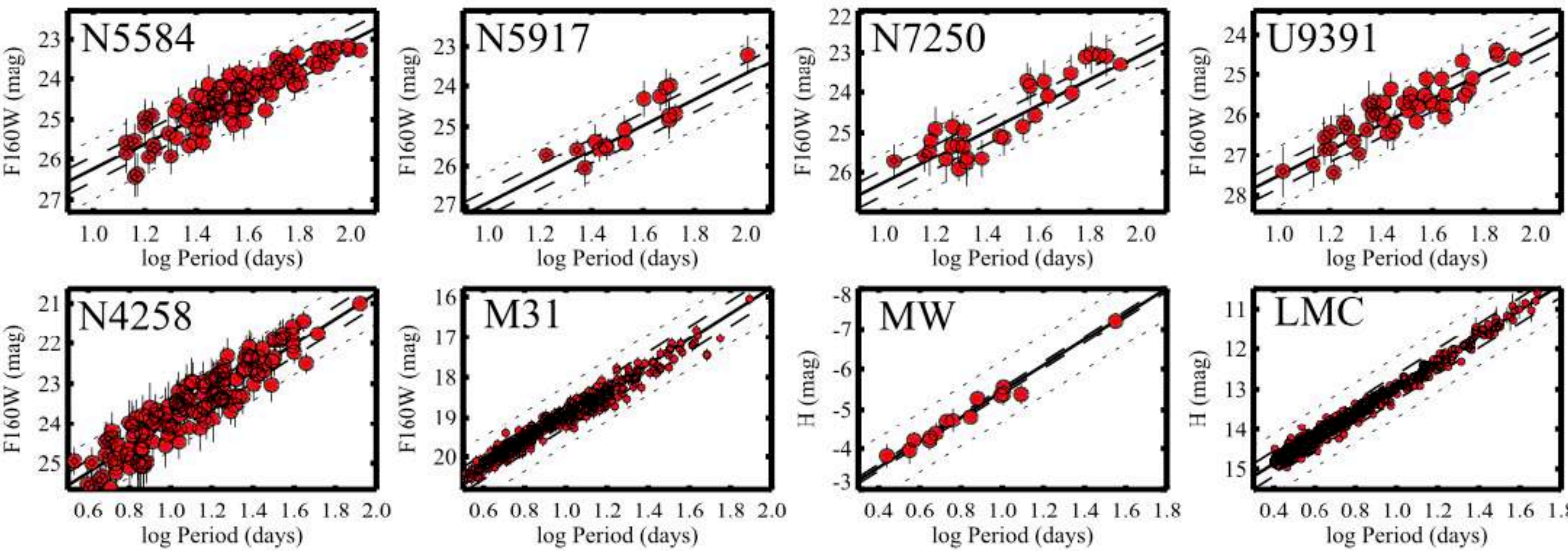
Cepheids in other galaxies



Riess et al. 2016

The distance ladder

Period-luminosity relations of Cepheids



Water-maser galaxy

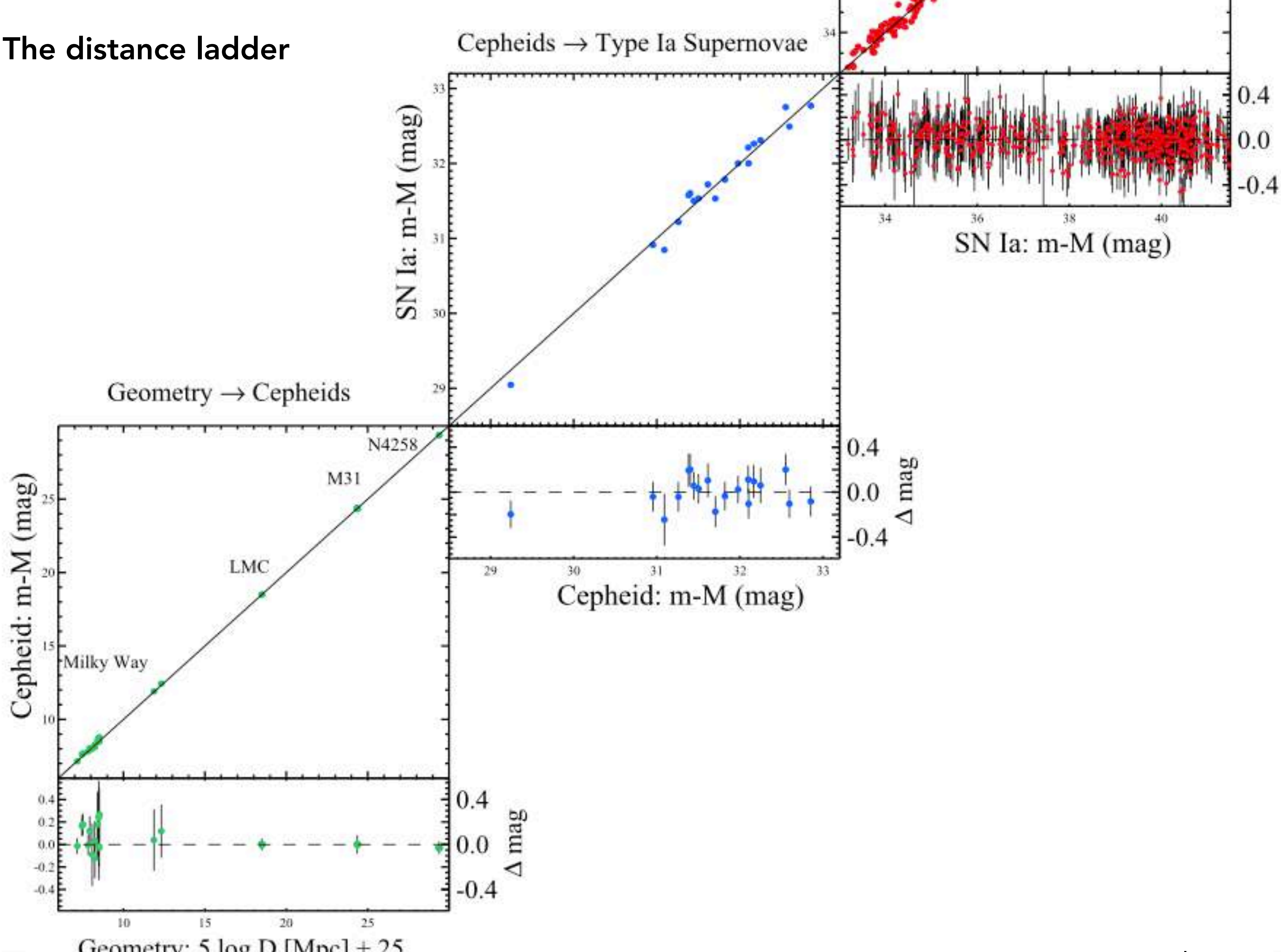
Andromeda

Milky Way

Large Magellanic Cloud

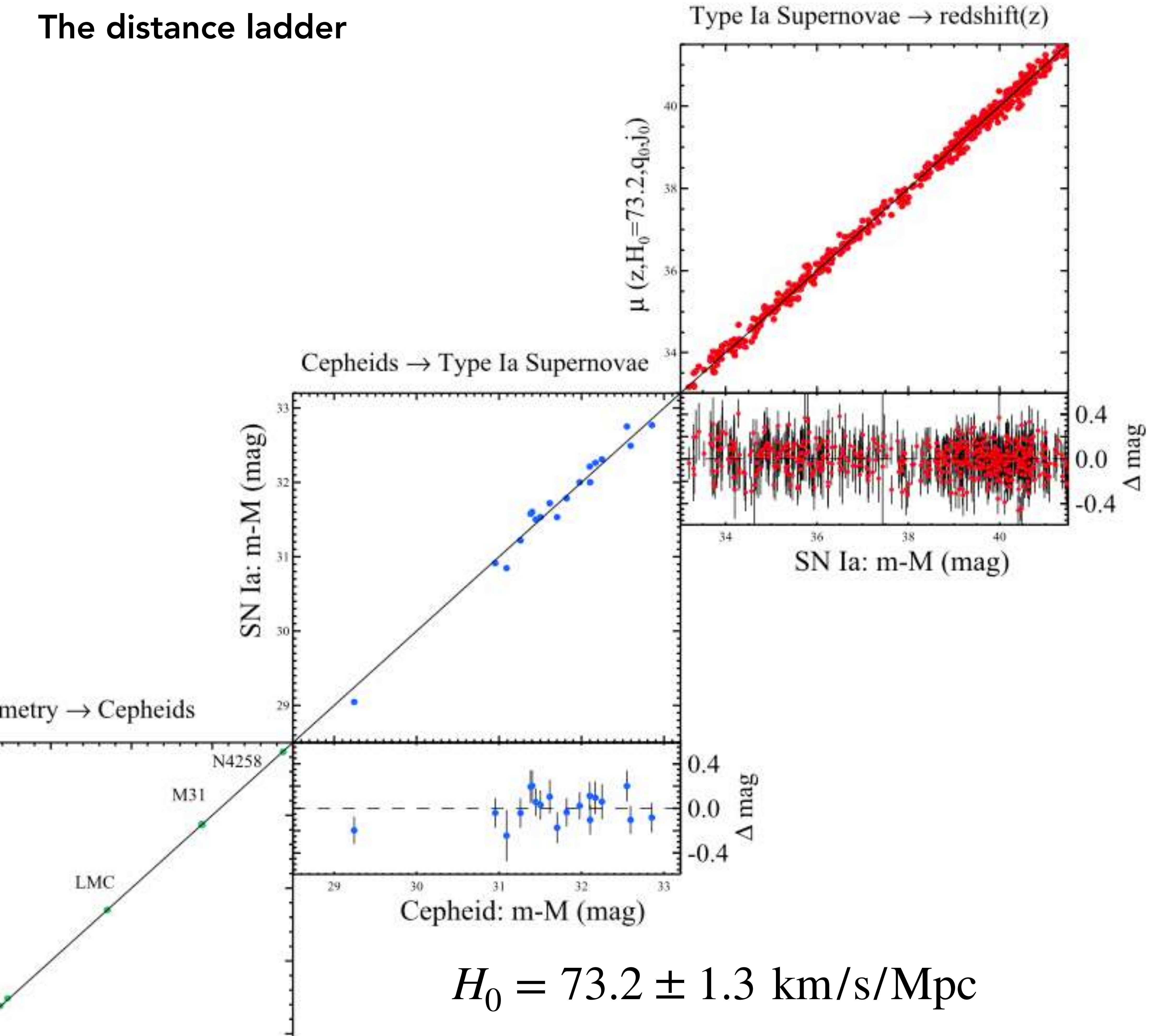
<u>Riess et al. 2016</u>

The distance ladder



Riess et al. 2016

The distance ladder



$$H_0 = 73.2 \pm 1.3 \text{ km/s/Mpc}$$

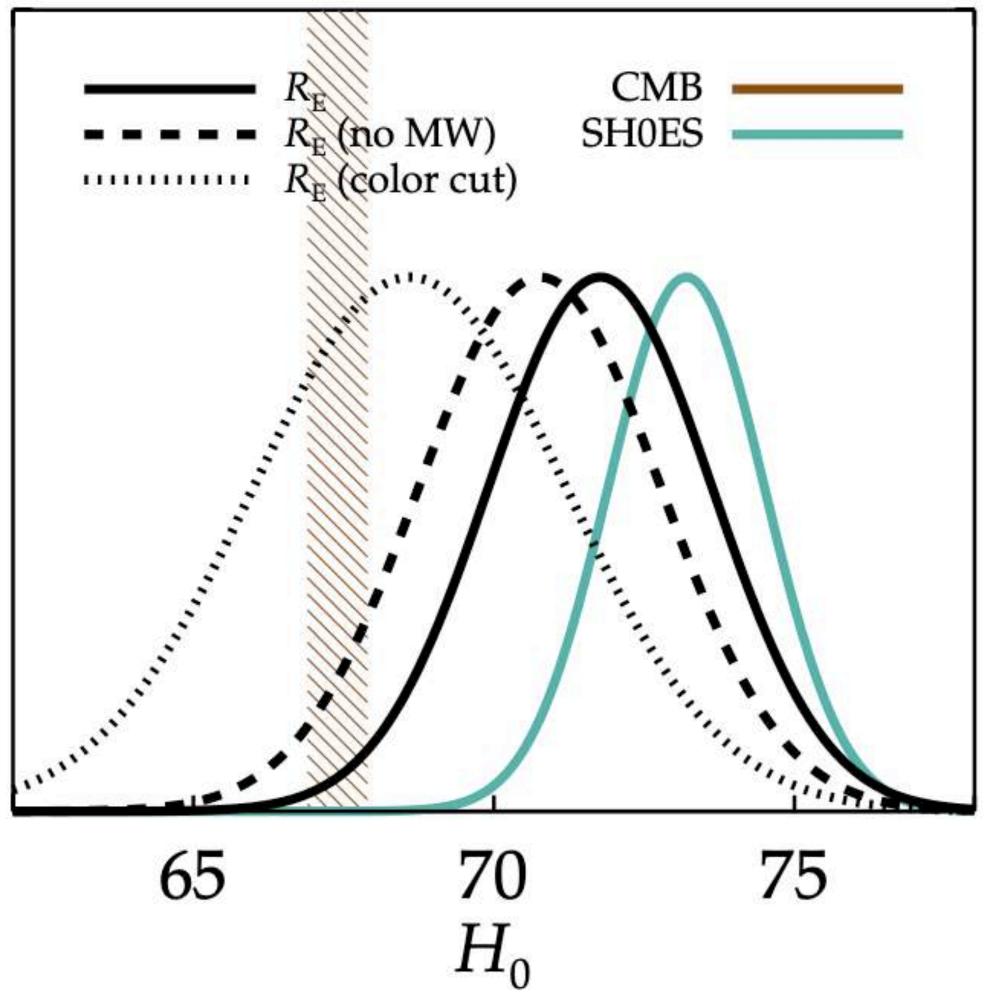
Riess et al. 2016

Riess et al. 2021

The distance ladder

Alternative analysis, same data

"Unlike the SH0ES [Riess et al.] team, we do not enforce a universal color-luminosity relation to correct the near-IR Cepheid magnitudes."



$H_0 = 73.2 \pm 1.3$ km/s/Mpc   Riess et al. 2021

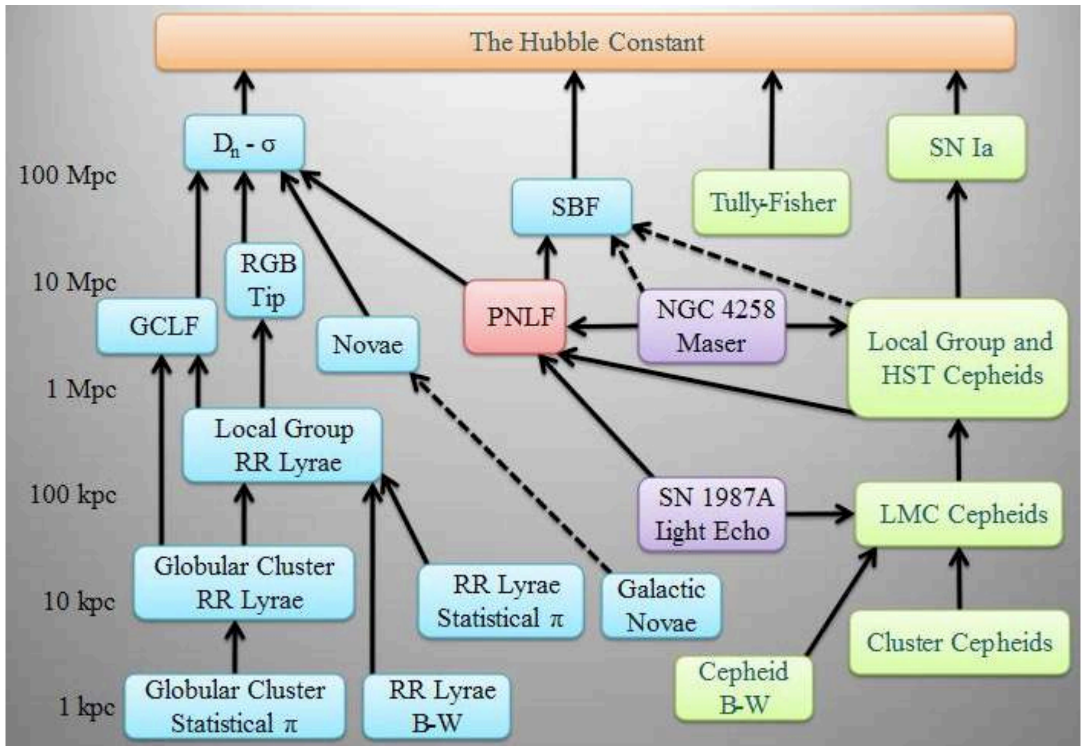
$H_0 = 71.8 \pm 1.6$ km/s/Mpc   Mörtsell et al. 2021a

$H_0 = 70.8 \pm 2.1$ km/s/Mpc   Mörtsell et al. 2021b

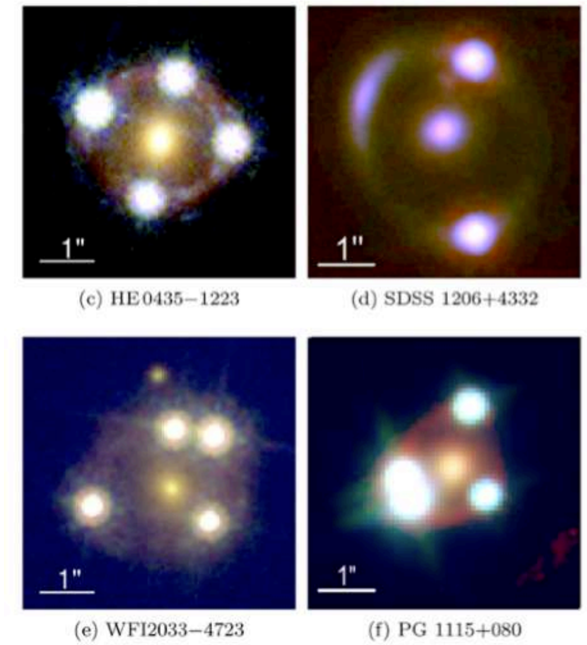
Is the tension with CMB really there ?

The Hubble Constant H_0

Distance ladder

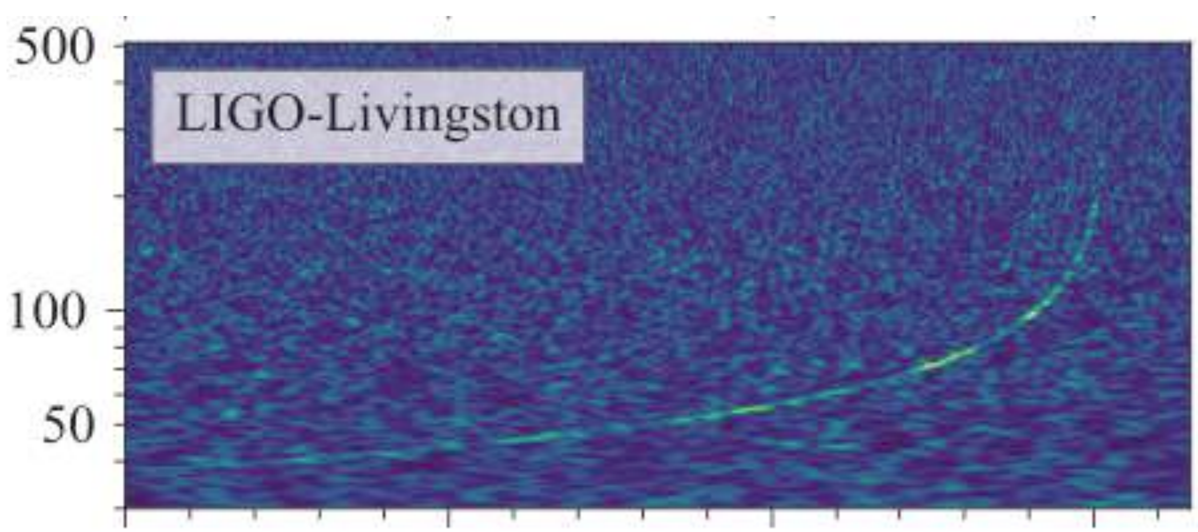


Strong lensing of variable quasars



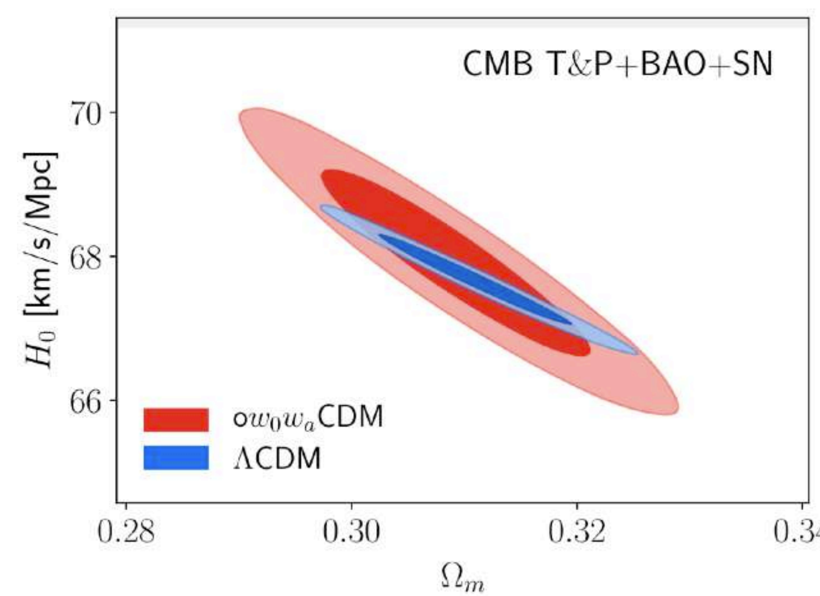
H0LiCOW (Wong et al. 2020)

Standard sirens



LIGO & Virgo 2017

Inverse distance ladder



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The Hubble Constant H_0

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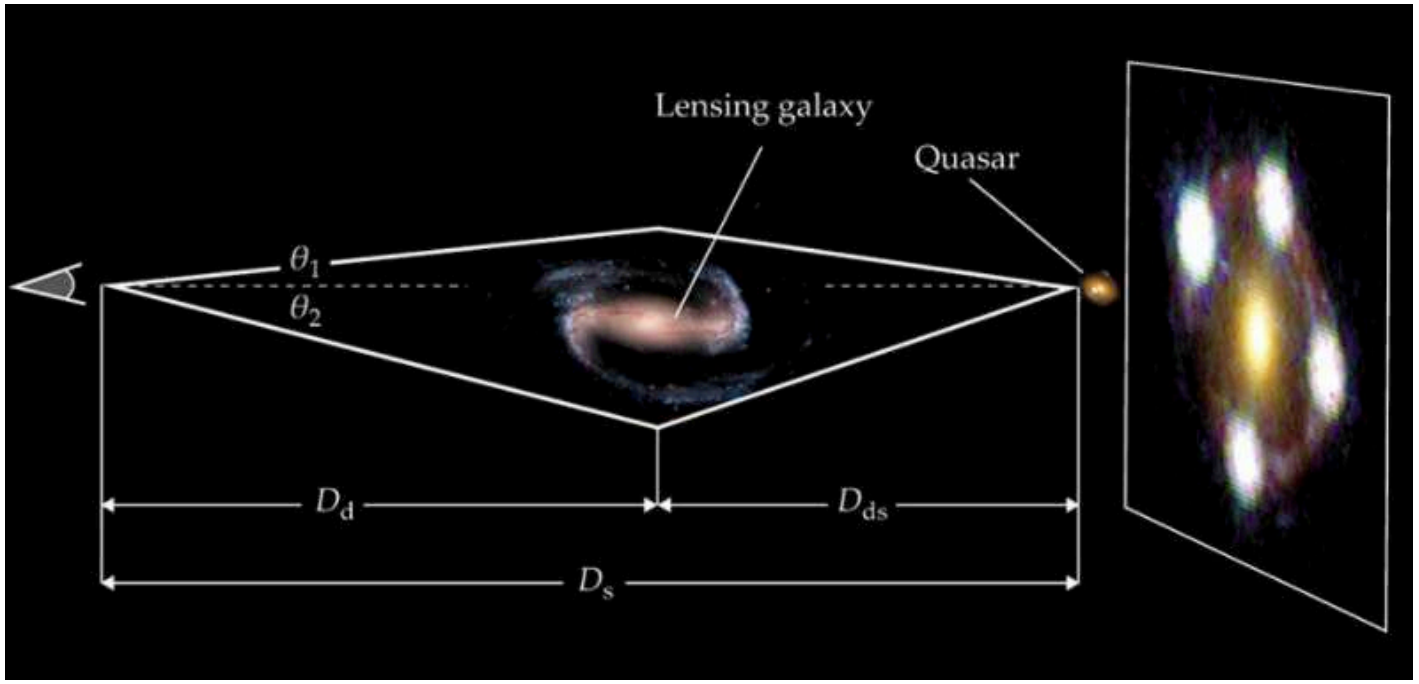
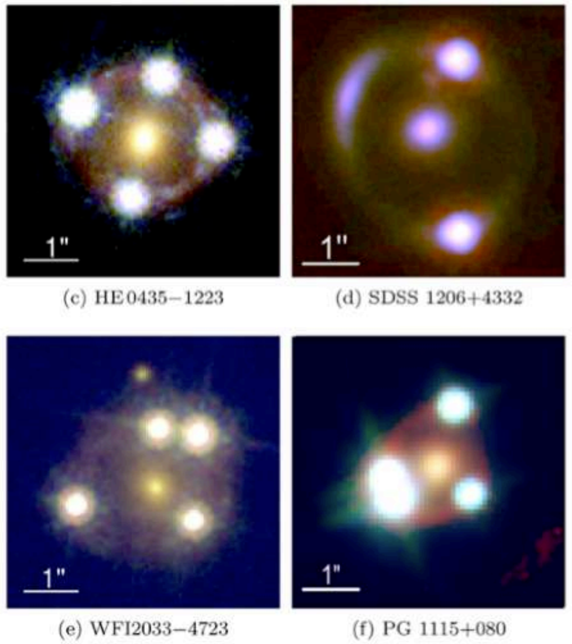
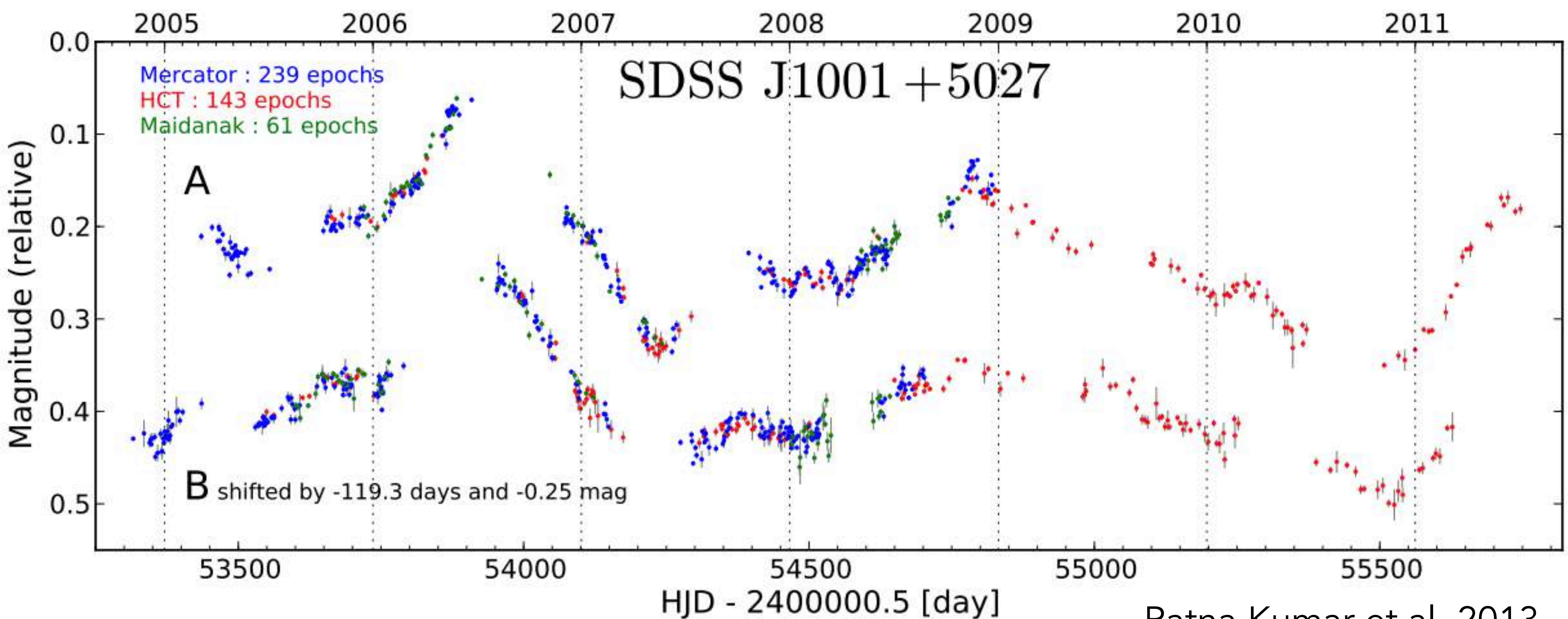


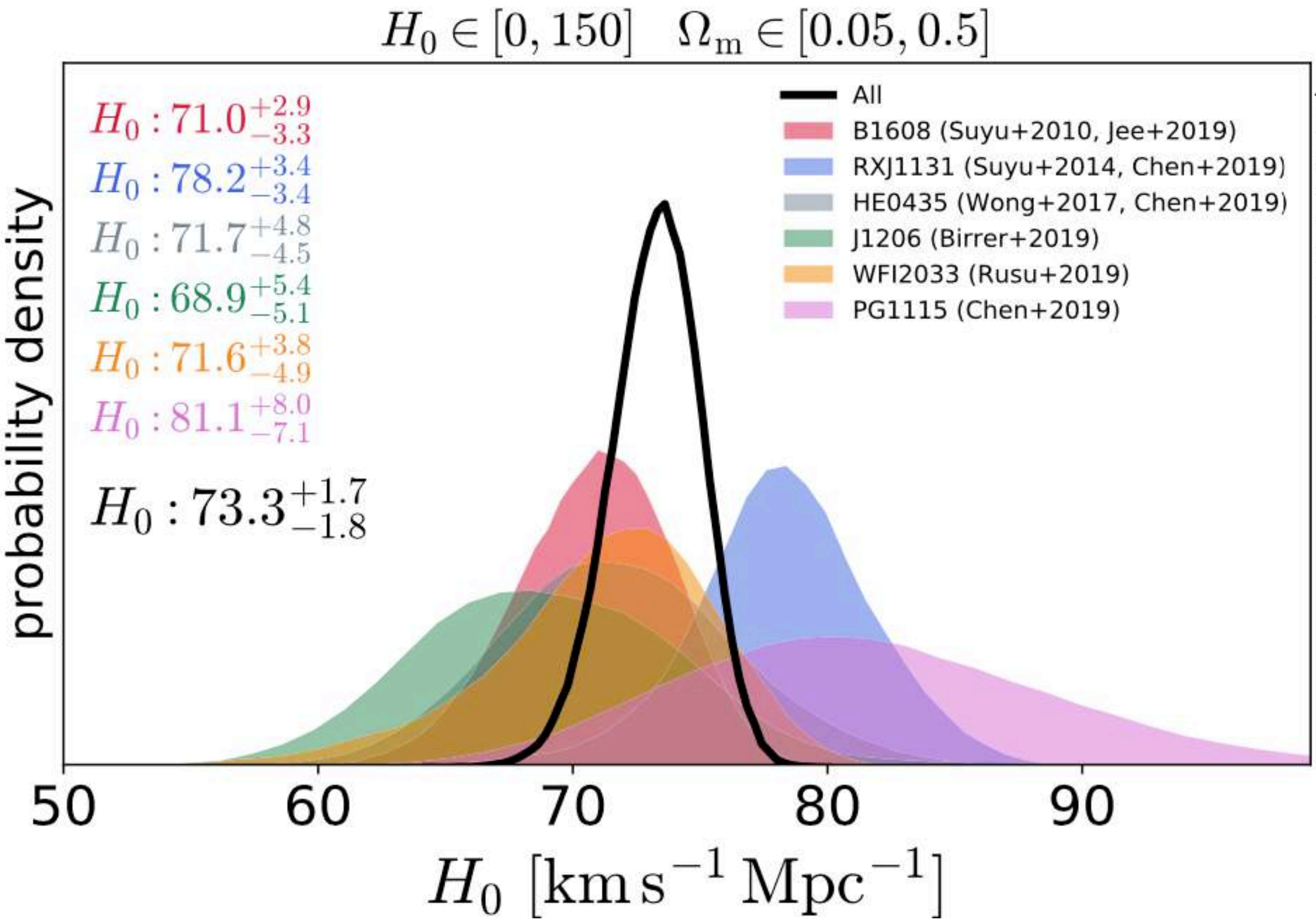




Ratna Kumar et al. 2013

The Hubble Constant H_0

Strong lensing of variable quasars



Redshifts of lens and source

z_d	z_s
0.6304[a]	1.394[b]
0.295[c]	0.654[d]
0.4546[f,g]	1.693[h]
0.745[j]	1.789[i]
0.6575[l]	1.662[h]
0.311[n]	1.722[m]

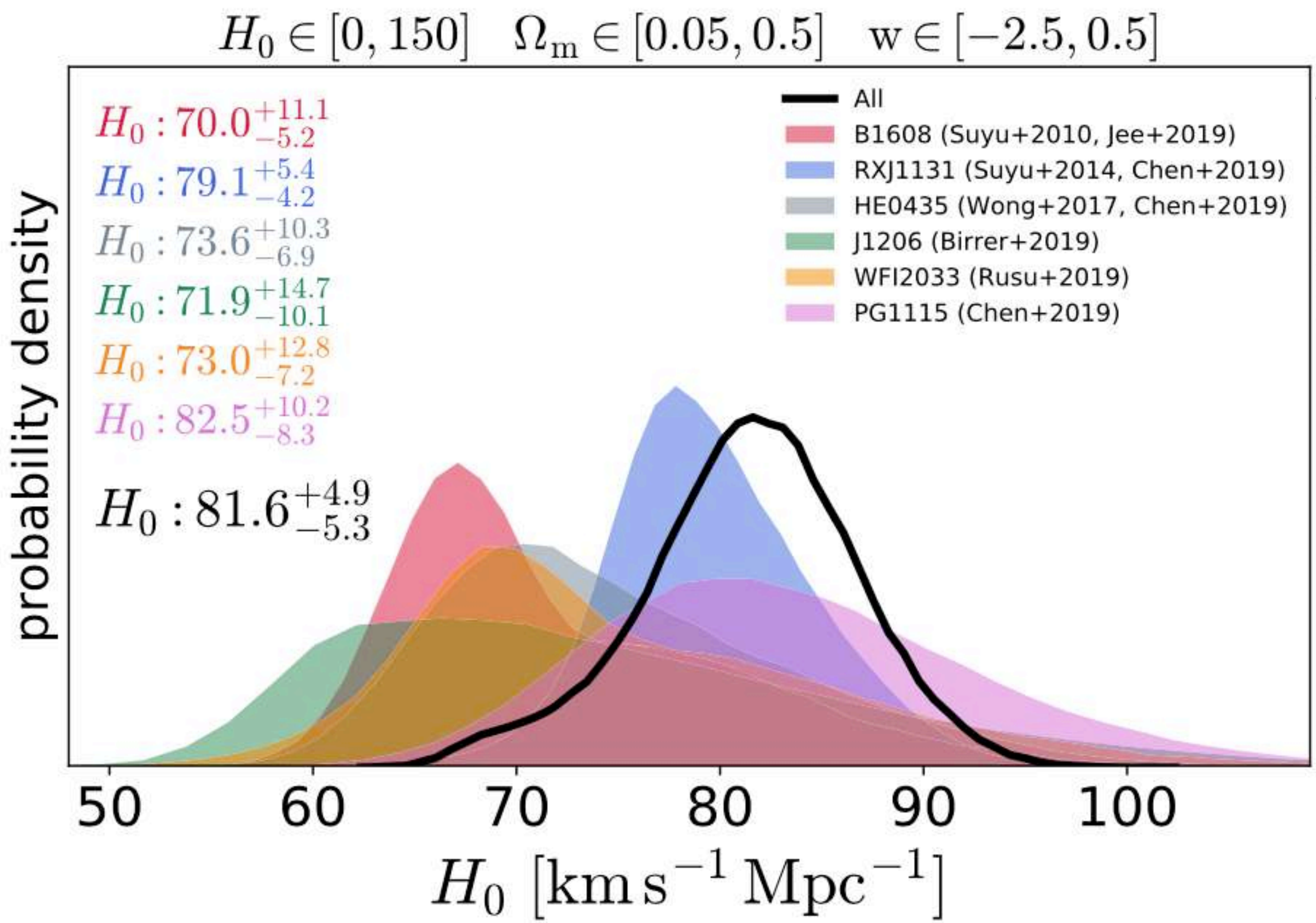
Assuming a flat ΛCDM model

$$H_0 : 73.3^{+1.7}_{-1.8}$$

H0LiCOW (Wong et al. 2020)

The Hubble Constant H_0

Strong lensing of variable quasars



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0.6575[l]	1.662[h]
0.311[n]	1.722[m]

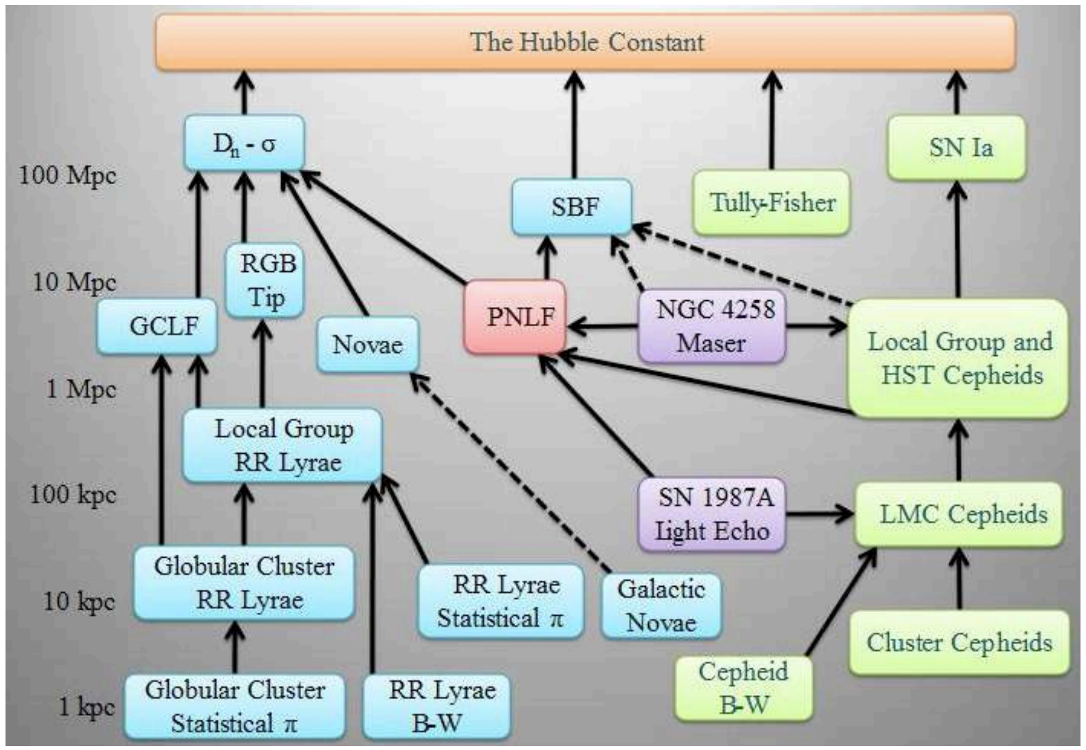
Assuming a flat **w**CDM model

$$H_0 : 81.6^{+4.9}_{-5.3}$$

H0LiCOW (Wong et al. 2020)

The Hubble Constant H_0

Distance ladder



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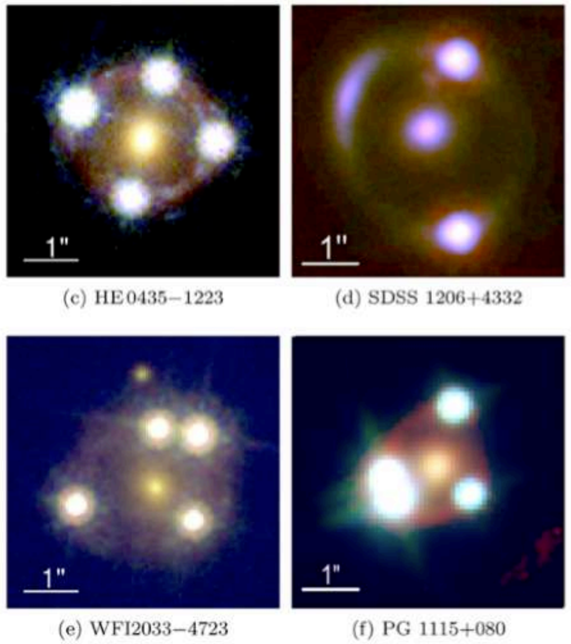

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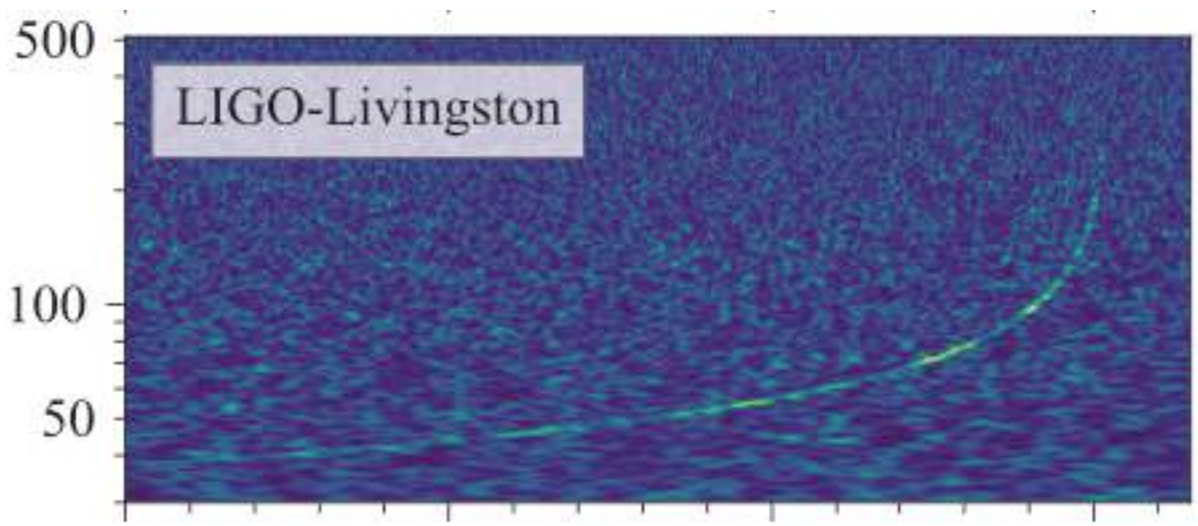
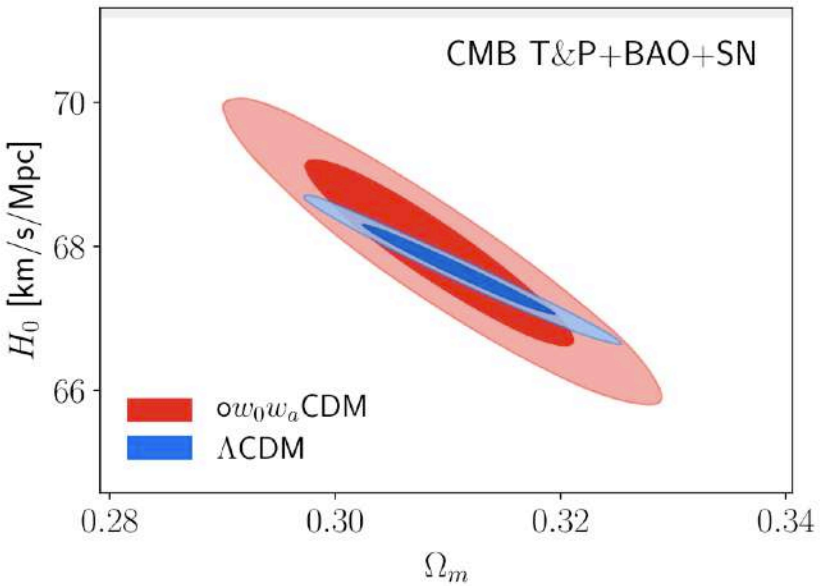
Standard sirens



LIGO & Virgo 2017

Inverse distance ladder



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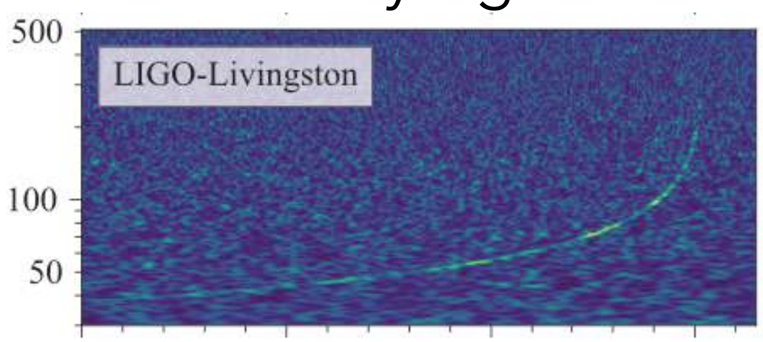
The Hubble Constant H_0

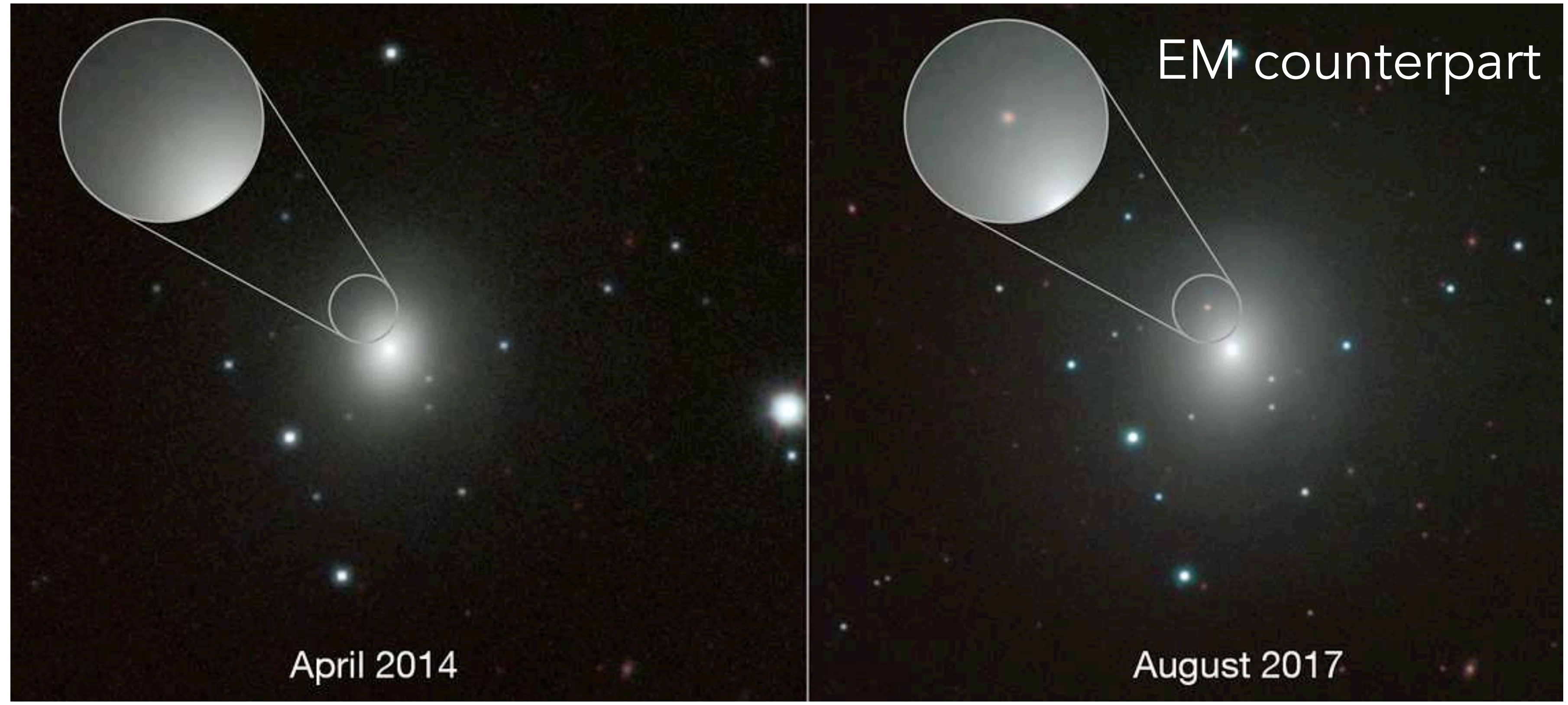
Standard sirens

Binary neutron star merger

Gravity signal



LIGO & Virgo 2017



Source: ESO/N.R. Tanvir, A.J. Levan and the VIN-ROUGE collaboration

From full GR simulations + GW signal:

- chirp mass $\mathscr{M} = \sqrt[5]{(m_1 m_2)^3/(m_1+m_2)} = 1.188^{+0.004}_{-0.002} M_\odot$
- mass ratio $q = m_2/m_1 = 0.7 - 1.0$
- spin
- **luminosity distance** $D_L = 40^{+8}_{-14}$ Mpc

From EM counterpart:

Redshift $v_H = 3017 \pm 166$ km/s

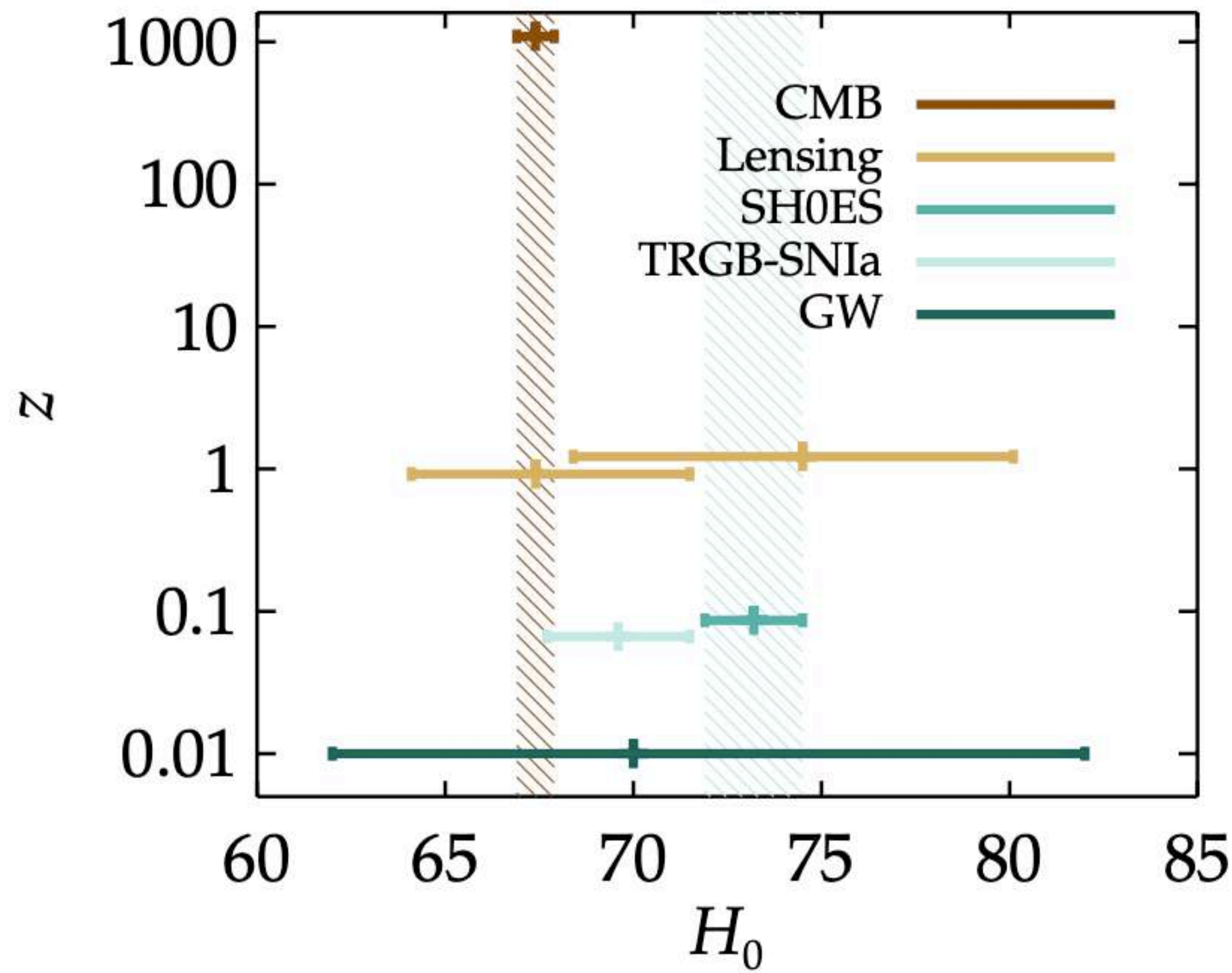
(removing peculiar velocities)

$$H_0 = 70.0^{+12.0}_{-8.0} \text{ km/s } (68\,\%\text{ C.L.})$$

The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration, The MASTER Collaboration, et al.

Nature 2017

The Hubble Constant H_0



Mörtsell et al. 2021a

Big Bang Nucleosynthesis (BBN)

Big Bang Nucleosynthesis (BBN)

Relic amounts of elements depends on battle between

Expansion rate : $H^2(z) \sim \rho_r(z) = \rho_\gamma(z) + \rho_\nu(z)$ (radiation-dominated era)

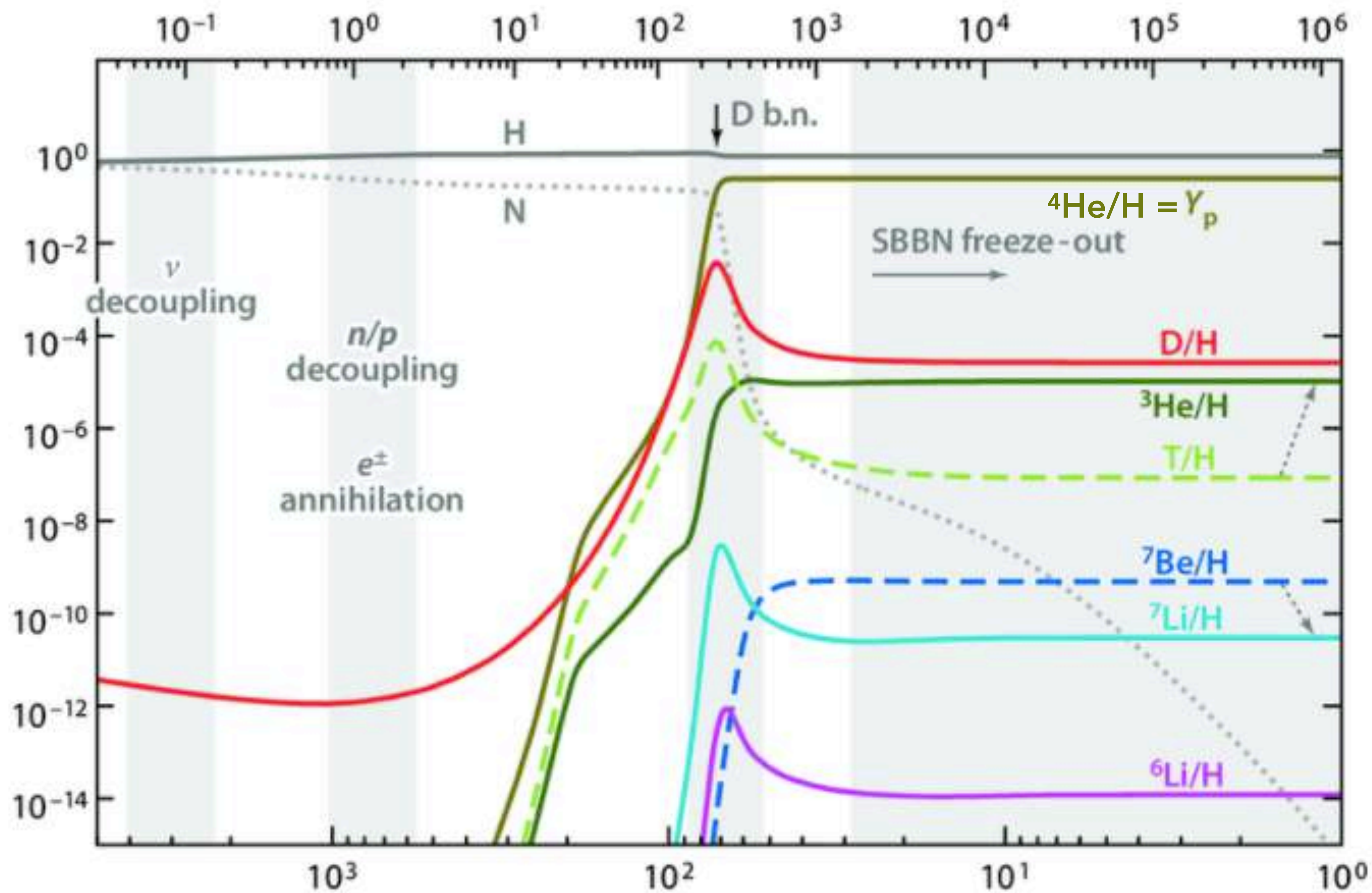
Reaction rates : nuclear cross-sections + baryon density $\rho_b(z)$

First:

$$n + e^+ \rightleftharpoons \bar{\nu}_e + p$$
$$n + \nu_e \rightleftharpoons p + e^-$$

Then:

$$p + n \longrightarrow {}^2H + \gamma$$
$$p + {}^2H \longrightarrow {}^3He + \gamma$$
$${}^2H + {}^2H \longrightarrow {}^3He + n$$
$${}^2H + {}^2H \longrightarrow {}^3H + p$$
$${}^3He + {}^2H \longrightarrow {}^4He + p$$
$${}^3H + {}^2H \longrightarrow {}^4He + n$$

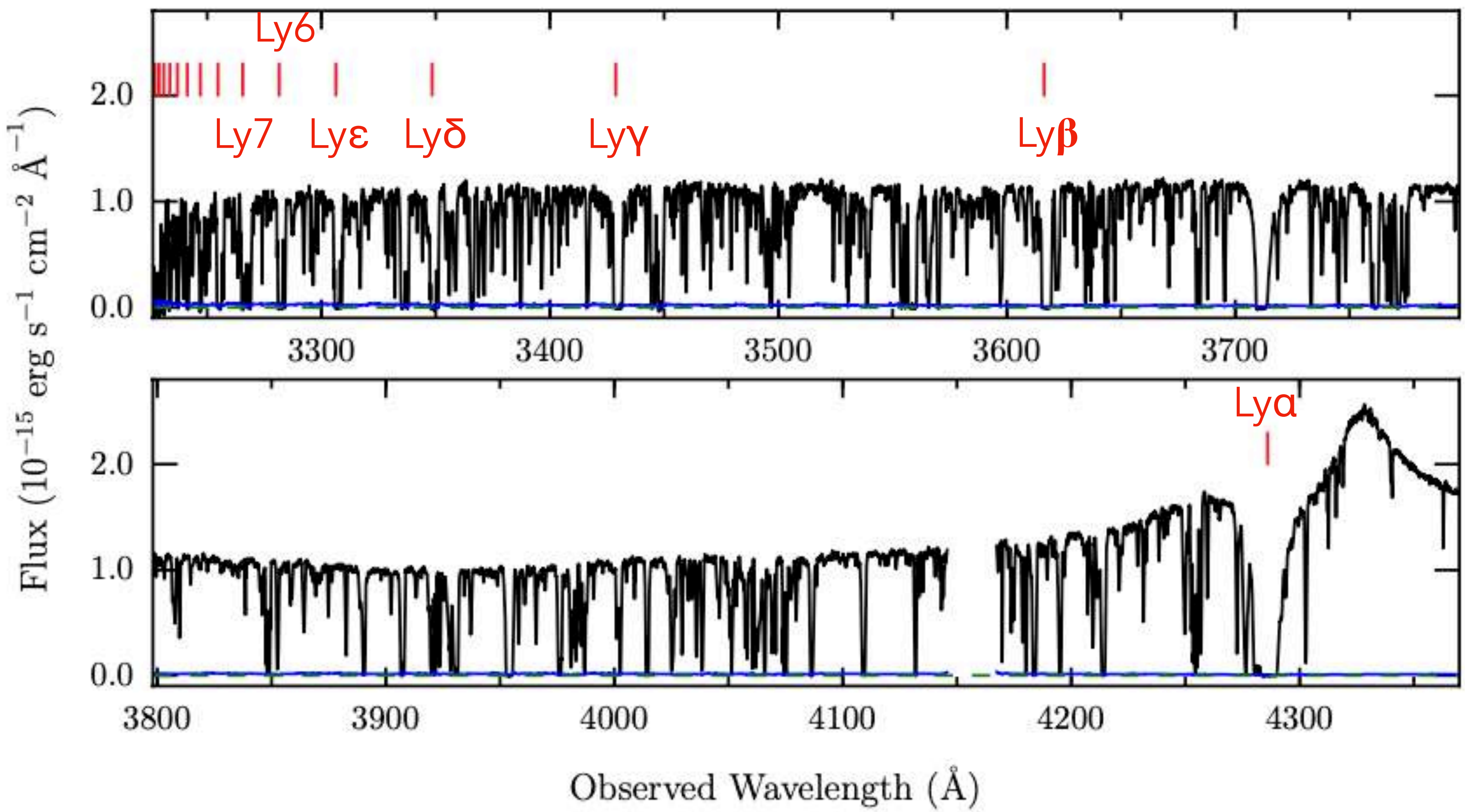


Theoretical model

Pospelov & Pradler 2010

Big Bang Nucleosynthesis (BBN)

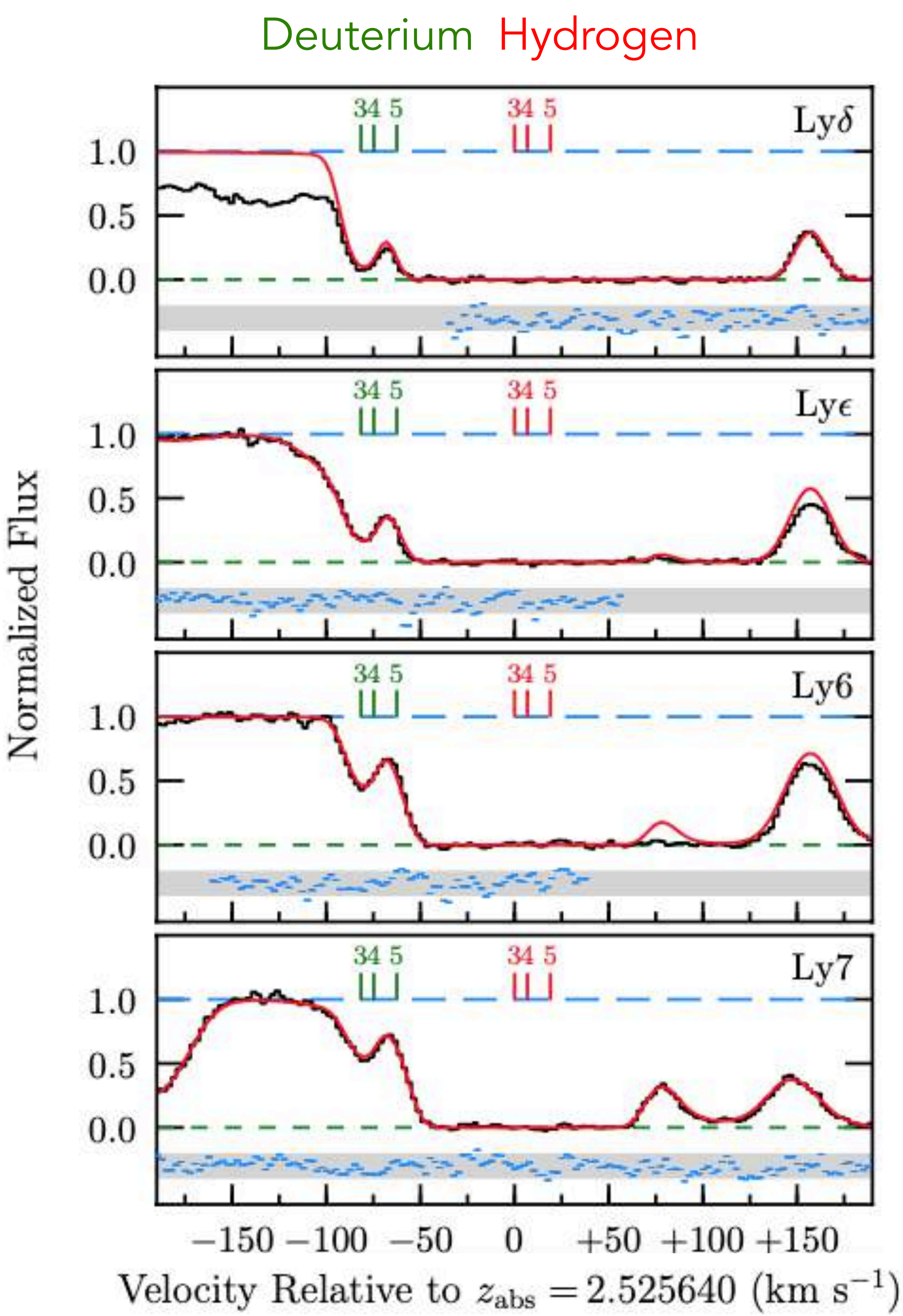
Absorption by a neutral hydrogen cloud at z=2.526
on a z=2.558 quasar spectrum



More than 20 hours of integration @ Keck Obs, Hawaii (10m) !

Cooke et al. 2018

Big Bang Nucleosynthesis (BBN)



Fit of hydrogen, deuterium and other metal lines yields:

$$\log_{10} N(\mathrm{D\,I})/N(\mathrm{H\,I}) = -4.622 \pm 0.015$$

Baryon density $\omega_b = \Omega_b h^2$

$$100\,\Omega_{\mathrm{B},0}\,h^2(\mathrm{BBN}) = 2.166 \pm 0.015 \pm 0.011$$

Cooke et al. 2018

Big Bang Nucleosynthesis (BBN)

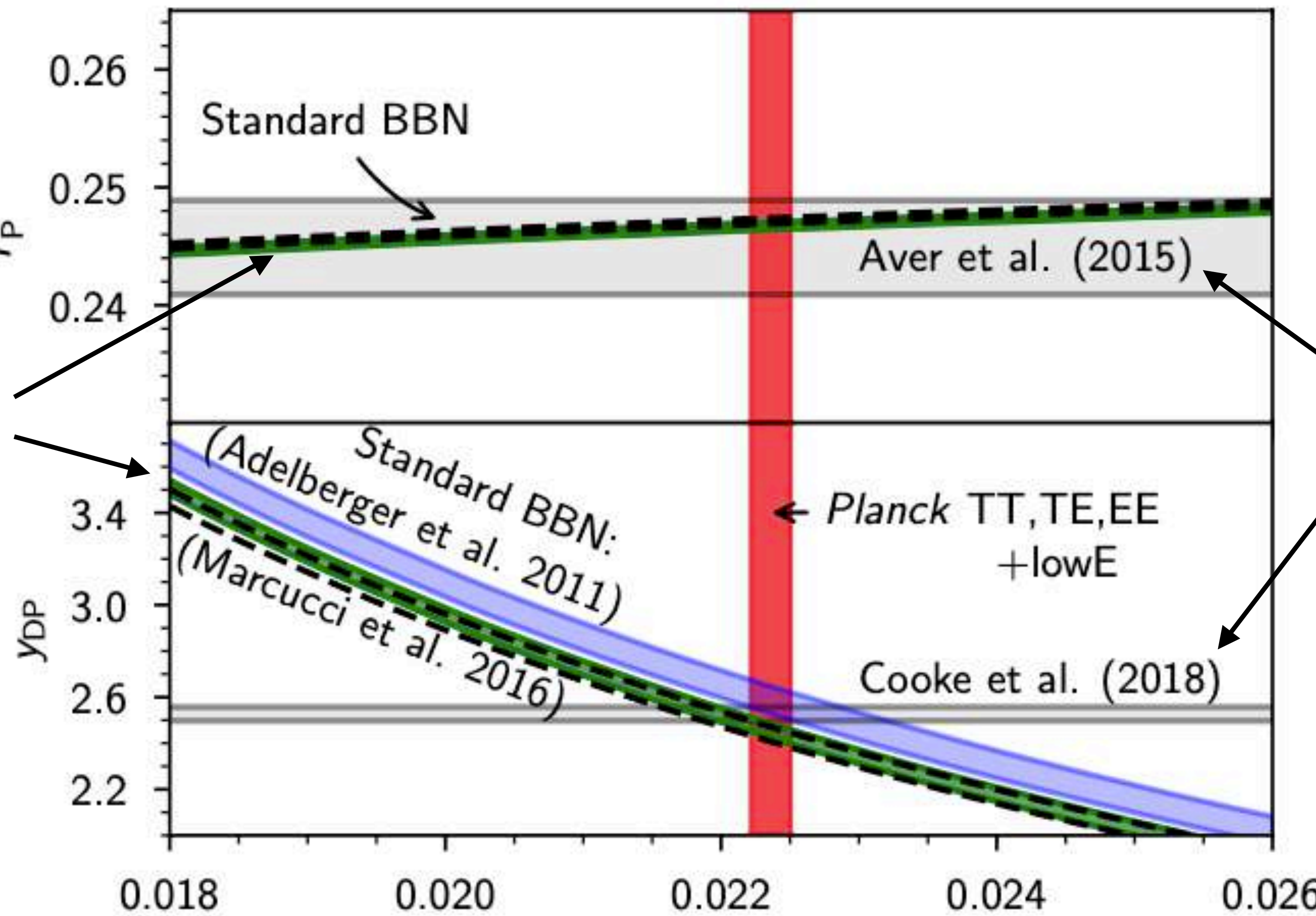
Planck Collab VI 2020

Helium abundance

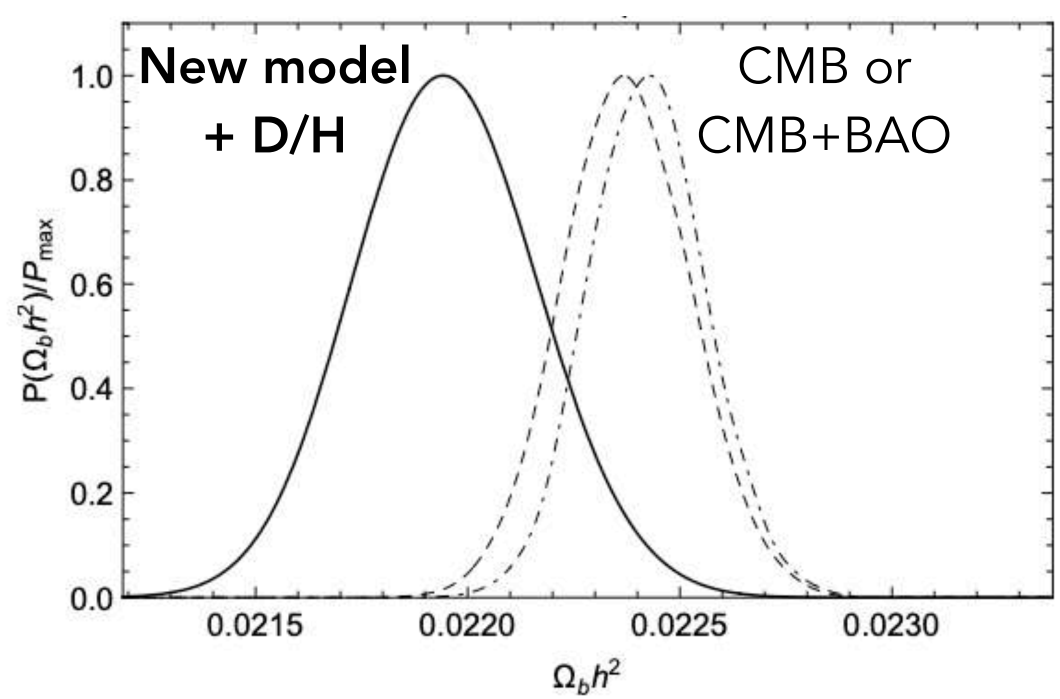
Theoretical models

Deuterium abundance

Measurements



Baryon density $\omega_b = \Omega_b h^2$

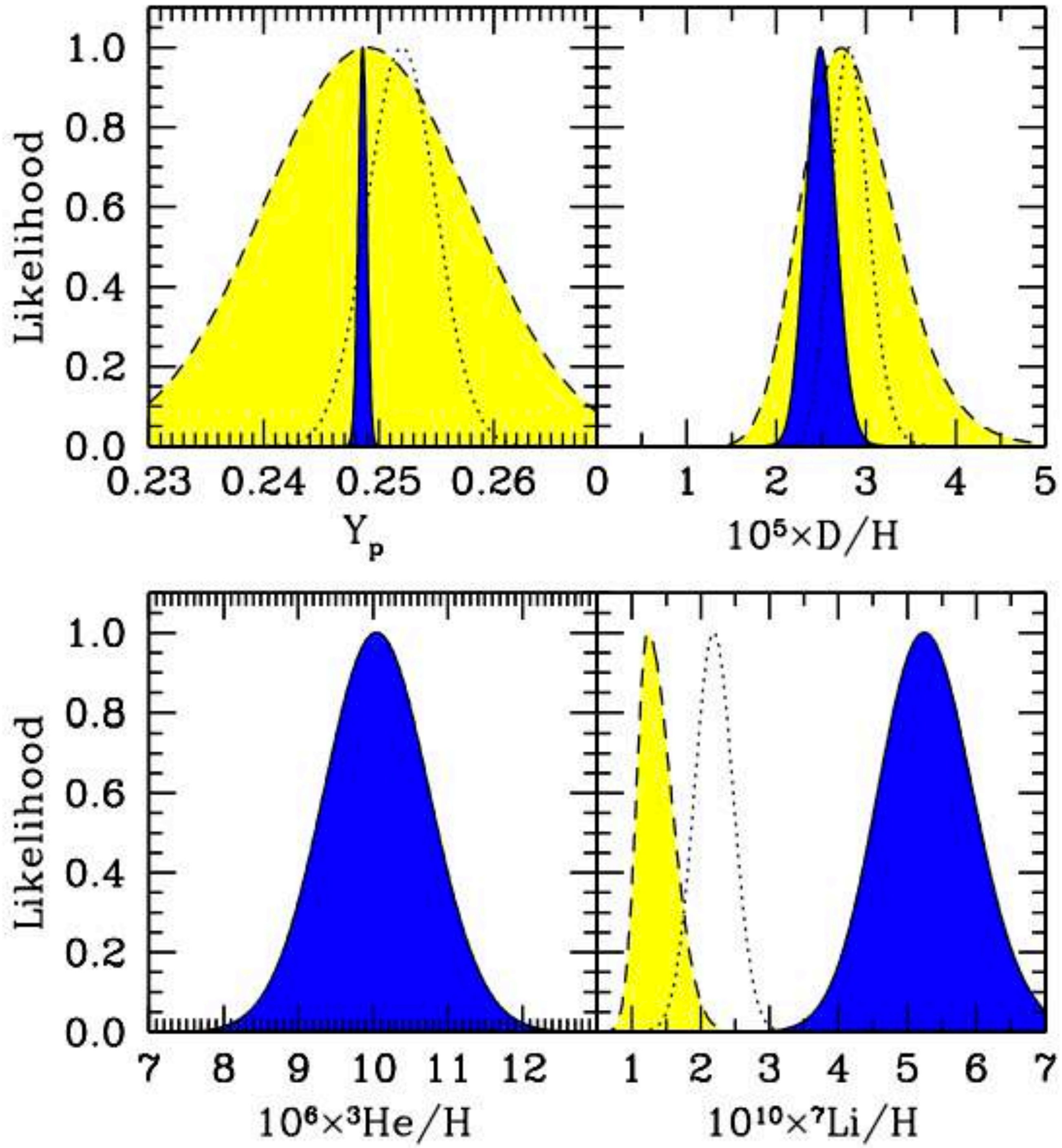


Latest calculations indicate **new tension** ?

See Pitrou et al. 2021

Big Bang Nucleosynthesis (BBN)

The Lithium problem : observations and theory do not match !



A factor of 3 or 4 that is a mystery !

Fields 2010 (review)

Type Ia Supernovae (SNIa)

Cosmology with Type Ia Supernovae (SNIa)

Constraints on dark-energy from the distance-redshift relation

$$H^2(z) \approx H_0^2 \left[\Omega_m(1+z)^3 + \Omega_{\mathrm{DE}}(z) + \Omega_k(1+z)^2\right] \quad \text{(at } z < 100\text{)}$$

Transition from matter to dark-energy dominated eras : z ~ 0.4

SNIa can cover redshifts before and after : powerful probe

Comoving distance

$$D_C(z) = \int_0^z \mathrm{d}z' \, \frac{c}{H(z')}$$

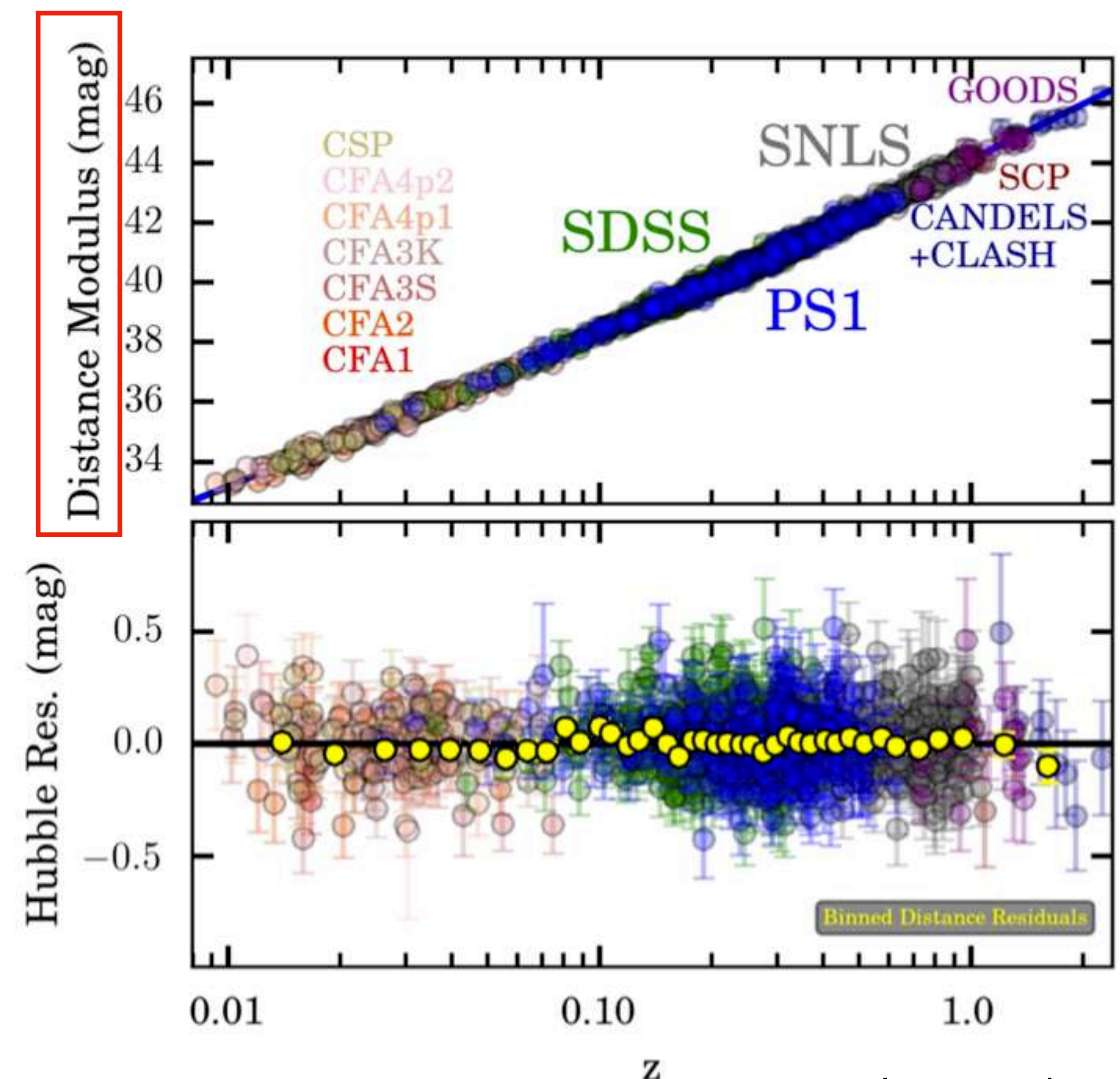
Luminosity distance

$$D_L(z) = (1+z) D_C(z) \mathrm{sinc}\left(\sqrt{-\Omega_k} \frac{D_C(z)}{D_H(z=0)}\right)$$

Distance modulus

$$\mu(z) = 5 \log_{10} \frac{D_L(z)}{10 \text{ pc}} = -2.5 \log_{10}(f_B(z)/L_B)$$

Theory **Observed**



Scolnic et al. 2018

Cosmology with Type Ia Supernovae (SNIa)

Constraints on dark-energy from the distance-redshift relation

$$H^2(z) \approx H_0^2 \left[\Omega_m(1+z)^3 + \Omega_{\rm DE}(z) + \Omega_k(1+z)^2\right] \qquad \text{(at } z < 100\text{)}$$

Transition from matter to dark-energy dominated eras : z ~ 0.4

SNIa can cover redshifts before and after : powerful probe

Comoving distance

$$D_C(z) = \int_0^z \mathrm{d}z' \, \frac{c}{H(z')}$$

Note that M_B and H_0 are degenerate

$$D_C(z) = \frac{c}{H_0}\int_0^z \mathrm{d}z' \, \frac{1}{E(z')} \equiv \frac{c}{H_0} I(\Omega_x, z)$$

Luminosity distance

$$D_L(z) = (1+z) D_C(z) \mathrm{sinc}\left(\sqrt{-\Omega_k}\frac{D_C(z)}{D_H(z=0)}\right)$$

$$D_L(z) = \frac{c}{H_0}(1+z) I(\Omega_x, z) \mathrm{sinc}\left(\sqrt{-\Omega_k} I(\Omega_x, z)\right)$$

Distance modulus

$$\mu(z) = 5\log_{10}\frac{D_L(z)}{10 \text{ pc}} = -2.5\log_{10}(f_B(z)/L_B)$$

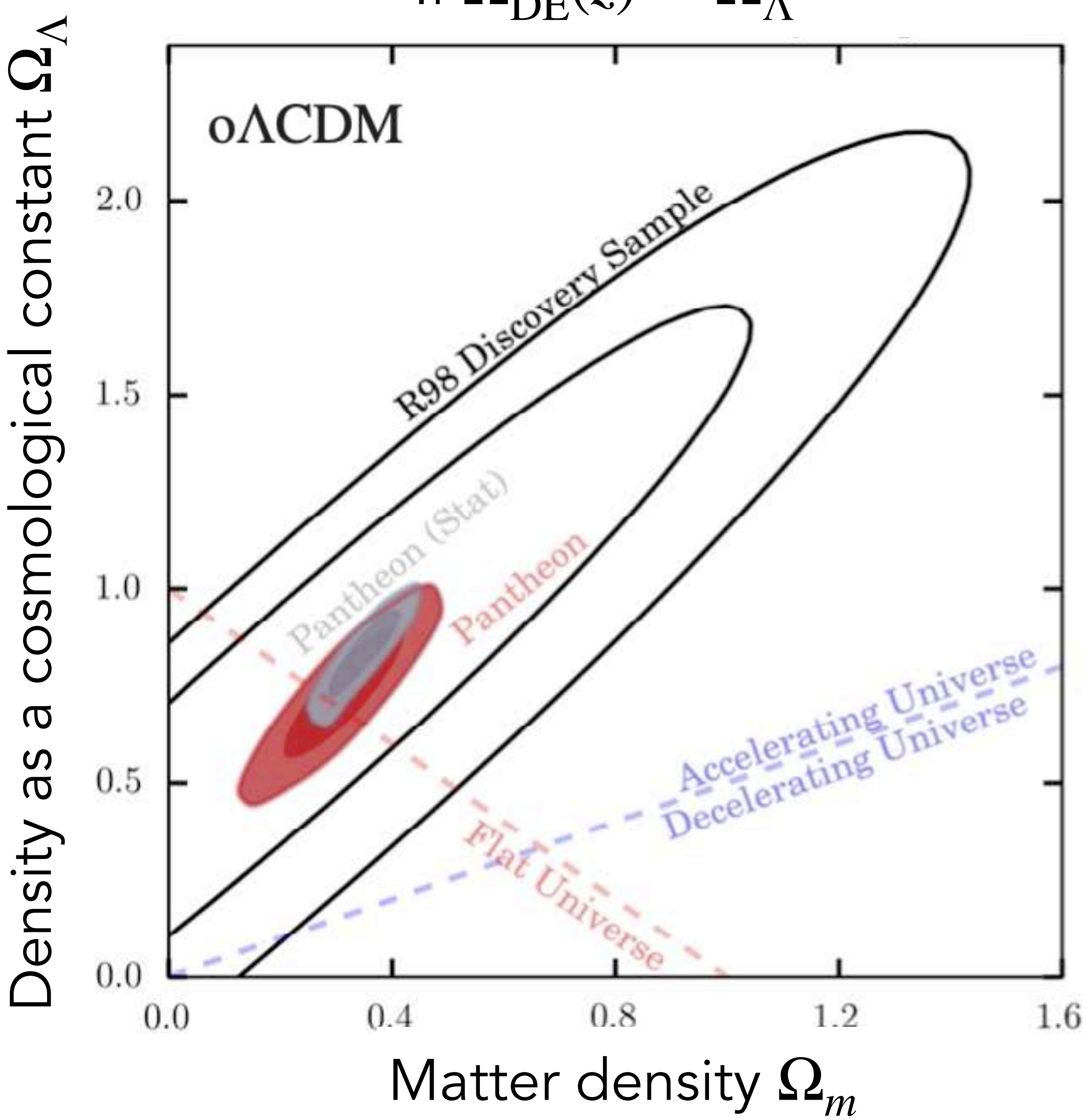
$$\mu(z) = 5\log_{10}\frac{I(\Omega_x, z)}{10 \text{ pc}} + \boxed{5\log_{10} H_0} = m_B(z) \boxed{- M_B}$$

Cosmology with Type Ia Supernovae (SNIa)

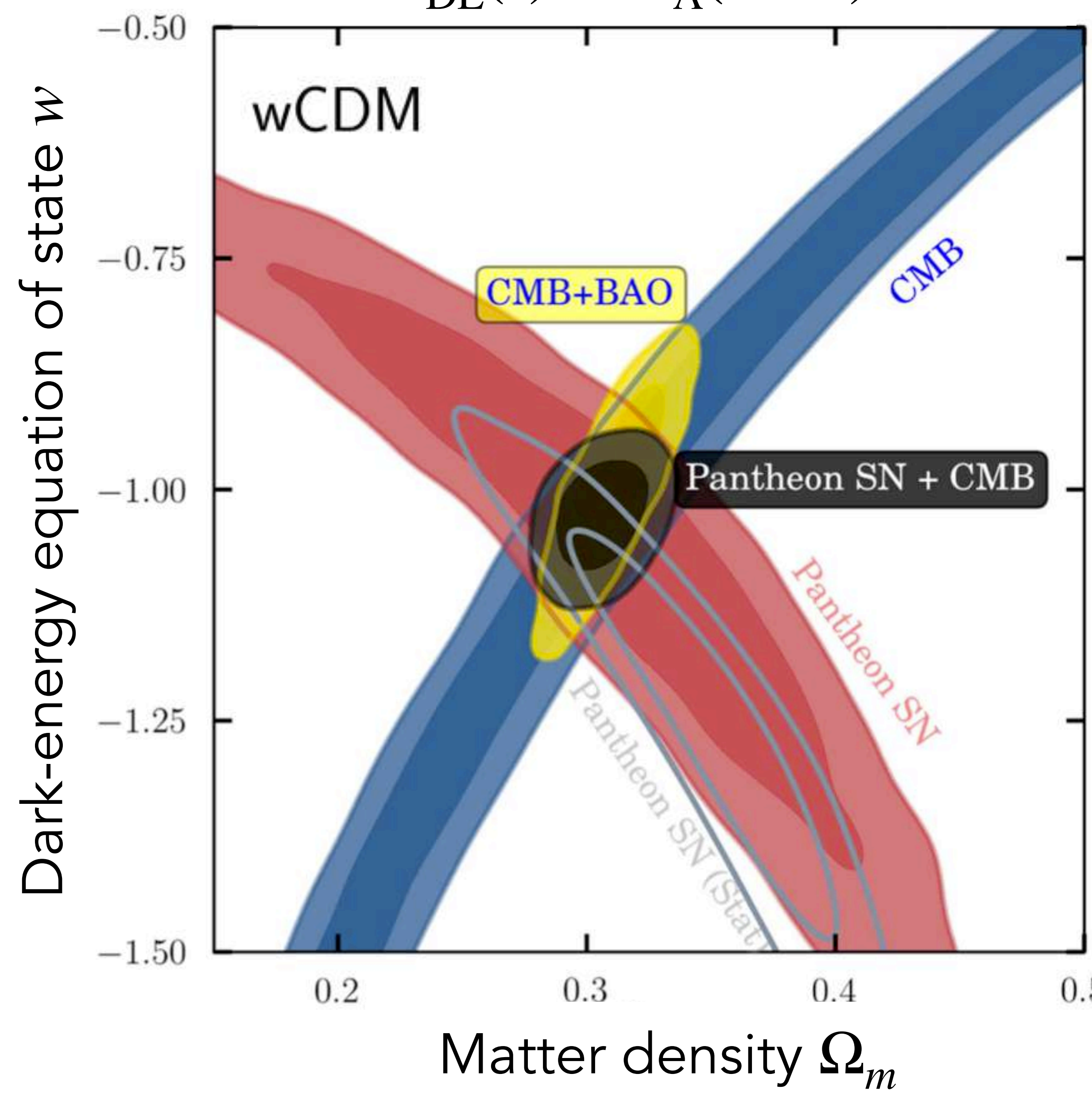
Constraints on dark-energy from the distance-redshift relation

$$H^2(z) \approx H_0^2\left[\Omega_m(1+z)^3 + \Omega_{\rm DE}(z) + \Omega_k(1+z)^2\right] \quad \text{(at z < 100)}$$

If $\Omega_{\rm DE}(z) = \Omega_\Lambda$



If $\Omega_{\rm DE}(z) = \Omega_\Lambda(1+z)^{3(1+w)}$

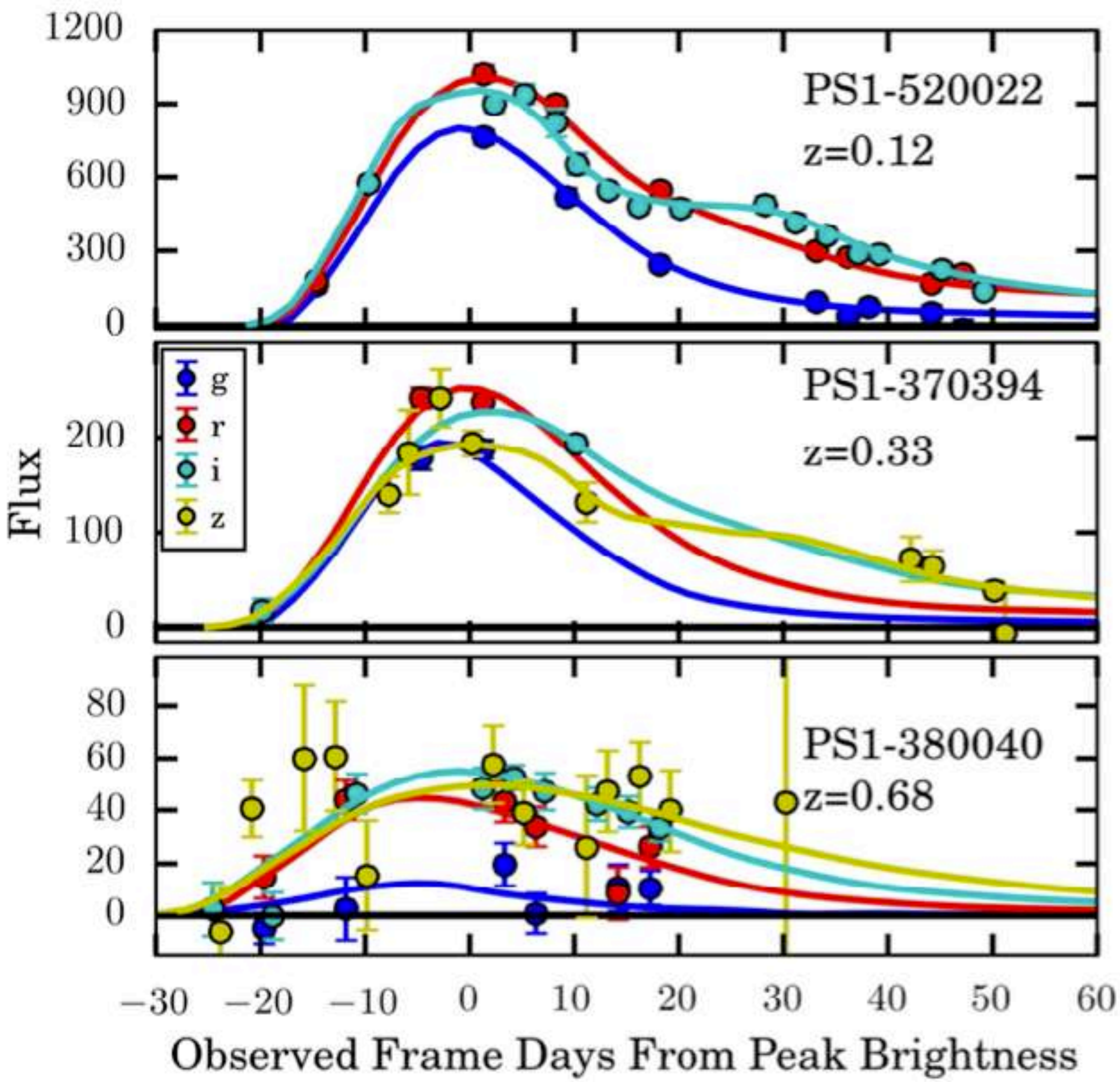


Scolnic et al. 2018

Cosmology with Type Ia Supernovae (SNIa)

How we derive distances ?

From the flux at the peak of the **light-curves** in the B band or m_B



Are light-curves sufficient to know it is a type Ia?
No !
Need **spectroscopic** follow-up

Need spectroscopic redshift of the host-galaxy

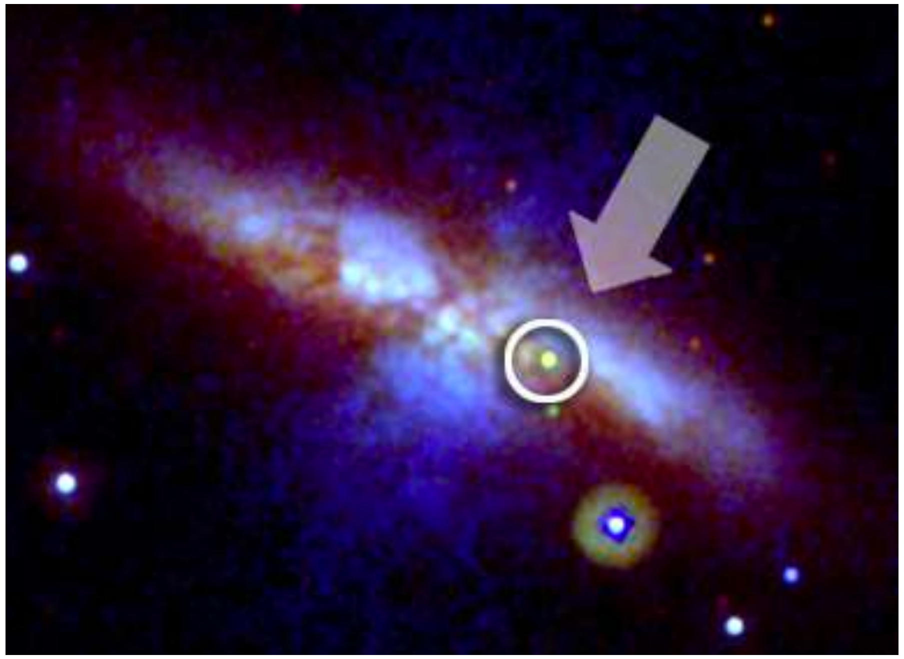
Fit light-curves with a model (SALT2/3, SUGAR, etc..) to **standardise** them

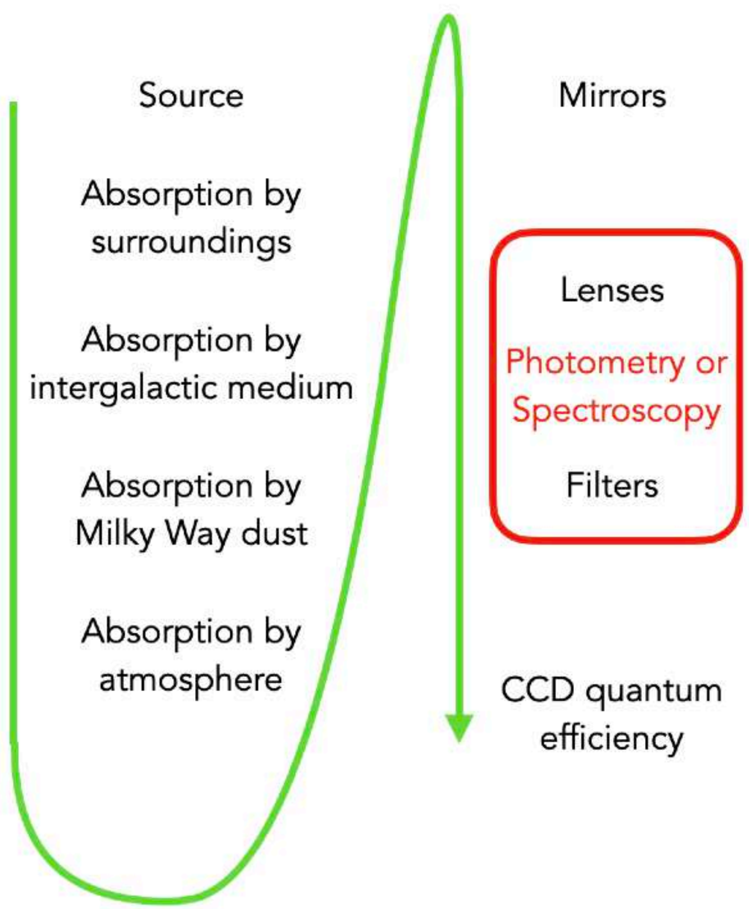
Hubble residuals reduce from 40% to **15% intrinsic scatter**

Scolnic et al. 2018

Cosmology with Type Ia Supernovae (SNIa)

Why is it complicated ?





Physics of explosion ? Orientation effects ?

Local environment of explosion ?

Dust in our Galaxy ?

Smearing by our atmosphere ?

Optical distortions or light contaminations ?

Can CCDs count precisely the number of photons ?

Calibration: convert CCD counts into physical fluxes ?

Can we compare fluxes between several (very) different telescopes/observations ?

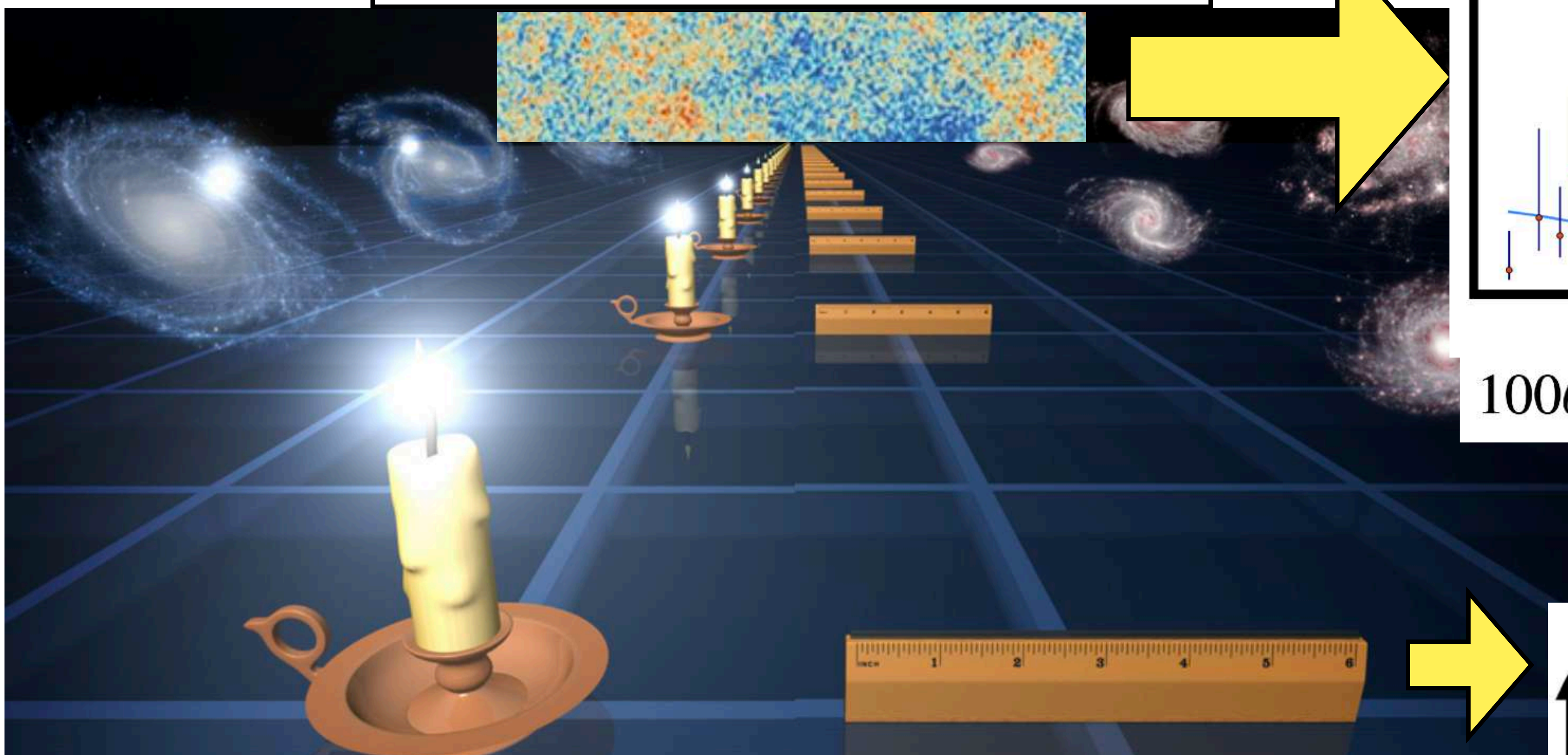
Selection effects ?

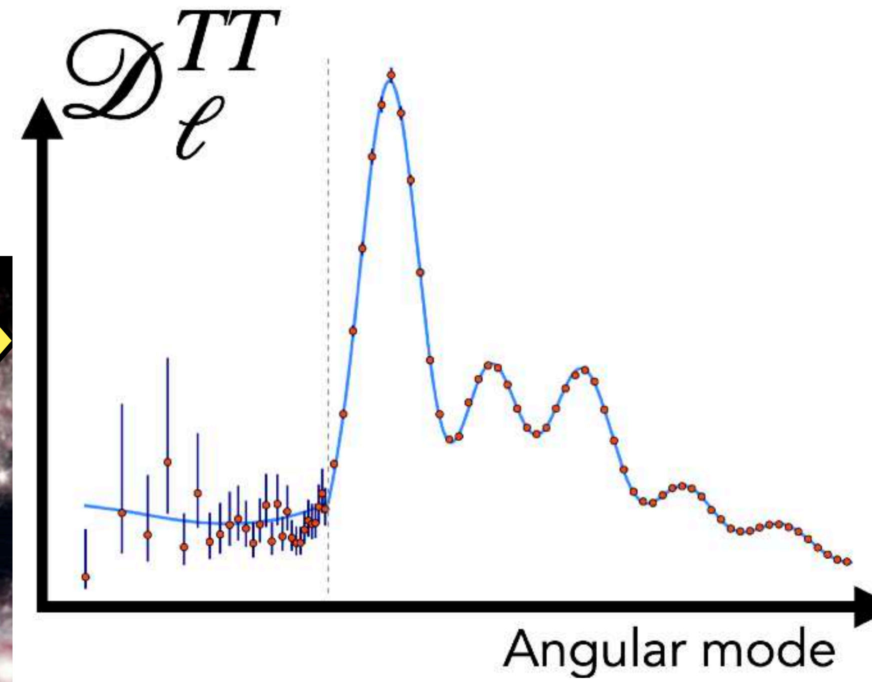
Systematic uncertainties are comparable to **statistical** uncertainties **!**

Baryon Acoustic Oscillations (BAO)

Baryon Acoustic Oscillations (BAO)

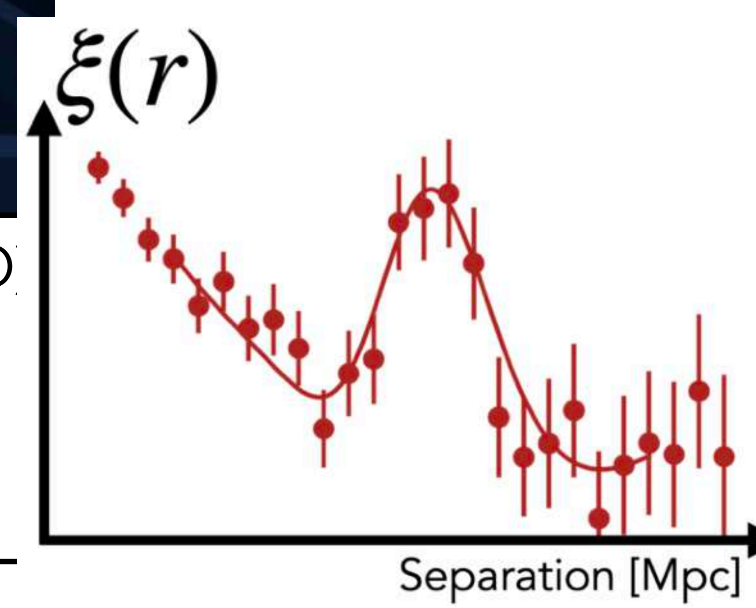
Cosmic microwave background (CMB)
z ~ 1100 or t ~ 380 000 years





$$100\theta_* = 1.04109 \pm 0.00030$$

$$\theta_* \equiv r_*/D_\mathrm{M}$$

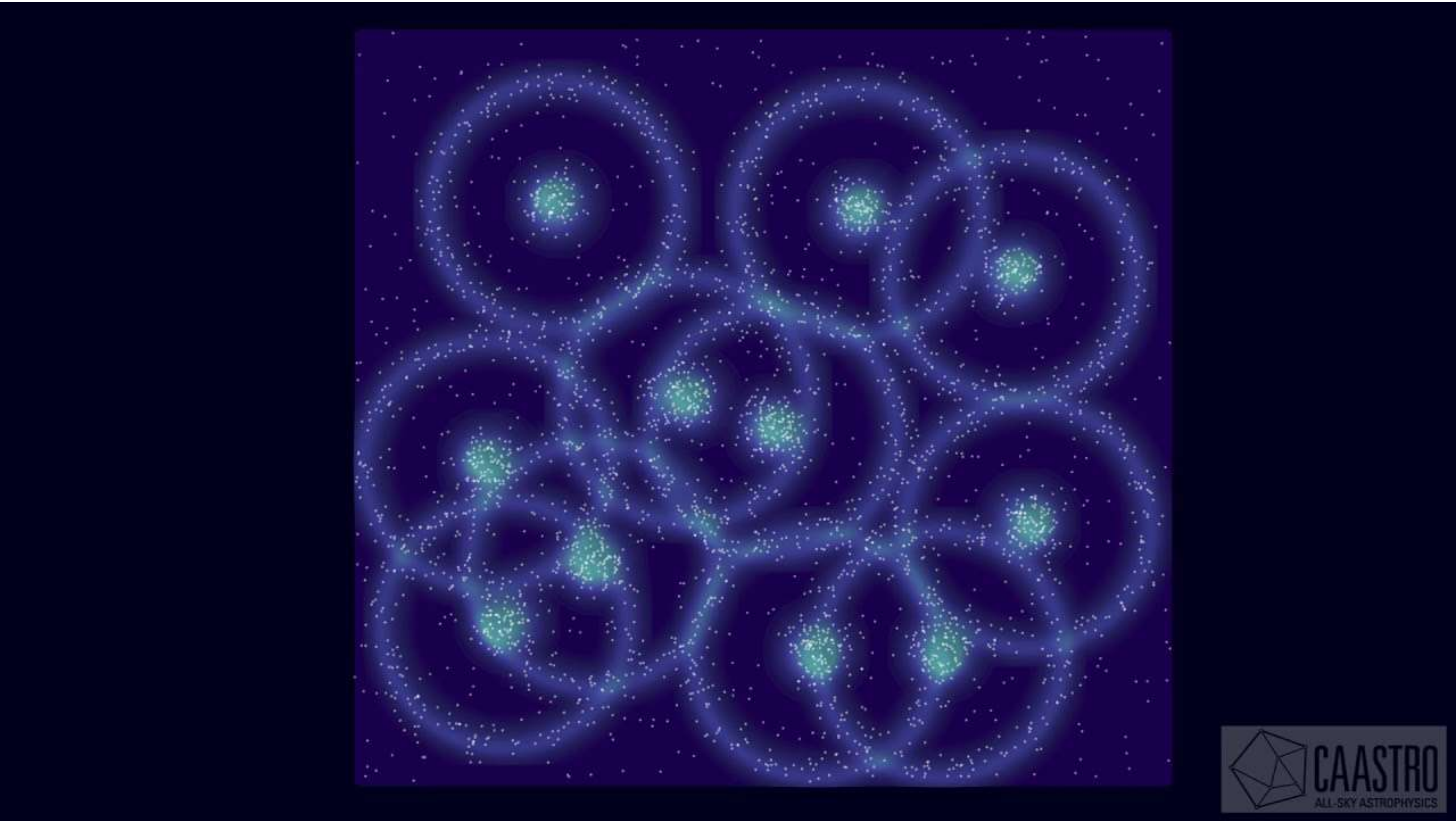


Type-Ia Supernovae (SNIa) as standard candles	Baryon Acoustic Oscillations (BAO) as standard ruler
0 < z < 1.5	0.1 < z < 2.5
5 Gy < t < 13.8 Gy	3 Gy < t < 13 Gy

$$F = \frac{L_\mathrm{candle}}{4\pi D_L^2(z)} \qquad \Delta\theta = \frac{r_\mathrm{ruler}}{D_M(z)} \qquad \Delta z = \frac{r_\mathrm{ruler}}{D_H(z)}$$

$r_\mathrm{ruler} \sim 101 h^{-1}\mathrm{Mpc}$
(comoving)

Baryon Acoustic Oscillations (BAO)



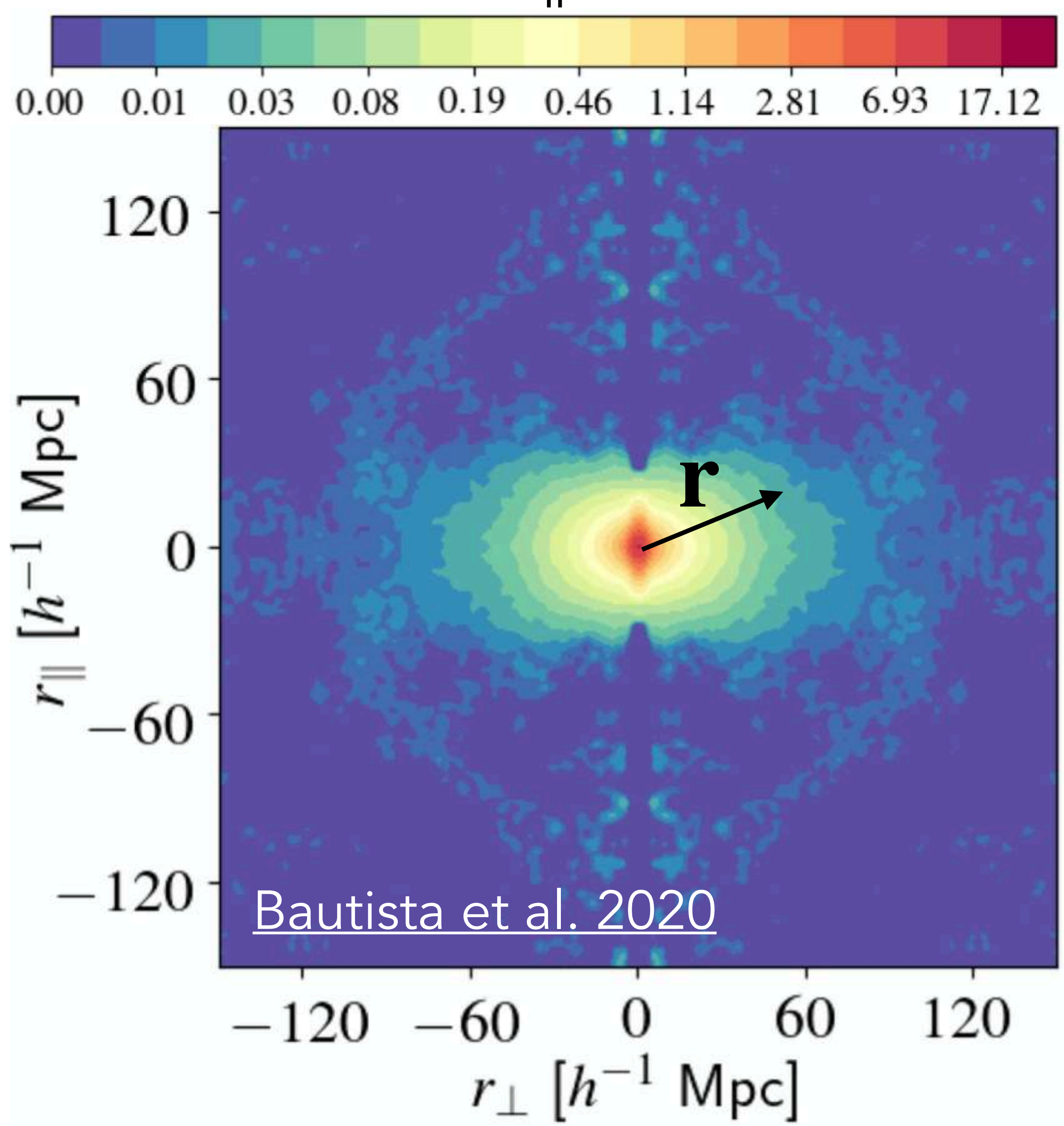
Link to video

Baryon Acoustic Oscillations (BAO)

in the transverse and radial directions

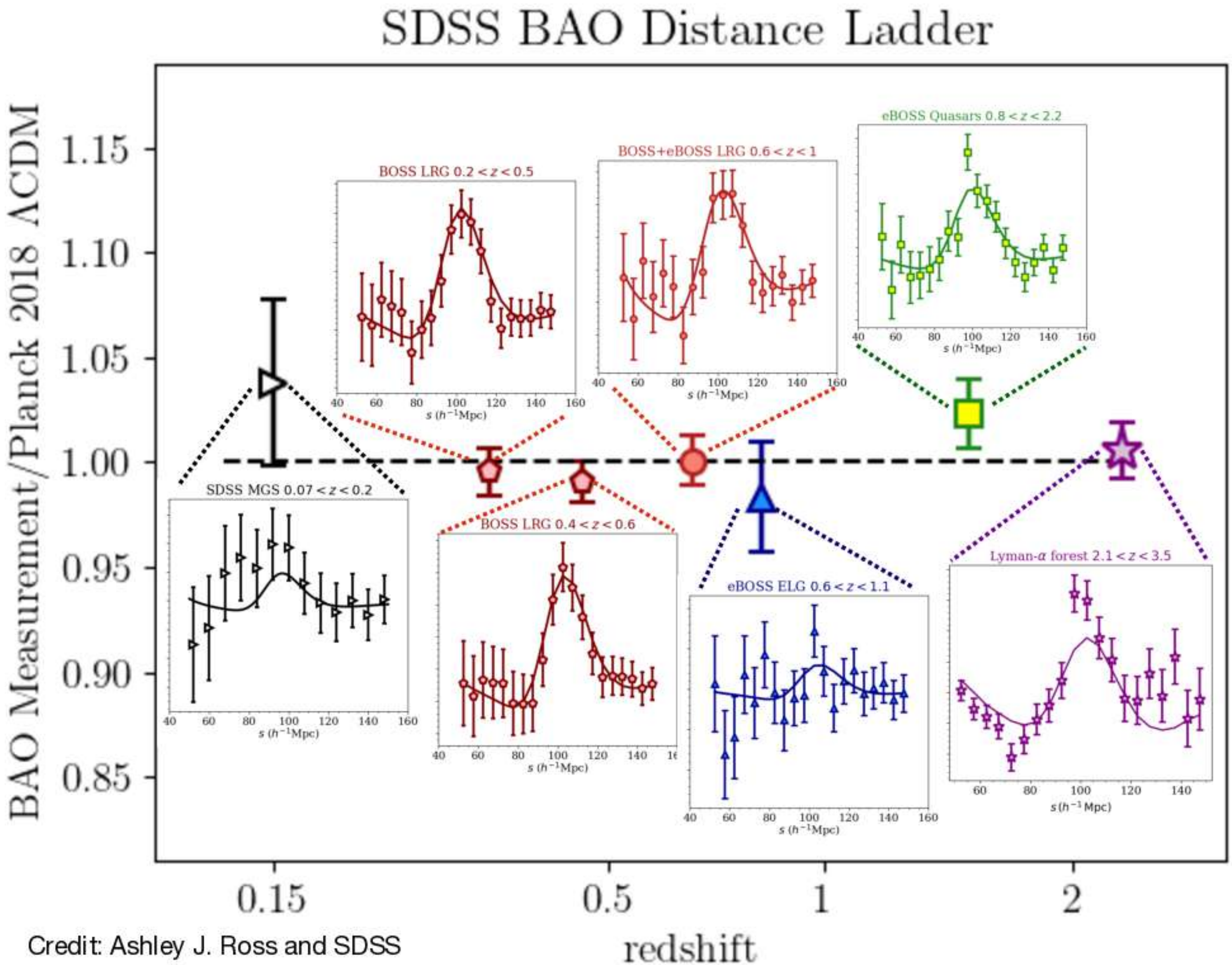
$$\Delta\theta = \frac{r_{\text{ruler}}}{D_M(z)} \qquad \Delta z = \frac{r_{\text{ruler}}}{D_H(z)}$$

$\xi(r_{\parallel}, r_{\perp})$



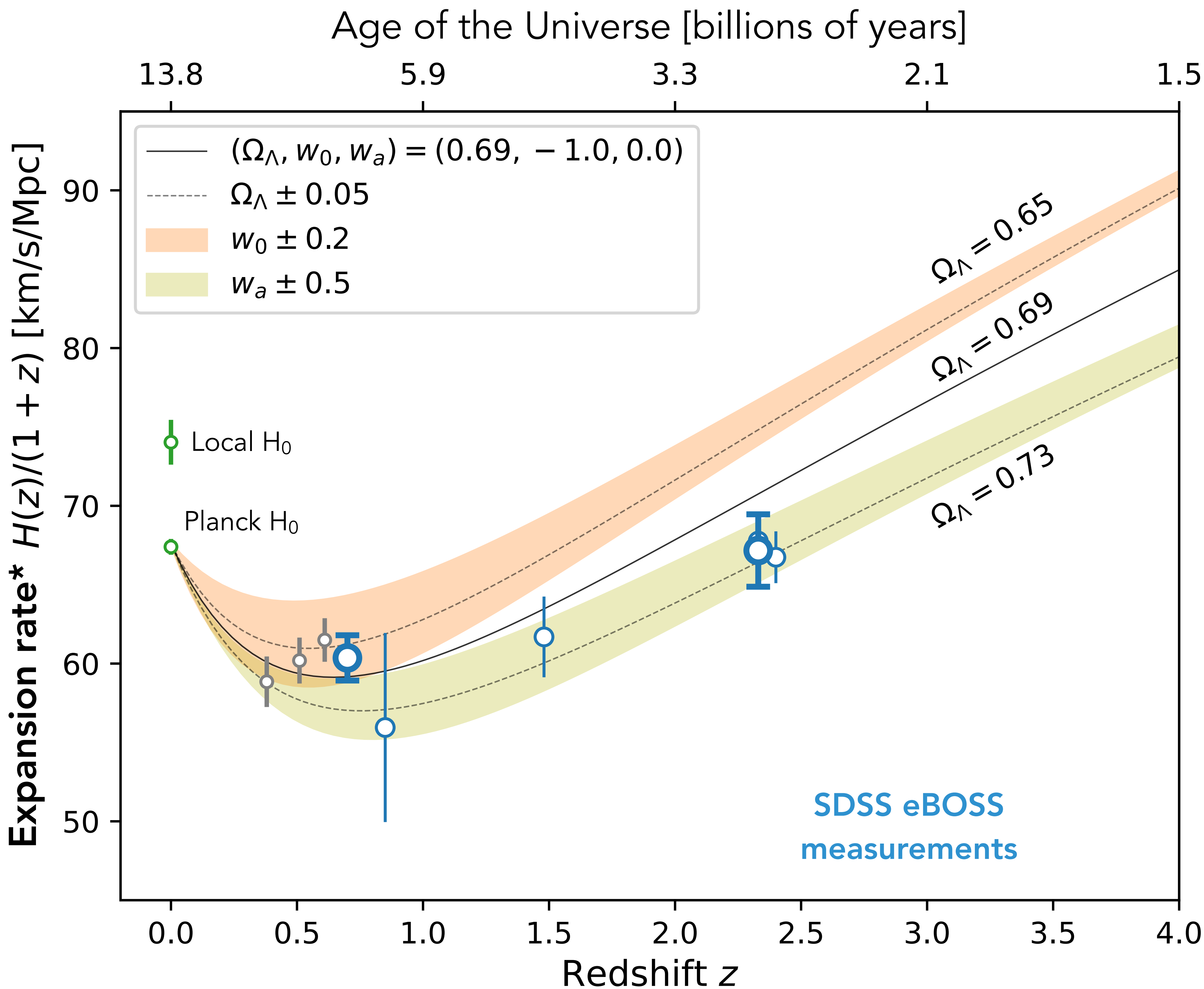
line-of-sight direction

Baryon Acoustic Oscillations (BAO)



Credit: Ashley J. Ross and SDSS

Baryon Acoustic Oscillations (BAO)



*assuming a value for r_d

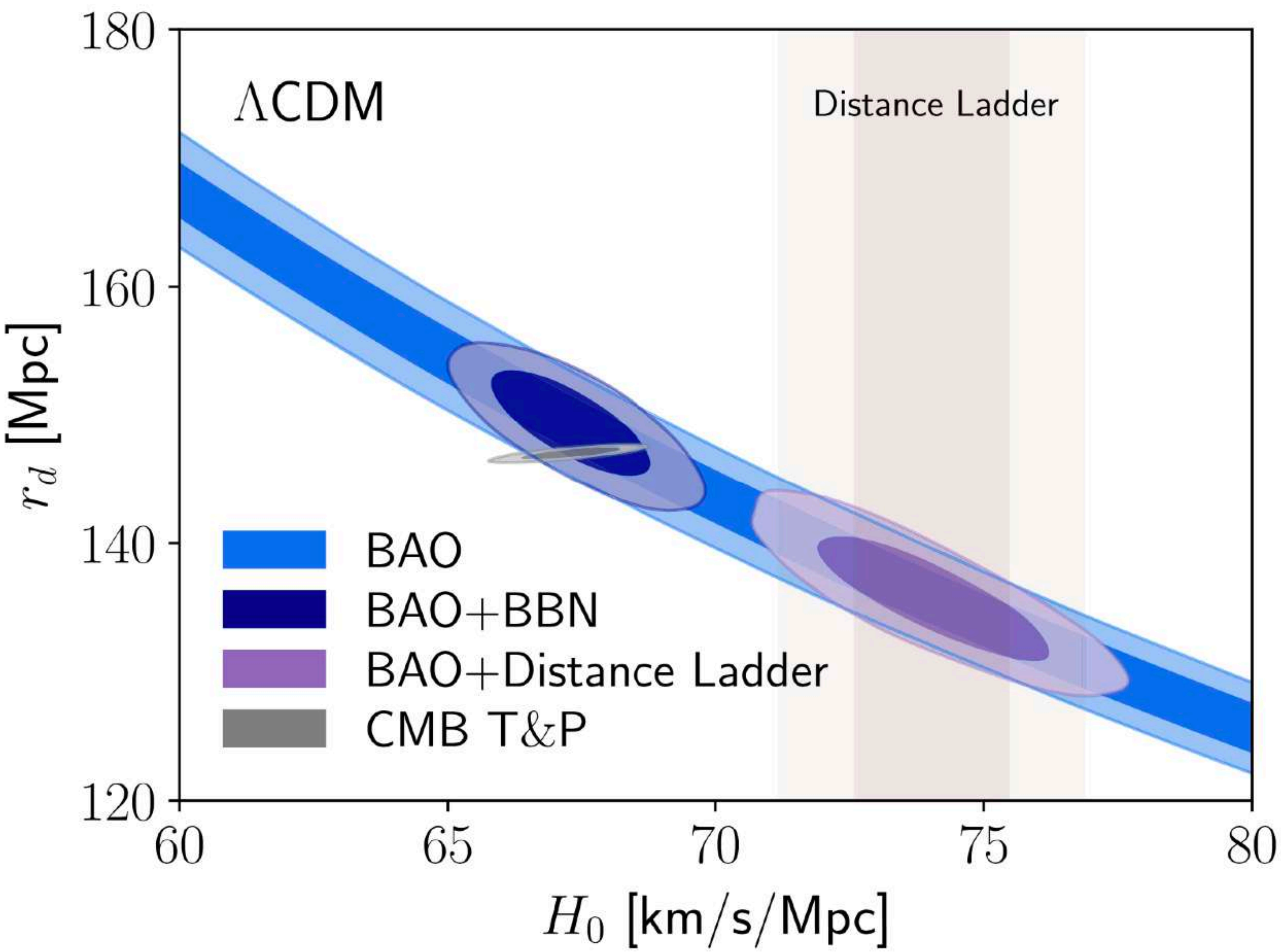
Baryon Acoustic Oscillations (BAO)

What does it measure ?

$$\Delta\theta(z) = \frac{r_{\rm ruler}}{D_M(z)} \qquad \Delta z(z) = \frac{r_{\rm ruler}}{D_H(z)}$$

degenerate

$$\Delta\theta(z) = \frac{r_{\rm ruler} H_0}{c\int_0^z {\rm d}z' \, [\Omega_m(1+z')^3 + \Omega_{\rm DE}(z')]^{-1/2}} \qquad \Delta z(z) = \frac{r_{\rm ruler} H_0}{c[\Omega_m(1+z')^3 + \Omega_{\rm DE}(z')]^{-1/2}}$$



BBN measures $\Omega_b h^2$, constraining $r_{\rm ruler}$

Distance Ladder measures H_0

CMB measures both
(in a flat ΛCDM model!)

Still, we can constrain dark-energy without knowledge of $r_{\rm ruler}$

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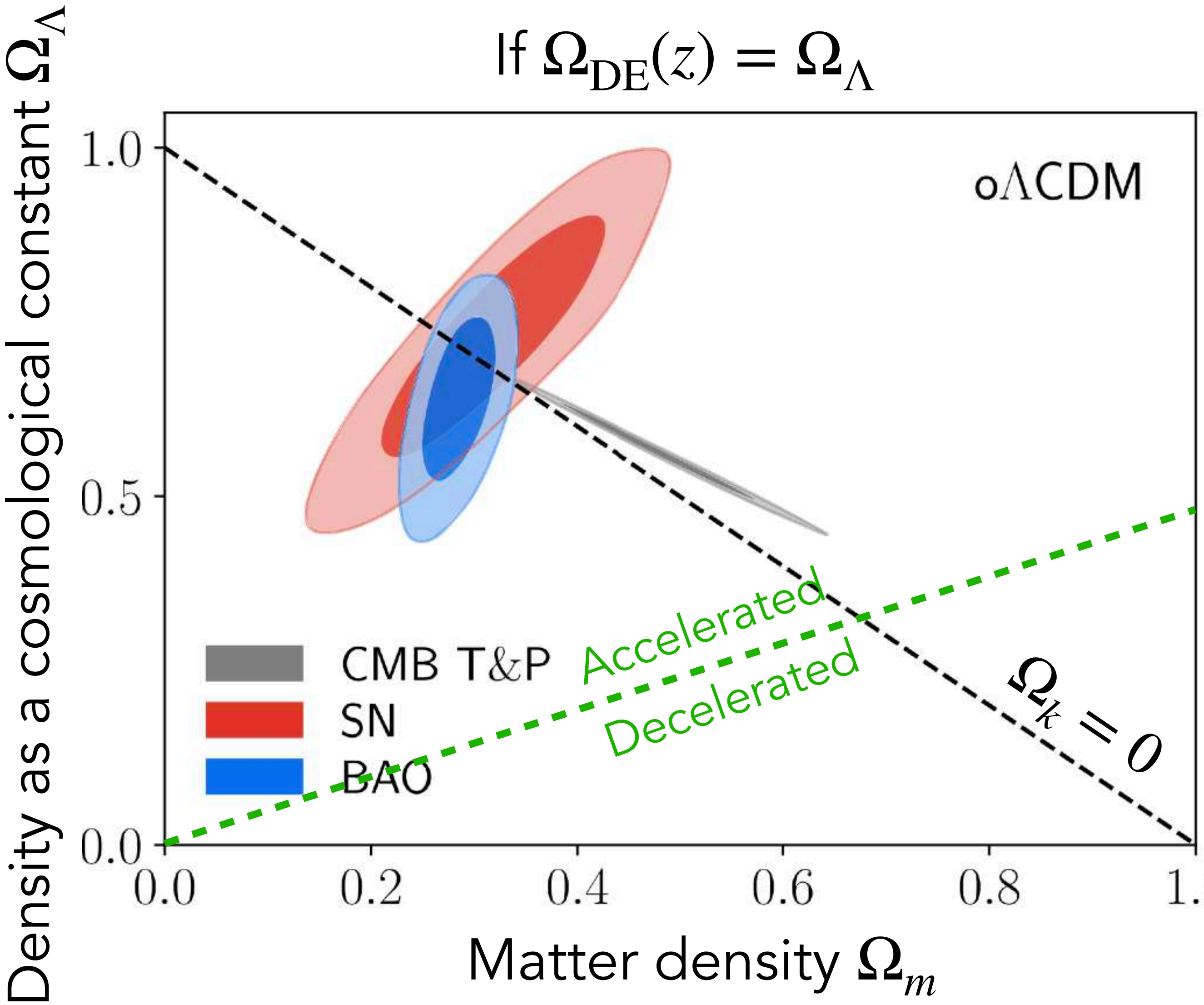
Baryon Acoustic Oscillations (BAO)

What does it measure ?

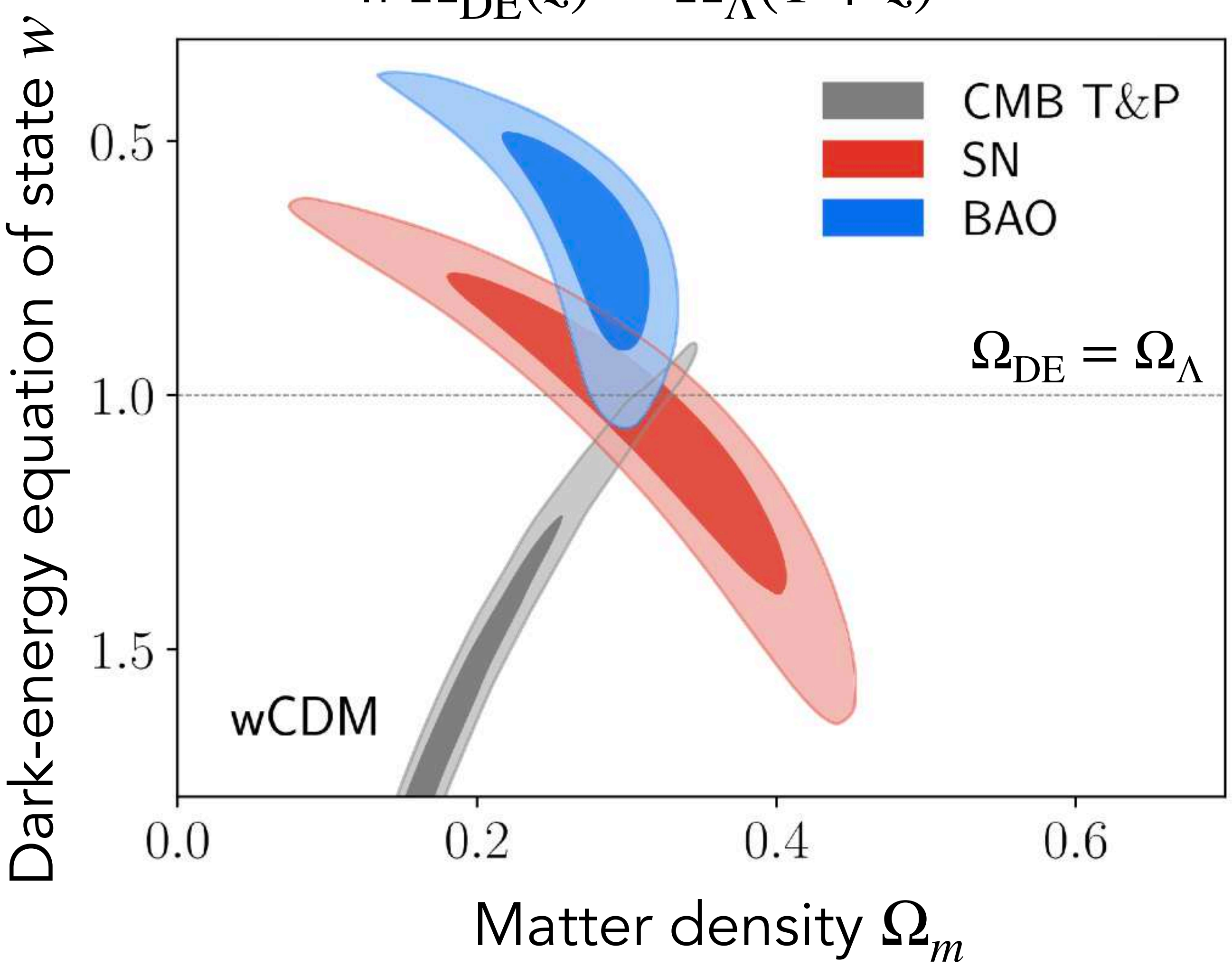
$$\Delta\theta(z) = \frac{r_{\mathrm{ruler}} H_0}{c \int_0^z \mathrm{d}z' \, [\Omega_m (1+z')^3 + \Omega_{\mathrm{DE}}(z')]^{-1/2}}$$

$$\Delta z(z) = \frac{r_{\mathrm{ruler}} H_0}{c [\Omega_m (1+z')^3 + \Omega_{\mathrm{DE}}(z')]^{-1/2}}$$

If $\Omega_{\mathrm{DE}}(z) = \Omega_\Lambda$



If $\Omega_{\mathrm{DE}}(z) = \Omega_\Lambda (1+z)^{3(1+w)}$



BAO as powerful as SNIa, and independently showing acceleration !

Baryon Acoustic Oscillations (BAO)

Why is it hard ?

Correlation function: $\langle \delta(\mathbf{x})\delta(\mathbf{y}) \rangle$

Fourier Transform

Power-spectrum: $\langle \tilde{\delta}(\mathbf{k})\tilde{\delta}(\mathbf{k}') \rangle$

Galaxy overdensity: $\delta_g(\vec{x}) = \dfrac{n_g(\vec{x})}{\bar{n}_g} - 1$

Random catalog

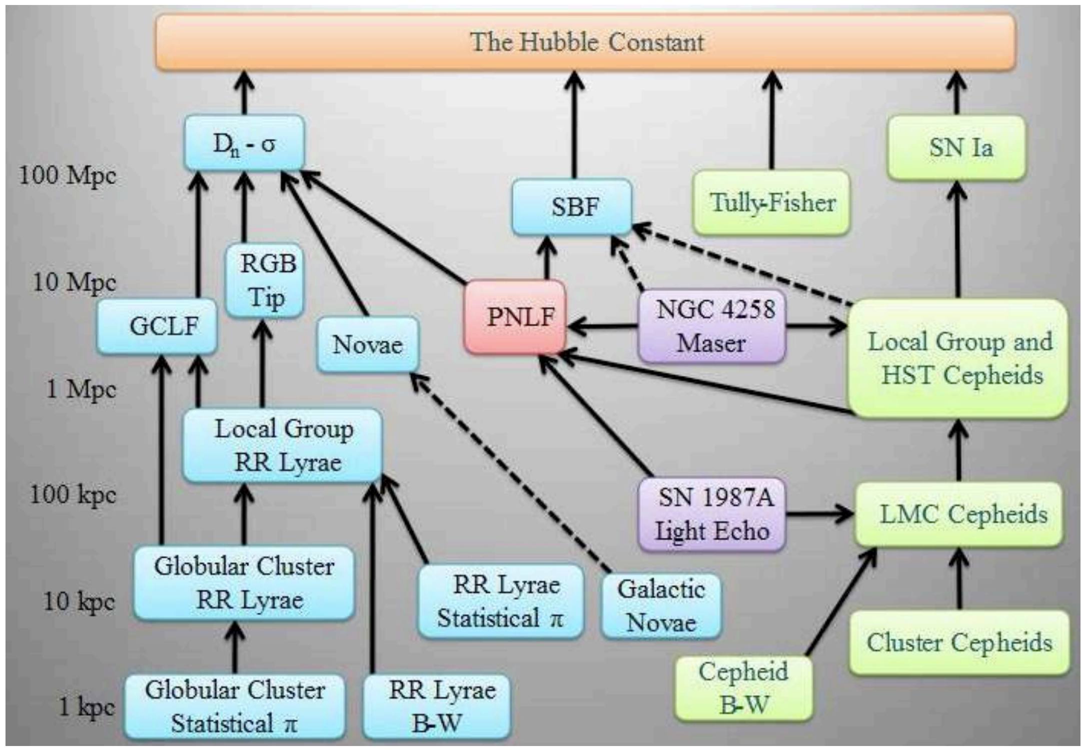
Survey footprint	Observational completeness	Fake overdensities caused by photometry
"Collisions" of fibers	Reconstruction of linear density field for BAO	Spectra without confident redshift measurement

1000 simulated surveys used to test methods, covariance, systematic errors

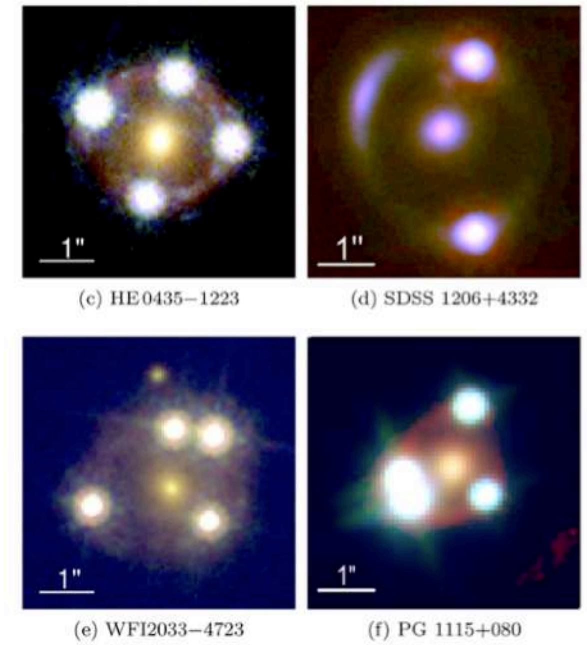
Systematic errors are **well below** current **statistical** errors

The Hubble Constant H_0

Distance ladder

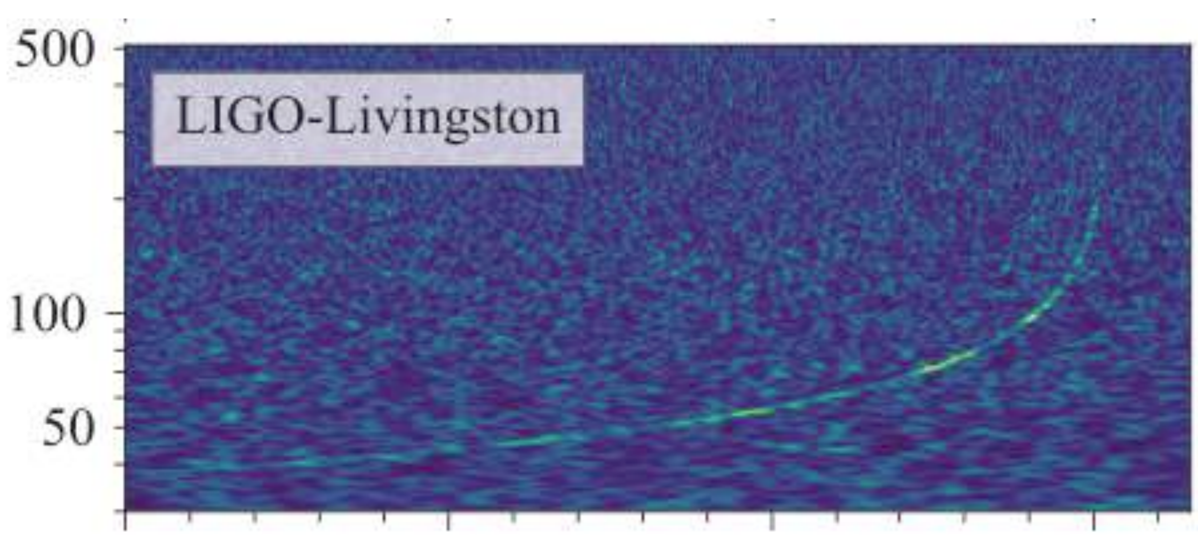


Strong lensing of variable quasars



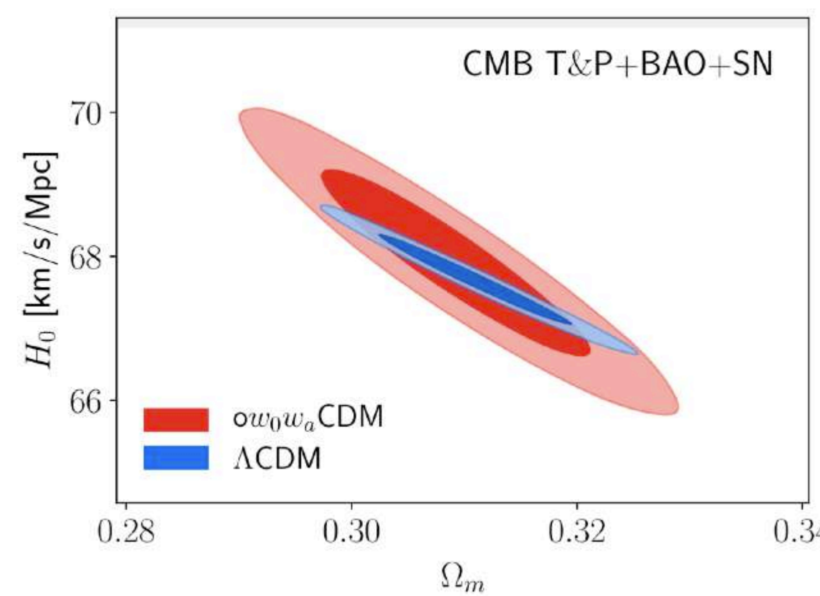
H0LiCOW (Wong et al. 2020)

Standard sirens



LIGO & Virgo 2017

Inverse distance ladder



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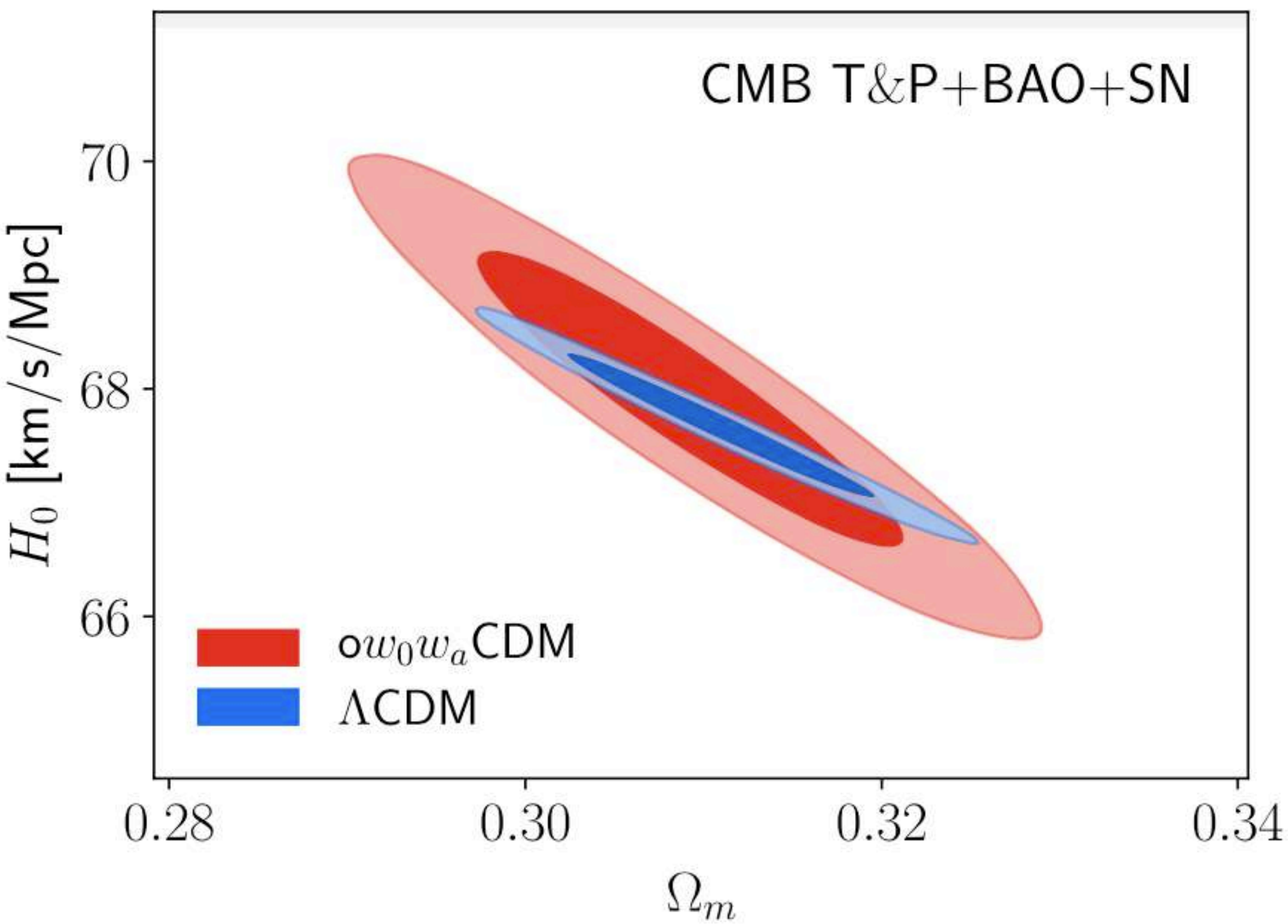
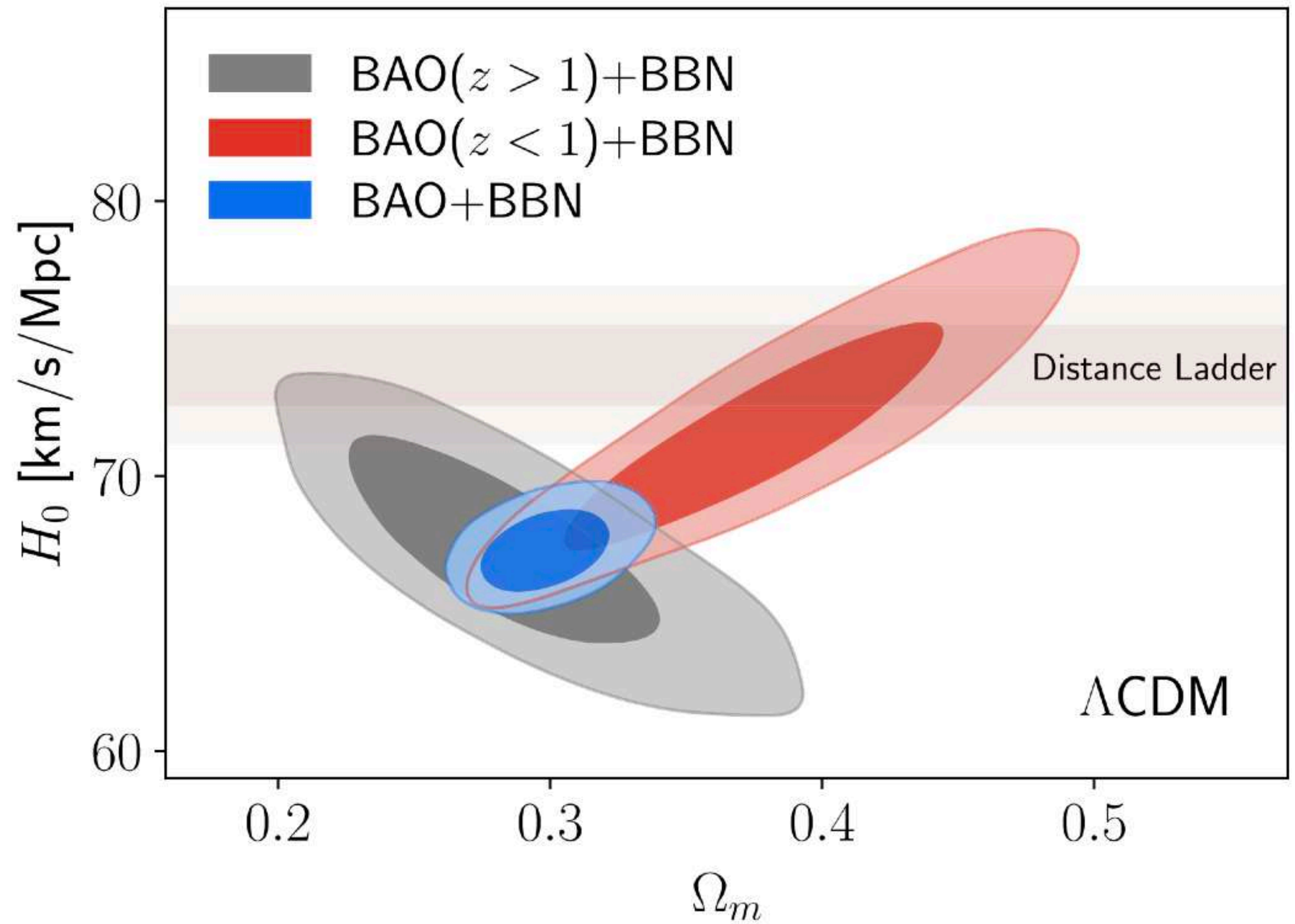
The Hubble Constant H_0

Inverse distance ladder





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The Hubble Constant H_0

Inverse distance ladder

Dataset	Cosmological model	H_0 (km s^{-1} Mpc^{-1})
CMB T & P + BAO + SN	ow_0w_aCDM	67.91 ± 0.87
BBN + BAO	ΛCDM	67.33 ± 0.98
CMB T&P	ΛCDM	67.28 ± 0.61
CMB T&P	oΛCDM	$54.5^{+3.3}_{-3.9}$
Lensing time delays	ΛCDM	73.3 ± 1.8
Distance ladder	...	74.0 ± 1.4
GW sirens	...	70 ± 10
TRGB	...	69.6 ± 1.9
TFR	...	76.2 ± 4.3
Maser galaxies	...	73.9 ± 3.0

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Cosmic Microwave Background (CMB)

Redshift-Space Distortions (RSD)

Weak Gravitational Lensing (WL)