



The BIG questions

Zuoz 2022

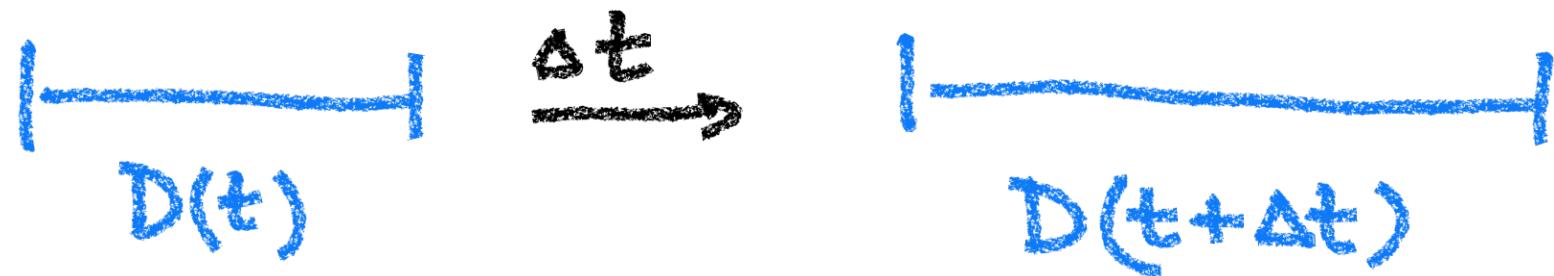
Martin Schmalz  
Boston University

# The Hubble tension ( $H_0$ crisis)

# Outline

- Hubble Law – measuring  $H_0$
- data review – the  $H_0$  crisis ( $5\sigma$ )
- a possible hint: sound horizon
- models with dark radiation

definition: the expansion rate of the universe



Expansion rate :  $H(t) \equiv \frac{\dot{D}}{D}$  uniform in space  
time - dependent

$$H_0 = H(t) \Big|_{t=\text{today}}$$

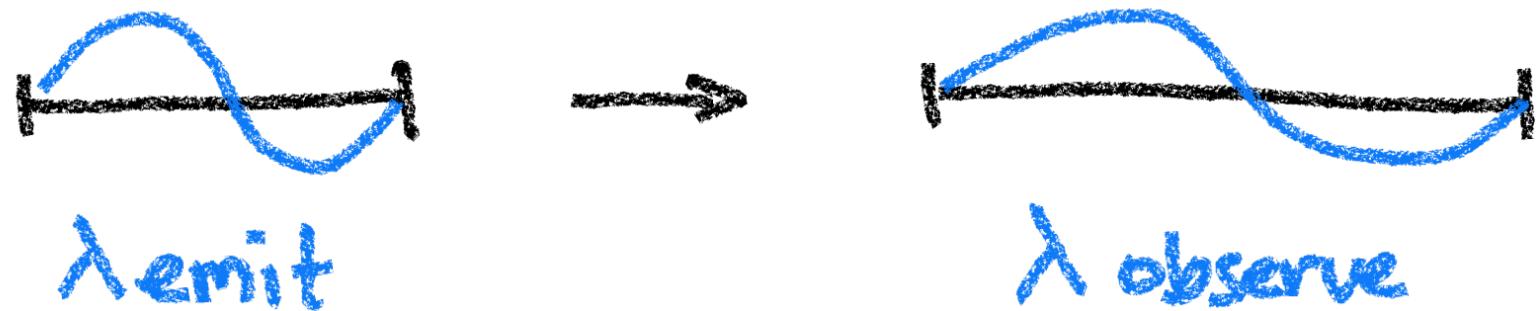
# measuring $H_0$



want to measure  $D$  &  $\delta$

# measuring $H_0$

expansion causes redshift of light



$\lambda_{\text{emit}}$

$\lambda_{\text{observe}}$

$$\frac{\lambda_{\text{obs.}}}{\lambda_{\text{emit}}} \equiv 1+z$$

"cosmological  
redshift"

measuring  $H_0$

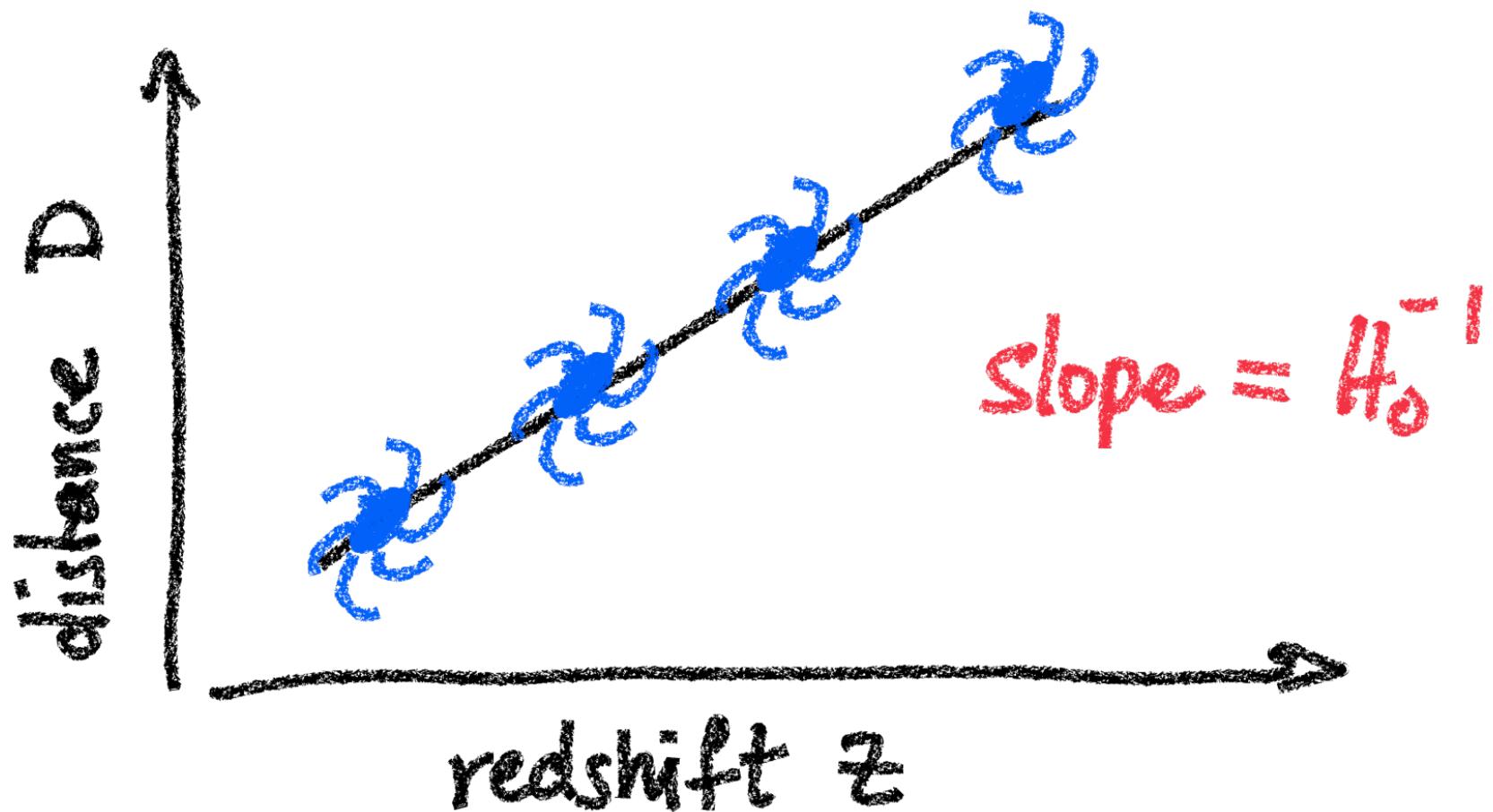


$$\frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} = 1+z = \frac{D(t+\Delta t)}{D(t)} \underset{\substack{\text{Taylor} \\ \text{expand}}}{\approx} 1 + \frac{\dot{D}\Delta t}{D} = 1 + H\Delta t$$

$$z = H_0 D \quad \text{"Hubble law"}$$

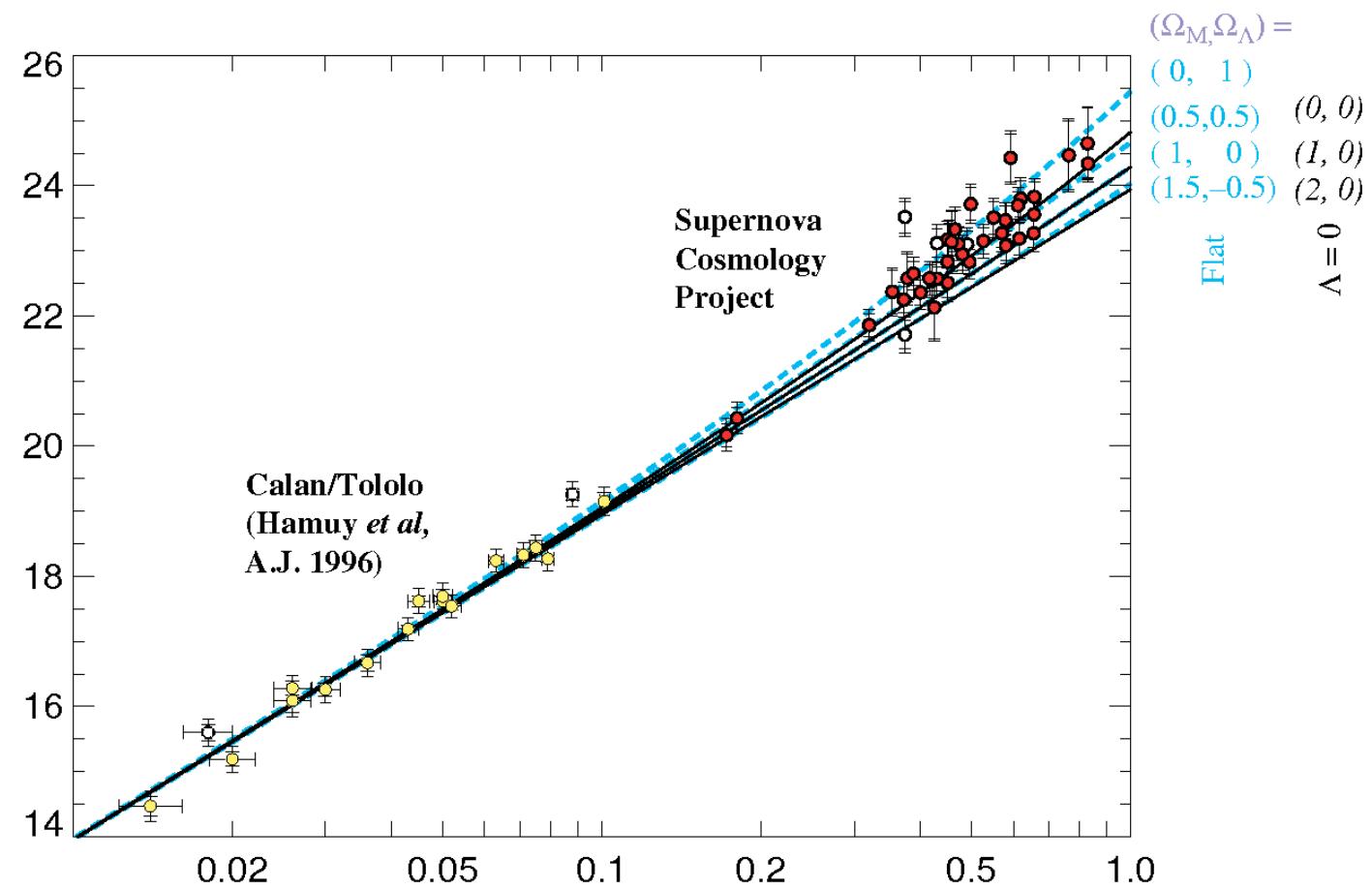
$H_0$  from linear Hubble law

$$H_0 = \frac{v}{D} = \frac{z}{D}$$



# $H_0$ from Hubble law

distance D



measure  $H_0$  with Hubble's law

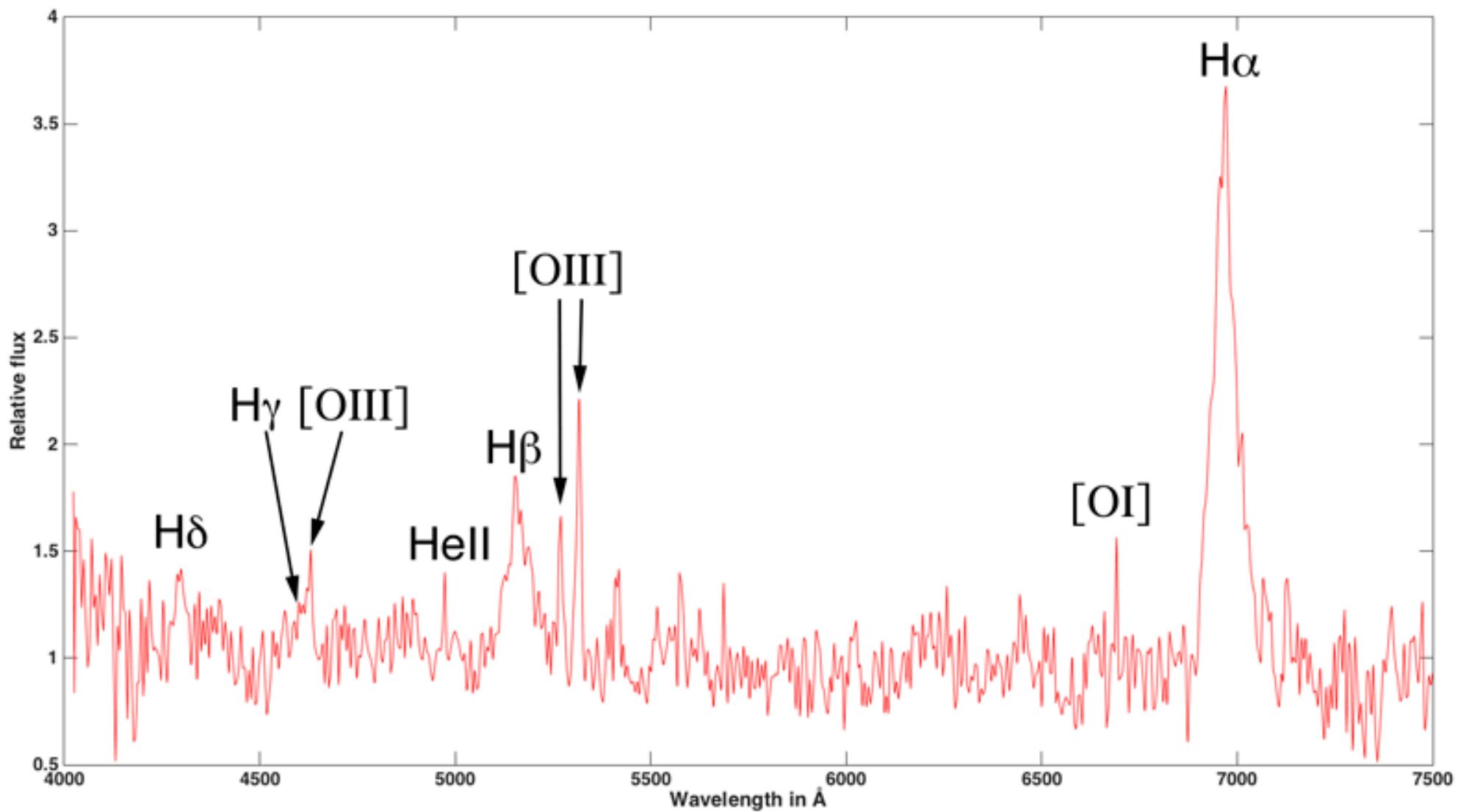
$$H_0 = \frac{z}{D}$$

redshift of light  
observed easy

distance to source  
of light hard

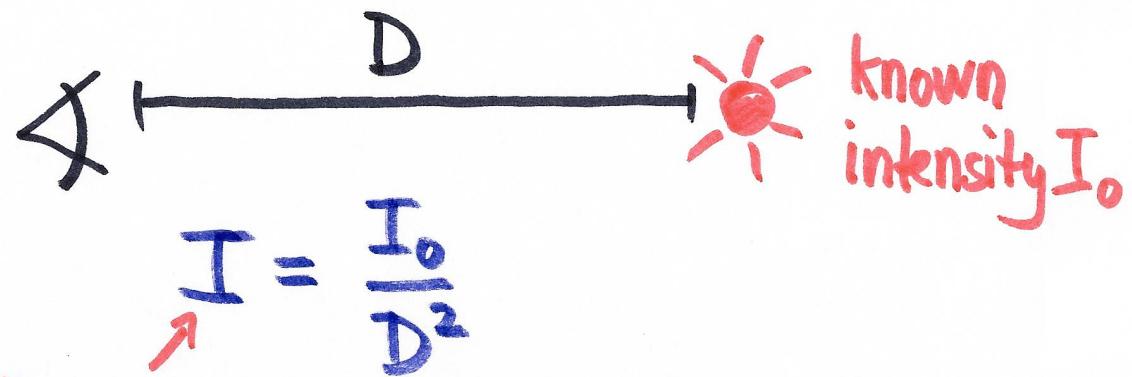
[ Hubble law is a small  $z$  expansion,  $z \ll 1$ .  
General idea works for  $z \gtrsim 1$ : measure  
 $z, D \Rightarrow H$  ]

# Measure $z$ : Spectral lines

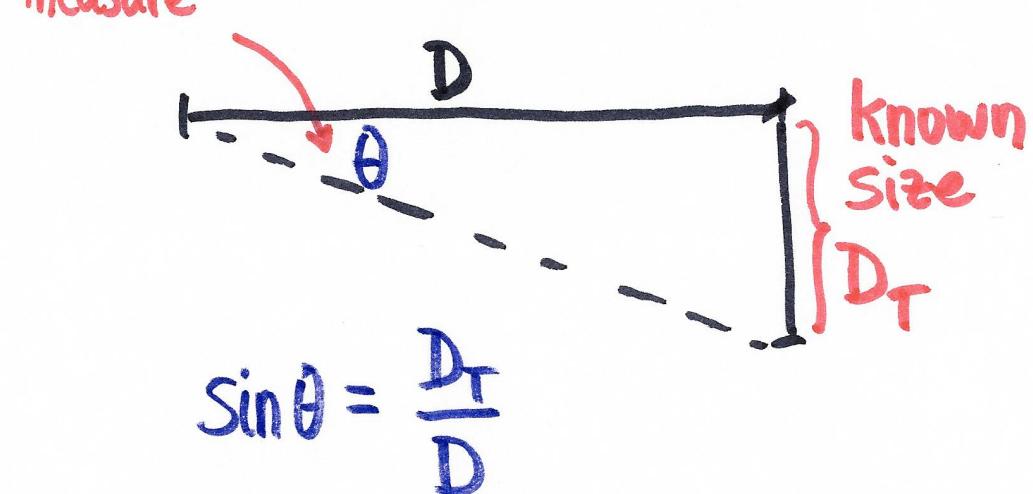


# Measuring D ... two basic techniques

- Luminosity



- triangulation

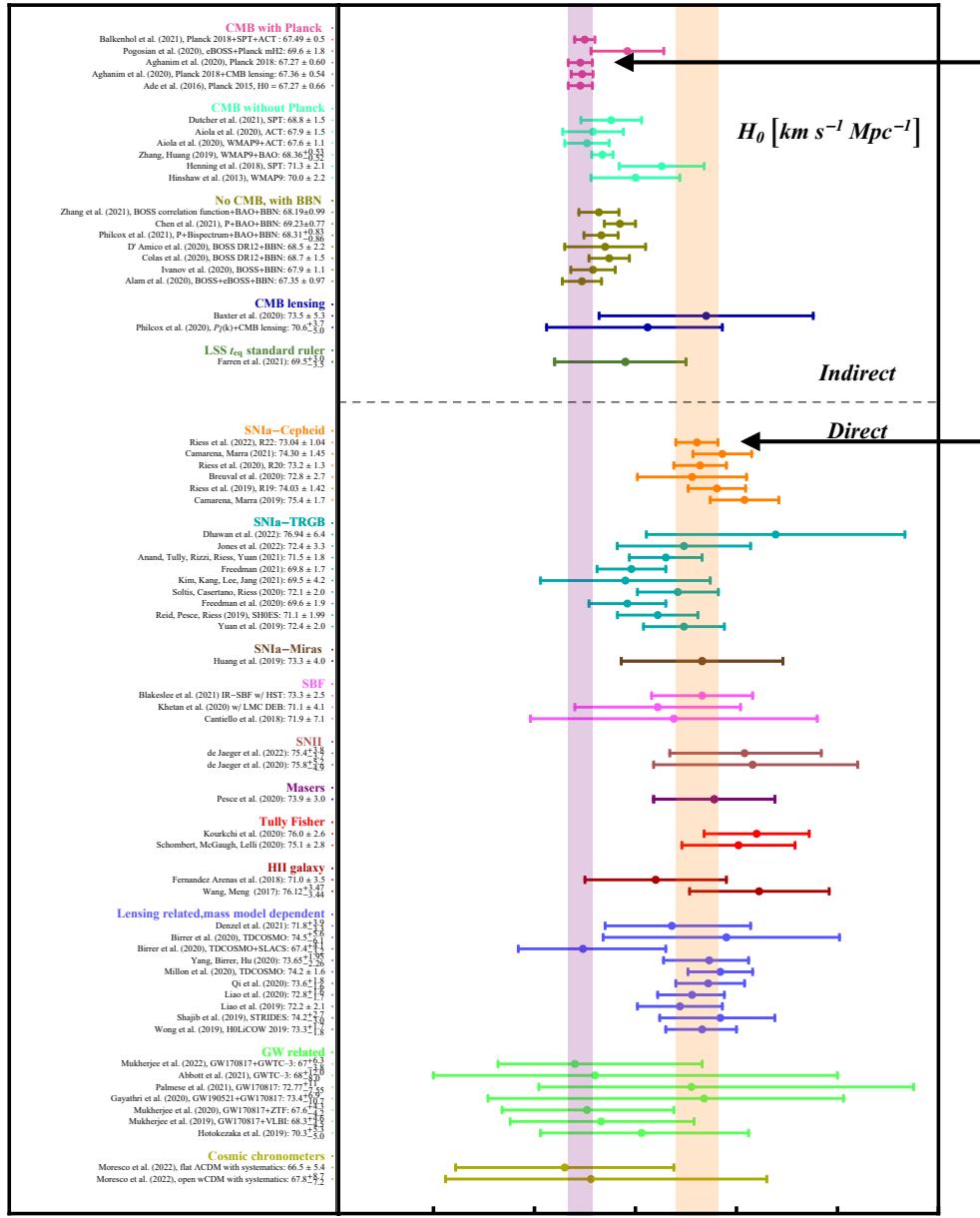


# example “objects”

- supernovae .....  $z \sim 0.01-1.5$
- megamasers .....  $z \sim 0.03$
- strong gravitational lenses ...  $z \sim 0.5$
- neutron star merger (GW) .....  $z \sim 0.01$
- galaxy clustering (BAO) .....  $z \sim 0.3-3$
- CMB .....  $z \sim 1100$

... all consistent with  $H_0 = 70 \pm 5 \frac{km/s}{Mpc}$

# Ho measurements summary 2022



arXiv:2203.06142v1

Planck 2018:  
 $67.27 \pm 0.60$

Riess et.al. 2022:  
 $73.04 \pm 1.04$

$4.8\sigma$

## Examples of "direct" measurements

- SHoES : Supernovae
- H0LiCOW : strong gravity lenses
- MCP : megamasers
- LIGO : neutron star mergers

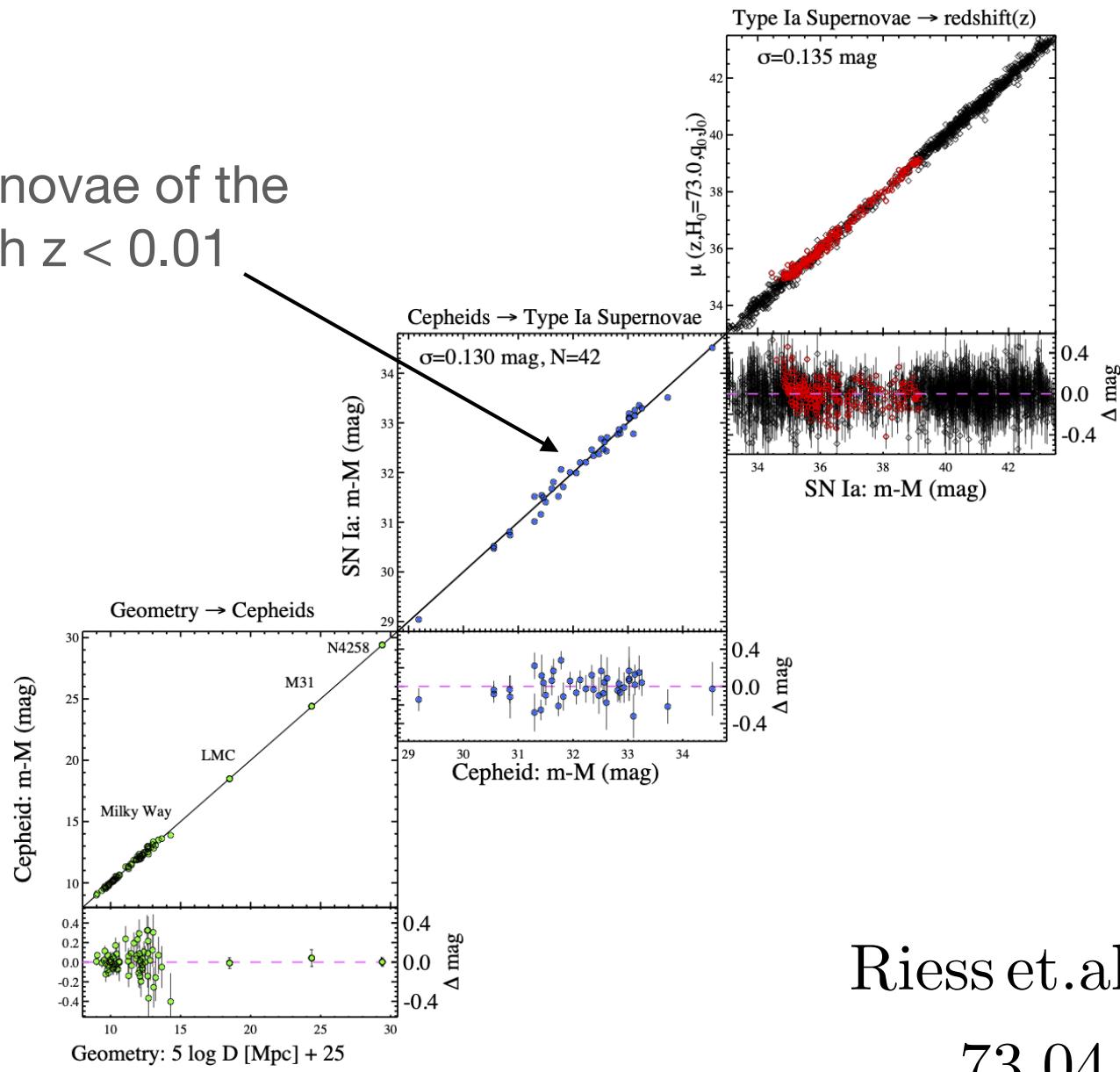
$SH_0ES$ : supernovae 1a as  
"Standard candles"



SN Ia observed luminosity  $I$  determines  
distance:  $I = I_0 / D^2$  needs  
calibration

# Geometry > Cepheids > SN1a luminosity calibration

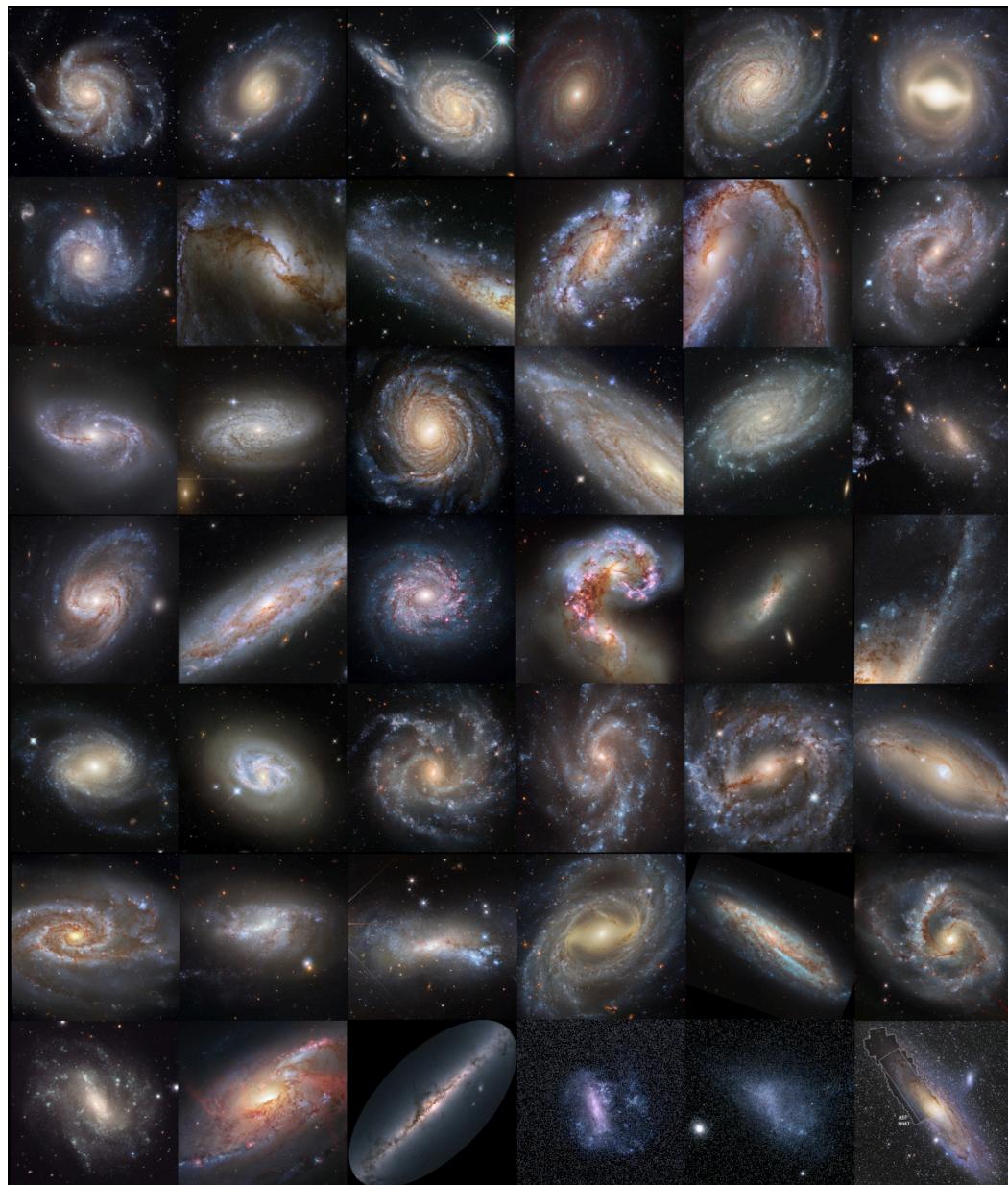
new: all 42 supernovae of the past 40 years with  $z < 0.01$



Riess et.al. 2022:

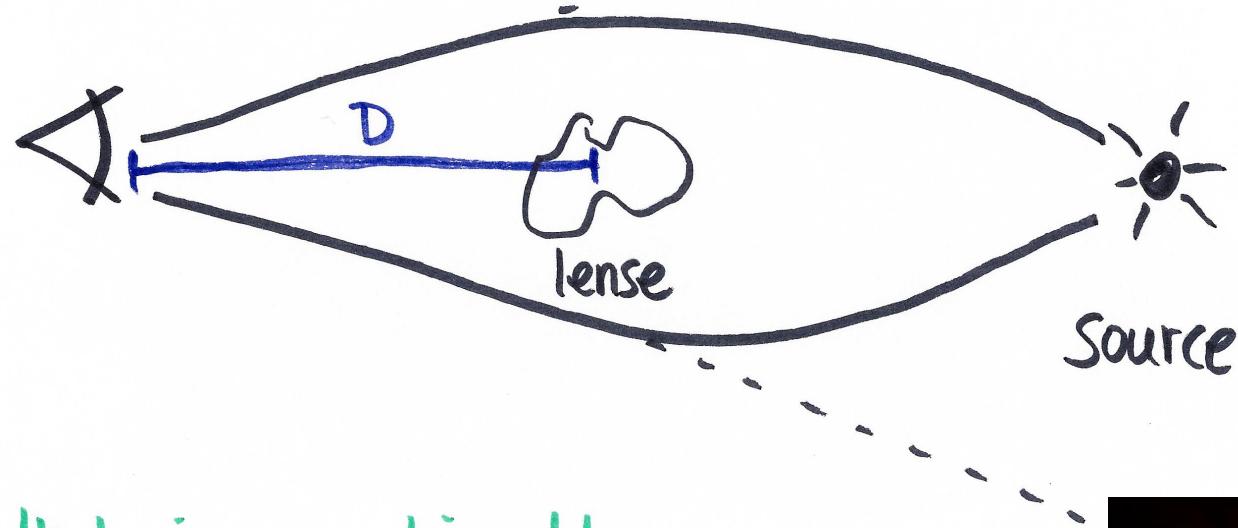
$$73.04 \pm 1.04$$

# all 37 SN1a calibration host galaxies

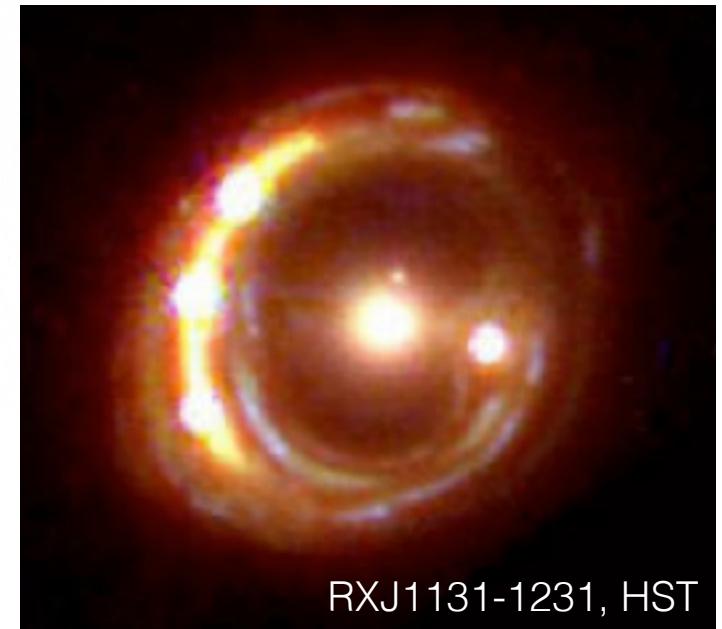


# HOLiCOW

## strong gravitational lensing



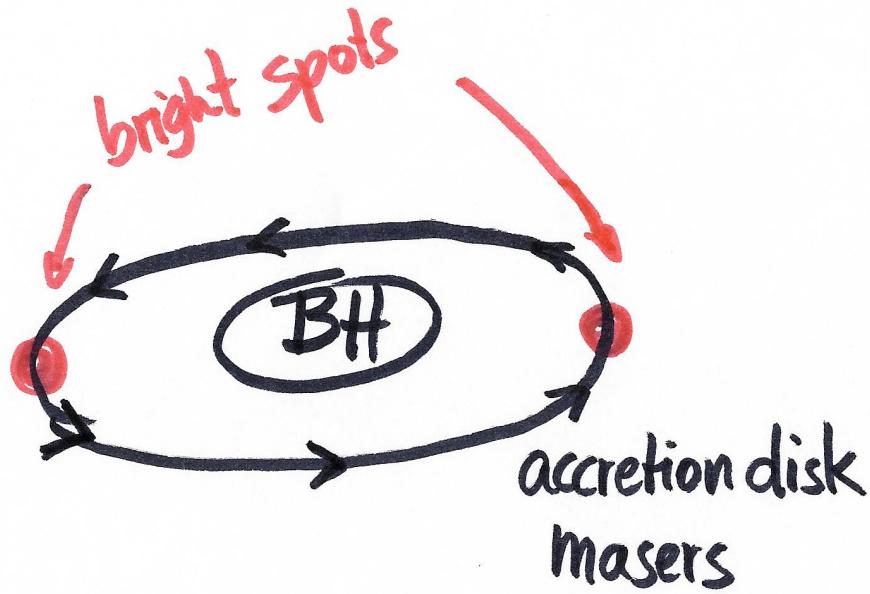
multiple images, time delay  
reconstruct lensing potential  
 $\Rightarrow$  get distances



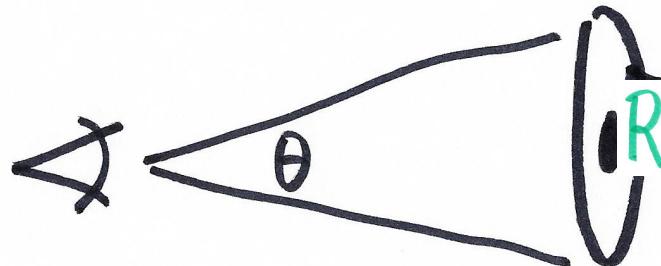
MCP

Megamasers

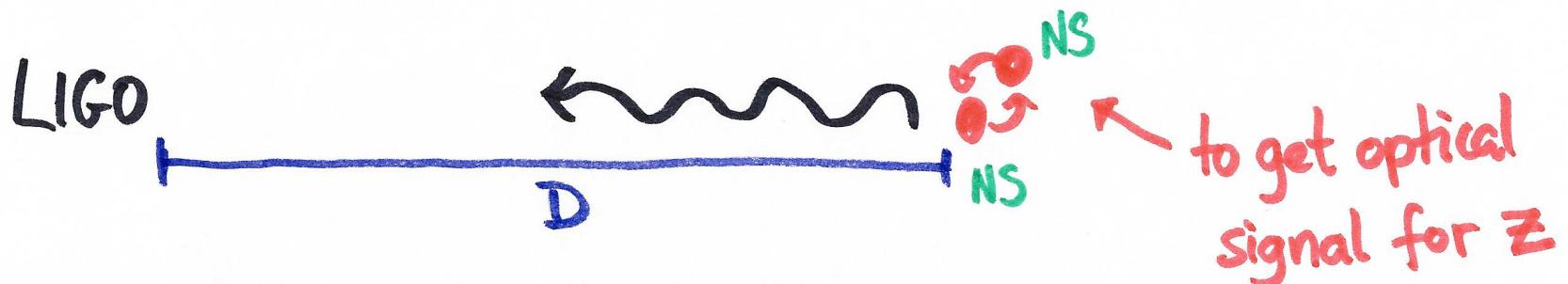
(only 4 good ones known)



reconstruct geometry using  
velocity of accretion disk



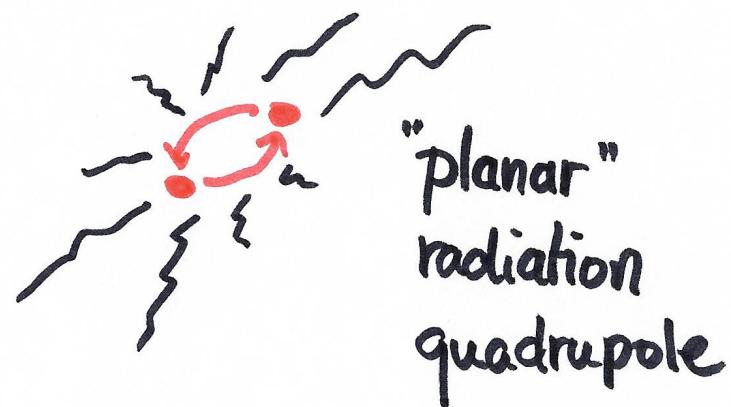
# LIGO gravitational waves



reconstruct masses from wave form

⇒ GR gives intensity of radiation  $I_0$ .

$$\Rightarrow I \approx \frac{I_0}{D}$$

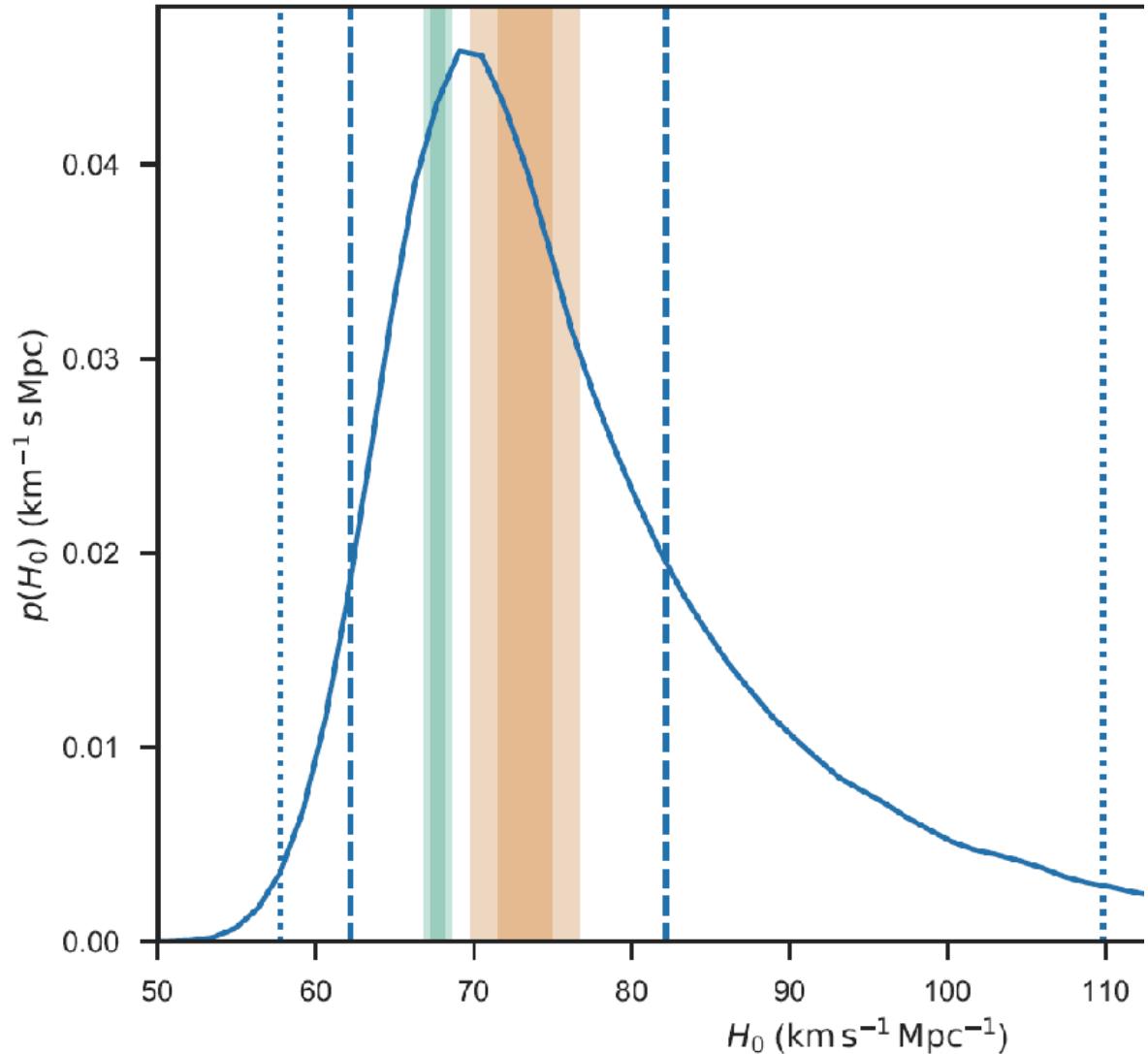


# Gravitational Wave Standard Sirens

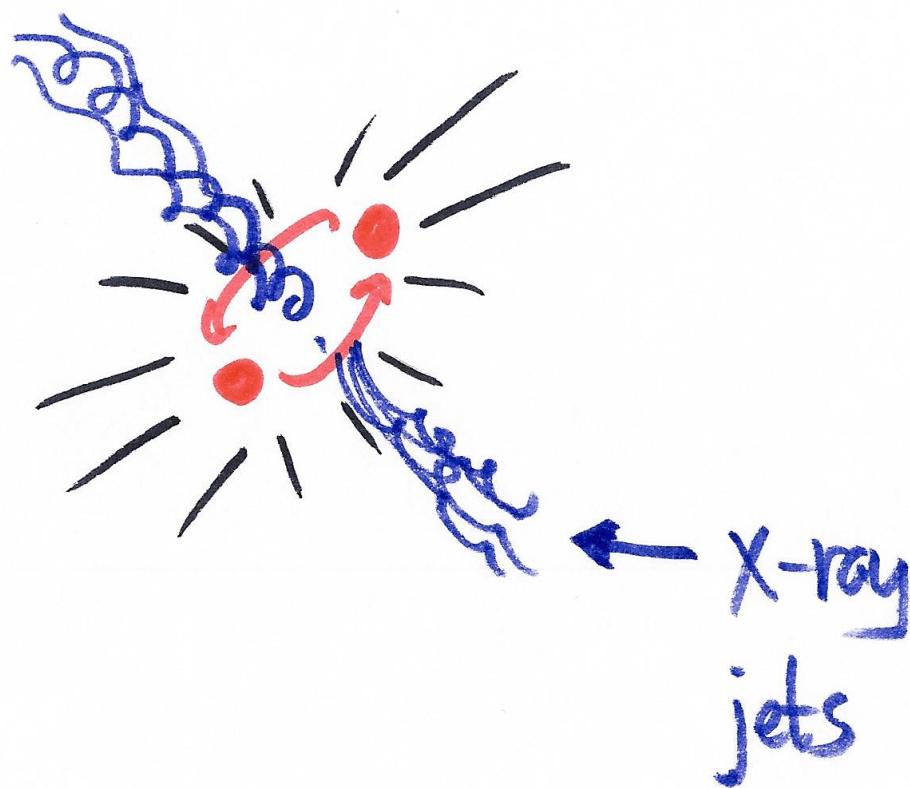
First Standard Siren  
Measurement: GW170817

$$H_0 = 70^{+12}_{-8} \text{ km/s/Mpc}$$

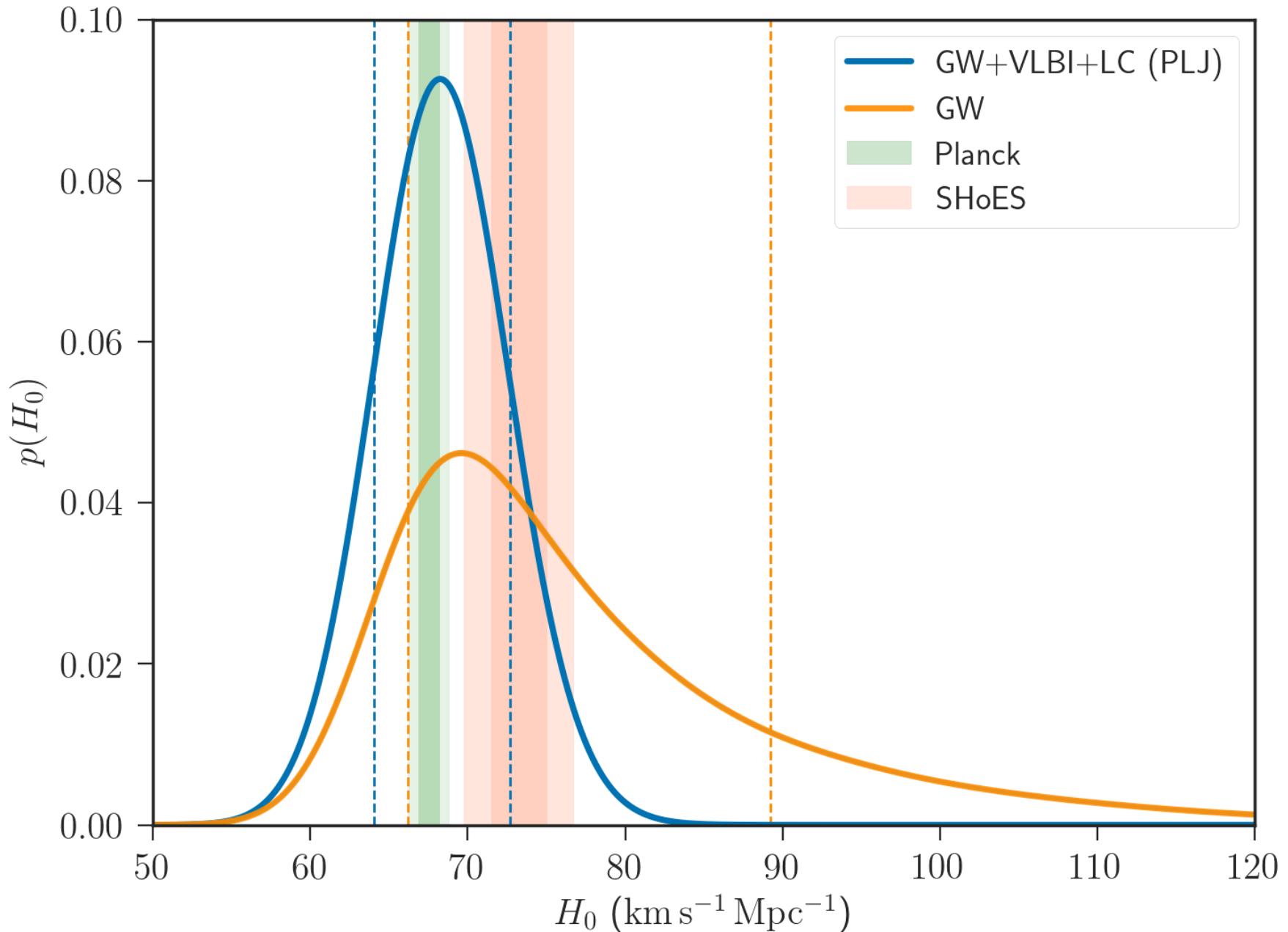
Abbott et al.



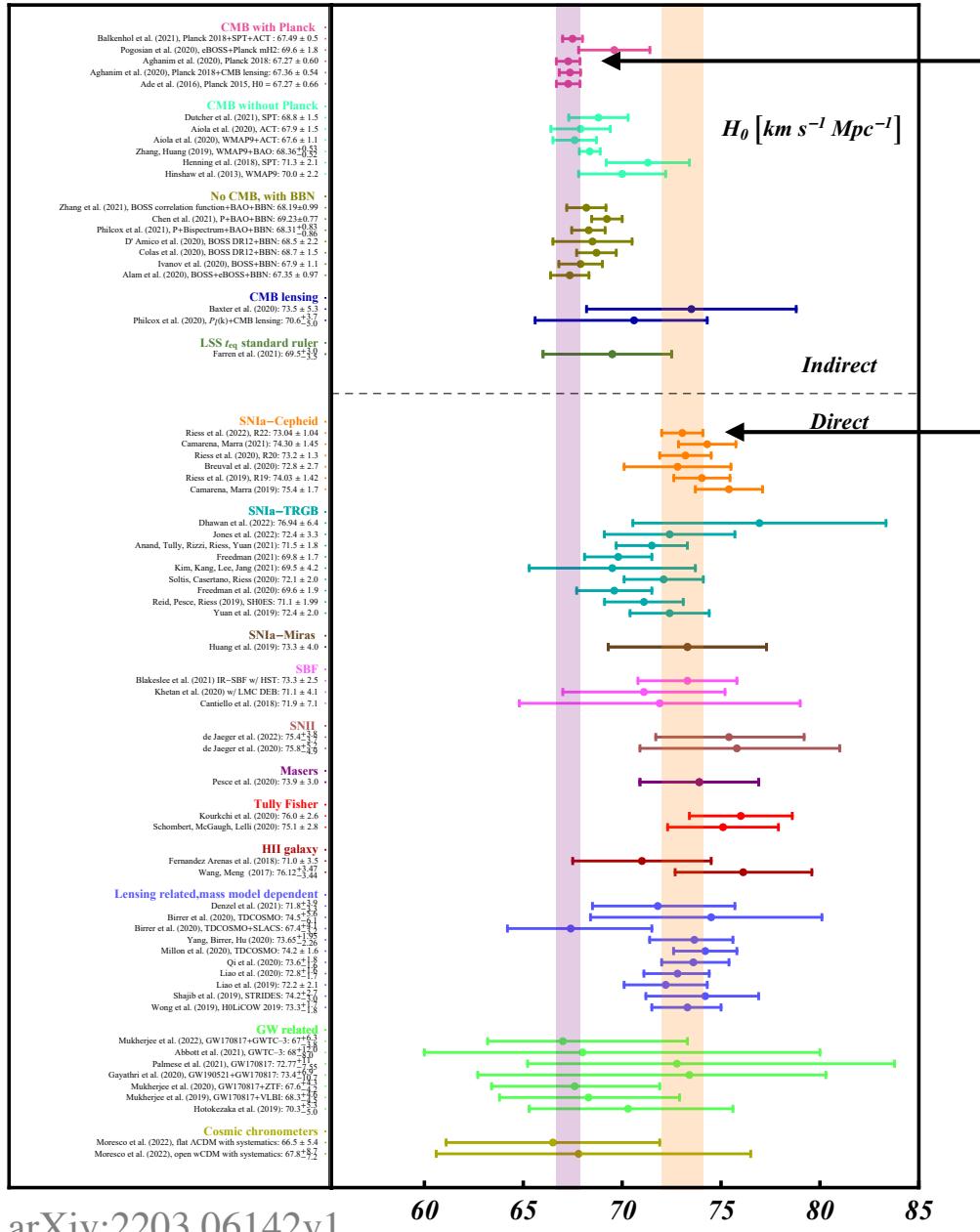
# orientation of radiation plane



# H<sub>0</sub> Posterior from single NS-NS merger event



# Ho measurements summary 2022



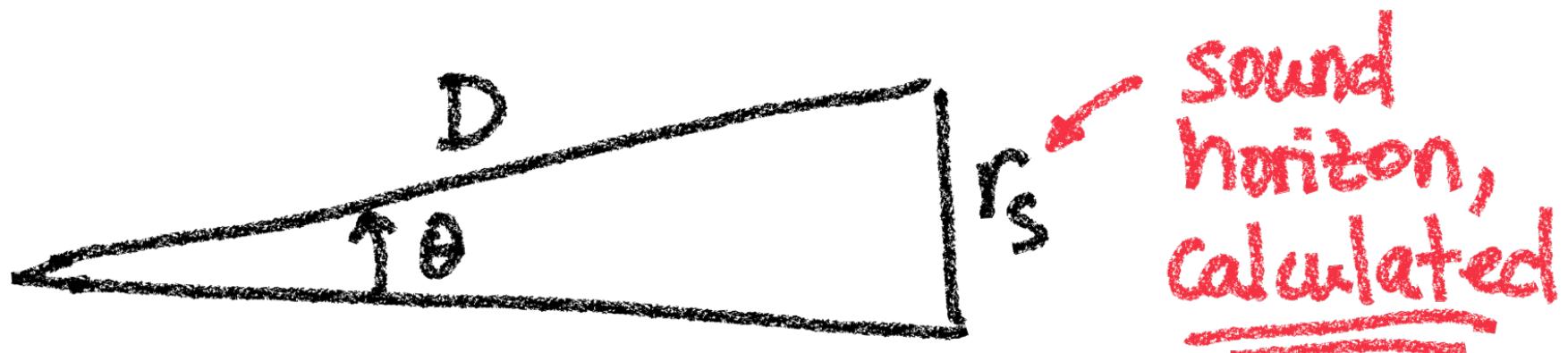
Planck 2018:  
 $67.27 \pm 0.60$

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$4.8\sigma$

## "indirect" measurements

- Baryon Acoustic Oscillations BAO
- Cosmic Microwave Background CMB



$$H_0 = \frac{z}{D} = \frac{z}{r_s} \tan \theta$$

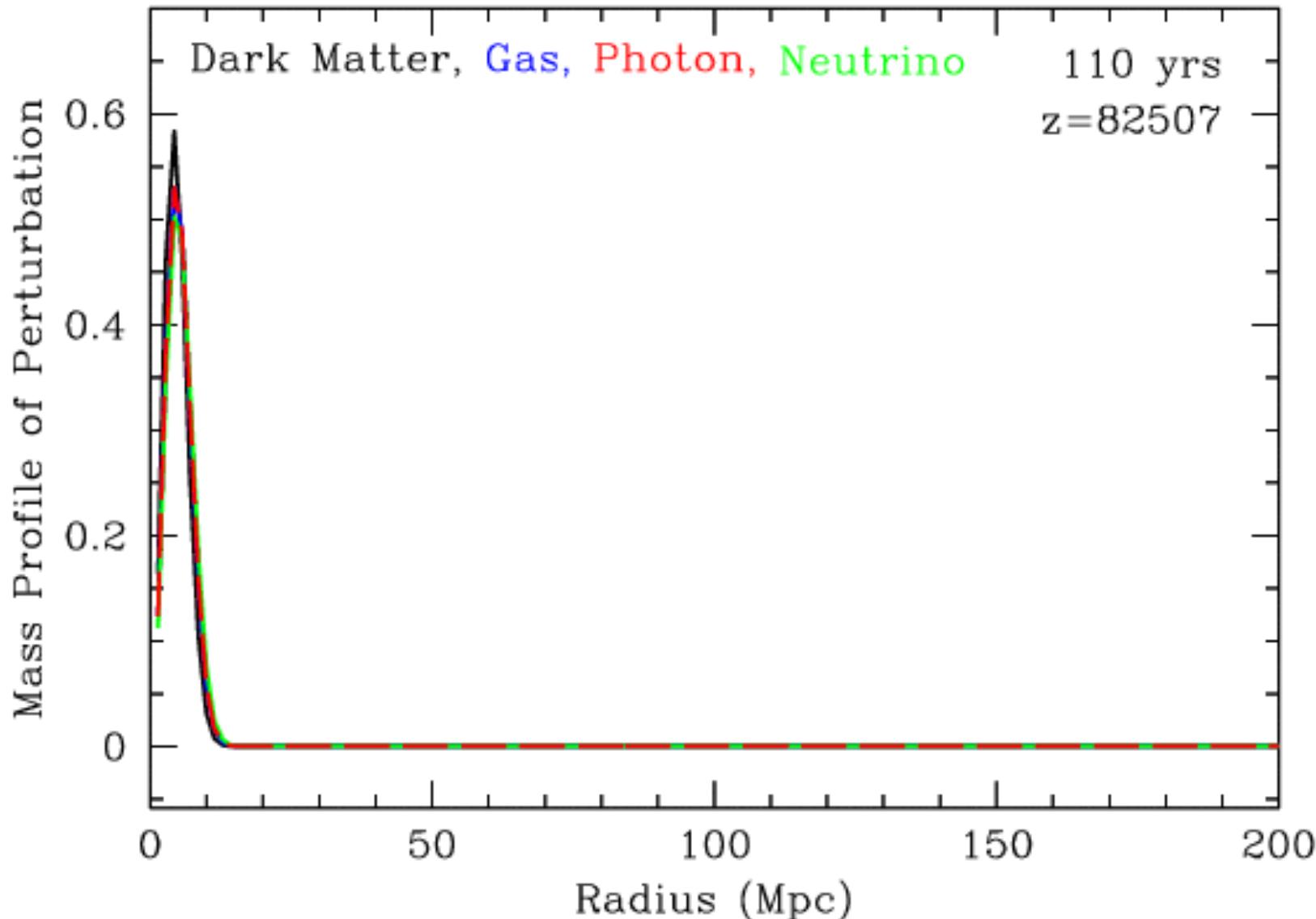
BAO, CMB :  $H_0 \propto \frac{1}{r_s}$

Could the prediction for  $r_s$  be wrong ?

$$\frac{H_0^{\text{Riess}}}{H_0^{\text{BAO}}} \approx 1.07$$

is  $r_s$  7% smaller than thought ?

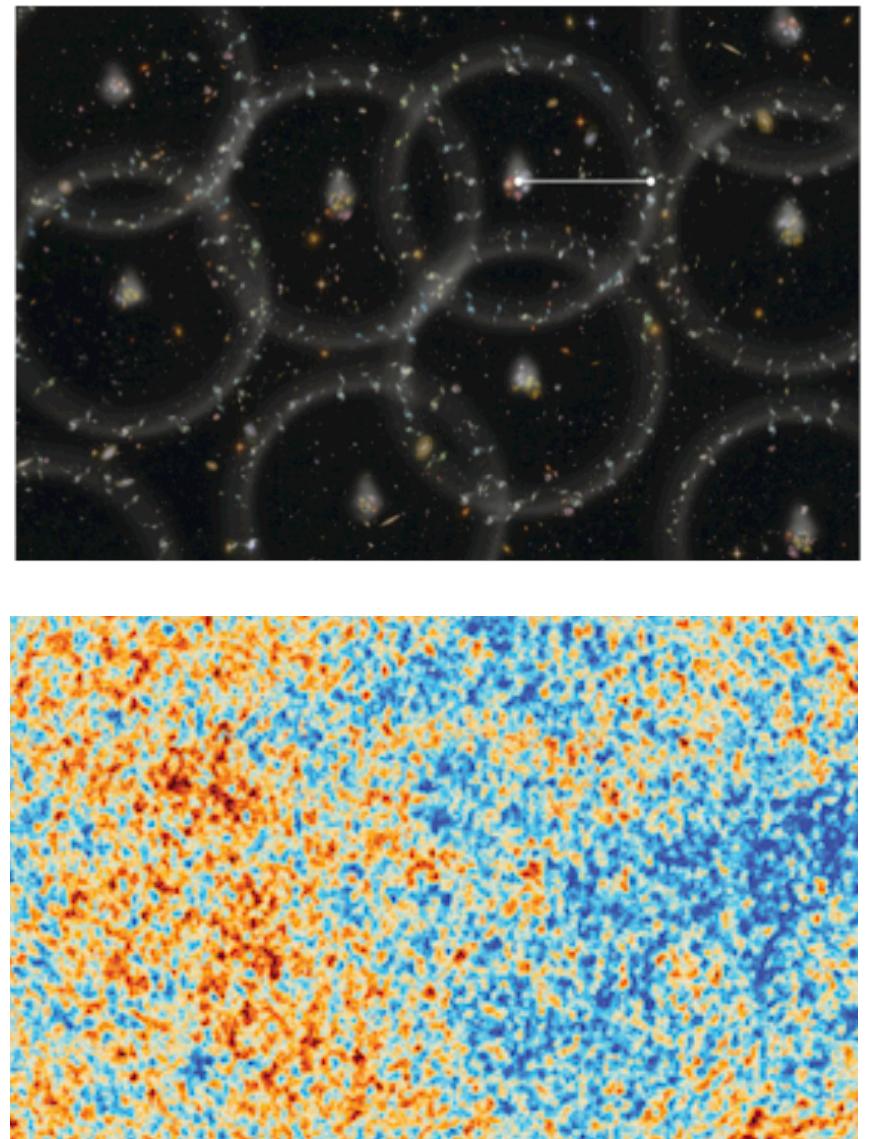
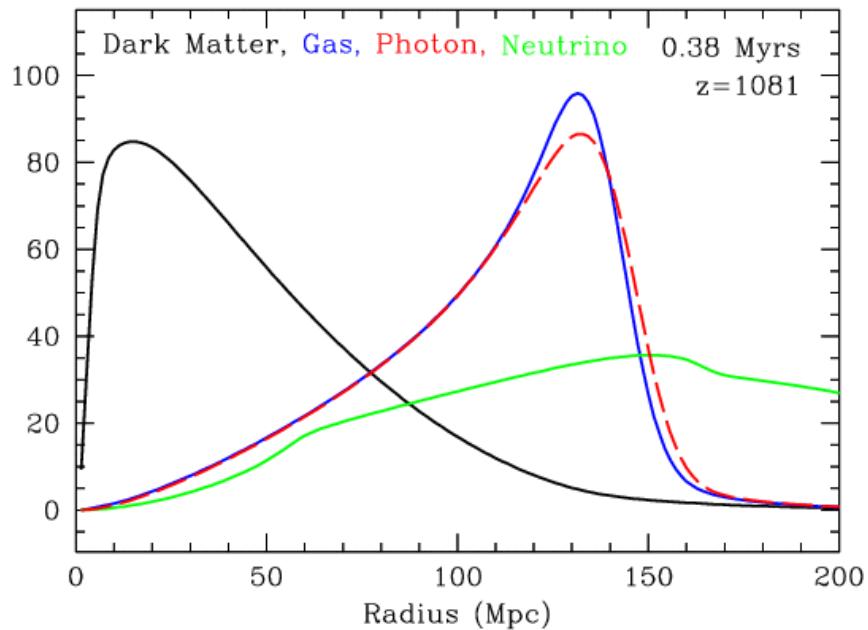
# BAO: Evolution of an over-density in the baryon photon fluid



Eisenstein et al 2007

**BAO: Over-densities in galaxy distributions today**

**CMB: temperature fluctuations in CMB today**



# Sound horizon calculation

$$r_s = \int_0^{z_*} c_s(t) dt = \int_0^{\infty} c_s(z) \left[ \frac{8\pi G}{3} N (\rho_m(z) + \rho_r(z)) \right]^{-\frac{1}{2}} dz$$

$\nearrow z_*$   
 $\sim v \Delta t$

theory, assumes  $\rho_r =$  photons  
neutrinos

want smaller  $r_s$ ? postulate more radiation!  
(or early dark energy)

radiation energy densities

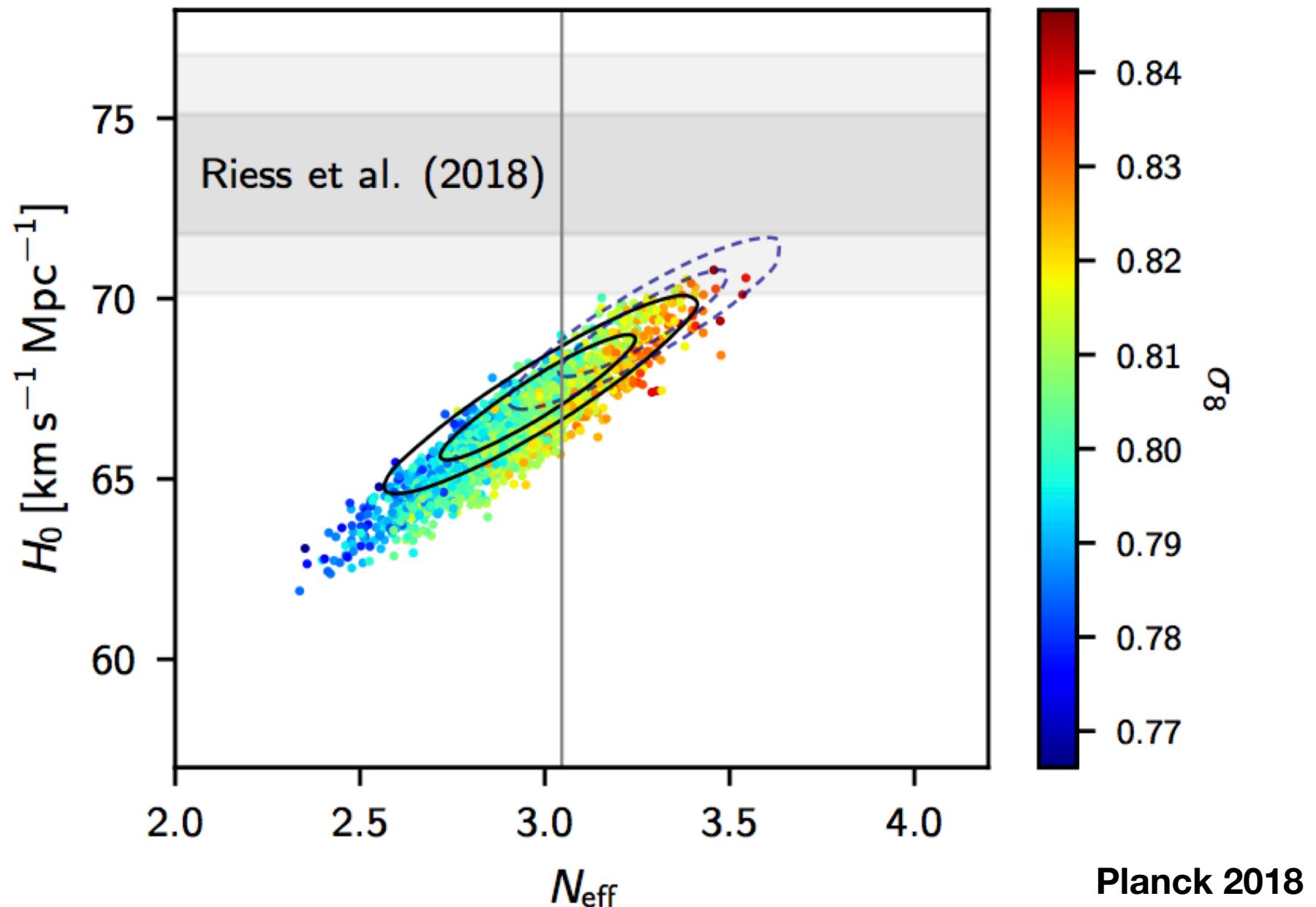
$$\rho_r = \rho_\gamma + \rho_\nu + \rho_{\text{dark}} \equiv \rho_\gamma + \rho_{\text{rad}} \left( 3 + \frac{\rho_{\text{dark}}}{\rho_N} \right)$$



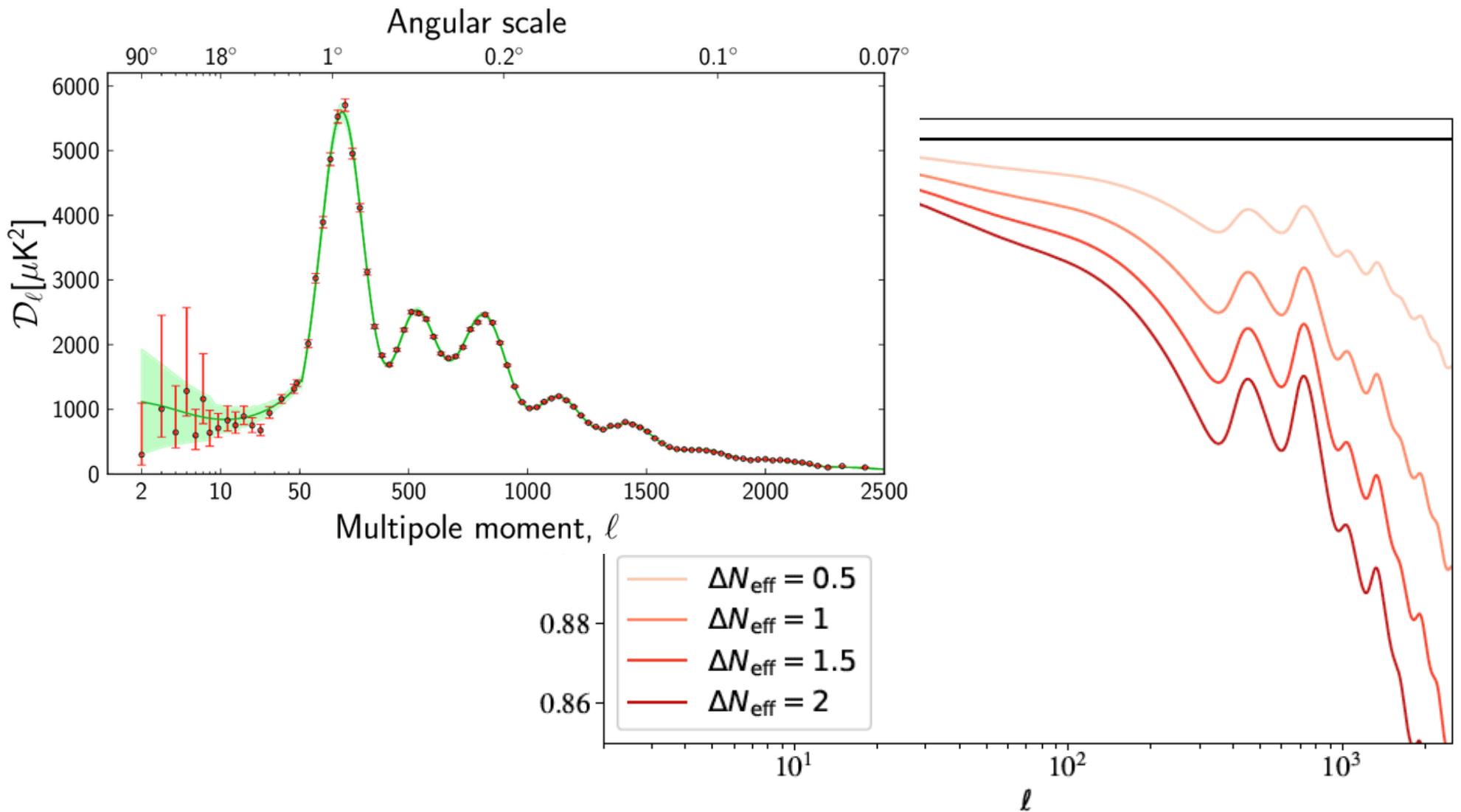
N<sub>eff</sub>

$$\text{N}_{\text{eff}} = 3.044 \quad \text{in } \Lambda \text{CDM}$$

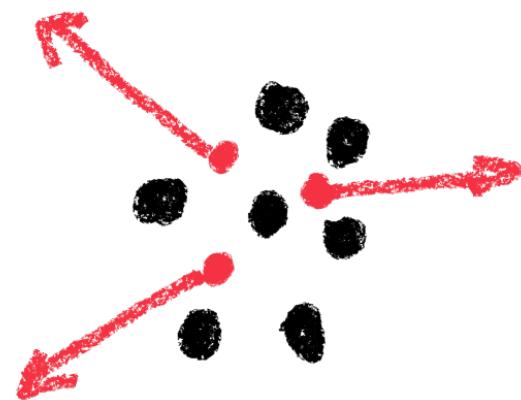
# Unfortunately ... $N_{\text{eff}} = 4$ is ruled out



# Neff > 3 dampens perturbations at small scales



damping of small scale perturbations is due to radiation carrying energy density out of gravitational potentials



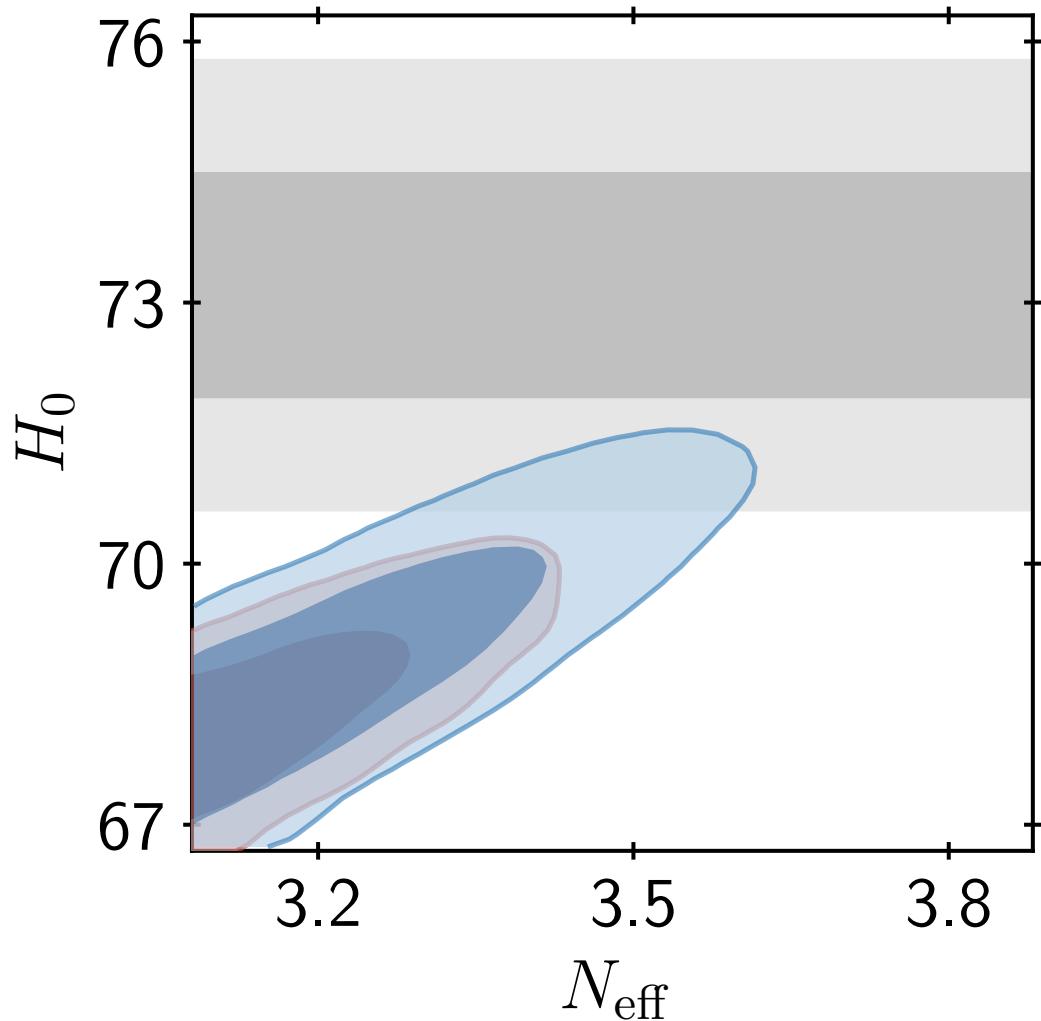
free-streaming



Self-interacting

# extra (dark) radiation

- Free-steaming:  
Good idea,  
doesn't work.
- Self-interacting:  
Better idea,  
doesn't quite  
work (Blinov,  
Marques-Tavares  
2003.08387).
- But... looks like  
the right way  
to go...

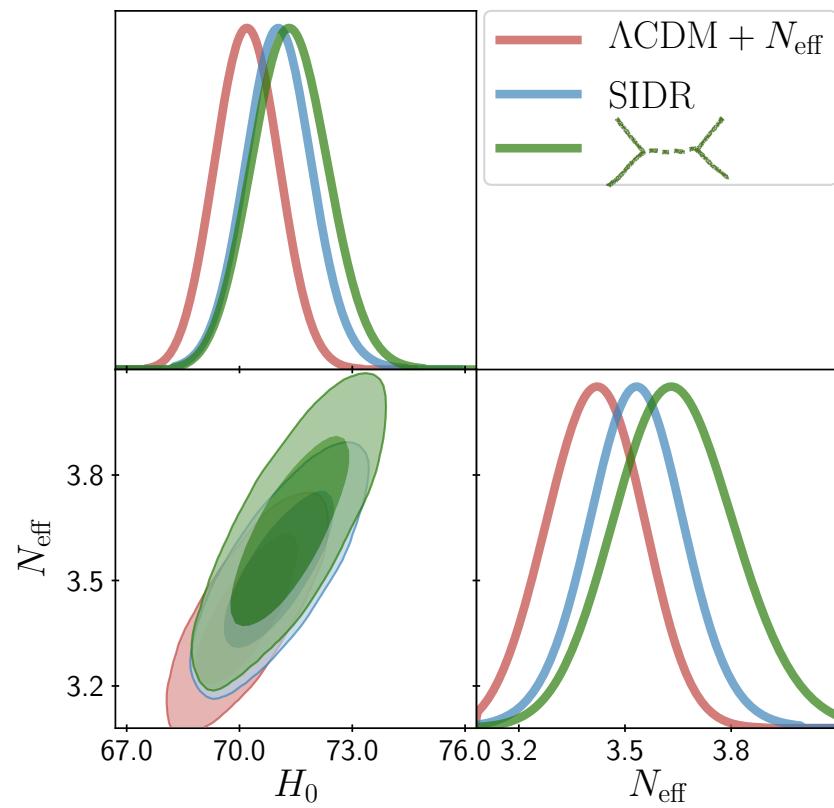


# "A step in understanding the Hubble tension"

astro-ph

2111.00014

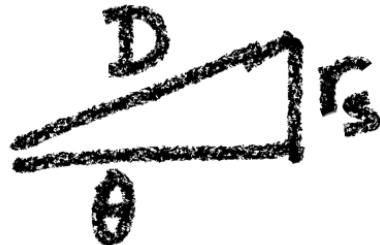
dark radiation  
is self-interacting  
with massive +  
massless particle



where might such dark radiation come from ?

- completely uncoupled from SM  
but why is  $g_{\text{dark}} \sim g_{\text{IV}}$  then?
- Coupled to the SM
  - through heavy messengers  $\rightarrow$  LHC  $\cancel{x_0}$
  - via the neutrinos  $\rightarrow$   $\nu$ -physics

# Summary:

- $H_0$  crisis: CMB BAO   $H_0 \propto \frac{1}{r_s}$   
vs. "direct", e.g. supernovae
- $r_s$  predicted in SM, modified if there is extra radiation
- what is this  $f_{\text{dark}}$ ? nice models?