# RÉSUMÉ SESSION THÉORIE

Photon energy-momentum tensor (with or without SuSy)

$$\theta^{\alpha}{}_{\rho} = \frac{1}{\mu_0}\left(f^{\alpha\nu} f_{\nu\rho} + \frac{1}{4}\delta^{\alpha}_{\rho} f^2 - \frac{1}{2} k^{\mathrm{AF}}_{\rho}\ {}^{*}f^{\alpha\nu} a_{\nu} + k_{\mathrm{F}}^{\alpha\nu\kappa\lambda} f_{\kappa\lambda} f_{\nu\rho} + \frac{1}{4}\delta^{\alpha}_{\rho} k_{\mathrm{F}}^{\kappa\lambda\alpha\beta} f_{\kappa\lambda} f_{\alpha\beta}\right) , \tag{11}$$

and its non-conservation

$$\partial_{\alpha}\theta^{\alpha}{}_{\rho} = j^{\nu} f_{\nu\rho} - \frac{1}{\mu_0}\Big[\left(\partial_{\alpha} F^{\alpha\nu}\right) f_{\nu\rho} + k^{\mathrm{AF}}_{\alpha}\ {}^{*}F^{\alpha\nu} f_{\nu\rho} +$$
$$\frac{1}{2}\left(\partial_{\alpha} k^{\mathrm{AF}}_{\rho}\right) {}^{*}f^{\alpha\nu} a_{\nu} - \frac{1}{4}\left(\partial_{\rho} k_{\mathrm{F}}^{\alpha\nu\kappa\lambda}\right) f_{\alpha\nu} f_{\kappa\lambda} + \left(\partial_{\alpha} k_{\mathrm{F}}^{\alpha\nu\kappa\lambda}\right) F_{\kappa\lambda} f_{\nu\rho} + k_{\mathrm{F}}^{\alpha\nu\kappa\lambda}\left(\partial_{\alpha} F_{\kappa\lambda}\right) f_{\nu\rho}\Big] . \tag{12}$$

Table: Simulation results for $\Omega_{\mathrm{rad}} = \Omega_{\mathrm{k}} = \Omega_{\Lambda} = 0$ and $\Omega_{\mathrm{m}} = 0.28$. The large value of the error on $k_i$ is due to the Hierarchical Bayesian Model (HBM) approach, considering different source of uncertainties to render homogeneous the photometric data of the distance modulus from different catalogues. **The simulation results provide a mean $z_{\mathrm{LSV}}$ blue-shift for types 1 and 2 and a $z_{\mathrm{LSV}}$ red-shift for type 3.**

| Type | 1 | 2 | 3 |
|---|---|---|---|
| $k_i$ | $2.8 \times 10^{-5} \pm 3.5 \times 10^{-3}$ | $2.6 \times 10^{-5} \pm 2.8 \times 10^{-3}$ | $< -10^{-6} \pm 1.3 \times 10^{-3}$ |
| rms | $1.34 \times 10^{-2}$ | $1.31 \times 10^{-2}$ | $1.05 \times 10^{-1}$ |

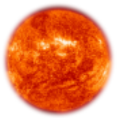
D. Spallici

# Free fall beyond GR

1. Non-universal coupling to gravity

$$S = S_{\mathrm{SM}}[\psi_i; \boldsymbol{g}_1] + S_{\mathrm{DM}}[\boldsymbol{\chi}; \boldsymbol{g}_2]$$

2. Violation of the strong equivalence principle

 $\neq$ • BH

3. Screened fifth force

 $\neq$ 

P. Fleury

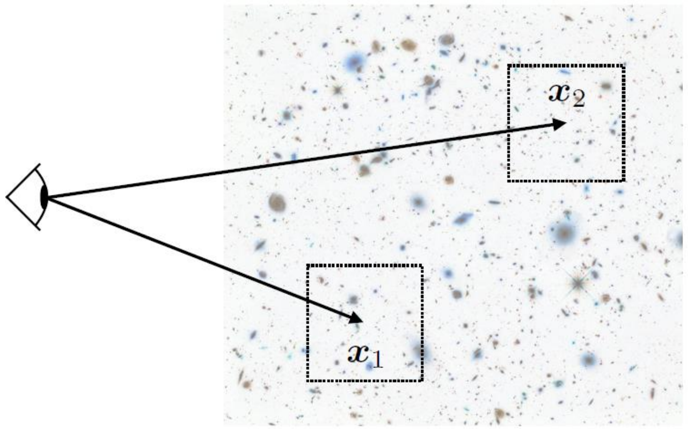
- Generalised Euler's equation

$$V' + \mathcal{H}\left[1 + \Theta(\eta)\right] V + \left[1 + \Gamma(\eta)\right] \Psi = 0$$

quantify deviations from Euler

## Correlation function

$$\langle \Delta(\boldsymbol{x}_1)\Delta(\boldsymbol{x}_2)\rangle \ni \langle \Delta_{\rm st}(\boldsymbol{x}_1)\Delta_{\rm rel}(\boldsymbol{x}_2)\rangle \propto \langle b\delta(\boldsymbol{x}_1)V_r(\boldsymbol{x}_2)\rangle$$




$$\langle \Delta(\boldsymbol{x}_1)\Delta(\boldsymbol{x}_2)\rangle \ni \langle b\delta(\boldsymbol{x}_1)V_r(\boldsymbol{x}_2)\rangle + \langle V_r(\boldsymbol{x}_1)b\delta(\boldsymbol{x}_2)\rangle$$

same dipole,
opposite sign

$$\xi(\boldsymbol{x}_1, \boldsymbol{x}_2) \equiv \langle \Delta(\boldsymbol{x}_1)\Delta(\boldsymbol{x}_2)\rangle$$

## The two-population trick

[McDonald 2009]
[Bonvin, Hui, Gaztañaga, 2013]

$$\langle \Delta_{\rm B}(\boldsymbol{x}_1)\Delta_{\rm F}(\boldsymbol{x}_2)\rangle \ni b_{\rm B}\langle \delta(\boldsymbol{x}_1)V_r(\boldsymbol{x}_2)\rangle + b_{\rm F}\langle V_r(\boldsymbol{x}_1)\delta(\boldsymbol{x}_2)\rangle$$

bright galaxies

faint galaxies

net dipole, proportional to $b_{\rm B} - b_{\rm F}$

Modified Euler

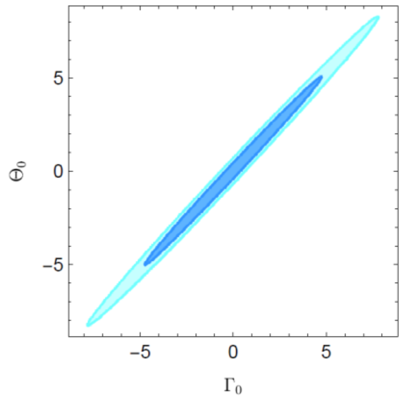
$$V' + \mathcal{H}[1+\Theta(z)]V + [1+\Gamma(z)]\Psi = 0$$

In principle, the linear growth changes

$$D(z) = D_{\rm GR}[1+\mu(z)]$$

Standard parametrisation: for $p = \Theta, \Gamma, \mu$

$$p(z) = \frac{\Omega_\Lambda(z)}{\Omega_{\Lambda 0}}\, p_0$$




$$\Delta\Gamma_0 = 0.26 \quad (1\sigma)$$

SKA

Comparison: with DESI $\Delta\Gamma_0 = 1.9 \quad (1\sigma)$

We need a **generalization of Newtonian gravity** for two particles species

| Type of matter | Type of matter | Interaction |
|---|---|---|
| + | + | Attraction |
| − | − | Repulsion |
| − | + | Repulsion |
| + | − | Repulsion |

- **Antimatter spreads uniformly**
- **Matter coalesces into structures**

Cannot be realized with a single Poisson's equation

$$\begin{aligned} \Delta\phi_+ &= 4\pi G m(+n_+ - n_-), \\ \Delta\phi_- &= 4\pi G m(-n_+ - n_-) \end{aligned}$$

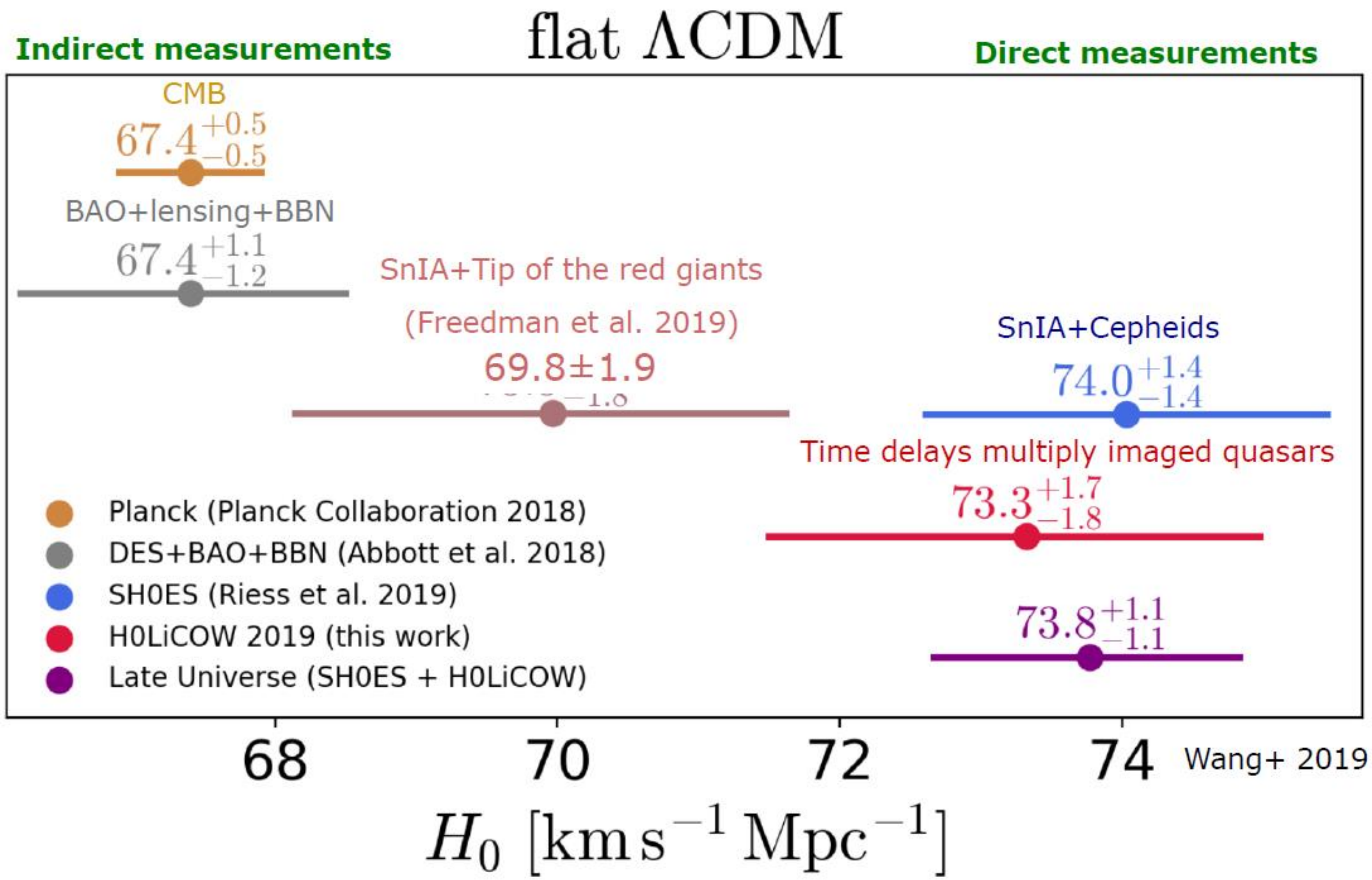
**Open question**: how to incorporate this approach into General Relativity

- Bimetric theory?

- Structure formation occurs for Dirac-Milne too
  - Earlier and faster compared to EdS
- Importantly, **structure formation in the Dirac-Milne universe stops after a few billion years**
  - Qualitatively similar to ΛCDM universe

G. Manfredi

# Strong tension between early and late universe probes of $H_0$.




S. Galli

# Indirect measurement of the Hubble constant from the CMB

Calculate the **physical dimension of sound horizon** assumes model for sound speed and expansion of the universe before recombination (after measuring $\omega_m$ and $\omega_b$)

$$r_s = \int_{z_s}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Measure the **angular scale of sound horizon** from the position of the peaks


$$D_A(z = 1100) = \int_0^z dz'/H(z')$$

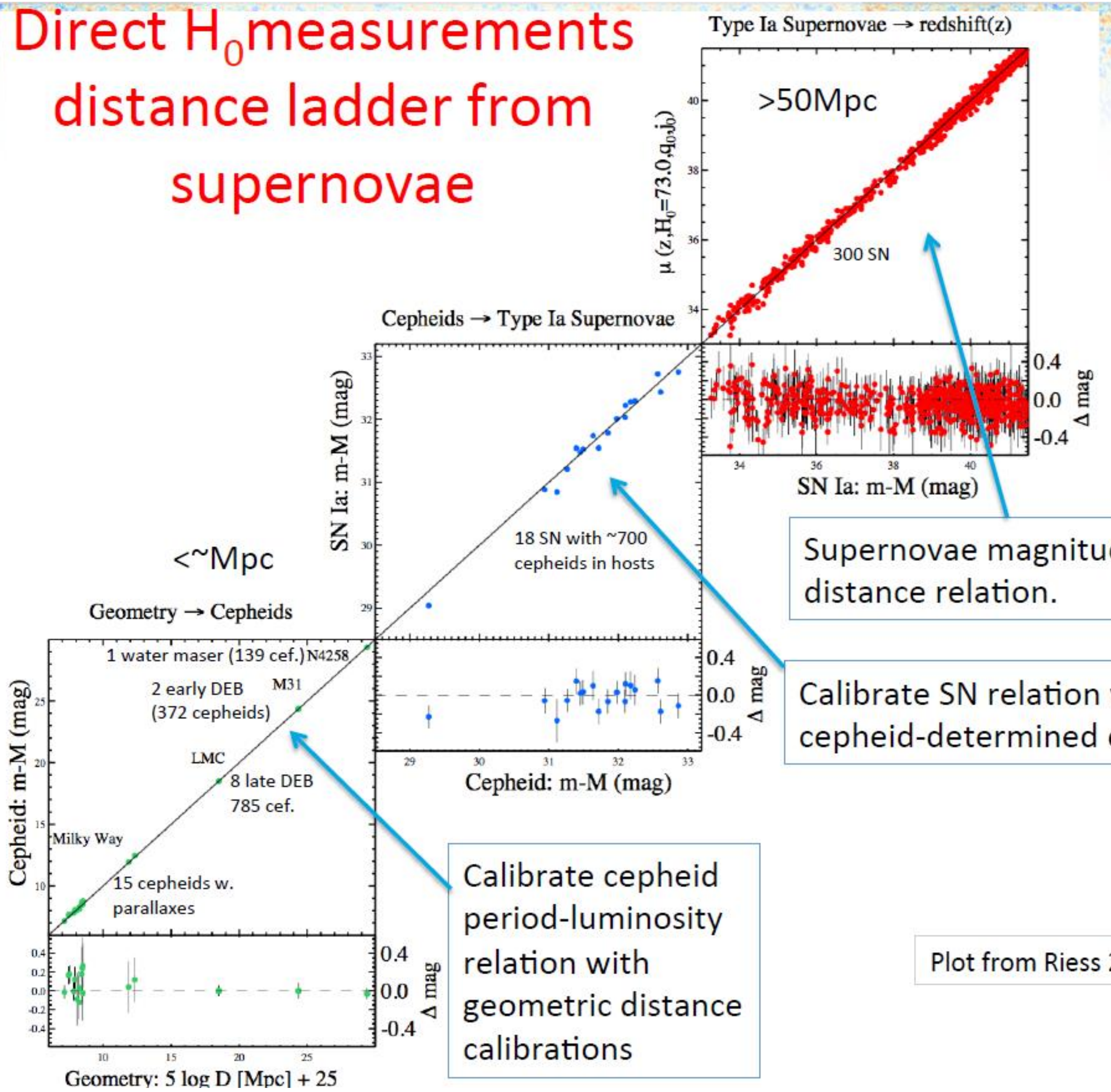
Infer the distance to the last scattering surface, which depends on $H_0$ Friedmann equation, infer $H_0$.

Expansion rate after recombination

$$H^2(z) = \mathbf{H_0}^2(\Omega_m (z+1)^3 + \Omega_{DE} + ..)$$

Model dependent!

# Direct $H_0$ measurements distance ladder from supernovae



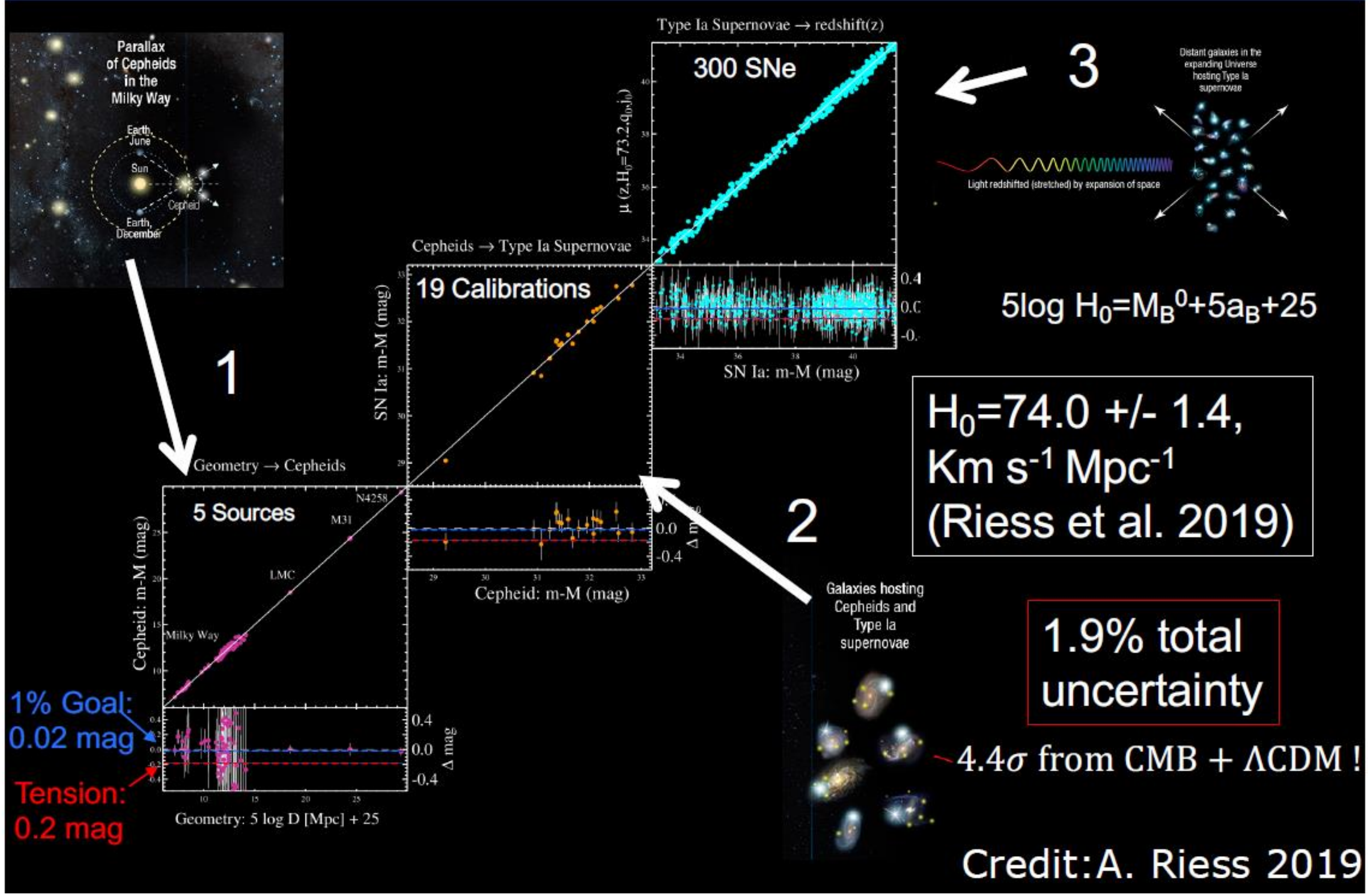

Supernovae magnitude-distance relation.

Calibrate SN relation with cepheid-determined distances

Calibrate cepheid period-luminosity relation with geometric distance calibrations

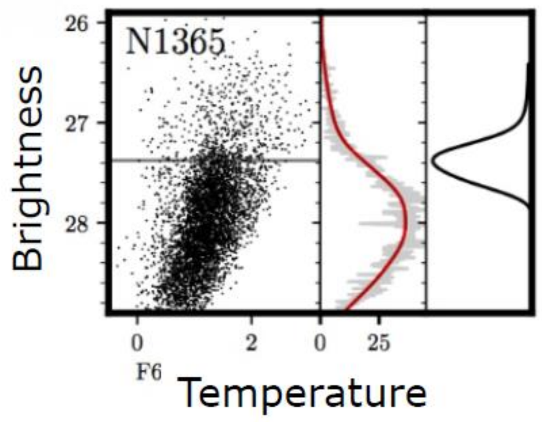
Plot from Riess 2016

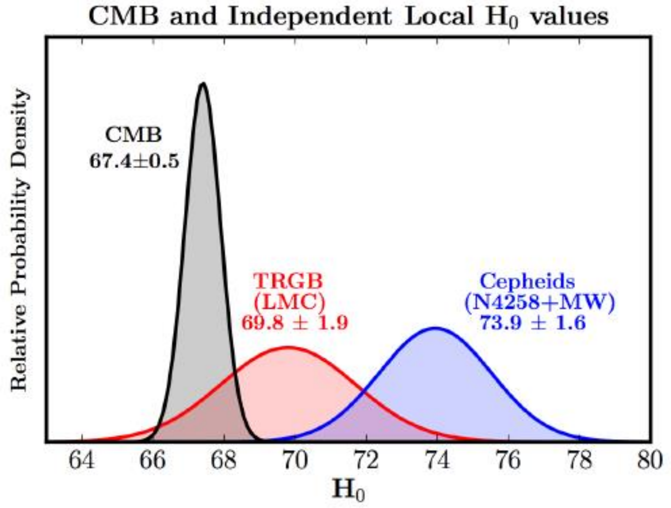
# The Hubble Constant in 3 Steps: Present Data



# Tip of the red giants branch

- Measure of the position of the brightest **luminosity** of Red Giants before helium flash (when helium core starts fusion), which is used as a standard candle.
- Used instead of cepheids to calibrate SnIA in second rung of the ladder.
- Brightness calibrated by measuring TRGB in the LMC, whose distance is determined from detached eclipsing binaries.
- CCHP program uses Carnegie Supernova Project I (CSP-I) sample containing about 100 well- observed SNe Ia, independent of Sh0ES program.
- In agreement both with Planck (1.2σ) and SnIA+cepheids (1.7σ).



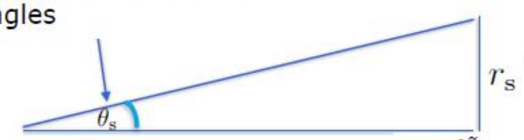
# Early and late time solutions

1. **Change in late time universe**
    - **(**late-time dynamics of dark matter and/or dark energy, e.g. dynamical dark energy, decaying DM (Poulin+ 2018, Vattis+ 2019) interacting dark matter-dark energy etc..) => highly constrained by BAO, Supernovae and other probes.
    - Modified gravity changes to Cepheid period-luminosity relation (Desmond et al. 1907.03778)=> but might be constrained by time delays.

See also e.g. Bernal +2016, Lemos+ 2018, Aylor 2018

2. **Change in the early time physics**. BAO and CMB measure angles, assuming calculation of sound horizon $r_s$.one can infer the distances and thus $H_0$=> changing $r_s$ can change inferred $H_0$, but hard because usually these models impact other observables as well.

BAO and CMB measure angles



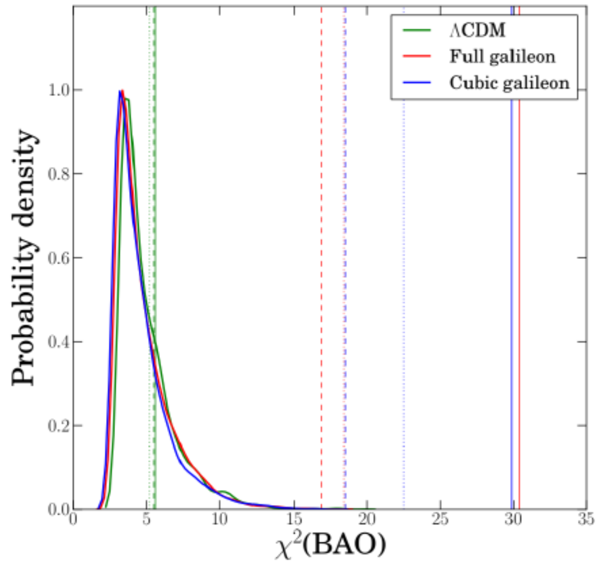

Need to calculate $r_s$ to infer distance

$$D_A(z=1100) = \int_0^z dz'/H(z')$$

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

# Galileon status

- Status of the general galileon model (see Leloup et al. 2019) :
  - No galileon model can fit all cosmological data (especially BAO)




  - Full galileon model excluded by GW170817
  - Nevertheless, non-tracker exploration useful

C. Leloup

# What is left?

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$

$$\alpha_K \quad \alpha_B \quad \alpha_M \quad \beta_1$$

What about:

1 - Screening

2 - Self-acceleration

M. Crisostomi

# Self-acceleration

[MC, Koyama]

[MC, Koyama, Langlois, Noui, Steer]

$$L = K + G_3 \Box\phi + G.R + \frac{3G_X^2}{2G}\phi^\mu \phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$

Background effect

$$K = c_2 X\,, \quad G_3 = \frac{c_3}{\Lambda^3} X\,, \quad G = \frac{M_P^2}{2} + \frac{c_4}{\Lambda^6} X^2 \qquad c_2, c_3, c_4 \sim \mathcal{O}(1)$$