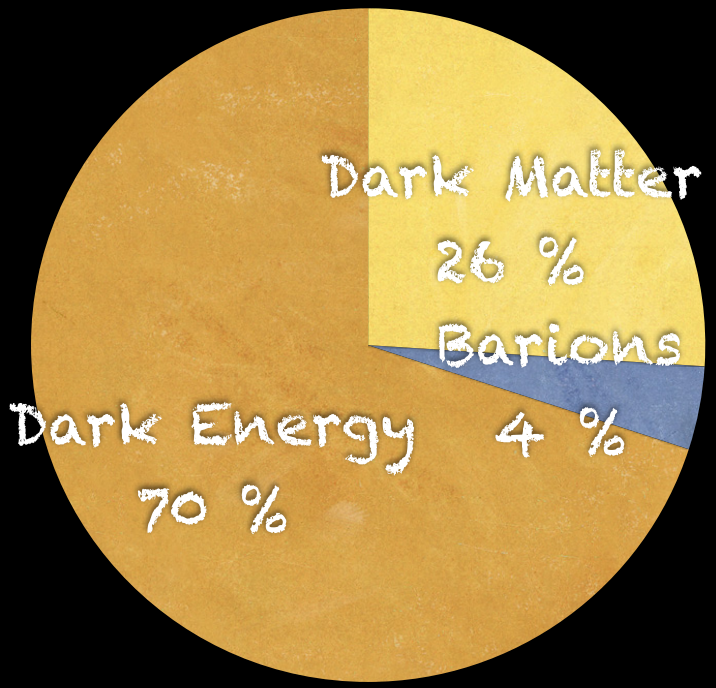
High precision local measurements of the Hubble constant as probes into the physics of the Accelerating Universe

Martino Romaniello
ESO & Excellence Custer Universe

The matter-energy content of the Universe

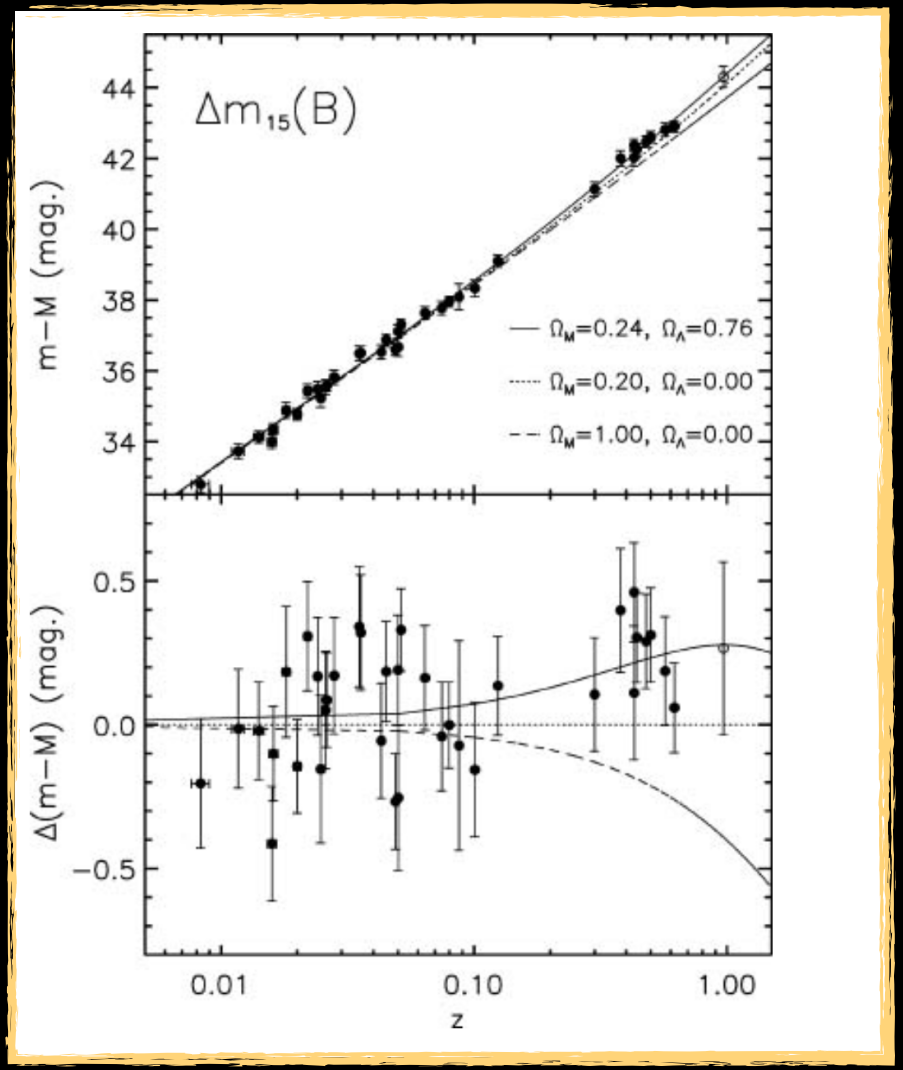


- 96% of the Universe is made of things whose very nature we dont understand

- In particular, there is no framework for Dark Energy, which challenges our understanding in a couple of interesting ways...

The Accelerating Universe

- Within General Relativity, available evidences favour a simple Cosmological Constant (Λ)



Rises et al (1998)

- ...or GR breaks down on cosmological scales...
- ...or there are more than 3 species of neutrinos...
- ...or...

Vacuum energy

- Cosmic Acceleration is driven by a smooth, spatially and temporally constant, elastic ($p/\varrho \simeq -1 \pm 0.5$ [stat] $\pm$ 0.5 [sys]) component

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

- ...which is mathematically equivalent to an energy density associated to the vacuum:

$$T^{\rm vac}_{\mu\nu} = -\rho_{\rm vac}\ g_{\mu\nu}$$

$$\rho_{\rm vac} = \rho_\Lambda \equiv \frac{\Lambda}{8\pi G}$$

The 120 orders of magnitude problem

- Λ has dimensions of $[L]^{-2}$, thus introducing a scale in the otherwise scale-free GR
- A natural expectation is for this scale to be comparable to the Planck scale:

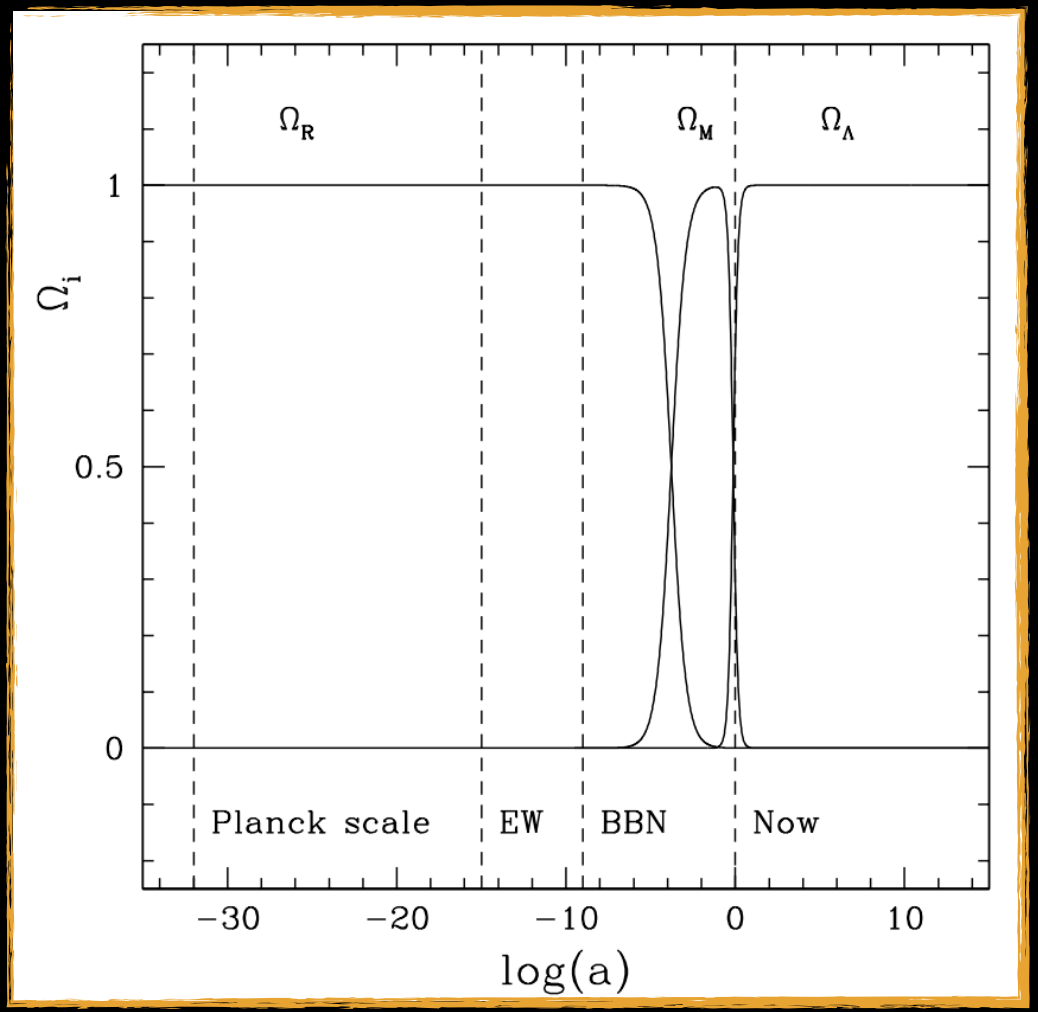
$$\Lambda^{\rm guess} \sim L^{-2}_{\rm Planck} \Longrightarrow \rho^{\rm guess}_{\rm vac} \sim M^4_{\rm Planck} \sim 10^{112}\ {\rm erg\ cm^{-3}}$$

- This is 120 orders of magnitude larger than observed (Λ=0.7):

$$\rho^{\rm obs}_{\rm vac} = \frac{\Lambda}{8\pi G} \sim 10^{-8}\ {\rm erg\ cm^{-3}}$$

The coincidence scandal

- We live in an epoch in which Dark Energy and (dark) matter are of the same order of magnitude



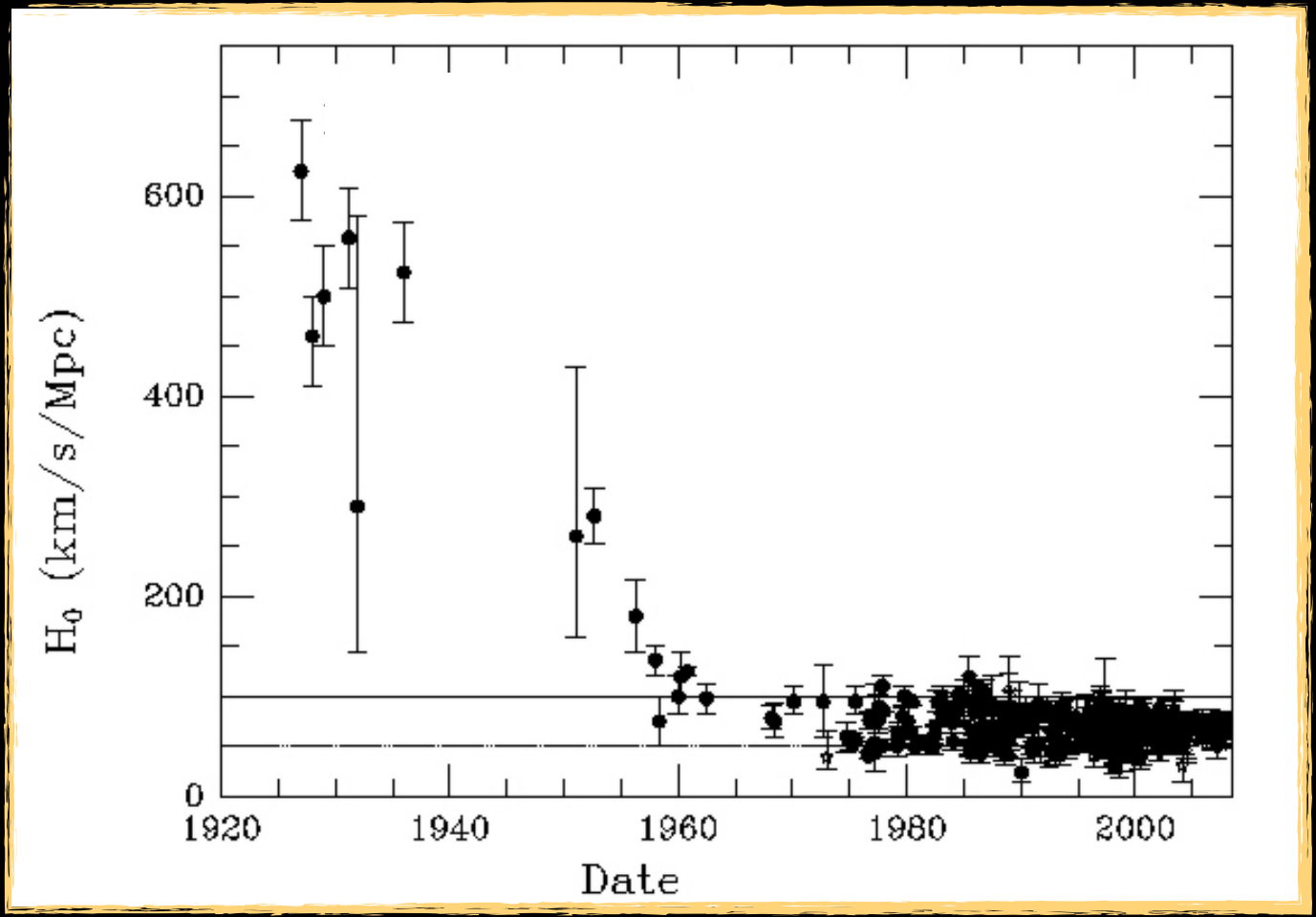
Carroll (2004)

The Hubble constant

The Hubble constant

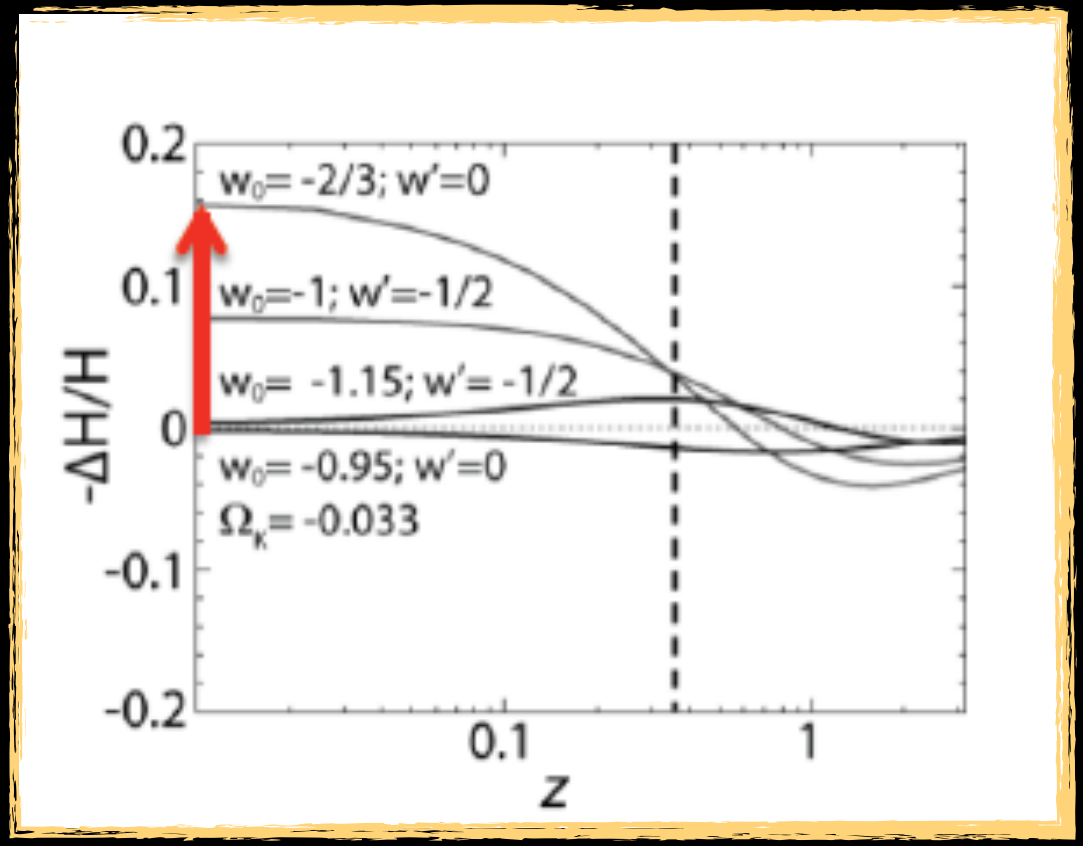
- Measures the expansion rate of the Universe

$$\mathrm{H} \equiv \frac{\dot{a}}{a} \; ; \text{locally } v = \mathrm{H}\, d$$



H and Dark Energy - I

- The CMB fixes the sound horizon at recombination, then, given a cosmology, the Friedmann equation yields $\dot{a}/a = H(z)$



Wayne Hu (2005)

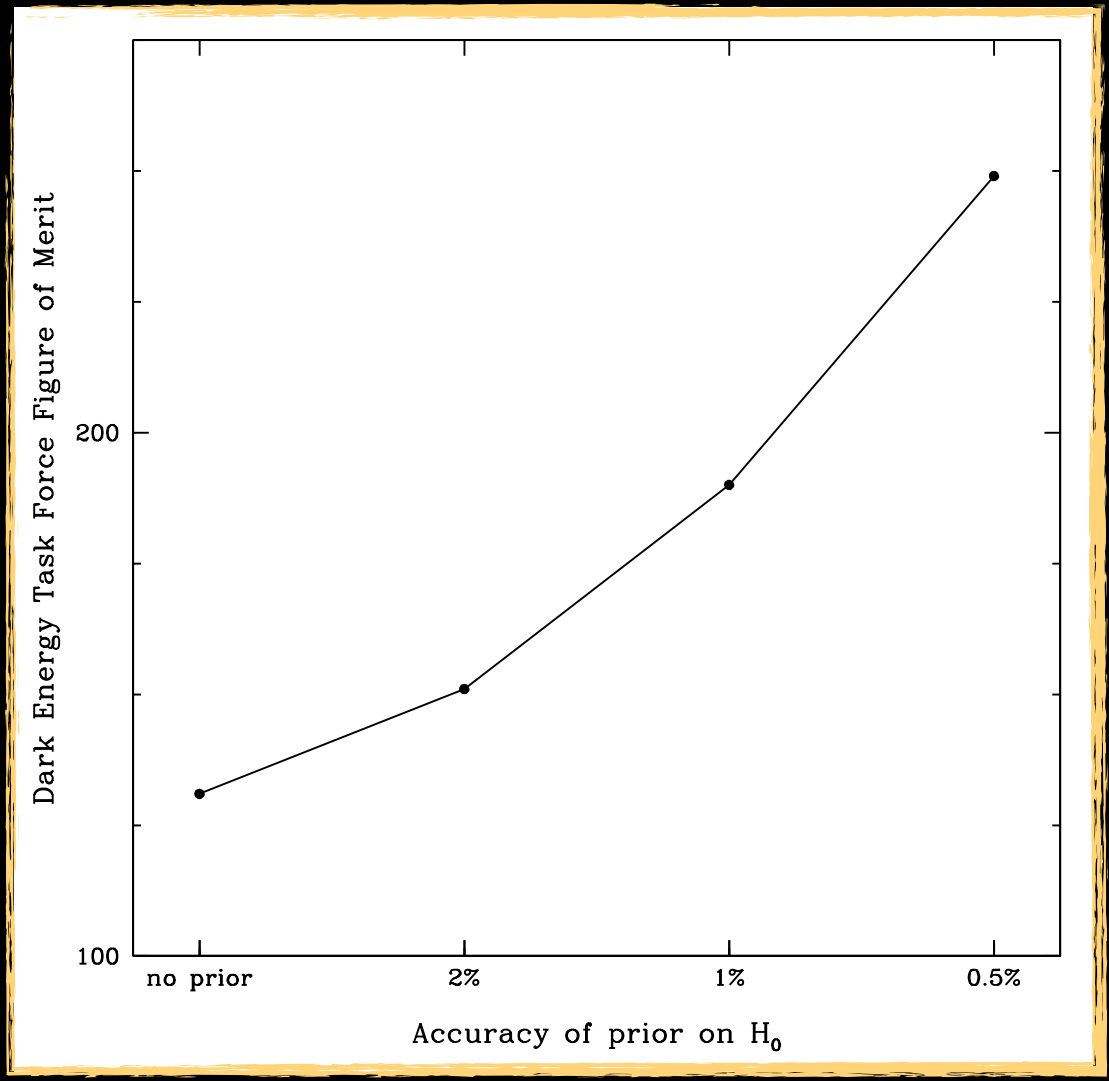
- The impact of varying cosmology on the Hubble parameter H is maximum at z=0

$\sigma(w_o) \sim 2\sigma(H_o)$

H and Dark Energy - II

- An accurate prior on Ho constrains the Dark Energy parameters

Courtesy of Lucas Macrì



H_0 and Dark Energy

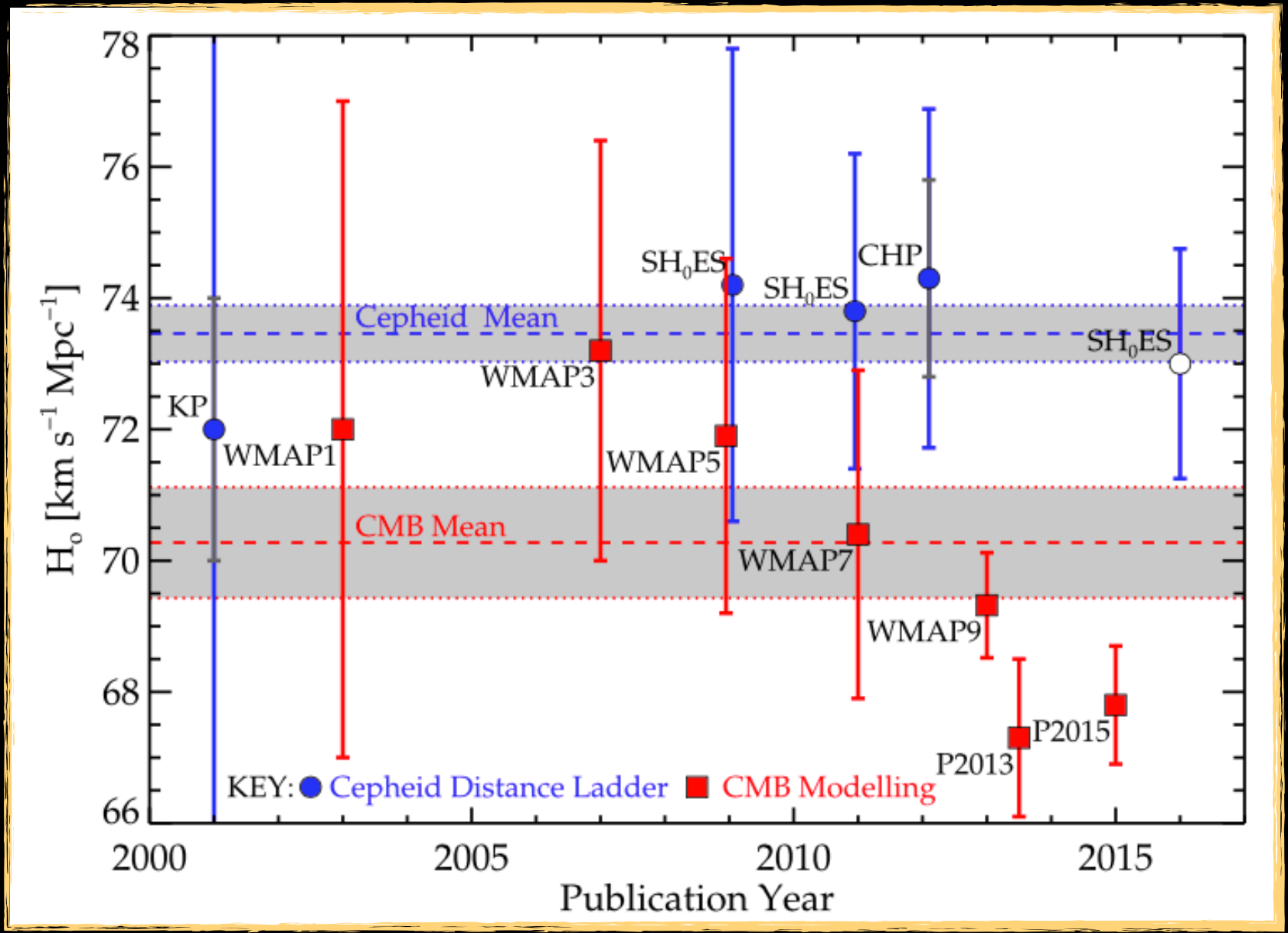
- In combination with other data, a high precision local measurement of H_0 provides direct insight into the physics of the accelerating Universe

- Local measurements, independent from cosmology, indicate a high H_0 (73.24±1.74 km/s/Mpc, Riess et al 2016; Freedman et al 2012)
- Estimates from CMB and concordance ΛCDM model indicate a low H_0 (67.8±0.9 km/s/Mpc, Planck 2015 results XIII)

- Is this ~3.3σ tension real???
  - If confirmed at a higher significance, it would be unambiguous indication of physics beyond ΛCDM

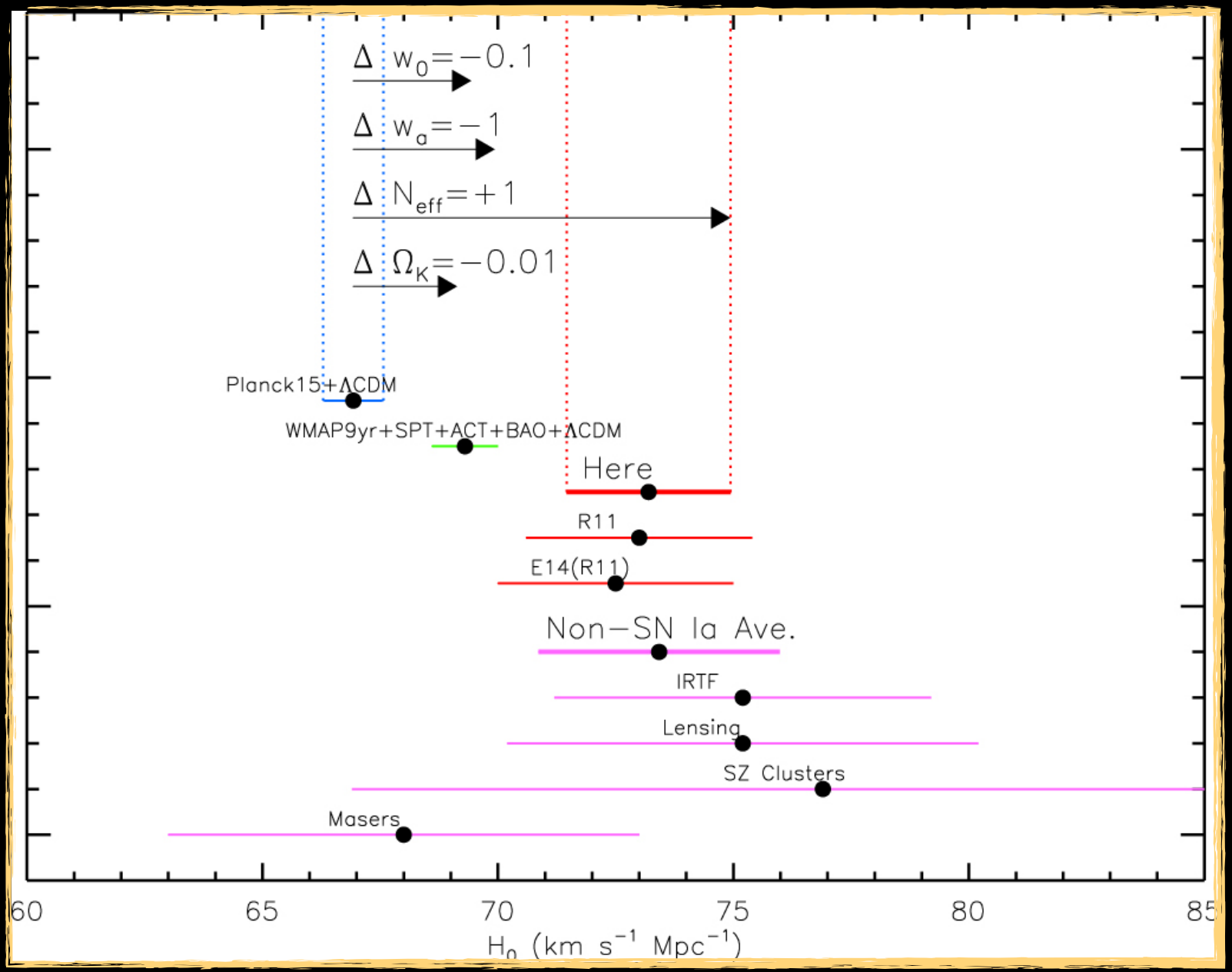
Determining H_0

Beaton et al (2016, ApJ, 832, 210)



H_0 and the Accelerating Universe

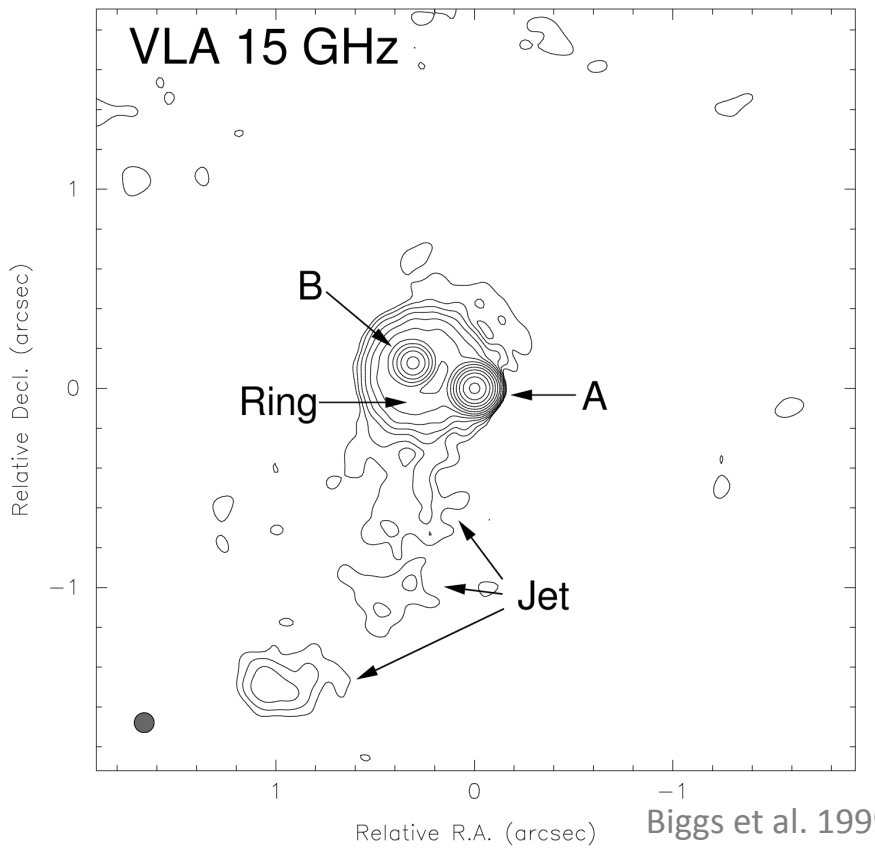
Rises et al (2016, ApJ, 826, 56)



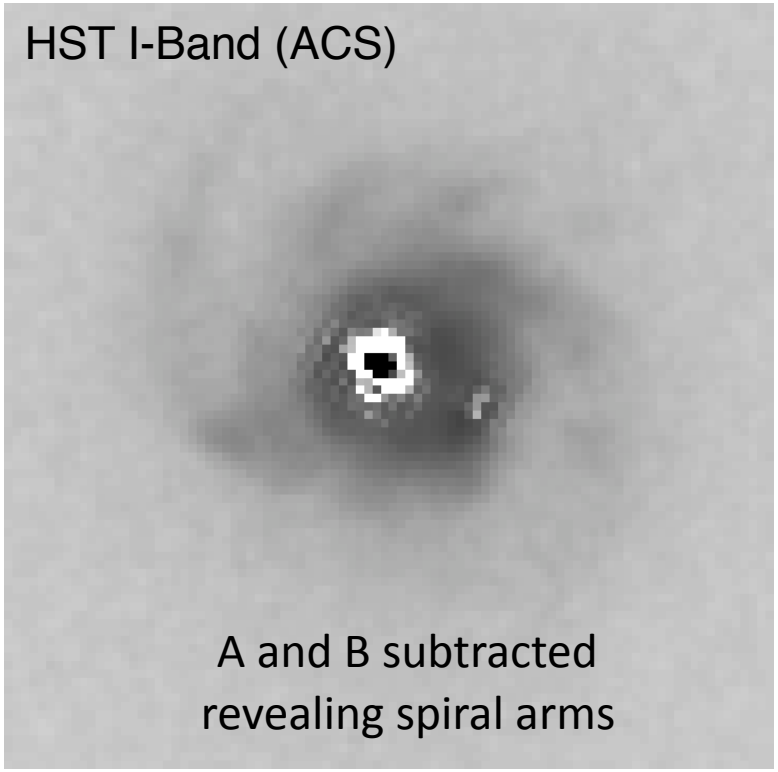
Measuring H_0

...it's all in the systematics...

JVAS B0218+357



Biggs et al. 1999



York et al. 2005

Smallest lens system yet discovered: A-B separation = 334 mas

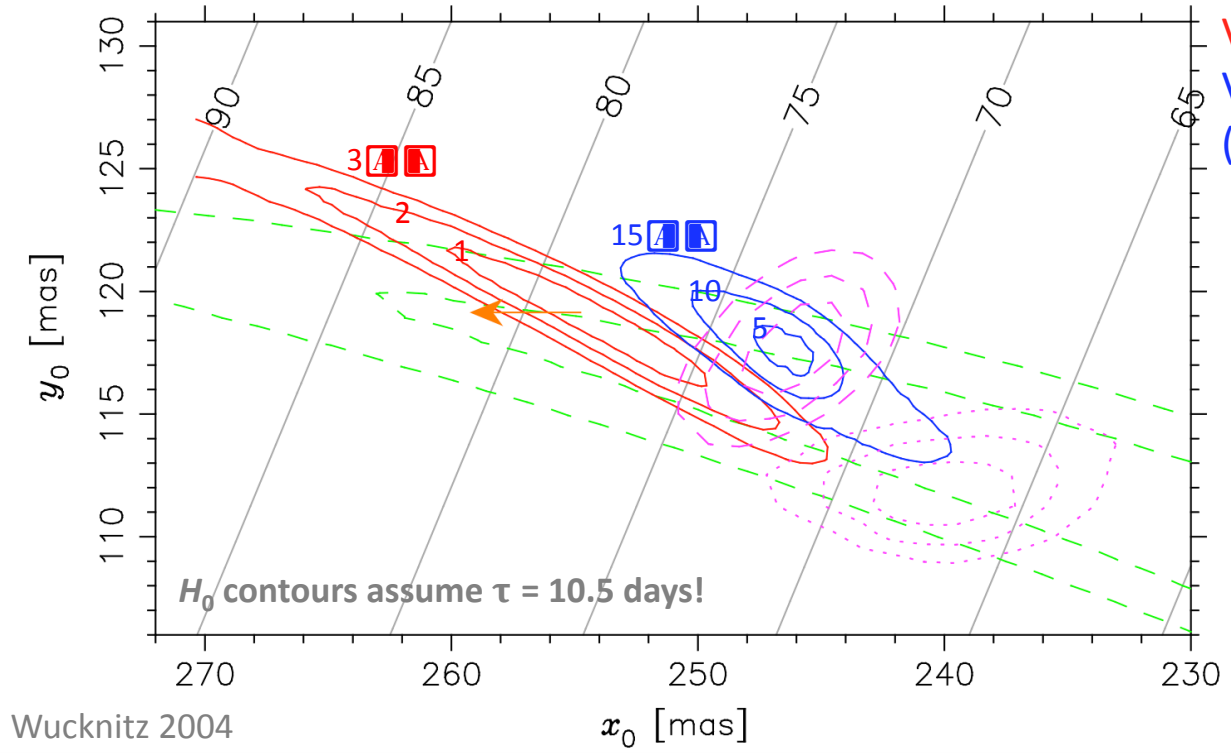
Excellent model constraints possible from Einstein ring

Lens galaxy is an isolated spiral (z = 0.6847)

Slide courtesy of Andy Biggs (ESO)

What does this mean for H_0?

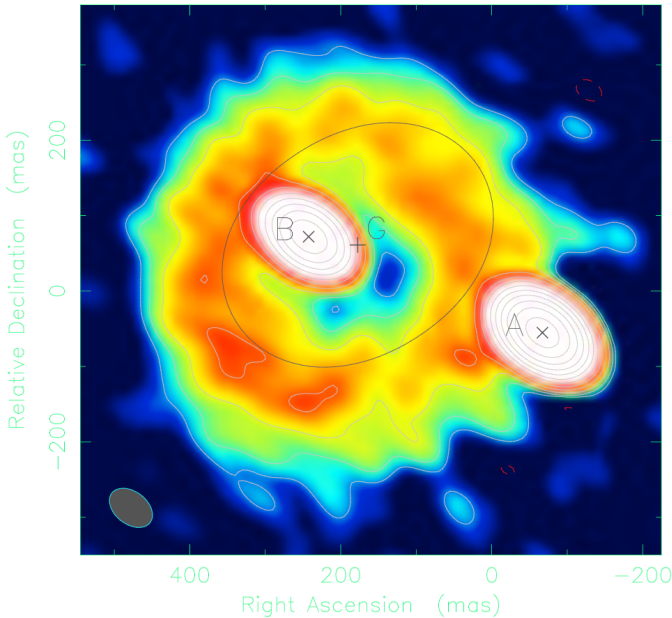
Einstein ring constrains position of lens galaxy



Wucknitz 2004

VLA 15 GHz – Wucknitz et al. 2004

VLA + Pie Town – Wucknitz 2004 (preliminary work)



Wucknitz 2004

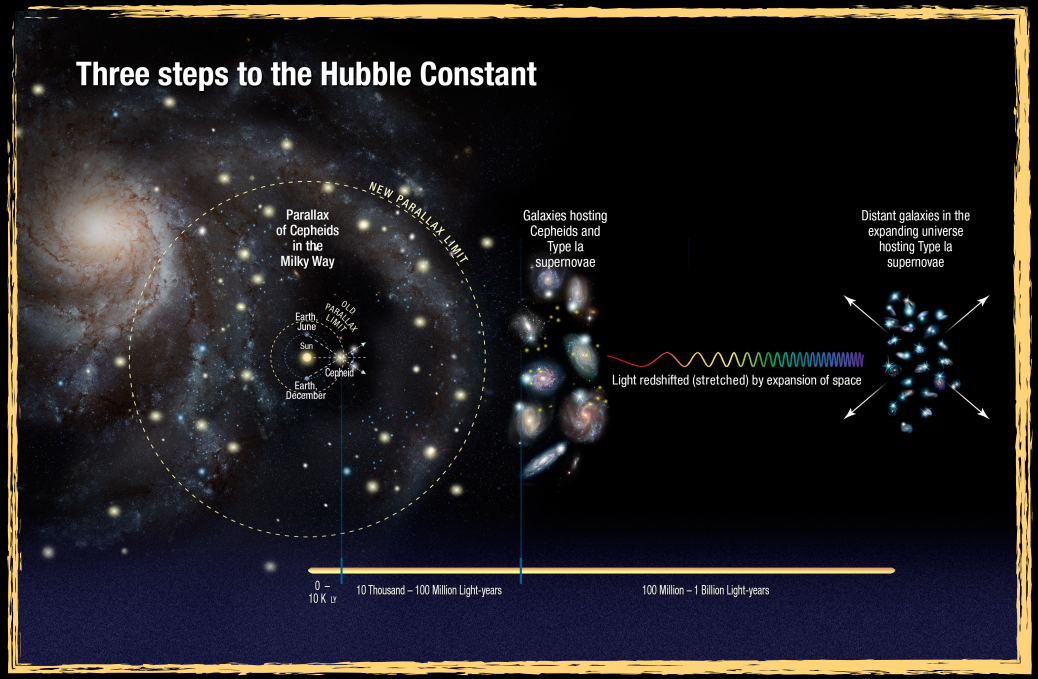
For τ = 11.5 days, $H_0 \cong 67 \pm 5$ km/s/Mpc (2σ)

Slide courtesy of Andy Biggs (ESO)

SH0ES

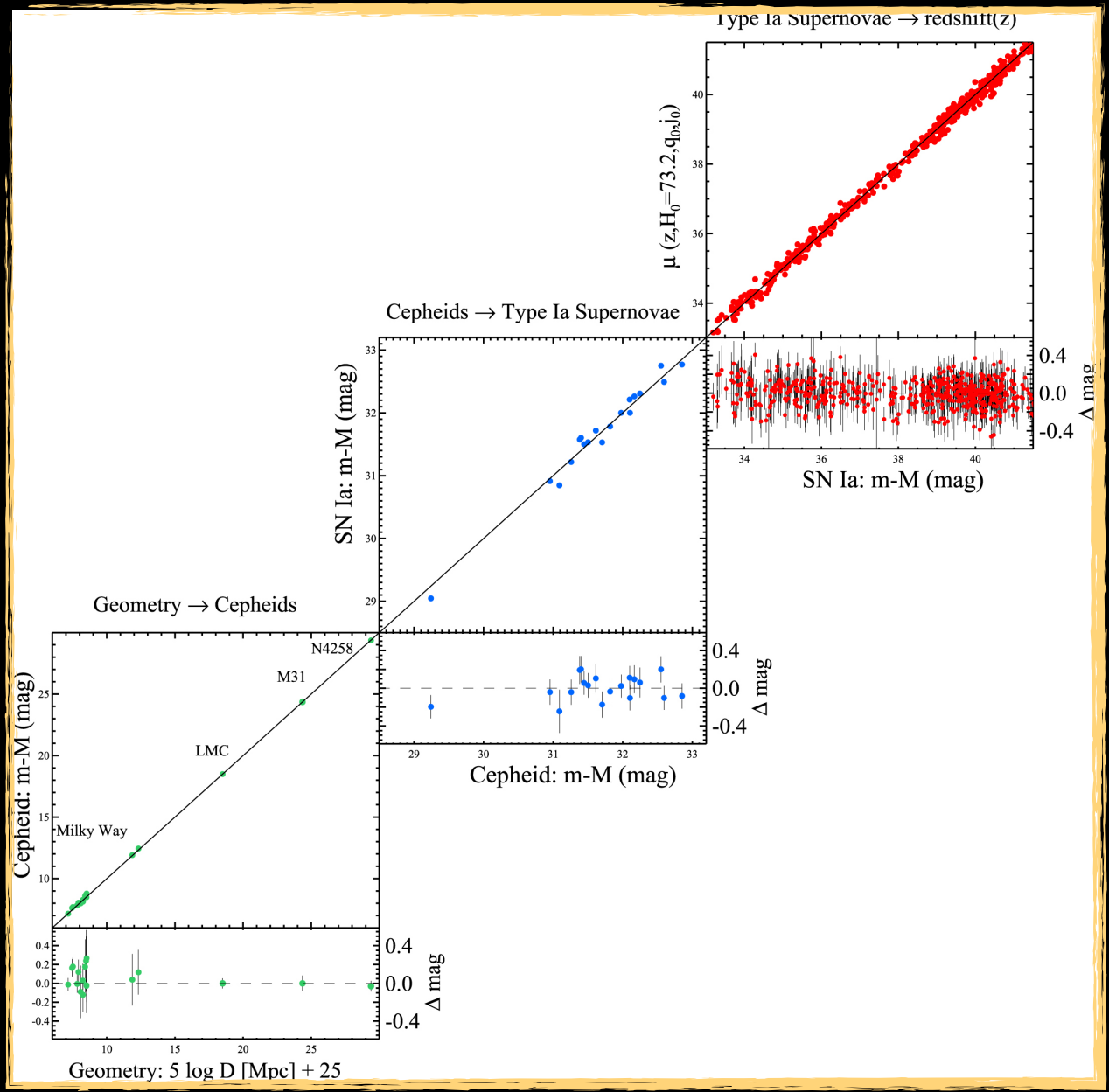
- The SH0ES (Supernovae and H_0 for the Equation of State) HST programme (PI Adam Riess) aims at measuring H_0 to percent precision to constrain Dark Energy. Three rung stellar distance ladder:
  - Cepheids to calibrate the peak luminosity of Supernovae type Ia that are, then, used to measure H_0 in the Hubble flow

Courtesy: Adam Riess

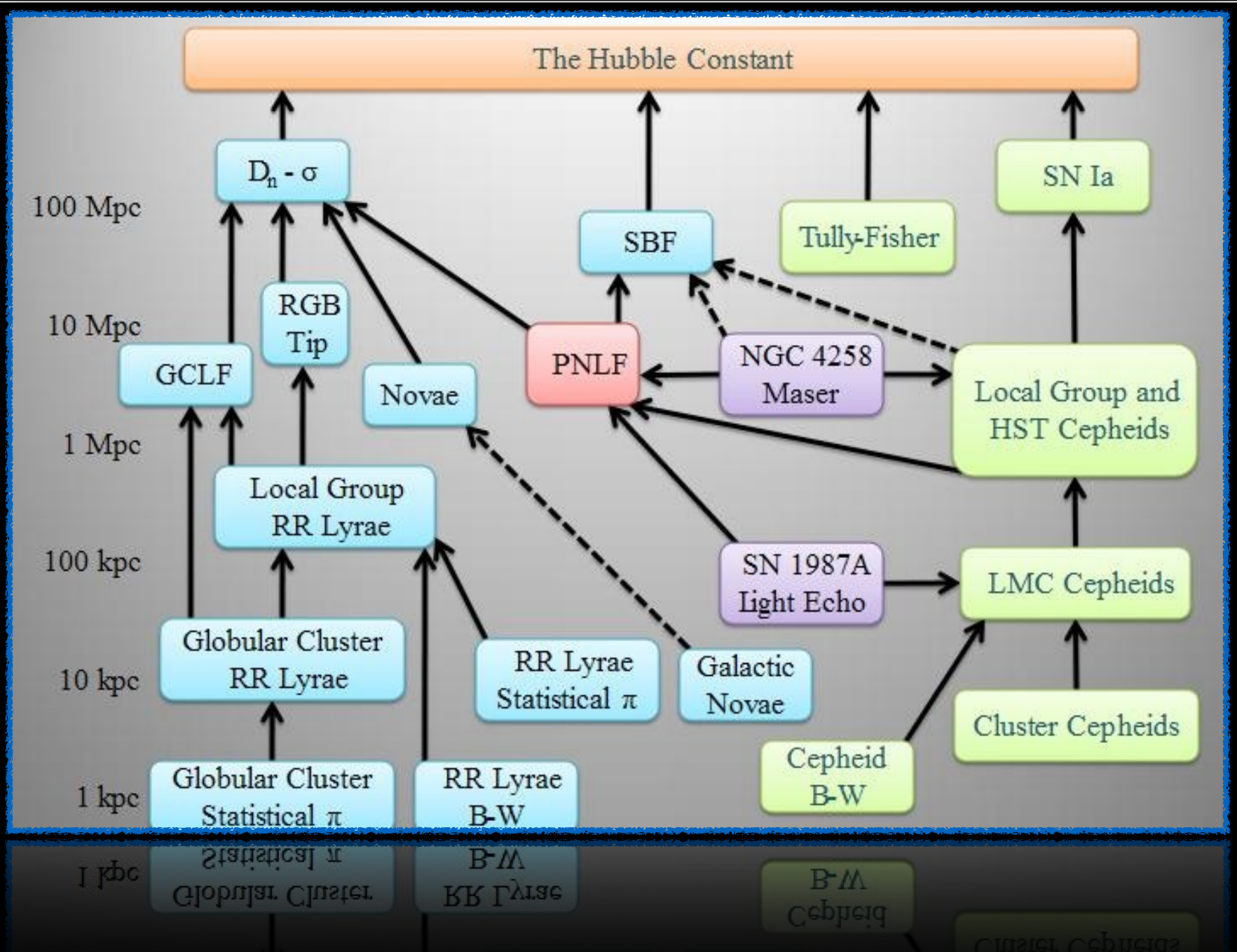


The SH0ES distance ladder

Riess et al (2016, ApJ, 826, 56)

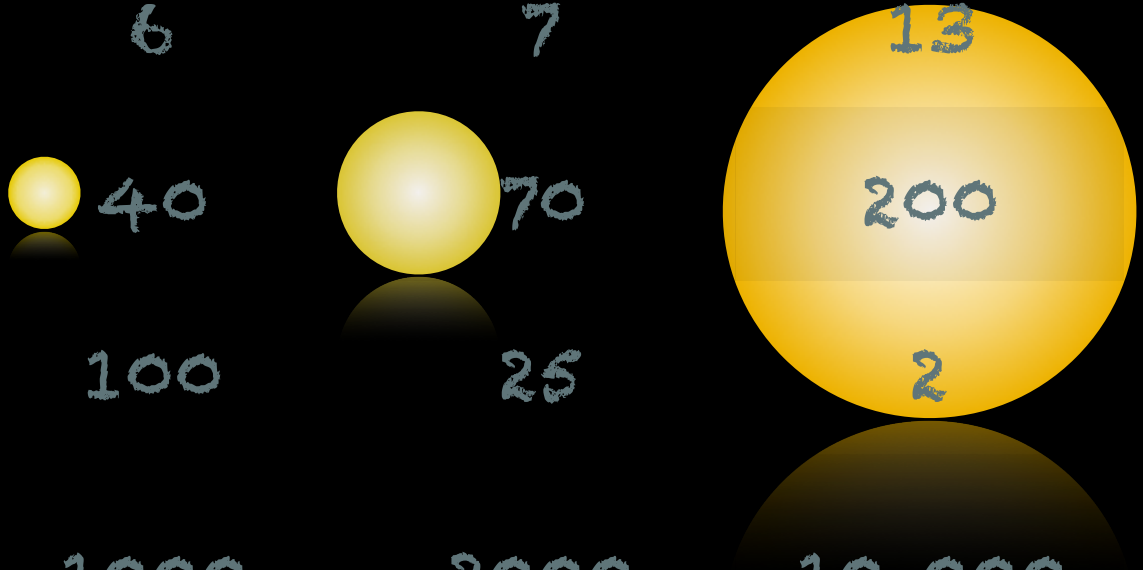


The extragalactic distance ladder



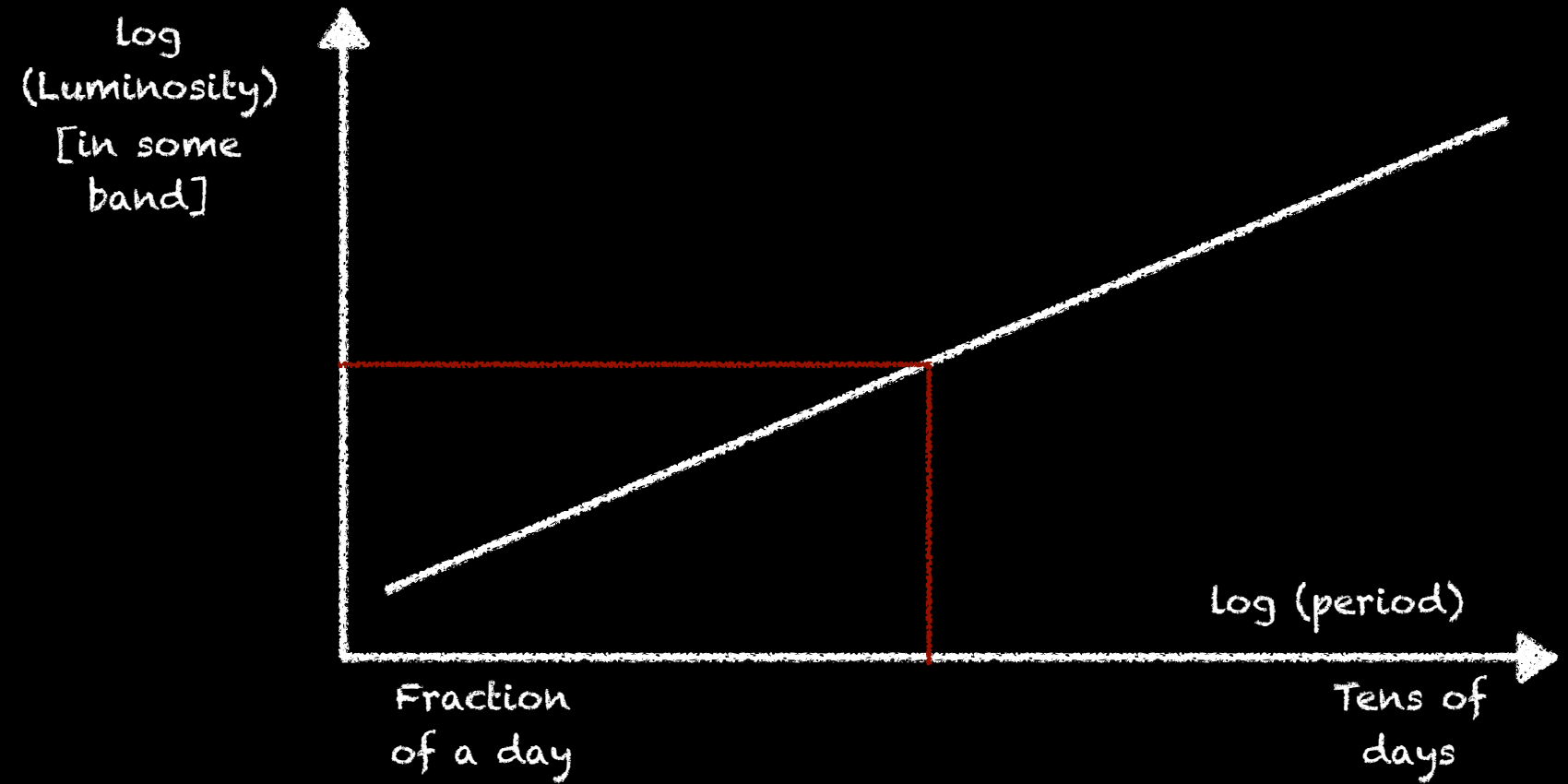
Cepheid primer

Period	5 days	10 days	40 days
Mass (sun)	6	7	13
Radius (sun)	40	70	200
Density (g/m^3)	100	25	2
Luminosity (sun)	1000	2000	10 000
Temperature (K)	6000	5600	5300
Age (Myr)	75	50	15



Courtesy of Pierre Kervella

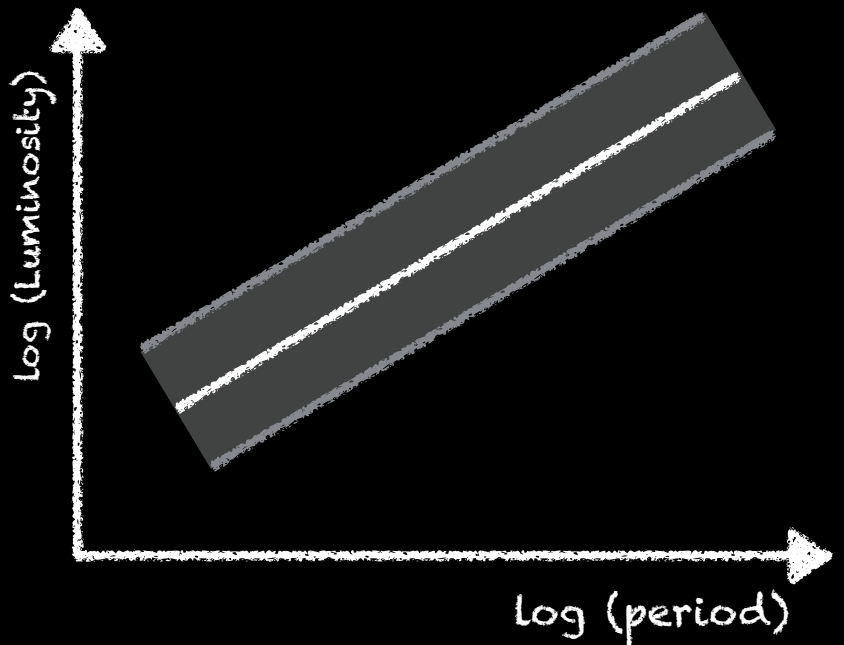
Cepheids as standard candles



- The principle is simple: measure the period, infer the star's absolute luminosity from Leavitt's relation (L), compare it with the measured one (l) and, presto!, get the distance: $d=(L/l)^{1/2}$ [10 pc]

Cepheids as standard candles

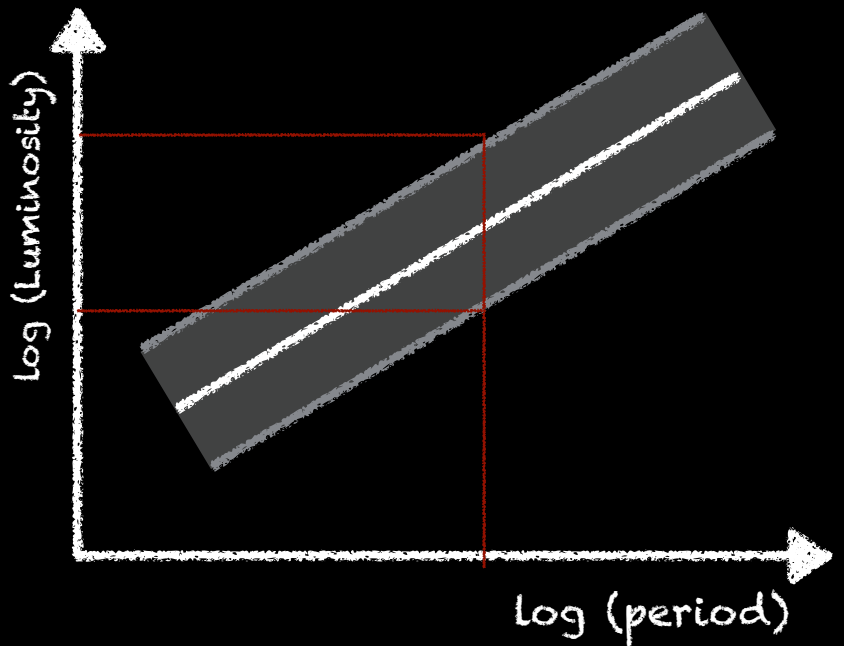
- Things are not quite that simple, because Leavitt's relation is not a line, it is actually a strip...



- Sandage (1958): "...the possibility exists that the PL relation is not unique and the scatter real...the existence of an intrinsic scatter in the P=f(L) suggests that a third parameter is involved...in what follows, a semi-theoretical relation is found which indeed involves three parameters [the third being (B-V)]..."

Cepheids as standard candles

- Things are not quite that simple, because Leavitt's relation is not a line, it is actually a strip...



- ...which means that there is an intrinsic limitation to the accuracy with which distances to individual stars can be determined: 15-20% at optical wavelengths, a few % in the near-infrared
- The accuracy of the distance to a group of stars scales ~ with the square root of number of stars themselves

The Wesenheit magnitude

- Period-Luminosity-Color relationships with the colour term determined not by Cepheid physics, but by some extinction law R

$$W(i,j,k) = m_i - \frac{R_i}{R_j - R_k} \times (m_j - m_k)$$

- W is "reddening-free"...

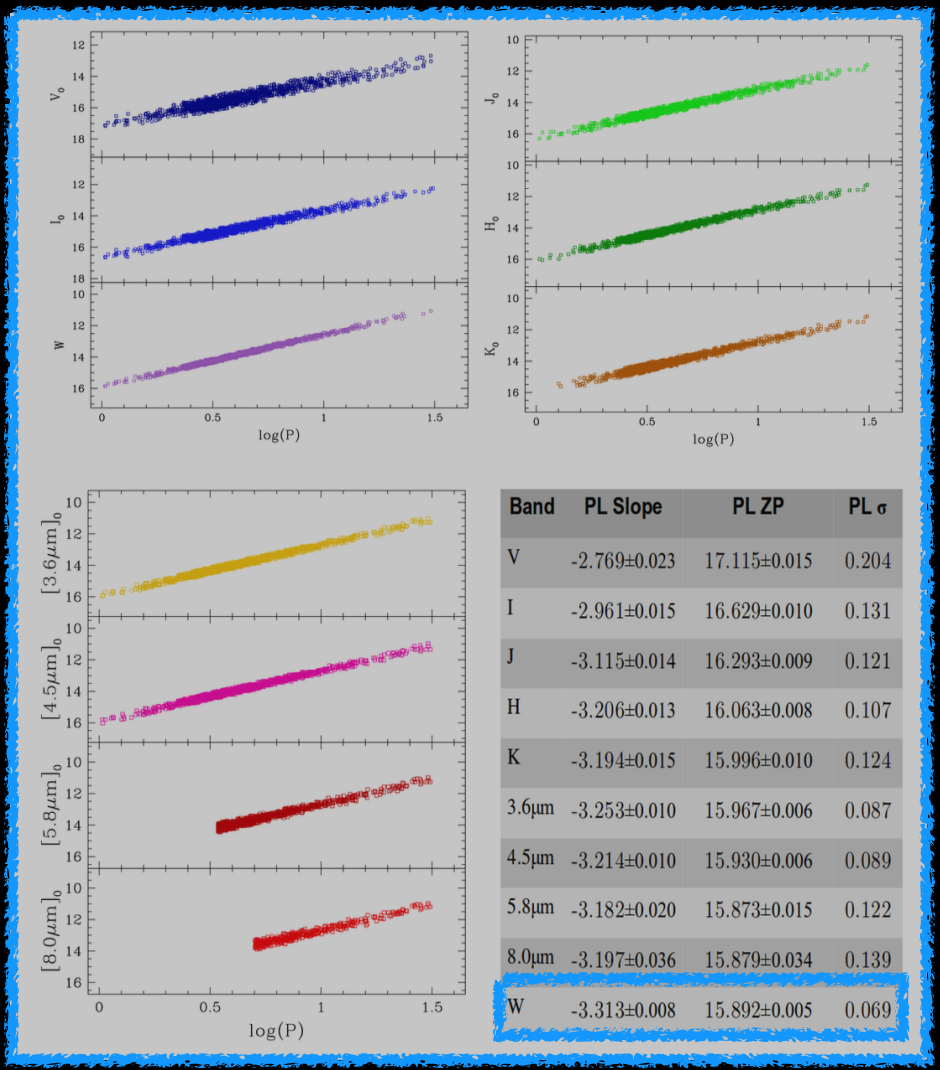
$$W(i,j,k) = m_{i,0} + \mathrm{A}_i - \frac{R_i}{R_j - R_k} \times (m_{j,0} - m_{k,0} + E(j-k)) = W_0(i,j,k)$$

- ...if R is known and small

The Wesenheit magnitude

- For selected combinations of bands, the scatter is indeed reduced

Ngeow and Kanbur (2016)



Band	PL Slope	PL ZP	PL σ
V	-2.769±0.023	17.115±0.015	0.204
I	-2.961±0.015	16.629±0.010	0.131
J	-3.115±0.014	16.293±0.009	0.121
H	-3.206±0.013	16.063±0.008	0.107
K	-3.194±0.015	15.996±0.010	0.124
3.6μm	-3.253±0.010	15.967±0.006	0.087
4.5μm	-3.214±0.010	15.930±0.006	0.089
5.8μm	-3.182±0.020	15.873±0.015	0.122
8.0μm	-3.197±0.036	15.879±0.034	0.139
W	-3.313±0.008	15.892±0.005	0.069

- OGLE

$$W(V, I) = I - 1.55 \times (V - I)$$

- SHOES (Riess et al 2016)

$$W(H, V, I) = H - 0.410 \times (V - I)$$

- Über-Wesenheit (Nataf et al 2016)

$$W(I, I, J) = I - 1.61 \times (I - J)$$

LACES

Locking the Abundances of Cepheids for SHOES

LACES

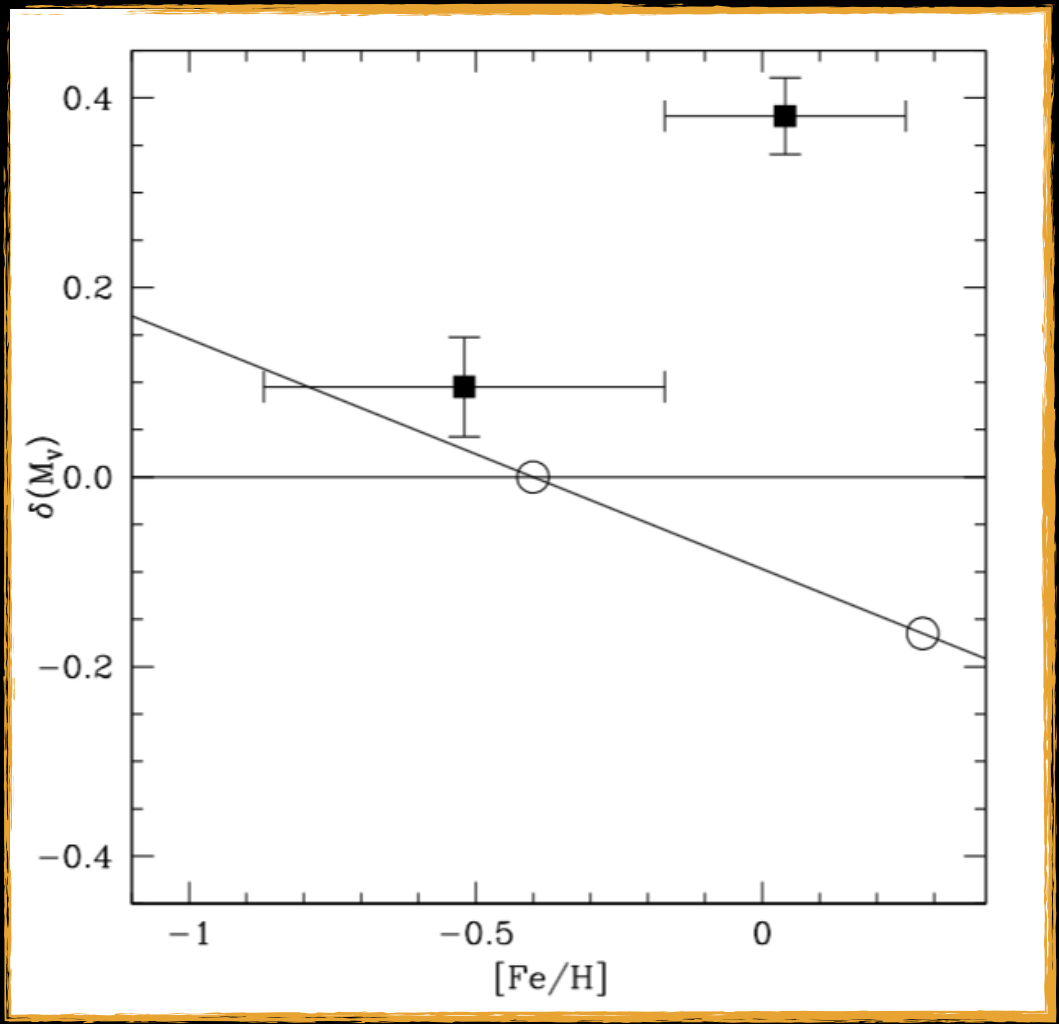
Accurately and precisely assess the influence of chemical composition on the SH$_0$ES Cepheid-SNIa distance ladder for H$_0$ to better than 2%

- Step 1. Magellanic Clouds (50 kpc): 1% calibration of Cepheid stars as standard candles
- Step 2. Magellanic Cloud sub-sample in the infrared (IR): calibrate potential wavelength-dependent systematics
- Step 3. IR Cepheids and Red Supergiants in the same galaxy (NGC6822, 0.5 Mpc): check for stellar population systematics
- Step 4. IR Red Giant Super Star Clusters: actual stellar chemical composition in the SHOES galaxies used to measure H$_0$ (20-30 Mpc)

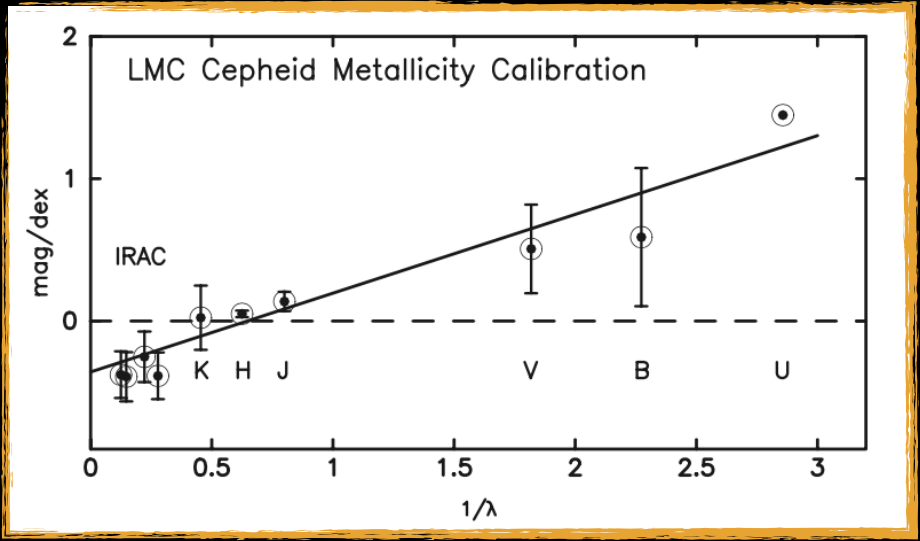
The people

- The LACES collaboration...
  - Romaniello (PI), Riess, Bono, Macrì, Kudritzki, Freudling, Inno, Casertano, Fiorentino, Urbaneja, Groenewegen, Storm, Anderson, Pietrzynski, Gieren, Lee, Ngeow, Kanbur, Matsunaga, Primas, Bresolin, Nonino, Bergemann, Bastian, Davies, Lardo, Patrick, Evans, Bergemann, Mancino, Bhardwaj
  - Conceived at the 2014 MIAPP workshop "The Extragalactic Distance Scale"
- ...and other local connections
  - Kudritzki, Suyu, Weller, Weiss, Bender, ...

Cepheids and chemical composition



Romaniello et al (2008, A&A, 488, 731)



Freedman & Madore (2011, ApJ, 734, 46)

The chemical ladder to H_0

- **Step 1.** Magellanic Clouds (50 kpc): 1% calibration of Cepheid stars as standard candles
- **Step 2.** Magellanic Cloud sub-sample in the infrared (IR): calibrate potential wavelength-dependent systematics
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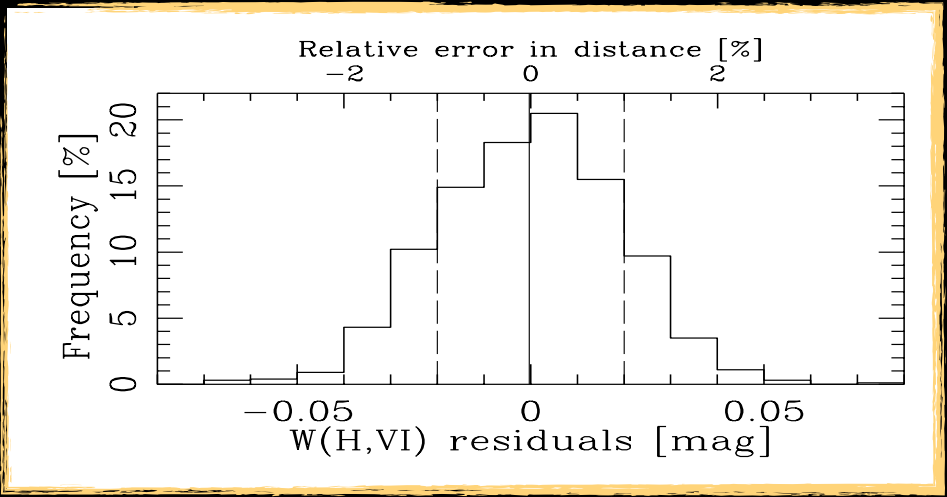
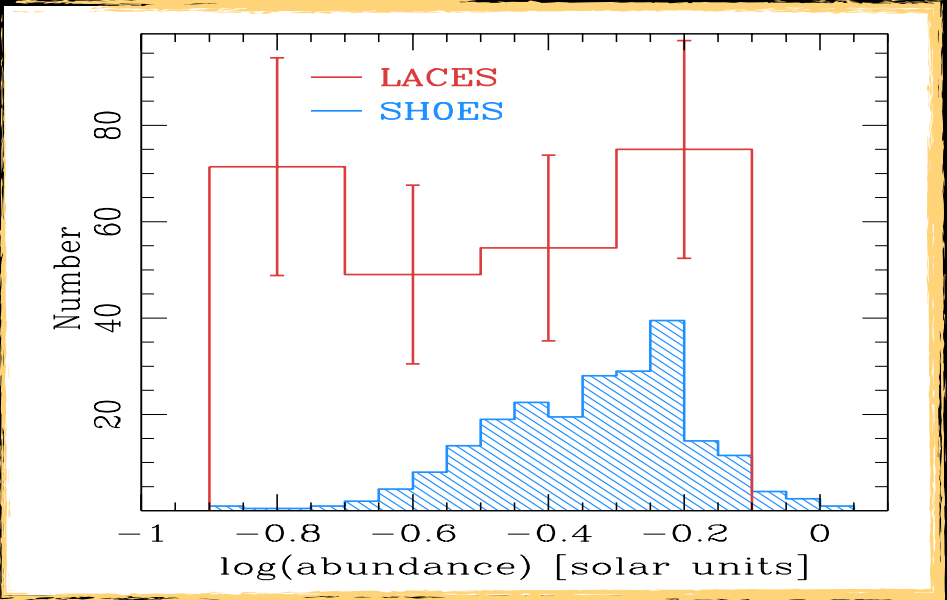
- **Step 4.** IR Red Giant Super Star Clusters: actual stellar chemical composition in the SHOES galaxies used to measure H_0 (20-30 Mpc)

Calibrating Cepheids to 1%

- Statistical ensembles of Cepheids

- 30 Cepheids per bin of metallicity: residuals on distance to 1%
- 5 metallicity bins to cover the range of SH$_0$ES galaxies
- 5 FLAMES@VLT pointings on the Magellanic Clouds in 4 settings (7.5+3 nights)



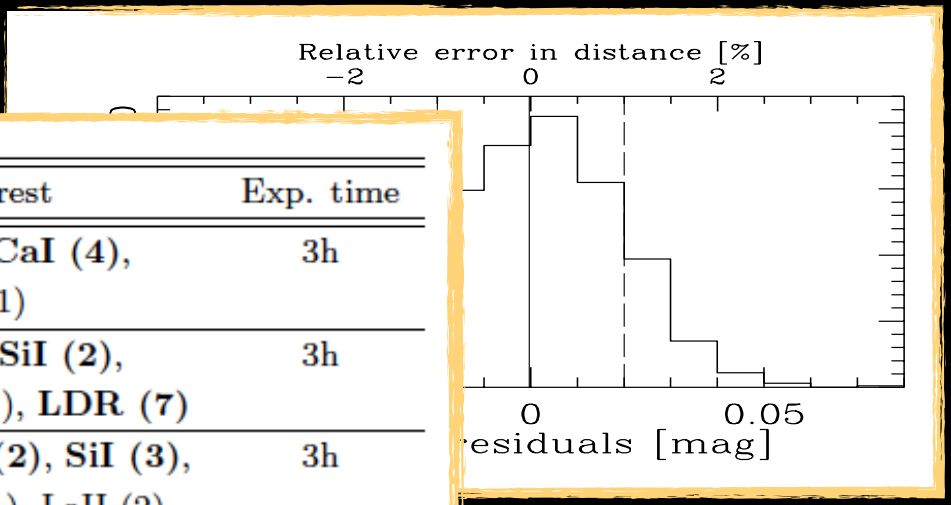


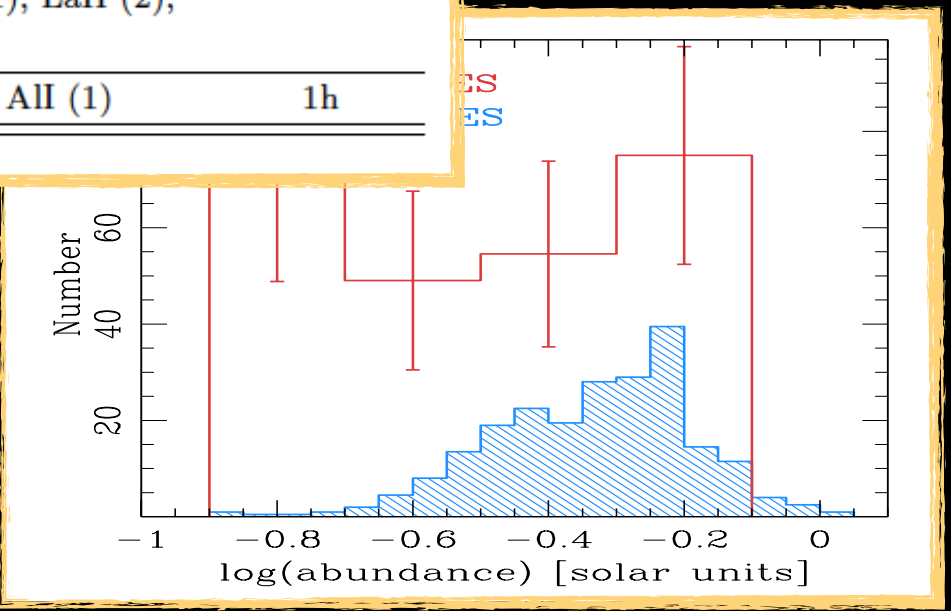
Calibrating Cepheids to 1%

- Statistical ensembles of Cepheids

- 30 Cepheids per bin of metallicity; distance to
- 5 metallici the range galaxies
- 5 FLAMES@VLT pointings on the Magellanic Clouds in 4 settings (7.5+3 nights)

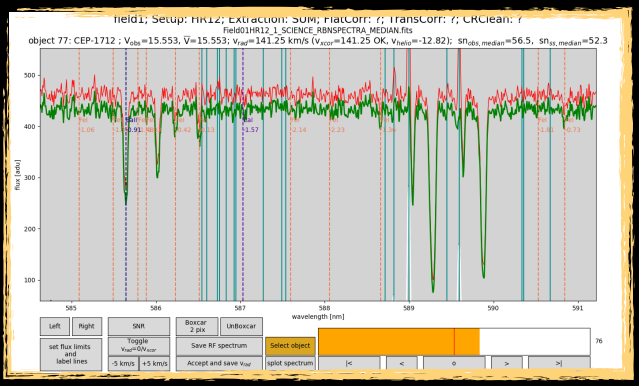
Setting	Elements of interest	Exp. time
HR10	**FeI (36)**, **FeII (4)**, **CaI (4)**, CeII (1), YII (1)	3h
HR12	**FeI (38)**, **FeII (2)**, **SiI (2)**, CaI (1), BaII (2), CeII (1), **LDR (7)**	3h
HR13	**FeI (31)**, **FeII (5)**, **OI (2)**, **SiI (3)**, CaI (1), NaI (2), BaII (1), LaII (2), **LDR (12)**	3h
HR21	**FeII (3)**, **MgI (2)**, AlI (1)	1h

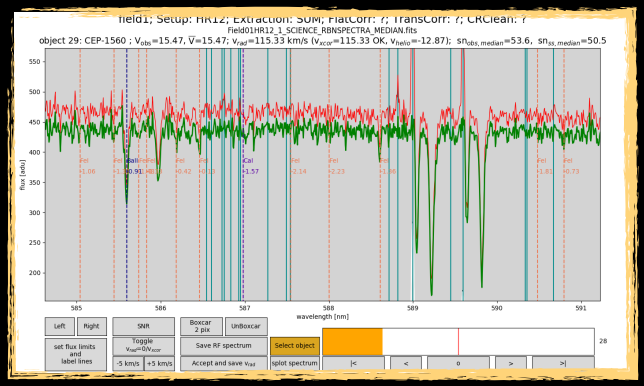


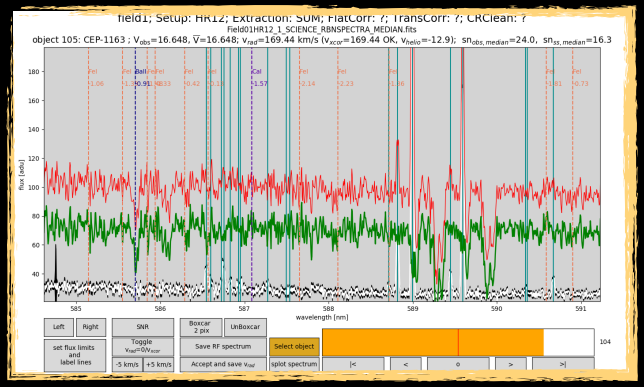


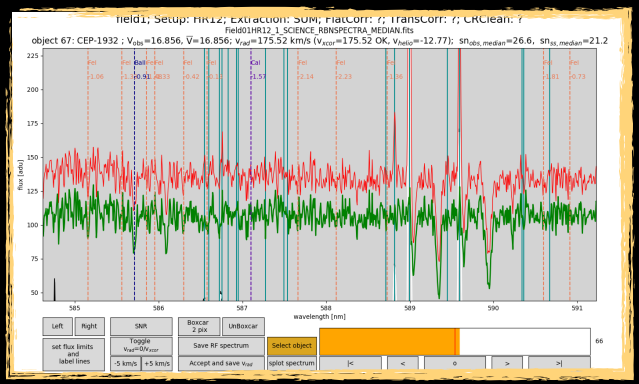
LACES data - I

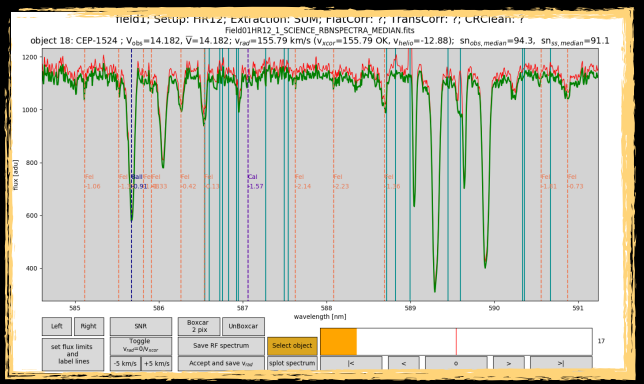
Giraffe spectra of Magellanic Cloud Cepheids

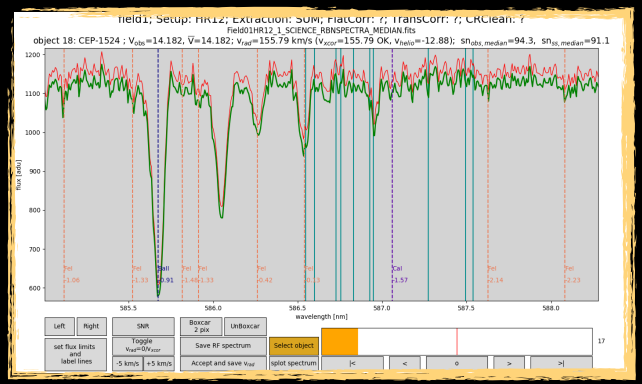


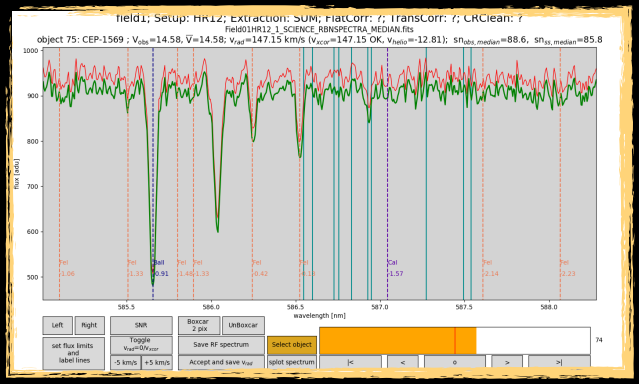


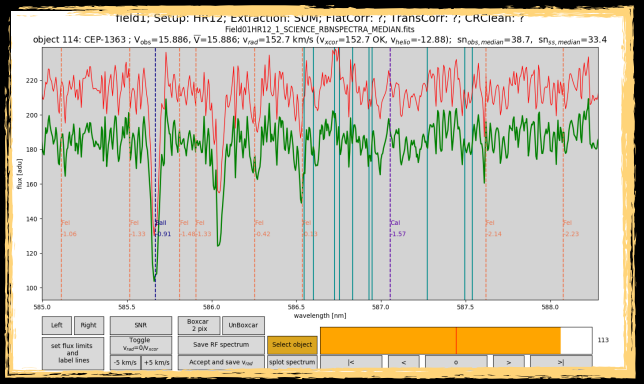


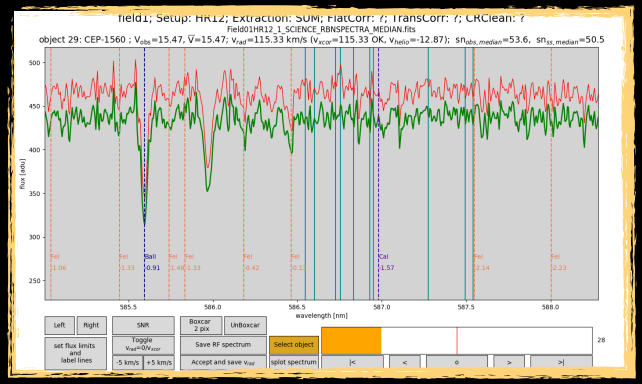






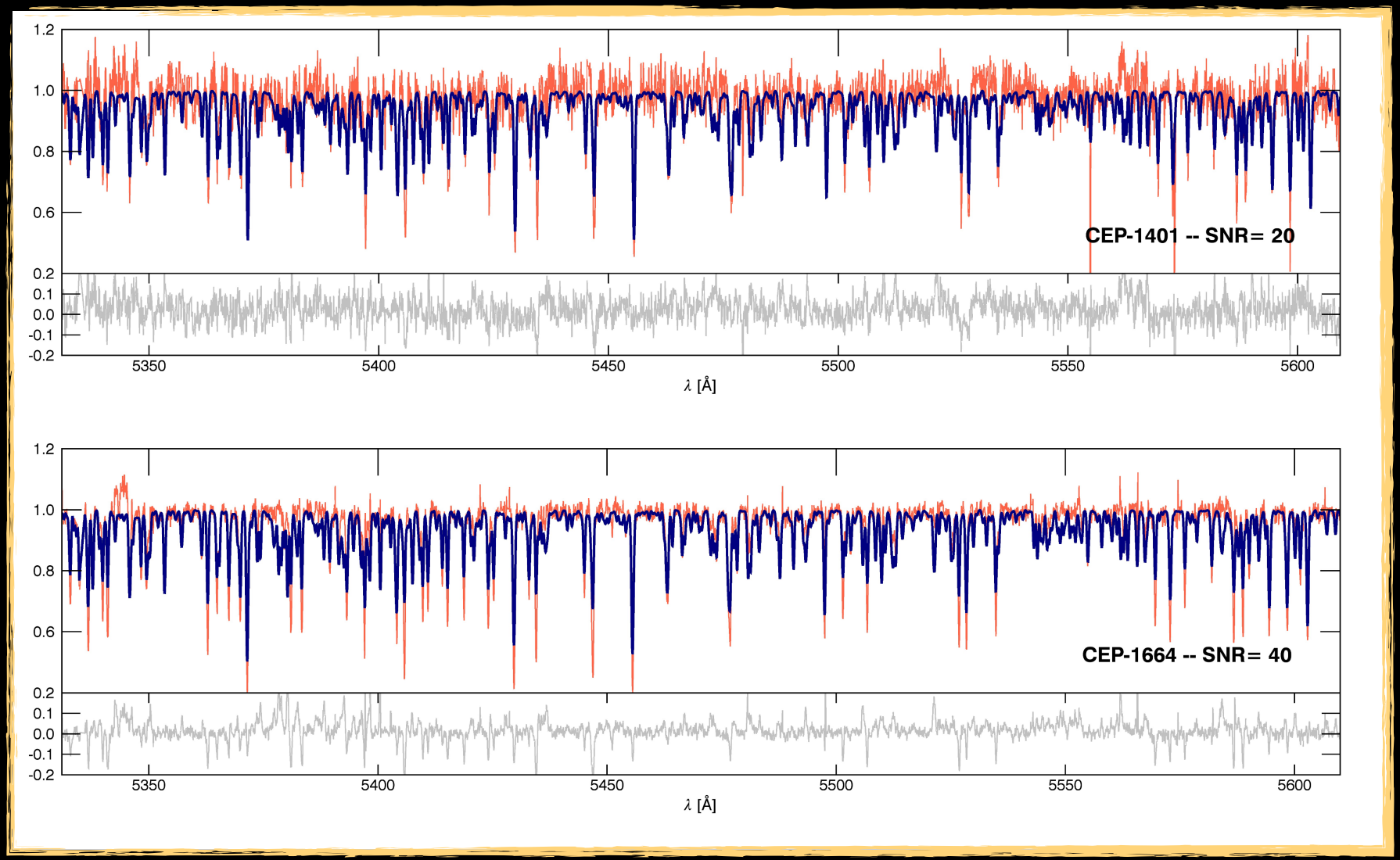






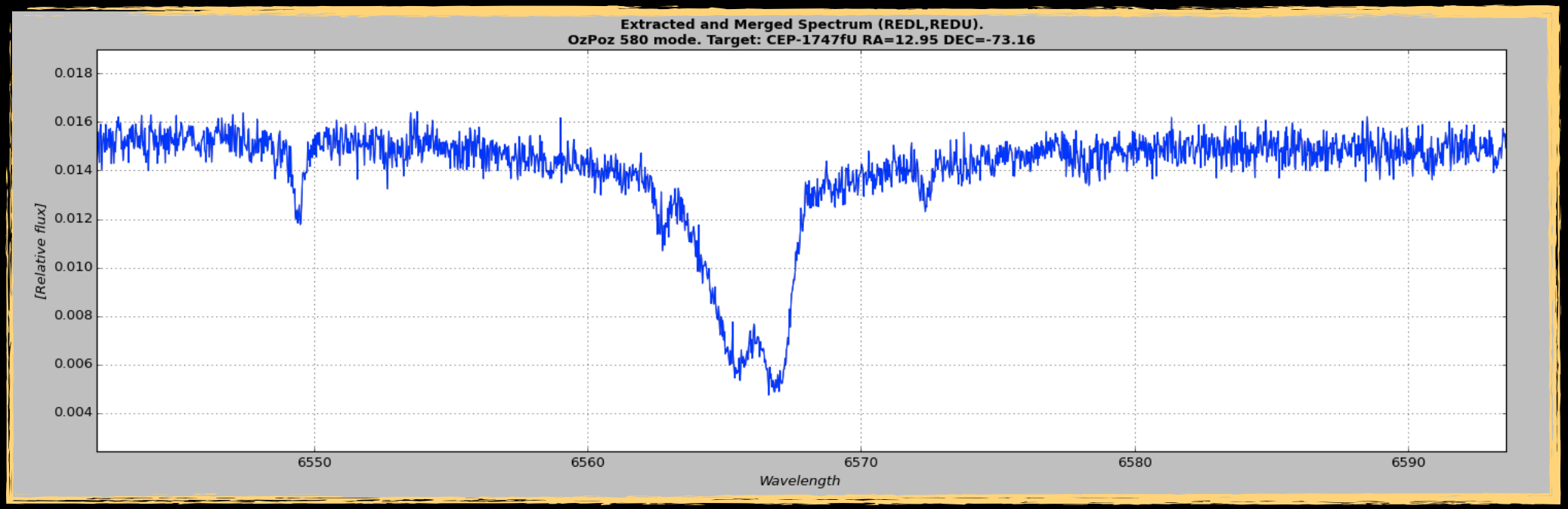
LACES data - II

Custom non-LTE stellar atmosphere models



LACES data - III

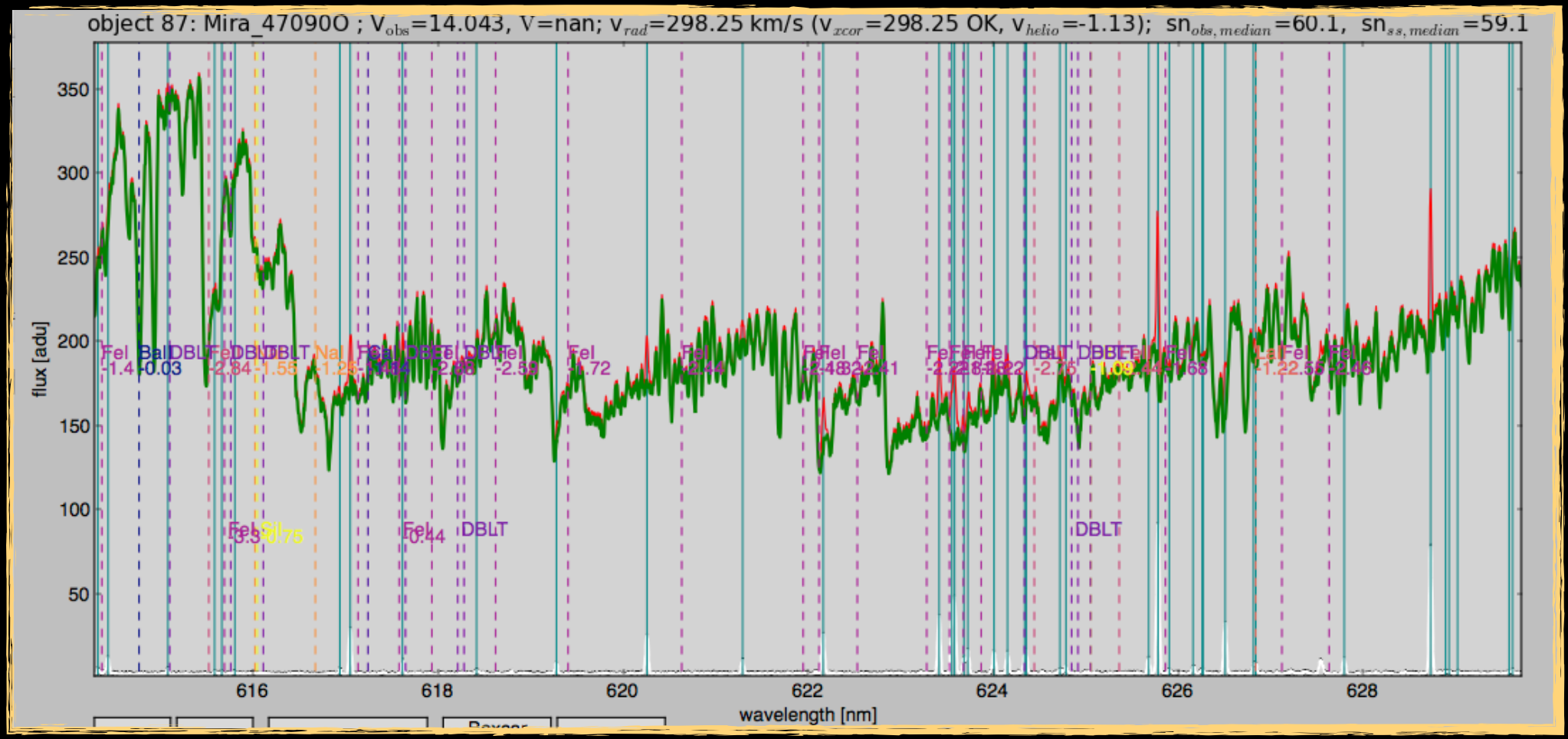
Hα from FLAMES-UVES (1 exposure out of 18)



Shock near minimum light (maximum compression)

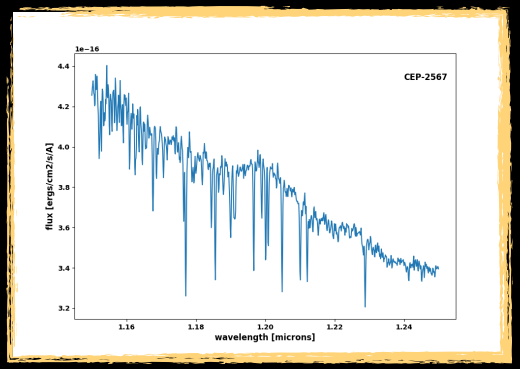
Spare fibre science

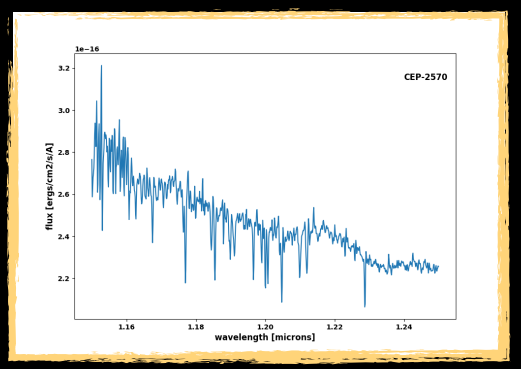
Miras in the LMC

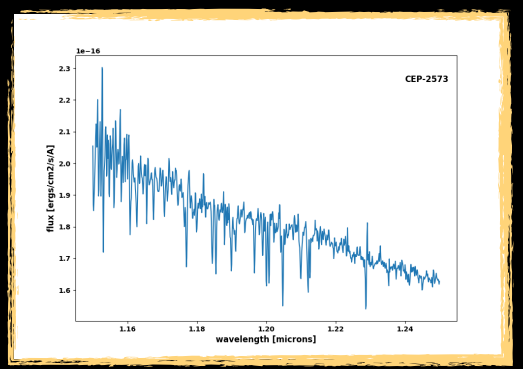


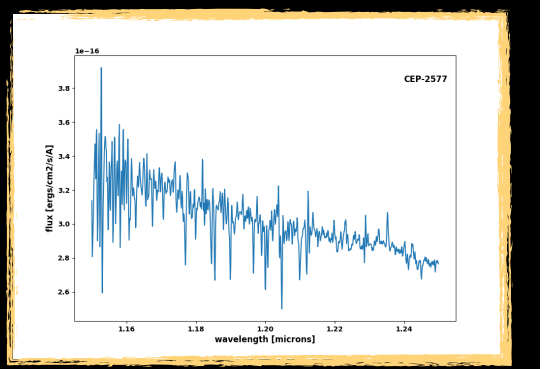
LACES data - IV

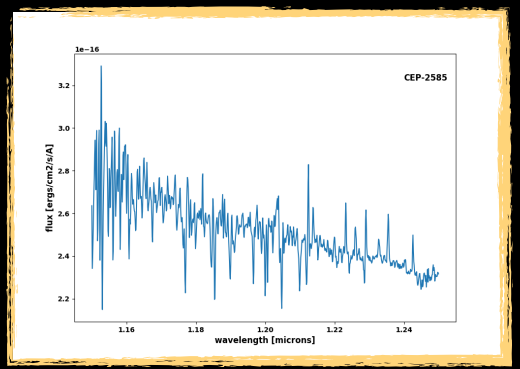
KMOS spectra of Magellanic Cloud Cepheids

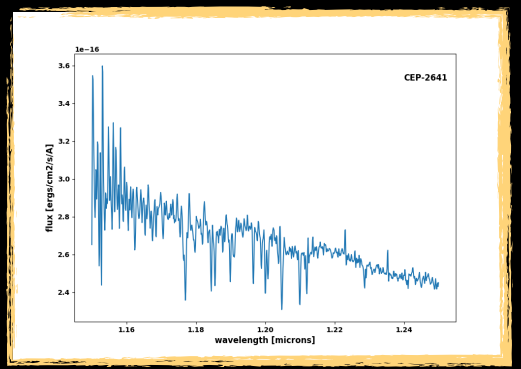


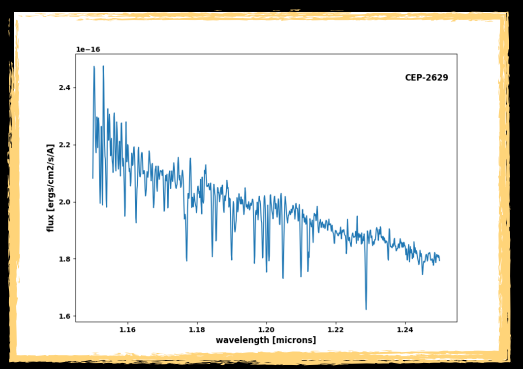


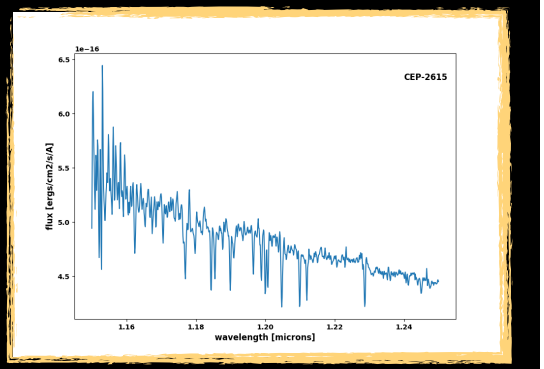


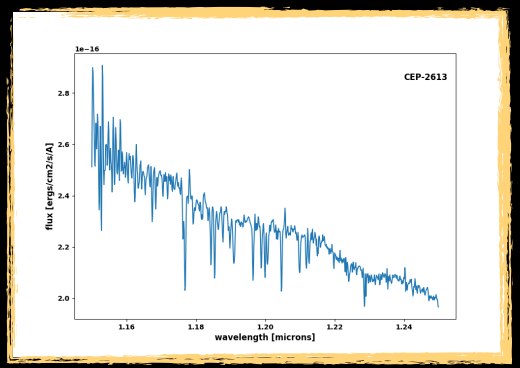


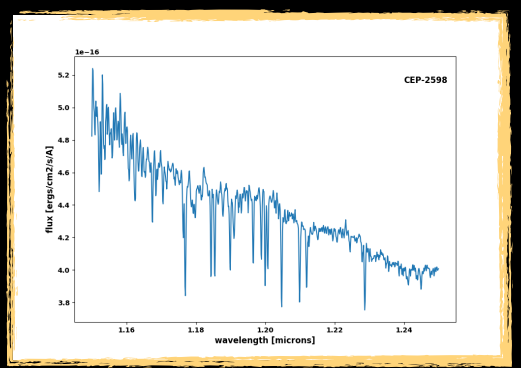


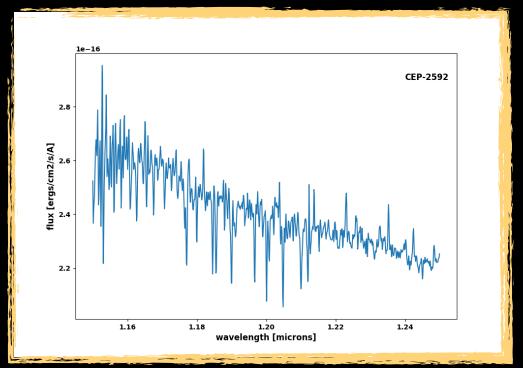


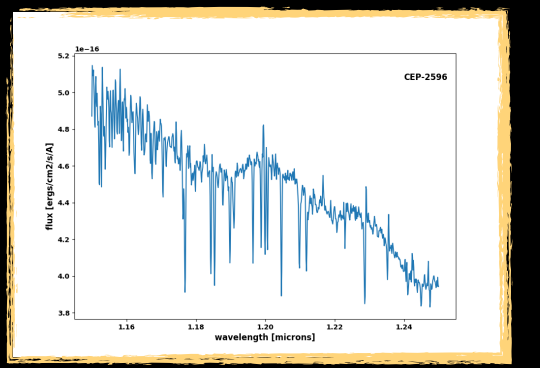






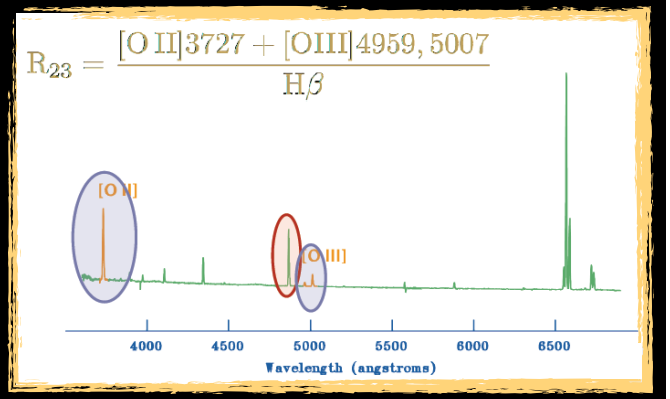


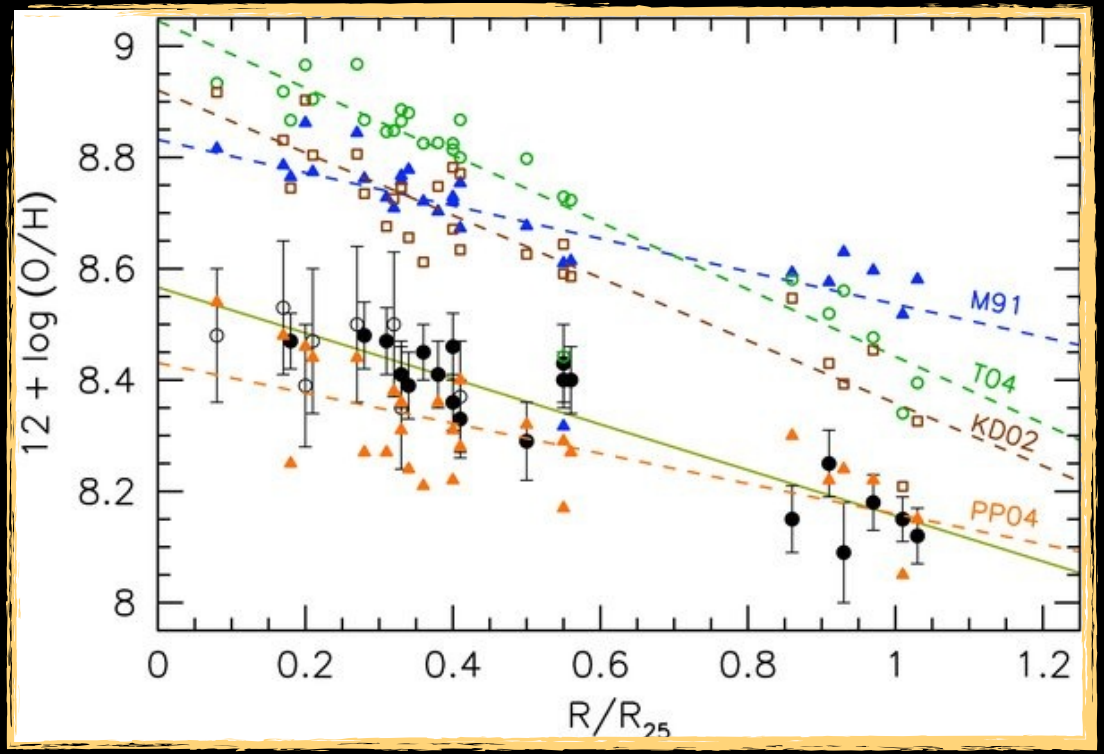




Extragalactic abundances

- HII region abundances from strong lines are very sensitive to poorly constrained detailed local conditions: electron temperature and density, nature of the ionizing stars, gas inhomogeneities, filling factors, depletion onto dust



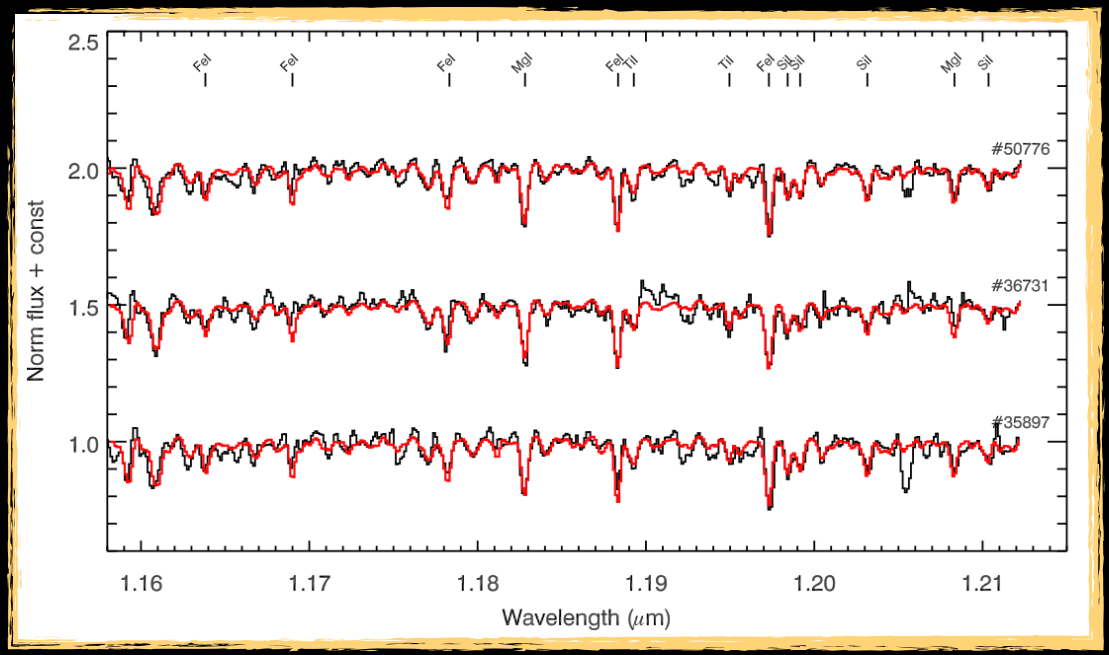


- Different calibrations have different shapes leading to variations in oxygen of several tenths of dex (Bresolin et al. 2009)

Extragalactic abundances from SSCs

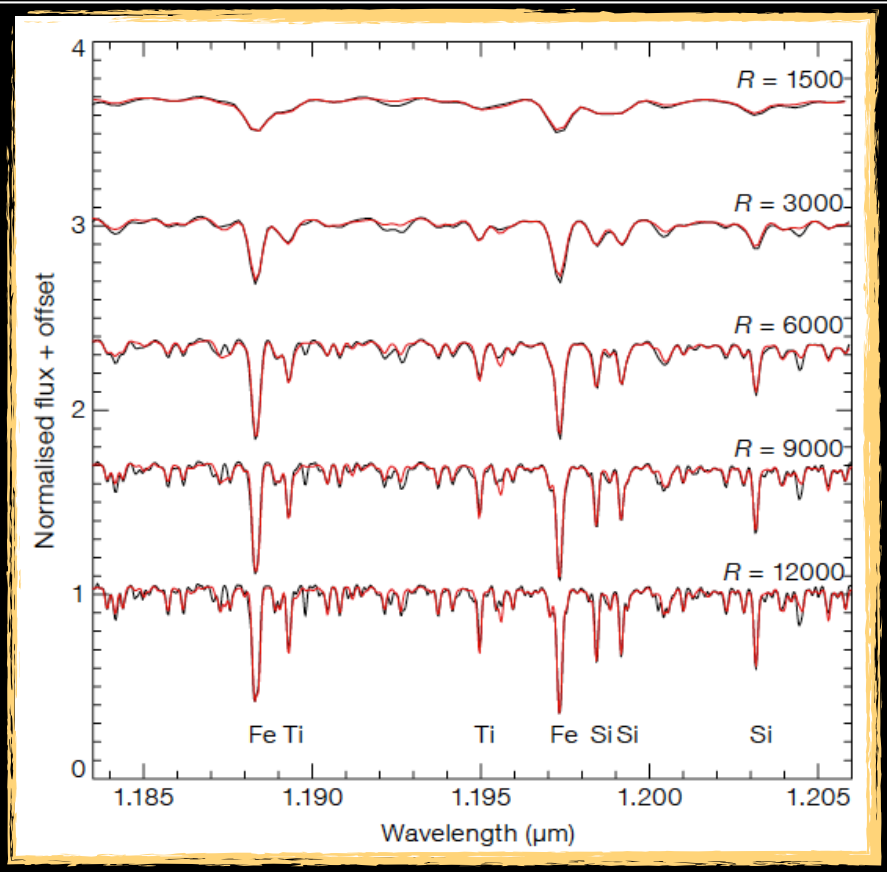
- **The problem:** how to measure reliable stellar abundances out to 15-20+ Mpc?
- **The solution:** Super Star Clusters (SSCs)!
  - Their integrated light is dominated by Red SuperGiants for which ±0.1 dex abundances can be derived from J-band spectroscopy at R≈2-3000 (Gazak et al 2014a,b)

Lardo et al (2015)
SSCs in the Antennae



Abundances from Red Supergiants

Gazak et al (2014)



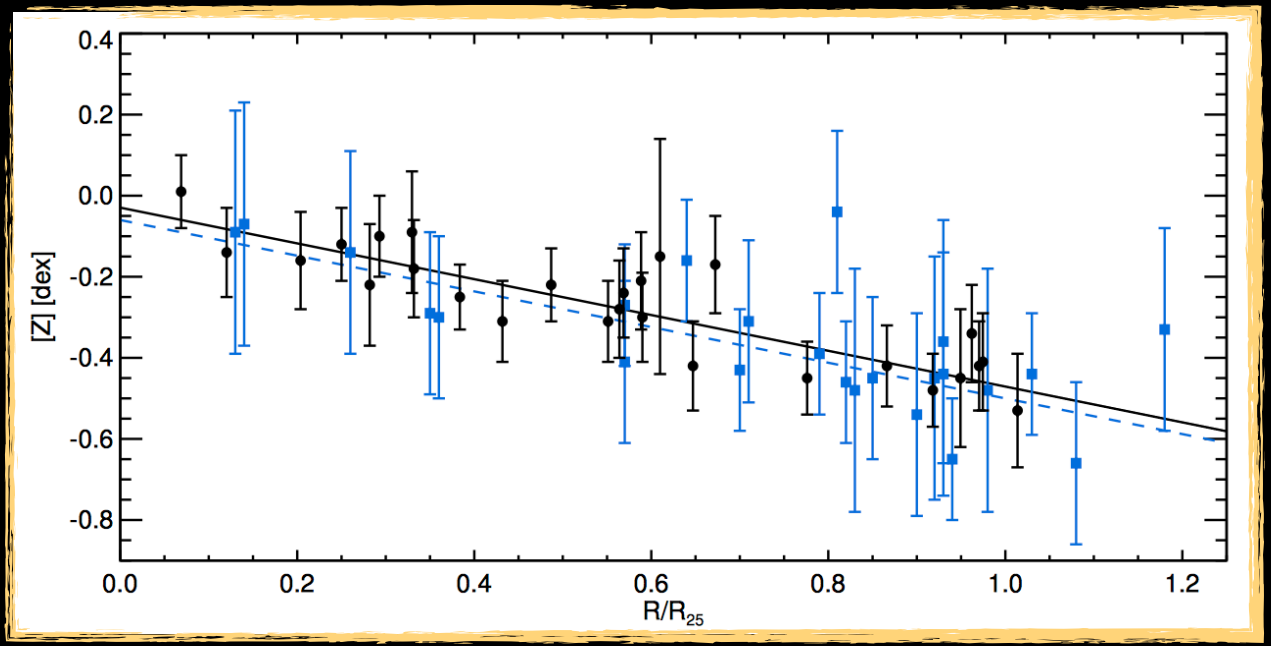
See also Davies et al 2015, The Messenger, 161, 32

- IRCS@Subaru spectrum of a Red Supergiant in Perseus, degraded in resolution down to 1500
- Abundance diagnostic lines in the J band are visible down to R=3000

Extragalactic abundances: RSGs and SSCs

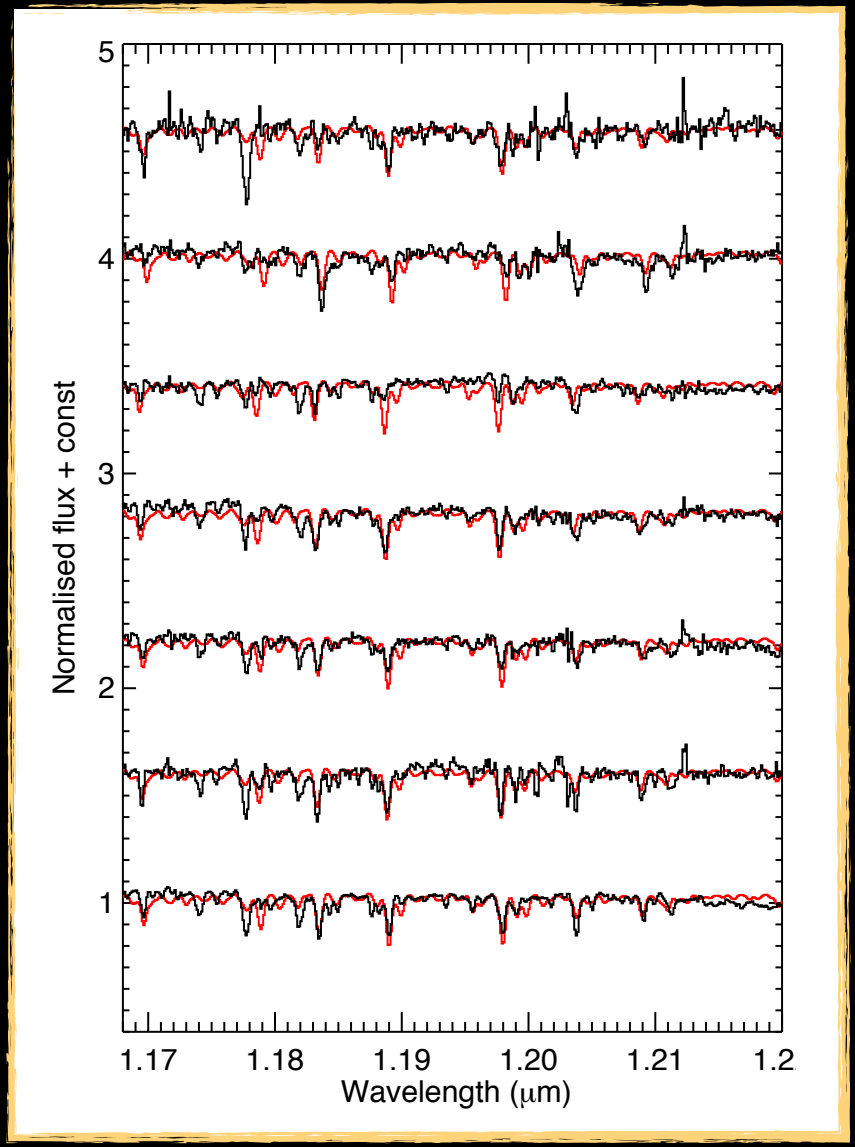
- Different stellar abundance indicators give very consistent results
  - HII region abundances from strong lines are typically overestimated by 0.2-0.3 dex

- E.g., metallicity gradient in NGC 300 from Blue and Red Supergiants (Gazak et al 2015)



LACES data - V

KMOS spectra of SuperStar Clusters in NGC1365



Courtesy of Ben Davies

In summary...

- Cosmic acceleration is arguably one of the most profound puzzles in contemporary physics
  - Its simplest explanation is quantum vacuum energy
  - All attempts to compute its value are many, many orders of magnitude too large: observations need to drive theory
- In combination with other data, a high precision local measurement of H_0 provides direct insight into the physics of the accelerating Universe
- We are going to provide a crucial missing piece towards measuring H_0 locally to ~1.5% with Cepheids-SNIas
  - ...or possibly prove that it's not actually attainable
- Plus quite some stellar astrophysics on spare fibres