Time-series photometry and light curves of periodic and transient phenomena

Erice, Oct 15th, 2015

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~~Time-series photometry and light curves of~~ Science with periodic and transient phenomena

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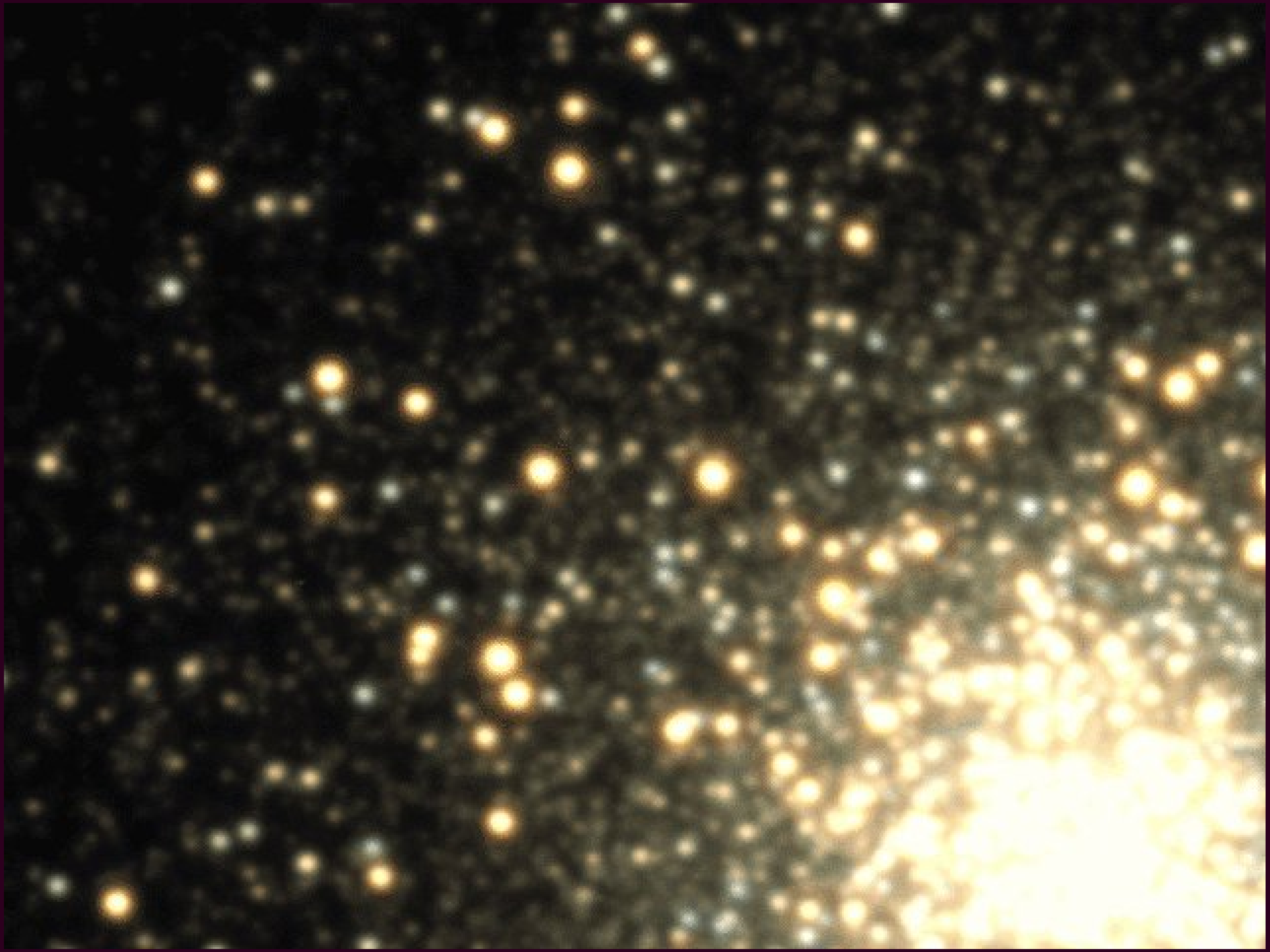
Why Variable Stars and Transients?

- Tracers of different stellar populations
- Physics Labs
- Standard Candles:
  - RR Lyrae → Old (≥ 10 Gyr) → all galaxies; distances within the LG
  - Cepheids → Young → disks, late type irregulars; distances up to ~ 25 Mpc
  - Type Ia SNe → ubiquitous; cosmological distances
  - Type IIP SNe (yes, type IIP SNe!) → young progenitors; current distances up to z ~ 0.4 (but we will go cosmological with E-ELT)
  - Type Ib, Ic and superluminous SNe as Standardizable Candles

Part I: RR Lyrae Stars observational properties

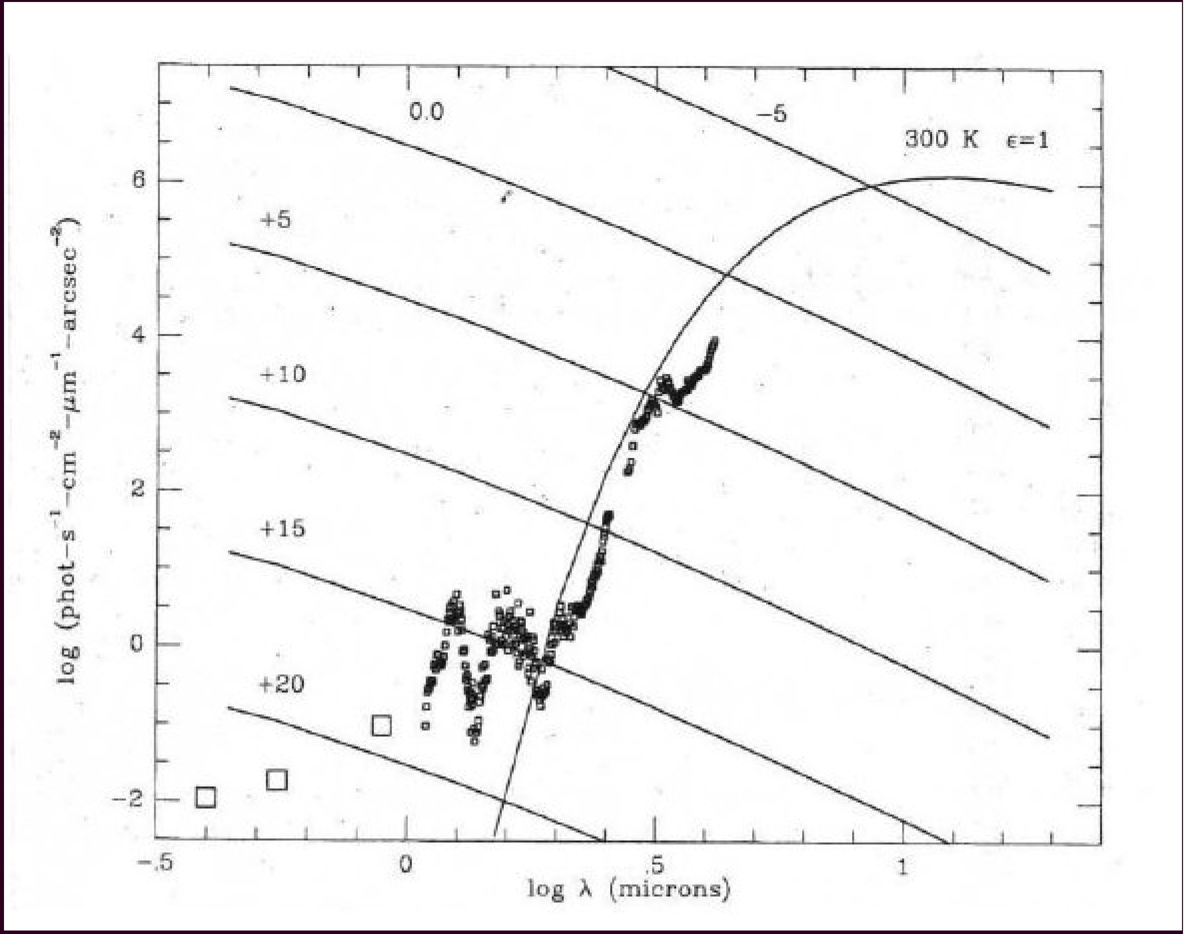
- Almost constant luminosity in the *V*-band, since their luminosity depends on the core mass (almost constant for the low-mass stars, due to degeneracy)
- Intrinsic brigthness *V* ~ 0.6 mag (some dependence on the metallicity)
- Periods between ~0.2 and ~ 0.8 days
- Magically, a Period-Luminosity relation appears in the *IJHK* bands, due to bolometric correction effects, with some dependence on the metallicity



M3, APOD, 2004 October 12

Now, let's move to Infrared

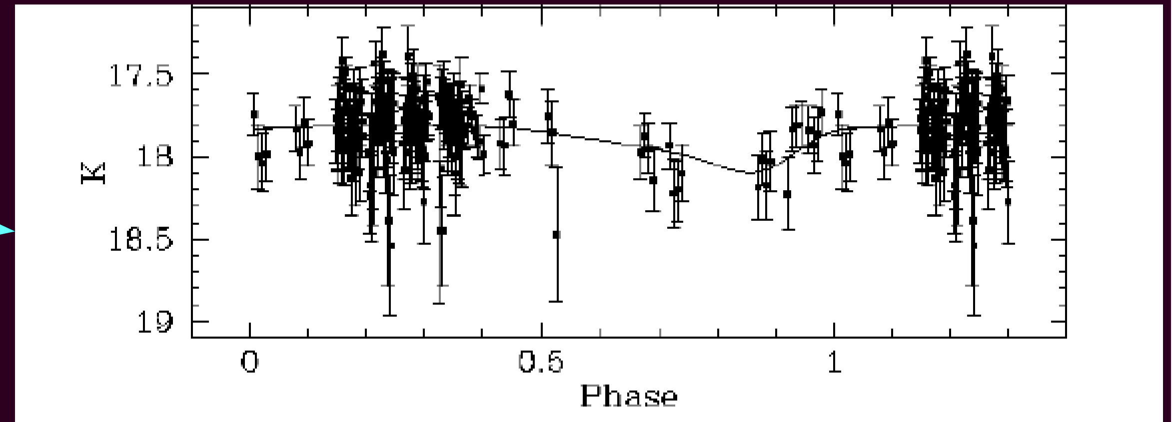
- Search and characterization of (not cold) pulsating variable stars in the NIR is a difficult task since:
  - the amplitude of the light curve is reduced
  - the sky is usually (even much) brighter than sources



Joyce, 1992

For example, to reach the LMC (at μ = 18.50 mag) with a 4-meter class telescope, this is the usual observed light curve...

Dall'Ora et al. 2004



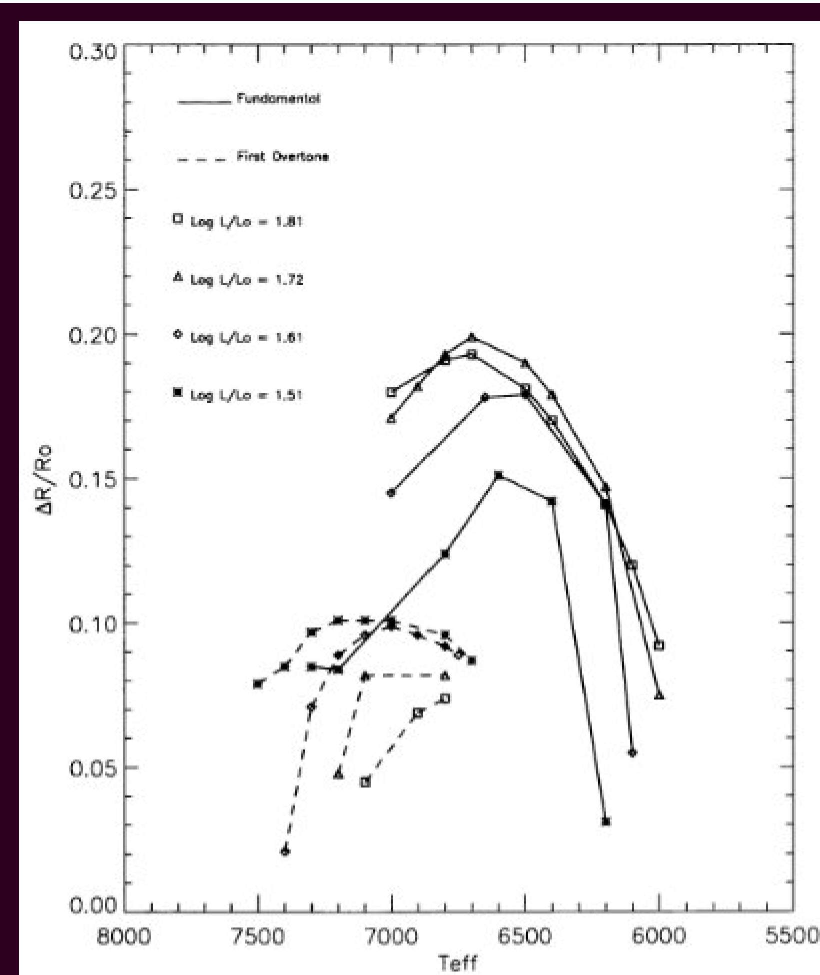
However, we can adopt long exposures (1 hr is safe, but be careful with the sky brightness!) than in the optical, since the blurring effect is reduced

The Physics behind is that at the optical wavelengths we trace basically temperature variations, but the NIR bands trace the radius variations

$$L = Flux * R^2$$

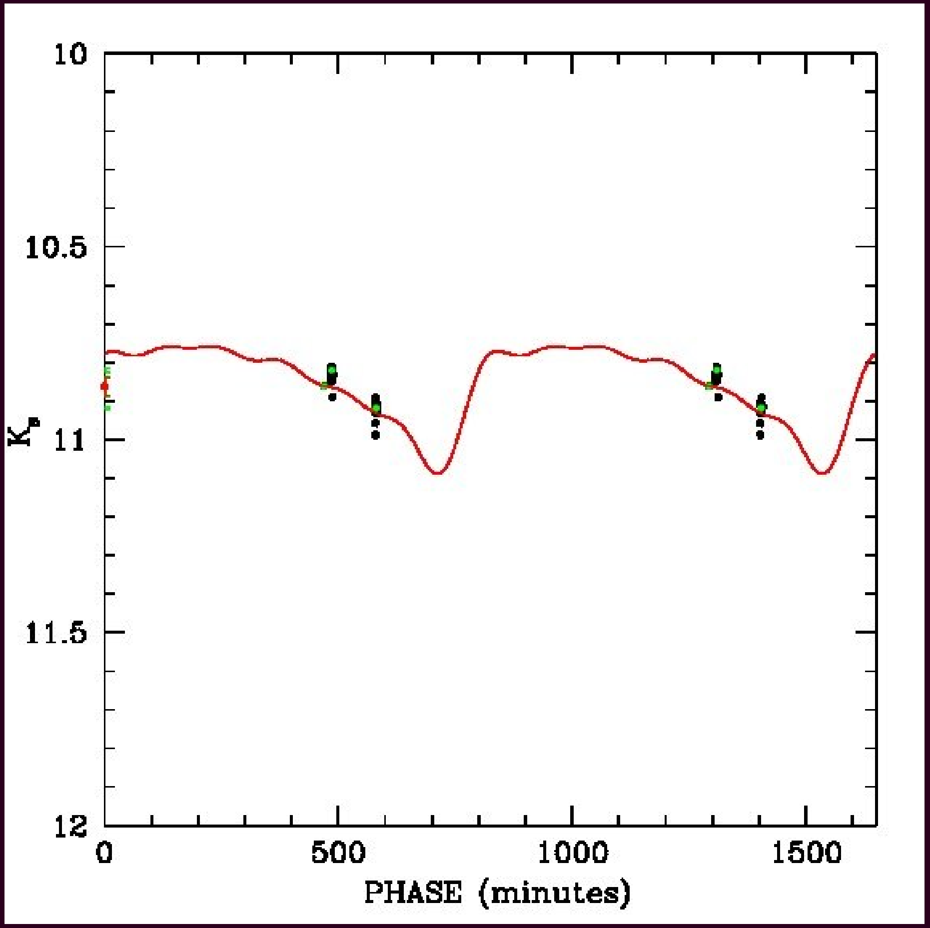
$$Flux\ \mu\ T \text{ (in the Rayleigh-Jeans tail)}$$

$$\rightarrow L\ \mu\ T * R^2$$



Bono & Stellingwerf, 1994

An important point

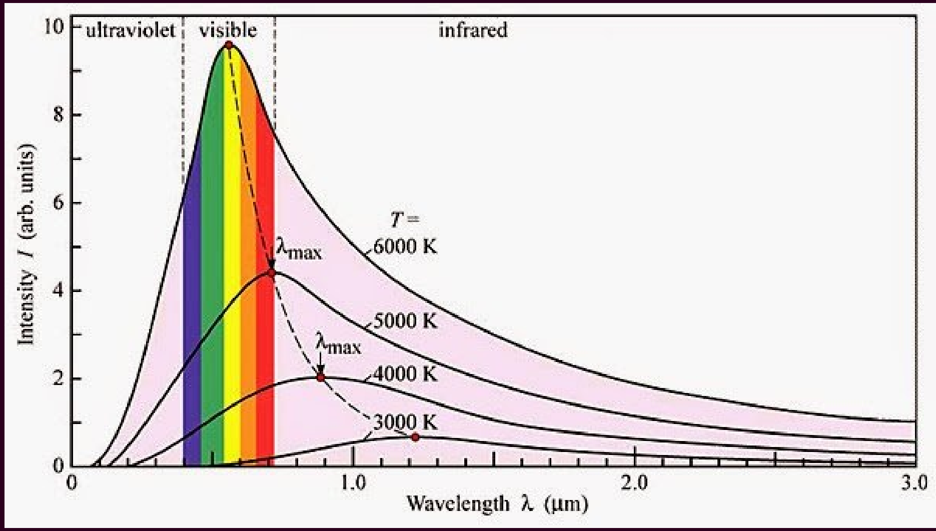


Can we really use exposure times as long as one hour, and still can correctly use the templates?

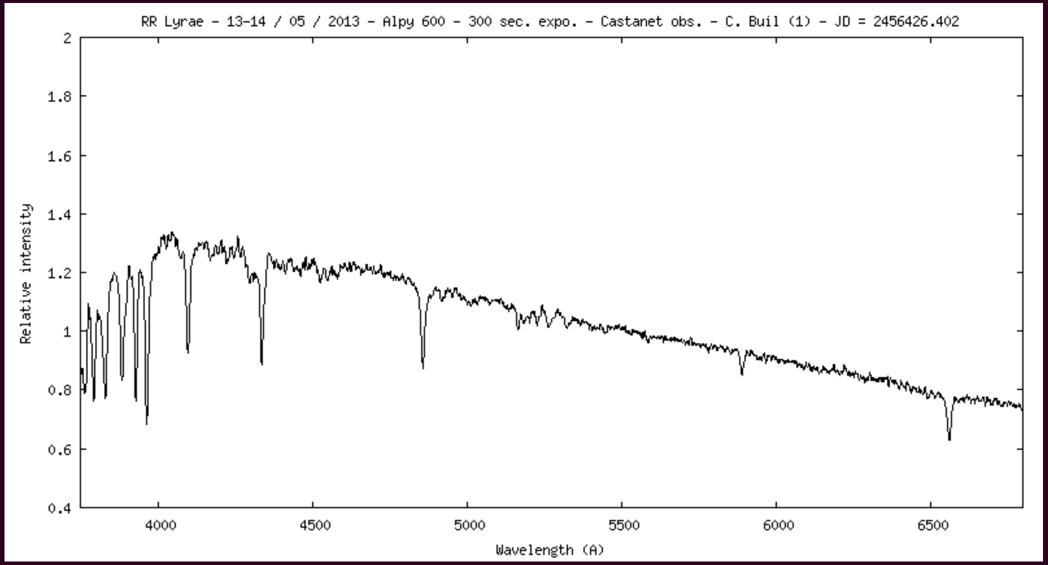
The answer is: "yes, but be careful", in the sense that you cannot trust the individual measurements, but the ensemble behavior

The RR Lyrae *K*-band Period-Luminosity relation

- In the optical bands we observe a horizontal distribution (wow, the Horizontal Branch!), since the luminosity level is set by the mass of the core. The *V*-band nicely follows the peak of the BB curve, according to Wien

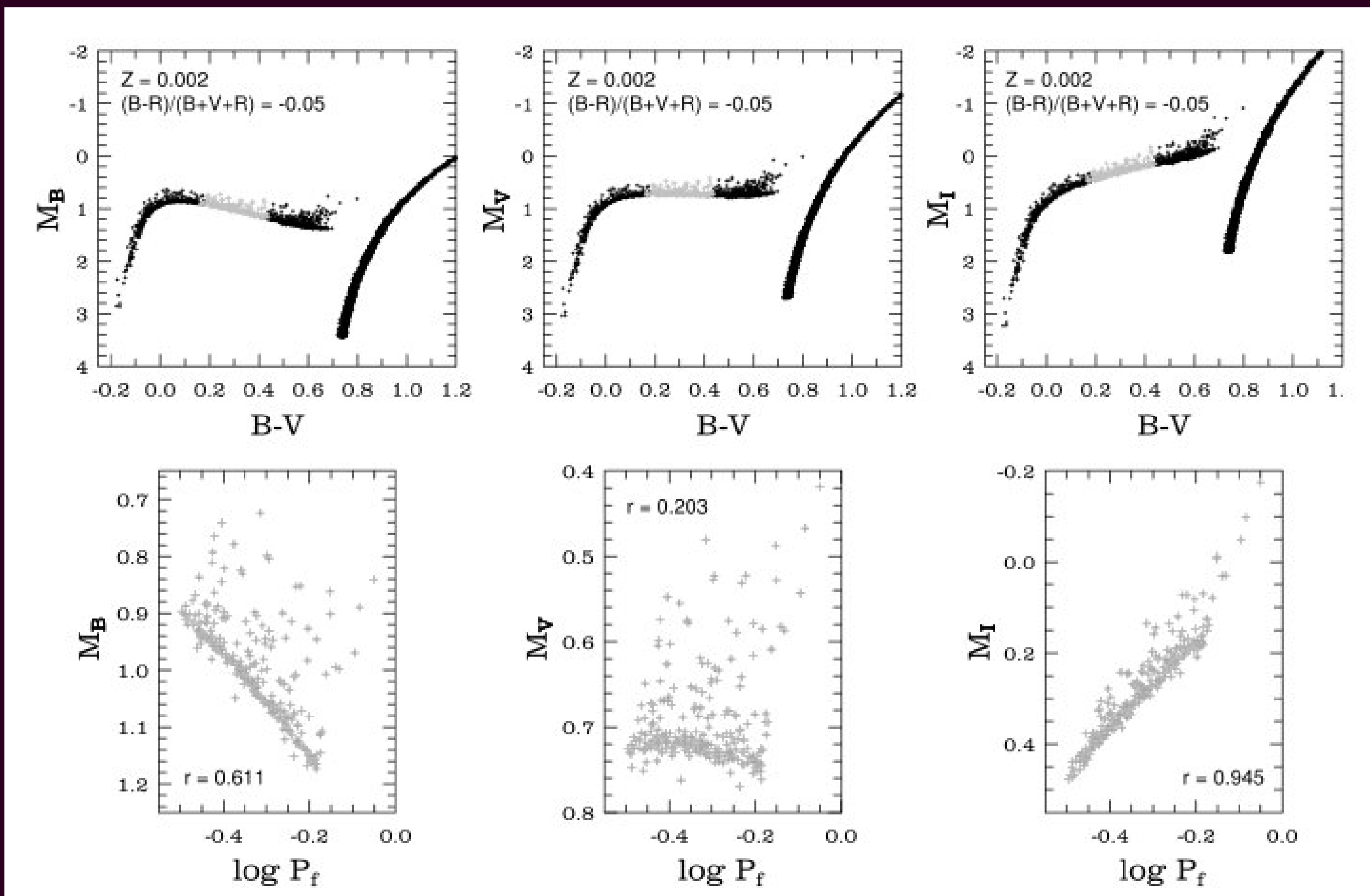


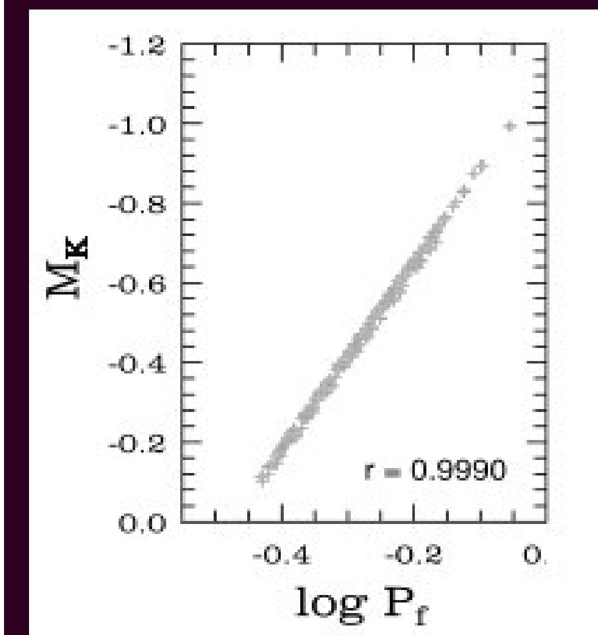
- In the near-infrared things go wild, since in the *K*-band RRLs are on their Rayleigh tail → the bolometric correction is the dominant effect



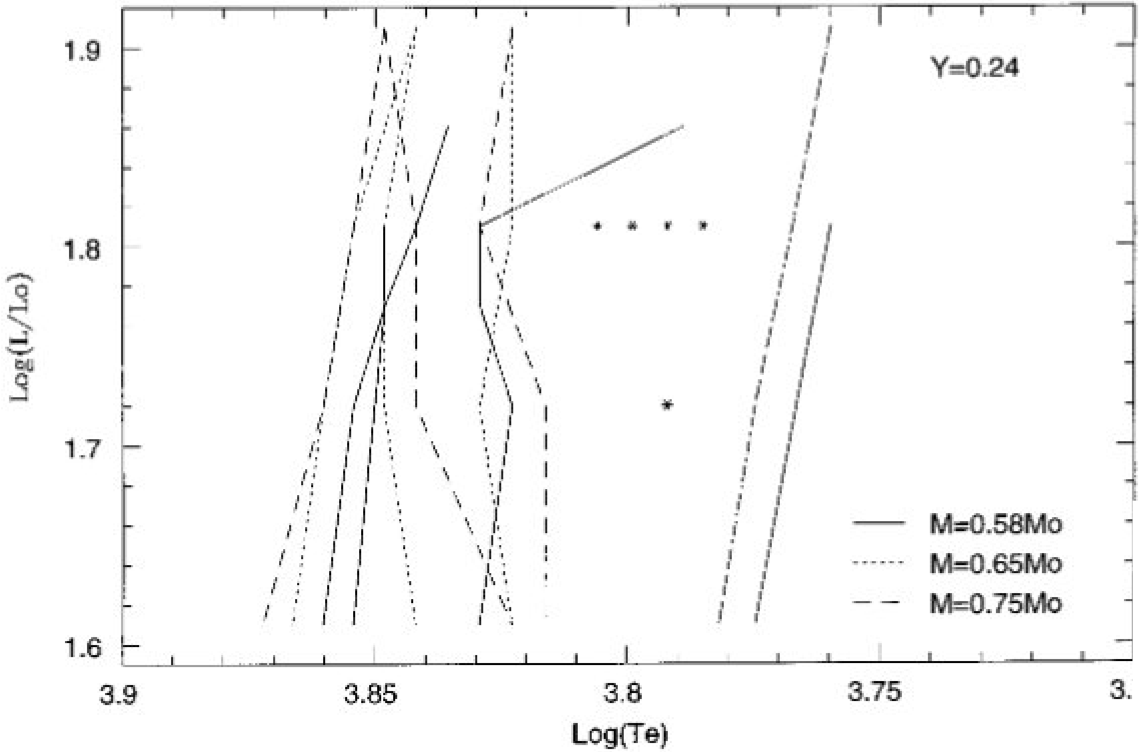
Credits: C. Buil

Effect of the bolometric correction when viewing the HB

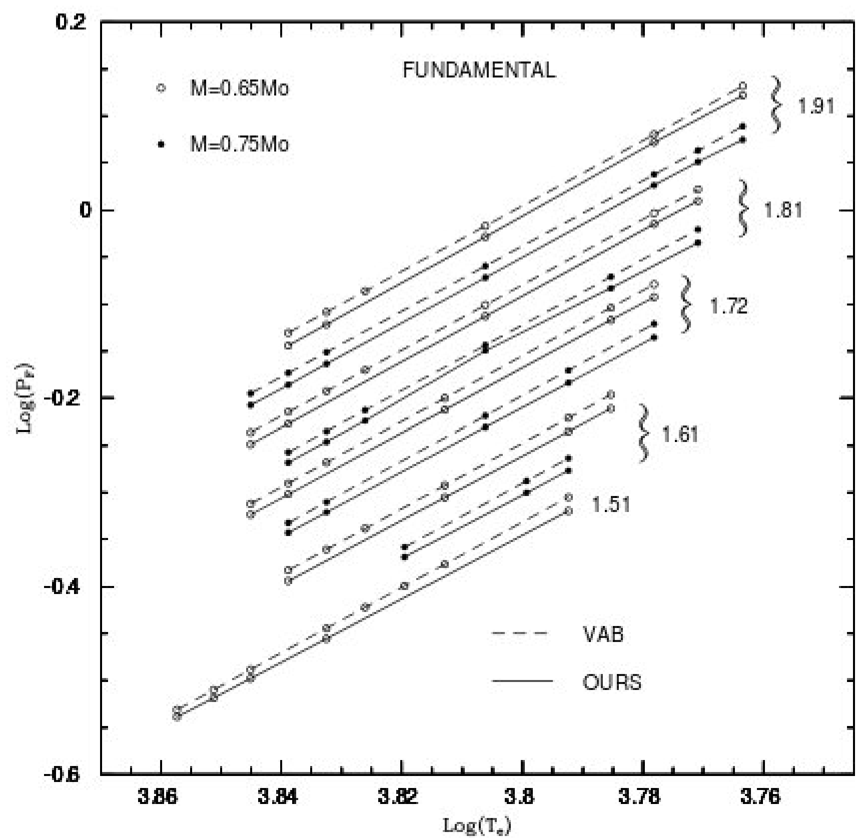




Catelan et al. 2004



$$M_K = -0.766 - 2.071 \log P + 0.167[Fe/H]$$



The trick is that, moving to cooler temperatures:

1. The bolometric correction steadily decreases from hotter to cooler RRLs
2. Hence RRLs become brighter (in the *K*-band) as they become cooler
3. Periods become longer with decreasing temperatures

$$\log P^F = 11.066(\pm 0.002) + 0.832 \log L - 0.650 \log M - 3.363 \log T_e$$

Bono et al. 1997

On the practical side...

We can adopt *K*-band templates (Jones et al. 1996) to measure mean magnitudes.

The cool thing is that, even with a *single* point, we can use a template, and measure correct mean magnitudes

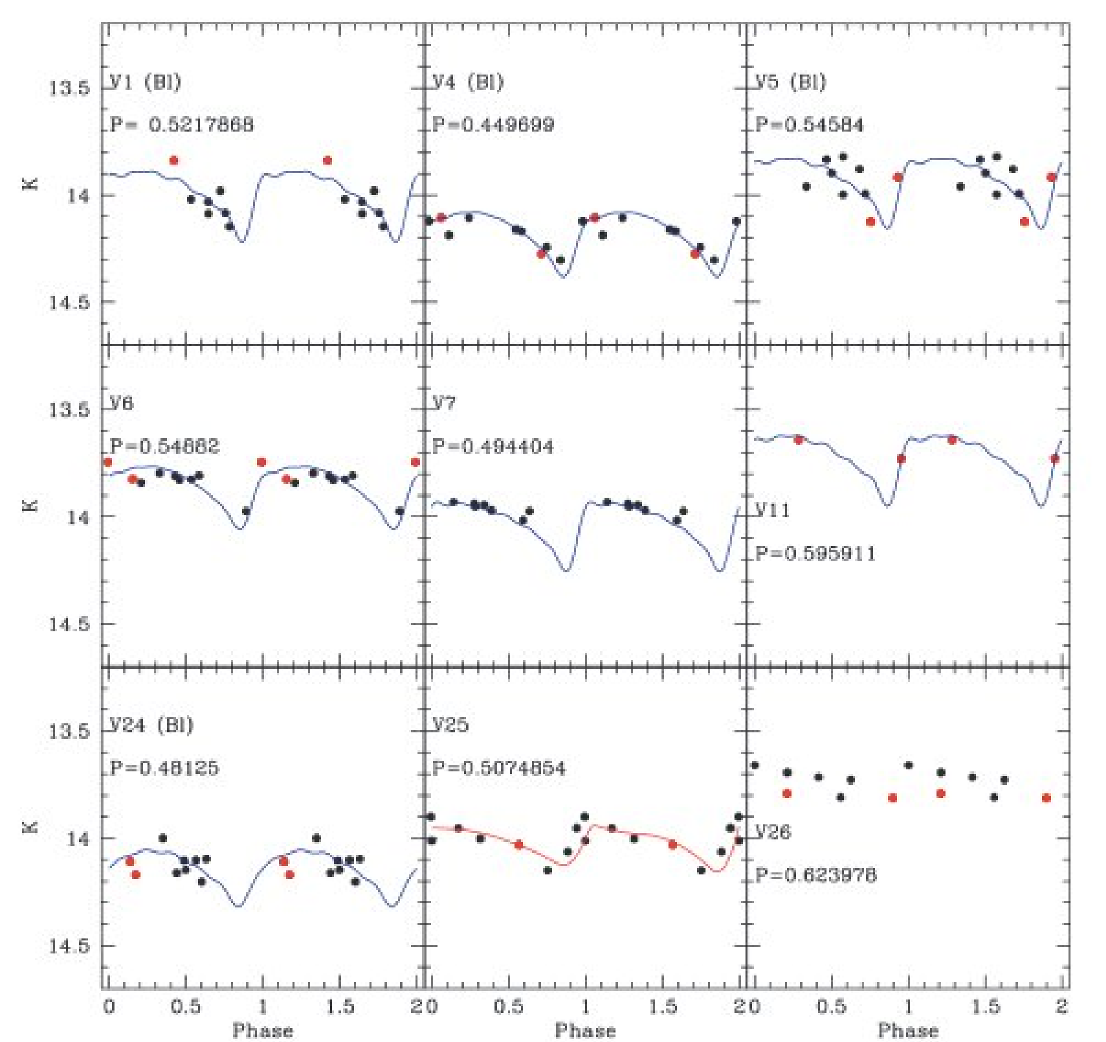
Of course, a single observation would cross the template at any point...

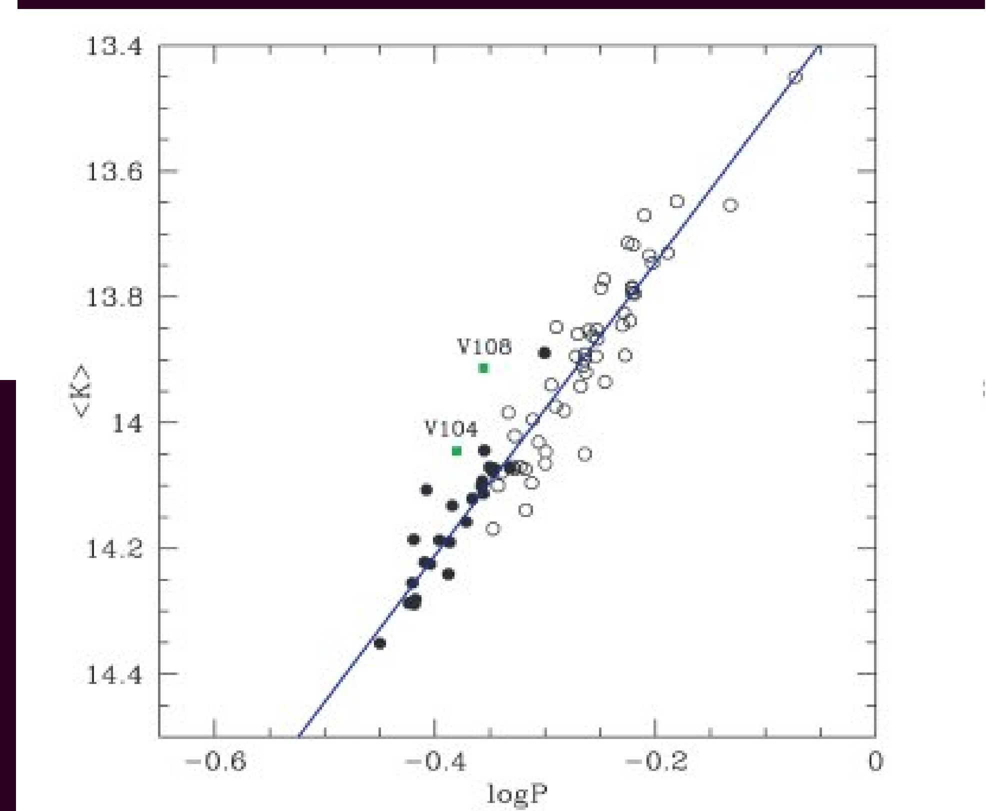
So, we need to know at which phase is located our observation

The ingredients we need are:

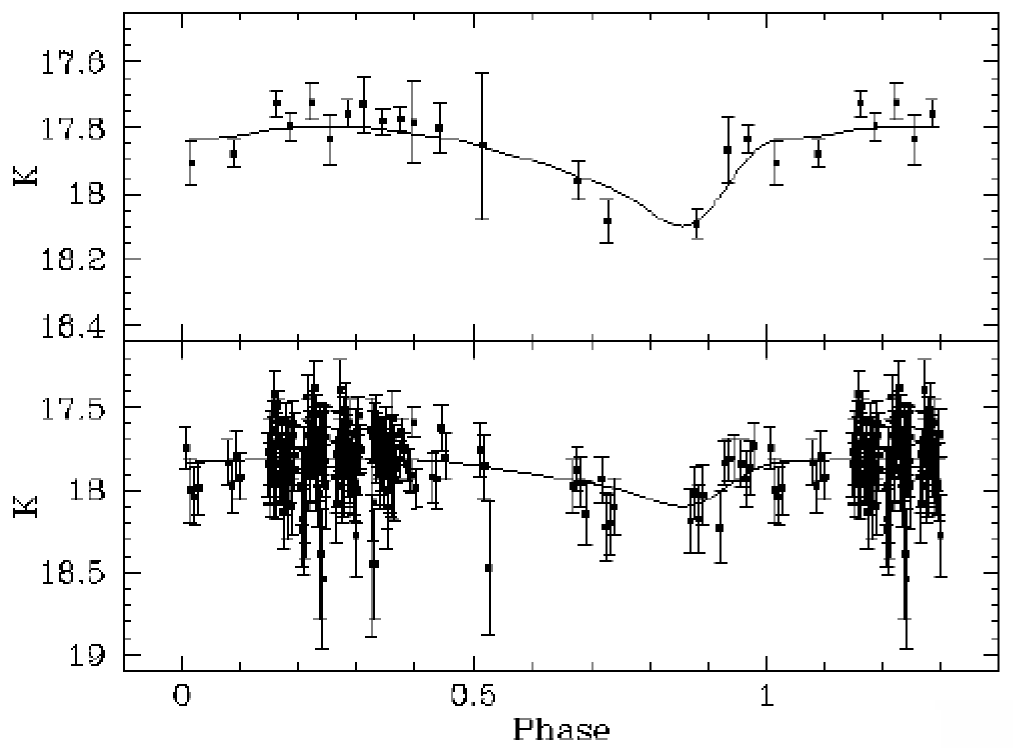
- ✓ Updated ephemerids of the variables
- ✓ That is, we need optical photometry

An example: The Galactic Globular Cluster M5





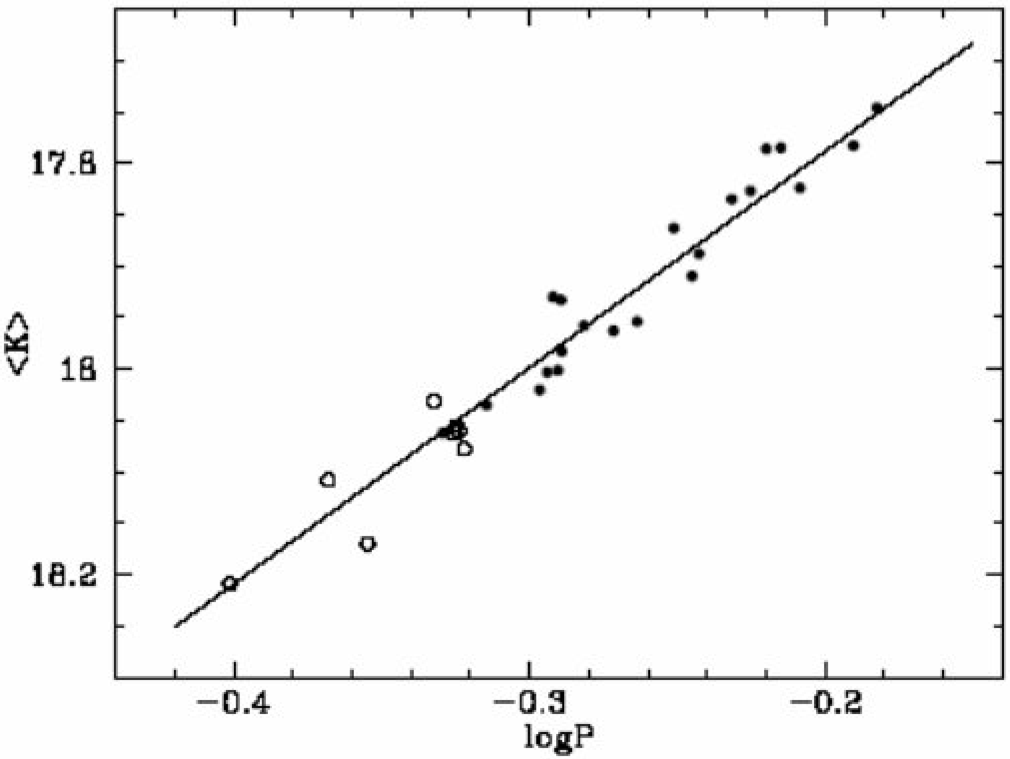
Coppola et al., 2011



Another example: the LMC old cluster Reticulum

Dall'Ora et al. 2004

$$<K> = -2.16(\pm 0.09)\log P + 17.352(\pm 0.025)$$



$$DM_0 = 18.523 \pm 0.005$$

(intrinsic spread only)

Playing with E-ELT

Why we want to use RRLs to measure distances with E-ELT?

All in all, we would go *local, and not cosmological*....

The reasons are:

RRLs Gaia distances → sound calibration of the PLK relation:

- anchor the Cepheids distances
- distances for early-type structures

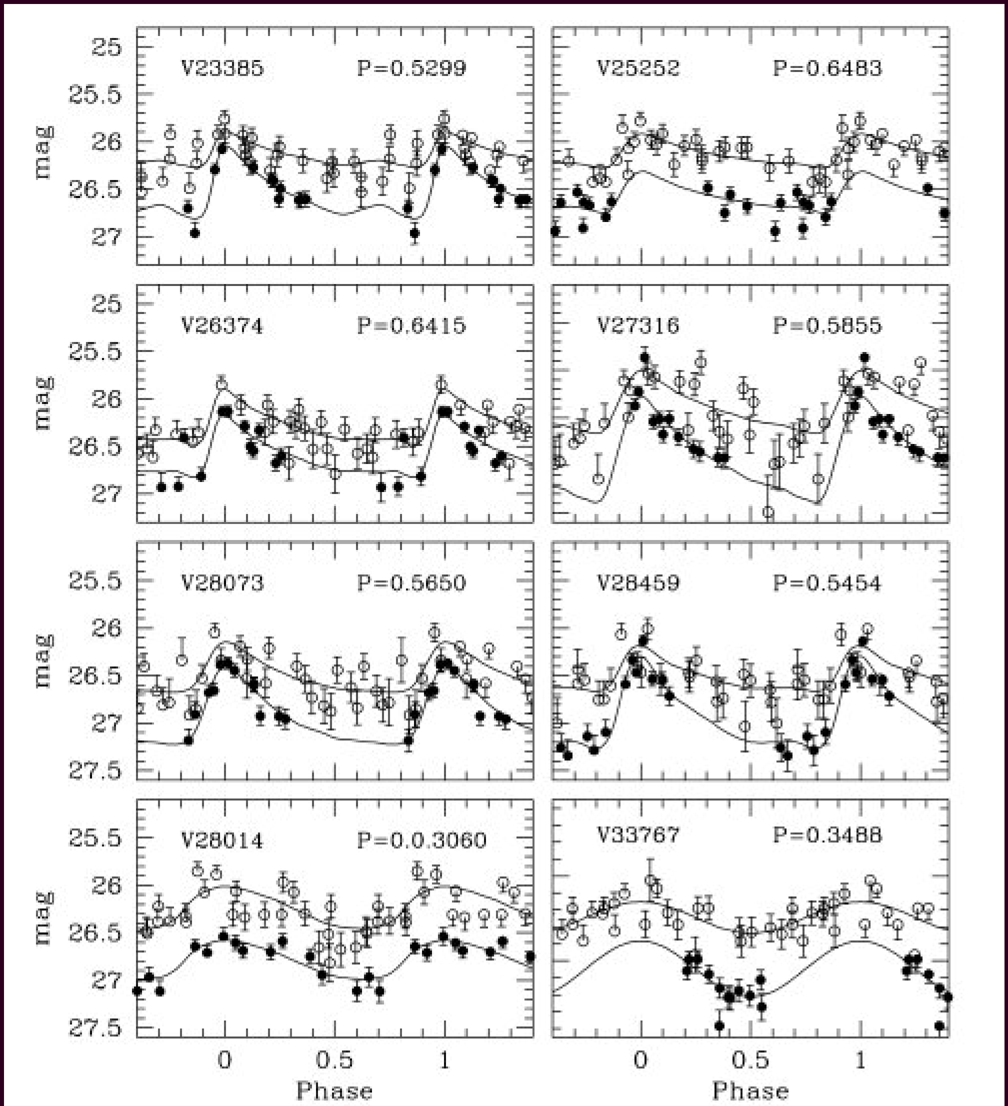
MICADO expected performances tell us that we can reach K ~ 29 mag with one hour integration

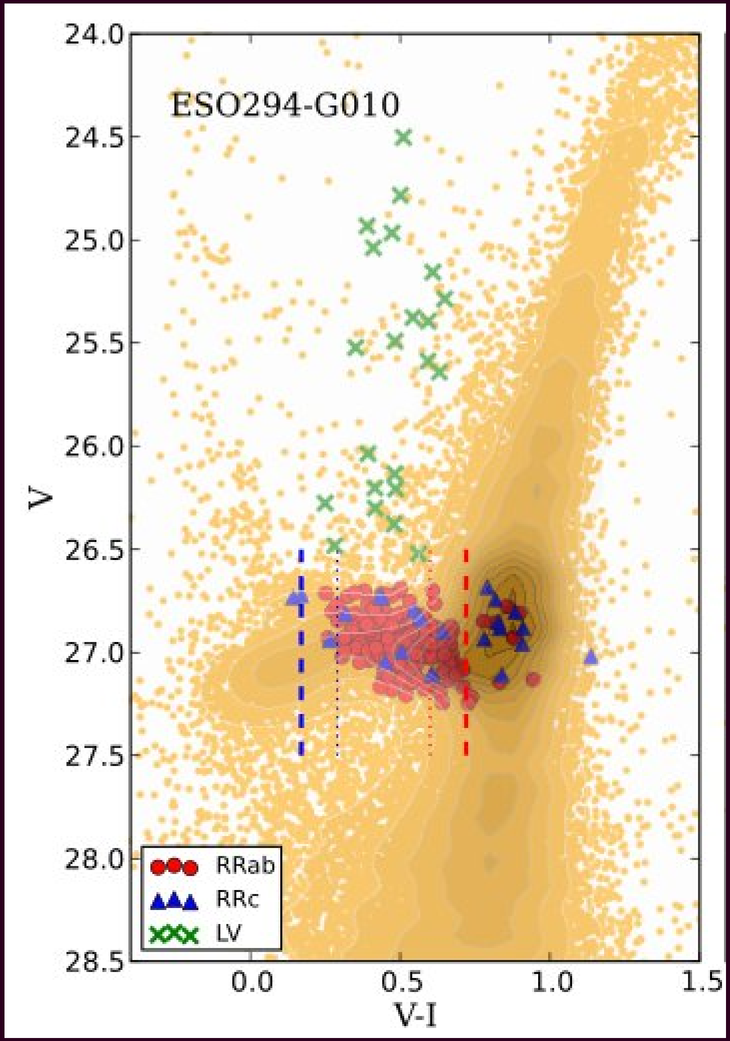
In principle, we could explore up to μ ~ 29.5 mag (~ 25 Mly)

But...

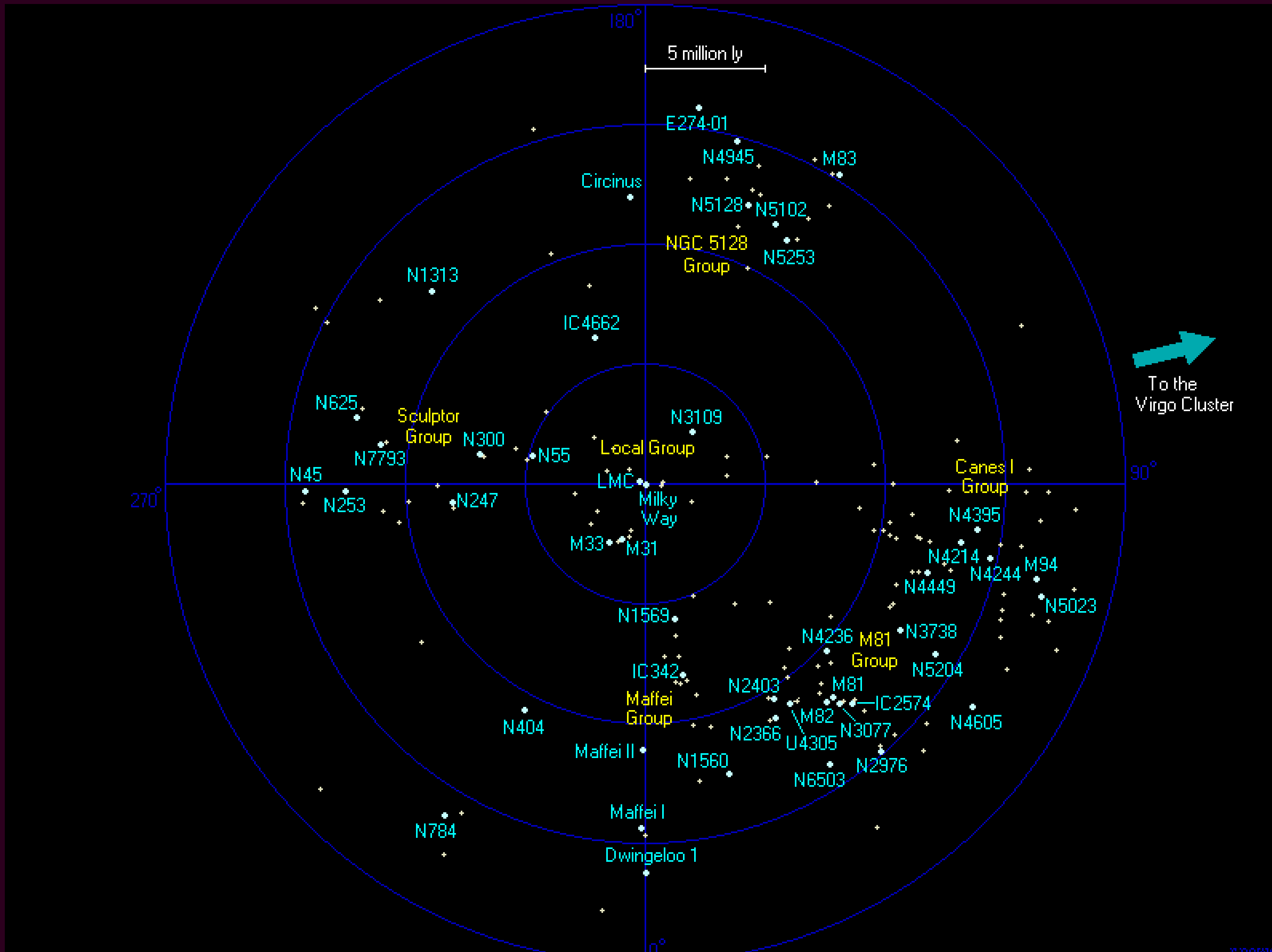
Remember that we need optical-based ephemerids (HST)

RRLs have been reported in the optical up to the Sculptor Group (~ 6.2 Mly, Yang+, 2014)





Yang et al. ApJ, 2014

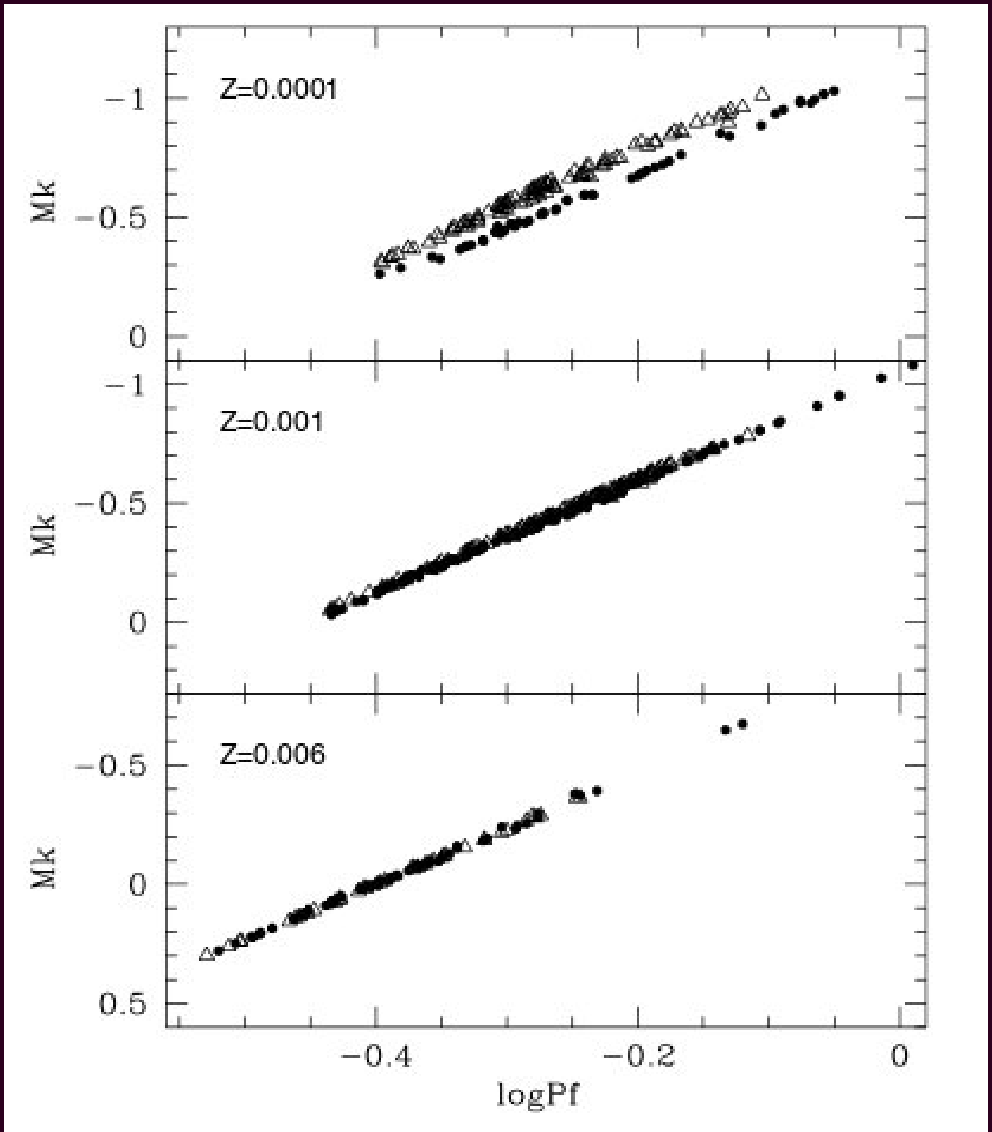


180°
5 million ly
E274-01
N4945
M83
Circinus
N5128
N5102
NGC 5128
Group
N5253
N1313
IC4662
N625
Sculptor
Group
N300
N55
N7793
N3109
Local Group
N45
LMC
Milky
Way
270°
N253
N247
M33
M31
90°
To the
Virgo Cluster
Canes I
Group
N4395
N4214
N4244
M94
N4449
N5023
N1569
N3738
N4236
M81
Group
N5204
IC342
N2403
M81
IC2574
Maffei
Group
M82
N3077
N4605
N404
N2366
U4305
Maffei II
N1560
N2976
N6503
Maffei I
N784
Dwingeloo 1
0°
r powell

Can we go farther than the optical limit?

The PLK relation is basically due to the bolometric correction, that is *intrinsically* a temperature-luminosity relation

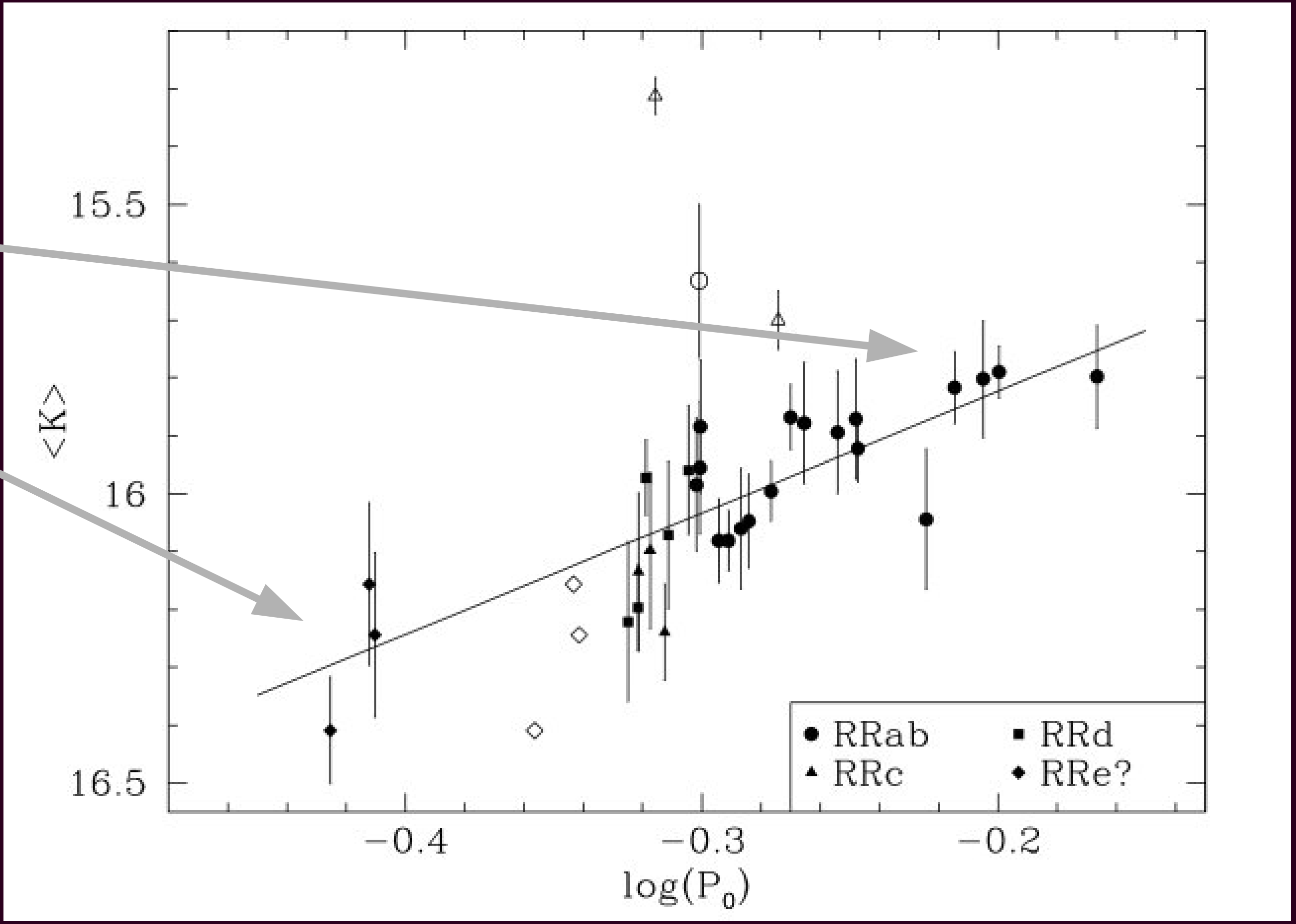
This means that we can adopt synthetic HB and pick up the observed *bona-fide* variable stars in the expected Instability Strip...



Cassisi et al. 2004

Small amplitudes and (almost) sinusoidal light curves

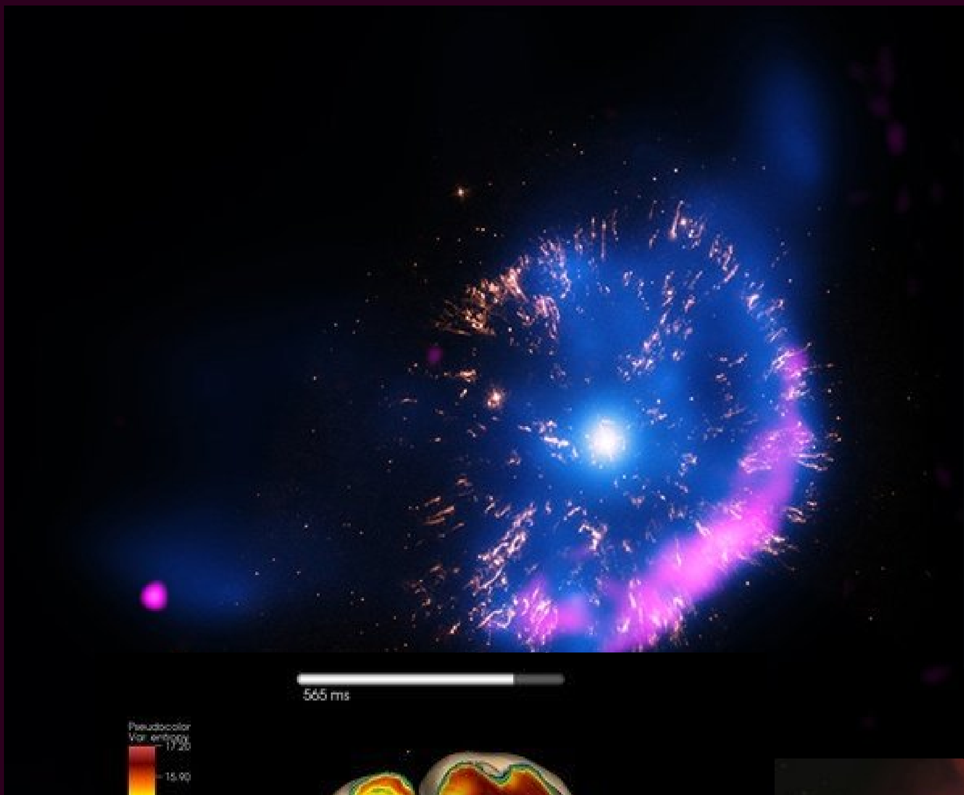
σ = 0.087 mag

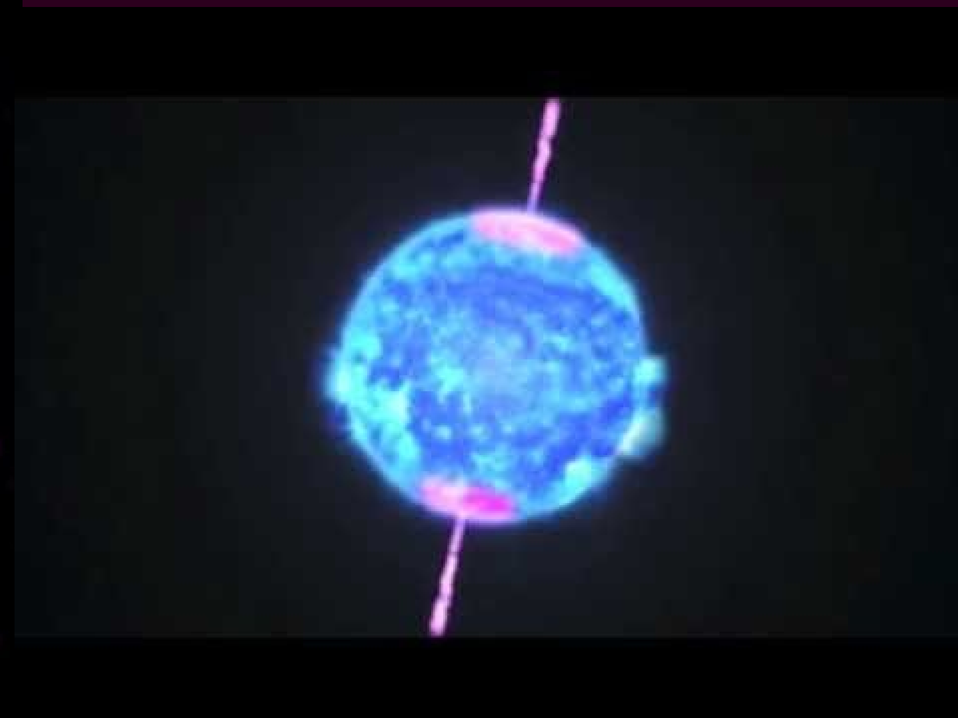


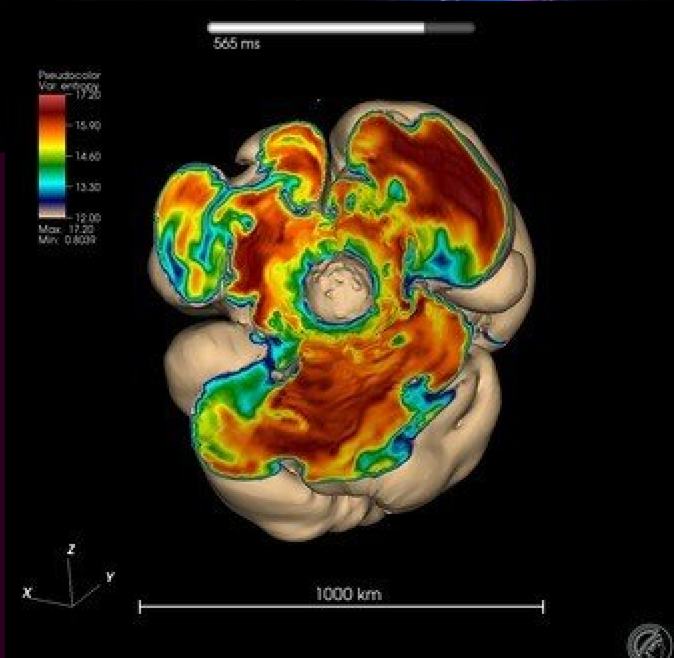
Storm, 2004

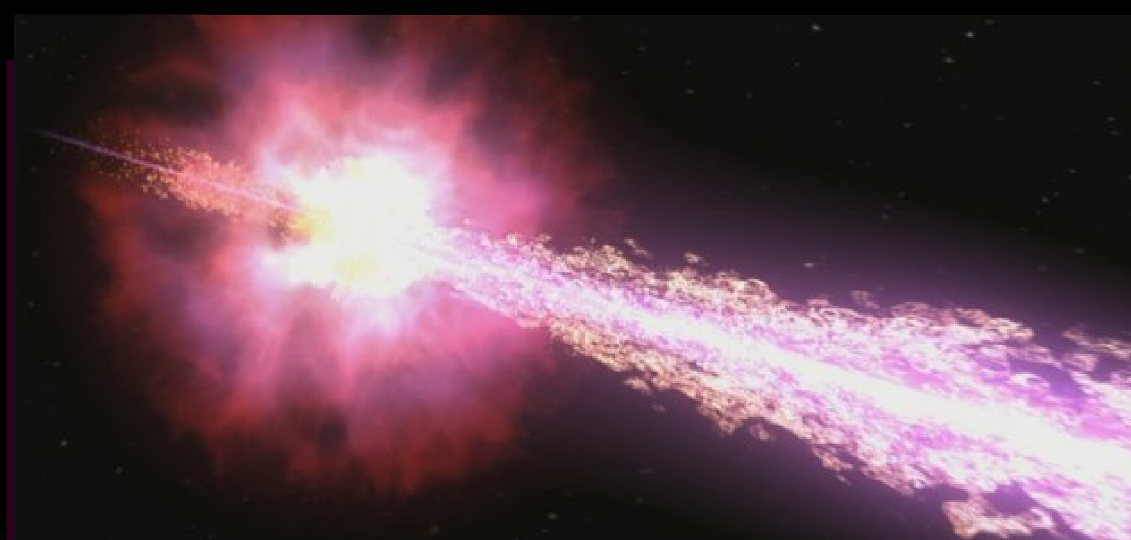
Example: the Galactic Globular Cluster IC 4499

Part II: Transient Phenomena

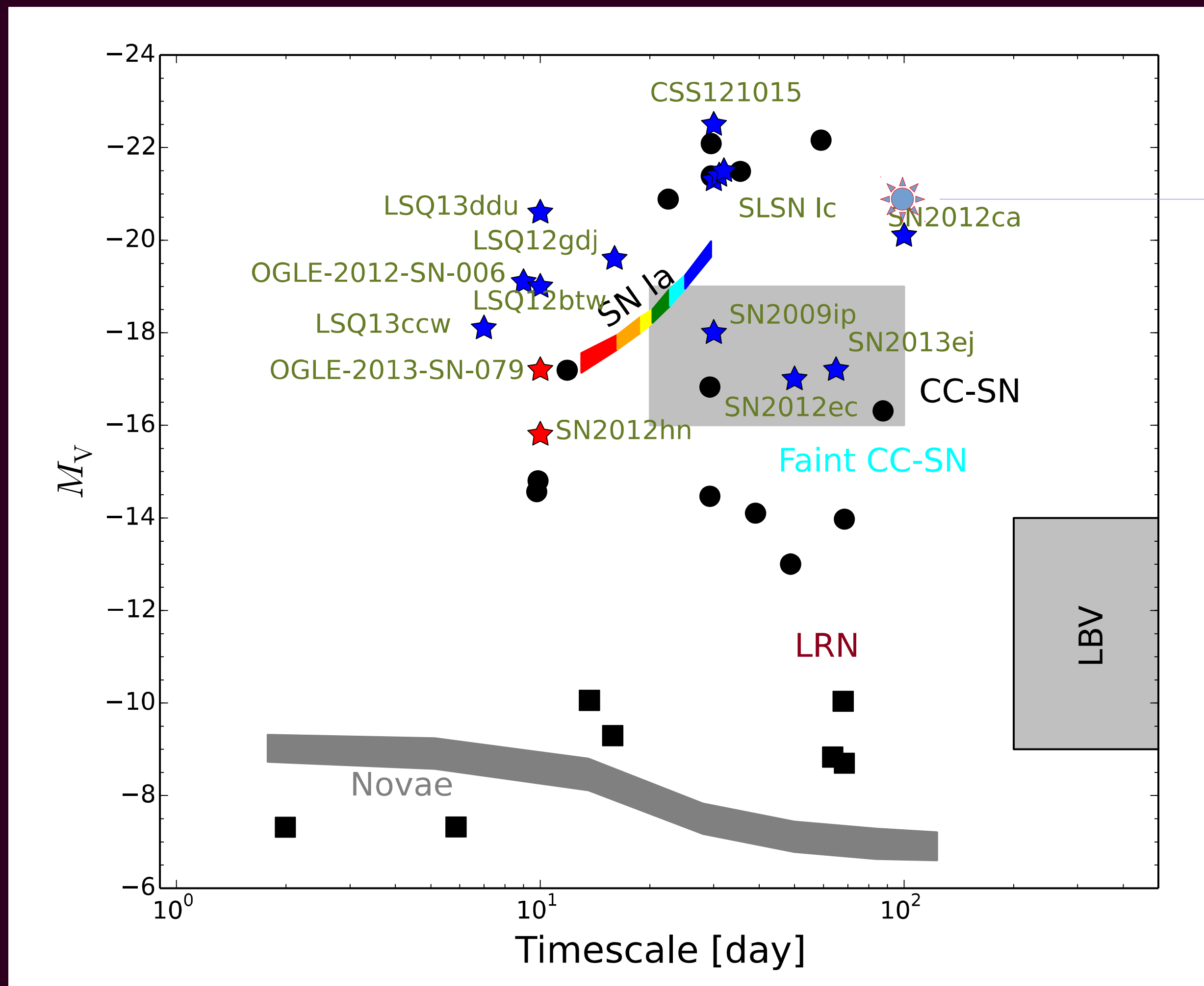








Transients : current science



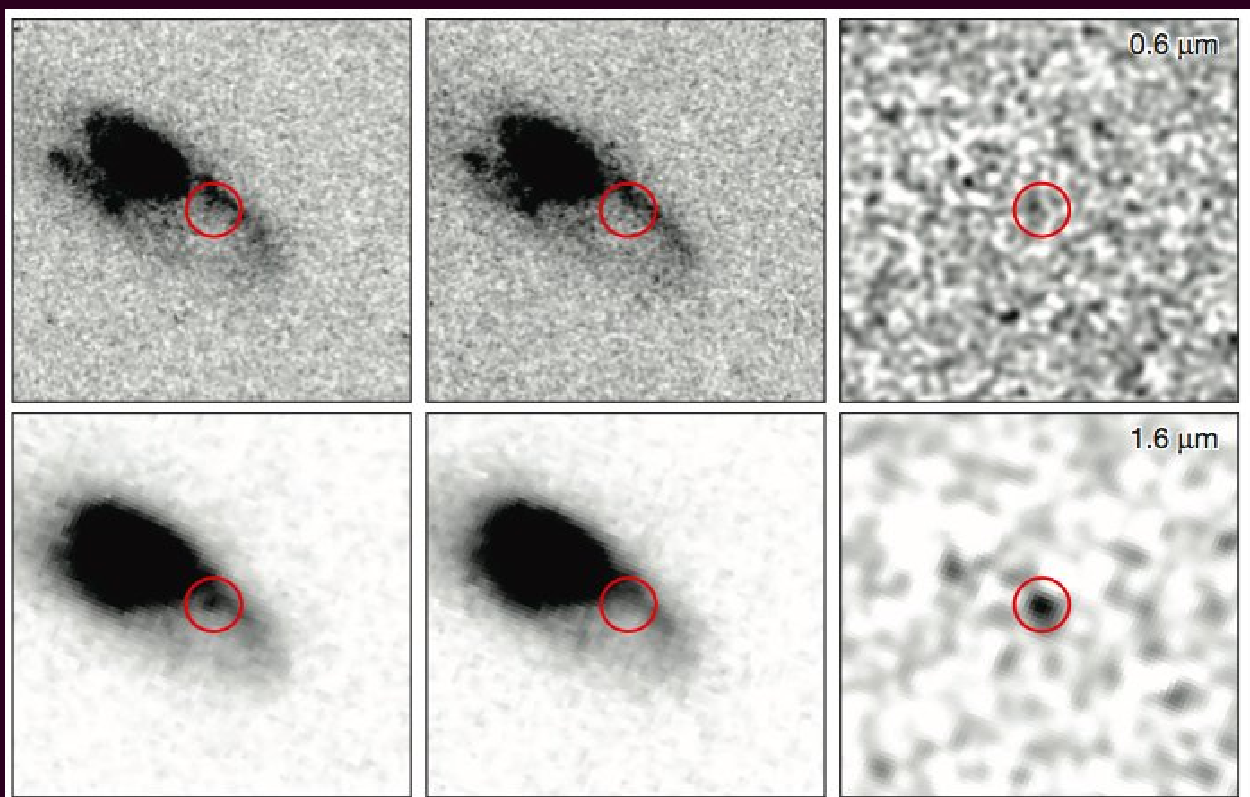
SN 2013dn
Dall'Ora et al, in prep.

Smartt et al. 2015:

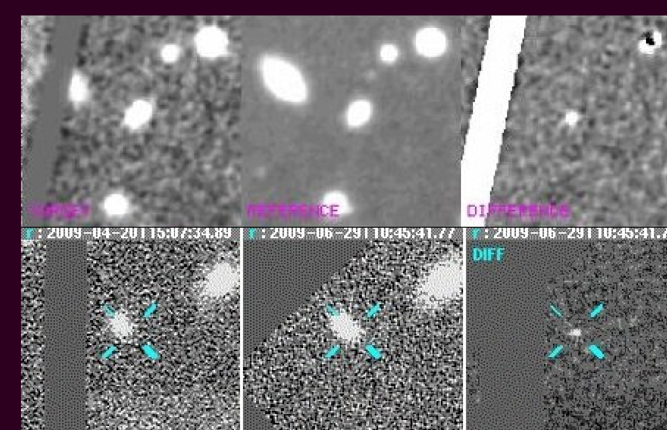
What are the limits of physical explosions and transients?
Can we use cosmological distance indicators other than Ia SNe?

Credits: S. Smartt

Transients: Detection



Time Series is still needed: we need to have knowledge of a “before” and of an “after” the phenomenon...



Images Credits: M.T. Botticella & S. Smartt

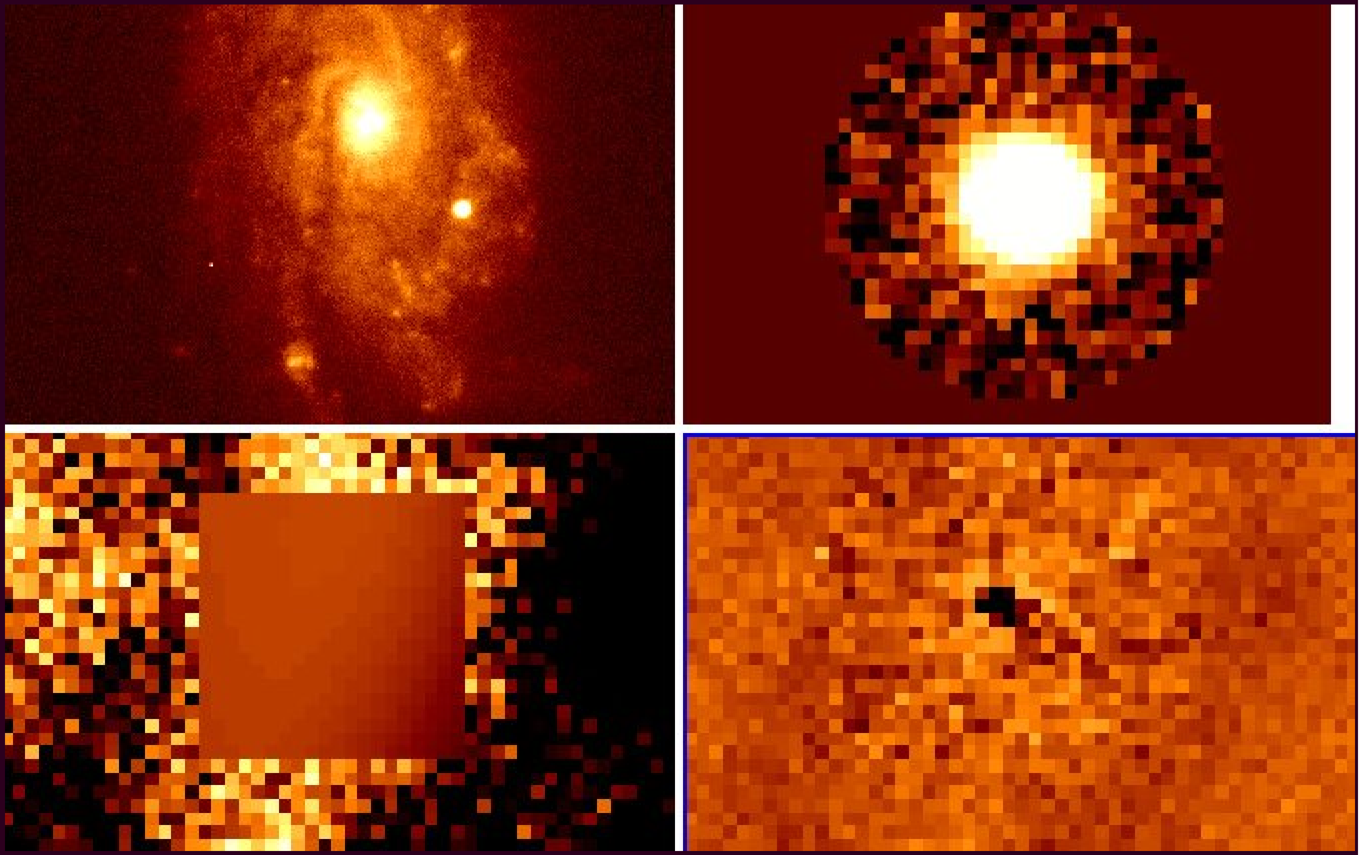
Ingredients for SNe photometry

To "cook" a SN, we need:

- PSF-based differential photometry
  - Found bright and isolated field stars
  - Calibrate the local sequence (in some cases you are lucky, and you can get the magnitudes from the released sky surveys)
  - Be sure that they are not variable stars...
- Possibility to model the background (even with a high-order polynomial)
- Alternatively, you can subtract a template image of the galaxy (collected when the SN was not exploded yet, or when it completely faded away

SNe are almost always embedded in the host galaxies → highly variable background
This is not a problem when the SN is bright, but it is really an issue when it fades

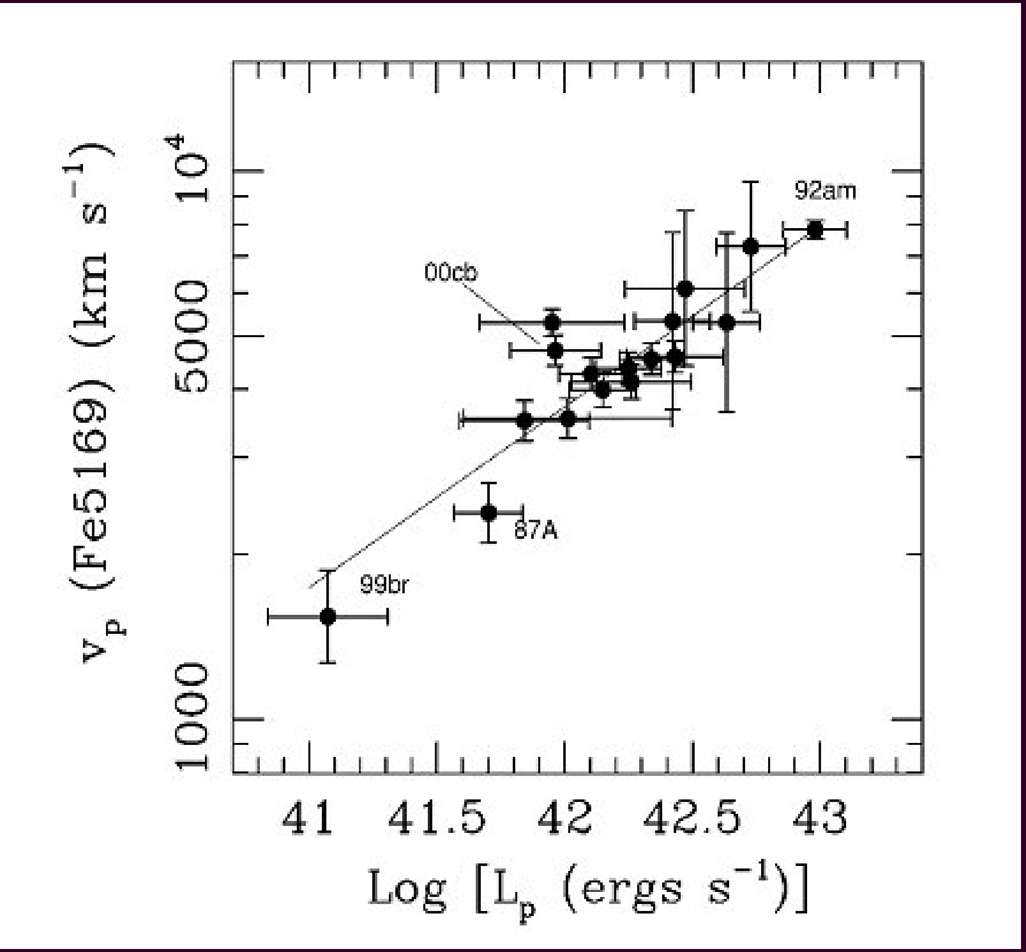
SN 2012ec, Barbarino et al. 2015



QUBA Pipeline, Valenti et al. 2011

An application: Type IIP SNe as Standard(ized) Candles

- Tight correlation between the luminosity and the photospheric velocity
- Cheap: all you need is a few epochs multi-band photometry and a good S/N low-res spectrum
- Reliable: IIP distance scale, with a few calibrators, has a 10-15% accuracy (Ia-based distance scale is at the 7% level)

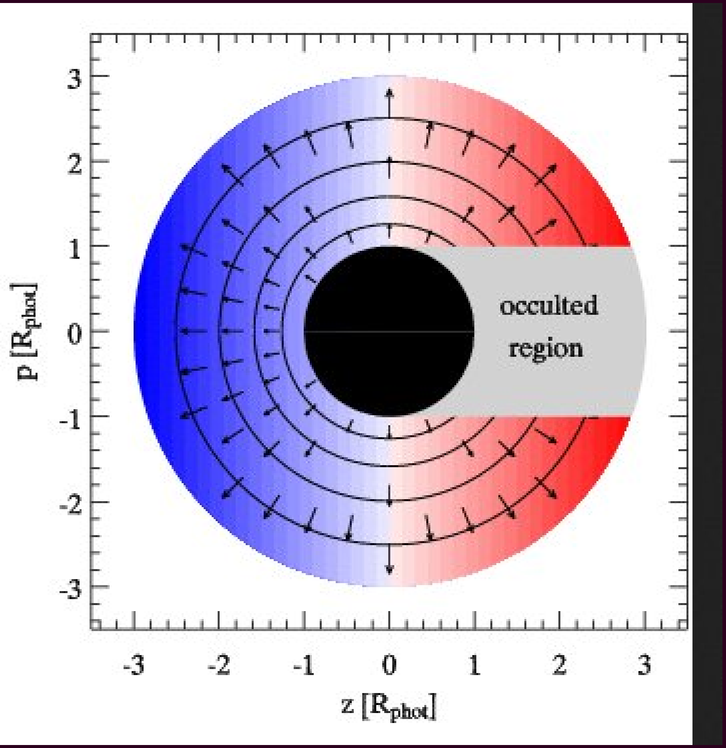


Hamuy & Pinto 2002

Why does the SCM exist?

- A higher luminosity implies a larger hydrogen recombination front
- ... but it also implies a higher photospheric velocity (homologous expansion)

$$L_p = 4\pi R^2 \sigma T_{\mathrm{I}}^4$$



$$v_{\mathrm{sn}} \approx (2E/M_{\mathrm{ej}})^{1/2}$$

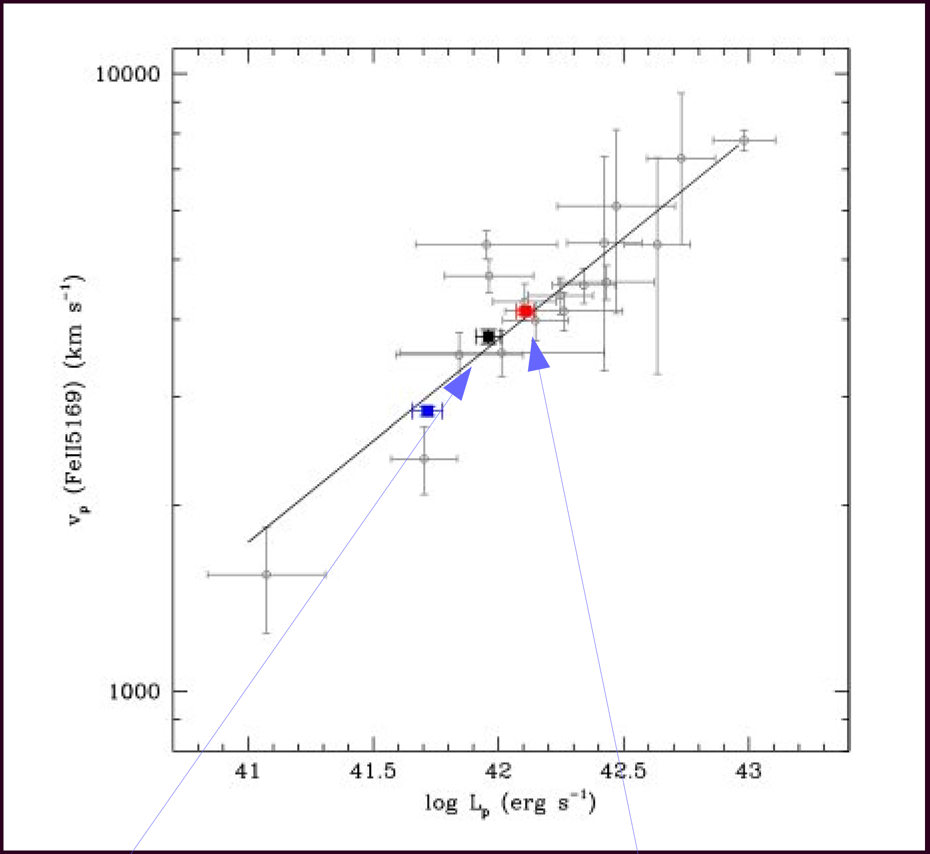
Why is SCM appealing?

- SCM is a fast and simple method, with a good accuracy (10-15%), with a known physics behind
- It can be used up to cosmological distances and it can provide a healthy check of the Ia SNe calibration
- IIP SNe rates could provide a higher statistics than Ia SNe (Hopkins & Beacon 2006)
- They are a homogeneous sample with respect to the age of the stellar population
- BUT.... we still lack a calibration on Primary Distance Indicators (Cepheids, TRGB)...

The Role of E-ELT

- To calibrate the SCM with Primary Distance Indicators we need to increase the number of host galaxies where IIP SNe have exploded, and also we have detected Cepheids and TRGB
- Currently, only a very few objects are available
- This means that we can either:
  - Wait for other IIP SNe to explode in nearby galaxies... 😂
  - Or... observe Cepheids and TRGB in more distant galaxies (yes, E-ELT), where IIP SNe have already exploded...

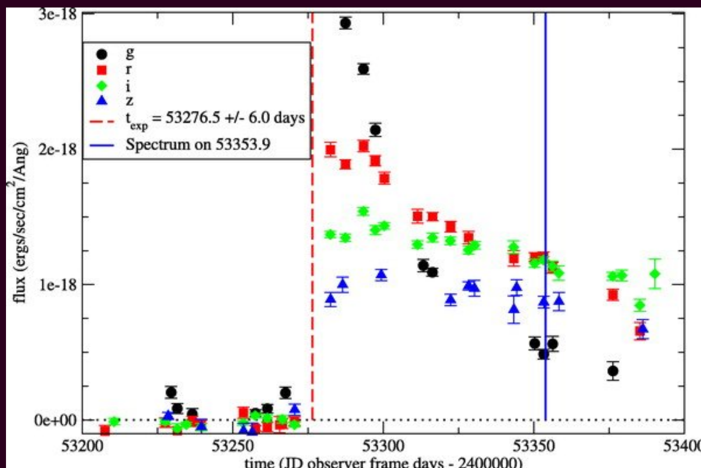
Barbarino et al. 2015



SN 2012ec, Barbarino et al. 2015

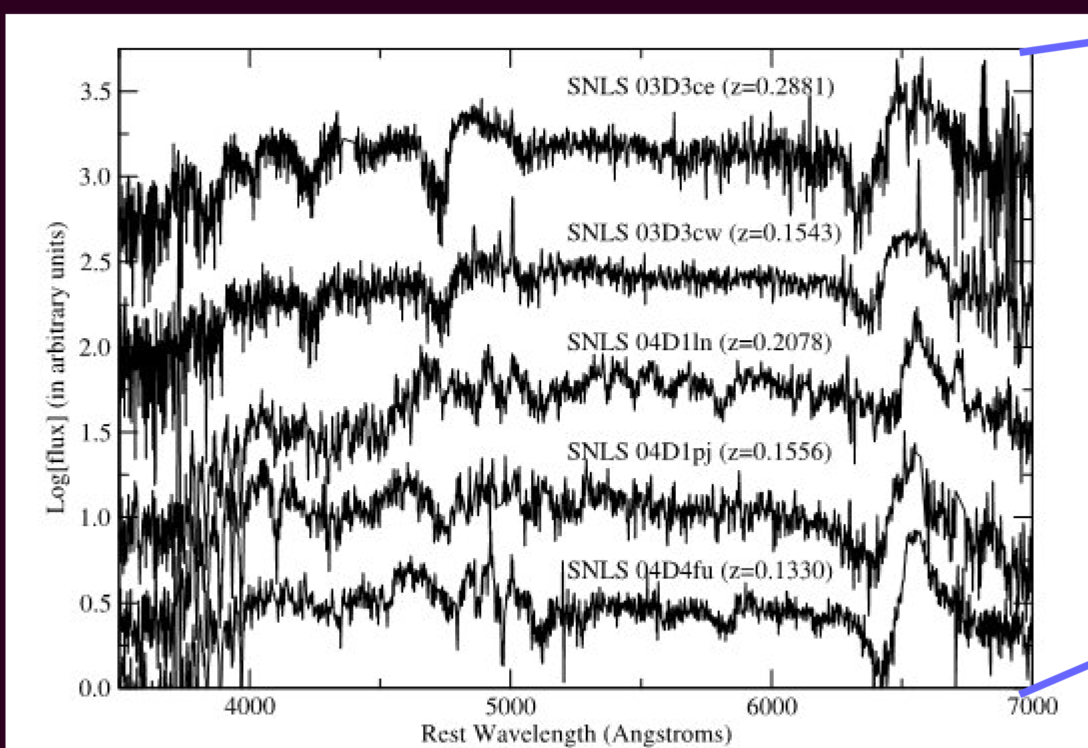
SN 2012aw, Dall'Ora et al 2014

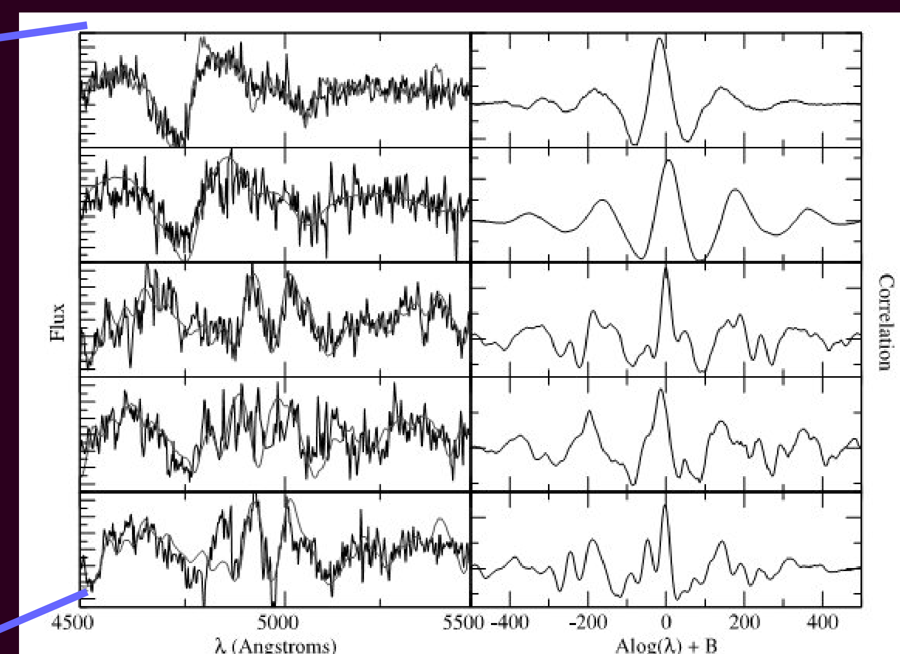
But... can we really measure distant IIP SNe?



→ CFHT

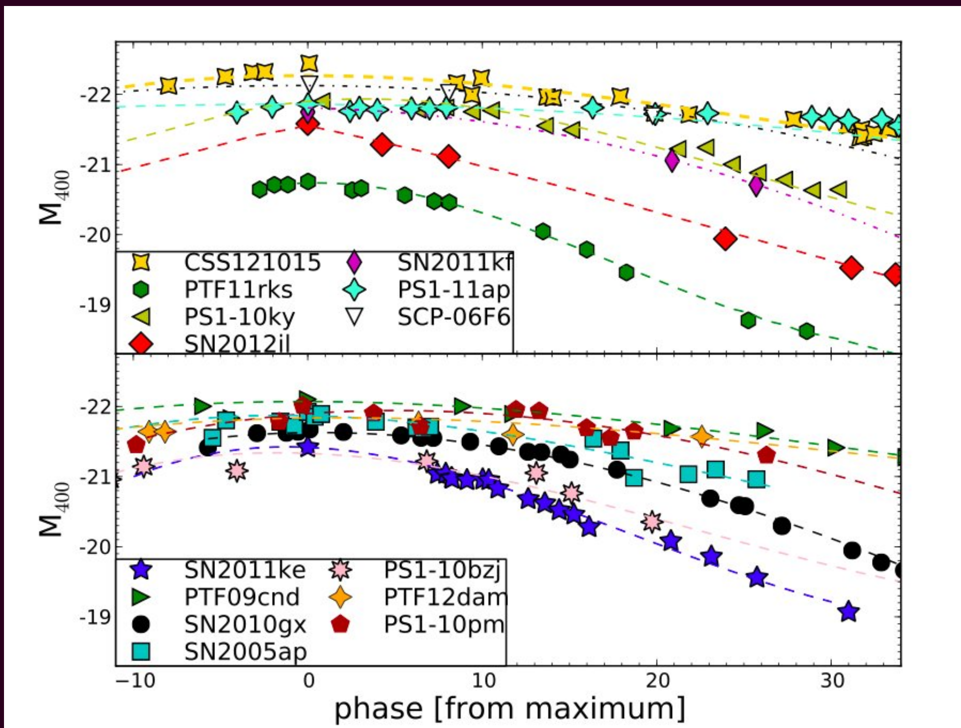
Nugent et al. 2006

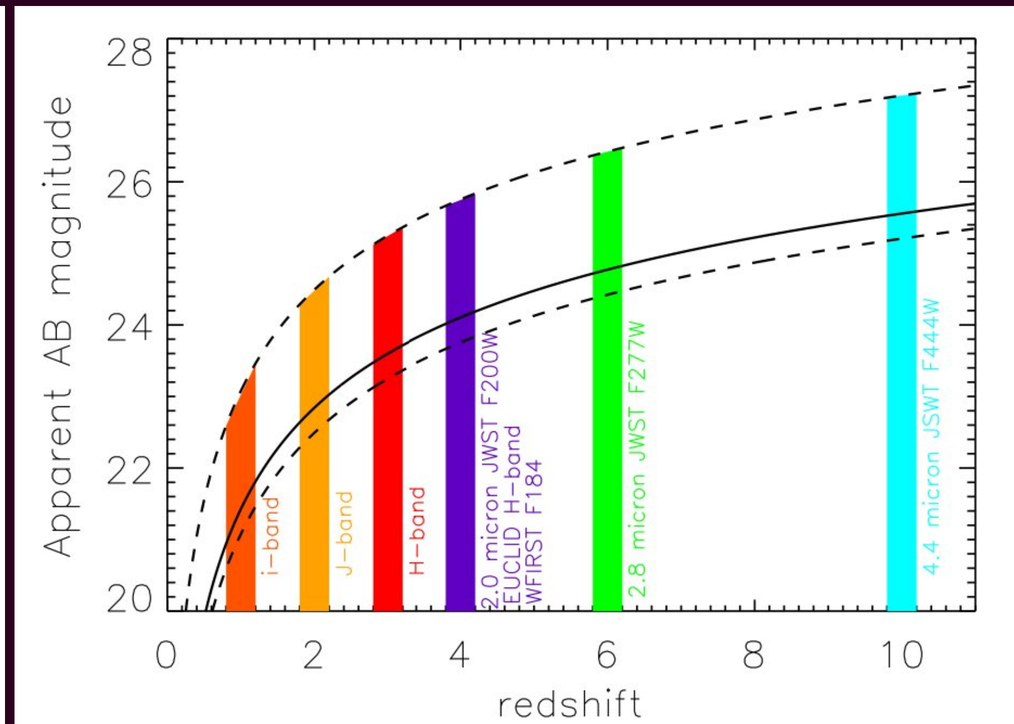




→ Keck

Another application: SLSNe as standardizable candles



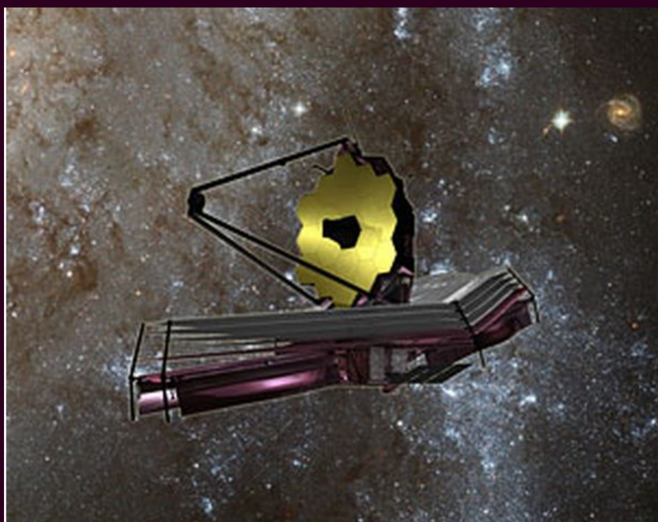


Inserra & Smartt 2014, ApJ, 796, 18

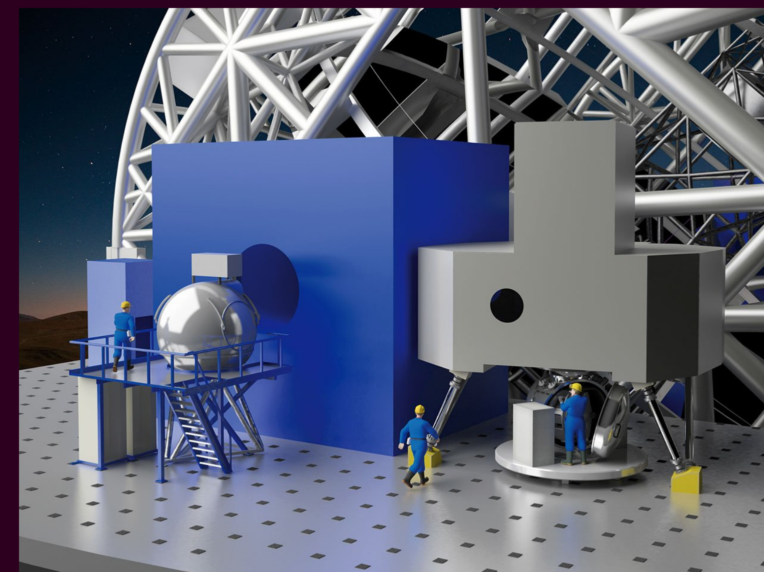
- Super-luminous SNe : hot, UV bright sources, M_{UV} ~ -22 mag
- Peak magnitude is (potentially) standardizable to ± 0.2 mag
- Already shown to be exclusively produced in low metallicity dwarf galaxies ($Z < 0.2Z_{\odot}$)
- Ideal high redshift probes : cosmology, star formation, beyond $z > 6$ with LSST, JWST, VLT and E-ELT

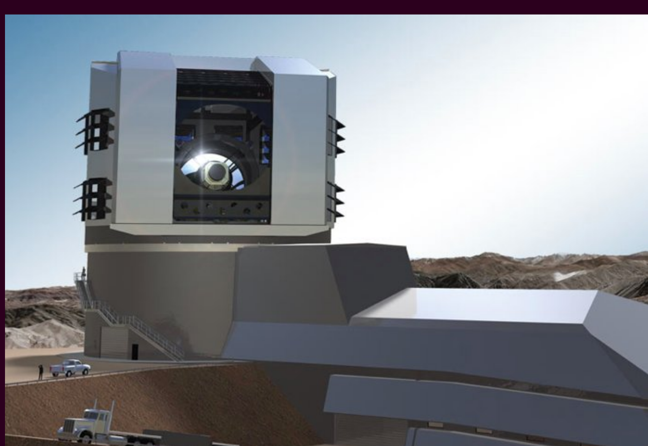
Credits: S. Smartt

High-z : JWST, LSST and E-ELT



NIRSPEC
Surveys
$H_{AB} > 25$



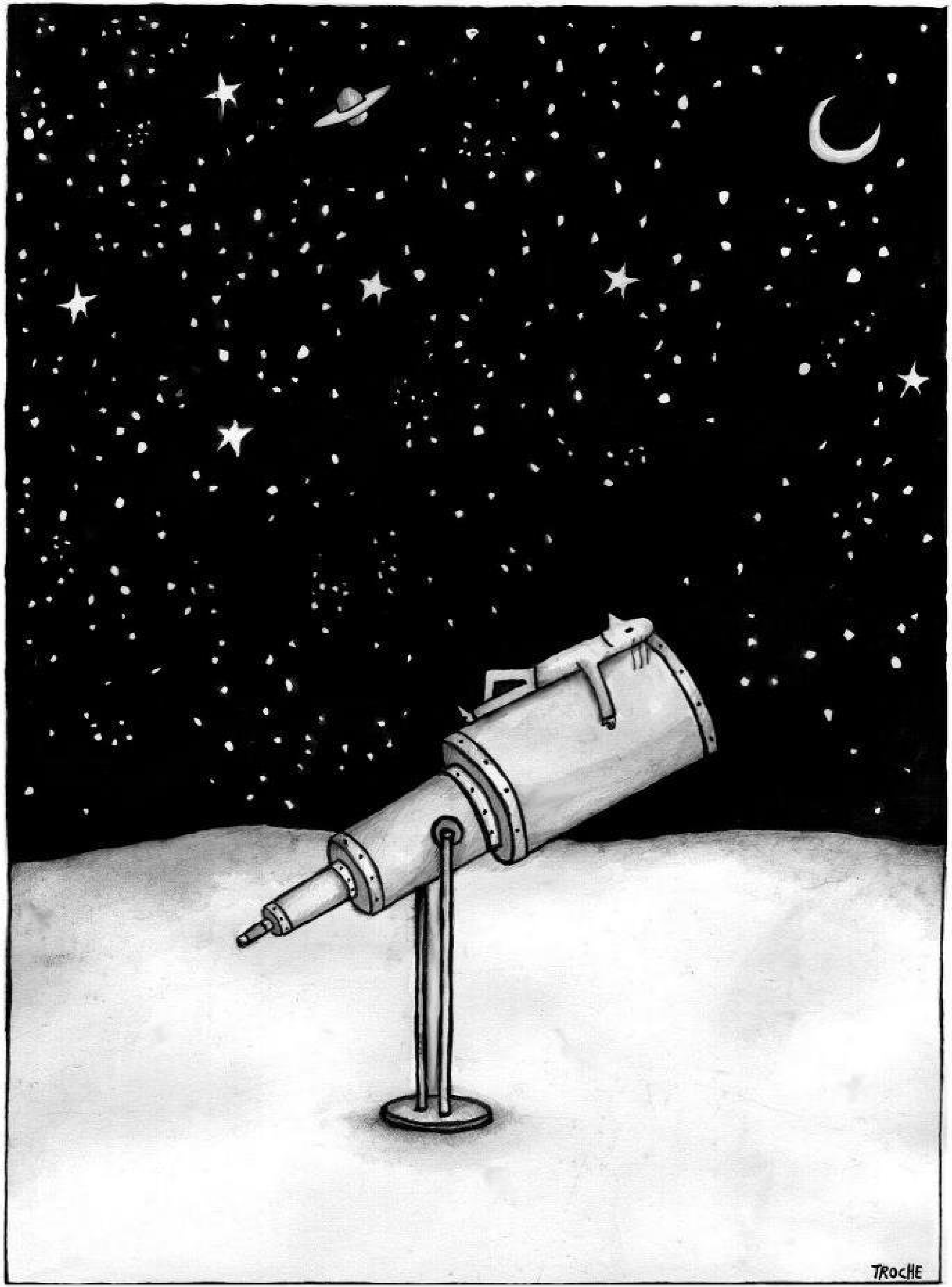


LSST
Surveys
$z_{AB} > 25$

- Feed for ELT spectra
- ELT + HARMONI
- 4hrs gets H_{AB}=25 at S/N~20 (R~500)
- SLSNe at *z = 6-10*

Credits: S. Smartt

Thank you



"Mirar el Cielo es un sentimiento"