Ultra-deep IR Imaging of the GC M4:
Hunting for Brown Dwarfs in Globular Clusters

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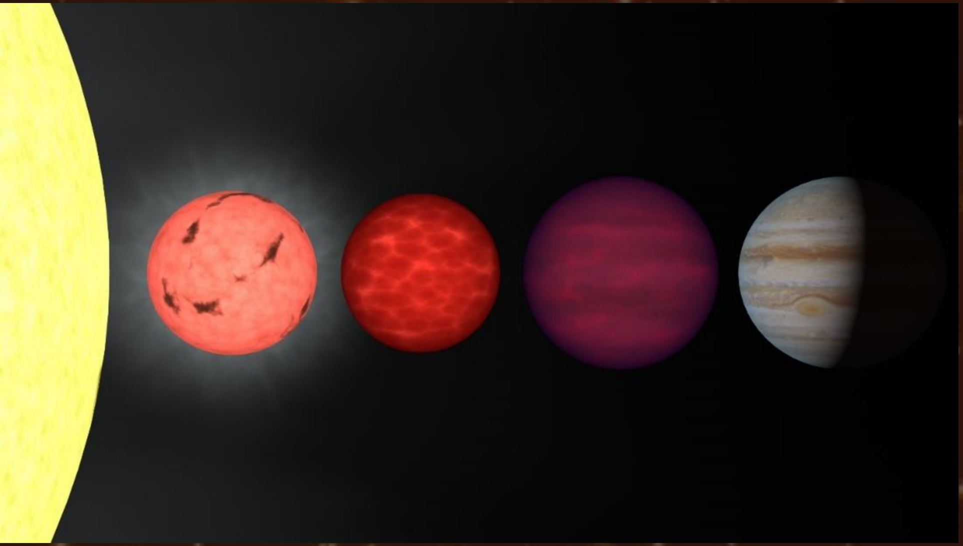
What is a Brown Dwarf?

- *Not a star:*
  - *cannot sustain H-fusion (sub-stellar, "failed stars")*
    → cool forever
  - *less massive than ≈ 0.07 $M_{\odot}$*
  - *cooler than ≈ 2100 K (Dieterich et al. 2014, solar neighbourhood)*

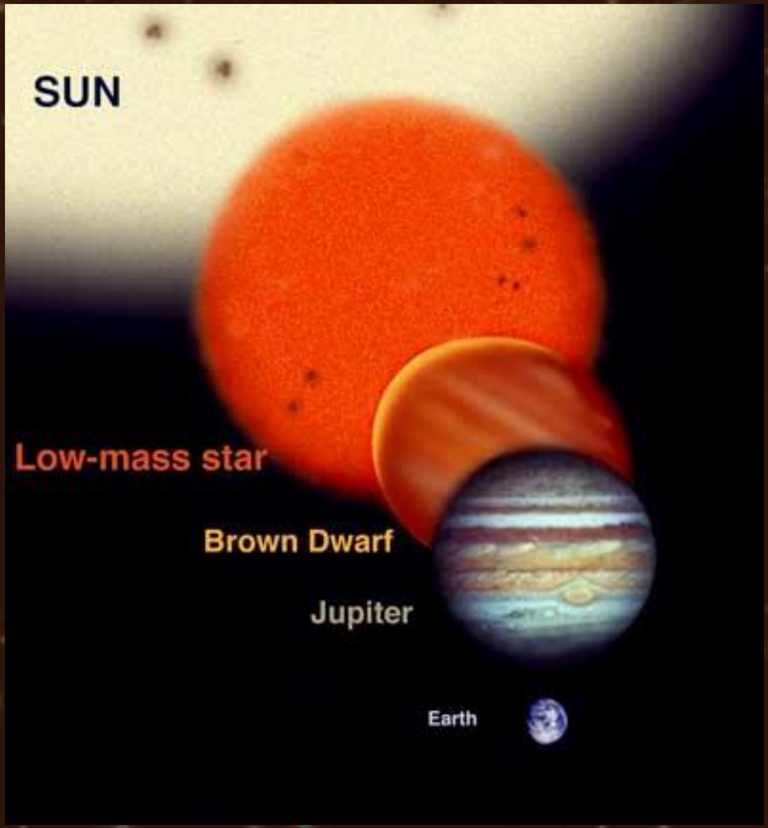


Artist's renditions: Dr. Robert Hurt of the Infrared Processing and Analysis Center, CALTECH

- *Not a planet:*
  - *different formation*
  - *$M_{BD} > 13\ M_{Jupiter}$*
  - *Can sustain D-burning*

(is there a distinction between lowest mass BDs and planets?)

What is a Brown Dwarf?



Credit: Gemini Observatory/Artwork by Jon Lomberg

- *Like a star:*
  - *BD form in the same way as stars do (Andre et al. 2012)*

  (But do they?)

- *Like a planet:*
  - *Complex atmospheres*

BDs represent a link between lowest mass stars and planets

And why do we want to study BDs?

BDs represent a link between lowest mass stars and planets

- ***Can teach us about the low mass end of the H-burning sequence***
  - ***Mass-Luminosity relation***
  - ***Initial Mass function***

- ***Can teach us about exoplanet atmospheres***
  - ***BD and planet structure and atmospheres***

- ***Star, BD and planet formation***

How do BDs form?

Several mechanisms have been proposed:

- ***Turbulent compression and fragmentation of molecular gas produce collapsing cores over a wide range of masses***
  → BDs form just like stars
  (e.g. Whitworth & Goodwin 2005, Hennebelle & Chabrier 2008)
- ***Ejection from multiple protostellar system, preventing the ejected stellar embryo to accrete more mass***
  (Reipurth & Clarke 2001)
- ***Photoionisation from nearby OB stars removes envelope and disk from low-mass protostars, producing BDs***
  (e.g. Kroupa & Bouvier 2003)
- ***Gravitational fragmentation of protostellar disks***
  (Thies et al. 2010, Basu & Vorobyov 2012)

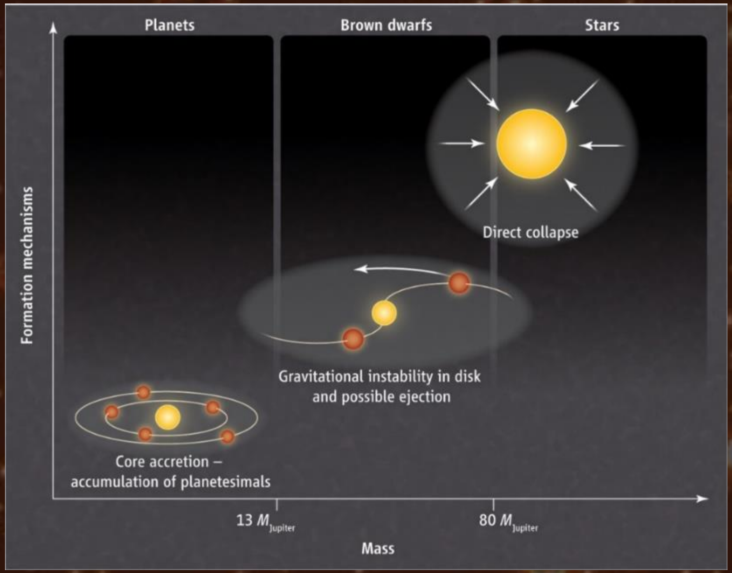


Image credit: P. Marenfeld & NOAO/AURA/NSF

Why Brown Dwarfs in Globular Clusters??

- *Large samples of BDs are known today (SDSS, 2MASS, WISE, UKIDSS, Pan-STARRS,…)*
- *DwarfsArchive.org: 1281 spectroscopically confirmed L, T and Y dwarfs*
- *But: all of those are rather metal-rich (solar neighbourhood)*

  or metallicity and age are unconstrained

→ determining the physical properties of BDs is difficult and the major hurdle in BD research!

Benchmark BDs at known age, distance & metallicity are crucial if we are to test and improve theories about star/BD/planet formation, evolution, and structure!!

Why Brown Dwarfs in Globular Clusters??

Finding BDs in star clusters can considerably improve the situation

→ BDs have been found in young, open clusters & star forming regions (e.g. de Oliveira 2013)

Need to find benchmark metal-poor BDs

But: Only very few halo BDs (i.e. old and metal-poor) are known (Burgasser et al. 2002, 2009;…; Deaconn et al. 2012; Burningham et al. 2014)

→ GCs are old (>10 Gyr) and metal-poor

- *harbour the oldest BDs from the era of star formation in MW & Universe*
- *GC IMF down to and beyond the H-burning limit:*
  - *universal IMF, breaks in IMF, BDs formation*
  - *dynamics of GC and impact on MF*
  - *formation & evolution of our Galaxy*

Which Globular Cluster? – Target Selection

GCs are distant and old, and BDs are faint!

→Target clusters should be close

→Ultra-deep optical data should be available

- *Matching BD candidates*
- *Testing predicted metallicity effects*
- *PM cleaning*

Ideal targets for deep IR observations:

M4 & NGC 6397

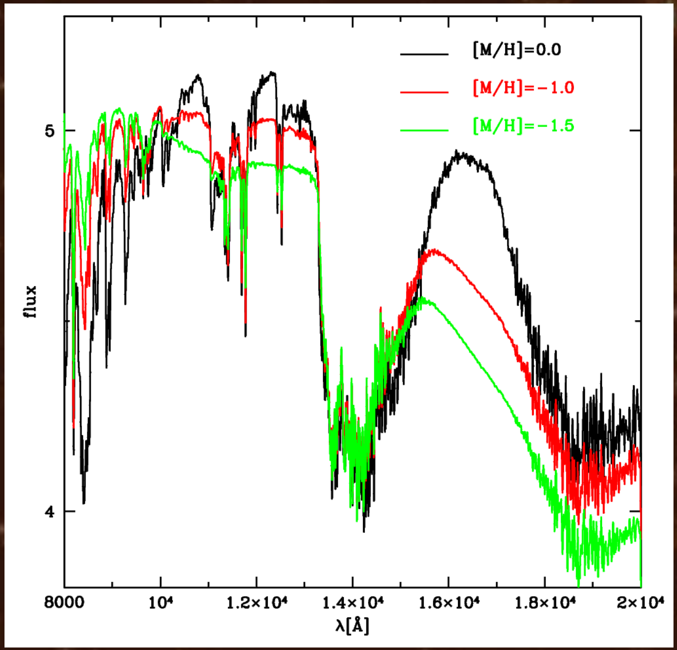
Theoretical Predictions: Spectral Energy Distribution

SED of VLMS and BDs is governed by molecular absorption.

- *TiO, VO – optical*
- *H_2O – IR*

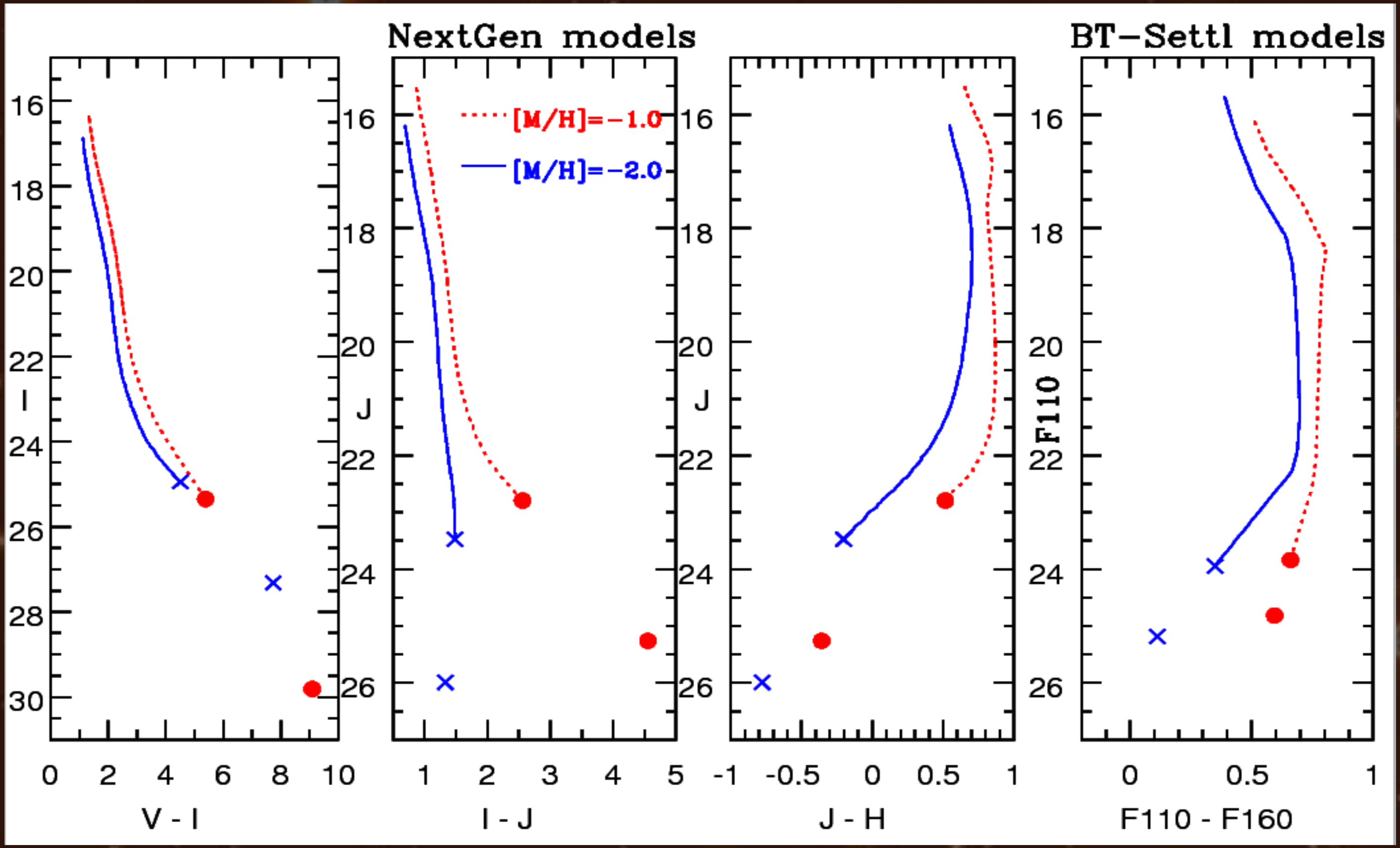
Collision induced absorption of H_2O depletion of TiO and VO become more dominant with decreasing metallicity
(e.g. Allard et al. 1997)

→ depresses IR and shifts flux to the near-IR
→ bluer SEDs with decreasing metallicity!



2000 K model spectra created with the Phoenix Web Simulator

Theoretical Predictions: CMDs

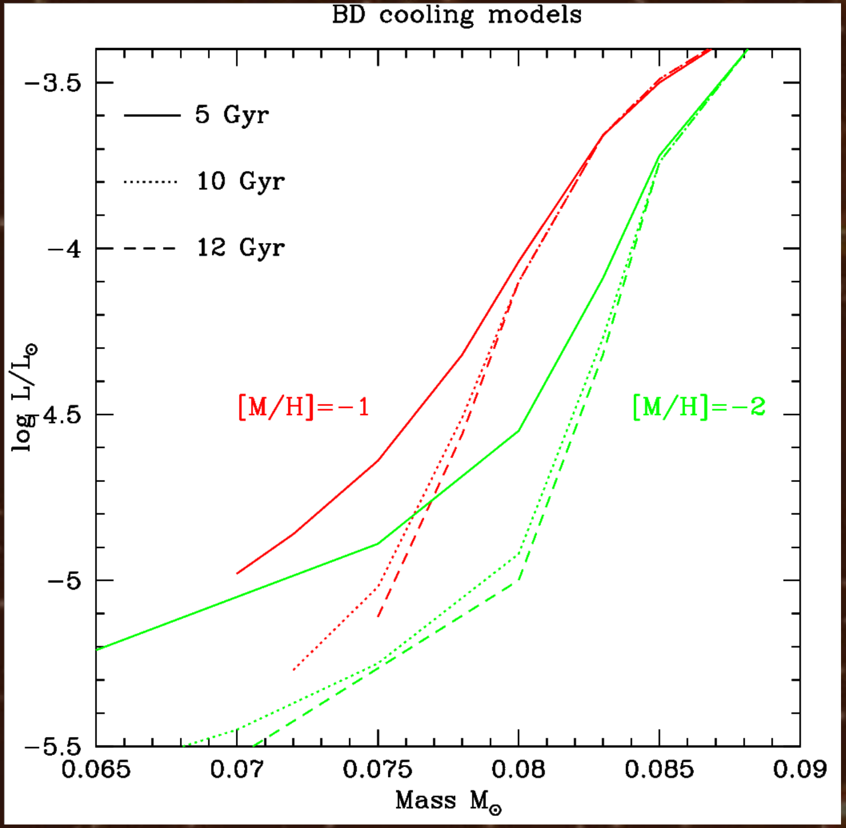


- *Optical: VLMS monotonically fainter & redder, independent of [Fe/H]*
- *IR-optical: VLMS of metal-poor isochrone turns blue*
- *IR: metal-poor much bluer than metal-richer isochrone*

Theoretical Predictions: Brown Dwarf Cooling Models

- *Stars at the H-burning limit retain the same luminosity for longer than the Hubble time*
- *As a BD cools, its luminosity decreases*

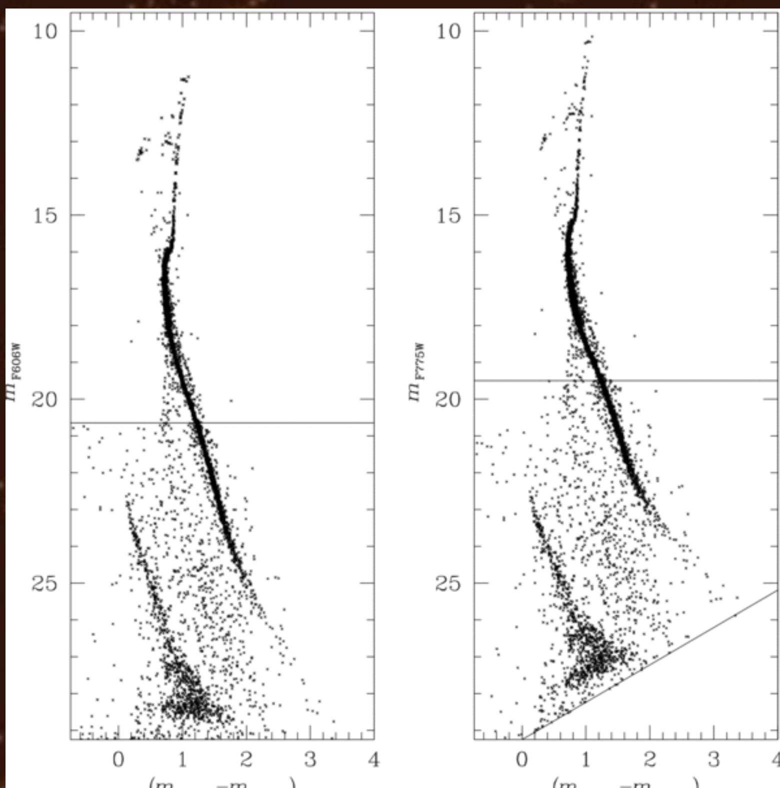
→ *gap in luminosity between the lowest mass stars and the brightest BDs could be a new age dating tool*

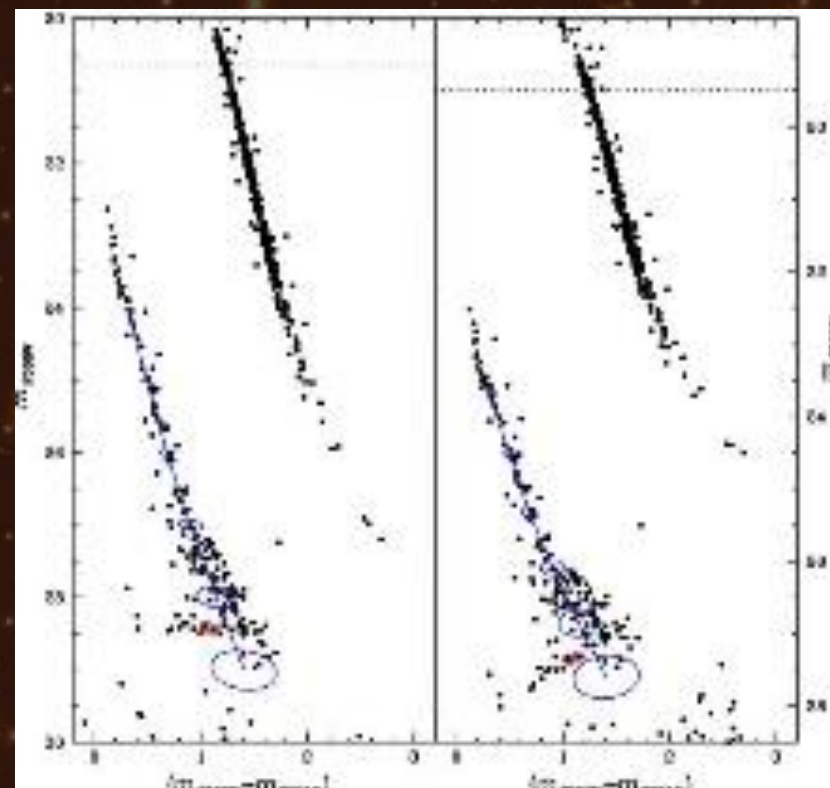


VLMS and BD cooling models kindly provided by I. Baraffe

The Globular Cluster M4: optical

- *Distance: 2.2 kpc, [Fe/H]= -1.16*
- *Deep optical HST ACS imaging: F606W 24000sec, F775W   8400sec*



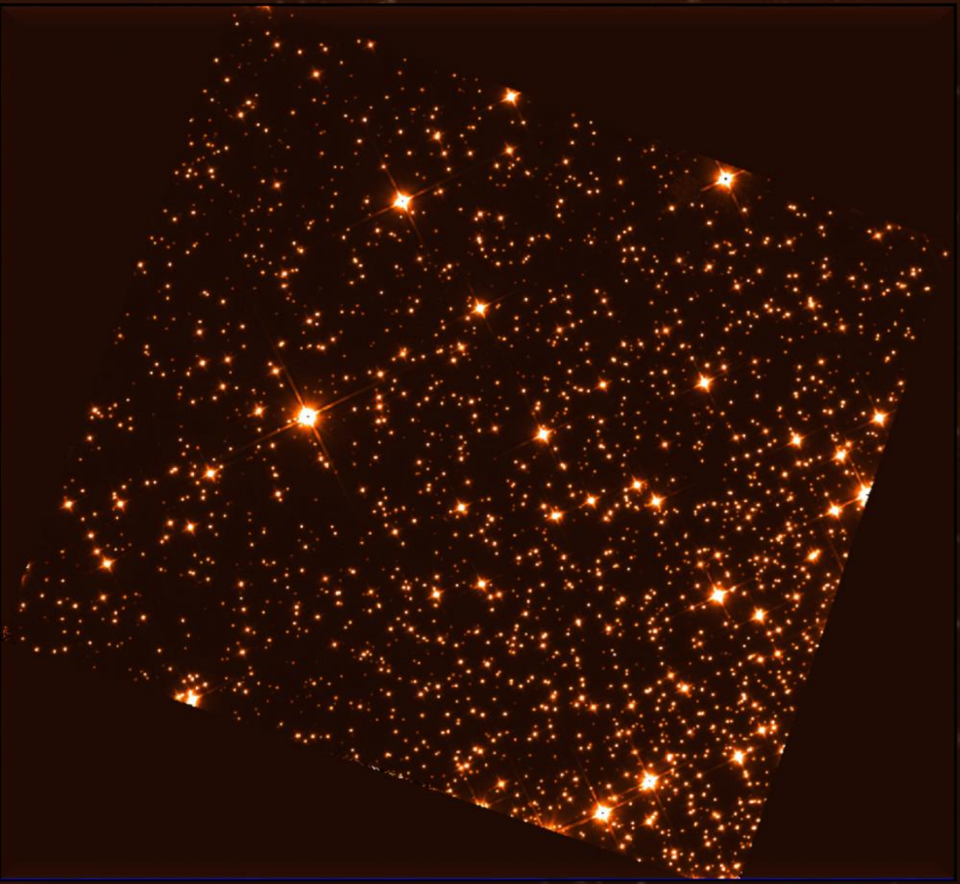


Bedin et al. 2009, ApJ, 697, 965

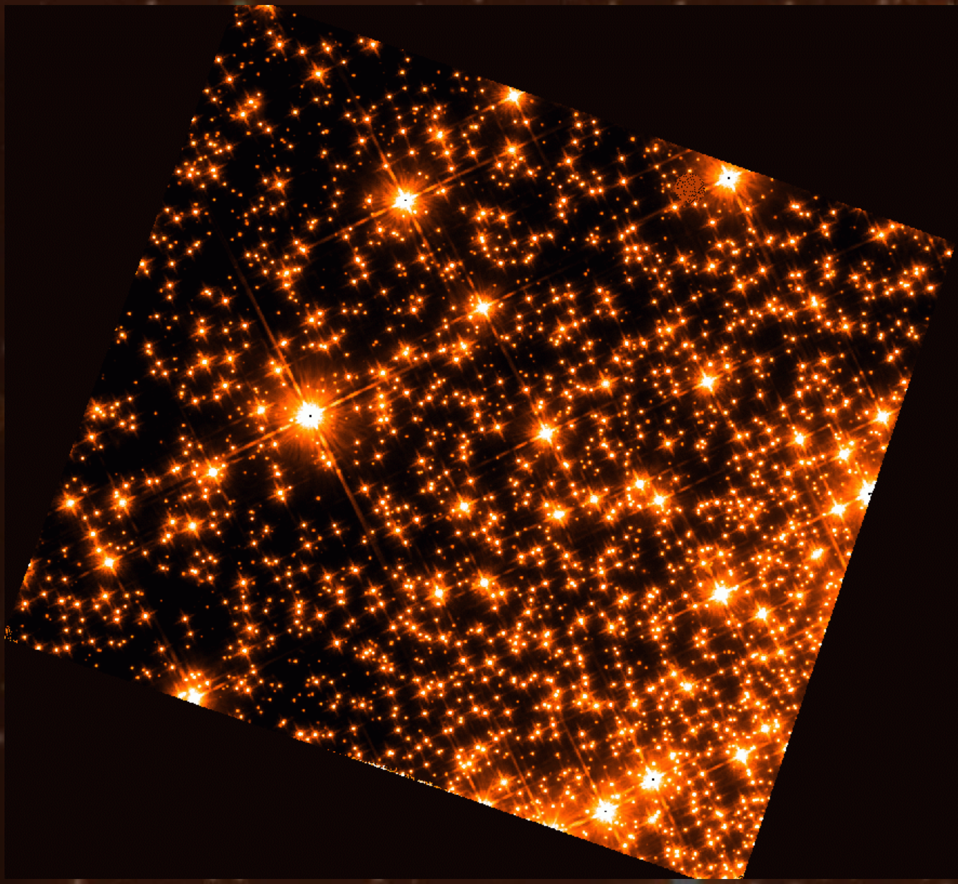
The Globular Cluster M4: IR

HST WFC3:

F110W 5220 sec

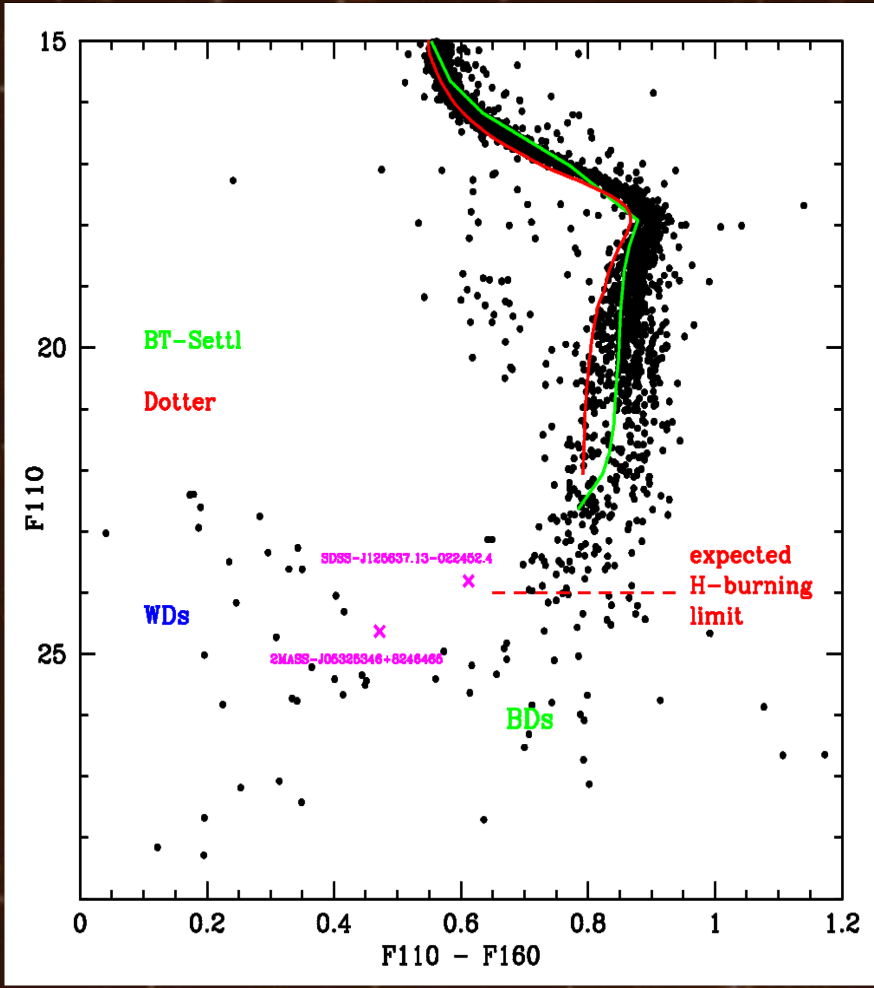


F160W 10440 sec

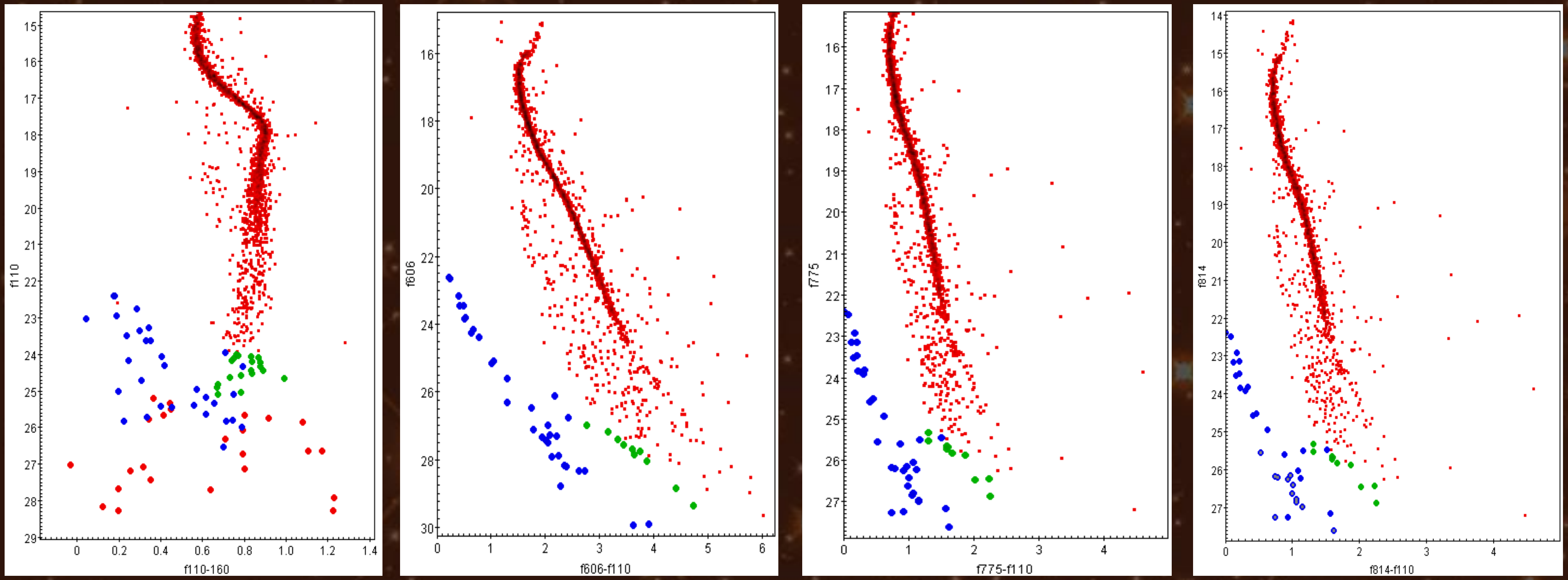


The Globular Cluster M4: IR CMD

- *Best-fit photometry*
- *Deepest IR CMD of a GC to date!*
- *Expected end of MS at F110W ≈ 24 mag*
- *CMD ≈ 4 mag deeper and well into the BD region*
- *WD sequence*
- *Split in VLMS*



The Globular Cluster M4: IR – optical CMDs



Unselected data
WDs
Bottom of IR MS (> 24 mag)

- *IR matches to optical WD candidates*
- *No optical matches fainter than F110W = 26 mag*

Deep IR Imaging of the GC M4:

Hunting for Brown Dwarfs in Globular Clusters

Conclusions – so far

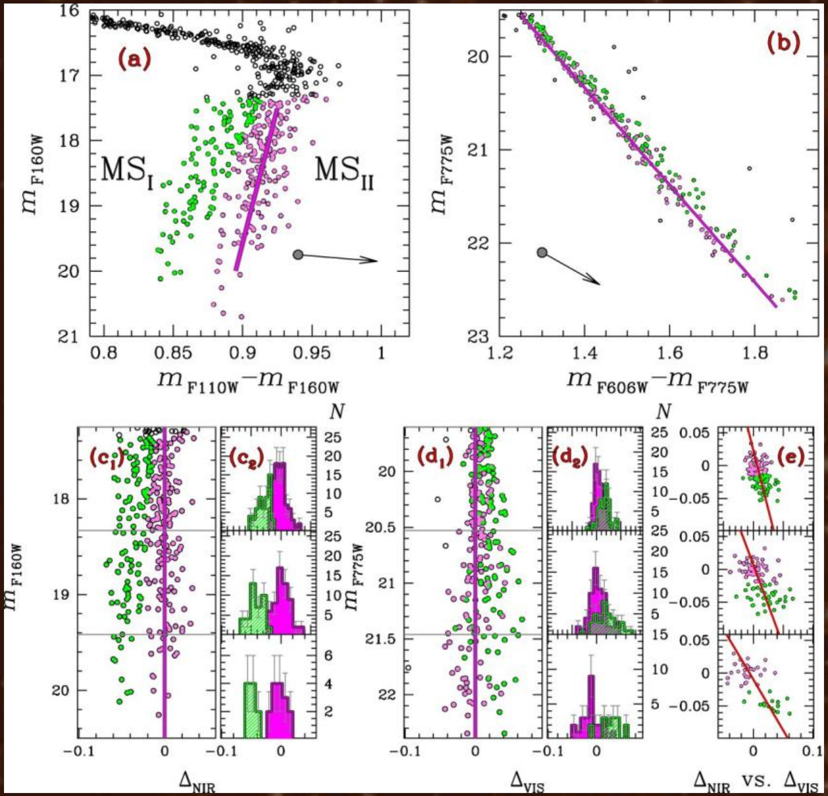
- *Deepest near-IR of a GC so far!*
- *Approx. 4 mags below the predicted end of the H-burning sequence*
- *Numerous BD candidates*
  - *However: so far no optical matches*
- *IR counterparts to optical WD sequence*

The Globular Cluster M4: Multiple Stellar Populations along the VLMS

M4 was previously not known to harbour multiple MSs

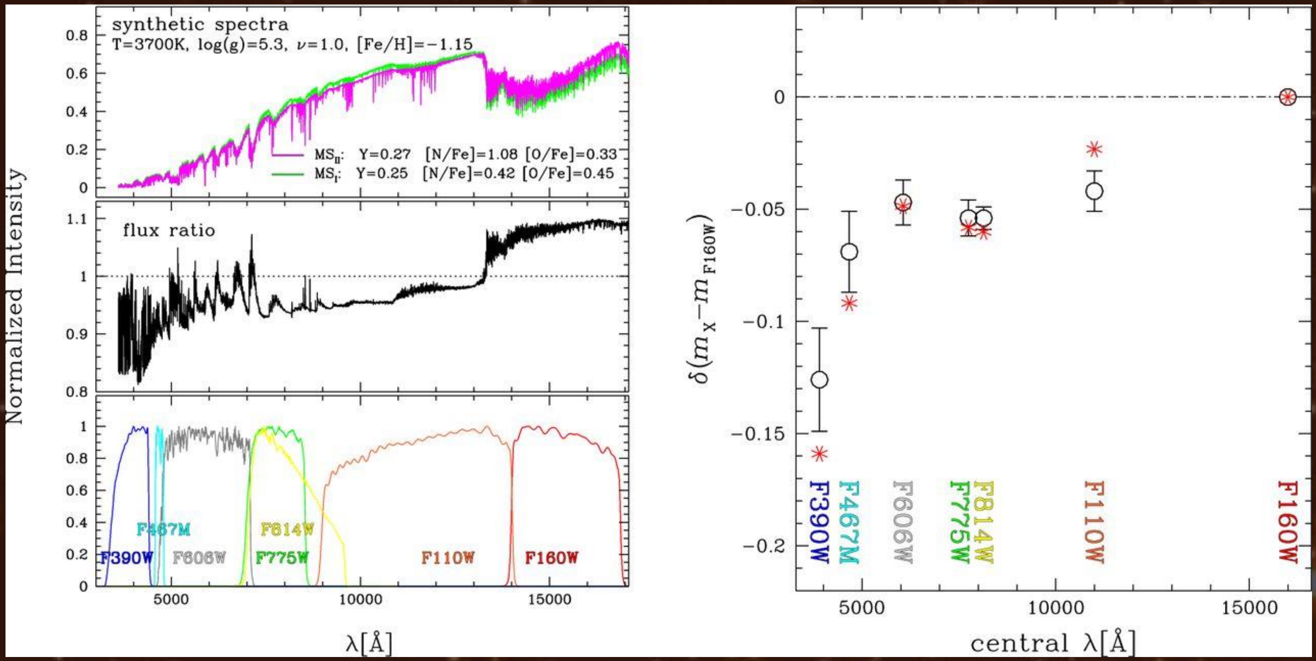
High precision photometry of ACS optical and IR data set , concentrating on the low-mass MS, reveals 2 populations of M-dwarfs below the MS knee:

- *~38 % (MSI, green)*
- *~62 % (MSII, magenta)*



Milone, Marino, Piotto, Cassisi, Dieball et al. 2014, MNRAS, 439, 1588

The Globular Cluster M4: Multiple Stellar Populations along the VLMS

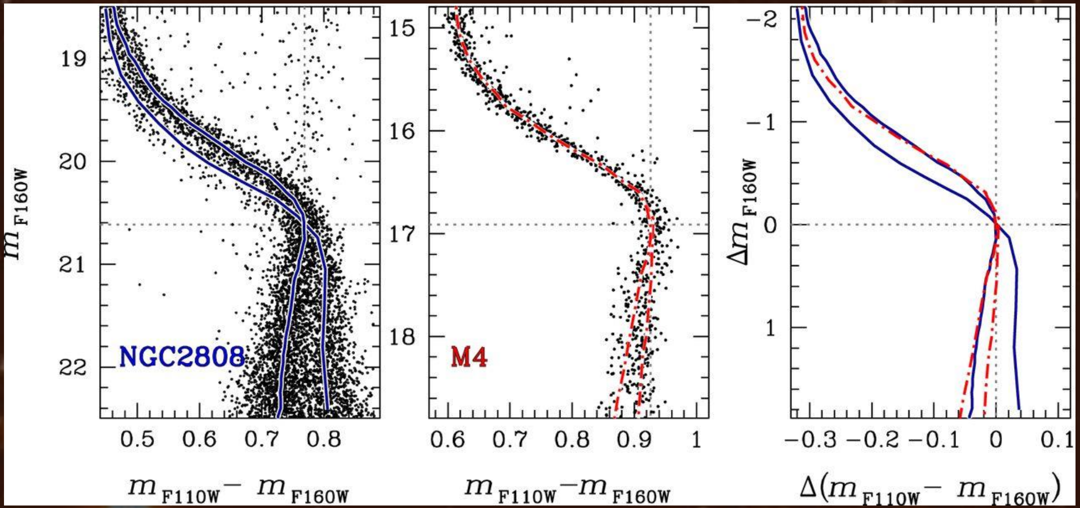


Comparing observed and predicted colours suggests

- *MSI: primordial abundance*
- *MSII: enhanced in He, N, Na and depleted in O*

Milone, Marino, Piotto, Cassisi, Dieball et al. 2014, MNRAS, 439, 1588

The Globular Cluster M4: Multiple Stellar Populations along the VLMS



M4 is now only the third GC (after NGC2808 and NGC5139) for which multiple stellar populations along the VLMS have been confirmed!

NGC 2808 – well known for its three MS sequences

- *Merge at the MS knee*
- *Split into 2 sequences along the VLMS*

M4 split smaller than in NGC 2808 due to small O-depletion of 2nd generation in M4

Milone, Marino, Piotto, Cassisi, Dieball et al. 2014, MNRAS, 439, 1588

Deep IR Imaging of the GC M4:
Hunting for Brown Dwarfs in Globular Clusters
Outlook

- *PM cleaning the deep IR data set*
  - *Based on optical data*
  - *2^{nd} epoch of IR data ?*
- *Add data from the M4 core project (WFC3/F775W)*

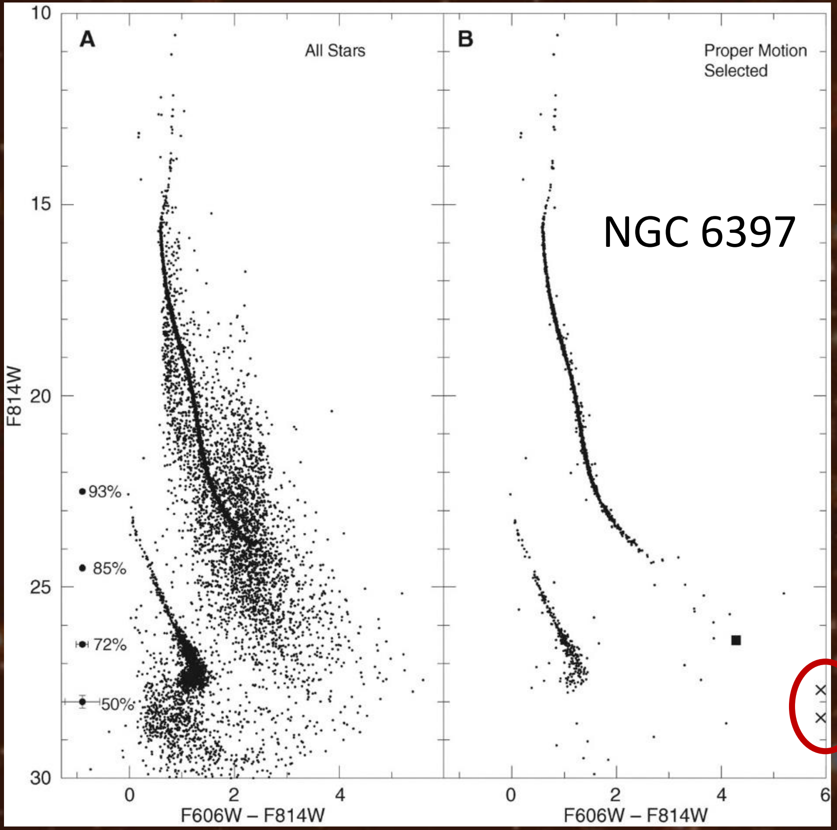
→ LF

→ low-mass MF

→ calibrate low-mass models

- *Deep near-IR imaging of NGC 6397 ?*

→ ideal target cluster as we already have 6 optical BD candidates!



Richer et al. 2008, AJ, 135, 2141