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Talk

The Million-Body Problem

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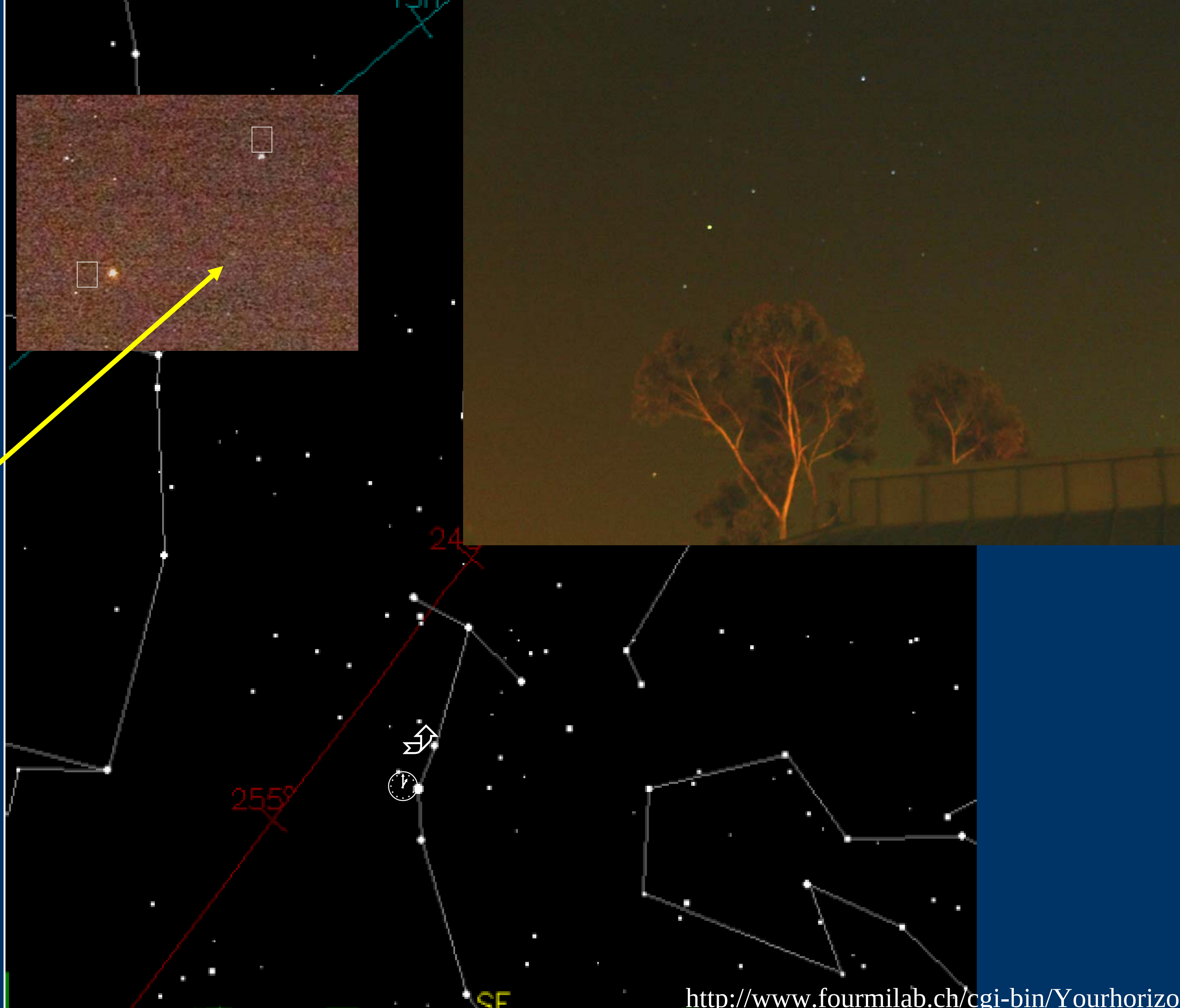

M4

http://www.fourmilab.ch/cgi-bin/Yourhorizon

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http://antwrp.gsfc.nasa.gov/image/0607/RhomosaicM_mmg_f45.jpg

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Part 1: Why Globular Star Clusters Matter

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The globular star cluster M4

http://www.noao.edu/

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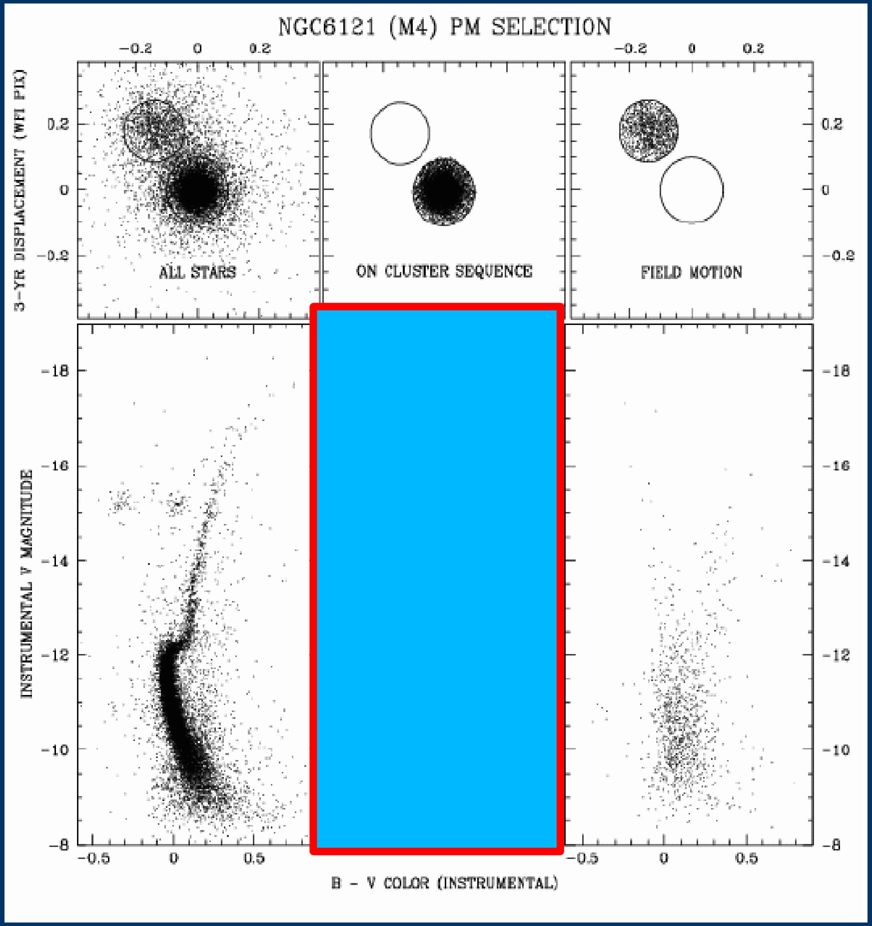
The Colour-Magnitude Diagram

Removing the non-members



Anderson et al, 2006, A&A, 454, 1029

Determining the age from the theory of stellar evolution

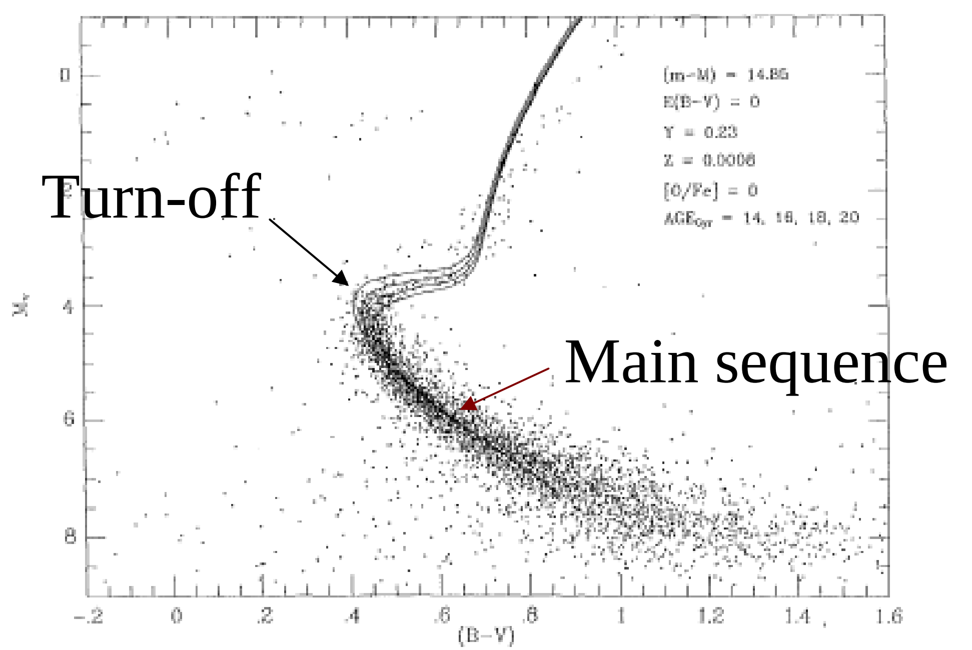


Fig. 1. Colour magnitude diagram for all the observed stars compared with a set of theoretical isochrones by Chieffi and Straniero (1989).

Paez et al, ApSpS,169,1990

The clusters are important for
- Stellar evolution
- Cosmology

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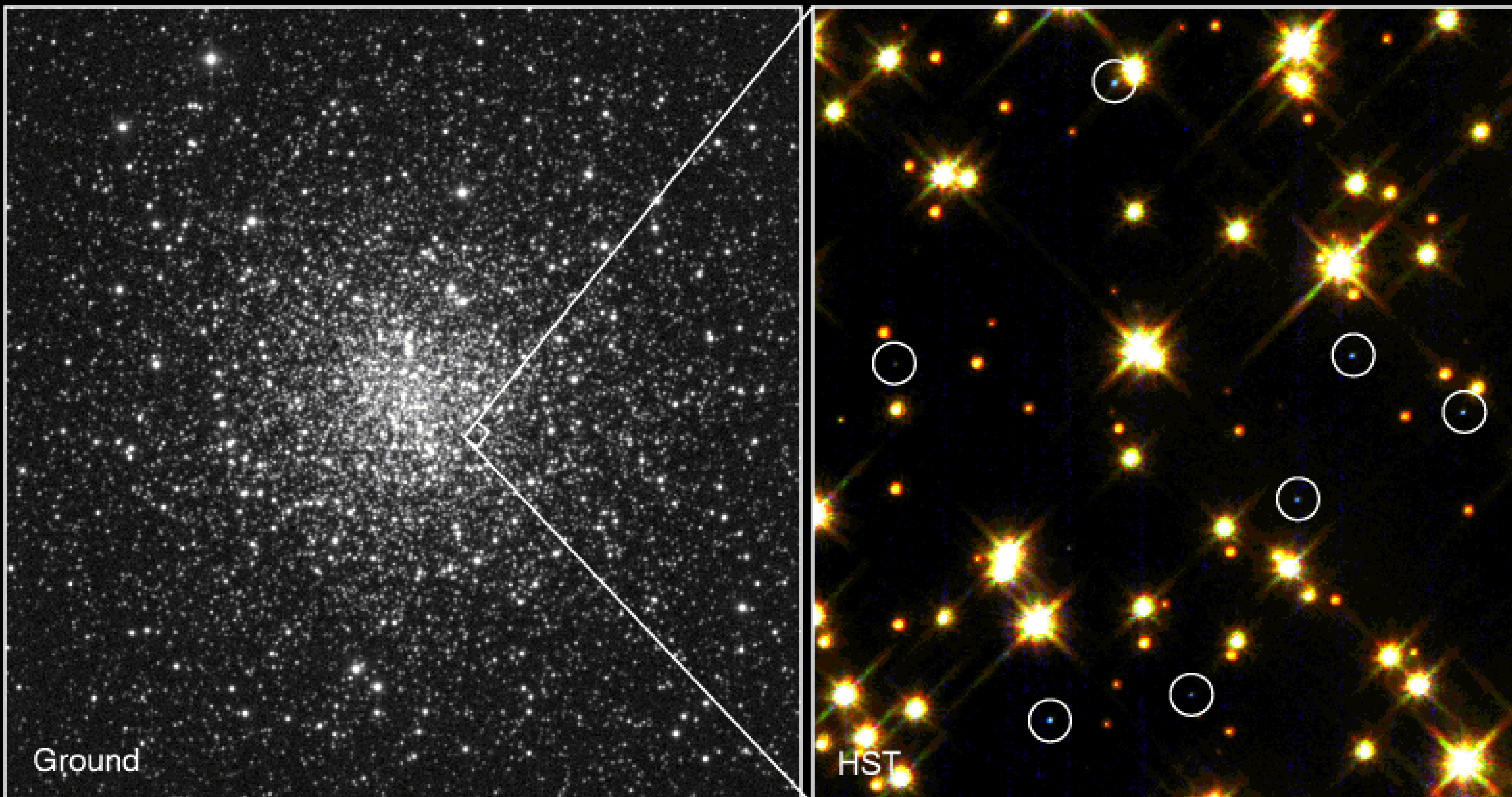
White dwarfs:
the end-point of the evolution of low-mass stars



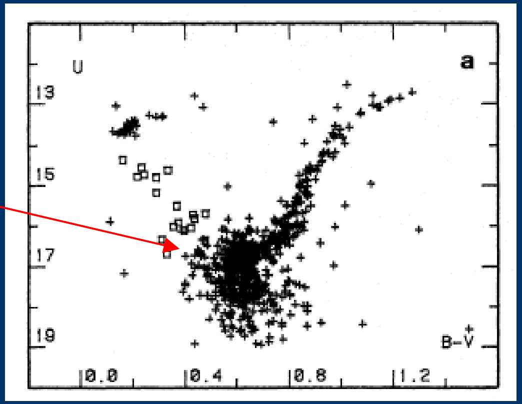
White Dwarf Stars in M4 HST • WFPC2

PRC95-32 • ST ScI OPO • August 28, 1995 • H. Bond (ST ScI), NASA

Blue stragglers in NGC 6397

young-looking massive stars formed by stellar collisions

Turn-off



Lauzeral, 1992, A&A, 262, 63L

Movie credit: J. Lombardi

http://webpub.allegheny.edu/employee/j/jalombar/movies/

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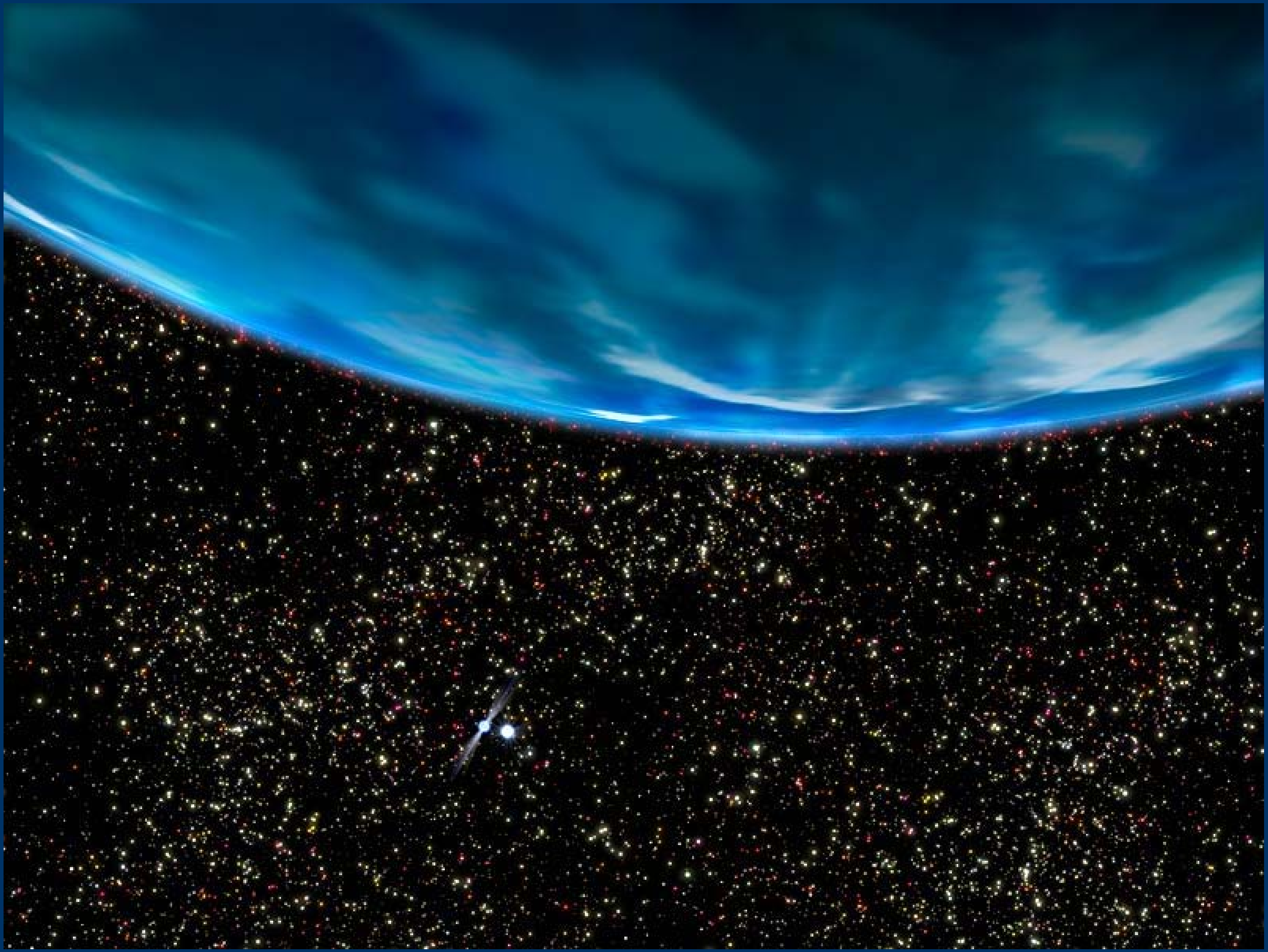
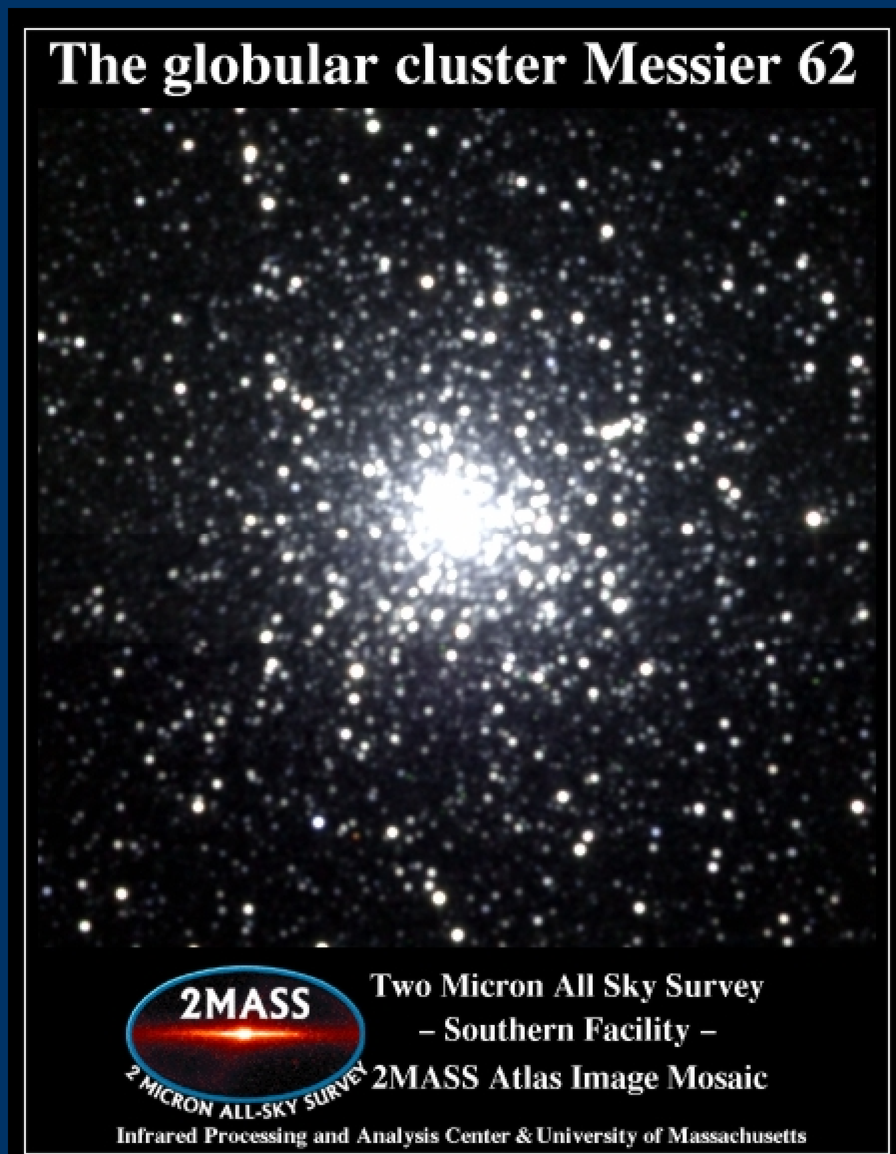
The pulsar triple in M4: a planet in a globular cluster

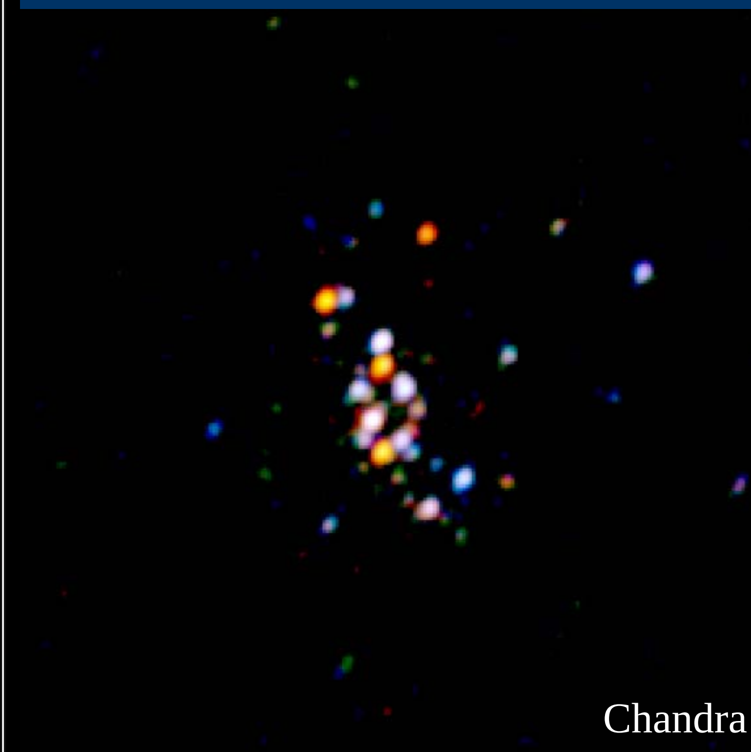


STScI-PRC2003-19a

X-rays from globular clusters



= NGC 6266



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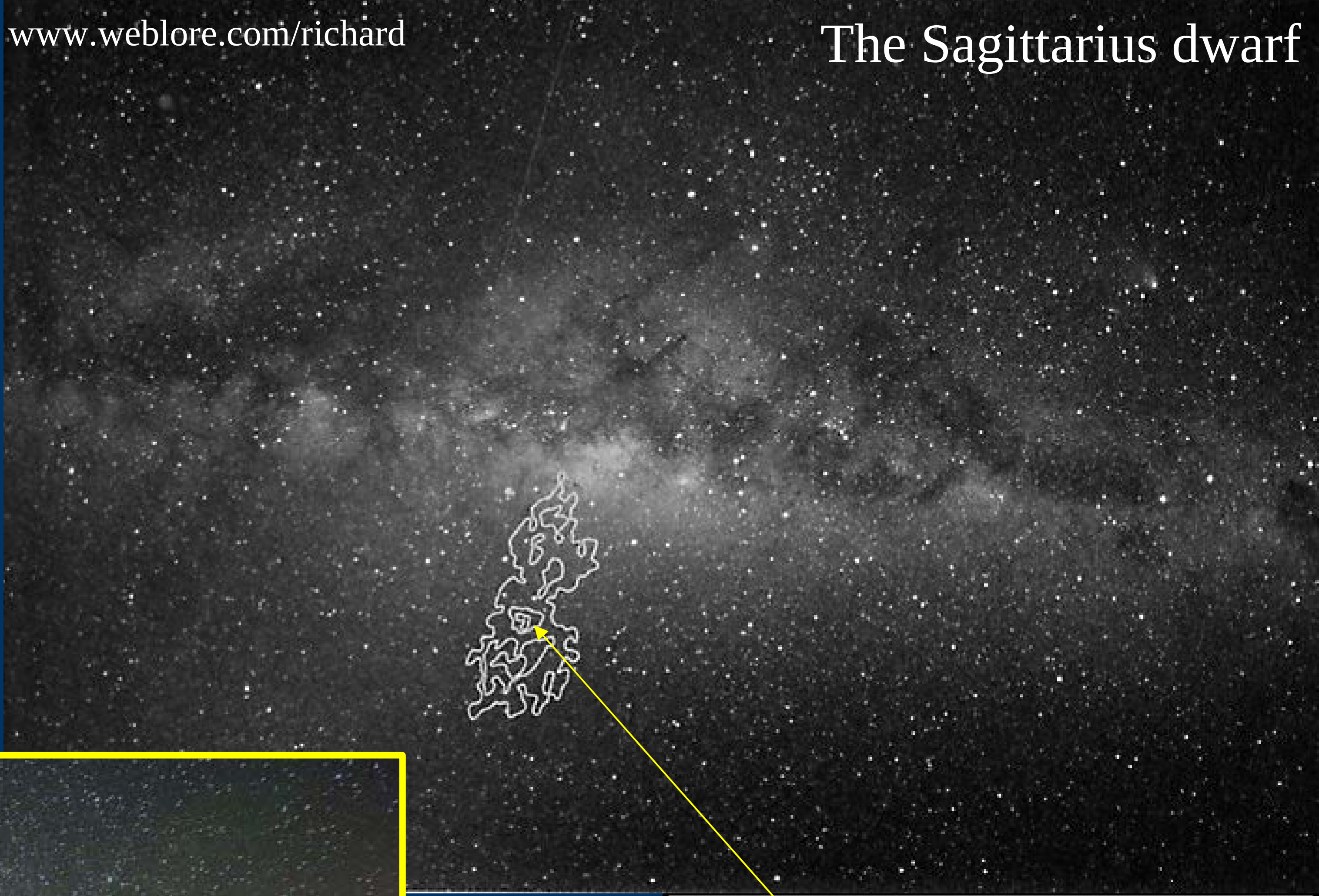
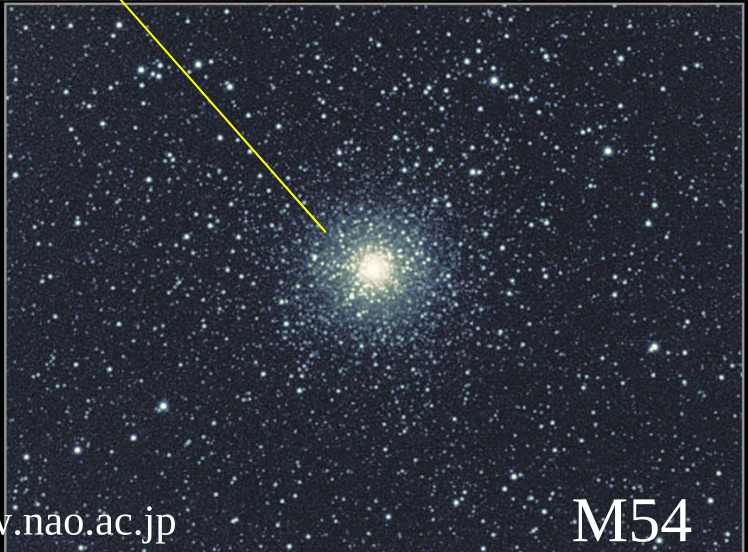
The Sagittarius dwarf

A globular cluster arriving with another galaxy



www.areavoices.com/astrobob



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The discoverer of the size of the galaxy – Harvard's Harlow Shapley

Three weeks later – Hollywood's shapely Harlow

Part 1: Why Globular Star Clusters Matter – Summary

Evolution of stars
The age of the universe
Stellar collisions
Pulsars
Planets
X-ray sources
The formation of the Galaxy
The formation of stars
The shape of the Galaxy....

Part 2:
....Stellar dynamics –
the motions of stars under the forces acting between them

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The Classical Gravitational N-Body Problem

N point-masses (stars)

Inverse-square law gravity (long-range)

Newton's equations of motion

" the "star gas"

An analogy – ideal gases

N point masses (atoms, molecules)

Electrostatic interactions ("collisions")

Newton's equations of motion

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Dynamic equilibrium – ideal gases

Example: ideal atmosphere

Rapid motion of atoms/molecules (few hundred m/s)

Gas at rest (on a good day)

Temperature gradient

Dynamic equilibrium – star gases

Example: a globular cluster

Rapid motion of individual stars (few km/s)

No overall motion (expansion/contraction)

Stars move faster at centre than in the surrounding halo

Computer simulation of a star cluster, showing dynamic equilibrium

http://www.maths.ed.ac.uk/~heggie/orbits_13.mpg

What happens in the long run?

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Thermal energy – ideal gases

Atoms/molecules in motion

Kinetic energy per particle = $\frac{1}{2}mv^2$

Temperature is proportional to average value of v^2

Thermal energy – star gases

Stars in motion

Kinetic energy per particle = $\frac{1}{2}mv^2$

By analogy, temperature proportional to $<v^2>$

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Heat conduction – ideal gases

In collisions, fast-moving particles tend to lose kinetic energy, slowly-moving particles tend to gain kinetic energy

Heat (thermal energy) is conducted from hot regions to cold

Heat conduction – star gases

In two-body encounters, fast-moving stars tend to lose kinetic energy, slowly-moving stars tend to gain it

Heat (kinetic energy) is conducted from hot regions to cold

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The paradoxical behaviour of motion under gravity – an example

As a satellite experiences friction from the Earth's atmosphere, it sinks into a lower orbit, and moves faster. Friction speeds things up.

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Specific heat – ideal gases

Addition of heat increases temperature

Specific heat – star gases

Addition of heat *decreases* temperature:

Addition of heat (kinetic energy) makes stars move faster
They move out from the cluster centre, losing kinetic energy
In fact they lose more kinetic energy than they gained initially
Star gases have *negative specific heat:*
if you add thermal energy (heat), they cool down.

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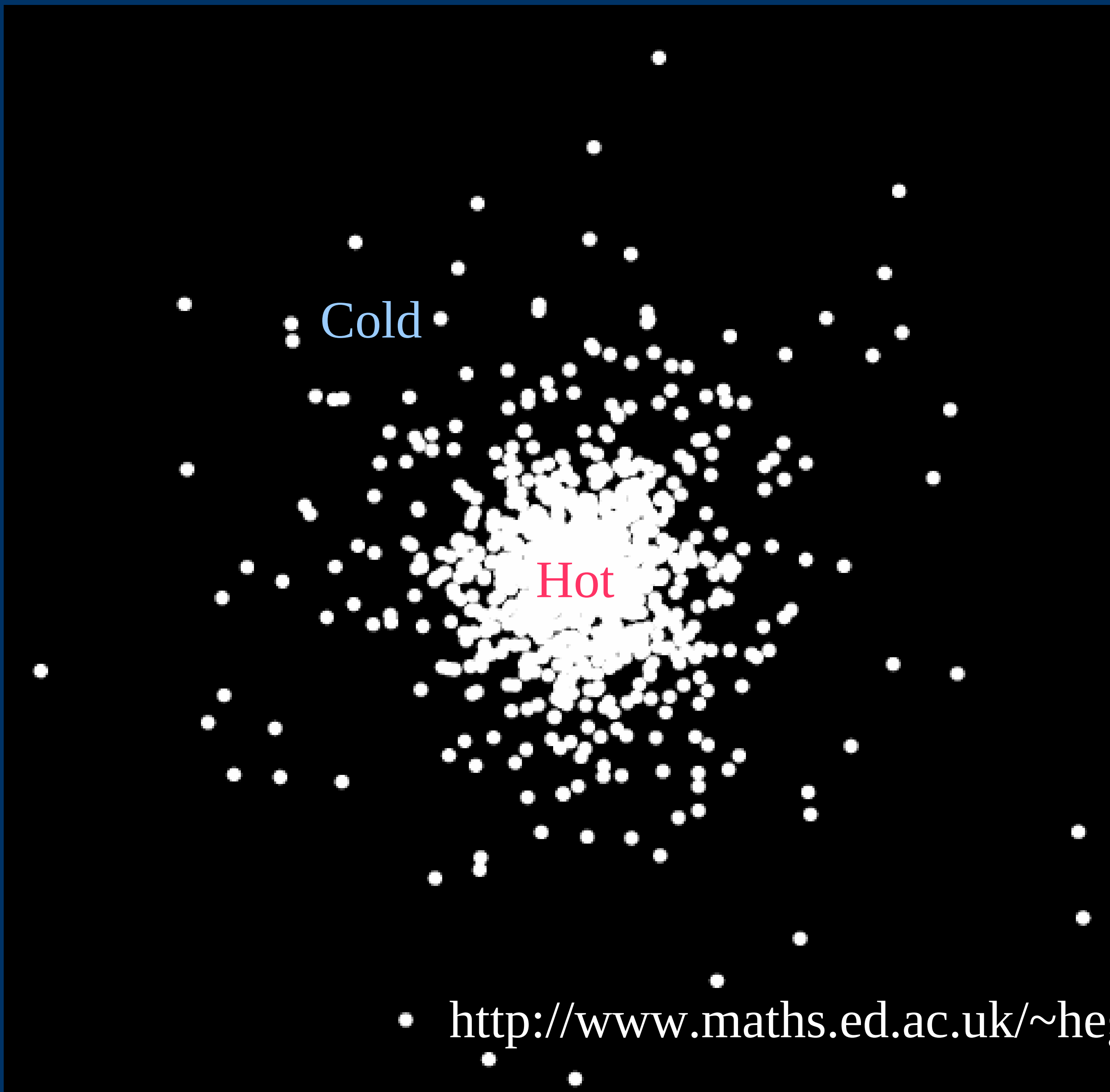
The Evolution of Star Clusters



Heat flows from the centre to the halo

The centre loses heat and gets hotter (and dense the halo gains heat and gets cooler

The temperature difference has increased; the flo of heat increases

This is called *“gravothermal instability”*, or *“core collapse”*

Movie

http://www.maths.ed.ac.uk/~heggie/plots_13.mpg

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Core collapse

A very slow process – billions of years

Central density becomes infinite (in theory)

The missing ingredient – binary stars
(the *molecules* of the star gas)

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Interactions between single stars

One star gains energy, the other loses

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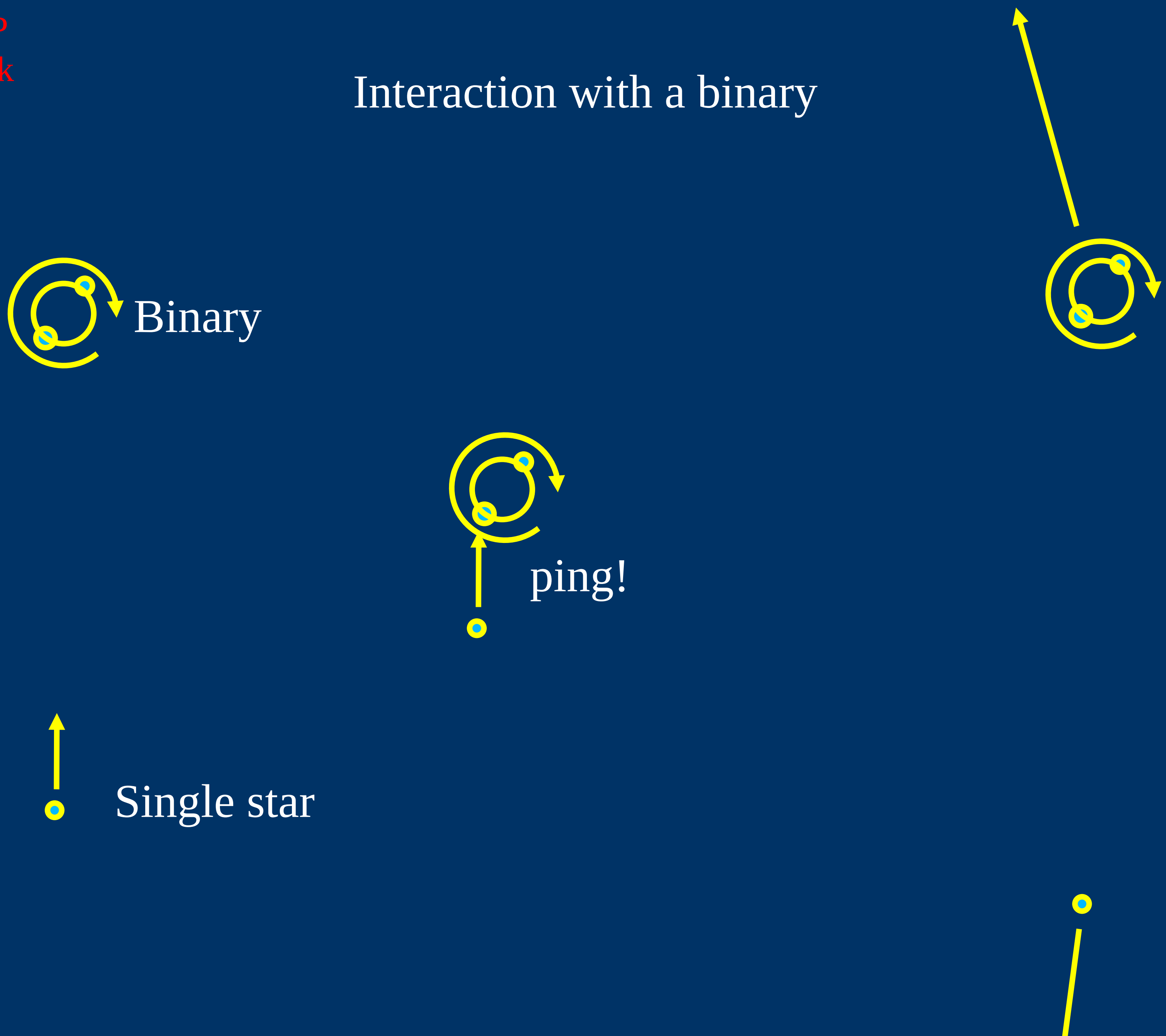
Interaction with a binary



Both objects gain energy

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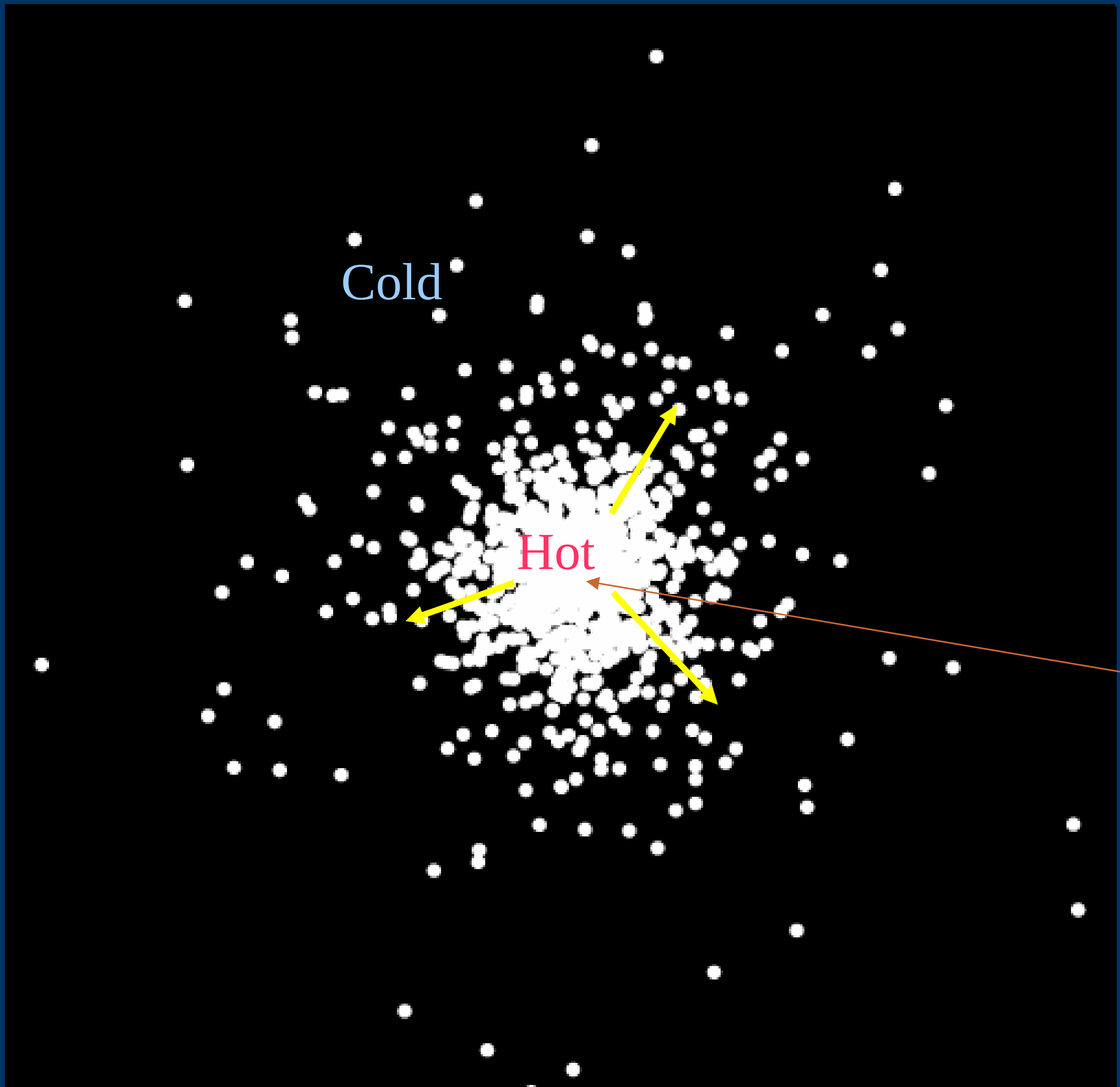
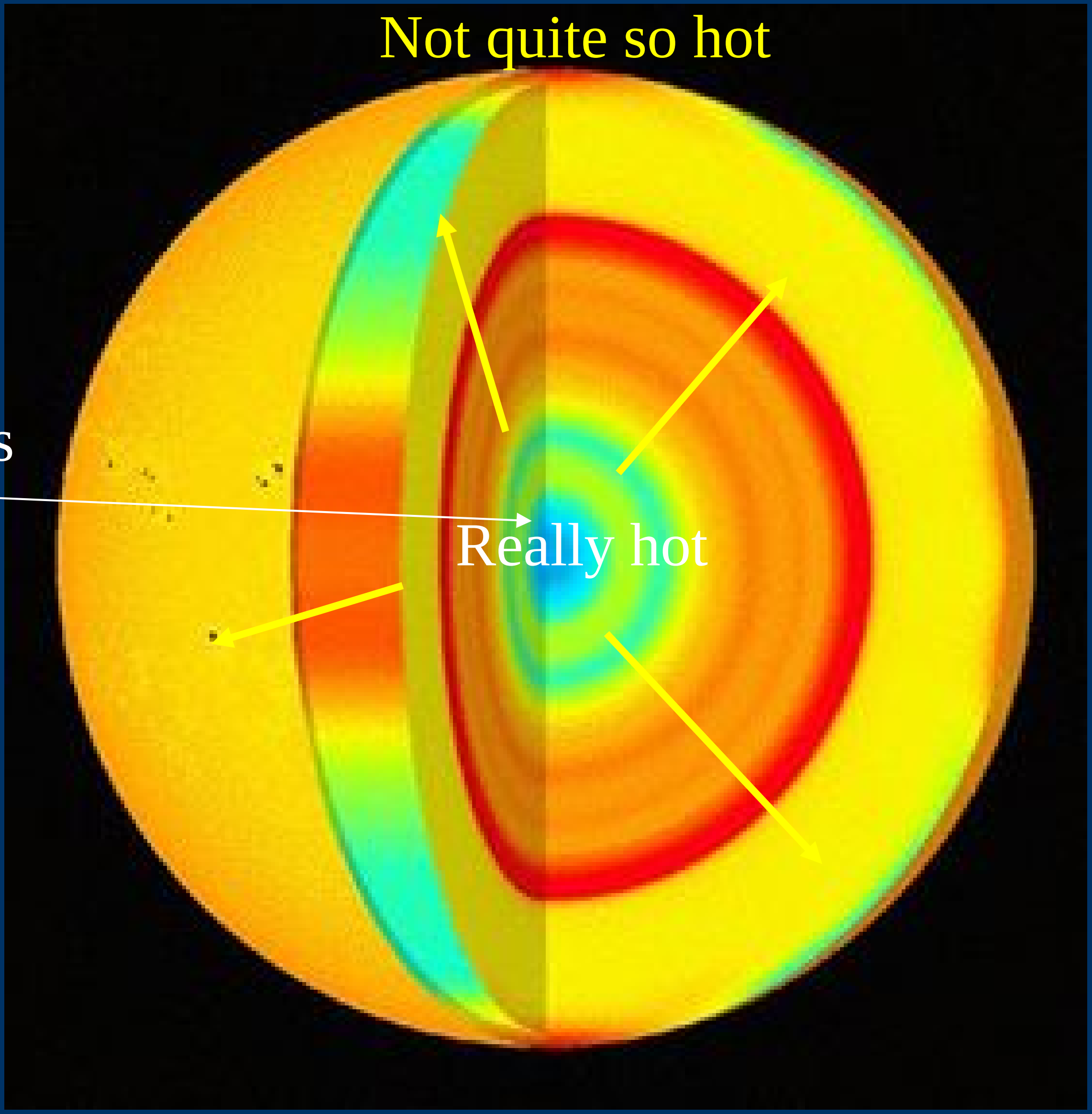
A post-collapse cluster



A star like the sun

Flow of heat

Nuclear reactions generate energy



http://www.bnsc.gov.uk

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Omega Centauri – a star cluster with an uncollapsed core

HST

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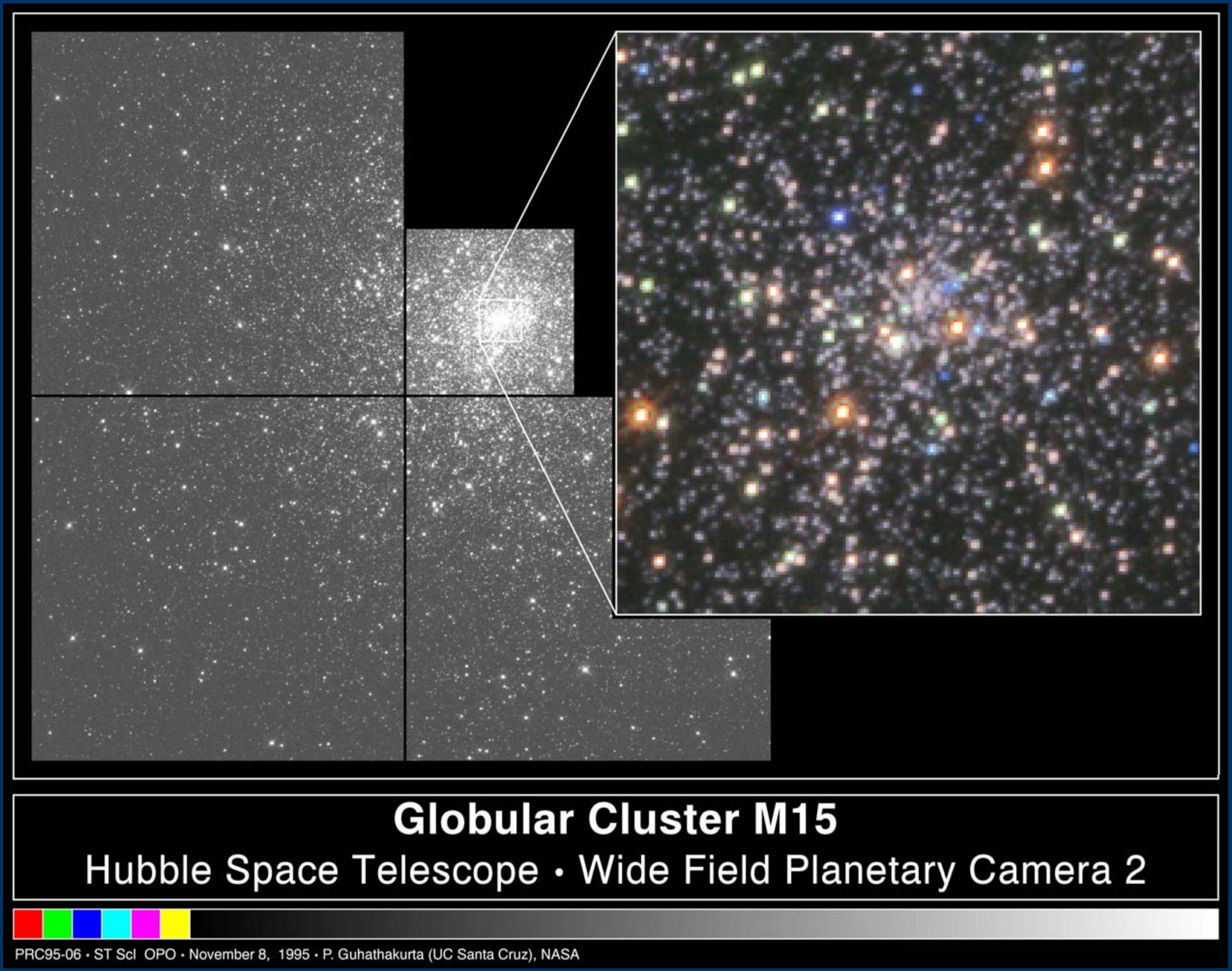
M15 – a star cluster with a collapsed core



For what could be more beautiful than the heavens, which contain all beautiful things?
Copernicus

N6397 (ESO)