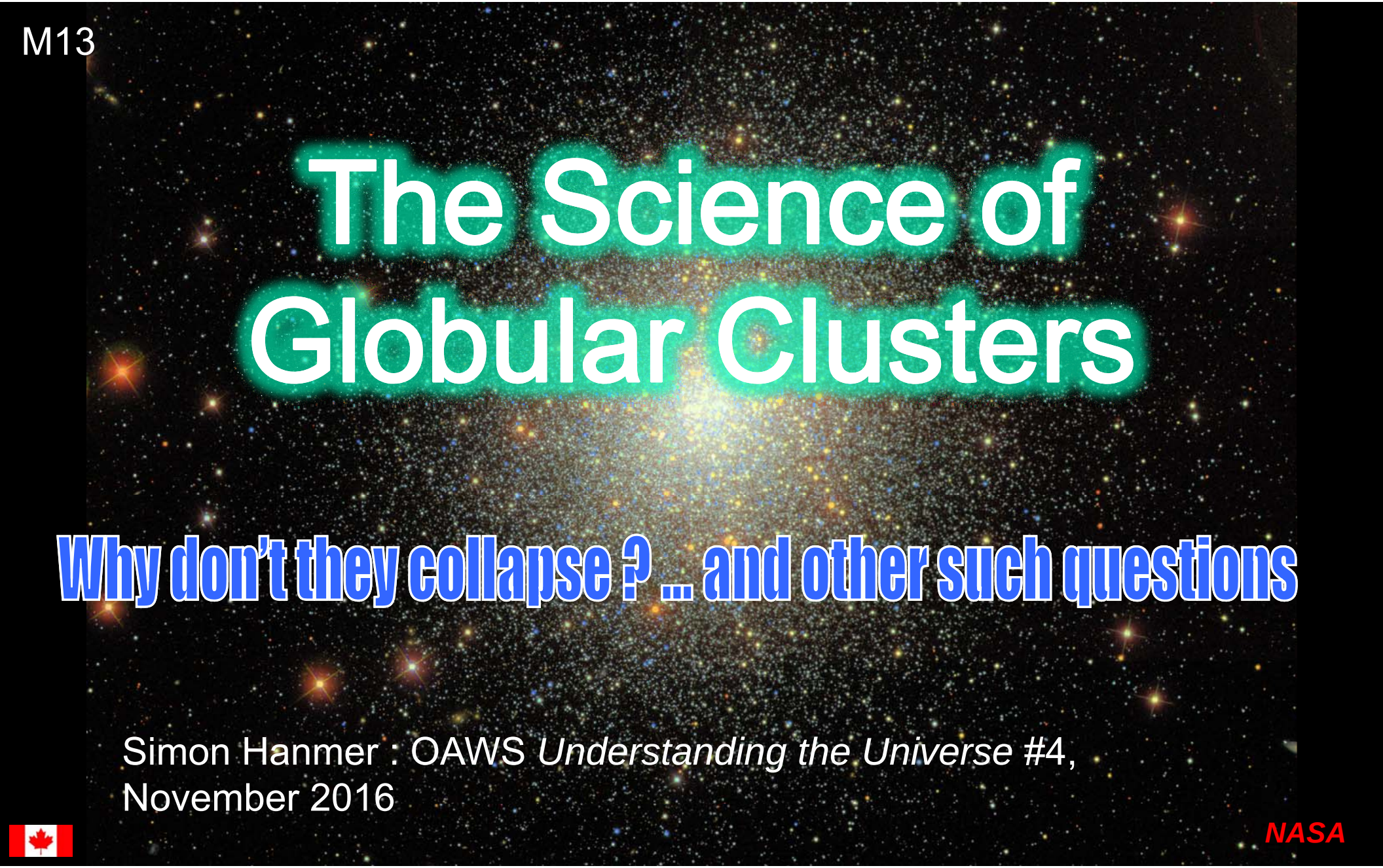

M13
The Science of Globular Clusters
Why don't they collapse ? ... and other such questions
Simon Hanmer : OAWS *Understanding the Universe* #4, November 2016
NASA

What is a “Globular Cluster” ? … 47 Tucanae

- An ***old*** *(~13-8 Ga)* close-packed, *gravitationally bound* association of 10^4 -10^6 stars, ~100 l.y. *diameter*, 1.0 l.y. *spacing* ... *Planets ?*
- Absence of inter-stellar gas
- Single or multiple types and ages of stars (*int/ext gas/dust*)
- Stellar packing distributions within clusters

NASA

What is a “Globular Cluster” ?

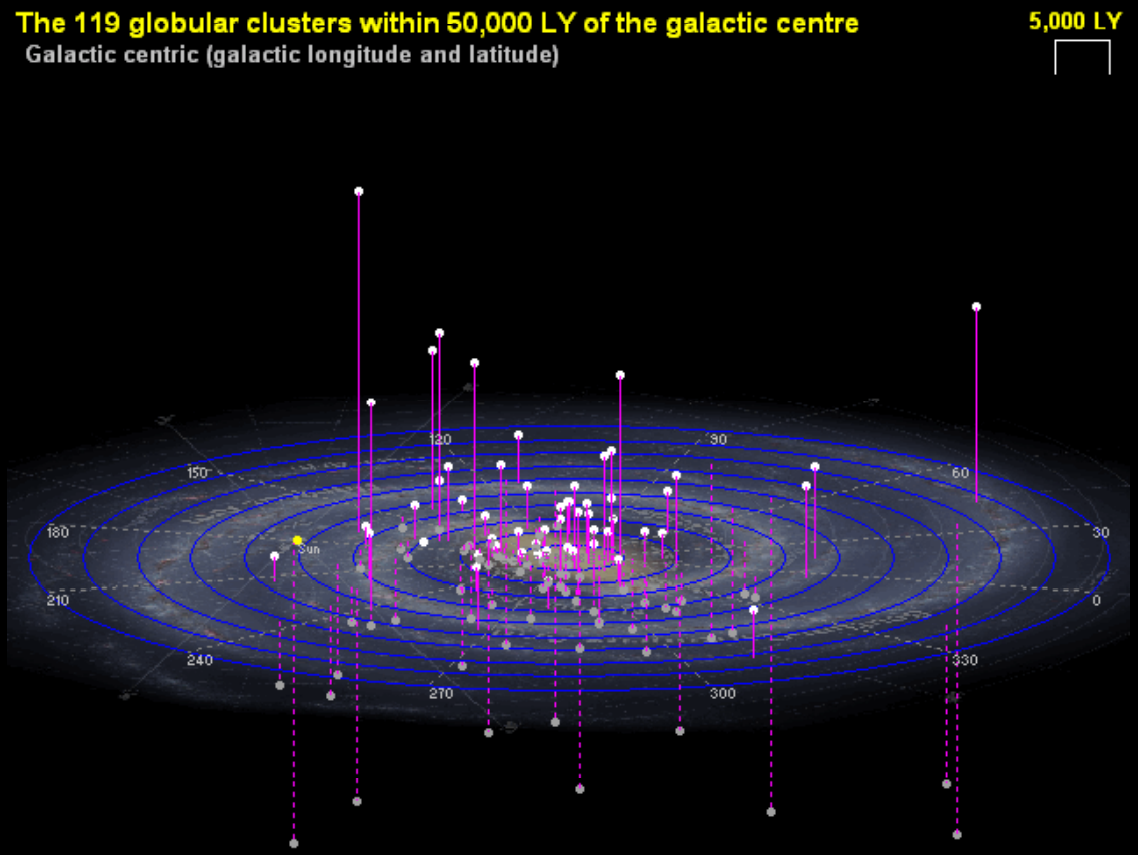
- Occurrence of globular clusters
  - Milky Way : ~160
  - M87 : 13,000 !
- Structure of globular clusters
  - Range of stellar numbers => range in cluster size
  - White dwarfs and neutron stars – **100/1**
  - Core-halo structure *
    - Some clusters are “looser” than others …
    - Two flavours : *collapsed core* and *non-collapsed core*

What is a “Globular Cluster” ?

- Measurements : length scales and time scales
  - *Core* (density), half-light and tidal (Roche) radii
  - *Crossing time* : ~0.1-1 Ma @ ~10 km/sec according to radius
  - *Relaxation time* * : randomisation of stellar orbits (*circular /radial*) by stellar gravitational interaction (2 and 3 body) … ~0.1-1 Ga according to radius *(more anon)*
    - *Relaxed cores* with *unrelaxed halos* after ~13 Ga !

See https://en.wikipedia.org/wiki/Globular_cluster
and http://relativity.livingreviews.org/Articles/lrr-2013-4/articlese2.html

Where do globular clusters occur ?



Data from William E. Harris, McMaster University
http://www.physics.mcmaster.ca/Globular.html

3D Diagram by Larry McNish

http://scienceblogs.com/startswithabang

Globular Clusters … in the Fornax dwarf galaxy

NASA

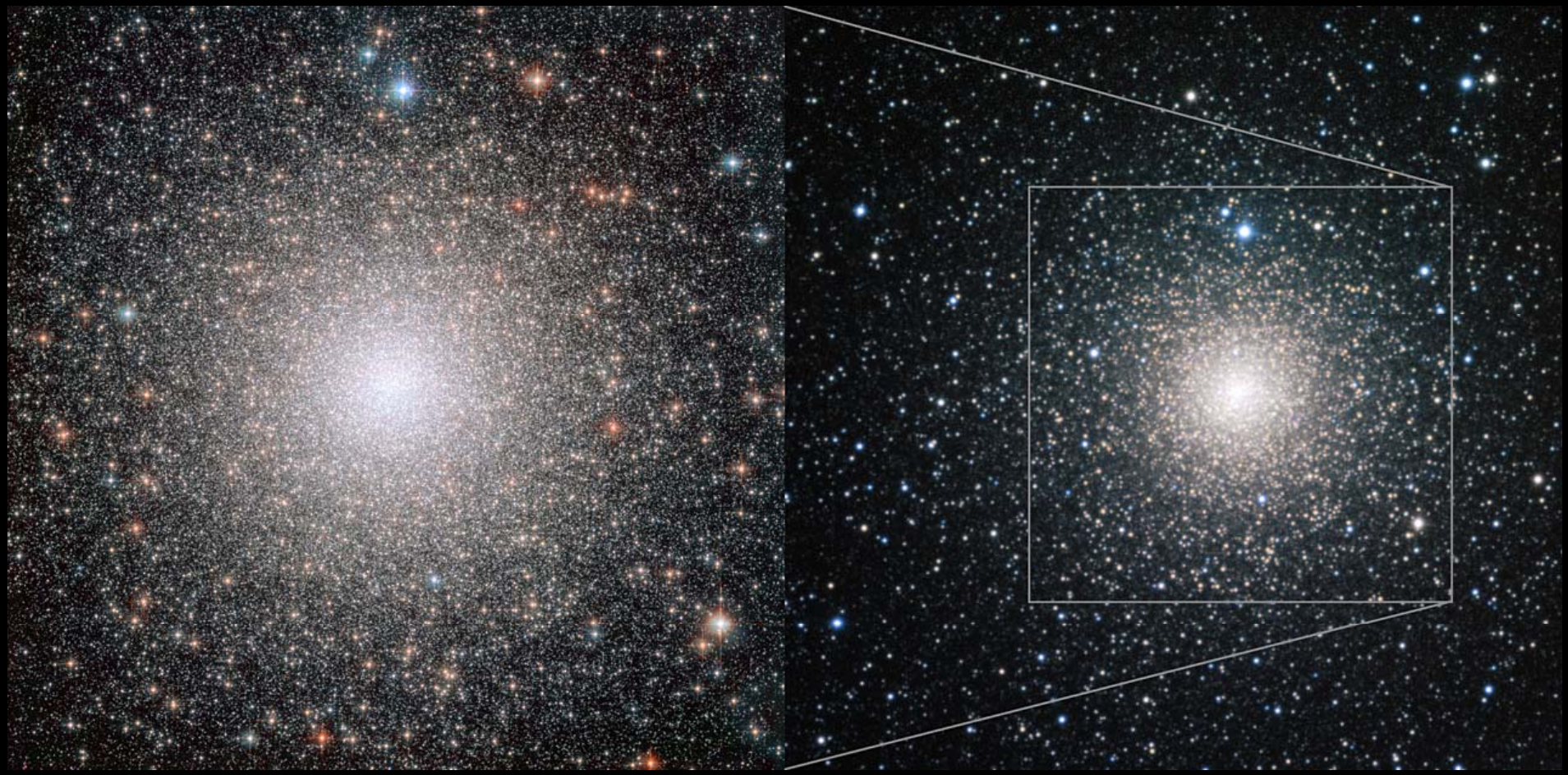
Globular Clusters … M15 (collapsed core)

NASA

Globular Clusters … M54 (collapsed core)

NASA

Globular Clusters … NGC 6388 (collapsed core)



NASA

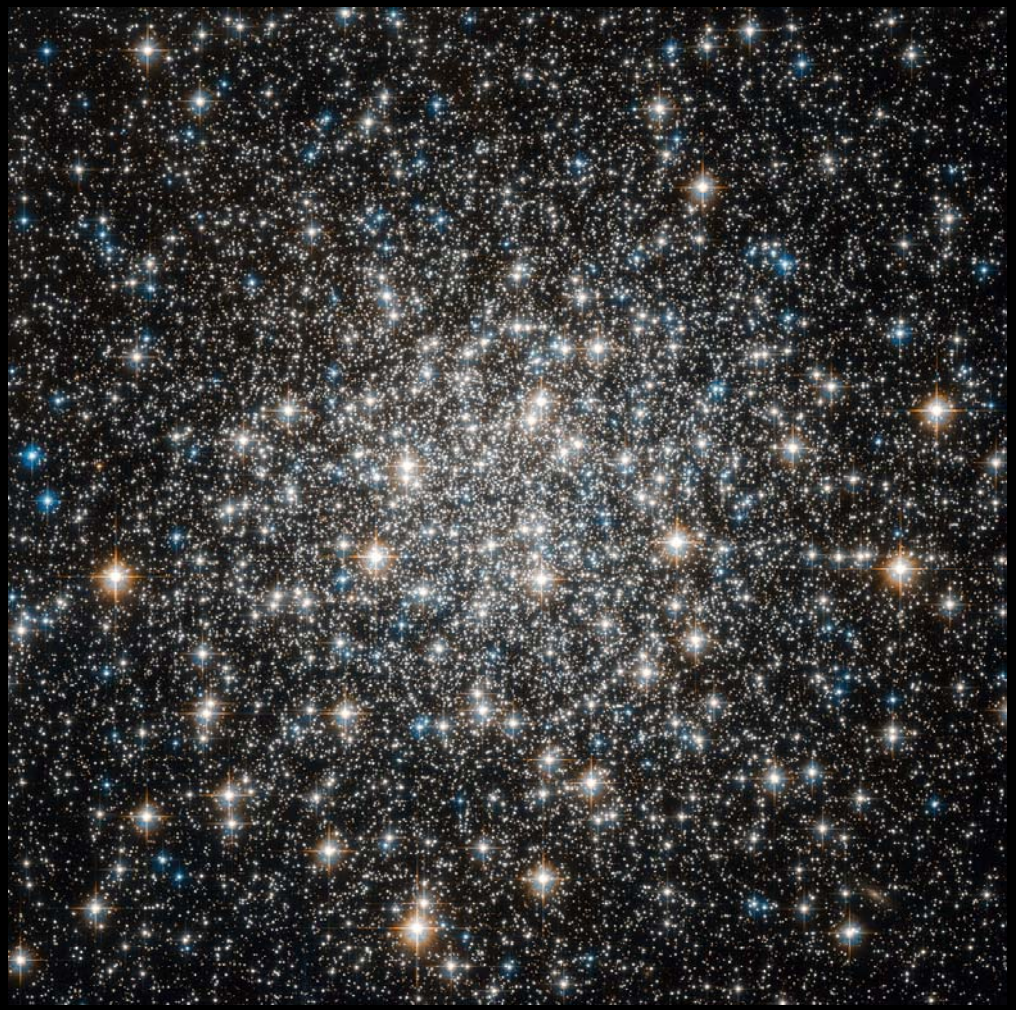
Globular Clusters … M80 (collapsed core)

NASA

Globular Clusters … M4 (non-collapsed core)

NASA

Globular Clusters … M10 (non-collapsed core)



NASA

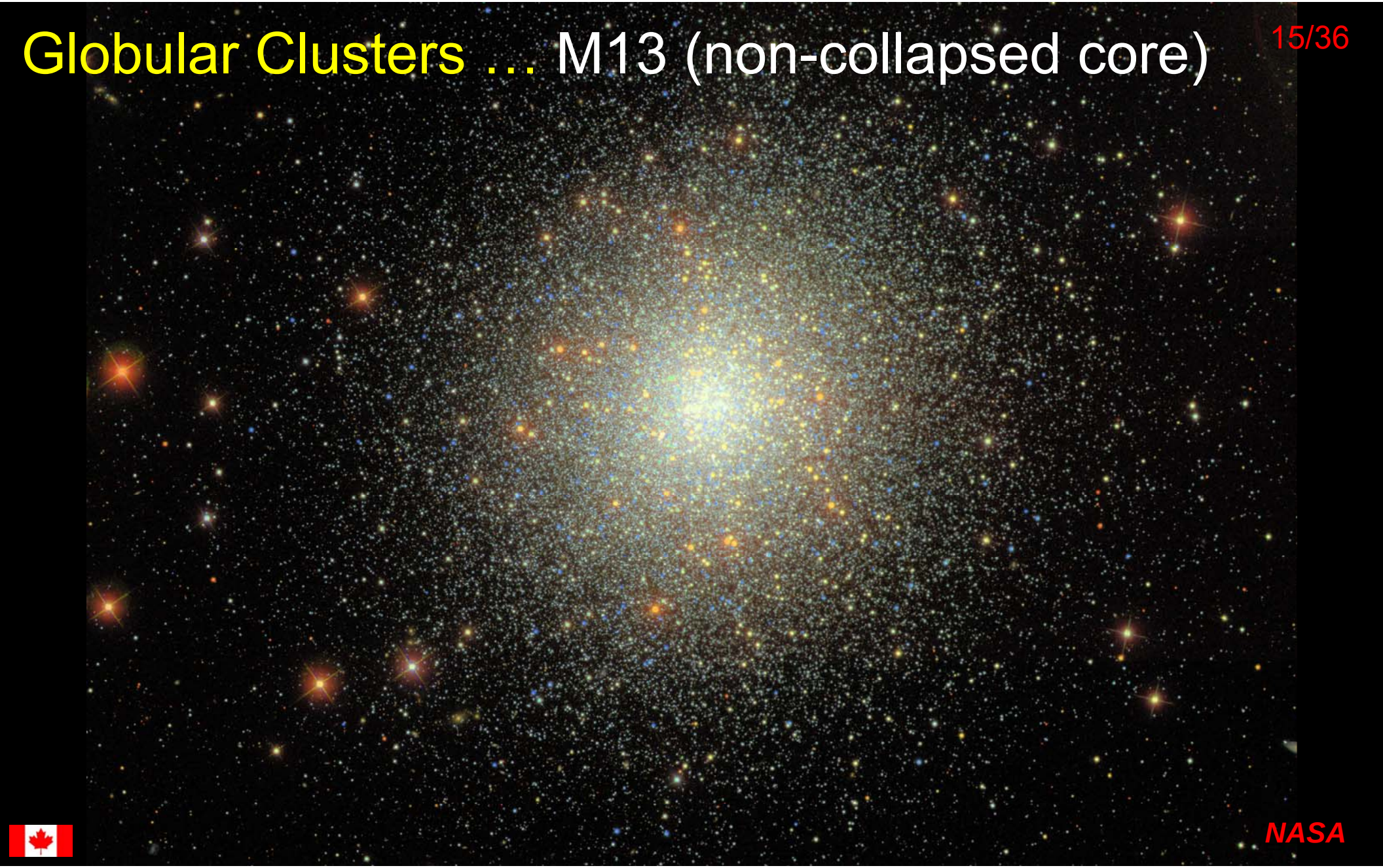
Globular Clusters … M5 (non-collapsed core)

NASA

Globular Clusters … M53 (non-collapsed core)

NASA

Globular Clusters … M13 (non-collapsed core)



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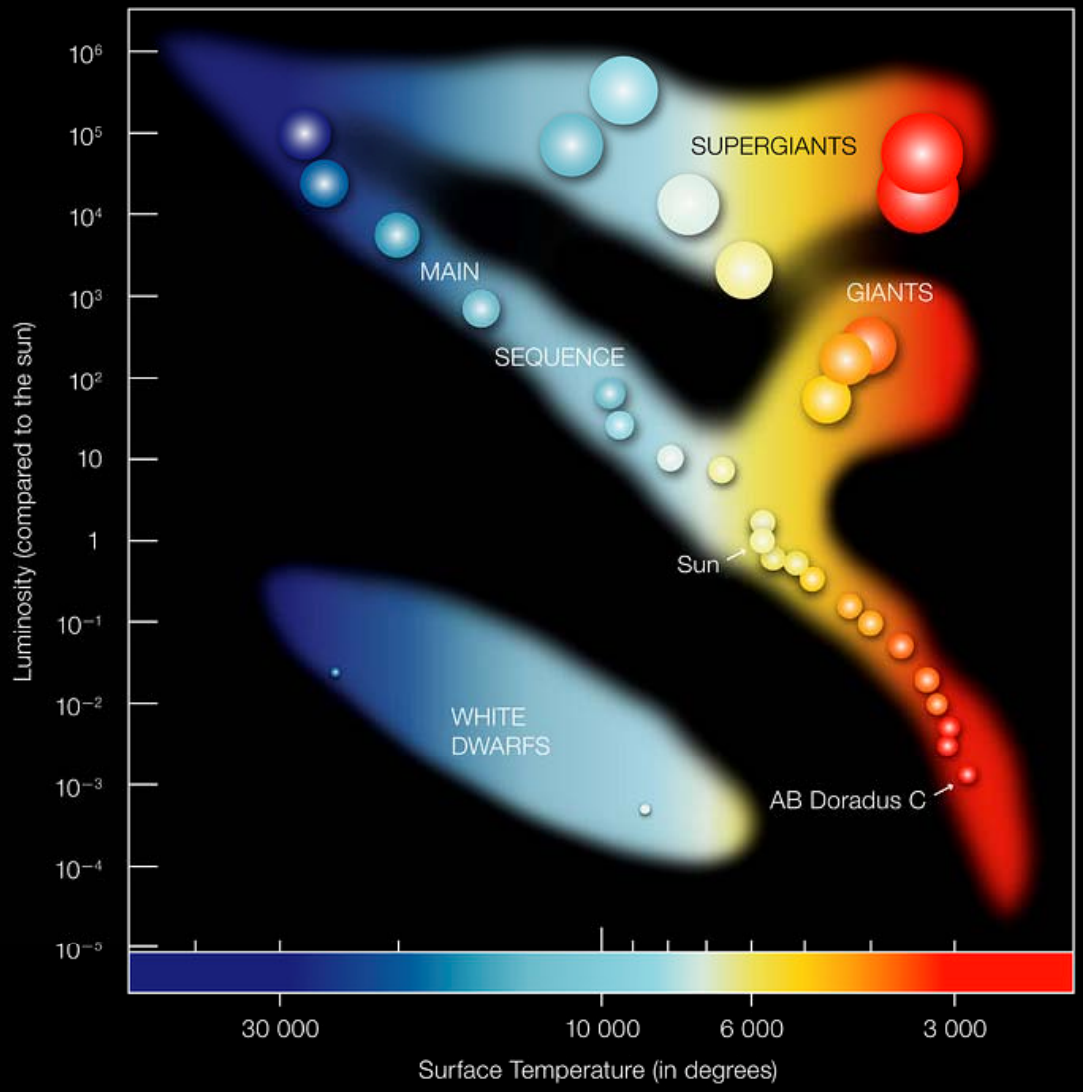
Globular Clusters … NGC 7006 (non-collapsed core)

NASA

Globular Clusters … NGCs 2808, 6362, 6388

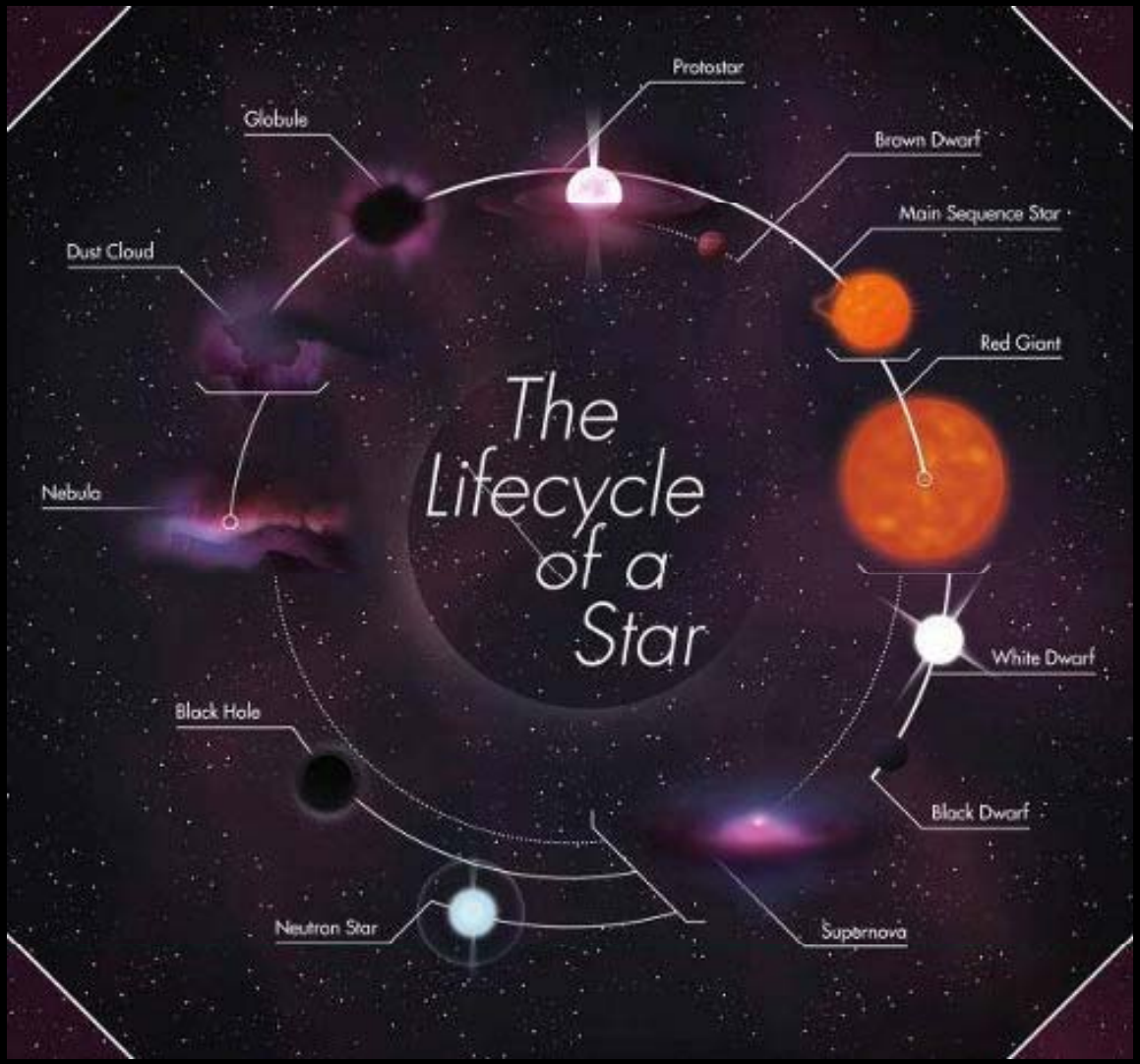
NASA

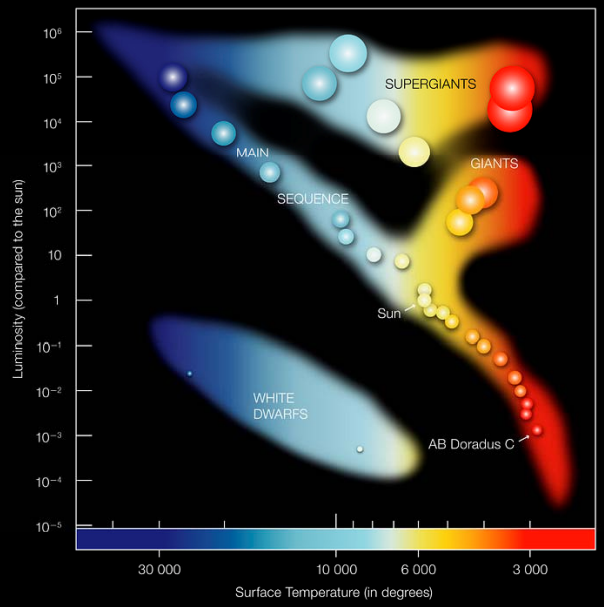
Stellar evolution refresher …



Magnitude/colour (L/T°) diagram for stars …

Stellar evolution refresher …





http://geekybytes.org/the-life-cycle-of-a-star

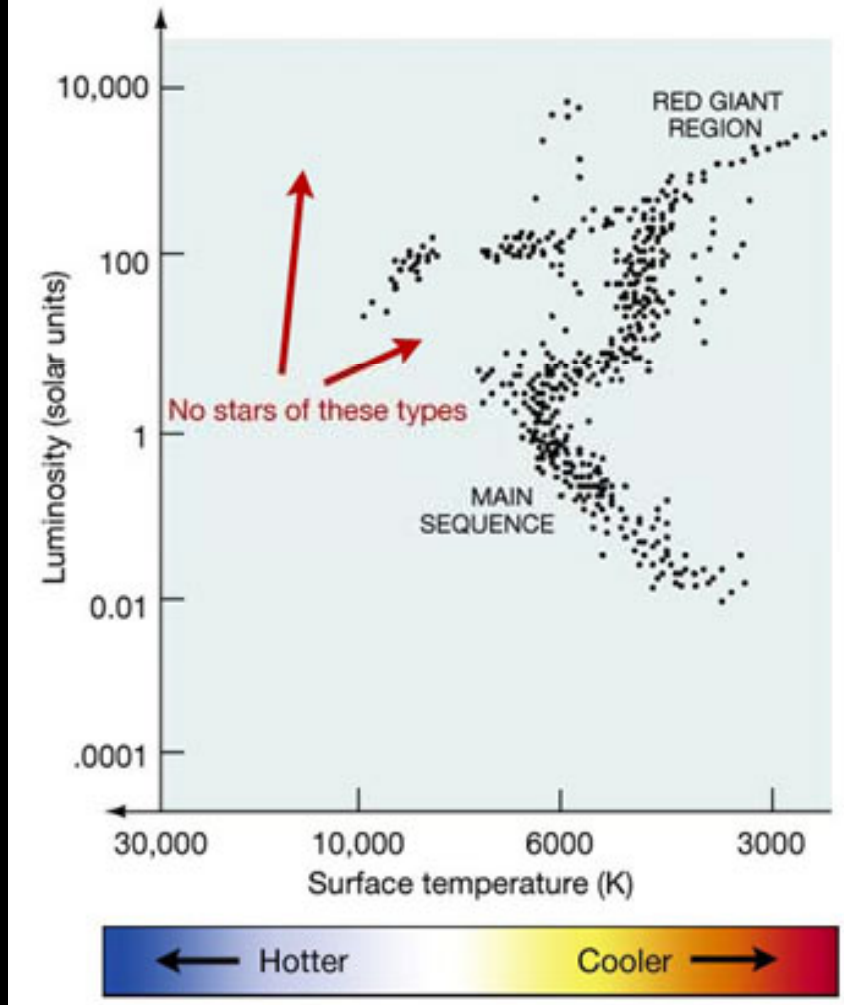
What is a “Globular Cluster” ? … revisited

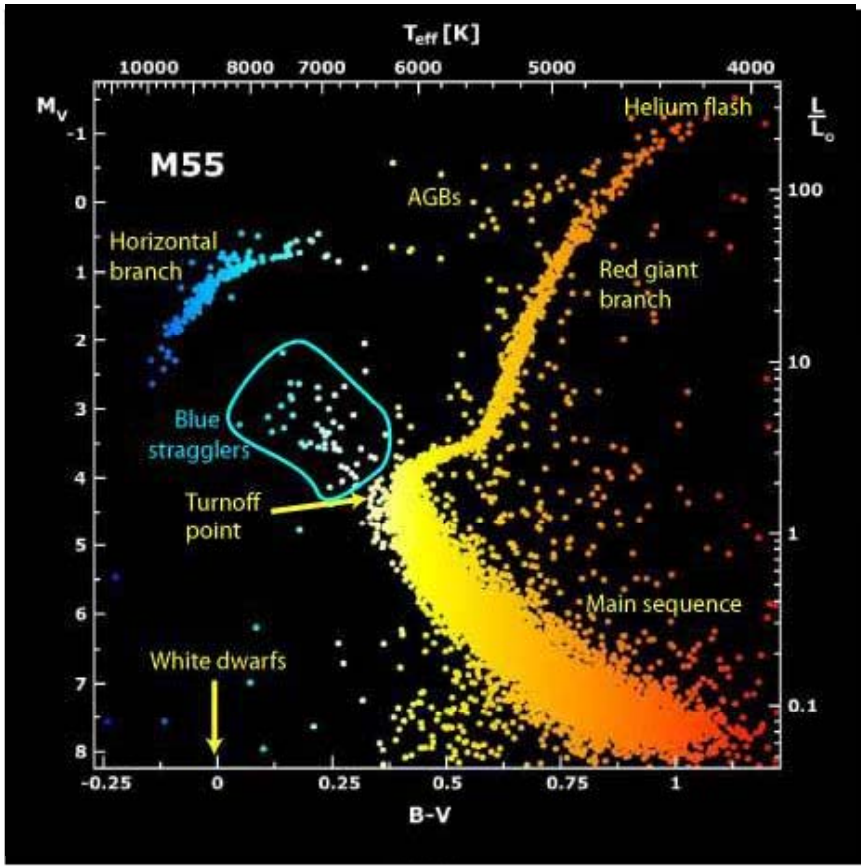
- Types and ages of stars in clusters
  - Clusters are *mostly* very old, uniformly low-metal pop II
    - No interstellar gas … no young stars (*in theory*)
  - Milky Way : ~13-8 Ga … as old as the galaxy (and the Universe!)

HOWEVER …

- LMC & SMC : clusters are < 3 Ga
- Galactic mergers (e.g. Antennae) : clusters may be forming !
- Multiple compositions (metallicity), multiple generations of stars
  - “*Blue Stragglers*”

Globular Clusters … magnitude/colour diagram M55





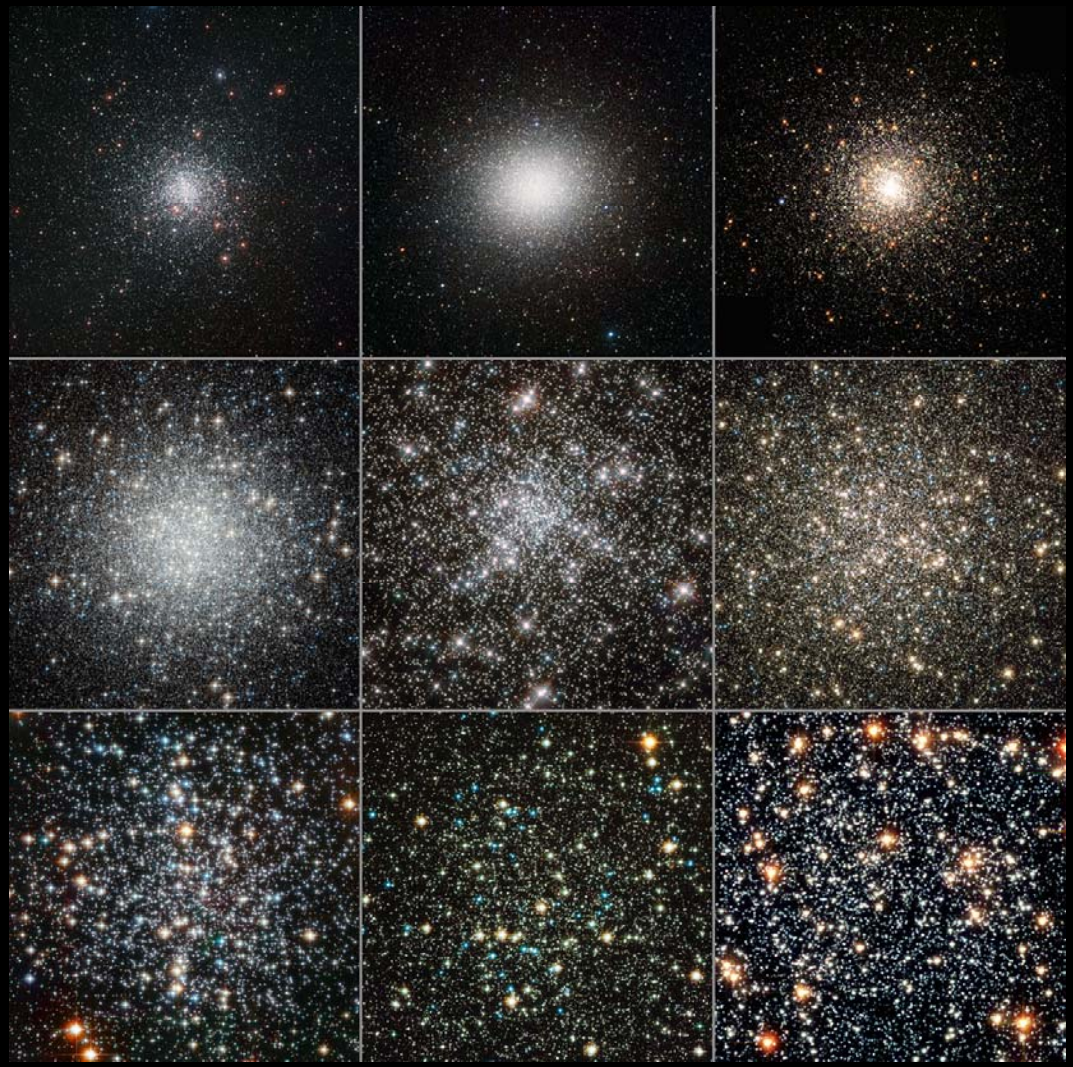
http://apod.nasa.gov/apod

Blue Stragglers …

- Young, hot, blue stars : what are they doing here ?
  - Collision model ?
  - Shedding gas model ?
  - Stray gas model ?

- Other multiple stellar generations : a failed model
  - Too many “polluted” stars : 50-100x N *cf.* other stars in cluster
  - Requires lots of >massive stars that exploded within cluster
    - Ratio requires stellar ejection – might work for Milky Way, but not Fornax Dwarf … *so not a general model*

Globular Clusters … in the Milky Way galaxy (I)



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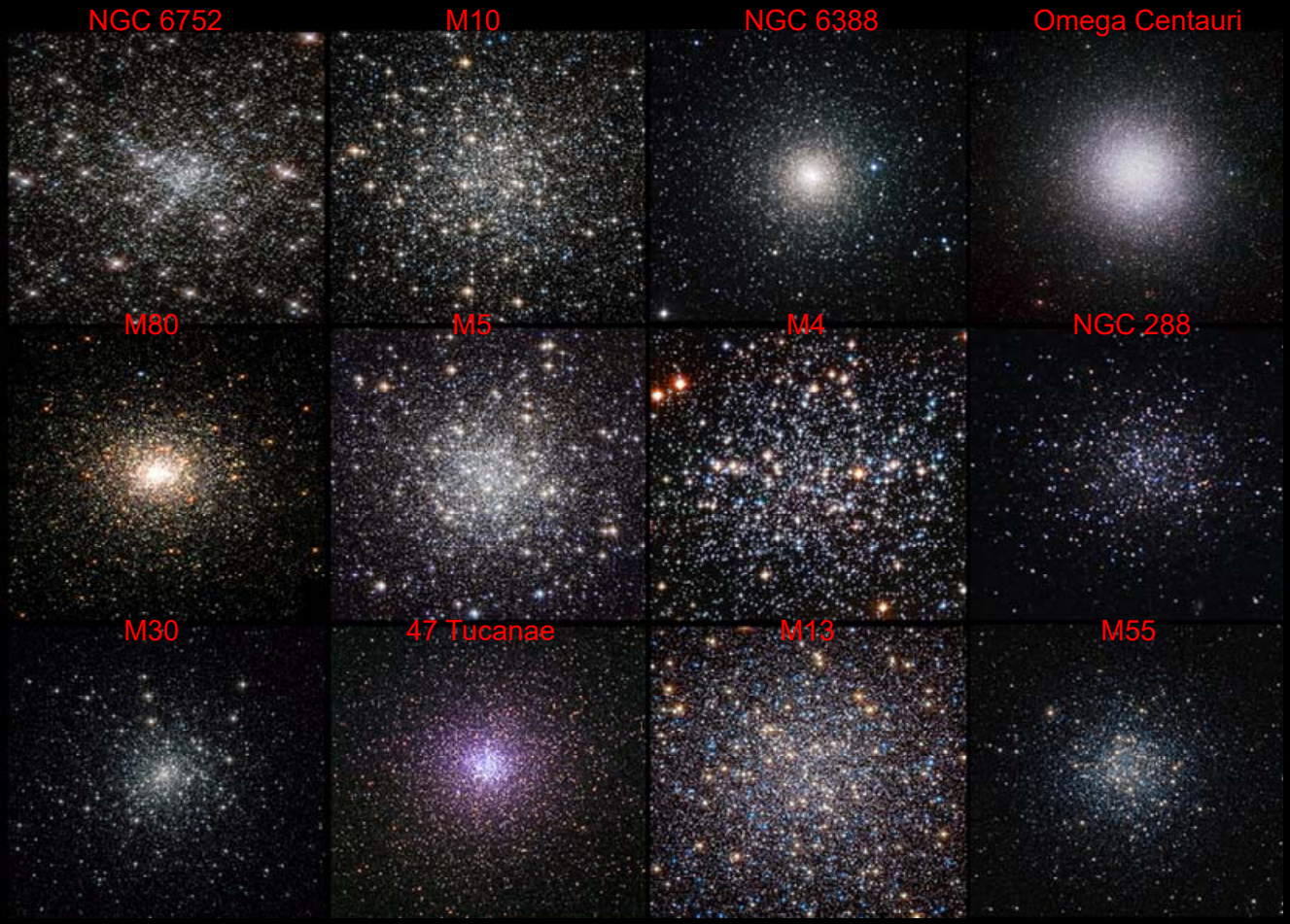
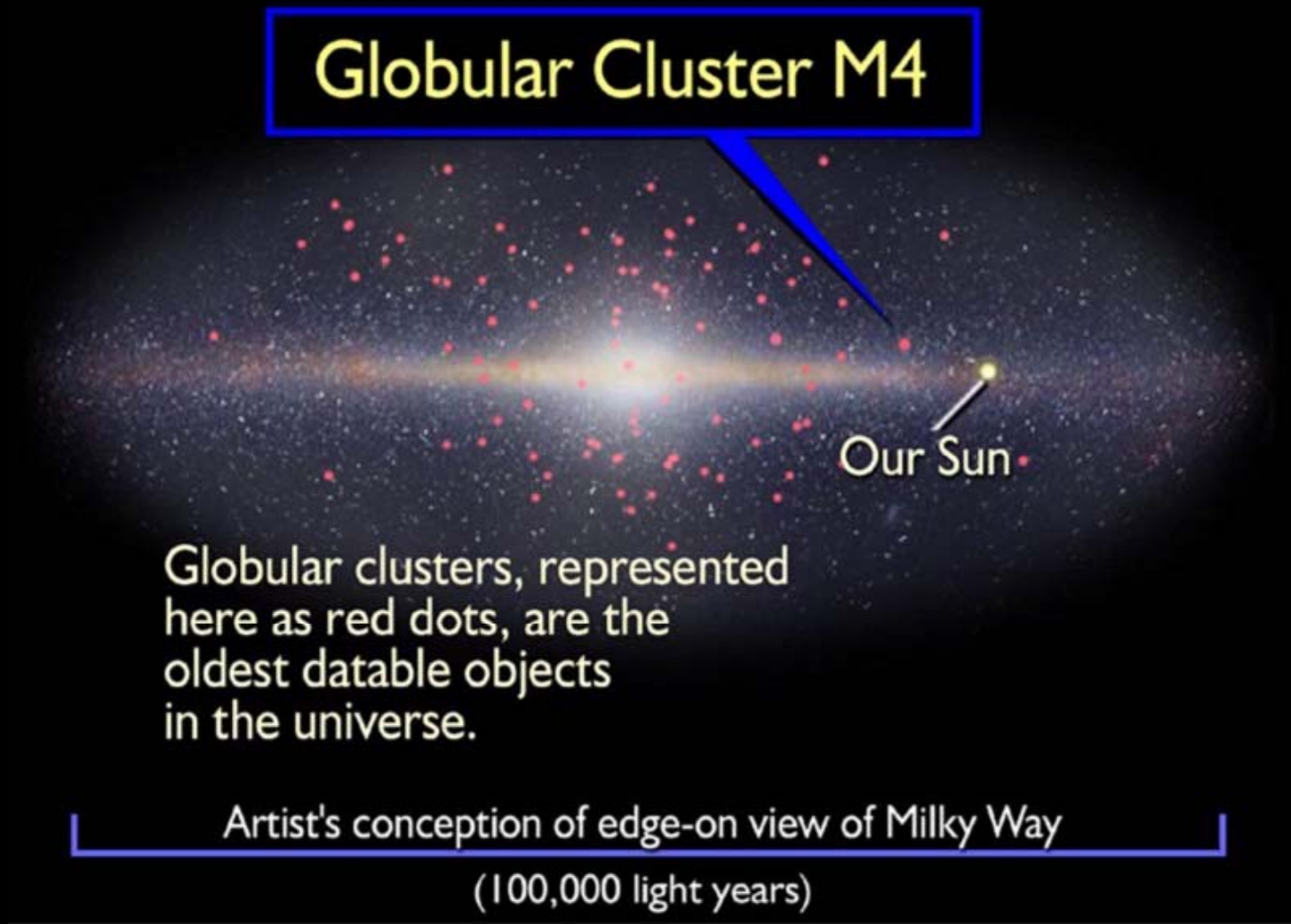
Globular Clusters … in the Milky Way galaxy (II)



M4 : Sco
M5 : Ser
M10 : Oph
M13 : Her
M30 : Cap
M55 : Sgr
M80 : Sco
NGC 288 : Scu
NGC 6388 : Sco
NGC 6752 : Pavo
Omega Centauri :
47 Tucanae :

NASA

Where do globular clusters occur ? … revisited



http://www.spacetelescope.org

Globular Clusters … with collapsed cores

CollapsedCore.m13

Galaxy View | Sky View | 3-D View

Zoom: Field of view = 119,635 light-years

Show	Name	Other Names	Type	Constellation	Gal Lon	Gal Lat	Luminosity (# Suns)	Size (ly)	Distance (ly)	Age (My)
☑	M15	NGC 7078	GC	Peg	65.0	-27.3	252,795	176 x 176	33,600	
☑	M30	NGC 7099	GC	Cap	27.2	-46.8	55,382	91 x 91	26,100	
☑	M62	NGC 6266	GC	Oph	353.6	7.3	94,288	98 x 98	22,500	
☑	NGC 6541	C78	GC	CrA	349.3	-11.2	122,096	97 x 97	22,300	
☑	NGC 6397	C86	GC	Ara	338.2	-12.0	24,000	68 x 68	7,500	
☑	NGC 6752	The Starfish, C93	GC	Pav	336.5	-25.6	95,055	110 x 110	13,000	
☑	NGC 362	C104	GC	Tuc	301.5	-46.2	171,811	113 x 113	27,700	
☑	NGC 5946		GC	Nor	327.6	4.2	14,068	71 x 71	34,600	
☑	NGC 6256		GC	Sco	347.8	3.3	1,843	56 x 56	27,400	
☑	NGC 6284		GC	Oph	358.3	9.9	50,850	81 x 81	49,900	

Show All | Hide All | Show Apparent Data | Black on White | 151 objects listed out of 1599 | Notes...

Globular Clusters … with non-collapsed cores

NonCollapsedCore.m13

Galaxy View | Sky View | 3-D View

Zoom:

Field of view = 139,524 light-years

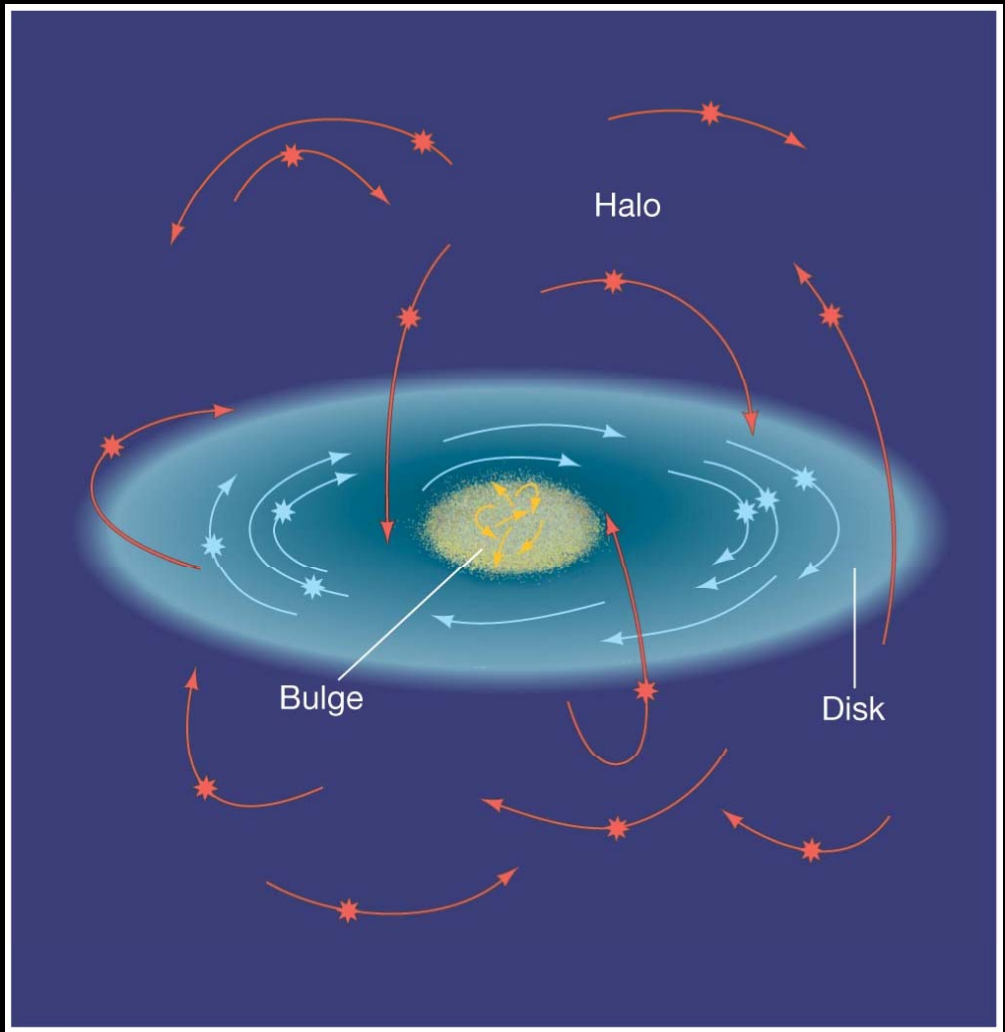
Show	Name	Other Names	Type	Constellation	Gal Lon	Gal Lat	Luminosity (# Suns)	Size (ly)	Distance (ly)	Age (My)
☑	M2	NGC 7089	GC	Aqr	55.0	-34.9	287,179	175 x 175	37,500	
☑	M3	NGC 5272	GC	CVn	42.2	78.7	257,330	177 x 177	33,900	
☑	M4	NGC 6121	GC	Sco	351.0	16.0	18,397	75 x 75	7,200	
☑	M5	NGC 5904	GC	Ser	3.9	46.8	233,573	164 x 164	24,500	
☑	M9	NGC 6333	GC	Oph	5.5	10.7	37,439	90 x 90	25,800	
☑	M10	NGC 6254	GC	Oph	15.1	23.1	38,086	83 x 83	14,300	
☑	M12	NGC 6218	GC	Oph	15.7	26.3	47,679	74 x 74	16,000	
☑	M13	NGC 6205, Hercules Cluster	GC	Her	59.0	40.9	223,583	146 x 146	25,100	
☑	M14	NGC 6402	GC	Oph	21.3	14.8	68,073	97 x 97	30,300	
☑	M19	NGC 6273	GC	Oph	356.9	9.4	84,025	138 x 138	28,000	
☑	M22	NGC 6656	GC	Sgr	9.9	-7.6	80,197	97 x 97	10,400	

Show All | Hide All | Show Apparent Data | Black on White | 149 objects listed out of 1599 | Notes...

How do globular clusters form ?

- We don't know … *but there are hypotheses* :
  - Early, intrinsic to galaxy formation ?
    - *but not a single event … ~13-8 Ga - or younger !*
  - Super star clusters ?
    - *stellar winds + tidal stripping ⇨ mass loss*
    - *contraction*
  - Late, captured as cores of dwarf galaxies ?
    - *Most low metallicity clusters aligned in a plane (MW)*

How do globular clusters behave ?



- External orbital behaviour
- Clusters orbit randomly around the host galaxy (+ retrograde)
  - *Buzzing of bees …*
- Clusters may interact gravitationally with the galactic disk
  - *"Hairy" outlines* (tidal radius or Roche limit)

How do globular clusters behave ?

M13

https://www.flickr.com/photos/68984892@N05/15124614479/in/album-72157647811945156/

How do globular clusters behave ?

- Internal stellar behaviour *(white dwarfs & neutron stars – 100/1)*
  - No stable equilibrium for self-gravitating systems
  - Stellar spacing in very tight cores ~ Sun to Pluto
  - Stars interact gravitationally with each other, both individually and at the scale of the cluster (*gas analogue*)
  - Stellar orbits ⇨ random with time (radial *vs* circular) : *how ?*
    - Clusters do not rotate … *with exceptions !* (eg M13)
    - https://www.spacetelescope.org/videos/heic0809h/
  - *"Stars" migrate toward or away from the cluster centre* *

How ? … and why don't globular clusters then collapse ?

* Mass segregation

Why don't globular clusters collapse ?

- Internal stellar behaviour (cont'd) : *virial or force theorem* *
  - *Stars interact gravitationally (PE*) with each other individually*
  - Core collapse (*gravothermal*/*gravokinetic* instability/catastrophe) :
    - *"Solar analogue"* : gravity vs *"pressure"* (thermodynamics)**
    - *Equipotential** ⇨ > massive stars slow down (*lo v*) ⇨ core
    - *Equipotential* ⇨ < massive stars speed up (*hi v*) ⇨ halo
      - ⇨ cluster *"relaxation"**** … or even *"evaporation"*
  - Hence : < orbital kinetic energy in core (*now add gravity*)
    - > orbital kinetic energy in halo (*slower core shrinks/speeds up*)
    - ⇨ mass segregation *then* core collapse *(runaway = catastrophe ?)*

** Thermodynamic equilibrium
*** 2 or 3 body

* Equipartition ⇩ $Ke_{star} = Mv^2/2$*

See Astroquizzical : Why doesn't a globular cluster collapse ?

Why don't globular clusters collapse ?

- Internal stellar behaviour (cont'd)
  - *Stars interact gravitationally with each other individually*
  - Binary star systems* : dynamical *"heating"* in 3 body interaction
    - Int/ext binary orbits contract : ⇨ energy (speed) to 3rd star
    - Binding energy, binary "hardness", "spring analogy"
      - "Harder" binary ⇨ more "spring"
      - Tighter binaries transfer more energy to speed-up 3rd star
    - ⇨ slow/prevent deep core collapse *(core bounce at ρ_{crit})*

* X-ray binaries (x1000)
* 10-20%

* 1° vs dynamic

See Piet Hut : Star Clusters, Globular, Gravothermal Instability (1992) also S.G. Djorgovski in Sky & Telescope, October 1998

Why don't globular clusters collapse ?

- Internal stellar behaviour (cont'd)
  - *Stars interact gravitationally with each other individually*
  - Binary star systems : dynamical *"heating"* in 3 body interaction
    - Kinetic energy ~ "heat"
    - Binary "burning" ⇨ > orbital speeds and > interactions in core
      - i.e. > "heat" (gravothermal)
      - … but also > dynamic binaries
      - "heat"* ⇨ core expansion ⇨ < density ⇨ "< T° "…
        - "< T° " ⇨ core collapse …
        - *Core oscillation ?* … *f(N) = f(mass distribution)***

* "Conduction" by "relaxation"

** see Breen & Heggie (2013) Mon. Not. R. Astron. Soc.

Why don’t globular clusters collapse ?

- Core collapse
  - 3 phases : pre-binary, binary-dominated, post-binary
  - 1° binaries arrest core collapse = quasi-equilibrium
  - 1° binaries exhausted ⇨ renewed core collapse (and halo expansion)
  - Initial collapse, middle-age pause, main collapse, post-collapse
    - Plus ejection (fast) and/or evaporation (very slow)
  - *But the globular clusters are still there ! Why ?*
  - 2° tight binaries form ⇨ > core energy ⇨ *cluster expansion !*
  - Globular clusters may oscillate in size … *what are we looking at today ?*

See http://relativity.livingreviews.org/Articles/lrr-2013-4/articlese2.html

M13

see S.G. Djorgovski in Sky & Telescope, October 1998

Ultimate fate ?

see https://astrosociety.org/pubs/mercury/9904/murphy.html