The Search for the First Stars:

Unravelling the creation of Star Dust

Mike Bessell

ANU

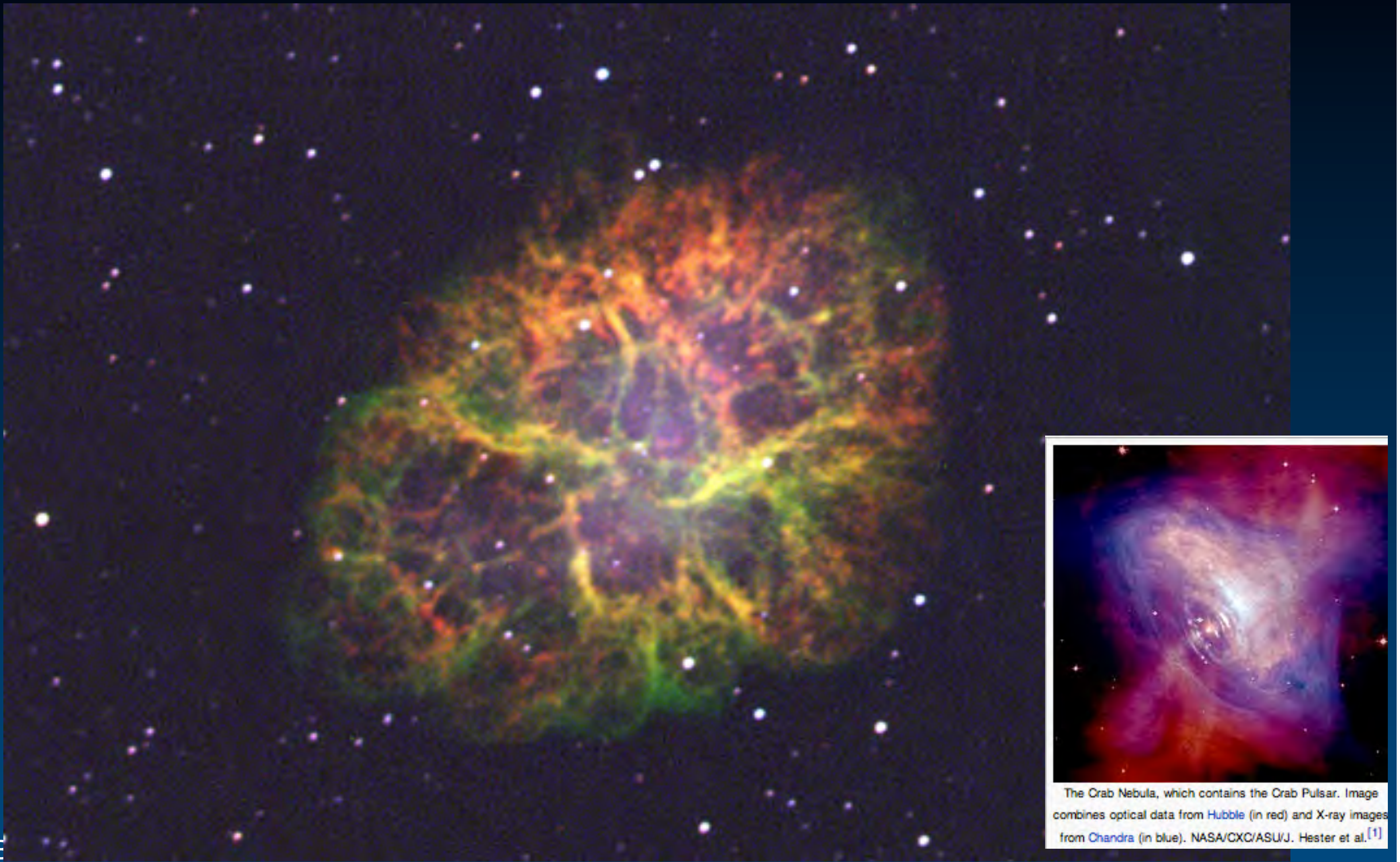
20^{th} century astronomical highlights

- The highlight of the first part of the 20^{th} century was the realisation that we lived in an Island Universe, the Milky Way galaxy, separated from other galaxies by large distances and that the galaxies are moving further apart.
- A major highlight of the second part of the 20^{th} century was the discovery that all the heavy elements, other than hydrogen and helium were formed inside stars. The atoms comprising the earth and the atoms we are built from have all been processed through many generations of stars.

Death of a star – creation of many new elements

- The conversion of H to He is the principal energy source of stars. Roughly 10% of a star's mass is consumed in this way. In later stages He is converted into C, N and O. The final stages of many massive stars is violent, a supernovae explosion, the brightness of which can be seen across the Universe.
- However, in the death of a such a star, many new elements are created, all the elements up to and including Fe and Ni, plus some heavier elements.

Crab Nebula – SN remnant



The Crab Nebula, which contains the Crab Pulsar. Image combines optical data from Hubble (in red) and X-ray images from Chandra (in blue). NASA/CXC/ASU/J. Hester et al.[1]

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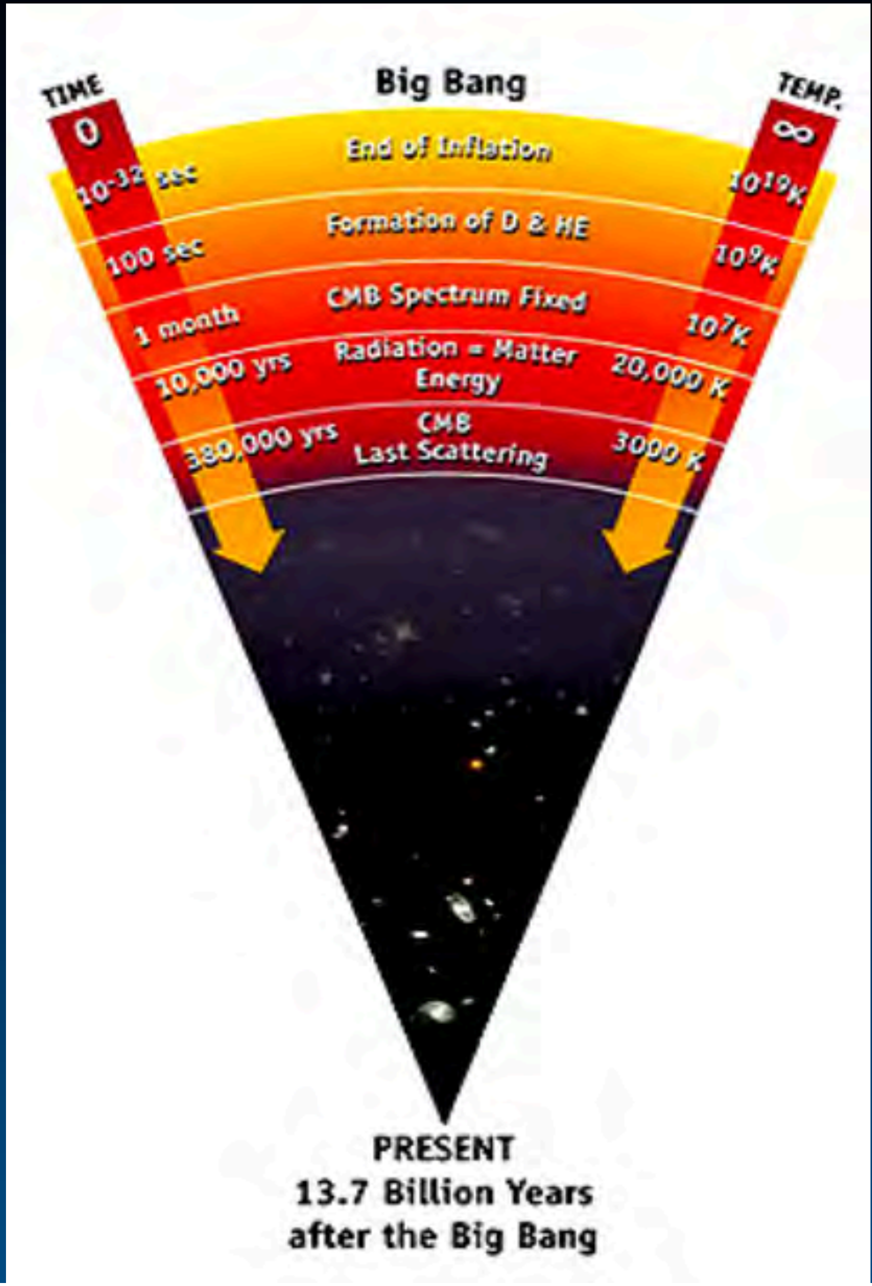
Vela-Puppis SN remnant

The Vela Pulsar and its surrounding pulsar wind nebula, Chandra X-Ray image

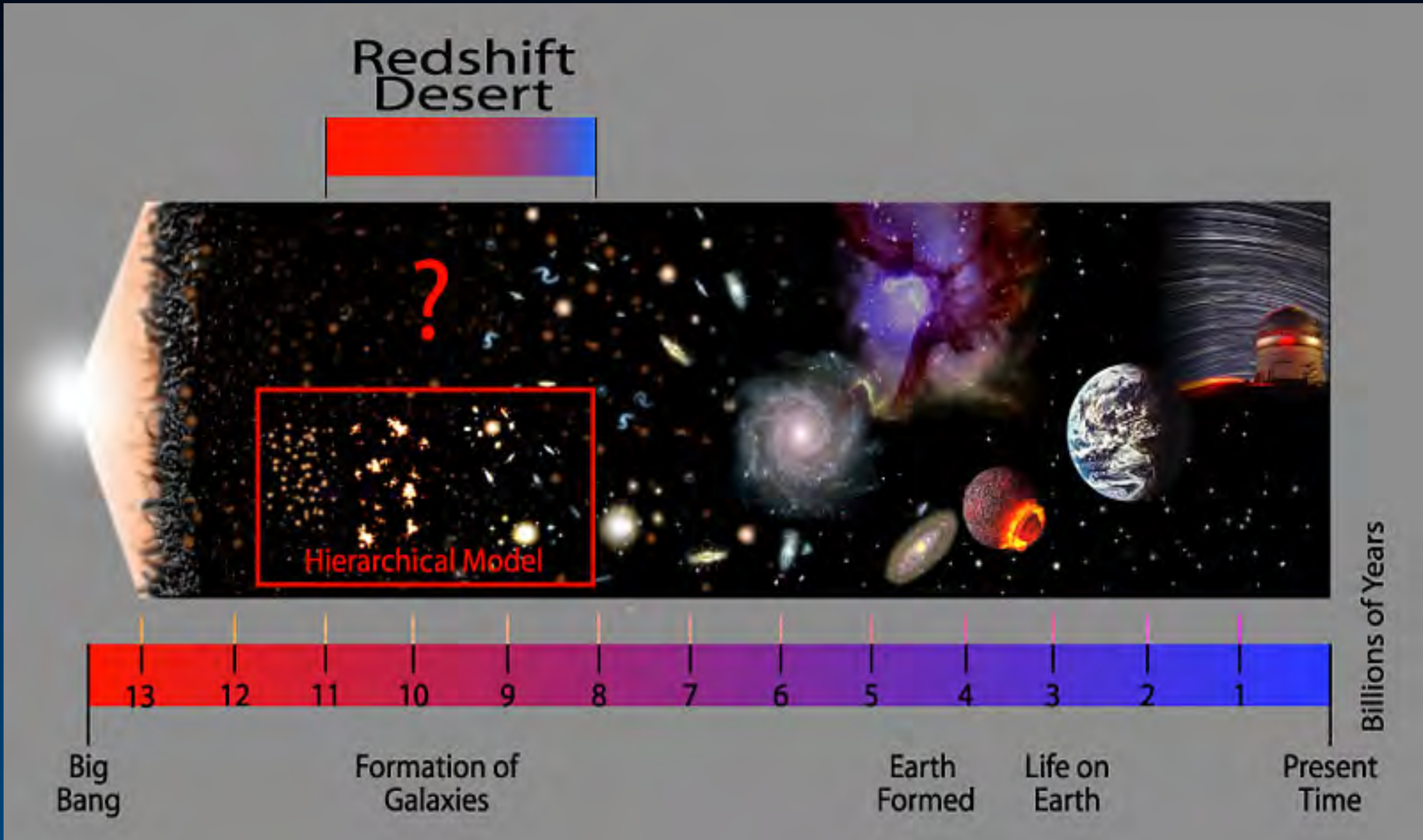
Details of Vela SN remnant

The Big Bang



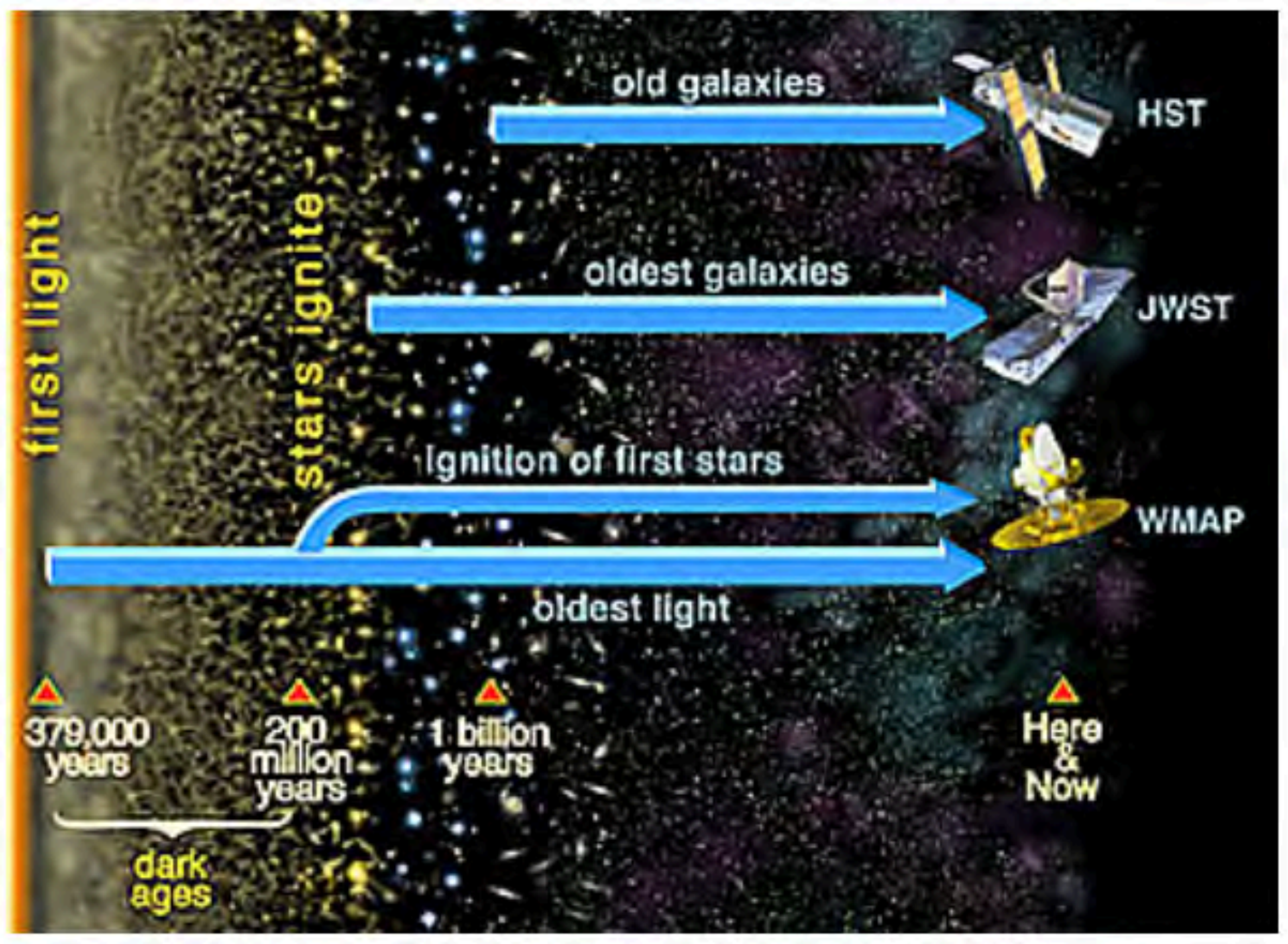
Big Bang
TIME
TEMP.
0
∞
End of Inflation
10-32 sec
10^19 K
Formation of D & HE
100 sec
10^9 K
CMB Spectrum Fixed
1 month
10^7 K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
PRESENT
13.7 Billion Years after the Big Bang

Time line of the Universe



http://www.gemini.edu/gdds

Look back in time



Computer simulations

- Using computer simulations we can now gain insight into the formation of galaxies, stars and soon planets.
- Structures in the distribution of galaxies predicted in computer modelling has been spectacularly verified by the AAO 2DF Galaxy survey.

Simulation of disk galaxy evolution.

Samland & Gerhard A&A 399, 961, 2003

Time scale of galaxy formation

Collapse starts at Z~5 with small dark halo of 2.1×10^{10} solar masses distributed over a 30kpc sphere in a LCDM universe with L = 0.7, W=0.3, Hubble constant h_0=0.7 and baryonic to dark matter ratio of 1:5. Final galaxy is rather like the Milky Way in kinematic and chemical properties.

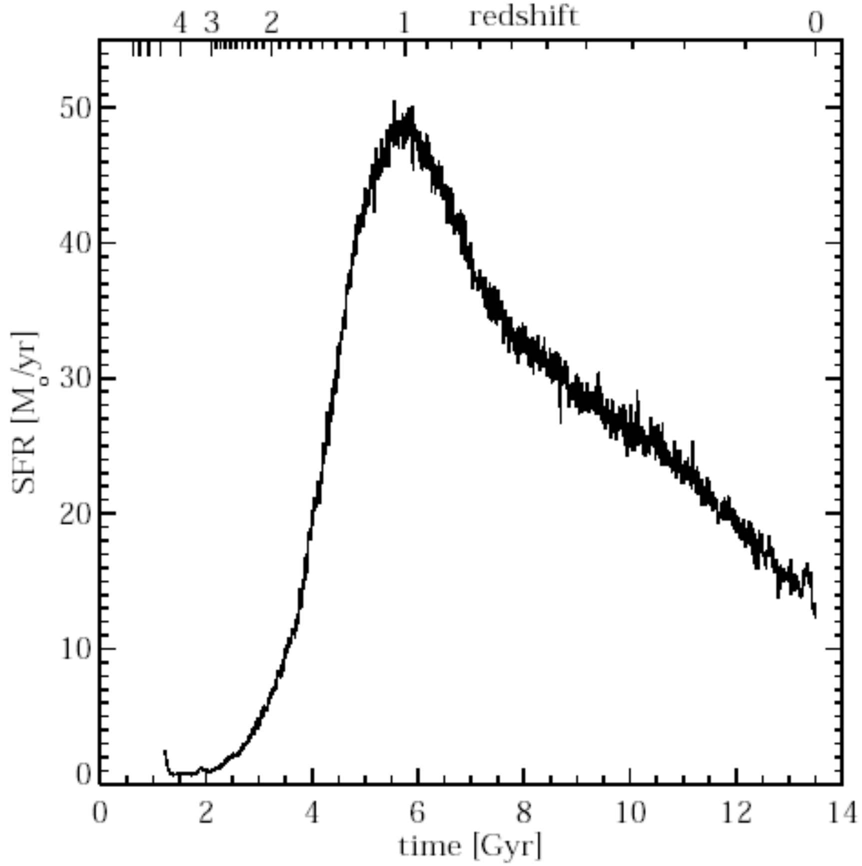
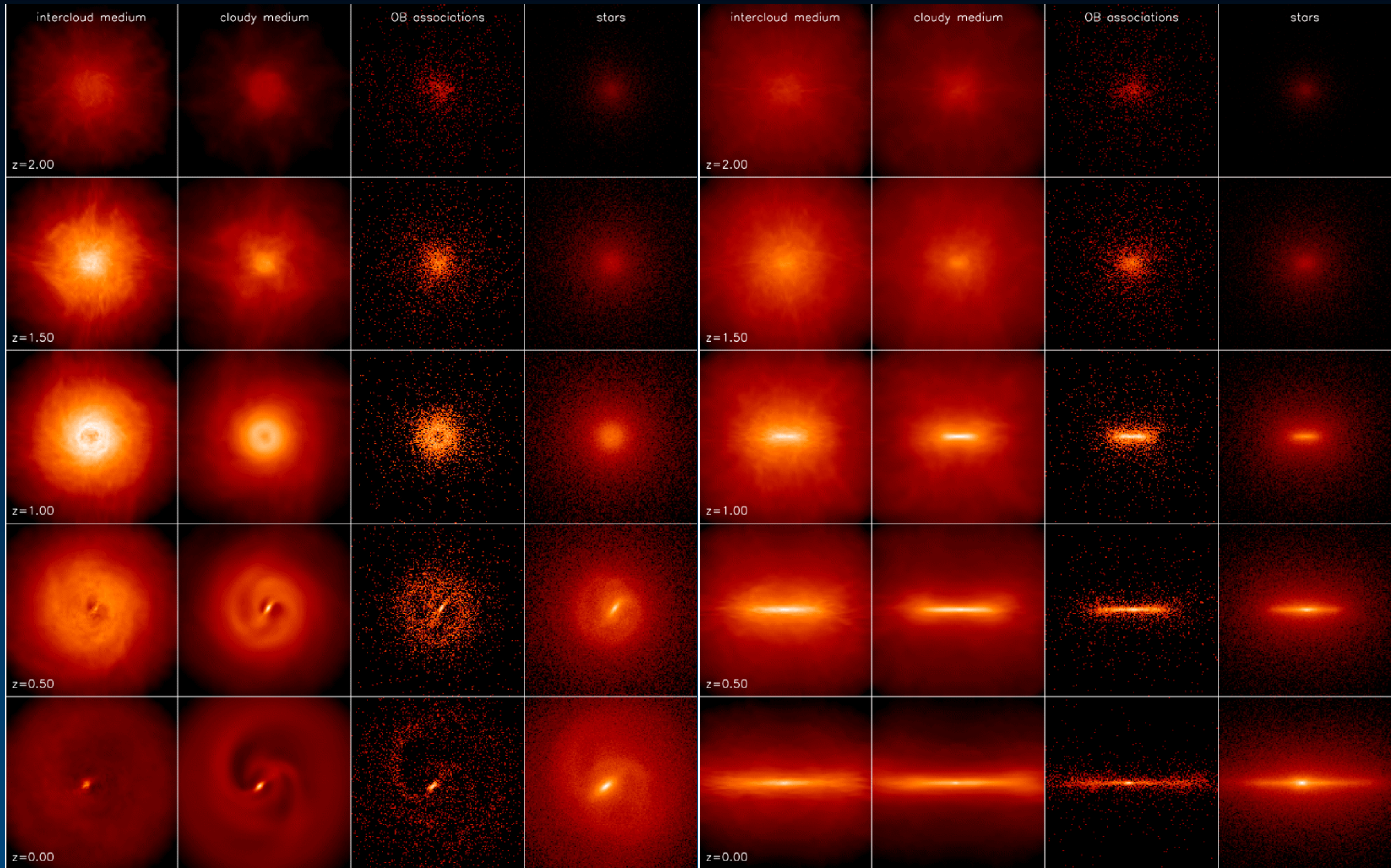


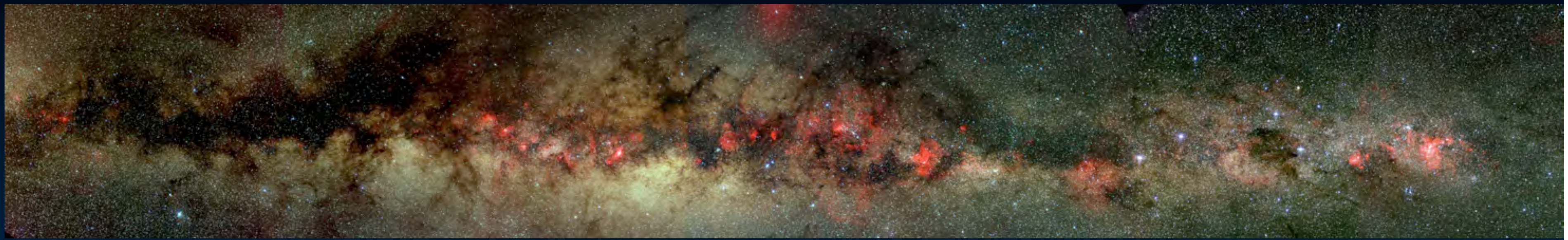
Fig. 6. Star formation rate (SFR) in the inner 20 kpc of the dark halo. The star formation rate peaks slightly later than the MIR (Fig. 5).

Simulation of disk galaxy evolution.
Samland & Gerhard A&A 399, 961, 2003



Sombrero galaxy

Disk Galaxies



The first stars

The Big Bang created mainly H and He with a little D, Li, Be, B

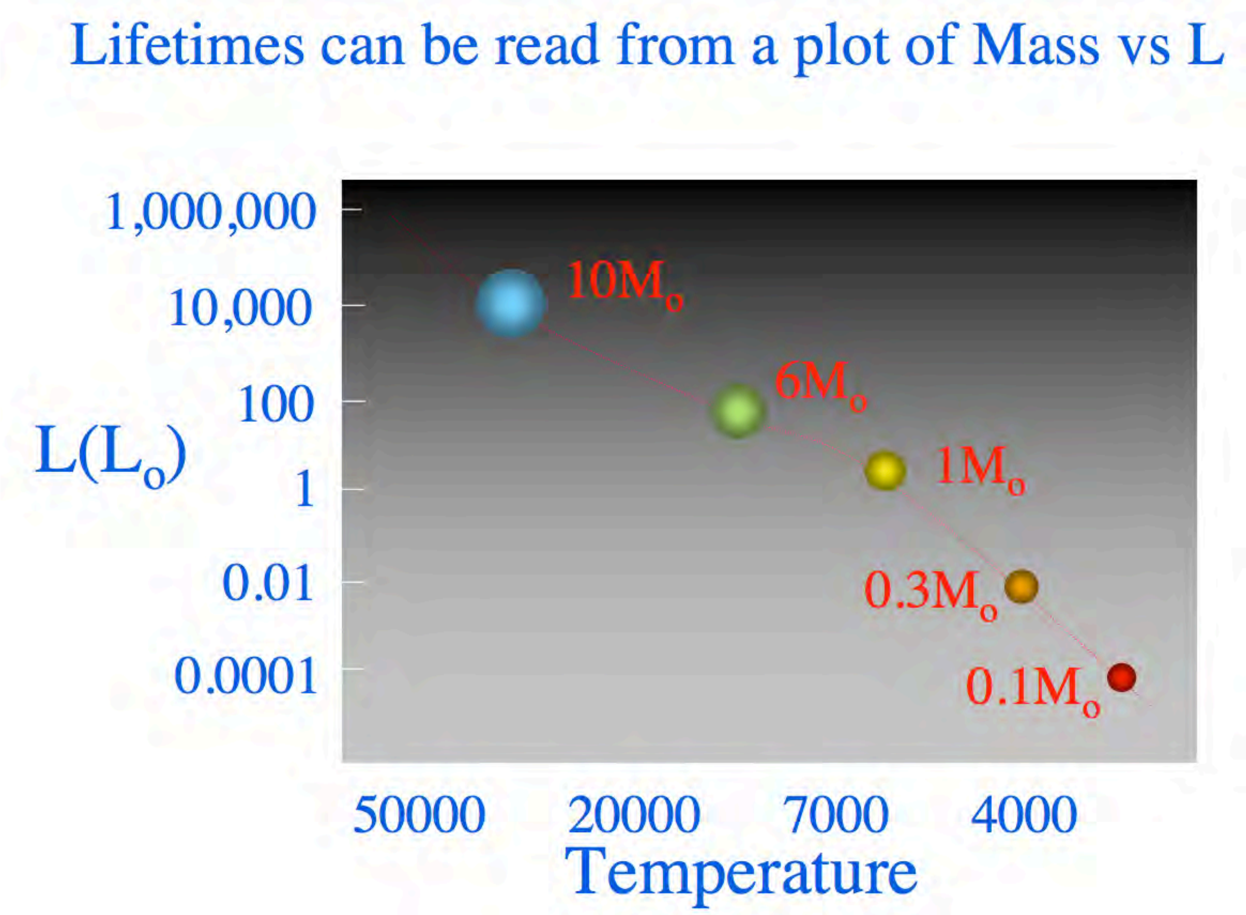
When "zero" metal gas cooled to 200K, stars of 80-300 solar masses formed. These stars evolved quickly heating the ISM.

For masses above 260 solar masses, black holes eventuated

140-260 solar mass stars underwent intense nuclear burning and complete disruption as extremely bright SN at Z=30-10

We are yet to identify any supernovae from stars heavier than about 50 solar masses, so perhaps they do not exist.

Stellar luminosity and age depends on mass



A measure of a stars lifetime is the ratio of its mass to its luminosity (rate at which it burns its fuel.)

A 10 solar mass star lives for only 1/1000th the life of our sun.

A 5 solar mass star lives for 1/20 the life of the sun.

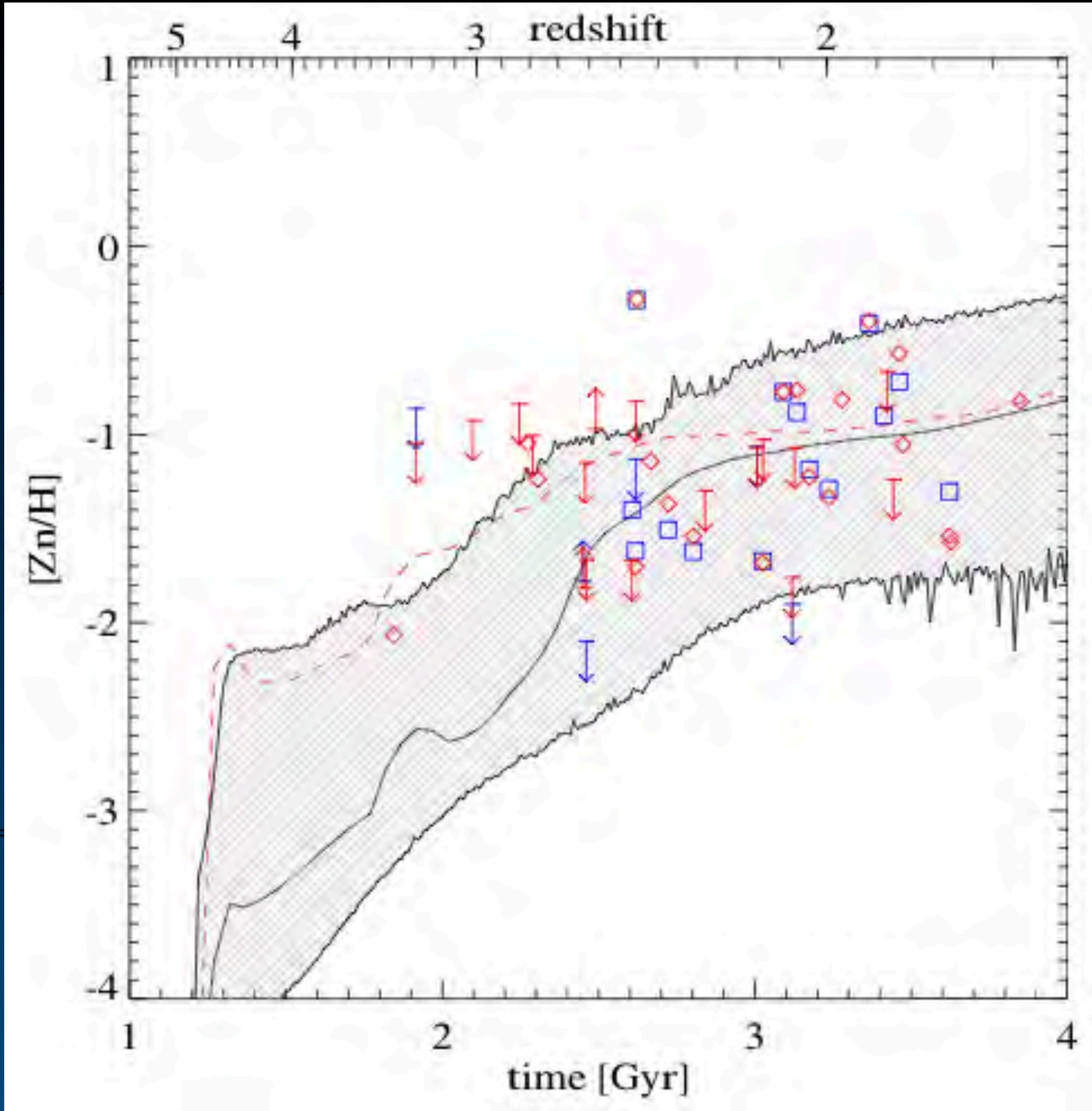
Stars with less than 80% the mass of the (if formed) would still be around today.

Second generation of stars

Metal enriched hot gas eventually cooled and globular clusters comprising 10^5 to 10^6 stars coalesced in less than 1 million years from fluctuations within primordial gas cloud. $6 < Z < 2$

This stellar generation could produce low mass stars which due to their slow rate of nuclear burning are still visible.

The protogalaxy accreted a dark halo, gas clouds collapsed dissipating energy and conserving angular momentum forming disk of Milky Way. $5 < Z < 0.8$



redshift
5
4
3
2
1
0
-1
-2
-3
-4
[Zn/H]
1
2
3
4
time [Gyr]

Stellar ages: Main sequence turnoff

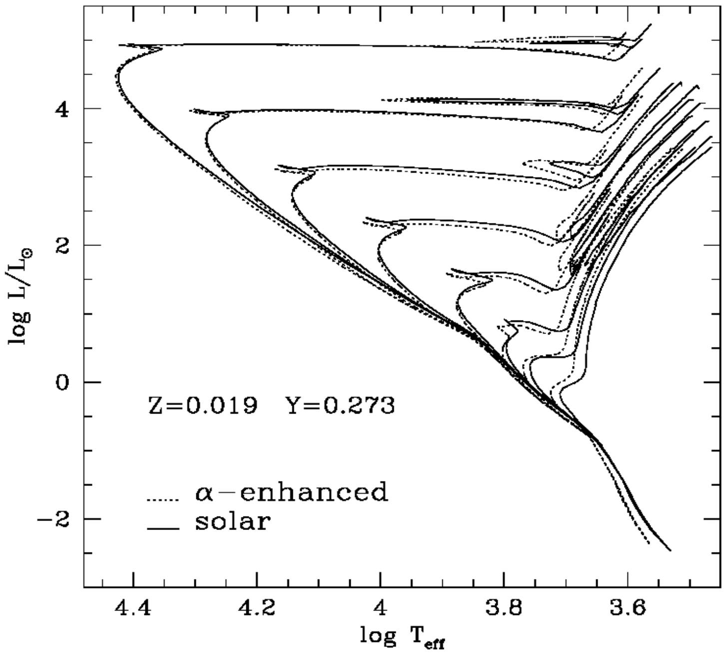


Fig. 8. Comparison of isochrones with chemical composition $[Z = 0.019, Y = 0.273]$ and different enhancement of α-elements. Dotted lines refer to the α-enhancedisochrones, continuous lines to the solar-scaled ones. Only the isochrones with ages between $\log(t/\mathrm{yr}) = 7.0$ and $\log(t/\mathrm{yr}) = 10.5$, in steps of $\Delta \log t = 0.5$ for the sake of clarity, are plotted.

Key uncertainties

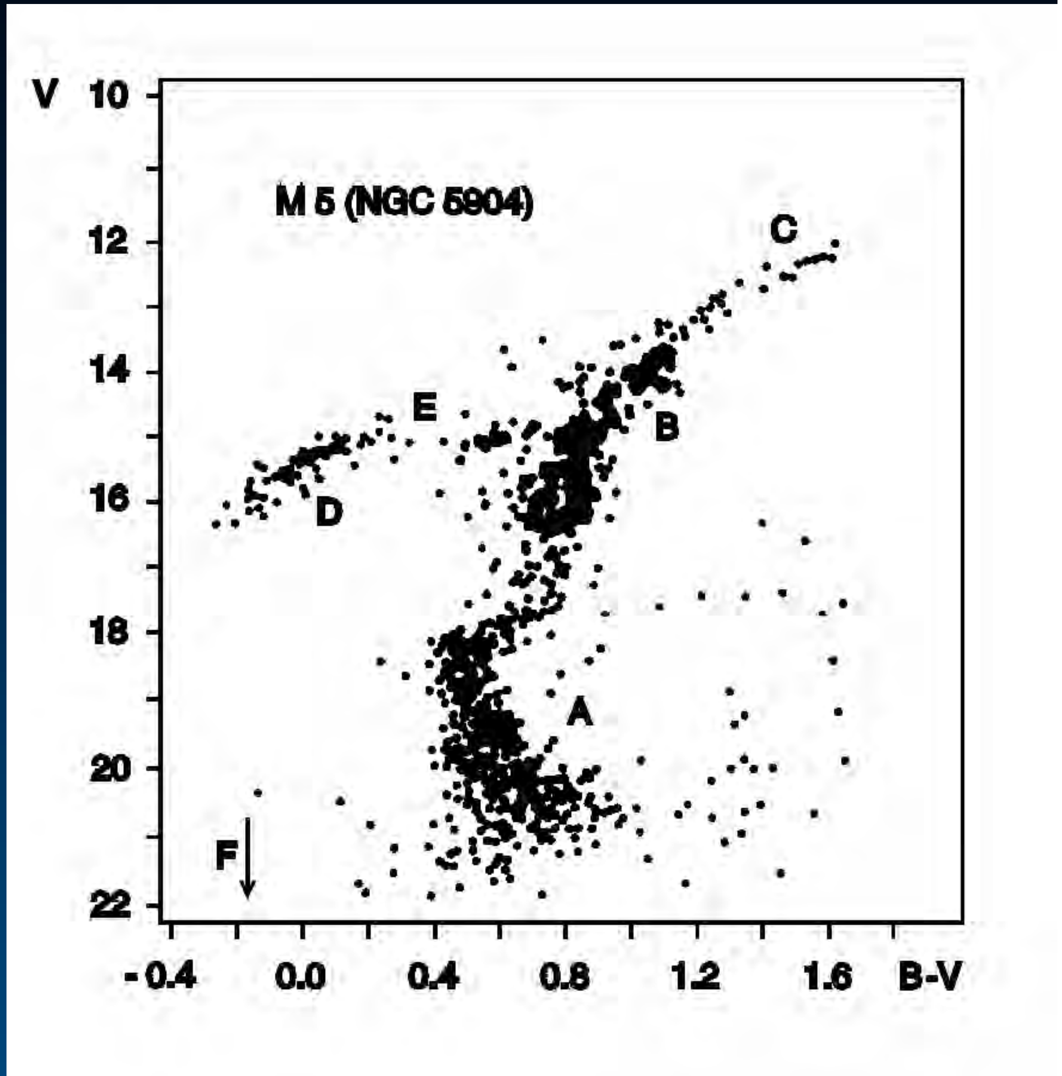
- Convection treatment

  Cool MS and RGB stars have surface convection

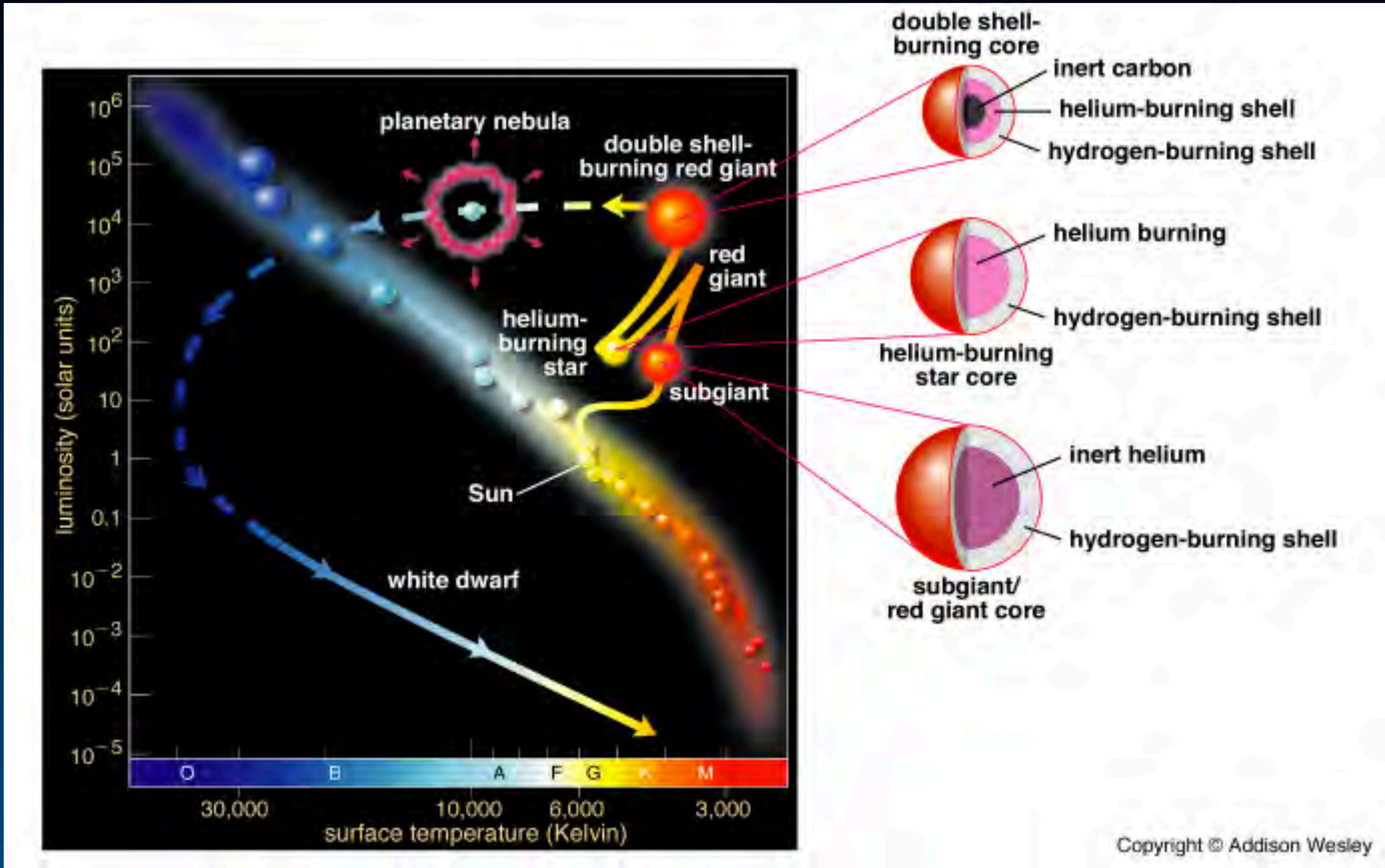
- Atomic diffusion treatment
- Metal composition
- Model atmospheres used for color transformation
- Cool opacity uncertainties
- $^{14}N + p > {}^{15}O + \gamma$ reaction rate

A globular cluster

M5 © Anglo-Australian Observatory
Photograph by David Malin



Evolution of the sun



Death of lower mass stars

Not all stars end their life in a supernovae explosion.

Lower mass stars eject their outside layers forming a planetary nebula rich in C, N and s-process elements produced in the previous evolutionary stages of the star.

The remnant is a white dwarf star that slowly cools giving another age estimate for the galaxy.

It also locks up a lot of heavy elements.

Chemical processes in the ISM produce dust grains from the heavy elements.

Helix nebula

Summary of halo age determinations

Krauss & Chaboyer: Science 299, 65, 2003

- Oldest globular clusters have an age of t_{gc} = 12.6 Gyr with a 95% CL lower bound of $t_{gc} > 10.4$ Gyr
- Radioactive decay age for metal-star poor star in the halo of the Milky Way: $t_{star} = 12.5 \pm 3$ Gyr
- Minimum age for white dwarfs in the globular cluster M4 is 9 Gyr, with a best estimate of 12 - 13 Gyr.
- Epoch of globular cluster formation likely occurred at t ~ 0.8 Gyr CMB observations combined with the assumption of a flat universe with adiabatic initial fluctuations yield $t_o = 14.0 \pm 0.5$ Gyr

The beauty of star forming regions

Trifid nebula

Stars form from Giant Molecular Clouds

- What comprises Giant Molecular Clouds?
- The interstellar medium is roughly 99% gas, 1% dust by mass.
- Of the gas, roughly 90% is hydrogen (H2 and H), and 10% is helium, with some CNO-based gases (i.e. hydrocarbons).
- Ice grains composed of CNO-based molecules (mainly water, ammonia, CO, etc.)
- Dirty sub-micron-sized grains of magnesium and iron silicates

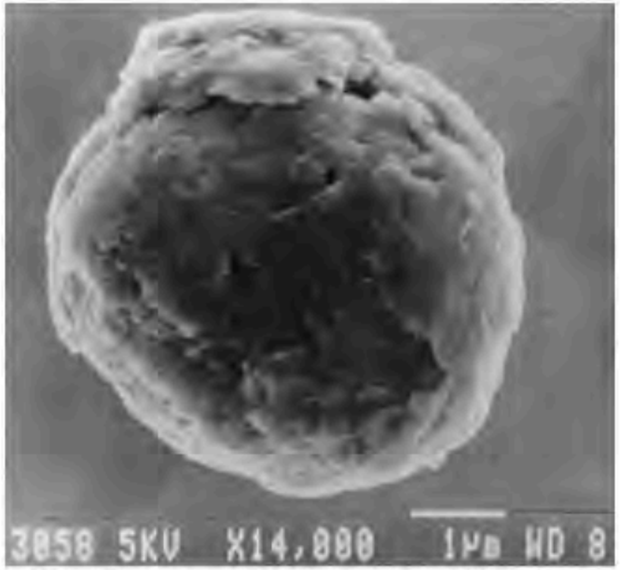
Unprocessed presolar material

Murchison CM2 Carbonaceous Chondrite

The Murchison meteorite fall occurred on September 28, 1969 over Murchison, Australia. Over 100 kilograms of this meteorite have been found. Classified as a carbonaceous chondrite, type II (CM2), this meteorite is of possible cometary origin due to its high water content of 12%. An abundance of amino acids found within this meteorite has led to intense study by researchers as to its origins. More than 92 different amino acids have been identified within the Murchison meteorite to date. Nineteen of these are found on Earth. The remaining amino acids have no apparent terrestrial source.

Star dust

SEM micrograph of presolar graphite grain, 5 micrometers in diameter, from the Murchison meteorite. Its surface texture resembles an onion. Photo courtesy of S. Amari, Washington University, St. Louis.



(Scale bar is 1μm.) Photo courtesy of S. Amari.

Since then, several types of presolar grains have been found, all of which have distinctive isotopic compositions of oxygen, carbon, nitrogen, magnesium, silicon, titanium, noble gases, and other elements. As an example of the dramatic deviation of isotopic composition, grains of silicon carbide (SiC) have $^{12}C/^{13}C$ ratios that range from 2 to 7000, compared to the range in earth materials of 88-90. These discoveries could not have been made without the techniques to isolate different types of presolar grains. These painstaking separation techniques were developed by S. Amari (Washington University, St. Louis), and R. S. Lewis and E. Anders (Univeristy of Chicago). Significant advances in instrumentation were also needed. The most important one was the ion microprobe which allows precise measurements of isotopic compositions of tiny, micron-sized grains. The ion microprobe techniques were refined by E. Zinner, T. Ireland, S. Amari (Washington University, St. Louis), P. Hoppe (Switzerland), and R. S. Lewis.

Star dust

Types and characteristics of presolar grains found in meteorites.

Type	Size	Concentration in Meteorites	Sources
Diamond (C)	1-5 nanometers	1000 parts per million	Supernovae
Silicon carbide (SiC)	0.1-10 micrometers	10 parts per million	Carbon-rich giant stars, or supernovae
Graphite (C)	1-10 micrometers	2 parts per million	Supernovae and carbon-rich giant stars
Aluminum oxide (Al_2O_3)	1-5 micrometers	0.1 parts per million	oxygen-rich giant stars
Spinel ($MgAl_2O_4$)	1 micrometer	2 parts per billion	oxygen-rich giant stars
Silicon nitride (Si_3N_4)	1 micrometer	2 parts per billion	Supernovae

Table adapted from a 1993 *Meteoritics* review by Edward Anders and Ernst Zinner, and Conel Alexander's *Carnegie Institution Yearbook 95*, report "Stardust in the Laboratory."

Where and how are the oldest stars found

Earliest stars were formed before the galaxy collapsed to a disk – globular clusters for example.

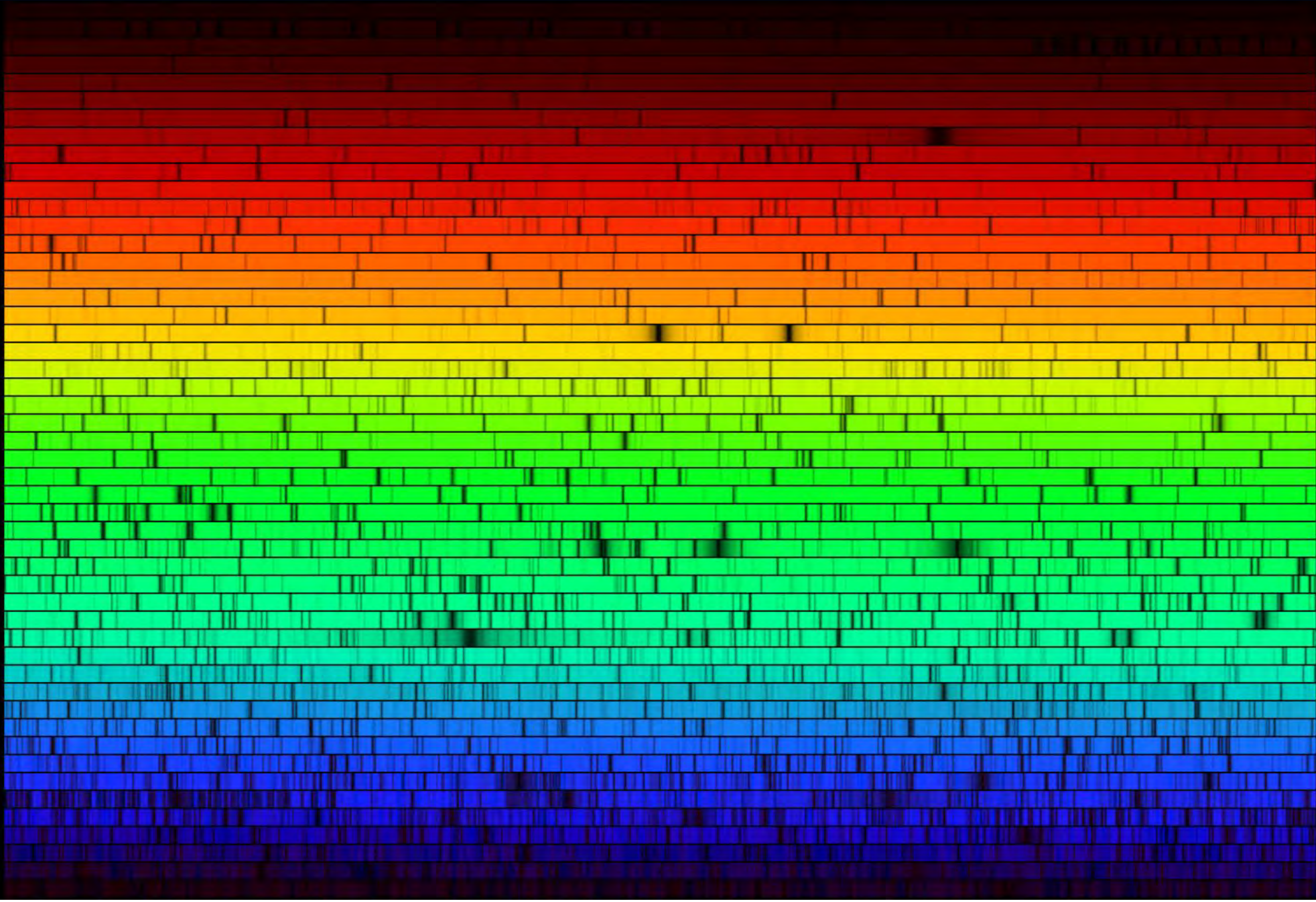
Search for stars in a direction away from disk or for stars with velocities showing their orbits are out of disk.

Search for low mass stars with extremely weak metal lines.

Use accurate photometric survey of stars with very low depressions due to metal lines.

Fewer than 1 star in a million has metallicity of 1/10000 sun.

The sun’s spectrum



Comparison of spectra

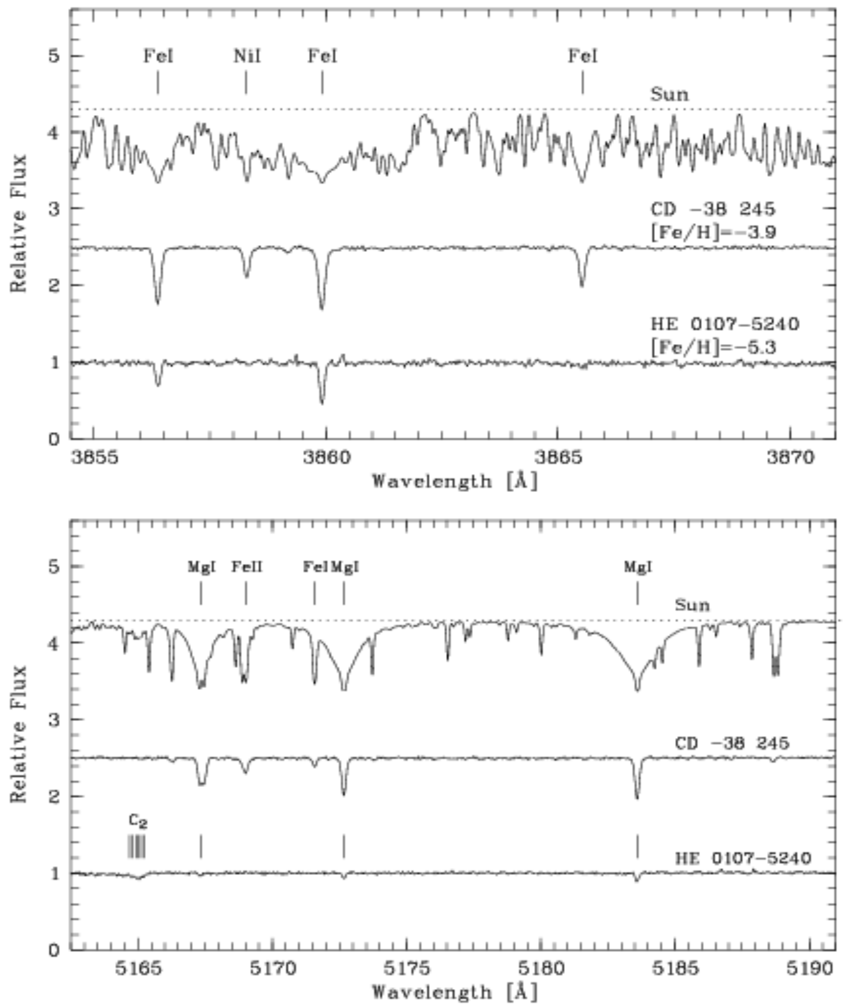
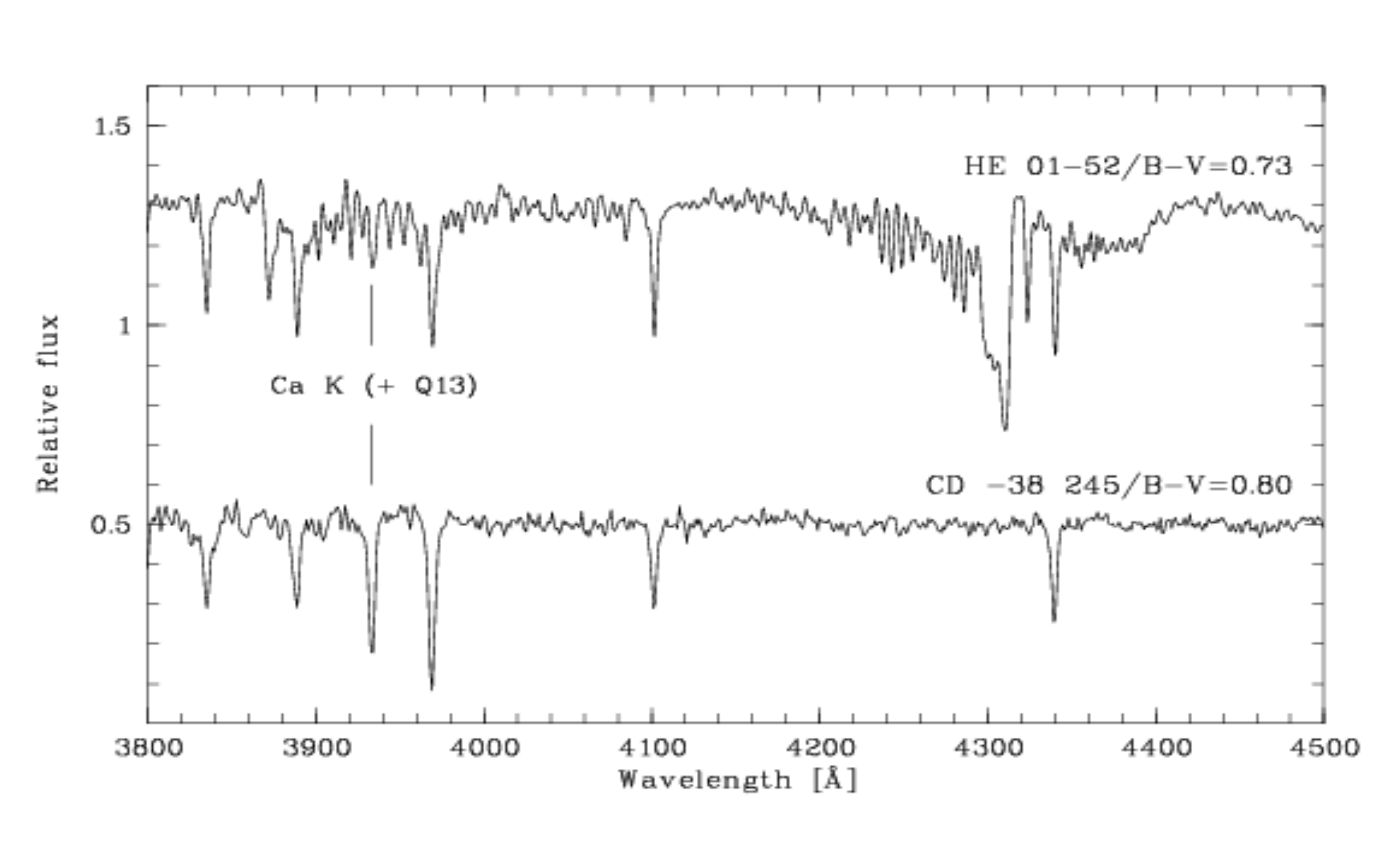


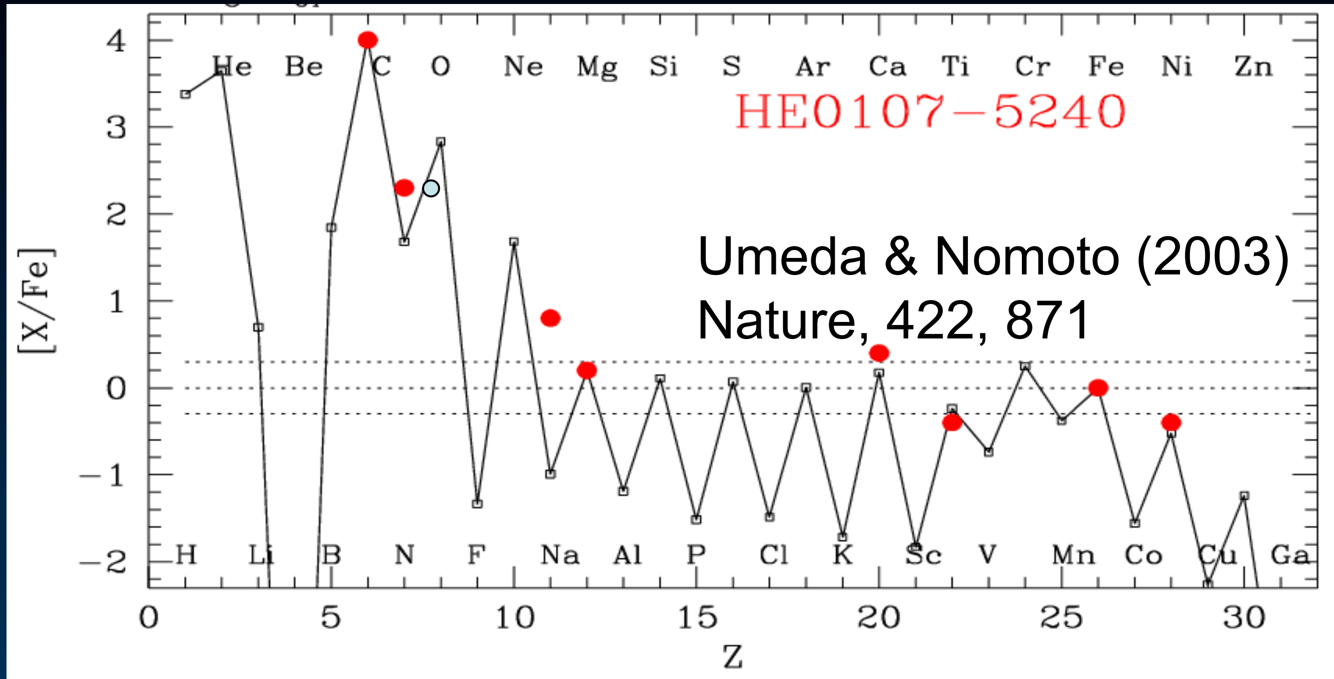
Fig. 1.— Spectrum of the Sun compared VLT/UVES spectra of CD −38° 245, the previously most metal-poor star, and HE 0107−5240. The spectrum of CD −38° 245, obtained in our program with the same setup. Note the very weak or absent Fe lines in the spectrum of HE 0107−5240, and the presence of the C_2 band at ∼ 5165 Å.

Discovery spectrum



First attempt to explain abundances

[Fe/H] = −5.3
[C/Fe] = 4.0
[Mg/Fe] = 0.2
[Ti/Fe] = −0.4
[N/Fe] = 2.3
[Ca/Fe] = 0.4
[Ni/Fe] = − 0.4



no s-, r- enhancement : no companion star

$M = 25M_\odot$ — $E = 3\times10^{50}$ergs

$M_{He} = 8M_\odot$ — C+N from He layer

$M_{CO} = 6M_\odot$ — M_{BH}

$M(Fe) \sim 10^{-5}M_\odot$

The origin of HE0107-5240

- Although the current model fit is not perfect, the jet ejection and fall-back model of a 25-30 solar mass supernovae explosion can probably be adjusted to explain the abundances of HE0107-5240.
- That is, HE0107-5240 formed from the ejecta of a single massive supernovae mixed in with the primordial H and He from the Big Bang in the earliest stages of the formation of the galaxy.
- More such stars need to be found to better understand the earliest stages of our galaxy's formation and the variety of SN outcomes.

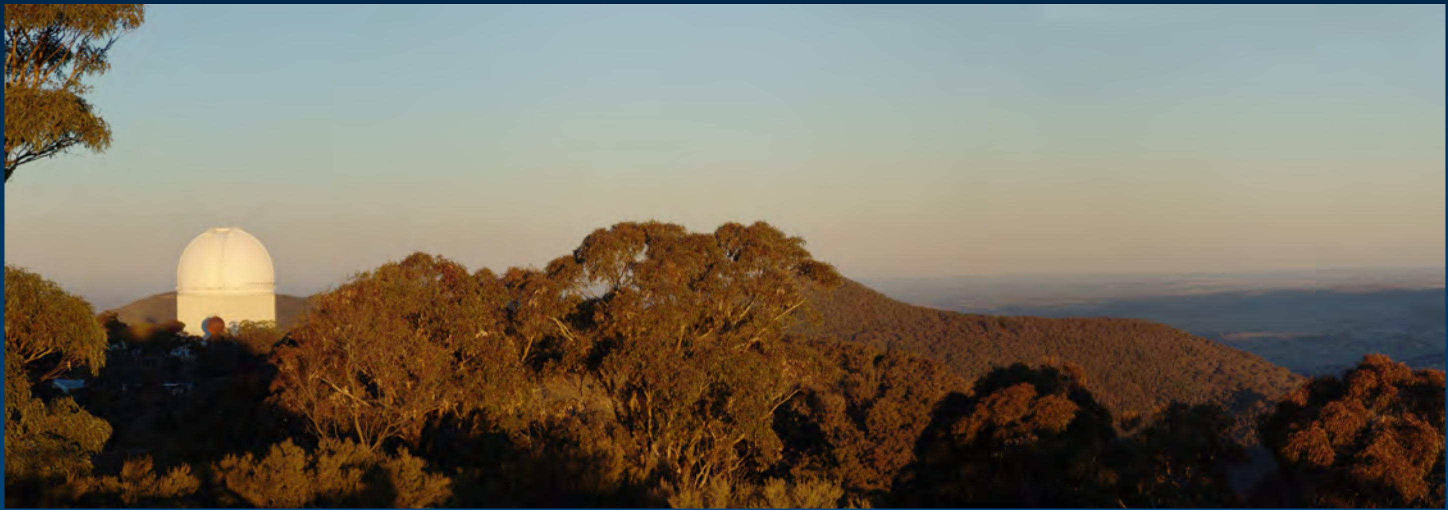
Future plans

- SkyMapper search for weak line stars
- 2.3m and AAT follow up of best candidates

then

- High resolution studies of extremely metal deficient stars with SUBARU, VLT, Magellan
- 3D Model atmosphere studies of cool stars

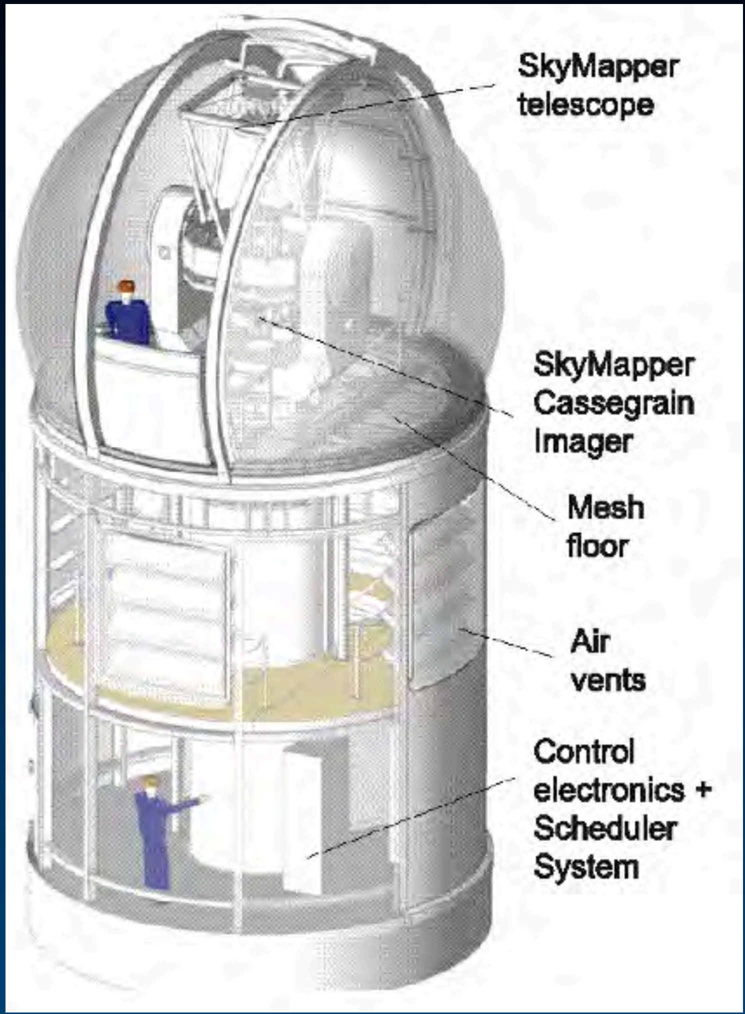
A clear night beckons



New telescopes for SSO

SSO hosts several new survey telescopes that will search the sky for the first stars and galaxies, distant supernovae, gravitational lensed stars and extra-solar planets.

The SkyMapper Telescope



Project is led by Nobel Laureate Brian Schmidt

1.35m telescope with a 5.7 sq. degree field of view

- Fully autonomous observing
- To conduct the Southern Sky Survey:
  - Five year Multi-colour (6 filters)
  - Multi-epoch (6 exposures, each filter)
  - Hα filter also available

SkyMapper field of view

Some Scientific Programs

•What is the distribution of large Solar-System objects beyond Neptune?

•What is the history of the youngest stars in the Solar neighborhood?

•How far does the dark matter halo of our galaxy extend and what is its shape?

•Gravity and metallicity for on the order of 100 million stars ⇒ the assembly and chemical enrichment history of the bulge, thin/thick disk and halo?

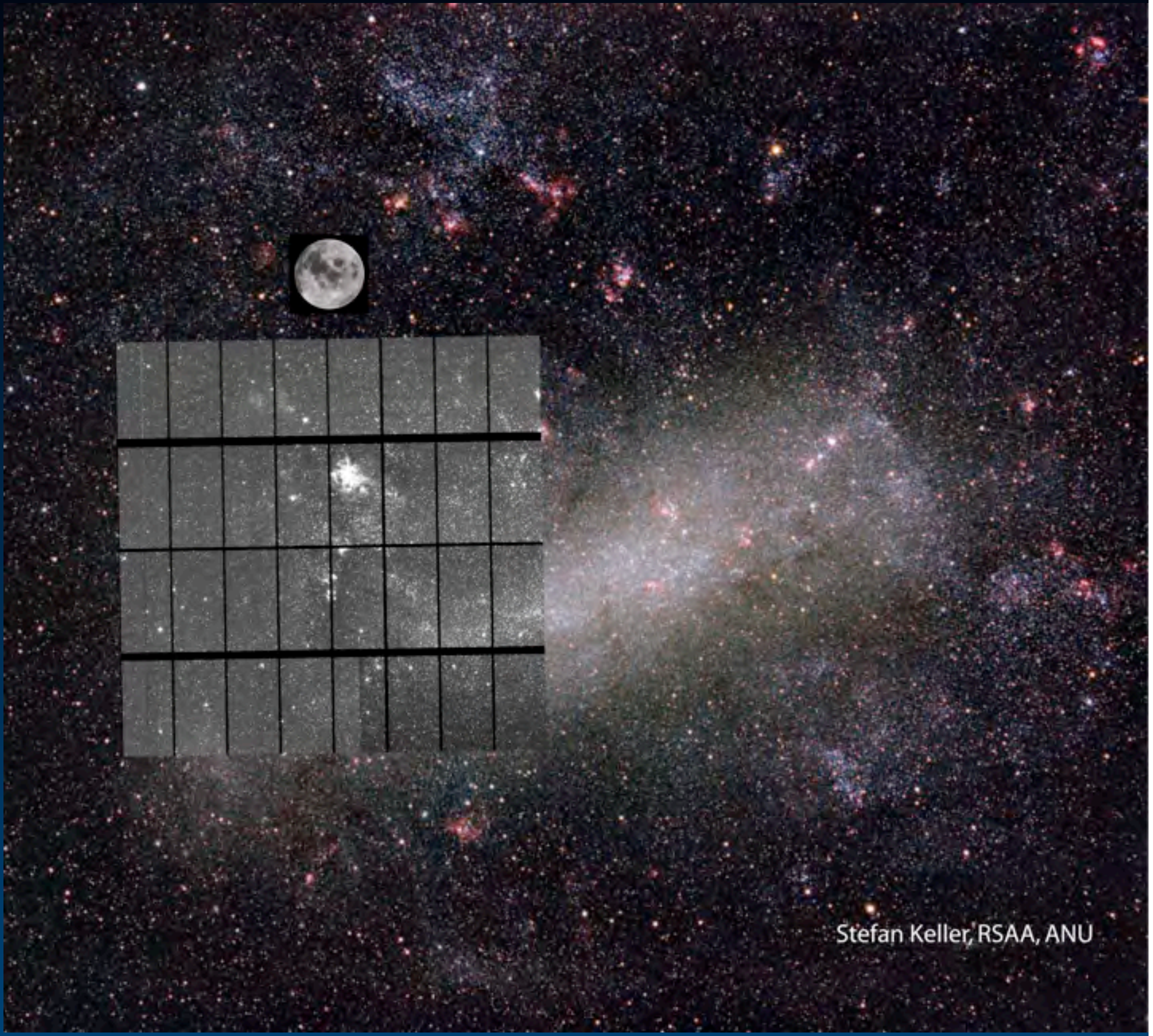
•Extremely metal poor stars.

•Undiscovered members of the local group – Sculptor,Cen too…

•Accurate photometric calibration of the galaxy redshift surveys: 2dF/6dF.

•Bright z>6 QSOs ⇒ probes of the ionization history of the Universe.

•Supernovae light curves



SkyMapper CCD camera

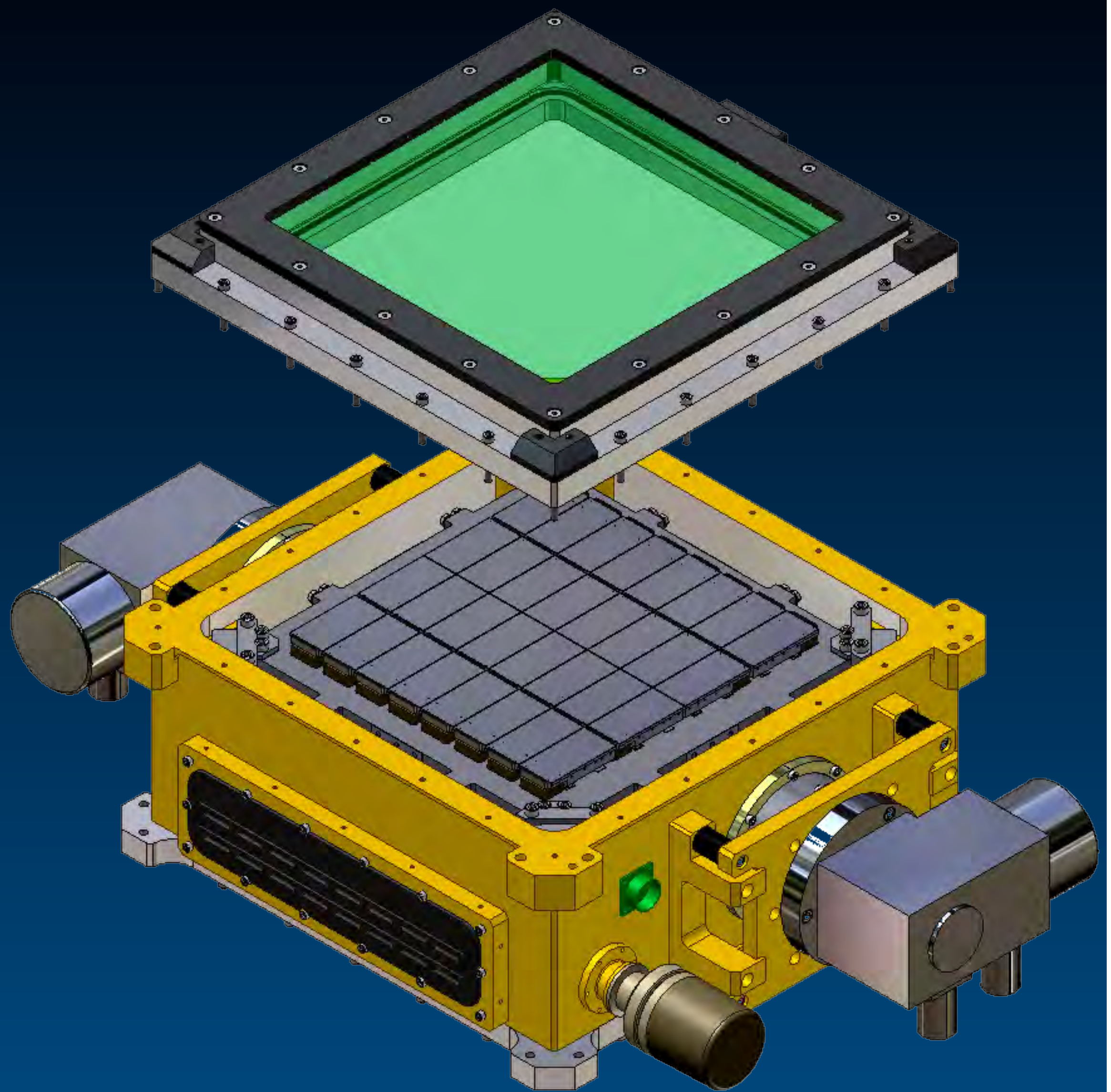
32 E2V CCD44-82 devices:

2048x4096 15 micron pixel CCDs

Broadband coated 40 micron (thick) deep depletion devices

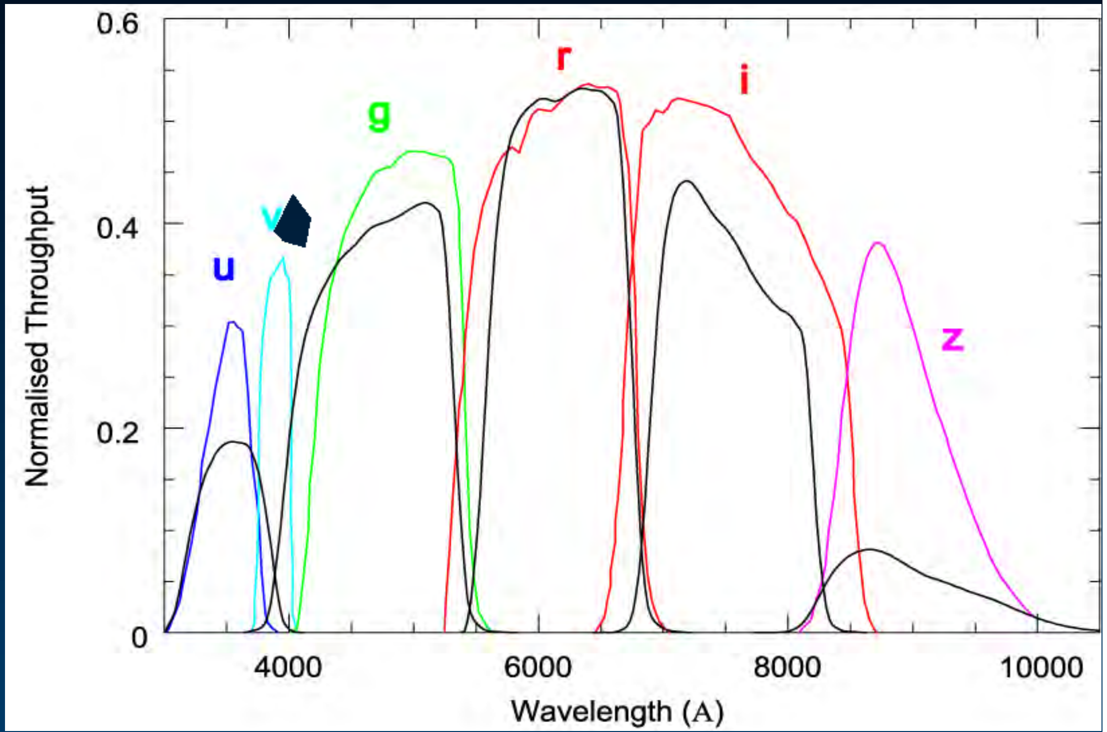
Reduced fringing, increased red response, and maintaining excellent blue response

16384x16384 0.5” pixels

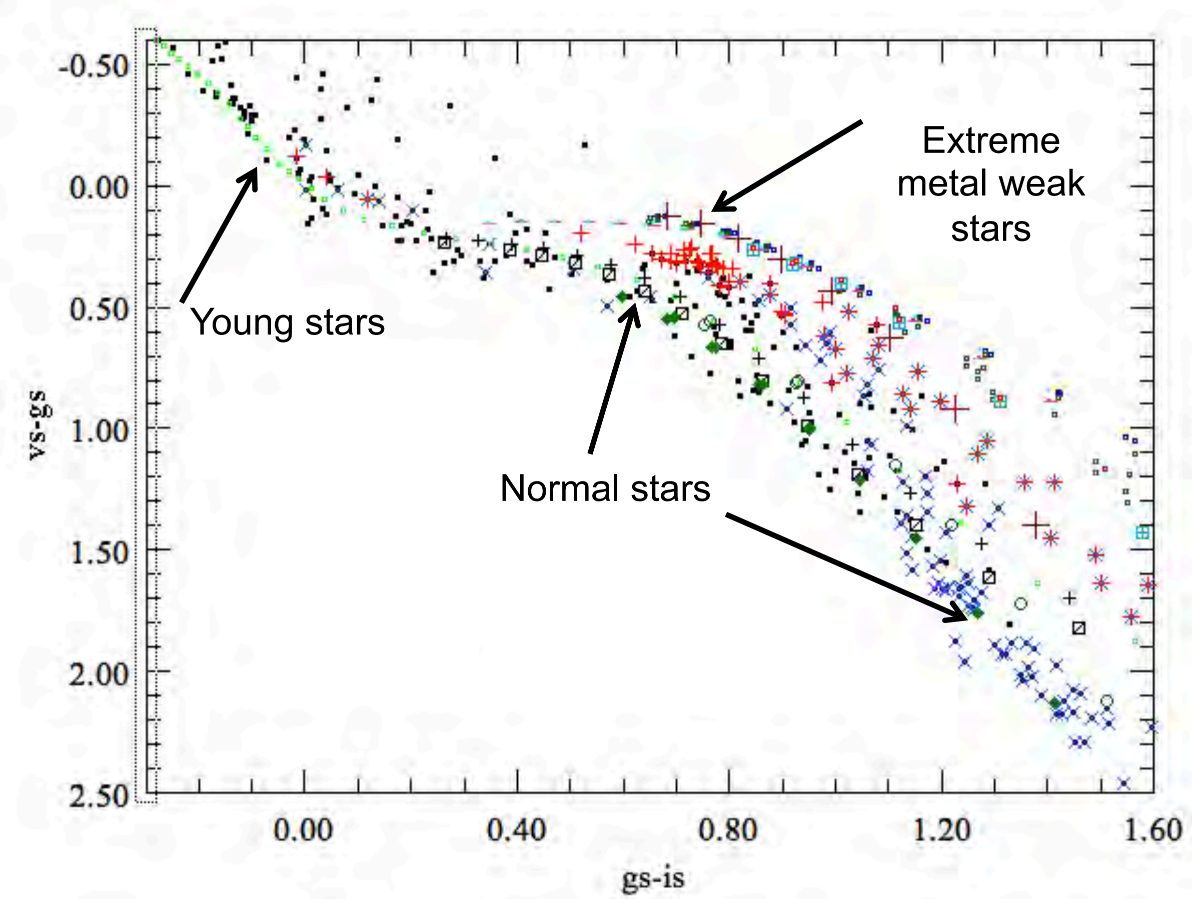


SkyMapper filters

Temperature, log(g), and metallicity are encoded in the spectrum of each star.
Using filters we can isolate portions of the spectrum.
In designing our survey we sought to optimise our ability to determine the three important stellar parameters.
SkyMapper not only complements survey efforts in the northern hemisphere but enables us to tackle important astrophysics in an exciting new way.



SkyMapper



SkyMapper will measure the brightness of all stars through 6 different filters that isolate different parts of the spectrum.

The weaker lines in the violet part of an old star's spectrum will result in a brighter measured violet magnitude.

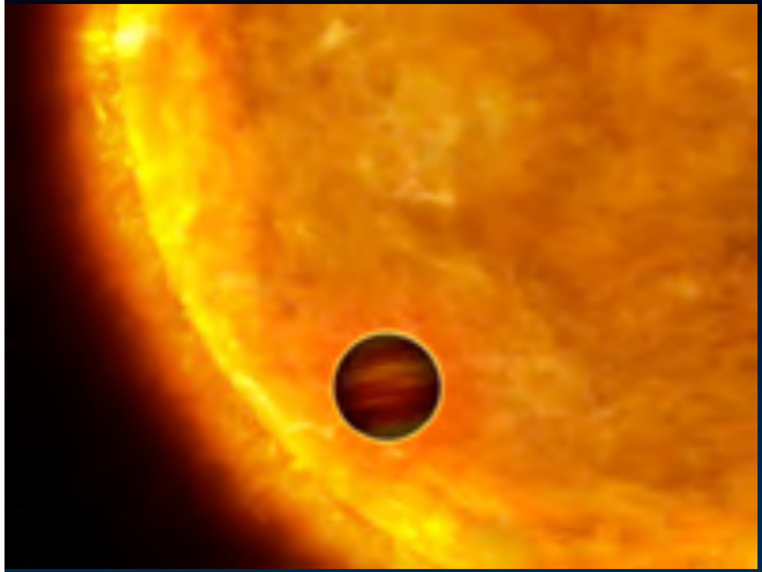
In this way we can identify the weakest line stars, the needles in the haystack.

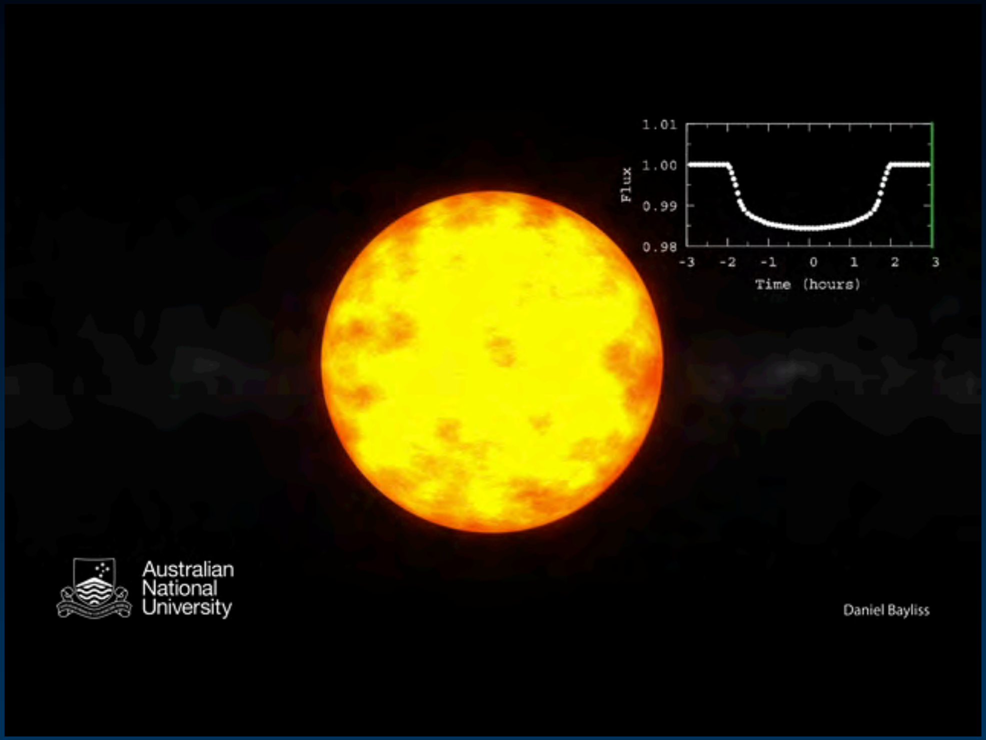
HAT-South Telescope

The HAT-South project is a collaboration between the Australia National University (ANU), the Harvard/Smithsonian Center for Astrophysics (CfA), and the Max Planck Institute for Astronomy (MPIA). Each site hosts two "TH4" units comprising four 0.18m Takahashi astrographs fitted with Apogee 4Kx4K CCDs. Each TH4 unit monitors 64 square degrees of sky at a time, so each site is capable of monitoring 128 square degrees of sky.

The HAT-South telescopes are located on three sites around the Southern Hemisphere: at Siding Spring Observatory (Australia), Las Campanas Observatory (Chile), and the Hess Site (Namibia). These locations allow fields to be monitored 24 hours per day, which greatly increase the rate at which planets can be discovered.

A search for hot Jupiters





HAT-South is a project to search for transiting extrasolar planets in the Southern Hemisphere. It uses a network of wide-field telescopes to monitor hundreds of thousands of bright stars, searching for the characteristic dip in light that occurs when a planet passes in front of its host star. With follow-up observations, the planets discovered in this project will be studied extensively to determine their density, temperature, and even atmospheric composition.

Solaris telescope

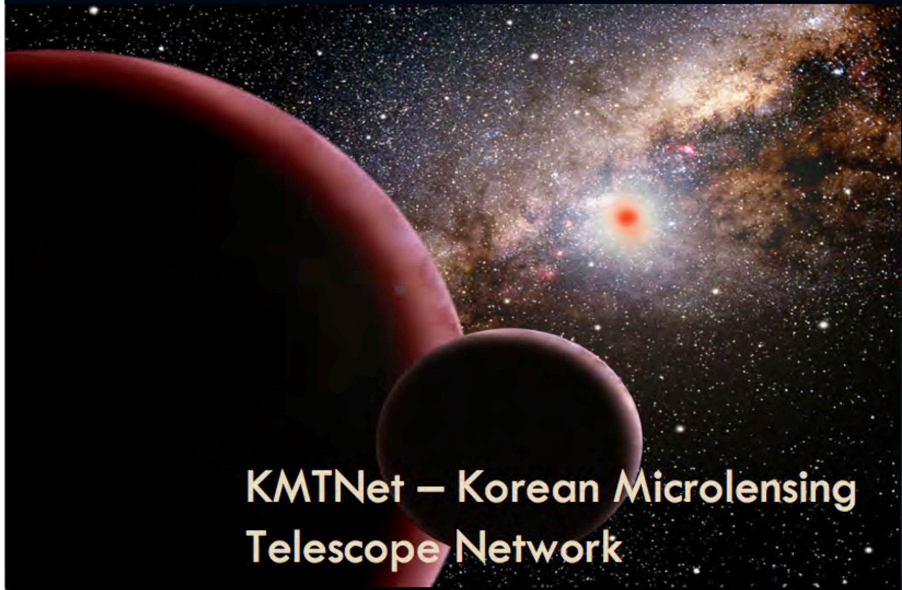
To detect circum-binary planets around a sample of up to 350 eclipsing binary stars using eclipse timing and precision radial velocities.

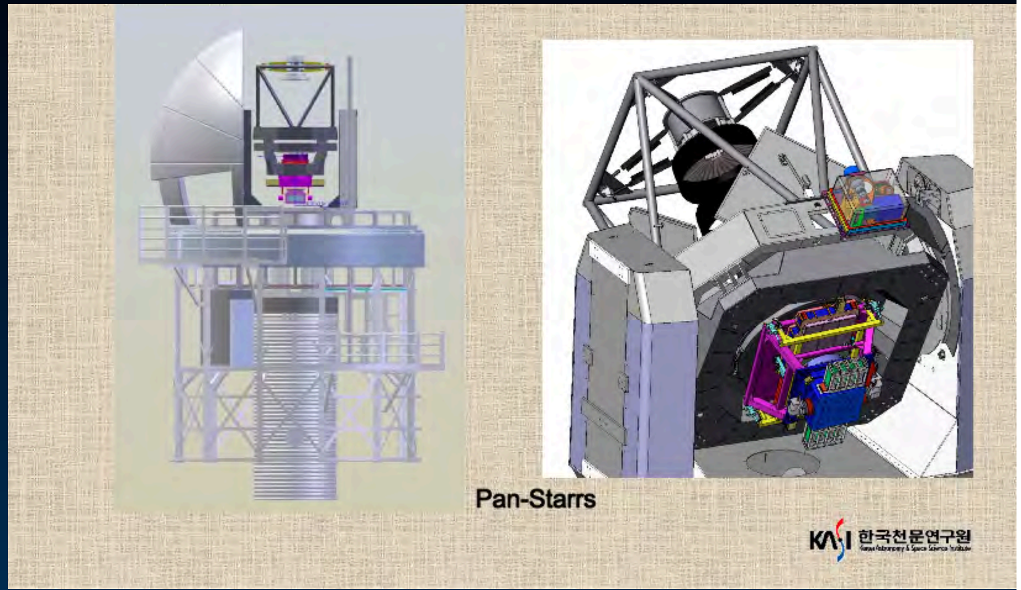
To characterize the binary stars with an unprecedented precision to test the stellar structure and evolution models..

The Solaris project (Poland) will establish a global network of four 0.5-meter robotic telescopes (Australia, Africa, South America) to collect high precision, high cadence light curves of the binaries.

The advances in remote and robotic operation are made possible by the advent of high speed internet connectivity across Australia and around the world.

Korean Microlensing telescope



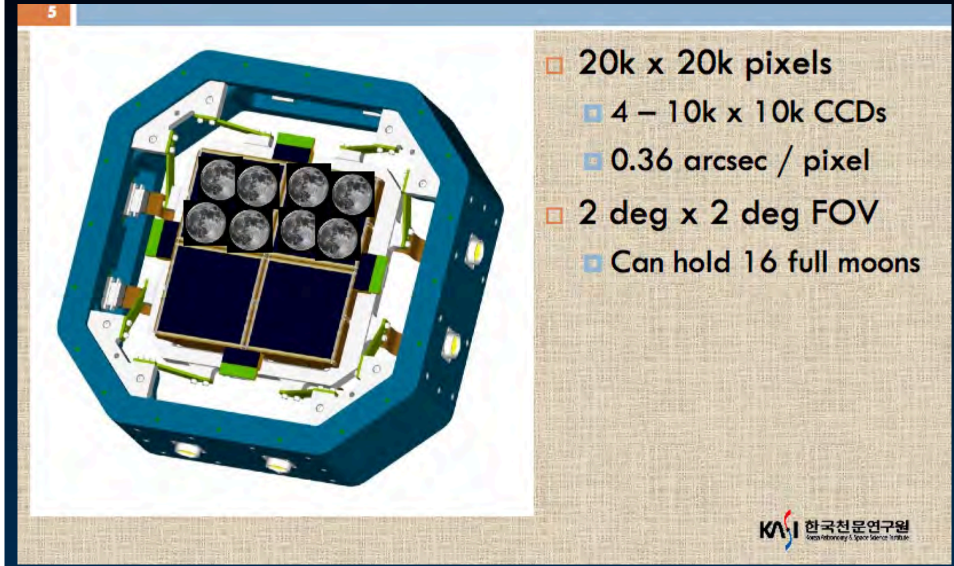


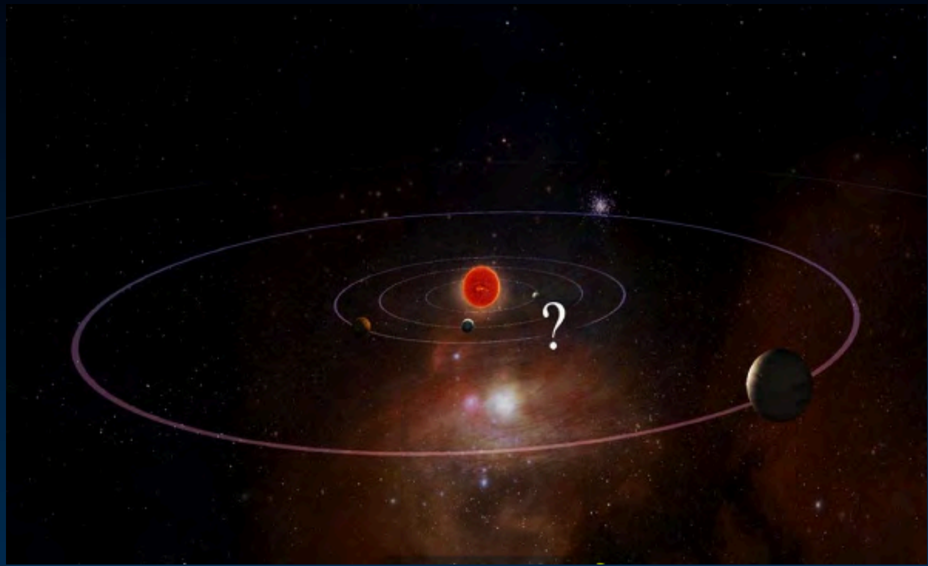
Aim of the project

Discover the first Earth-mass exoplanet. A huge number of exoplanets in wide mass range can be detected by microlensing.

A huge number of variable stars can be detected and studied (e.g. OGLE)

Korean Project to detect Earth size planets





Large Aperture : 1.6m diameter

Wide observing field : 4 degree x 4 degree
More frequent observation : 1 exposure /10 min

24-hour coverage : 3 telescopes in 3 continents
Australia, South Africa and Chile

No more Alert & Follow-up observations

Higher detection rate for microlensing events due to larger field & short interval observation

More sensitive to small and short anomalies in light curve due to low-mass planets

Existing and Prospective SSO telescopes

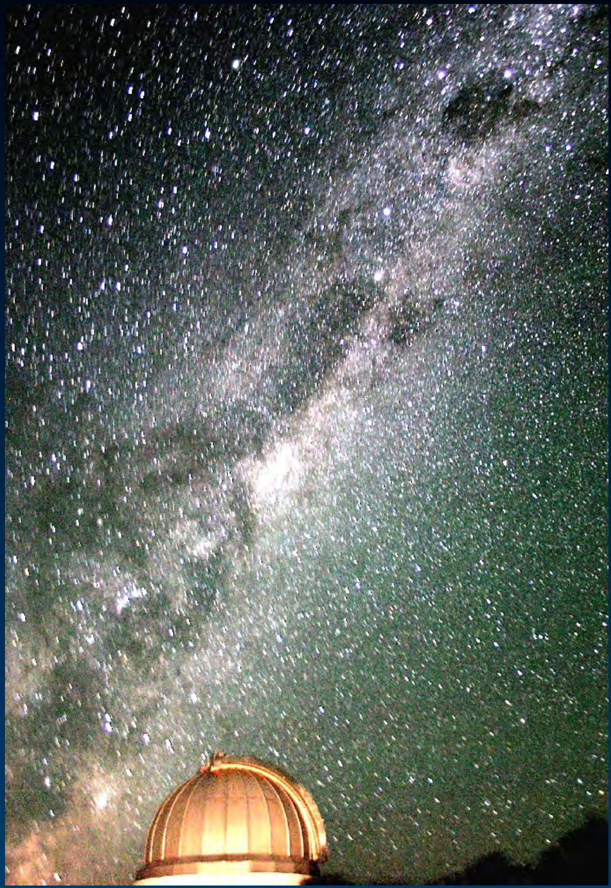
Current
Australian Astronomy Observatory - 3.9m, UK Schmidt
Australian National University- 2.3m, SkyMapper
HAT-South - 4 x 18cm - extra-solar planetary transits
Las Cumbres Obs Global Network - previously FAULKES - Universities and schools
University of Arizona - NEO survey
Korean Yonsei University - YSTARR
University of NSW - APT Baker-Nunn camera

Underway
Nicolaus Copernicus Astronomical Centre - SOLARIS 0.5m
ITELESCOPE Net P/L - “rentascope”
University of North Carolina - PROMPT

Korean Astronomy & Space Science Institute -1.6m, microlensing
Tzec Maun Foundation - student internet observing - 4”, 6”, 7”

Possible
SLOOH -

Astronomishes Institute Switzerland - satellite tracking
University of North Carolina - 24”



Thank you for the dark
Coonabarabran skies