GLAO @ Subaru

Globular Clusters & the Galactic Centre

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with thanks to Harvey Richer (UBC)
Globular Clusters & GLAO Imaging

1. Proper motion cleaning

2. IMBH at cluster centres?

2. White dwarf cooling curve (ages & EoS)

3. WD debris disks & planets?
Nearby globular clusters at distances of <5 kpc

Velocity diff.s of the cluster to the field ~100 km/s, thus proper motion > 4 mas/year
Easily separate cluster from field with <1” resolution.

With good S/N (70) proper motions measurable to ~ 0.5 mas/year

Internal kinematics
Cleaning 47 Tuc of foreground & SMC stars: 
*larger GLAO FOV helps!*

- remove foreground, etc.
- lower main sequence dynamical cleaning.
- binary frequency
- Multiple populations / Helium rich branch?
- internal kinematics
Cleaning 47 Tuc shows ends of the WD cooling curve:  
*Larger FOV helps!*

Empirical WD cooling sequence does not fit the hottest WD models (MESA, Paxton et al.)

Neutrino or axion cooling important?
Predictions for IMBH in centre of Omega Cen ($M10$, etc.)

From IFS spectra, Noyola et al. 2010 report higher velocity dispersions in their central fields, consistent with a $10^4 M_\odot$ blackhole.

Surface brightness profile also consistent with a shallow central cusp consistent with an IMBH.
Yet, no change in proper motion kinematics of inner Omega Cen

Figure shows there are the same number of high velocity stars in the centre of the cluster as at 10”.

An IMBH would have induced increasing velocities towards the center with RMS $\alpha R^{-1/2}$.

Also, they relocated the centre of Omega Cen by 12” from Noyola, Gebhardt, and Bergmann 2010.
Are IR excesses Exoplanets, Debris Disks, QSOs, noise?
WDs with IR excesses in GCs? Are these debris disk?, planets?, or just backgnd quasars, binaries, etc.?

*Metal-poor systems* would require a new way to form planets, e.g., perhaps through disk instabilities.
Globular Clusters

Open Clusters

Galactic Centre
Proper motion cleaning of Galactic Open Clusters too:
*Larger FOV helps*

Harder since OCs more embedded in the disk, velocities differences with the field stars is less.

- Disk holds 3/4 of baryonic mass.
- Star Formation History of the disk?
- Gradients in the Galactic disk?
- Changes in gradients with age?
- Universal IMF?
- Universal binary fractions?
- Outer warps, structures, kinematics. (e.g., warp vs CMaj dwarf)
Proper Motion Cleaning of open cluster NGC 188 shows binary sequence very nicely.
Open Clusters indicate metallicity gradients steeper in the inner Disk, but difficulties in comparing the datasets.
Galactic Centre & GLAO with Spectroscopy

1. 3D kinematics (RV with p.m.)

2. SMBH - asymmetries?

3. Properties of stars in the Galactic Centre

4. Search for First Stars, remnants, earliest evolution.
SWEEPS FOV in the Galactic Bulge:
Sagittarius Window Eclipsing Extrasolar Planet Search

ACS/WFC FOV ~ 200” × 200”
SWEEPS FOV in the Galactic Bulge:
*Sagittarius Window Eclipsing Extrasolar Planet Search*

Proper Motion cleaned CMD of Galactic Bulge (tiny FOV) shows old & metal-rich (Clarkson et al. 2008)

ACS/WFC FOV ~ 200” x 200”
But the Galactic Bulge has Structure
Bar and X-shape

Bissantz & Gerhard 2002
Babusiaux & Gilmore 2005
Cabrera, Lavers, et al. 2008 etc.

Red clump stars show two overdensities along the minor axis:

McWilliam & Zoccali 2010
Nataf et al. 2010
Saito et al. 2011
ARGOS survey of Galactic Bulge
metallicities, [\(\alpha/\text{Fe}\)], velocity dispersions

Freeman (March 2013 ngCFHT meeting) suggests:

A: thin disk interlopers
B: true boxy/peanut bulge
C: old thick disk which may be part of the bulge

Ness et al. 2012
Bulge Spectral Surveys

ARGOS (AAO)  R ~10,000 optical
ESO Bulge LP (ESO)  R ~ 5000 & 20,000 optical
APOGEE (SDSS-III)  R ~ 20,000, H-band
MOSFIRE ??  R ~ 5000

APOGEE only one that uses fibers:
300 low-OH (‘dry’) fused silica fibers with 2” FOV at focal plane,
using VPH gratings & H2RG CCDs (loan from JWST NIRCam)

- Yet these surveys cannot go into crowded fields (no AO),
- Optical surveys have to deal with variable reddening (bad Av)
- All have bright limiting magnitudes (V<19, H<12).
Figure 7. Projected distribution at \( z = 0 \) for stars (red), compared to that of the dark matter for the Aq-A-2 halo. As significant fraction of the stars end up in dark matter subhalos. The image is 1080 kpc on a side, approximately twice the diameter of the virialised dark matter halo.

Figure 8. Cumulative distribution of second generation, first star relics, stars at redshift \( z = 0 \) for Aquarius haloes (colour lines), compared to the dark matter profile for the Aq-A halo (dashed black line). The peculiar abundance pattern characteristic of Pop. III nucleosynthesis. However, stars that form later may have been enriched by the elements produced by the previous generation of relatively metal rich stars, so that eventually the net abundance pattern loses its characteristic Pop. III star signature. To implement this idea we proceed as follows.

We assume that each first galaxy halo contains a fixed total mass of 'first star relics' - stars that form in an environment enriched solely by truly primordial stars - independent of redshift. To trace the location of such stars at later times, we tag the \( N = 100 \) most bound particles at the time the virial temperature of the halo first exceeds \( T = 10^4 \) K. This assumes that these second-generation stars form in the centres of such dark-matter haloes. Once a halo has started forming stars, it will grow in mass, and may merge with other haloes. The number of first star relics in a halo will only change if it merges with a halo that contains its own population of first star relic stars. We continue tagging first star relics in haloes that reach the threshold \( T_{\text{vir}} \) until \( z = 10 \), after which we assume that reionisation of the Universe evaporates all mini-haloes.

In summary, we identify the epoch when a halo is first capable of sustaining gas that can cool through atomic processes and tag its \( 100 \) most bound particles as the first star relics, until \( z = 10 \). We can then investigate the spatial distribution of these first star fossils at any later epoch by tracing the tagged particles. The location of the first star relics today is illustrated in Fig. 7 where, for clarity, we show only a fraction of the stars. The image shows that most of the first star relics end up in the central regions of the halo, but some survive inside subhalos.

Search for remnants of the First Stars:
- linked to Cosmic Dawn, reionization
- early chemical evolution in the Universe
- remnants may at centres of galaxies
**First Stars may have bimodal mass distribution**

If fractionation occurs:
(e.g., Schneider 2004, 2006, Clark et al. 2008).

in high density regions, H$_2$ cooling becomes optically thick and the cloud fragments

or, dust formation in pair instability supernovae can lead to efficient cooling and fragmentation

0.08 Mo stars would still exist today

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**Diagram**

- Black Holes
- Metal Enrichment
- White Dwarfs

**Stellar Mass (M$_\odot$)**

- Mass Fraction

Nakamura & Umemura 2001
e.g., $H < 16$, $\Delta H > 2$ within 2", SWEEPS field (T. Brown) but this is a tiny FOV of the Bulge, and off centre. Larger FOV would be valuable!
Thus, AO-IR spectroscopic survey of the Galactic Bulge

R=2000 will be okay for $[\text{Fe/H}] > -2.5$
R=5000 okay for $[\alpha/\text{Fe}]$ in the IR?
R>20,000 for $[X/\text{Fe}]$

--> an IR SDSS?
--> unknown if features available or errors
--> APOGEE (bright) calibrations.

\[
\begin{align*}
[\text{Fe/H}] &= -2.5 \\
[\text{Fe/H}] &= -1.5 \\
[\text{Fe/H}] &= -0.5
\end{align*}
\]
How do you know if you got a First Star?

Predict a unique chemical pattern: no elements > Zn

GLAO Workshop, Sapporo - 14 June 2013
First Star Candidates will require TMT HRS but GLAO + IR spect would identify candidates and connect us to Cosmic Dawn.
GLAO Workshop questions:

Two science cases:  - proper motion cleaning (WF imaging)  
- first star remnants (spectroscopy)

Q1. WF imager (p.m.) & MOS (R~5000, GCentre)
Q2. prefer <0.1" for proper motion cleaning
Q3. GLAO & TMT (preselect first star candidates)
Q4. GLAO & JWST (IMBH easier with JWST).

Qa. Will need spectroscopy for GCentre.  
Not MOIRCS, too low spectral resolution (+other cons)