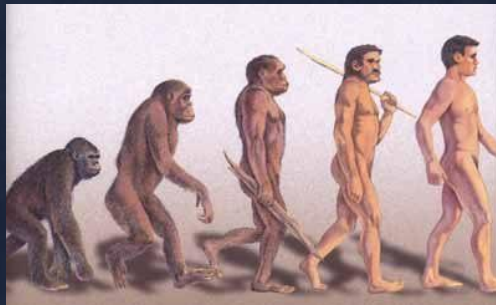


Dwarf Galaxy Kinematics and Metallicities:

The cusp/core problem and early chemical evolution

Josh Simon
Carnegie Observatories



The Cusp/Core Problem

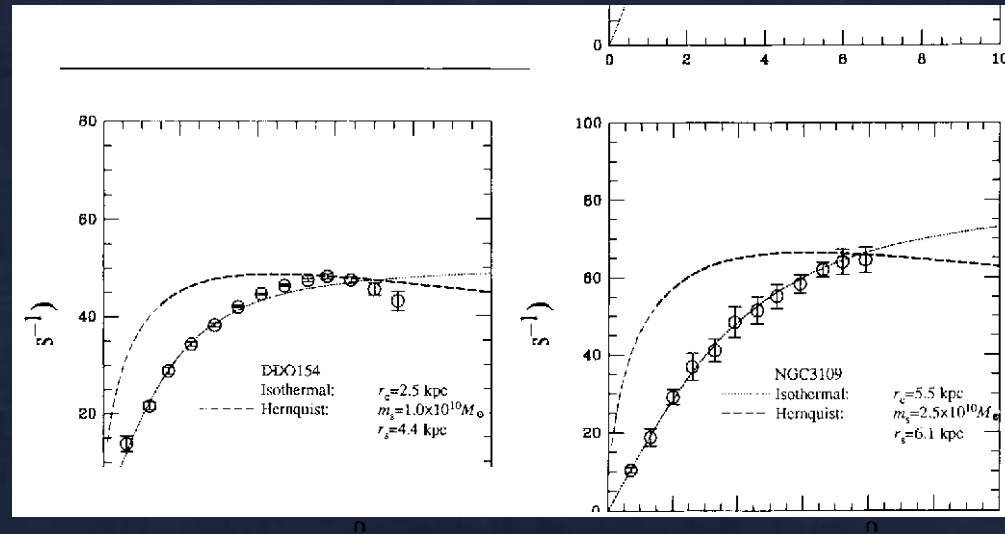
- First recognized in 1994 that dwarf galaxy rotation curves are too shallow

FLORES & PRIMACK

2. DWARF SPIRAL GALAXIES

The unusual properties of the dwarf spiral galaxy DDO 154 (Carnignan & Freeman 1988; Carnignan & Beaulieu 1994) make it an ideal laboratory to test the distribution of DM densities, at least on small scales. The luminous components of DDO 154 are neutral hydrogen gas, visible through 21 cm emission, and stars. With a gas mass-to-blue light ratio $M_{\text{HI}}/L_B \approx 5$, which makes it a very gas-rich system, DDO 154 offers the advantage that the mass of the dominant luminous component, the gas, is quite insensitive to the uncertain mass-to-light ratio. The inferred contribution of the luminous components to the circular velocity reveals a system dominated by its DM down to very small distances from the center. At the largest distance at which the H I is detected, more than 90% of the mass is invisible. Thus, the DM distribution is well constrained in this system.

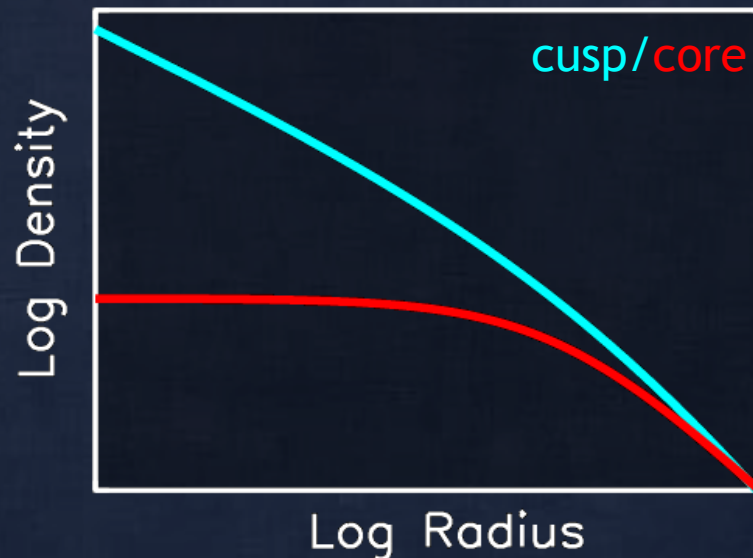
In Figure 1a we show the inferred contribution of the DM to the circular velocity as a function of the distance r from the center of DDO 154. We have used the parameters of Carlini & Beaulieu (1989) for the two luminous components to extract the DM contribution from the data; thus, we model the stellar component as a thin exponential disk of mass and scale length $M_* = 5 \times 10^7 M_\odot$ and $b_* = 0.5$ kpc. The H I surface density profile of DDO 154 is well approximated for $r \gtrsim b_{\text{HI}}$ by



The Cusp/Core Problem

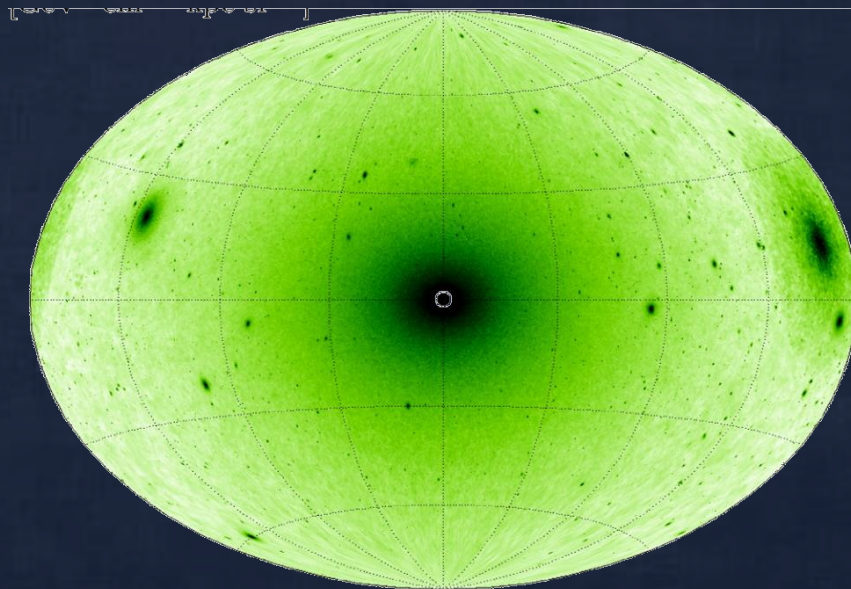
- Navarro, Frenk, & White (1996)

$$\rho(r) \sim \frac{1}{(r/r_s)(1 + r/r_s)^2}$$



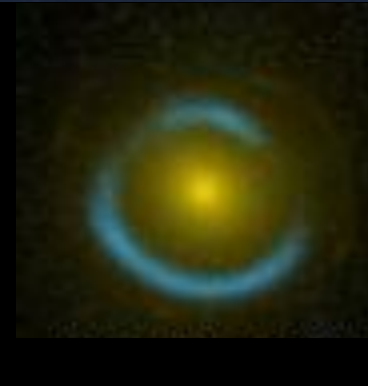
The Cusp/Core Problem

- This is important because:
 - Measurements of the mass distribution within galaxies could provide clues to DM physics
 - DM annihilation signals go as ρ^2



The Cusp/Core Problem

- Four primary regimes in which dark matter density profiles can be measured
 - Local Group dwarf spheroidals
 - Low-mass spiral/irregular galaxies
 - Massive galaxy lenses
 - Galaxy clusters



Dwarf Spheroidals as DM Probes

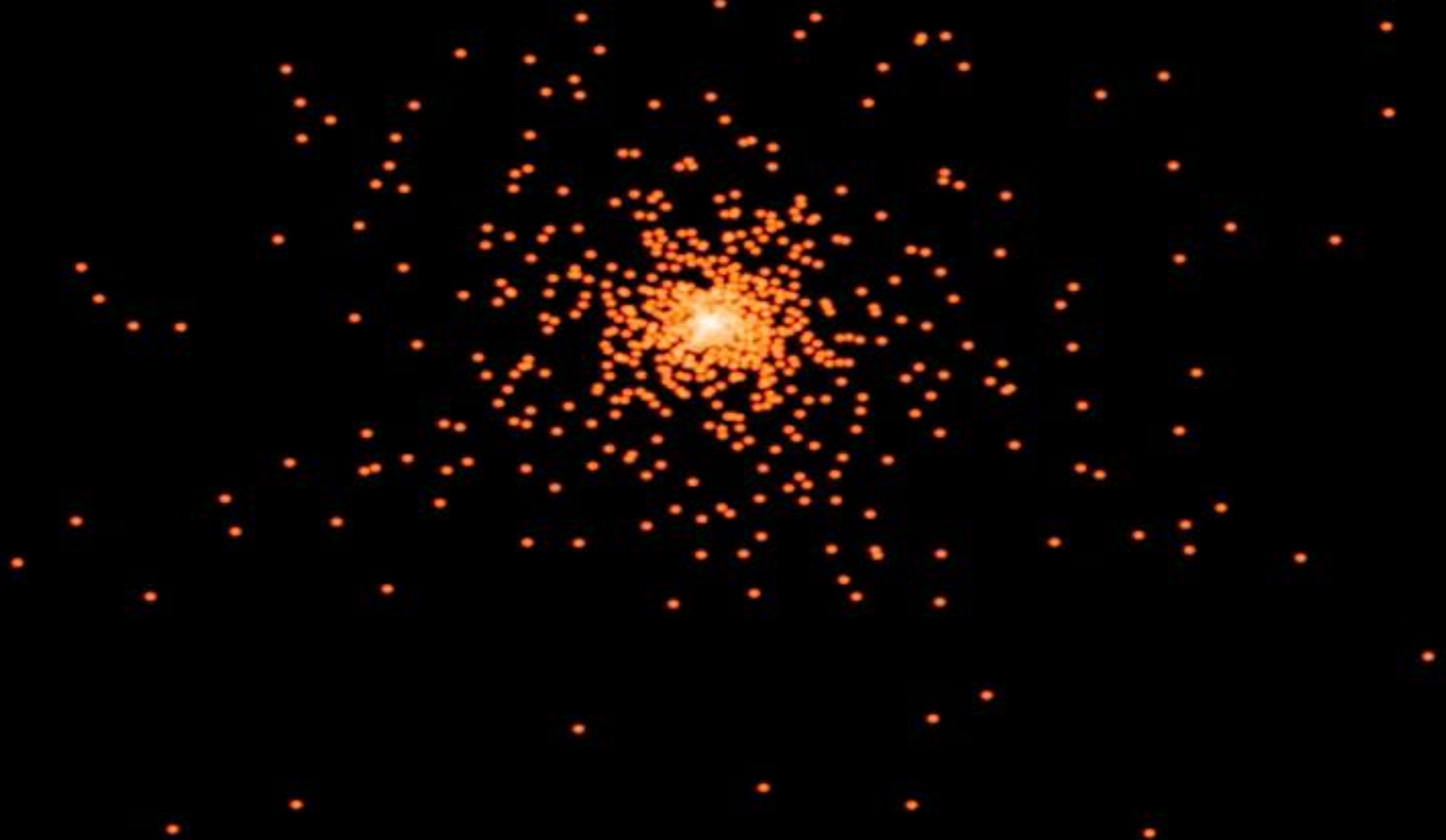
- Closest and most dark matter-dominated galaxies known
 - luminosities from 10^3 to $10^7 L_{\odot}$
 - sizes from 30 to 1000 pc
 - masses of $\sim 10^9 M_{\odot}$



Dwarf Spheroidal Density Profiles

- Cleanest systems in principle
 - Baryons of little importance
 - Less interpretation of observations necessary
- But: radial velocities provide only one component of the 3D motion of each star

Dwarf Spheroidals as DM Probes



movie courtesy of TJ Cox

Dwarf Spheroidal Density Profiles

- Cleanest systems in principle
 - Baryons of little importance
 - Less interpretation of observations necessary
- Jeans equation:

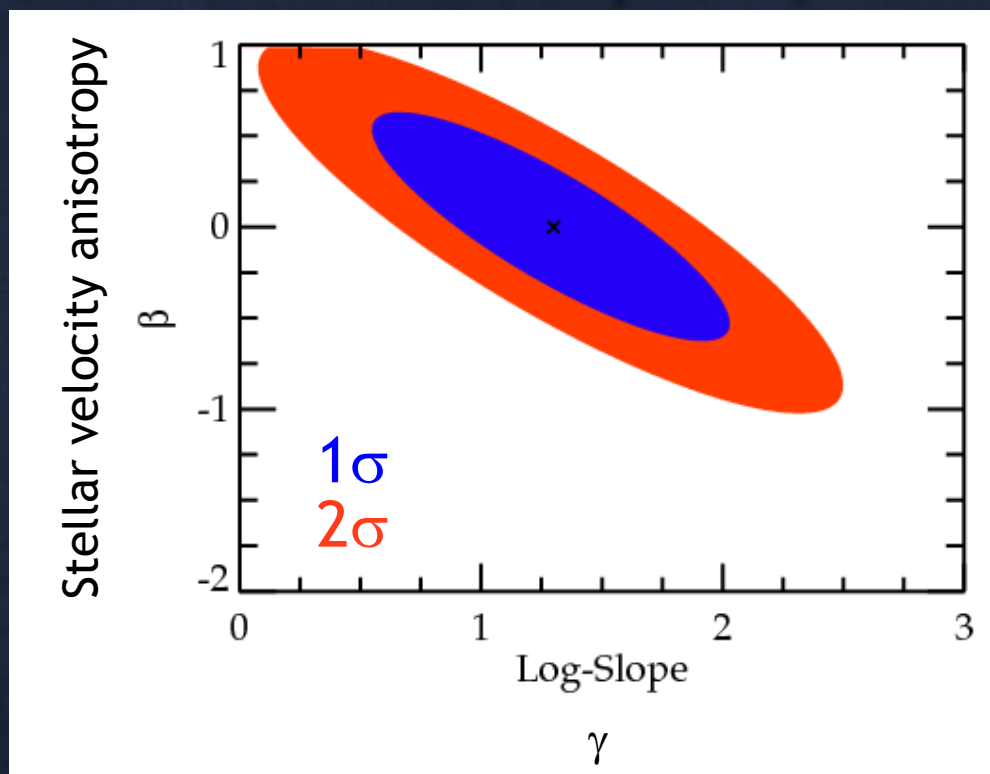
$$r \frac{d(\rho_* \sigma_r^2)}{dr} = - \rho_* \frac{GM(r)}{r} - 2\beta(r) \rho_* \sigma_r^2$$

observed
unknown

$M(r)$ and $\beta(r)$ are degenerate!

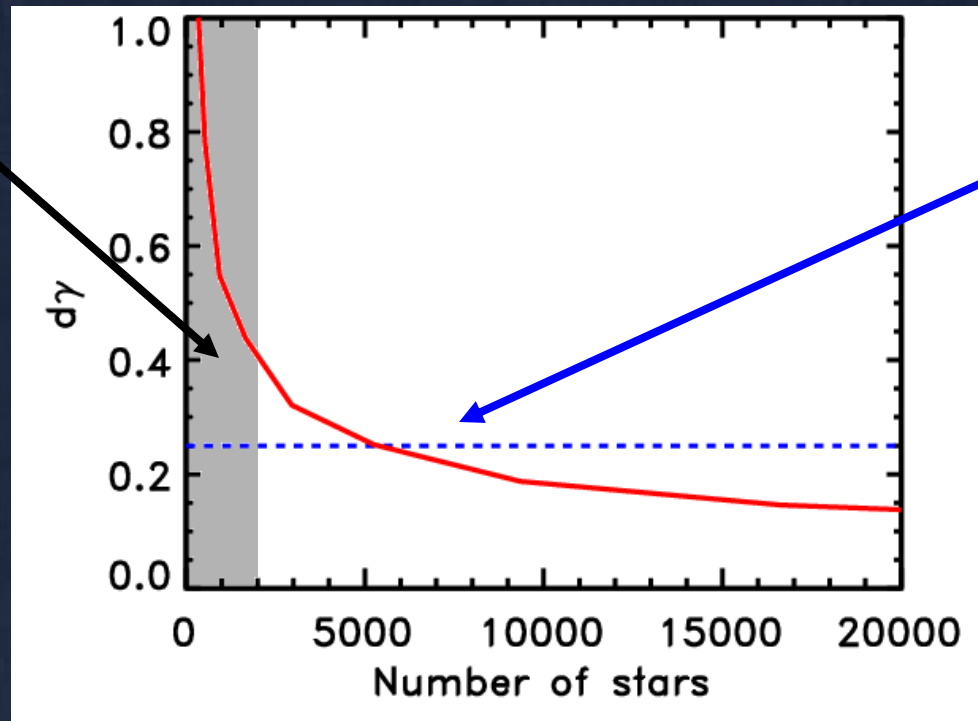
Dwarf Spheroidal Density Profiles

- Assume $\rho(r) \propto r^{-\gamma}$
 - Want to distinguish $\gamma \sim 0$ (CDM is wrong)
from $\gamma \sim 1$ (DM is cold)



How Many Stars Does It Take?

current
studies



Requirement
to usefully
constrain γ

$d\gamma < 0.25$ requires 5000 stars

$d\gamma < 0.20$ requires 9000 stars

Published RV Samples

- Fornax: 2483
- Sculptor: 1365
- Carina: 774
- Sextans: 441
- Draco: 210
- Ursa Minor: 182
- Leo I: 827

Walker et al. (2009)

Muñoz et al. (2005)

Kirby et al. (2010)

dSph Density Profile Results

- Fornax

- $\gamma = 0.39^{+0.37}_{-0.43}$ (Walker & Penarrubia 2011)
- **core** (Jardel & Gebhardt 2012)
- **core** or **cusp** (Breddels & Helmi 2013)

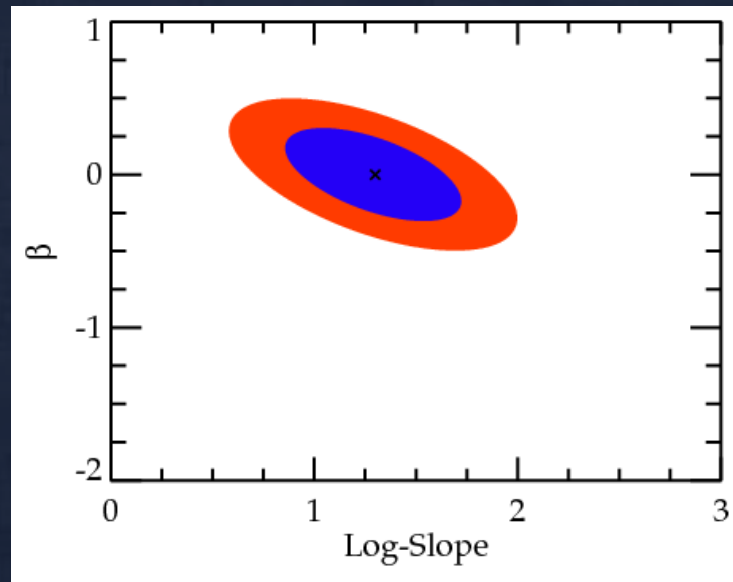
- Sculptor

- **core** or **cusp** (Battaglia et al. 2008)
- $\gamma = 0.05^{+0.39}_{-0.51}$ (Walker & Penarrubia 2011)
- **core** (Amorisco & Evans 2012)
- $\gamma = 0 \pm 1.2$ (Breddels et al. 2013)
- **core** or **cusp** (Breddels & Helmi 2013)
- $\gamma = 0$ or **1.2** (Richardson & Fairbairn 2014)

Dwarf Spheroidal Density Profiles

- Instead of using radial velocities alone, add proper motions
 - Directly determines the velocity anisotropy
 - $5 \text{ km s}^{-1} \sim 11 \mu\text{as yr}^{-1}$

RVs plus proper motions



Future Outlook

- Currently little agreement in derived density profile slopes
- Radial velocity sample sizes are still being increased
- Possibility of measuring proper motions with HST, Gaia, JWST, or ELTs

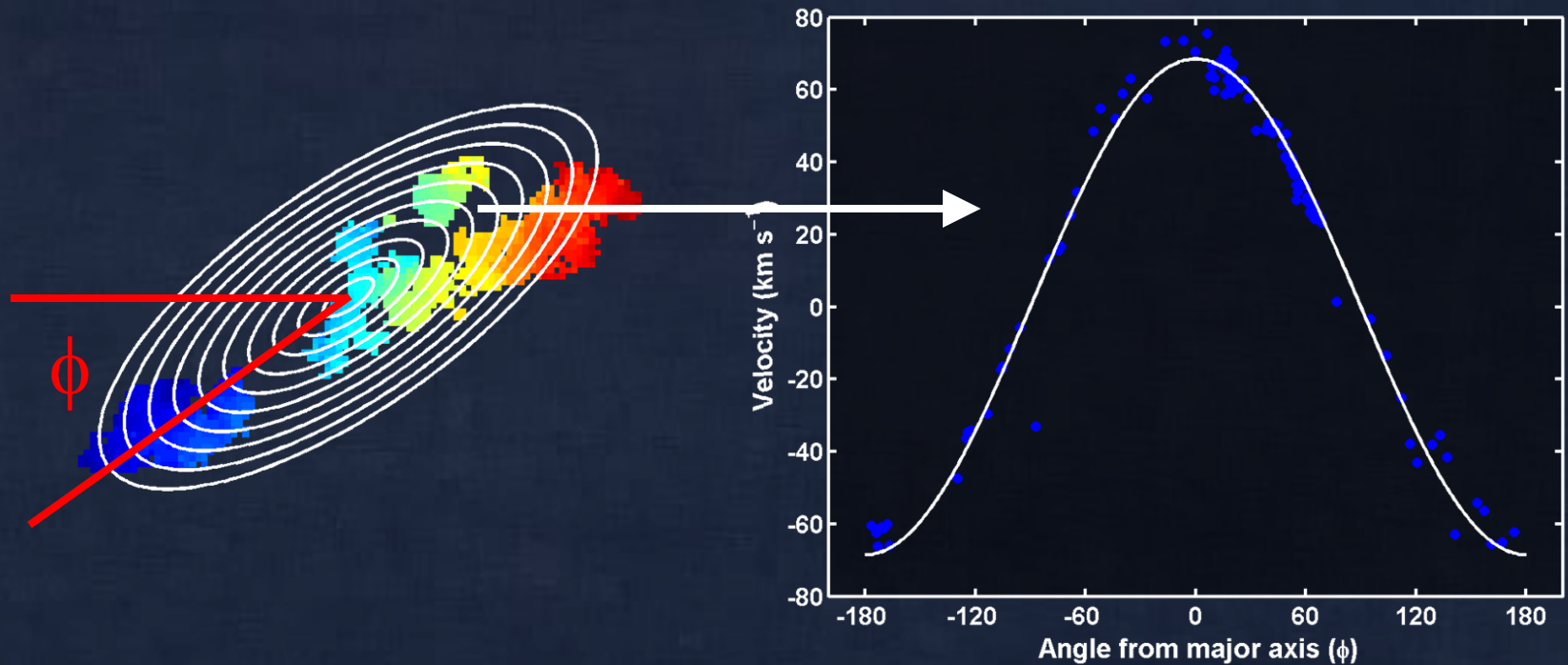
Late-Type Dwarf Galaxies



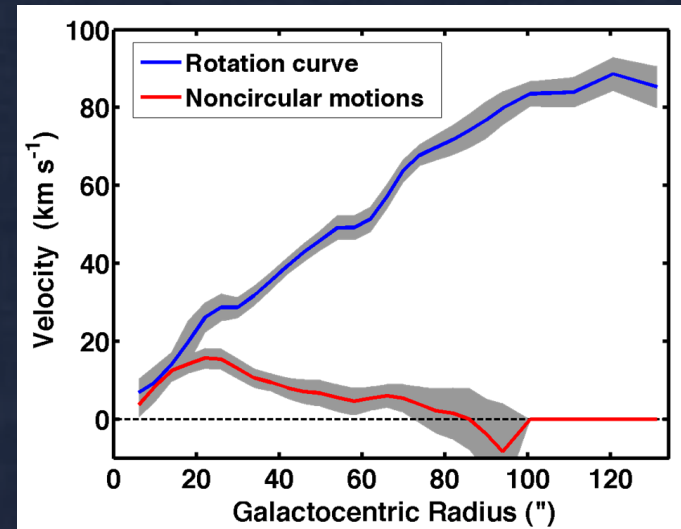
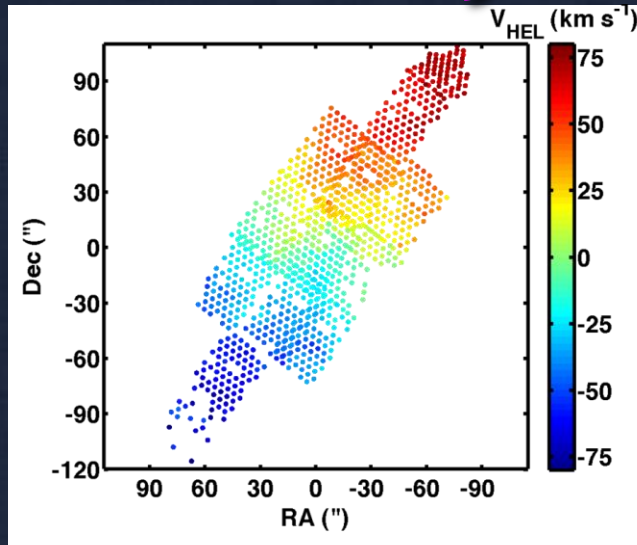
movie courtesy of Lucio Mayer

Measuring Density Profiles

- Galaxy rotation curve is determined by a harmonic fit: $V_{\text{obs}} = V_{\text{sys}} + V_{\text{rot}} \cos\Phi + V_{\text{rad}} \sin\Phi$



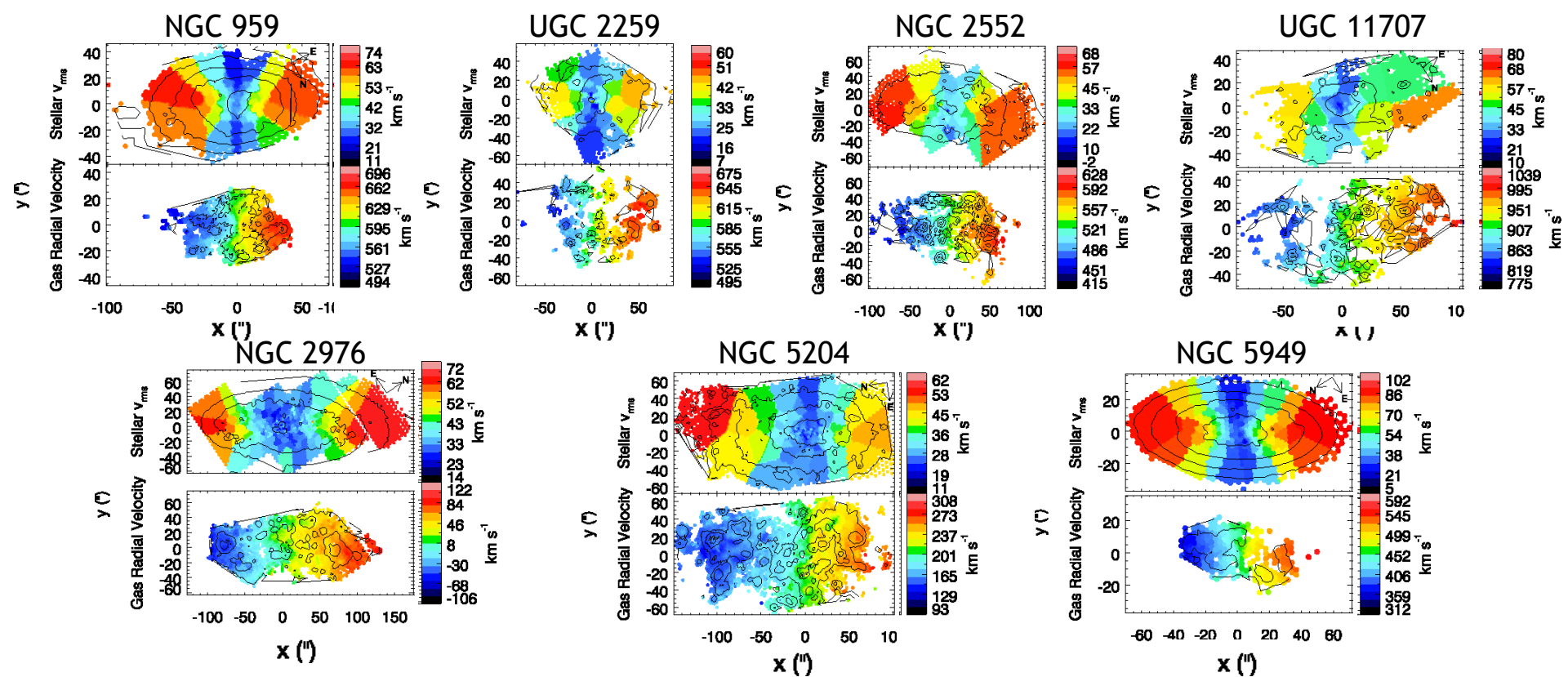
Disk Galaxy Rotation Curves



- Interpretation complicated by:
 - Non-circular motions
 - Bars
 - Unknown stellar M/L
 - Disk geometry (warps, etc.)
 - Adiabatic contraction

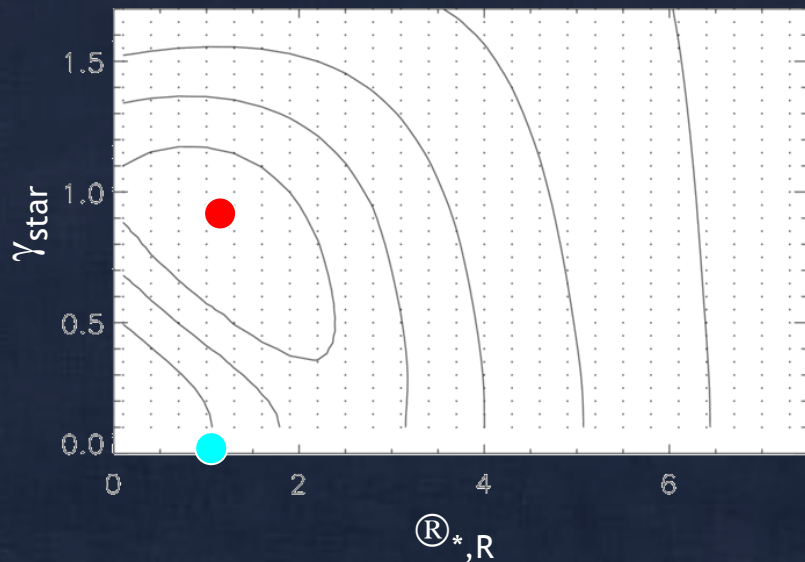
Simon et al. (2003, 2005)
Kuzio de Naray et al. (2006, 2008)
(2011) Oh et al.

Stellar + Gas Velocity Fields of 7 Dwarfs



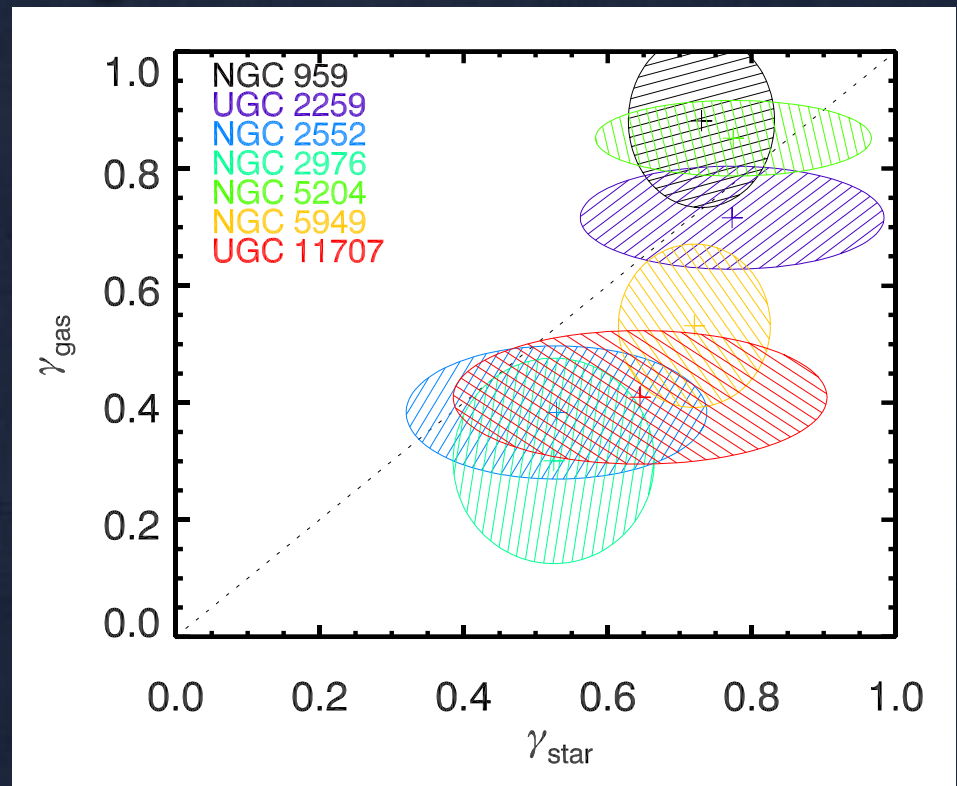
Stars vs. Gas

- Initial suggestions of disagreement between stars and gas, now resolved



Adams et al. (2012) - stars

Simon et al. (2003) - gas

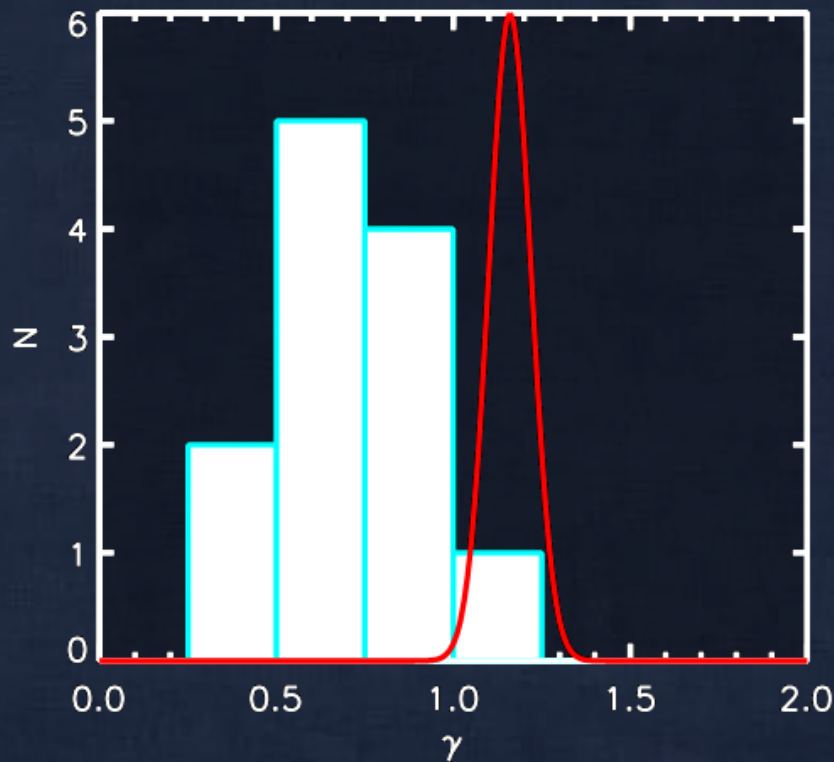


Adams et al. (2014)

Stars vs. Gas

- $\gamma_{\text{star}} = 0.68$
standard error on the mean: 0.06
standard deviation 0.10
- $\gamma_{\text{gas}} = 0.67$
standard error on the mean: 0.04
standard deviation 0.24
- What does the difference in standard deviations mean?

Observed Distribution of Central Slopes



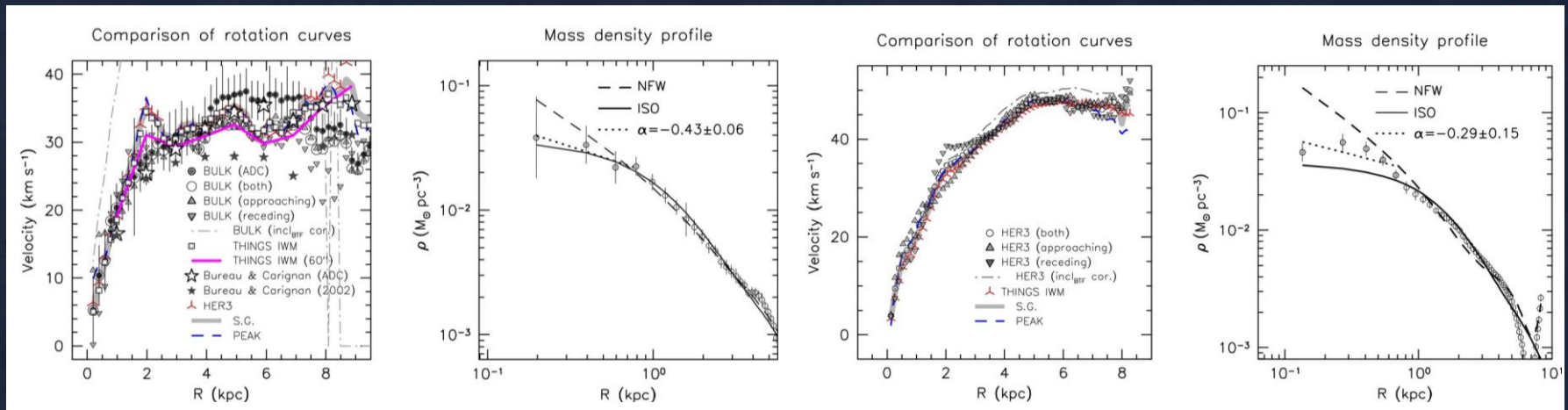
Galaxy sample: Adams et al. (2014) + Simon et al. (2005) + Oh et al. (2011)

Simulations: Diemand et al. (2004)

Average DM profile has $\odot = 0.63 \pm 0.28$

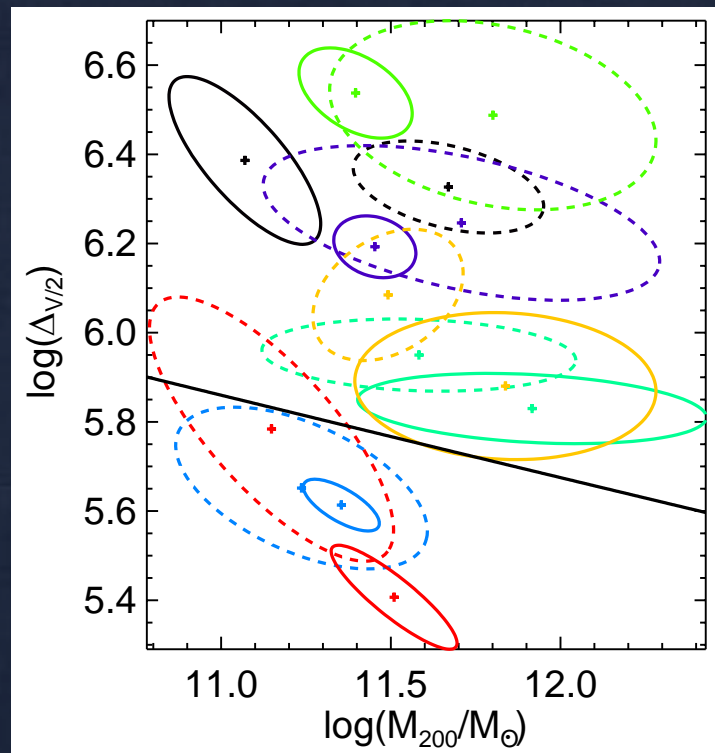
Observed Distribution of Central Slopes

- Significantly steeper than previous results: $\alpha = 0.29 \pm 0.07$



Central Mass, Not Density Profile?

- Mass enclosed may be more robust than inner density profile slope



Future Outlook

- Survey of 25 galaxies in H α (Palomar) and CO (CARMA) is underway
 - Will provide best available constraints on distribution of γ
 - Test predictions of different models to explain non-CDM slopes
- Still unclear whether $\gamma < 1$ is because of DM properties or baryonic physics

Metal-Poor Stars in Dwarf Galaxies

- Unraveling the formation of the Milky Way halo
 - Are present-day dwarfs similar to the building blocks of the halo? (Robertson et al. 2005; Frebel, Kirby, & Simon 2010)
- The first stars
 - Dwarf galaxies may be the best places to look for the most metal-poor stars (Kirby et al. 2008; Muñoz et al. 2009; Frebel, Simon et al. 2010)
- Nucleosynthesis and chemical evolution in the early universe (Koch et al. 2008; Simon et al. 2010; Frebel et al. 2014; Simon et al. 2014)

Where Do $[\text{Fe}/\text{H}] < -3$ Stars Live?

- Milky Way bulge: ?? (Tumlinson 2010)

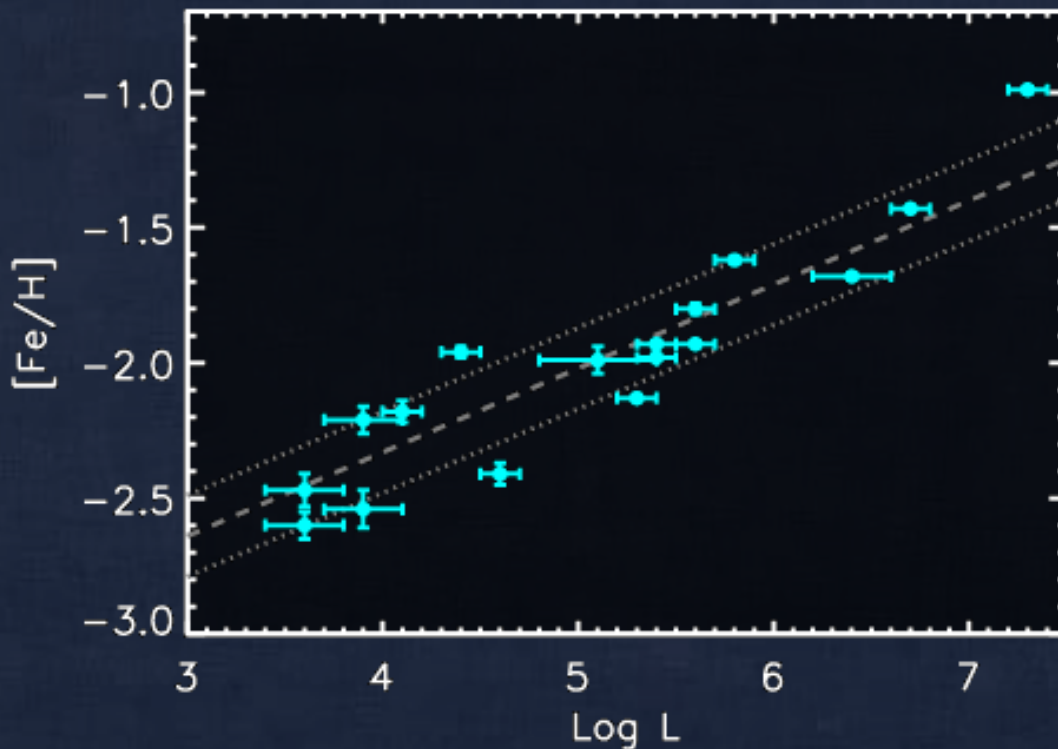
Where Do $[Fe/H] < -3$ Stars Live?

- Simulations predict that the oldest stars are near the center of the Galaxy



A Hint

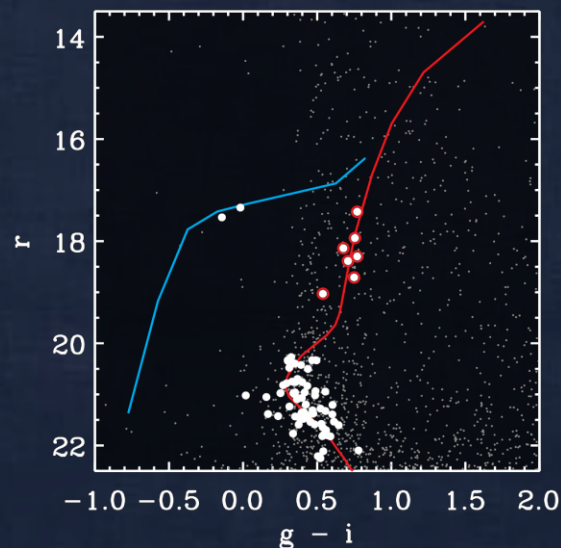
- Metallicity-luminosity relationship



- Faint dwarfs \neq tidally-stripped bright dwarfs
- Stars know what luminosity system they live in

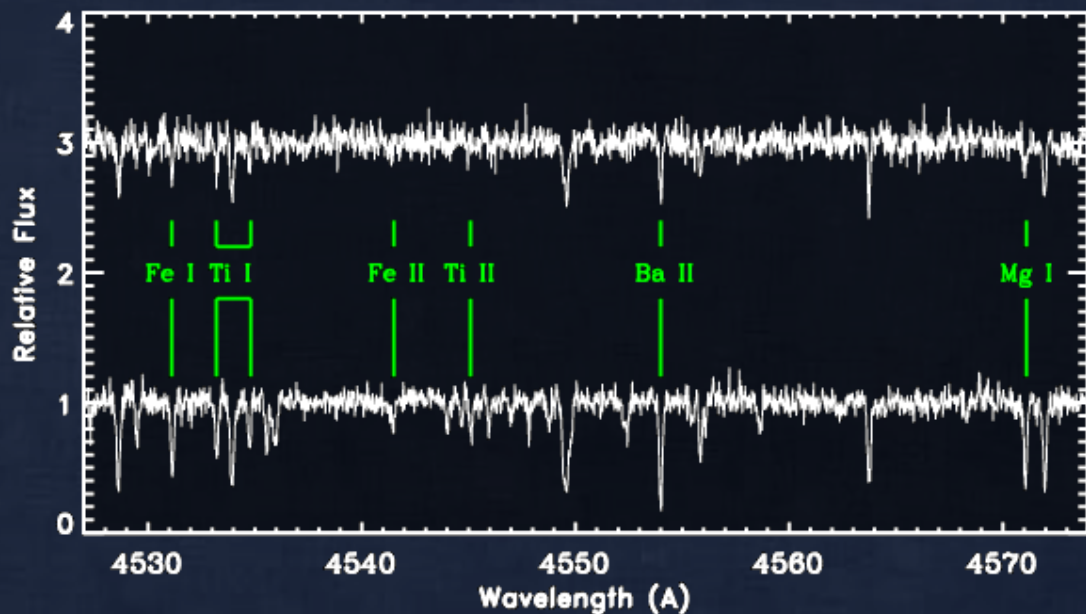
Where Do $[Fe/H] < -3$ Stars Live?

- Milky Way halo: $< 1\%$ (Schörck et al. 2009)
- $M_V < -8$ dwarfs: 1-5% (Starkenburg et al. 2010)
- $M_V > -8$ ultra-faint dwarfs: $> 10\%$ (Simon et al. 2010)
- Segue 1 ($M_V = -1.5$): 42% (Frebel et al. 2014)



Measuring Abundances in Dwarfs

- High-resolution spectroscopy
 - Accurate abundances for many elements
 - Requires bright targets + long integrations



← $[\text{Fe}/\text{H}] = -3.24$

$V = 17.4$, $t_{\text{exp}} = 3 \text{ hr}$

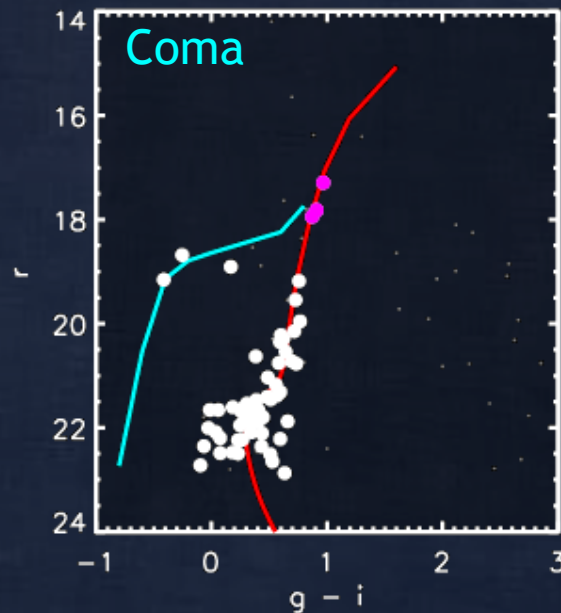
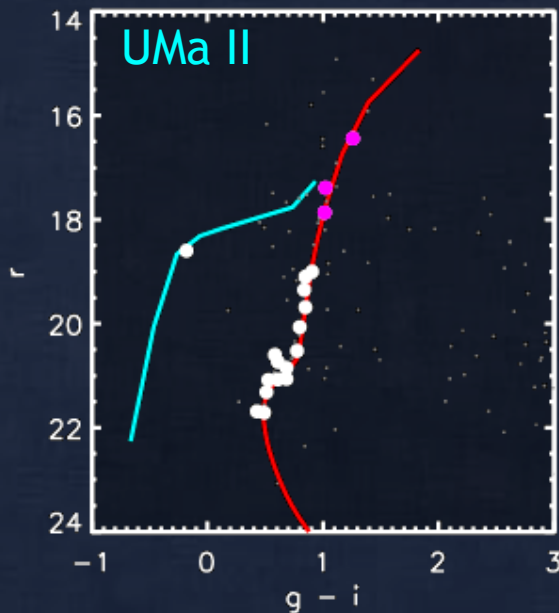
← $[\text{Fe}/\text{H}] = -2.34$

$V = 16.5$, $t_{\text{exp}} = 1 \text{ hr}$

Frebel et al. (2010)

Measuring Abundances in Dwarfs

- High-resolution spectroscopy
 - Accurate abundances for many elements
 - Requires bright targets + long integrations

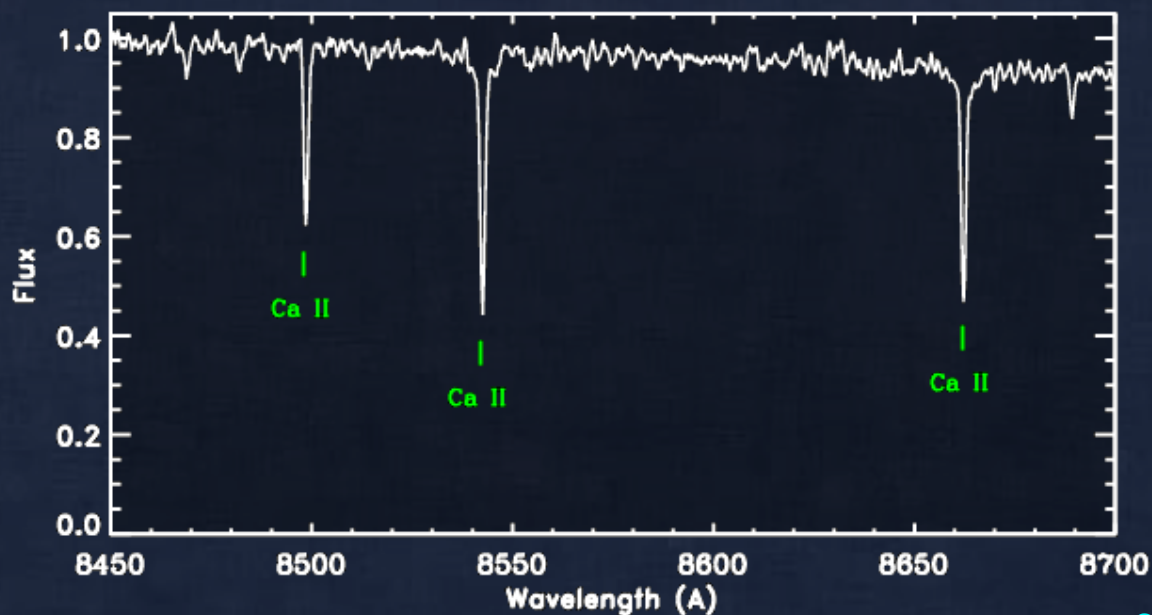


- members
- HIRES targets
- nonmembers

Measuring Abundances in Dwarfs

- Ca triplet (CaT)

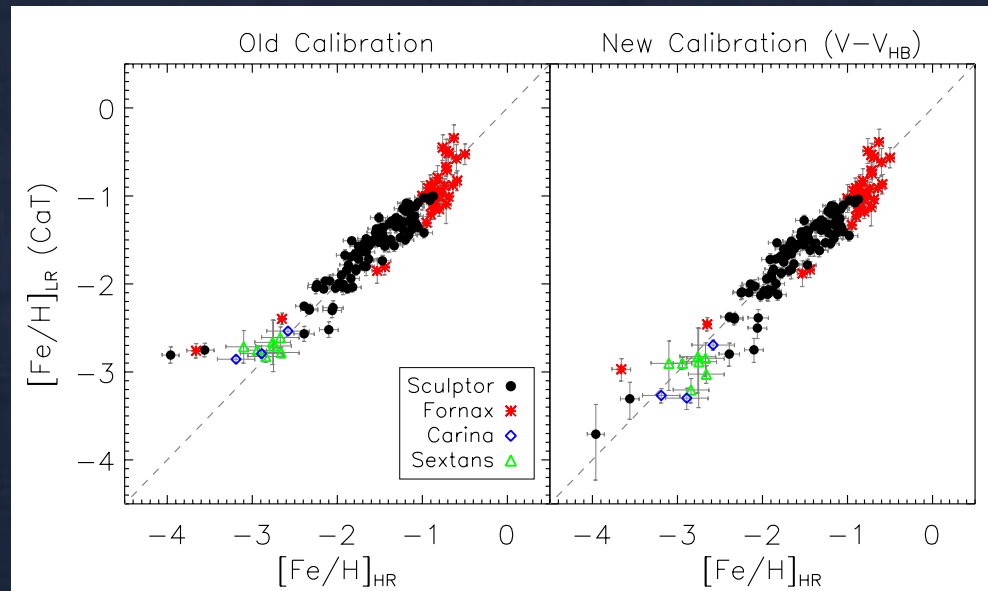
- Requires only low/medium resolution spectroscopy
- Can be used for much fainter stars!



e.g., Rutledge et al. (1997)

The CaT at Low Metallicity

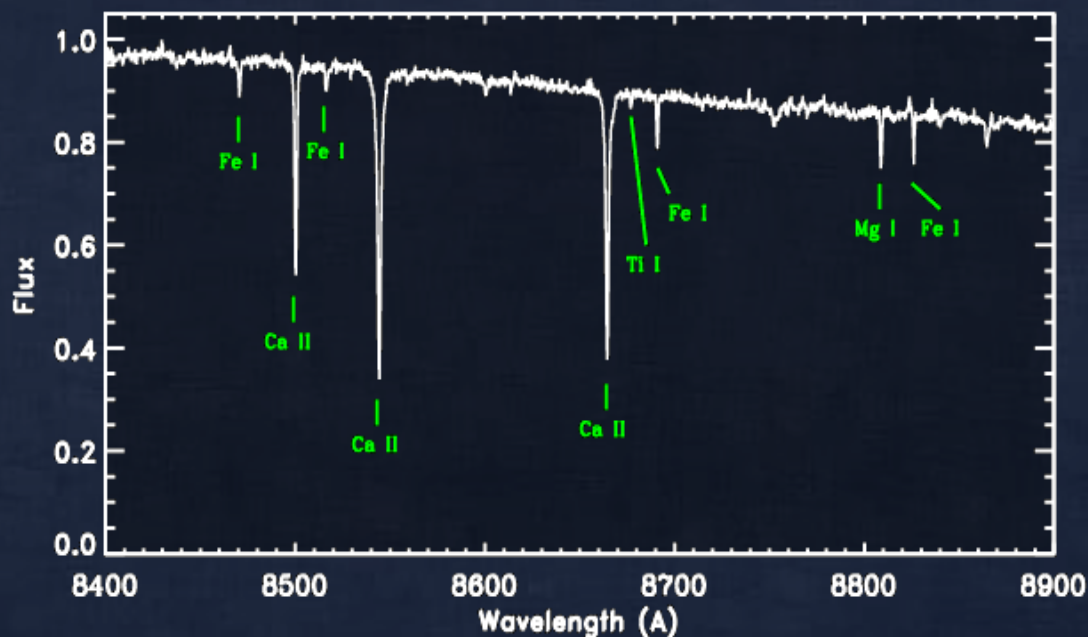
- Early calibrations biased against metal-poor ($[\text{Fe}/\text{H}] < -2.5$) stars
- Starkenburg et al. (2010) fixed this, but uncertainties are still large



Starkenburg et al. (2010)

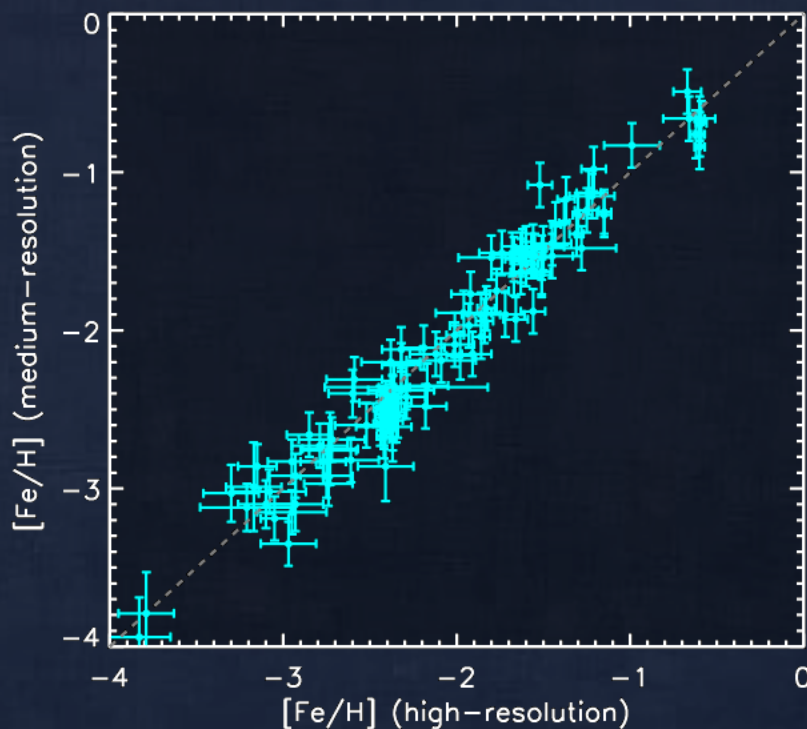
Measuring Abundances in Dwarfs

- Spectral synthesis with medium resolution spectroscopy
 - Lots of lines other than the CaT in R=6000 spectra



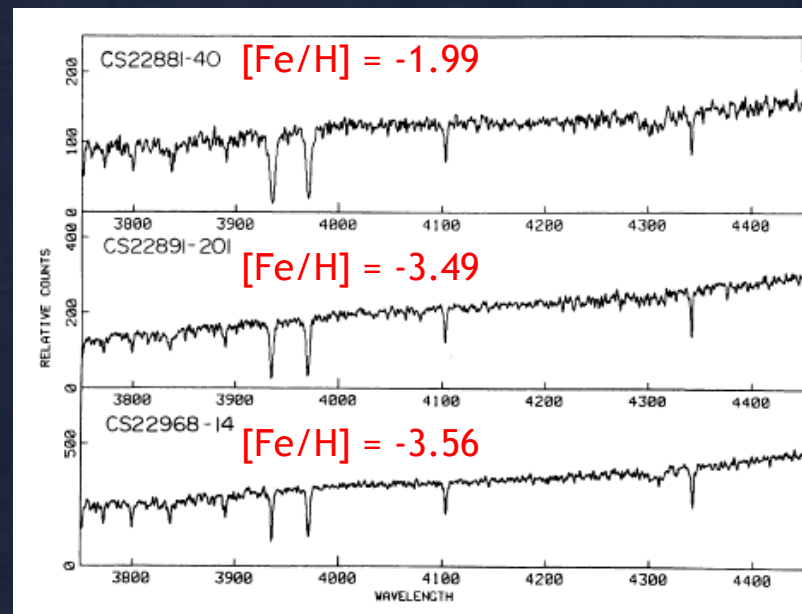
Measuring Abundances in Dwarfs

- Spectral synthesis with medium resolution spectroscopy



Finding the Most Metal-Poor Stars

- Ca triplet - uncertainties at low metallicity
- Spectral synthesis - requires large λ range
- Ca K - just right



Beers et al. (1985)

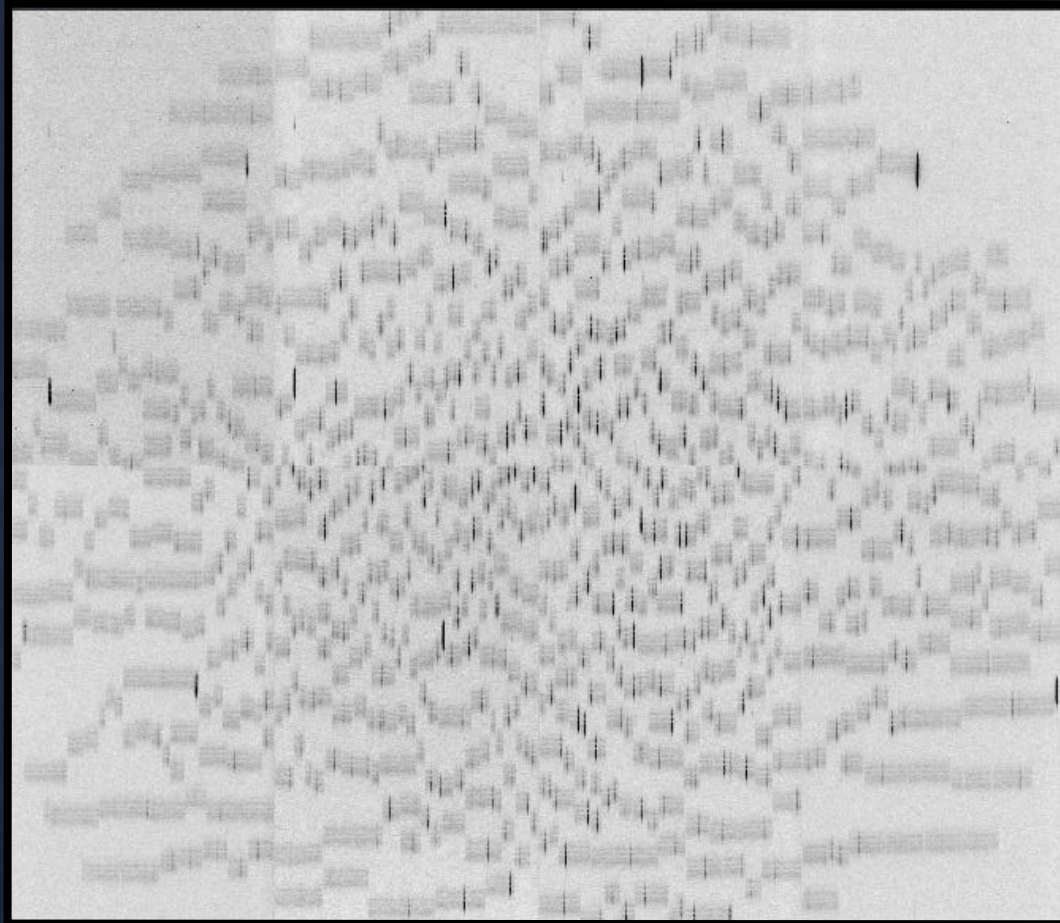
Ca K Survey

- Complete, magnitude limited survey (to $V \sim 20$) of southern dSphs
- Uses IMACS spectrograph at Magellan



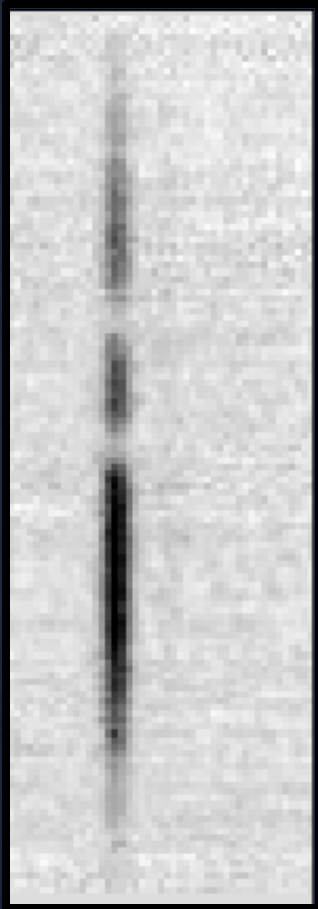
CCKSUMOMPSDG

(Complete Ca K SURvey for the MOst Metal-Poor Stars in
Dwarf Galaxies)

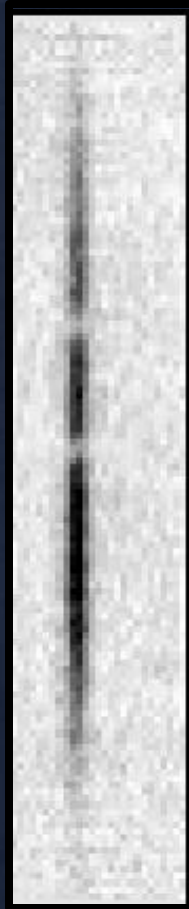


IMACS Survey Data

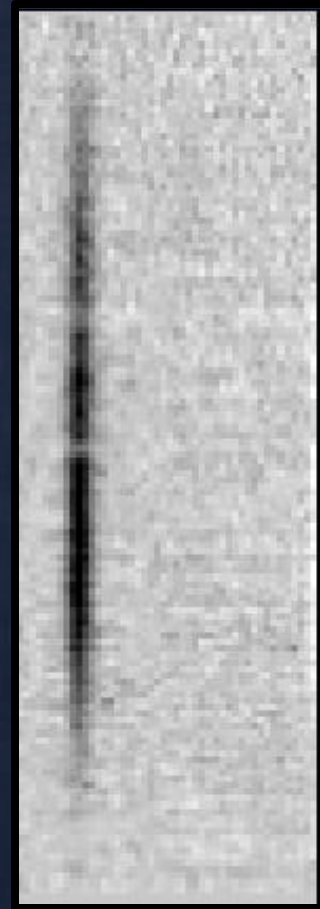
$[\text{Fe}/\text{H}] = -1.5$



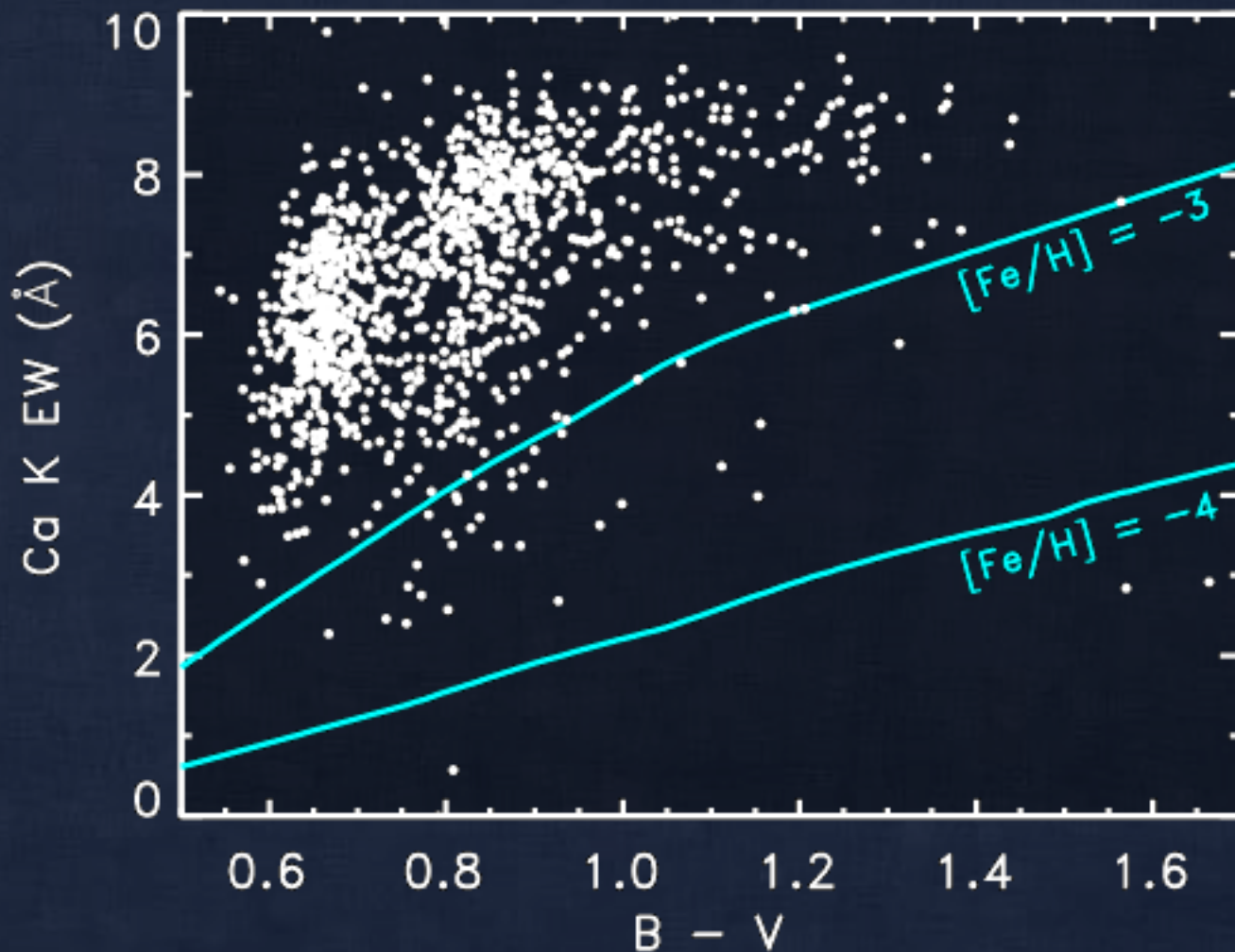
$[\text{Fe}/\text{H}] = -2.5$



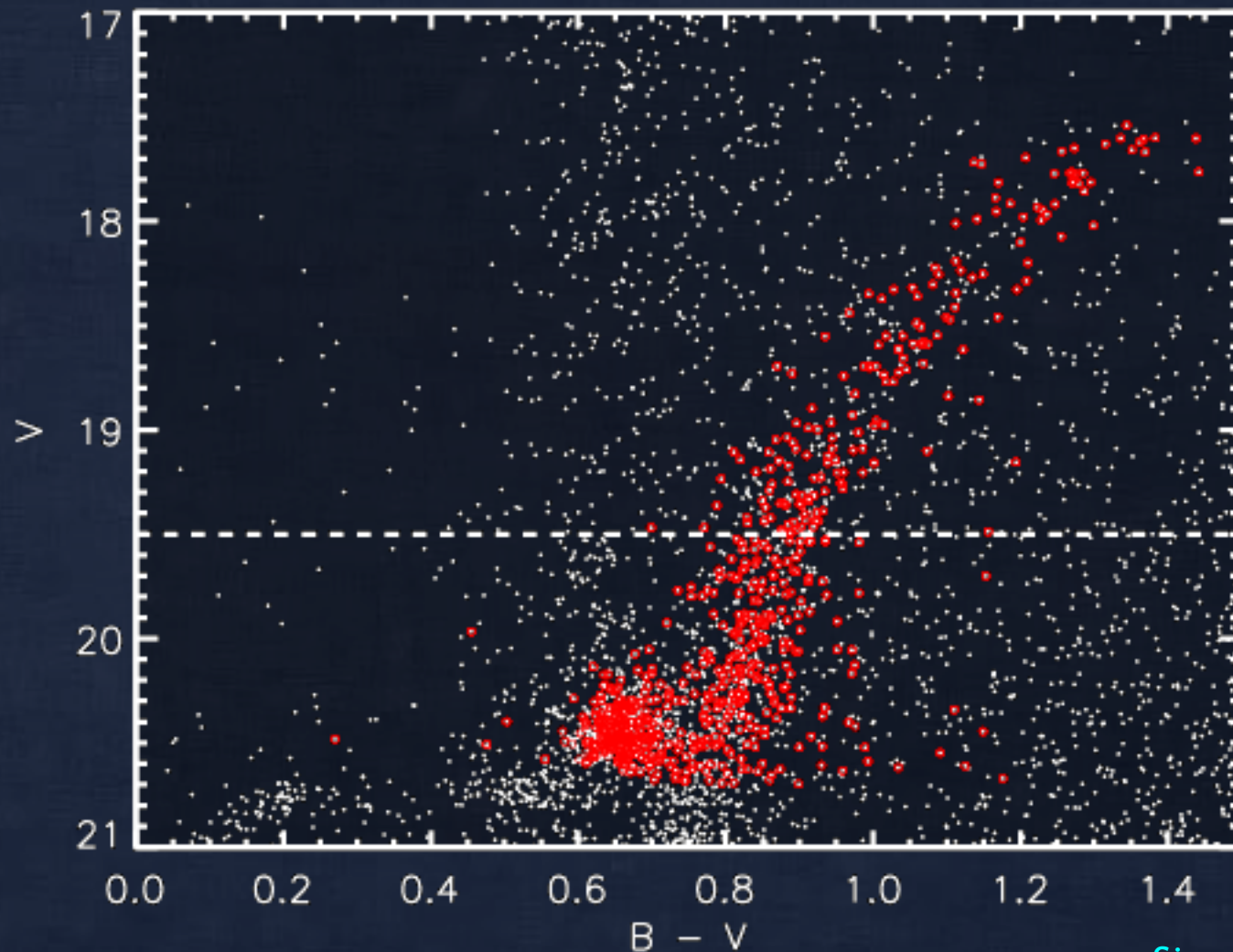
$[\text{Fe}/\text{H}] = -3.8$



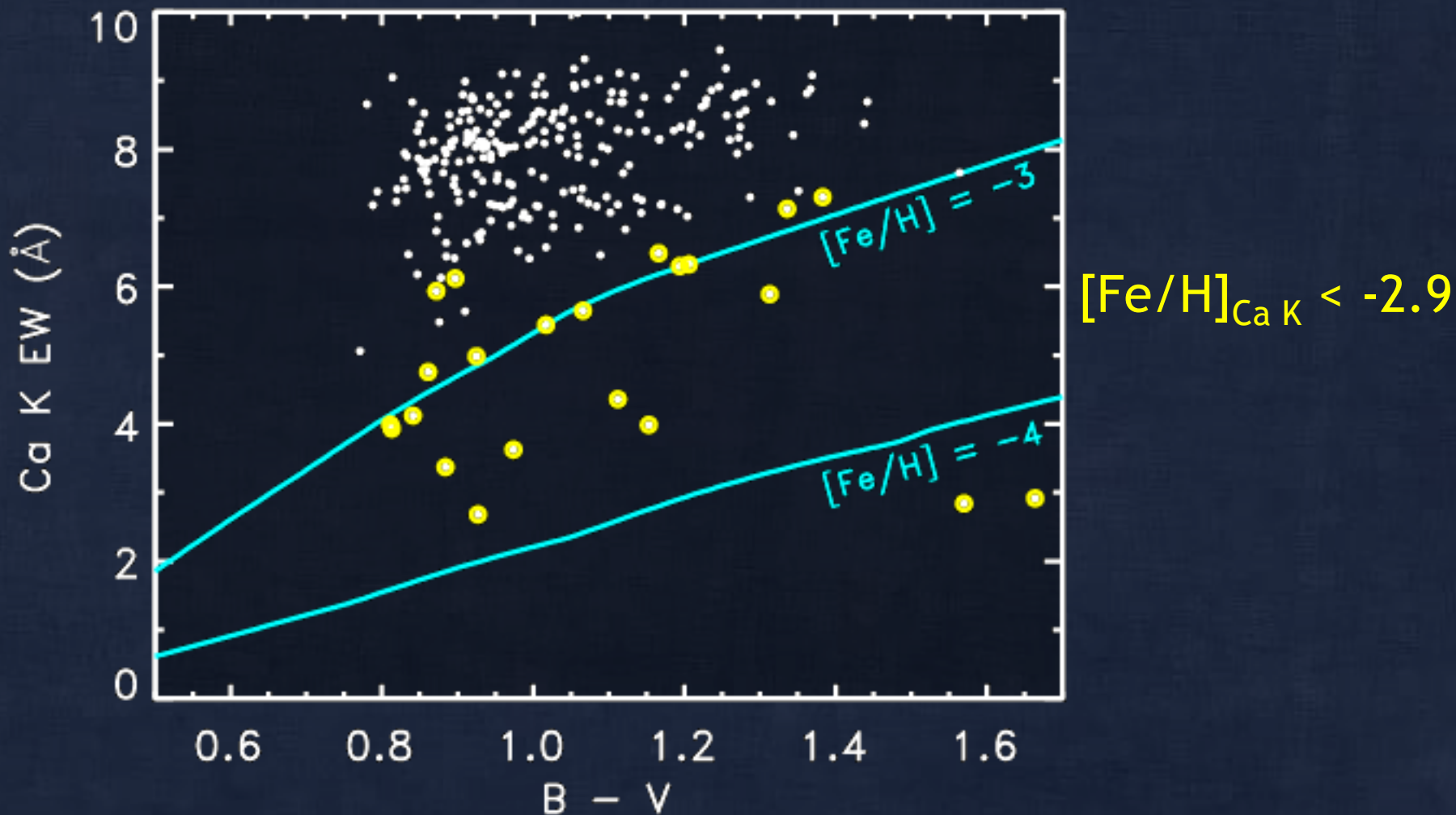
Survey of 1200 Stars in Carina



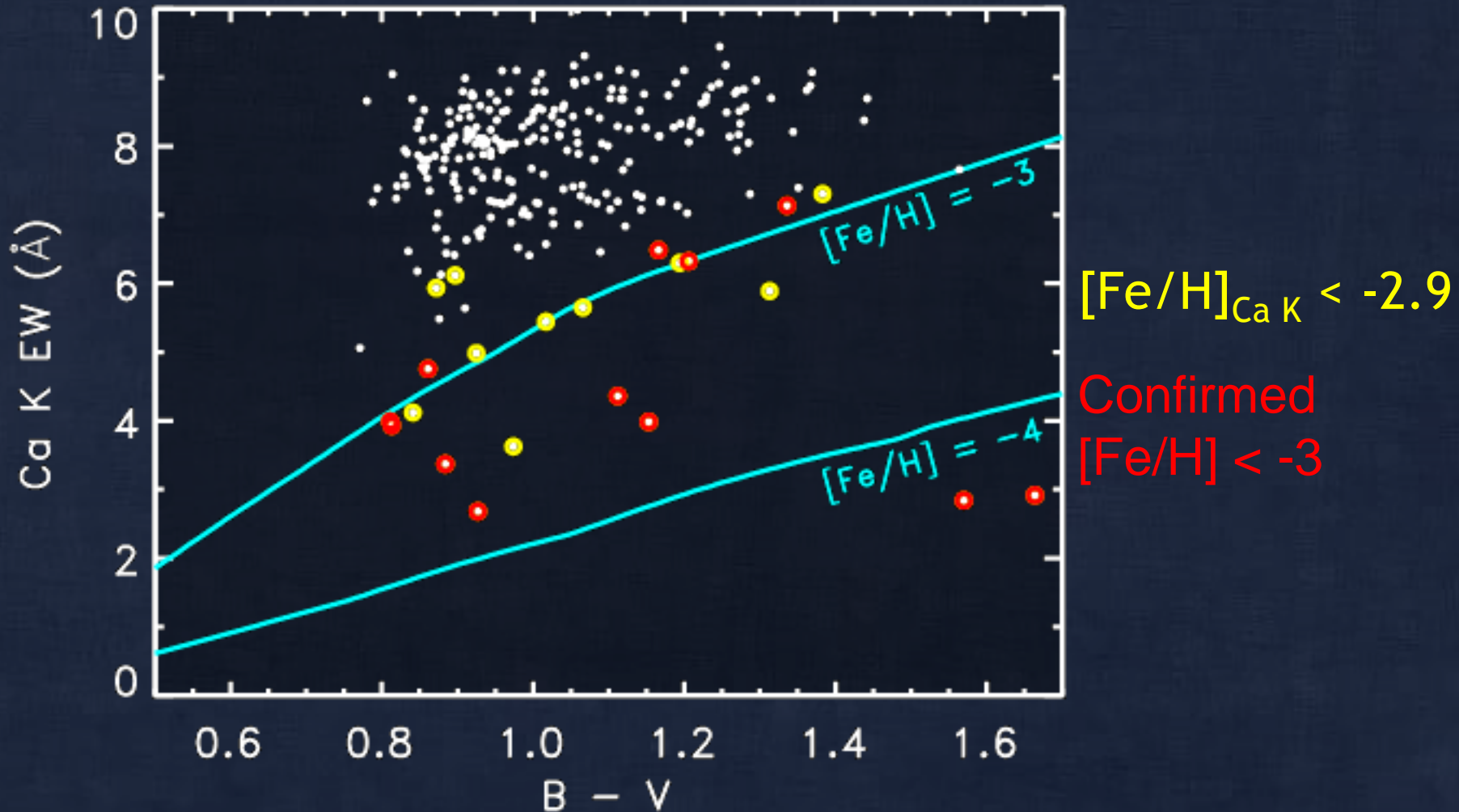
Survey of 1200 Stars in Carina



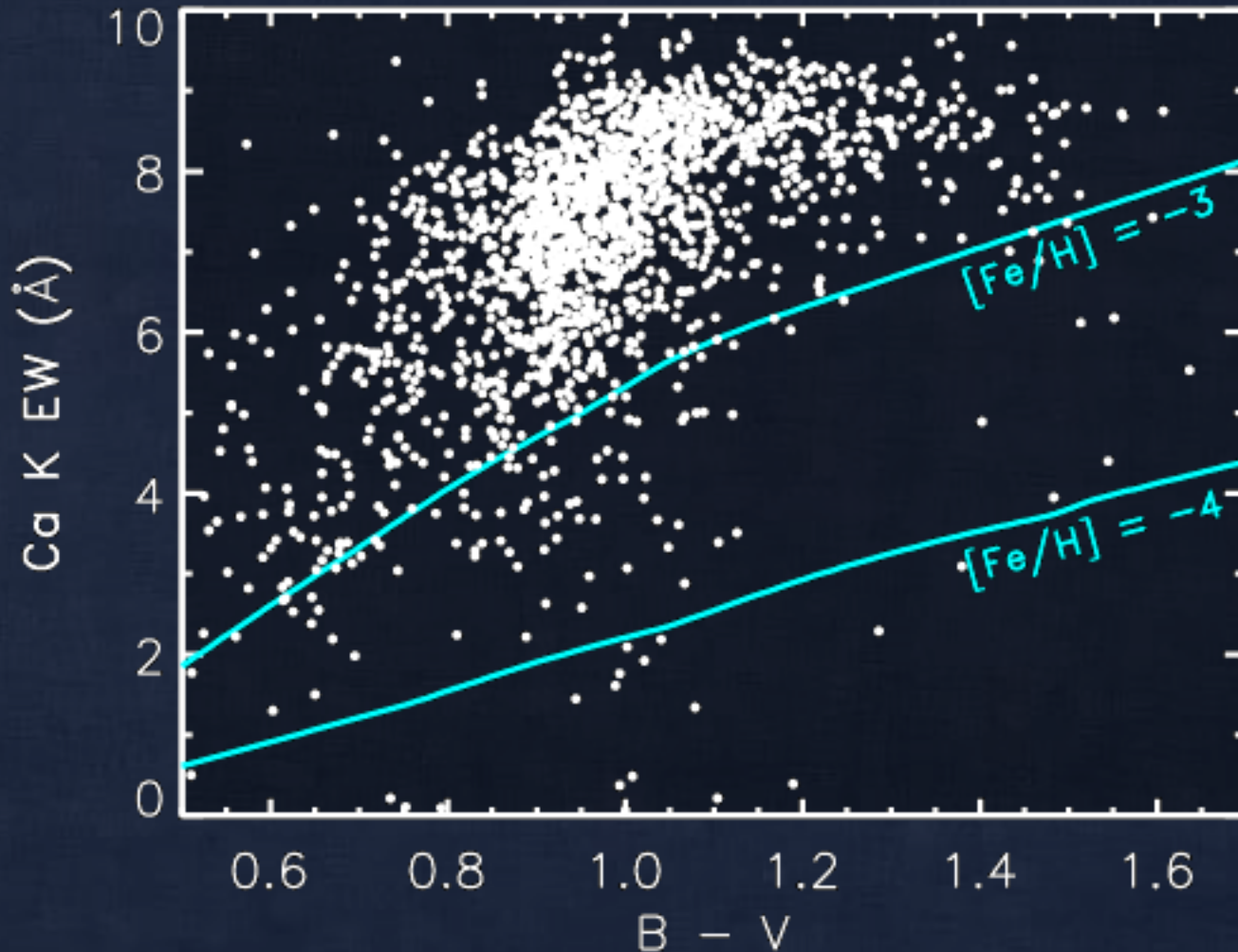
Bright ($V < 19.5$) Stars in Carina



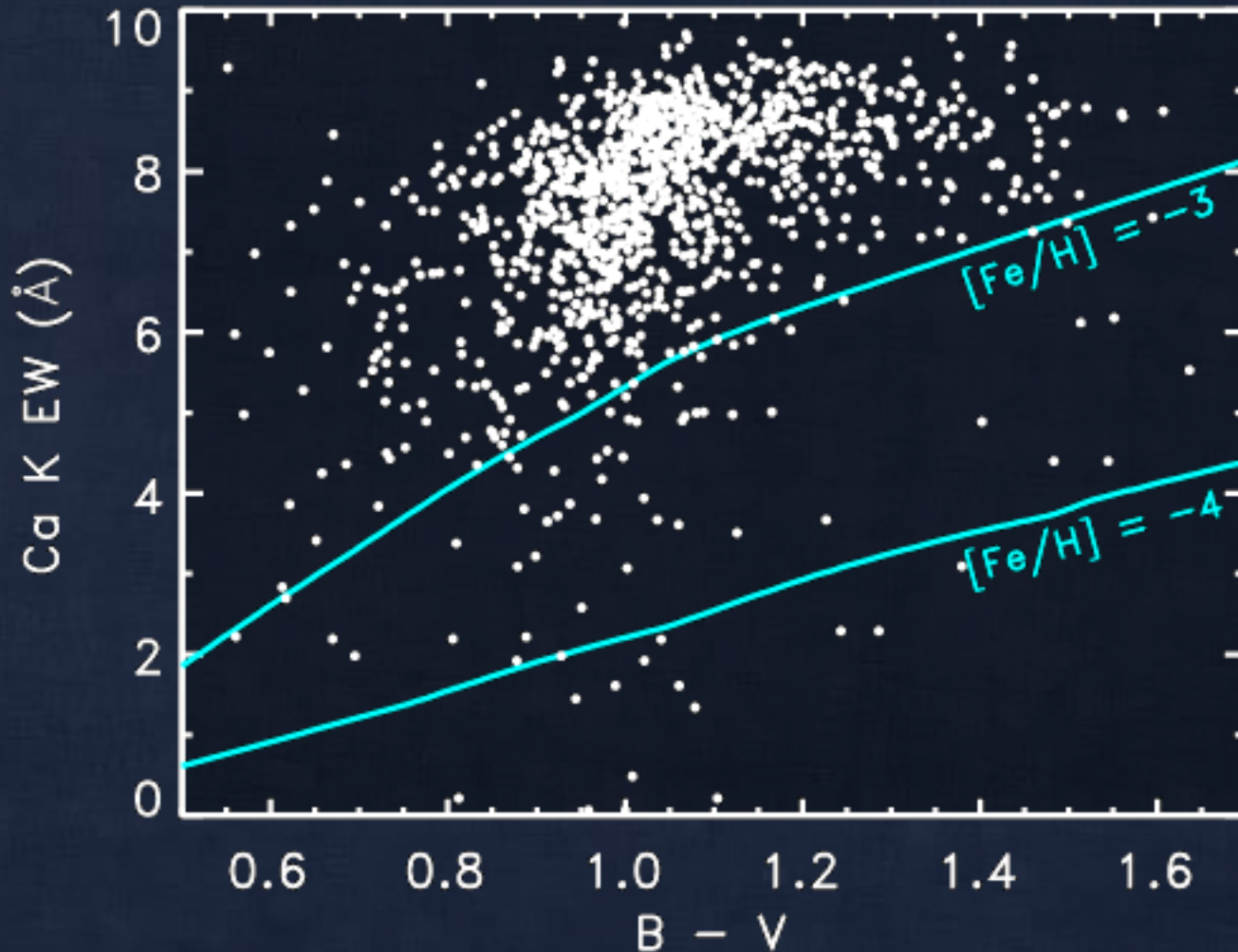
Confirmed EMP Stars in Carina



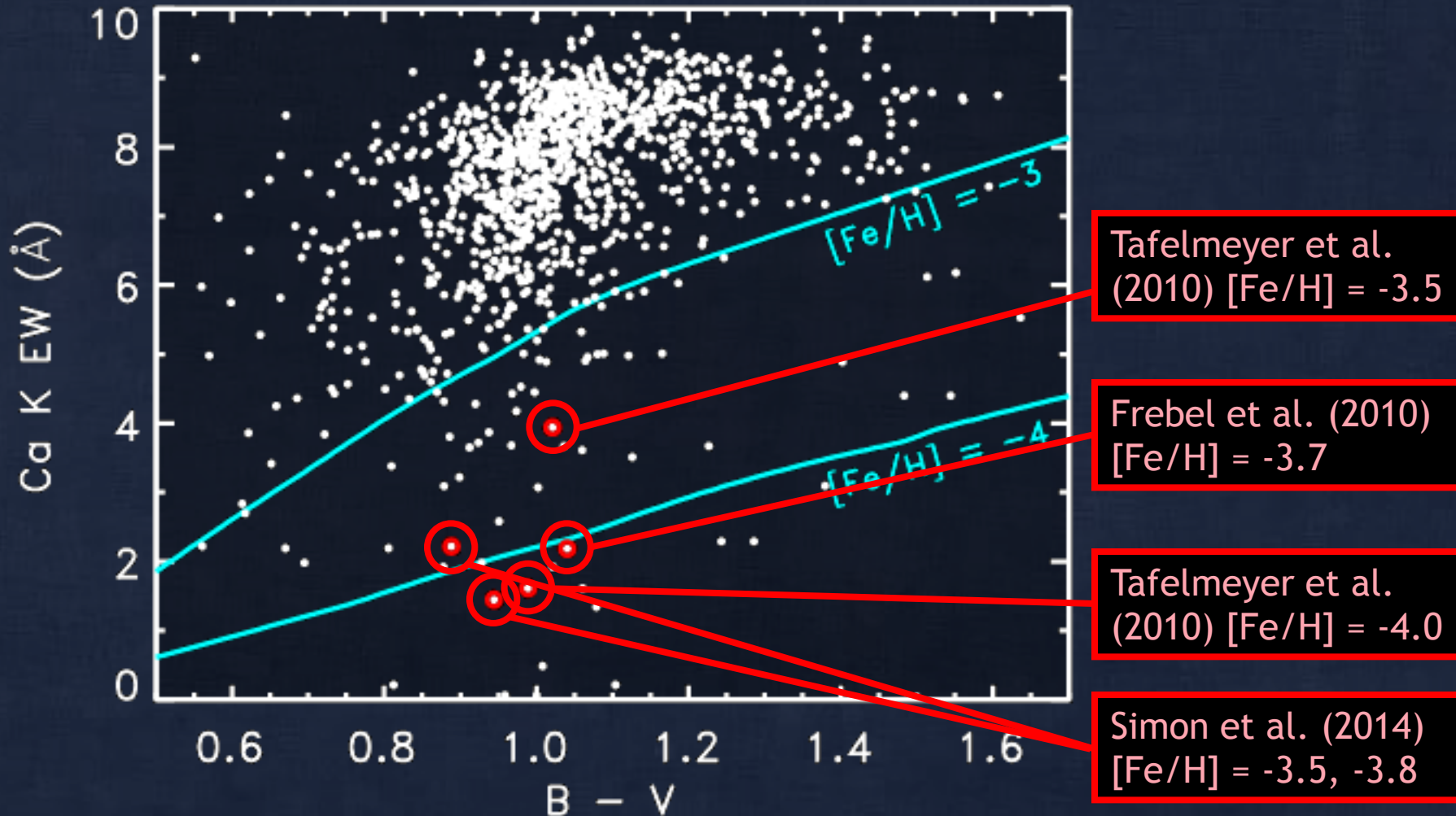
1800 Stars in Sculptor



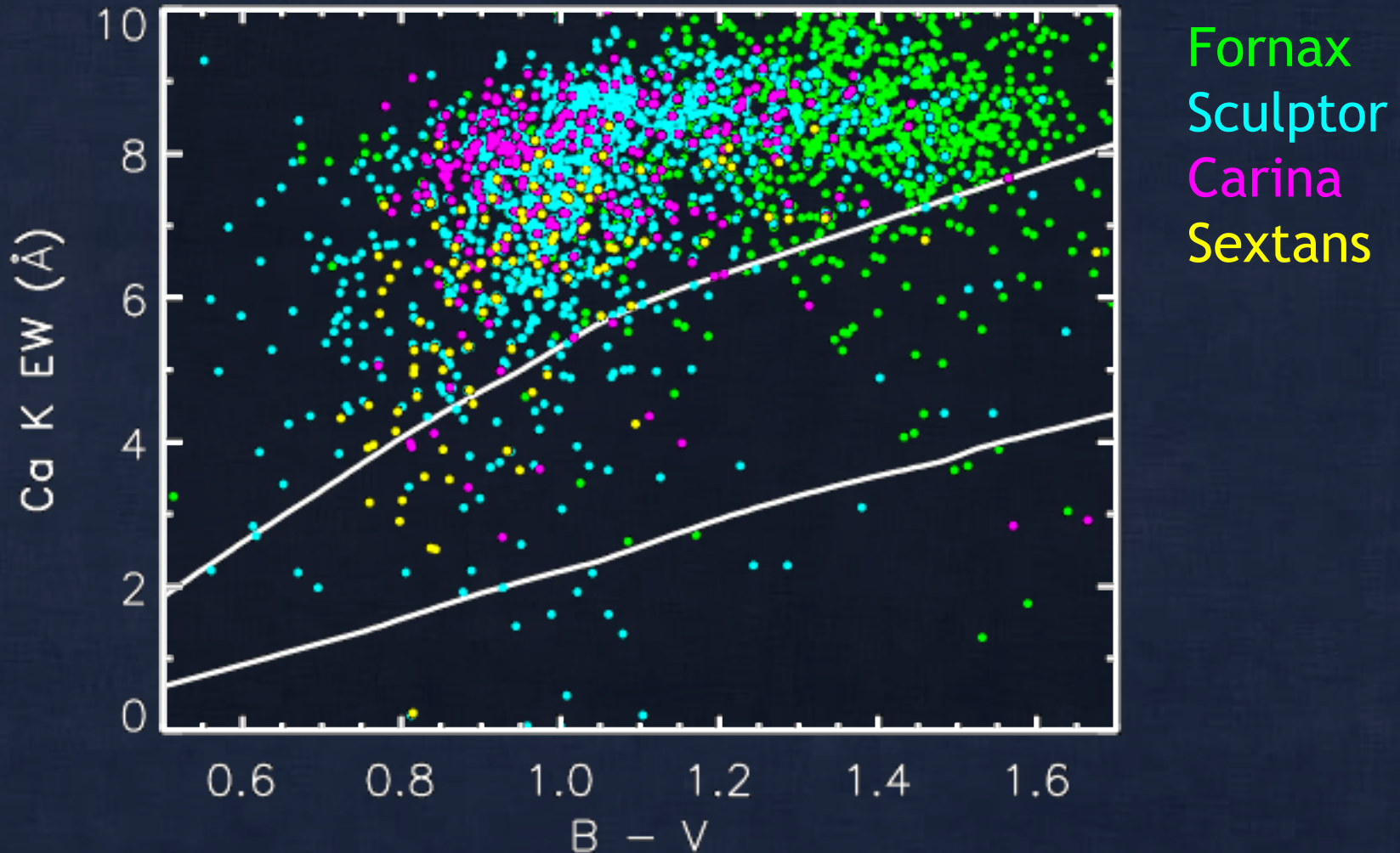
Bright ($V < 19.5$) Stars in Sculptor



Bright ($V < 19.5$) Stars in Sculptor

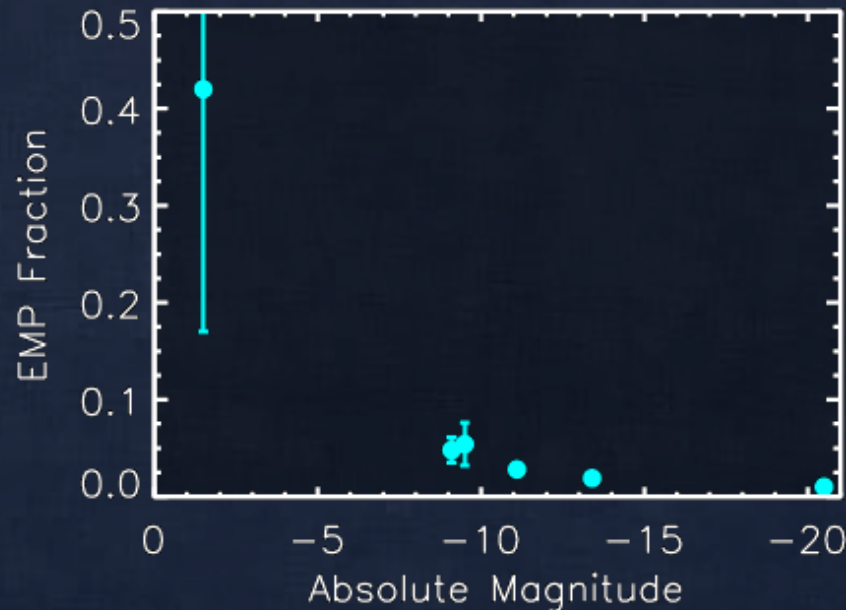


Full Survey ($V < 19.5$ Only)



EMP Fractions

- ~3% of stars in Sculptor have $[\text{Fe}/\text{H}] < -3$
- ~5% in Carina
- ~5% in Sextans



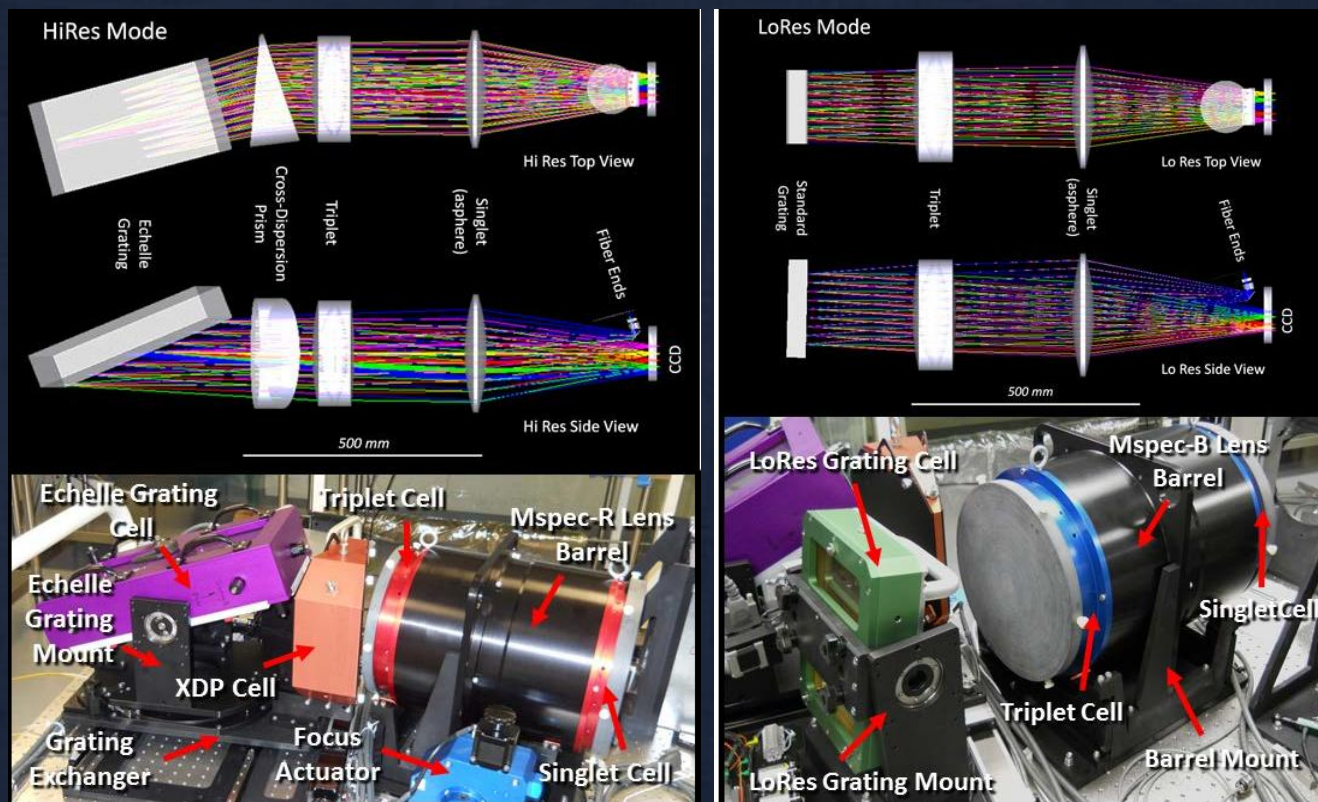
Survey Status

- >1850 stars in Sculptor (513 in Helmi et al. 2006)
- 2912 stars in Fornax (933 in Helmi et al. 2006)
- 1209 stars in Carina (437 in Koch et al. 2006)
 - Medium-resolution follow-up completed to $V=19.5$
- 794 stars in Sextans (202 in Helmi et al. 2006)

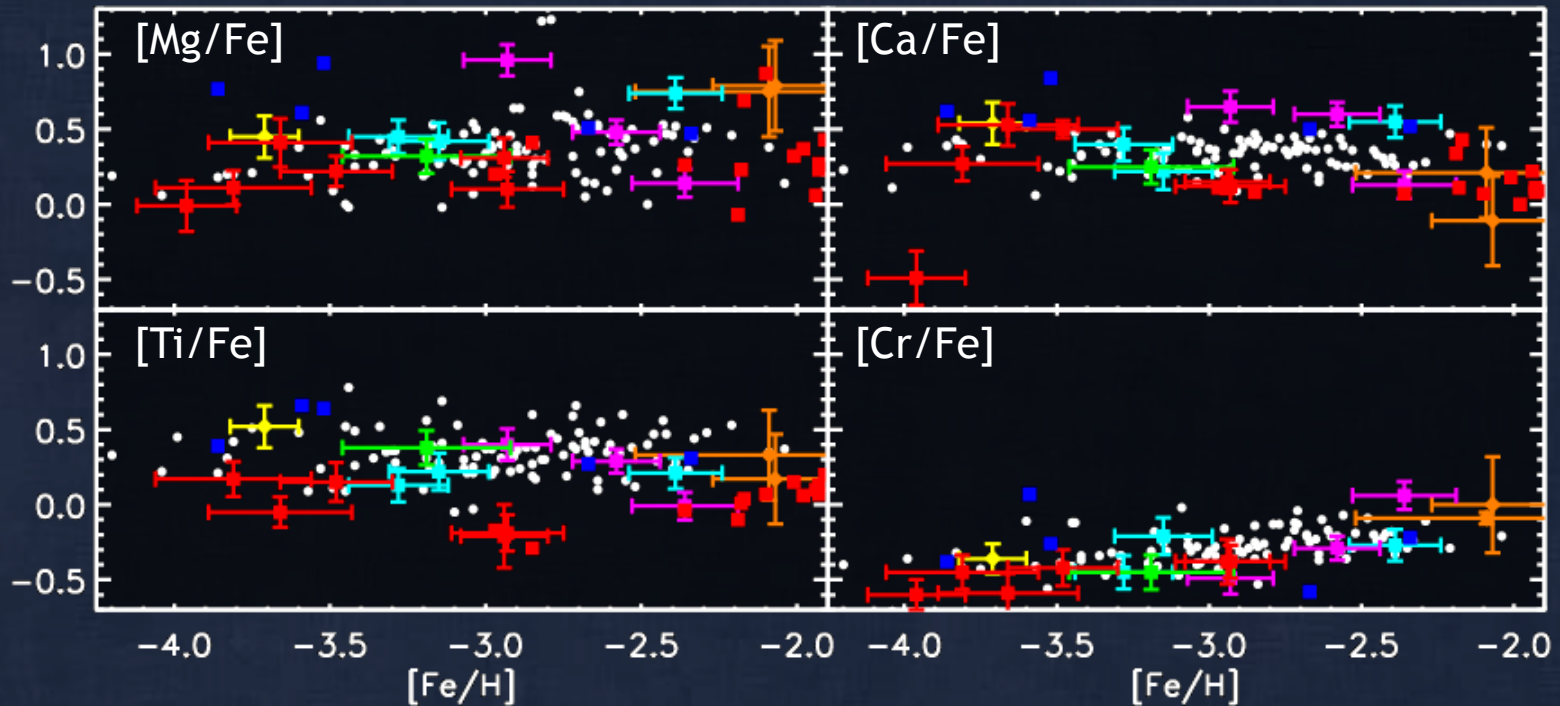
[Fe/H] < -3 stars confirmed in all four galaxies

Michigan/Magellan Fiber System

- New 256 fiber spectrograph at Magellan



Universal Early Chemical Evolution?

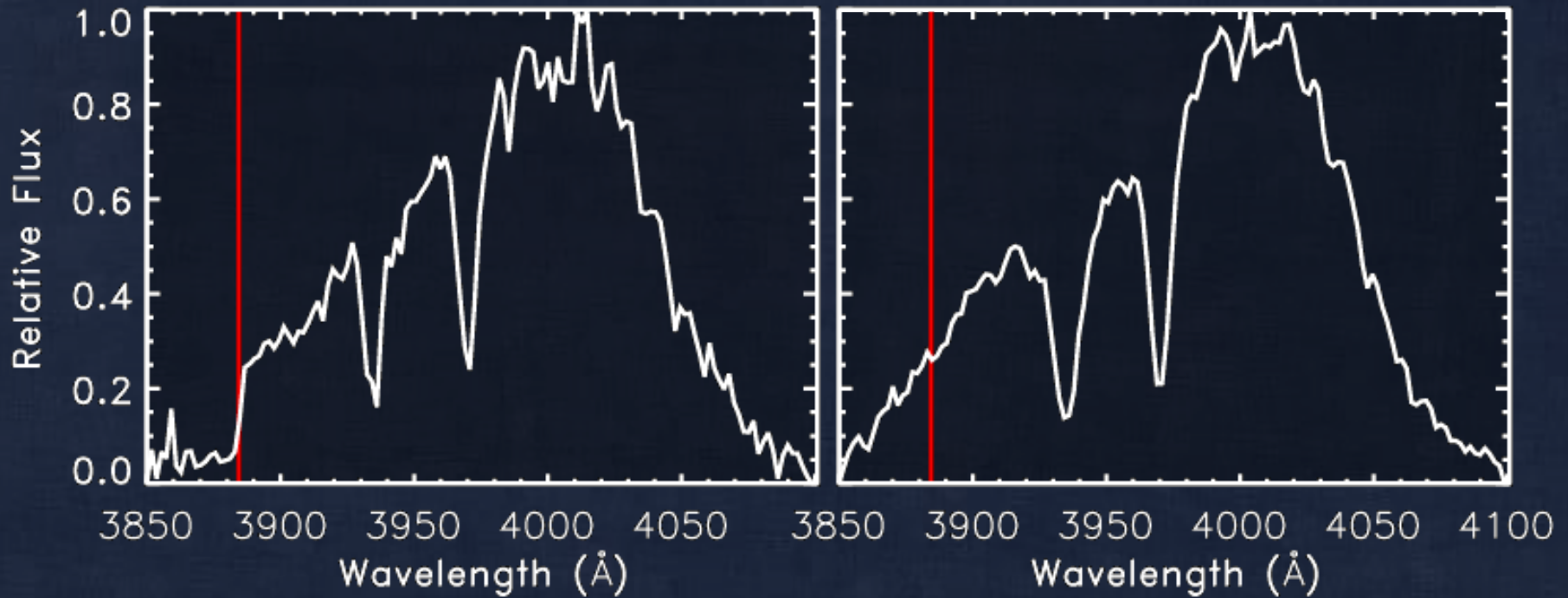


$M_V = -20.5$	$M_V = -5.7$
$3.9 < M_V < -14$	$M_V = -$
$M_V = -6.6$	$M_V = -$
$M_V = -6.3$	$M_V = -$

Data from Cayrel, Frebel, Norris, Shetrone, Simon, etc.

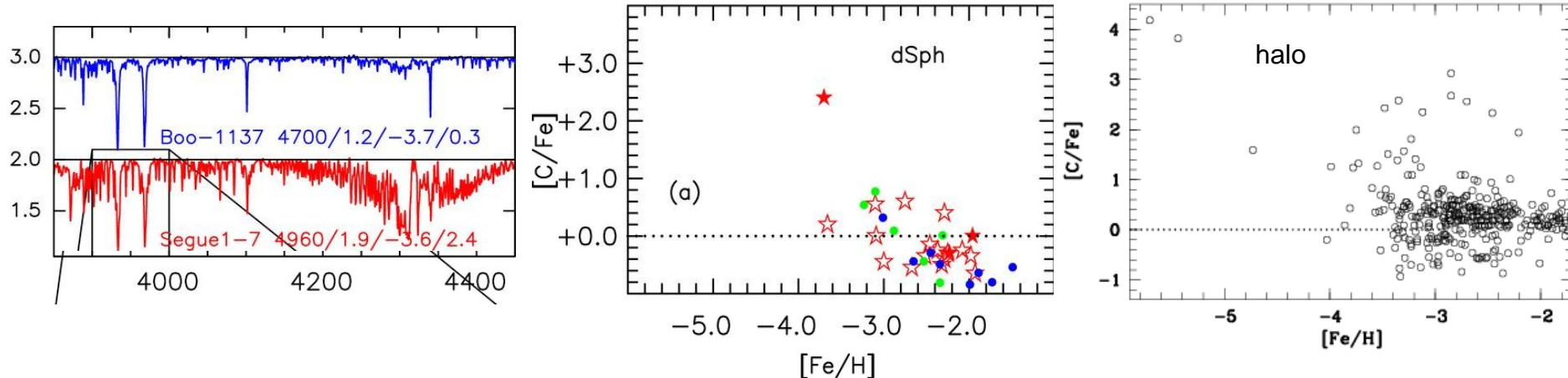
Carbon-Enhanced Stars in CCKSU...

- CN bandhead at 3883 Å



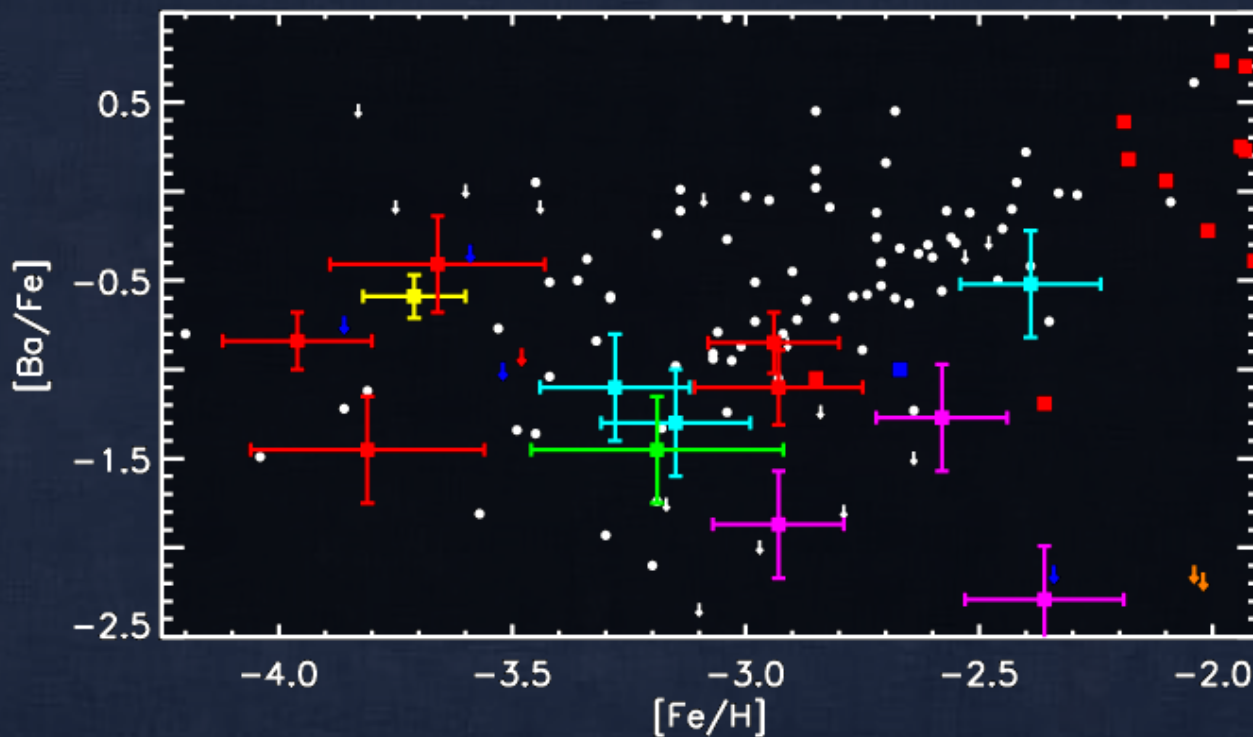
Carbon-Enhanced Stars in CCKSU...

- 20% of metal-poor halo stars are carbon-enhanced (Cohen et al. 2005; Frebel et al. 2006)
- Fewer in dSphs? (Starkenburg et al. 2013)



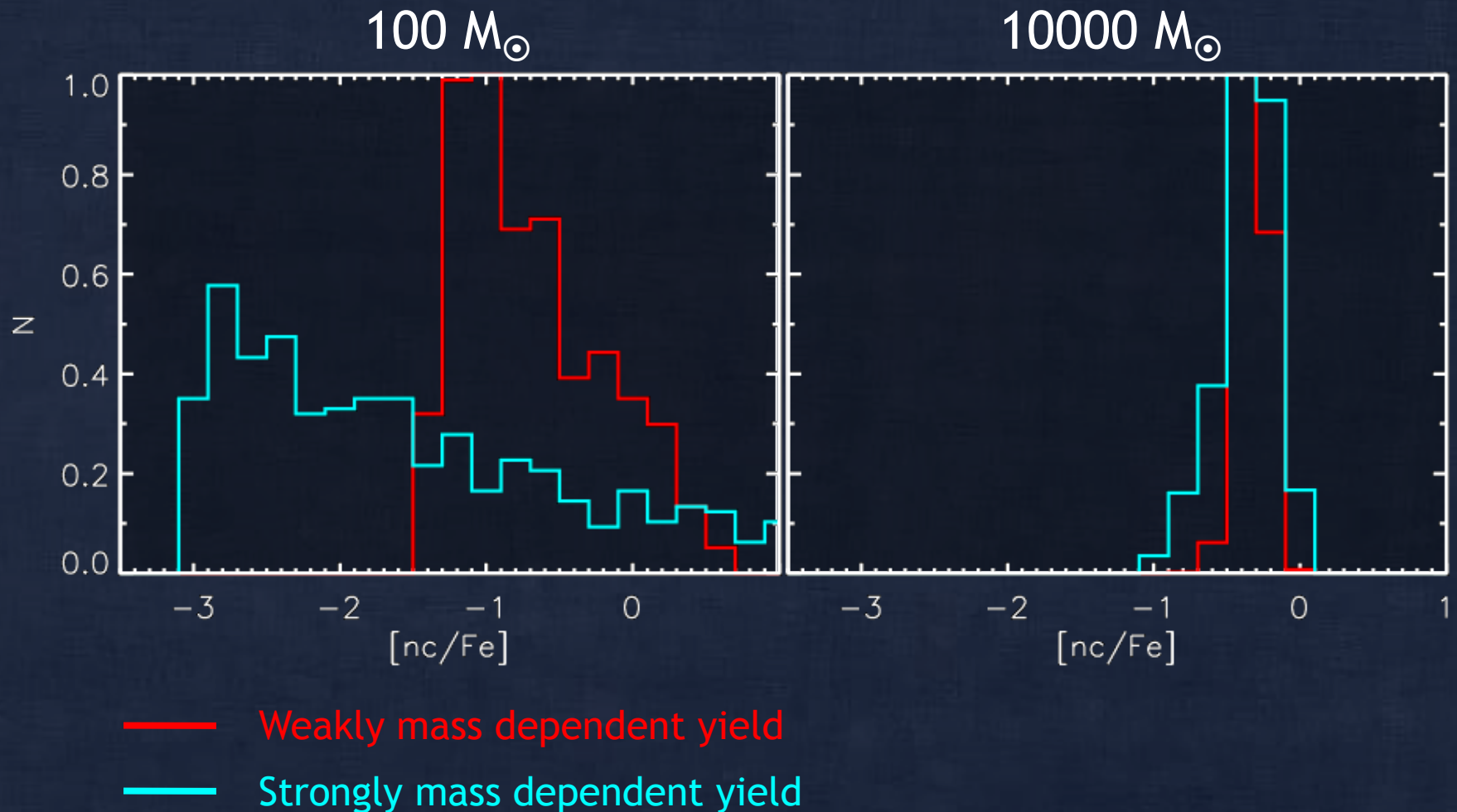
Norris et al. (2010); Frebel & Norris (2012)

The Heaviest Elements

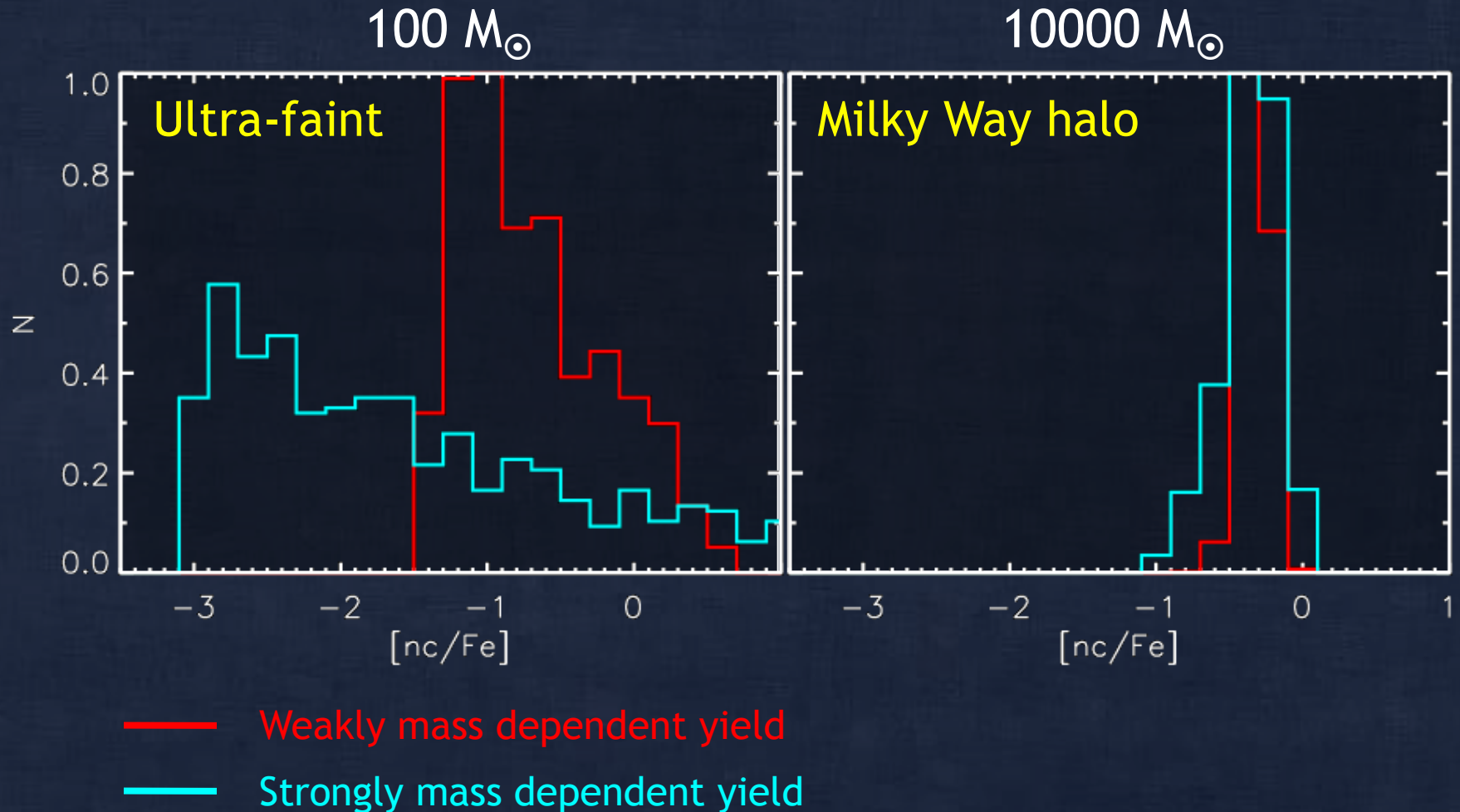


$M_V = -20.5$ (Francois07,
Cohen04,Aoki05,Lai08)
 $-8 < M_V < -14$ (Shetrone/
Frebel10b/Tafelmeyer10)
 $M_V = -6.6$ (Koch08)
 $M_V = -6.3$ (Norris10)
 $M_V = -5.7$ (Simon10)
 $M_V = -3.9$ (Frebel10a)
 $M_V = -3.8$ (Frebel10a)
 $M_V = -1.5$ (Frebel14)

Mass Dependent SN Yields?



Mass Dependent SN Yields?

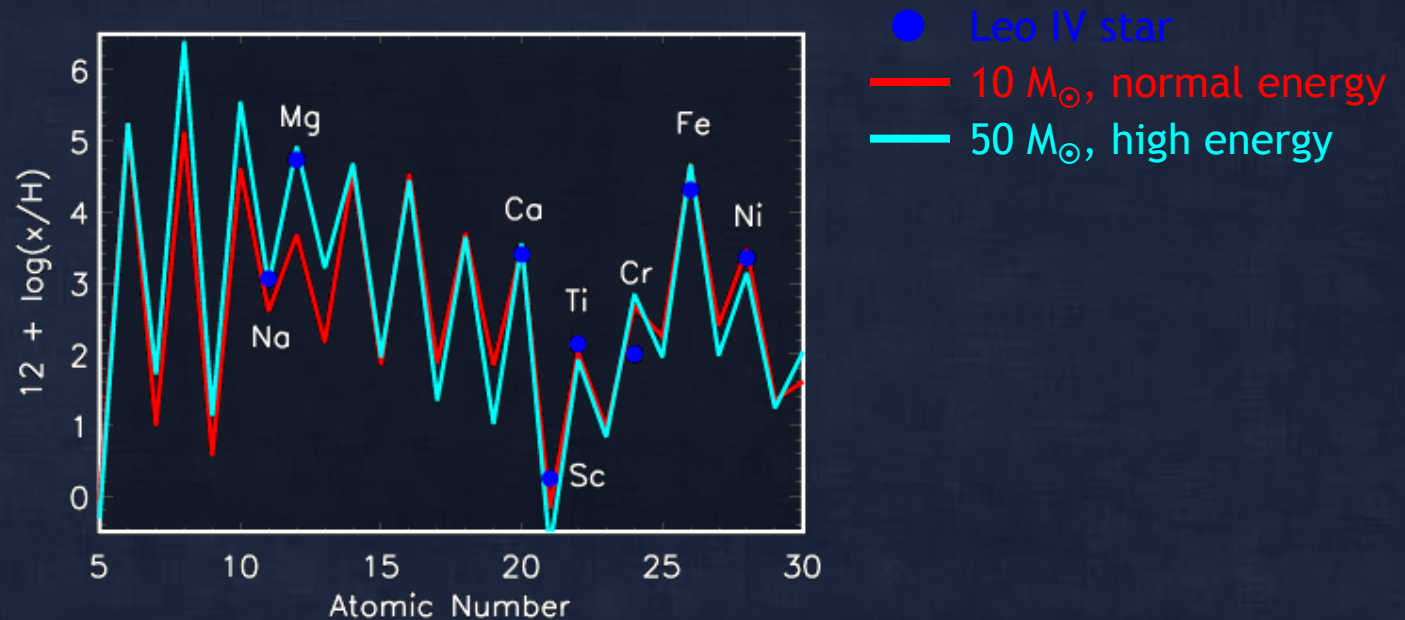


The First Supernova in Leo IV

- Leo IV has a luminosity of $14000 L_{\odot}$
(Sand et al. 2009)
- Total iron content of the galaxy is $0.04 M_{\odot}$
- A single Pop III supernova produces $>0.03 M_{\odot}$ of Fe (Heger & Woosley 2008)
- Were *all* of the metals in Leo IV synthesized by a single star??

The First Supernova in Leo IV

- Leo IV abundance pattern compared to Pop III supernova models



Finding the Most Metal-Poor Stars

- With more stars, we may be able to:
 - Detect the signatures of the first stars and supernovae
 - Constrain the production mechanisms of heavy elements
 - Compare the early chemical evolution of different galaxies with statistically significant samples

Summary

- Dwarf galaxies are unique laboratories for:
 - Dark matter - missing satellites, indirect detection, density profiles
 - Early galaxy formation - IMF, chemical evolution
- Archaeological evidence from nearby dwarfs
 - Dwarfs contain many of the most metal-poor stars
 - EMP fraction is a function of luminosity
 - Early chemical evolution of galaxies is nearly universal
 - CCKSUMOMPSDG will provide first significant sample of EMP stars in other galaxies