Astronomy 330

Lecture 3

10 Sep 2010

Outline

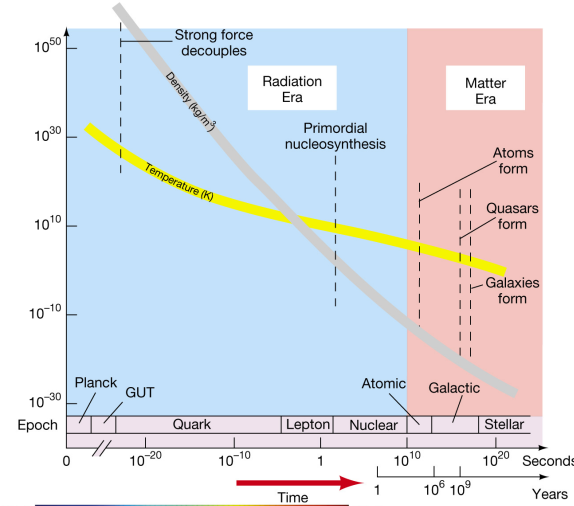
- Review & a little more on reionization
- Stellar Classification
  - Photometry/classification
- Stellar Evolution
- Interpreting H-R diagrams
- Reading: "Old Main Sequence Turnoff Photometry in the Small Magellanic Clouds" Noël et al. (2007, AJ, 133, 2037)
  - What is the data they use?
  - Compare Figures 3 and 7 to some of the CMDs in the lecture notes – what are the similarities and differences?

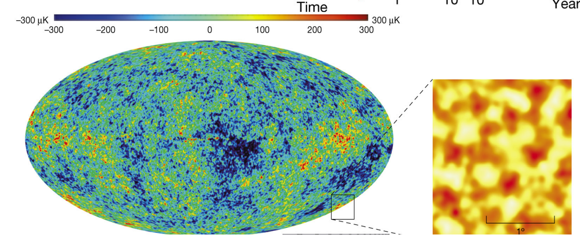
Review: Big Bang / Creation of Matter

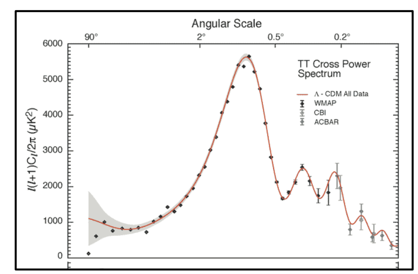
- Expansion & evolution: GR and Friedman equations: $R=1/1+z$, $\dot{R}, \ddot{R}$
- Early Universe
  - Inflation (10^{-34} sec)
  - Particle genesis (10^{-15} to 1 sec)
  - BBNS (3 minutes) ➔ Cosmic He abundances
  - *Recombination* ($4x10^5$ yr) ➔ CMBR
- Dark Ages (?)
- *Reionization* and onward
  - When the first stars and AGN formed *(z=12?)*
  - Galaxy formation
  - Evolution of galaxies, their stars and planets

↑ rad^n dom. ↓

↑ matter dom. ↓

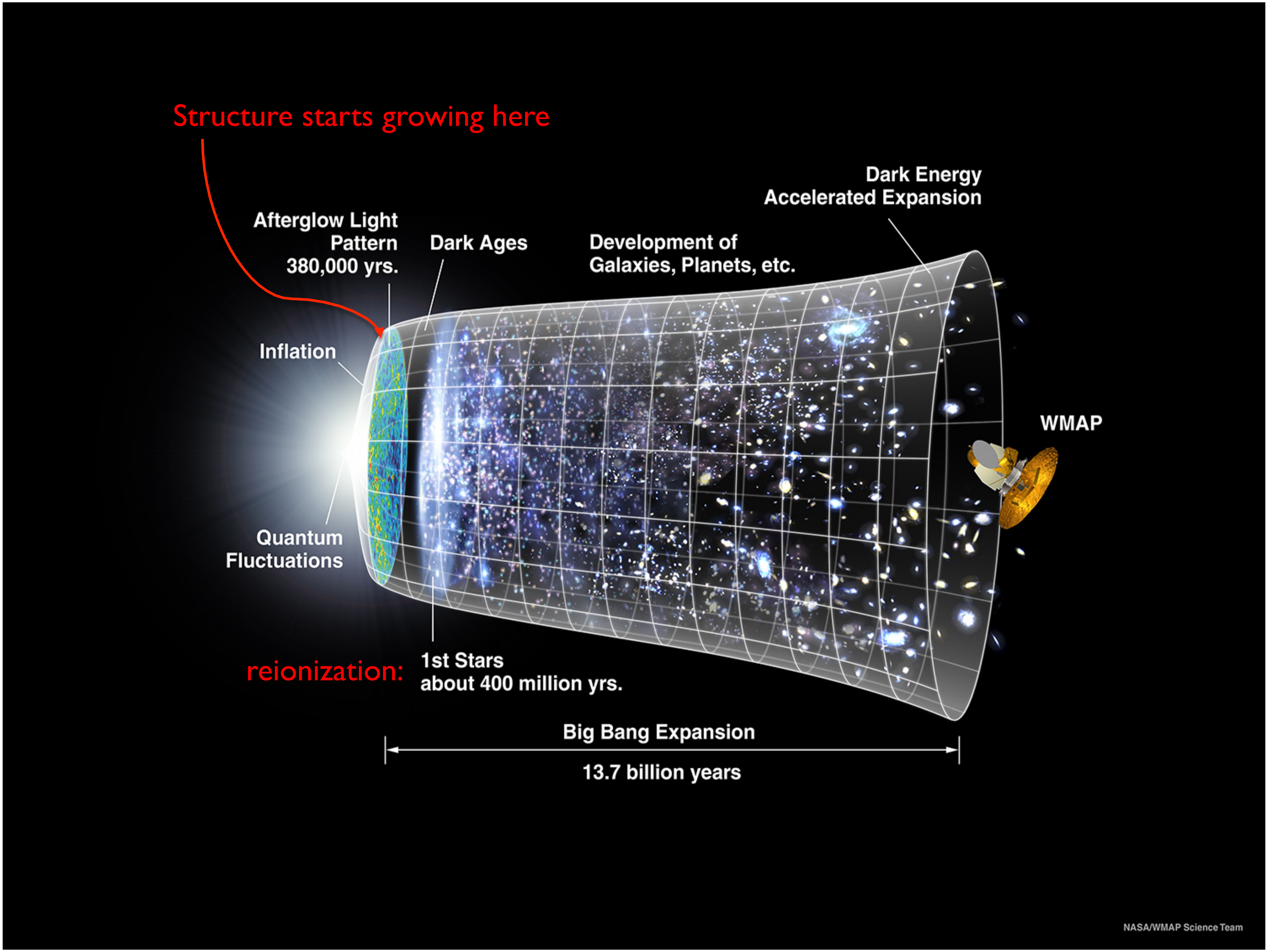






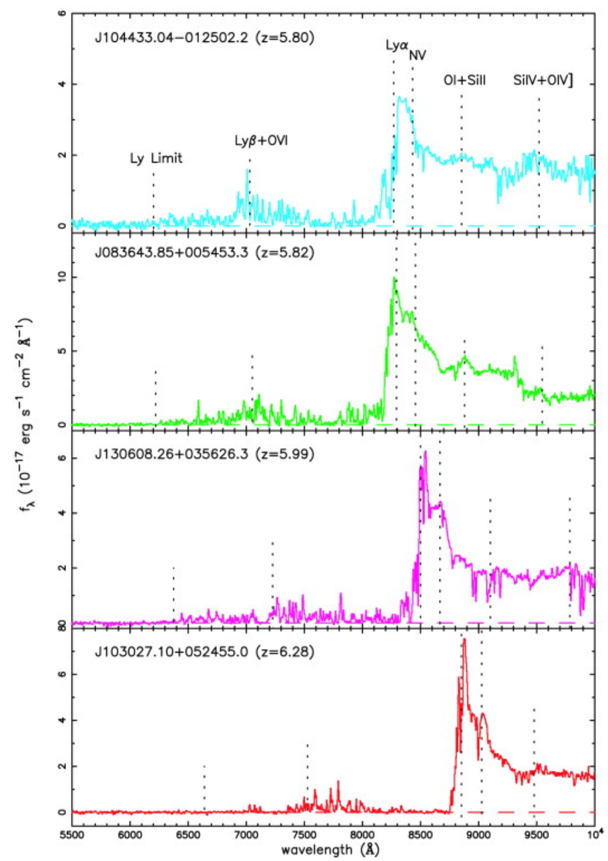
Structure grows via gravity in matter dominated era

precision cosmology & first glimpse of structure ←


Structure starts growing here
Afterglow Light Pattern 380,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
Inflation
WMAP
Quantum Fluctuations
reionization:
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

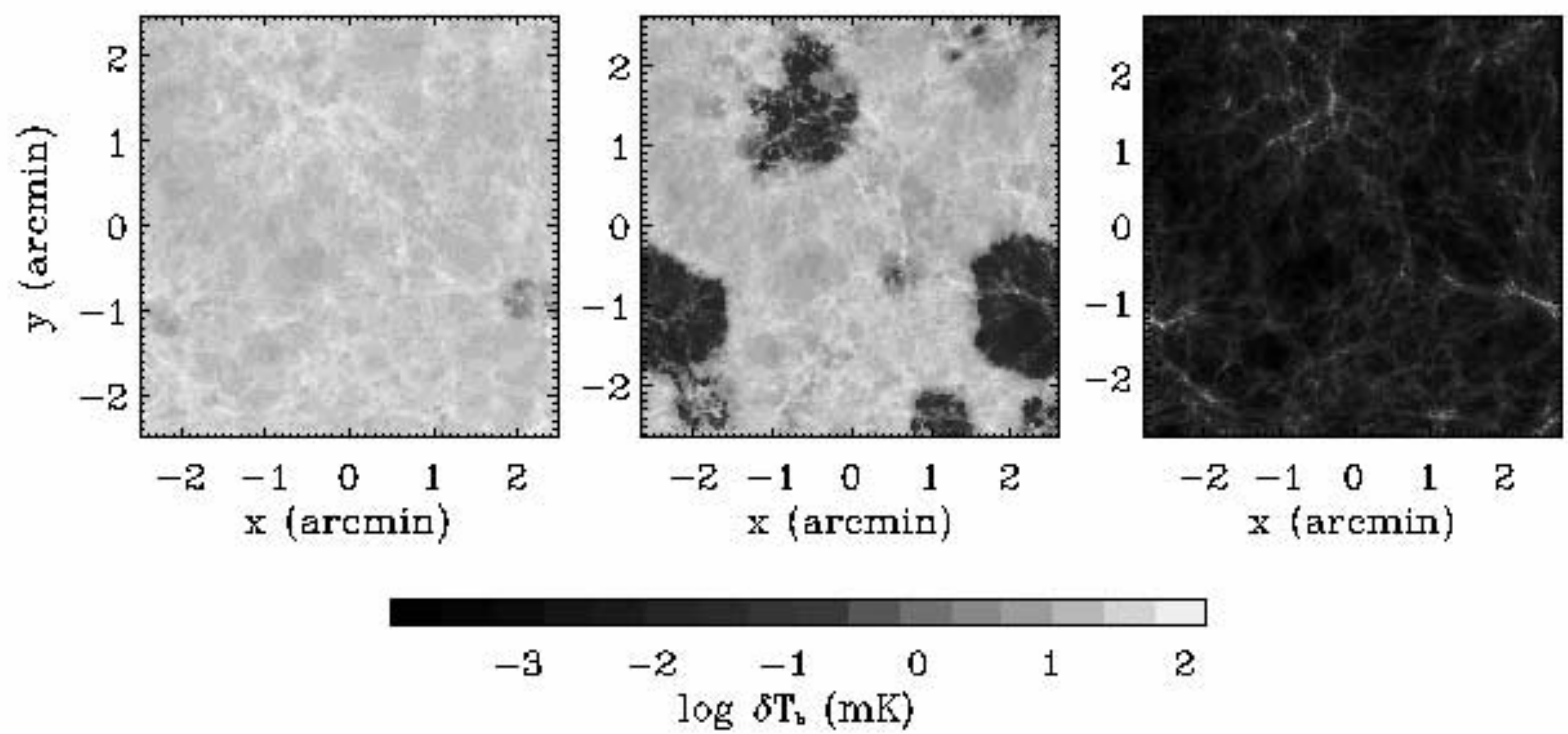
Epoch of Reionization

- Somehow, somewhere stars formed…
- …and ionized the surrounding IGM and the Universe emerged out of the "Dark Ages"
- WMAP says somewhere near z~12…
  - But possibly two phases, one early (z>12, and incomplete)
- When did the 1st stars/galaxies form?
  - Gunn-Peterson trough in quasar absorption
  - Directly observing 1st stars (NGST, TMT)
  - 21 cm line absorption/redshifted emission (SKA)
  - High redshift objects (VLA, GMRT, SKA)
  - Primordial, high redshift black holes (SKA)



21 cm Observations: Emission

z = 12.1 z = 9.2 z =7.6

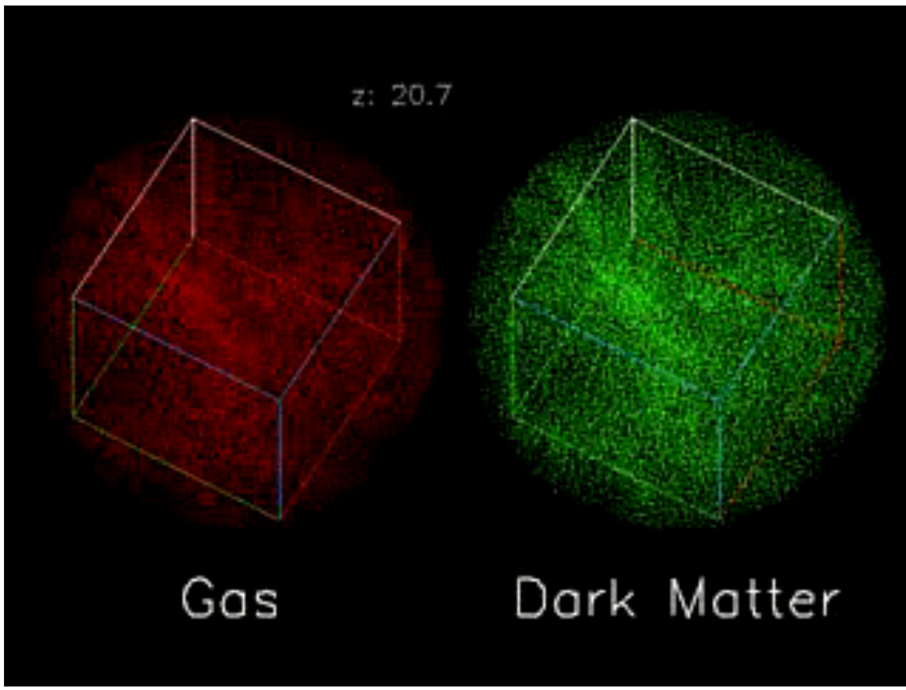


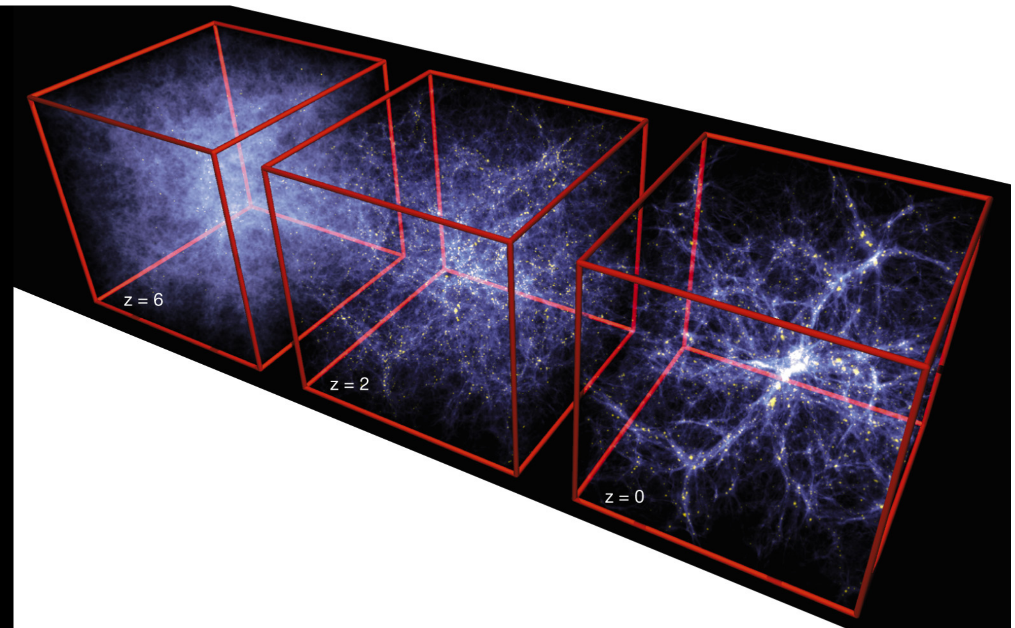
10 Mpc comoving
$\Delta \nu$ = 0.1 Mhz

Furlanetto et al. 2004

Large scale structure: simulated

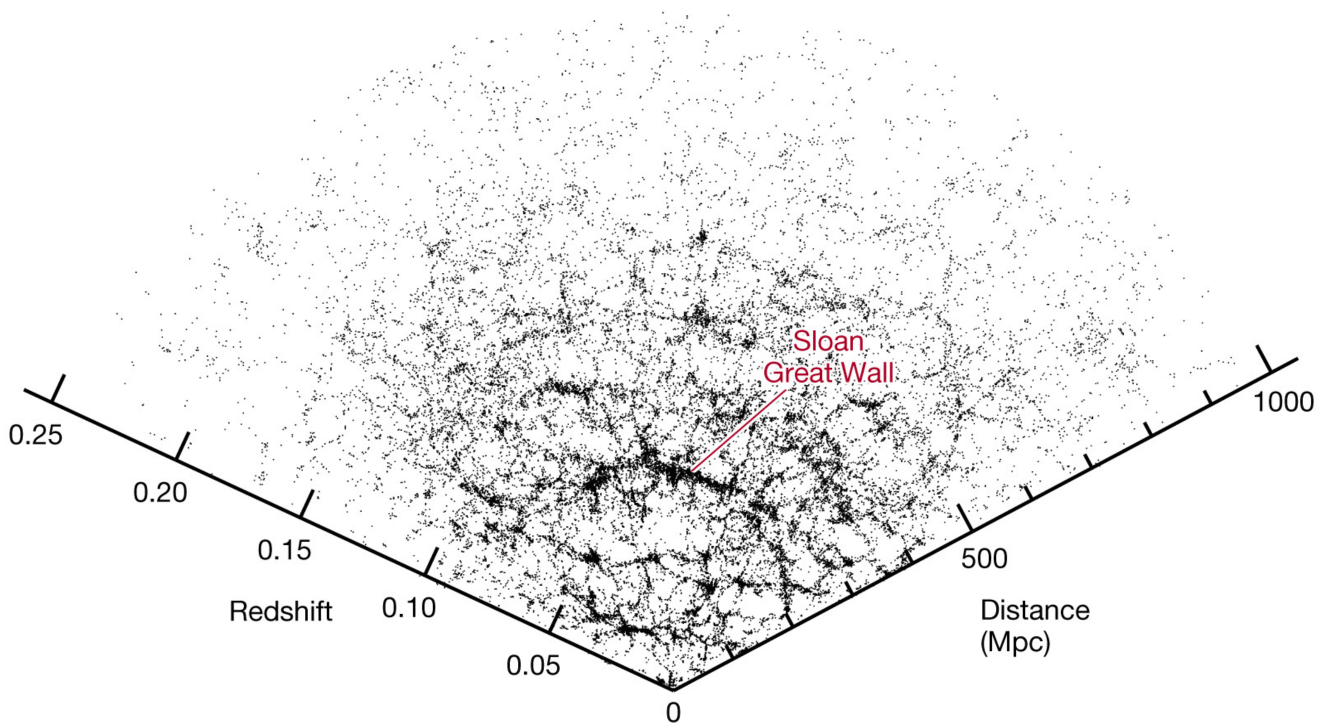
- Fly-through of the Cosmic Web





Large Scale Structure: observed

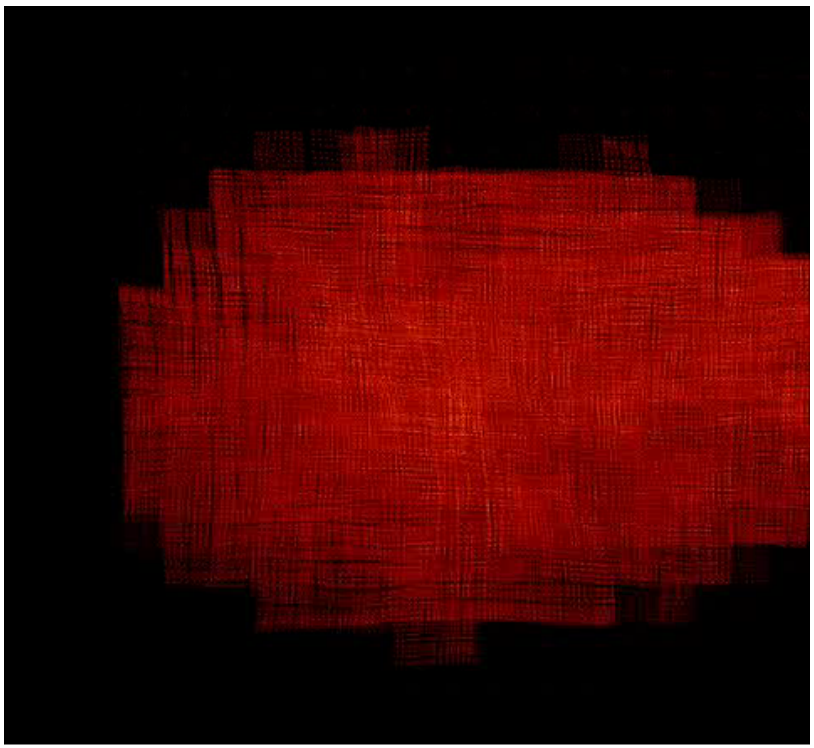
- Filaments and voids
  - Great Attractor
  - Characteristic scales: 40-120 Mpc



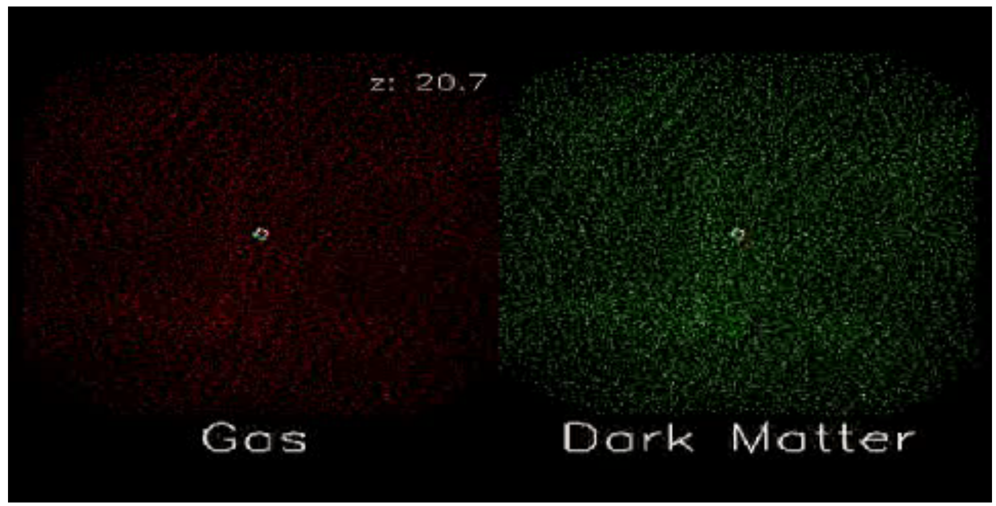
Large scale structure of the Universe

- Structure and Galaxy Formation

elliptical



spiral



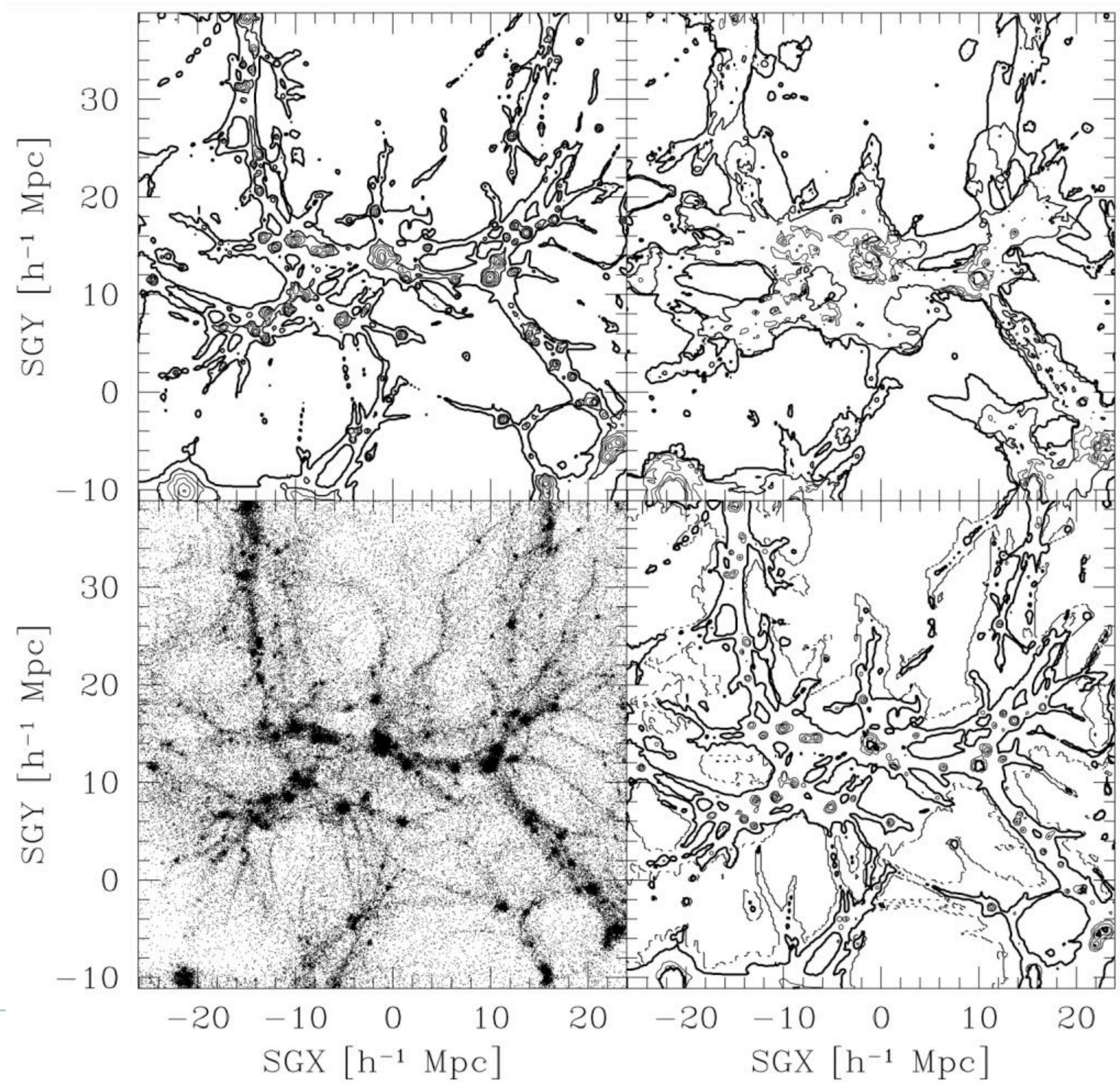
The WHIM: Warm-Hot Intergalactic Medium

density

T/10^6 K

Dark matter

WHIM



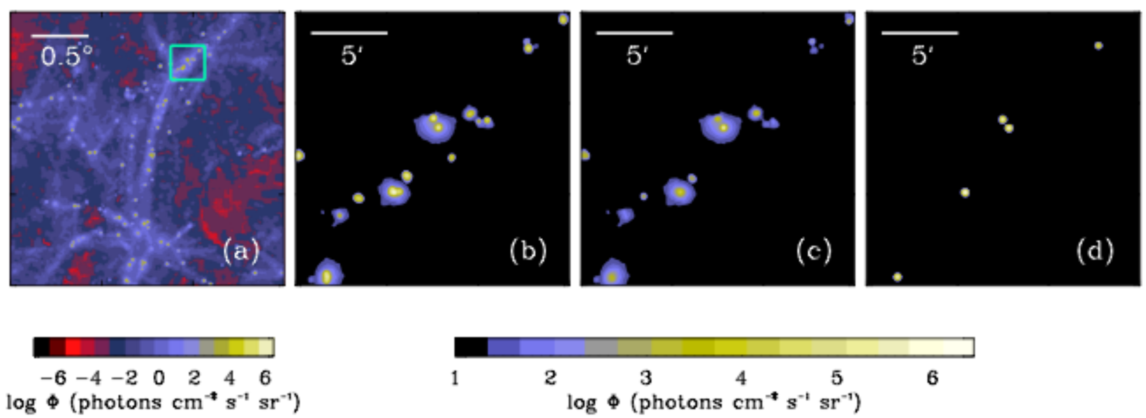
Physical Processes in the Cosmic Web

- Large scale shocks as baryons accrete onto collapsing structures
- Gas is shock-heated to 10^5-10^7 K
  - WHIM origins, or AGN and star-formation too?
- Shock accelerate particles (cosmic ray ions) to 10^{18}–10^{19}eV
- Inter-cluster B-fields: 10^{-7}–10^{-12} G
  - Origin and amplification?

Mapping the Cosmic Web

- Galaxies are only the high density islands in the web
- Most of the web is in the form of diffuse WHIM
  - Detected primarily via QSO absorption sightlines
  - Fraction of kinetic power converted to radiative energy
- Diffuse emission should be detectable in the optical (nebular line emission, e.g., redshifted Lyα) but suitable instrumentation has yet to be built.
- Diffuse synchotron emission (radio) another possibility
  - Parameters:
    - Infall velocity
    - Density of in-falling baryonic gas
    - Magnetic field strength
    - Efficiency of shock acceleration
    - Fraction of kinetic power converted to radiative energy

Furlanetto et al. 2003:
Ly α surface-brightness



Role of Stars in Extragalactic Astronomy

- Dynamics
  - Stars are point masses –
    - collisionless tracers of the potential
  - Distinctions between stars irrelevant
    - But, which stars most accurately trace the "true" morphology and dynamics of a galaxy?
- Chemical evolution
  - Stars are responsible for producing and distributing the elements
- Metric of evolution
  - Star formation rate (SFR)
  - Star formation history (SFH)
    - H-R diagram are all diagnostics of evolution
- Feedback
  - evolution/organization of ISM in galaxies driven by gravity, hydrodynamics, and input of energy from stars

Digression & Review: Flux Units

- Flux (f_ν): measured in Janskys
  - 1 Jy = 10^{-26} W m^{-2} Hz^{-1}= 10^{-23} erg sec^{-1} cm^{-2} Hz^{-1}
- Flux (f_λ): measured in ergs s^{-1} cm^{-2} A^{-1} (cgs units)
- Photon flux (f_γ) is useful for calculating signal-to-noise (counting statistics):
  - Define *neper* = $\Delta\lambda/\lambda = \Delta\nu/\nu = \Delta \ln \nu$
  - The photon flux is:
    - photons sec^{-1} cm^{-2} neper-1 = f_ν/h
    - where h=6.6256 x 10^{-27} erg sec
  - Useful identify:

1 microJy = μJy = 15.1 photons sec^{-1} m^{-2} $neper^{-1}$

Apparent magnitudes

$$m_1 - m_2 = -2.5\log_{10}\left(\frac{f_1}{f_2}\right) = -a\ln\left(\frac{f_1}{f_2}\right)$$

$$a = 2.5\log_{10} e = 1.08574$$

$$m = -2.5\log_{10}\left(\frac{f_1}{f_0}\right) + m_0$$

f_n: the apparent flux of object n.

Pogson's ratio (MNRAS, 1856, 17, 12)

Will drop "10" here on out.

m_0 : zeropoint of the magnitude system

$f = f_0$ dexp[-0.4(m-m_0)] ← how to get your money back

Absolute Magnitudes

$$m_\lambda - M_\lambda = 5\log_{10} d - 5 + A_\lambda$$

$$\therefore \quad \frac{f_1}{f_2} = \left(\frac{d_2}{d_1}\right)^2$$

- Absolute magnitude is the apparent magnitude that would be observed if the object were at a distance, *d*, of 10 pc.
- A_λ is the total extinction due to interstellar dust, in magnitudes, typically take to be only the Galactic foreground screen (Burstein & Heiles 1982, AJ, 87, 1165; Schlegel et al. 1998, ApJ, 500, 525):

HI → (Burstein & Heiles 1982)

IRAS → (Schlegel et al. 1998)

  - $f = f_0 \exp(-\tau_\lambda)$,
  - $A_\lambda = 1.086\ \tau_\lambda = -2.5 \log(f/f_0)$

See nedwww.ipac.caltech.edu/help/extinction_law_calc.html

Absolute Magnitudes

- For extragalactic observers: *d* in Mpc, plus the so-called k-correction, κ, which accounts for effects of the cosmological expansion
  1) effects of redshifting the rest-frame spectrum in the observed band-pass; and
  2) photon dilution.

$$m_\lambda - M_\lambda = 5\log_{10} d + 25 + A_\lambda + \kappa_\lambda$$

See, e.g.: Schneider, Gunn & Hoessel (1983, ApJ, 264, 337)

Astronomical Magnitude Systems

Table 3.1: Fluxes for m = 0

How are these determined?

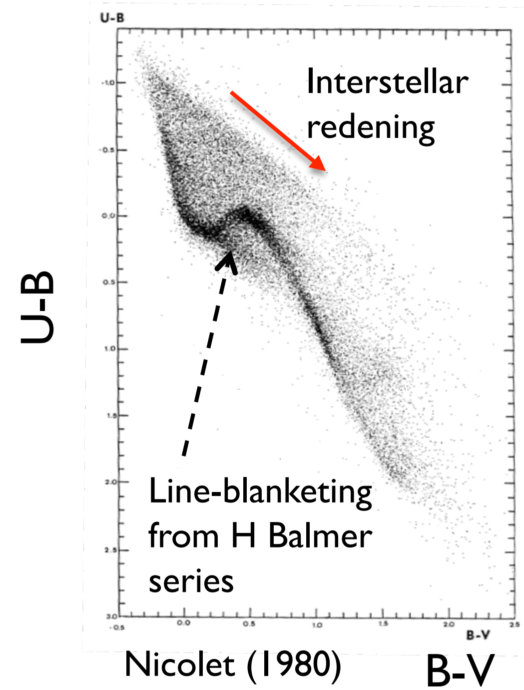
	Band	λ_c (μ)	$\Delta\lambda/\lambda$	Jy	Reference
Johnson	U	0.36	0.15	1810	Bessell (1979)
	B	0.44	0.22	4260	"
	V	0.55	0.16	3640	"
	R	0.64	0.23	3080	"
	I	0.79	0.19	2550	"
	J	1.26	0.16	1600	Campins, Rieke & Lebofsky (1985)
	H	1.60	0.23	1080	"
	K	2.22	0.23	670	"
griz	g	0.52	0.14	3730	Schneider, Gunn & Hoessel (1983)
	r	0.67	0.14	4490	"
	i	0.79	0.16	4760	"
	z	0.91	0.13	4810	"
SDSS AB_{95}	u'	0.35	0.18	3631	Fukugita et al. (1996)
	g'	0.48	0.29	3631	"
	r'	0.63	0.22	3631	"
	i'	0.77	0.29	3631	"
	z'	0.91	0.16	3631	"

Note uniformity in $\Delta\lambda/\lambda$

nepers

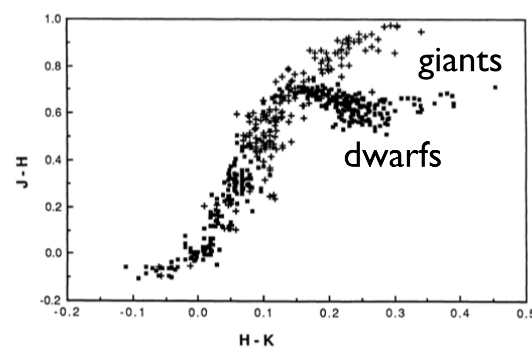
Stellar Classification

- Photometry : Based on optical and near-infrared (NIR) colors
  - First order: stars are blackbodies, so any two flux-points constrain temperature
  - Combination of two bands yield "color" = temperature
  - Second-order: stars have line-blanketing, so e.g., colors are degenerate for massive stars
  - Need observations in at least three bands.
  - NIR can break degeneracy between cool giants and dwarfs.



Nicolet (1980)

- Spectroscopy : individual line ratios very tightly constrain temperature, surface gravity, etc.
  - Yields the OBAFGKM classification
  - Further sub-classification is the luminosity class



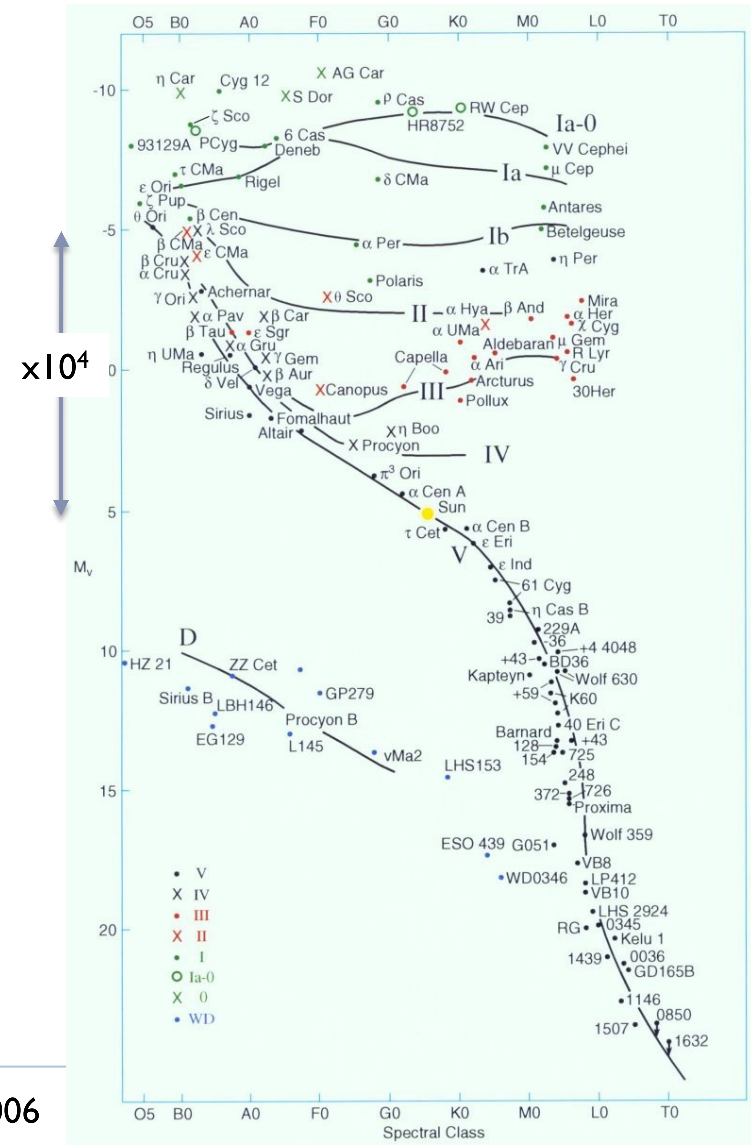
Bessell & Brett (1988)

Basic Properties of Stars (chapter 1.1)

Spec. type	Absorption lines	T_{eff} (K)	M_v (V, I)	(B-V)
O	He II, C III	40-50,000	-6,-8	<-0.33
B	He I, S III, H	12-30,000	-1.5, -7	-0.2
A	H, Mg II	7-9,000	1.0, -7	0
F	Ca II	6-7,000	3.0,-7	0.4
G	Ca II, CH	5.5-6,000	5.0,-7	0.6
K	CH, CN	4-5,500	6.0,-7	1.2
M	TiO	2.5-4000	9.0,-7	1.6

Luminosity class

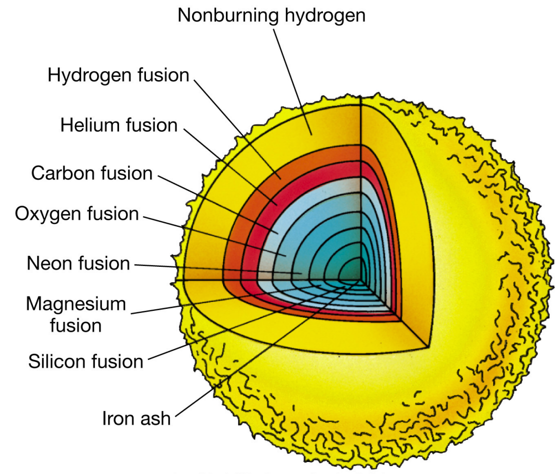
- Ia – most extreme supergiants
- Ia – moderate supergiants
- Ib – less luminous supergiants
- II – bright giants
- III – normal giants
- IV – subgiants
- V - dwarfs

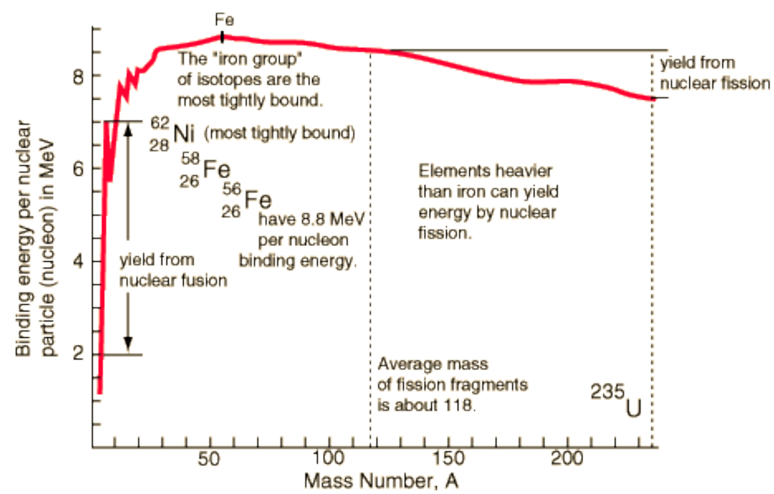


Kaler 2006

Fundamentals of Stellar Evolution

- History: BBNS cannot account for the abundances of all the elements; Burbridge, Burbridge, Fowler, & Hoyle laid out the model for stellar nucleosynthesis.
- Main sequence: H to He fusion via proton-proton chain & CNO bi-cycle
- Post-MS: H depletion in core, interior pressure decreases, collapse of core and interior, H shell burning ignites, envelope expands and star becomes a red giant.
- Later phases: repeat with heavier and heavier elements via α-processes, faster and faster rates (more energy production per unit time), more and more shells.
- Fusion ends depending on mass sufficient to overcome core degeneracy, or when core burns to Fe.





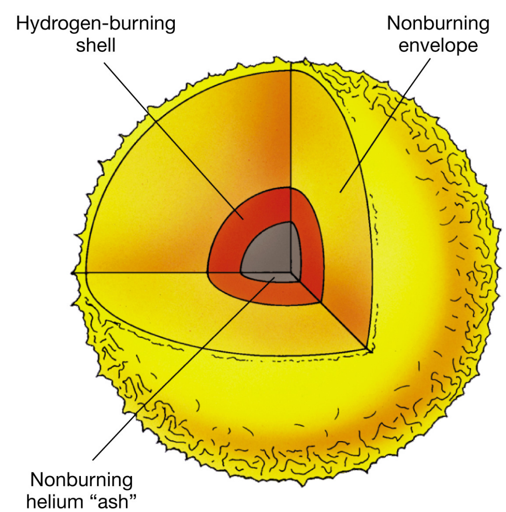
MS Stellar Lifetimes

- Because H burning lifetime depends on mass there is a nice correlation between turn-off mass and age
  - Spectral types are determined by surface-temperature (T_{eff})
  - T_{eff} set by mass *on the main sequence:*
  - more mass burns brighter and hotter
    - $L_{MS}/L_{\odot} \sim (M/M_{\odot})^{2.14}$ $(M/M_{\odot} > 20)$
    - $L_{MS}/L_{\odot} \sim (M/M_{\odot})^{3.5}$ $(2 < M/M_{\odot} < 20)$
    - $L_{MS}/L_{\odot} \sim (M/M_{\odot})^{4.8}$ $(M/M_{\odot} < 2)$

So: $\tau_{MS} = 10\ (M/M_{\odot})(L/L_{\odot})^{-1}$ Gyr

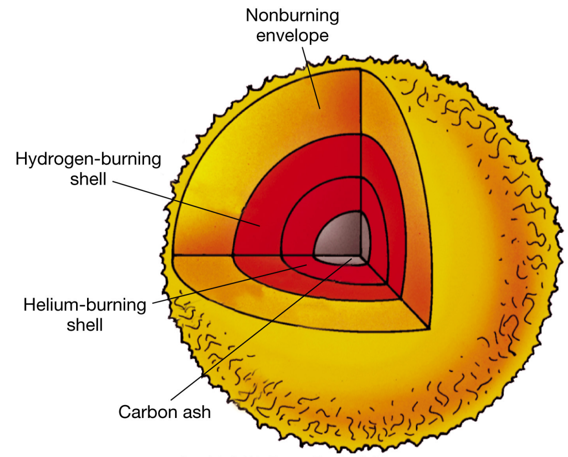
Post-MS Stellar Evolution

- RGB to Horizontal Branch (HB)
  - Core contraction/core mass increases
  - $T \sim 10^8$ K, $\rho \sim 10^4$ g cm^{-3} get He burning
    - $2\alpha \rightarrow {}^8Be$, ${}^8Be + \alpha \rightarrow {}^{12}C$
    - In stars w/ $M > 2M_\odot$, its not degenerate and we get core expansion
    - Essentially a He-burning main sequence
    - In more massive stars get ${}^{12}C + \alpha \rightarrow {}^{16}O$; for stars with M up to 8 $M_\odot$ we're left with a degenerate CO core (white dwarf)
  - He-burning lifetime ~10^8 years
- Evolution to Asymptotic Giant Branch ($M > 8\ M_\odot$)
- Further Burning Stages…



Fundamentals of Stellar Evolution

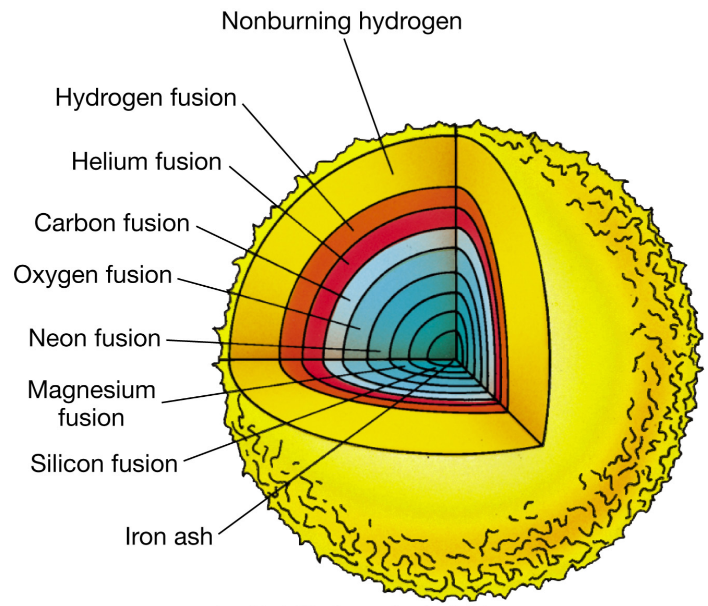
- Evolution to AGB
  - He-burning, growing CO core
    - Low mass stars can't lift degeneracy, end up as planetary nebula + white dwarf
  - Eventually get He shell burning that drives expansion of envelope and luminosity increases (plus unburned H, H shell burning)
    - Occurs with a series of "dredge-ups" that produce chemically bizarre stars (convection)
    - Site of "s-process" nucleosynthesis



- Neutron capture processes
  - S-process ("slow") – yields elements like Ba and Tc largely in AGB stars (all those free n from previous burning processes)
  - R-process ("rapid") – yields very heavy elements like Ur, usually in SNe

Fundamentals of Stellar Evolution

- Further Burning Stages
  - $^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$
  - $^{16}O + ^{16}O \rightarrow ^{28}Si + \alpha$
  - $^{20}Ne + ^{4}He \rightarrow ^{24}Mg + \gamma$
  - Leads ultimately to the production of ^{56}Fe, core collapse, and supernova explosion (Type II SNe)
  - Can also get n production via, e.g., $^{12}C + ^{12}C \rightarrow ^{23}Na + n$

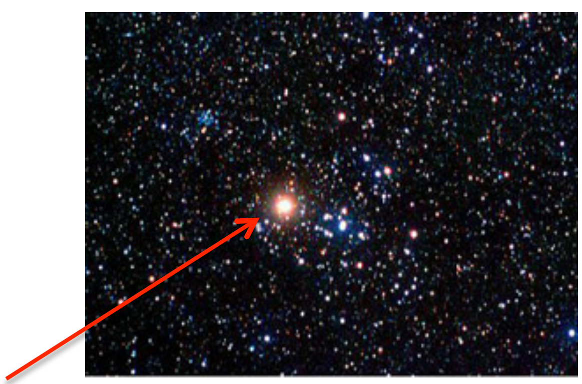


Understanding Stellar Populations

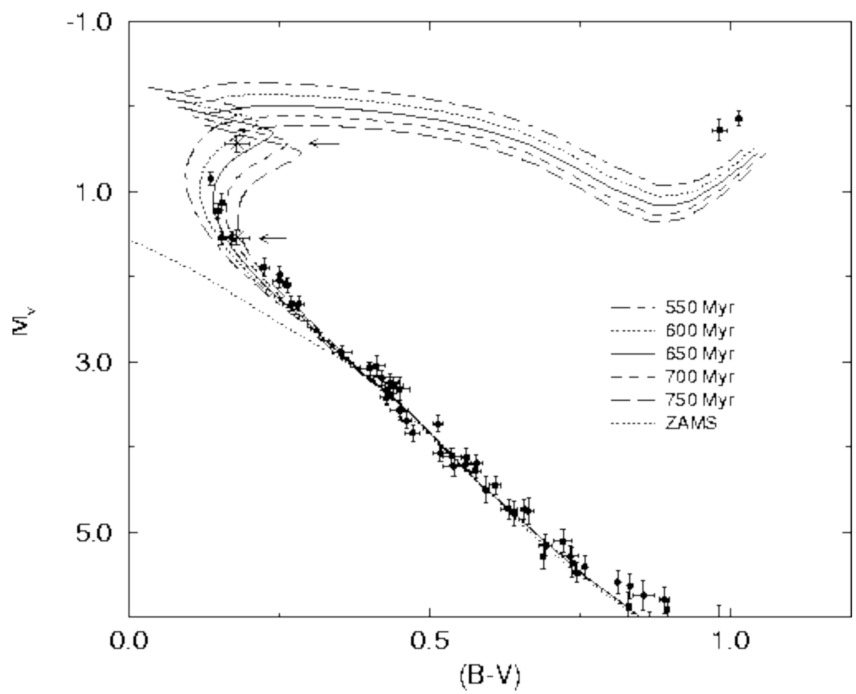
- Color – temperature – mass – lifetime relationships mean the observed "color-magnitude" diagram (CMD) can tell us something about the age/evolutionary status of a stellar population (especially if it's a single age)
- CMD can also hint at the production of metals

H-R Diagram

- Stars spend most of their lives on the "main sequence"
- "turn-off" age is primary indicator of the age of a stellar population



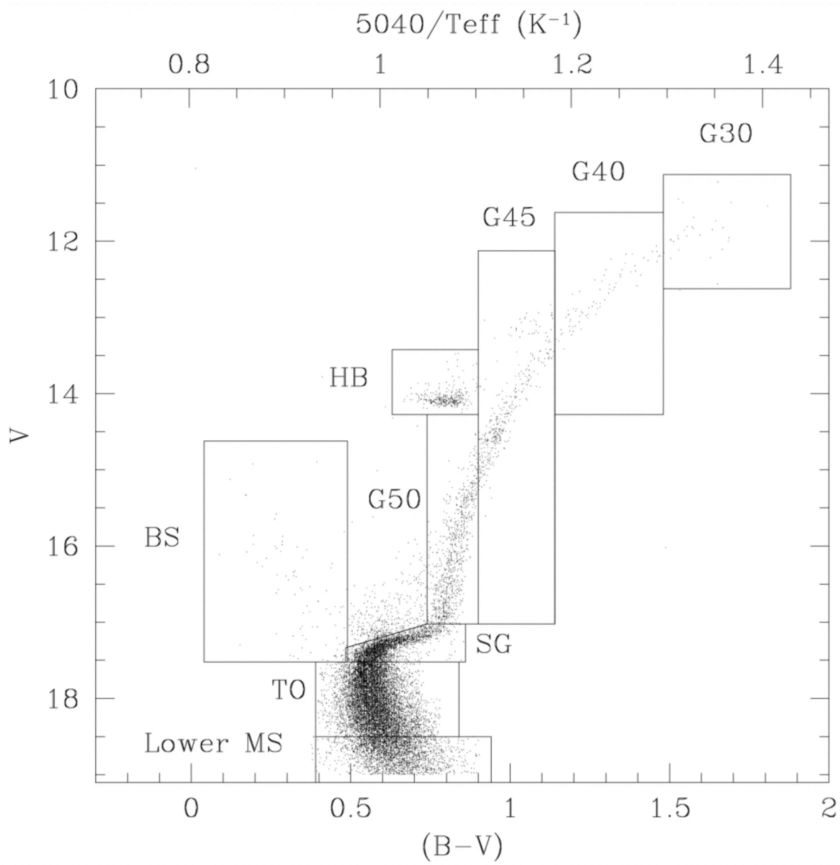
Aldeberan – not part of cluster



Hyades open cluster; Perryman et al. 1998

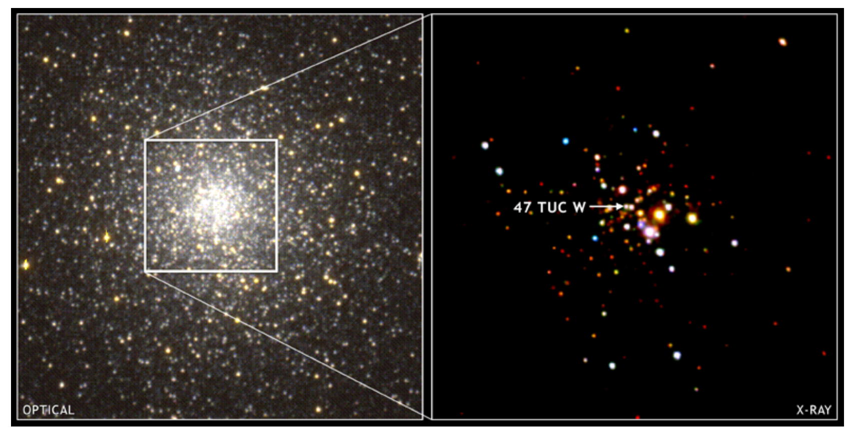
ZAMS = zero-age main sequence

H-R Diagram continued



Globular cluster 47 Tuc
(Edmonds et al. 2002)

- Tracing evolution of a stellar population
- (B-V) ➔ temperature
- V ➔ luminosity



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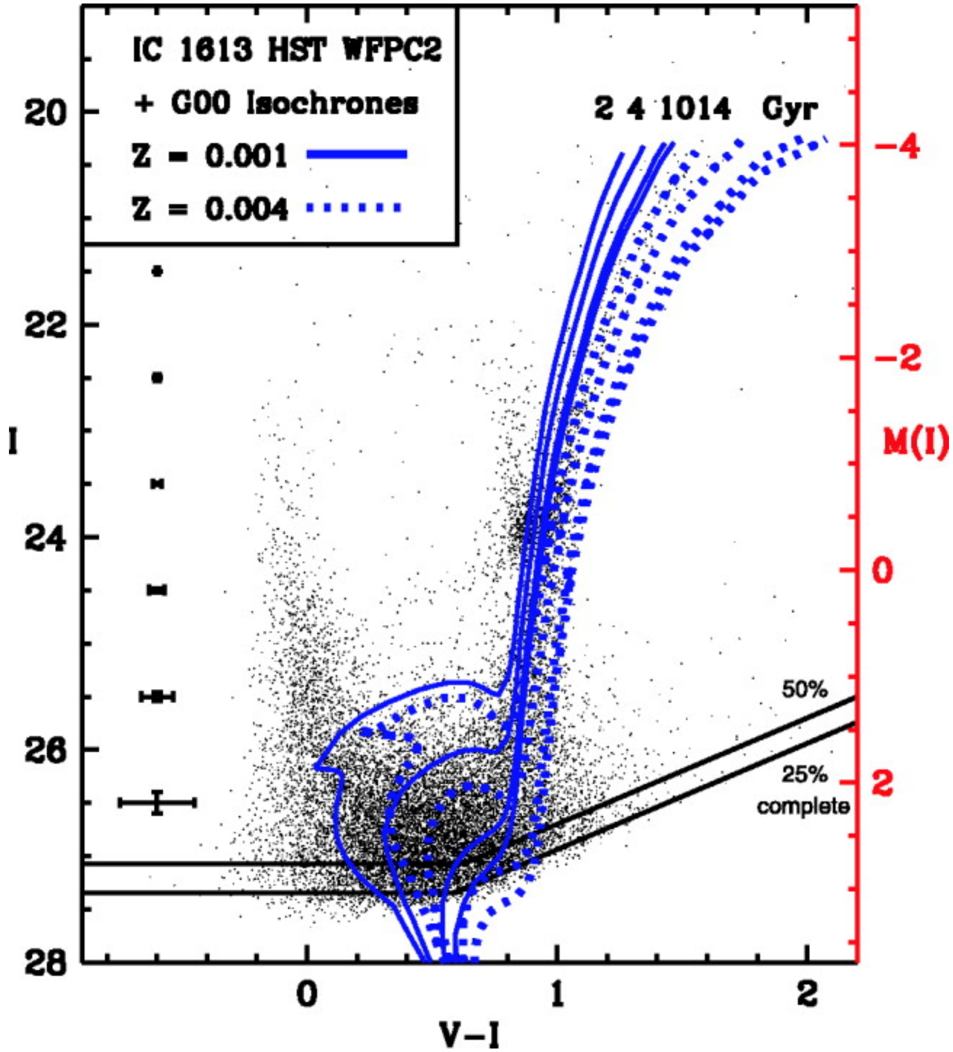
H-R Diagram



- Gets more complicated with a mixed-age stellar population
- Multiple turn-offs, multiple HBs
- Dwarf spheroidal galaxies are ideal labs for this

Statistical Stellar Astrophysics

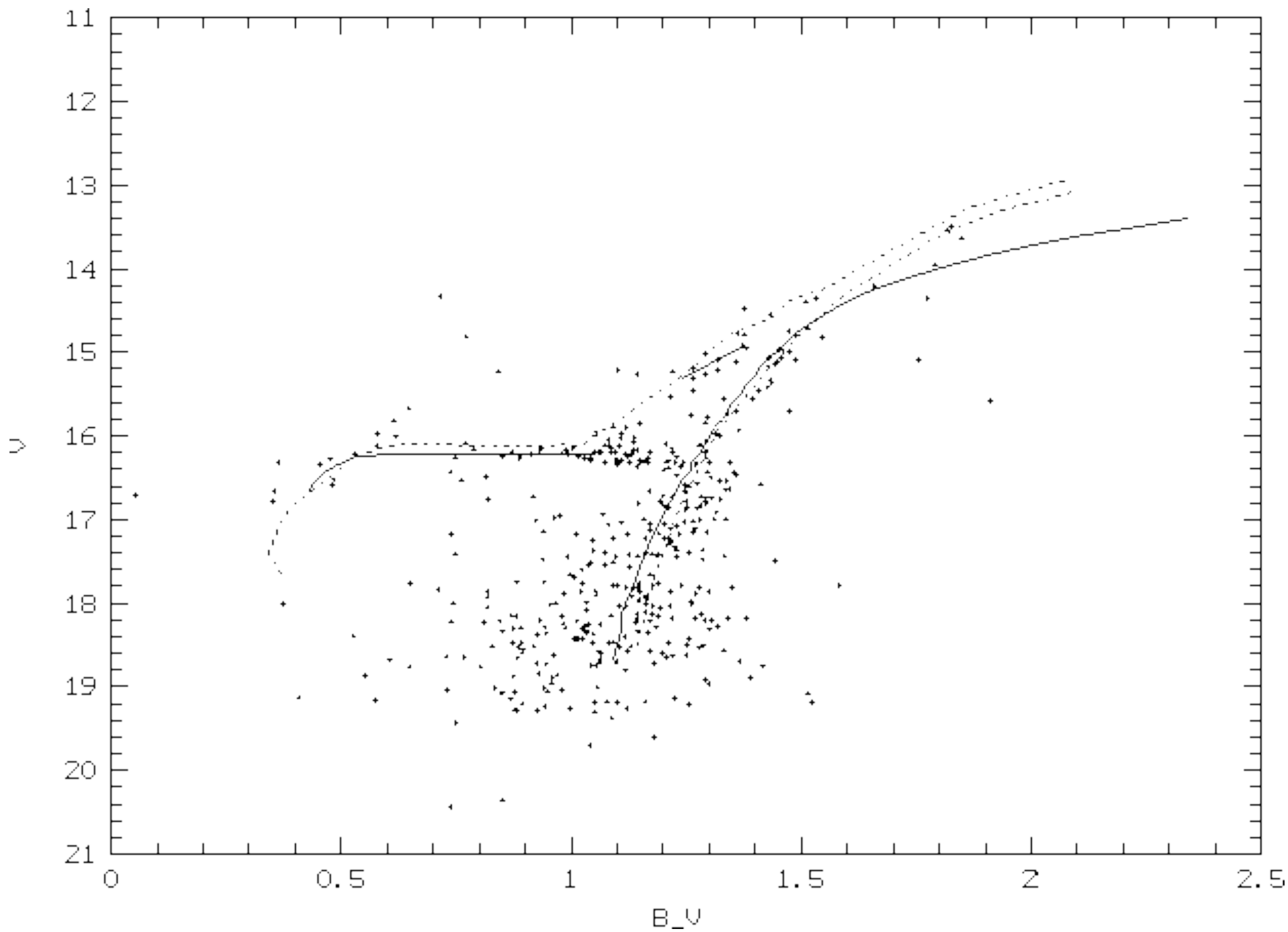
- Stellar initial mass function
  - $dN = N_o \xi(M) dM$
  - $N_o \int dM\, M\, \xi(M)$ = total mass of burst/episode
  - Observationally: $\xi(M)$ goes as $(M/M_\odot)^{-2.35}$
    - "Salpeter IMF"
    - Slight variation with mass (time? environment?), according to some
    - Upper mass limit in the 80-120 $M_\odot$
      - but note small-number statistics become important
    - Turn-over likely below 0.1 $M_\odot$

Stellar Populations

- Integrated Colors
  - Population I – "Disk Population" – open clusters, circular orbits, confined to a disk, "blue"
  - Population II – "Halo Population" – globular clusters, large random velocities, elliptical orbits, spherical distribution, "red"
  - Population III – extremely metal poor, not yet detected
    - Cosmic Mystery #2: Where are the Pop-III stars?
- Correlations
  - Color vs kinematics
    - Blue stars are disk-like
  - Color vs metallicity
    - Red stellar populations tend to be metal poor, strong Galactic correlation between kinematics and metallicity

Interpretting CMDs

- Density of any locale on a CMD is a function of IMF, SFR, mass, and age
  - $C(M_V, V\text{-}I) = \iint \xi(\log m, t) \times SFR(t)\, dt\, d\log m$
    - Small mass bin (i.e. single mass)
    - Constant IMF (ξ)
    - Can recover star formation history from a complex CMD
- Statistical Approach
  - What is the probability that a certain distribution of points on the CMD came from one particular set of stellar evolution models (Tolstoy & Saha 1996)



11
12
13
14
15
16
17
18
19
20
21
V
0
0.5
1
1.5
2
2.5
B_V