Black holes and neutron stars in globular clusters

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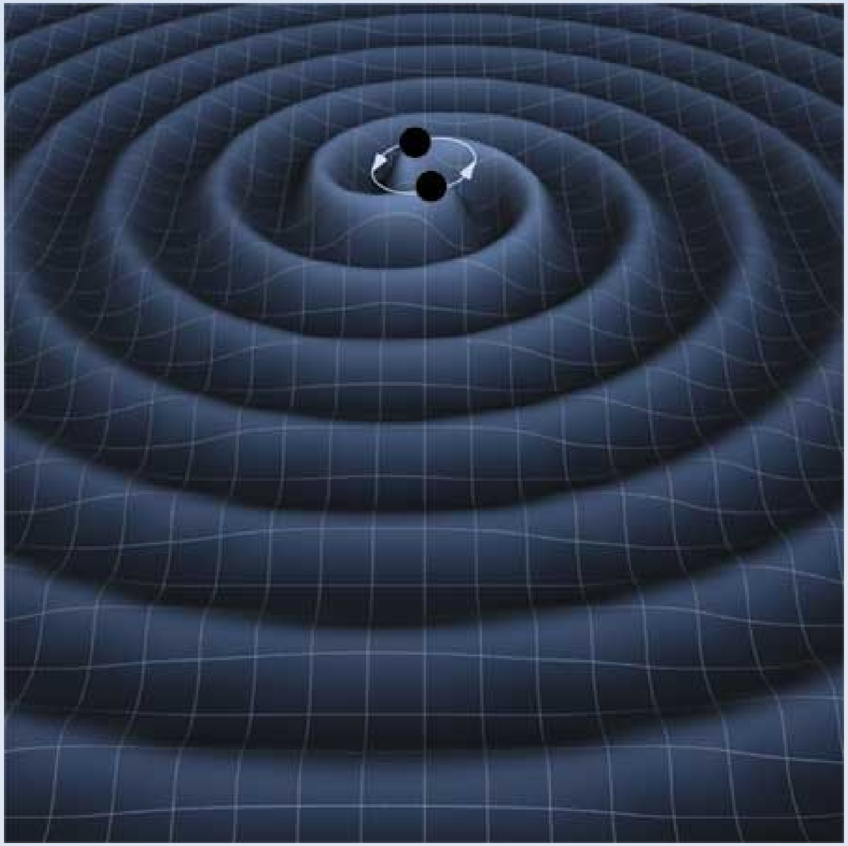
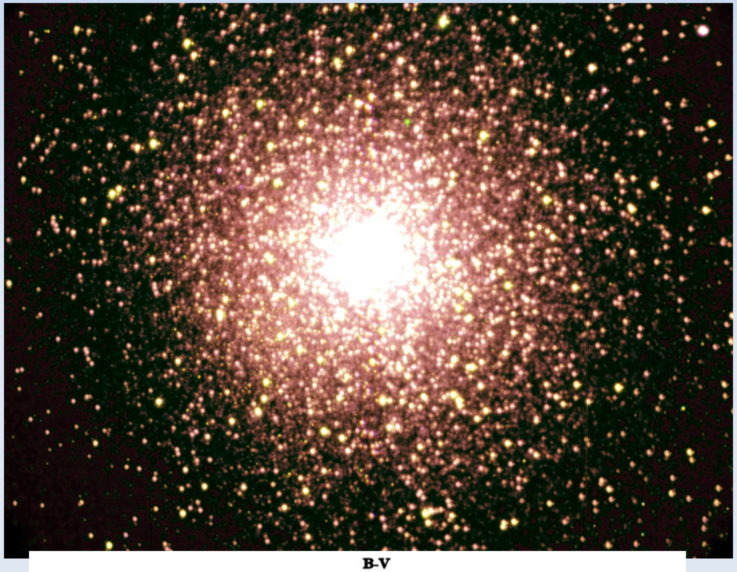
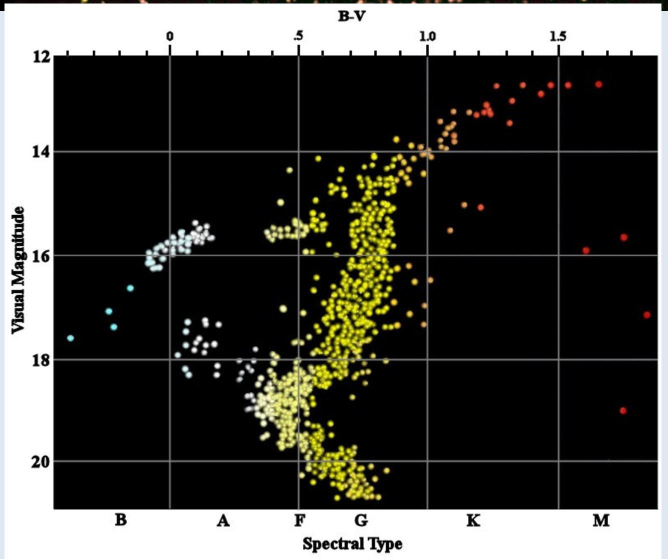
Overview

- Overview of stellar dynamics of clusters
- Finding black holes
- X-ray sources in extragalactic star clusters
- The first globular cluster black hole
  - Populations of globular cluster black holes
  - Unusual emission lines from these systems
- Along the way: some fundamental physics we can do with GC black holes, and some useful constraints on galaxy evolution that were “by-products” of this work

Motivations for understanding binary stars in clusters







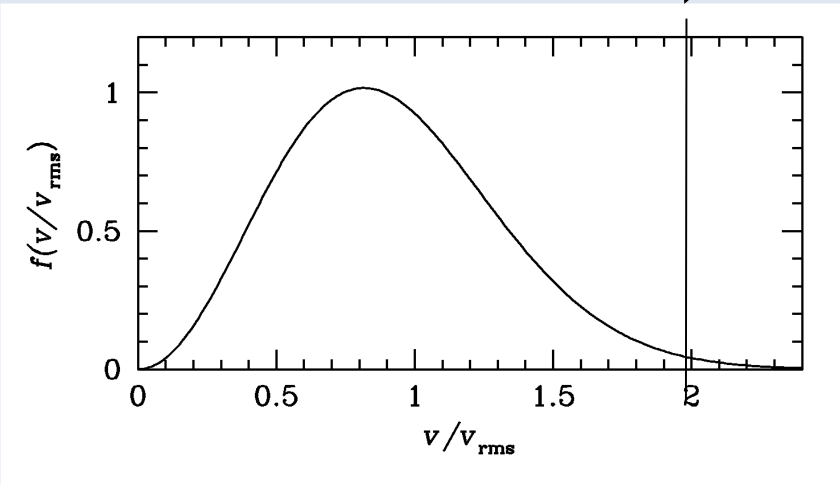
History of black holes in GCs

- First suggestion: quasar remnants (Wyller 1965;1970)
- Later, X-ray emission suggested to be Bondi accretion onto central black holes (Bahcall & Ostriker 1975)
- Debate over M15 dynamical signature (Newell et al. 1976; Illingworth & King 1977)
- Discovery of X-ray bursts proved the X-ray sources were neutron stars (Grindlay et al. 1976; Woosley & Taam 1976)

Key timescales

- Crossing time
  - $t_{cross} = R/v = 10^6$ years
- Relaxation time
  - $t_{rel} = (0.1N)/(\ln N) * t_{cross} = 10^9$ yrs
- Evaporation time
  - start with Maxwellian distribution of stars
  - $t_{evap} = 136\ t_{relax}$

Escape velocity if self grav.



Mass segregation

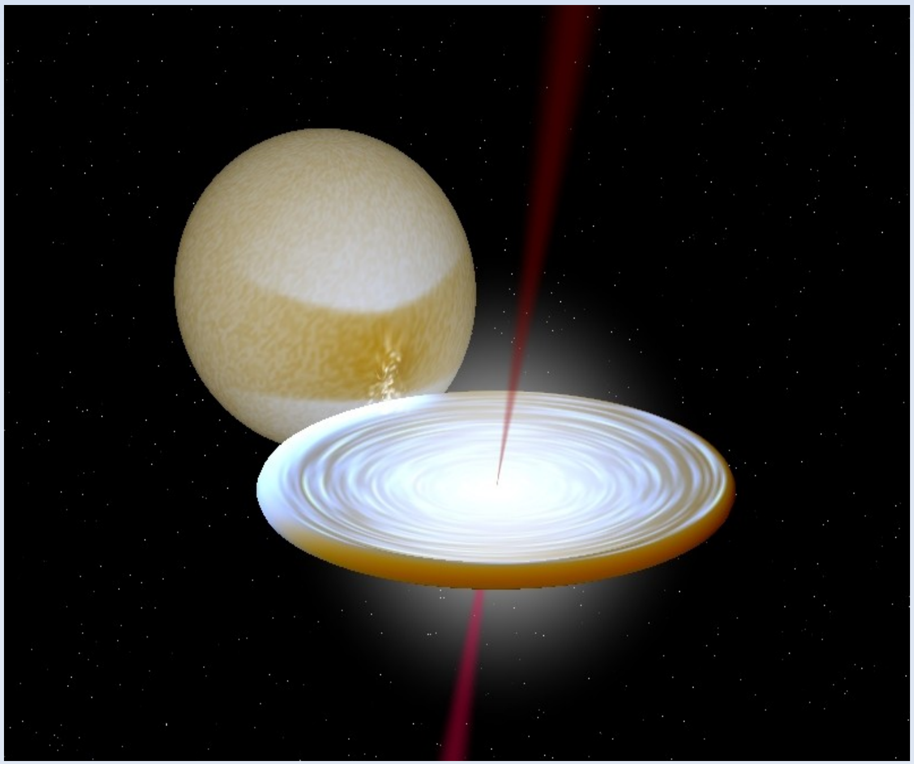
- Stellar interactions lead to energy exchange
- Kinetic energies of the stars will approach thermal distribution
- This means the heaviest objects will have the lowest velocities and sink to the center

Black holes: severe mass segregation means ejection

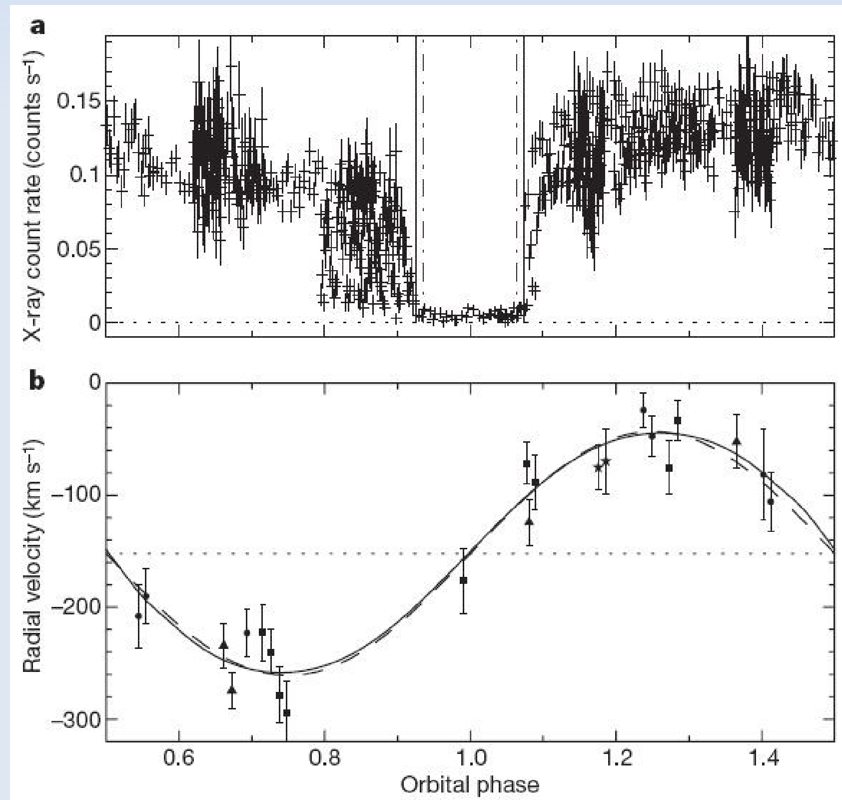
- Old star clusters – no massive stars left
- Black holes ~5 times heavier than everything else
- Become fully segregated – do not interact with other stars substantially
- Leads to a cluster with only a few hundred stars – very rapid evaporation

Spitzer 1969; Kulkarni et al. 1993; Sigurdsson & Hernquist 1993; Portegies Zwart & McMillan 2000

Detecting black holes and neutron stars in binaries



From binsim by Rob Hynes



Orosz et al. 2007

Forming low mass X-ray binaries

- Difficult in field star populations, especially for neutron star accretors
  - Supernova should drive off more than half the mass of the system
  - Initial masses of components in binaries are usually well correlated
- “Common envelope evolution” is almost certainly required

Forming LMXBs II: in clusters

- Tidal capture
  - Controverisal – may unbind the star entirely
- Direct collision
  - See movie from Lombardi
- Exchange interactions
  - Doesn't form new binary, but forms tighter binaries involving heaviest components

Fabian et al. 1975, Hills 1976; Verbunt 1987

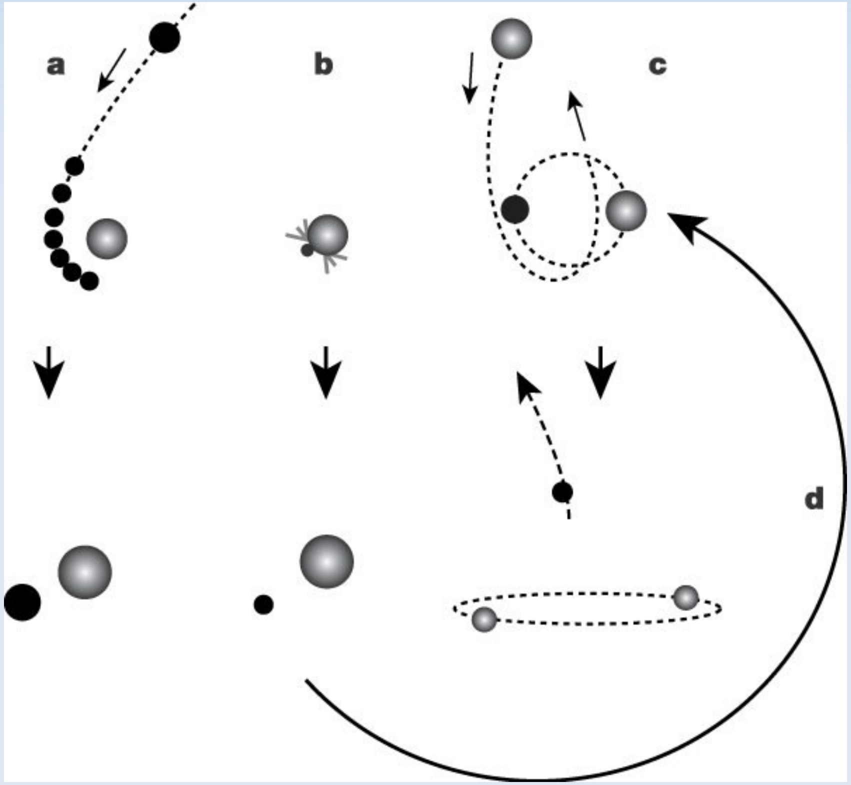
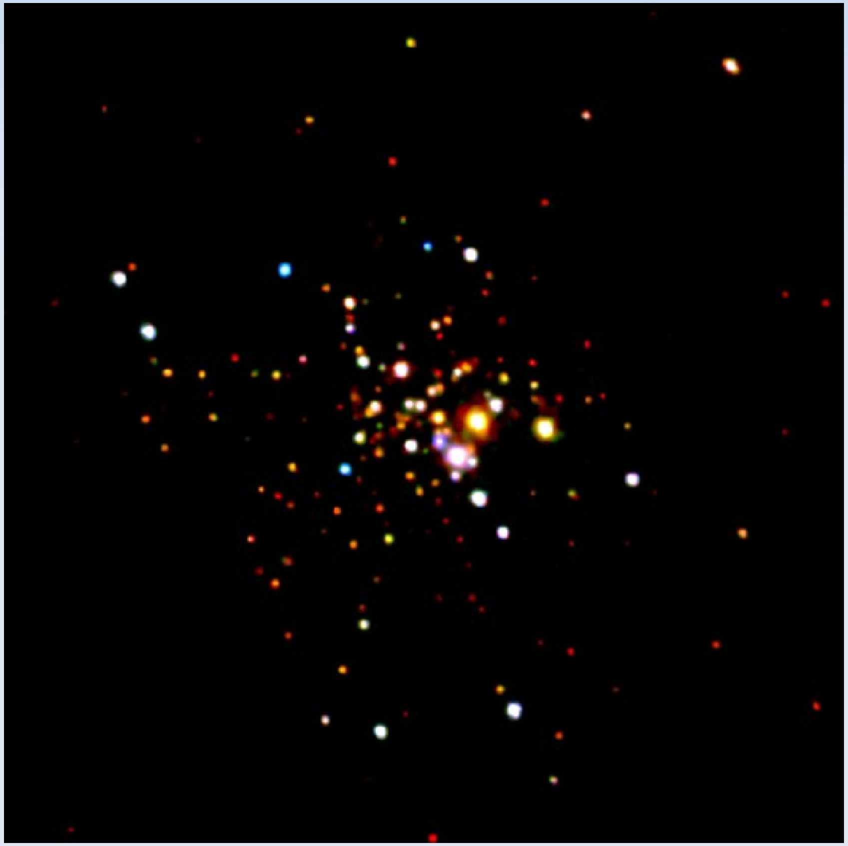


Figure from Funato et al. (2004)

Globular cluster X-ray sources

- Milky Way has 15 known "bright" GC X-ray sources (in 12 clusters)
- None is thought to be a black hole
- Also many faint X-ray sources in clusters
- Dense stellar environments lead to creation of tight binaries



The cluster 47 Tucanae in X-rays – Heinke et al., APOD

Extragalactic Studies

- Milky Way: not enough objects
- Need other galaxies to understand what cluster properties are important for producing X-ray sources
- Also need them to find rare objects like black holes (but maybe not...)

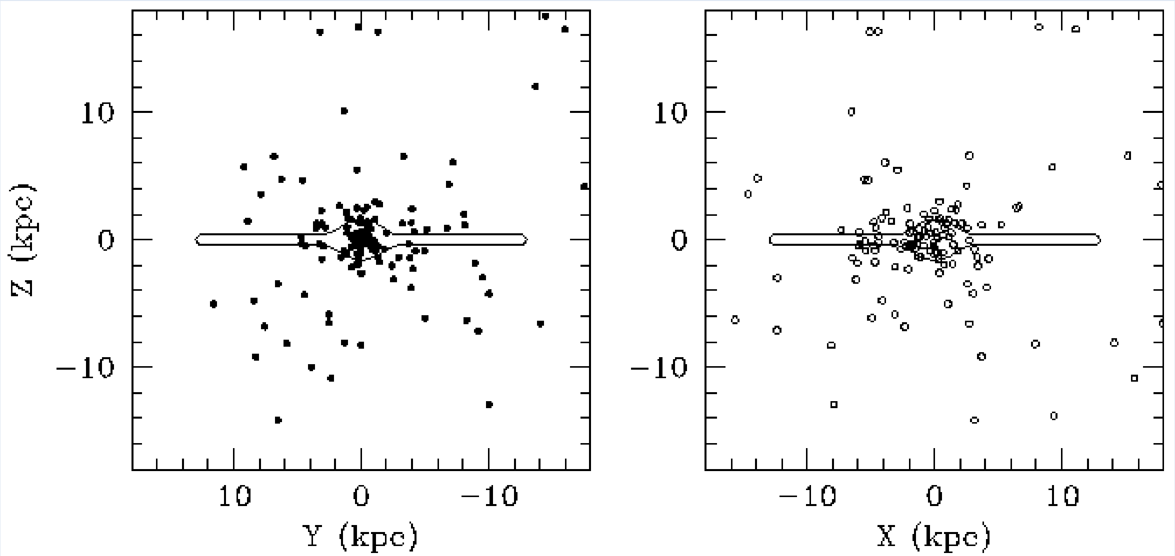
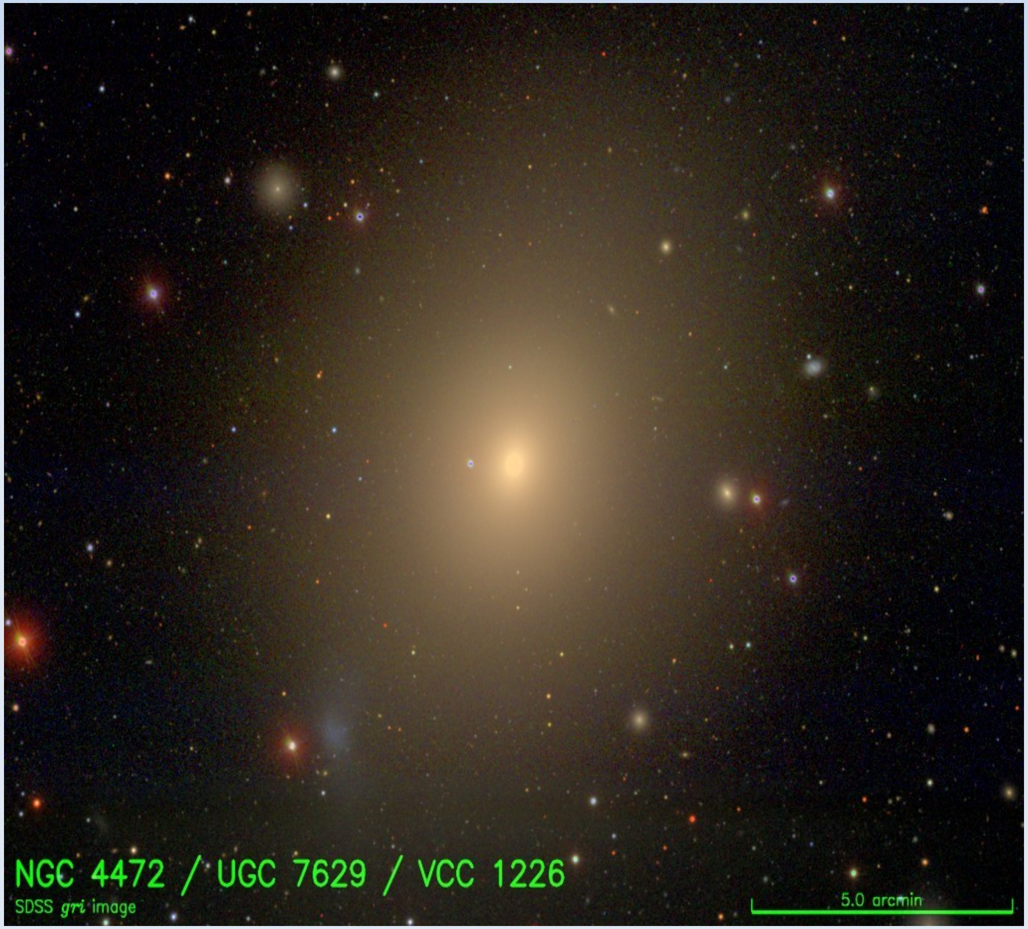


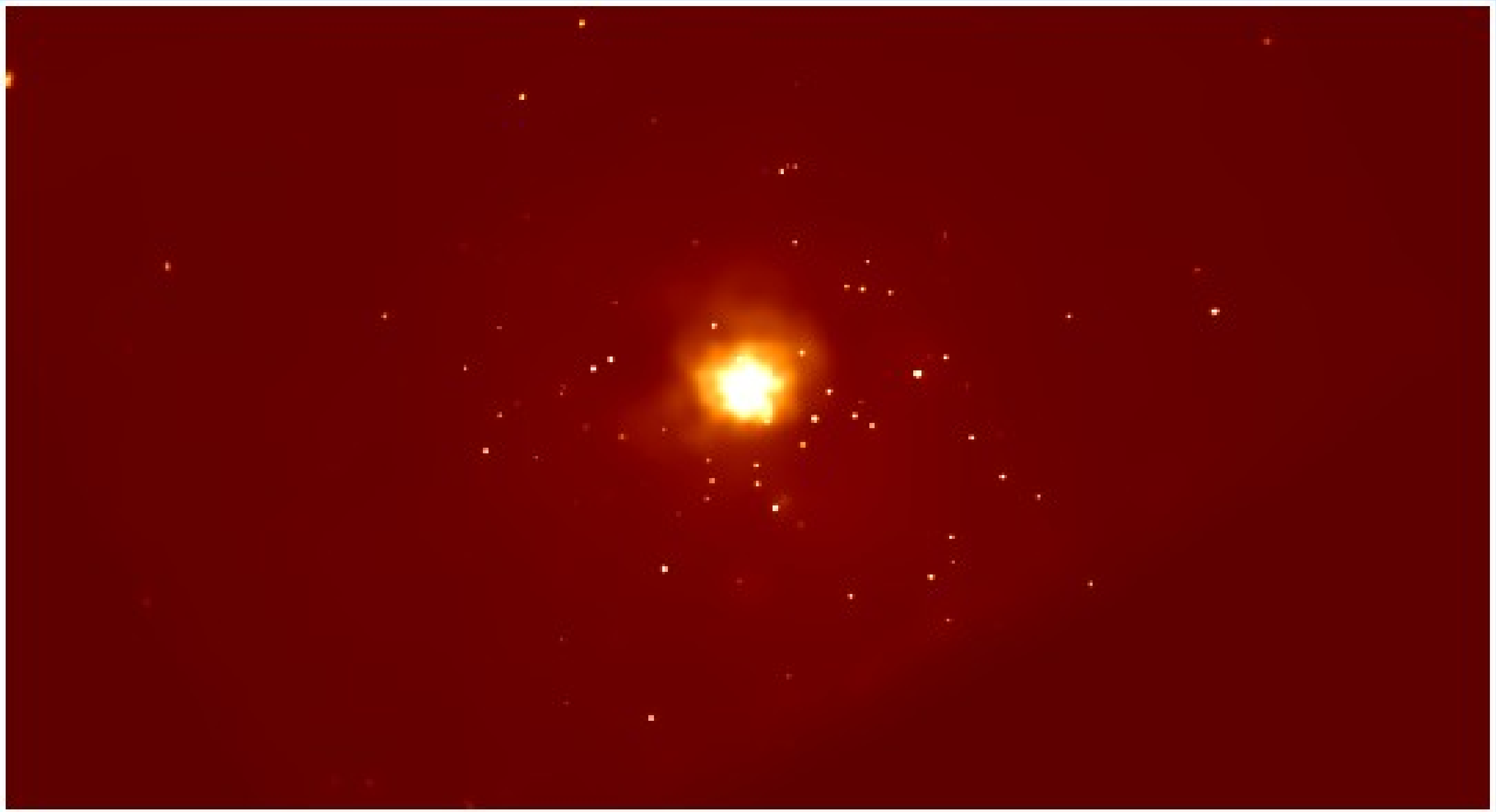
Figure of Milky Way GC system from Harris (1999)

Elliptical galaxies

- Ideal places for such searches
- Smooth light profile
  - Easy to see the clusters
- Large numbers of clusters
  - about 10 times as much of stellar mass is in clusters



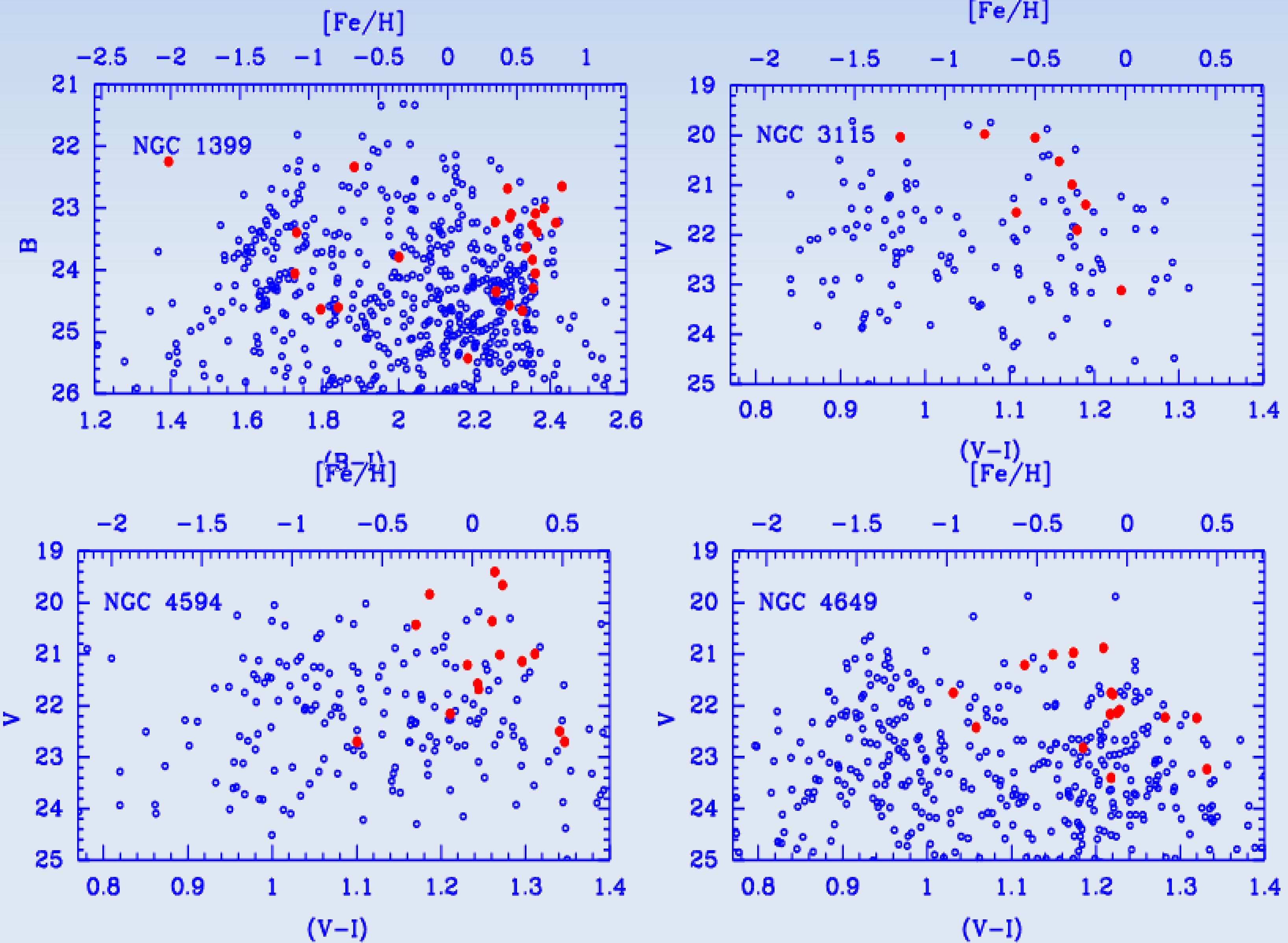
NGC 4472 in X-rays



Maccarone, Kundu & Zepf 2003

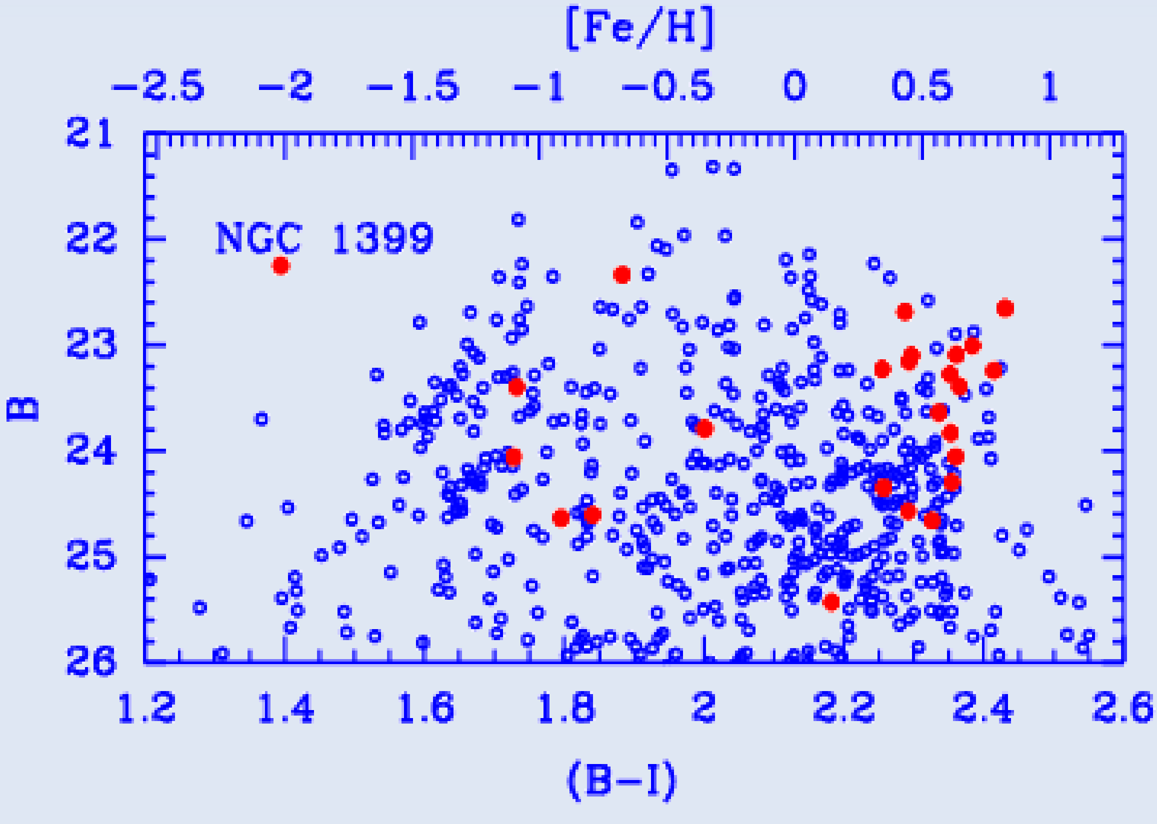
Which clusters have X-ray sources?

Kundu, Maccarone & Zepf 2007



Evidence for super-solar clusters?

- Reddest clusters **very** likely to have X-ray sources
- May have important implications for recent suggestion that bimodality of cluster colors is an artifact of color-metallicity relation, rather than real evidence of bimodality
- Only seen in NGC 1399, so may be related to location deep in a central cluster galaxy (Kundu et al. 2007)



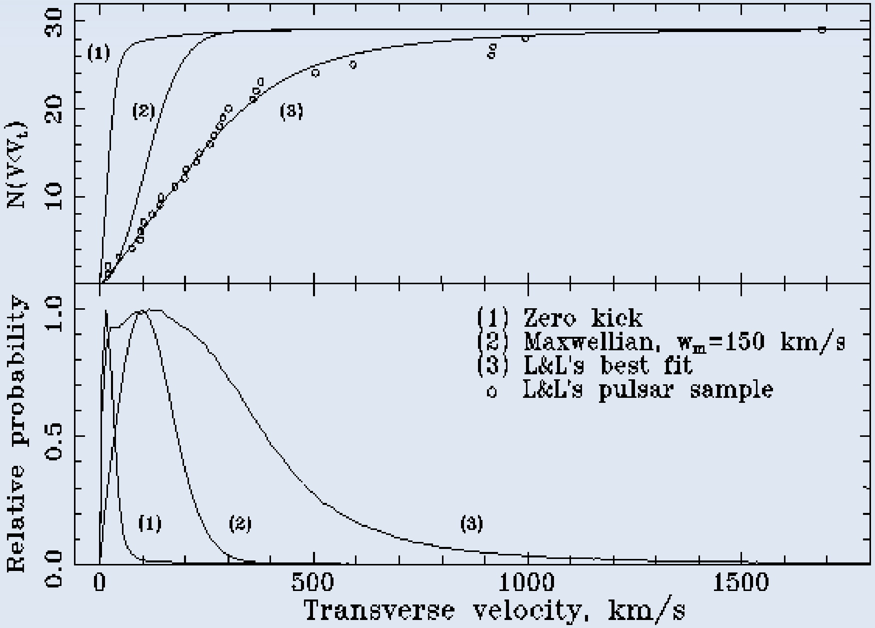
Interesting supernova physics

The number of LMXBs is proportional to the collision number (Peacock et al. 2009) and to the stellar mass (Smits et al. 2006)

Under normal supernova physics, would expect only the low kick velocity tail to be retained

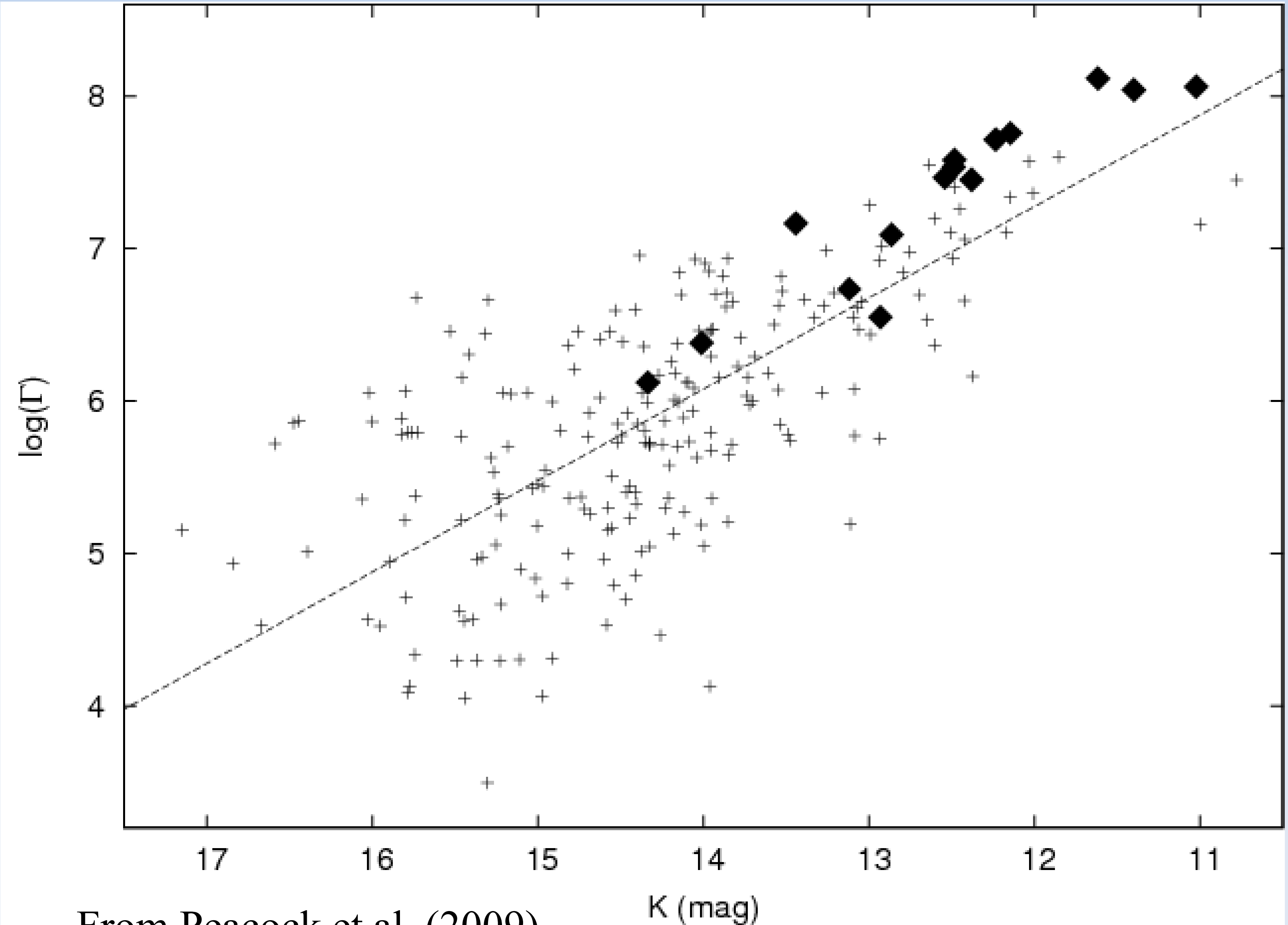
This would give a strong mass dependence

We probably have electron capture supernovae producing the retained neutron stars



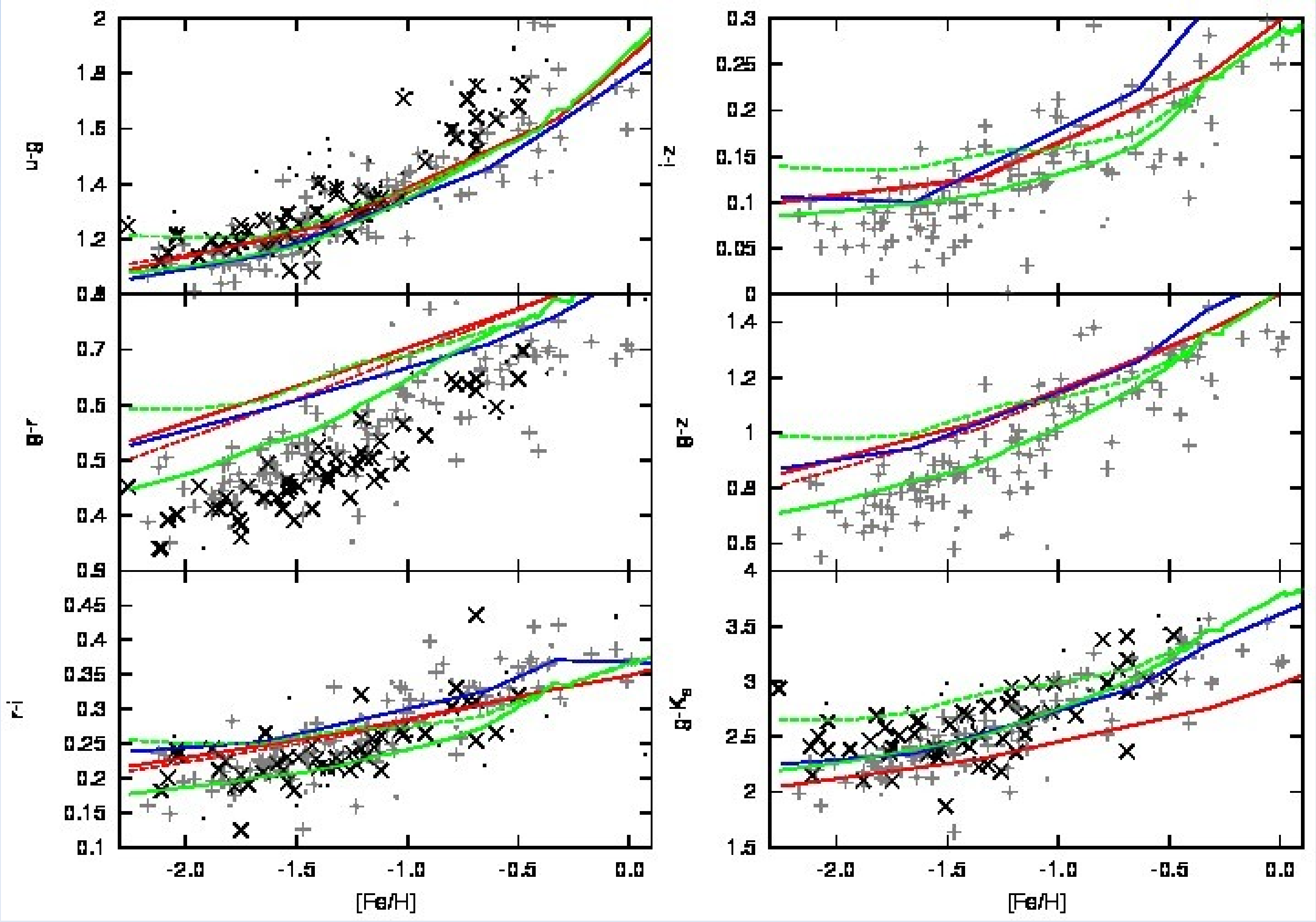
From Lipunov et al. 1996

M31: Best place to look at interaction rates



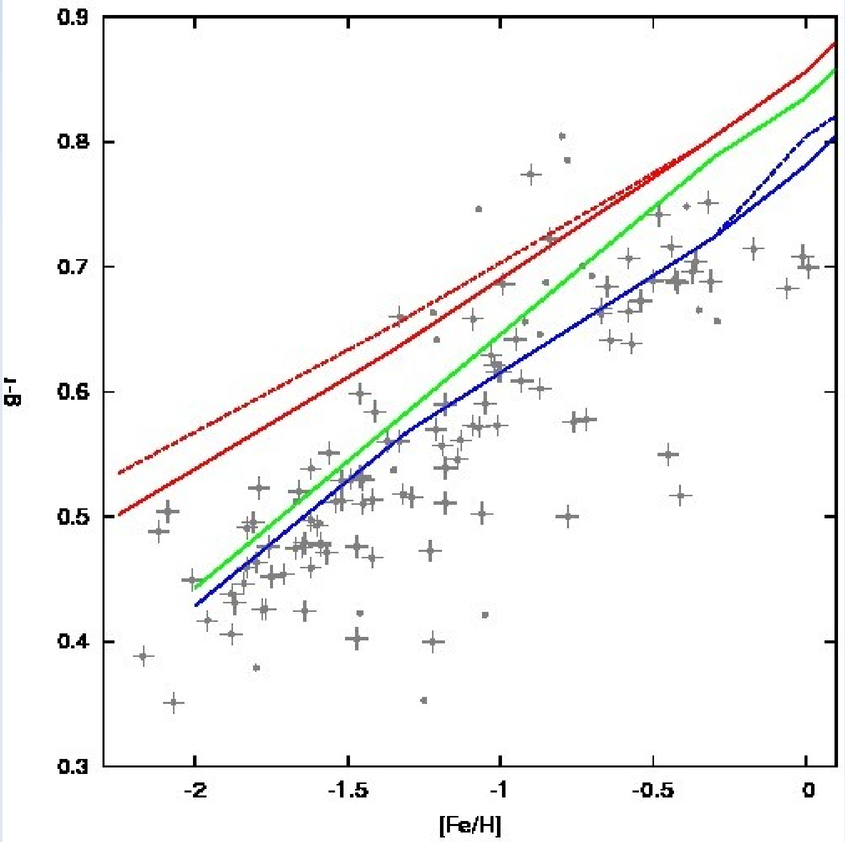
From Peacock et al. (2009)

Stellar pops from the M31 data



Variety of stellar population models fit, except with g-r problems

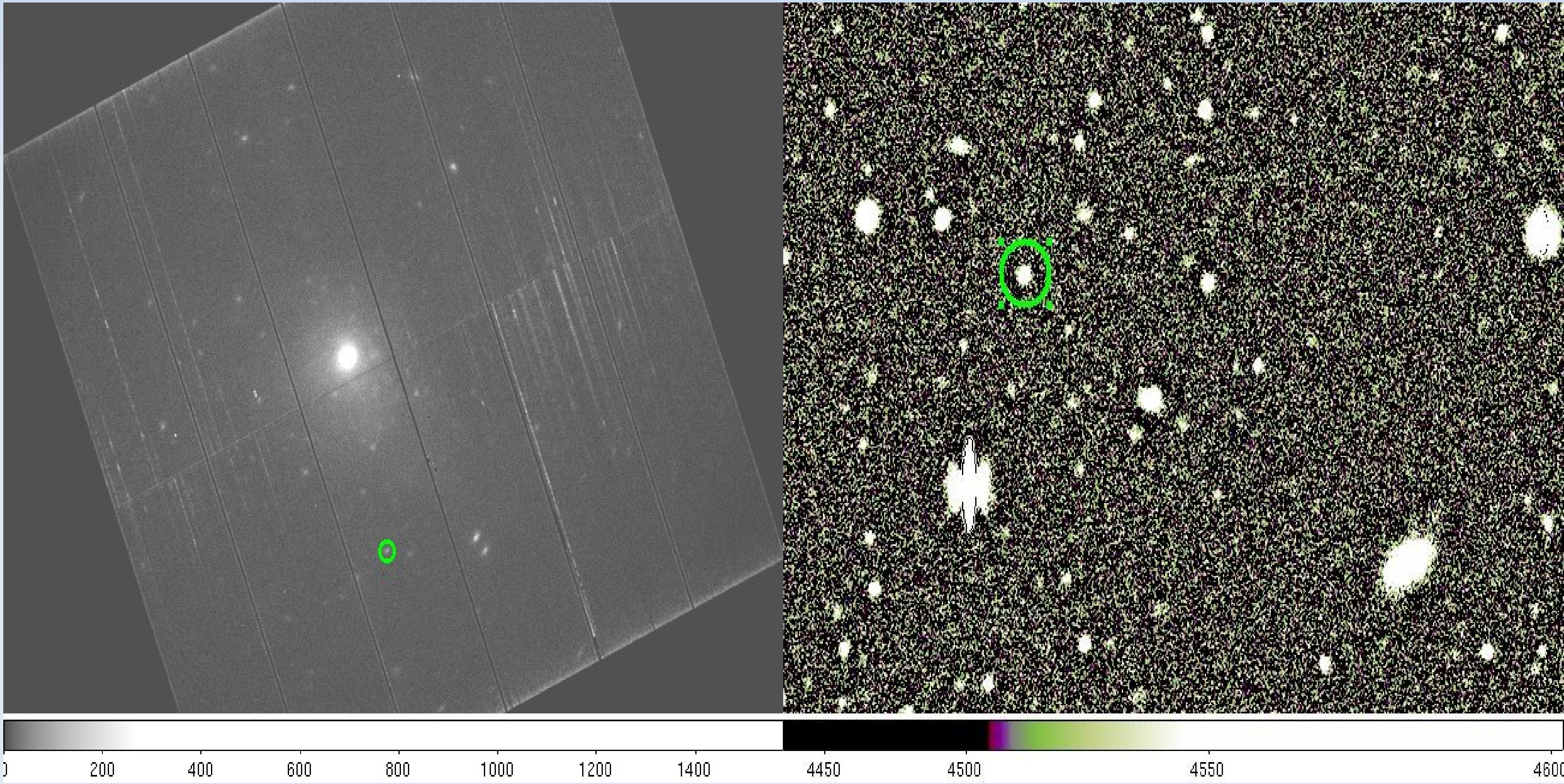
Fixing the g-r problem



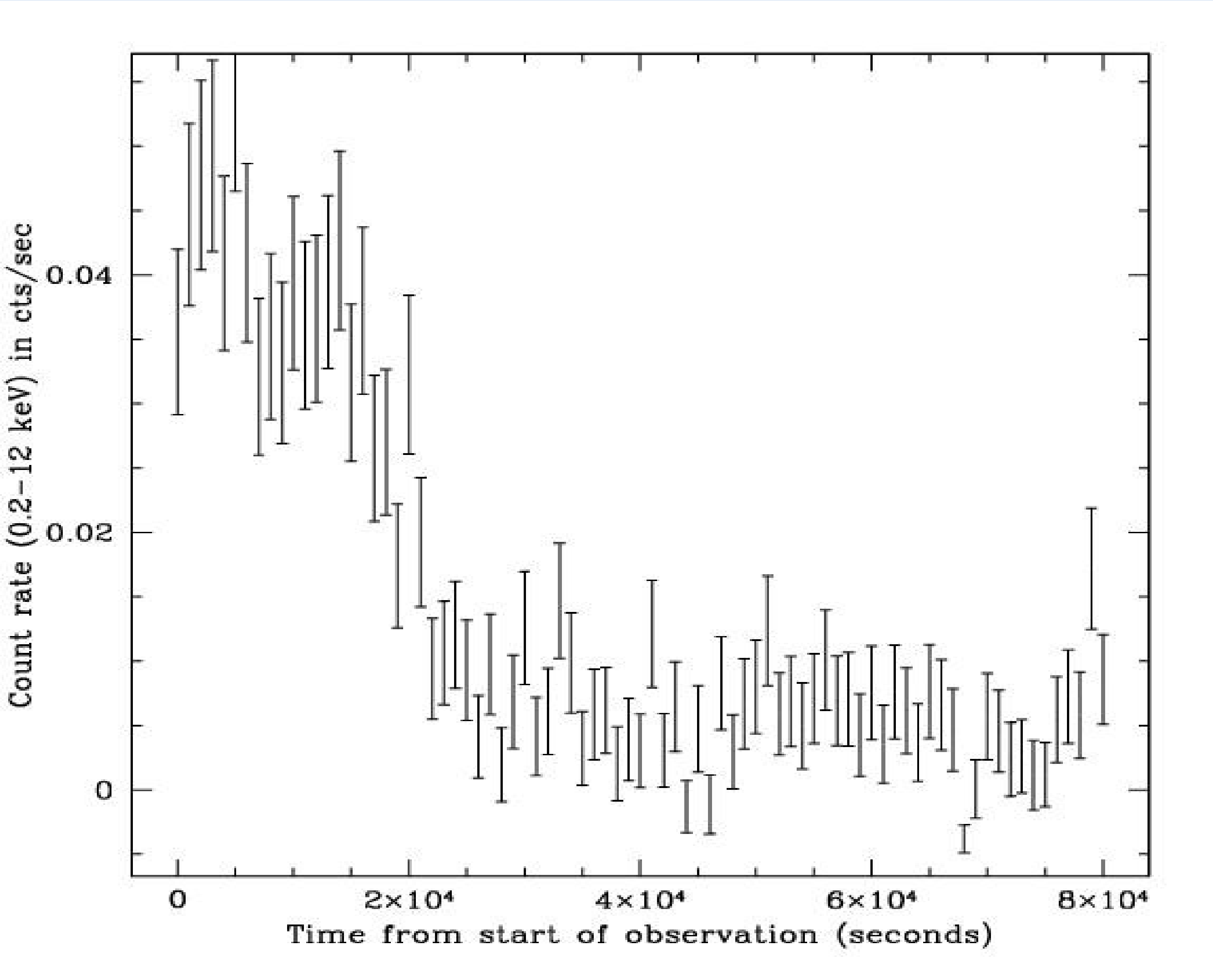
- Using empirical stellar atmospheres (a la Maraston et al. 2009), rather than Kurucz models fixes the g-r problem
- Important for understanding star formation histories of distant massive galaxies

From Peacock et al 2011

Back to NGC 4472



Highly variable

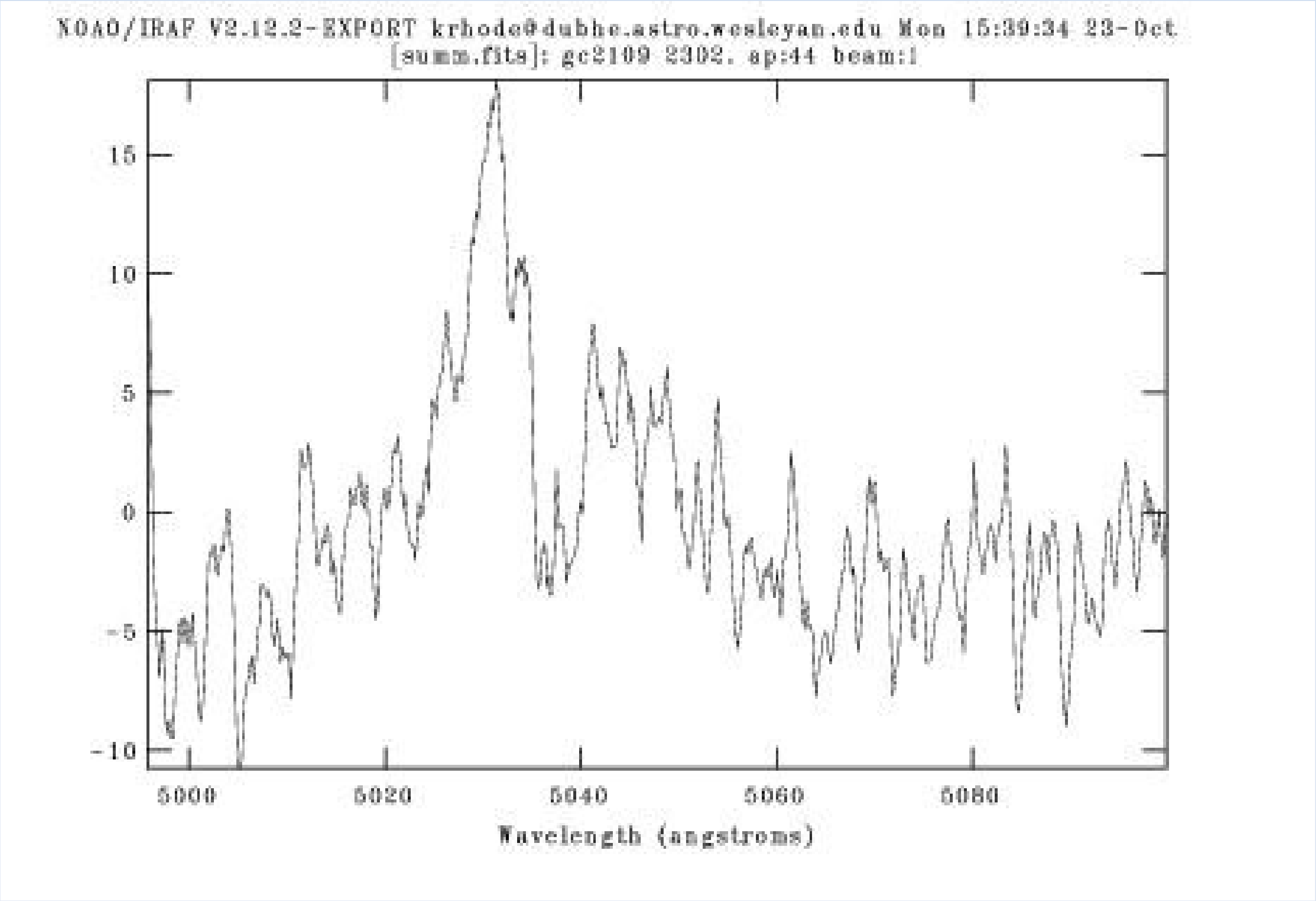


What is this object?

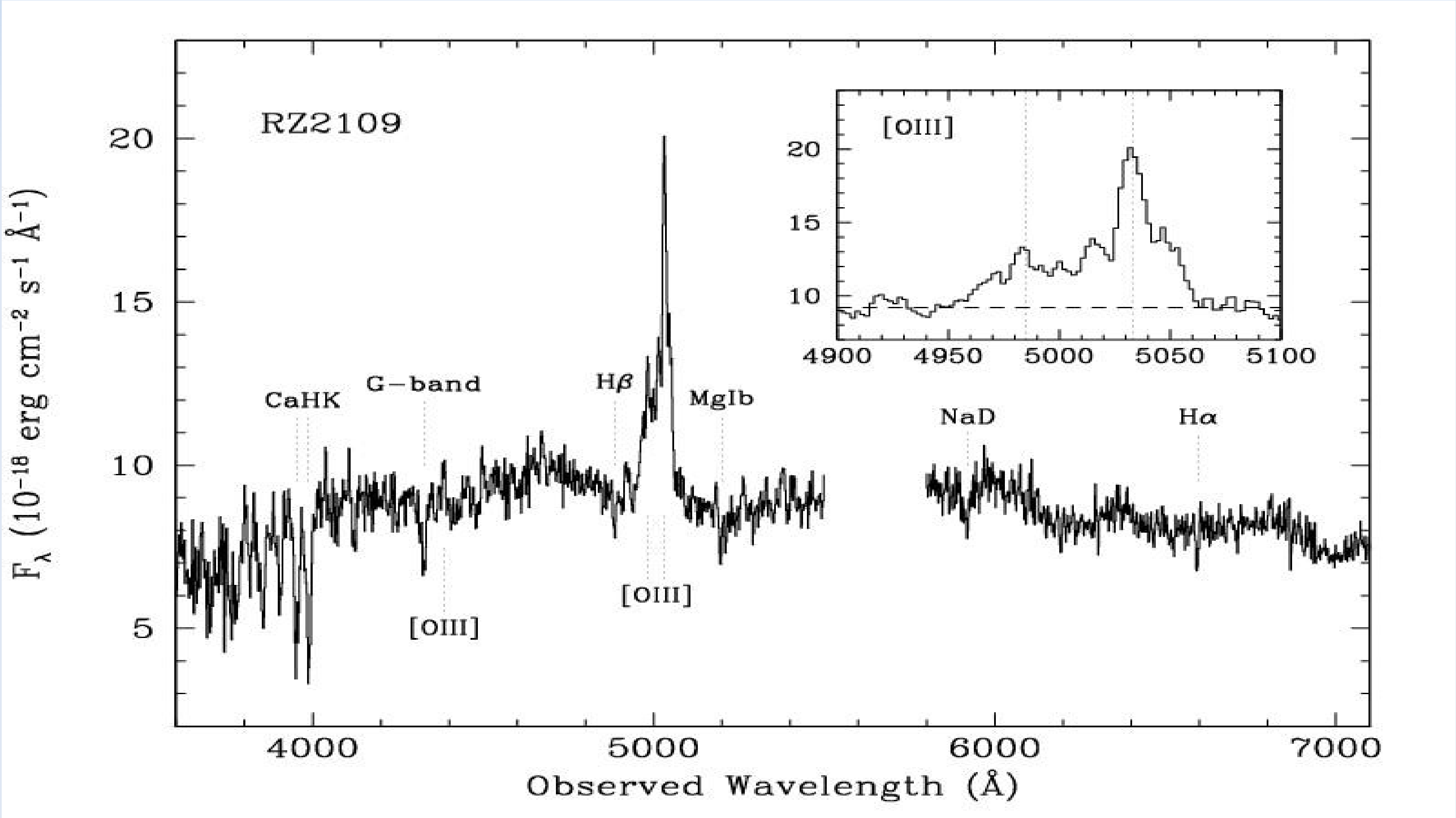
- Variability indicates that it is clearly a single object, and at this luminosity, it must be a black hole
- X-ray spectrum dominated by a 2 million K blackbody component
- Not initially clear what the black hole mass is
  - luminosity and temperature hint at something much larger than 10 solar masses
  - character of the variability (all below ~0.7 keV, and sporadic) suggested, though, that this may be super-Eddington accretion

Maccarone, Kundu, Zepf & Rhode 2007

The VLT optical spectrum



Keck spectrum



No hydrogen in optical spectrum!

- Our optical spectrum shows strong [O III] lines, but no Balmer emission
- Most obvious way to reconcile these points is with a white dwarf donor star (Gnedin et al. 2009)
- May require a triple star for formation (Ivanova et al. 2009)
- This could then lead to eccentricity cycles which could modulate the accretion rate (Maccarone et al. 2010)
  - Source is clearly strongly variable, but probably not periodic
- Or: photoionized nova shell (Steele et al. 2011; Ripamonti & Mapelli 2012) – but this probably would result in much more variability of the emission line than is seen, now ruled out by Peacock et al. (2012)

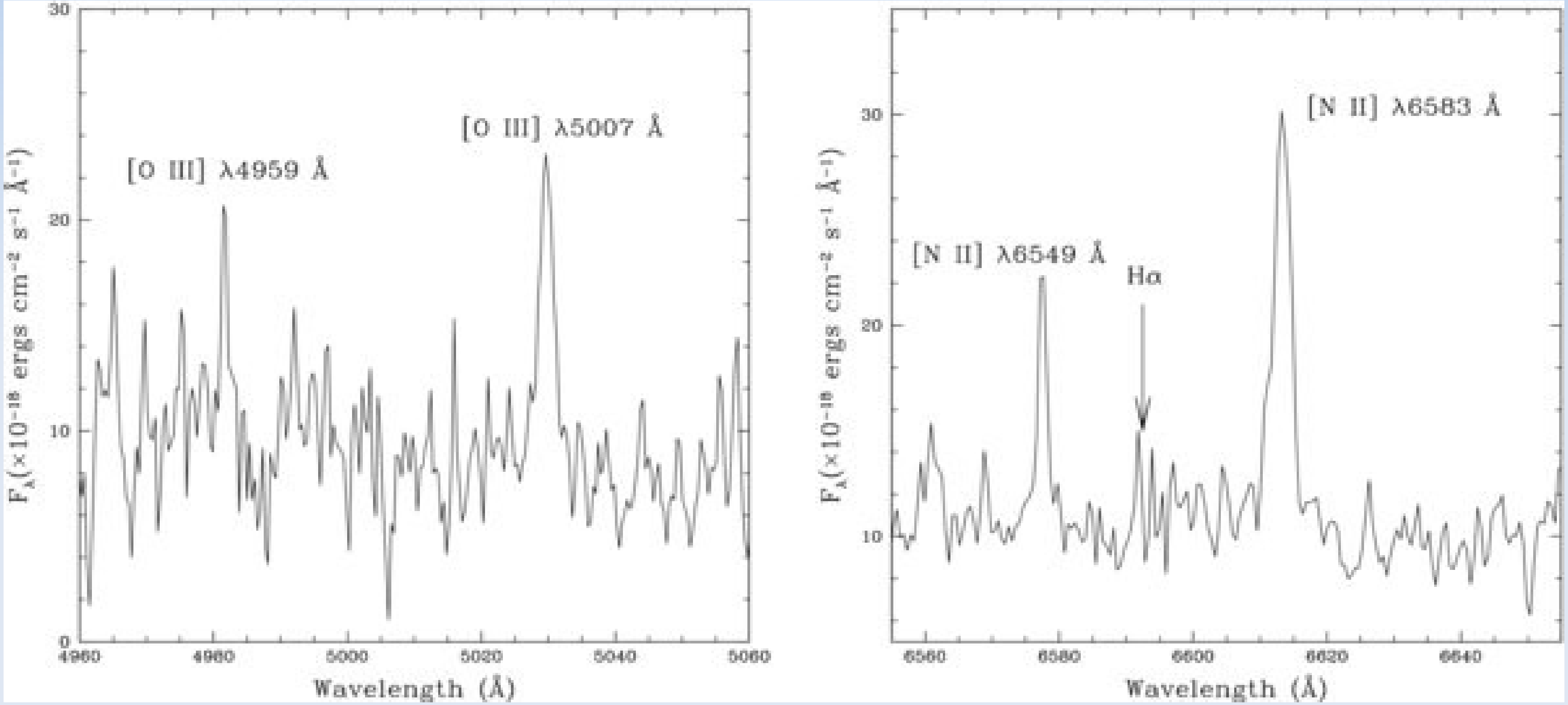
Impact for braneworld models

- Braneworld models: can solve the “weakness of gravity” problem by invoking extra dimensions of finite size
- Hawking radiation is more efficient in these models, is more parameter space into which to evaporate black holes (Emparan et al. 2003)
- A stellar mass black hole that is ~10 Gyrs old implies an extra dimension size of <3 microns, an order of magnitude smaller than the best constraint from torsion pendula (Gnedin, TJM, et al. 2009)

Many more GCBHs

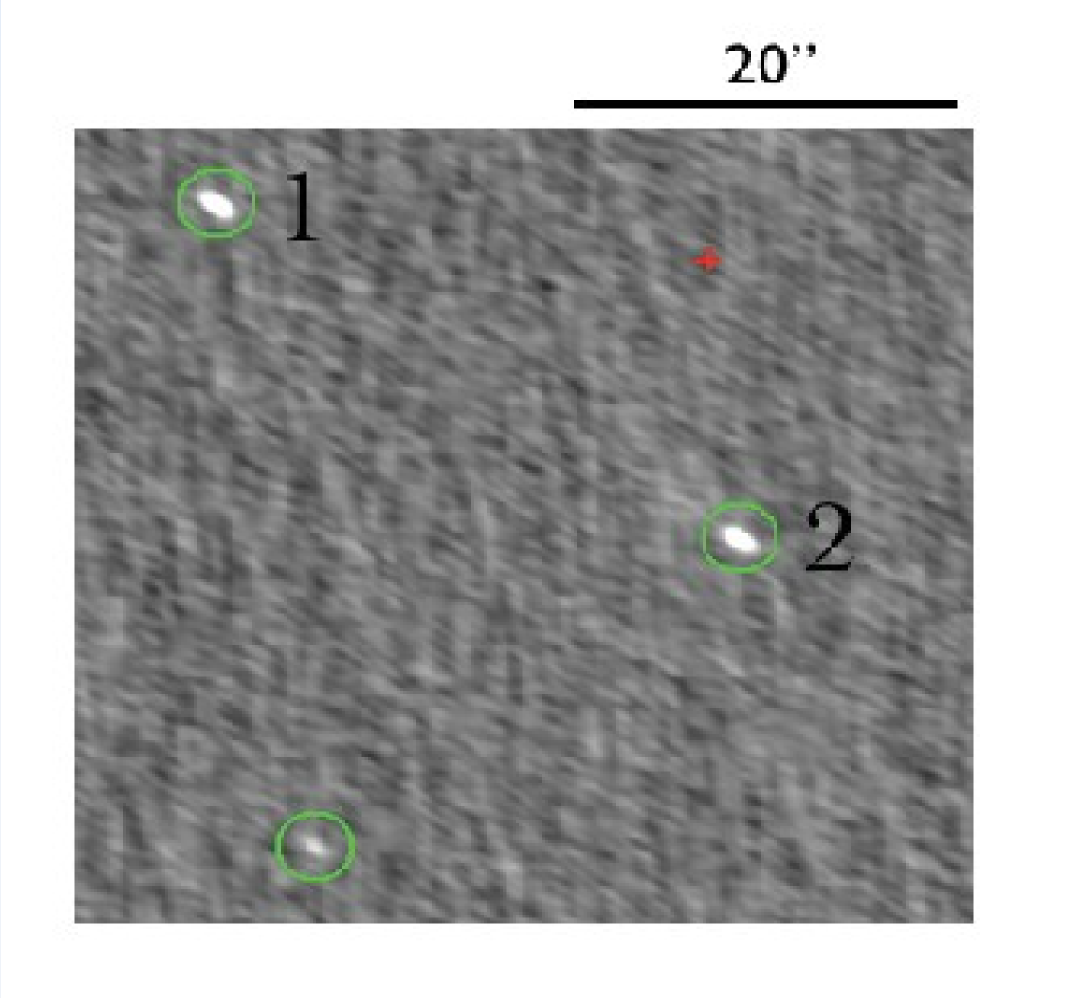
- Several more such objects have been confirmed by variability
  - Another in NGC 4472, one in NGC 3379, and one in NGC 1399 (TJM et al 2010; Brassington et al. 2010; Shih et al. 2010)
- A few have X-ray luminosities and spectra which are not characteristic of neutron stars - both in M31 (Barnard et al. 2009)
- One in NGC 1399 seems to show “super-Eddington state” plus standard black hole spectral states (Shih et al. 2010)
- Another in NGC 1399 shows unusual emission lines and a high X-ray luminosity (Irwin et al. 2010)

The NGC 1399 source



- Strong [O III], [N II] in optical spectrum
- No Balmer emission
- WD tidally disrupted by IMBH ? (Irwin et al 2010)
  - But then why is there nitrogen?
  - Disrupted HB star? (Claussen et al. 2012) But requires finely tuned triple evolution
- R Corona Borealis star whose wind is photoionized by an unrelated BHXB? (Maccarone & Warner 2010)
- Suggests we should search for RCB stars in Milky Way clusters – they should be a dynamically enhanced population

Two black holes in a Milky Way cluster



Strader, Chomiuk, Maccarone, Miller-Jones & Seth, 2012, Nature

Conclusions

- Properties of cluster which predict formation rate of X-ray sources include metallicity and collision rate
    - Metallicity effect is not well understood but gives fundamental information about the most metal rich clusters
- Black holes in globular clusters are starting to appear to be common
    - Seem to be in the same type of clusters as X-ray sources on the whole, but more objects are needed to be sure
    - Emission line objects present some interesting puzzles
    - Can do fundamental physics with these objects, but they are also important probes of globular cluster dynamics
    - We are starting to see the first Milky Way globular cluster black holes