How Fossil Are Fossil Groups?

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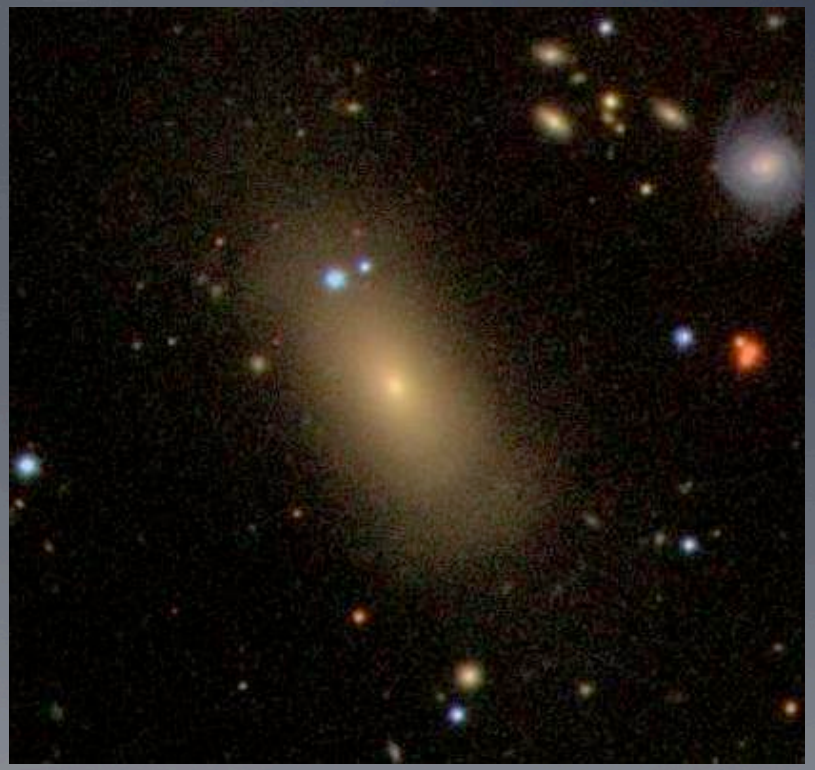
What is a fossil group?

- Formal Definition (e.g. Jones et al. 2003, D'Onghia et al. 2005, Santos et al. 2007):
  - $\Delta m_{12} = 2$ (or $\Delta m_{14} = 2.5$) → dominated by a single, massive elliptical
  - Extended X-ray halo with L_x greater than 10^{42} erg s^{-1}
  - Some number of less luminous ($< L_*$) companions
  - 10-40% of groups with M = 10^{13}-10^{14} M_o

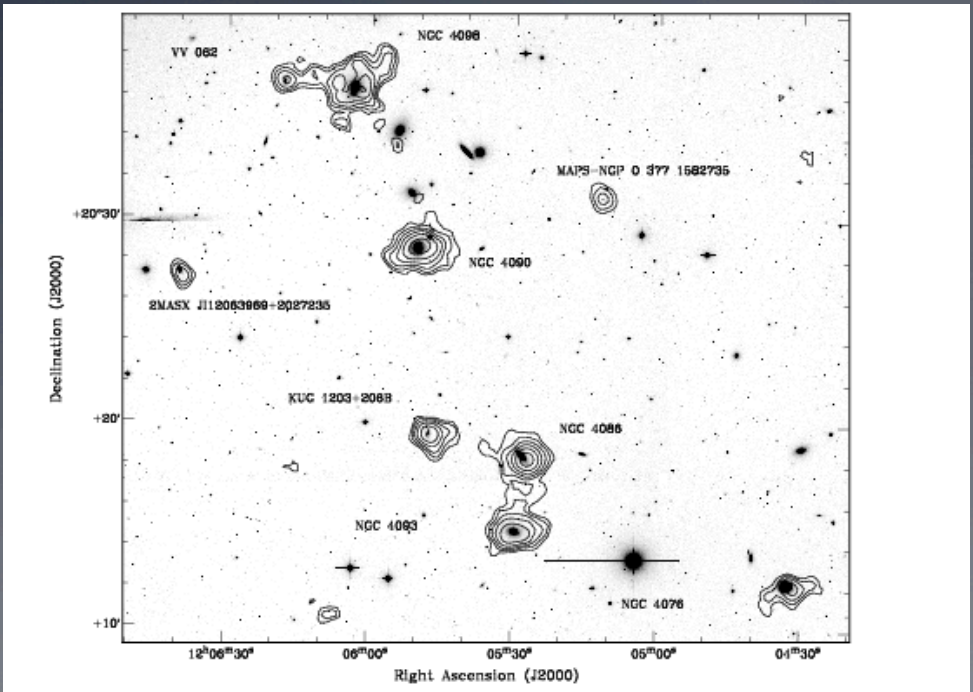


Fossil group, Sloan Digital Sky Survey (SDSS)

Fossilizing a Galaxy Group (via simulations)

- Preface: The "age" of a galaxy group = *assembly time* = lookback time at which the halo has accreted 50% of its mass (e.g. Dariush et al. 2010)

Early Dynamical Evolution of Galaxy Groups



Freeland et al. 2009

- Interaction rate in spiral-dominated groups is high.
- A number of cases in which galaxies reside in a common HI envelope
- HI detected galaxies in evolved groups reside well outside the X-ray extent
- Spiral dominated/HI rich → elliptical dominated/X-ray rich

Dynamical History of Groups

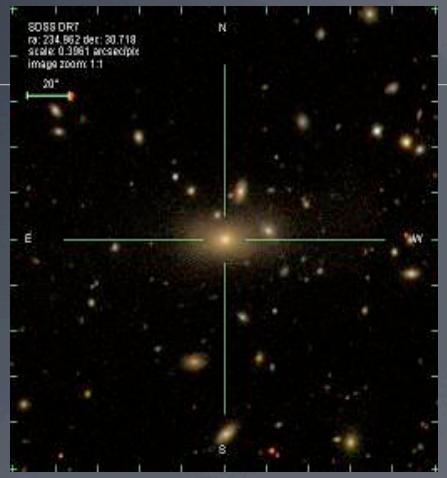
- It is a question of assembly…
  - How long ago did the galaxies in the group become gravitationally bound?
- "Evolved" groups
  - Assembly times ~ 5-8 Gyr (Dariush et al 2010)
  - Dynamically relaxed
  - X-ray luminous, elliptical dominated
  - Possible "fossil"
- "Young" groups
  - Recent assembly times, still collapsing
  - Lack luminous diffuse x-ray emission (Rasmussen et al. 2006)
  - More spiral rich
  - Local Group?

Fossilizing a Galaxy Group (via simulations)

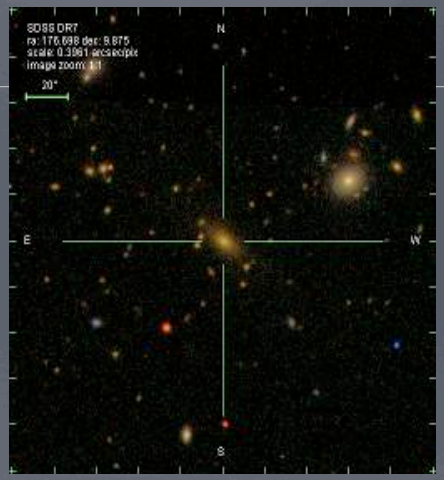
- Preface: The "age" of a galaxy group = *assembly time* = lookback time at which the halo has accreted 50% of its mass (e.g. Dariush et al. 2010)
- "complete" merging of L_* galaxies into a single object
- Fossils accreted most of their mass earlier than non-fossils
  - Last major merger > 3 Gyr ago
  - Accrete larger satellites earlier than non-fossils
- Older = more dynamically relaxed
- It's just a phase → most fossils transition to non-fossils within 4 Gyr

Example Fossil Groups

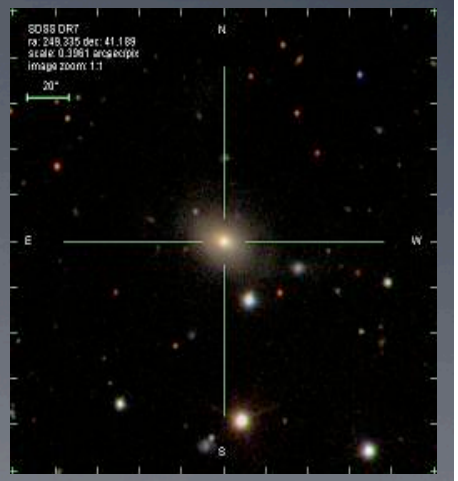
SDSS J141004+ 414520



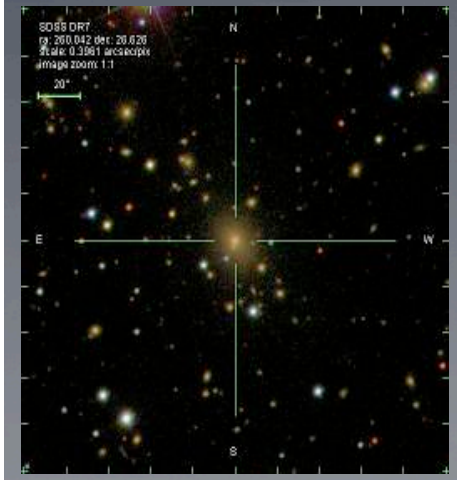
SDSS J153950+ 304303



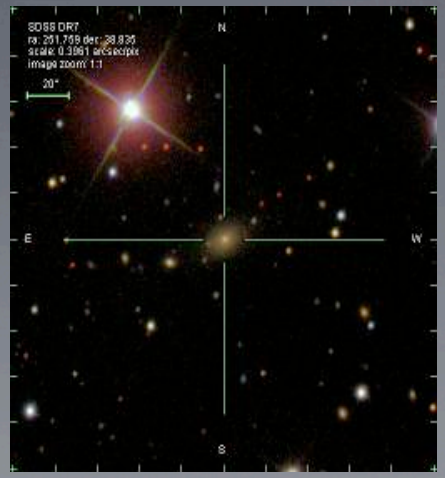
SDSS J114647+095228



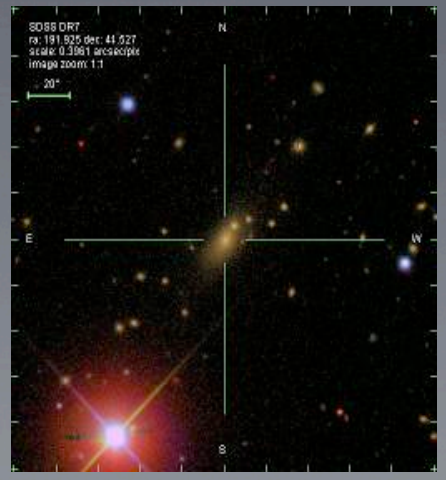
SDSS J163720+411120



SDSS J172010+263732



SDSS J164702+ 385004



SDSS J124742+413137

Some questions….

- Do the stellar populations of fossil groups reflect a quiescent past ~ 3 Gy?
- Does the observed radio continuum emission in fossil groups reflect systems that have not had a major merger in recent times?
- Are AGN responsible for maintaining the thermal properties of the extended X-ray emission in fossil groups?
- Do the velocity distributions of galaxies surrounding fossil groups suggest imminent infall of luminous satellites?

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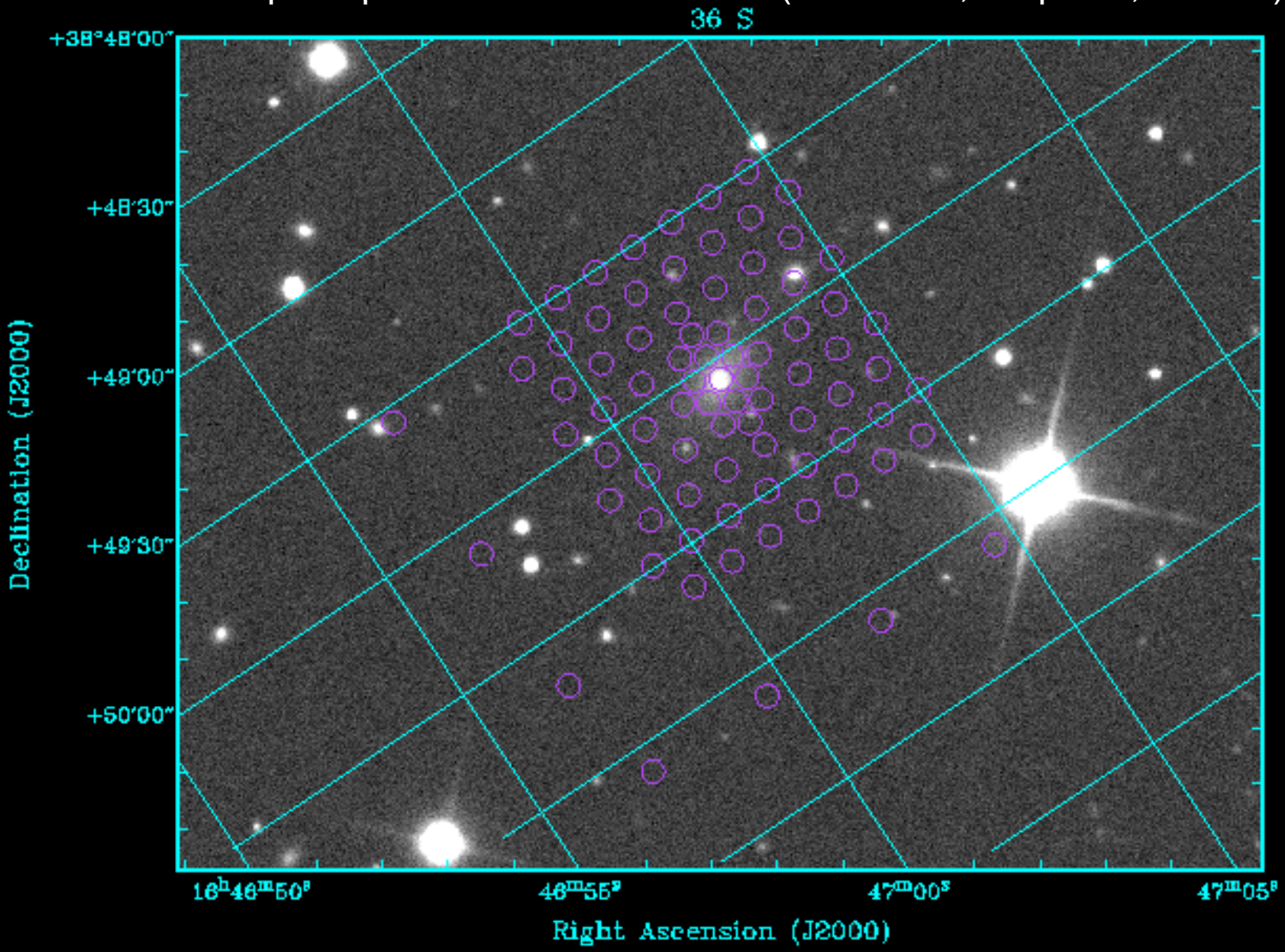
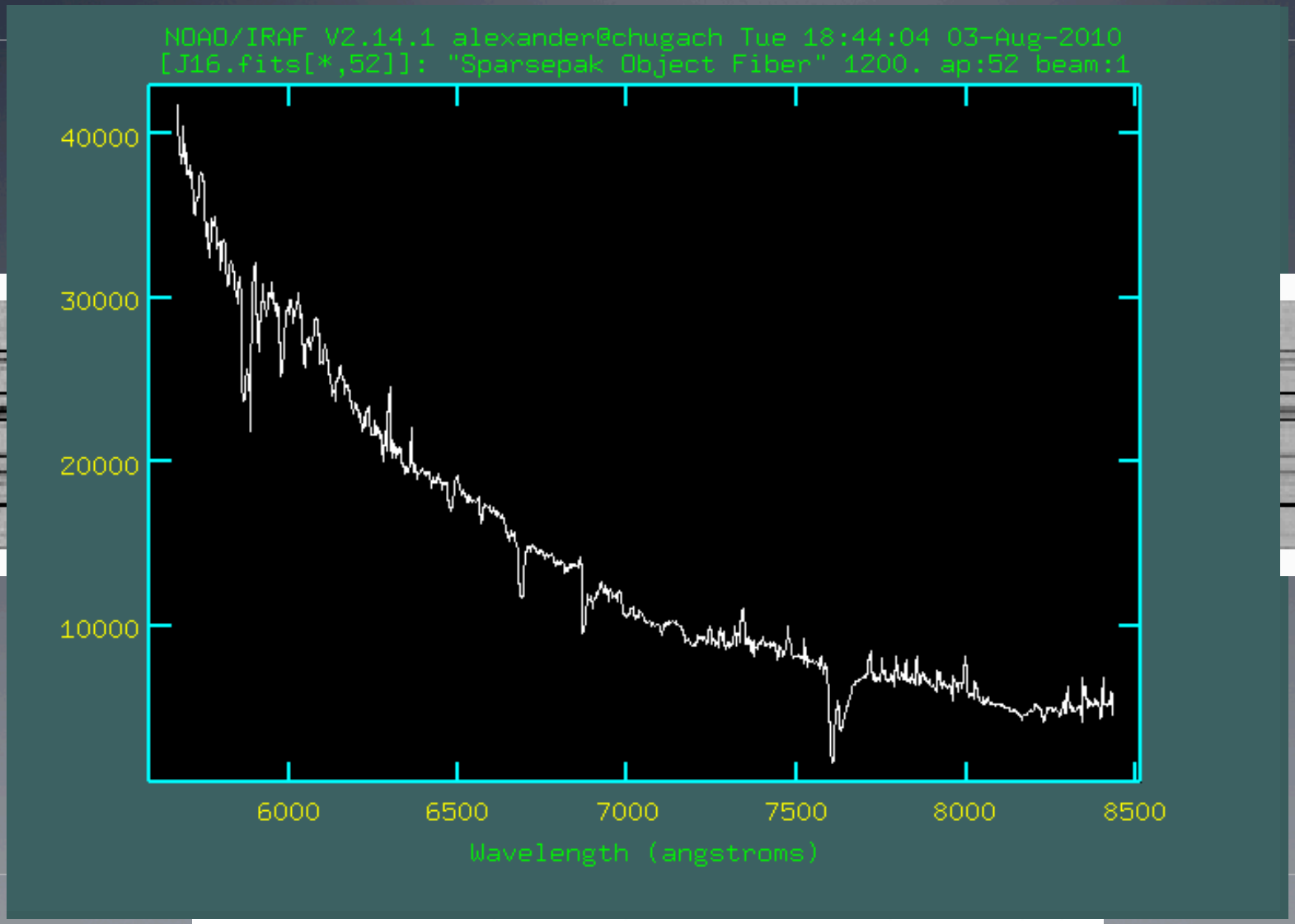
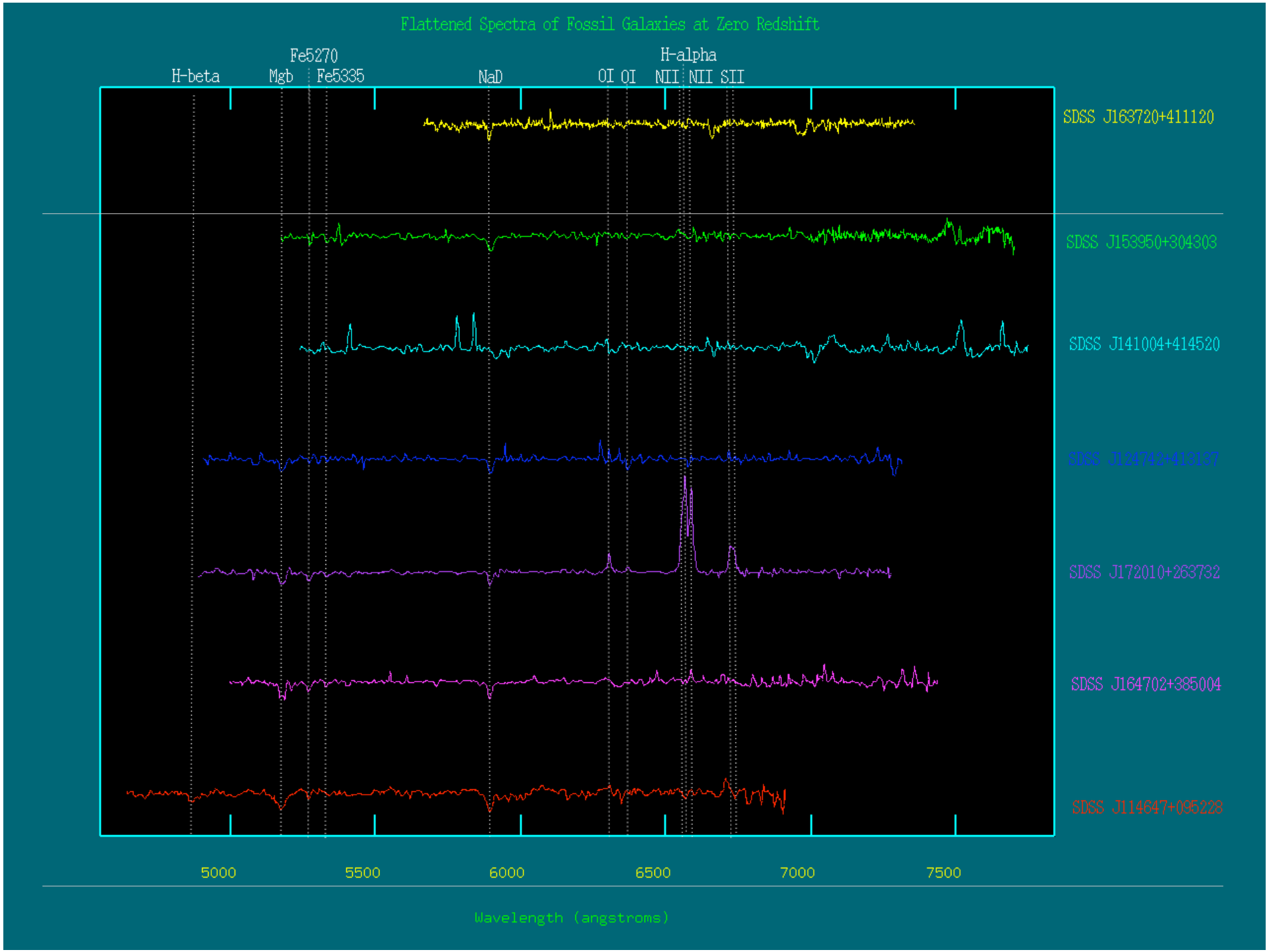
WIYN 3.5m Sparsepak observations of FGs (Alexander, Paquette, Wilcots)



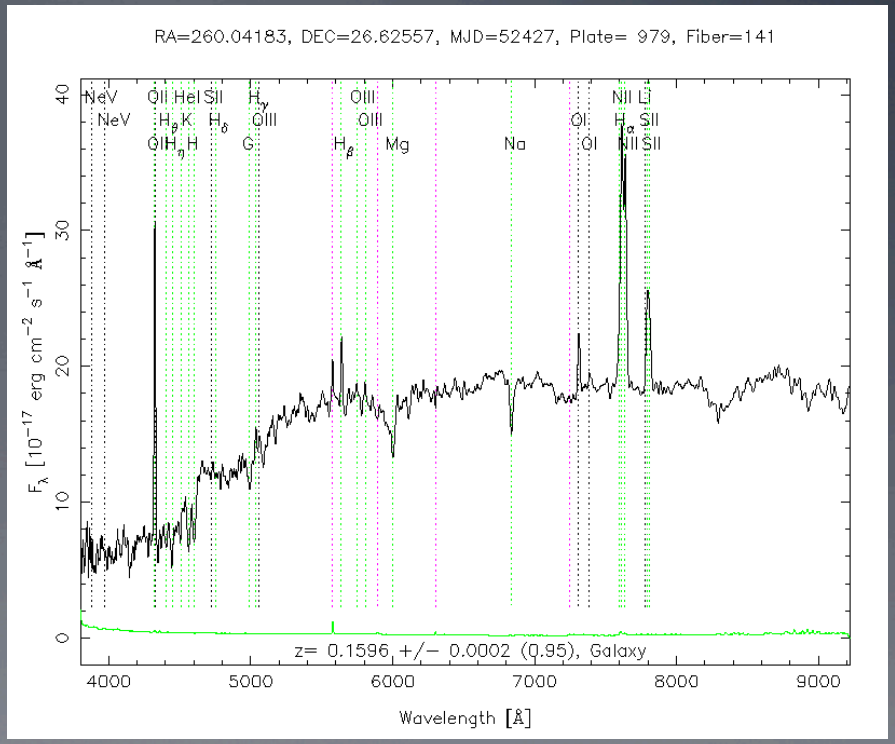
Data Reduction



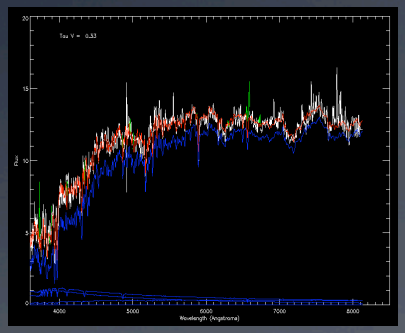

Flattened Spectra of Fossil Galaxies at Zero Redshift
H-beta
Mgb
Fe5270
Fe5335
NaD
OI OI
NII
H-alpha
NII SII
SDSS J163720+411120
SDSS J153950+304303
SDSS J141004+414520
SDSS J124742+413137
SDSS J172010+263732
SDSS J164702+385004
SDSS J114647+095228
5000
5500
6000
6500
7000
7500
Wavelength (angstroms)

SSP Modeling

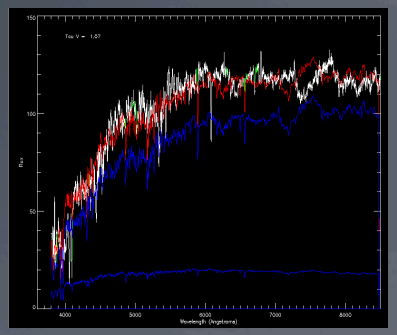
- SSP model courtesy of Christy Tremonti
- Models galaxy spectrum as linear superposition of up to 10 different model stellar spectra
- Used WIYN+SDSS spectra



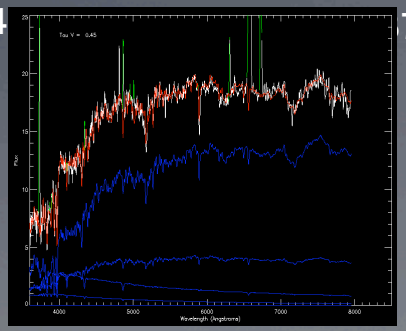
Preliminary Fits



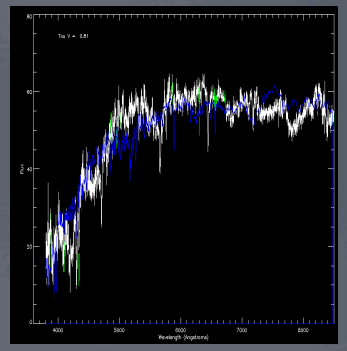
SDSS J164702+385004



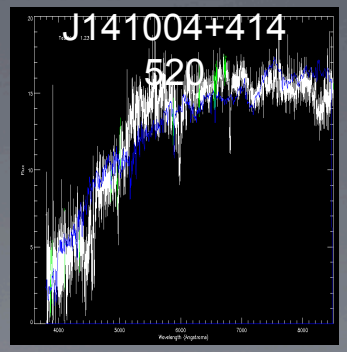
SDSS 720+411120



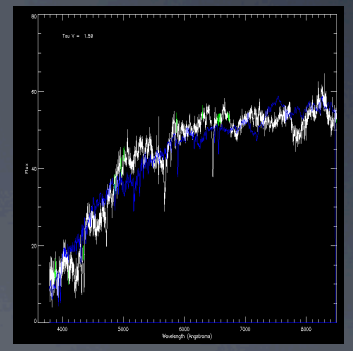
SDSS J172010+263732



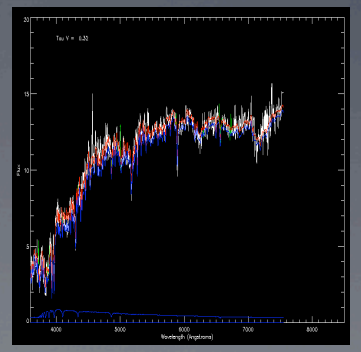
SDSS



SDSS J124742+413137



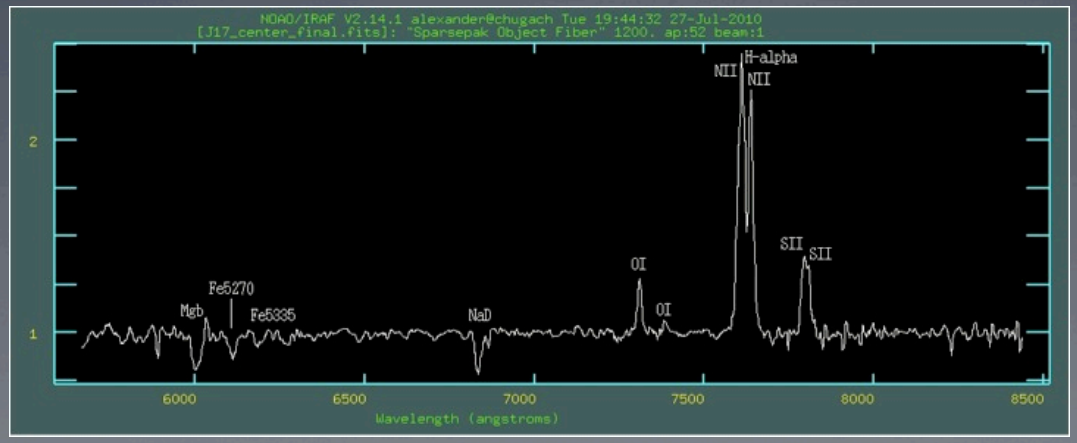
SDSS



SDSS J114647+095228

What did we learn?

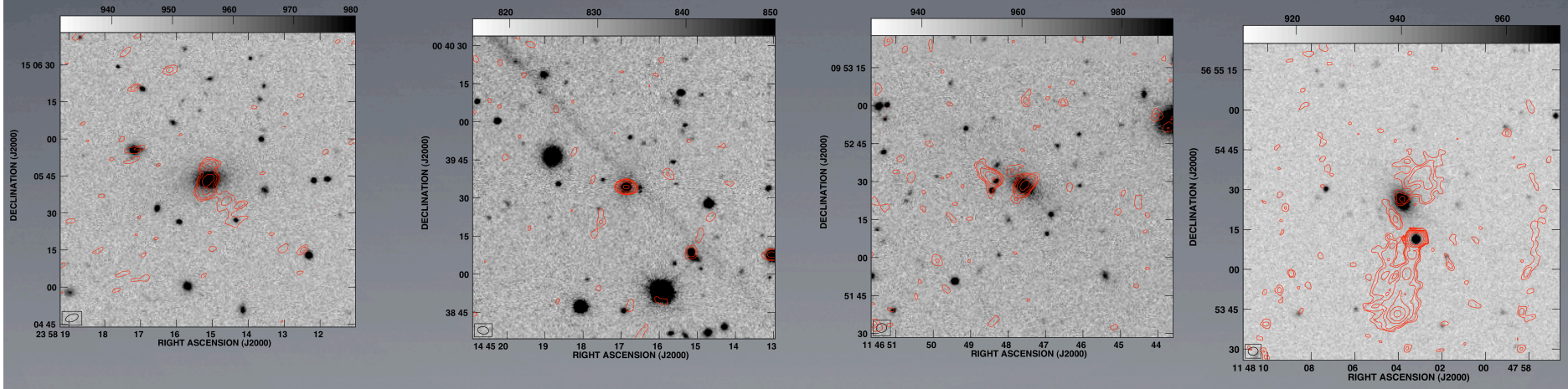
- SSP modeling → no significant SF in past ~ Gyr → 90% of stellar population is older than ~2.5 Gyr
- One object - SDSS J172010.03+263732.0 – had strong optical emission lines



- Detected faint (Δmag > 2) companions centered around FGs

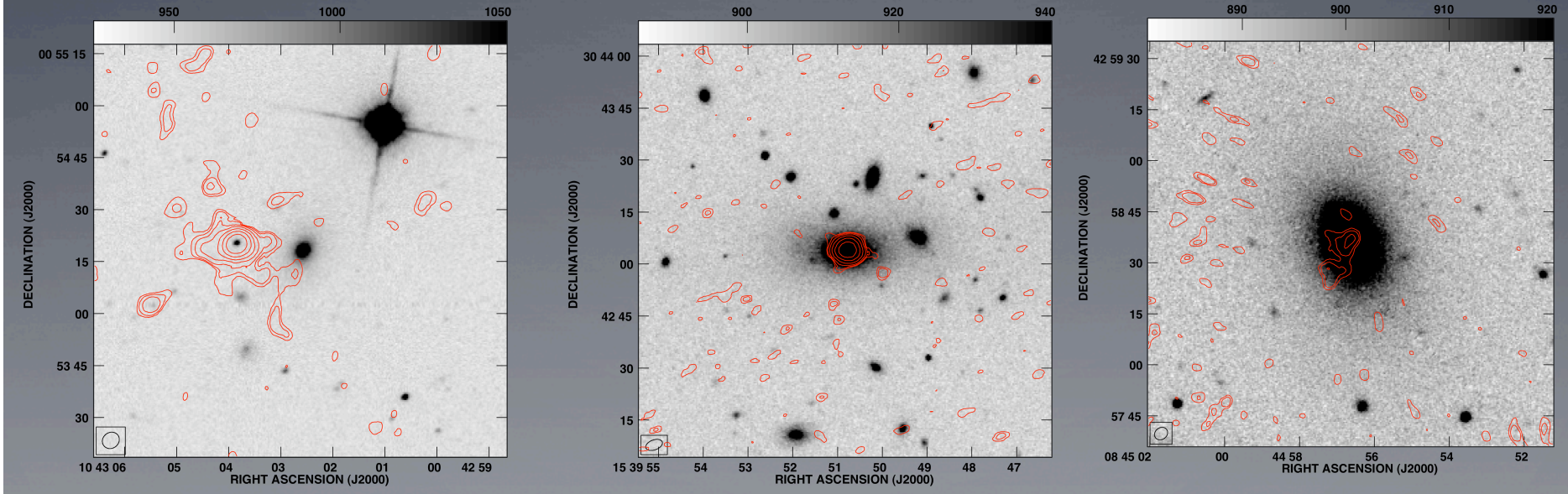
1.4 GHz Continuum survey of FGs (Hess, Wilcots, Hartwick 2012)

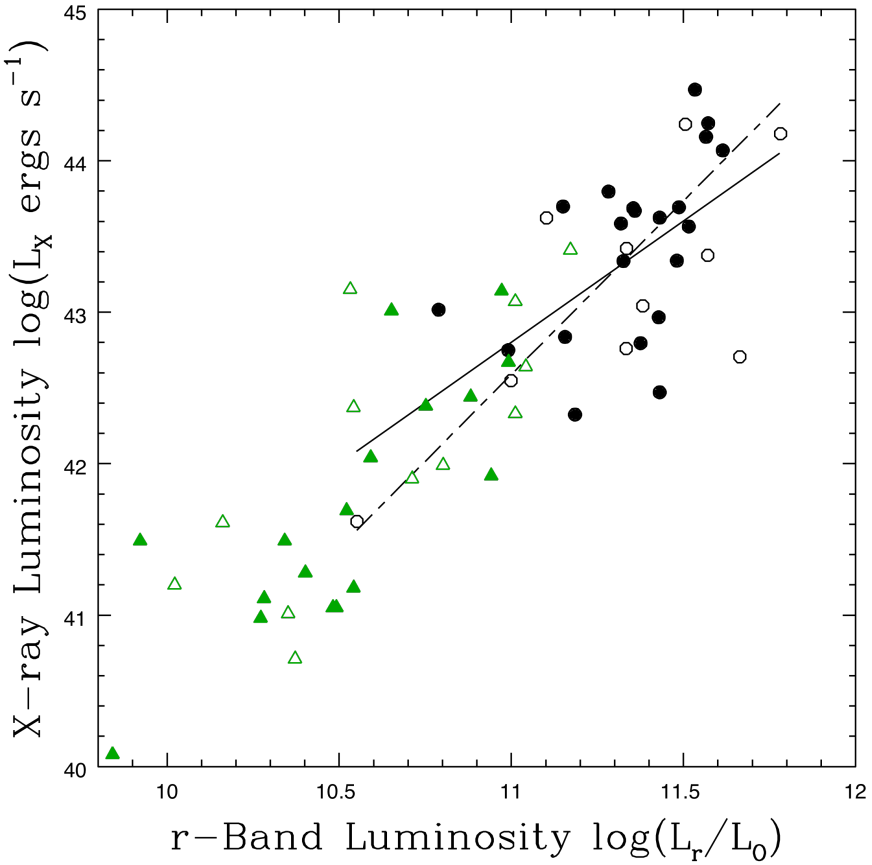
- 33 FGs from Santos et al (2007) sample
- VLA 1.4 GHz survey, 30-90 μJy beam^{-1},
- Detect 20/33, 19/20 have $L_{1.4GHz}>10^{23}$ W Hz^{-1} → *radio loud*



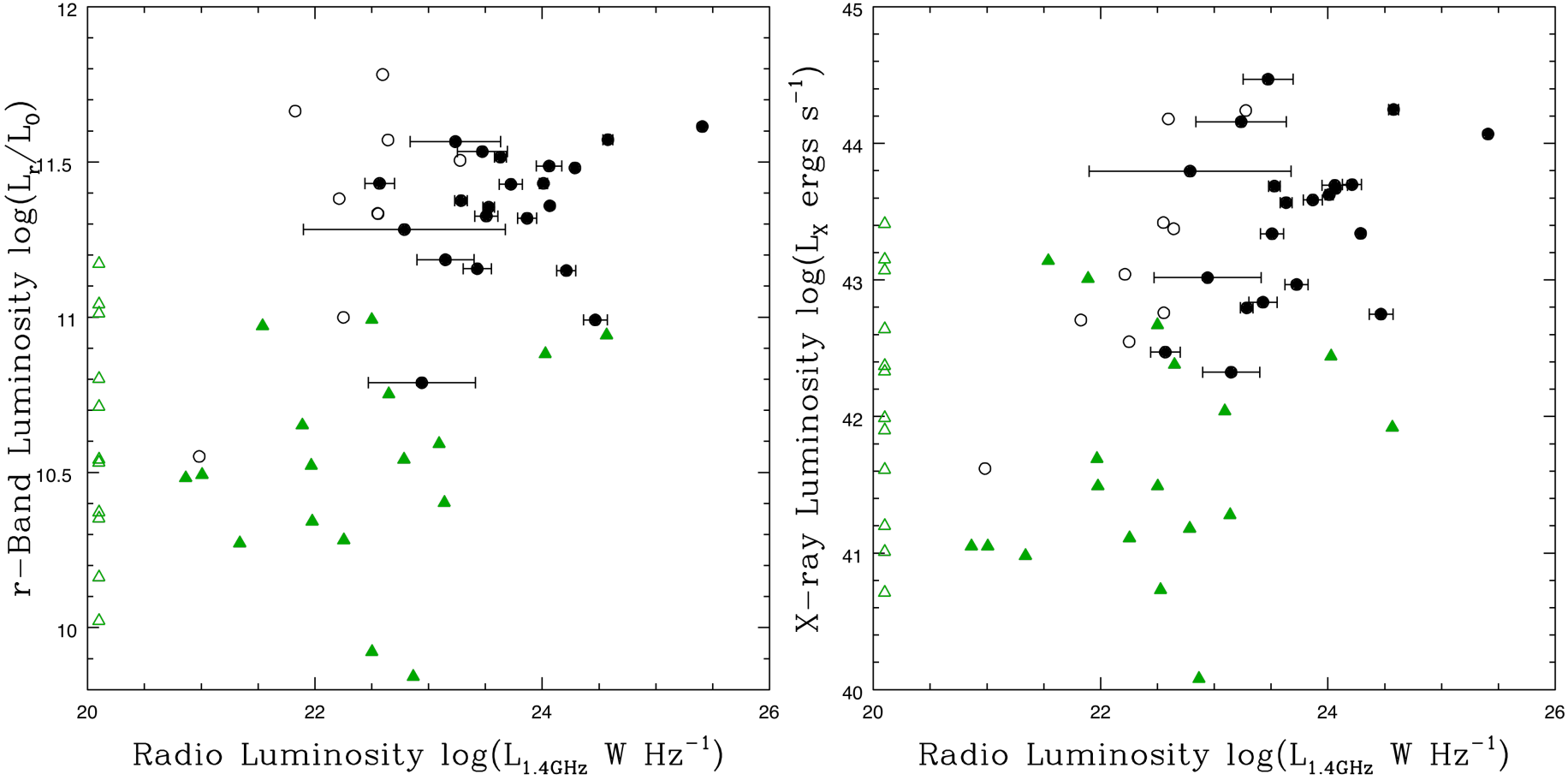
1.4 GHz Continuum survey of FGs (Hess, Wilcots, Hartwick 2012)

- Compare with X-ray luminous, non-fossils (Croston et al. 2005 survey of GEMS sample)
- Where do FGs lie on various correlations established for non-fossils?





Filled circles indicate radio detections, open circles are 3-sigma upper limits for those FGs for which we do not detect a radio source.



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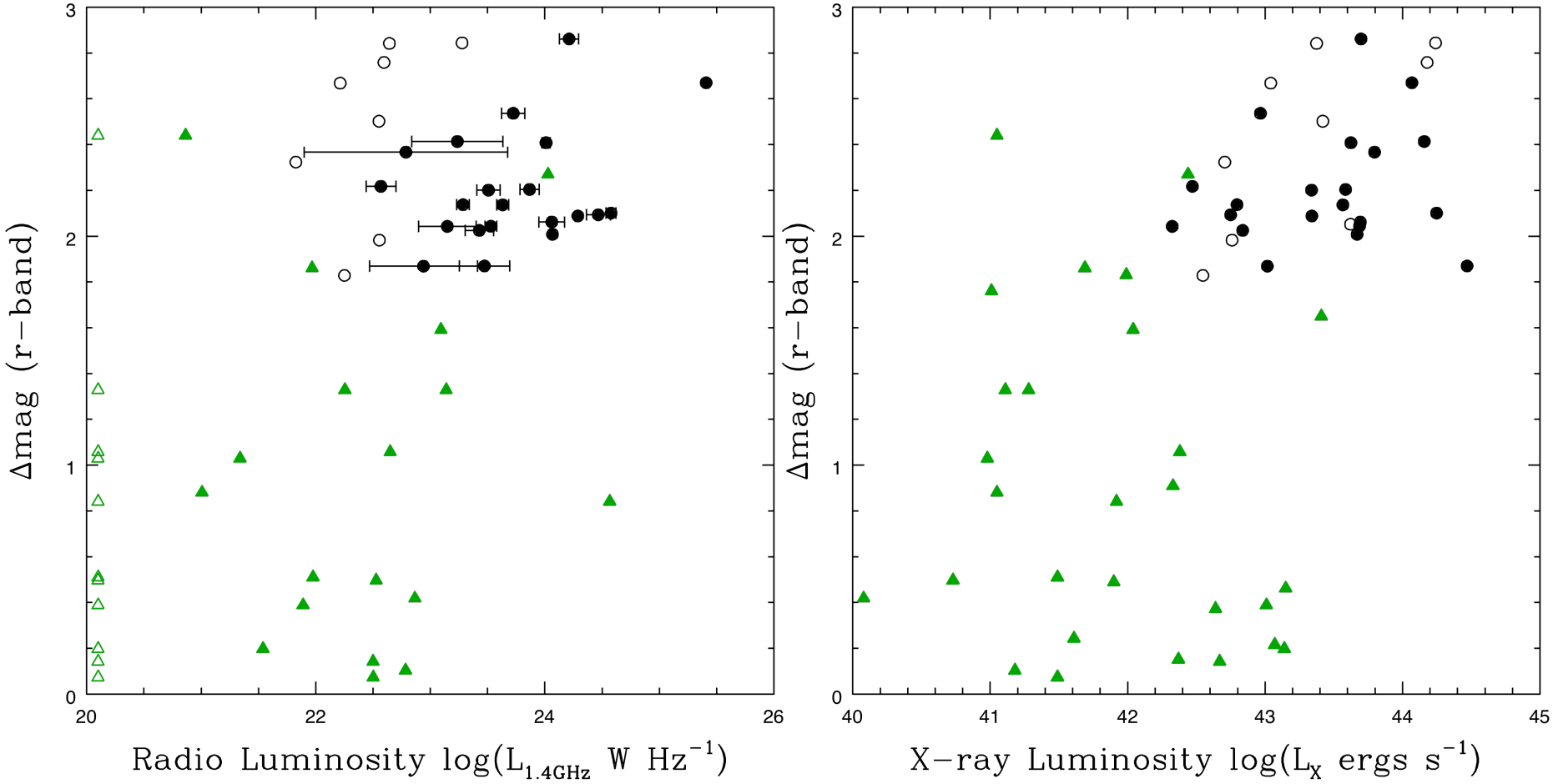

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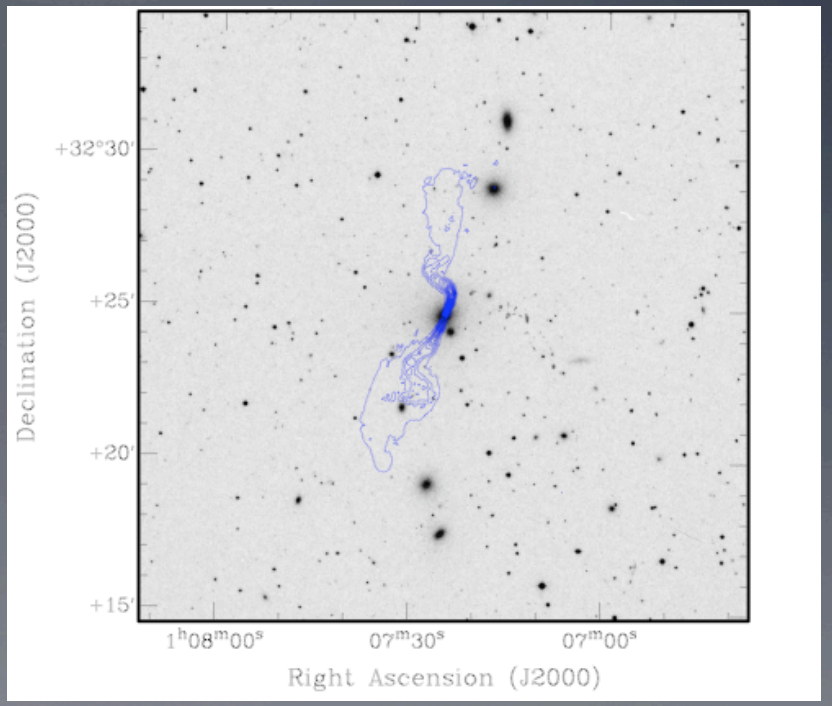
AGN Feedback in Groups

- How much energy is dumped into the IGM?
  - Assume AGN is triggered by cooling, turns on after t_{cool}
  - duty cycle of 5 x 10^8 yrs, jet luminosity 10^{43} erg s^{-1}
  - Efficiencies of ~0.1% can impart ~1 keV per particle over group virial radius



610 MHz map of NGC 383

Jacquart, Hess, Wilcots

Radio Continuum properties of FGs

- FGs are radio bright and the radio properties are roughly correlated with stellar mass, X-ray luminosity, assembly time.
  - Fraction of early type galaxies with AGN increases with increasing stellar mass (e.g. Best et al.)
- Evidence for AGN activity:
  - radio and x-ray detections of most groups
  - spectral evidence in SDSS J172010+263732 (also evidence of jets)
- What powers the AGN in FGs?
  - Recall – supposed lack of major mergers over past 1-3 Gyr
  - 1.4 GHz emission is short-lived (~400 Myr) unless production is continual or episodic
    - Cooling flows?
    - Minor mergers (i.e. accretion) of less massive companions?
    - Residual gas leftover from last merger?

- Fossil groups are more luminous at 1.4 GHz than their non-fossil counterparts
- $L_{1.4GHz}$ vs $L_{x\text{-}ray}$ – extended to higher luminosities for fossil groups
- $L_{1.4\,GHz}$-Δmag_{12} correlation – groups with $\Delta mag_{12} > 2$ have higher 1.4 GHz luminosities

Some questions….

- Do the stellar populations of fossil groups reflect a quiescent past ~ 3 Gyr?
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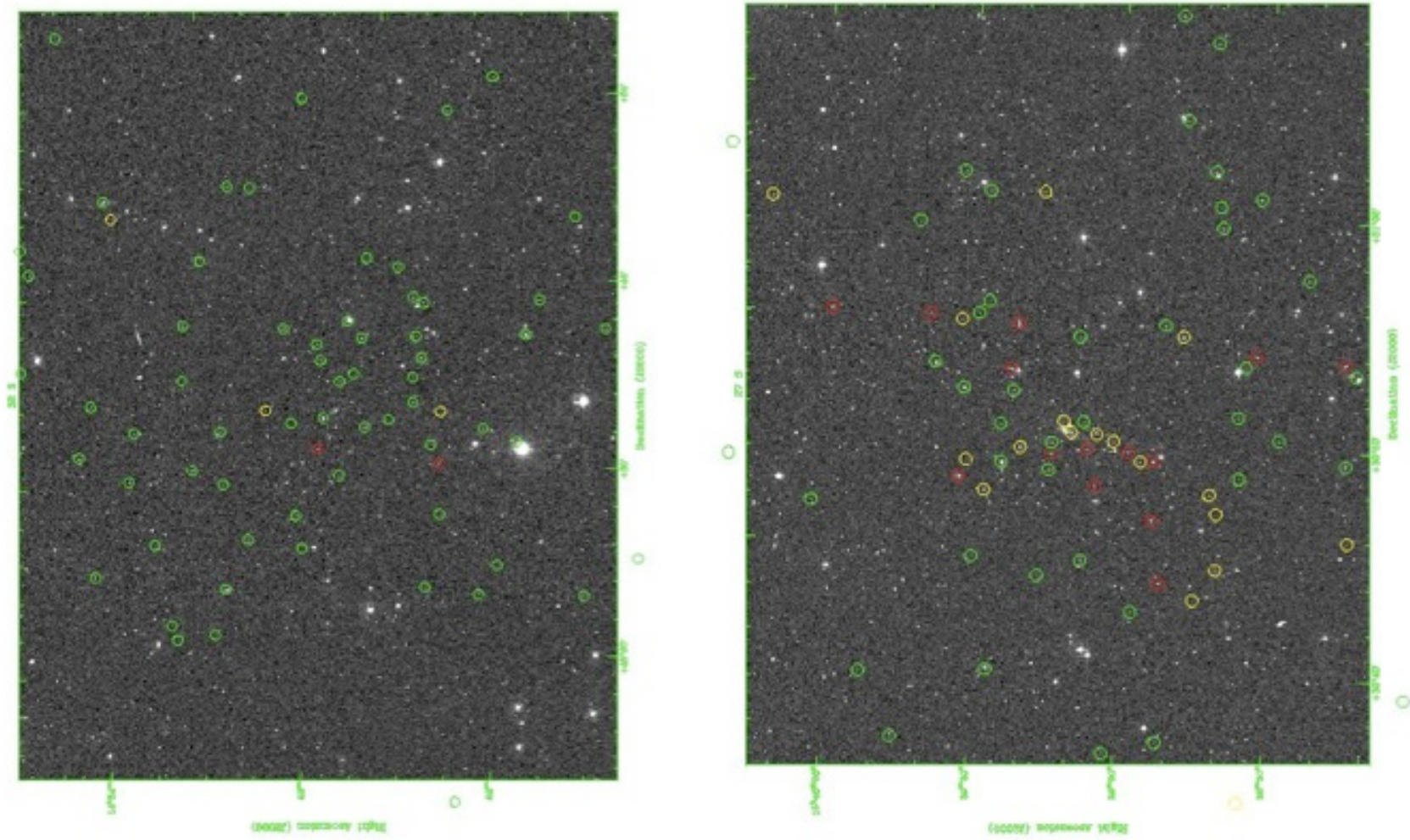
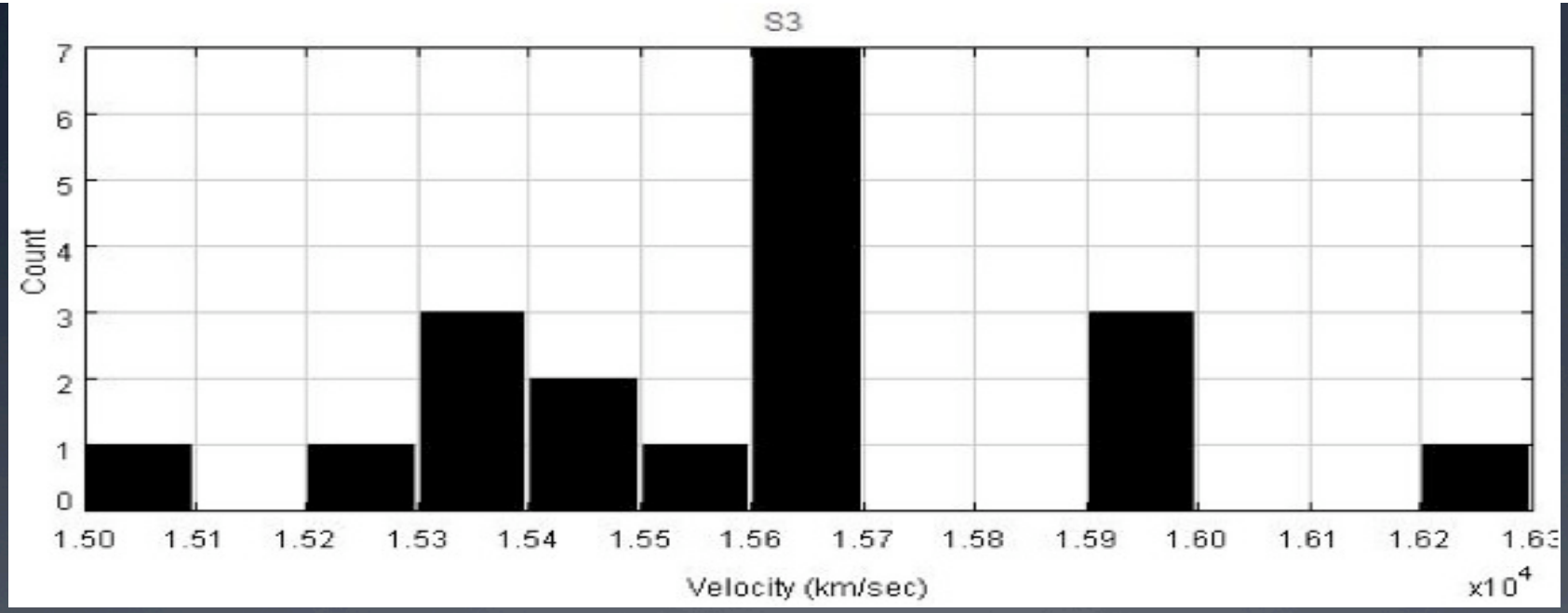
Is It "Just a Phase"?

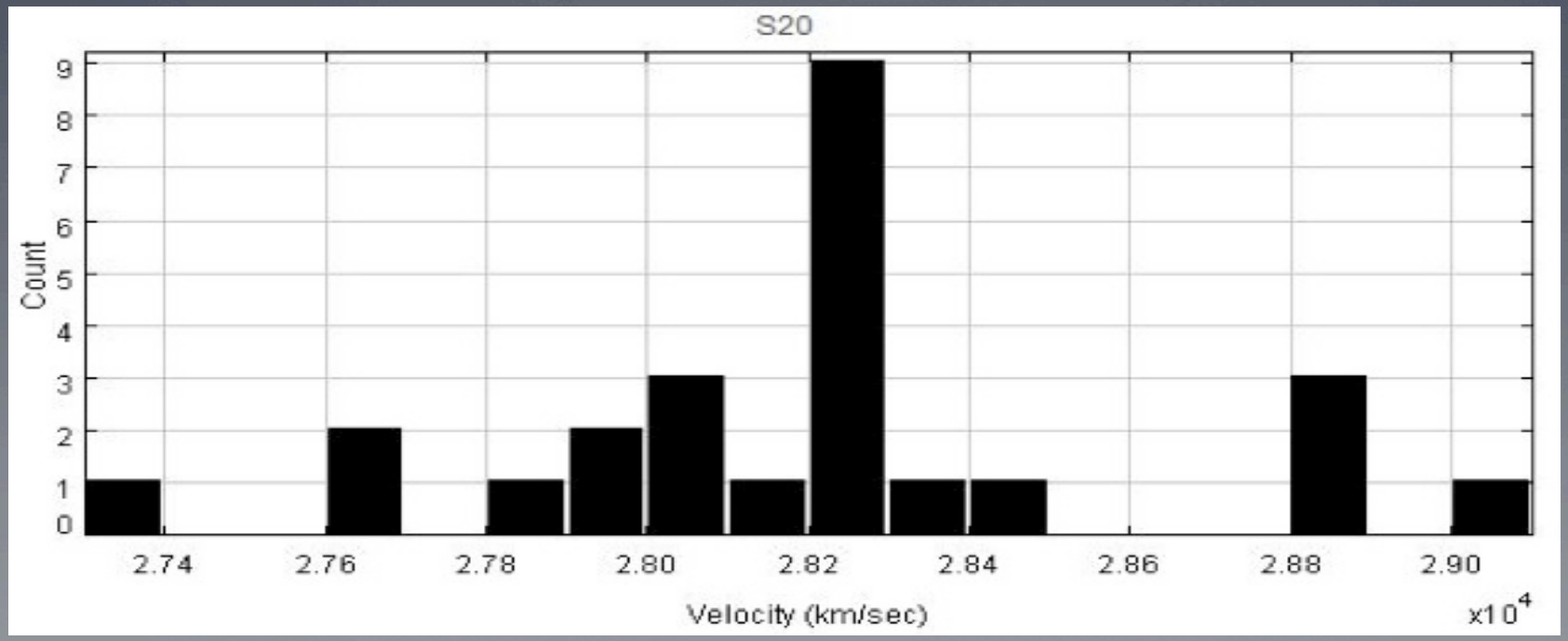
- Sanchez-Janssen et al → SDSSJ105452.03+552112.5 is a fossil cluster comparable to Coma
- WIYN multi-object spectroscopy of five FGs
  - 20-25 spectra of galaxies to $m_r \sim 19.5$ ($M_r \sim -20.5$) within a 1 Mpc radius of the FG
  - Do the shapes of the velocity distributions suggest infall?

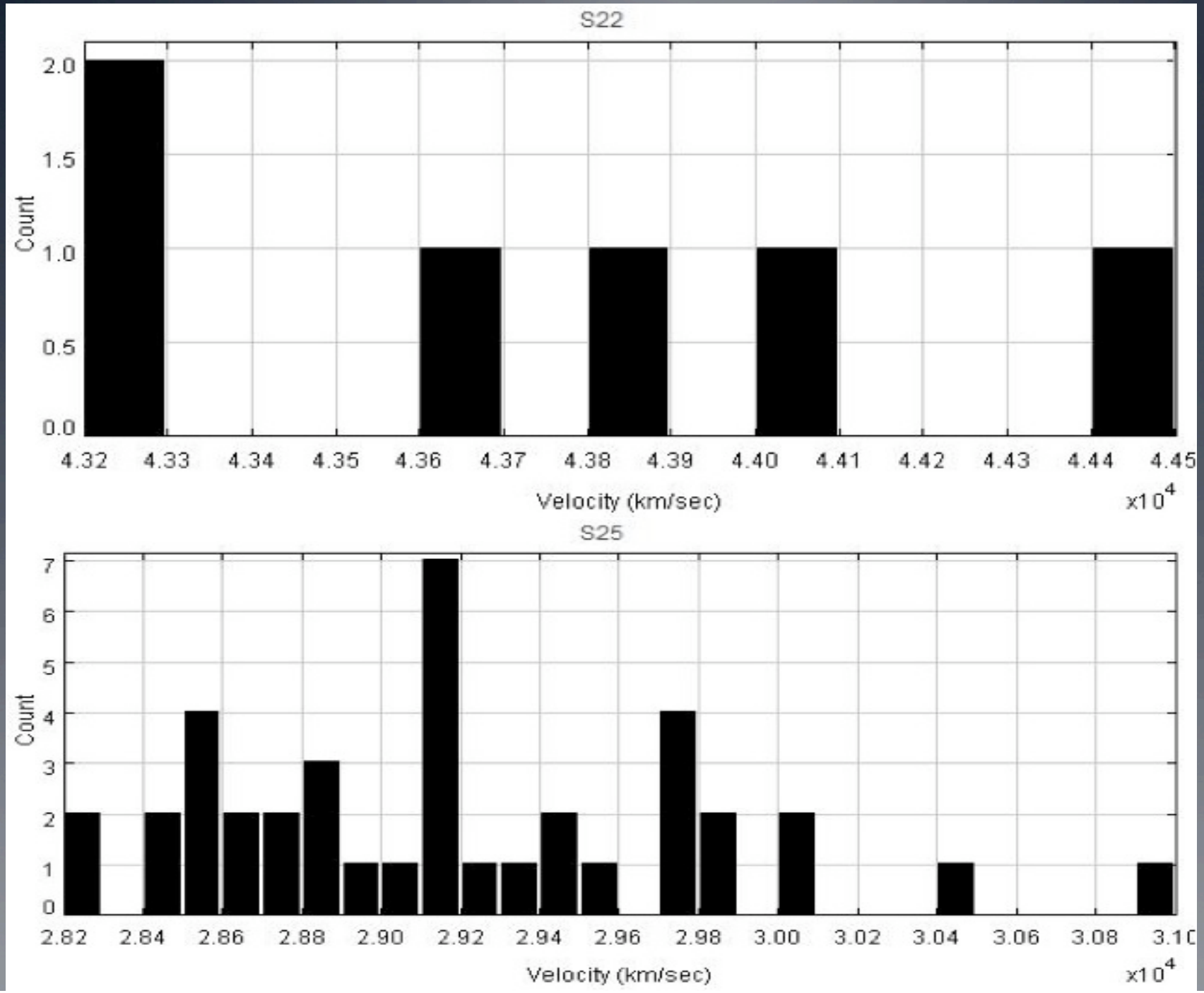


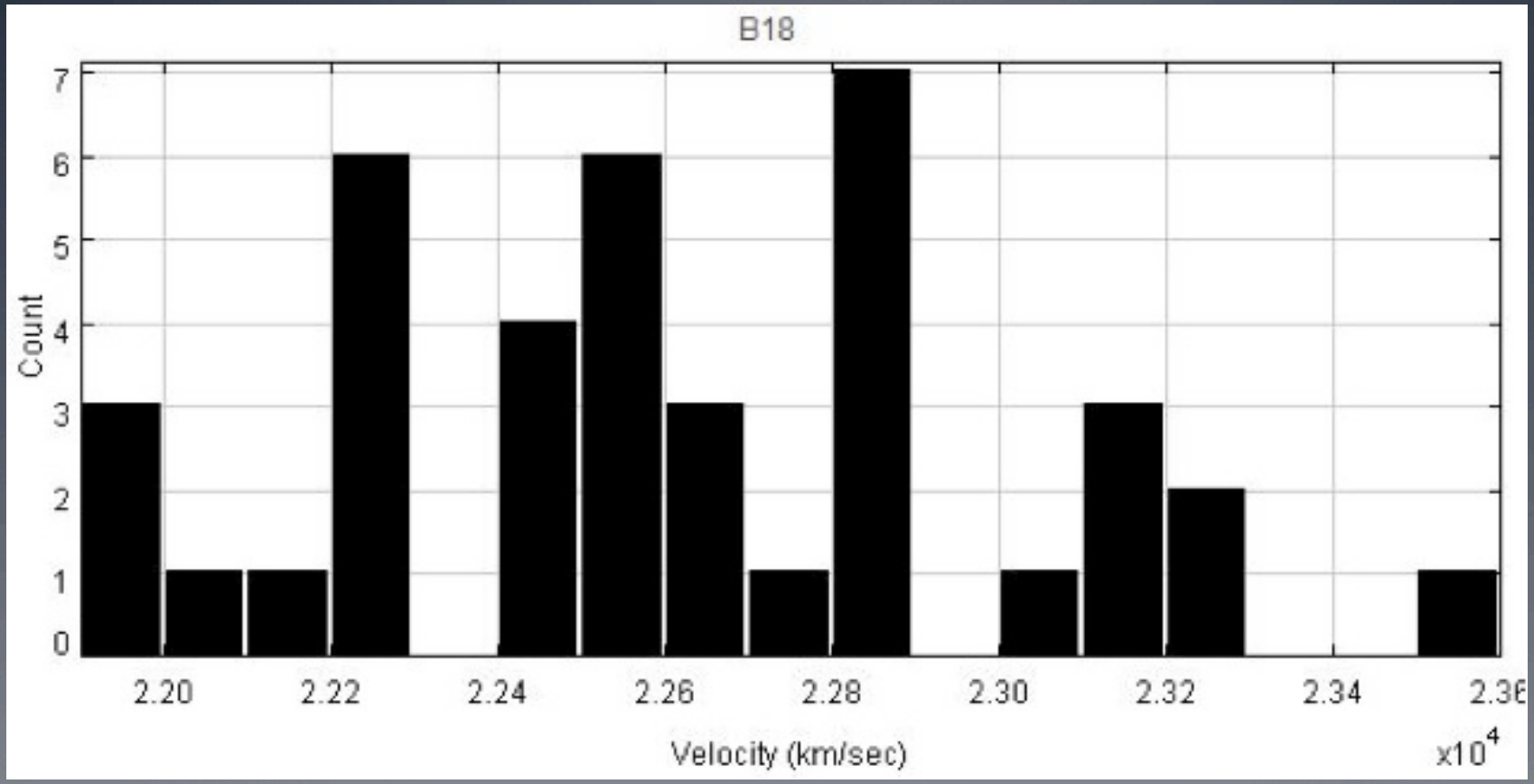
Example Fields

S22(left) and S25(right). Green shows all Hydra targets, yellow shows sources with measured velocities near that of the fossil galaxy, red shows sources with SDSS velocities near that of the fossil galaxy.


S3
Count
0
1
2
3
4
5
6
7
1.50
1.51
1.52
1.53
1.54
1.55
1.56
1.57
1.58
1.59
1.60
1.61
1.62
Velocity (km/sec)
x10^4


S20
Count
0
1
2
3
4
5
6
7
8
9
2.74
2.76
2.78
2.80
2.82
2.84
2.86
2.88
2.90
Velocity (km/sec)
x10^4


S22
Count
2.0
1.5
1.0
0.5
0.0
4.32
4.33
4.34
4.35
4.36
4.37
4.38
4.39
4.40
4.41
4.42
4.43
4.44
4.45
Velocity (km/sec)
x10^4
S25
Count
7
6
5
4
3
2
1
0
2.82
2.84
2.86
2.88
2.90
2.92
2.94
2.96
2.98
3.00
3.02
3.04
3.06
3.08
Velocity (km/sec)
x10^4


B18
Count
0
1
2
3
4
5
6
7
2.20
2.22
2.24
2.26
2.28
2.30
2.32
2.34
Velocity (km/sec)
x10^4

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  - 20-25 spectra of galaxies to $m_r \sim 19.5$ ($M_r \sim -20.5$) within a 1 Mpc radius of the FG
  - Do the shapes of the velocity distributions suggest infall?
- Preliminary masses: $4 \times 10^{13} - 6 \times 10^{14}\ M_\odot$
- Some are central to a larger dynamically relaxed system
- Some fields exhibit little structure in the velocity distribution

Some questions…and maybe some answers.

- Do the stellar populations of fossil groups reflect a quiescent past ~ 3 Gyr?
  - Yes
- Does the observed radio continuum emission in fossil groups reflect systems that have not had a major merger in recent times?
  - No. But maybe there is another process responsible for radio loud fossil groups.
- Are AGN responsible for maintaining the thermal properties of the extended X-ray emission in fossil groups?
  - Very likely.
- Do the velocity distributions of galaxies surrounding fossil groups suggest imminent infall of luminous satellites?
  - The data is incomplete and the jury is still out.

Fossil Groups – The Prequel

- Is there a population of groups/clusters that are the precursors of fossil groups?
- AWM/MKW Clusters
  - Defined as poor clusters with cD-like galaxies that aren't central (Albert et al. '77, Morgan et al. '75)
  - A broad range of Δmag (up to 1.8)
  - Fraction of radio-loud sources similar to what Hess et al. (2012) find for FGs
  - But see the posters….