Giant cosmic tsunamis:
the impact of merger shocks on galaxy evolution

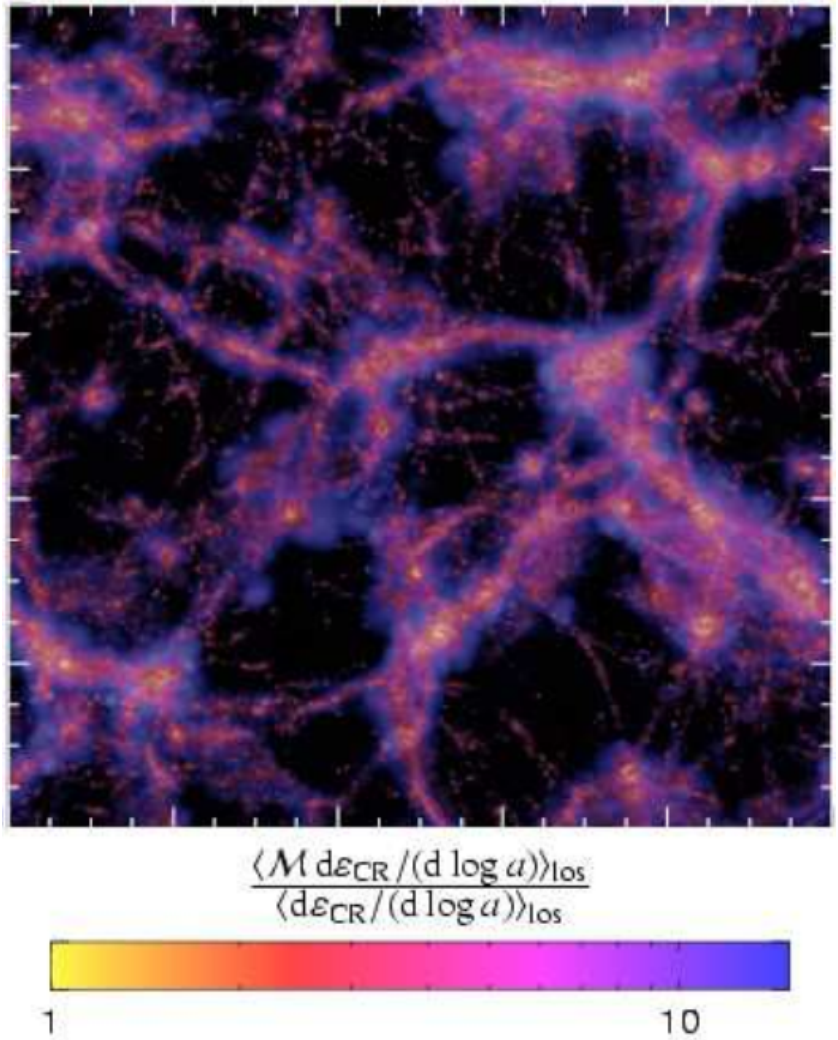
Andra Stroe
ESO Fellow
astroe@eso.org
Twitter: @Andra_Stroe
www.eso.org/~astroe

D. Sobral, M. J. Jee, W. Dawson, H. Hoekstra, H. Röttgering, T. Oosterloo

GalPath, Aug 2016

Structure formation leads to shocks!

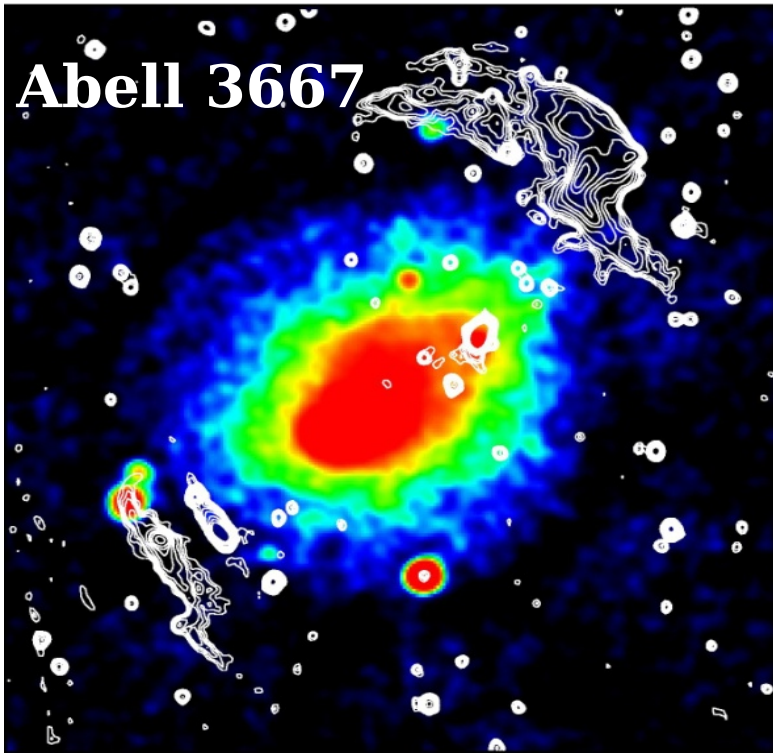
- Clusters grow through mergers
- Structure formation is a very violent process which leads to energy releases of up to 10^{64} erg (e.g. Hoeft et al. 2004)
- Some of the energy is released in the form of shocks



Spatial Mach number distribution in a cosmological structure formation simulation (Pfrommer et al. 2006)

Cluster radio relics

- Extended patches of radio synchrotron emission
- Located at the outskirts of merging clusters
- No obvious optical counterpart
- Shock accelerated electrons



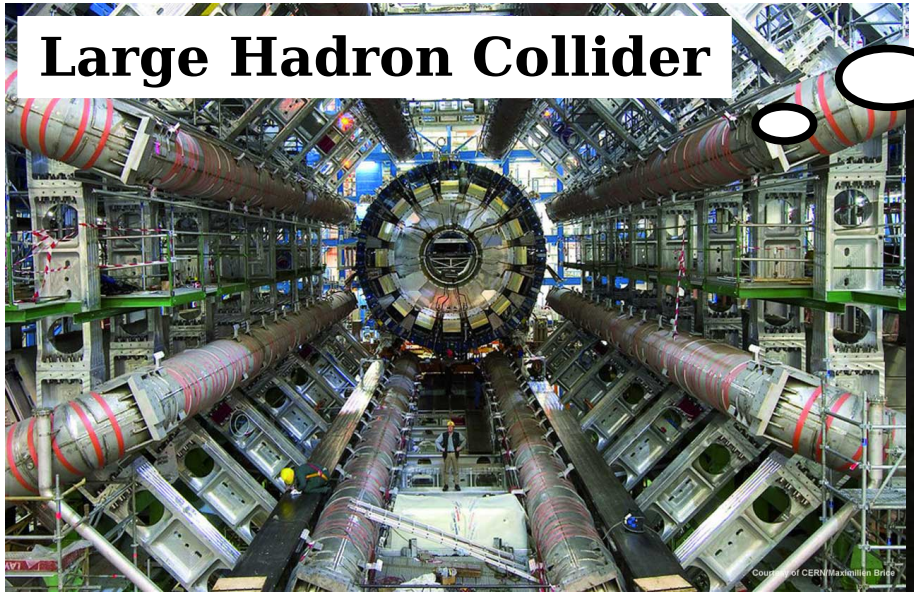
X-ray intensity in color, radio emission in white contours (Rottgering et al. 1997)

Radio (red) and X-ray (blue) emission on top of an optical image (ESO)

Why are relics important?

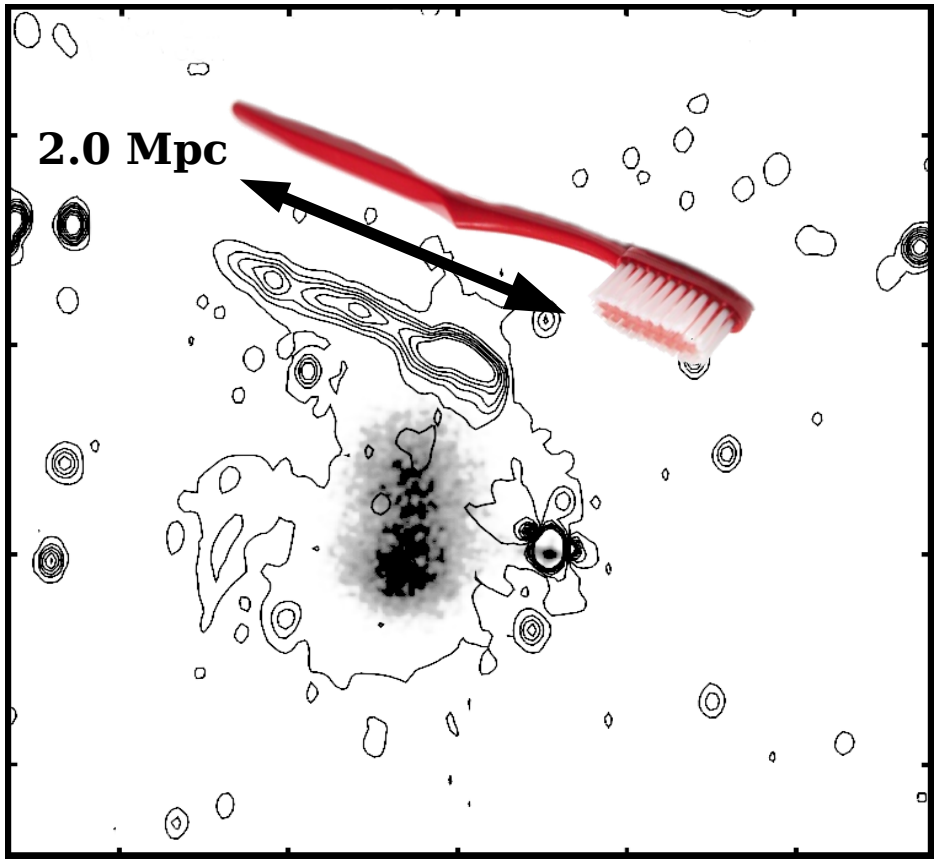
- The largest particle accelerators in the world!
- Complementary way to discover clusters
- 10-40% of clusters are undergoing mergers
- Study effect of cluster merger on galaxies

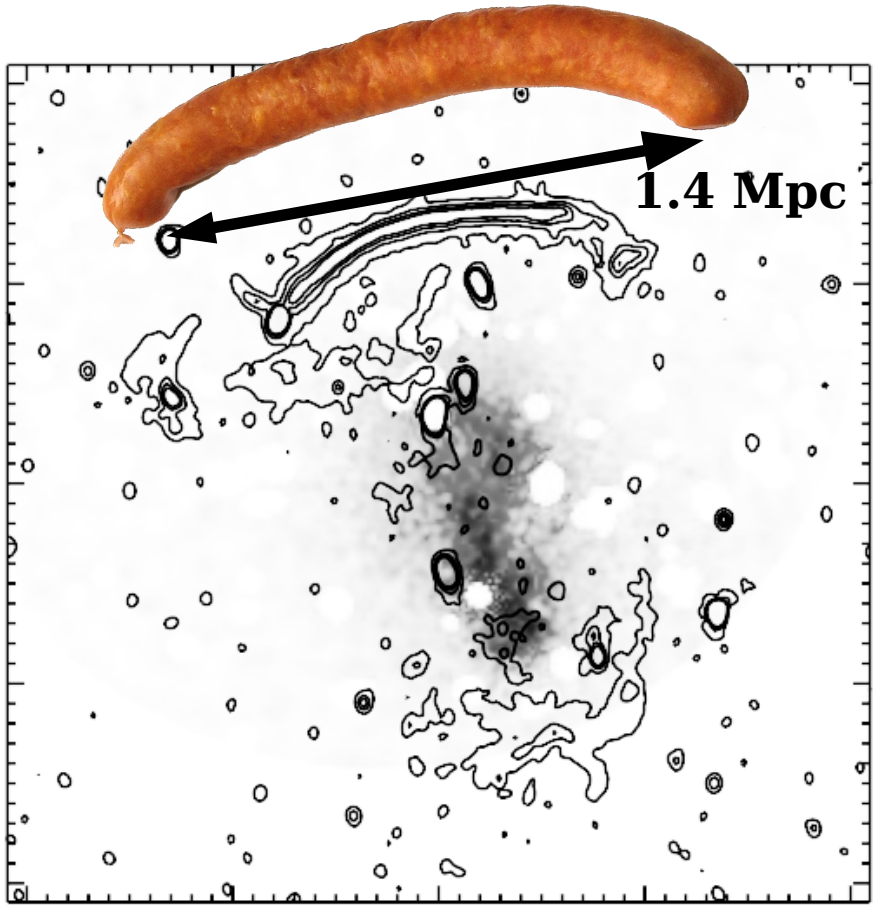
The LHC is not impressed with radio relics! Maybe it's just jealous!



The 'Toothbrush' and 'Sausage' clusters

- z~0.2
- X-ray luminous, disturbed morphology
- Merger in the plane of the sky → twin, outward traveling shock waves

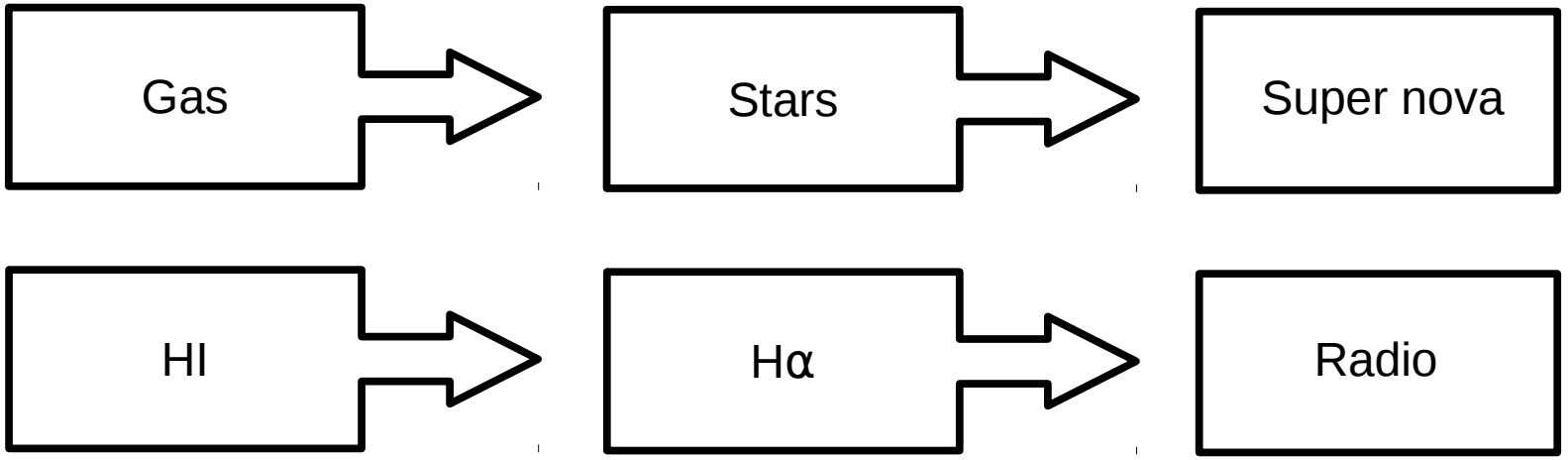




X-ray intensity, radio overlays (Stroe et al. 2013, 2016, van Weeren et al 2010, 2012, Akamatsu & Kawahara 2013, Ogrean et al. 2013)

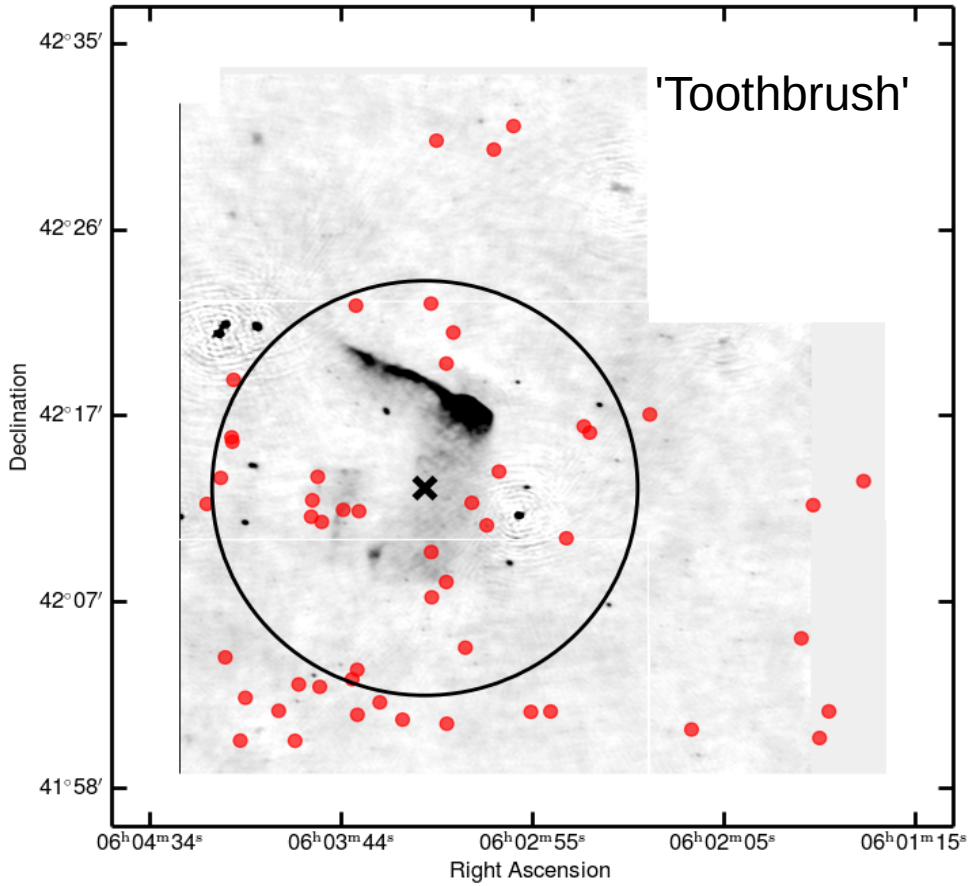
Interaction between shocks and galaxies

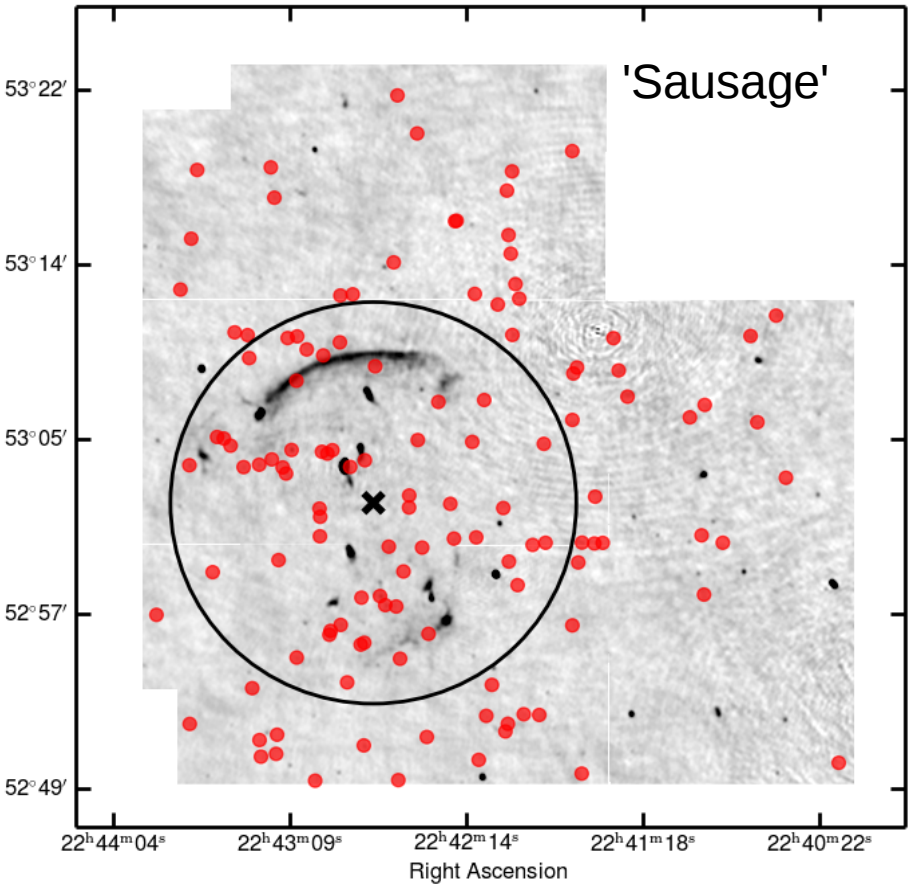
- Does the shock wave inhibit or trigger star formation?
- Look at past, present and future star formation



Hα emission line as star formation tracer

- 323 MHz radio intensity in gray
- Hα line emitters in red circles
- Many extended Hα emitters around the relic areas in the 'Sausage' cluster
- The 'Toothbrush' almost devoid of Hα emitters

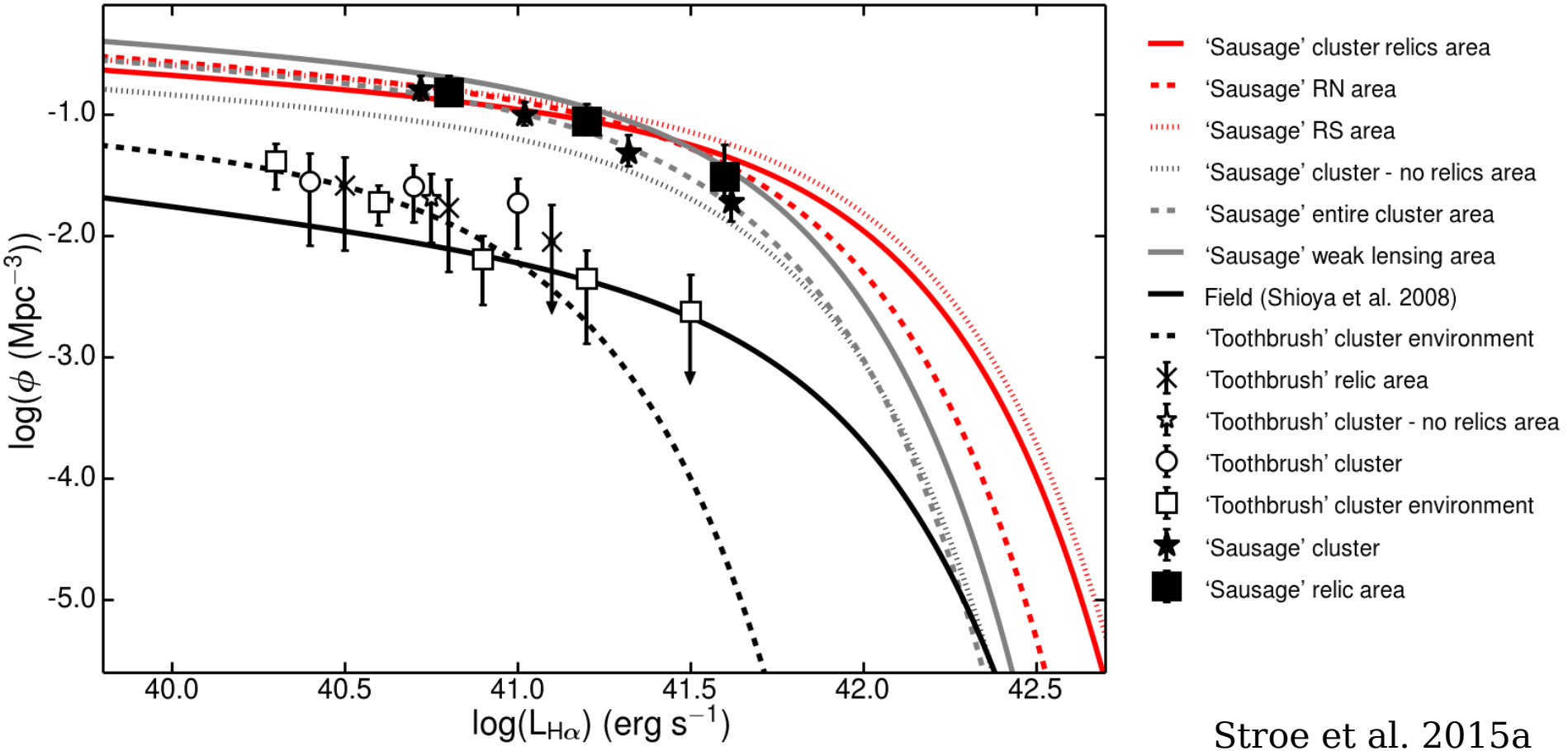




Stroe et al. 2014a, 2015a

Hα luminosity function for the cluster volume

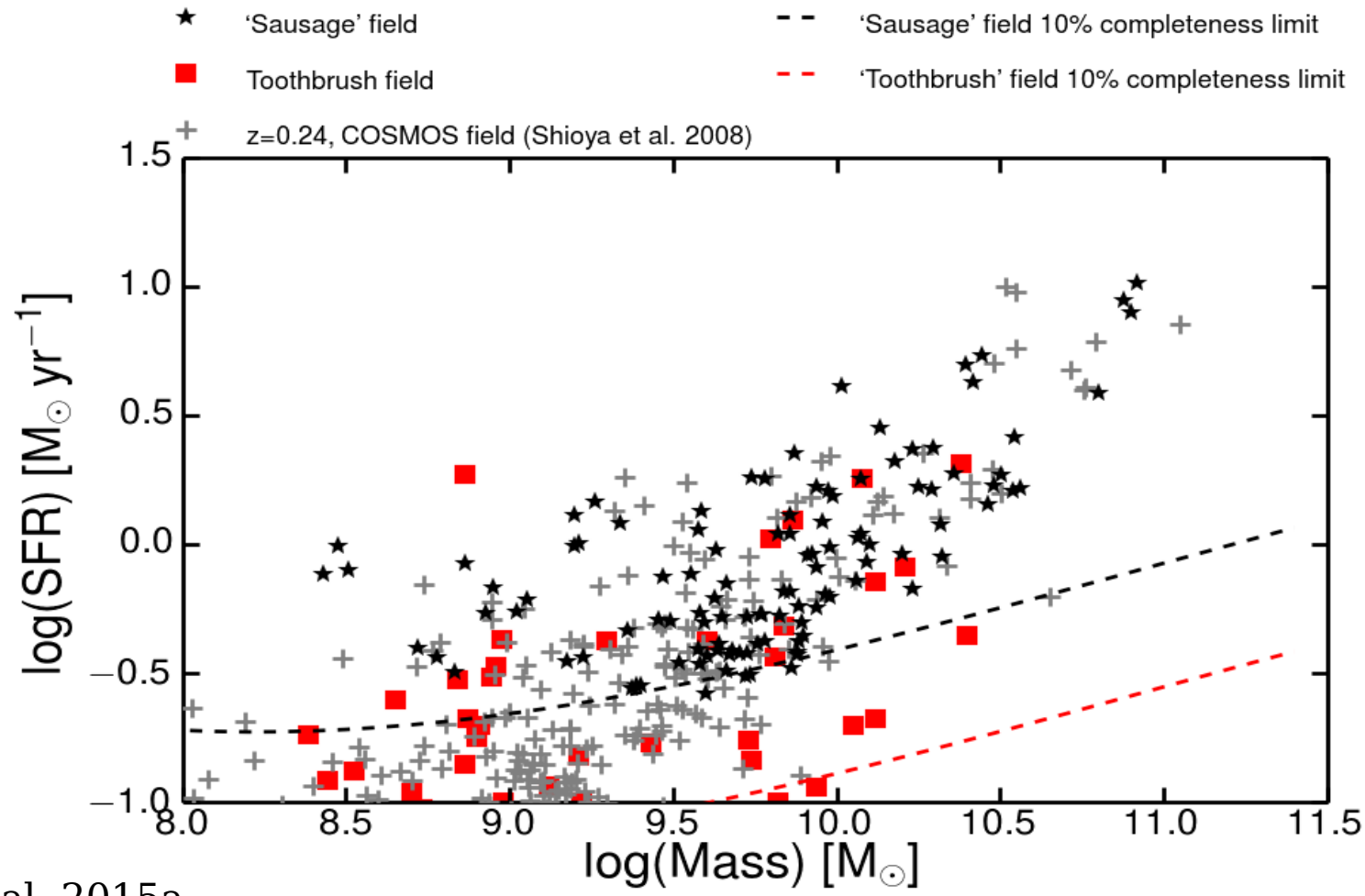
- Bin emitters located in different areas within the clusters
- 'Toothbrush' is consistent a blank field – same number of emitters, but slightly less luminous (=less star-forming)
- 'Sausage' emitters – higher normalization → many more luminous emitters than blank fields



Stroe et al. 2015a

Main sequence

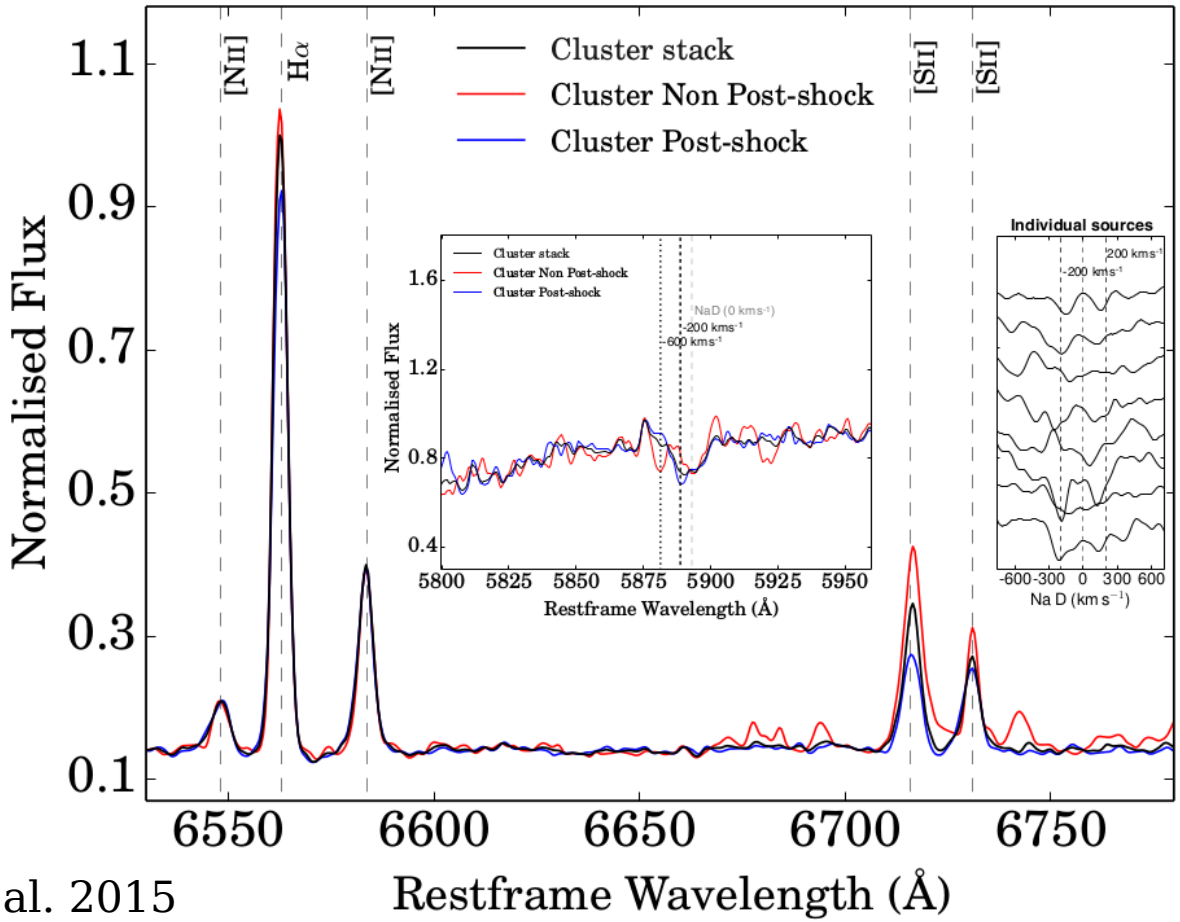
- 'Sausage' and 'Toothbrush' galaxies fall on the star-formation – stellar mass relation



Stroe et al. 2015a

Focusing on the 'Sausage' cluster

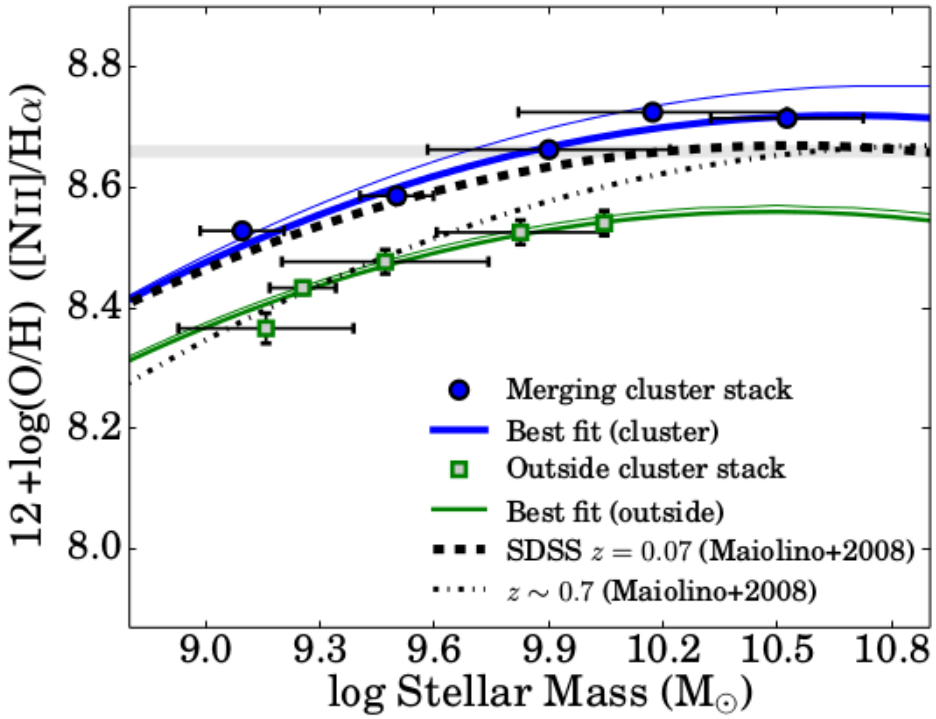
- Star forming galaxies in the hottest X-ray gas and/or in the cluster sub-cores (away from the shock fronts) show very low electron densities (<30 times lower than field galaxies)
- Significant contribution from supernovae
- Supernovae + AGN drive outflows (blue/red shifted [SII]+NaD) → remove fuel for star-formation

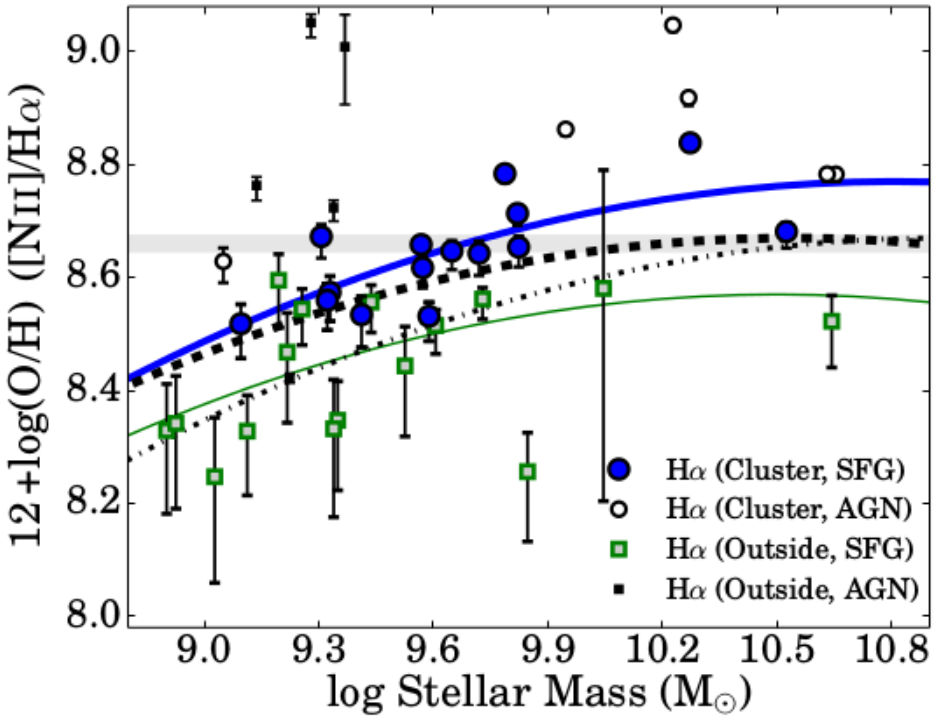


Sobral, Stroe et al. 2015

Increased metallicity

- Star forming galaxies in the cluster follow the local mass-metallicity relation
- Suggesting that these Hα emitters are using relatively metal rich gas to form new stars at all stellar masses
- Source of metal rich gas?
  - Pre-enriched gas from supernovae in the past that was retained in the galaxies

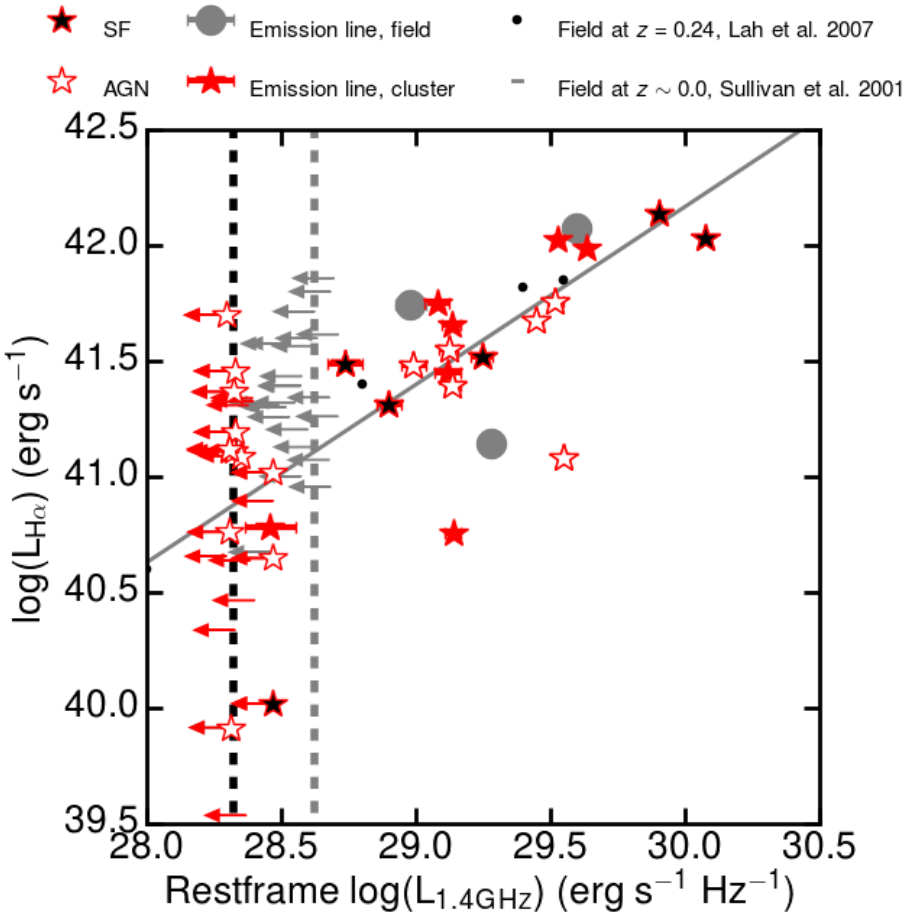




Sobral, Stroe et al. 2015

Star formation on longer timescales

- Use radio emission to trace super nova remnants
- Hα emission correlates with radio emission → star formation averaged over 10 Myr & 100 Myr
- A large fraction of cluster Hα emitters have radio → many more super novae in cluster galaxies compared to the field

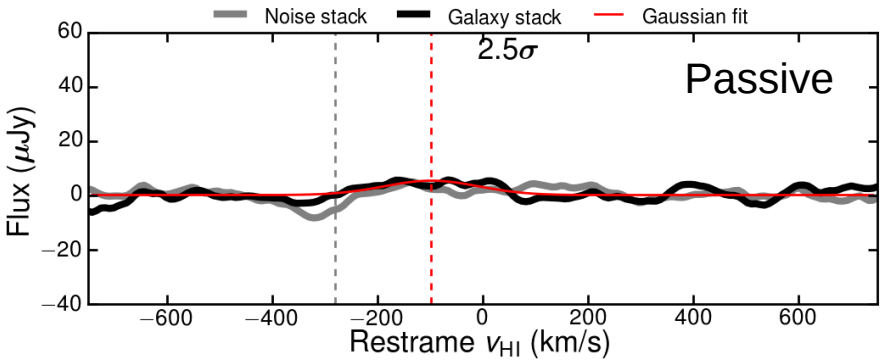


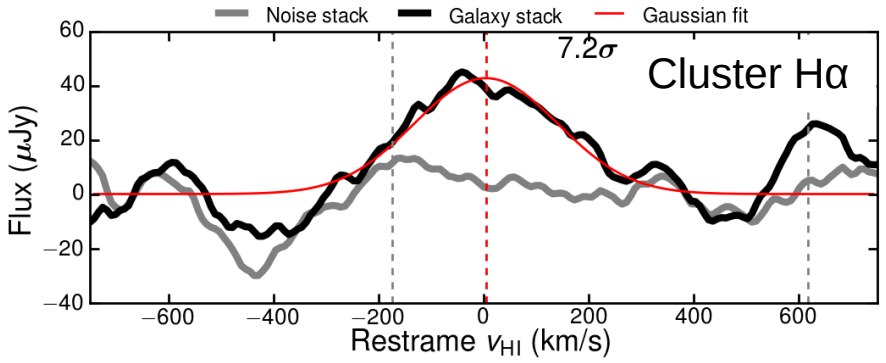
Stroe et al. 2015b

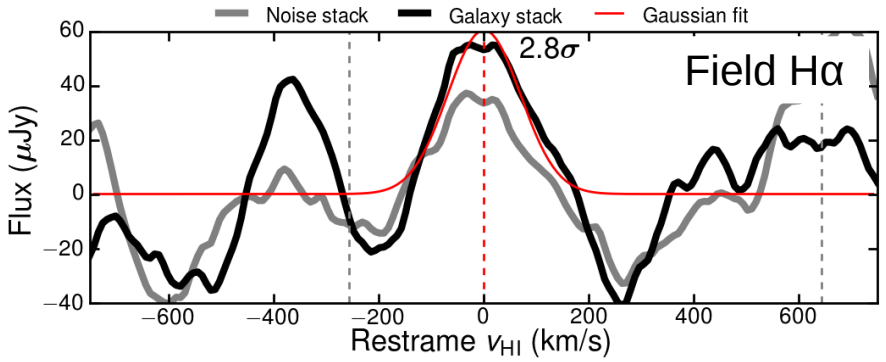
HI to trace neutral gas content in the 'Sausage' field

- HI at the position of Hα emitters
- No direct detections
- Use stacking:
  - Passive galaxies
  - Cluster line emitters
  - Field line emitters
- Passive galaxies have very little HI
- Cluster Hα emitters have just as much HI as their field counterparts → against previous research
- HI gas should get stripped by cluster environment

	M_{HI} (10^9 $M_\odot$)	$M_\star$ (10^9 $M_\odot$)
Passive	0.21 ± 0.15	25.6 ± 0.4
Cluster Hα	2.50 ± 0.62	7.4 ± 0.5
Field Hα	1.86 ± 1.20	4.8 ± 0.8





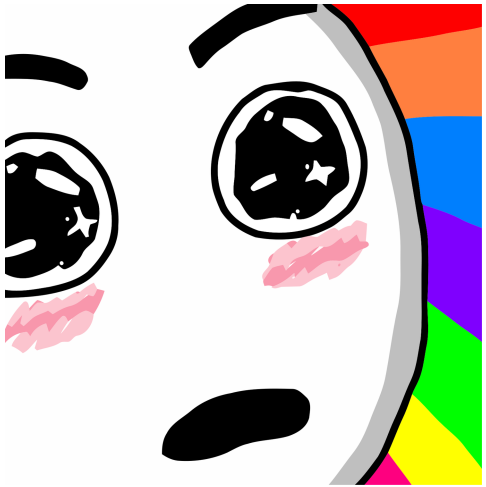


Stroe et al. 2015b

Star-formation process?

- Cluster galaxies interact strongly with their environment
- Two sub-clusters moving in opposite directions, behind the radio shock fronts
- **Shock fronts** have traveled more than 1 Mpc though the ICM → **interacted with the cluster members?**

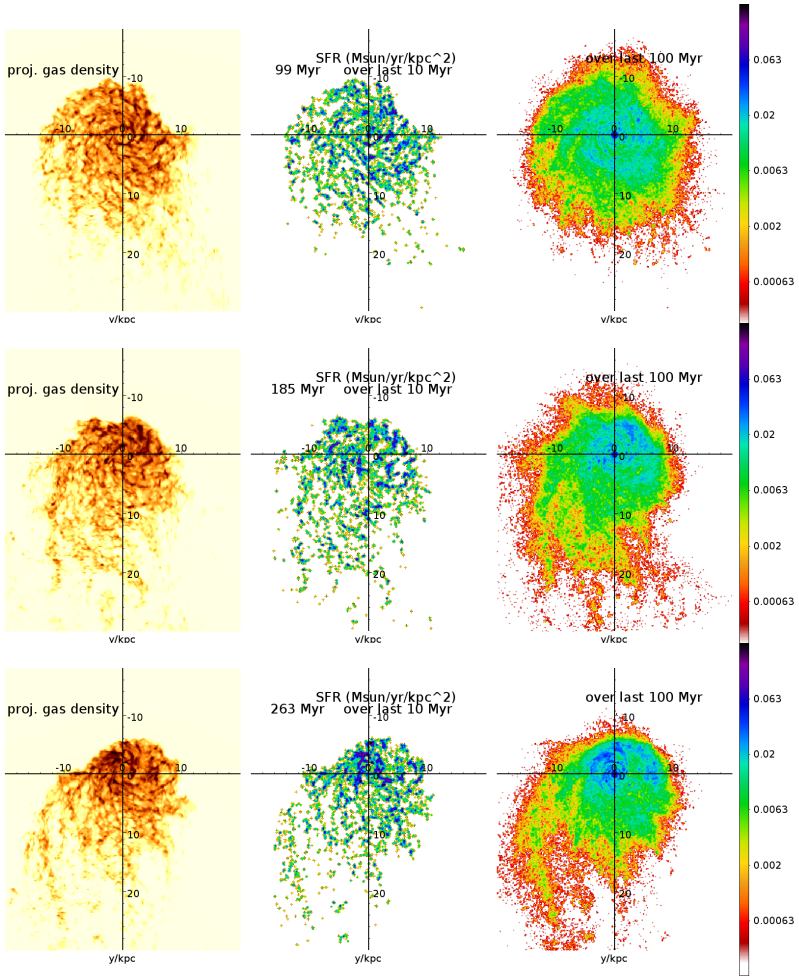
Shock induced star-formation?



The gas in the galaxies is shocked!!

Shock induced star-formation?

- Roediger et al. (2014): after passage of a shock, star-formation starts in the galaxy for a few hundred million years



'Sausage' vs 'Toothbrush'

- Hα luminosity function and star-forming properties of the 'Sausage' and 'Toothbrush' are wildly different

Hα luminosity function – 'Sausage' vs 'Toothbrush'

- Hα luminosity properties of the 'Sausage' and 'Toothbrush' are wildly different

	'Sausage'	**'Toothbrush'**
Redshift	0.19	0.22
Temperature	7 keV	8 keV
Radio	2 relics	2 relics
Morphology	Elongated north-south	Elongated north-south
Orientation	In the plane of the sky	In the plane of the sky
Merger history	**2 equal mass clusters** (van Weeren et al. 2011; Jee, Stroe et al. 2015)	**2 equal mass clusters + smaller sub-cluster** (Brüggen et al. 2011; Jee et al. 2016)
Core passage time	**~1 Gyr** (van Weeren et al. 2011, Stroe et al. 2014c)	**~2 Gyr** (Brüggen et al. 2011)

Star formation – 'Sausage' vs 'Toothbrush'

- Observe the cluster when shock-induced star formation is still active
- We are viewing the 'Toothbrush' cluster at a more evolved 'time-slice' → galaxies evolved into ellipticals
- The 'Sausage' is full of massive galaxies → numerous gas-rich galaxies for the shock to 'light-up'
- Even though clusters could go through episodes of vigorous star formation, the total stellar mass added is little

Take away messages

Cluster shocks rejuvenate cluster galaxies!