Shocking news from the ICM

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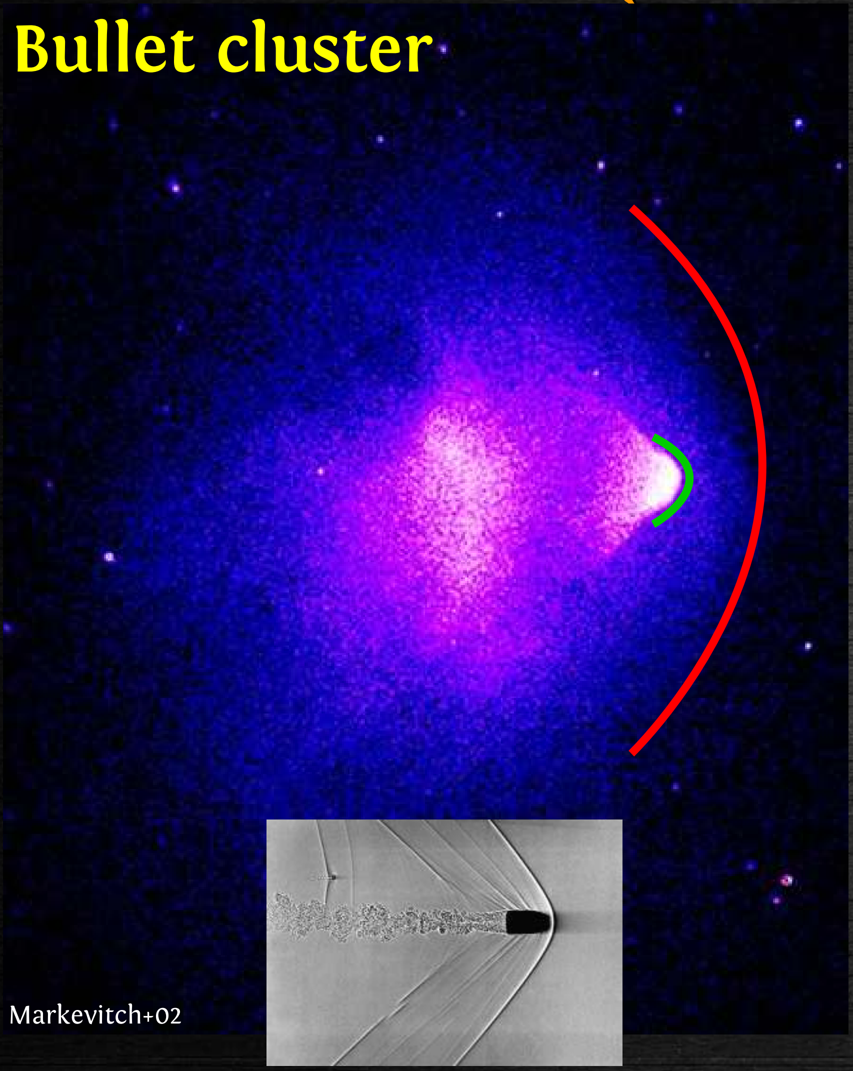
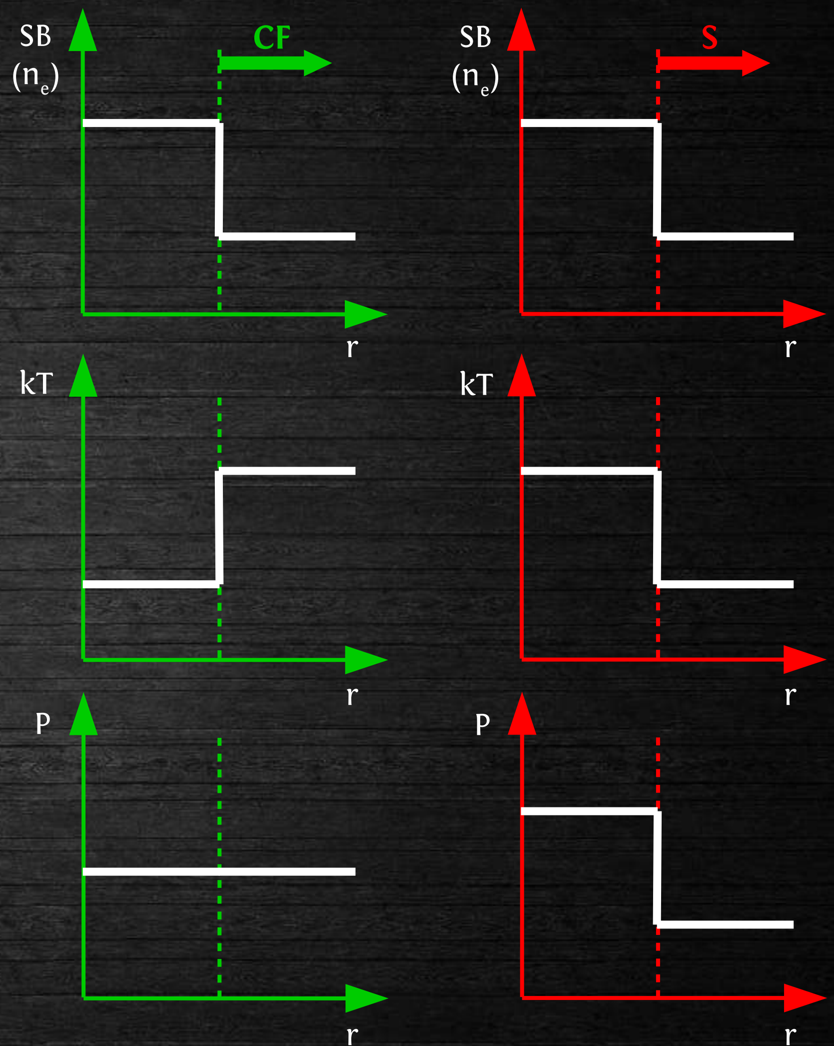
Sterrewacht Leiden

September 10, 2019 – X-ray Astronomy 2019, Bologna

Shocks (and cold fronts)

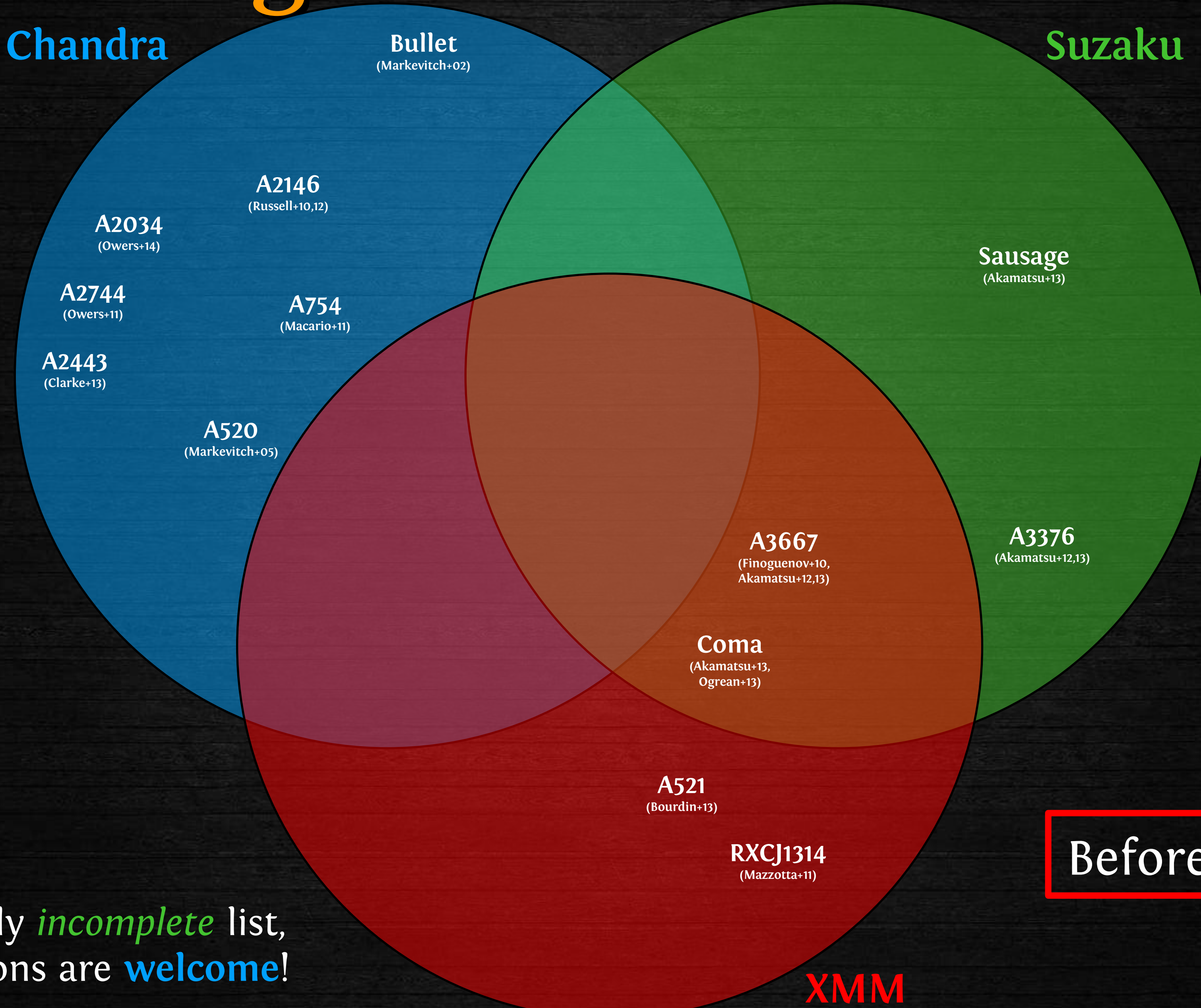




Looking for *SB* (n_e) and *kT* **jumps**

$$\begin{cases} \dfrac{\rho_d}{\rho_u} = \dfrac{4\mathcal{M}_{\rm SB}^2}{\mathcal{M}_{\rm SB}^2 + 3} \\[2ex] \dfrac{T_d}{T_u} = \dfrac{5\mathcal{M}_{\rm kT}^4 + 14\mathcal{M}_{\rm kT}^2 - 3}{16\mathcal{M}_{\rm kT}^2} \end{cases}$$

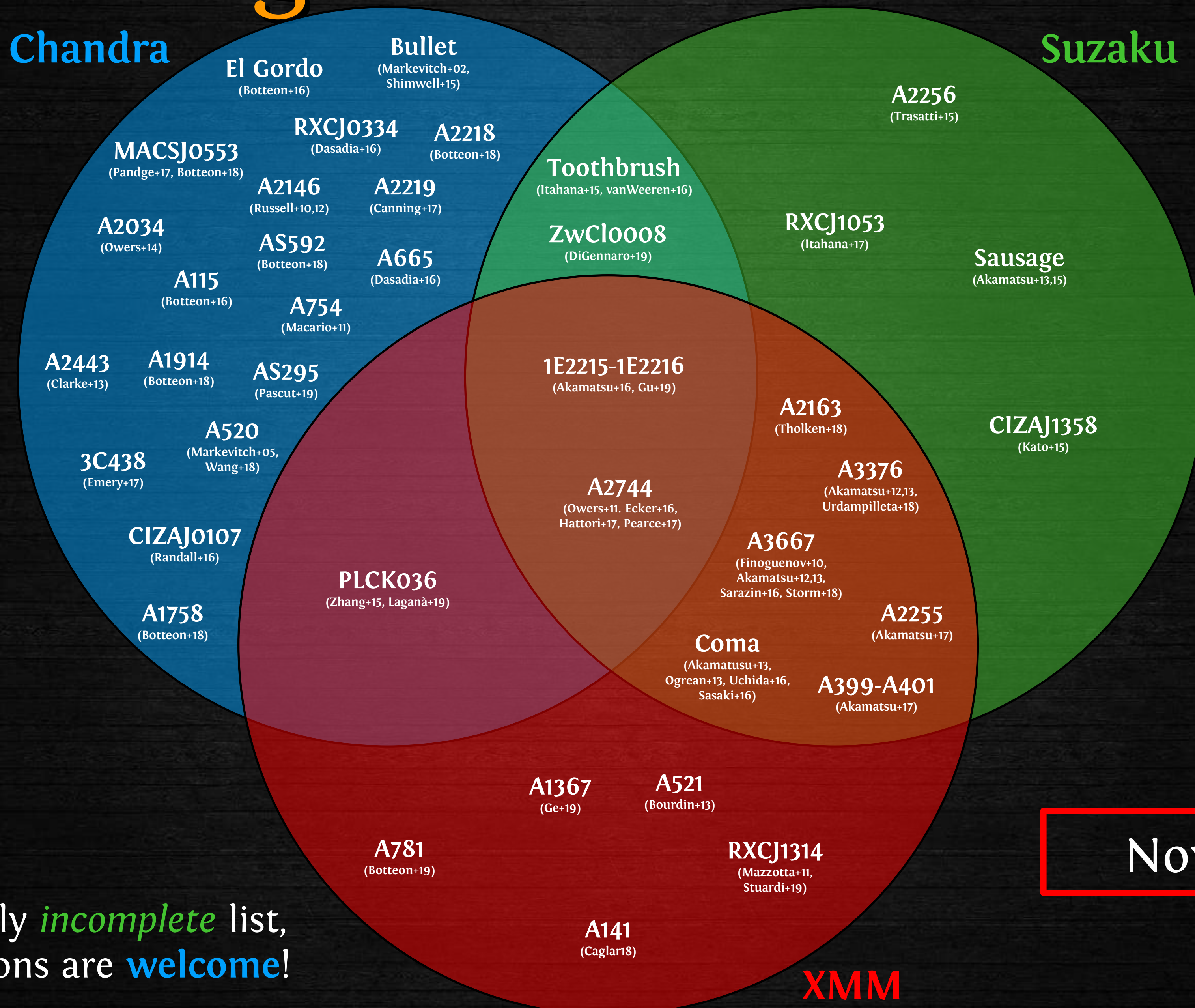
Merger shocks in GCs*



Before 2015

*a likely *incomplete* list, additions are **welcome**!

Merger shocks in GCs*

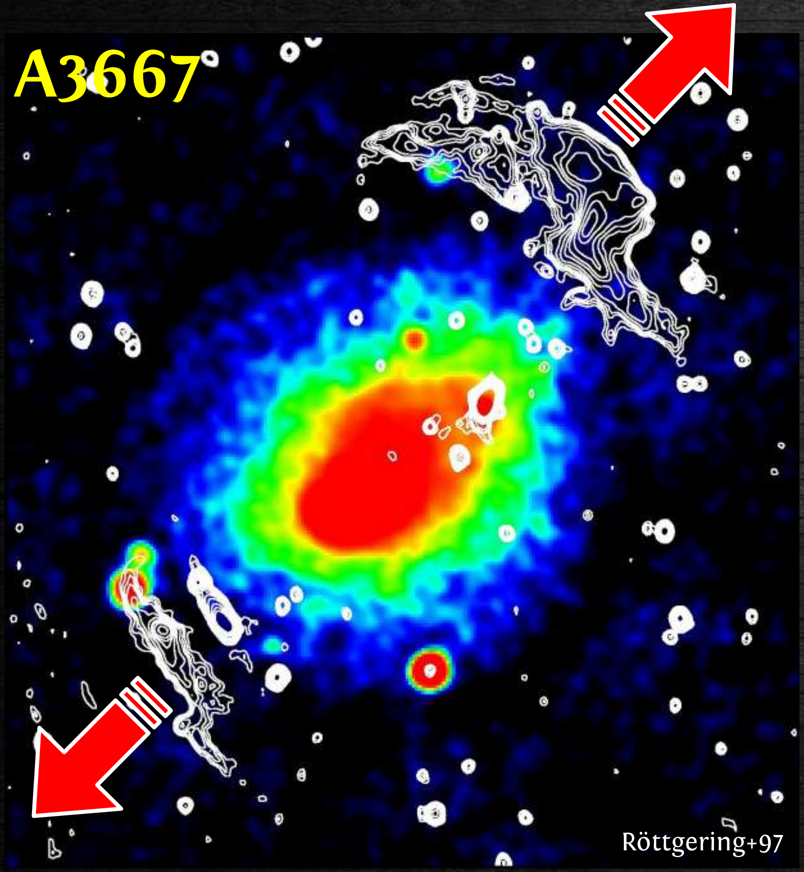


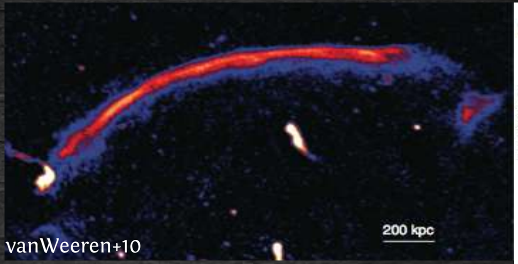
Now

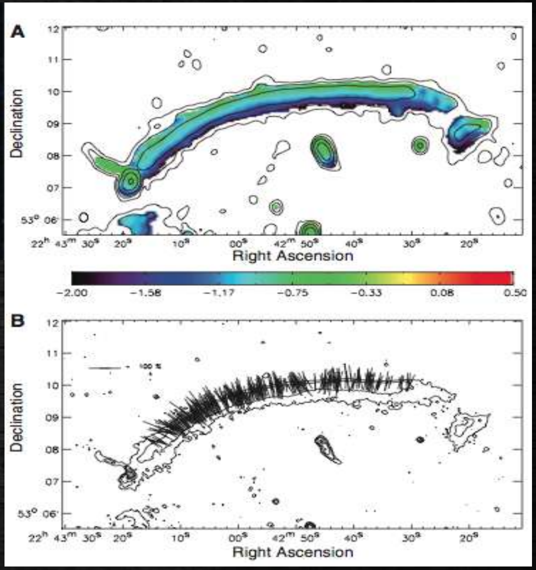
*a likely *incomplete* list, additions are **welcome**!

Radio relics

Elongated and arc-shaped polarized sources found in the *outskirts* of *some* GCs in a **merging state**





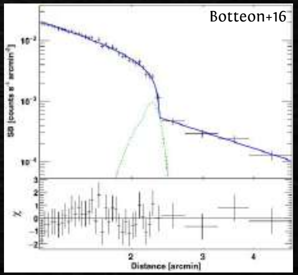


Relic-shock connection:

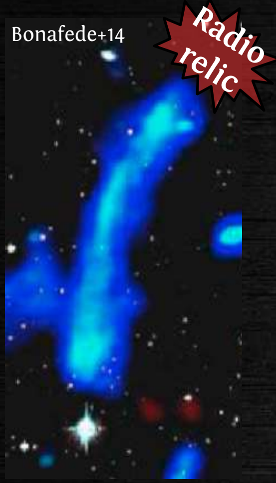
- *Position+morphology*
- *Spectral steepening*
- *Polarization*

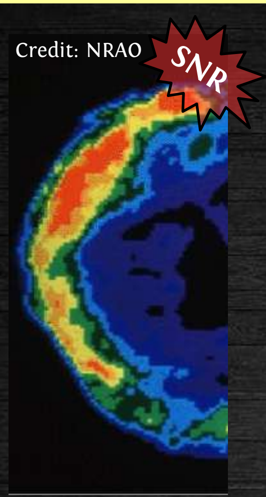
...shocks are also **observed**!

(Finoguenov+10, Bourdin+13, Akamatsu+Kawahara13, Shimwell+15, Eckert+16. Botteon+16, Akamatsu+17)



Origin of radio relics

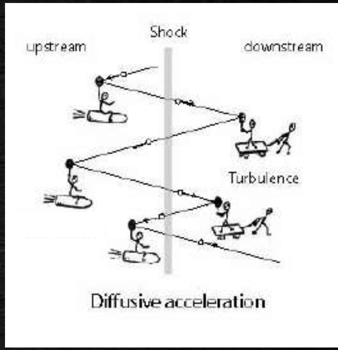




$\mathcal{M} \lesssim 3 \neq \mathcal{M} \sim 10^3$

Direct acceleration

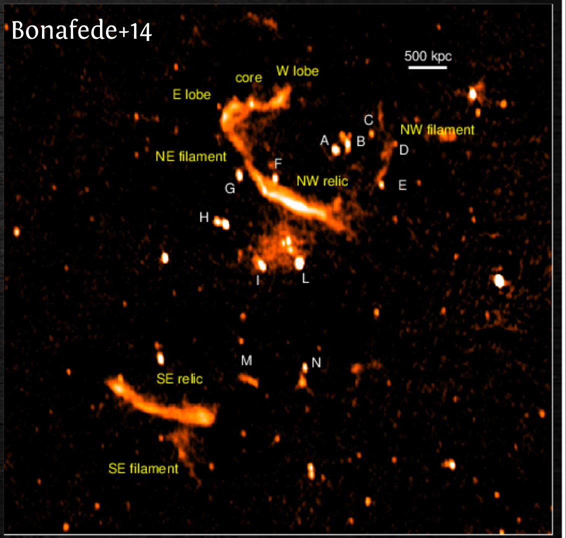
- Diffusive shock acceleration (*DSA*)
- Similar to *supernovae*
- Starts from *thermal pool*
- Low acceleration efficiency
- $\alpha = \frac{\mathcal{M}^2+1}{\mathcal{M}^2-1}$



(Krymskii77, Bell78, Drury83, Blandford+Eichler87, Jones+Ellison91, Malkov+Drury01)

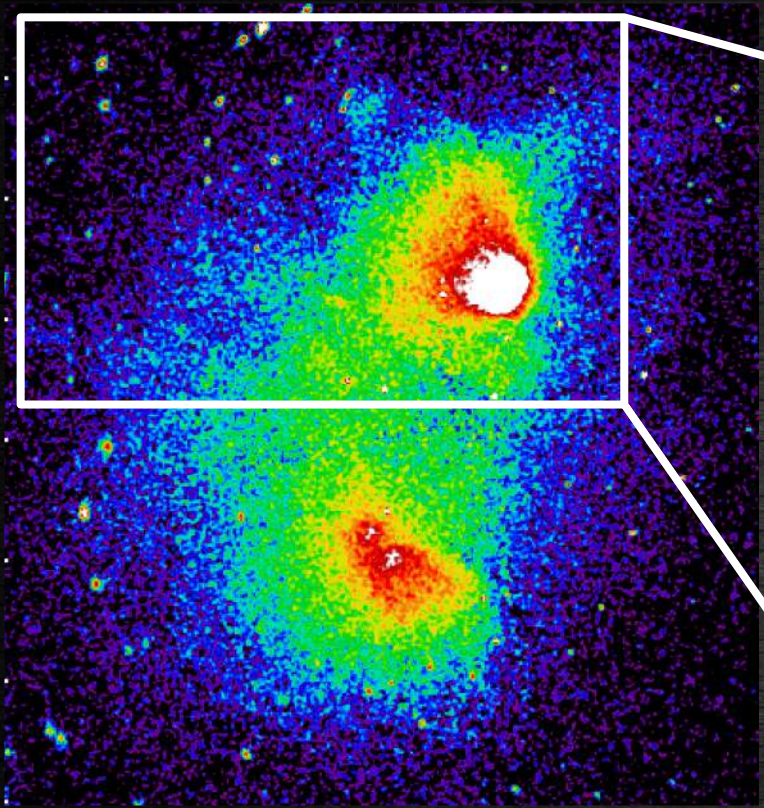
Re-acceleration

- *Seed* relativistic e⁻ required
- Works better for *low Mach numbers*
- Still *DSA*, but different *spectra*

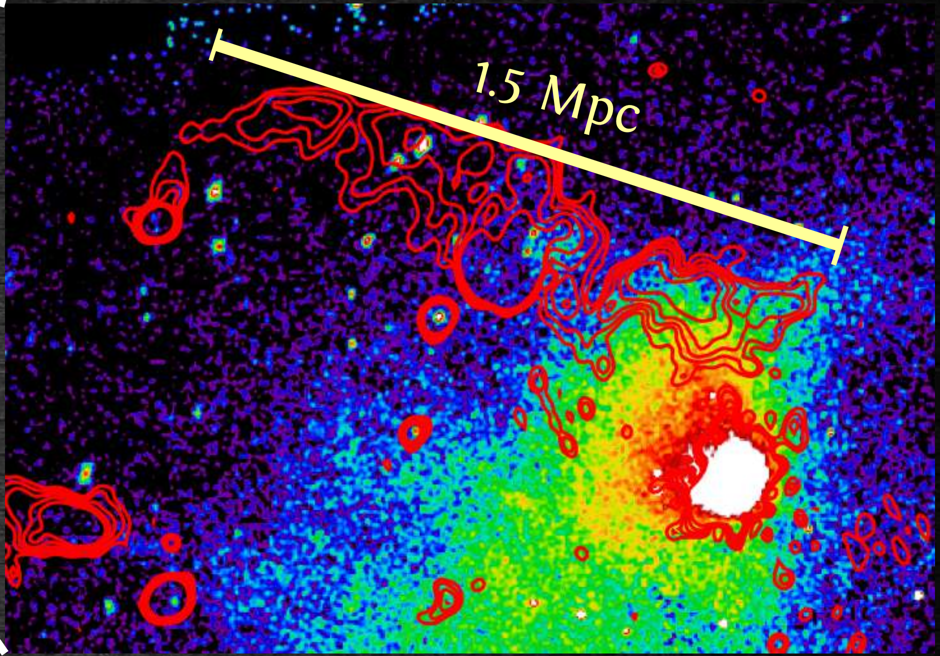


(Markevitch+05, Kang+12,14,16, Pinzke+13, Caprioli+Spitkovsky14, Guo+14 Bonafede+14, Shimwell+15, Botteon+16, vanWeeren+17)

Abell 115



Botteon et al. 2016, MNRAS, 460, L84-L88



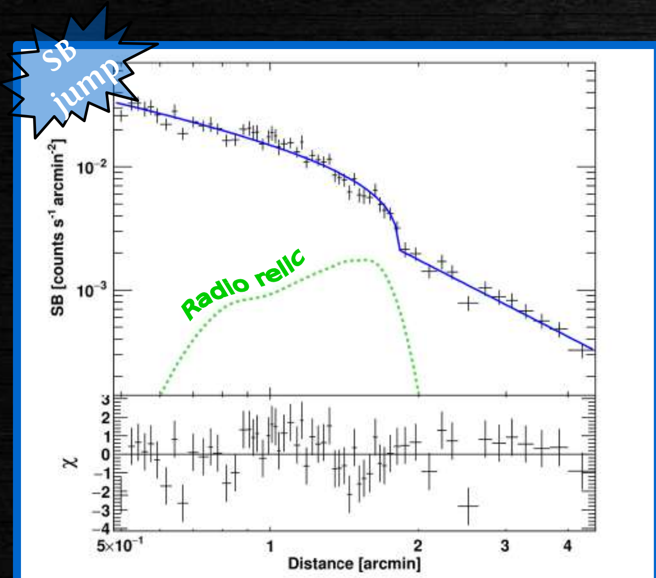
- Dinamically disturbed
- Off-axis merger
  (Gutierrez+Krawczynski05, Barrena+07)

- *Chandra* 360 ks

- Giant radio relic (Govoni+01)

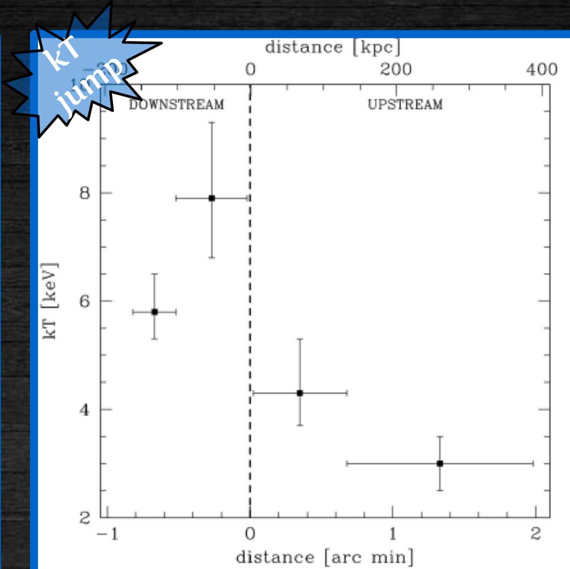
- VLA @ 1.4 GHz
  Resolution 15'' x 14''
  r.m.s. 70 μJy/beam (1σ level)

The shock



$$\frac{\rho_d}{\rho_u} = \frac{4\mathcal{M}_{\rm SB}^2}{\mathcal{M}_{\rm SB}^2+3}$$

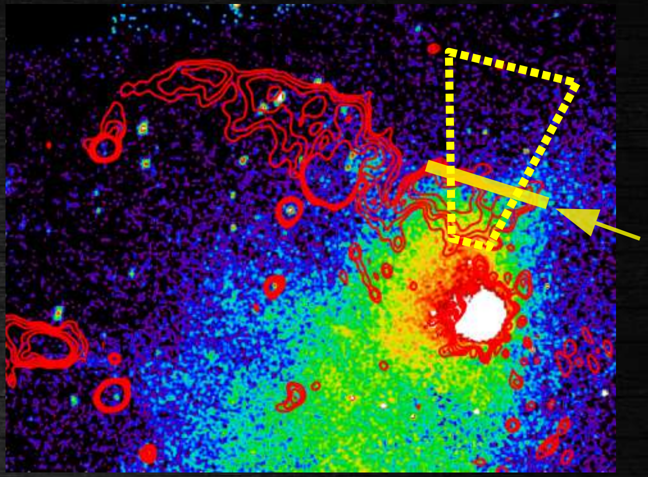
$$\mathcal{M}_{\rm SB} = 1.7 \pm 0.1$$



$$\frac{T_d}{T_u} = \frac{5\mathcal{M}_{\rm kT}^4 + 14\mathcal{M}_{\rm kT}^2 - 3}{16\mathcal{M}_{\rm kT}^2}$$

$$\mathcal{M}_{\rm kT} = 1.8^{+0.5}_{-0.4}$$

Excellent agreement between **SB** and **kT** jumps



From **D**iffusive **S**hock **A**cceleration:

$$\boxed{\alpha = \frac{\mathcal{M}^2+1}{\mathcal{M}^2-1} = 2 - 1.4}$$

NOT consistent with

$\alpha \sim$ 1.1 (Govoni+01)

Relic radio luminosity

Dissipated kinetic power

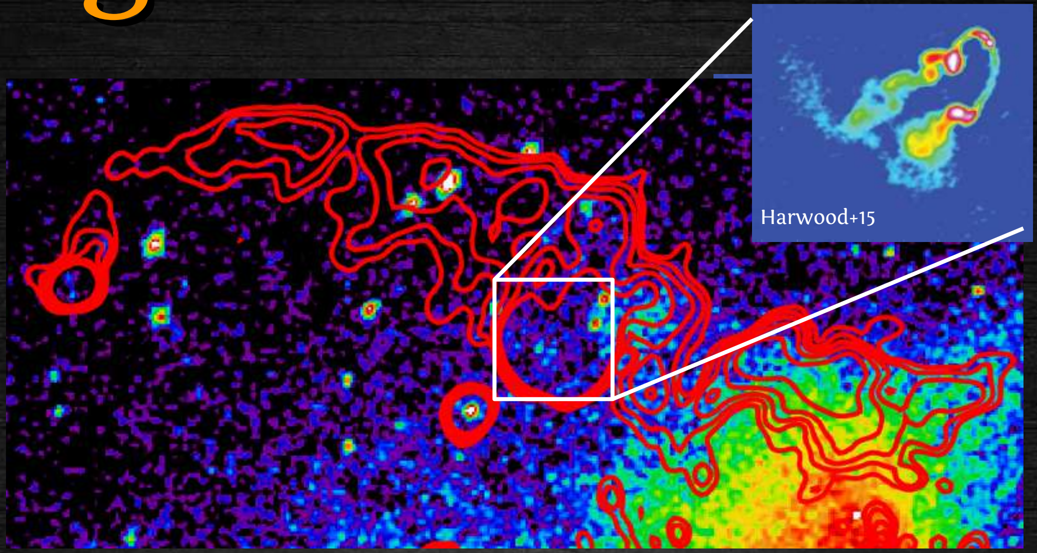
Fraction of accelerated e$^-$ visible in radio

Radiative losses

$$\int_{\nu_0} L(\nu)\,\mathrm{d}\nu \simeq \frac{1}{2} S \rho_u V_{sh}^3 \eta_e \Psi \frac{B^2}{B_{cmb}^2 + B^2}$$

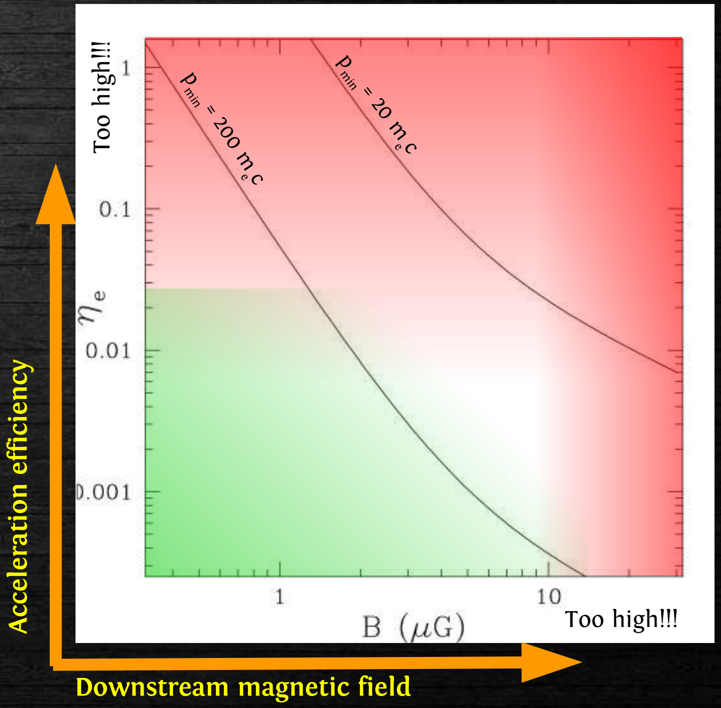
Acceleration efficiency

The origin of the radio relic



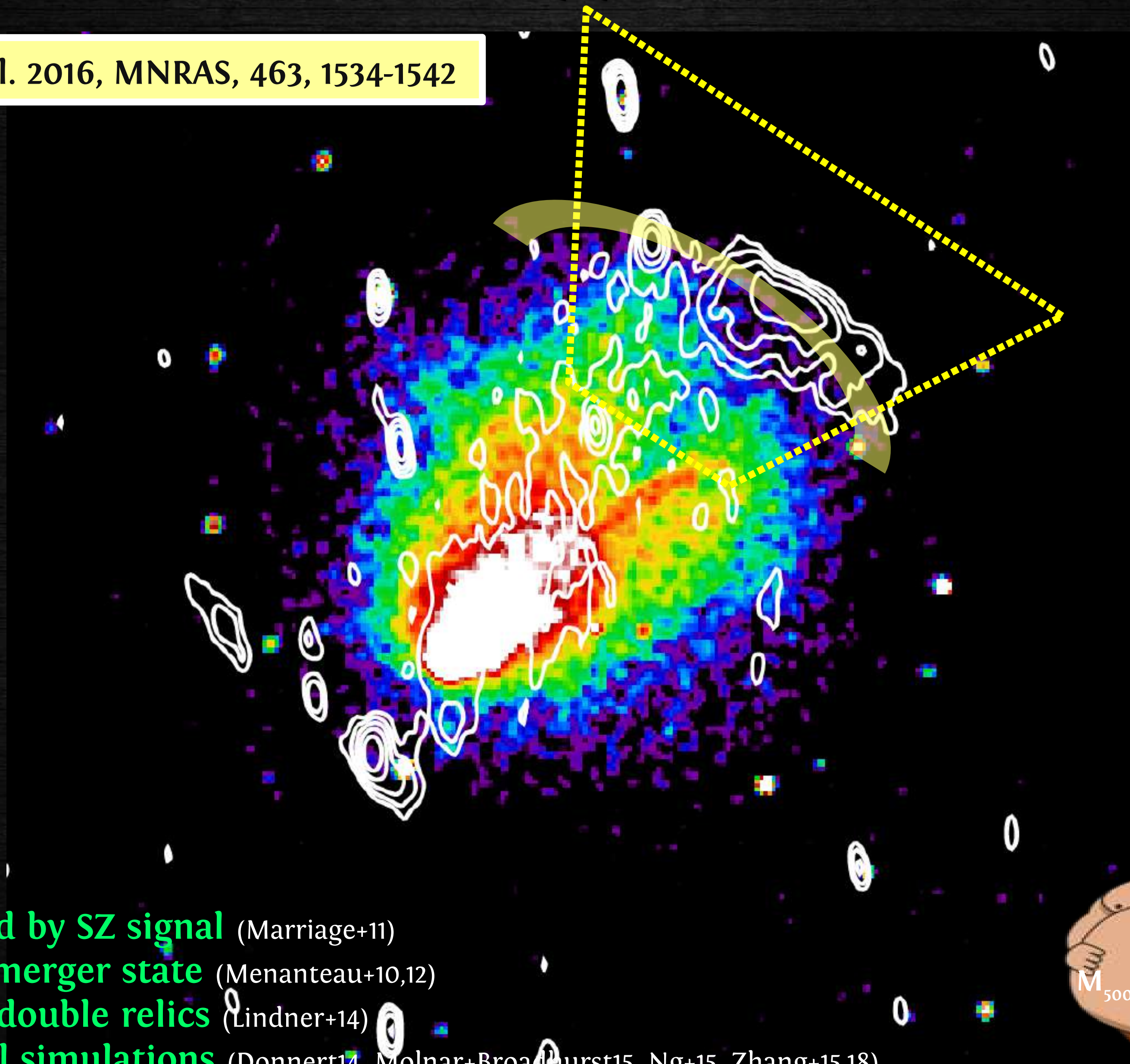
DSA from the *thermal pool* is readily ruled out by the relic spectrum...
Computing η_e assuming $p_{min} > p_{th}$

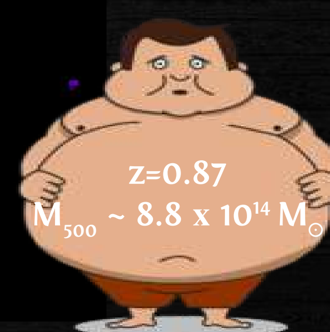
The **RE-acceleration** of *seed e⁻* provided by cluster radio galaxies alleviates the requirement of *high* acceleration efficiencies



El Gordo NW radio relic

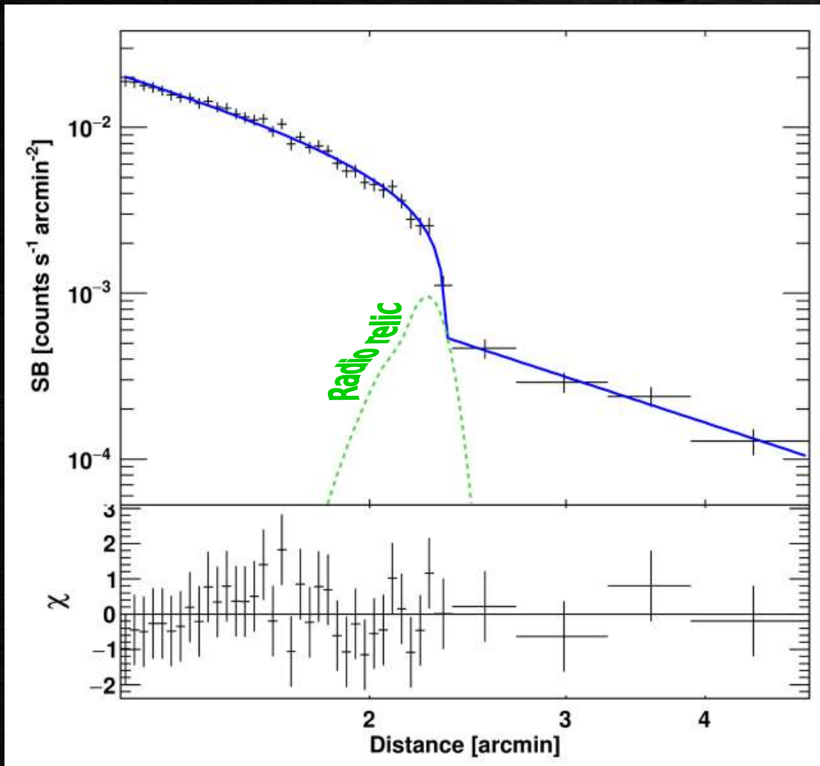
Botteon et al. 2016, MNRAS, 463, 1534-1542

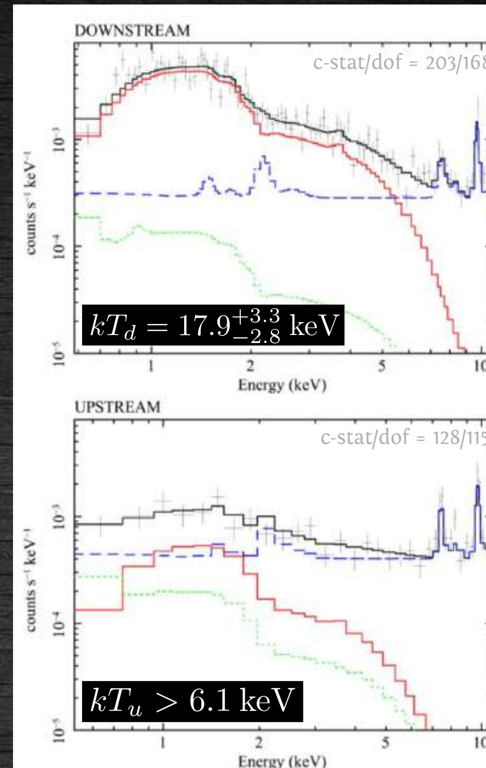




- Discovered by SZ signal (Marriage+11)
- Complex merger state (Menanteau+10,12)
- Halo and double relics (Lindner+14)
- Numerical simulations (Donnert14, Molnar+Broadhurst15, Ng+15, Zhang+15,18)

Strong shock & DSA



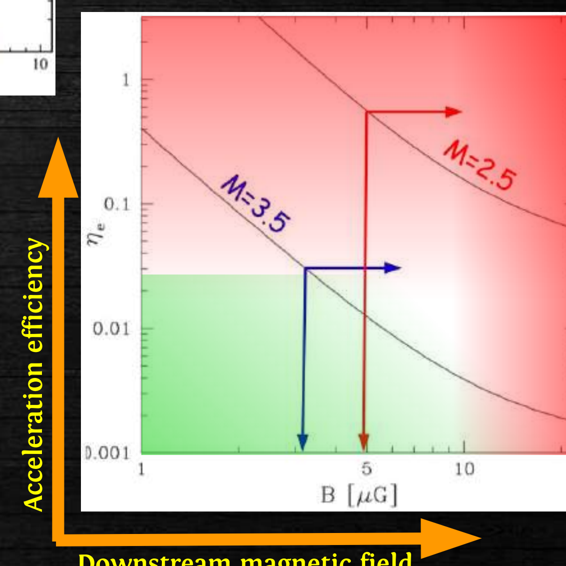


$$\mathcal{M} \gtrsim 3$$

Strong shock

Other **M > 3** shocks:
Markevitch+02
Dasadia+16

Constraints improved by the limits on IC emission



Relic spectrum **α=1.37±0.20**
(from 330 MHz to 610 MHz)

$$\boxed{\alpha = \frac{\mathcal{M}^2+1}{\mathcal{M}^2-1}}$$

DSA can not be ruled out in this case!

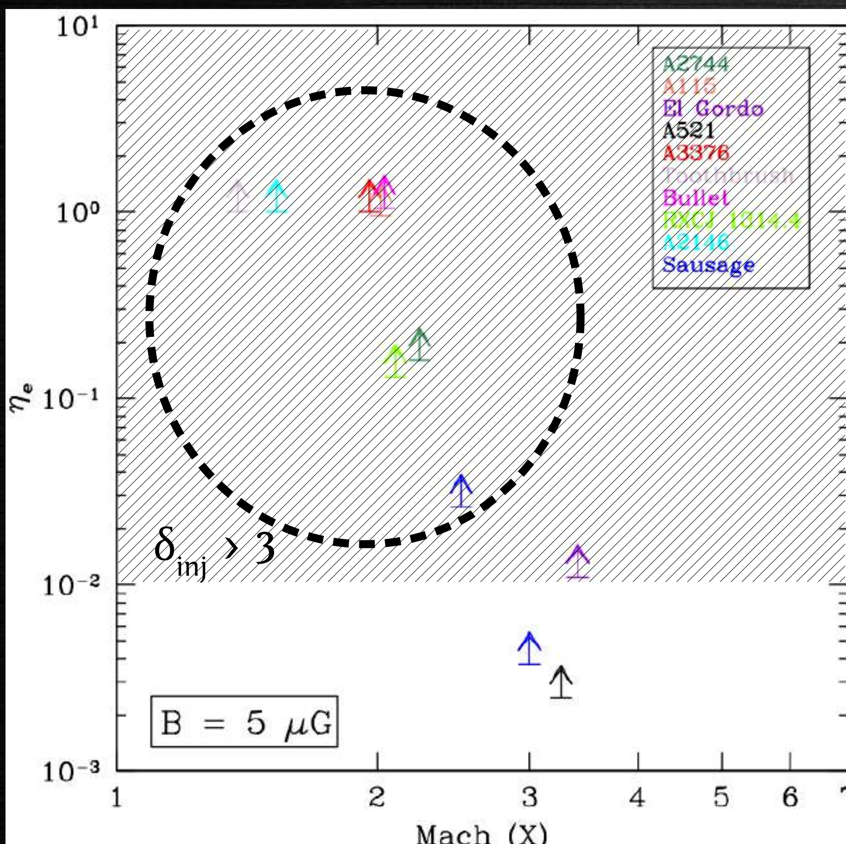
...entering in a different regime?

(Giacintucci+08, Akamatsu+15)

Efficiency in a sample

Recent discoveries of **shocks** co-located with *radio relics* made possible to extend the study to a **sample**!

Cluster name	RA_{J2000} (h,m,s)	DEC_{J2000} (°,′,″)	M_{500} (10^{14} $M_\odot$)	z
A2744	00 14 19	−30 23 22	9.56	0.308
A115	00 55 60	+26 22 41	7.20	0.197
El Gordo	01 02 53	−49 15 19	8.80	0.870
A521	04 54 09	−10 14 19	6.90	0.253
A3376	06 01 45	−39 59 34	2.27	0.046
Toothbrush Cluster	06 03 13	+42 12 31	11.1	0.225
Bullet Cluster	06 58 31	−55 56 49	12.4	0.296
RXC J1314.4-2515	13 14 28	−25 15 41	6.15	0.247
A2146	15 56 09	+66 21 21	3.85	0.234
Sausage Cluster	22 42 53	+53 01 05	7.97	0.192



Botteon et al., A&A submitted (arXiv:1907.00966)

$$\int_{\nu_0} L(\nu)\,\mathrm{d}\nu \simeq \frac{1}{2} S \rho_u V_{sh}^3 \eta_e \Psi \frac{B^2}{B_{cmb}^2 + B^2}$$

η_e is computed assuming the *upper* bound on the shock Mach number

DSA can not explain the origin of the relics in case of **weak shocks**

Search for new shocks

1) $M_{500} > 5 \times 10^{14}\ M_{\odot}$

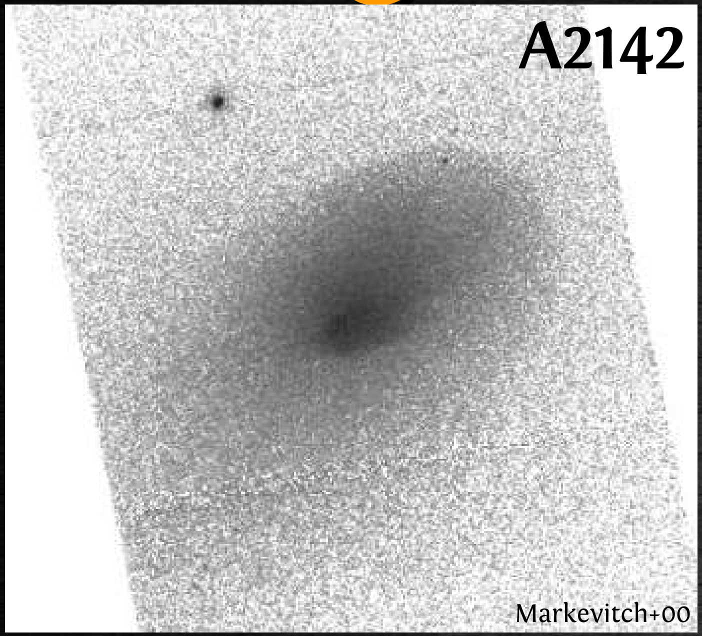
2) $K_0 > 30\text{-}50$ keV cm^2

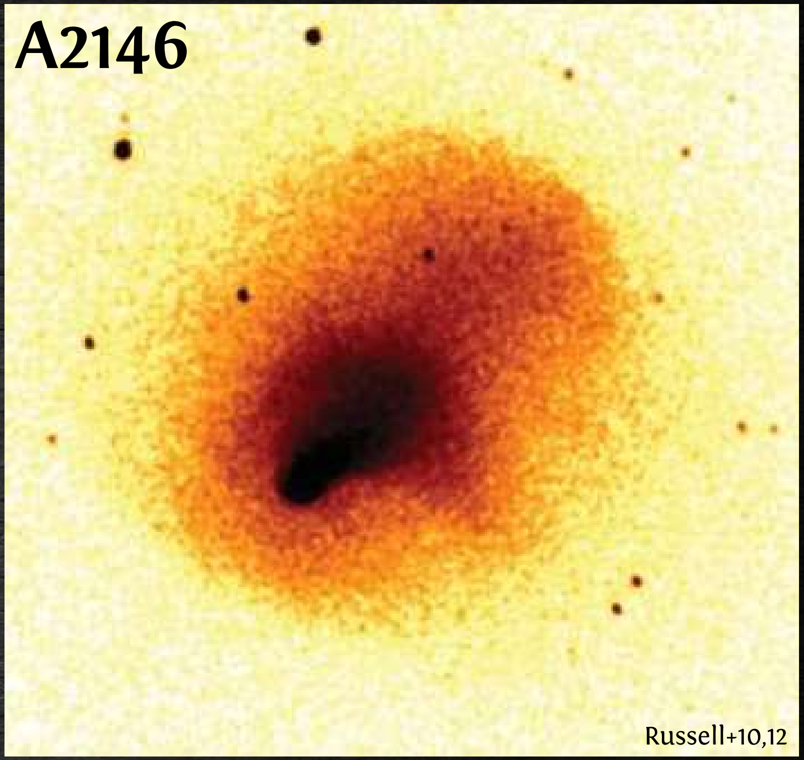
3) > 40.000 – 50.000 cts @ 0.5-7.0 keV

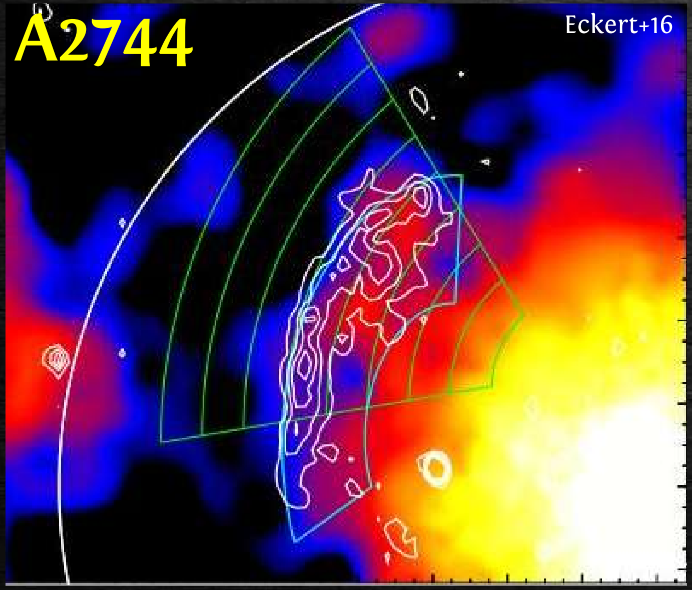
Cluster name	$\mathrm{RA}_{\mathrm{J2000}}$ (h,m,s)	$\mathrm{DEC}_{\mathrm{J2000}}$ (°,′,″)	M_{500} (10^{14} $\mathrm{M}_{\odot}$)	z	K_0 (keV cm^2)
A2813	00 43 24	−20 37 17	9.16	0.292	268 ± 44
A370	02 39 50	−01 35 08	7.63	0.375	322 ± 91
A399	02 57 56	+13 00 59	5.29	0.072	153 ± 19
A401	02 58 57	+13 34 46	6.84	0.074	167 ± 8
MACS J0417.5-1154	04 17 35	−11 54 34	11.7	0.440	27 ± 7
RXC J0528.9-3927	05 28 53	−39 28 18	7.31	0.284	73 ± 14
MACS J0553.4-3342	05 53 27	−33 42 53	9.39	0.407	...
AS592	06 38 46	−53 58 45	6.71	0.222	59 ± 14
A1413	11 55 19	+23 24 31	5.98	0.143	164 ± 8
A1689	13 11 29	−01 20 17	8.86	0.183	78 ± 8
A1914	14 26 02	+37 49 38	6.97	0.171	107 ± 18
A2104	15 40 07	−03 18 29	5.91	0.153	161 ± 42
A2218	16 35 52	+66 12 52	6.41	0.176	289 ± 20
Triangulum Australis	16 38 20	−64 30 59	7.91	0.051	...
A3827	22 01 56	−59 56 58	5.93	0.098	165 ± 12

Botteon et al., 2018, MNRAS, 476, 5591-5620

Edges in the literature

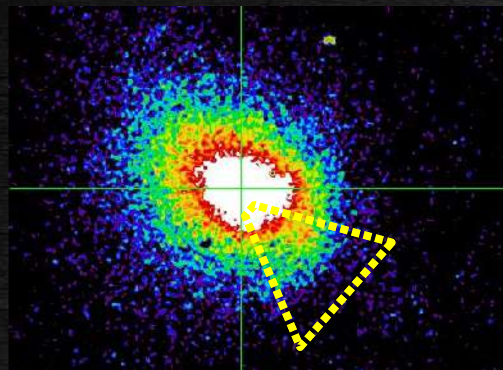


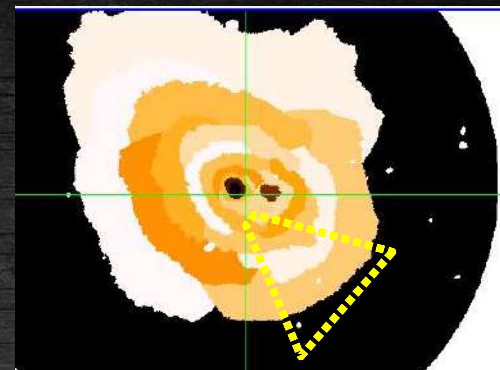




Walk through

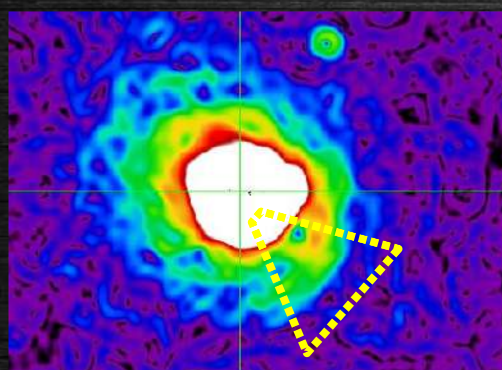
1) Unrelaxed cluster

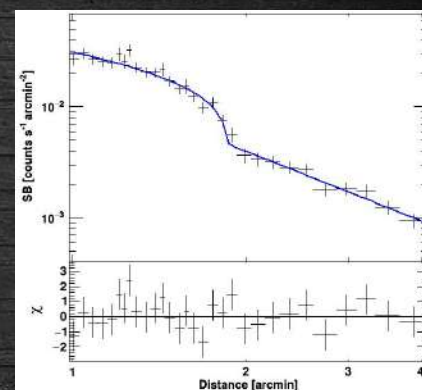




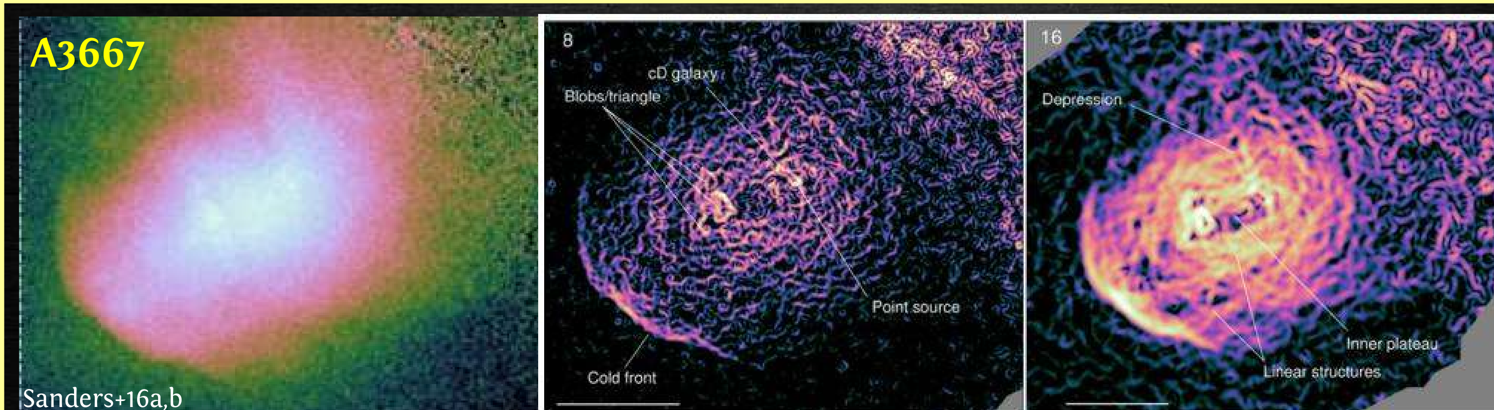
2) Thermo-dynamical maps

3) Edge-detection algorithms





4) Surface brightness profiles



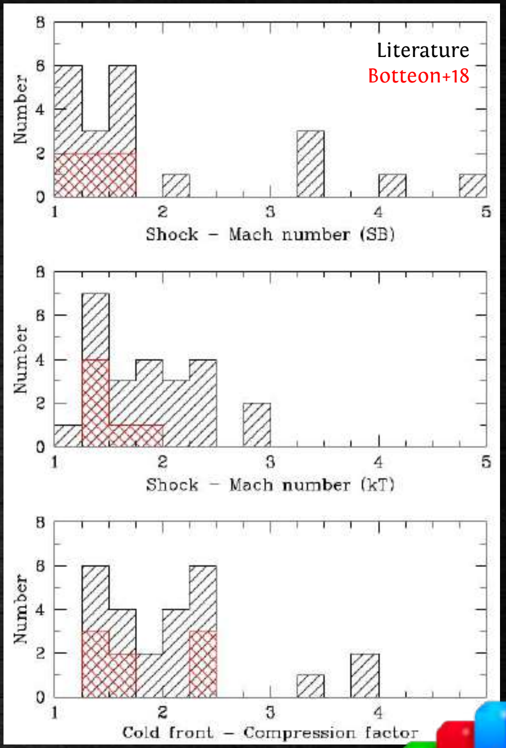
Gaussian

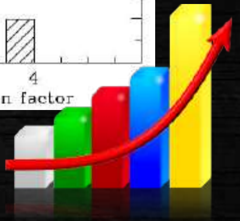
Gradient

Magnitude

New shocks and cold fronts

Cluster name	Position	$\mathcal{C}$	$\mathcal{R}$	$\mathcal{P}$	$\mathcal{M}_{SB}$	$\mathcal{M}_{kT}$	Nature
A370	E	$1.48^{+0.11}_{-0.10}$	...	...	$1.33^{+0.08}_{-0.07}$	...	U
	W	$1.56^{+0.13}_{-0.12}$	...	...	$1.38^{+0.10}_{-0.09}$	...	U
A399	E inner	$1.72^{+0.13}_{-0.12}$	$0.74^{+0.14}_{-0.12}$	$1.27^{+0.26}_{-0.22}$	n.a.	n.a.	CF
	E outer	$1.45^{+0.10}_{-0.10}$	$1.20^{+0.39}_{-0.26}$	$1.74^{+0.58}_{-0.40}$	$1.31^{+0.07}_{-0.07}$	...	U
A401	SE	$1.39^{+0.04}_{-0.04}$	$0.78^{+0.07}_{-0.06}$	$1.08^{+0.10}_{-0.09}$	n.a.	n.a.	CF
MACS J0417.5-1154	NW	$2.50^{+0.29}_{-0.25}$	< 0.59	< 1.64	n.a.	n.a.	CF
	SE	$2.44^{+0.31}_{-0.25}$	$0.44^{+0.17}_{-0.10}$	$1.07^{+0.44}_{-0.27}$	n.a.	n.a.	CF
RXC J0528.9-3927	E	$1.51^{+0.10}_{-0.09}$	$0.73^{+0.25}_{-0.14}$	$1.10^{+0.38}_{-0.22}$	n.a.	n.a.	CF
MACS J0553.4-3342	E inner	$2.49^{+0.32}_{-0.26}$	$0.62^{+0.33}_{-0.18}$	$1.54^{+0.85}_{-0.48}$	n.a.	n.a.	CF
	E outer	$1.41^{+0.14}_{-0.13}$	$2.00^{+1.14}_{-0.63}$	$2.82^{+1.63}_{-0.93}$	$1.28^{+0.10}_{-0.09}$	$1.94^{+0.77}_{-0.56}$	S
	W	$1.70^{+0.12}_{-0.11}$	$0.33^{+0.22}_{-0.12}$	$0.56^{+0.38}_{-0.21}$	n.a.	n.a.	CF
AS592	SW	$1.99^{+0.17}_{-0.15}$	$1.61^{+0.66}_{-0.43}$	$3.20^{+1.34}_{-0.89}$	$1.72^{+0.15}_{-0.12}$	$1.61^{+0.54}_{-0.42}$	S
A1914	E upper	$1.48^{+0.11}_{-0.12}$	$0.40^{+0.21}_{-0.12}$	$0.59^{+0.31}_{-0.18}$	n.a.	n.a.	CF
	E lower	$1.64^{+0.13}_{-0.12}$		$0.66^{+0.35}_{-0.20}$			
	W	$1.33^{+0.08}_{-0.07}$	$1.27^{+0.26}_{-0.21}$	$1.69^{+0.36}_{-0.29}$	$1.22^{+0.06}_{-0.05}$	$1.28^{+0.26}_{-0.21}$	S
A2104	SE inner	< 1.47	$1.33^{+0.27}_{-0.19}$	< 2.36	< 1.32	$1.34^{+0.26}_{-0.20}$	S
	SE outer	$1.54^{+0.16}_{-0.14}$	$0.77^{+0.30}_{-0.21}$	$1.19^{+0.48}_{-0.34}$	$1.37^{+0.12}_{-0.10}$	...	U
	SW	$1.27^{+0.07}_{-0.06}$	$0.85^{+0.20}_{-0.15}$	$1.08^{+0.26}_{-0.20}$	$1.18^{+0.05}_{-0.04}$	...	U
A2218	N	$1.47^{+0.21}_{-0.18}$	$1.38^{+0.40}_{-0.28}$	$2.03^{+0.66}_{-0.48}$	$1.32^{+0.15}_{-0.13}$	$1.39^{+0.37}_{-0.29}$	S
	SE inner	$1.38^{+0.14}_{-0.11}$	$0.84^{+0.35}_{-0.17}$	$1.16^{+0.50}_{-0.25}$	$1.26^{+0.10}_{-0.08}$	...	U
	SE outer	$1.26^{+0.14}_{-0.14}$	$1.44^{+0.48}_{-0.33}$	$1.81^{+0.64}_{-0.46}$	$1.17^{+0.10}_{-0.09}$	$1.45^{+0.43}_{-0.33}$	S
	SW	$1.41^{+0.23}_{-0.21}$	$1.41^{+0.83}_{-0.49}$	$1.99^{+1.21}_{-0.75}$	$1.28^{+0.17}_{-0.14}$	...	U
Triangulum Australis	E	$1.34^{+0.04}_{-0.04}$	$1.00^{+0.15}_{-0.10}$	$1.34^{+0.20}_{-0.14}$	$1.23^{+0.03}_{-0.03}$	...	U





22 edges: **6 shocks**, **8 cold fronts** and **8 uncertain**

- Statistics of detected shocks and cold fronts in the ICM **increased**
- General **agreement** between the Mach numbers derived from kT and SB jumps
- All the shocks found have **low Mach number** (M < 2)

Summary

- When clusters collide, *shocks happen*
- Number of shocks *increasing*
- **Merger shocks** are responsible of **radio relics**

- Relic-shock connection in **A115** & **El Gordo** (Botteon+16a,b)
- First *constraints* on the acceleration efficiency in a sample of radio relics (Botteon+, submitted)
- **DSA** is not responsible of *radio relics*

- Detection of new **shocks** (and **cold fronts**) (Botteon+18)

Thank you