Some physical issues related with Radio Relics

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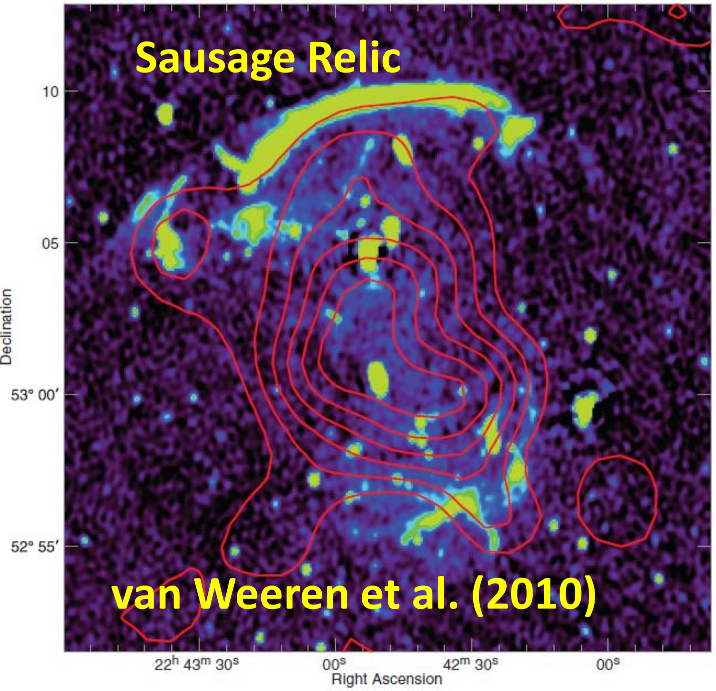
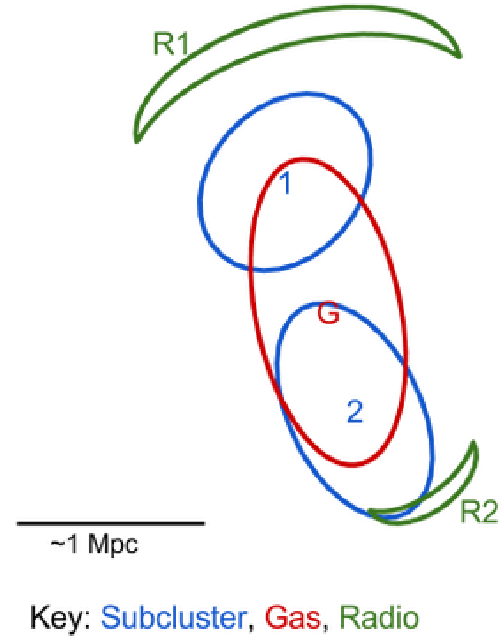
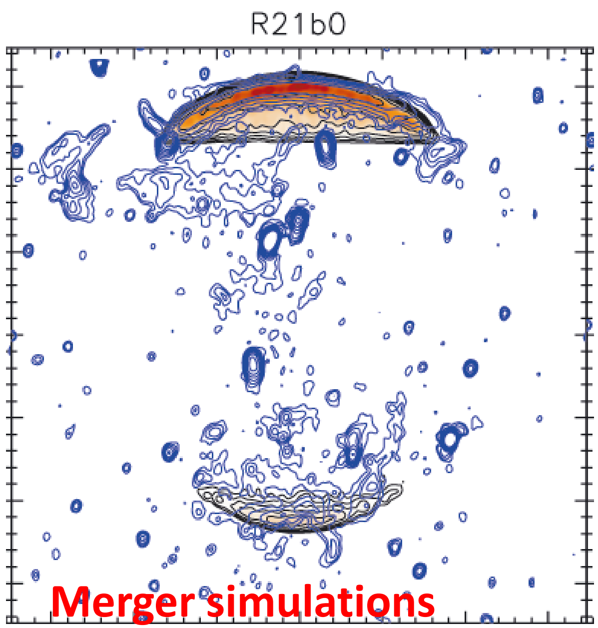
1. Uniform surface brightness along the Sausage relic
2. Cooling length behind the shock
3. Break frequency in volume-integrated spectrum
4. Comparison of high and low B field cases
5. Curvature of the integrated spectrum of the Sausage relic

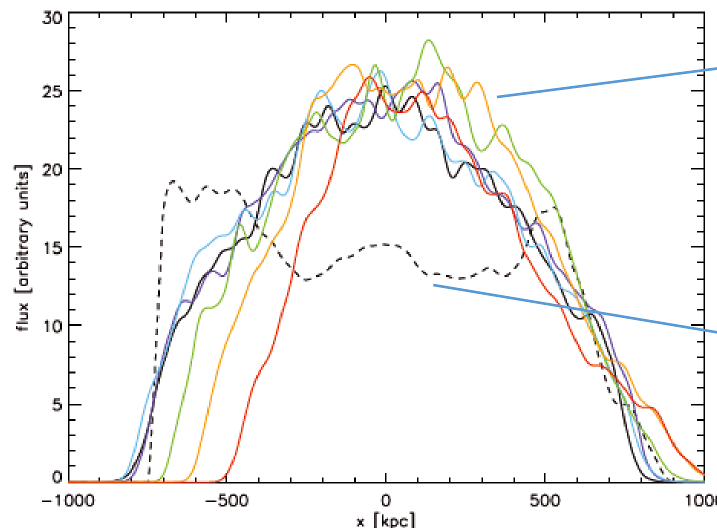




Merger geometry



Merger simulations
van Weeren et al. (2011)

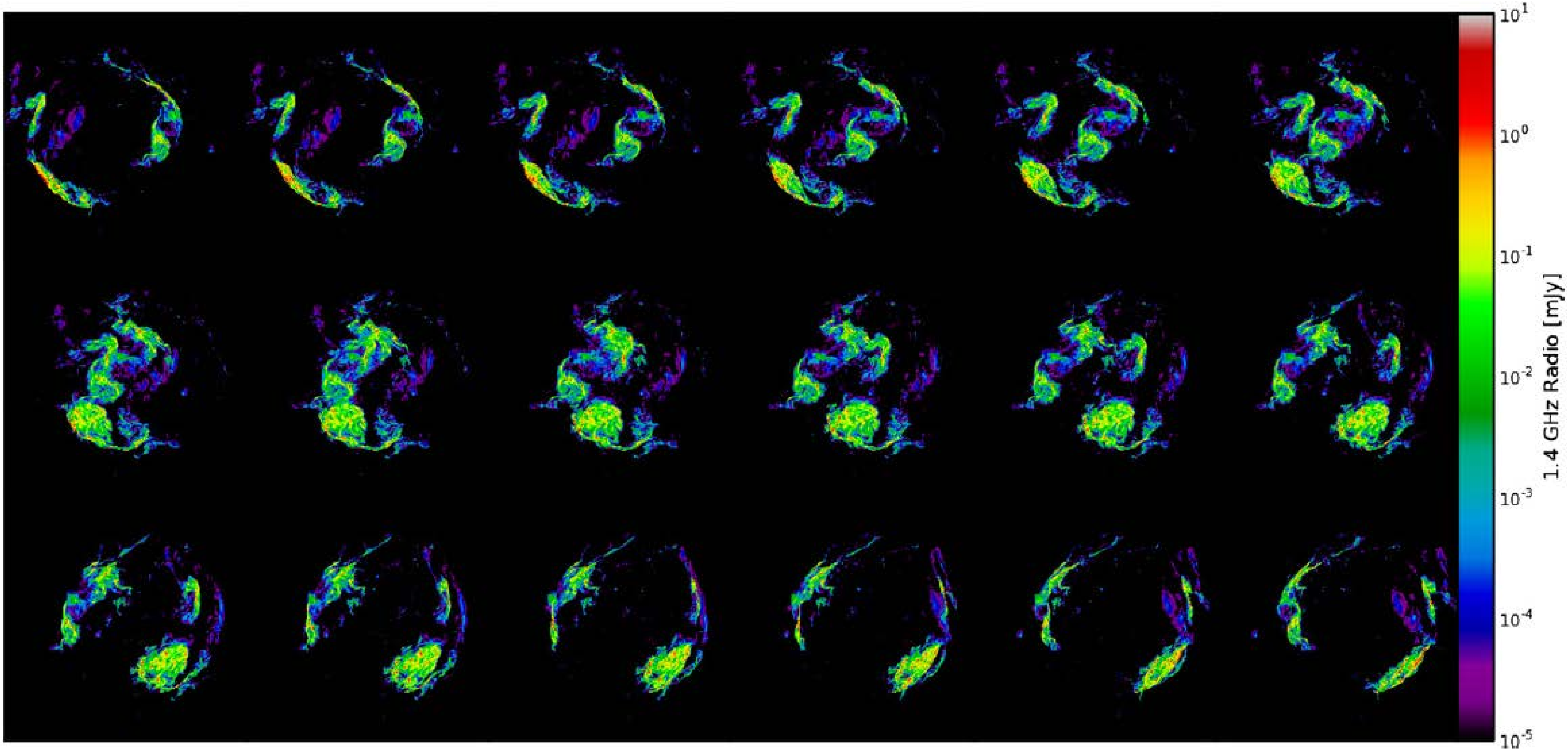


Merger simulation

Observed profile

Why uniform surface brightness along the relic ?

Radio emission from cosmic-ray electrons in merging galaxy clusters



Significant dependence of the observed morphology on the viewing angle:
180◦ rotation of radio emission. Each panel is rotated by 10◦ from the previous, moving left to right, top to bottom (**Skillmann et al. 2013**).

The bulk of the radio emission comes from gas with $T > 5 \times 10^7$ K , B ~ 0.1–1.0μG, and shock Mach numbers of M~ 3–6.

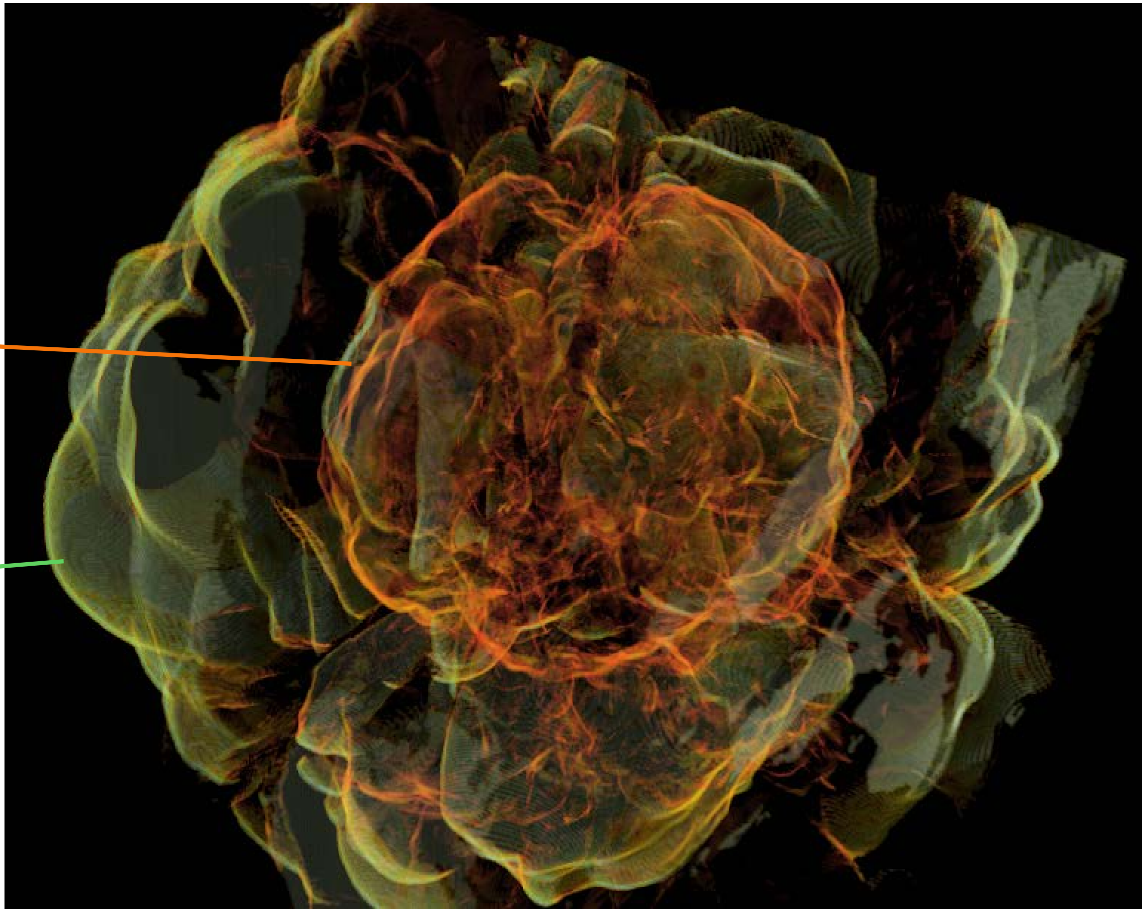
Shocks in Clusters of Galaxies in the Structure Formation Simulations

Vazza, Jones et al 2015 (in prep).

Weak shocks with M<4 (orange)

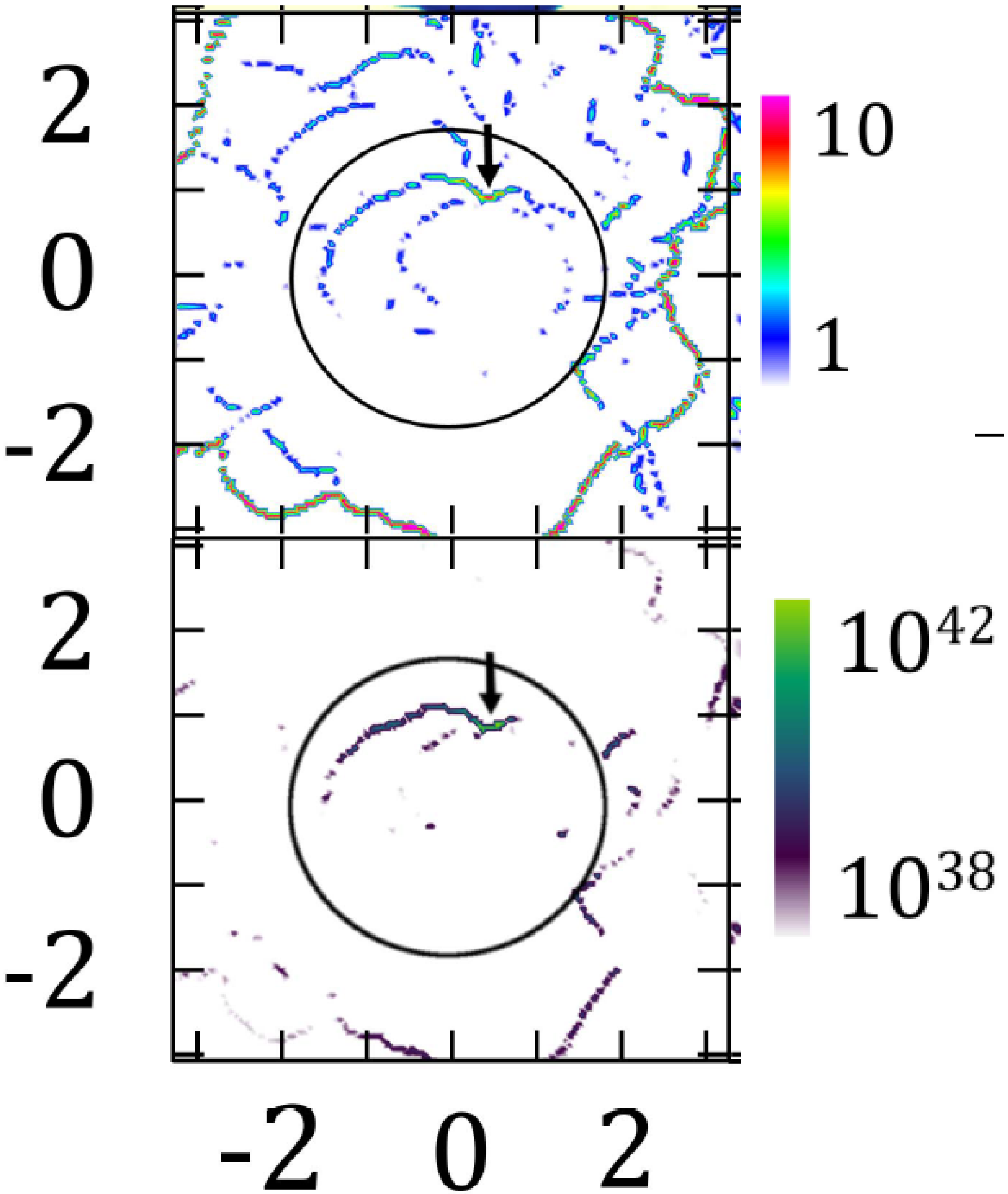
Accretion shocks with M>10 (green)

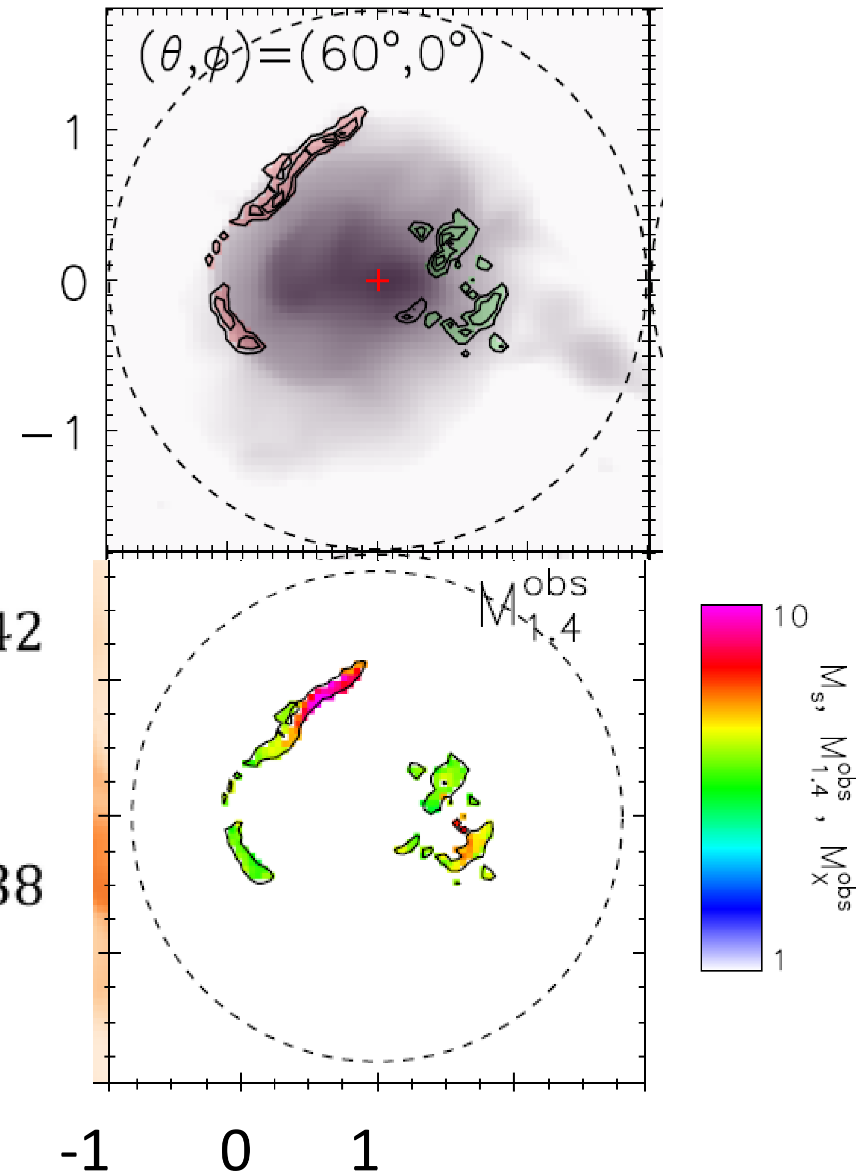
Spherical bubbles blowing out from the cluster center during major episodes of mergers or infalls from adjacent filaments.



Evolution of shock distribution in a merging cluster

https://www.youtube.com/watch?v=yV3KPz0cPqk

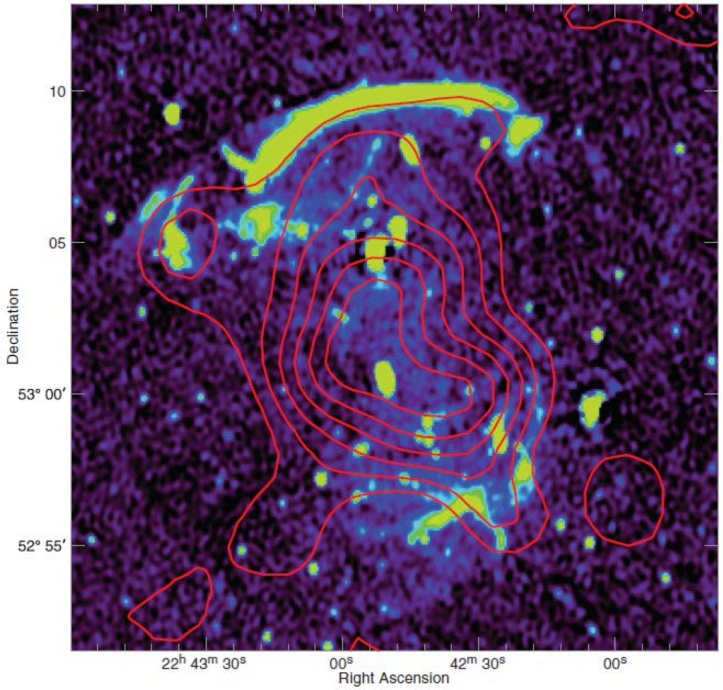


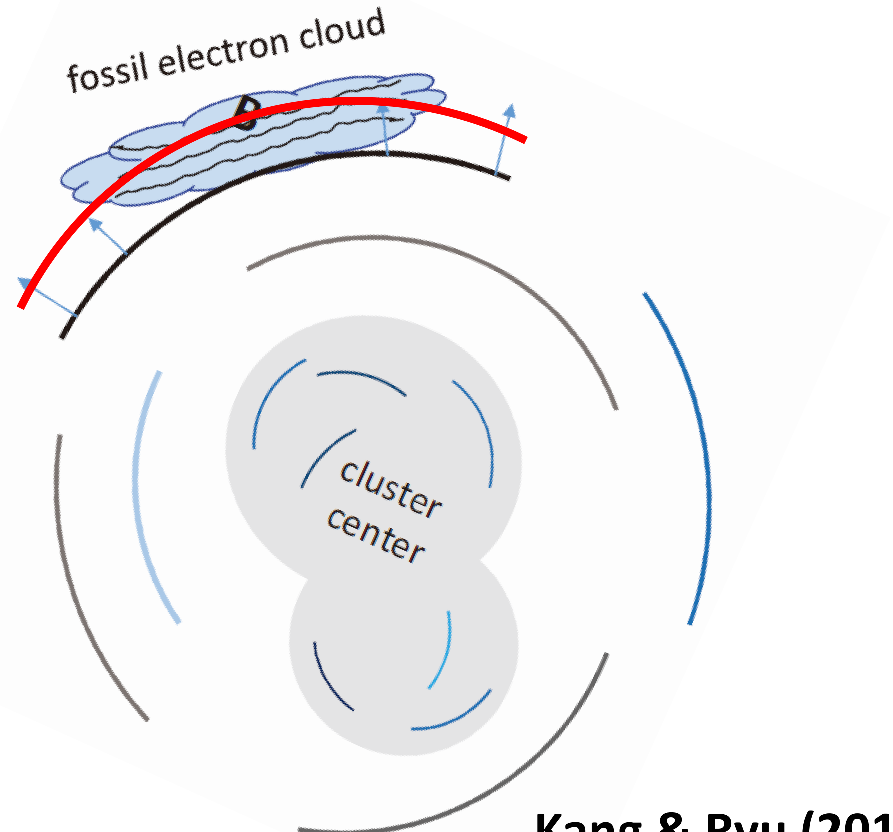


Mpc-long relic with uniform SB: quite rare

Hong et al. 2014, 2015

Sausage Relic: Re-acceleration model





Kang & Ryu (2015)

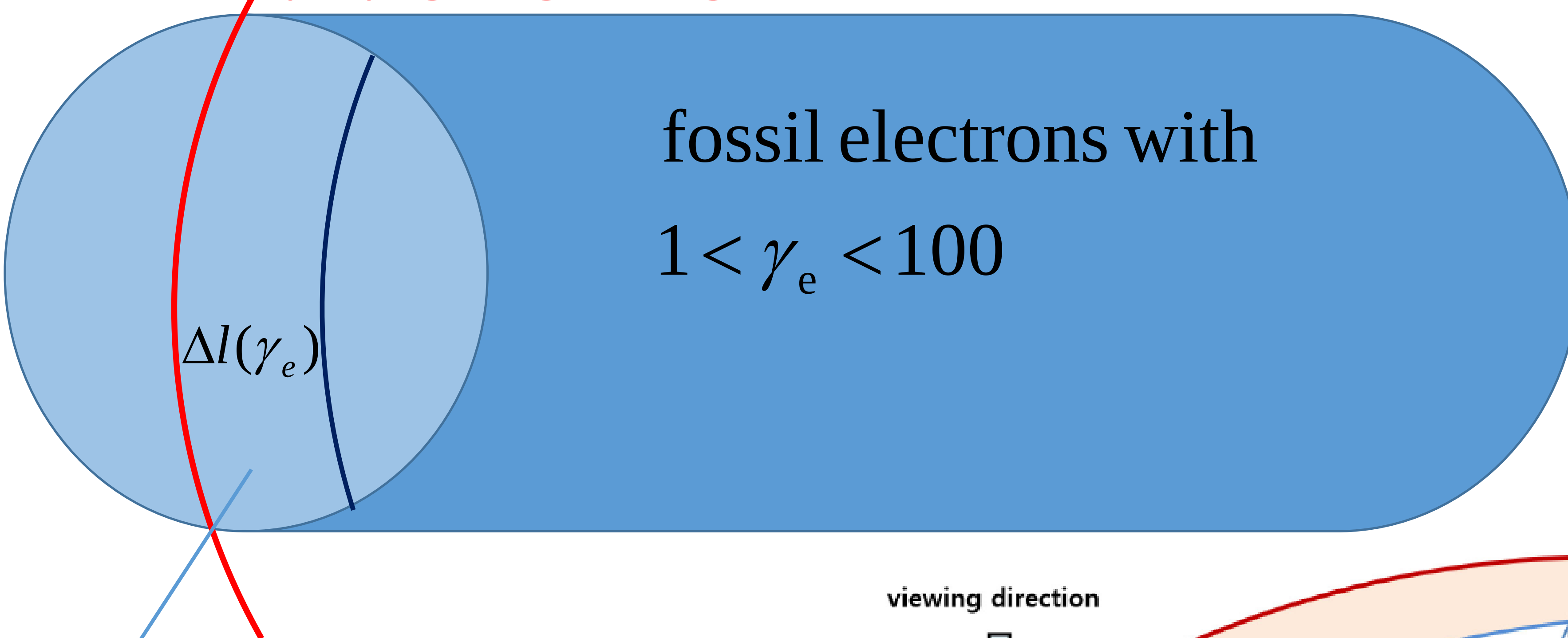
-According to structure formation simulations, shocks are abundant in merging clusters.

-Fraction of merging clusters with radio relics: < 10 %.

Why relics are so rare ?

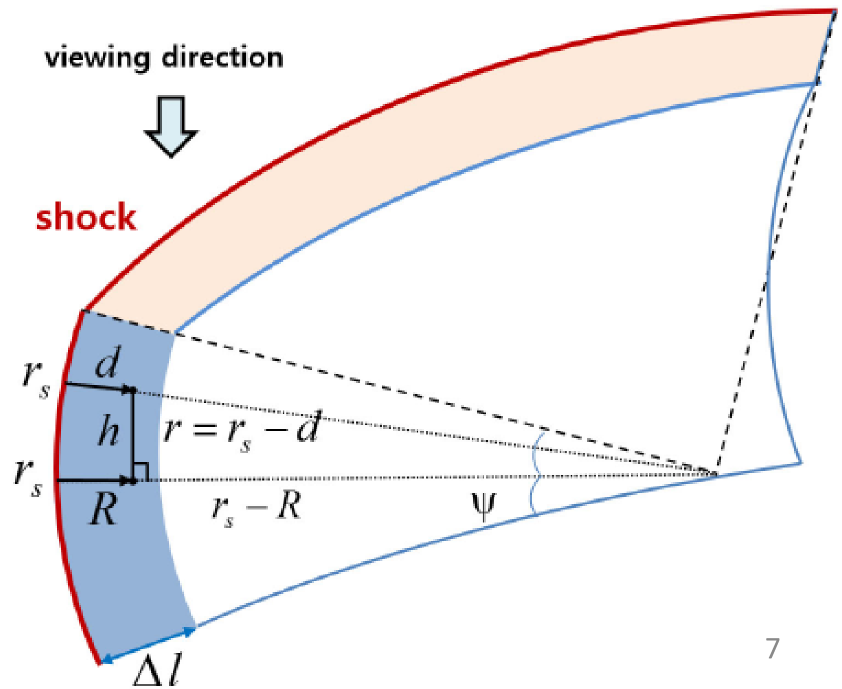
A spherical shock impinges on an elongate cloud of fossil relativistic electrons.

Shock is propagating through a cloud of fossil electrons

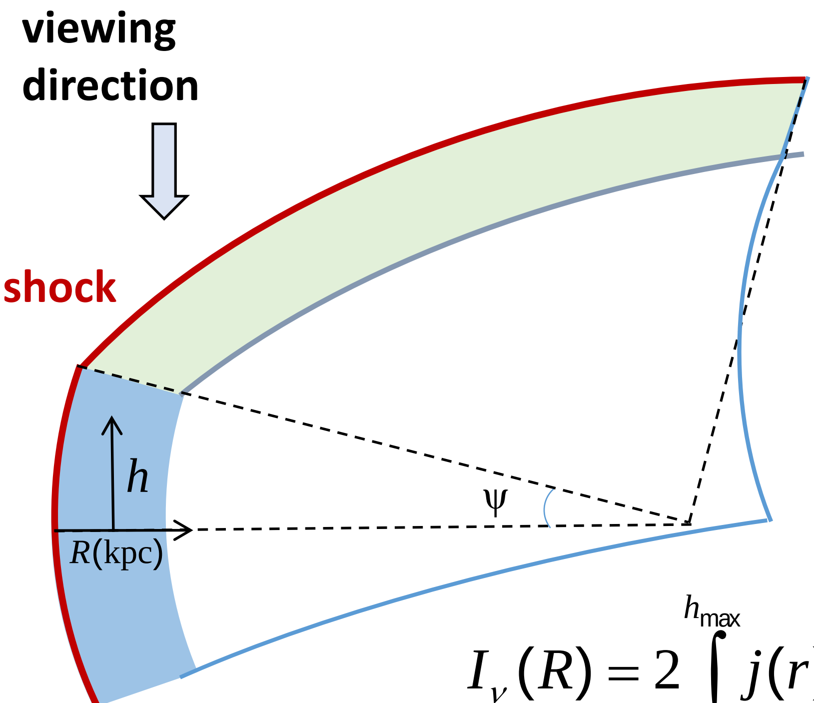


Radio emitting volume of CR electrons cooling behind the shock.

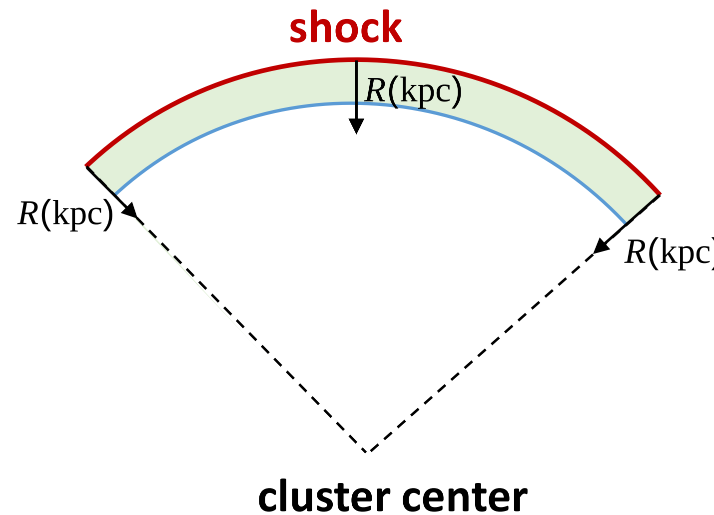
$$10^3 < \gamma_e < 10^5$$



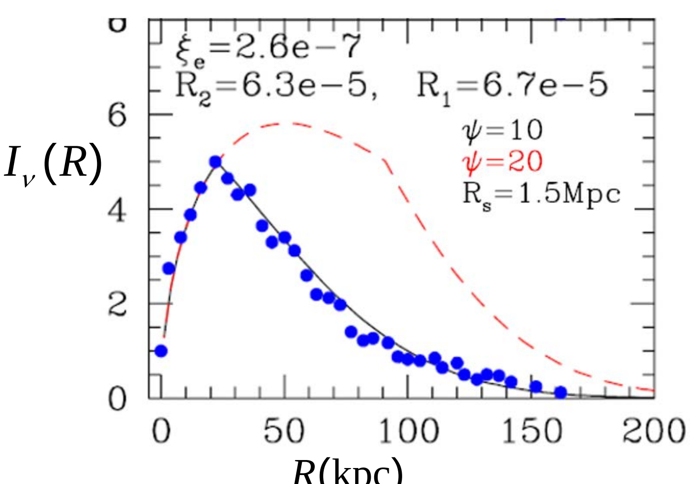
Shock into a fossil electron cloud ➔ Thin arc-like uniform surface brightness

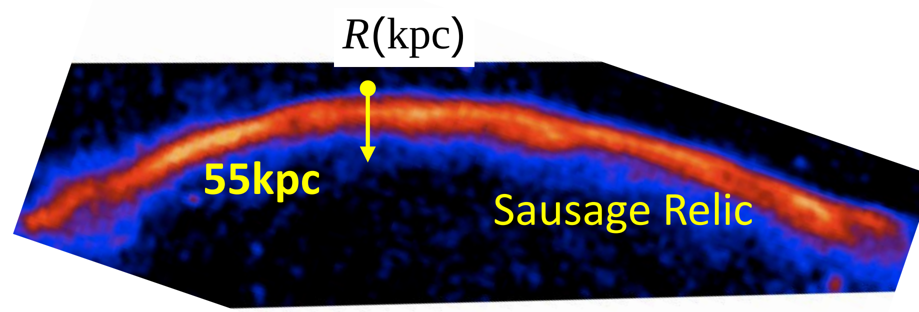


Projection onto the sky plane



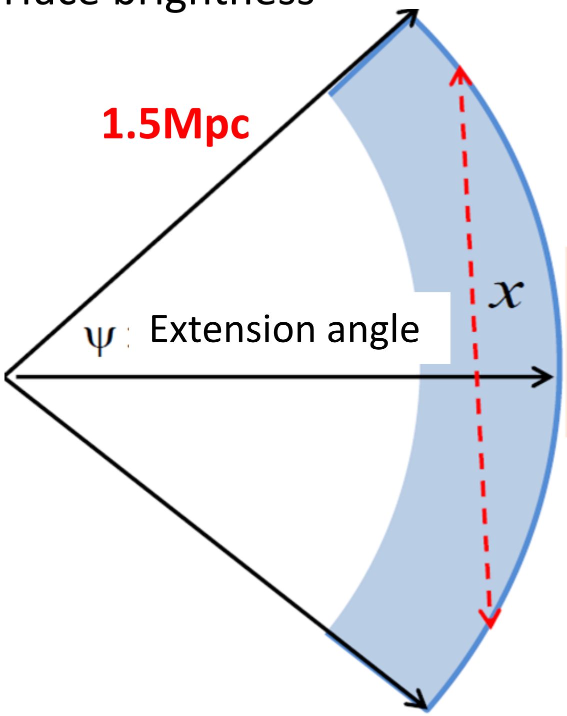
$$I_\nu(R) = 2\int_0^{h_{\max}} j(r)\,dh$$





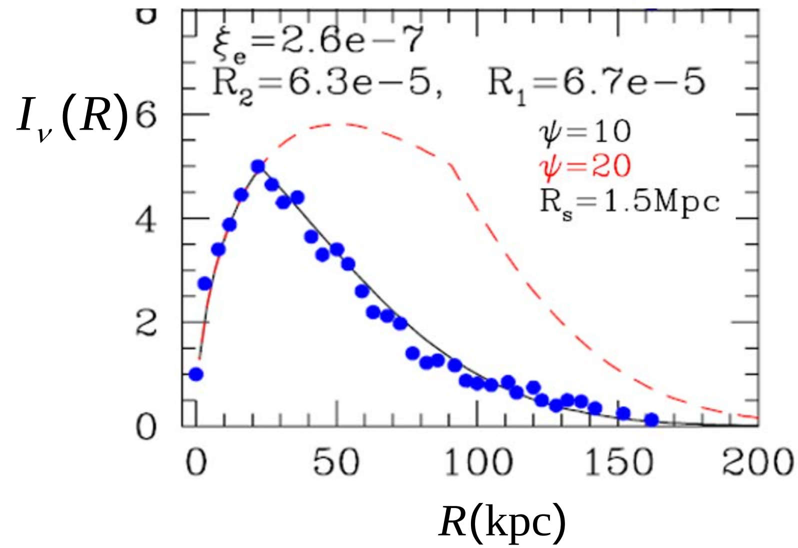
van Weeren et al. (2010)
Kang, Ryu, Jones (2012)

Surface brightness

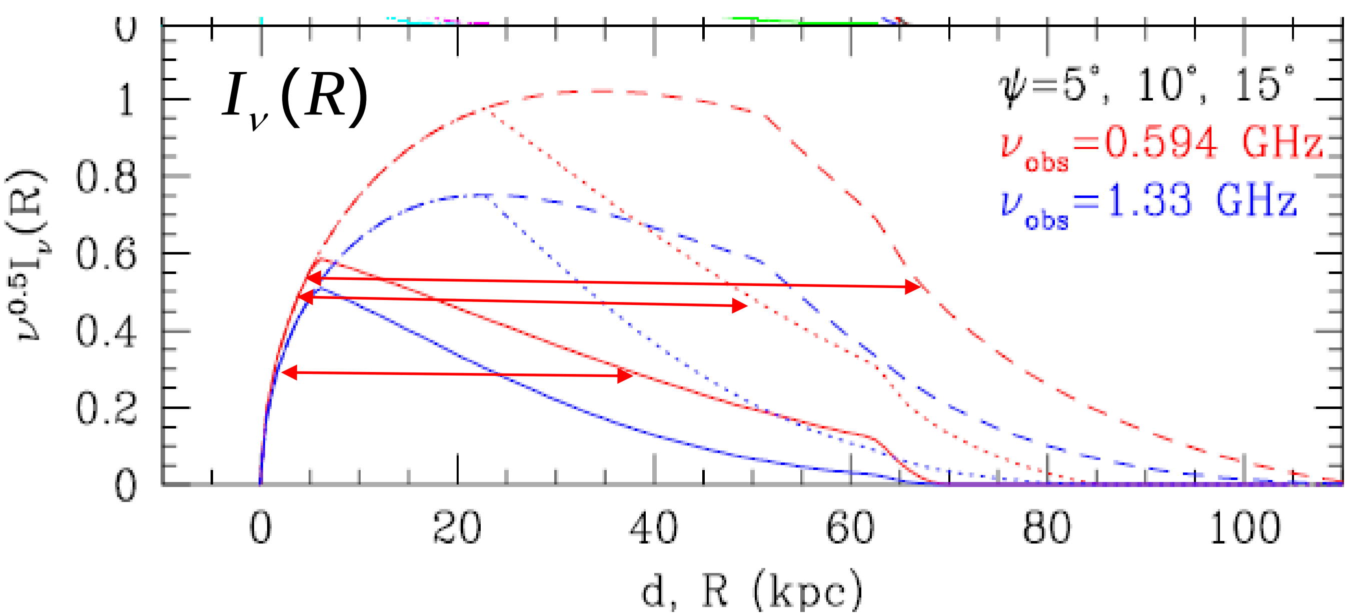


$$I_\nu(R) = 2\int_0^{h_{max}} j(r)\,dh$$

integration along lines of sight



Kang, Ryu, Jones (2012)



Surface brightness profile and width of relics depend on the extension angle and obs. frequency in addition to B.

Synchrotron + IC cooling of Electrons ➔ break frequency & cooling length

$$t_{\rm rad}(\gamma_e) = \frac{p}{b(p)} = 9.8\times10^7\ {\rm yr}\left(\frac{B_{\rm e}}{5\ \mu{\rm G}}\right)^{-2}\left(\frac{\gamma_e}{10^4}\right)^{-1}$$

$$\boxed{\gamma_{\rm e,br} \approx 10^4 \left(\frac{t_{\rm age}}{100{\rm Myr}}\right)^{-1}\left(\frac{B_{\rm e,2}}{5\ \mu{\rm G}}\right)^{-2}}$$

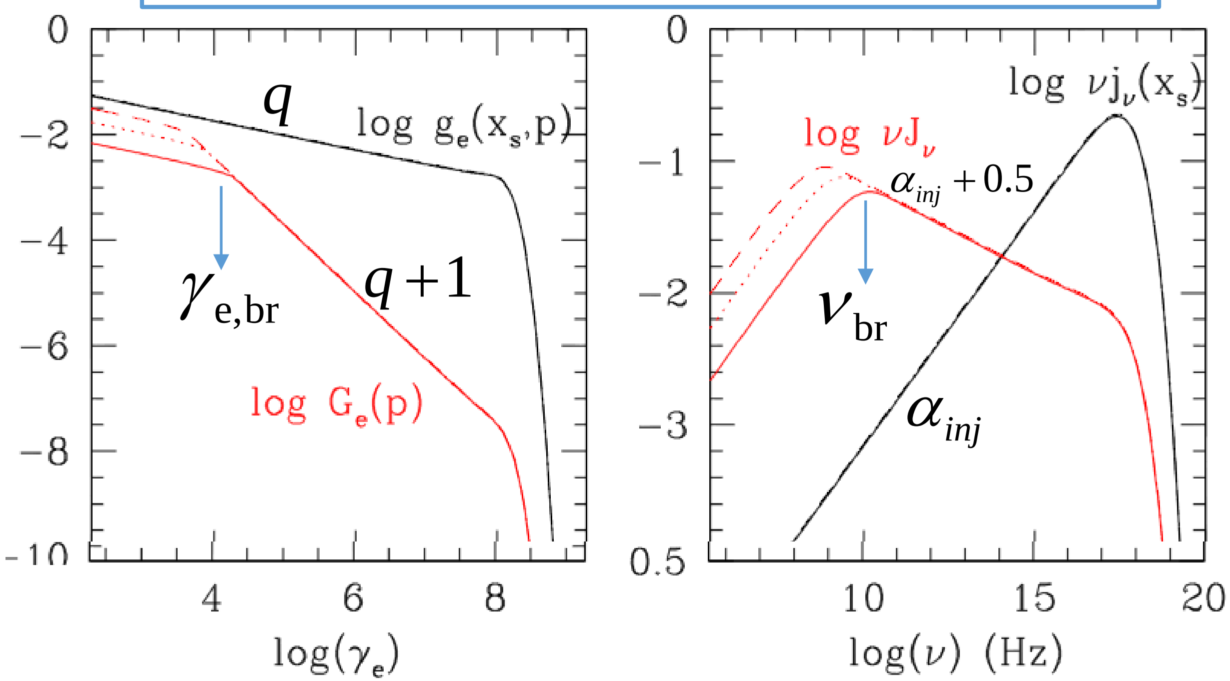
Break in N_e

$$\nu_{\rm peak} \approx 0.3\left(\frac{3eB}{4\pi m_e c}\right)\gamma_e^2 \approx 0.63\ {\rm GHz}\cdot\left(\frac{B}{5\ \mu{\rm G}}\right)\left(\frac{\gamma_e}{10^4}\right)^2$$

$$B_{e,2} = \sqrt{B_2^2 + B_{\rm rad}^2}$$

$$\boxed{\nu_{\rm br} \approx 0.63{\rm GHz}\left(\frac{t_{\rm age}}{100{\rm Myr}}\right)^{-2}\left(\frac{5^2}{B_2^2+B_{\rm rad}^2}\right)^{2}\left(\frac{B_2}{5}\right)}$$

Break in J_nu



Postshock volume-Integrated spectra

$$f_e(r_s,p) \propto p^{-q}$$

$$F_e(p) = \int f_e(p)dV \propto p^{-(q+1)}$$

for $\gamma_{\rm e} > \gamma_{\rm e,br}$

$$j_\nu(r_s) \propto \nu^{-\alpha_{inj}}$$

$$\alpha_{\rm inj} = (M^2+3)/2(M^2-1)$$

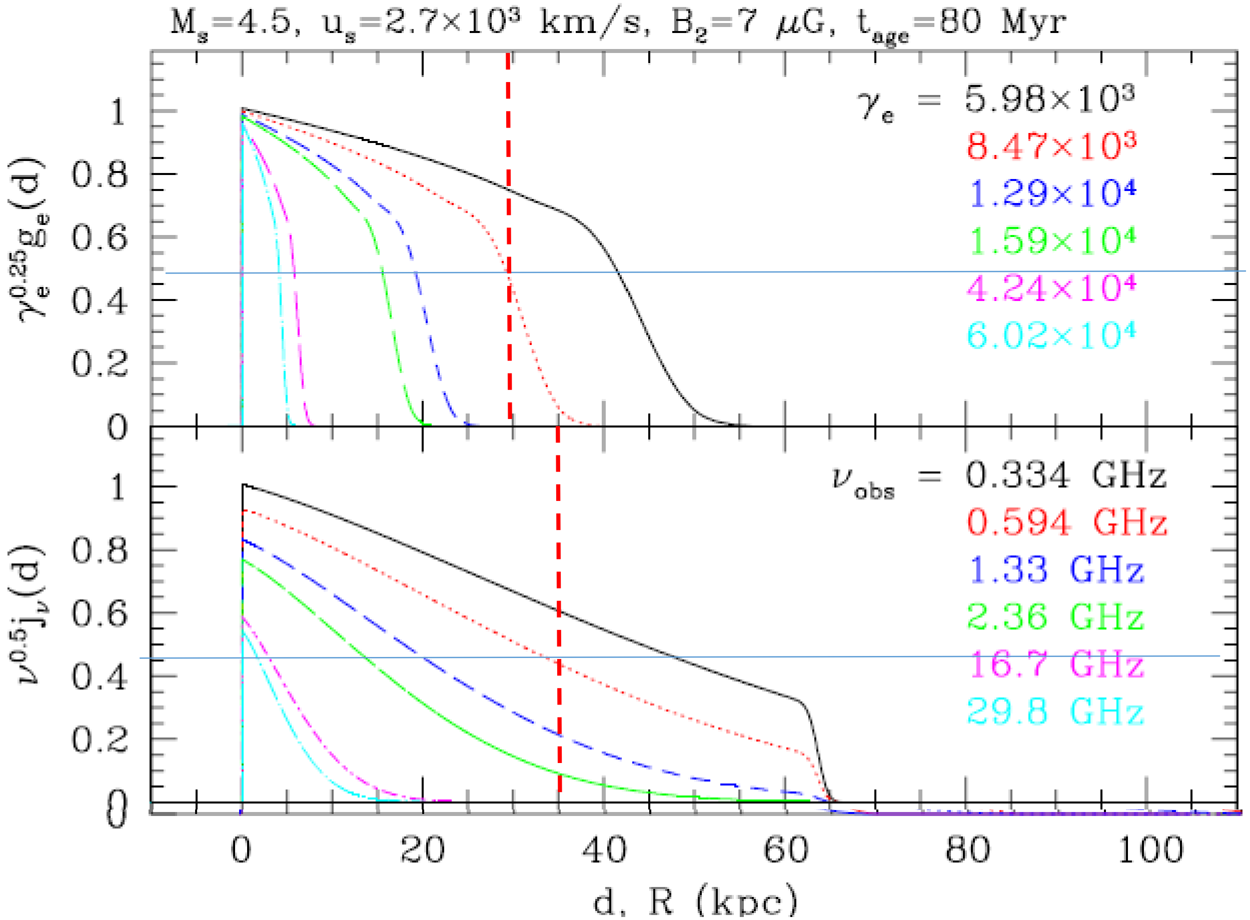
$J_\nu \propto \nu^{-A_\nu}$ with $A_\nu = \alpha_{inj} + 0.5$

for $\nu_e > \nu_{\rm br}$

Cooling length & width of radio relic

$$\Delta l_{\nu_{\rm obs}} \approx W \cdot \Delta l_{\rm cool}(\gamma_e) \approx W \cdot u_2 t_{\rm rad}(\gamma_e)$$

$$\Delta l_{\nu_{\rm obs}} \approx W \cdot 100 \text{ kpc} \cdot \left(\frac{u_2}{10^3 \text{ km s}^{-1}}\right)\left(\frac{5^2}{B_2^2 + B_{\rm rad}^2}\right)\left(\frac{B_2}{5}\right)^{1/2}\left[\frac{\nu_{\rm obs}(1+z)}{0.63\text{GHz}}\right]^{-1/2}$$



$\Delta l_{cool} \sim 30$ kpc

$\Delta l_{\nu_{obs}} \sim 35$ kpc

$W \approx 1.2 - 1.3$

Estimation of B_2 from the width of radio relics

$$\Delta l_{\nu_{obs}} \approx W \cdot 100\ \mathrm{kpc} \cdot \left(\frac{u_2}{10^3\ \mathrm{km\ s^{-1}}}\right) \boxed{\left(\frac{5^2}{B_2^2 + B_{\rm rad}^2}\right)\left(\frac{B_2}{5}\right)^{1/2}} \left[\frac{\nu_{obs}(1+z)}{0.63\mathrm{GHz}}\right]^{-1/2}$$

For Sausage Relic, observed width~55kpc,

B_2 = 1.2 or 5 μG (van Weeren et al. 2010)

Estimation of B_2 from the break in the integrated spectrum

$$\nu_{\rm br} \approx 0.63\mathrm{GHz} \left(\frac{t_{\rm age}}{100\mathrm{Myr}}\right)^{-2} \boxed{\left(\frac{5^2}{B_2^2 + B_{\rm rad}^2}\right)^2 \left(\frac{B_2}{5}\right)}$$

For Two values of $B_{\rm high}$ and $B_{\rm low}$ $\Delta l_{\nu_{\rm obs}}$ and $\nu_{\rm br}$ are identical.

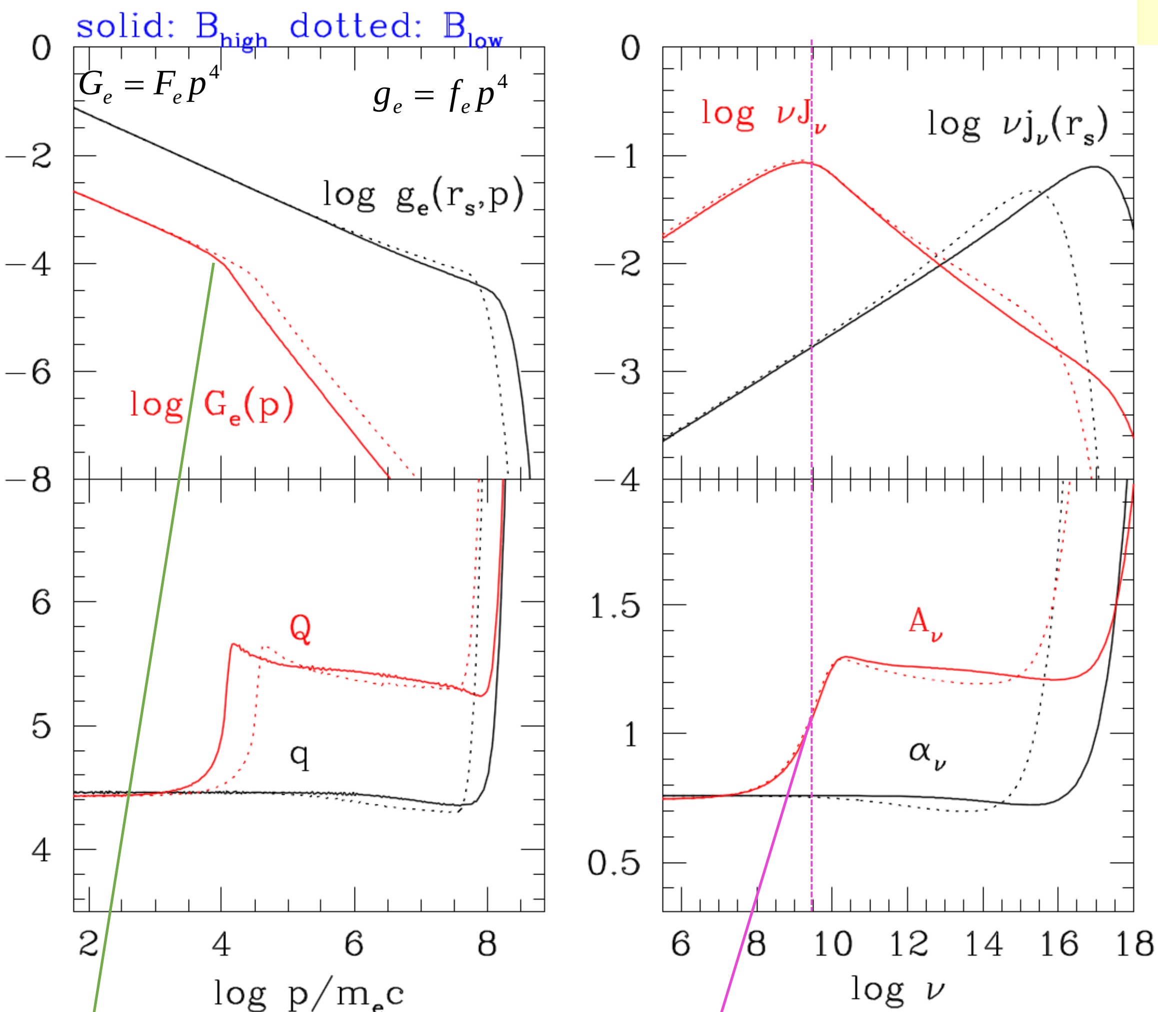
e.g. $B_{high} \approx 6.5\mu\mathrm{G}$ or $B_{low} \approx 0.65\mu\mathrm{G}$

$$\Rightarrow \frac{J_\nu(B_{\rm high})}{J_\nu(B_{\rm low})} \sim \frac{n_e(\gamma_{e,high})}{n_e(\gamma_{e,low})} \left(\frac{B_{\rm high}}{B_{\rm low}}\right)^2$$

So for weaker field strength, higher electron density is required. ➔ IC emission

Comparison of two models with $B_{\rm high}$ and $B_{\rm low}$

$u_s \approx 3{,}000\,{\rm km/s},\ \ M_s \approx 3.0,$
pre-existing CRe with $\gamma_{\rm e} \sim 30$



$B_{high} \approx 6.5\mu G$

$B_{low} \approx 0.65\mu G$

$\nu_{\rm br,high} \approx \nu_{\rm br,low}$

$$q = -\frac{d\ln f_e(r_s,p)}{d\ln p}$$

$$Q = -\frac{d\ln F_e(p)}{d\ln p} \approx q+1$$

$$\alpha_\nu = -\frac{d\ln j_\nu(r_s)}{d\ln \nu}$$

$$A_\nu = -\frac{d\ln J_\nu}{d\ln \nu} \approx \alpha_\nu + 0.5$$

$$\gamma_{\rm e,br} \approx 10^4 \left(\frac{t_{\rm age}}{100{\rm Myr}}\right)^{-1} \left(\frac{B_{\rm e,2}}{5\ \mu{\rm G}}\right)^{-2}$$

$$\nu_{\rm br} \approx 0.63{\rm GHz} \left(\frac{t_{\rm age}}{100{\rm Myr}}\right)^{-2} \left(\frac{5^2}{B_2^2+B_{\rm rad}^2}\right)^2 \left(\frac{B_2}{5}\right)$$

ν_{br} is the same in the two models.

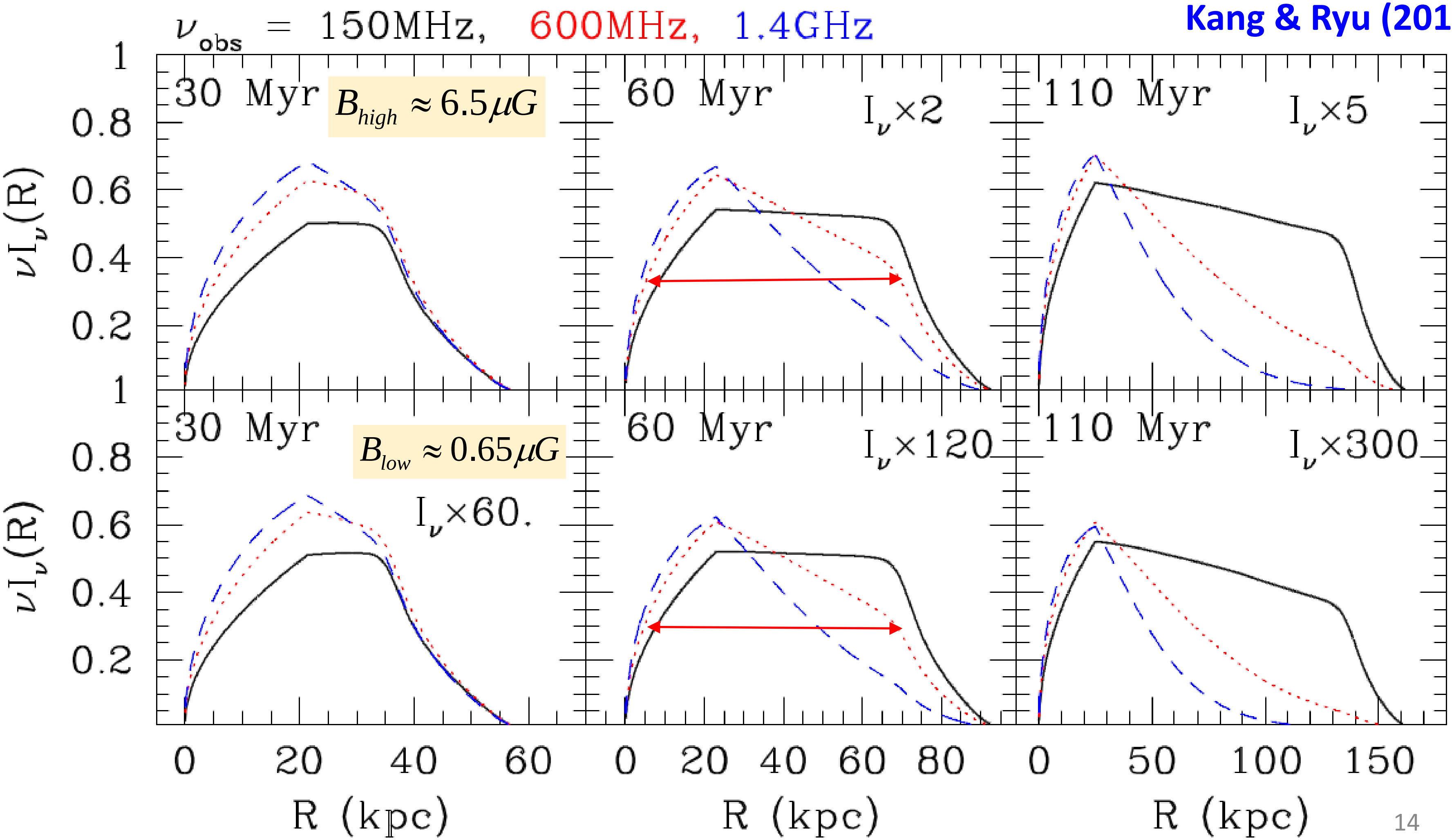
Surface Brightness profile: Comparison of two models with $B_{\rm high}$ and $B_{\rm low}$

$u_s \approx 3{,}000 \mathrm{km/s},\ M_s \approx 3.0,$ pre-existing CRe with $\gamma_e \sim 30$

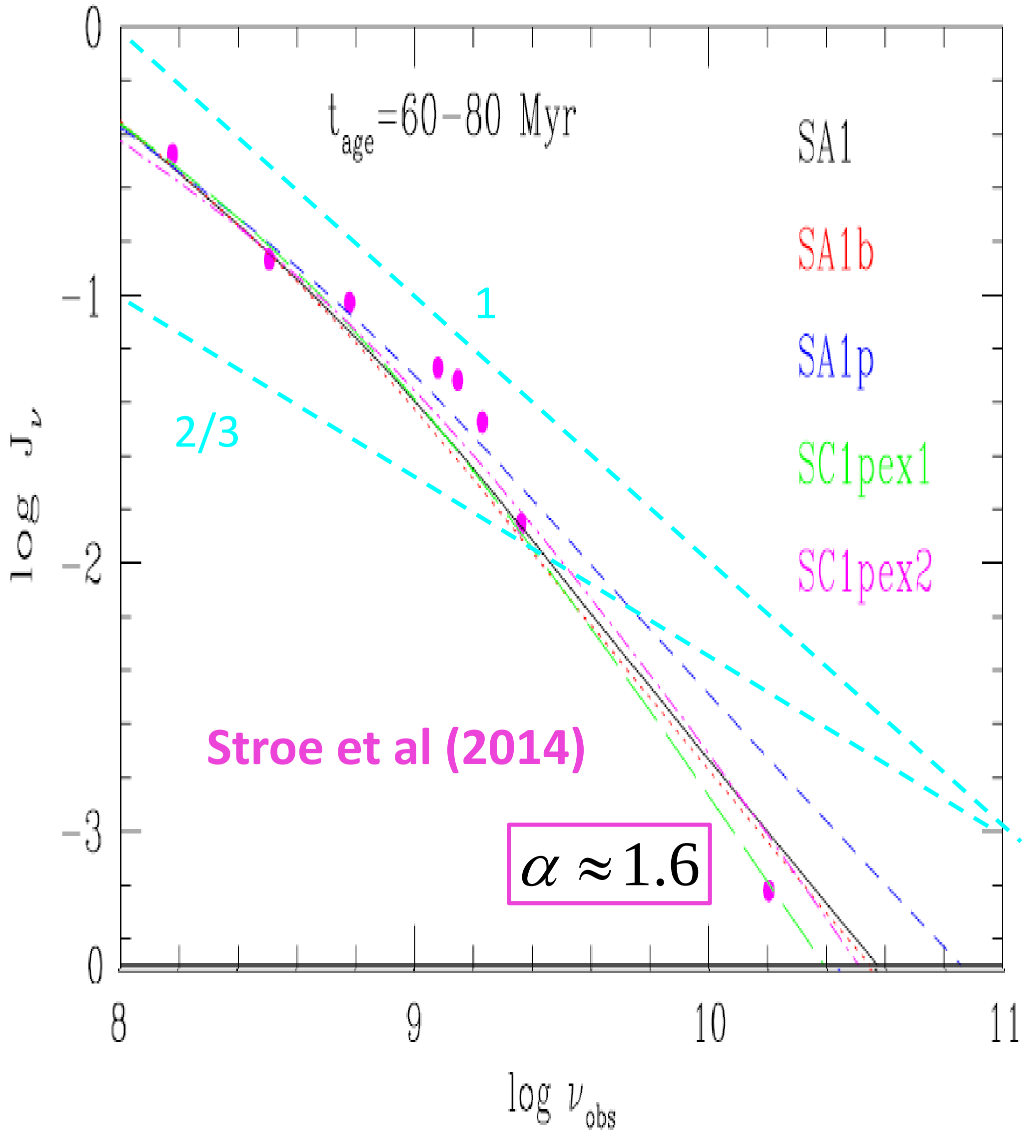
$\psi = 10^\circ$ is adopted.

$\Delta l_{\rm high} \approx \Delta l_{\rm low}$

Kang & Ryu (2015)



Integrated Spectrum of Sausage Relic: curvature due to cooling



$$\text{SA1}: \ u_s \approx 3{,}000\text{km/s},$$
$$M_s \approx 3.0,$$
$$\text{pre-existing CRe with } \gamma_e \sim 30$$

$$\text{SC1pex}: \ u_s \approx 2{,}000\text{km/s},$$
$$M_s \approx 2.0,$$
$$f_{e,1} \propto p^{-4.2} \exp[-(\gamma_e / \gamma_{e,cut})^2]$$

transition from α_{inj} to $\alpha_{\text{inj}} + 5$

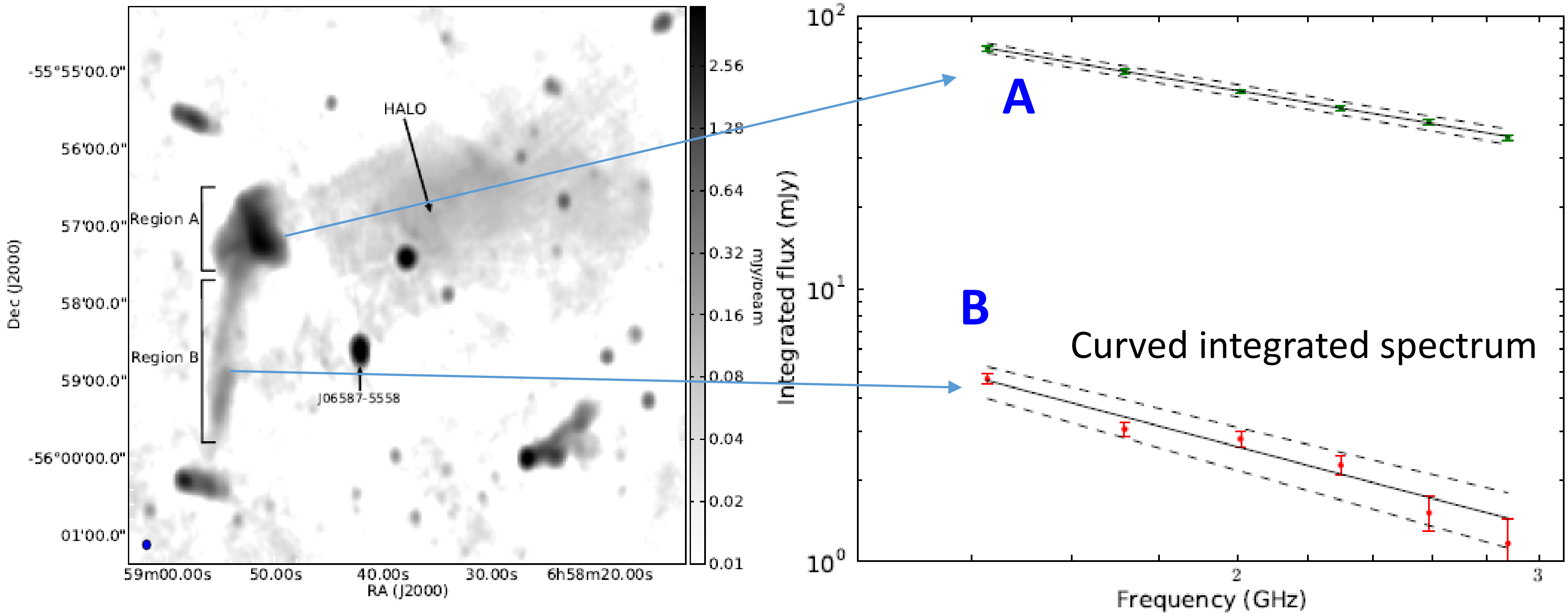
occurs smothly over 0.1-10 ν_{br}

➔ **Curved spectrum**

DSA + radiative cooling alone cannot explain the abrupt curvature above 1.5 GHz. In the observed spectrum➔ additional physics ?

Another shock for the Bullet cluster, and the source of seed electrons for radio relics

Shimwell et al. 2015



"A relic forms when a shock crosses a well-defined region of the ICM polluted with aged relativistic plasma."

"The shape of the relic traces the underlying region of excess density of seed electrons (remaining from an old radio galaxy lobe)."

X-ray and Radio shocks in Bullet cluster 1E 0657−55.8

Markevitch & Vikhlinin 2007