Particle Acceleration on Cluster Scales: Getting Inside Extended Radio Emissions

Tom Jones (University of Minnesota)

Outline

I. Context – Cluster Formation

II. Roles of Shocks

III. (Some) Contributions from AGN

IV. Roles of Turbulence

Underlying Physics Drivers:

-Cluster-scale Diffuse Radio Emissions Strongly Associate with Merging[†] Clusters—

- ✓ **Shocks**
- ✓ **Turbulence**

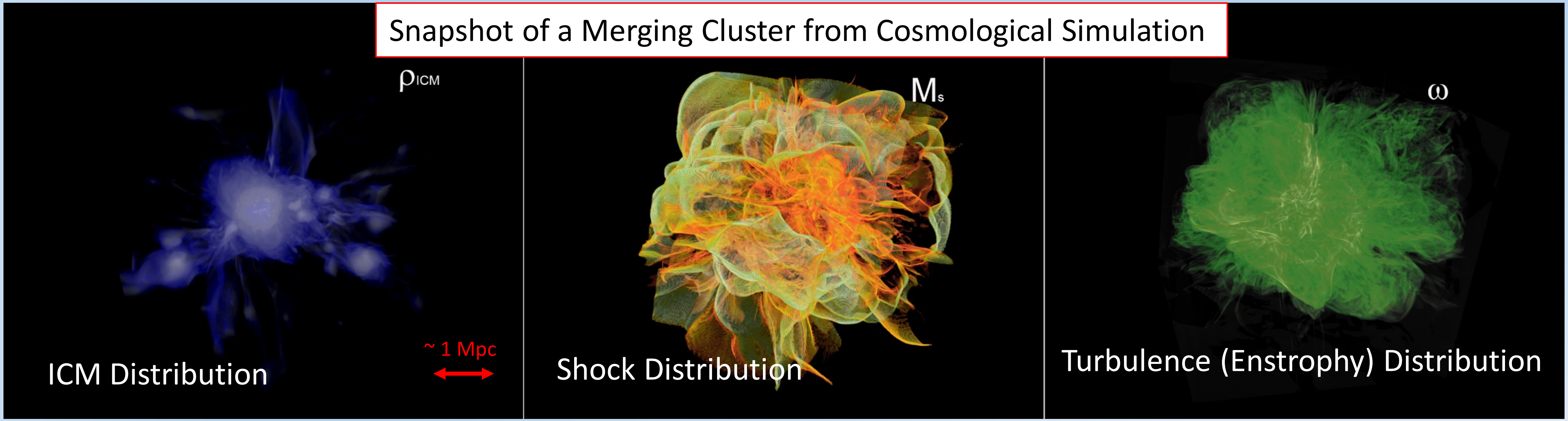
-Visible CRe (> GeV) have short lifetimes (< 10^8 yr), But are "trapped" by turbulent magnetic fields

- ✓ **Locally "sourced"**

- ICMs are weakly collisional (collective effects dominate)

[†]Are Obvious Exceptions: e.g., "mini halos" in cool core clusters

Connecting Insight Regarding Mergers:
Cluster Formation Leads to Mpc-scale Shocks & Turbulence – Huge Energy Reservoirs (Galaxies – AGNs– Also Likely Players)

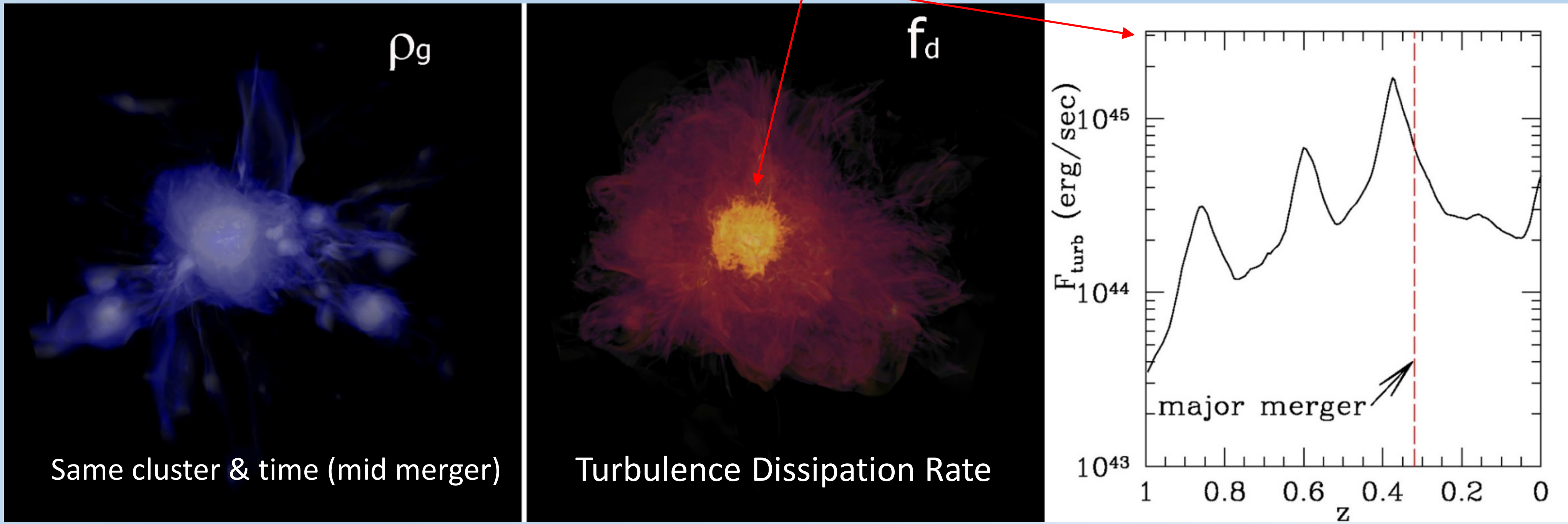


Volume Renderings Zoomed to ~2-3 R_{virial}

Vazza + (TWJ) ’17

Both Formation-Driven Shock and Turbulent Energy Dissipation Max During Mergers:

Here We See Turbulence Dissipation Relation to Mergers



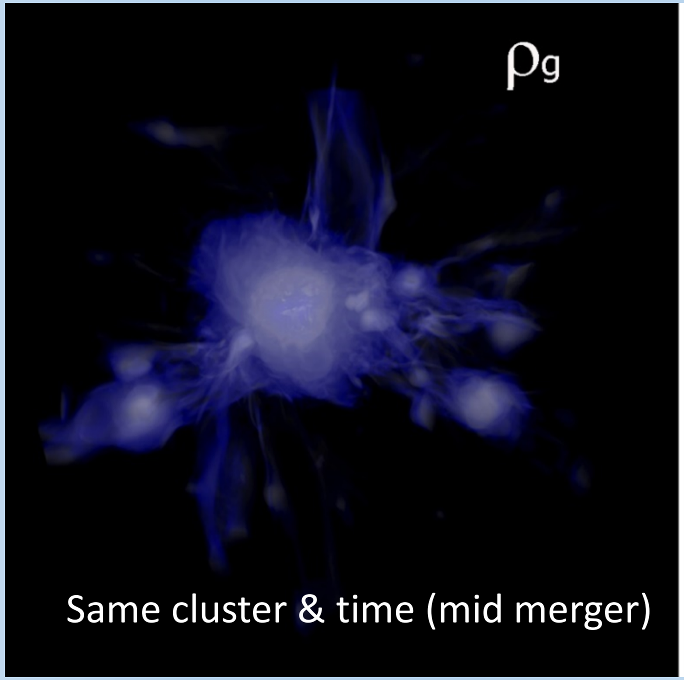
Vazza + (TWJ) ’17

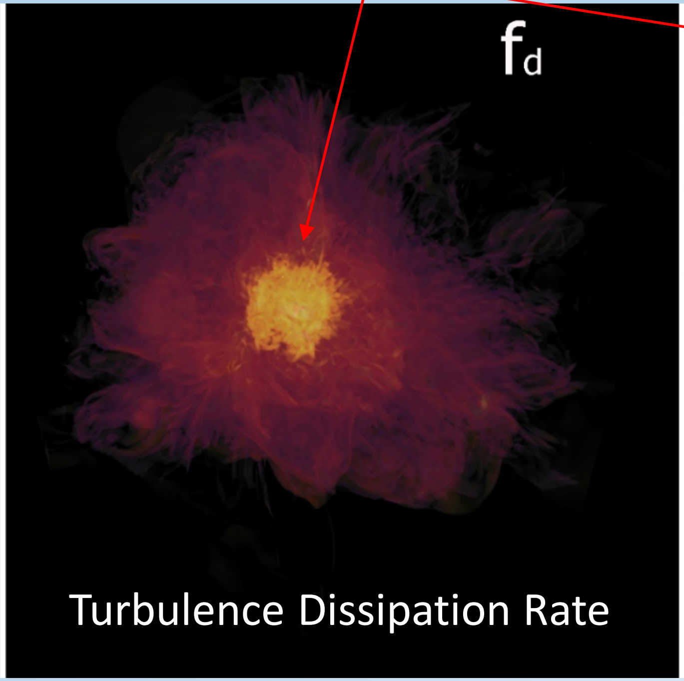
Turbulent Energy Dissipation (central ~1 Mpc^3 volume)

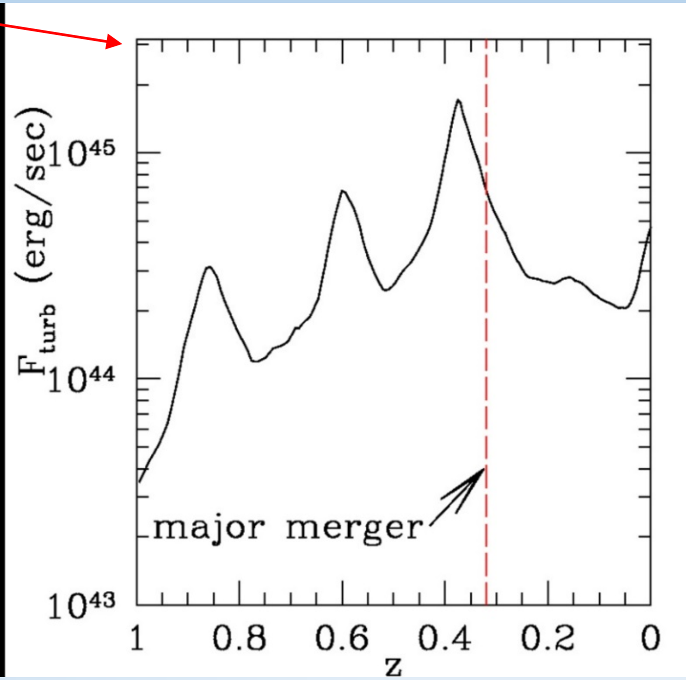
Both Formation-Driven Shock and Turbulent Energy Dissipation Max During Mergers:

Interactions Between Shocks and Turbulence Also Likely to Be Important

Here We See Turbulence Dissipation Relation to Mergers







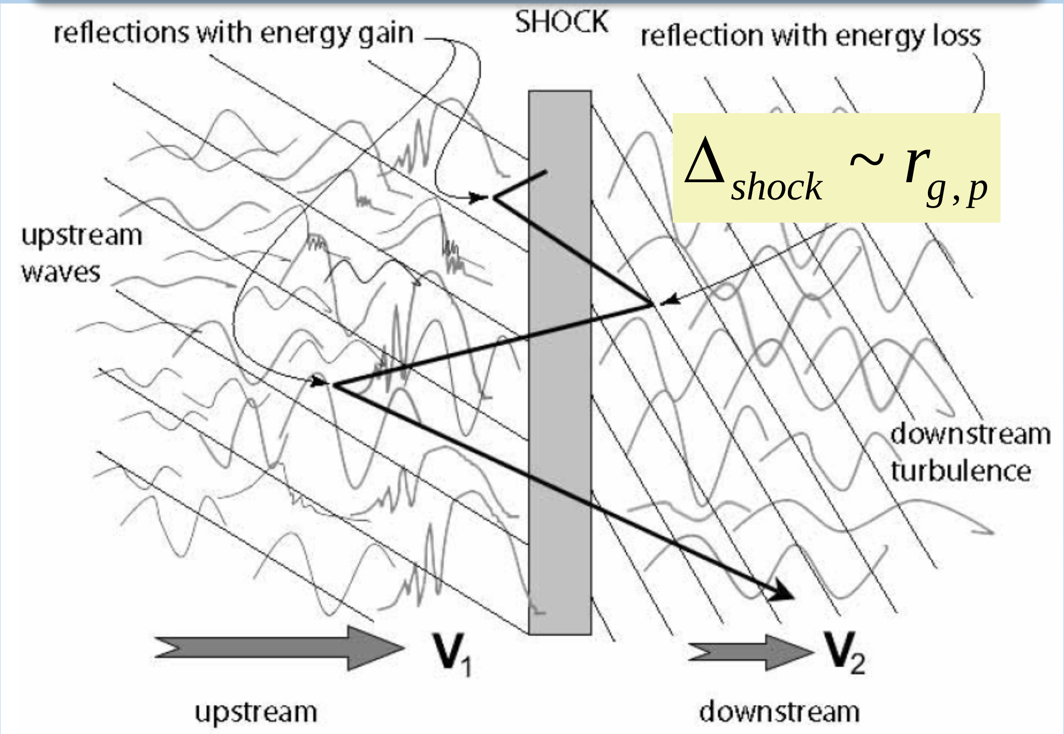
Vazza + (TWJ) ’17

Turbulent Energy Dissipation (central ~1 Mpc^3 volume)

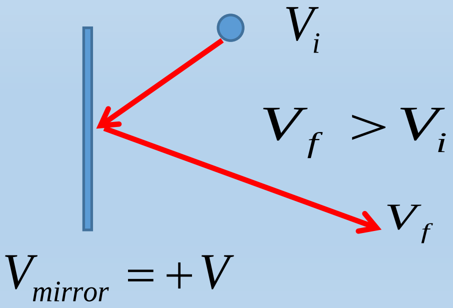
Shocks

Fermi I Acceleration of "Energetic" Particles at Collisionless Shocks
-- Enough rigidity that they can "pass through" the shock--

"Classic" Diffusive Shock Acceleration (DSA)



Fermi I cartoon



Approaching mirror
→ gain energy

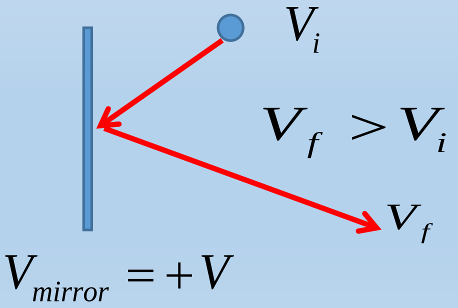
Alfven waves in a converging flow act as converging mirrors

→ particles crossing the shock are scattered by waves and isotropized in local fluid frame

→ cross the shock many times $\frac{\Delta p}{p} \sim \frac{u_1 - u_2}{c}$ at each shock crossing for particle speed ~ c

Fermi I Acceleration of "<u>Energetic</u>" Particles at Collisionless Shocks
-- Enough rigidity that they can "pass through" the shock--

Fermi I cartoon



Approaching mirror
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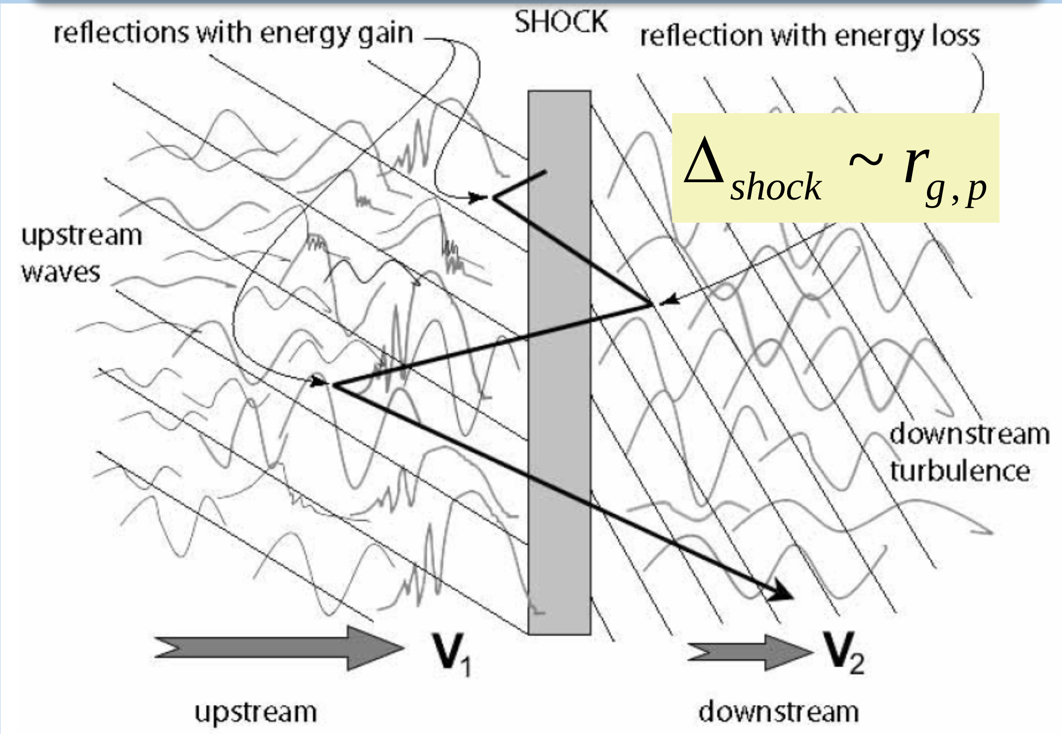

"Injection" of cold particles at shocks likely depends on "reflection" back into upstream region, accompanied by multiple energy boosts; SDA (more on this below).
<u>Distinct Issue from DSA itself</u>

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DSA CR spectrum and electron synchrotron cooling (cartoon version)

CR spectrum in test - particle regime for $p > p_i$, with p_i the momentum at injection to this shock

$$f_{DSA}(p) \propto p^{-q}, \ q_{DSA} = \frac{3\sigma}{\sigma - 1} : \text{shock compression}, \sigma = u_1 / u_2$$

$$\mathrm{q}_{\mathrm{DSA}} = \frac{4\mathrm{M}_s^2}{\mathrm{M}_s^2 - 1}, M_{DSA} = \sqrt{\frac{q_{DSA}}{q_{DSA} - 4}}$$

$$\boxed{\tau_{acc}} \sim \frac{\sigma(\sigma+1)}{\sigma - 1}\left(\frac{p}{mc}\right)\frac{1}{\omega_c}\left(\frac{c}{V_s}\right)^2\left(\frac{B}{\delta B}\right)^2 \sim \boxed{\left(\frac{pc}{GeV}\right)\left(\frac{B}{\delta B}\right)^2 yrs}(B \sim \mu Gauss)$$

Fast!

for $M >> 1$

$\sigma = \rho_2 / \rho_1 = 4$

$q = 4, \quad N(E) \propto E^{-2}$

$\alpha_{\text{shock}} = 0.5$

electron synchrotron *or* IC scattering photon spectrum

$$j_\nu \propto \nu^{-\alpha}, \ \alpha_{\mathrm{DSA}} = (q_{DSA} - 3)/2$$

$\tau_{cool} \propto \frac{U}{p}$

With U either U_{rad} for iC (CMB) or $B^2/8\pi$ for Synch.

volume integrated spectrum of downstream (radiatively cooling) electrons

$$F_e(p) = \int f_e(p,x)dx \propto p^{-(q_{DSA}+1)} \quad \text{(due to cooling at uniform rate)}$$

integrated photon spectrum (unresolved observation) (uniform cooling and emission)

$$J_\nu \propto \nu^{-\alpha}, \ \alpha_{\text{integ}} = \alpha_{\mathrm{DSA}} + 0.5$$

Injection of Cold Particles into DSA
One of the Big Questions About the Role of Shocks

Big Recent Progress from PIC/Hybrid Simulations
--Details in Coming Talks--

- Different physics for Electrons and Ions
- Both depend on reflection of a fraction of particles from upstream at shock
  & multiple episodes of small boosts by “Shock Drift Acceleration” (SDA)
- Ions reflected by Electrostatic Potential in Shock Foot
  (quasi-parallel B & at least moderately strong shock). Cross-B drift leads to energy gain (SDA)
- Electrons reflected by Magnetic Mirror
  (quasi-perpendicular B, possibly local by-product of CRp). Gradient drift leads to energy gain (SDA)
- If upstream scatterings return particles sufficient times they may enter DSA

Illustration of CRp Injection (2D Hybrid Parallel M_A = 100 ~ M_s Shock Simulation)

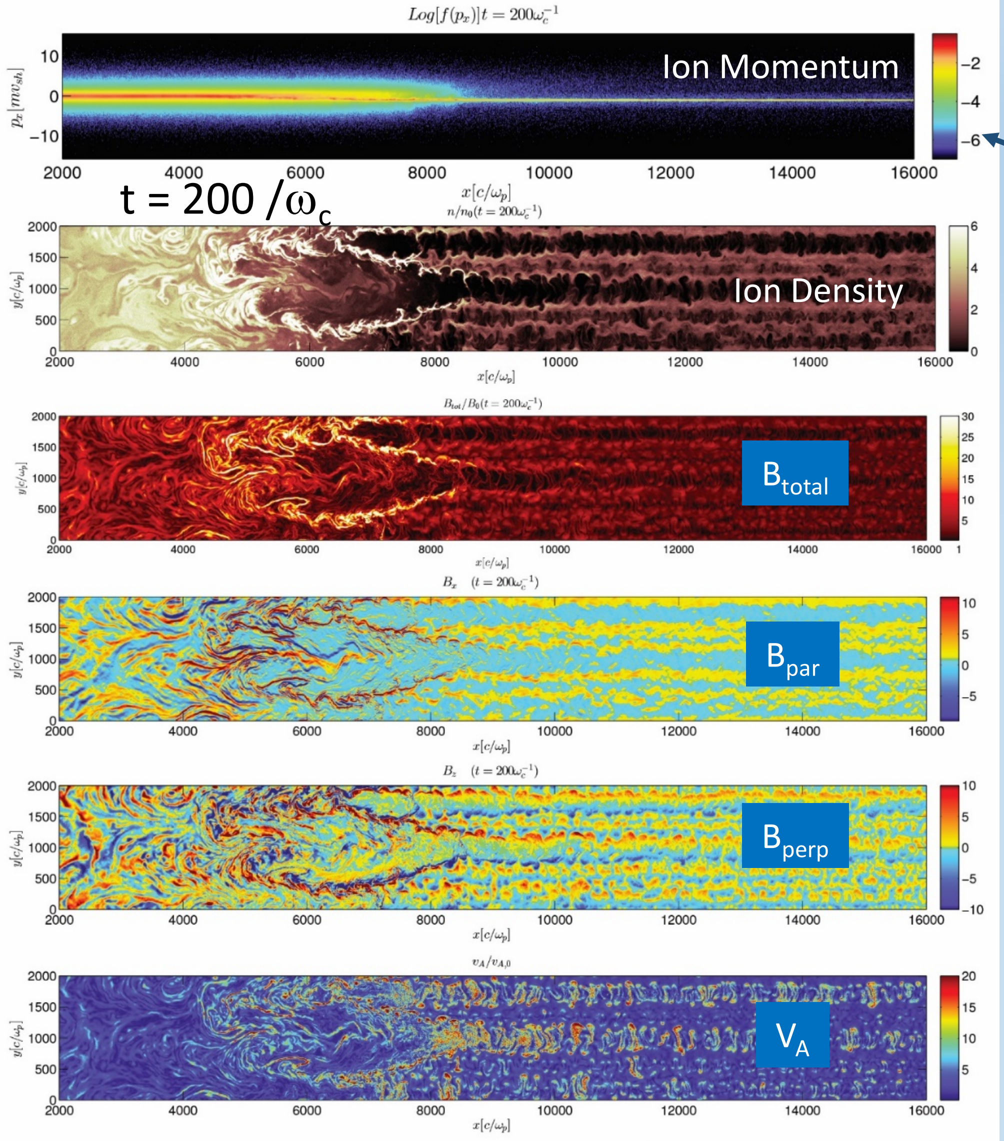


Figure 3. Relevant physical quantities for a parallel shock with $M = 100$ at $t = 200\omega_c^{-1}$, as a function of x (Run C in Table 1). From top to bottom: parallel component of the ion momentum, ion density, total magnetic field, parallel and out of plane components of the magnetic field, and Alfvén velocity. *A color figure is available in the online journal.*

Caprioli & Spitkovsky 14

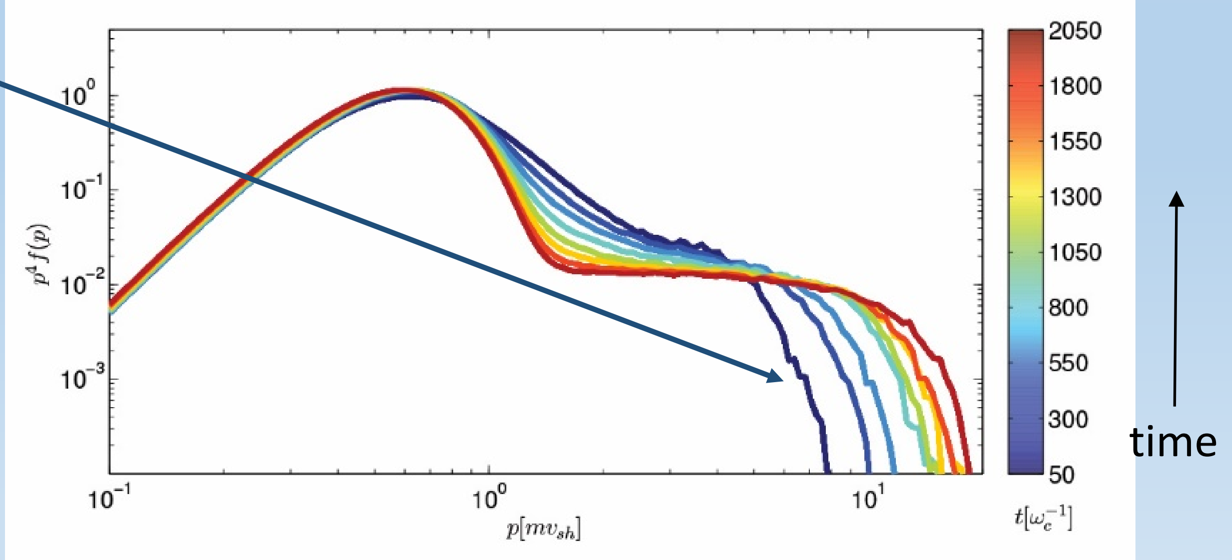
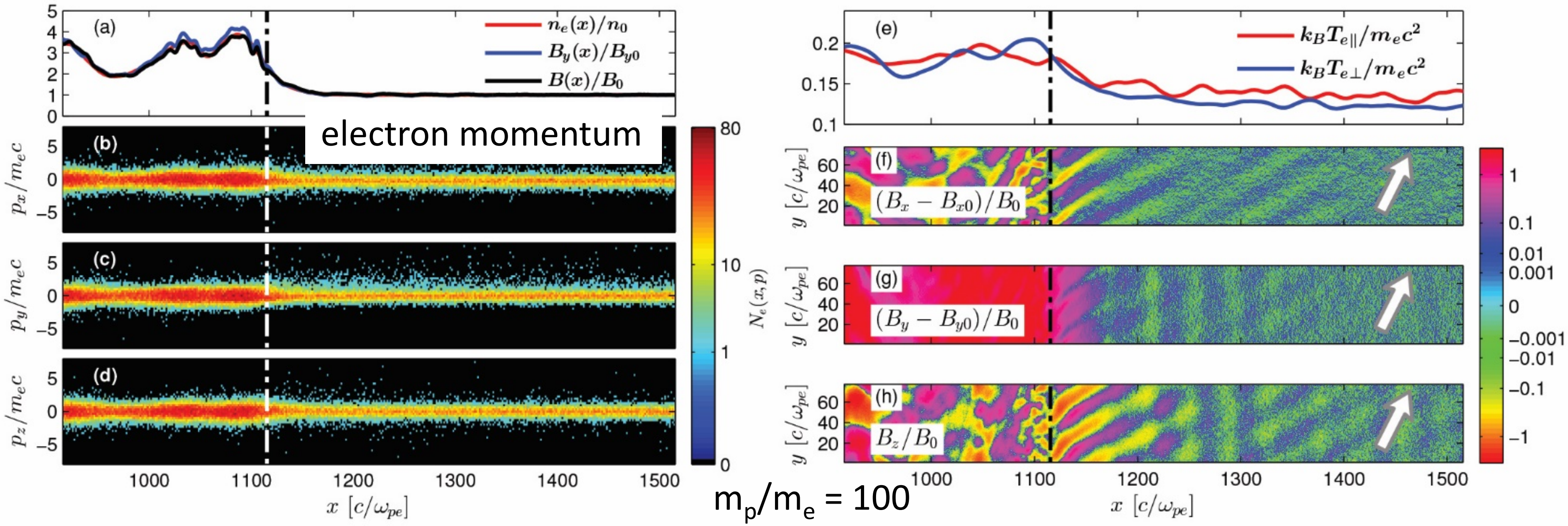


Figure 2. Time evolution of the downstream ion momentum spectrum for $M = 20$ parallel shock (Run B, see Table 1), showing both the thermal component ($p \lesssim 2mv_{sh}$), and accelerated particles. The non-thermal power-law tail $\propto p^{-4}$ agrees with DSA prediction at strong shocks (see Paper I). The maximum momentum increases until $t \approx 2000\omega_c^{-1}$, when the diffusion length of the most energetic ions becomes comparable with the box size.

Illustration of CRe Injection (2D PIC M_s = 3, M_A ~ 12 Quasi Perp (θ = 63^o) Shock Simulation)

Guo + 14

$$M_A = \sqrt{\left(\frac{5}{6}\right)\beta M_s}$$



m_p/m_e = 100

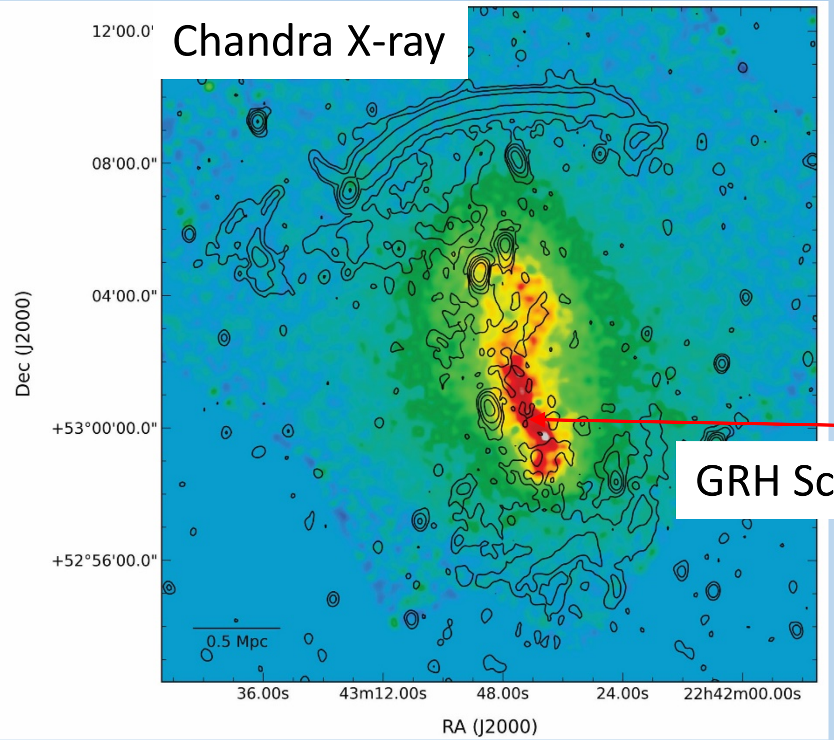
β_p = 20

FIG. 1.— Shock structure of the **reference** run at time $\omega_{pe}t = 14625$ ($\Omega_{ci}t = 26.9$). The shock is at $x \simeq 1115\ c/\omega_{pe}$, as indicated by the vertical dot-dashed lines, and moves to the right. Downstream is to the left of the shock, and upstream to the right. Panel (a) shows the ratios n_e/n_0 (red line), B_y/B_{y0} (blue line) and B/B_0 (black line). Panels (b)-(d) show the electron momentum phase spaces p_x-x, p_y-x, p_z-x, as a function of the longitudinal coordinate x. Panel (e) shows the electron temperatures parallel ($T_{e\parallel}$) and perpendicular ($T_{e\perp}$) to the magnetic field. Panels (f)-(h) show 2D plots of the magnetic field components in units of B_0, after subtracting the background field $\vec{B}_0$ (i.e., we show $(B_x - B_{x,0})/B_0$, $(B_y - B_{y,0})/B_0$ and B_z/B_0, respectively). The white arrows indicate the orientation of the upstream background magnetic field $\vec{B}_0$. Note that there are upstream waves in all three components of the magnetic field.

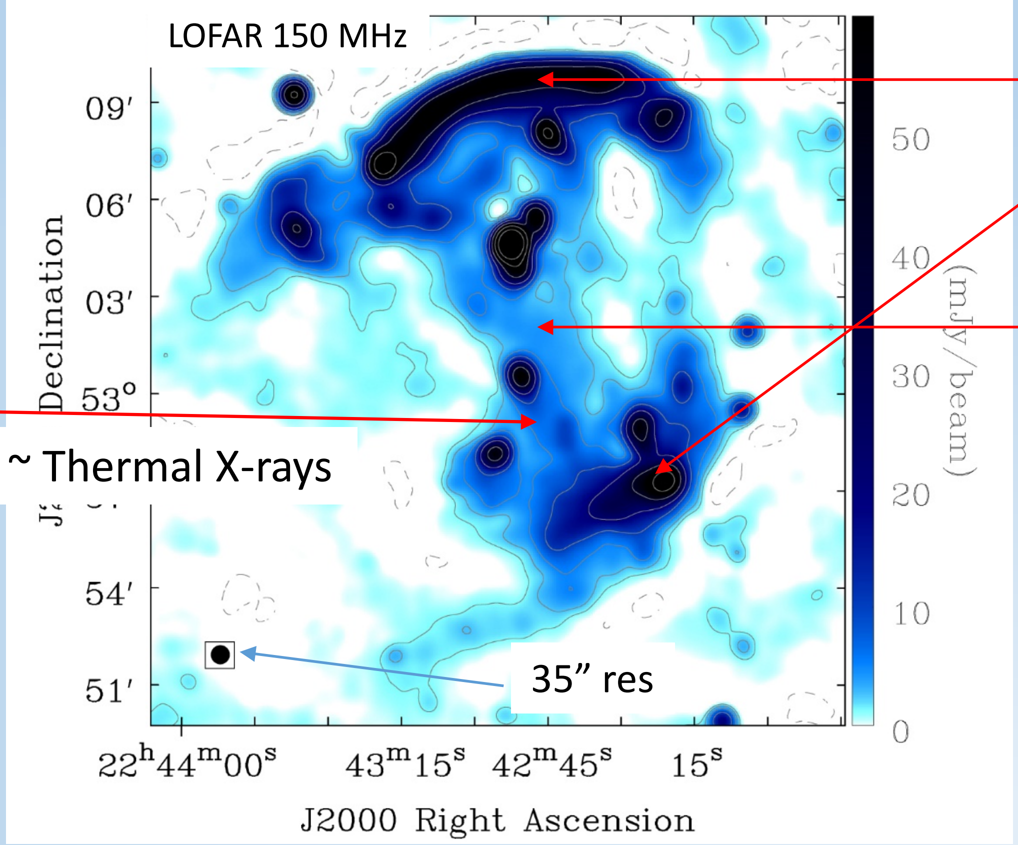
Looks at a Couple of "Poster Children" Clusters

CIZA J2242.8 + 5301 ("Sausage")

(Low Res Look)



GRH Scale ~ Thermal X-rays



Radio Relics

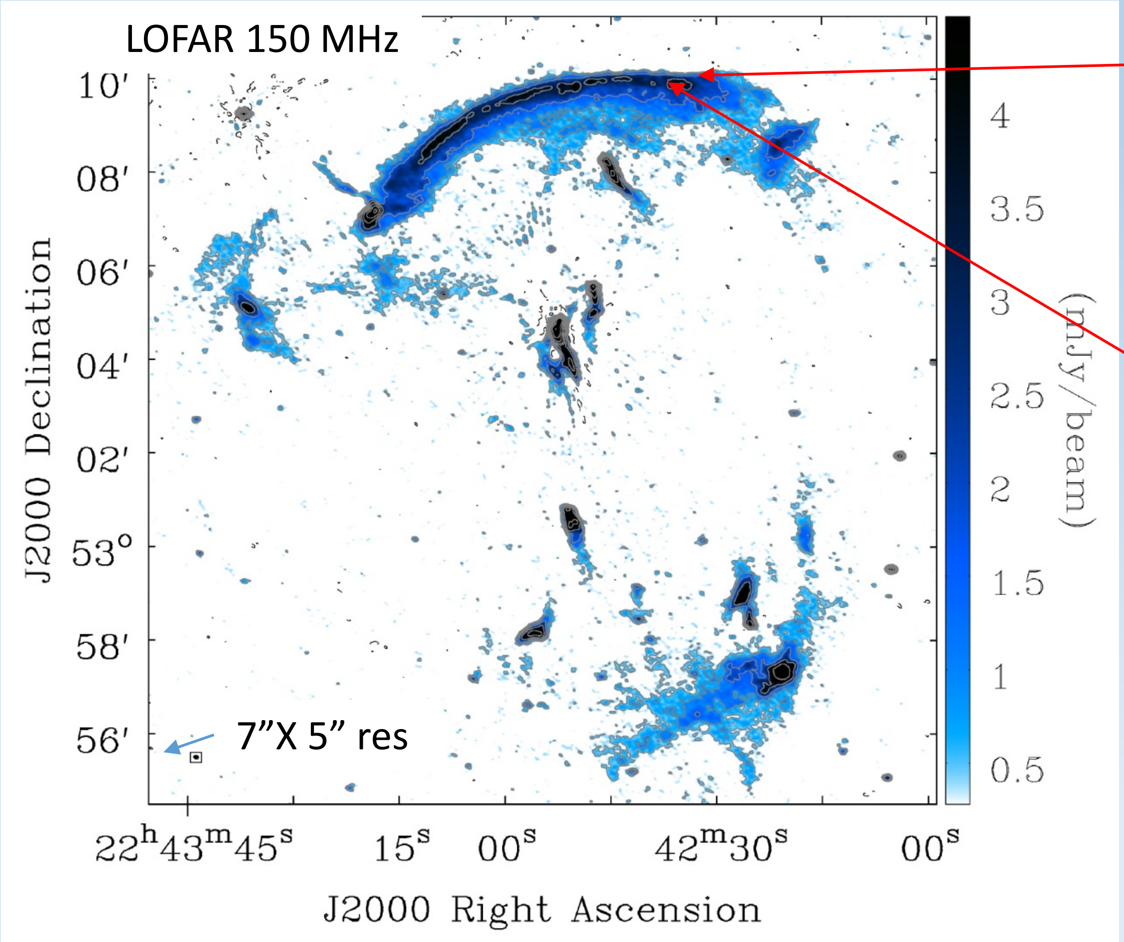
Giant Radio Halo (GRH)

Ogrean + 14

Hoang + 17

Relics Seen to Associate with X-ray Merger Shocks
The Expectation/ Hope: Relics Represent DSA of CRe

CIZA J2242.8 + 5301



Relic

M_s ~ 2.5
Merger Shock
(Edge On)

Hoang + '17

Relics Seen to Associate with X-ray Merger Shocks
The Expectation/ Hope: Relics Represent DSA of CRe

But, there are significant "issues":

- Only ~ 10% of merging clusters
Show relics (so far?)
--Shocks should be common--

- Merger Shocks have low M_s (< 4)
  => Injection efficiency probably low

Sometimes:

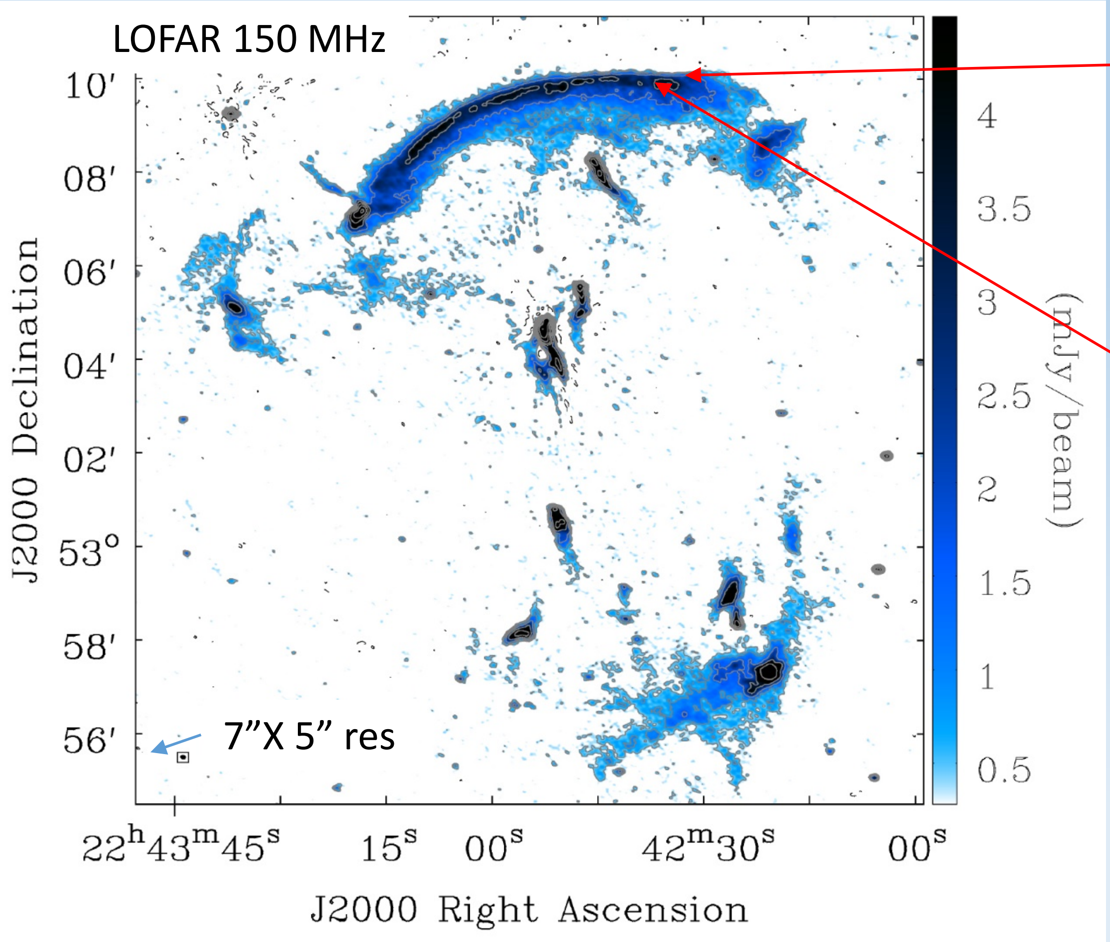
- M_s (DSA) > M_s (X-ray)

- Radio spectra inconsistent with
"simple" DSA & "ageing"

…

Likely More Complicated!

CIZA J2242.8 + 5301



Hoang + '17

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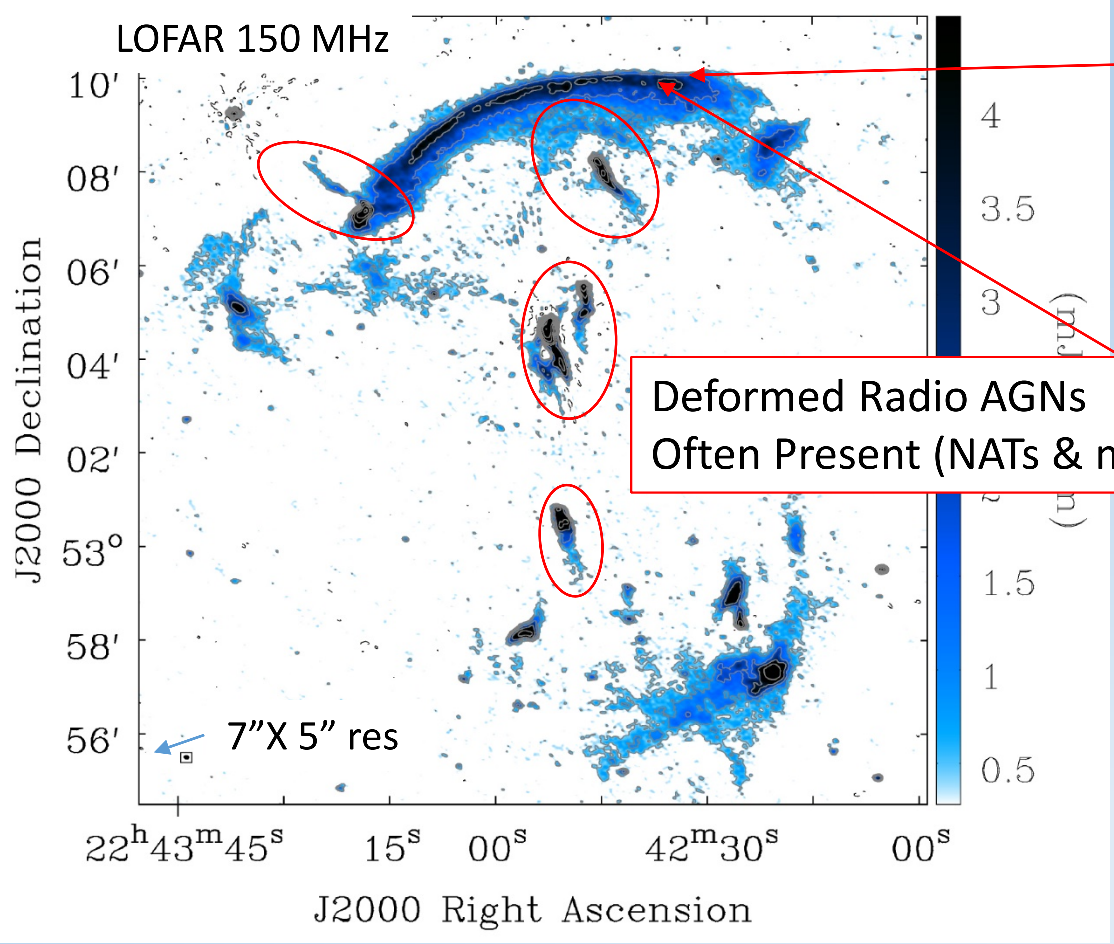


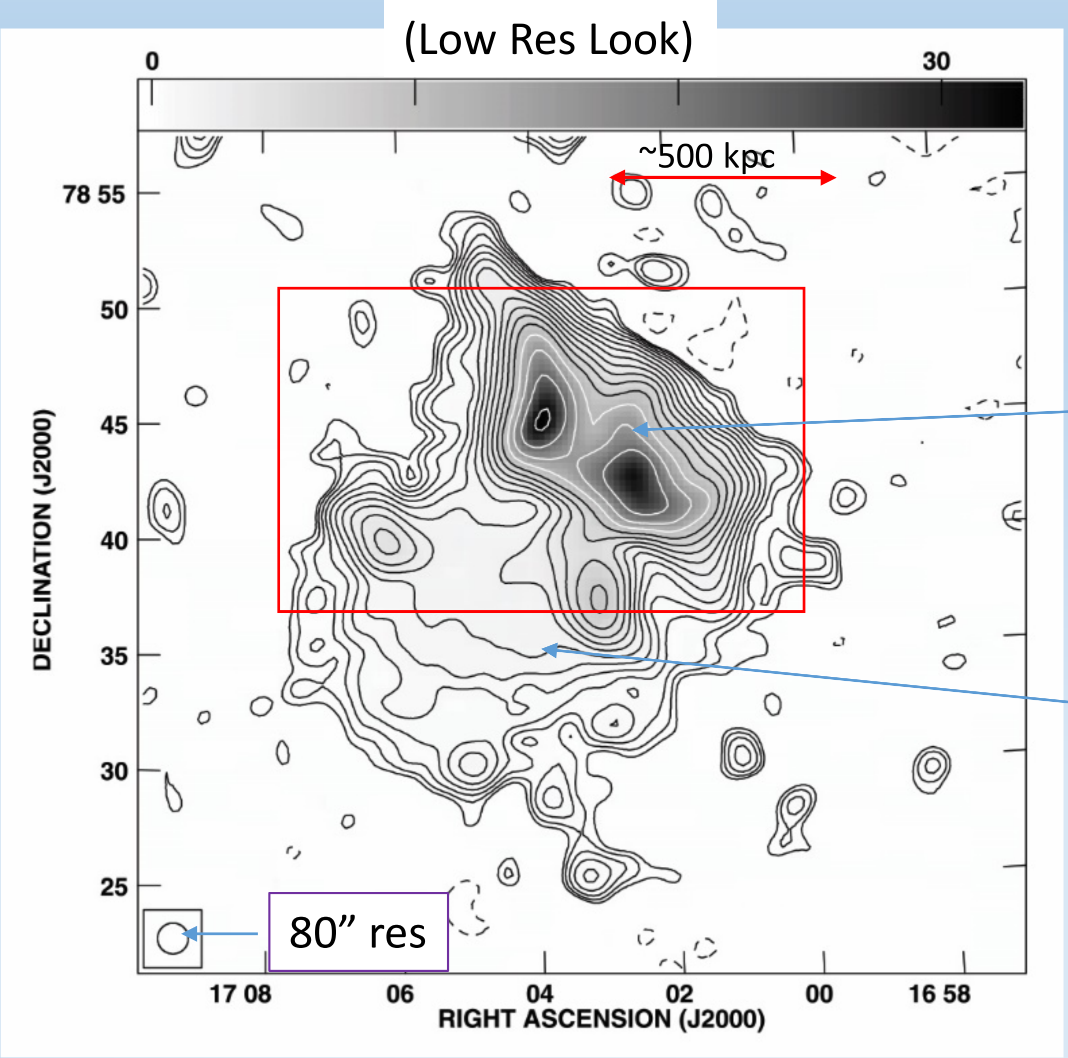
Relic

M_s ~ 2.5
Merger Shock
(Edge On)

Hoang + '17

A2256: Massive Merging Cluster (GRH & Relic)
(Again with Obviously Deformed AGNs)

VLA 1.4 GHz

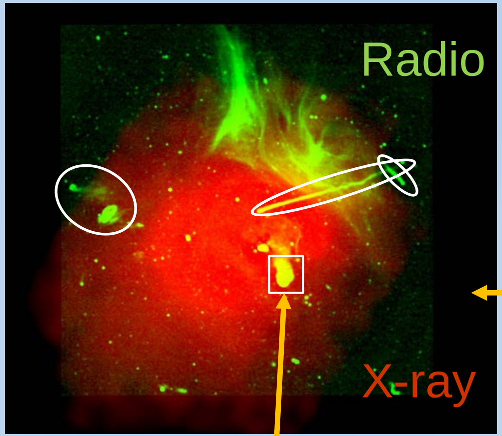


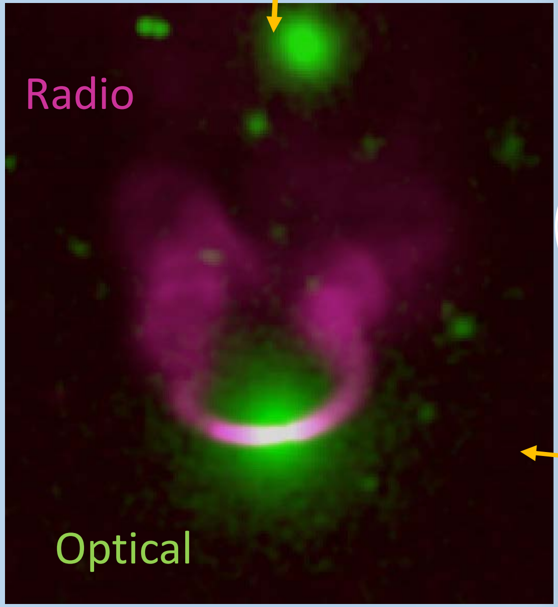
Relic
(perhaps almost face on)

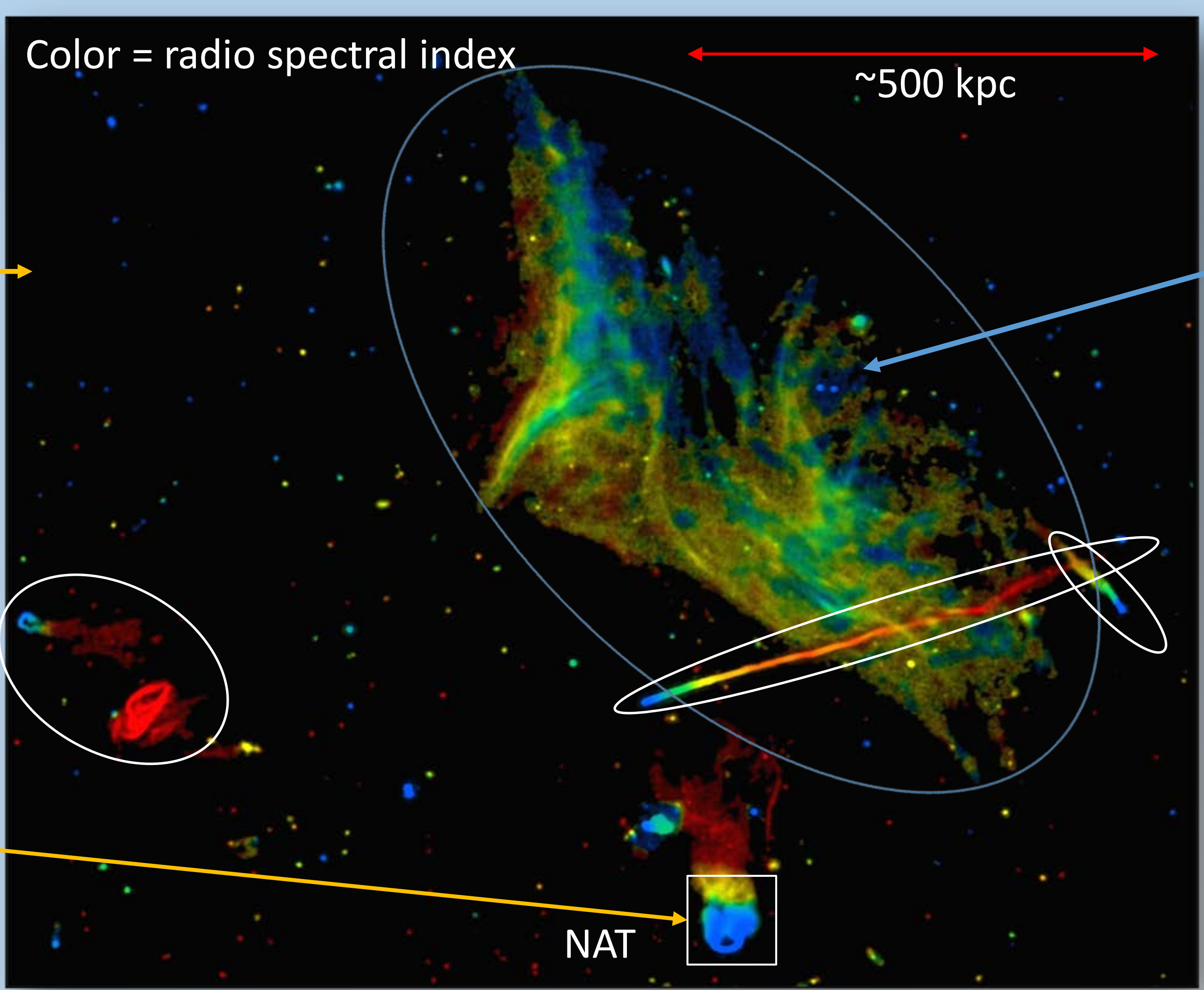
GRH

Clarke & Ensslin ’06

A2256: Some Distorted Radio AGNs Encircled in White: Interactions with Merger Shock? (Not Detected -- Not Edge On)







Relic

VLA
1-8 GHz
6" res

Owen + 14

AGN/Merger Shock Interactions
(Possible Environmental Probes)
Two Illustrative Examples

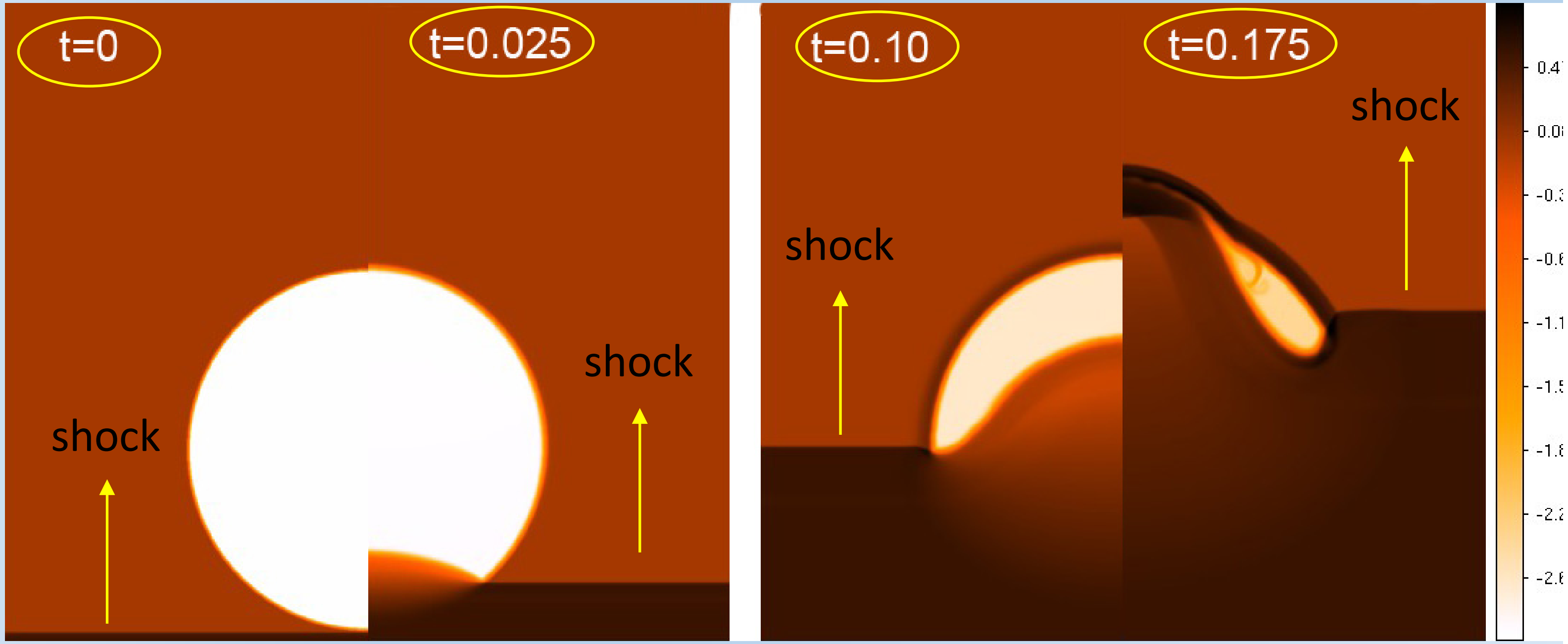
Highly Idealized MHD Simulations Including CRe

--UMN Grads: Chris Nolting & Brian O'Neill--

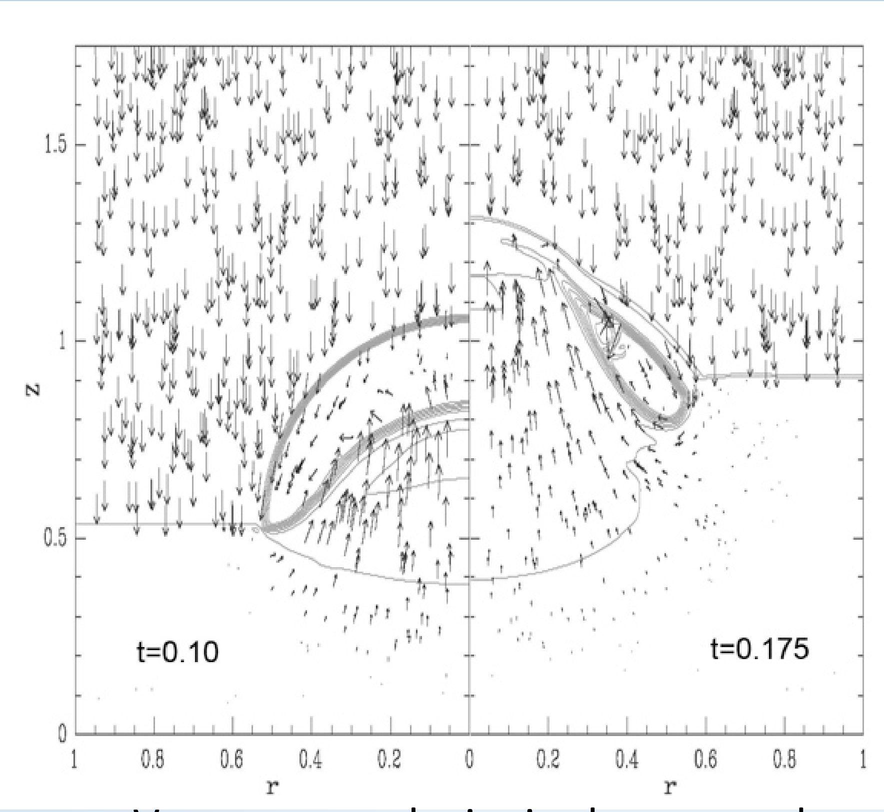
Case I: M_s = 4 shock runs head on into active jets

Case 2: M_s = 4 shock crosses NAT

For Context: Familiar Case of Shock Crossing Low Density Bubble: Bubble Crushed ⇒ Strong Vorticity ⇒ "Smoke Ring" (Shock is faster inside bubble; Also much weaker)



Pfrommer & Jones 2011

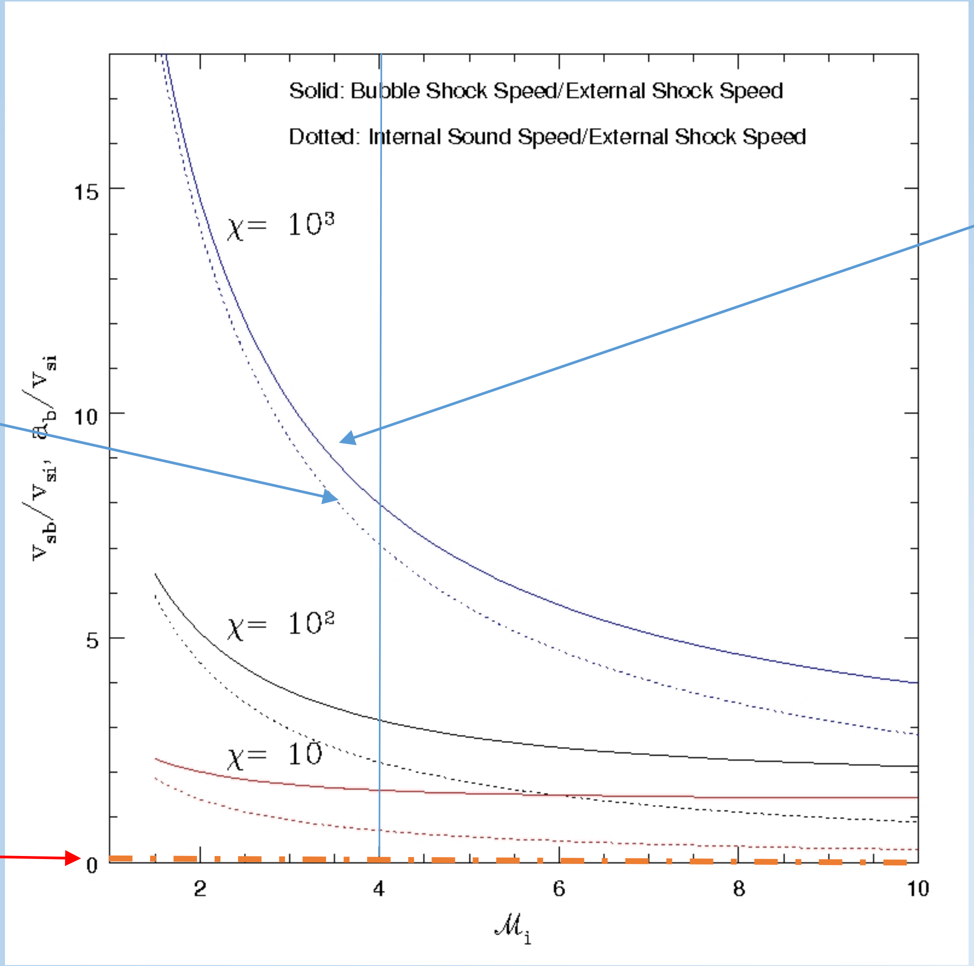


Vectors are velocity in the external Shock frame

Shock is faster inside bubble; <u>But Also weaker</u>

$\chi = \rho_{ambient} / \rho_{bubble}$

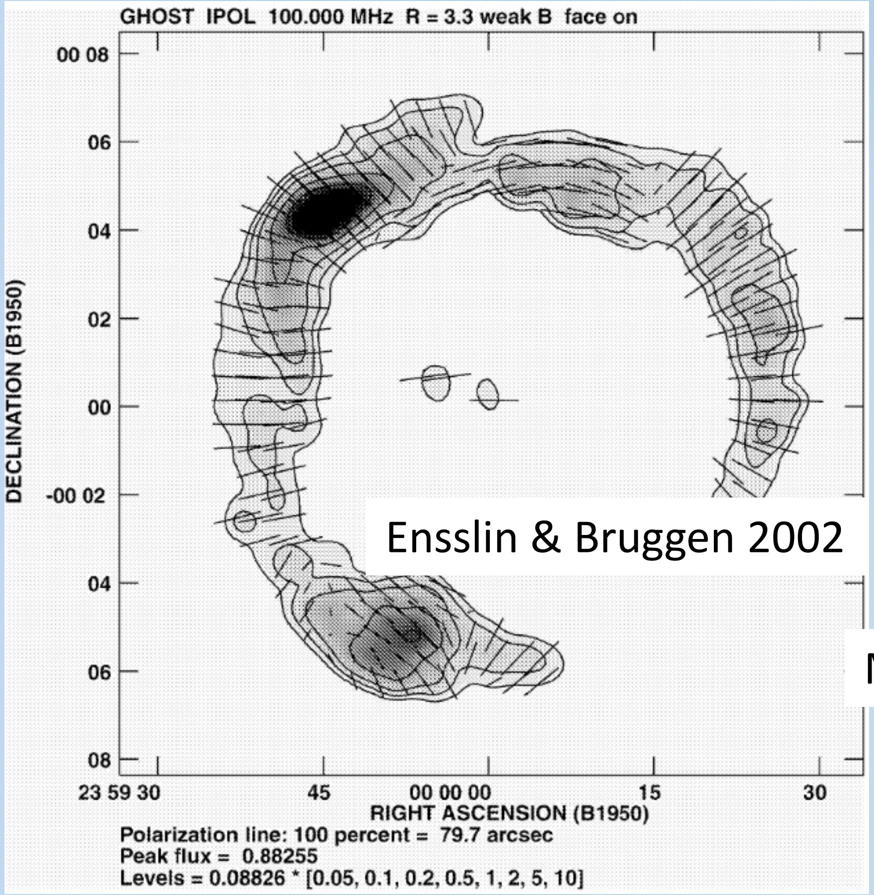
$a_{bubble} / V_{shock}(ambient)$



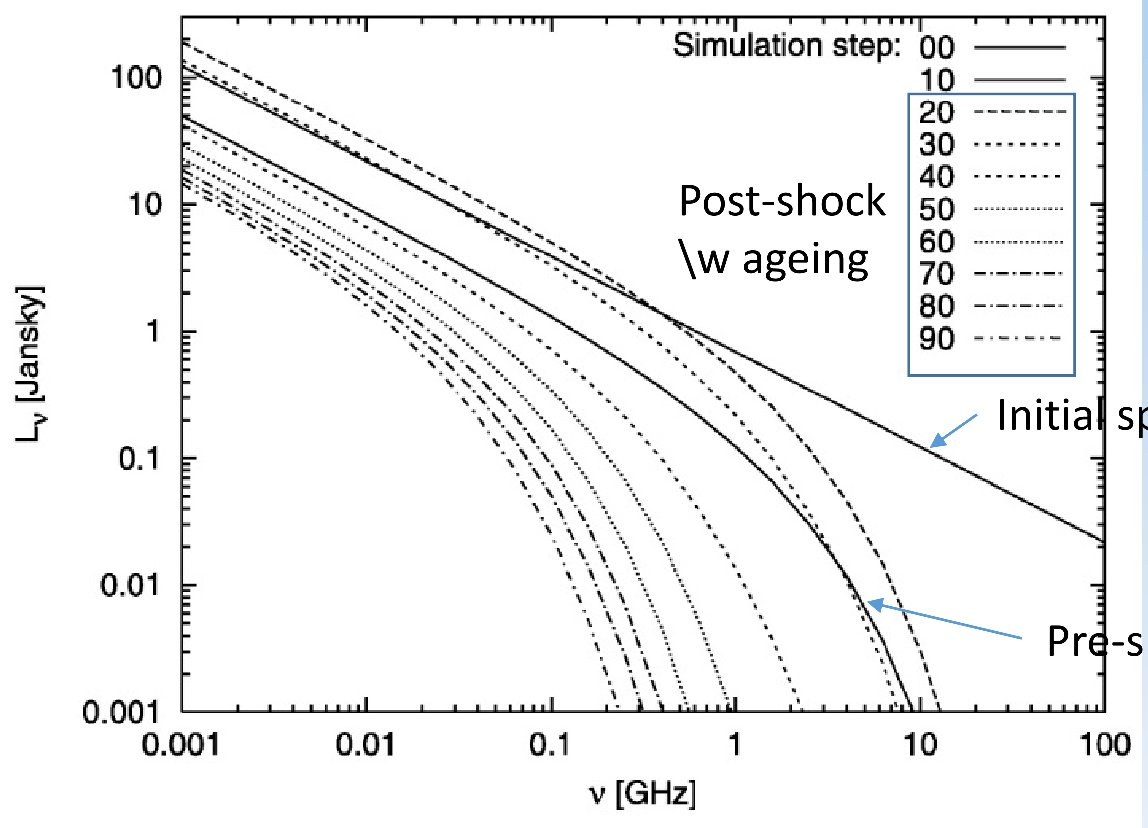
$V_{shock}(bubble)/V_{shock}(ambient)$

$V_{shock}(bubble) = V_{shock}(ambient)$

Basis for the "Radio Phoenix" Concept; Ensslin & Co:
Fast, but weak shock in cavity => Adiabatic Compression of CRe (AC only?)



$M_s = 3.8$



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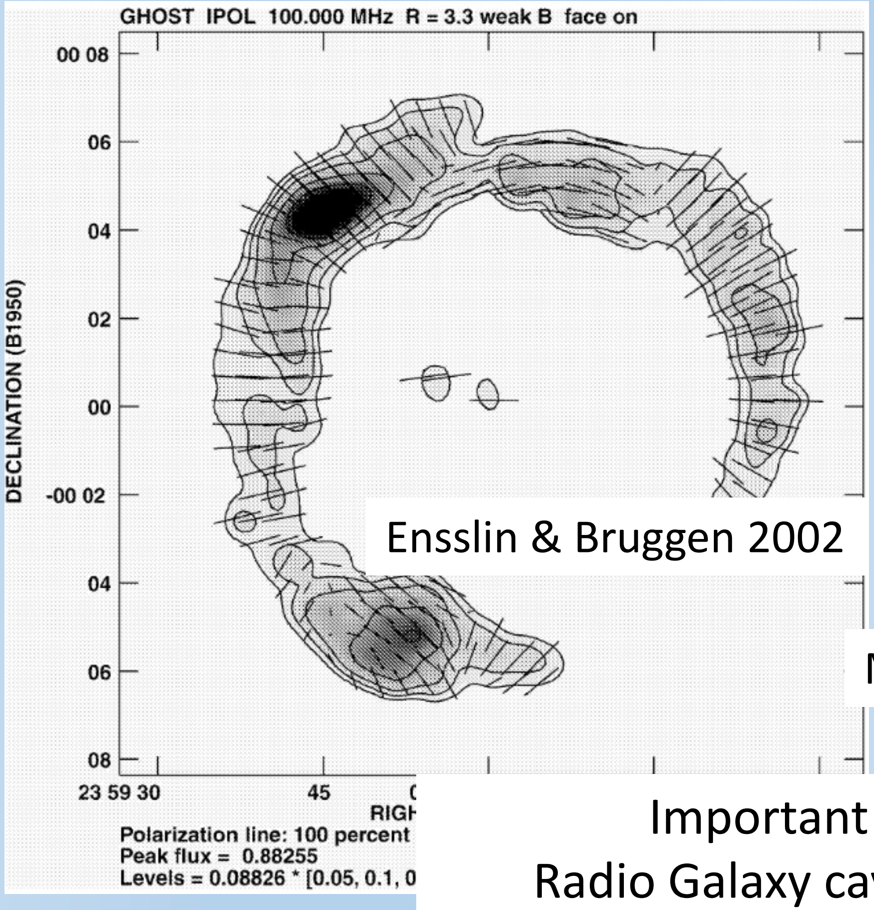
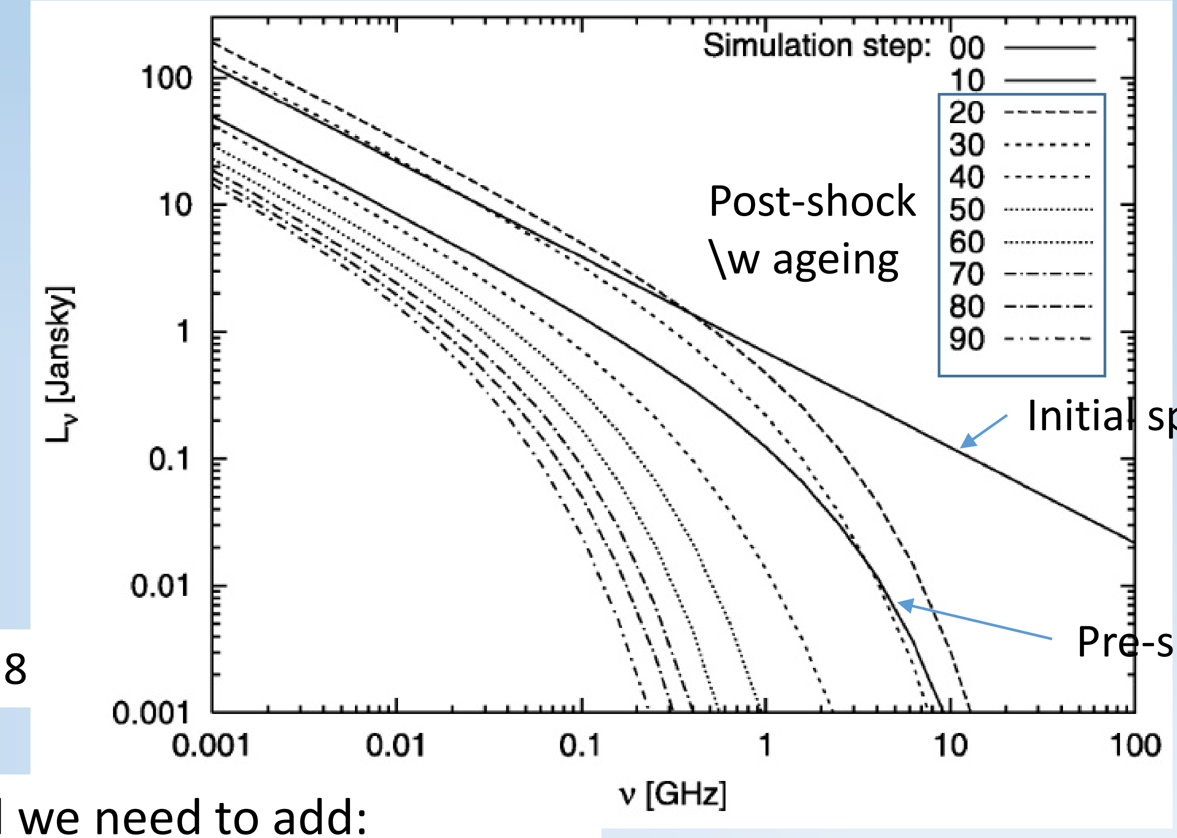


Ensslin & Bruggen 2002

M_s = 3.8



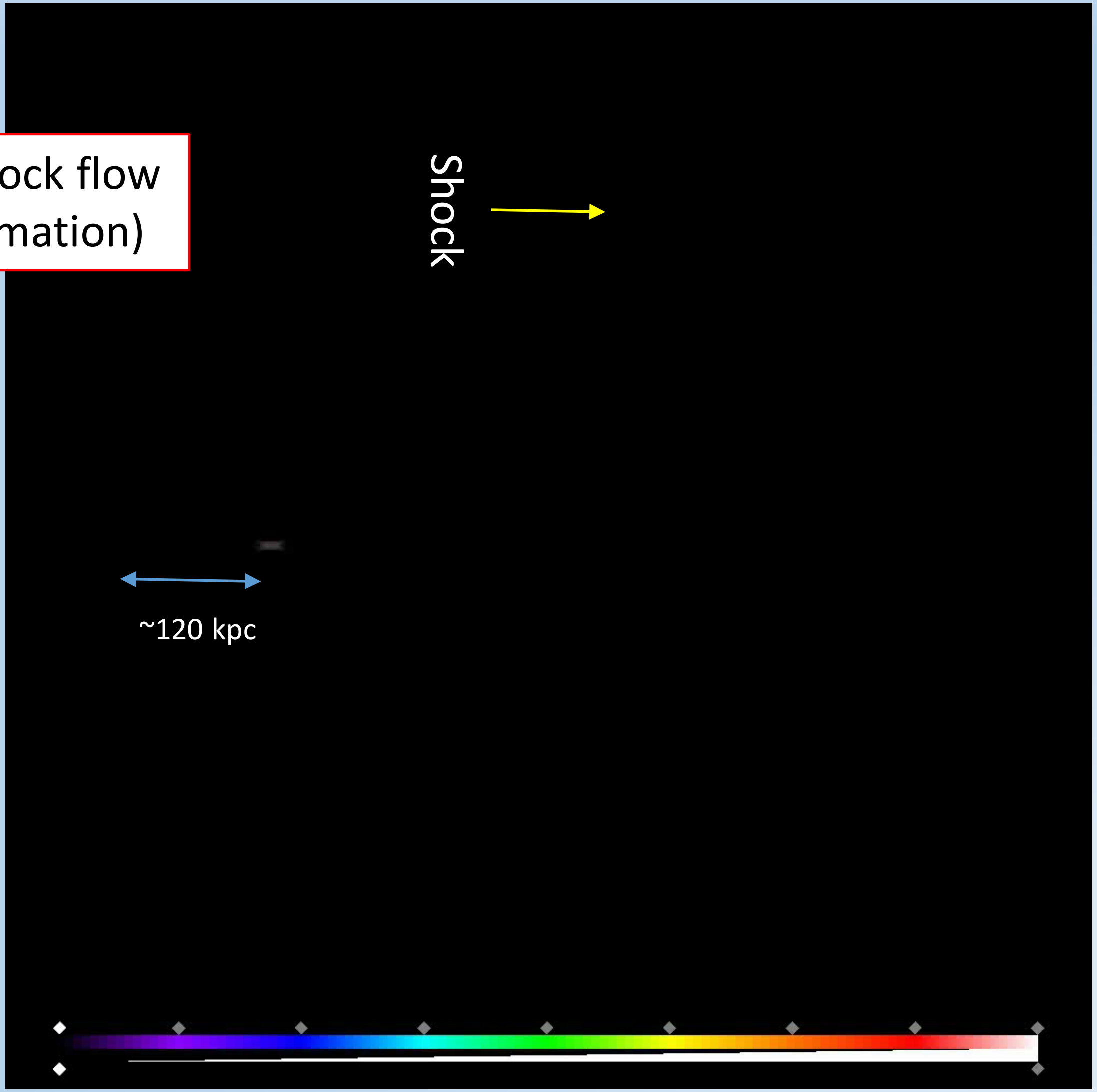
Important detail we need to add:
Radio Galaxy cavities are not static bubbles;
They form dynamically – This can make a difference!

Case 1 Illustration: M_s = 4 Shock Impacts AGN Jet Pair (M_j = 3.5) Head-on

“upwind” jet is reversed by post-shock flow
(analogous to deflection in NAT formation)

$M_s = 4$

$v_s \Rightarrow$



Simulation Spans ~ 300 Myr

Evolution of Jet “mass fraction”
White = 100% jet
Red ~ 80% jet
Green ~ 50% jet

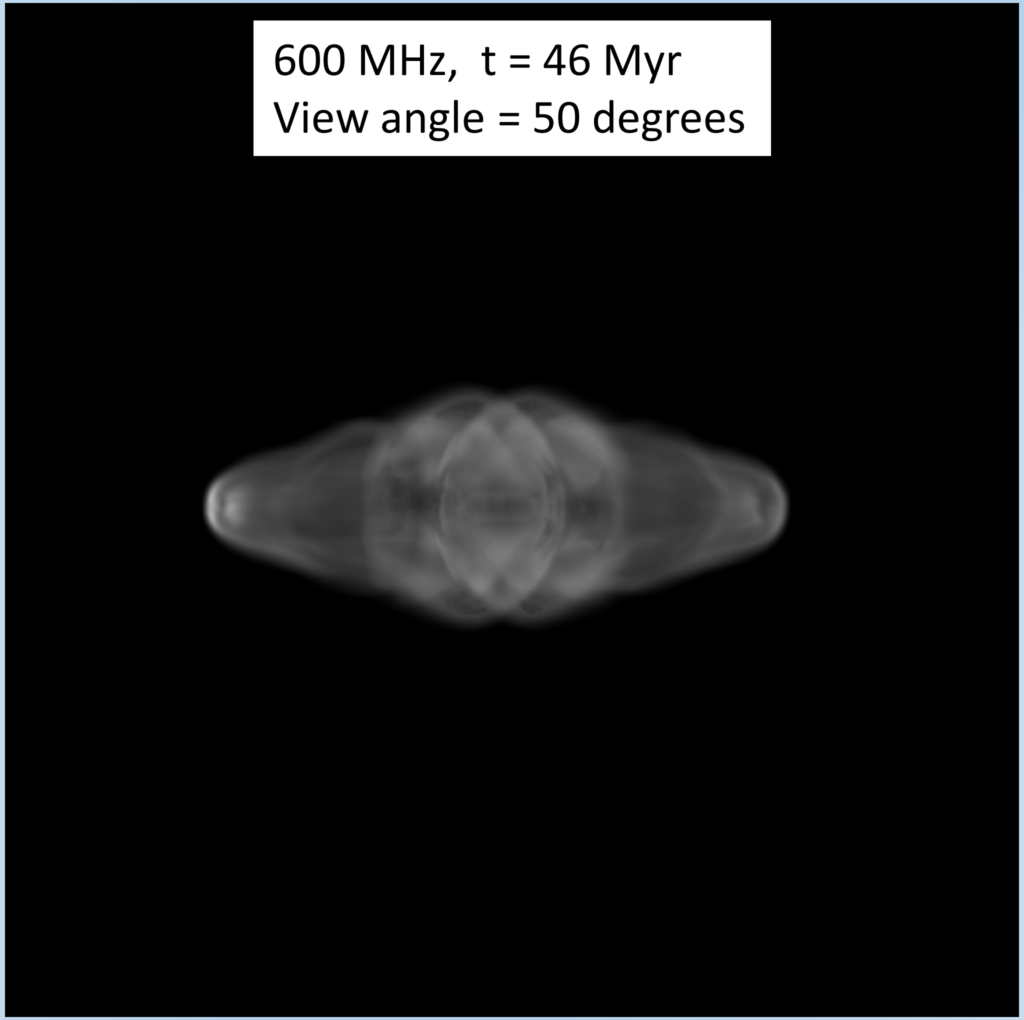
(Note strong mixing)

Viewed in plane (v_j, v_s)

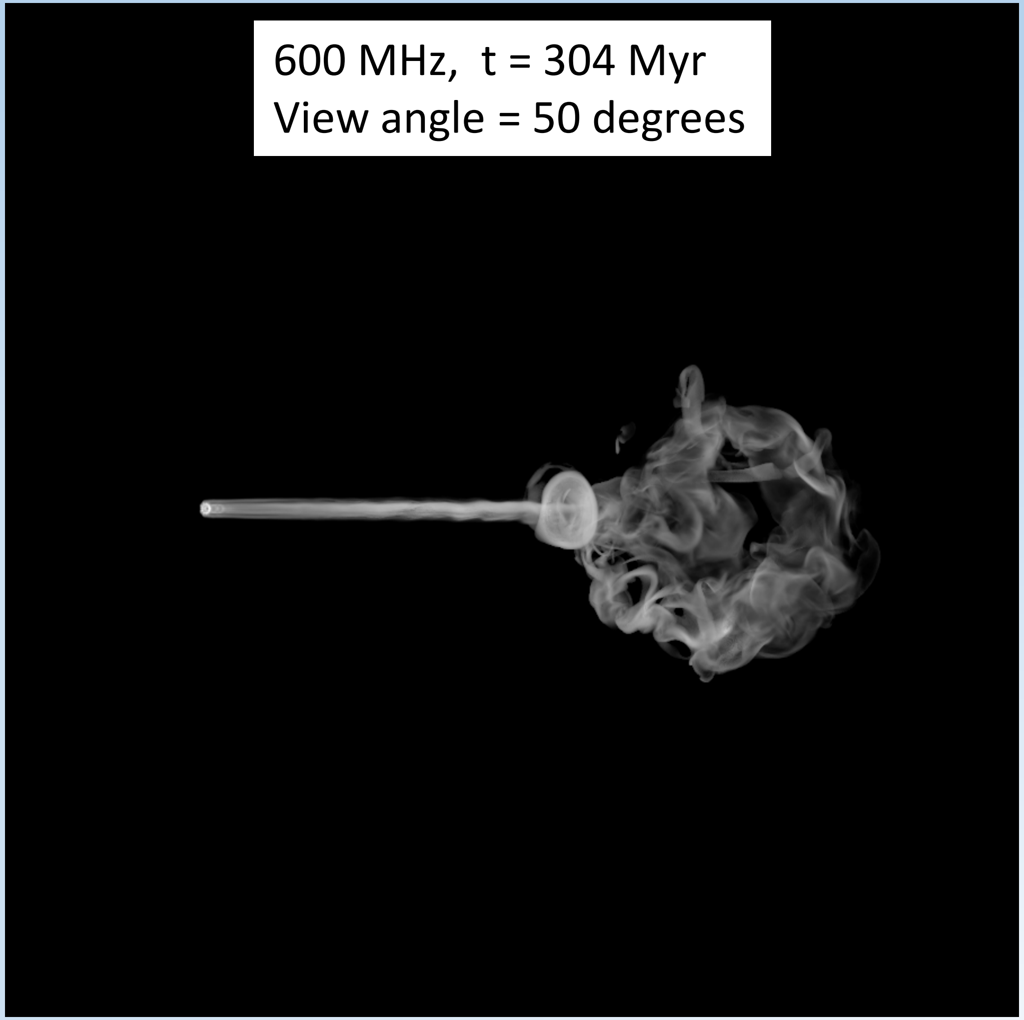
Nolting + (TWJ) (in prep)

Case 1 Synchrotron Images

Just Before Shock Impact



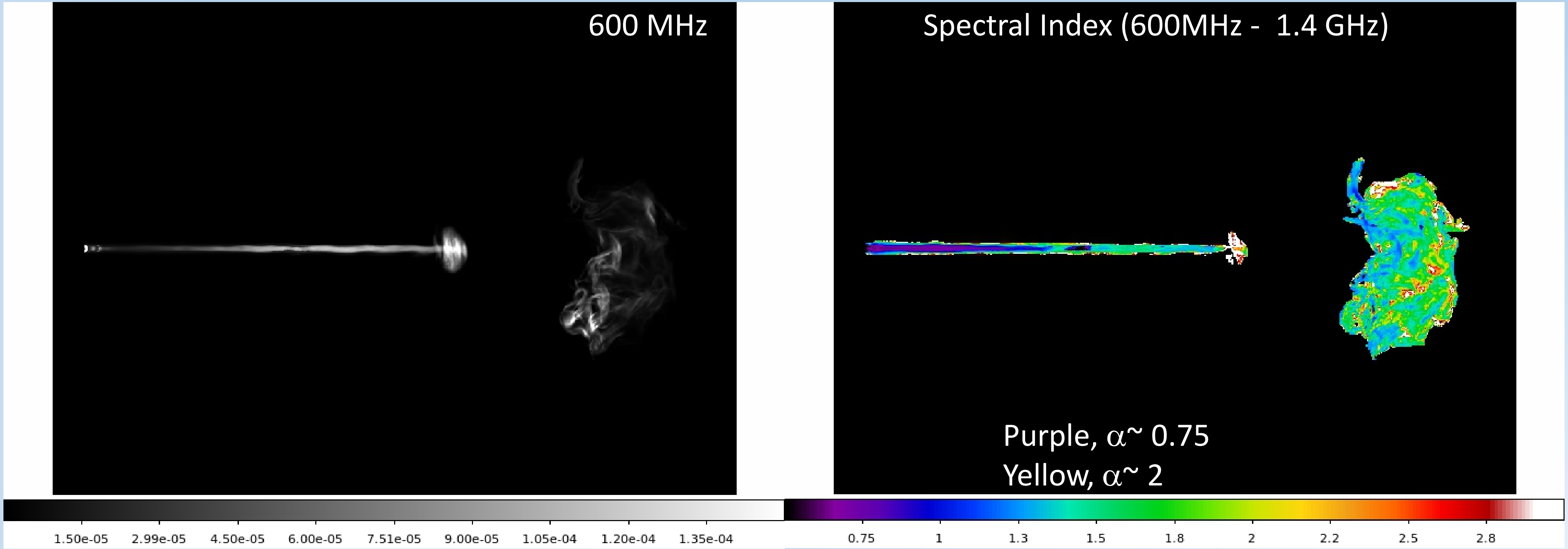
250 Myr After Shock Impact



Case 1 Synchrotron Images

t = 304 Myr (250 Myr after impact)

(Jet in the plane of the sky)



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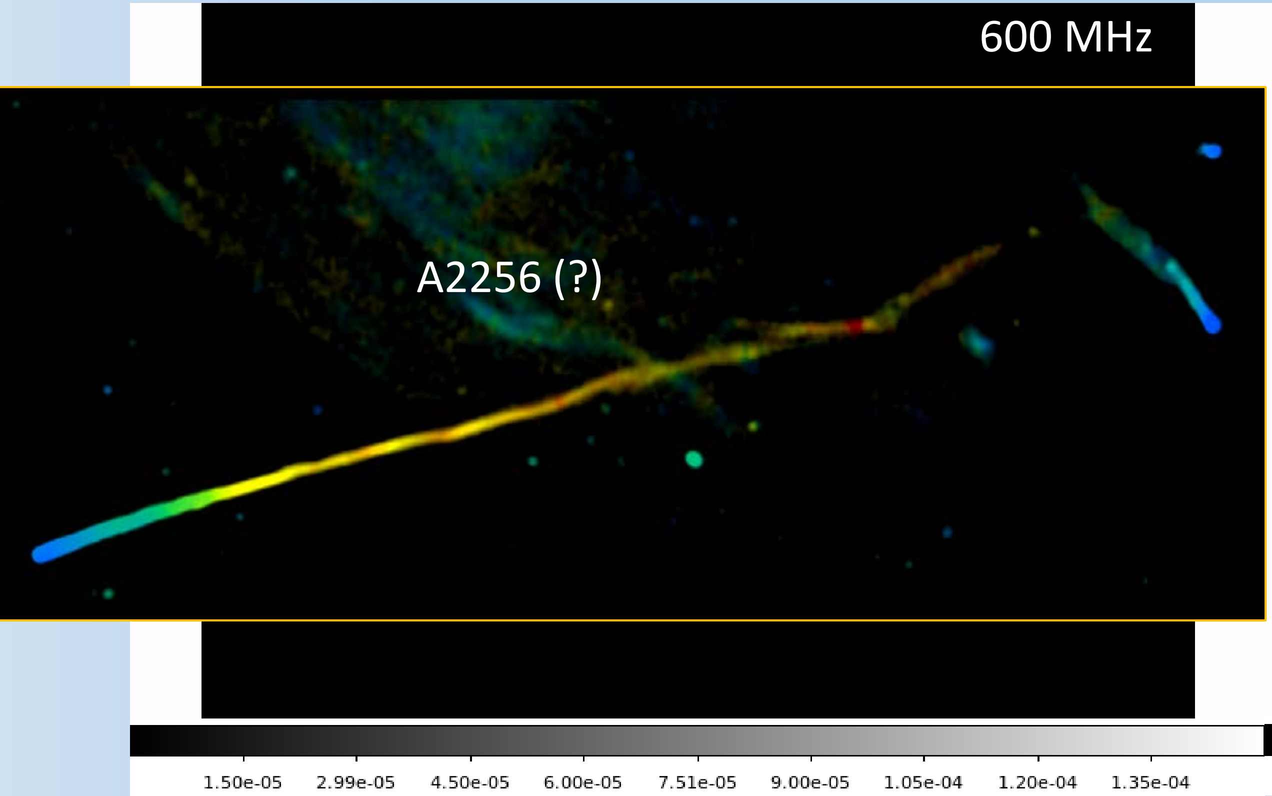
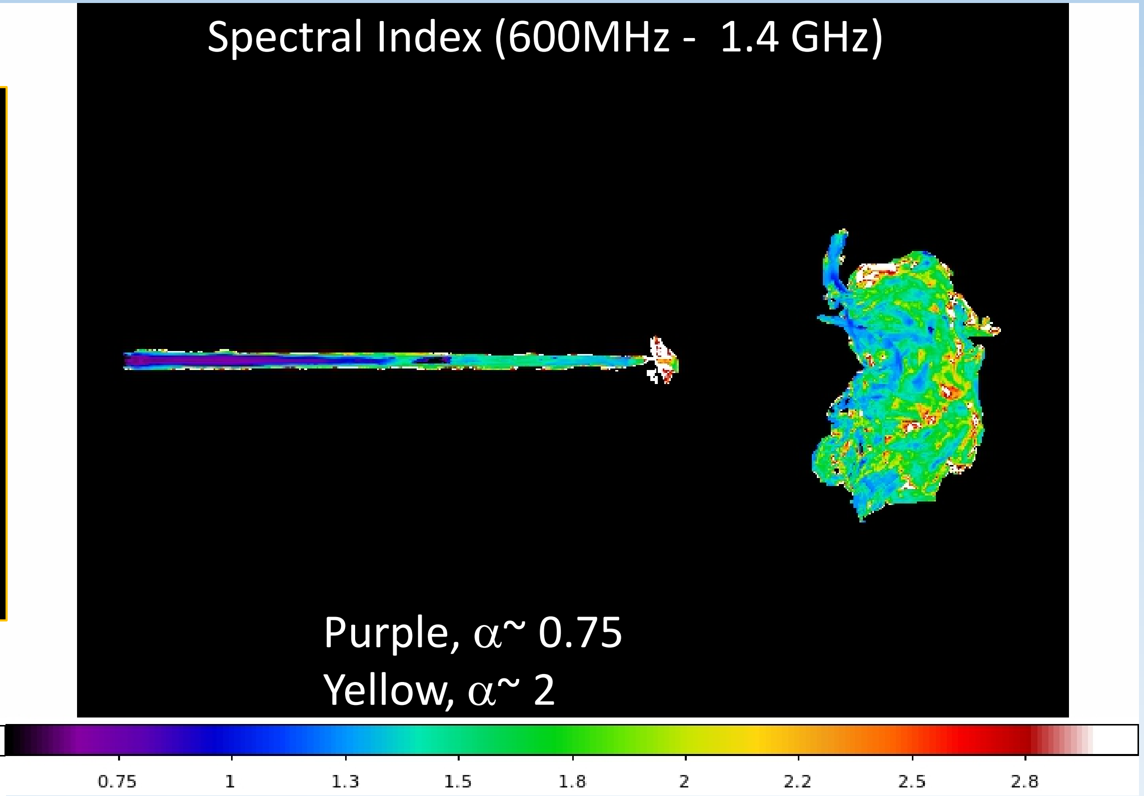




Case 2: M_s = 4 Shock Crosses Pre-formed Narrow Angle Tail (NAT)

Total time for shock to cross both tails ~ 80 Myr (Comparable to visible CRe cooling time

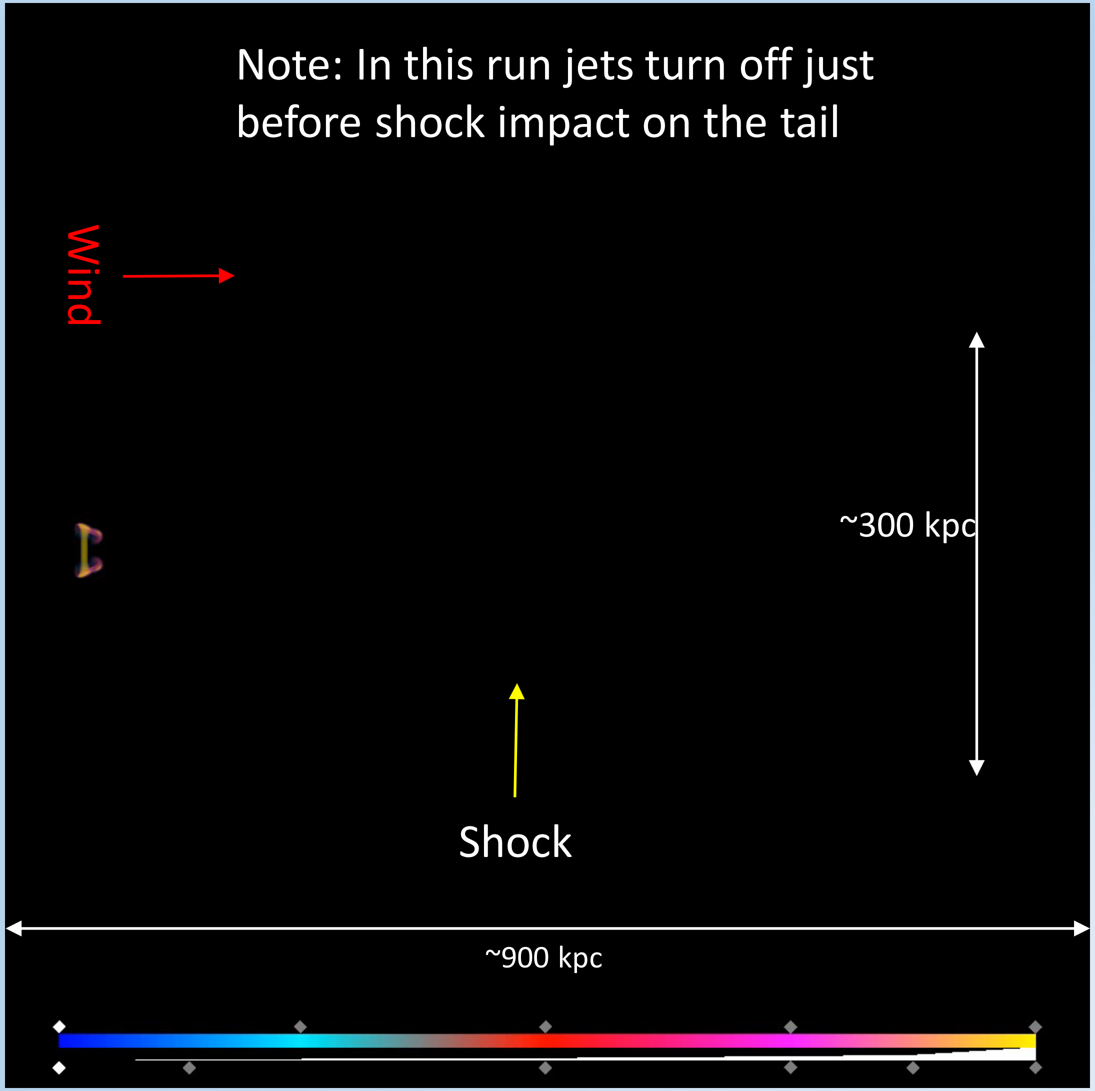
$M_w = 0.9$

$v_w \Rightarrow$

Simulation spans ~ 650 Myr

Ms = 4

$v_s \Uparrow$



Evolution of Jet "mass fraction"
Yellow = 100% jet
Lavender ~ 80% jet
Red ~ 50% jet

(Note strong mixing-- especially after impact)

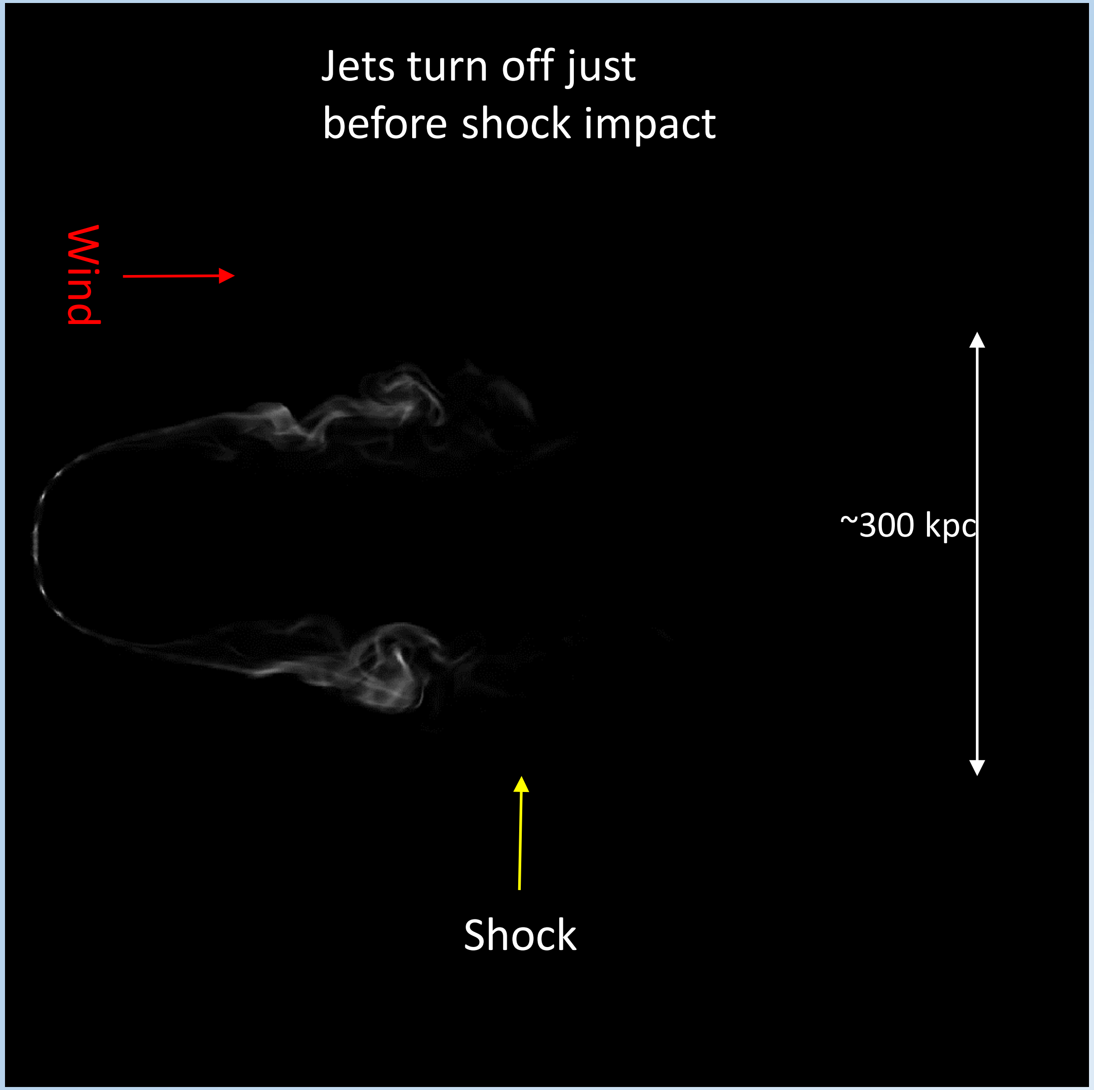
Viewed in (v_j, v_w, v_s) plane

O'Neill + (TWJ) (in prep)

Case 2: 150 MHz Synchrotron Evolution

Total time for shock to cross both tails ~ 80 Myr

$v_w \Rightarrow$



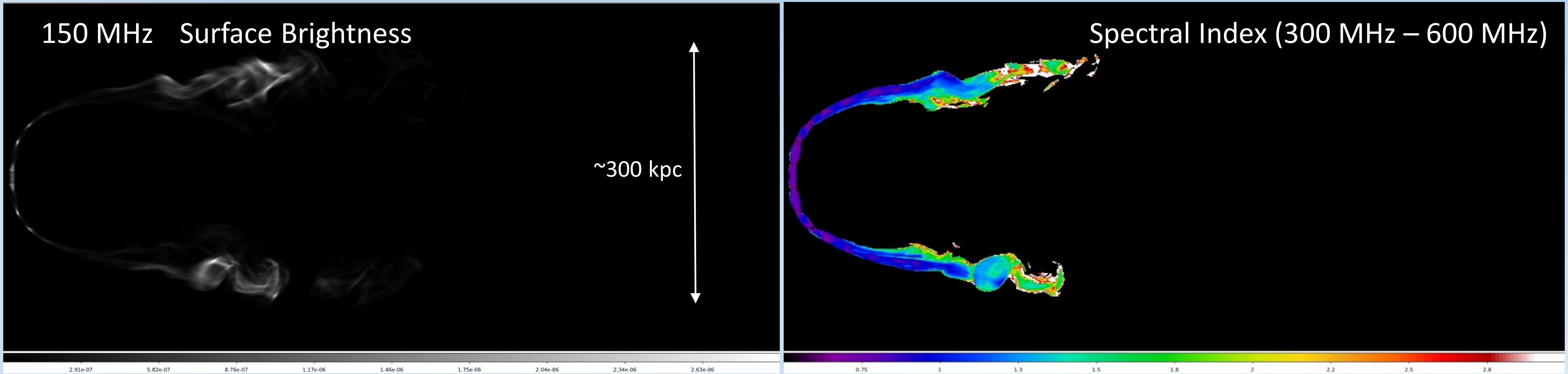
$\Uparrow$ v_s

Evolution of 150 MHz Brightness distribution

Viewed in (v_j, v_w, v_s) plane

Case 2: Synchrotron Emission Just Before Impact

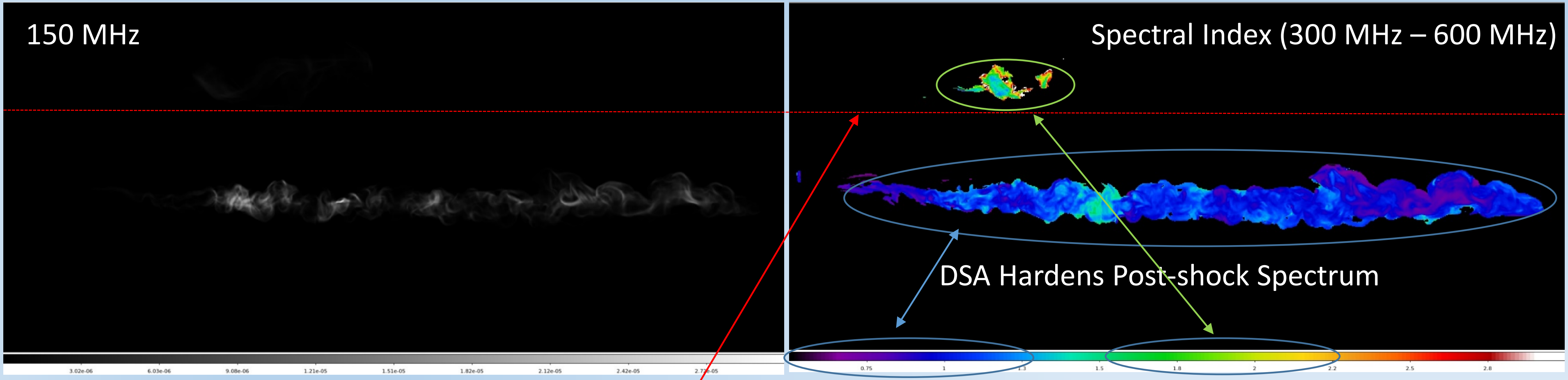
t = 587 Myr



Case 2: Synchrotron Emission After Impact

Jets turn off before impact

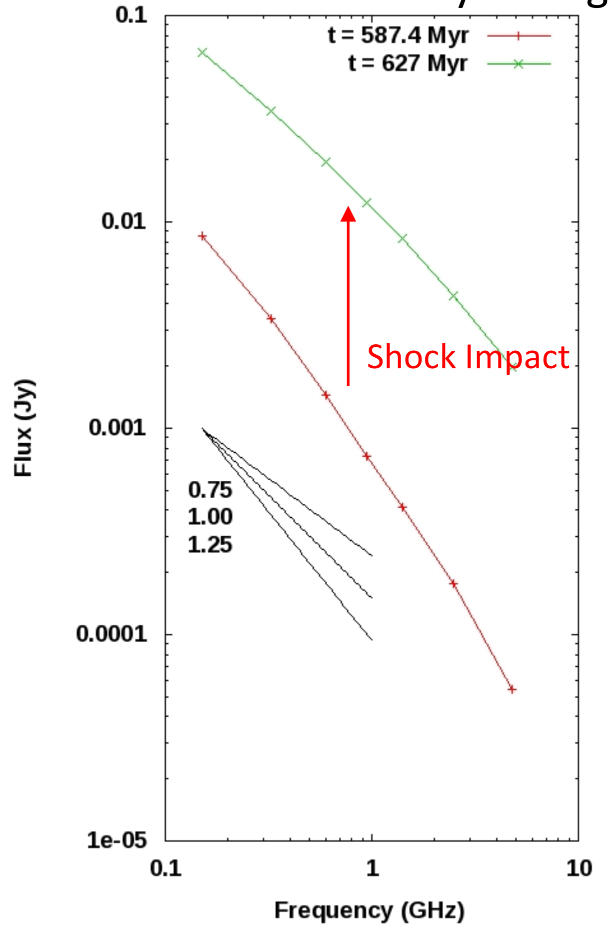
Synchrotron Distribution at t = 627 Myr
(Shock Between Tails)



Rough shock location

Total time for shock to cross both tails ~ 80 Myr

Shock Hardens Spectrum!
Some Regions show DSA:
Shock can be moderately strong



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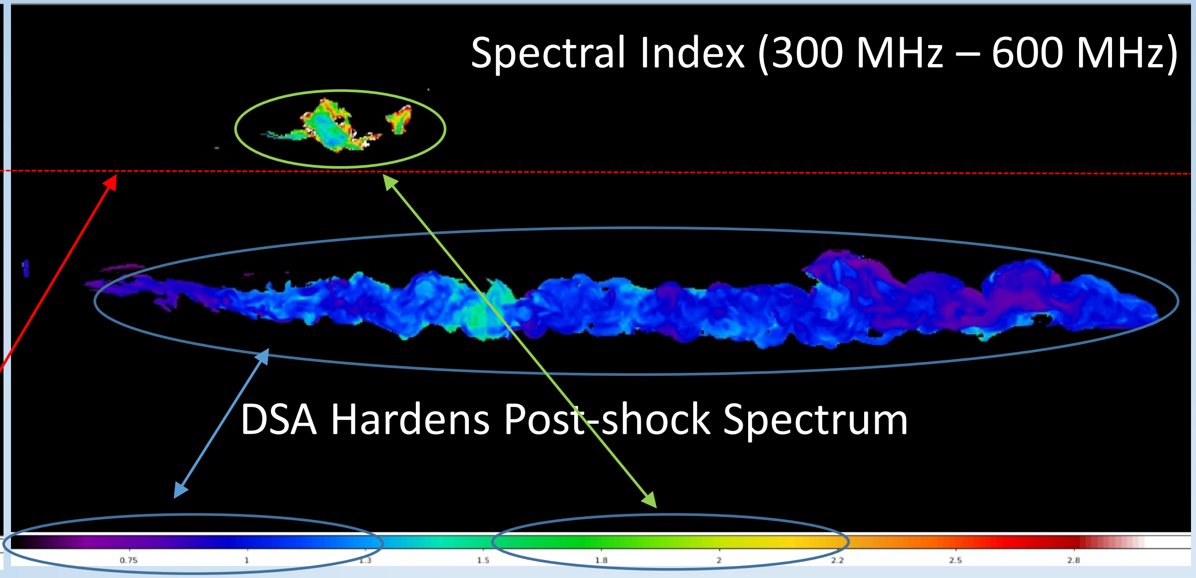
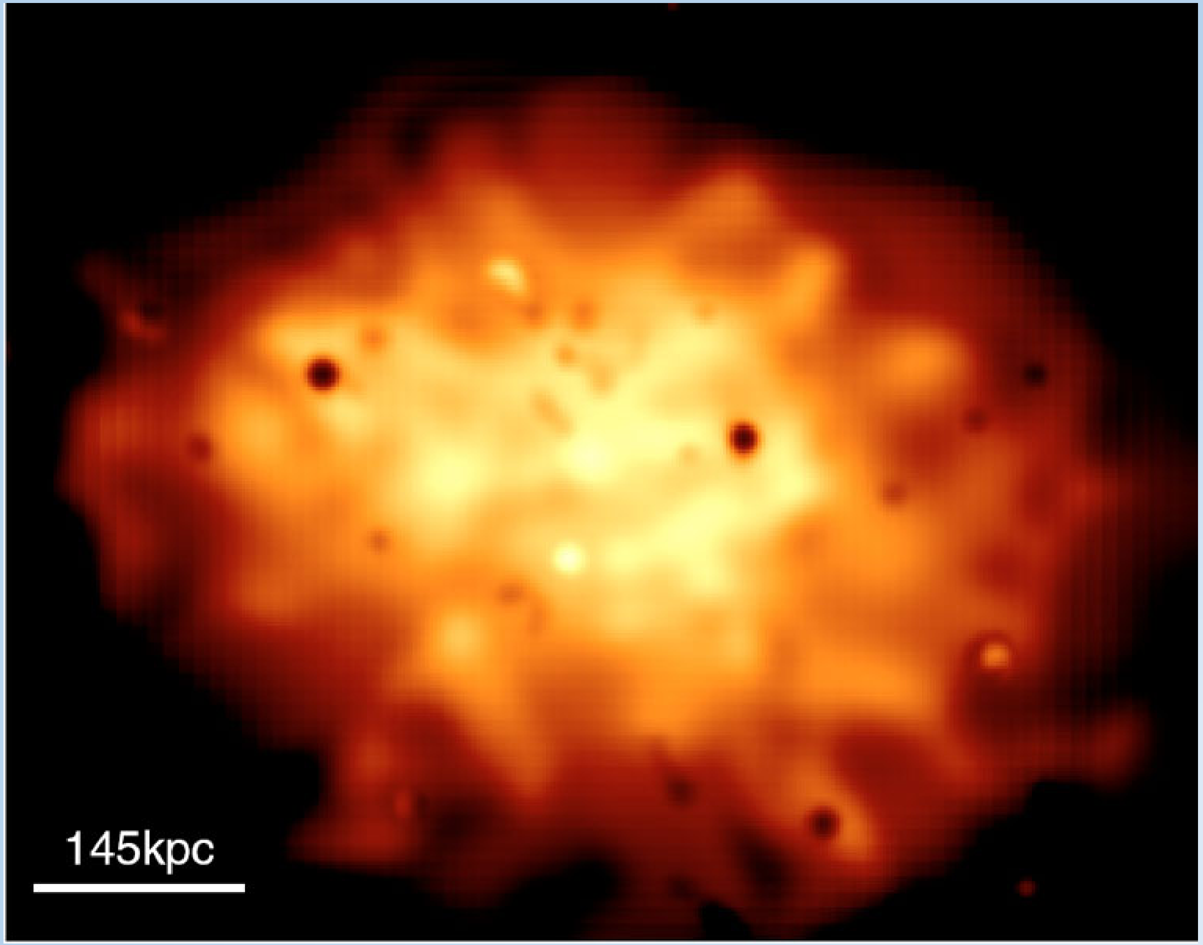


gh shock location

Total time for shock to cross both tails ~ 80 Myr

Turbulence

ICM Turbulence in Coma Cluster



Projected Pressure Fluctuations from Thermal X-rays

P_{turb} ~ 10% P_{th}
δv_{turb} ~ (1/2) c_s

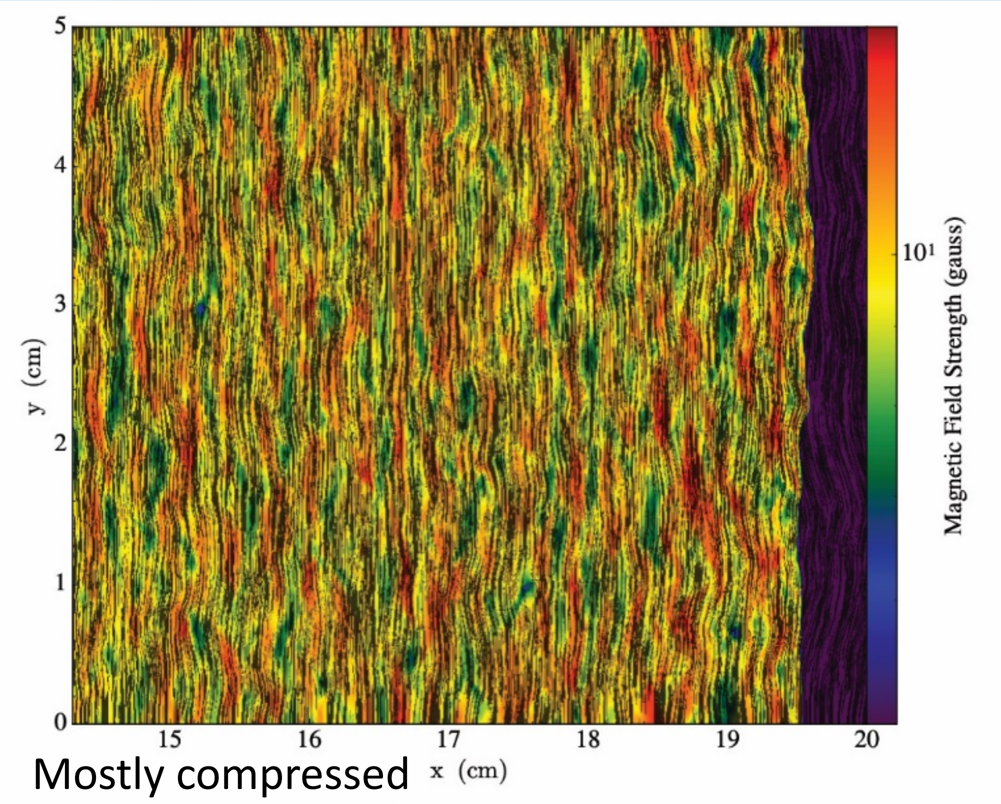
Scheucker + ‘04

Note: Shocks Also Generate, Modify and are Modified by Turbulence

Details depend on M_s, M_A, field geometry & turbulent strength (another talk)

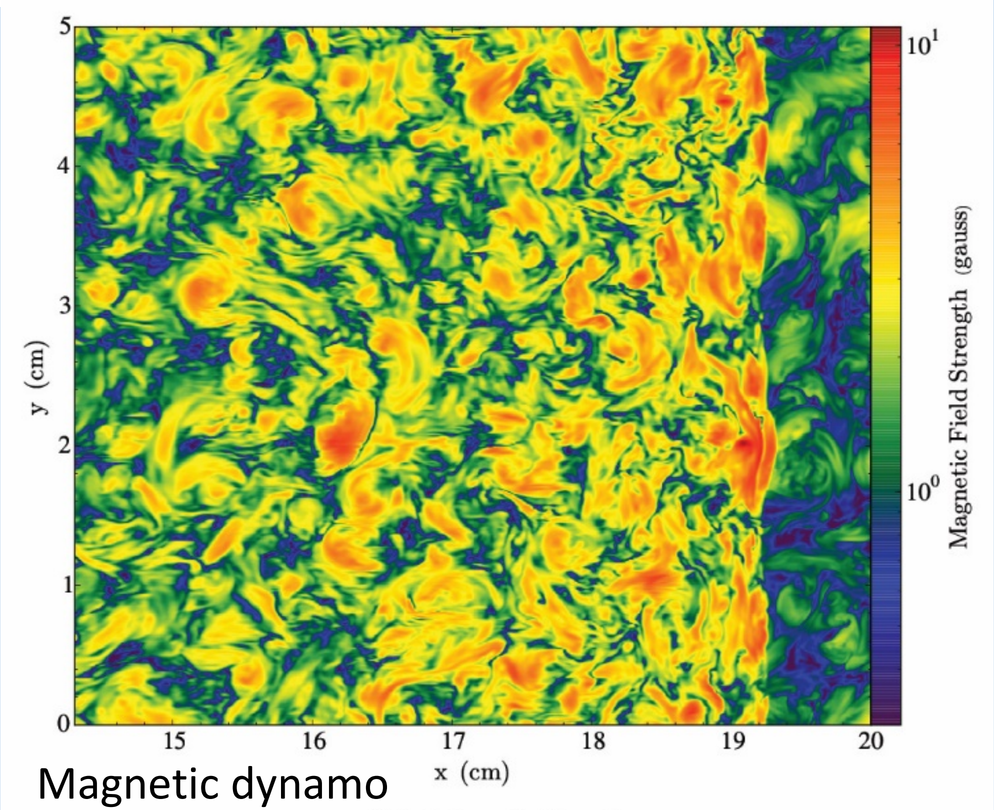
Simulations illustrating B-field modifications by <u>Mach 4</u> shocks in turbulence

Ji + 16



(b) $\mathcal{M} = 4, \beta = 1$

Perp B_o
(2D)



(b) $\mathcal{M} = 4, \beta = 1$

Isotropic B_o
(3D)

Turbulence in a Compressible, High β, Weakly-collision Plasma (ICM):

Even subsonic ($V_T = \delta v_{max} < c_s$) turbulence <u>must include both</u> circulation (<u>solenoidal motions, $\omega=\nabla\times\delta v\neq 0$</u>) and <u>compressional motions</u> ($\delta P \sim (\delta v)^2\rho \sim \delta\rho\, c_s^{\,2}$)
(Balance depends on forcing processes; likely to be mixed in ICM)

ICMs are "High-β"
$\beta = P_g/P_B = (2/\gamma)(c_s^{\,2}/v_A^{\,2})>>1$

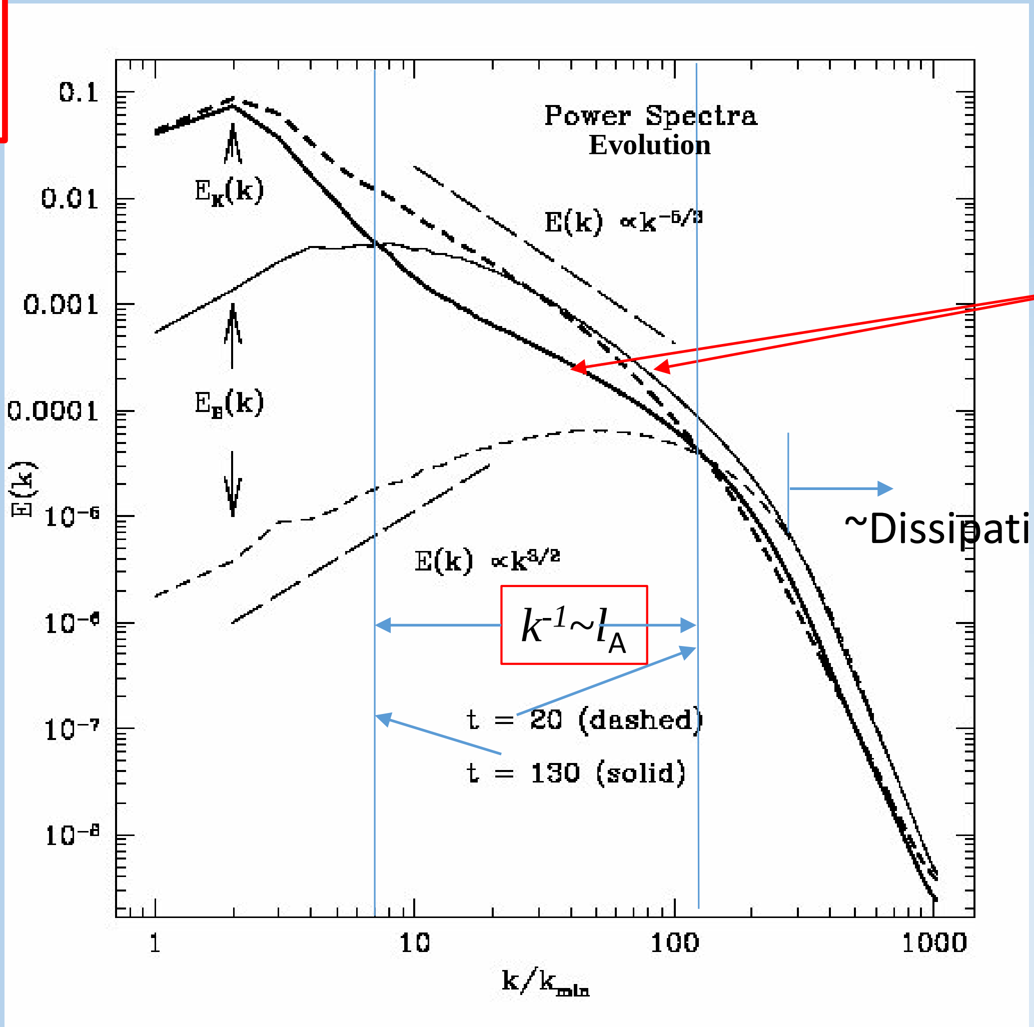
$\underline{c_s \sim 1000\ \text{km/sec}\ T_{5kev}^{\ 1/2}}$
$= 1\ \text{kpc/Myr}\ T_{5kev}^{\ 1/2} = 0.003\ c\ T_{5kev}^{\ 1/2}$
$\underline{v_A \sim 130\ \text{km/sec}\ B_{2\mu G}/\sqrt{n_{e-3}}}$
$\underline{\beta \sim 70\ T_{5kev}\, n_{e-3}/\ B_{2\mu G}^{\ 2}}$

If $V_T > v_A$ on driving scale, L_0, large scale motions are hydrodynamic:
Cascade as $\delta v \sim V_T\ (l/L_0)^{1/3}$ down to "Alfven scale", l_A ,($\delta v = v_A$), then MHD below

Compressible MHD Fluid Turbulence Properties Depend on Time and Forcing: Component (Solenoidal & Compressive)Proportions & Spectral Slopes

Solenoidal Forcing
$\nabla\cdot\delta v = 0$, $\nabla\times\delta v\neq 0$

$M_s \sim ½$
B_0 uniform
$\beta_0 = 10^6$



(Compressive Modes < 10%)

After ~ 20 - 25 t_{Leddy}
B saturates to rough equipartition with solenoidal modes

Porter + (TWJ) 15

Compressible MHD Fluid Turbulence Properties Depend on Time and Forcing: Component Proportions & Spectral Slopes

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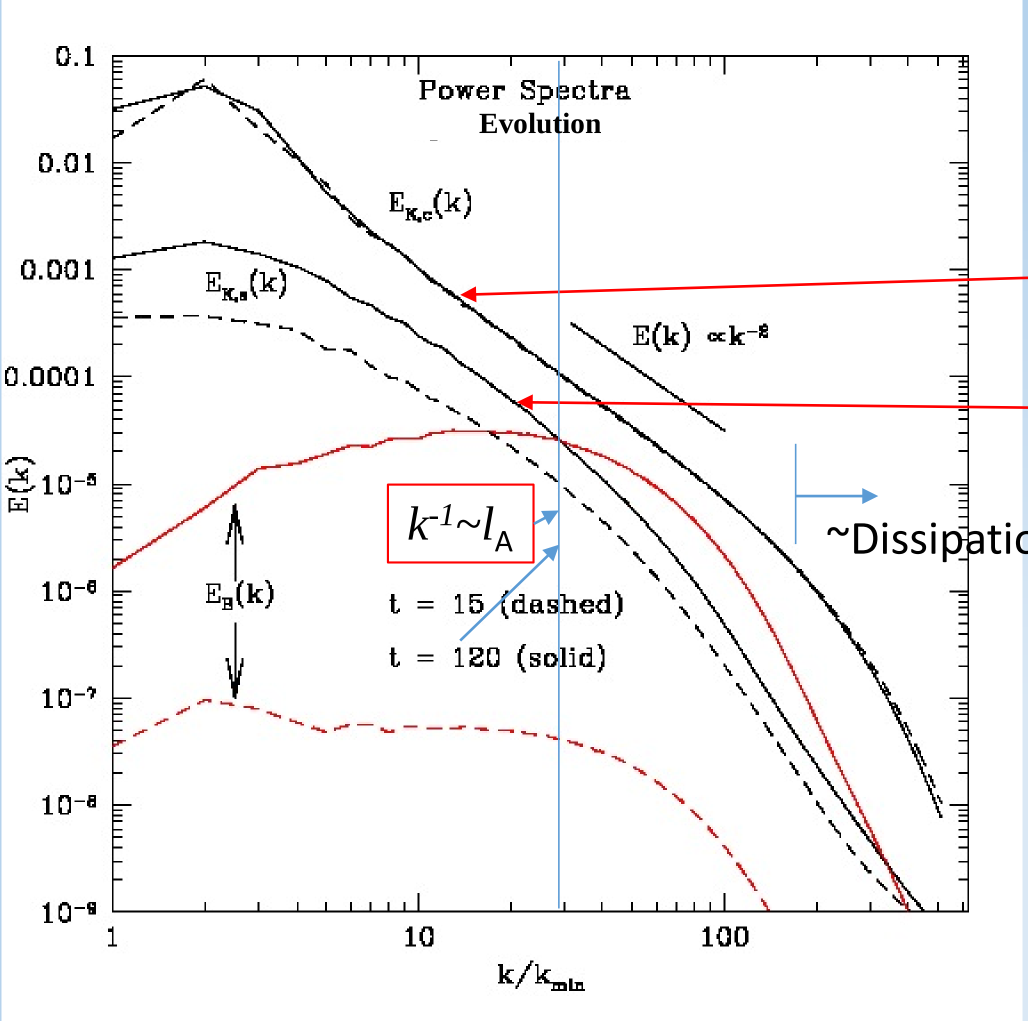


Compressive Modes

Solenoidal Modes
(< 10%)

~Dissipation scales

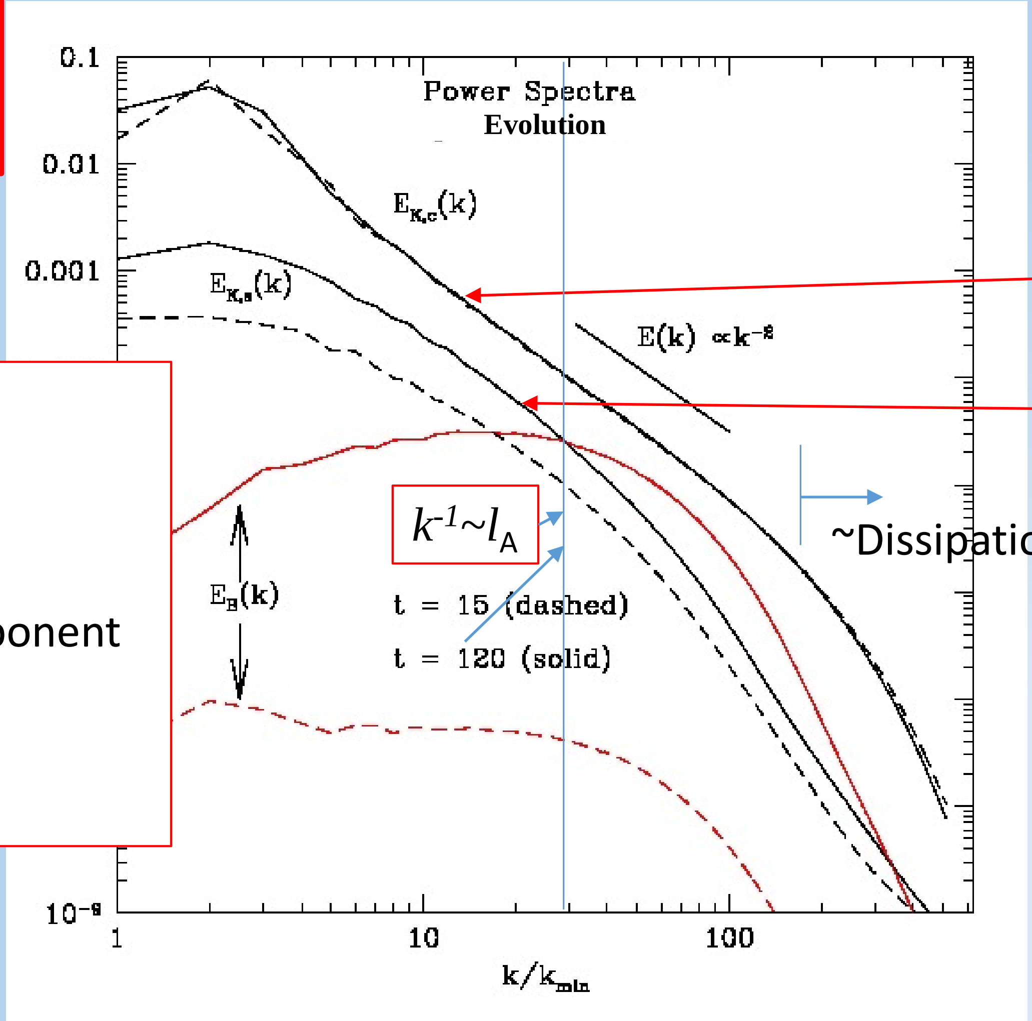
Porter + (TWJ) 15

Compressible MHD Fluid Turbulence Properties Depend on Time and Forcing: Component Proportions & Spectral Slopes

Compressive Forcing
$\nabla\times\delta v=0$, $\nabla\cdot\delta v \neq 0$,

ICM Turbulence Forcing includes both Solenoidal and Compressive Forcing:

⇒ Variable Compressive Component
⇒ Variable Steepness
⇒ Intermittent Distribution



Porter + (TWJ) 15

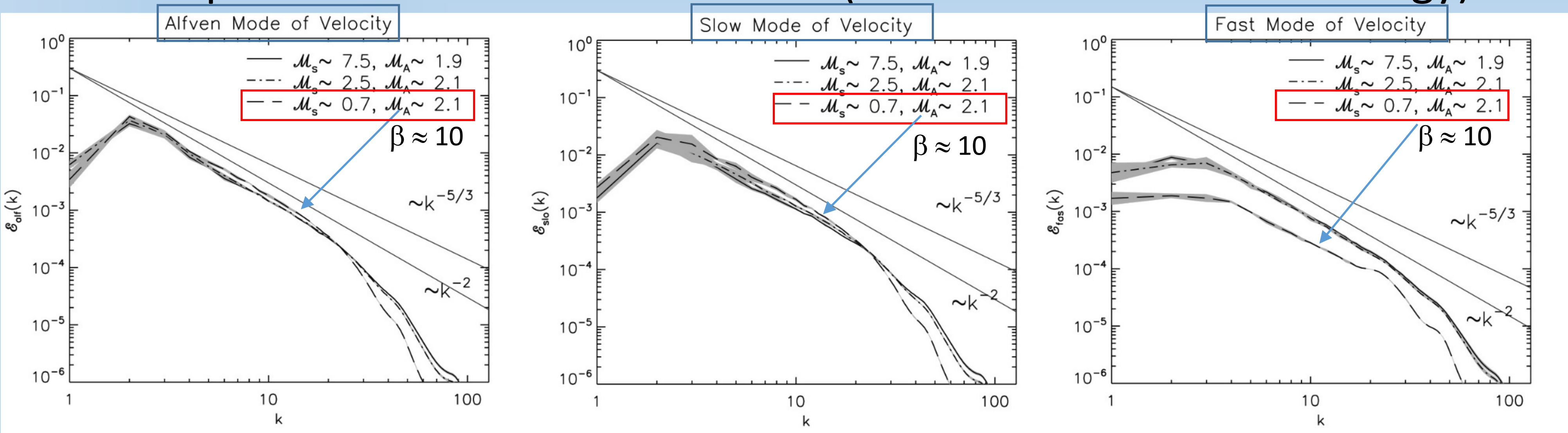
Compressible MHD Domain Turbulence:

Velocity Power Spectra By Mode-

For $l < l_A$ ($\delta v < v_A$) in the MHD Domain

Solenoidal => Alfven Mode (energetically dominant overall)

Compressive => Fast & Slow Modes (Slow modes dominate energy)



Kowal & Lazarian 2010

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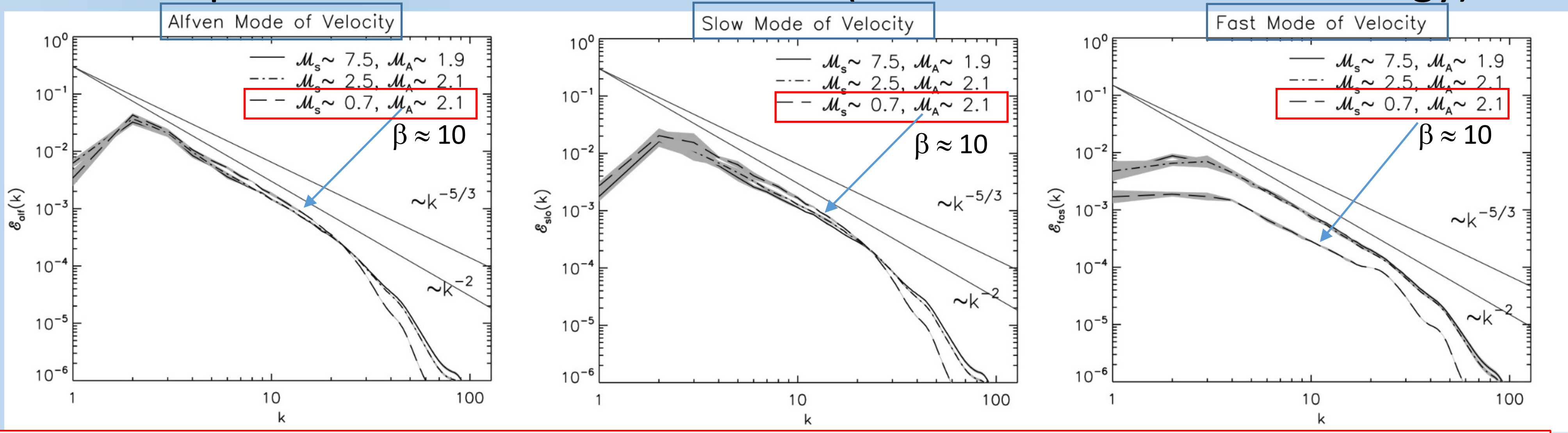

Fast mode = magnetosonic => $\delta\rho$ correlates with δB (pressure fluctuations enhanced); $v_{ph} \approx c_s$ in high β

Slow mode => $\delta\rho$ anti-correlates with δB (little or no total pressure fluctuation); $v_{ph} < v_A$ in high-β

Kowal & Lazarian 2010

Quick Turbulent Acceleration Overview: Turbulent Re-Acceleration Comes from Stochastic (Fermi II) Gains

The CRe particle distribution f(p,x,t) evolves according to Fokker-Planck Equation:

$$\frac{\partial f}{\partial t} = \cdots \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)\cdots$$

where

$$D_{pp} = \left.\frac{\left\langle (\Delta p)^2 \right\rangle}{\Delta t}\right|_{acc}$$

Δp is characteristic energy change per event of duration/separation, Δt

The momentum diffusion coefficient, D_{pp}, can result from several stochastic processes provided by fluctuations, waves in the turbulence.

Note: Energy changes require an E field

The time to accelerate a particle: $\tau_{acc} = \frac{p}{dp/dt} \sim \frac{p^2}{D_{pp}}$ where D_{pp} will depend on process

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Being 2nd order, turbulent re-acceleration
Typically much slower than DSA

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But, many possibilities

Bei -acceleration
Typically much slower than DSA

Some Potential Contributors to Turbulent Re-Acceleration:

Nonresonant scattering off compressive wave mode waves (e.g., Ptuskin '88)
(similar to 'classic' -1949- Fermi II; depends on λ_{mfp})

$$D_{pp} \sim p^2 \left(\frac{V_o}{c_s}\right)^2 \kappa \left(\frac{1}{L_o l_{\min}^2}\right)^{2/3} \sim \frac{p^2}{\tau_{acc}}$$

for 'slow' spatial diffusion ($\lambda_{mfp} < l_{min}$) (Brunetti & Lazarian '07)

min scale of turbulent cascade

L_0 is the outer turbulence scale; l_{min} is the minimum eddy scale
$V_0 = V_T$ is turbulent velocity, δv, on outer scale

$$\tau_{acc} \sim \frac{p^2}{D_{pp}} \sim \tau_{Leddy} \left(\frac{c_s}{c}\right)\left(\frac{c_s}{V_T}\right)\left(\frac{l_{min}}{\lambda}\right)\left(\frac{l_{min}}{L_0}\right)^{1/3} \sim \text{ constant}$$

$$\tau_{Leddy} \sim \left(\frac{L_0}{V_T}\right) \sim 300Myr \left(\frac{L_0}{100kpc}\right)\left(\frac{300km/sec}{V_T}\right)$$

$\tau_{acc} > \tau_{Leddy}$; Probably too slow for GRH or relic needs

MHD Resonant Wave Scattering (n = 0, $\pm$1)

$$k_{\|} v_{\|} - \omega = n\Omega_g , n = 0, \pm 1, \cdots$$

Traditional model: Gyro-resonance, n = $\pm$1
with low frequency Alfven waves (circularly polarized)
$\omega << \Omega_g$, so $r_g k_{||} \sim 1$, $l \sim r_{g,CR}$. ($r_{g,CR} \sim 10^8$ km (~AU) for GeV CRe in ICM)

*However, in strong, balanced MHD turbulence (so, $\delta v < v_A$) Alfvenic 'eddies' elongate along B on smaller scales. => Highly anisotropic on smallest scales (critical balance $\rightarrow k_\perp \sim [k_{||}]^{3/2}\, l_A^{1/2}$) (Goldreich & Sridhar '95). Coherent, resonant interaction with gyrating CR is lost, so, gyro-resonance scattering efficiency greatly reduced (e.g., Chandran, Lazarian, etc)

`Transit Time Damping' (TTD) ~ `Landau resonance' (n = 0)

$\mathbf{k_{||} v_{||}} = \omega = \mathbf{v_{ph}\, k}$ (wave surfing)

Force from magnetic moment (orbiting charge) in `magnetic bottle'

Oblique Fast (& Slow?)* waves in the MHD regime ($\delta\mathbf{B}$ in **k-B** plane)

$$\dot{p}_{||} = -\mu \nabla_{||} |B| = p_\perp v_\perp k_{||} \frac{\delta B(k_{||})}{2B_0}$$

$$\Delta p \sim \dot{p}\,\delta t$$

*Turbulent fast modes isotropic; slow modes anisotropic & `slow' so n = 0 resonance not important *in QLT*

$$D_{pp} \sim (\Delta p)^2 / \delta t$$

Fast modes =>

$$D_{pp,f} \sim \text{few } \mathrm{p}^2 \frac{\mathrm{c_s^2}}{\mathrm{c}\,\ell} \frac{(\delta \mathrm{B_f})^2}{\mathrm{B_0^2}}$$

$$\tau_{acc} \sim \frac{p^2}{D_{pp}} \sim \text{constant}$$

Depends critically on the magnetic energy in cascade to FM dissipation scale, ℓ

Note: In High-β ICM, magnetic fluctuations are small fraction of FM wave energy. Reduces effectiveness for a given wave energy

$$\delta B_f^2 \sim \frac{\rho}{\beta}\, \delta v_f^2 \propto \frac{1}{\beta}\, \delta \mathcal{E}_f$$

Smaller ℓ works faster

Resonant Scattering Acceleration Rates Depend on Smallest-scale Scattering:
-Need to get substantial turbulent EM power to small scales

Several important ICM turbulence length scales: "MHD" or "Alfven" scale (l_A; $\delta v = v_A$)

$$l_A \sim \; 10\ kpc \left(\frac{B}{2\mu G}\right)^3 \left(\frac{L_o}{300kpc}\right) \left(\frac{V_T}{500km/sec}\right)^{-3} \left(\frac{n_e}{10^{-3}}\right)^{-3/2}$$

Coulomb Collision Length (dissipation?):

$$\lambda_{Coul} \sim 1\ kpc \left(\frac{T}{2keV}\right)^2 \left(\frac{n_e}{10^{-3}}\right)^{-1}$$

Plasma coupling lengths (micro-instabilities, e.g., firehose):

Ion inertial length (p-e coupling scale)

$$\lambda_i = \frac{c}{\omega_{pi}} \sim 6000\ km \left(\frac{n_i}{10^{-3}}\right)^{-1/2}$$

Very small!

Ion gyro radius

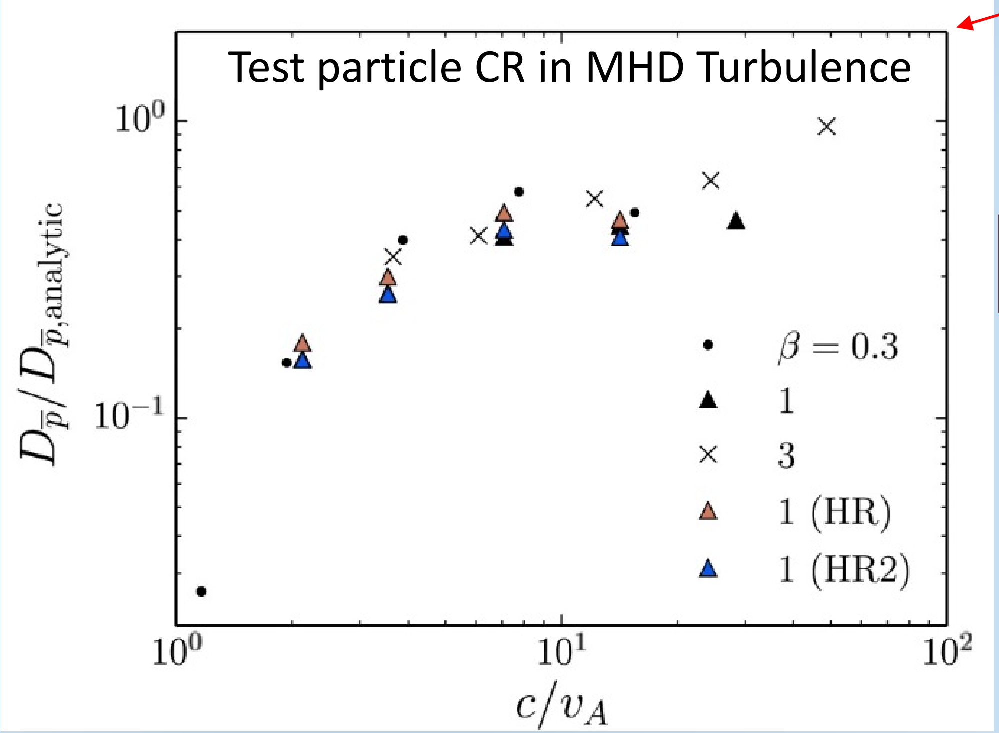
$$r_{gp} \sim 5.6 \times 10^4\ \mathrm{km} \frac{T_{keV}^{1/2}}{B_{\mu G}}$$

Nonlinear, `Resonance Broadening'* in Slow Modes
=> Effective TTD Acceleration (?) Lynn+ 2014

$$D_{pp} \sim (\Delta p)^2/\delta t$$

Slow modes =>

$$D_{pp,s} \sim \mathrm{few}\ \mathrm{p}^2 \frac{\mathrm{v_A^2}}{\mathrm{c\ L}} \frac{(\delta \mathrm{B_s})^2}{\mathrm{B_0^2}} \propto \mathrm{D_{pp,f}} \frac{1}{\beta} \frac{\delta \mathrm{B_s^2}}{\delta \mathrm{B_f^2}}$$



*Waves near dissipation scale decorrelate on ~ a wave period, allowing resonance

Magnetic fluctuations are ~ ½ wave energy

$$\delta B_s^2 \sim \rho \delta v_s^2 \propto \delta \mathcal{E}_s$$

$$\frac{D_{pp,s}}{D_{pp,f}} \propto \frac{\delta \mathcal{E}_s}{\delta \mathcal{E}_f} \ (\sim \text{dissipation scale}, \ell)$$

Magnetic Reconnection:
Short Comment

- In turbulent, high β plasma magnetic reconnection should be fast and ubiquitous.
- Direct magnetic field energy dissipation is small, but CR trapped on shortening field lines & in amplifying fields may, in association, gain and lose energy stochastically (e.g., Kowal + ’11, Brunetti & Lazarian ’16).
- Energy would be extracted from solenoidal (dominant) kinetic energy
- Details need further work

Summary

- Diffuse, cluster-scale radio emissions require distributed, ”local” sources of CRe
- Shocks may play a significant role in CRe acceleration, but other sources of seed CRe likely (note: CRe with ~ 100 MeV can be stored a long time)
- AGN may be major players in multiple ways
- Turbulent re-acceleration very likely to be important (also maybe in association with shocks)
- Effectiveness of turbulent re-acceleration depends critically on physics determining the dissipation scale (get EM energy flux to small scales!)
- Next progress requires full understanding of ICM micro-physics (dissipation physics) and higher resolution information from both observations and simulations

Bedankt!