Acceleration of Cosmic Rays in Galaxy Clusters: constraints from radio and gamma-rays

- A mini review -

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Alexander von Humboldt Stiftung/Foundation

European Commission

Clusters of galaxies:

the largest gravitational structures in the Universe ($M \approx 10^{14}$-$10^{15} M_{sun}$, $R_V \approx$ 2-3 Mpc)

≈30-300 galaxies

Galaxy cluster matter :

Barions

- 10% of stars in galaxies
- 15-20% of hot diffuse gas

Dark Matter 70%

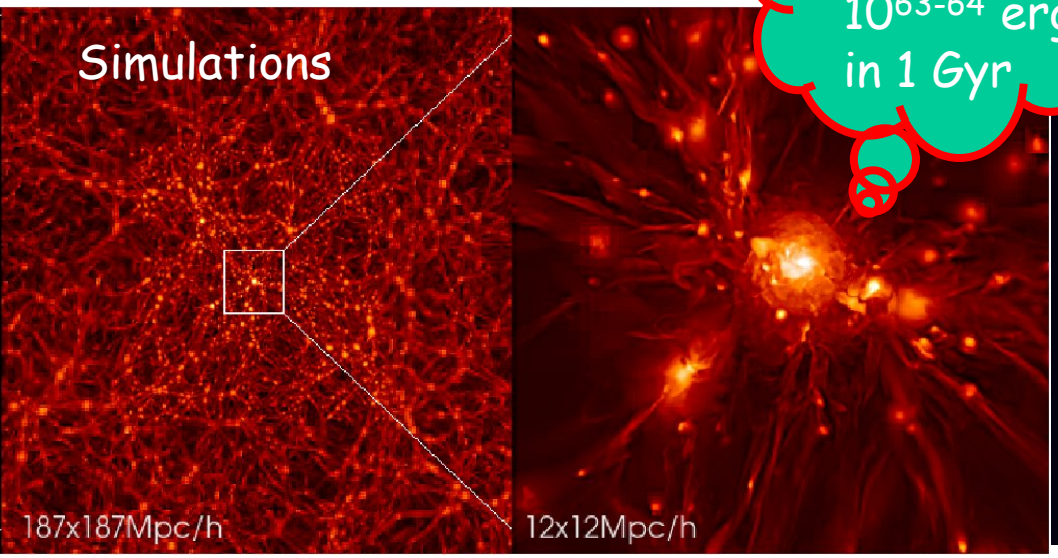
$n \approx 10^{-3} cm^{-3}$

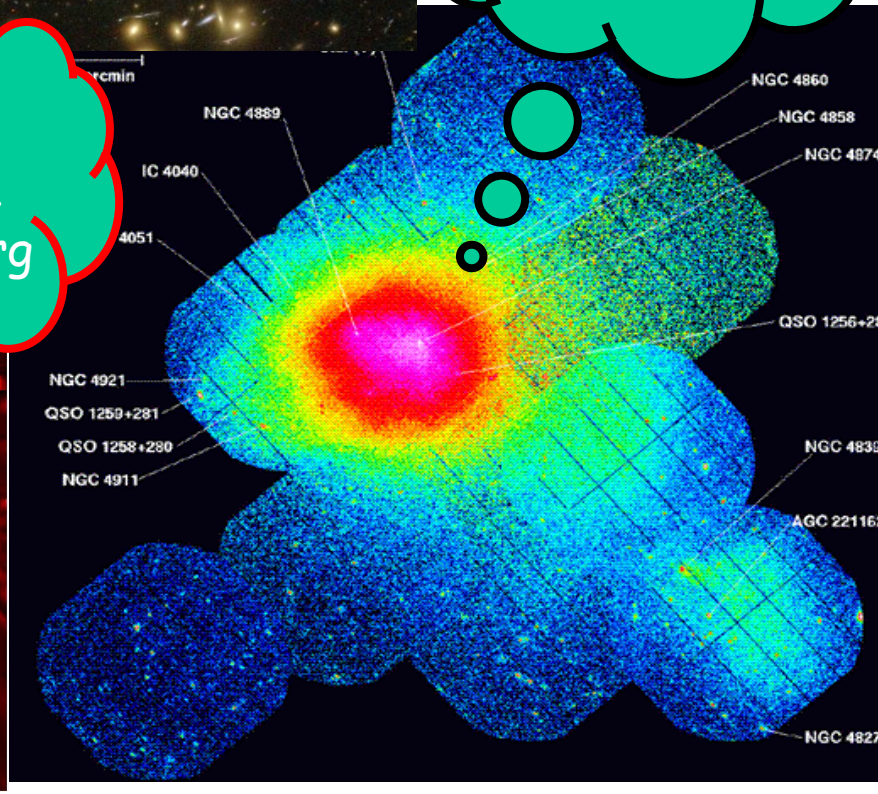
$T \approx 10^{7}$-10^{8}K

High beta

Weakly coll.

Mergers dissipate 10^{63-64} erg in 1 Gyr

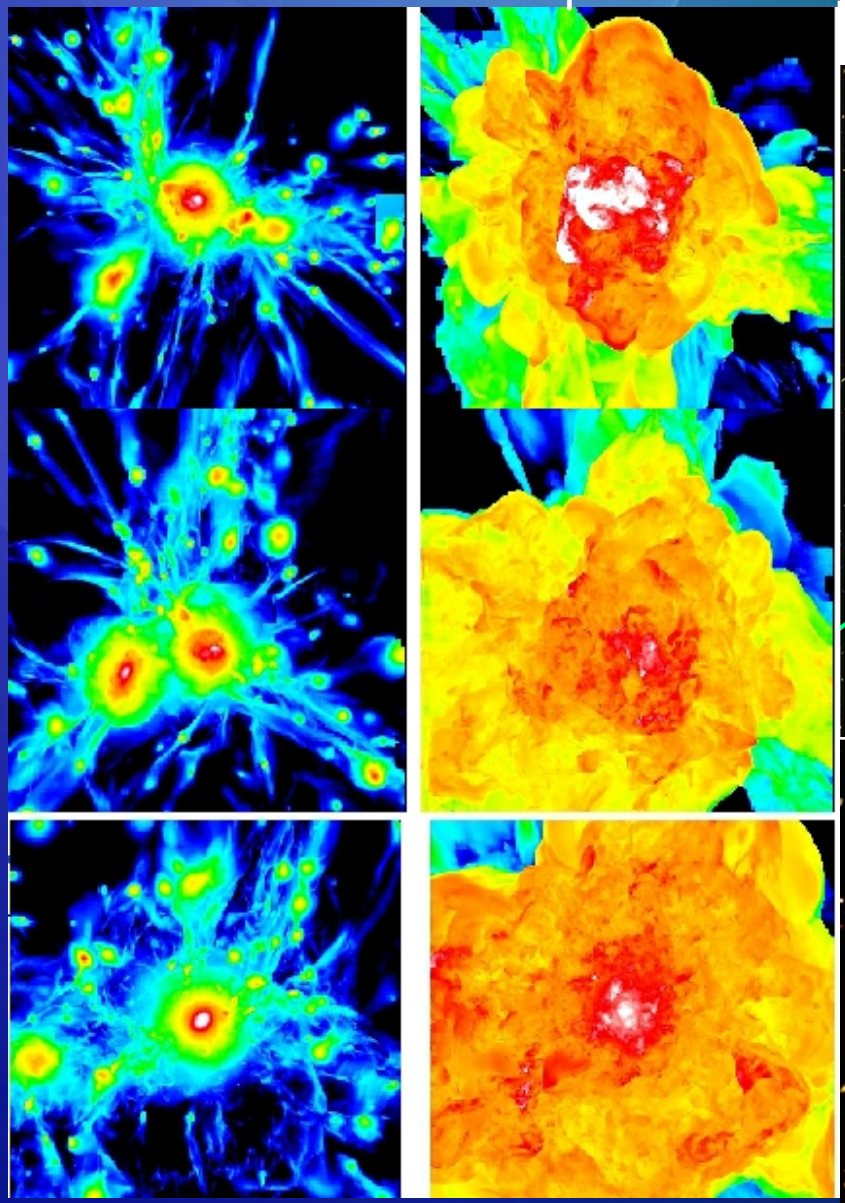




Clusters Mergers

Matter

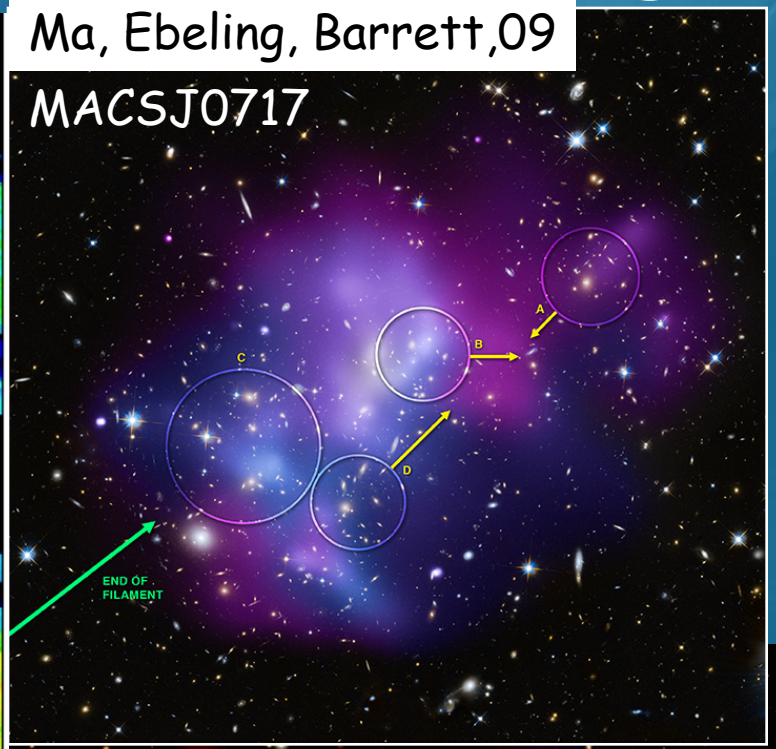
Temperature

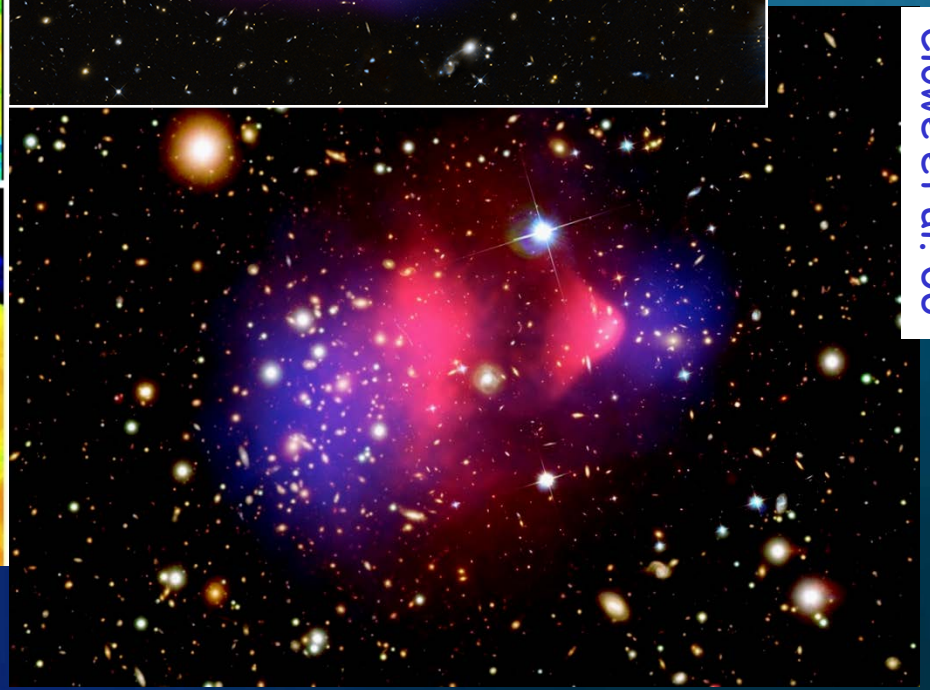


E_{diss} ~10^{63}-10^{64} ergs

Ma, Ebeling, Barrett,09

MACSJ0717





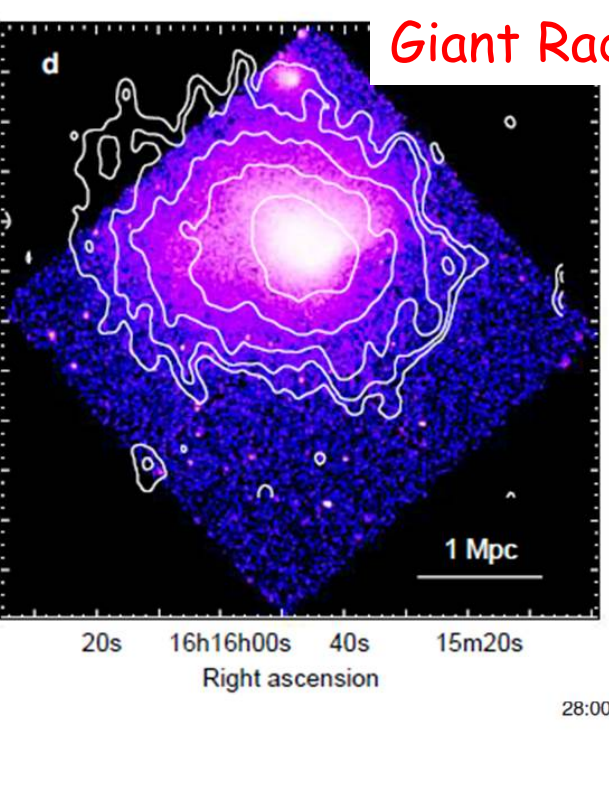
Clowe et al. 06

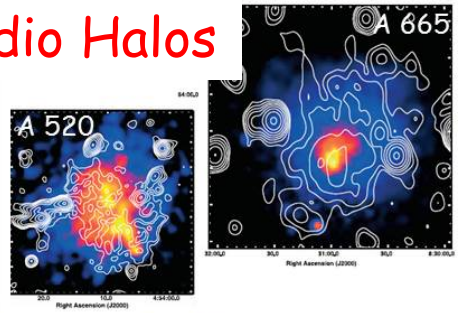
Cluster-scale radio emission

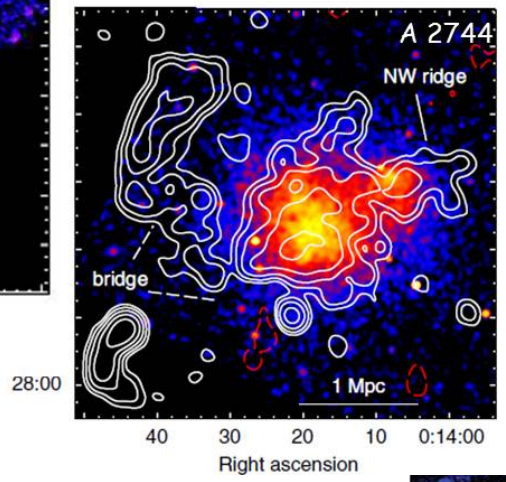
- Steep spectrum sources
- Low brightness

- ✓ Synchrotron radiation FROM the ICM
- ✓ Relativistic GeV+ electrons (protons?) and B distributed on Mpc-scales…

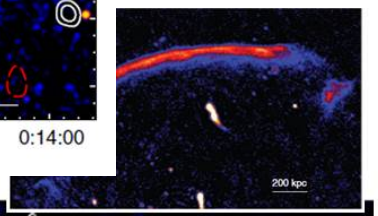
Giant Radio Halos

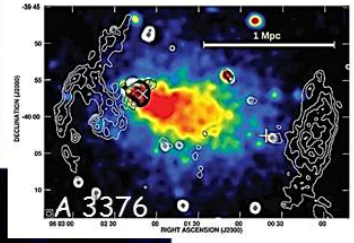


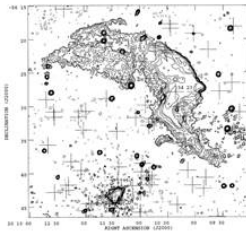


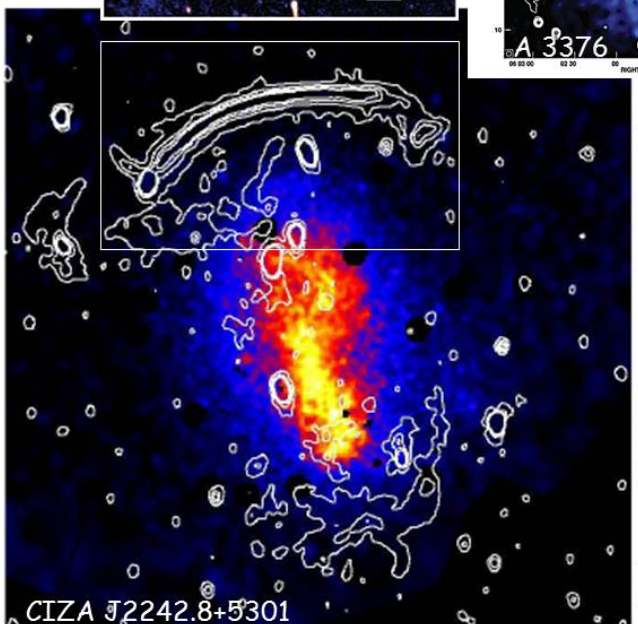


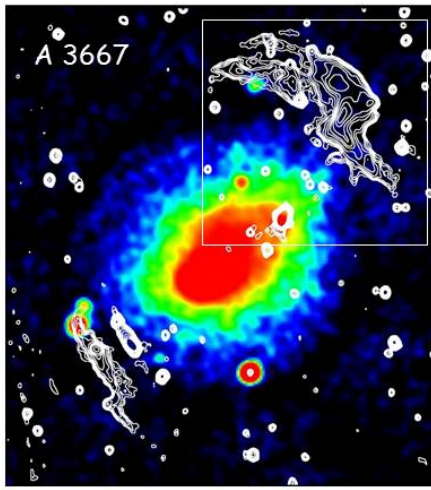
Giant Radio Relics











Syn+IC lifetime of radio electrons

T_{rad}~100-300 Myr << diffusion time

ICM acceleration site !

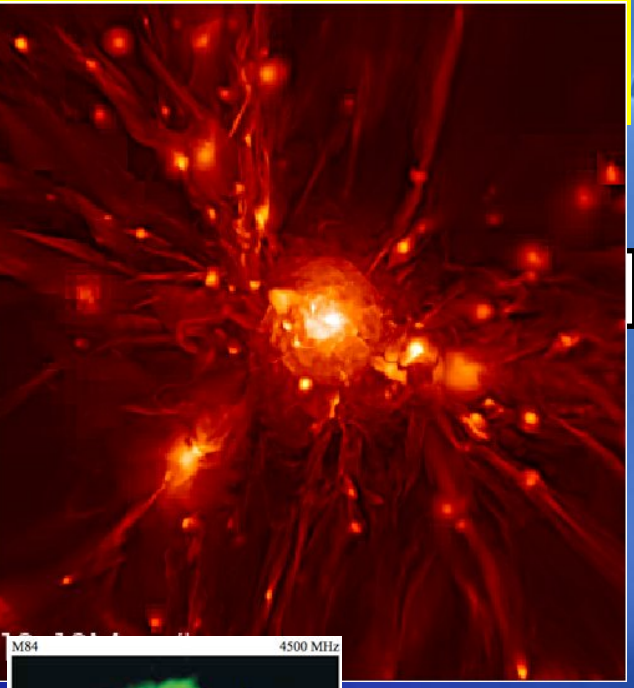
- ➢ ORIGIN & Physics ??
- ➢ IMPACT on thermal ICM ?? (microphysics & dynamics)

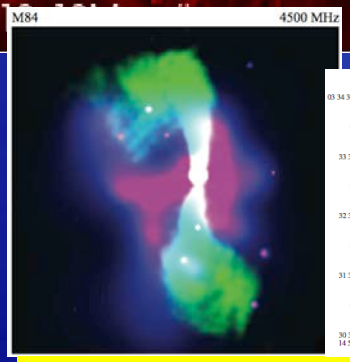
[Brunetti & Jones 14 for rev]

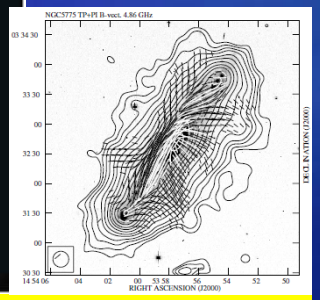
CR-acceleration

(eg Brunetti + Jones 14)

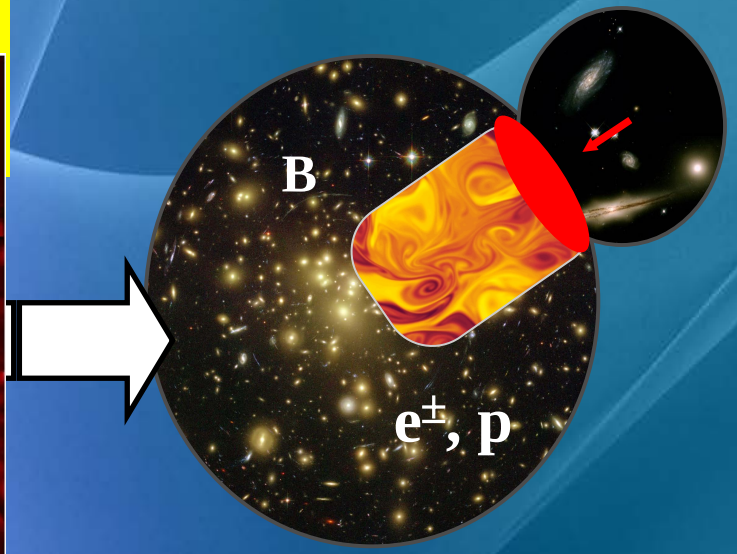
Mergers guide CRe acceleration/dynamics and/or amplify B

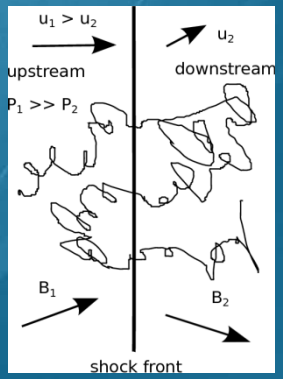






Astrophysical sources
Galaxies (SN), AGN..





(1)

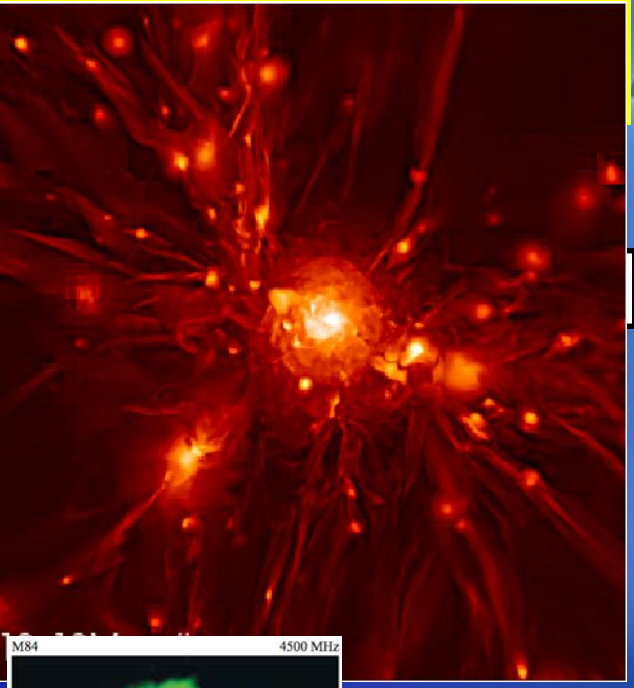
SHOCKS

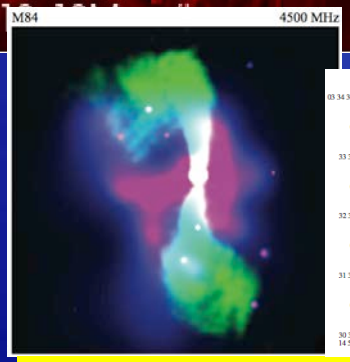
accelerate CRe±,CRp

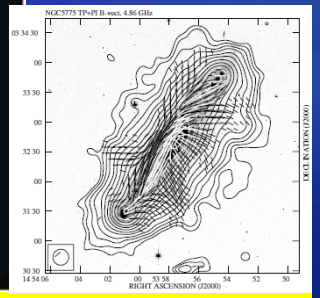
CR-acceleration

(eg Brunetti + Jones 14)

Mergers guide CRe acceleration/dynamics and/or amplify B







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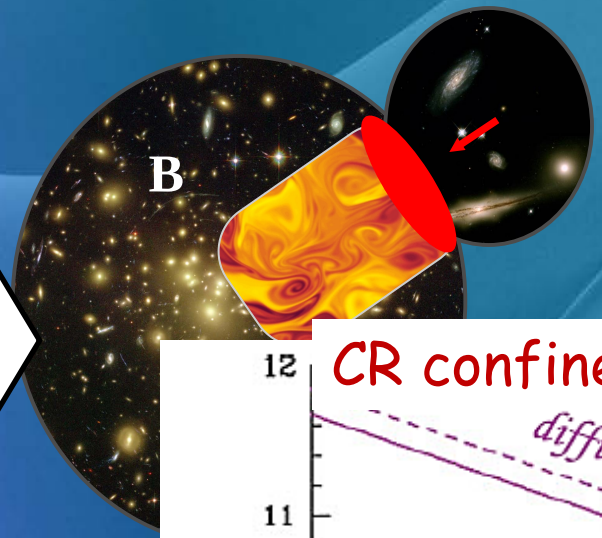
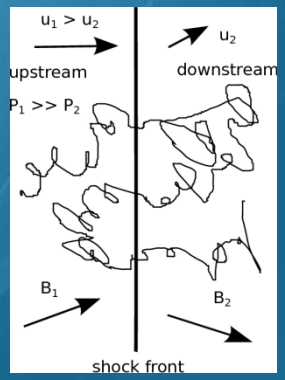


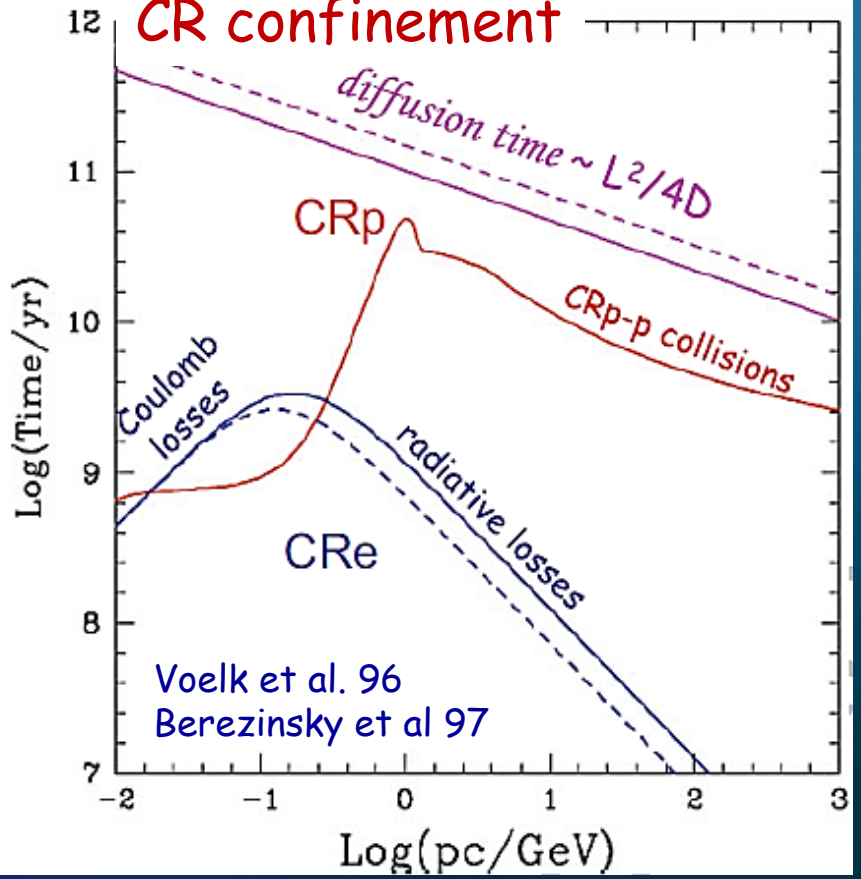


(1)

SHOCKS

accelerate $CRe^{\pm}$, CRp

CR confinement



Brunetti & Jones 2014

CR-acceleration

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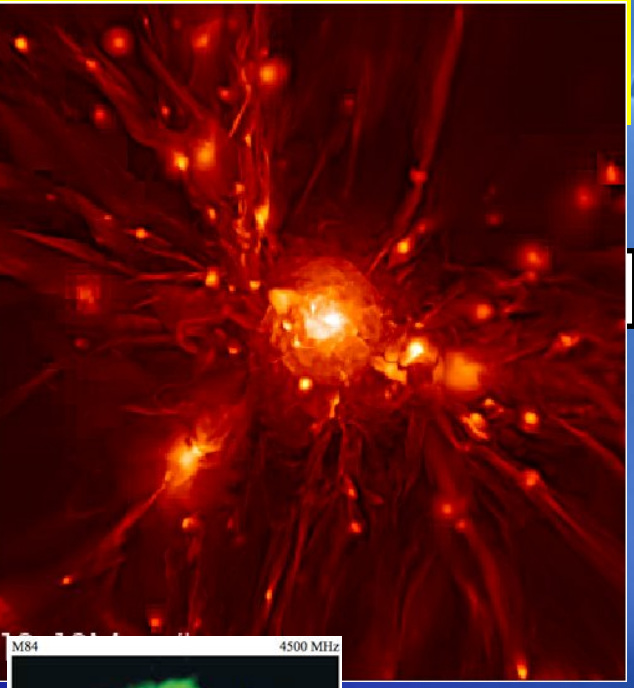

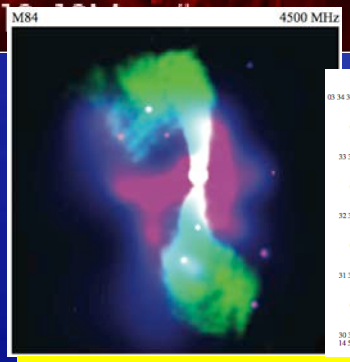

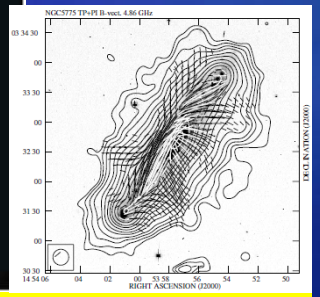

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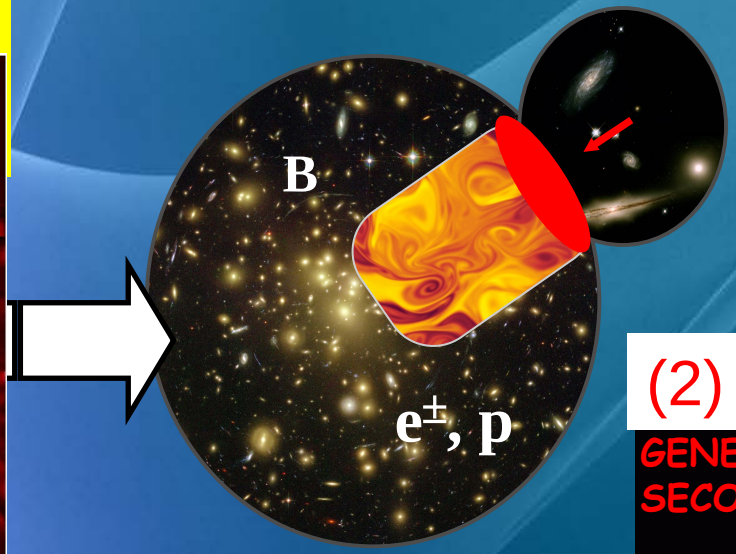

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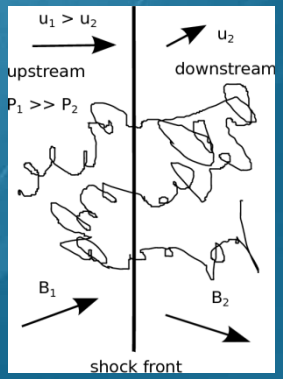
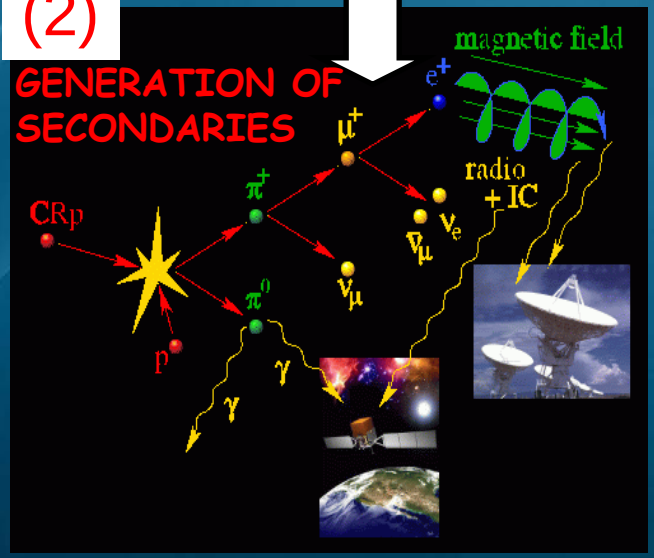


SHOCKS

accelerate CRe±,CRp

(2)



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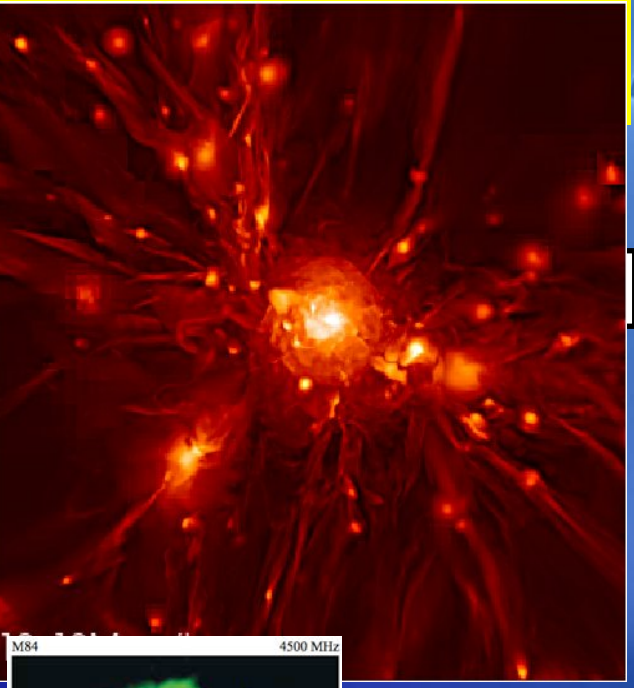

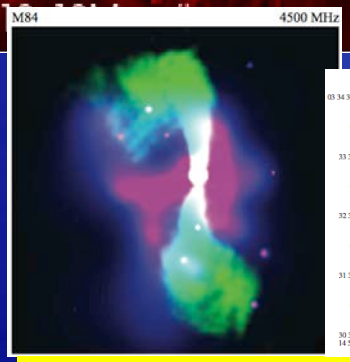

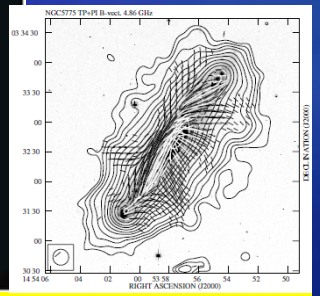

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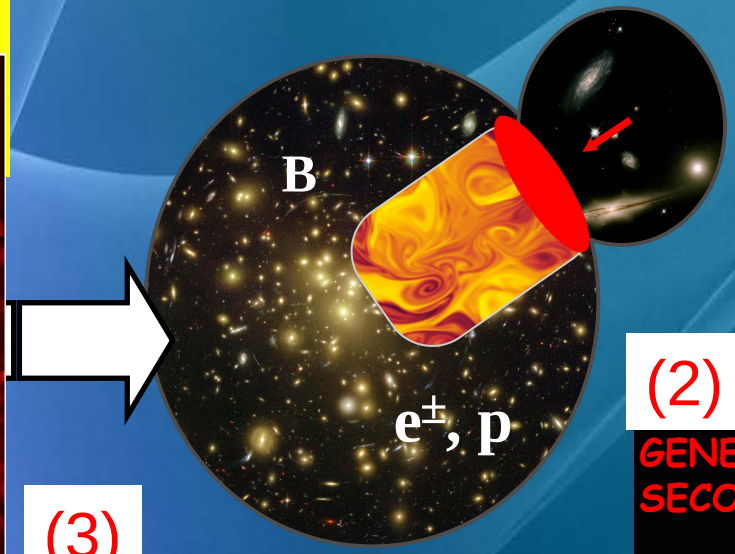

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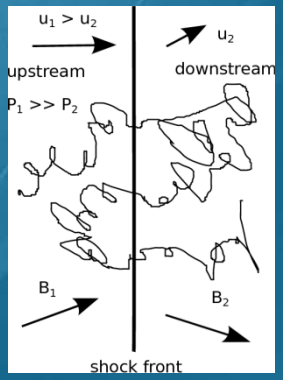

SHOCKS

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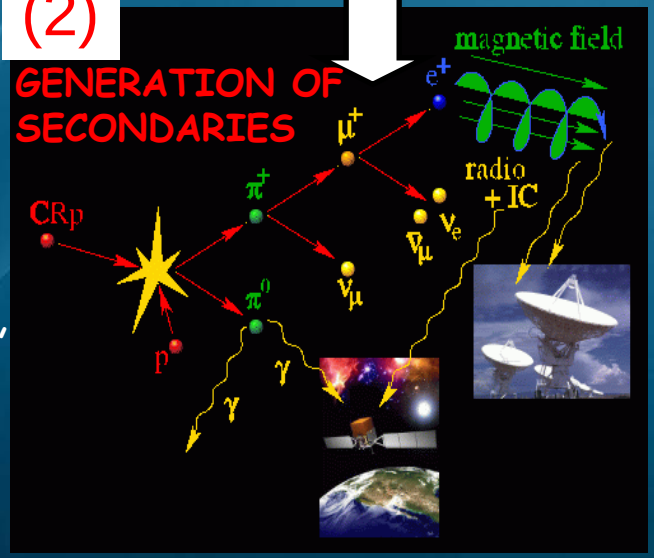
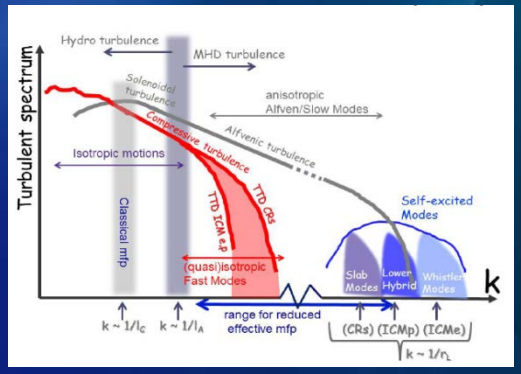
(2)



(3)

TURBULENCE

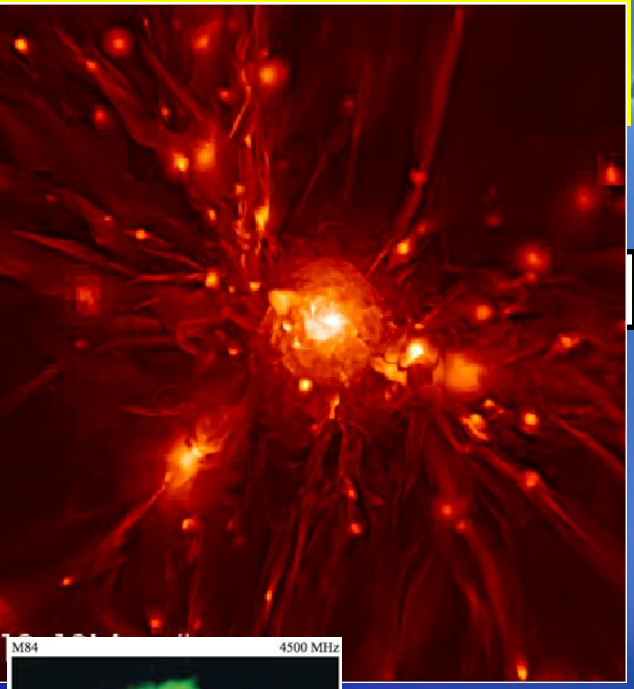
reaccelerates fossil CRe± , CRp and secondaries CRe±

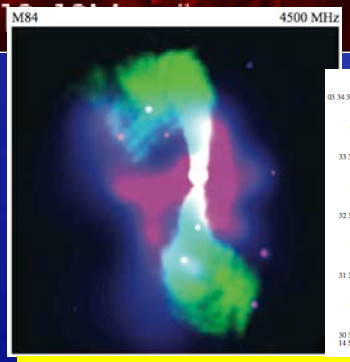


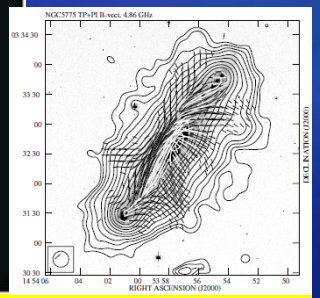
CR-acceleration

(eg Brunetti + Jones 14)

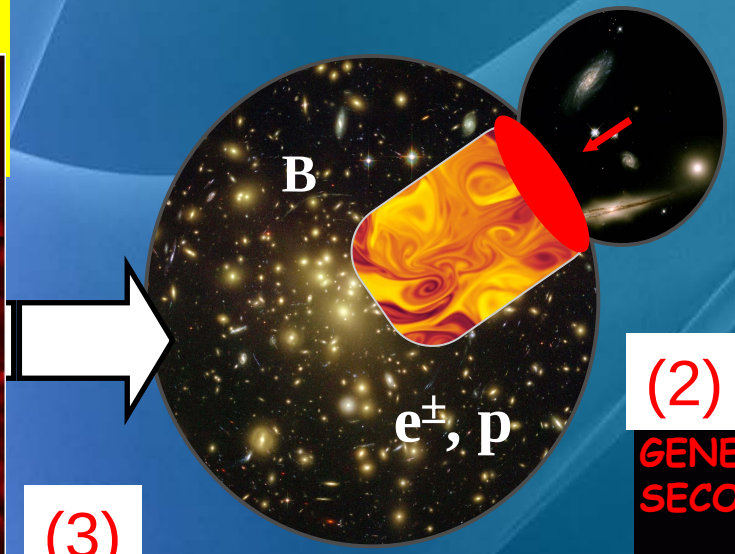
Mergers guide CRe acceleration/dynamics and/or amplify B







Astrophysical sources
Galaxies (SN), AGN..



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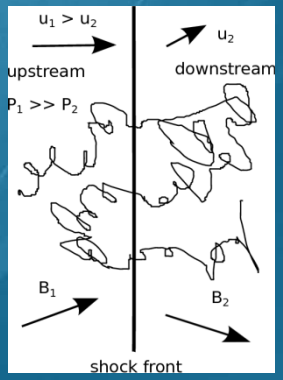
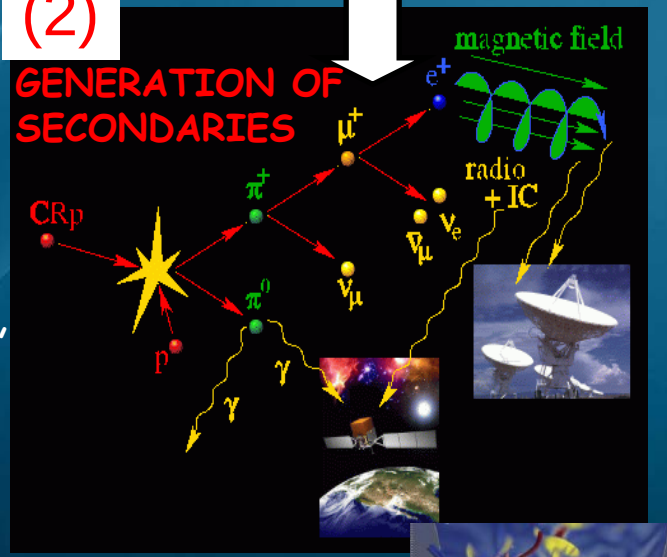


SHOCKS

accelerate CRe±,CRp

(2)



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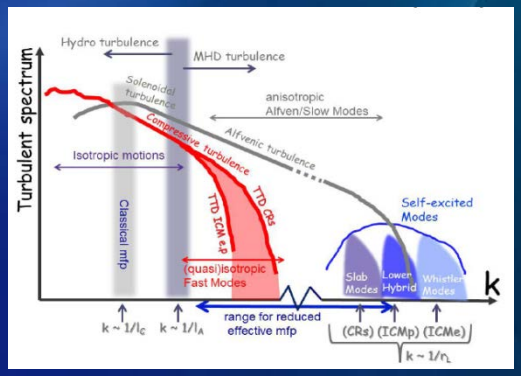
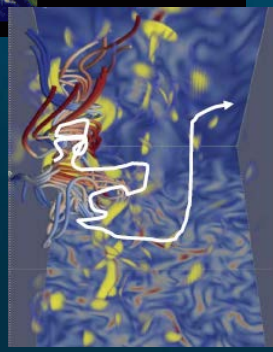


(4)

MAGNETIC RECONNECTION

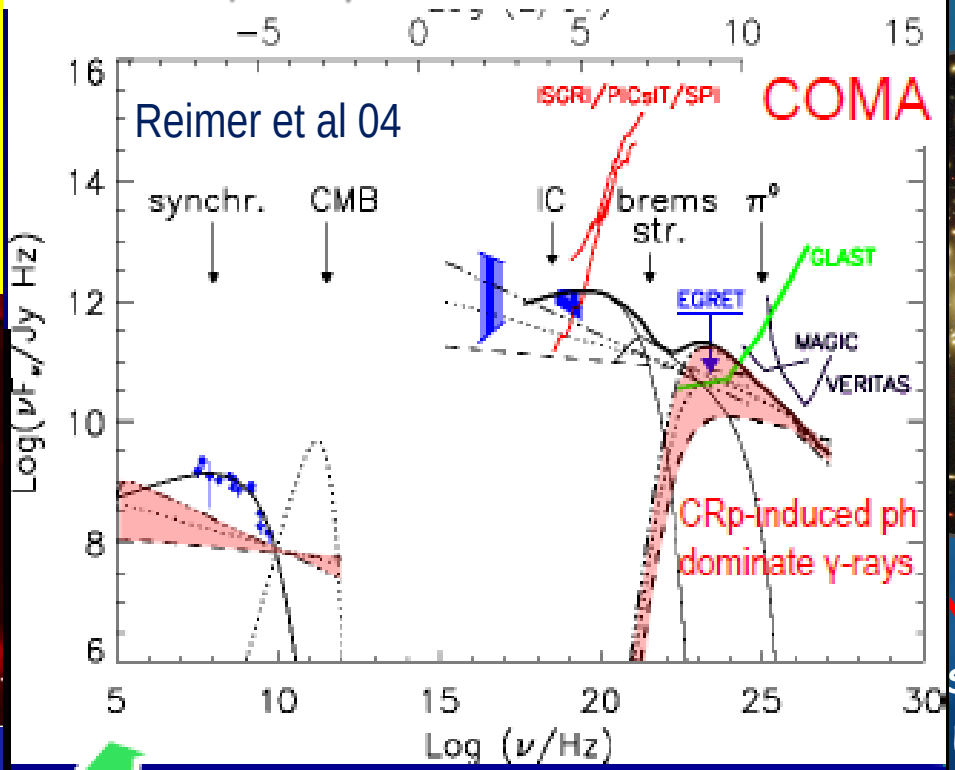


CR-acceleration

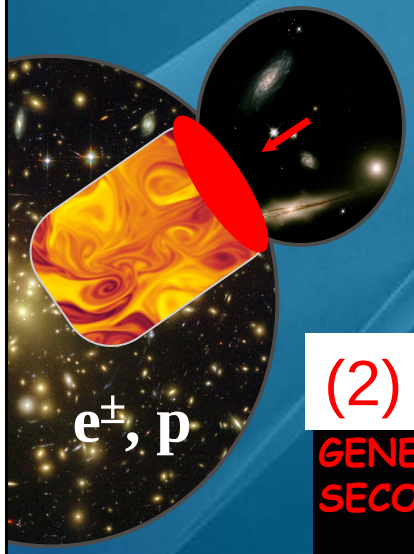
(eg. Brunetti + Jones 14)

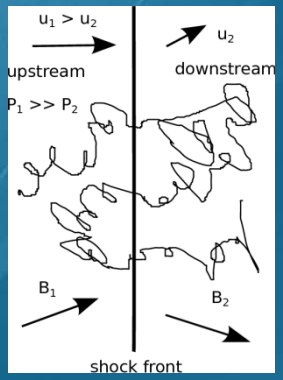
Mergers guide CRe acceleration/dynamics

Multifrequency emission + neutrino



Miniati et al 01, Brunetti & Blasi 05, Blasi et al 07, Pfrommer et al 08, Brunetti & Lazarian 11





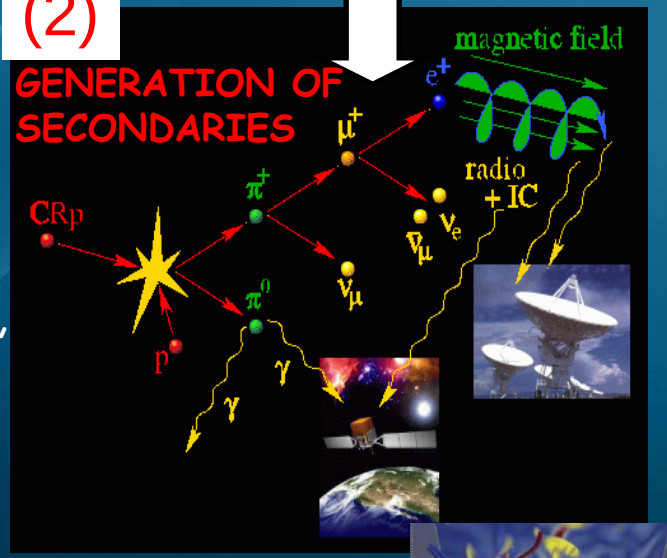
(1)

SHOCKS

accelerate CRe±,CRp

(2)

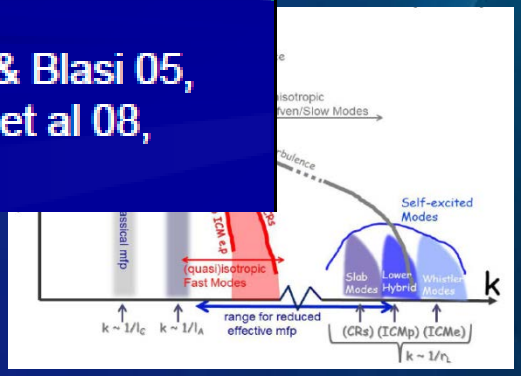
GENERATION OF SECONDARIES



NCE

s fossil CRe± ,

ndaries CRe±



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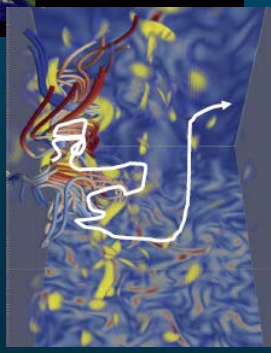
MAGNETIC RECONNECTION



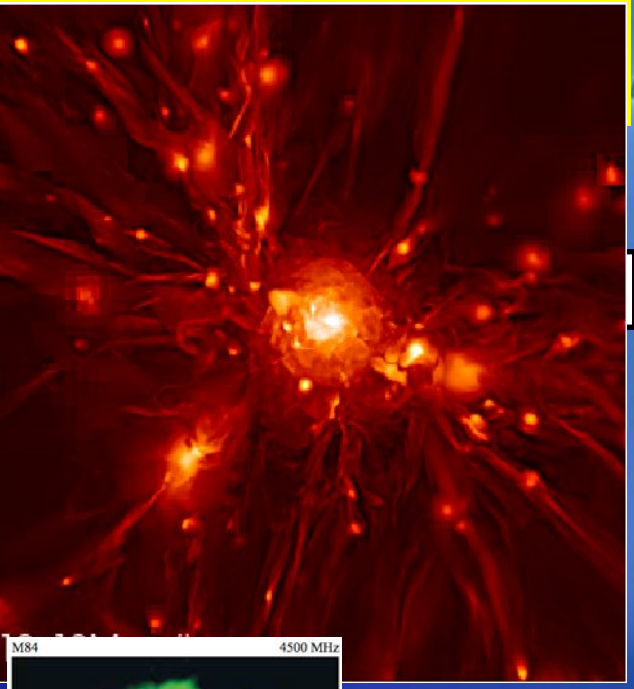
Astrophysical sources

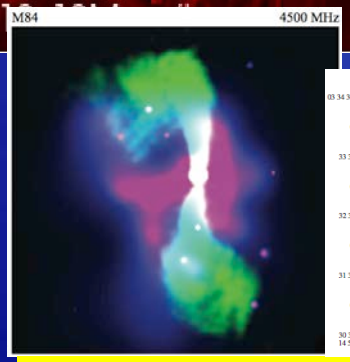
Galaxies (SN), AGN..

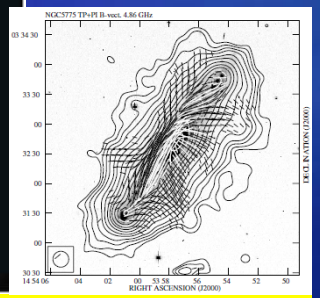
CR-accelerati

(eg Brunetti + Jones 14)

Mergers guide CRe acceleration/dynamics and/or amplify B







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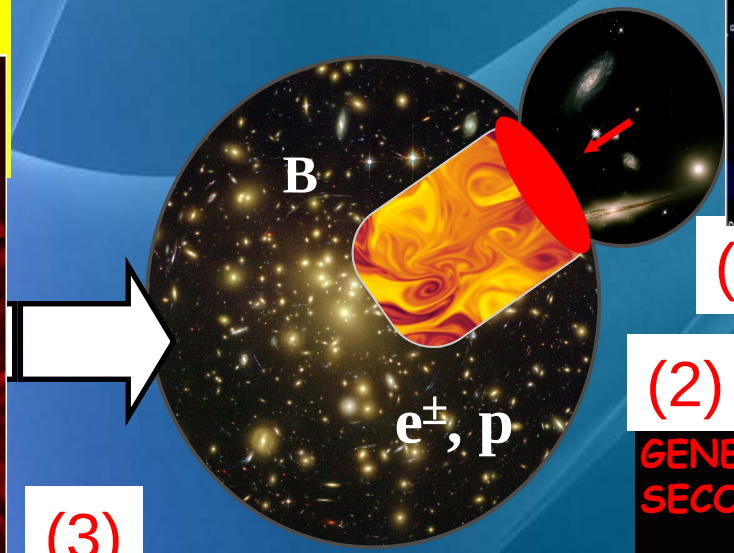
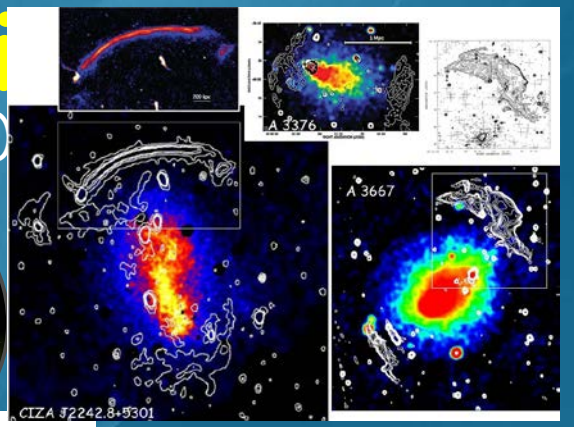
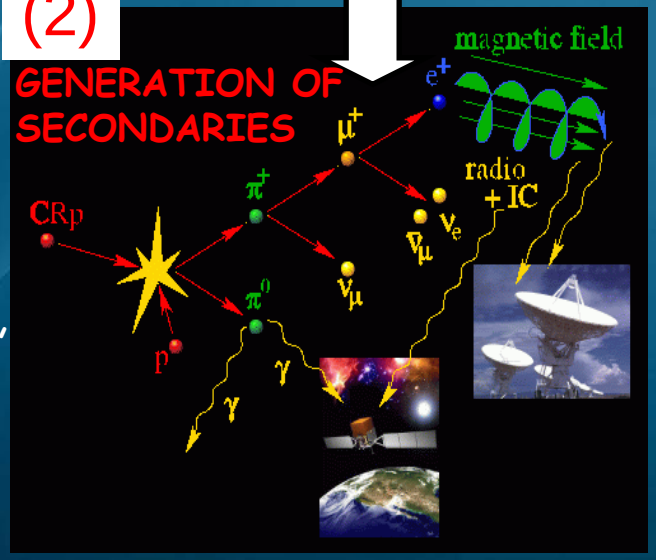




(1) SHOCKS

accelerate CRe±,CRp

(2)



(3)

TURBULENCE

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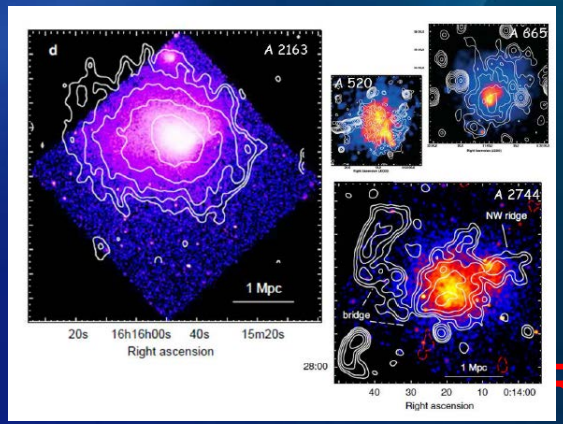
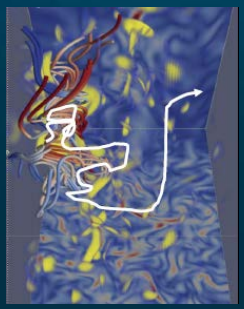


(4)

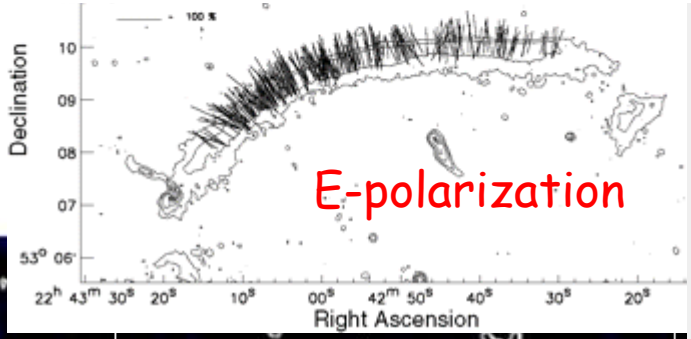
MAGNETIC RECONNECTION

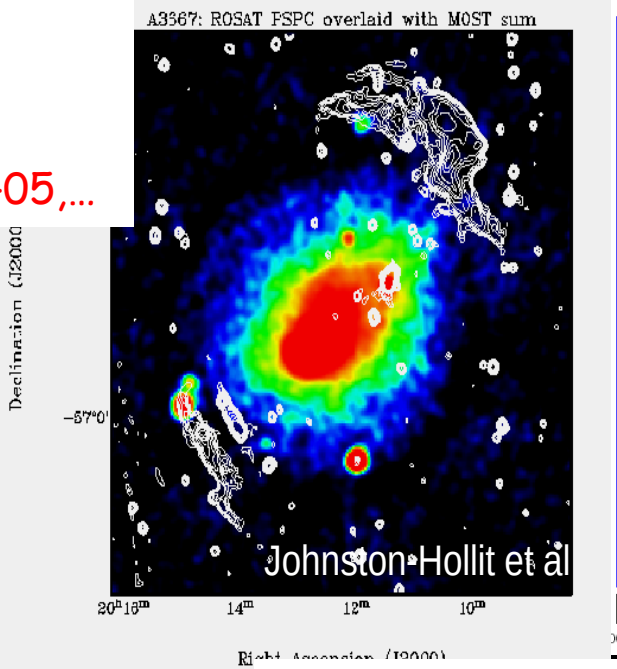


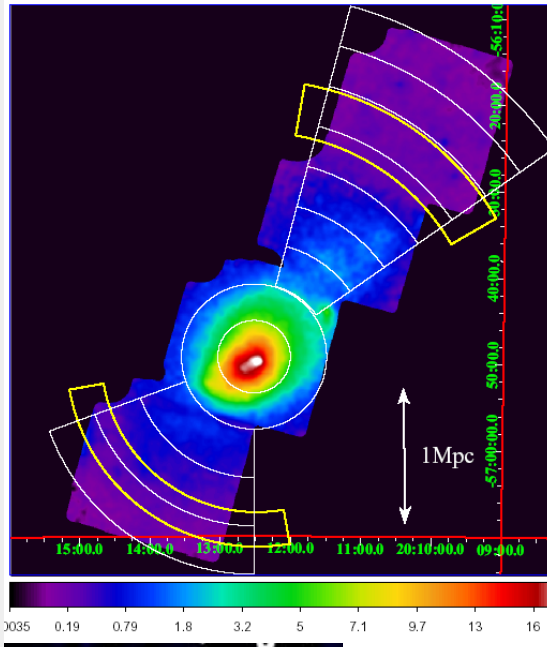
Giant Radio Relics

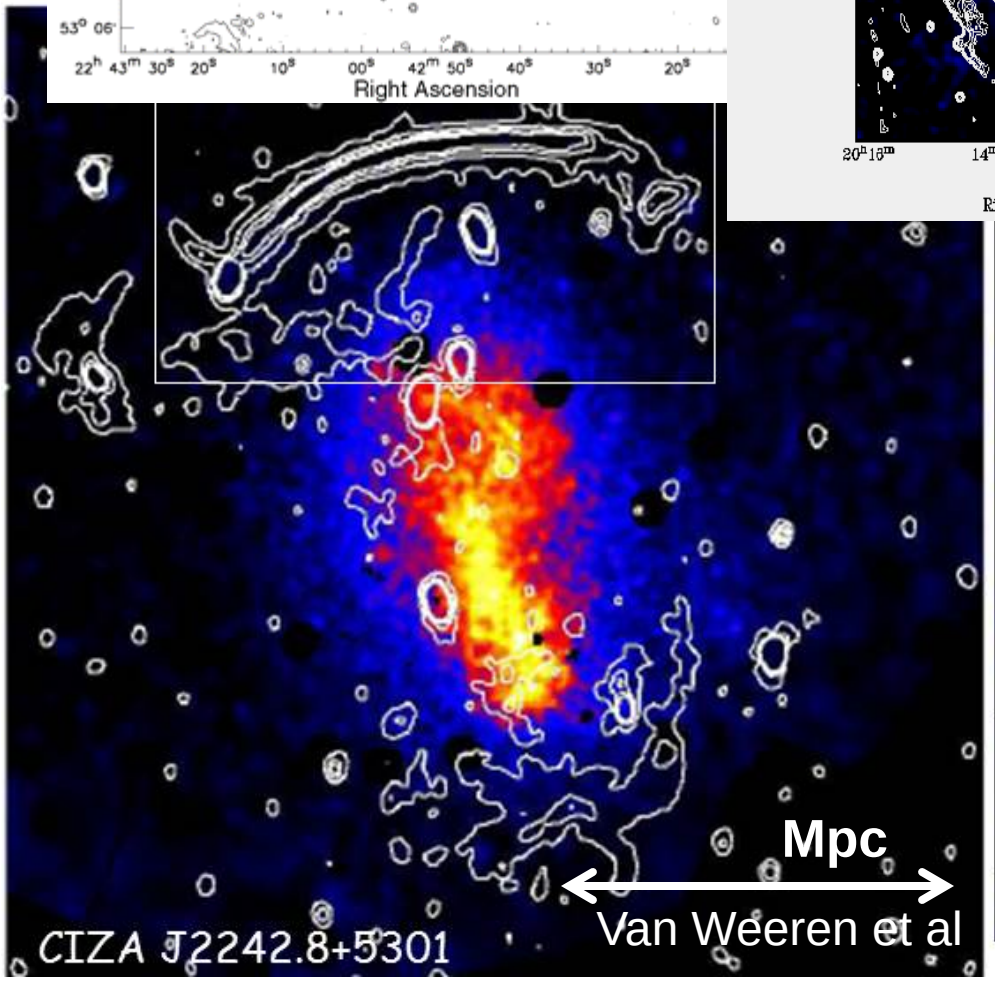
- shock connection -

Ensslin+98,Roettiger+99,Markevitch+05,...

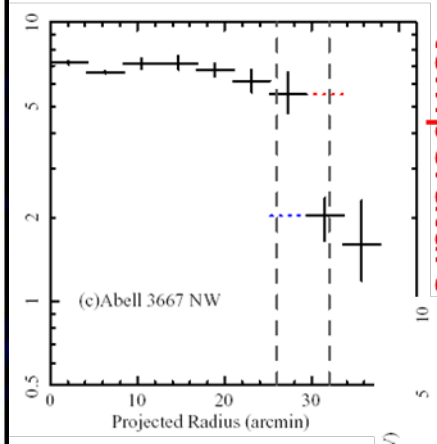






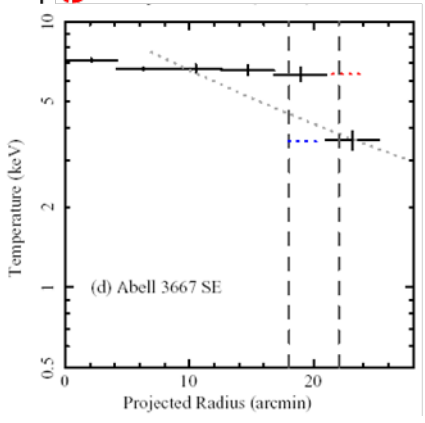


Akamatsu & Kawahara 12



temperature

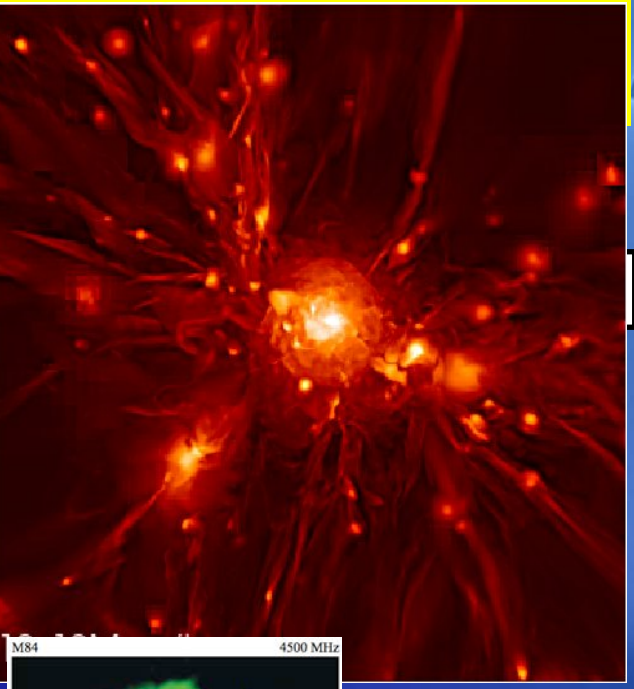
Mach=2 - 4

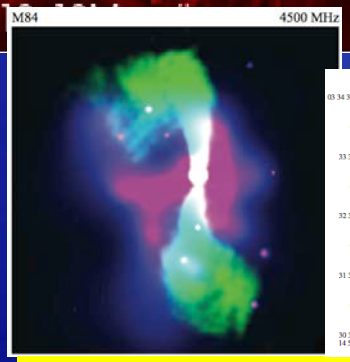


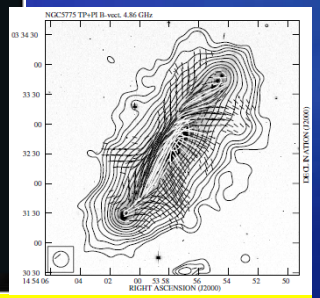
CR-accelerati

(eg Brunetti + Jones 14)

Mergers guide CRe acceleration/dynamics and/or amplify B







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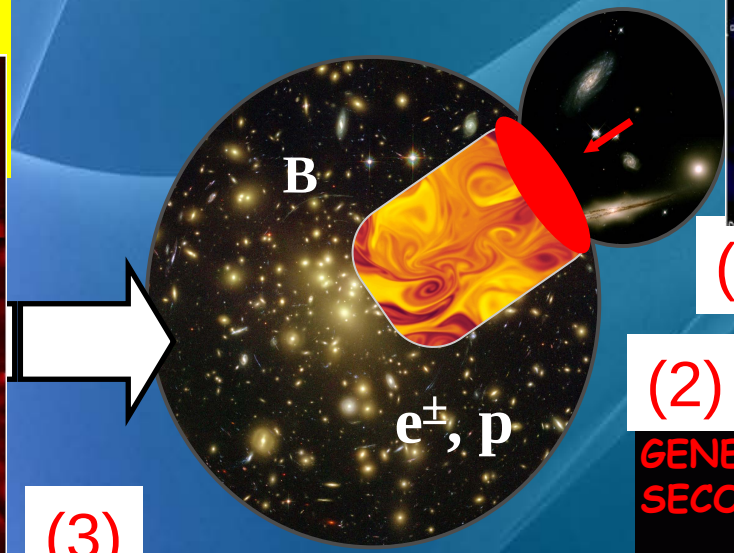

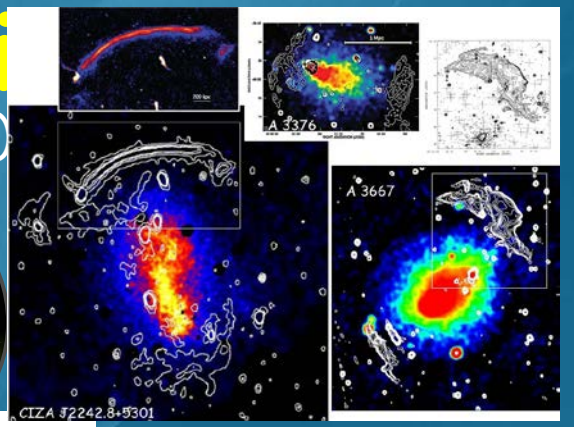

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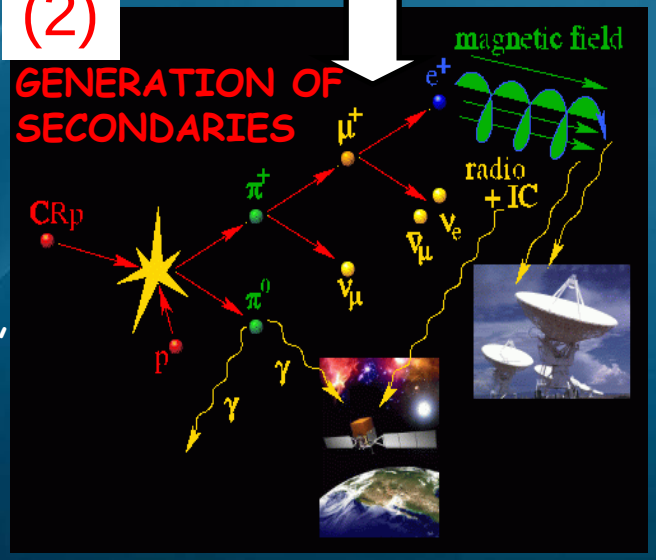

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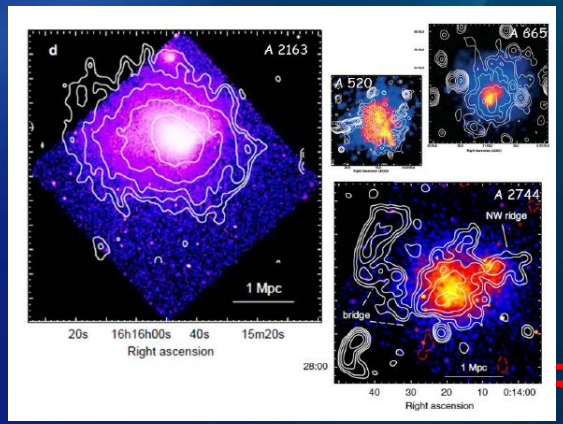

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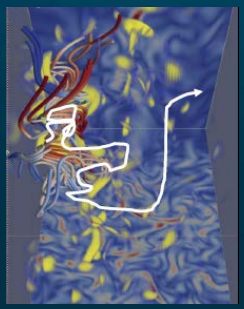
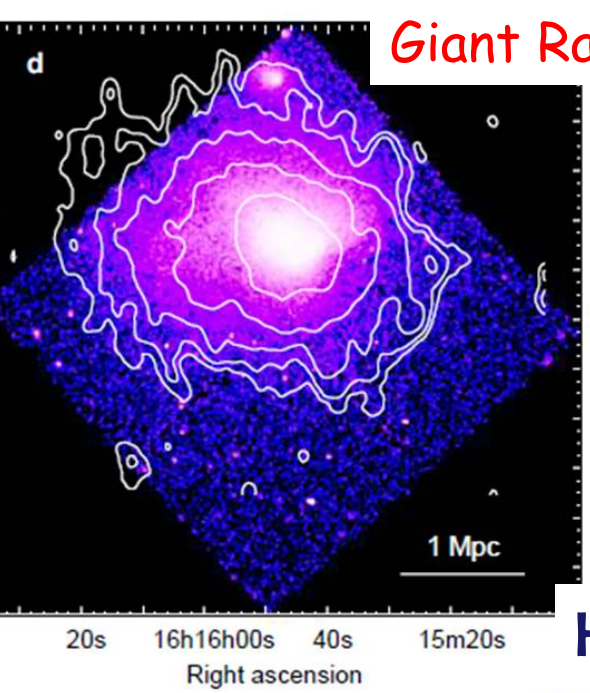
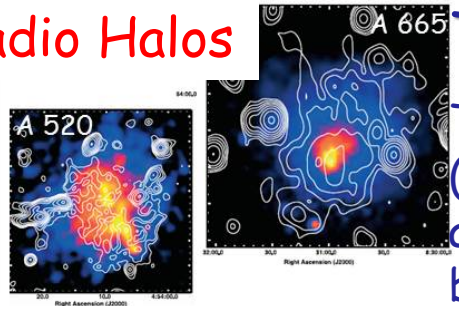


Giant Radio Halos





Turbulent acceleration scenario:

Turbulence is generated during mergers (shocks, DM sloshing, instabilities etc) and powers reacceleration mechanisms based on second-order Fermi

Brunetti+01, Petrosian 01, Ohno+02, Fujita+03, Cassano+Brunetti 05, Brunetti+Lazarian 07,Brunetti+Lazarian 11, Beresnyak+al 13, Miniati 15, Brunetti+Lazarian 16, Pinzke+al 17…]

Halos – Mergers connection

Manifestation of complex microphysics in the ICM:

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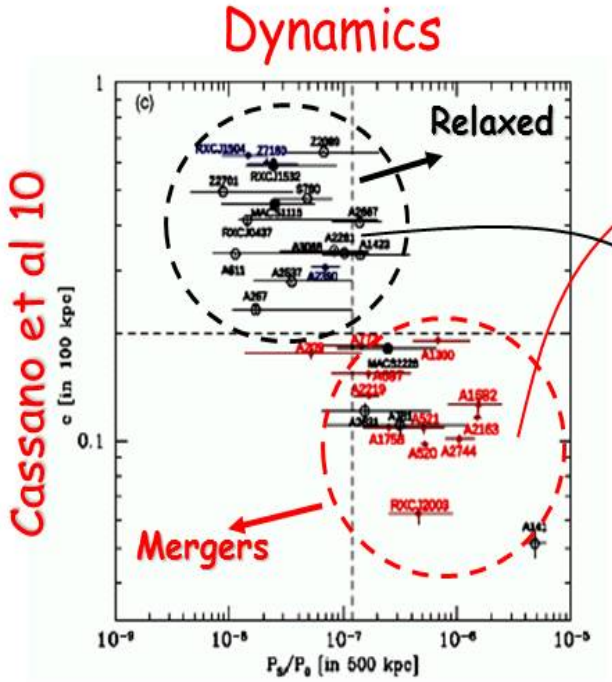
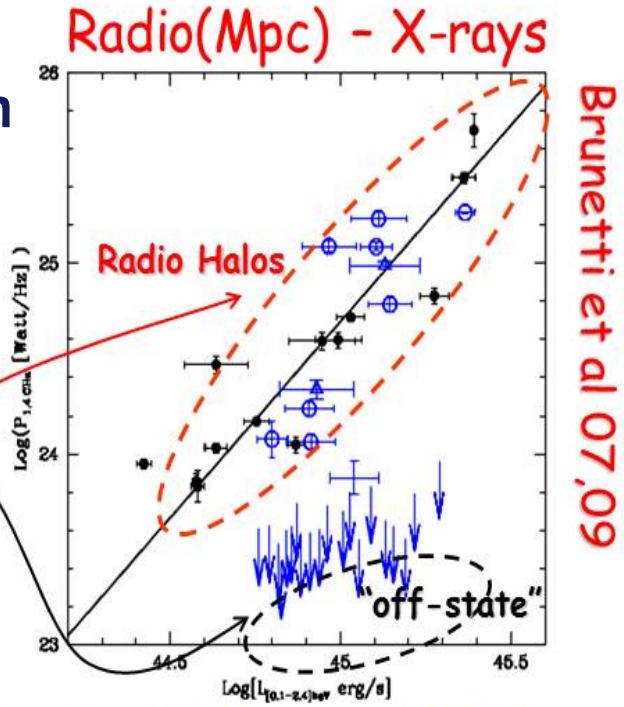
This requires a hierarchy of complex mechanisms and plasma/kinetic effects!

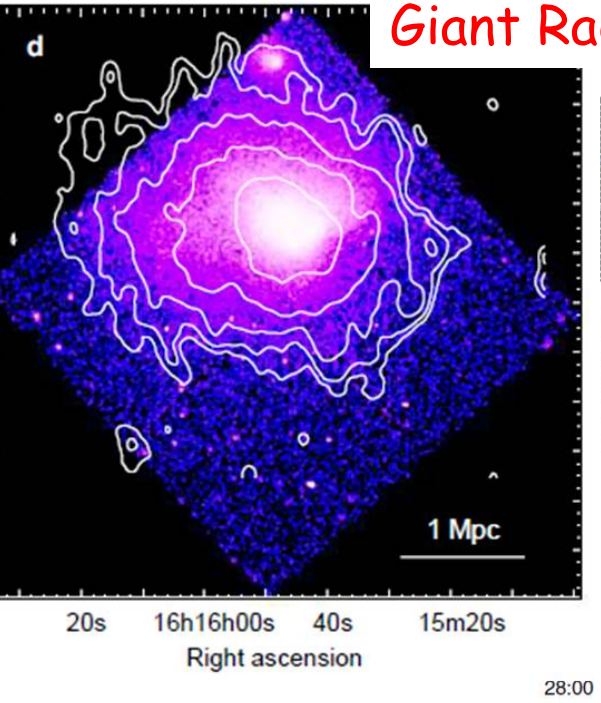
[eg Brunetti+Jones 14 rev]

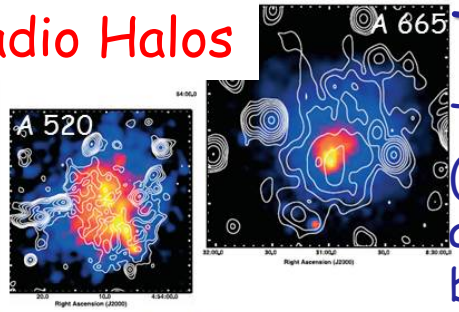




Venturi et al 08, Cassano et al 10,13,16, Brown et al 11, Rossetti et al 11, Basu 12, Sommer+Basu 14, Kale et al 15, Yuan et al 15, Cuciti et al 15, Sommer+17

Giant Radio Halos





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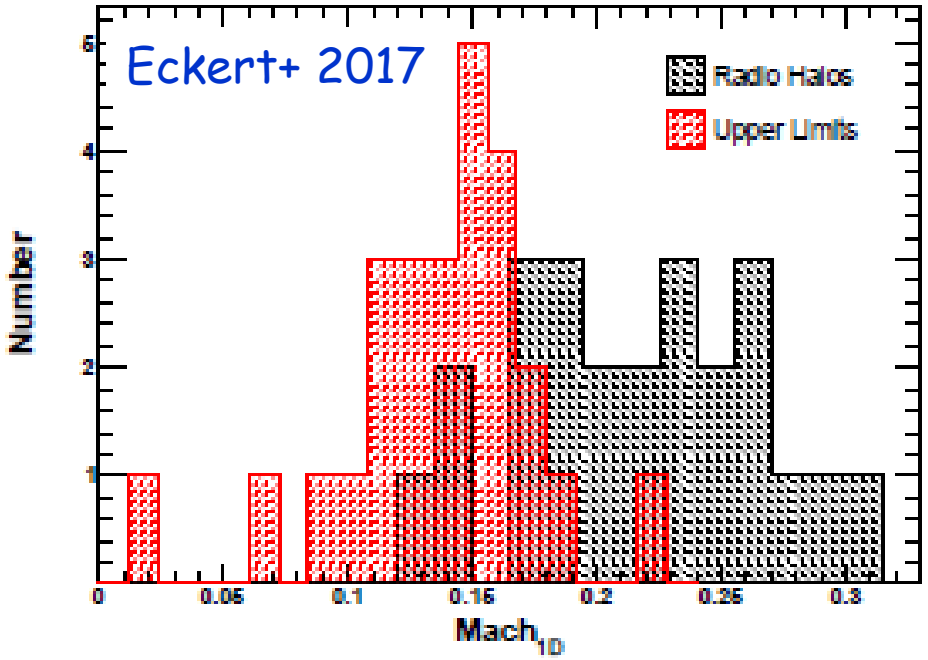
Halos – Turbulent Mach number connection?



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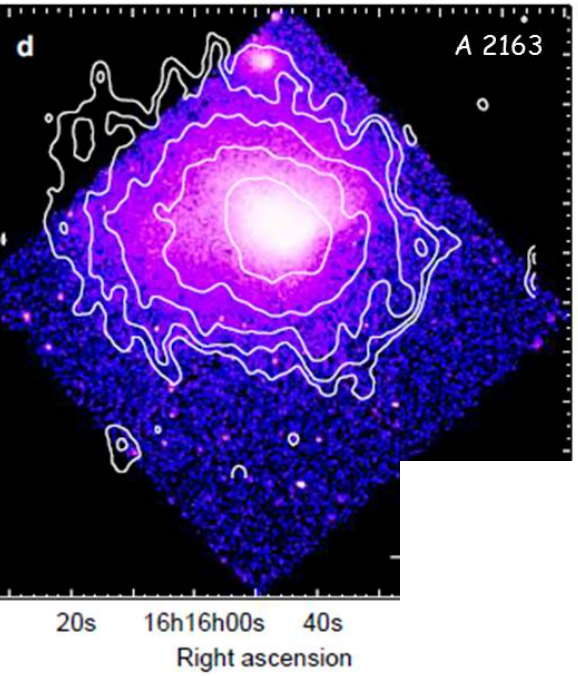

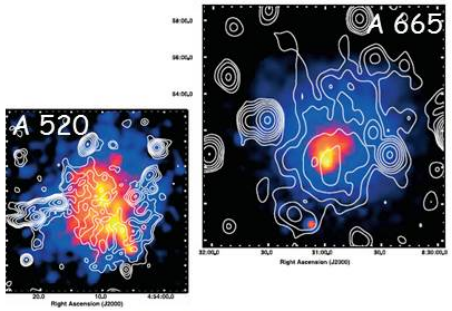

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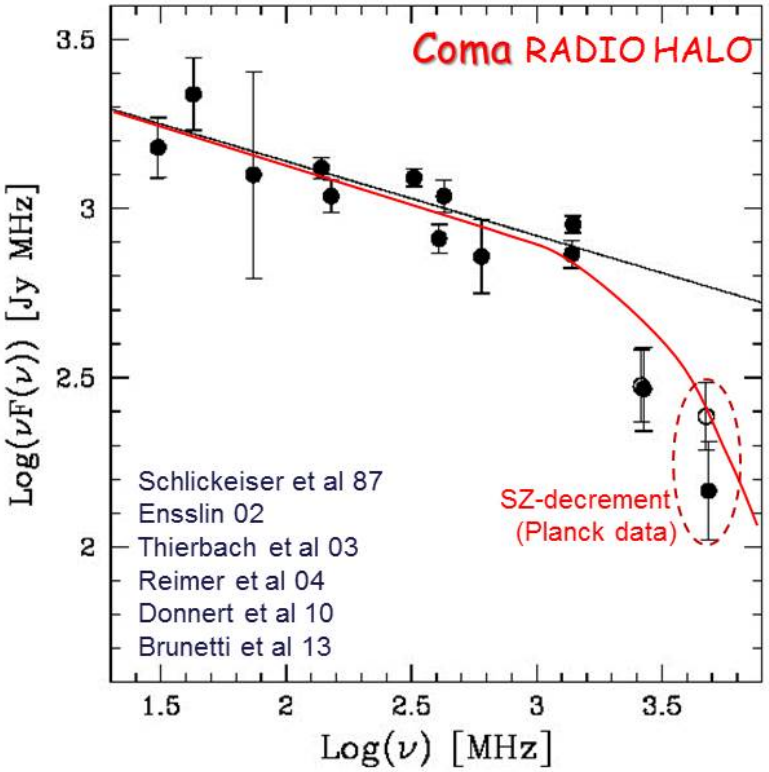
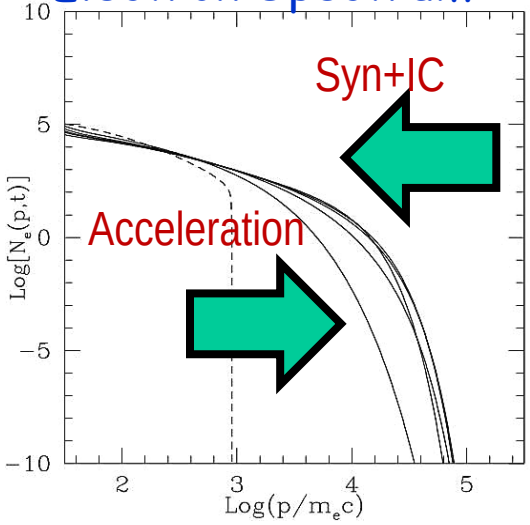
Synchrotron Spectrum



Electron Spectrum



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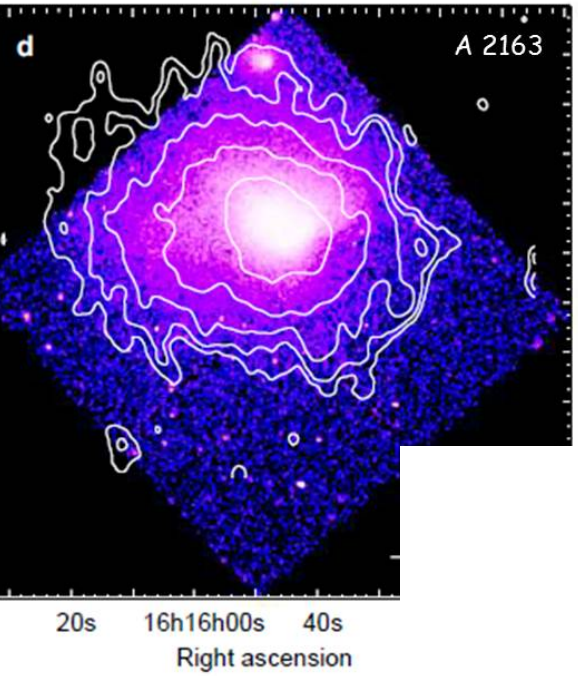
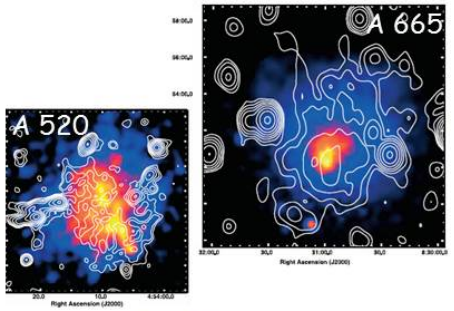
$T_{acc} \sim T_{rad}(GeV+)$ =100-300 Myr





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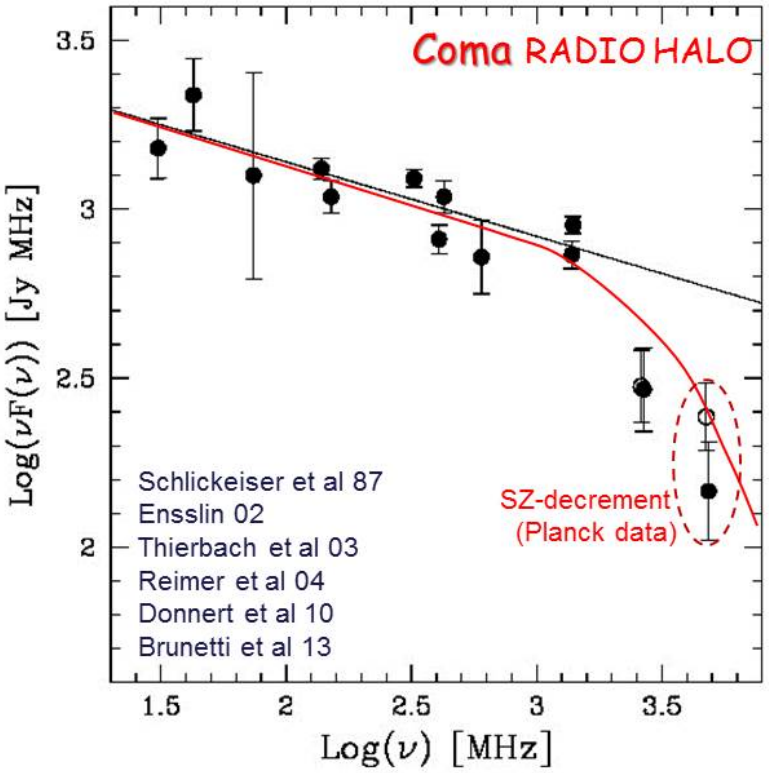

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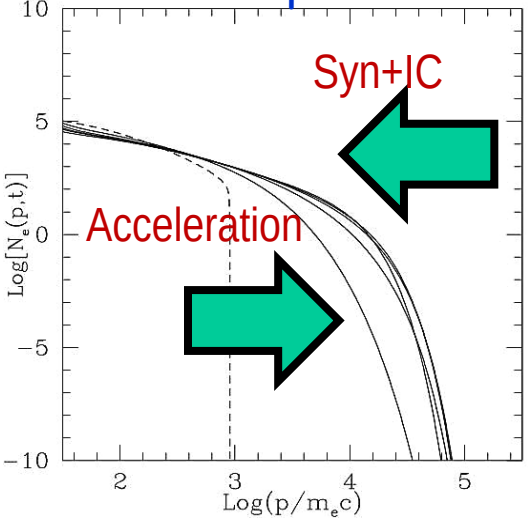

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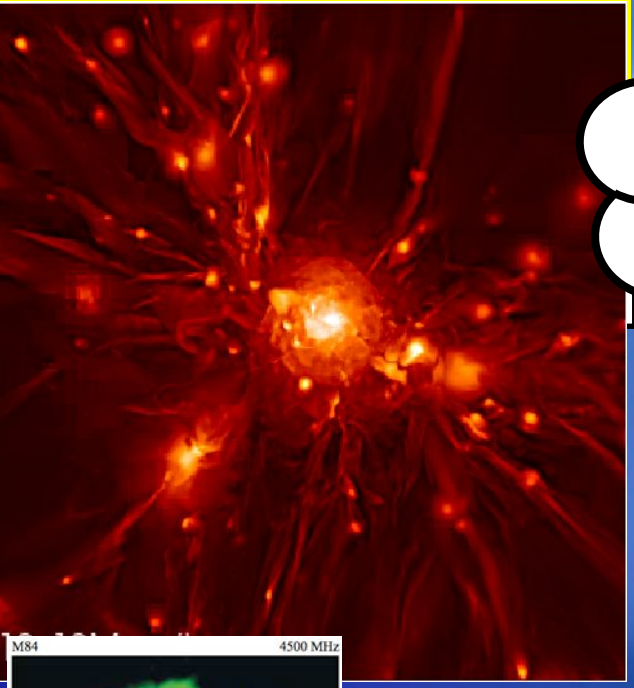
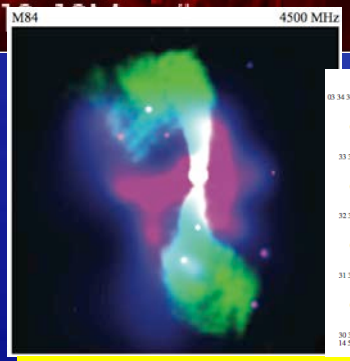
LOFAR + MWA are unveiling many examples of gentle reacceleration in the ICM

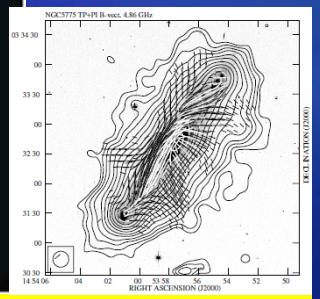
CR-accelerati

(eg Brunetti + Jones 14)

Mergers guide CRe acceleration/dynamics and/or amplify B



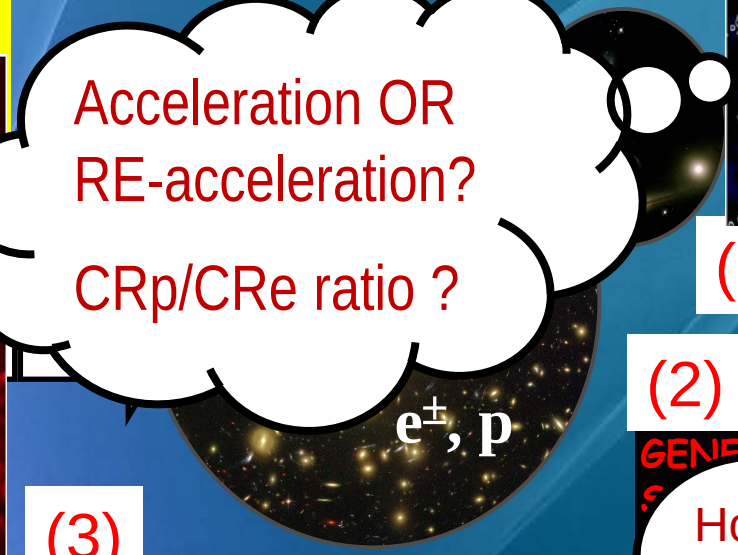


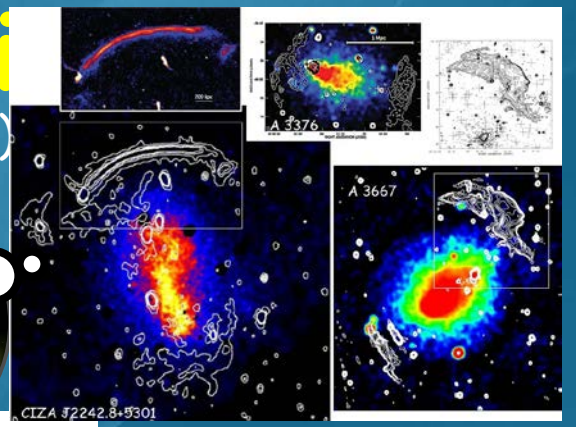


Astrophysical sources
Galaxies (SN), AGN..

Acceleration OR
RE-acceleration?

CRp/CRe ratio ?





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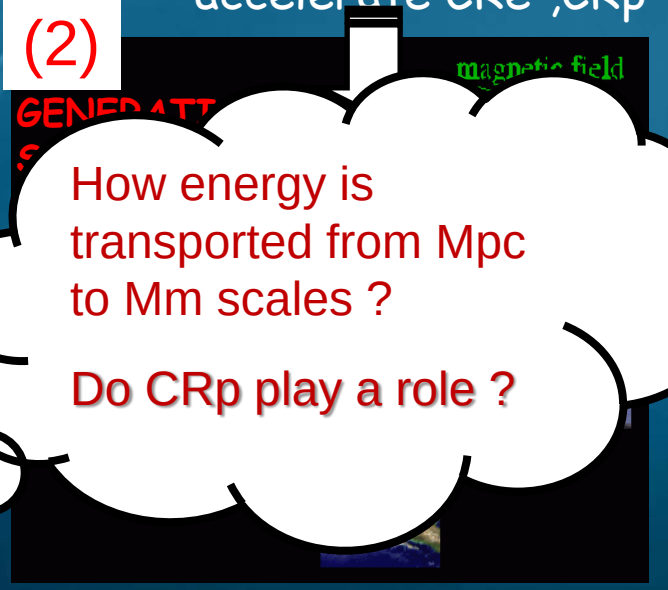

How energy is transported from Mpc to Mm scales ?

Do CRp play a role ?

(3)

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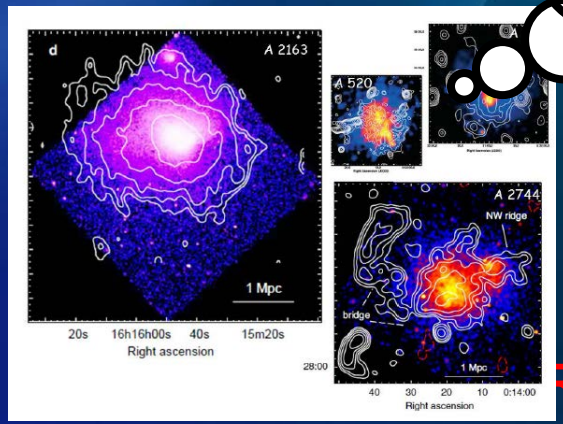
CRp and secondaries CRe



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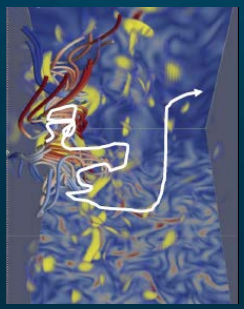
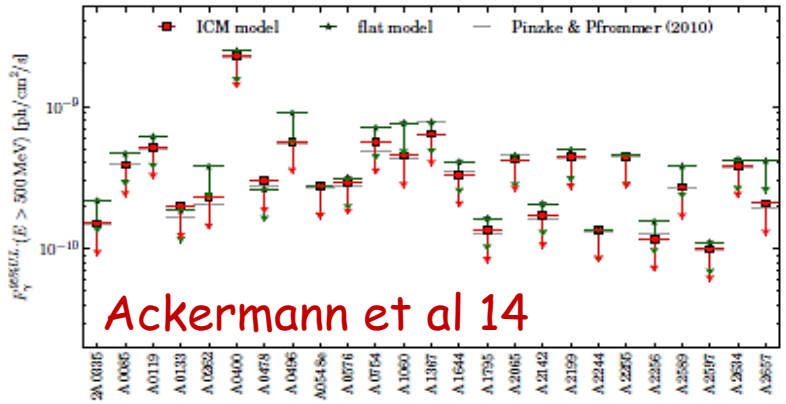
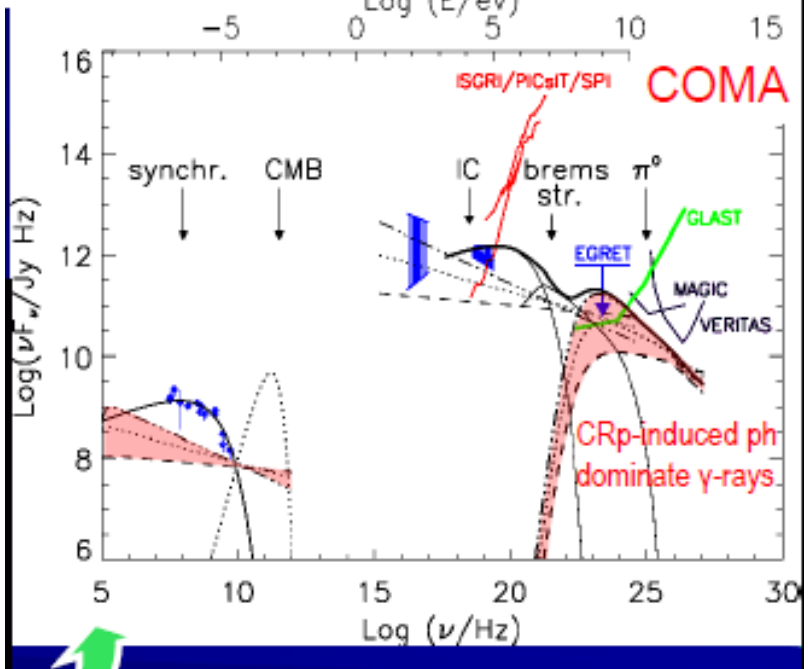


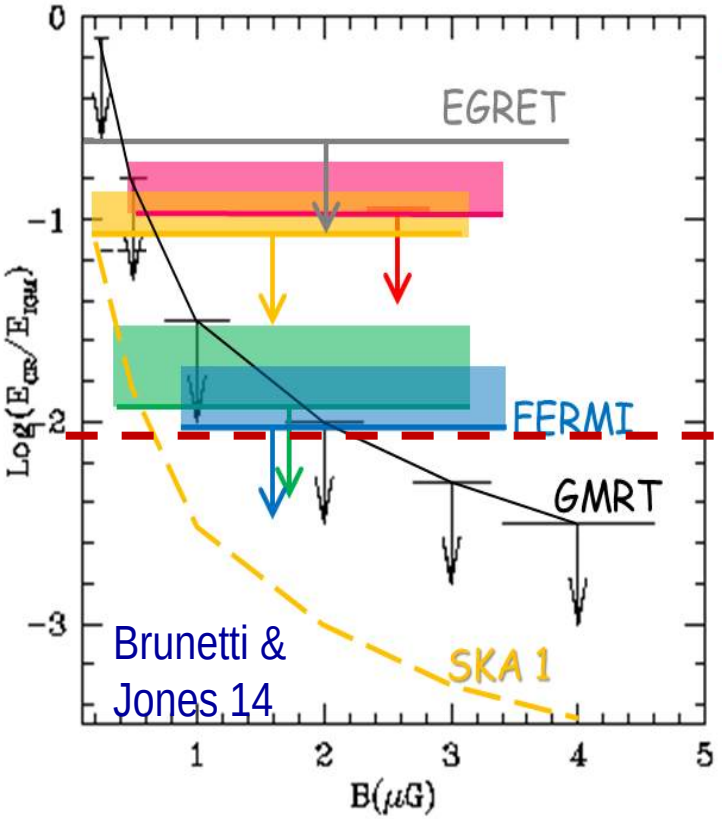
No gamma-rays : Where are the CRp ?
Limits to their energy budget



Reimer et al 04



$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$
$$\pi^0 \rightarrow \gamma\gamma$$
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu), \quad \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e).$$

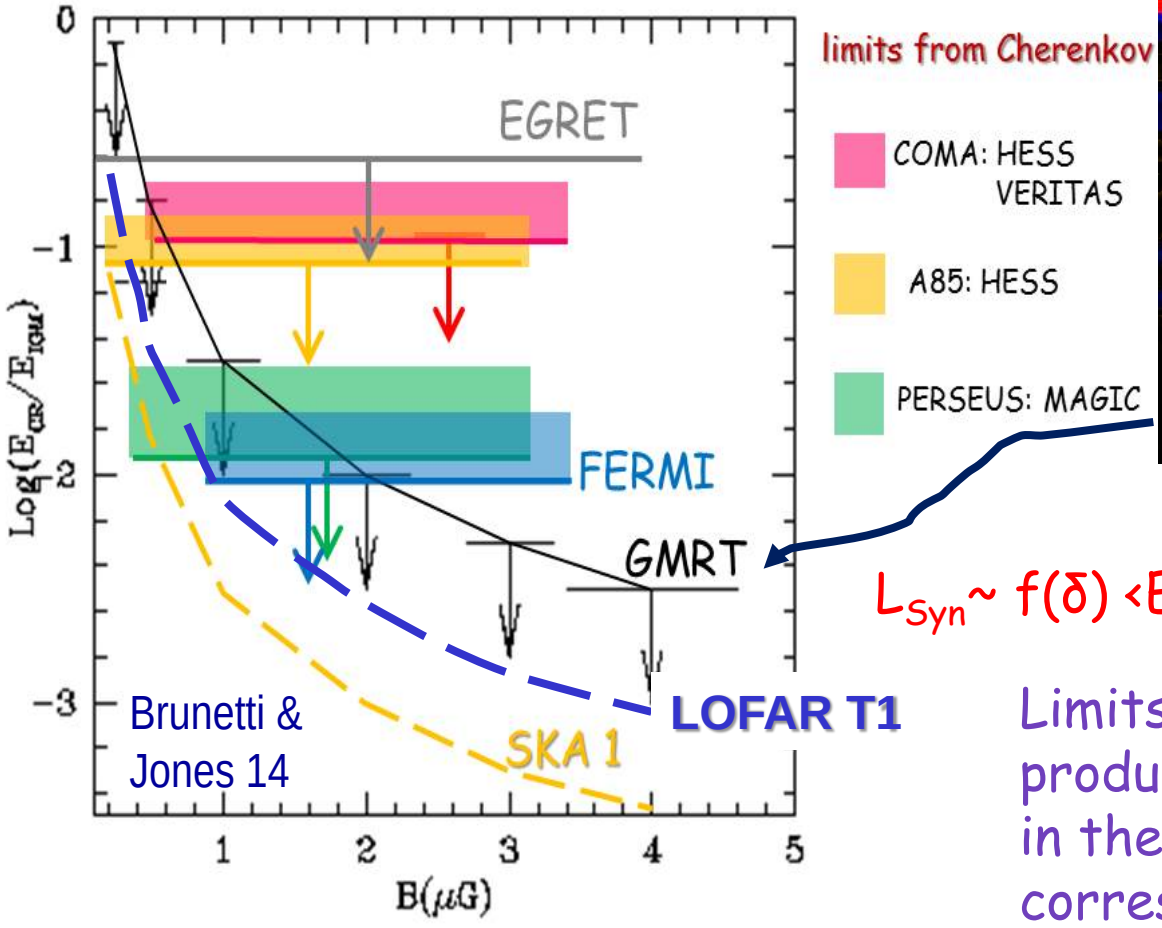


limits from Cherenkov

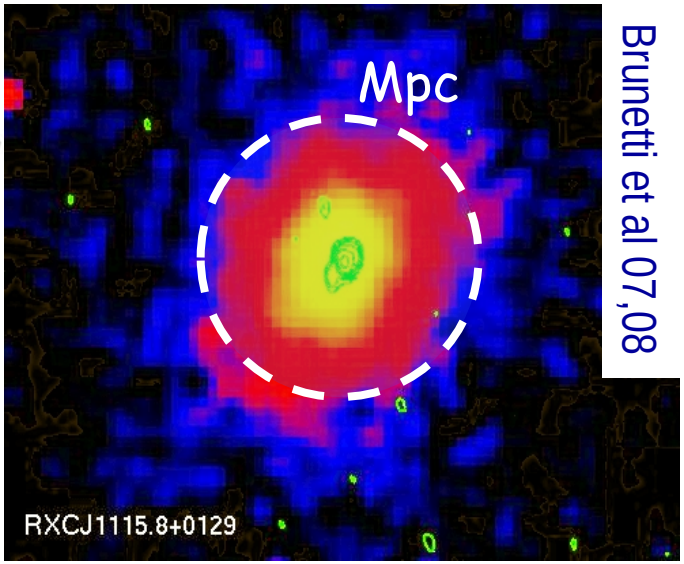
- COMA: HESS VERITAS
- A85: HESS
- PERSEUS: MAGIC

< 1%

Where are the CRp ?
Limits to their energy budget



Syn radio limits :



$L_{Syn} \sim f(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle V_{Syn} B^2/(B^2+B_{IC}^2)$

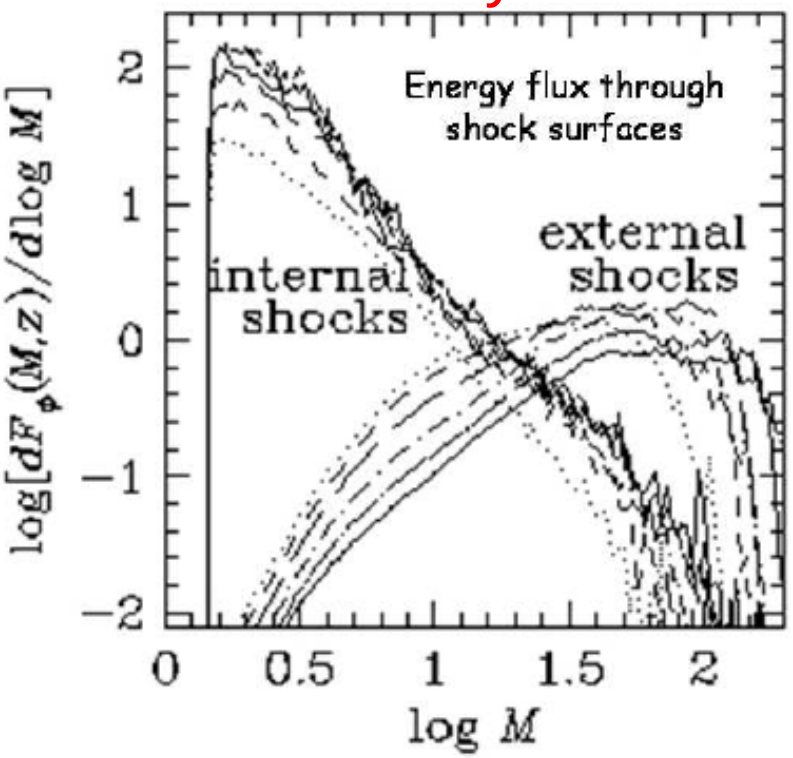
Limits on the synchrotron flux produced by secondary electrons in the ICM allow to calculate corresponding limits on (B, ECRp).

Reimer et al. 04, Pfrommer & Ensslin 04,Perkins et al. 06, 08, Brunetti et al. 07,08, Aharonian et al. 09, Aleksic et al. 09,12, Ackermann et al 10,14, Arlen et al 12, Griffin et al 14, Zandanel & Ando 14, Prokhorov & Churazov 14, Vazza et al 15, Ahnen et al 16, ...

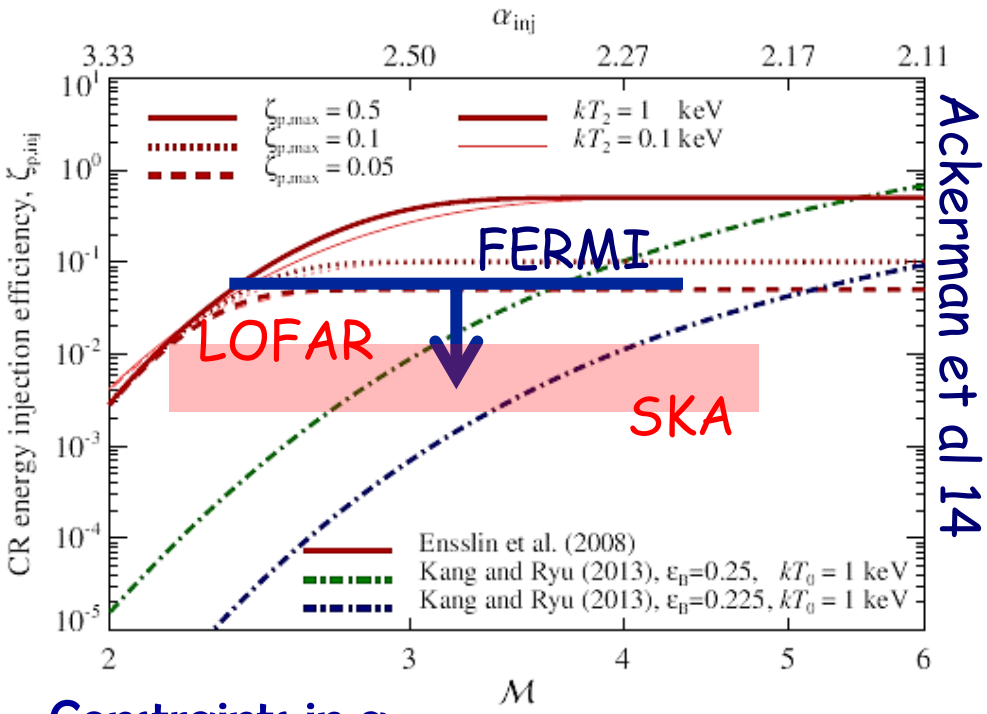
Constraining CRp acc efficiency +dynamics

Acceleration efficiency + confinemnet set the level of energy accumulated in CRp

Ryu et al 03

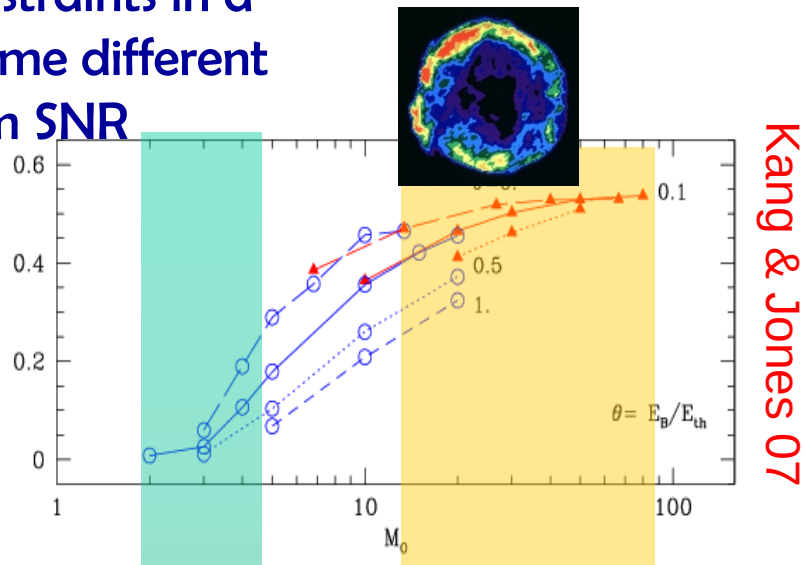


The bulk of ICM heating is due to shocks, so current limits imply an efficiency of CRp acceleration at shocks << 0.1.



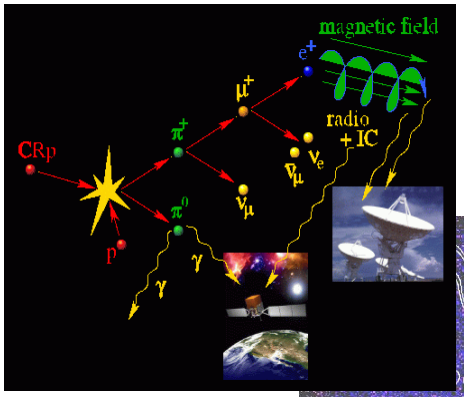
Ackerman et al 14

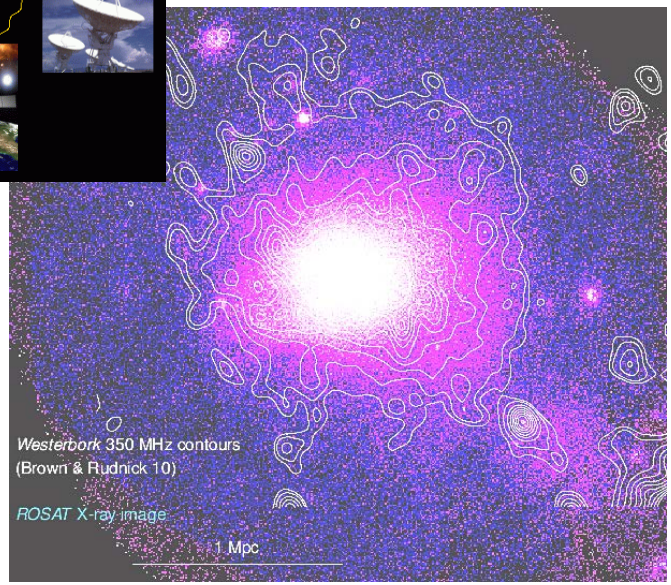
Constraints in a regime different from SNR

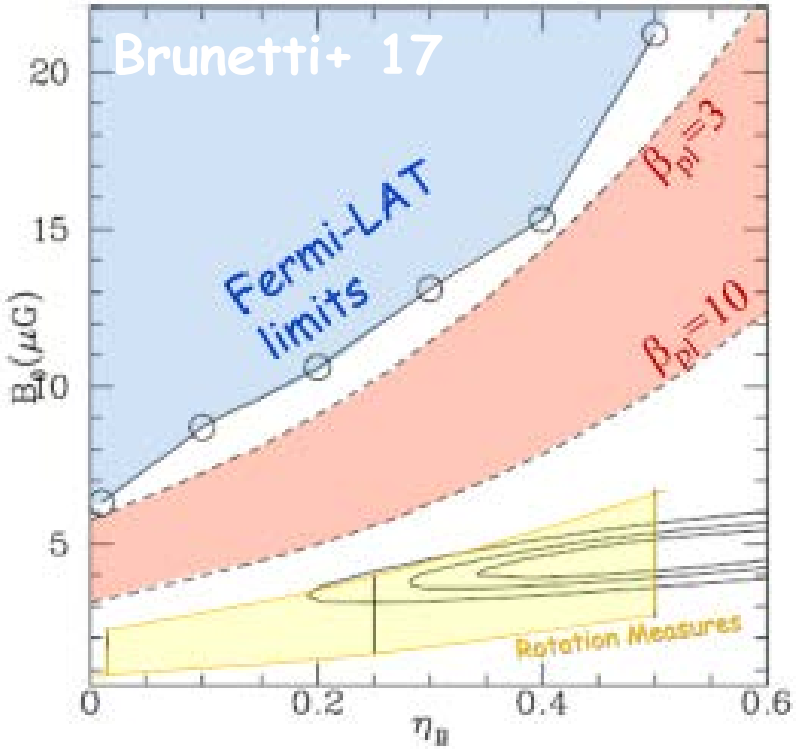


Kang & Jones 07

Giant Radio Halos: How much is contributed by secondaries ?







$$\frac{L_{radio}}{L_\gamma} \propto \left(\frac{B^{\alpha+1}}{B^2 + B^2_{cmb}}\right)$$

Gamma-ray limits + Syn Flux constrain the magnetic field

$$B(r) = B_0 \left(\frac{n_{ICM}(r)}{n_{ICM}(0)}\right)^{\eta_B}$$

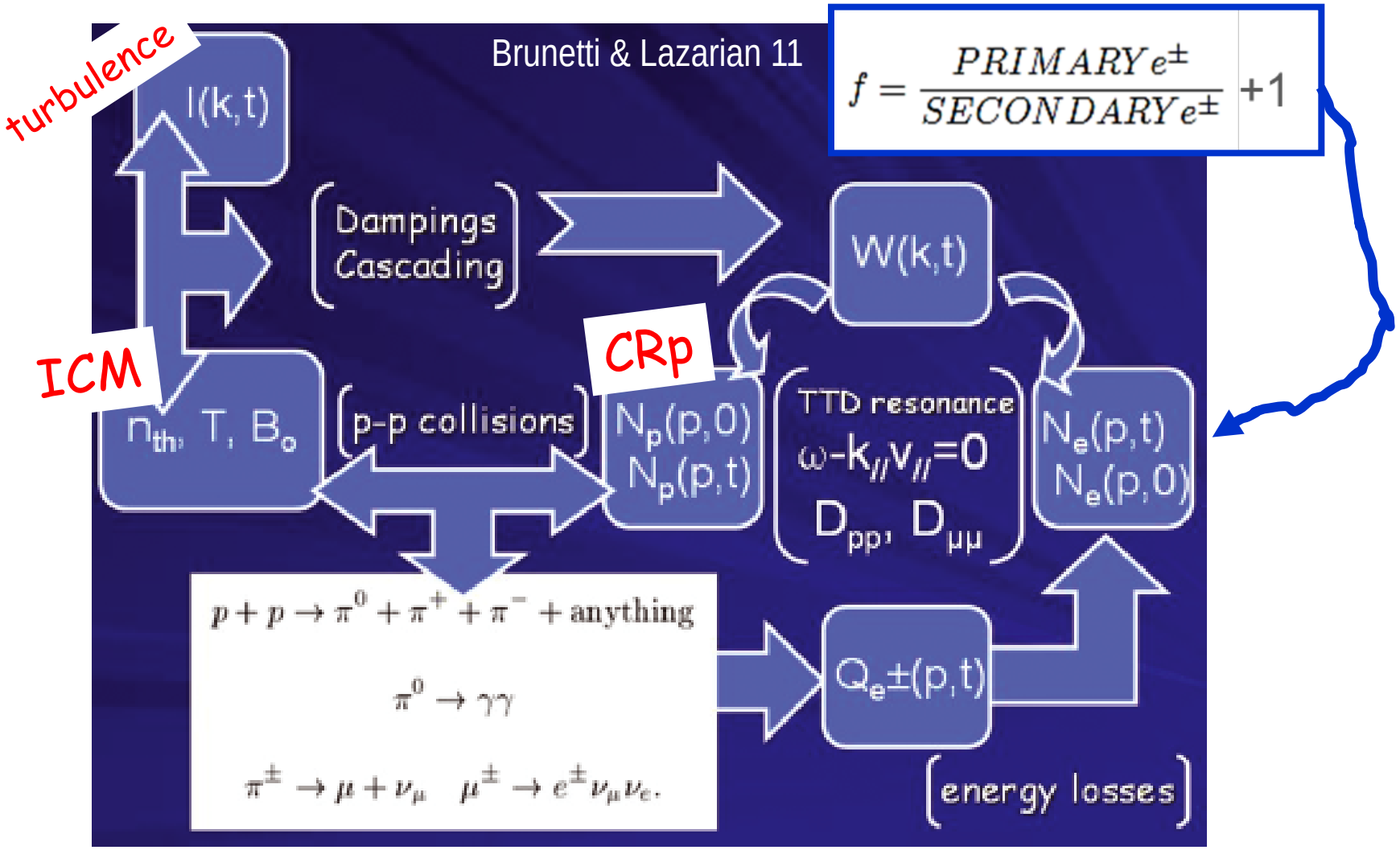
- Radio Halo spectrum
- Radio Halo brightness distribution

- B much higher than RM
- B dynamically important

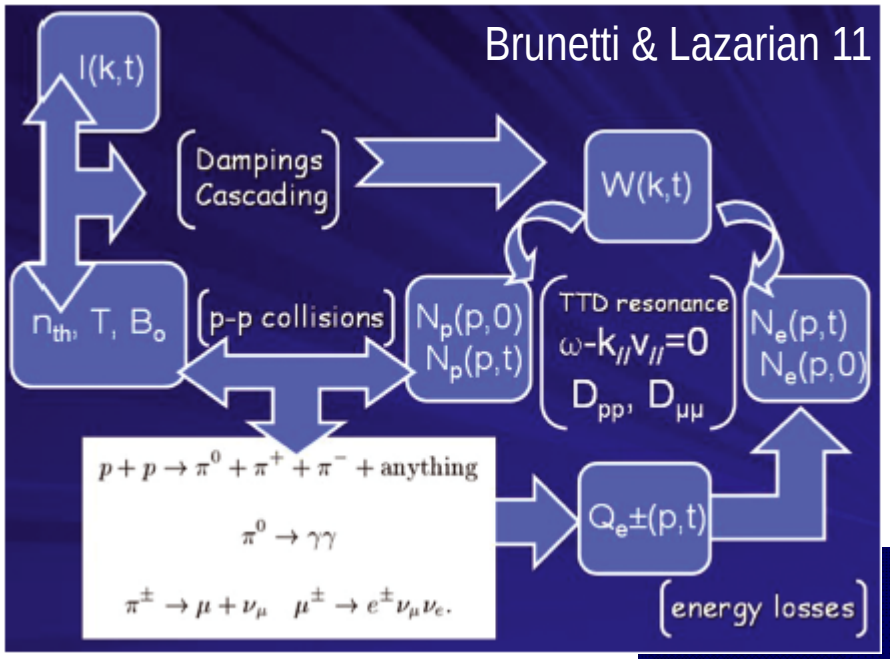
Jeltema+Profumo 11, Brunetti+12, Zandanel+Ando 14, Ackermann+16

Too many CRp are necessary to contribute significantly

Can CRp play a role in reacceleration models ?
- Reacceleration of CRp & secondaries -



Reacceleration of CRp & secondaries



$$f = \frac{PRIMARY\, e^{\pm}}{SECONDARY\, e^{\pm}} + 1$$

Electrons/Positrons

Q_e: secondaries from CRp-p collisions

$$\frac{\partial N_e(p,t)}{\partial t} = \frac{\partial}{\partial p}\left(N_e(p,t)\left[\left(\frac{dp}{dt}\right)_{rad} + \left(\frac{dp}{dt}\right)_i - \frac{2}{p}D_{pp}\right]\right) + \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial N_e(p,t)}{\partial p}\right) + Q_e(p,t)$$

losses + sys acceleration — p-diffusion

Protons

$$\frac{\partial N_p(p,t)}{\partial t} = \frac{\partial}{\partial p}\left(N_p(p,t)\left[\left(\frac{dp}{dt}\right)_i - \frac{2}{p}D_{pp}\right]\right) + \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial N_p(p,t)}{\partial p}\right) + Q_p(p,t)$$

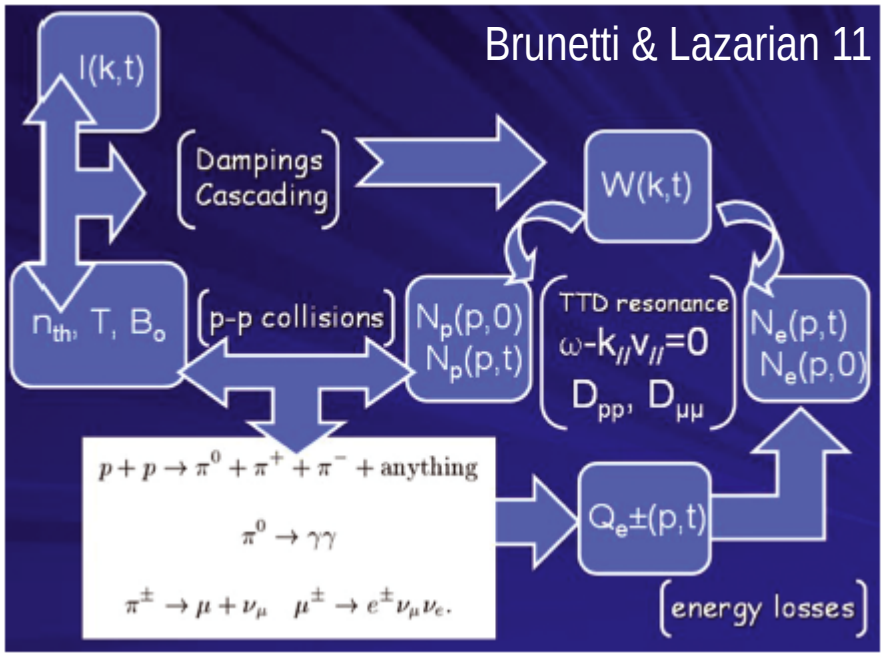
losses + sys acceleration — p-diffusion — injection

Turb. Modes

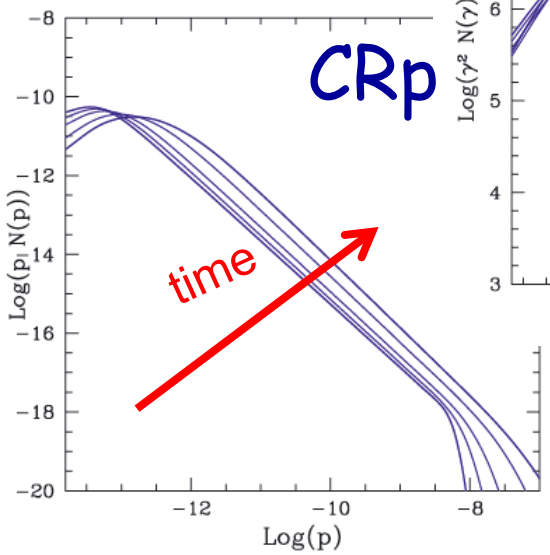
$$\frac{\partial \mathcal{W}(k,t)}{\partial t} = \frac{\partial}{\partial k}\left(k^2 D_{kk}\frac{\partial}{\partial k}\left(\frac{\mathcal{W}(k,t)}{k^2}\right)\right) - \sum_i \Gamma_i(k,t)\mathcal{W}(k,t) + I(k,t)$$

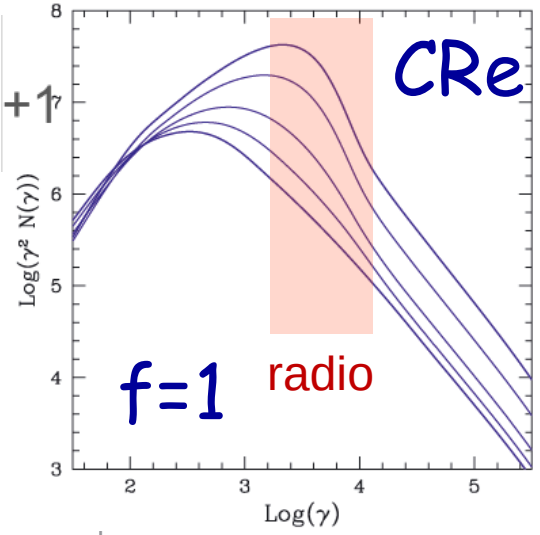
mode coupling — collisionless dampings — injection

Reacceleration of CRp & secondaries



$$f = \frac{PRIMARY\, e^{\pm}}{SECONDARY\, e^{\pm}} + 1$$





- The Syn/gamma ratio is much higher
- Less CRp are necessary to generate the observed radio emission

Weaker magnetic field are constrained by current gamma-ray limits

Relativistic protons in the Coma galaxy cluster: first gamma-ray constraints ever on turbulent reacceleration

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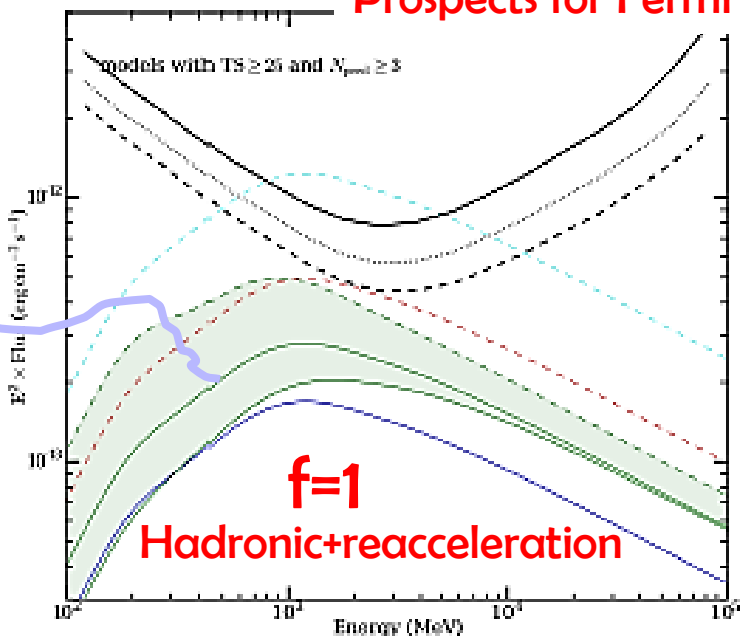
[2] DPNC, University of Geneva, 24 Quai Ernest-Ansermet, CH-1211 Geneva,
[3] GRAPPA, University of Amsterdam, Science Park 904, 1098XH, Amsterda

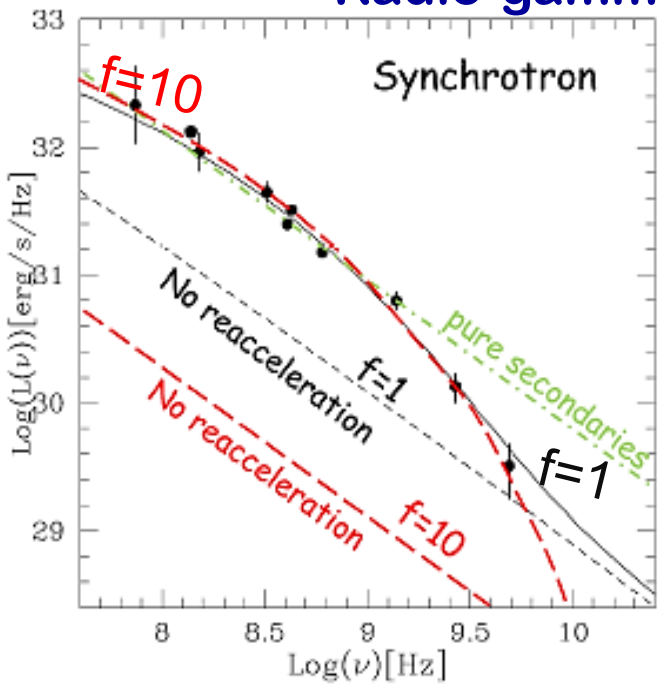
Prospects for Fermi

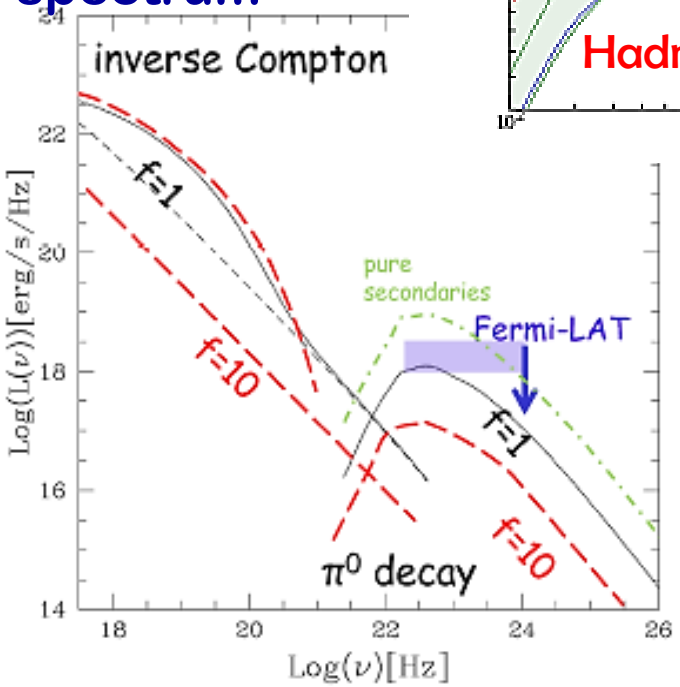


Models with
B consistent
with Faraday RM

$$f = \frac{PRIMARY\, e^{\pm}}{SECONDARY\, e^{\pm}} + 1$$

Radio-gamma spectrum





A signal at 3σ level can be detected in 15 yrs of observations if CRp play a role

Few..take home messages :

Galaxy clusters are unique environments for CR acceleration & plasma astrophysics: energy generated on Mpc scales is dissipated on smaller (Mm??) scales into CRs and B .

Observed Mpc-scale Syn emission results from several players (shocks, turbulence, CRp-p, reconnection?) .

CRp should be the most important non-thermal component but only limits from gamma-rays.

- Leptonic models favoured ? : high CRe/CRp ratio ?
- reacceleration of CRp+secondaries ?
- Constraints on CRs acceleration and dynamics

Future :

- LOFAR+MWA (& SKA-Low) : steep spectrum sources !
- Fermi-LAT 10-15 (& CTA) : possible detections ?
- Athena : turbulence & connection with Syn emission