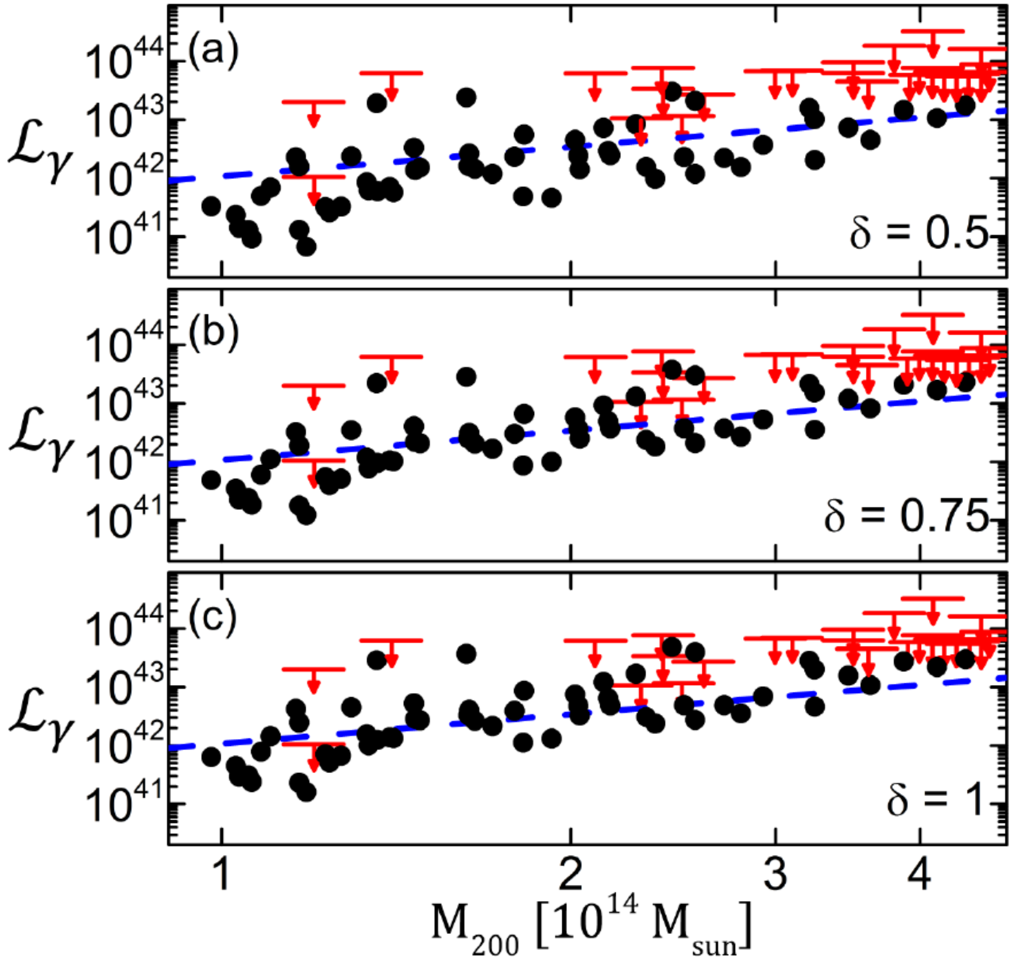
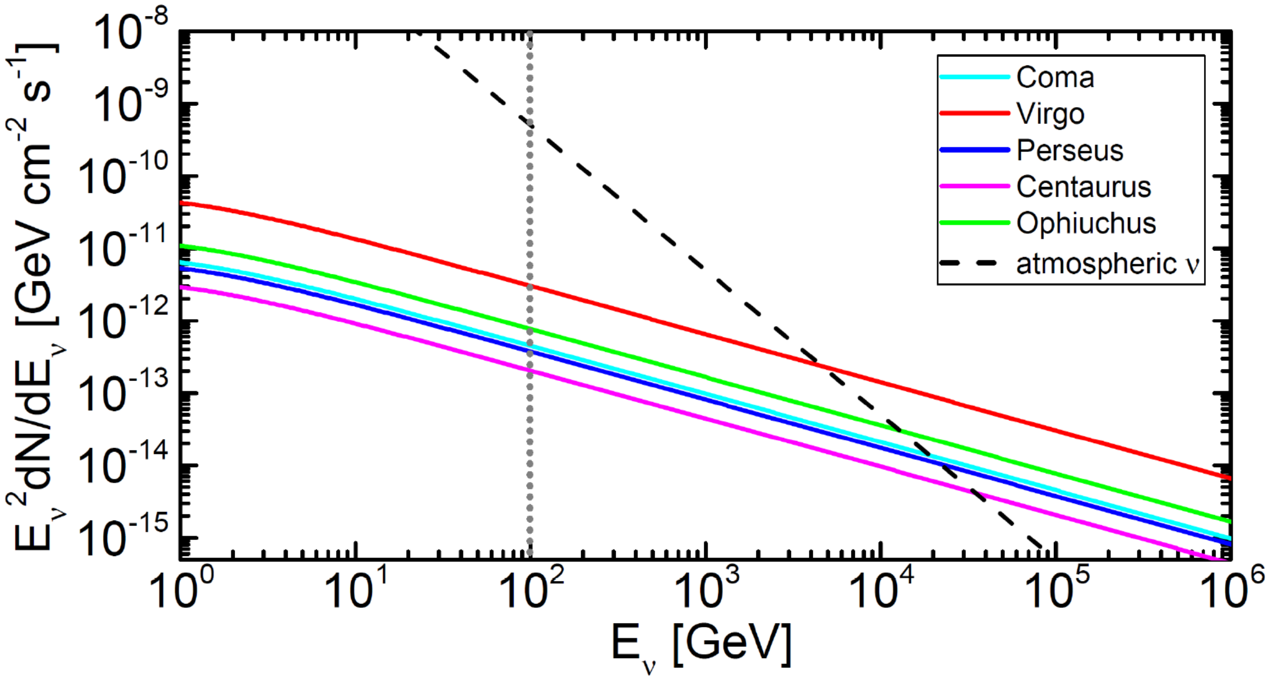
Proton Acceleration in Intracluster Shocks and Gamma-ray (and Neutrino Emissions) from Galaxy Clusters





UNIST
ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY
2009

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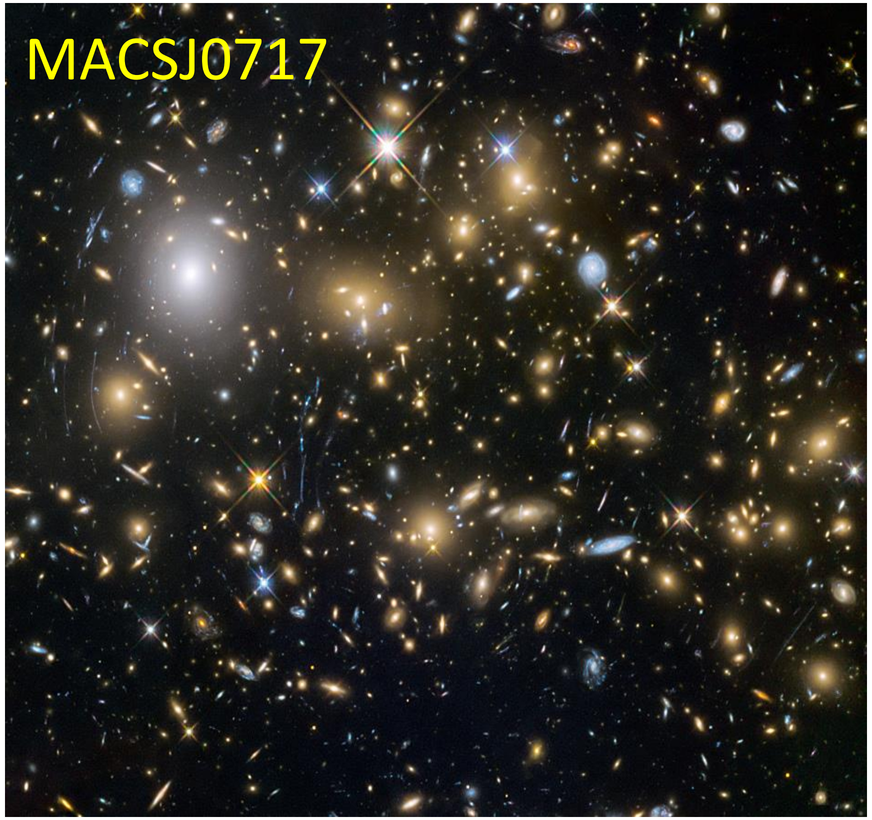
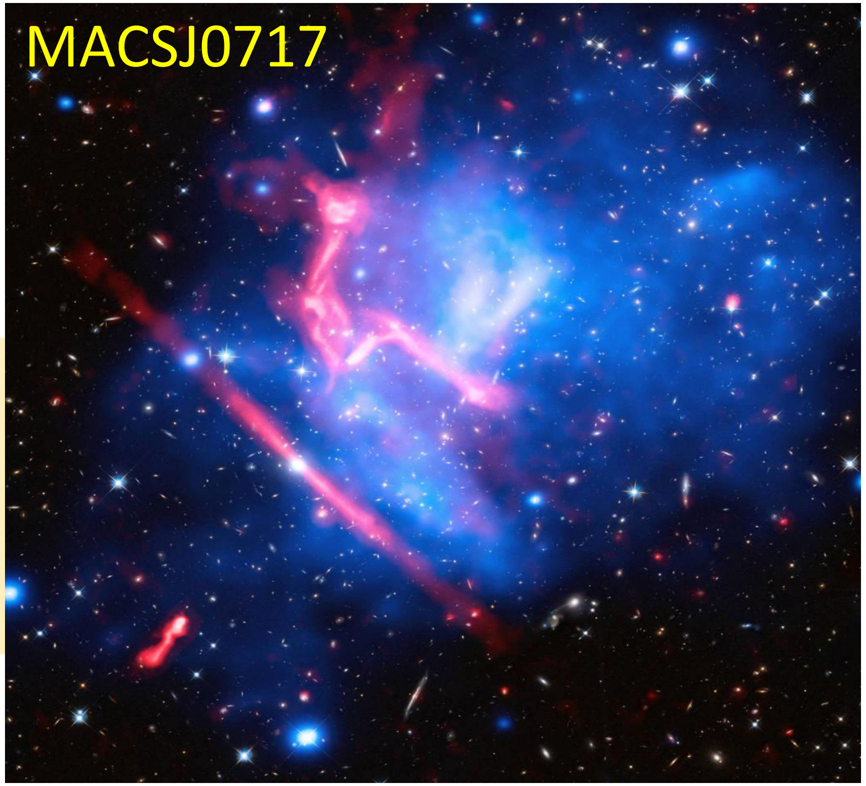


Hubble space telescope image

Clusters of galaxies: aggregates of galaxies, which are the **largest known gravitationally bound objects** to have arisen thus far in the process of cosmic structure formation

optical (Hubble, white)
X-ray (Chandra, blue) ← hot gas
radio (VLA, red) ← cosmic rays



The intracluster medium (ICM):

the superheated **plasma with T ~ a few to several keV**, presented in clusters of galaxies

Fluid quantities in the ICM from observations

size of clusters	$L_{cluster}$ ~ a few Mpc ~ 10^{25} cm
baryon number density	n ~ 10^{-3} cm
gas temperature	T ~ 10^{8} K (8.6 keV) → c_s ~ 1,500 km/s
flow velocity	v ~ several x 100 km/s → M_s ~ ½ < 1
magnetic fields	B ~ a few x μG → c_A ~ 100 km/s, $M_A > 1$

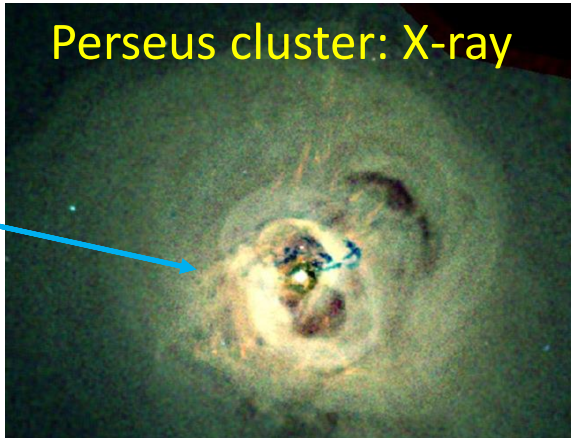
→ flows are subsonic (M_s ~ 0.5) but super-Alfvenic ($M_A > 1$)

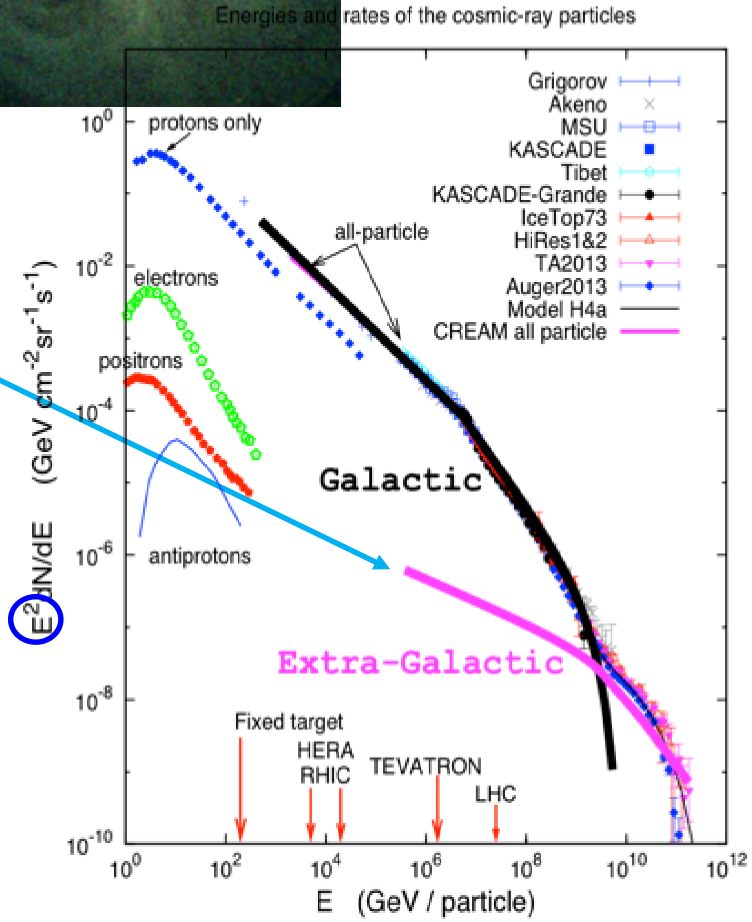
gas thermal energy	$E_{thermal}$ ~ a few x 10^{-11} erg/cm^3
gas kinetic energy	$E_{kinetic}$ ~ a few x 10^{-12} erg/cm^3
magnetic energy	$E_{magnetic}$ ~ a few x 10^{-13} erg/cm^3
cosmic-ray energy	E_{CR} <~ a few x 10^{-13} erg/cm^3

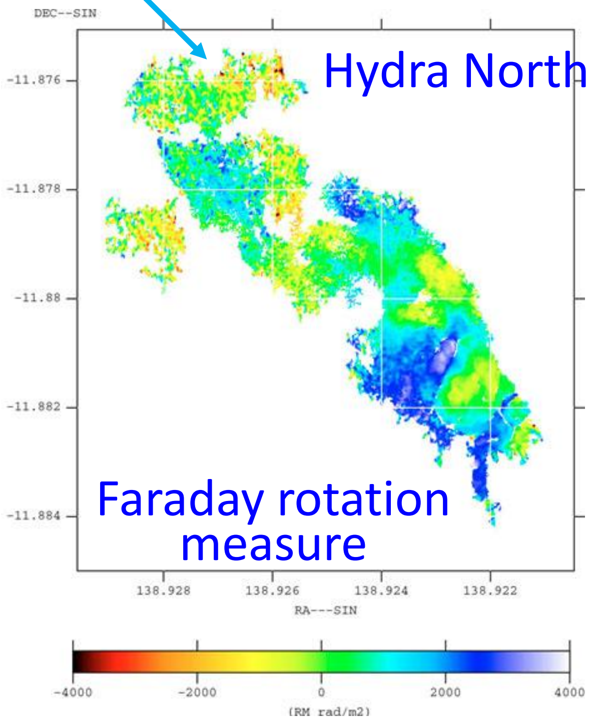
→ $E_{kinetic}$ ~ 1/10 $E_{thermal}$, $E_{magnetic}$ ~ 1/10 $E_{kinetic}$, β ~ 100

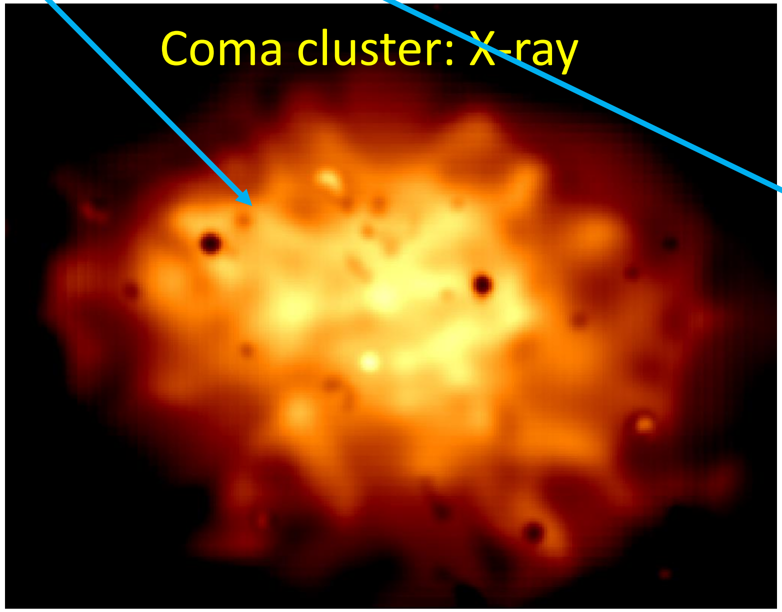
ICMs are highly dynamical

- large-scale flow motions
- **shock waves**
- cosmic-rays
- turbulent flow motions
- magnetic fields

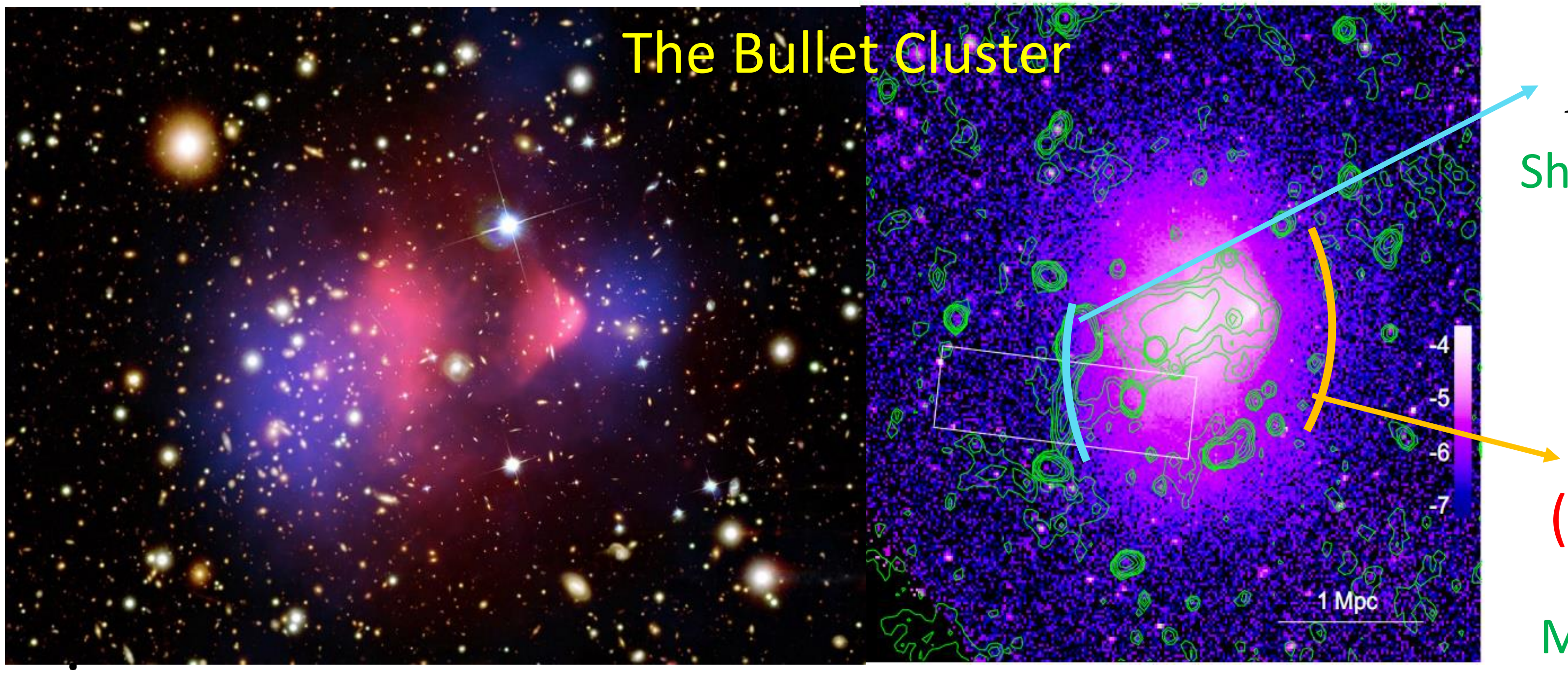








Observation of shocks in clusters: X-ray



$M_X \approx 2.5$

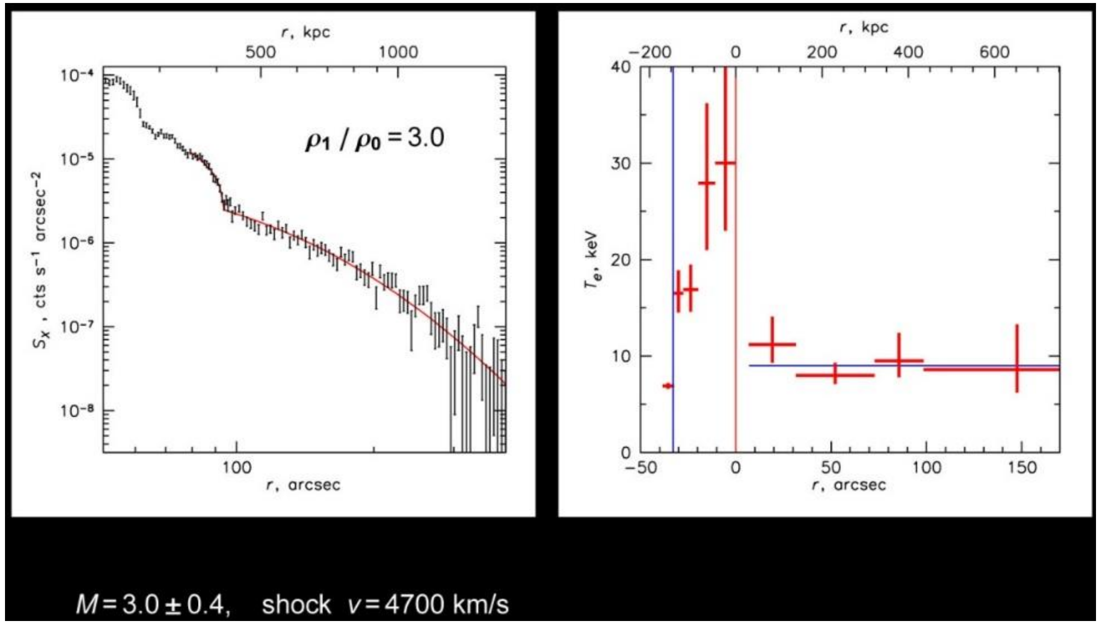
Shimwell et al. 2015

$M_X \approx 3.0$

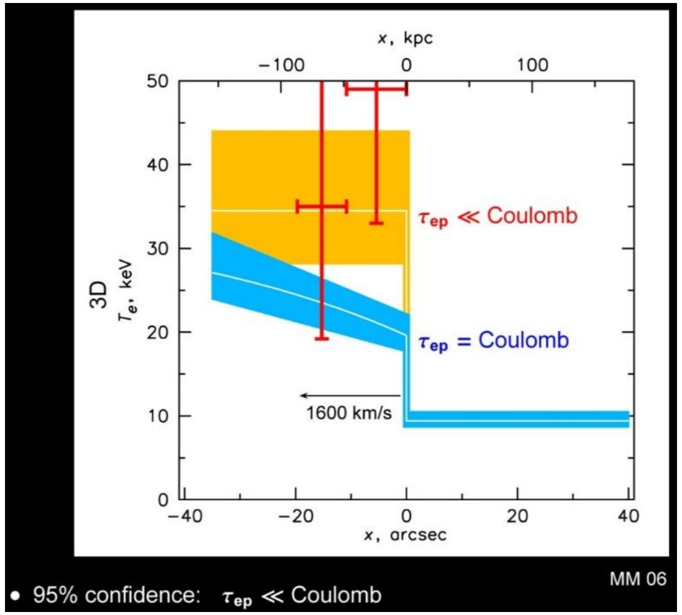
(no associated radio relic)

Markevitch 2006

Shock wave in 1E0657-56 (Bullet cluster)



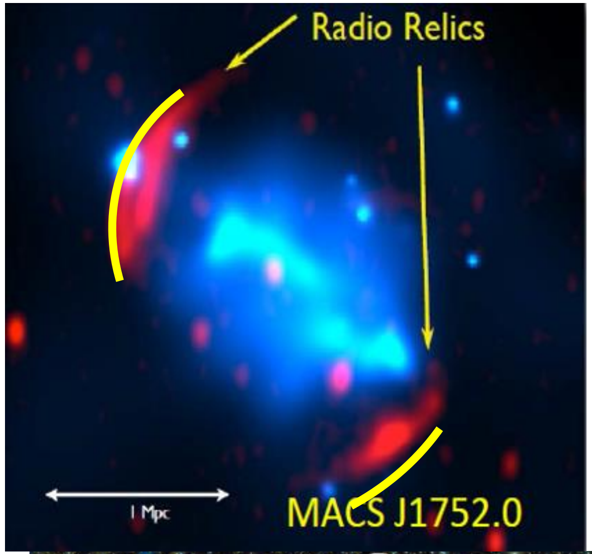
$M = 3.0 \pm 0.4$, shock $v = 4700$ km/s

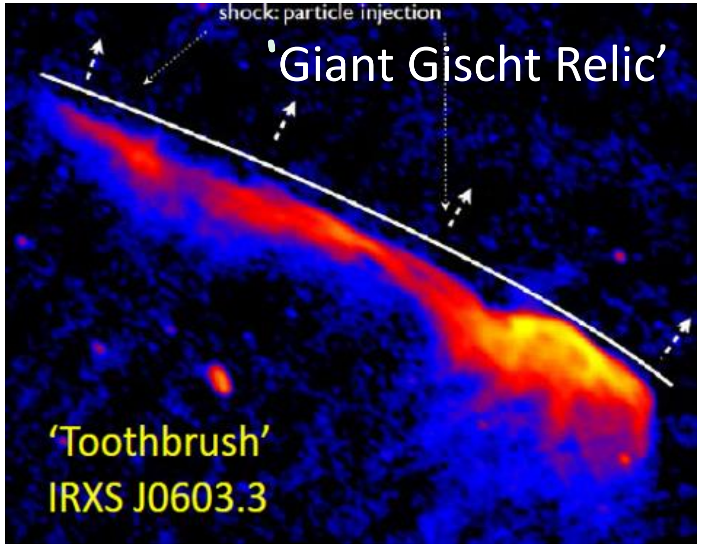


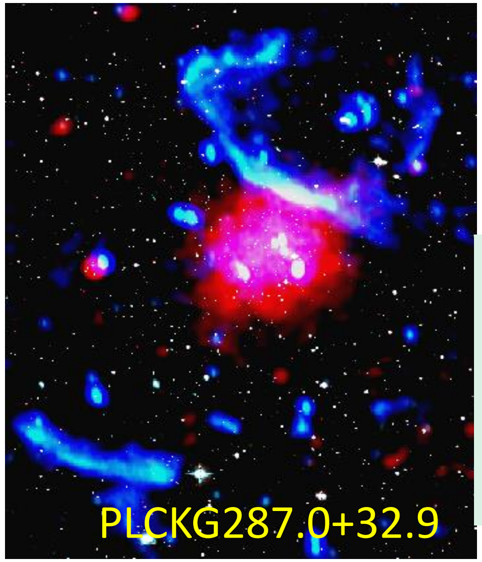
- 95% confidence: $\tau_{ep} \ll$ Coulomb

Mach number of X-ray shocks in ICMs: M_{shock} <~ a few

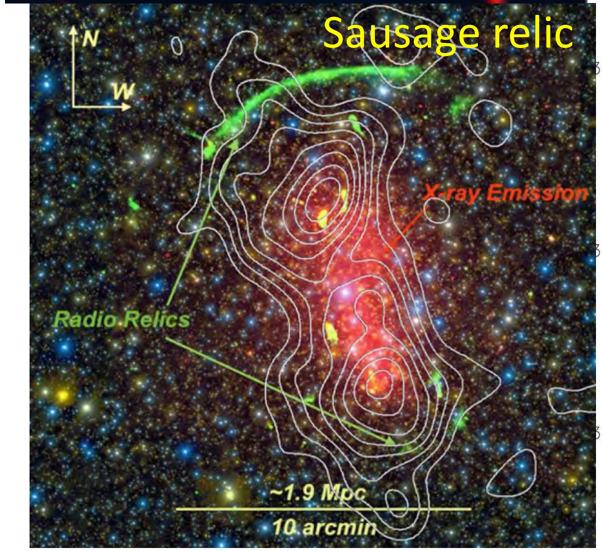
Observation of shocks in clusters: radio relics

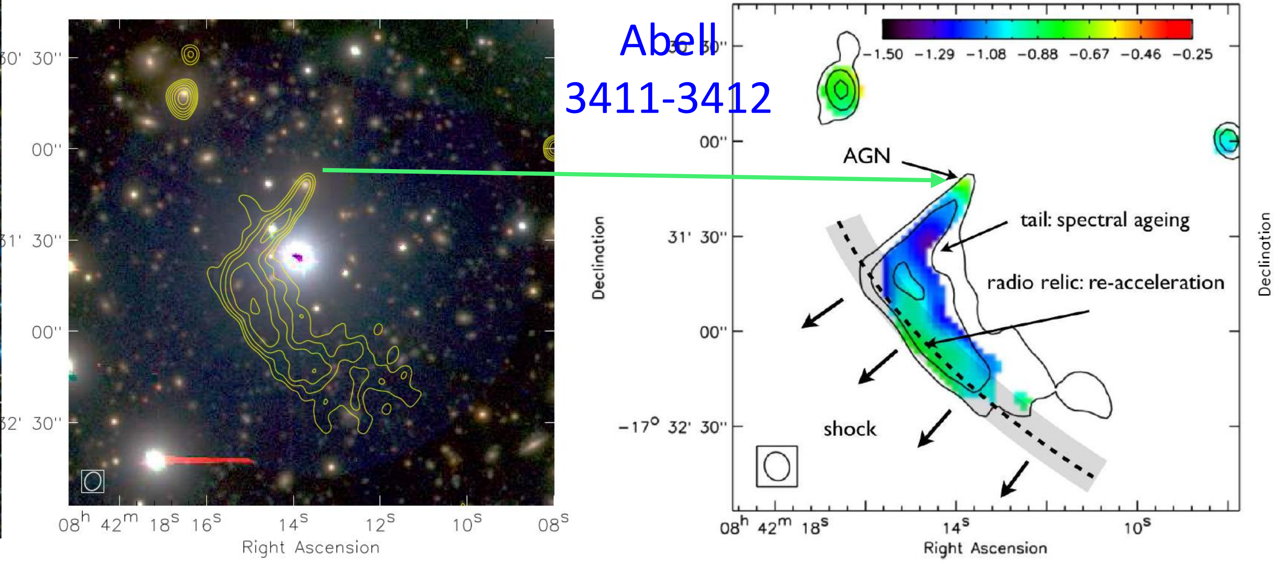




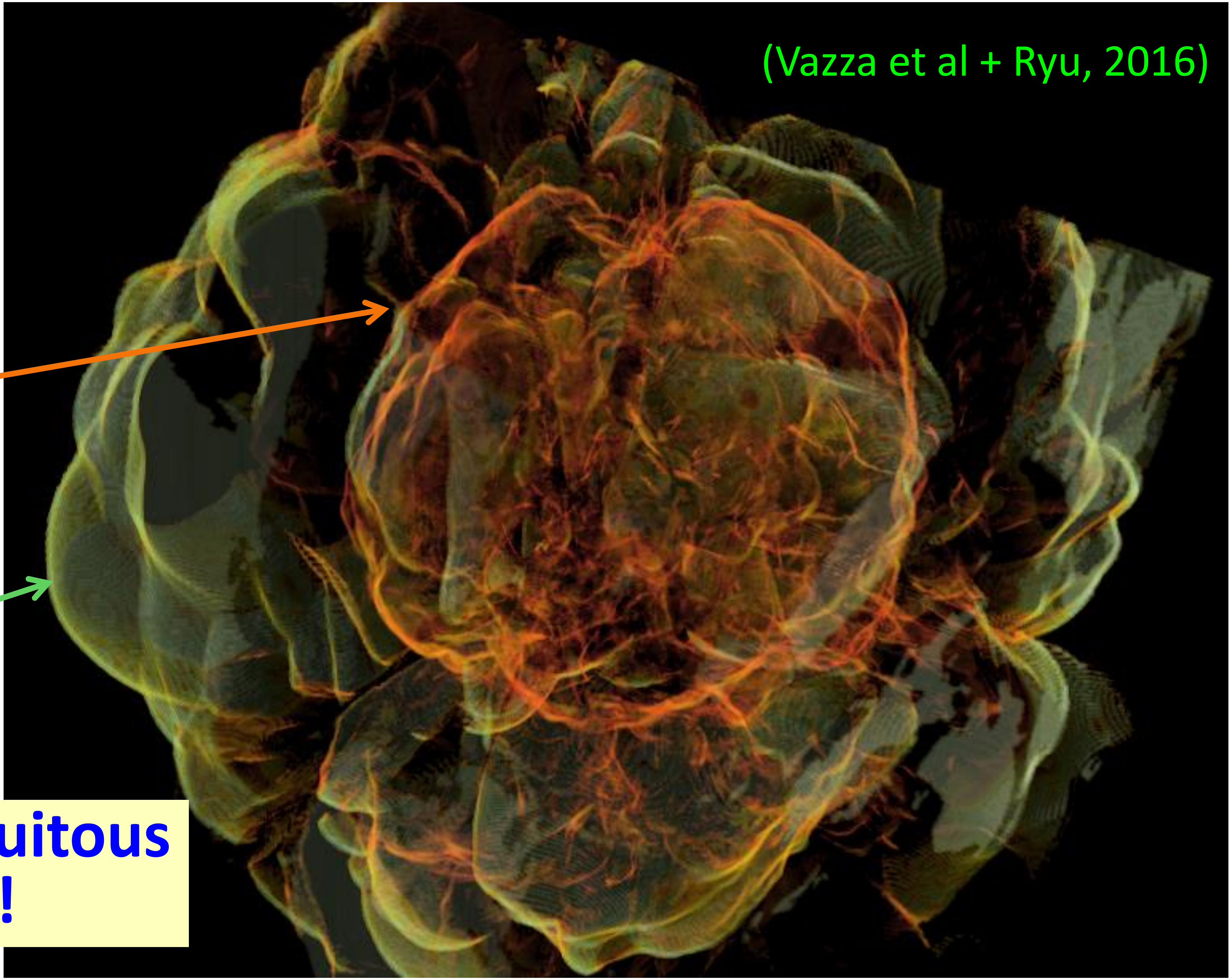


Mach number of radio shocks in ICMs: M_{shock} <~ several




Abell 3411-3412

Shock waves in simulation



weak inreacluster shocks with M < a few to several (orange)

strong accretion shocks with M > ~10 (green)

Shocks are ubiquitous in the ICM!

The nature of shock waves in clusters of galaxies during the hierarchical structure formation

1) **accretion shocks** around clusters formed by accreting void gas

2) **intracluster shocks** inside cluster

   a) **turbulence shocks** - induced by turbulent flow motions

   b) **infall shocks** - accretion of the WHIM (Warm-Hot Intergalactic Medium) to the hot intracluster medium along filaments

   c) **merger shocks** - induced by merger of gas/DM clumps during the hierarchical formation of galaxy clusters, **M_{shock} < ~ a few to several**

a major merger of ~$10^{13} – 10^{14}\ M_\odot$ of gas clumps
with speed of ~1,000 km/s ➔ $E_{merger} \sim 10^{63} – 10^{64}$ ergs
→ "**energetically important**"

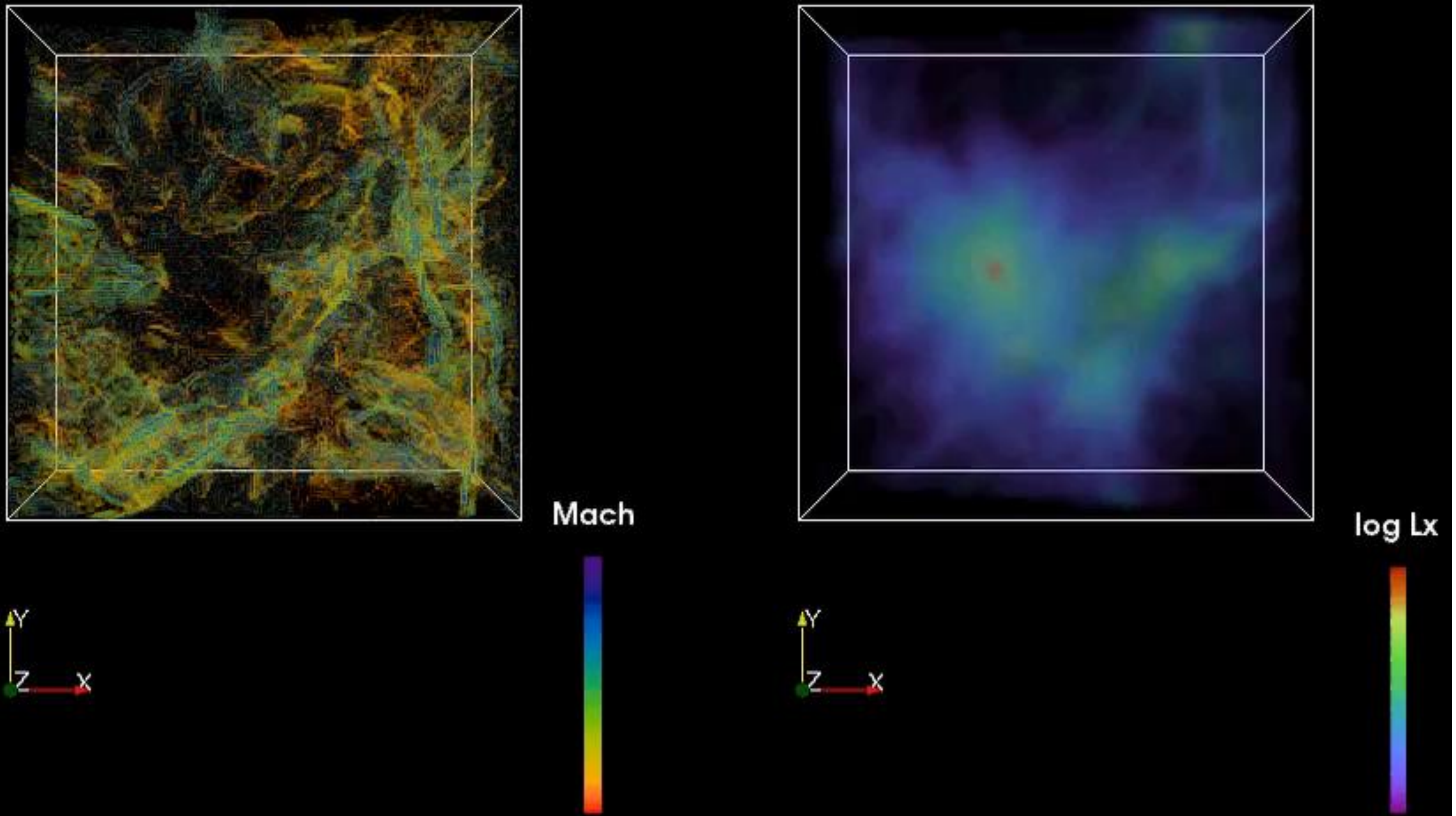
Shock waves in a merging cluster from a simulation for large-scale structure formation in 100 h^{-1} Mpc box: a binery merger case

(Ha, Ryu, & Kang 2017)

from $z = 0.5$ to 0.05, box size = 5 h^{-1} Mpc

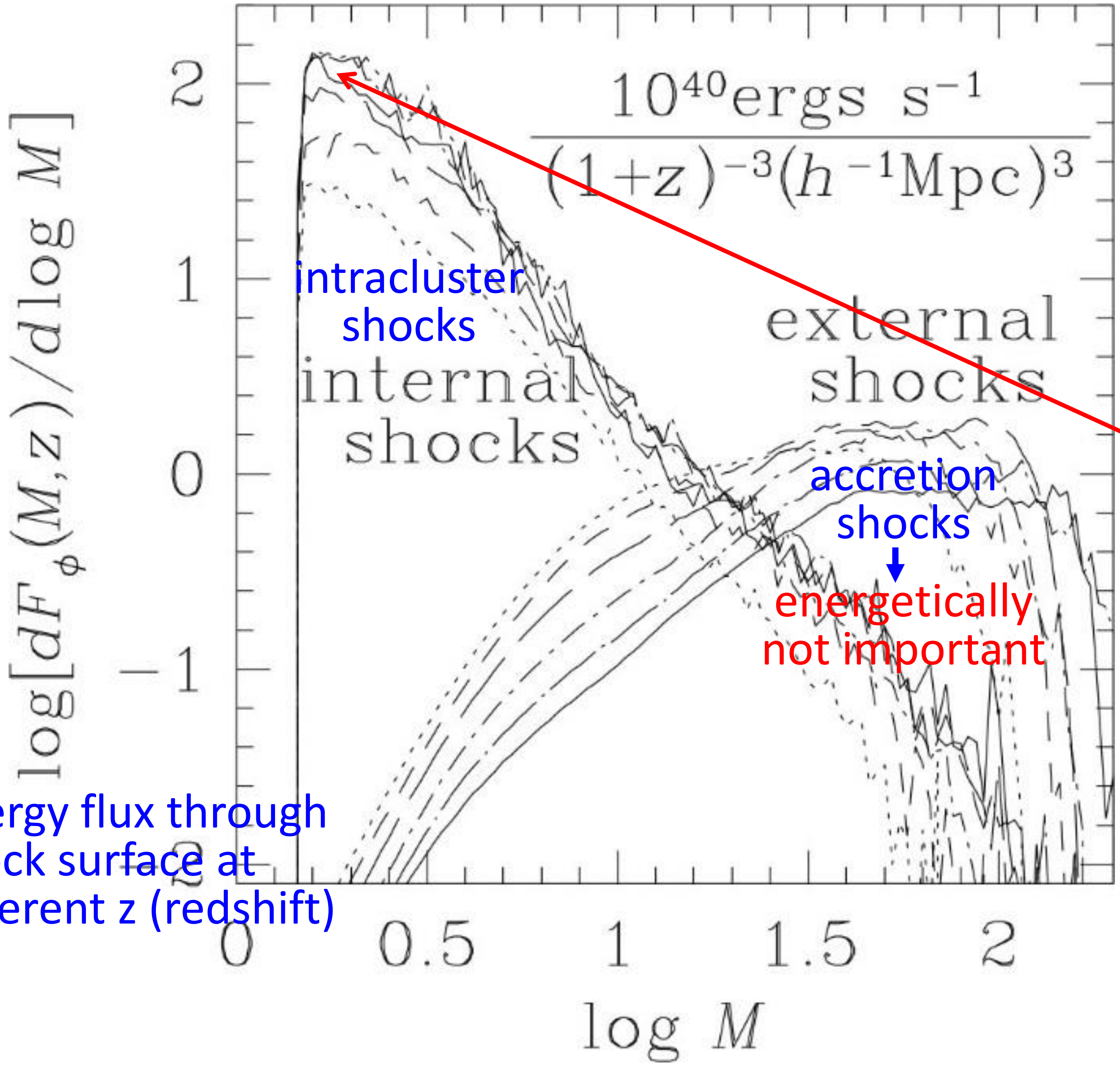
shocks with $1 < M_s < 10$

X-ray emissivity



Shock waves inside and around clusters

(Ryu et al. 2003)



intracluster shocks

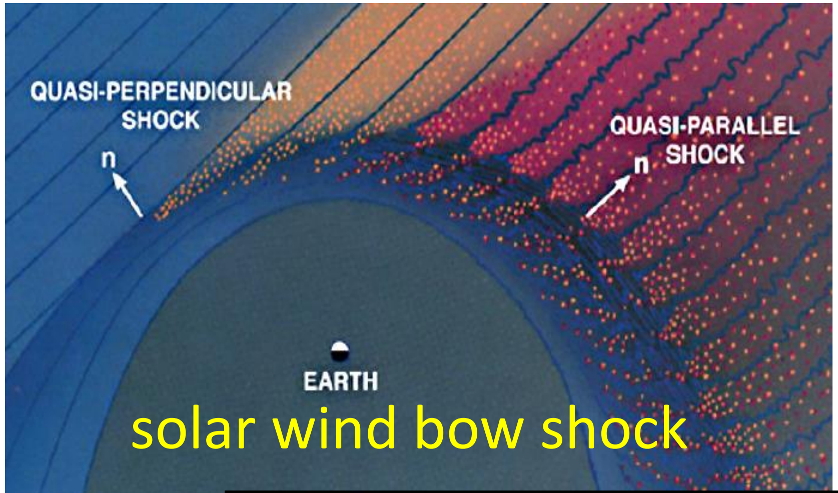
accretion shocks

energetically not important

energy flux through shock surface at different z (redshift)

Weak intracluster shocks with M_s ~ a few, V_s ~ 2,000 km/s are energetically more important.

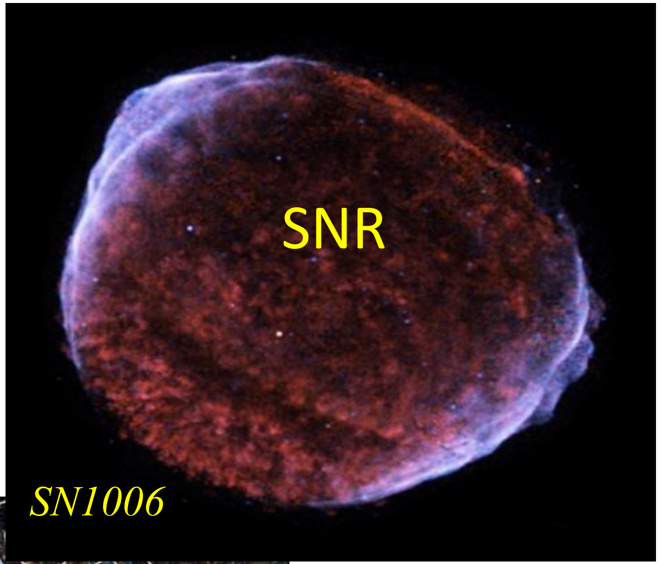
Shocks in astrophysical environments are collisionless, and CRs are accelerated at collisionless shocks !



solar wind bow shock

pulsar wind

Crab



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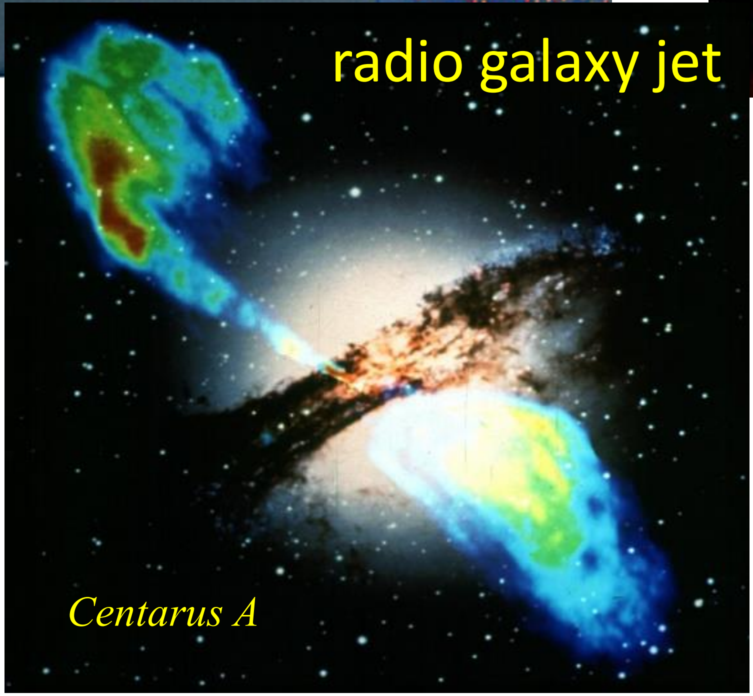
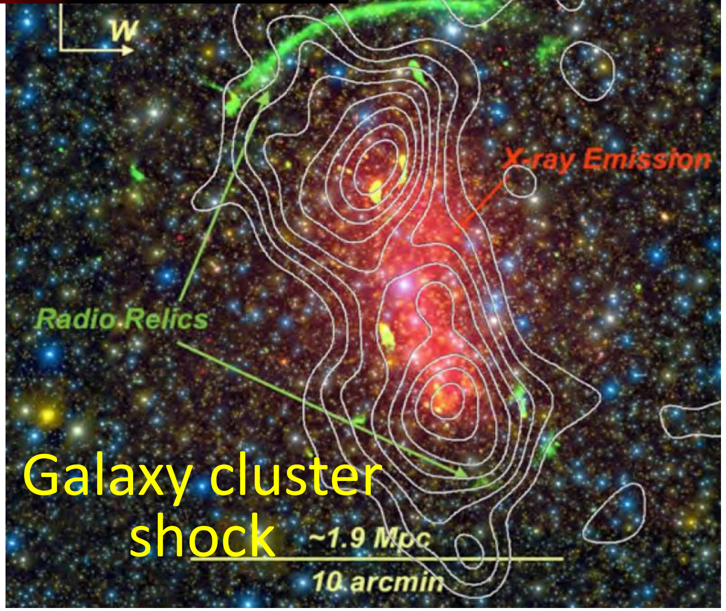


radio galaxy jet

Centarus A



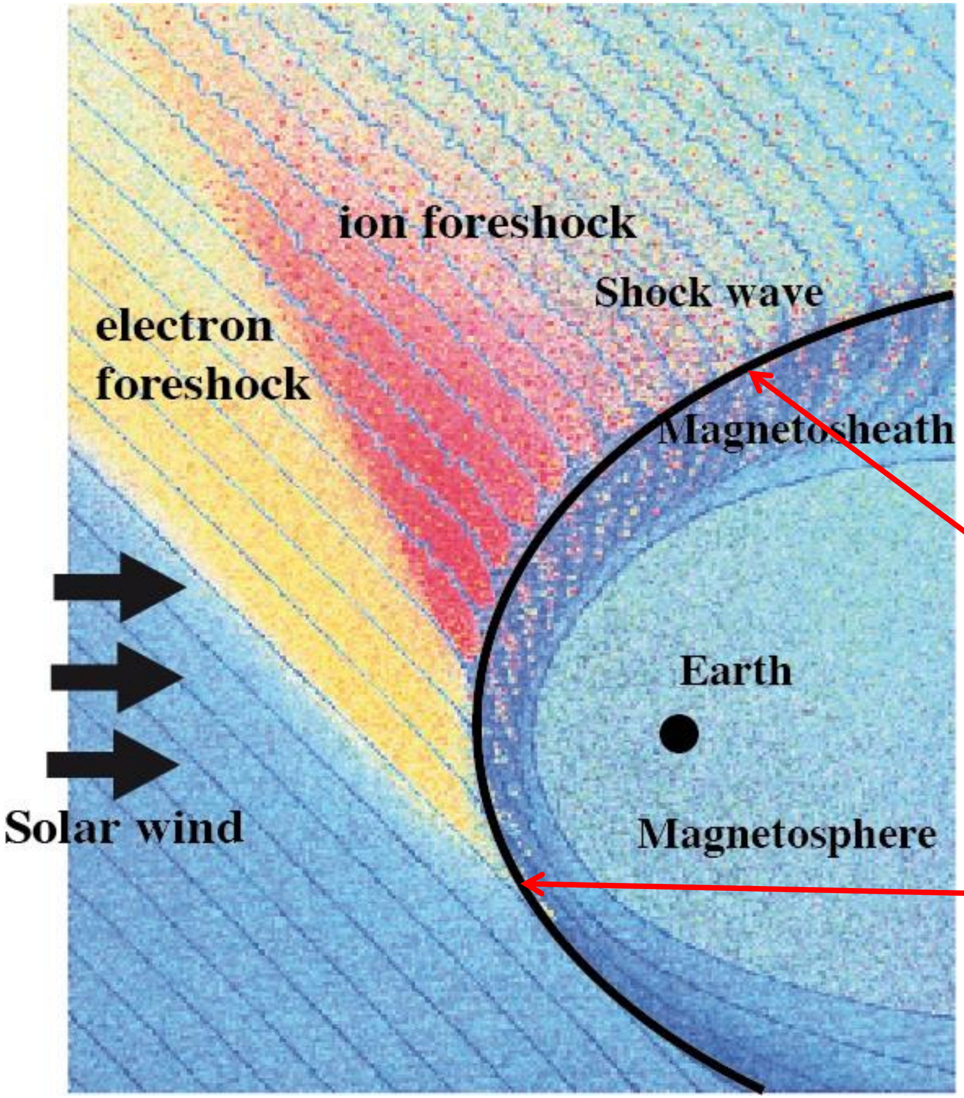
Galaxy cluster shock

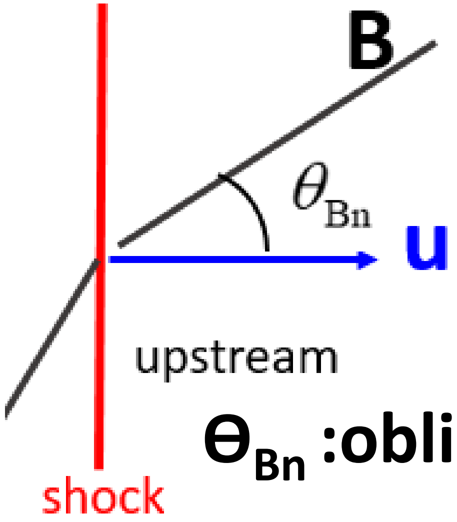
Properties of astrophysical shocks

	solar wind shocks	supernova shocks in ISM	ICM shocks
size	~ 10^{12} cm	~ 10^{21} cm	~ 10^{25} cm
particle density	~ 10 cm^{-3}	~ 0.1 cm^{-3}	~ 10^{-3} cm^{-3}
gas temperature	~ 10^5 K	~ 10^4 K	~ 10^8 K
B strength	~ 10^{-4} G	~ 10^{-5} G	~ 10^{-6} G
c_s (km/s)	~ 50	~ 15	~ 1,000
c_A (km/s)	~50	~ 15	~ 100
$B = p_g/p_B$	~ 1	~ 1	~ 100
v_{shock} (km/s)	~ 500	~ 3,000	~ 3,000
M_s	~ 10	~ 200	~ 3
M_A	~ 10	~ 200	~ 30

ICM shocks are fairly strong in terms of M_A, but weak in terms of M_s !

CR acceleration at astrophysical shocks





Θ_{Bn} :obliquity angle

quasi-parallel shock with Θ_{Bn} <~ 45^o

→ proton acceleration ←

quasi-perpendicular shock with Θ_{Bn} >~ 45^o

→ electron acceleration

CR acceleration at collisionless shocks depends on M_A, M_s and Θ_{Bn}

Simulation of proton acceleration at quasi-parallel ICM shocks

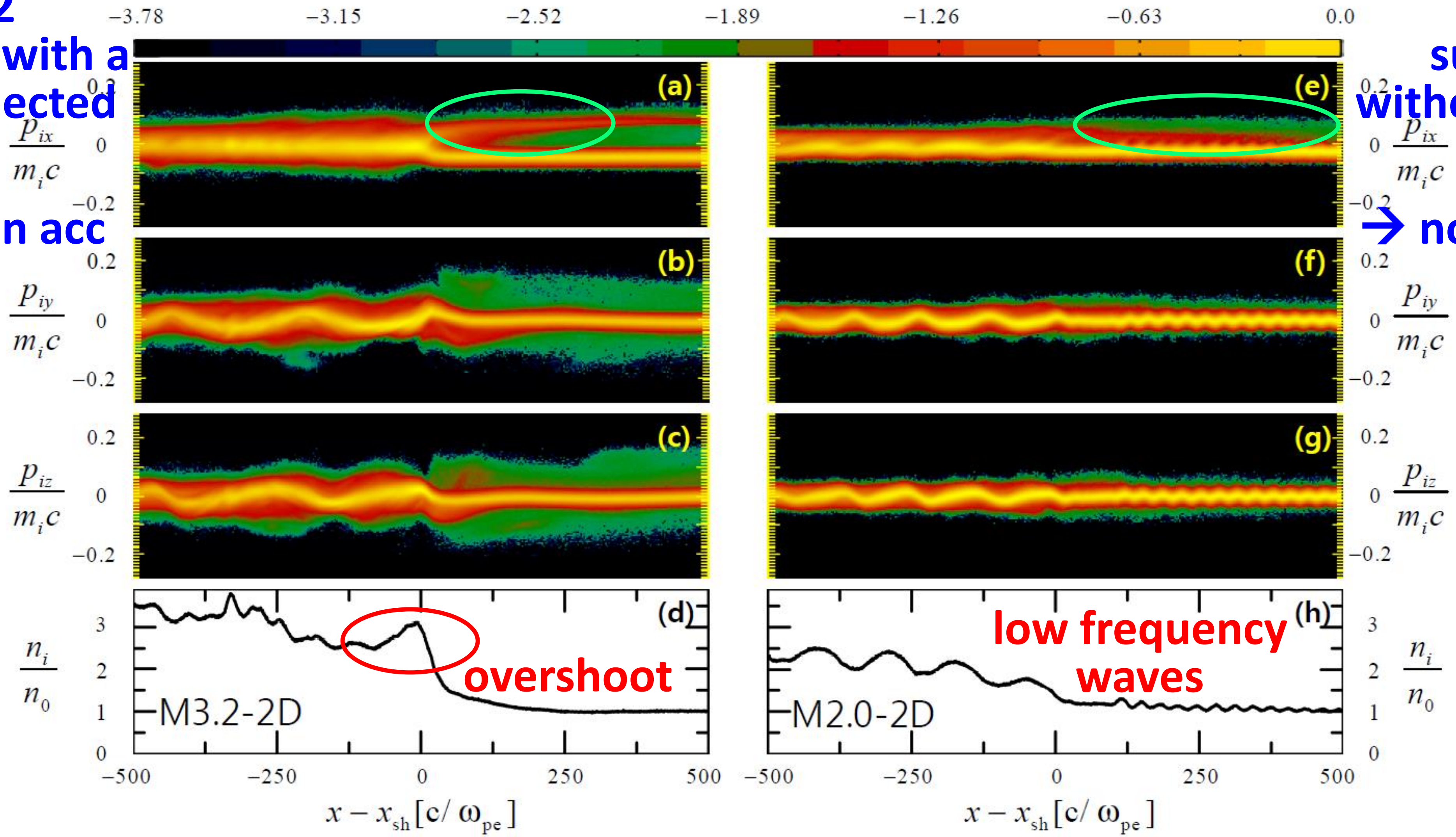
(Ha, Ryu, Kang, van Marle 2018)

$M_s = 3.2$
supercritical with a beam of reflected ions

→ CR proton acc

$M_s = 2.0$
subcritical without reflected ions

→ no accleration

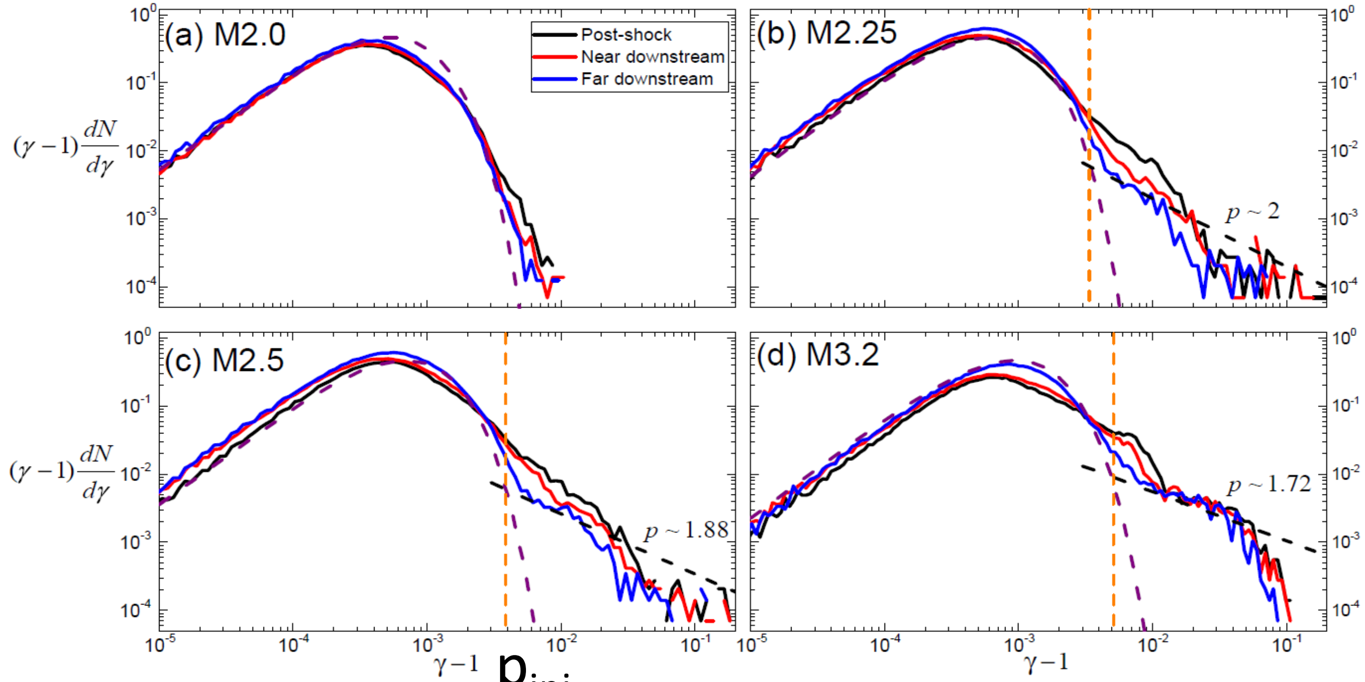


overshoot

low frequency waves

PIC simulation $\theta_{Bn} = 13^\circ$ $r_{\mathrm{L,i}} \equiv \frac{m_i v_0 c}{e B_0} = M_{\mathrm{A},0}\sqrt{\frac{m_i}{m_e}}\frac{c}{w_{\mathrm{pe}}} \sim 200\,\frac{c}{w_{\mathrm{pe}}}$

Proton acceleration at quasa-parallel ICM shocks



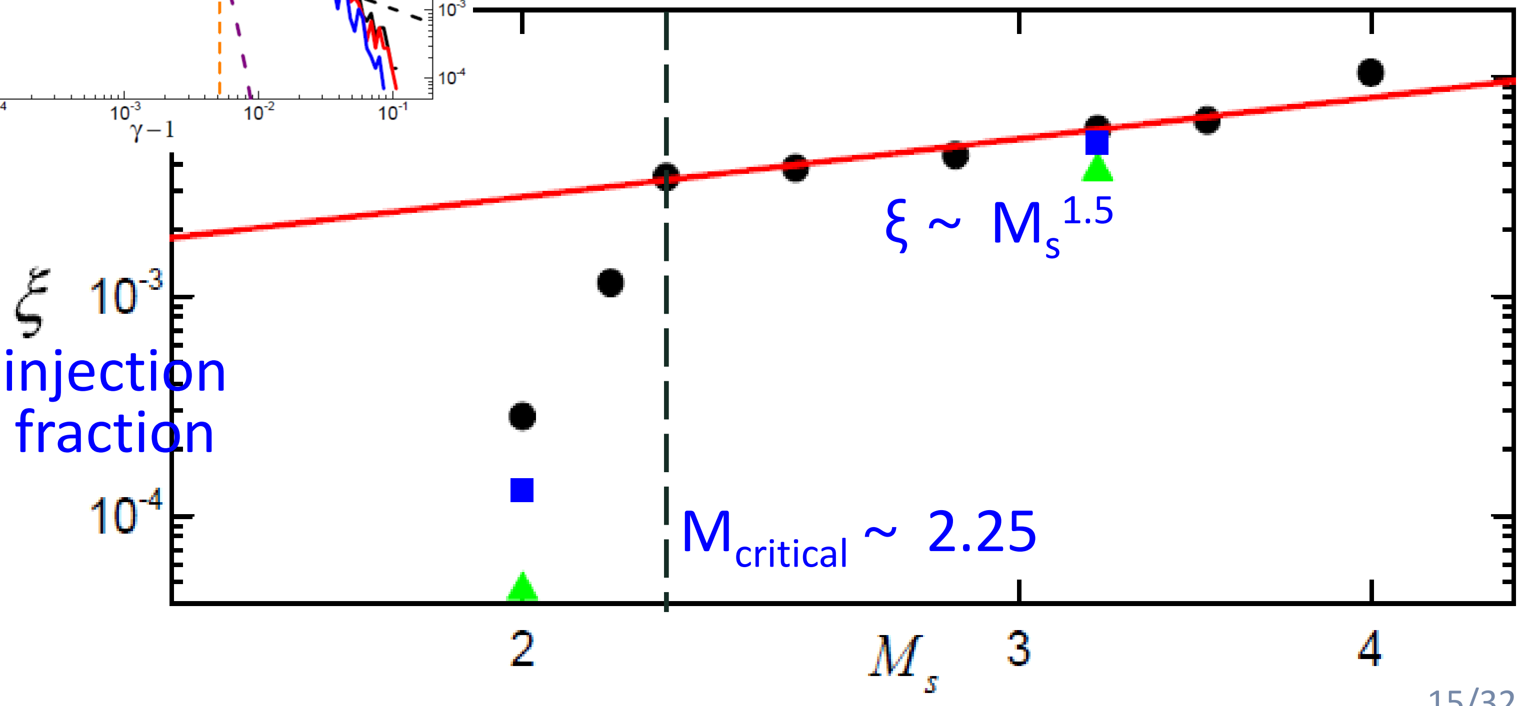
p_{inj}

$(\Omega_{ci}t \approx 90)$

injection fraction

$$\xi \equiv \frac{1}{n_2}\int_{p_{\min}}^{p_{\max}} 4\pi f(p)p^2dp,$$

$$p_{min} = 3.8\, p_{th} = \sqrt{2}\, p_{inj}$$



injection fraction

$\xi \sim M_s^{1.5}$

$M_{critical} \sim 2.25$

- **not efficient acceleration below $M_{critical}$**
- **injection fraction: $\xi \sim$ a few – several x 10^{-3}**

Gamma-ray (and neutrino emission) through p-p interaction

Interaction between CR proton and baryonic matter

1. In inelastic p-p collisions, π's are produced

$$P_{\mathrm{CR}} + P_{\mathrm{ICM,thermal}} \rightarrow \pi^{\pm} + \pi^{0}$$

2. π^0 decays into two gamma-rays

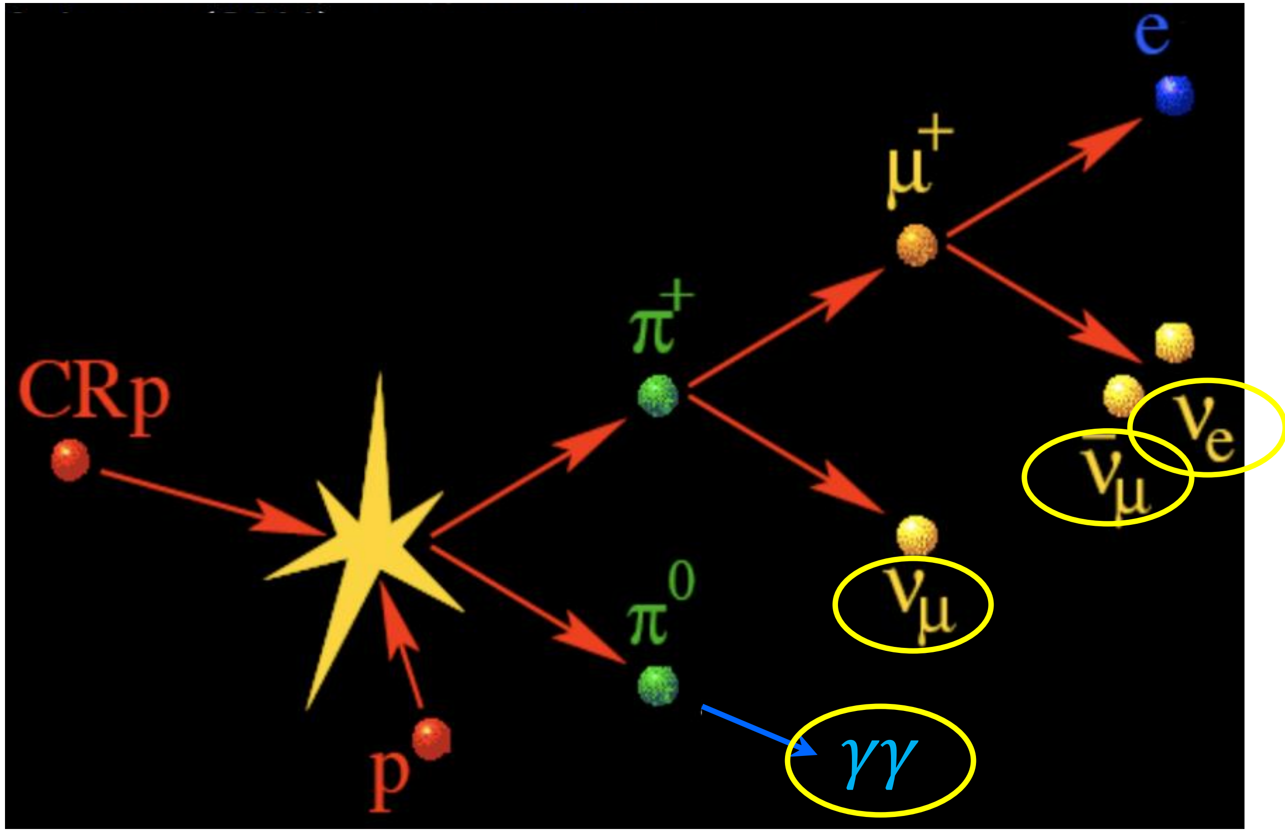
$$\pi^{0} \rightarrow \gamma\gamma$$

3. $\pi^{\pm}$ decays into $\mu^{\pm}$ and μ-neutrino

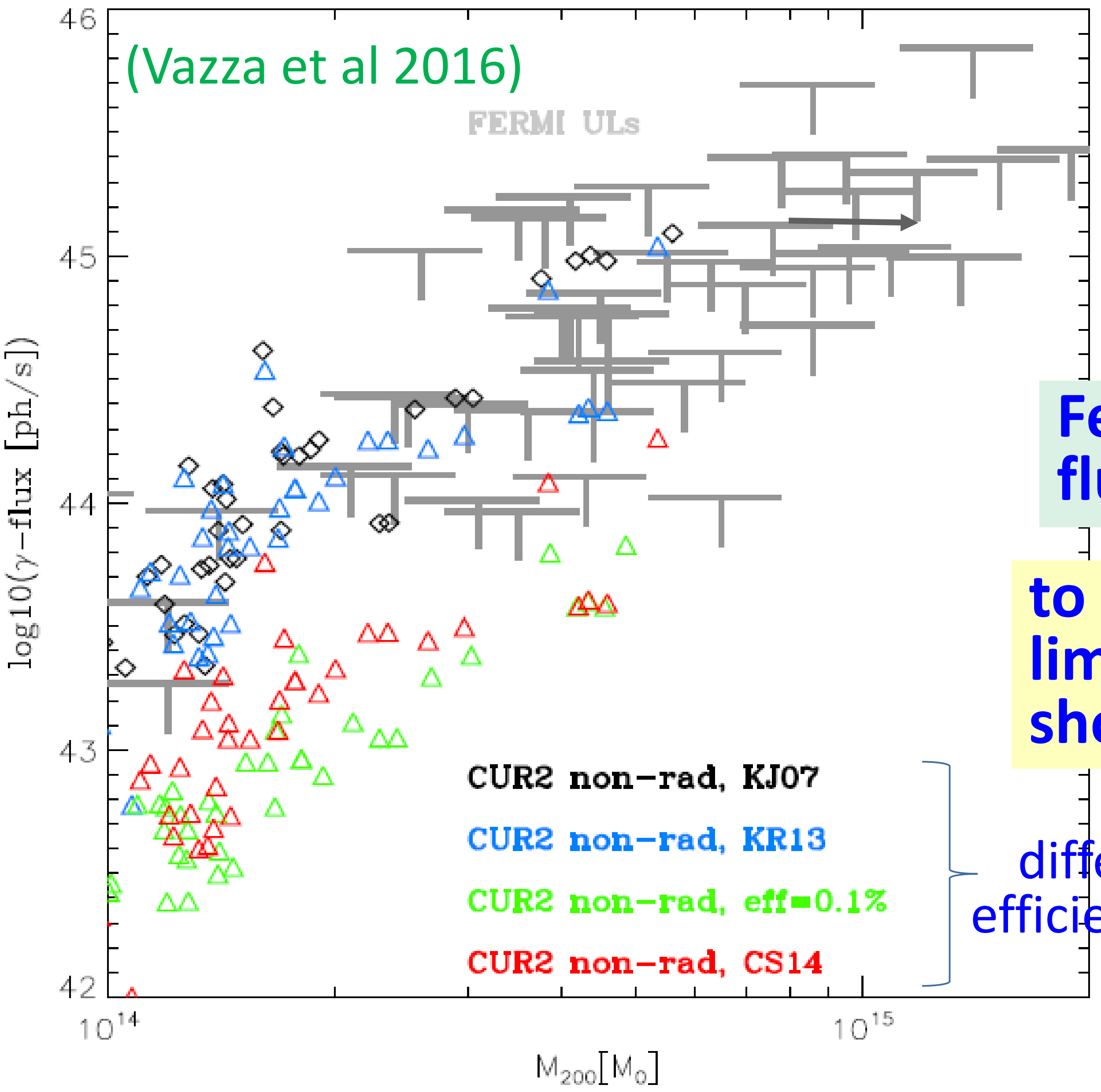
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu_{\mu}})$$

4. $\mu^{\pm}$ decays into $e^{\pm}$, e and μ-neutrinos

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\overline{\nu_{e}}) + \nu_{\mu}(\overline{\nu_{\mu}})$$



Constraint on CR protons in the ICM from gamma-ray obs



(Vazza et al 2016)

different DSA efficiency models

acceleration efficient
of CR protons

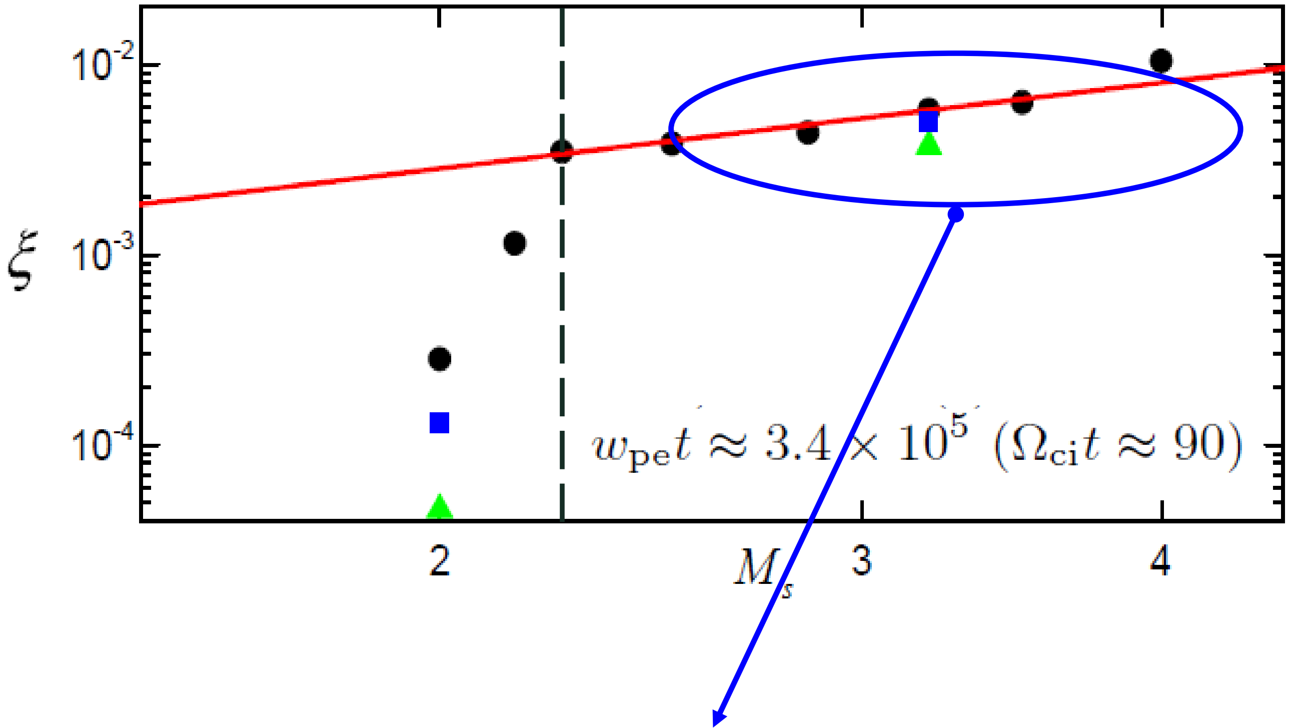
→ the fraction of shock
energy transferred to
CR protons

$$\eta \equiv \frac{E_{CR} u_2}{1/2 \rho V_s^3}$$

Fermi LAT upper limits on gamma-ray flux from individual clusters

to be compatible with Fermi upper limits, the CR proton acceleration eff. should be η < ~0.1% for 2 < M < 5

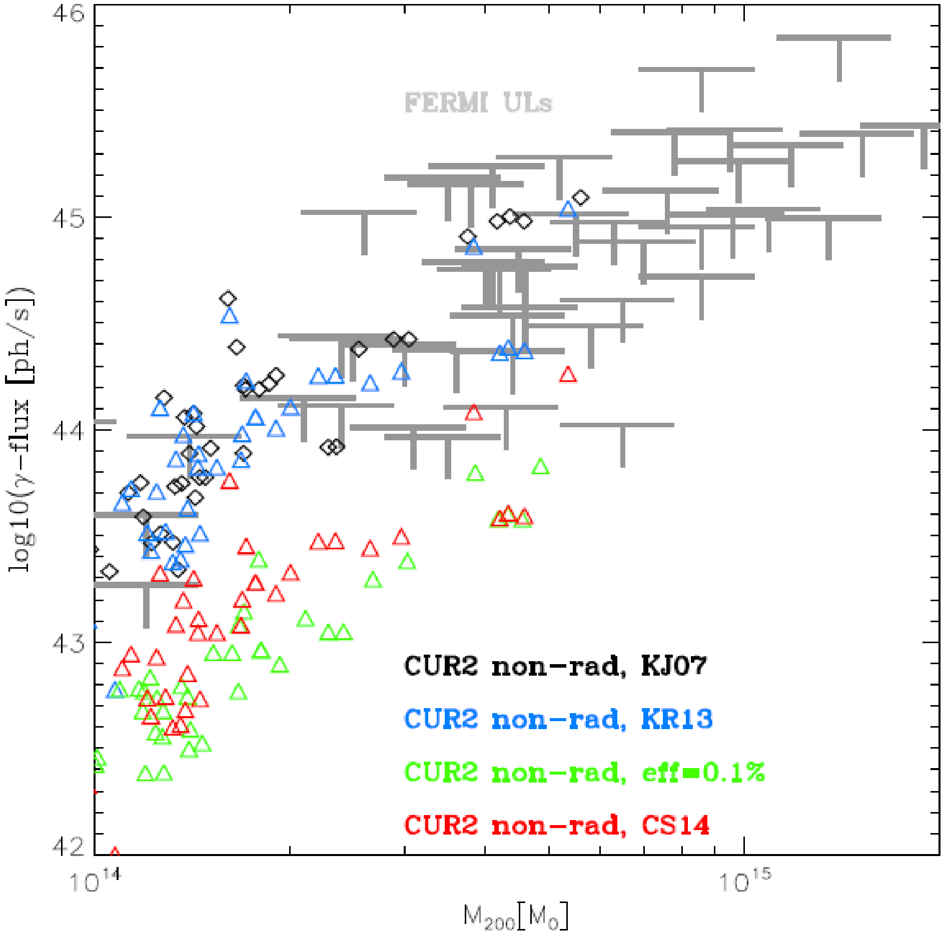
Injection fraction and acceleration efficiency



injection fraction **ξ ~ a few x 10^{-3}**

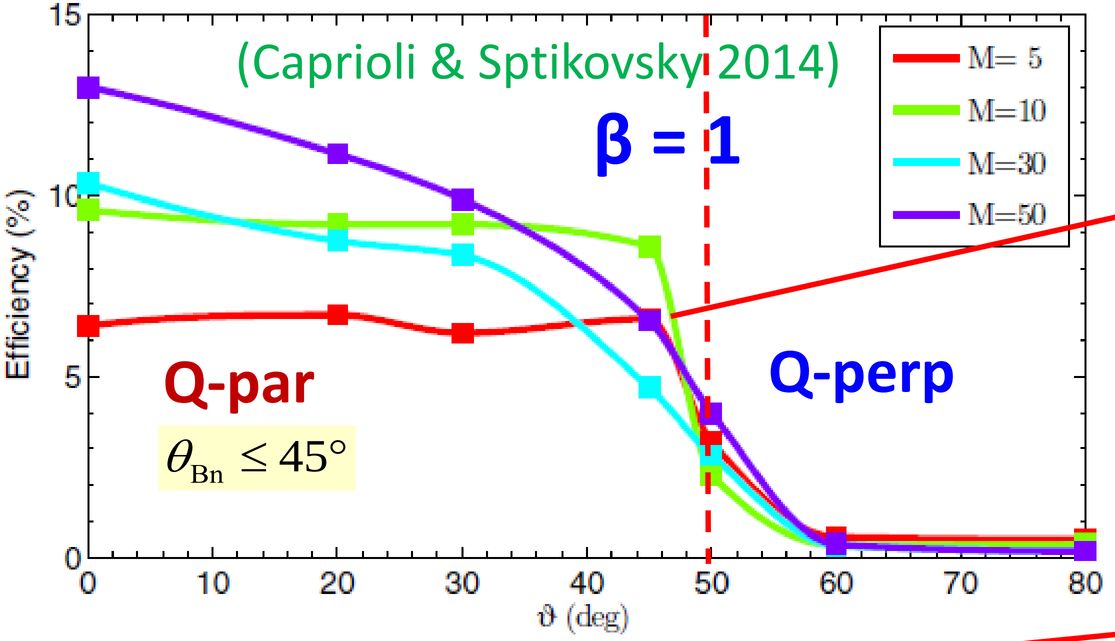
→ acceleration efficiency **η ~ a few %**

PIC simulations → too large ξ and η inconsistent with observation!



to be compatible with Fermi upper limits, the CR proton acceleration eff. should be **η < ~0.1% for 2 < M < 5**

CR proton acceleration efficiency from hybrid simulations



(Caprioli & Sptikovsky 2014)

β = 1

Q-par

$\theta_{\rm Bn} \leq 45°$

Q-perp

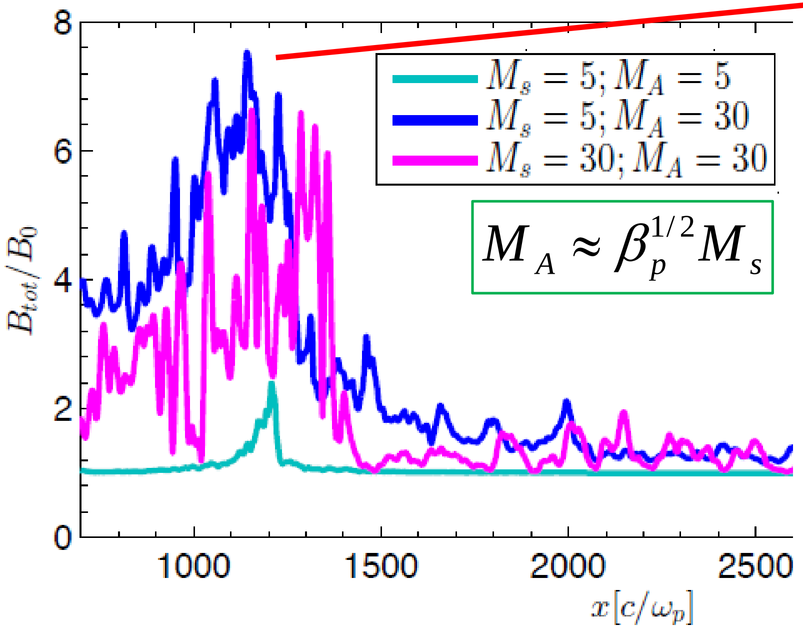
$$\frac{E_{CR,2}}{E_{CR,2}+E_{th,2}} \approx 0.06$$

$$\eta \equiv \frac{E_{CR,2}u_2}{1/2\rho V_s^3} = \frac{1}{r}\frac{E_{CR,2}}{E_{sh}}$$

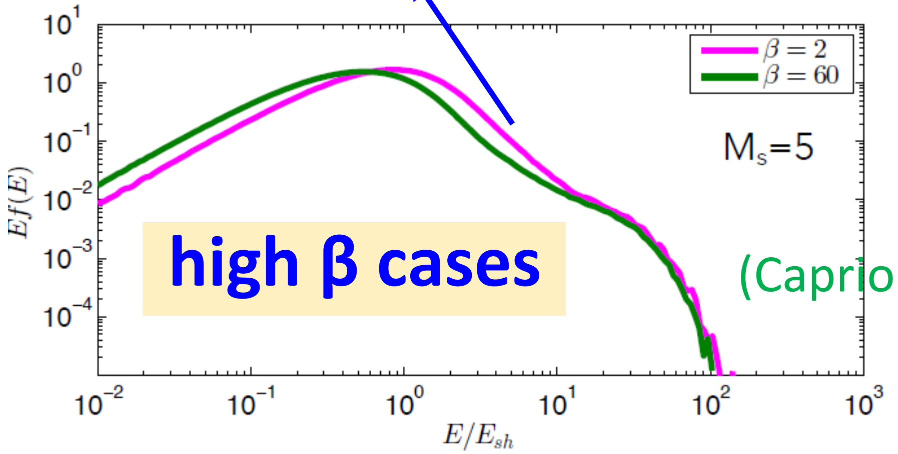
$$\eta \approx 0.036 \;\text{ for }\; M_s \approx 6.3\;(M = 5.0)$$

at $Q_{\|}$ shocks

- $\eta \sim 0.006 M_s$ for $M_s < 5$
- B amplification is controlled by M_A
- CR acceleration is governed by M_s



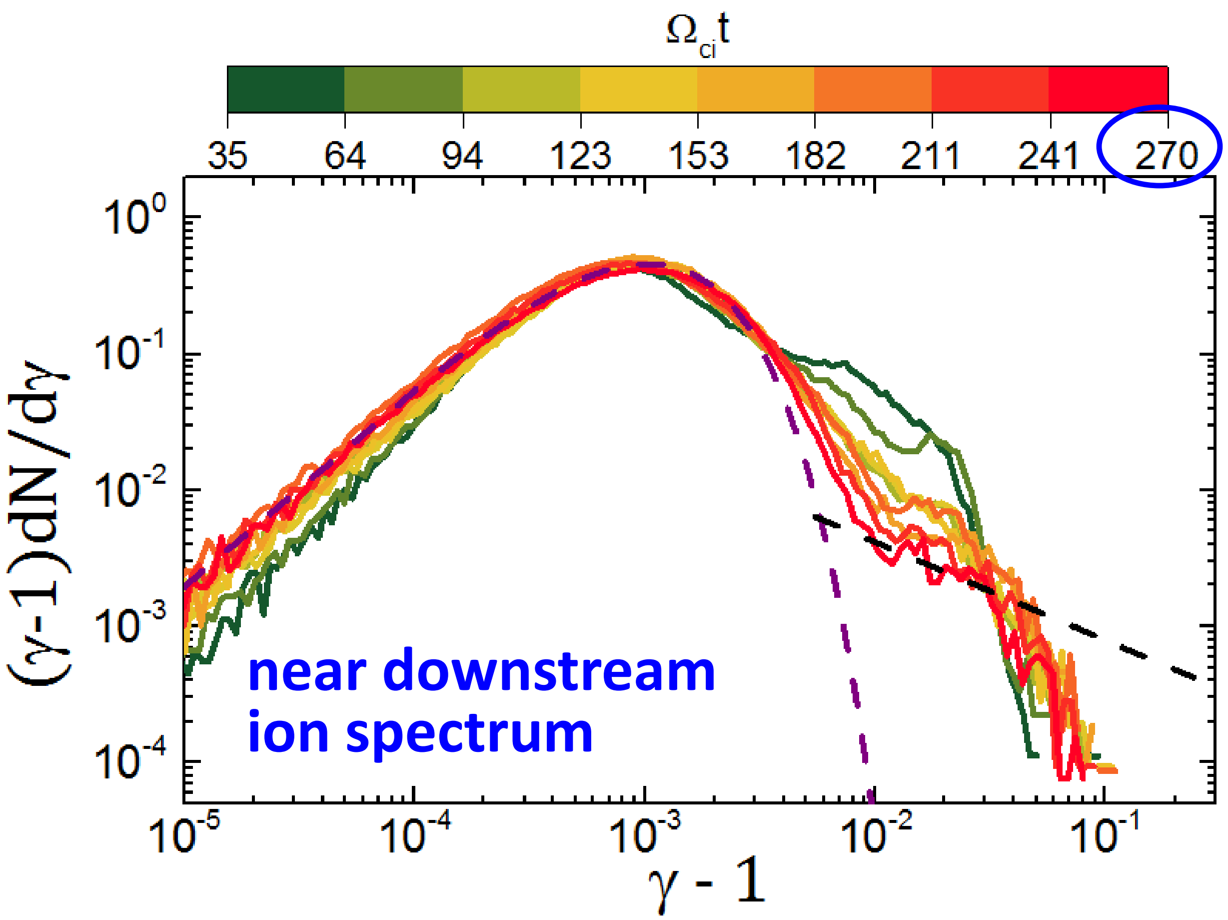
$$M_A \approx \beta_p^{1/2} M_s$$

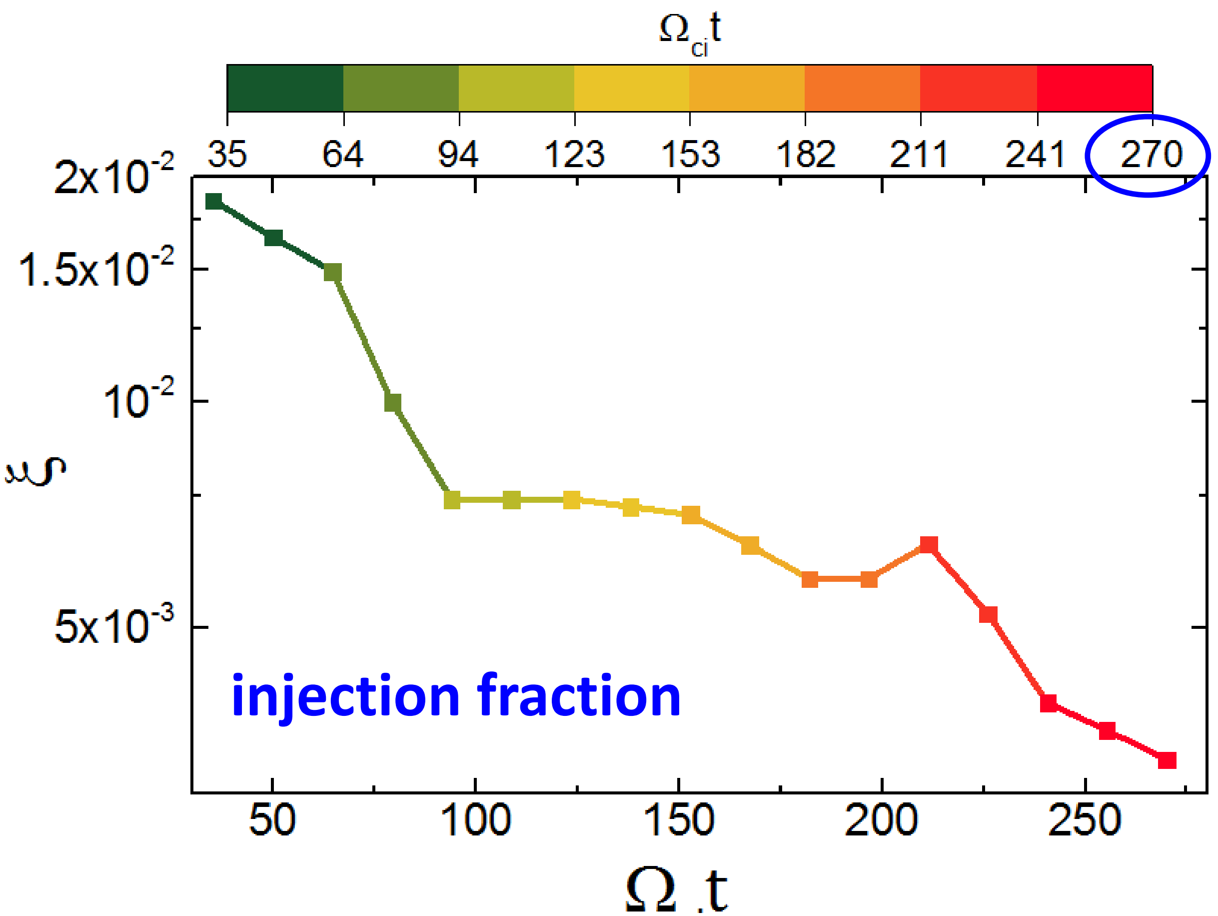


high β cases

(Caprioli 2017 KAW9)

Long-term evolution of Q-par shocks and proton acceleration





(Ryu, Kang, Ha 2019)

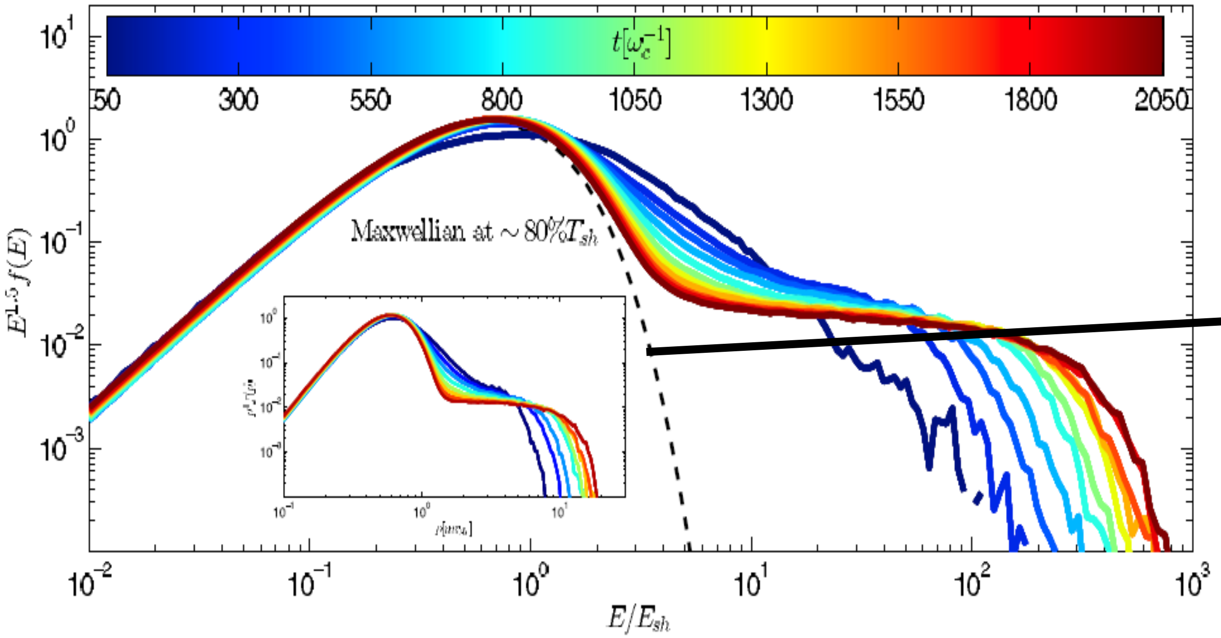
PIC simulation

ICM shock with M_s = 3.2

the spectrum extends to higher energies,
but the injection faction decreases as the time goes on.

Long-term evolution in hybrid simulation

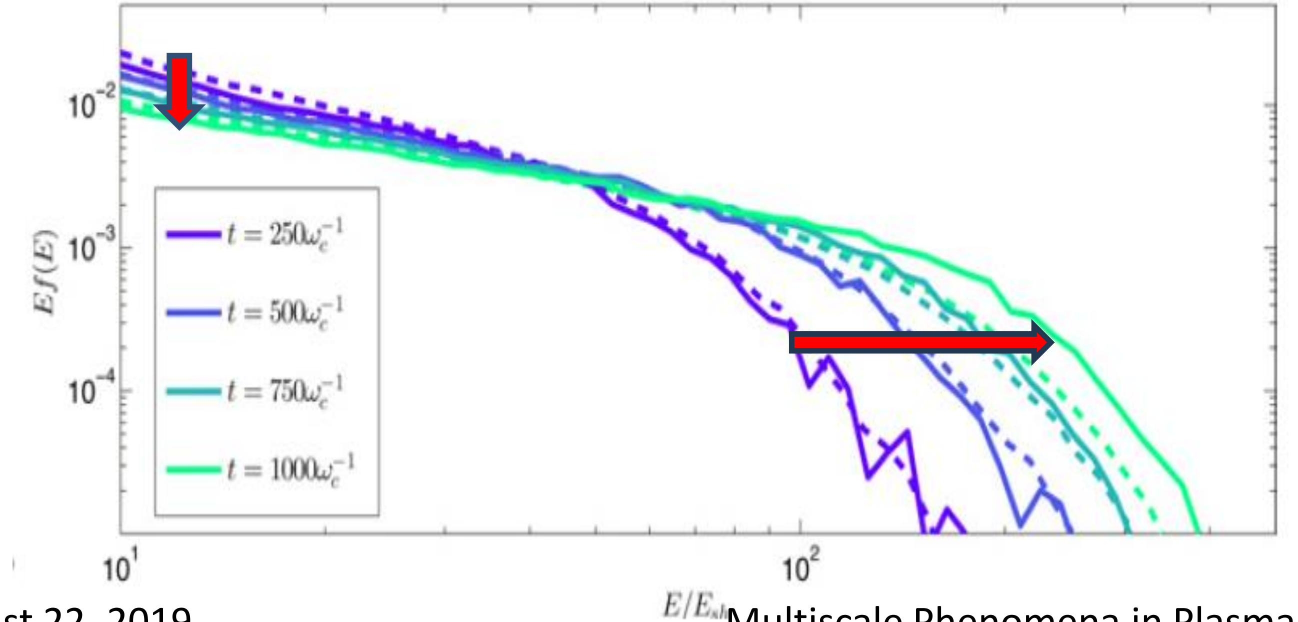
(Caprioli & Sptikovsky 2014)



β = 1, M_A ~ M_s ~ 20

cooled Maxwellian

+ DSA power-law above p_{inj}



as the spectrum extends to higher p_{max} in time, amplitude of f(p) decreases
→ acceleration efficiency ??

"Very" long-term evolution of collisionless shocks is beyond the scope of kinetic simulations!

A model for DSA of protons in ICM shocks

(Ryu, Kang, Ha
2019, in press)

(1) **The CR proton spectrum follows the test-particle DSA power-law**

$$f_{\rm CR}(p) \propto p^{-q} \qquad q = 3r/(r-1)$$

← weak shocks

(2) **The transition from the postshock thermal to CR spectra occurs at the injection momentum**

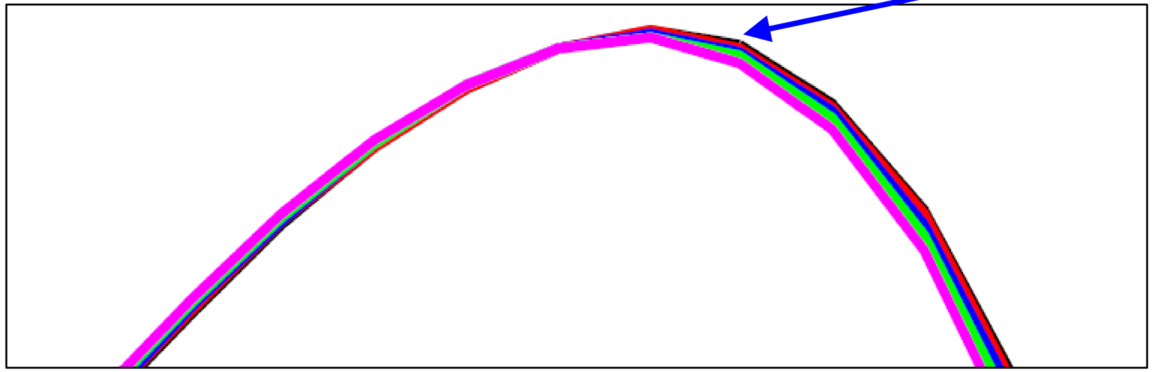
$$p_{\rm inj} = Q_{\rm i} \cdot p_{\rm th,p}$$

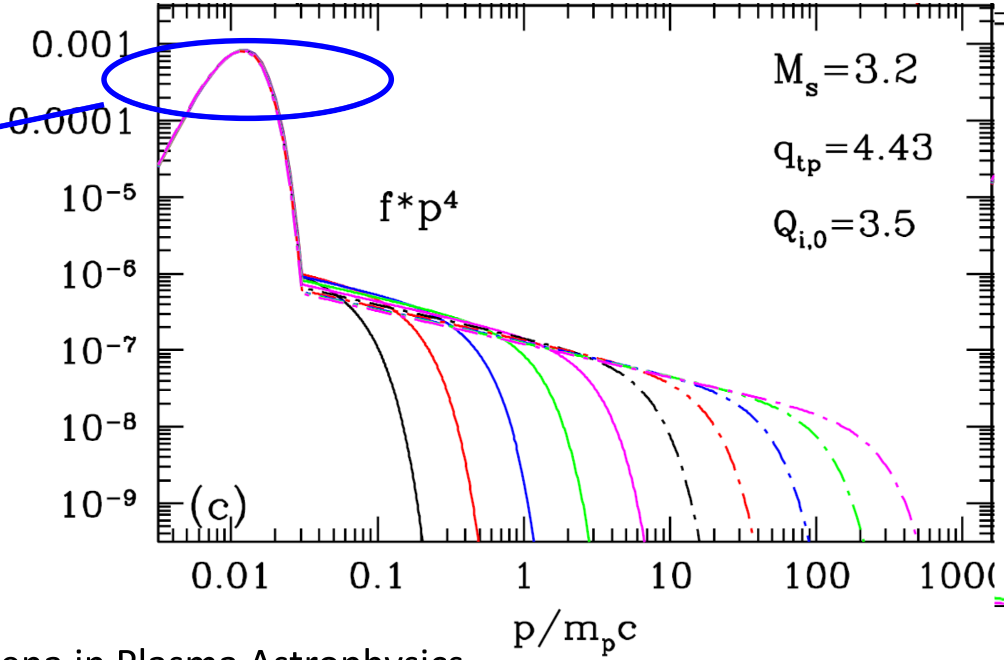
Q_i the injection parameter ~ 3 – 3.5 (hybrid sim)

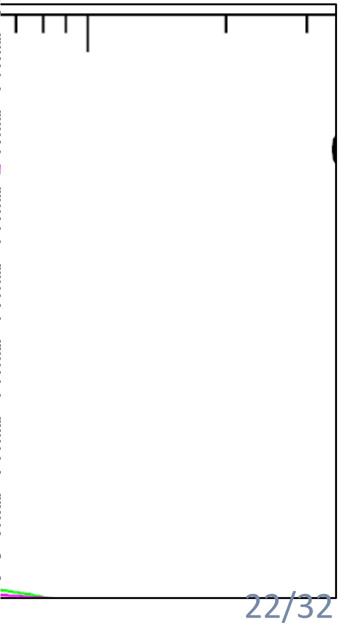
← "free parameter"

(3) **As the fraction of the shock energy transferred to CR protons, the postshock temperature decreases**

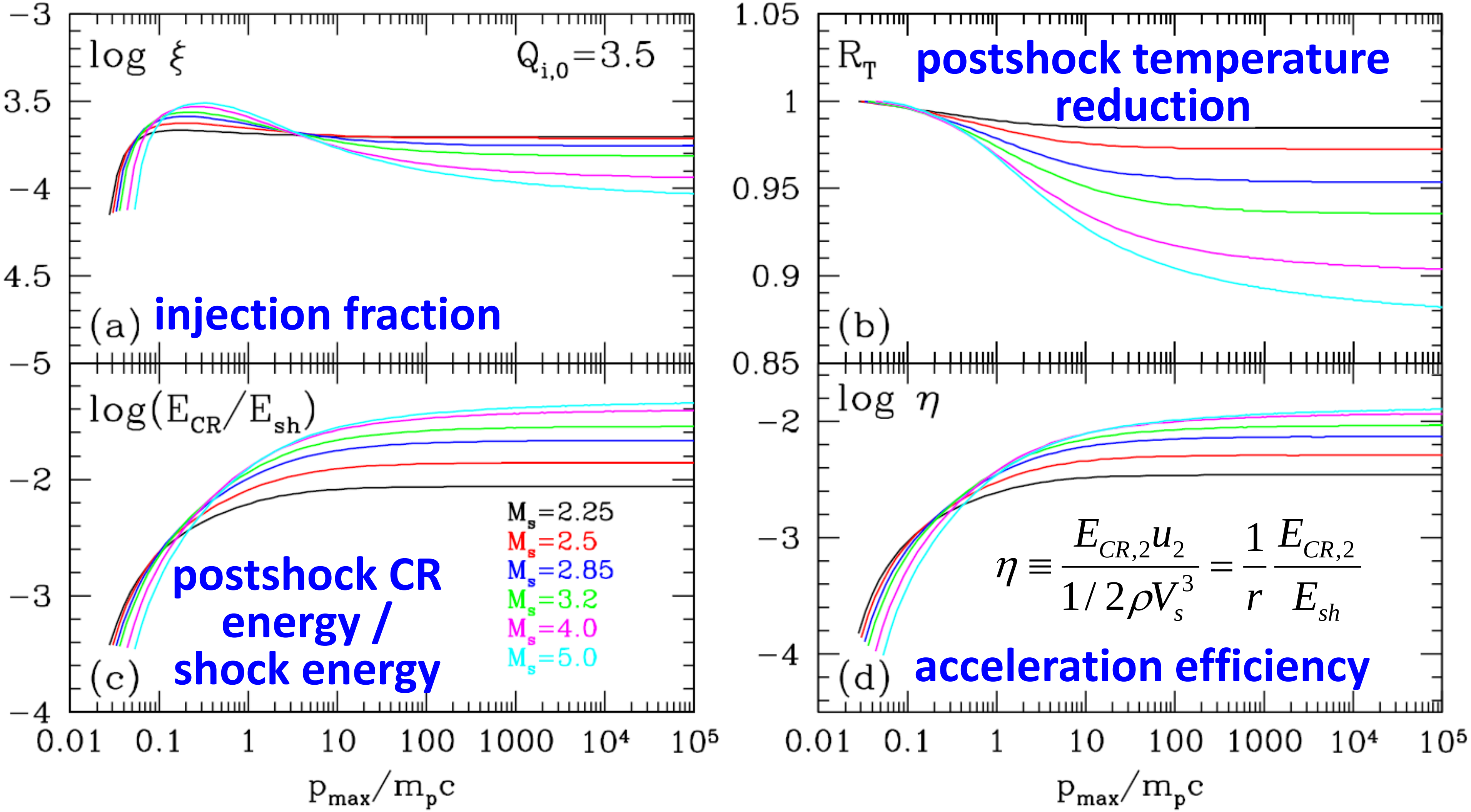
← energy conservation







Change of parameters in the model as p_{max} increases



injection fraction

postshock temperature reduction

postshock CR energy / shock energy

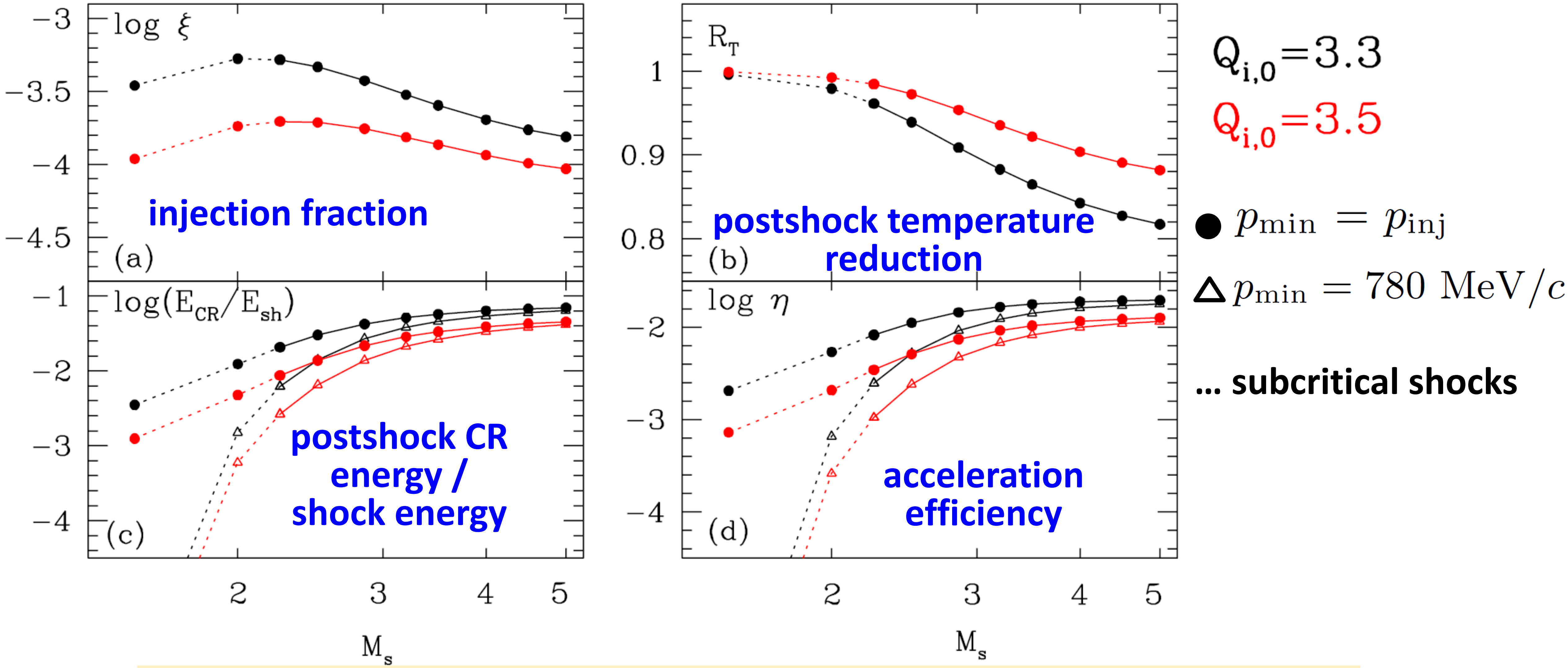
acceleration efficiency

$$\eta \equiv \frac{E_{CR,2}u_2}{1/2\rho V_s^3} = \frac{1}{r}\frac{E_{CR,2}}{E_{sh}}$$

as the CR proton spectrum extends to higher energies, the above parameters converge

$$p_{\min} = p_{\rm inj}$$

Converged value of parameters in the model

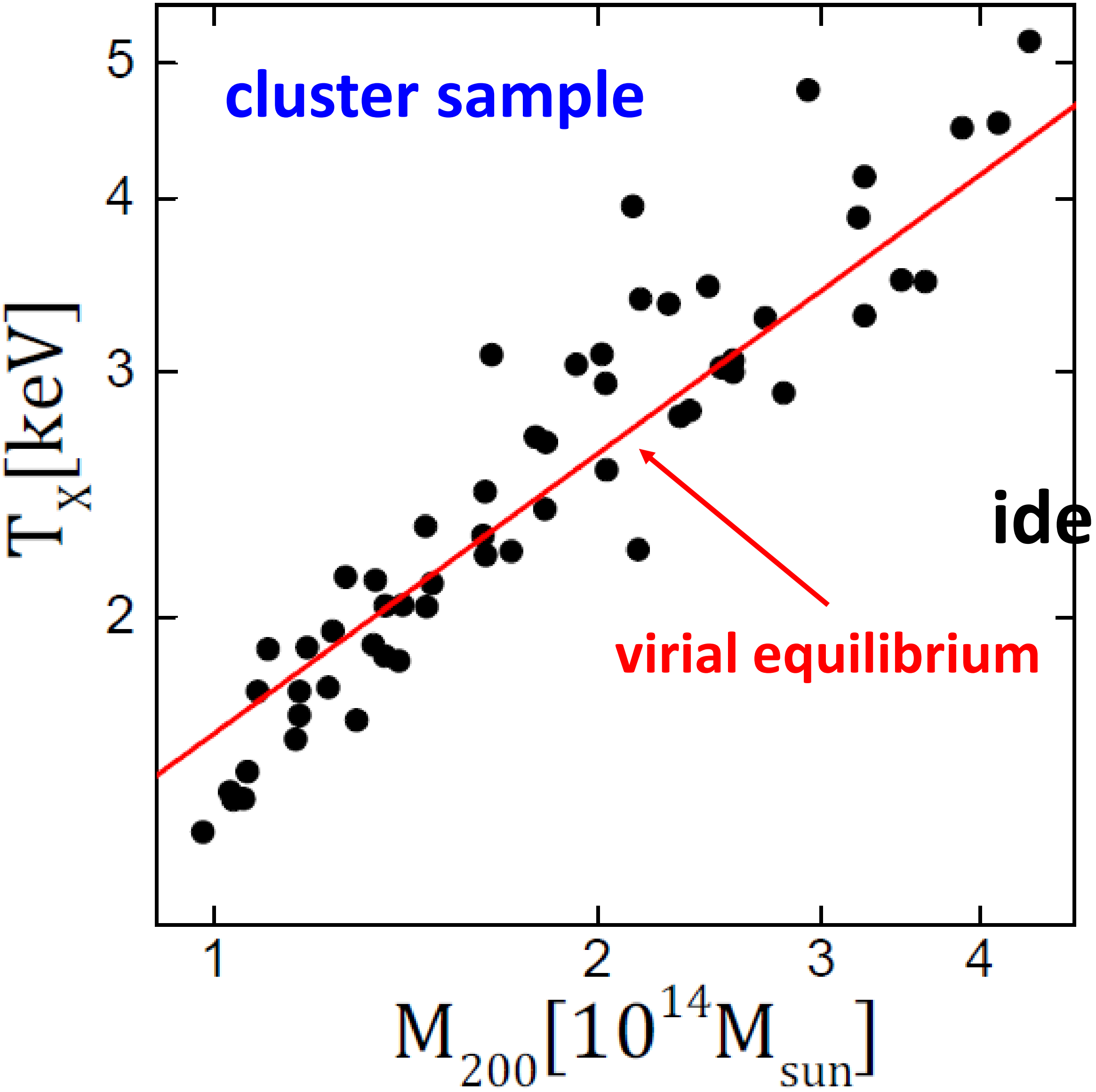


… subcritical shocks

The model predicts the acceleration efficiency ~ 10^{-3} to 0.02 for supercritical quasi-parallel shocks with M_s < 5 in the ICM

Gamma-ray from simulated galaxy clusters with the new efficiency

(Ha, Ryu, Kang, to be submitted)



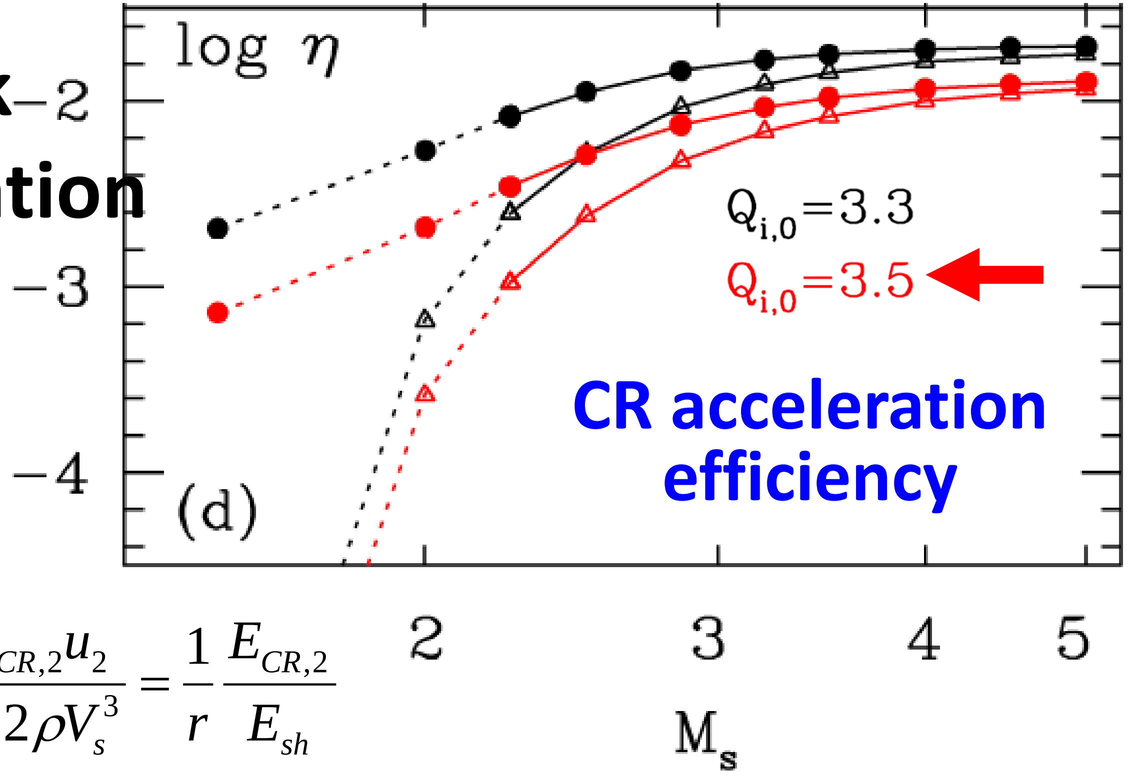
cluster sample

virial equilibrium

4 simulations of the large-scale structures of the universe in 57 h^{-1} Mpc box using 1650^3 uniform grid zones

shock identification

+



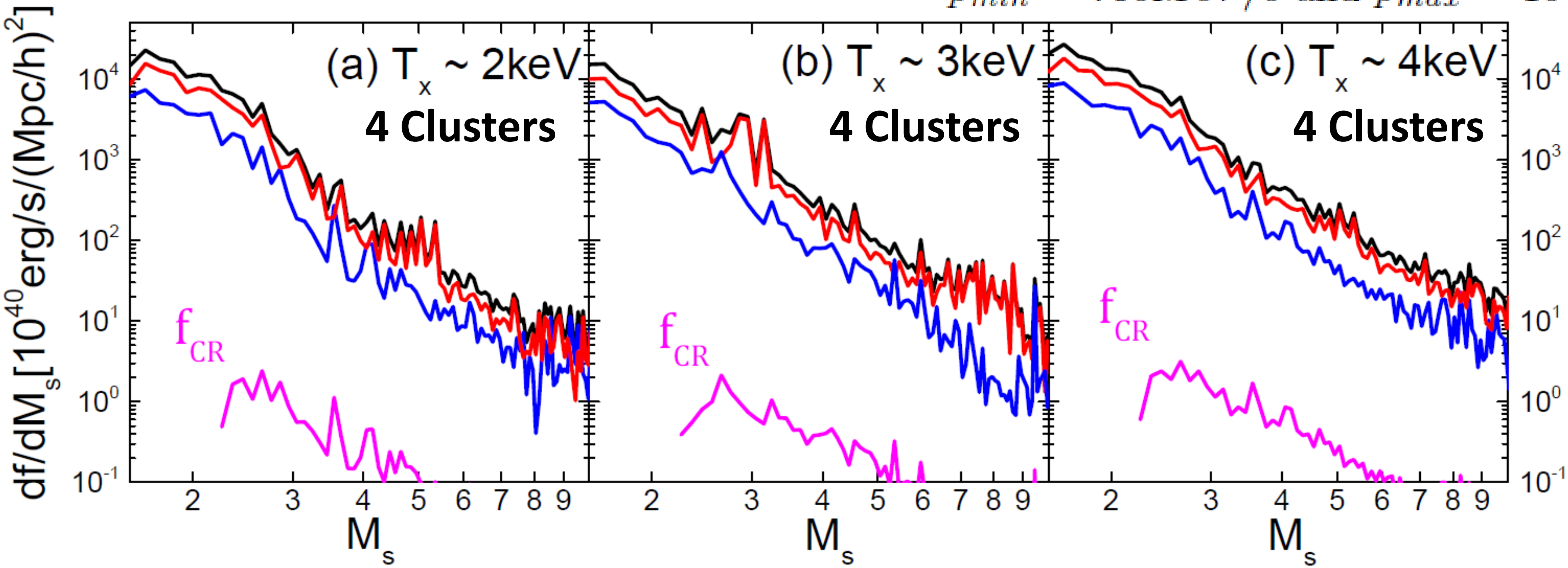
CR acceleration efficiency

$$\eta \equiv \frac{E_{CR,2}u_2}{1/2\rho V_s^3} = \frac{1}{r}\frac{E_{CR,2}}{E_{sh}}$$

Kinetic and CR energy fluxes through shocks in galaxy clusters

$$f_\phi = (1/2)\rho_1 v_s^3 \qquad f_{\rm CR} = 4\pi c u_2 \int_{p_{min}}^{p_{max}} (\sqrt{p^2+(m_p c)^2} - m_p c) f_{p,i}(p) p^2 dp.$$

$$p_{min} = 780 MeV/c \text{ and } p_{max} = 10^5 MeV/c.$$



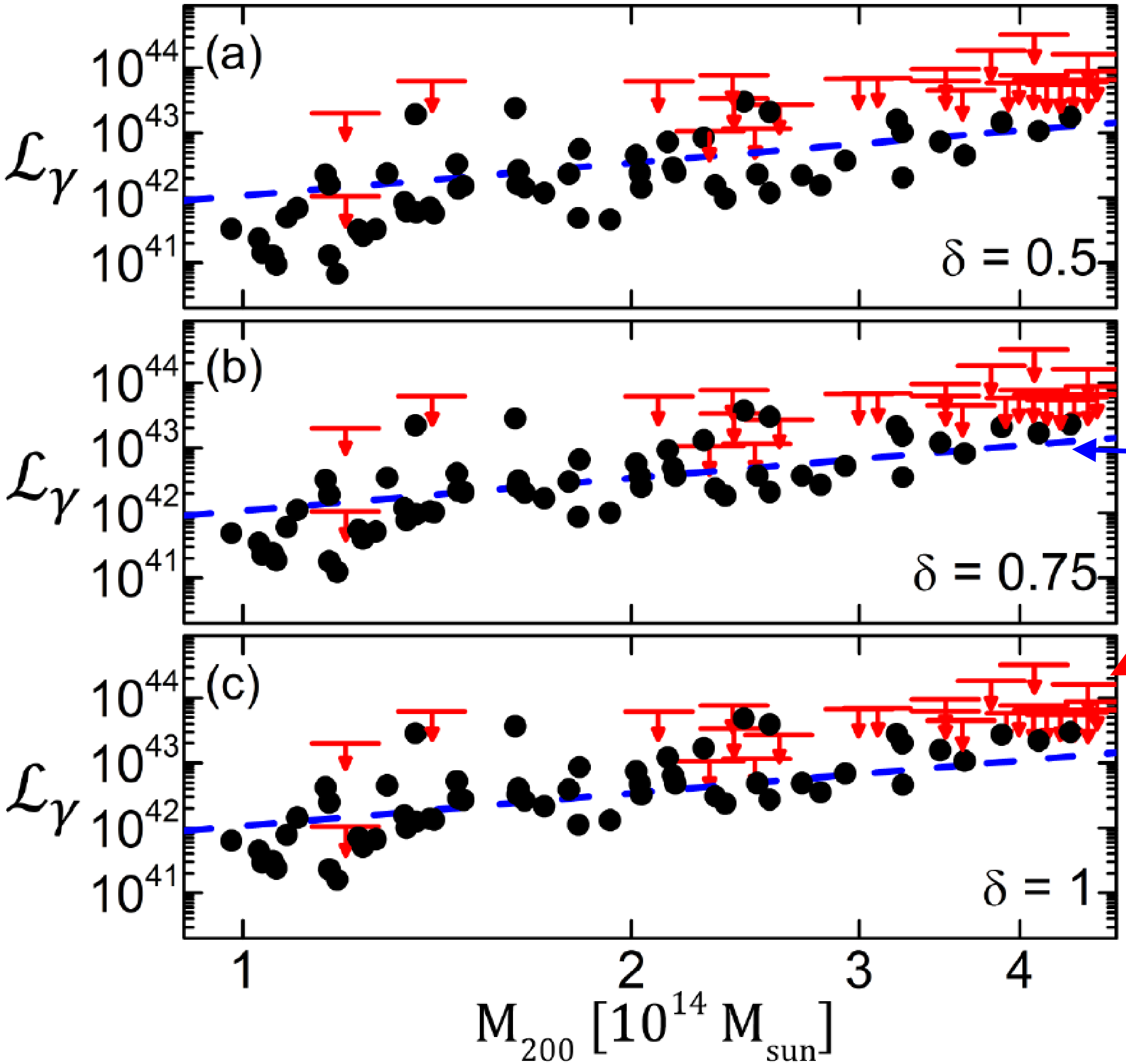
at z = 0,
r < virial
radius

1) ~30%(~23% Q-perp + ~7% Q-para) kinetic energy: $M_s > 2.25$

2) ~70%(~46% Q-perp + ~24% Q-para) kinetic energy: $1.5 < M_s < 2.25$

CR protons produced in clusters: CR energy flux ~ 10^{-4} shock kinetic energy flux

Gamma-ray luminosity of simulated galaxy clusters



$$\mathcal{L}_\gamma = \int_0^{r_{200}} 4\pi r^2 dr \int_{E1}^{E2} q_\gamma(r, E_\gamma) dE_\gamma$$

$$[\mathrm{E1},\ \mathrm{E2}] = [0.5,\ 200]\ \mathrm{GeV}$$

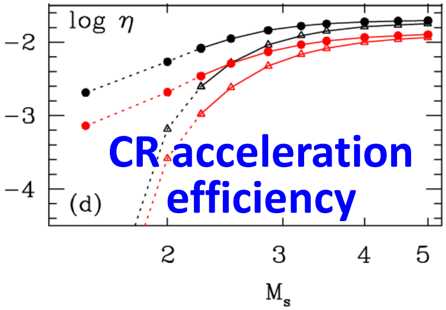
using the source q_γ in Pfrommer & Ensslin (2004)

$$n_{CR,p} \propto \rho_{gas}^{\delta}$$

$$L_\gamma \propto M_{200}^{5/3}$$

Fermi LAT upper limit

● simulated clusters



CR acceleration efficiency

consistent with the Fermi LAT upper limit

Gamma-ray (and neutrino emission) through p-p interaction

Interaction between CR proton and baryonic matter

1. **In inelastic p-p collisions, π's are produced**

$$P_{\rm CR} + P_{\rm ICM,thermal} \rightarrow \pi^{\pm} + \pi^{0}$$

2. **π^0 decays into two gamma-rays**

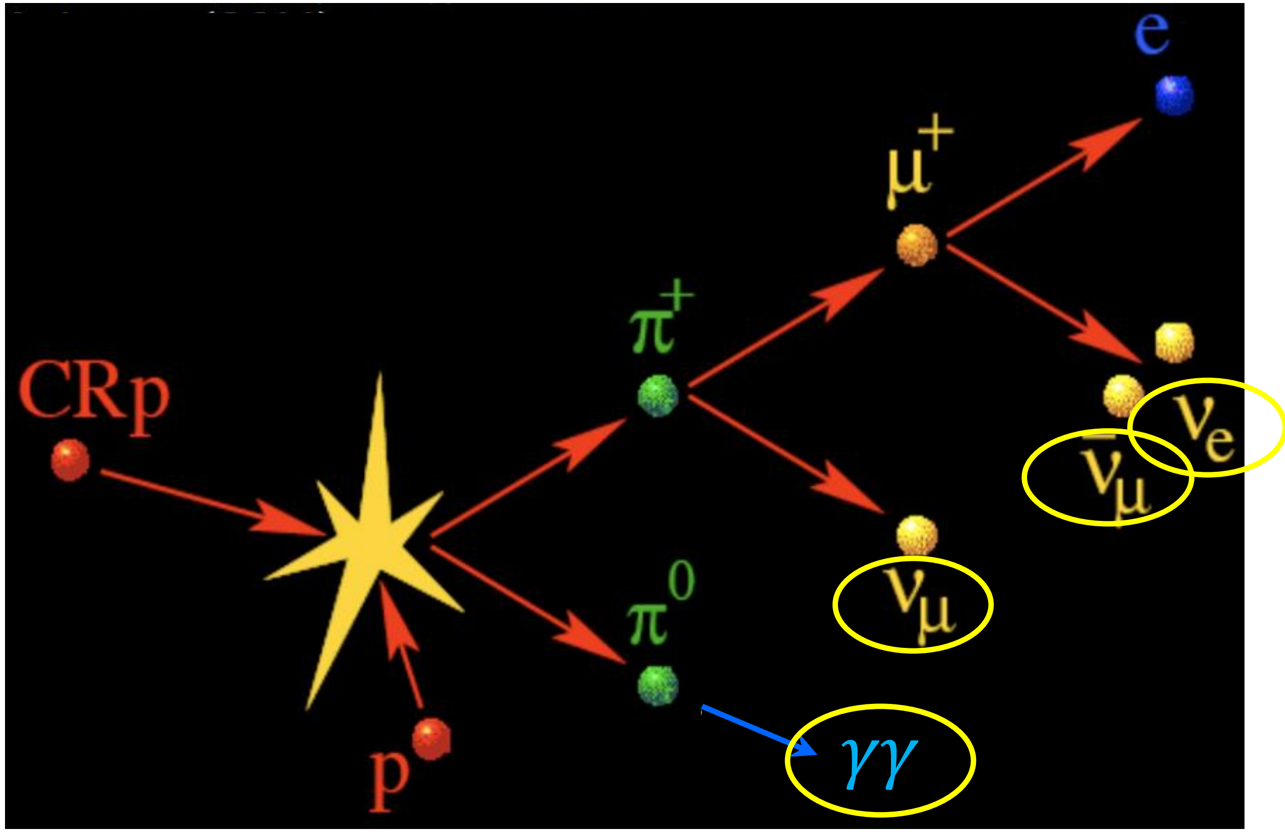
$$\pi^{0} \rightarrow \gamma\gamma$$

3. **$\pi^{\pm}$ decays into $\mu^{\pm}$ and μ-neutrino**

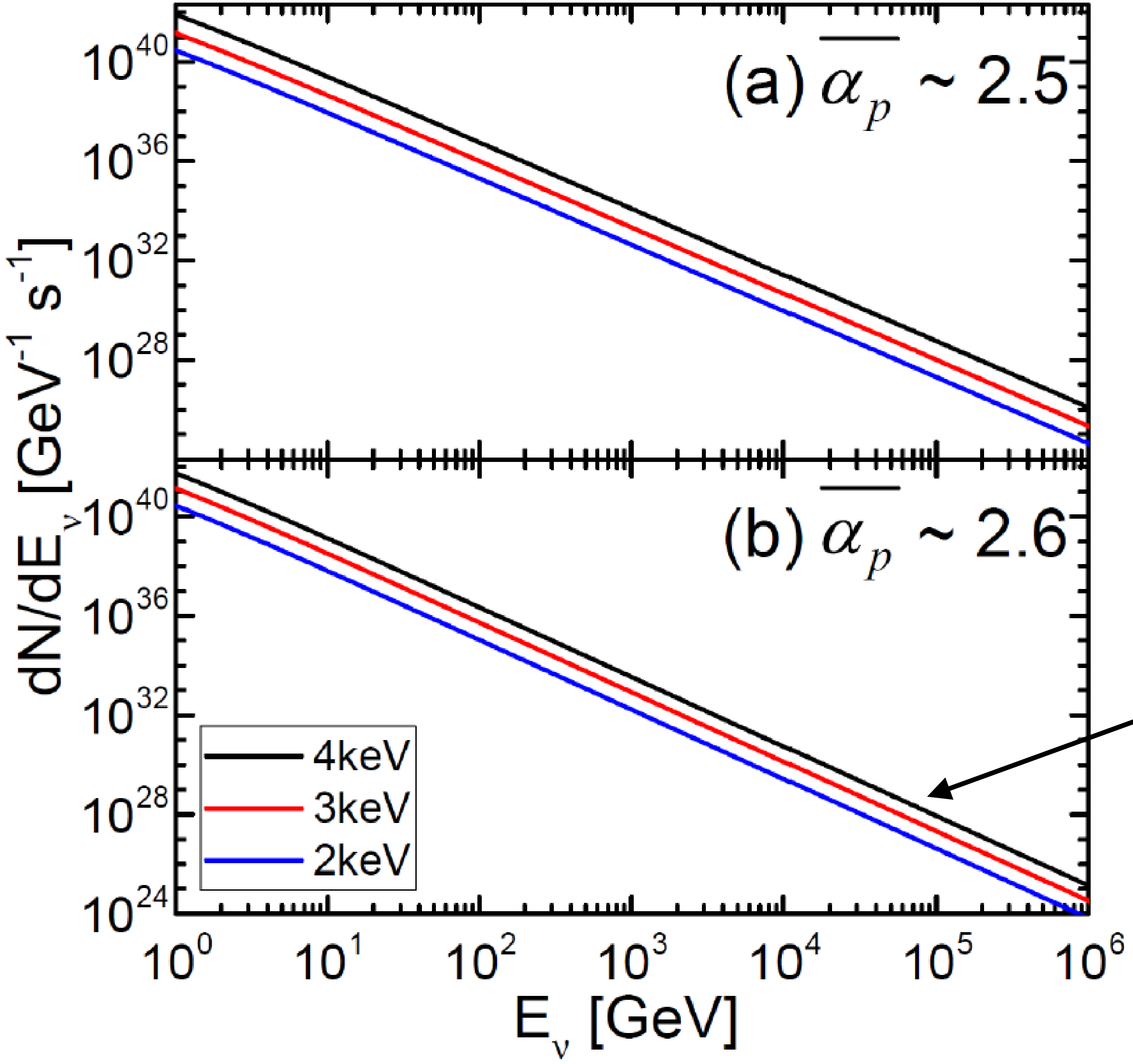
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu_{\mu}})$$

4. **$\mu^{\pm}$ decays into $e^{\pm}$, e and μ-neutrinos**

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\overline{\nu_{e}}) + \nu_{\mu}(\overline{\nu_{\mu}})$$



Neutrinos emitted from simulated galaxy clusters



neutrino energy spectrum

$$\frac{dN}{dE_\nu} = \int_{<r_{200}} q_\nu(r, E_\nu) 4\pi r^2 dr$$

using q_ν/q_γ from Kelner et al. (2006)

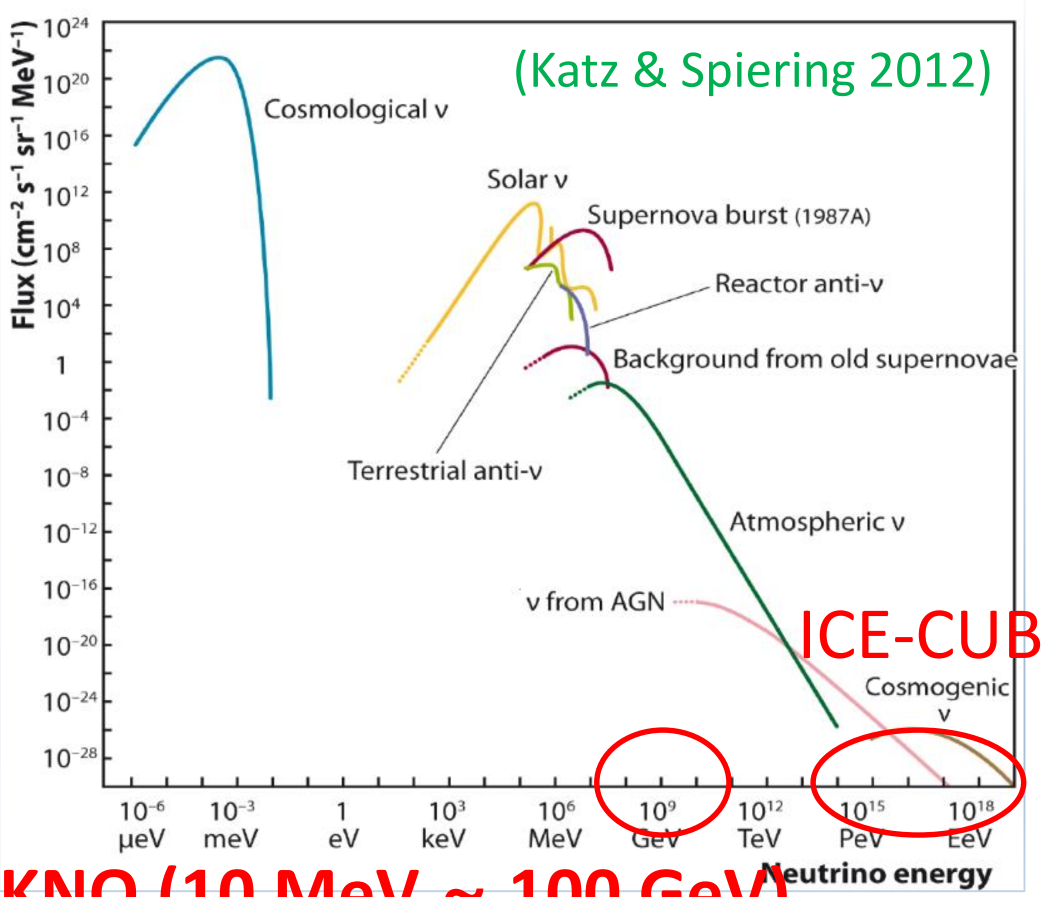
$\overline{\alpha_p}$:the slope of the momentum spectrum of volume-integrated CR protons

clusters of different temperatures

our N_ν is an order of magnitude or more smaller than Zandanel et al (2015)

Can neutrinos from galaxy clusters be detected?

a typical neutrino flux plot commonly shown in the particle physics community

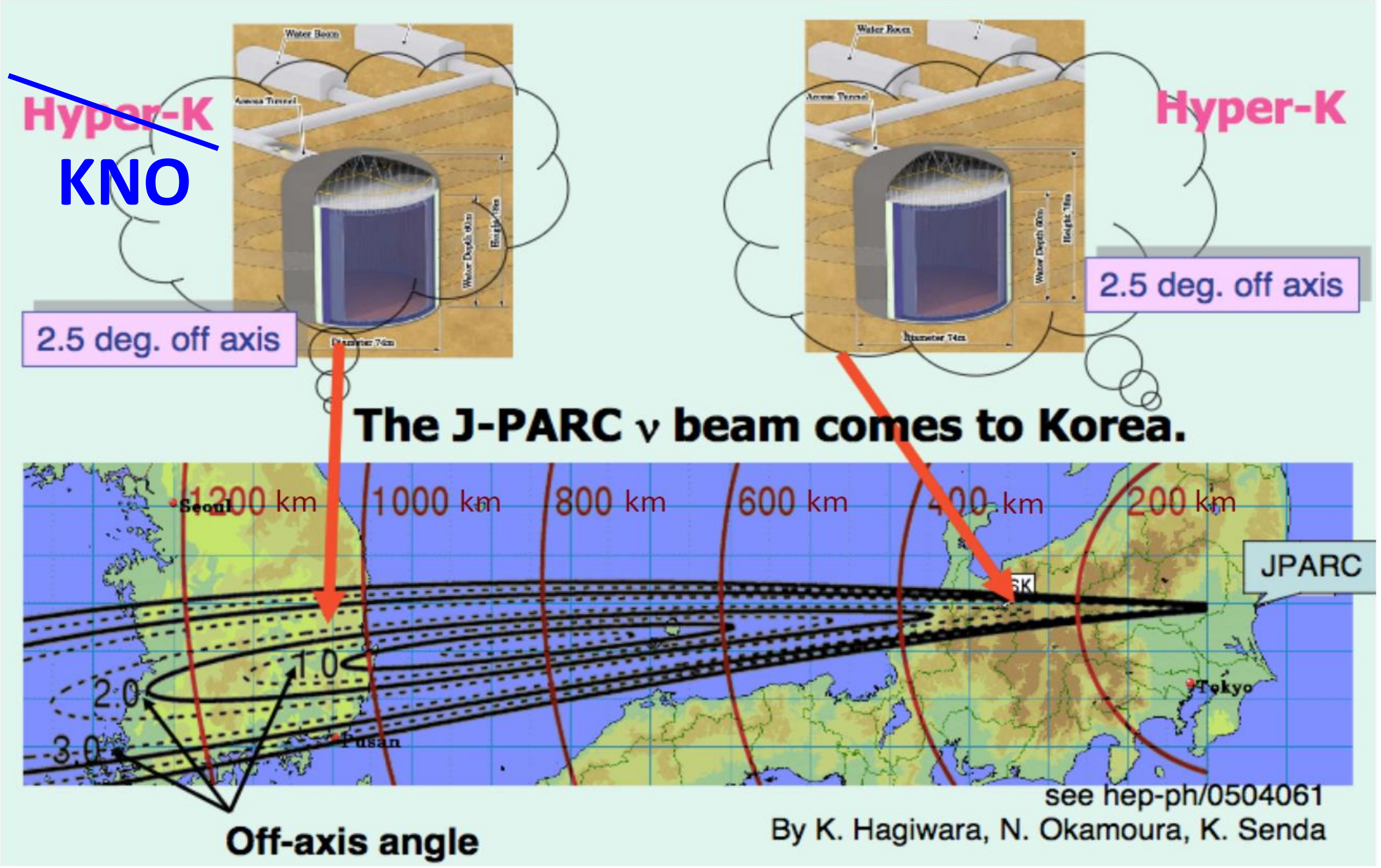


(Katz & Spiering 2012)

ICE-CUBE

KNO (10 MeV ~ 100 GeV)

2nd Hyper-K Detector in Korea



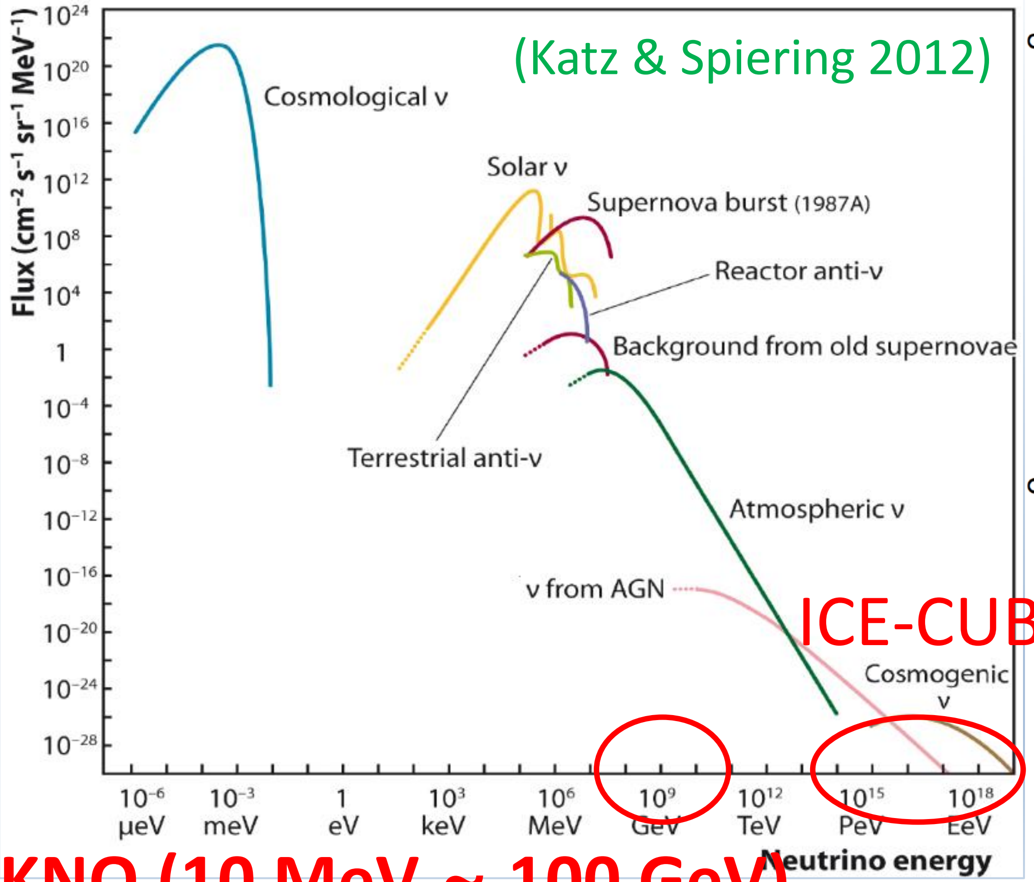
The J-PARC ν beam comes to Korea.

see hep-ph/0504061
By K. Hagiwara, N. Okamoura, K. Senda

Korean Neutrino Observatory (KNO), which is tuned for astrophysical neutrinos as well as for reactor neutrinos, has been "proposed"

Can neutrinos from galaxy clusters be detected?

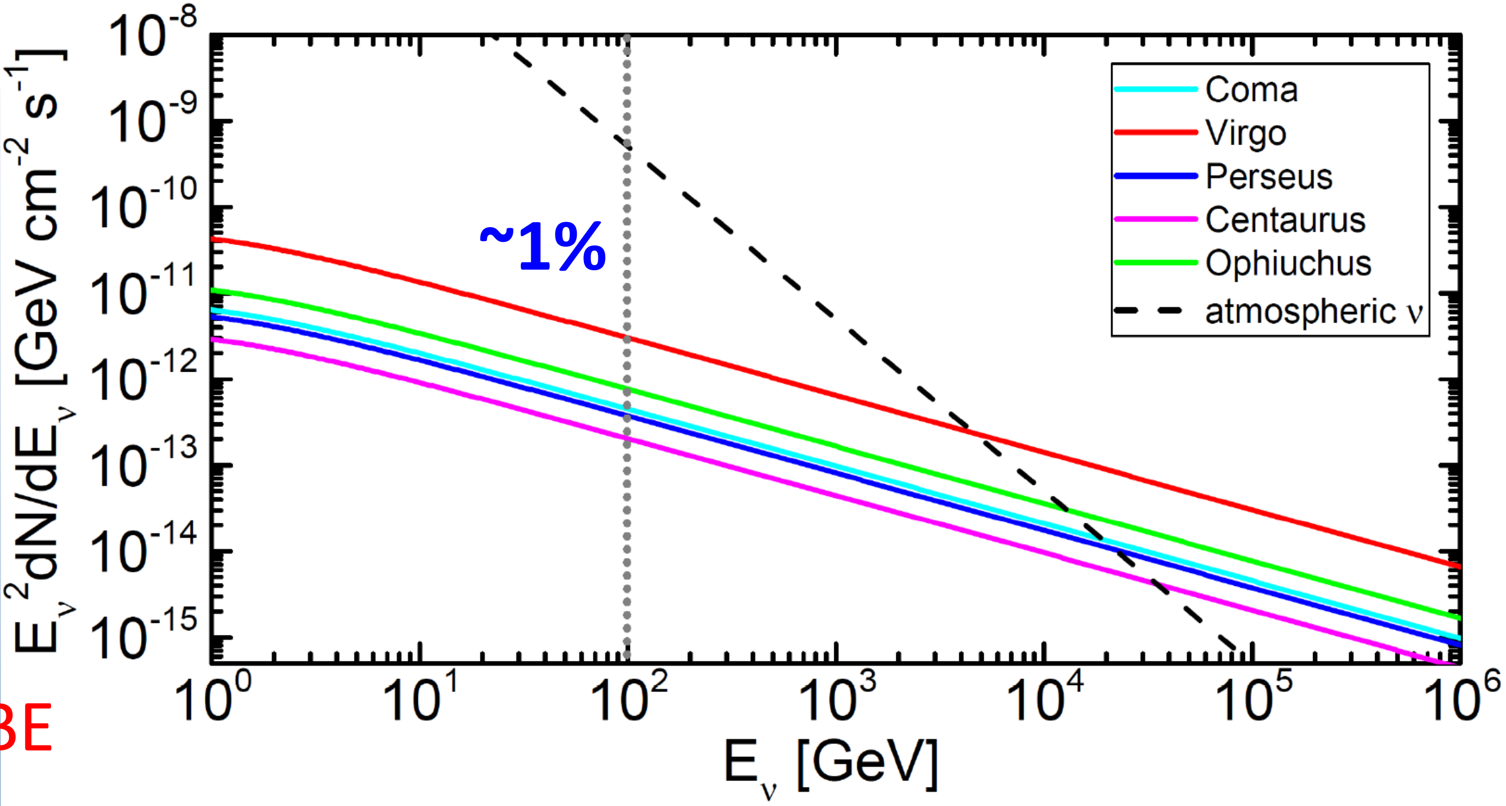
a typical neutrino flux plot commonly shown in the particle physics community



ICE-CUBE

KNO (10 MeV ~ 100 GeV)

neutrino flux in a circular beam of 5° diameter



the neutrino flux from nearby galaxy clusters is ~ 1% of that of atmospheric neutrino at 100 GeV – can it be detected?

Summary

1. Shocks are ubiquitous in galaxy clusters:
   merger shocks of Ms < ~ a few to several are energetically most important.

2. In high beta ICM, supercritical quasi-parallel shocks with $M_s > \sim 2.3$ may
   inject suprathermal protons to DSA and accelerate CR protons.

3. A model for DSA of protons is suggested:
   - in the model, the acceleration efficiency of CR protons is predicted to be ~ 10^{-3} to 0.02 for ICM supercrical shocks

4. With the acceleration efficiency of ~ 10^{-3} to 0.02
   - the estimated gamma-ray lum is consistent with the Fermi-LAT upper limit
   - the neutrino flux from nearby galaxy clusters is ~ 1% of that of atmospheric neutrino at 100 GeV

We need to understand the long term evolution of collisionless shocks!

Thank you !