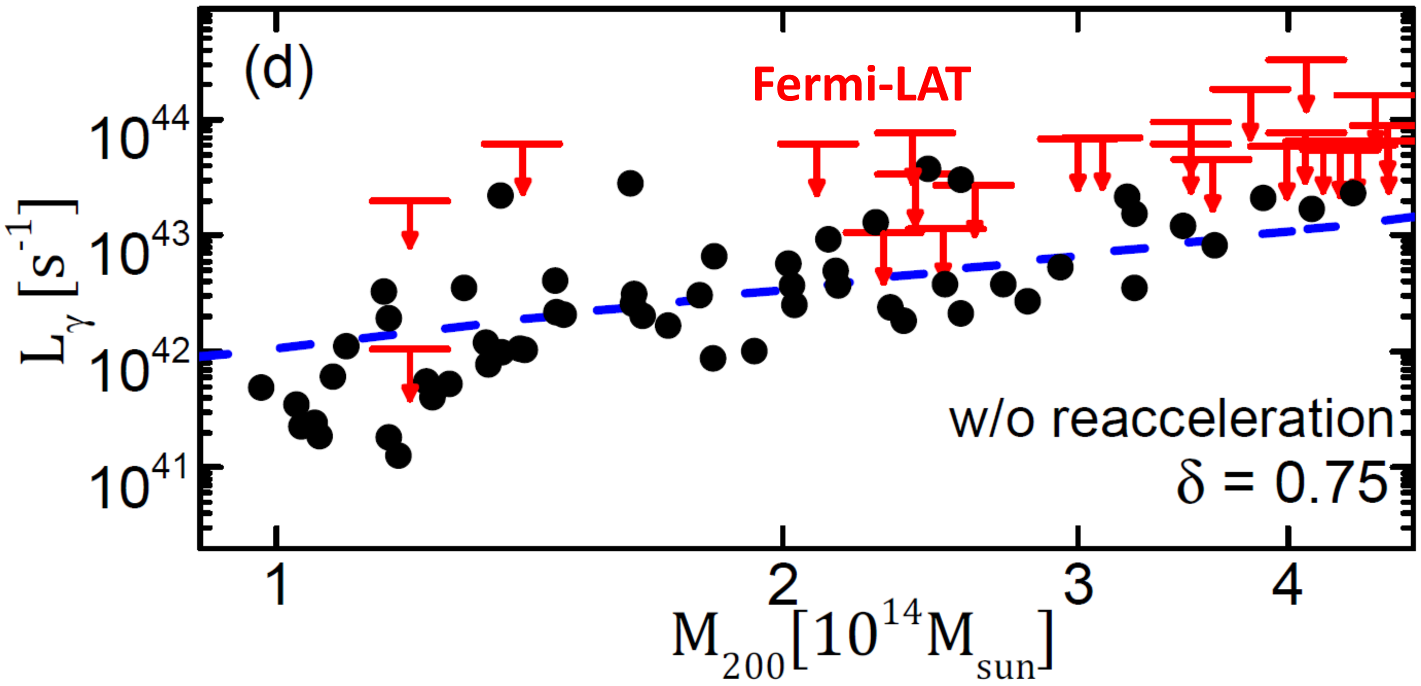
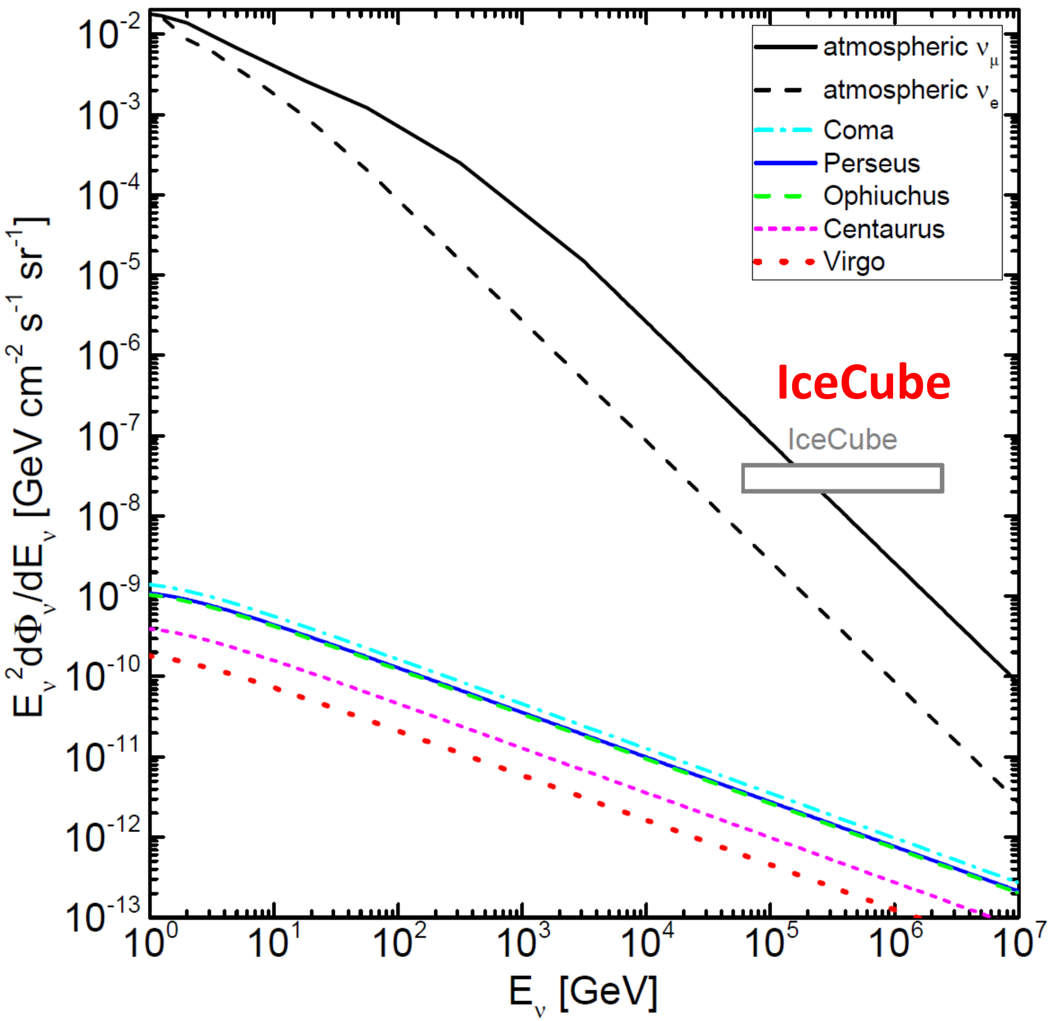
Neutrinos (and Gamma-rays) from Galaxy Clusters



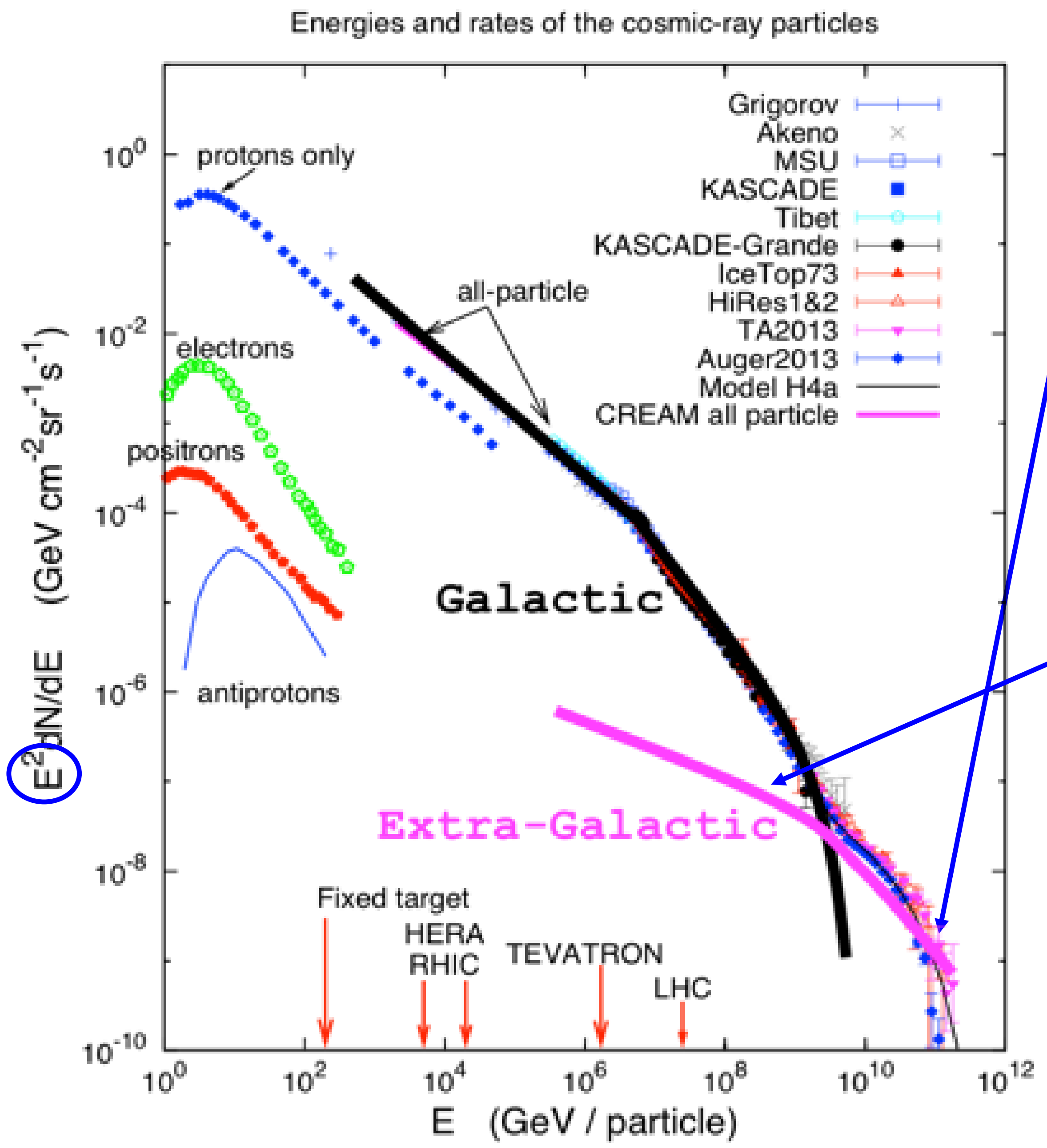


Dongsu Ryu (UNIST, Korea)

Ji-Hoon Ha (UNIST, Korea),

Hyesung Kang (Pusan Nat. Univ., Korea)

Extragalactic cosmic rays (CRs)



ultra-high energy cosmic rays (UHECRs) with E > 10^{18} ~ 10^{19} eV

mostly hadrons (P, CNO, Fe, …)

"**sources**" ?

extragalactic CRs in lower energies:

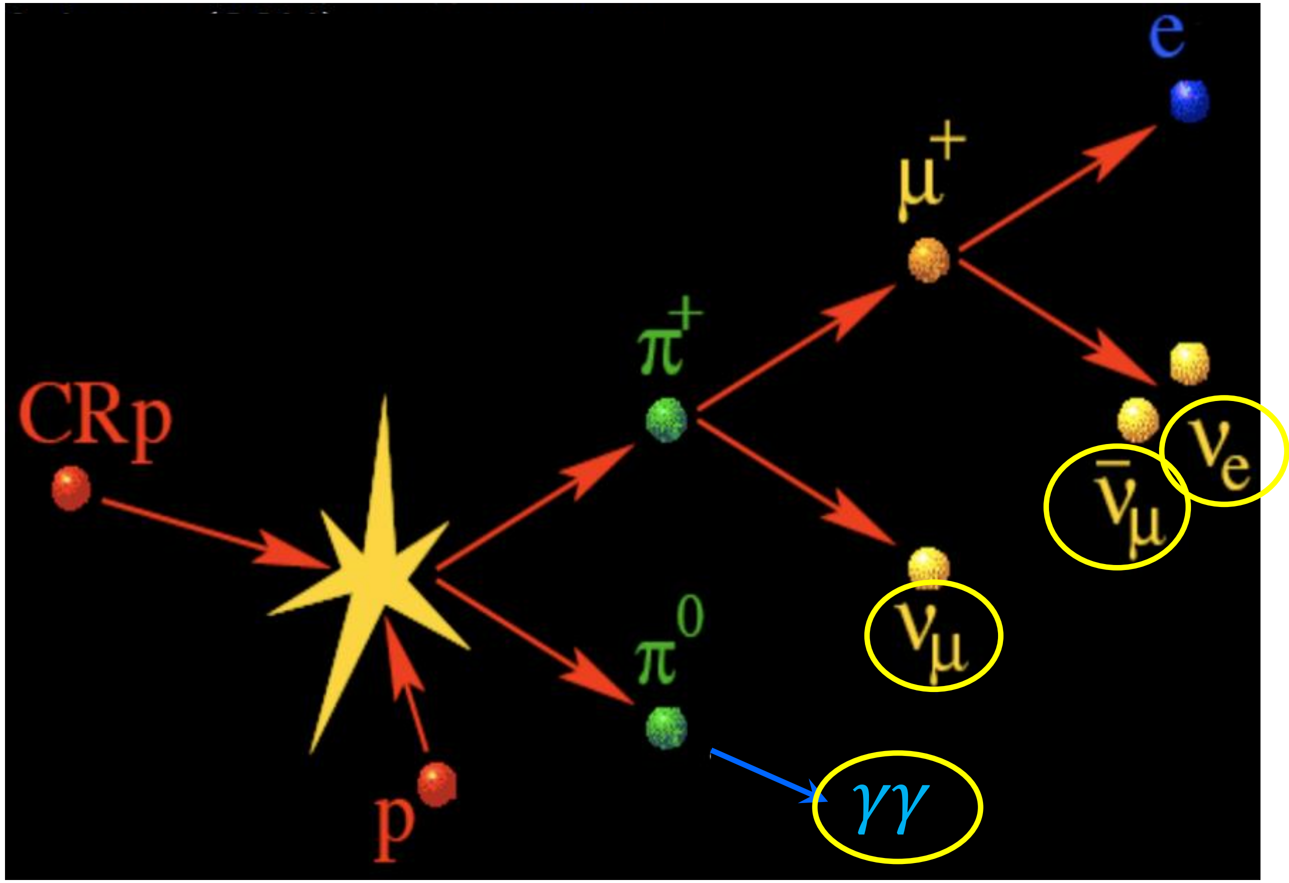
do they exist? how much? what are they?

where do they come from?

from "start-burst galaxies", "galaxy clusters", "AGNs", "GRBs", …

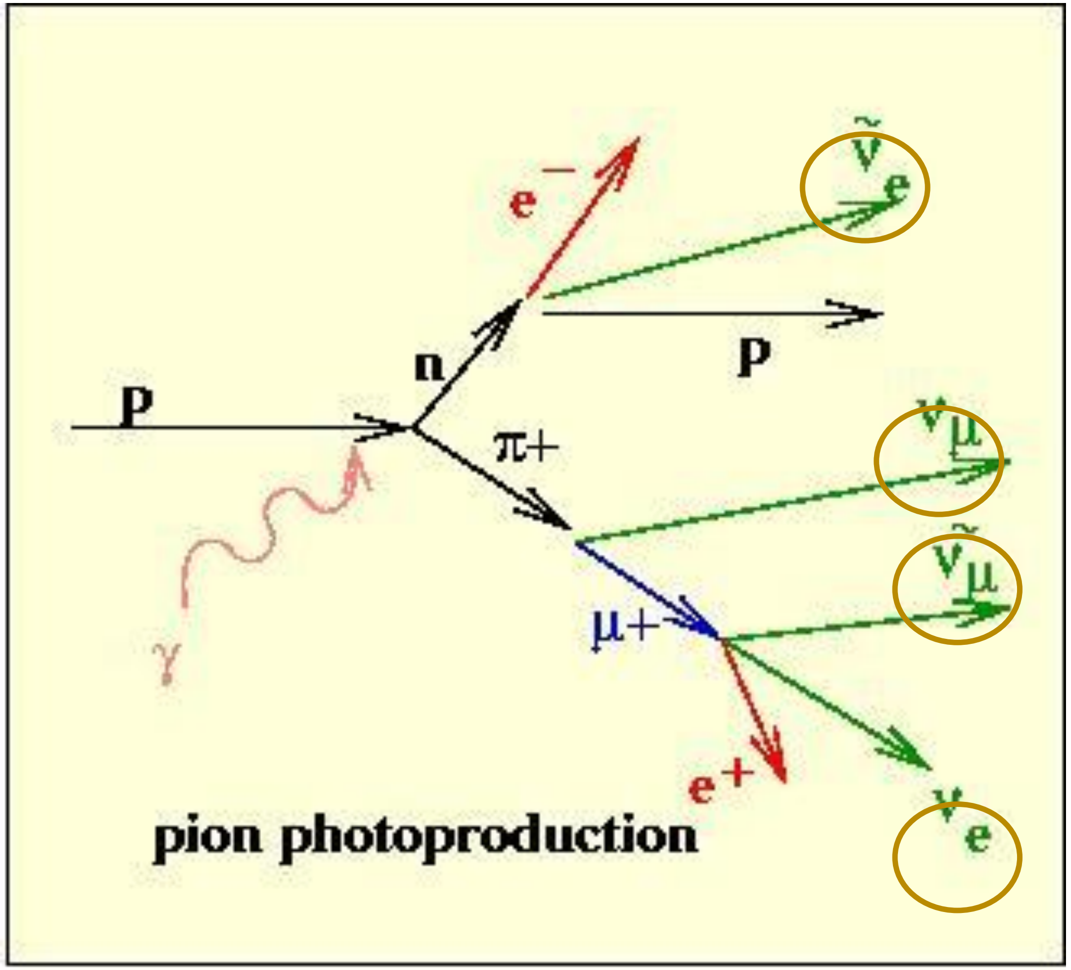
Neutrino (and gamma-ray) emission due to cosmic-ray protons

Collision of CR proton and background "protons"



dominant in "start-burst galaxies", "galaxy clusters",

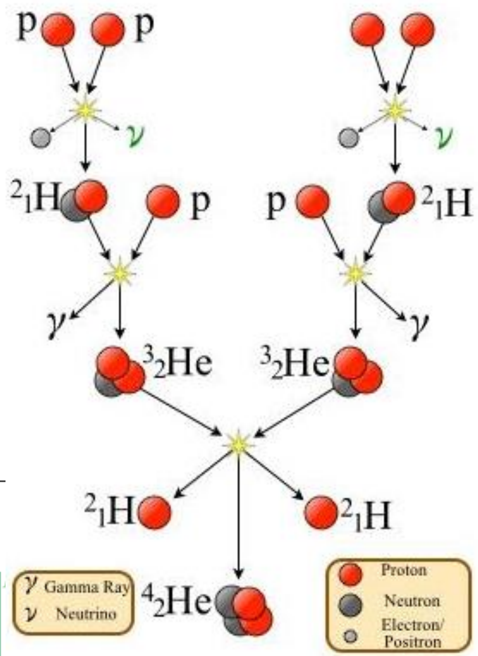
Collision of CR proton and background "photons

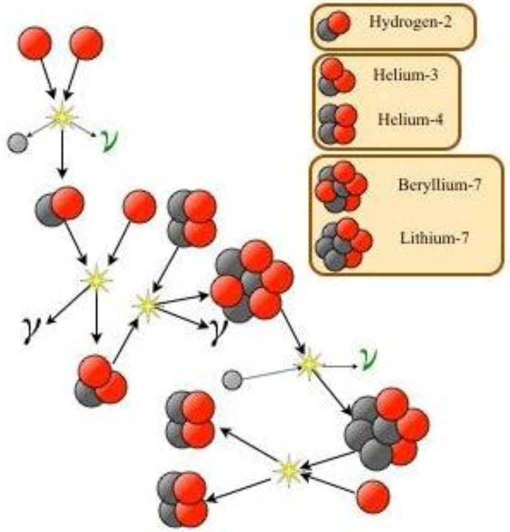


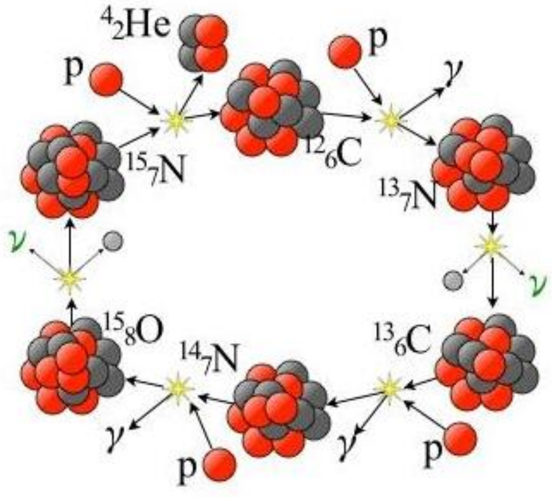
dominant in "AGNs"

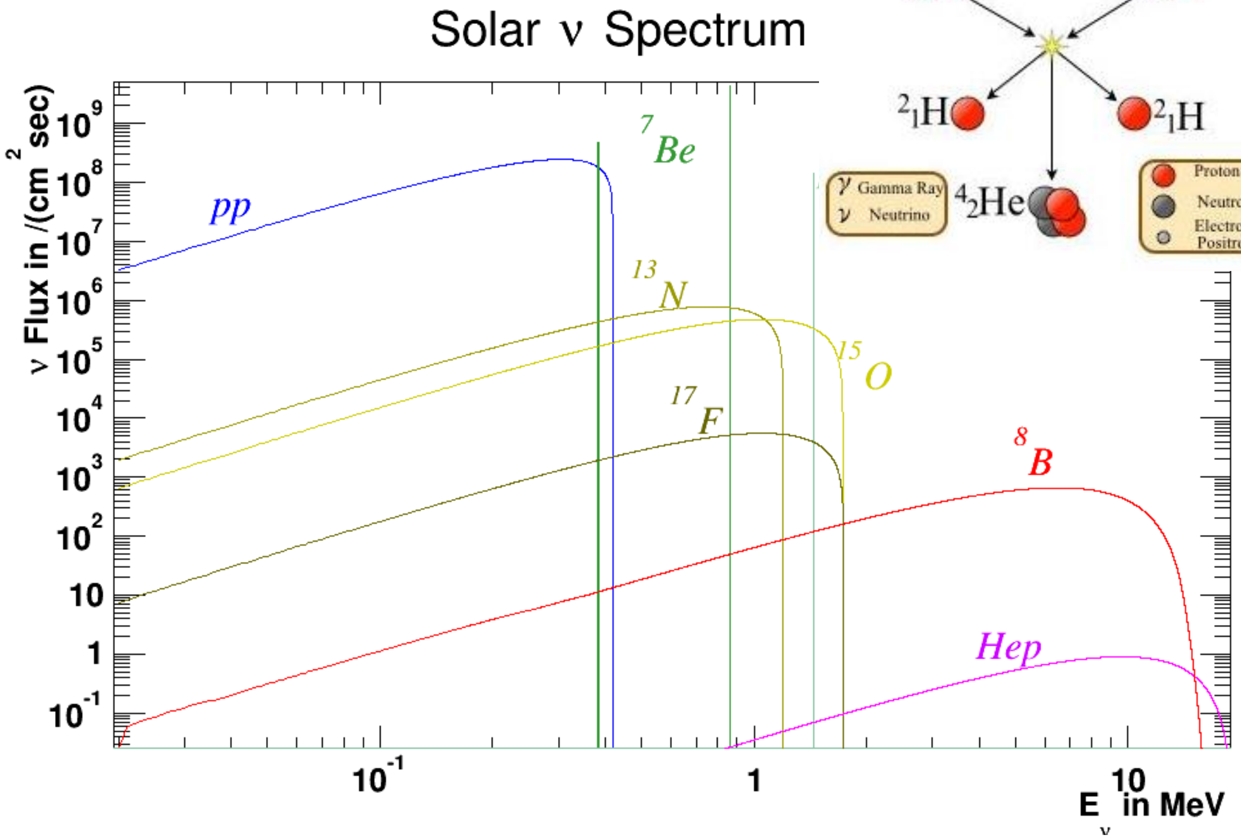
Thermal neutrino production through nuclear reactions

solar neutrino generation



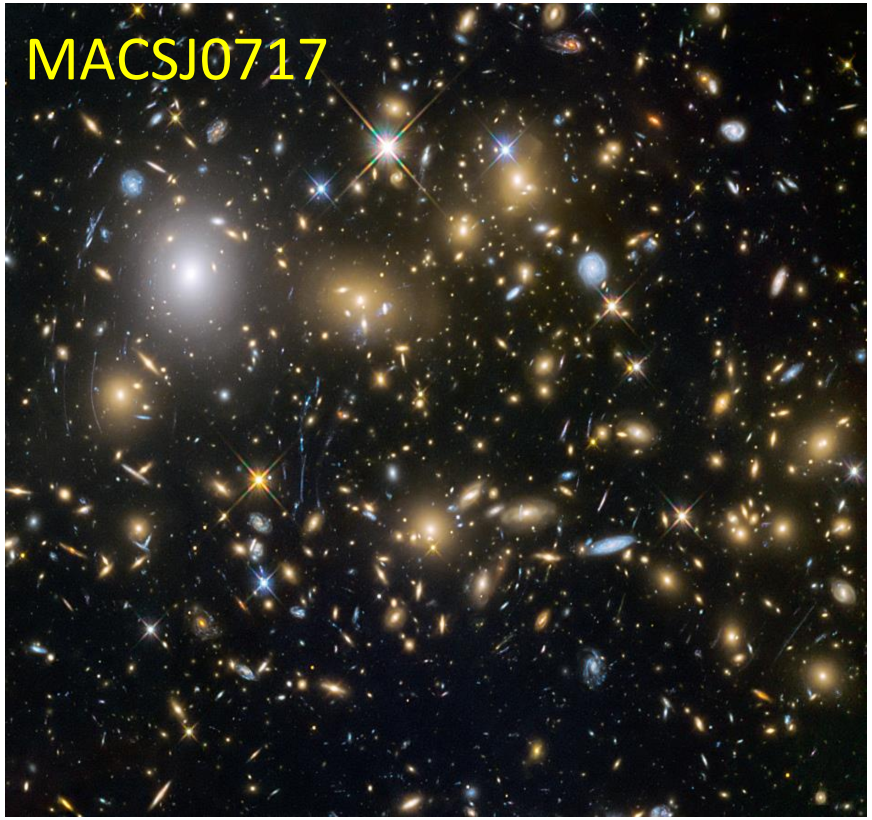






thermal neutrinos: mostly E_ν < a few x 10 MeV

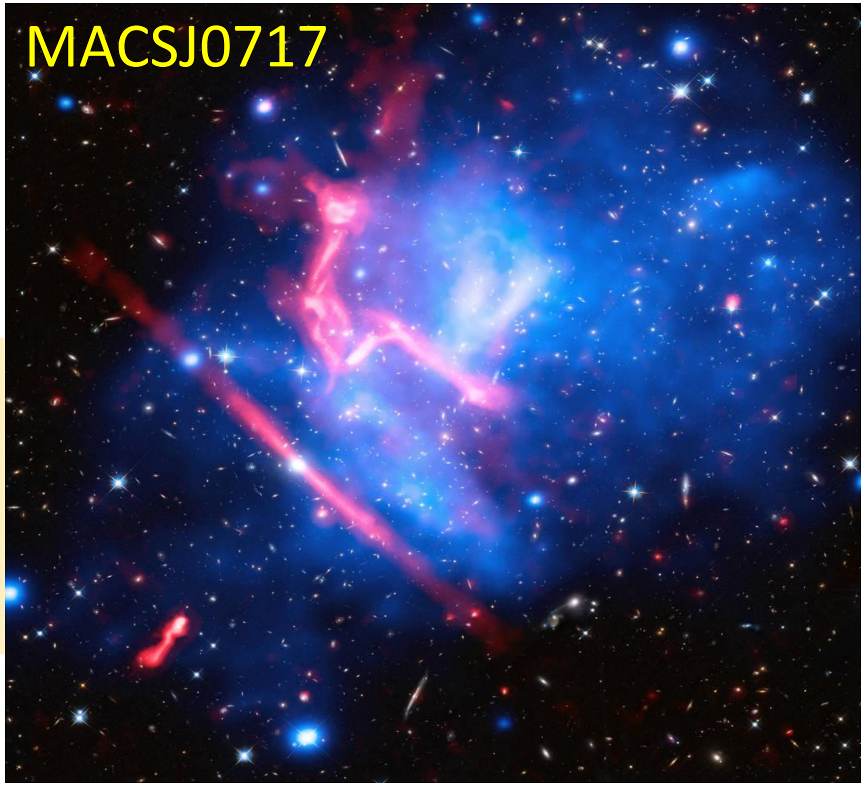
neutrinos from CR protons: higher E_ν, even up to EeV



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

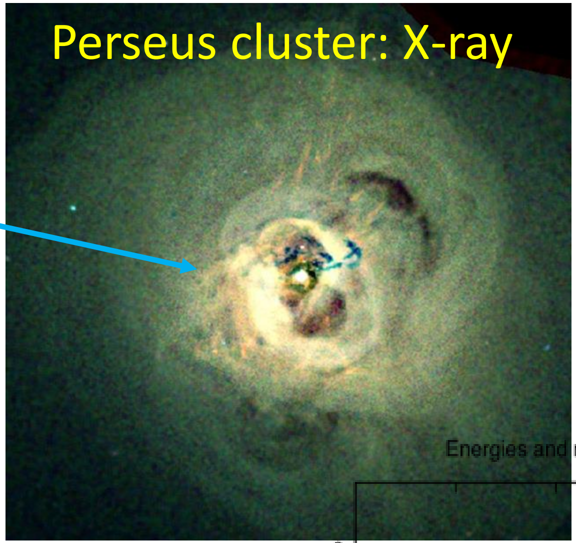
optical (Hubble, white)
X-ray (Chandra, blue) ← hot gas
radio (VLA, red) ← cosmic rays

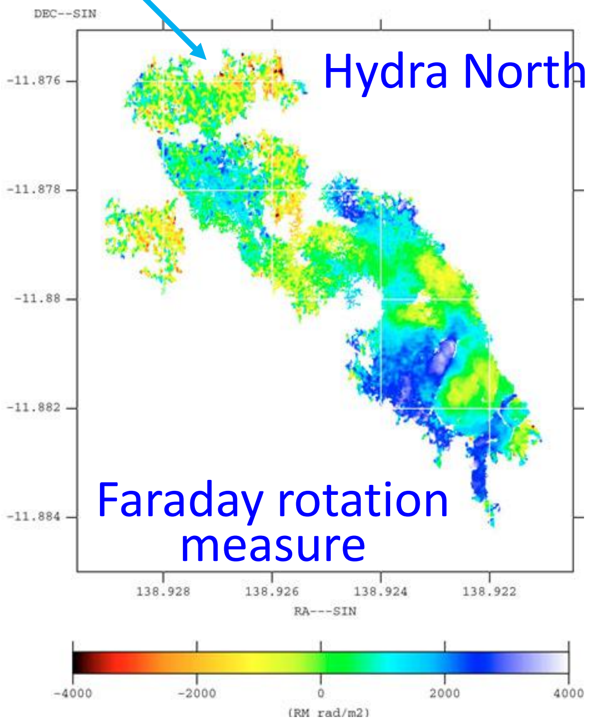


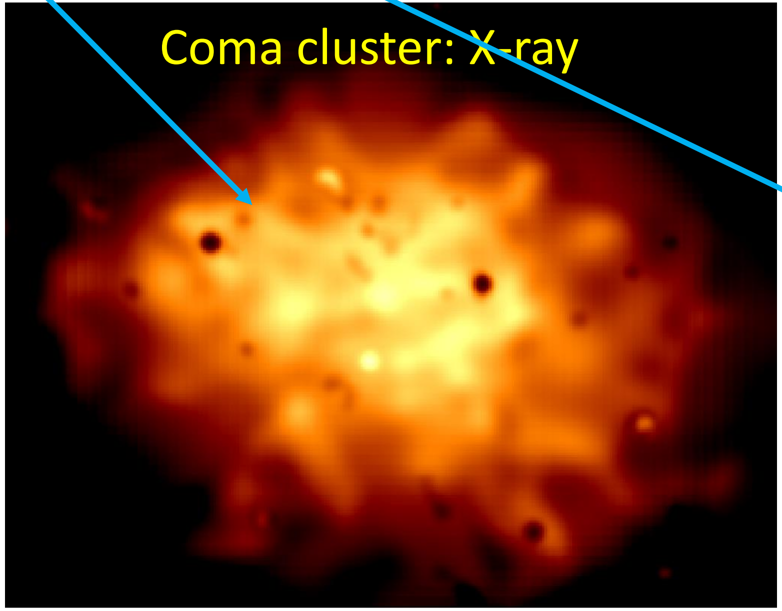
The intracluster medium (ICM):
the superheated **plasma with T ~ a few to several keV**, presented in clusters of galaxies

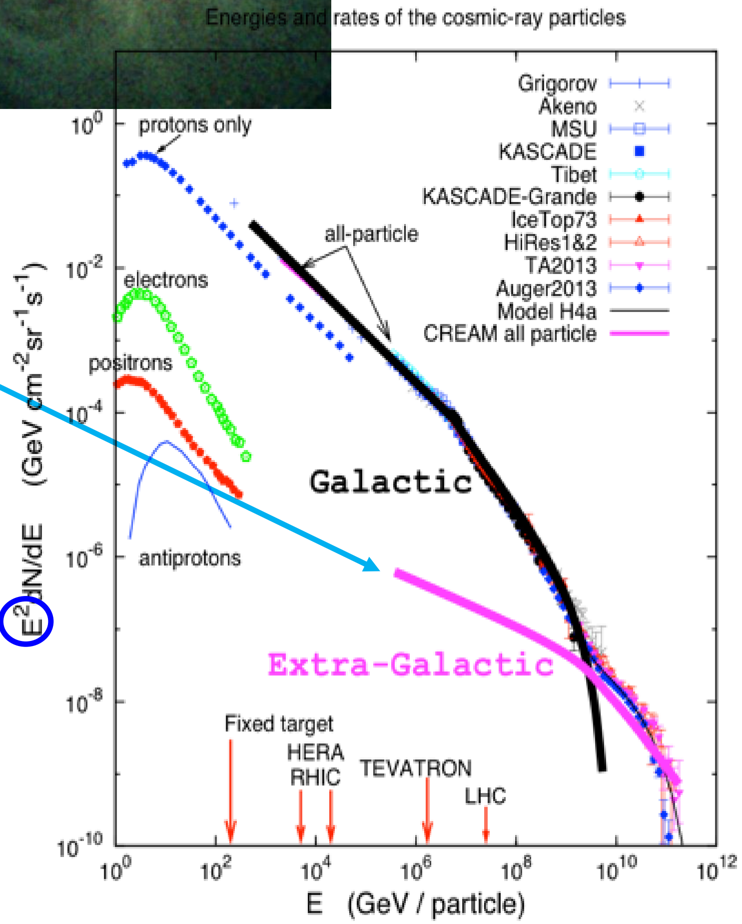
ICMs are highly dynamical

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

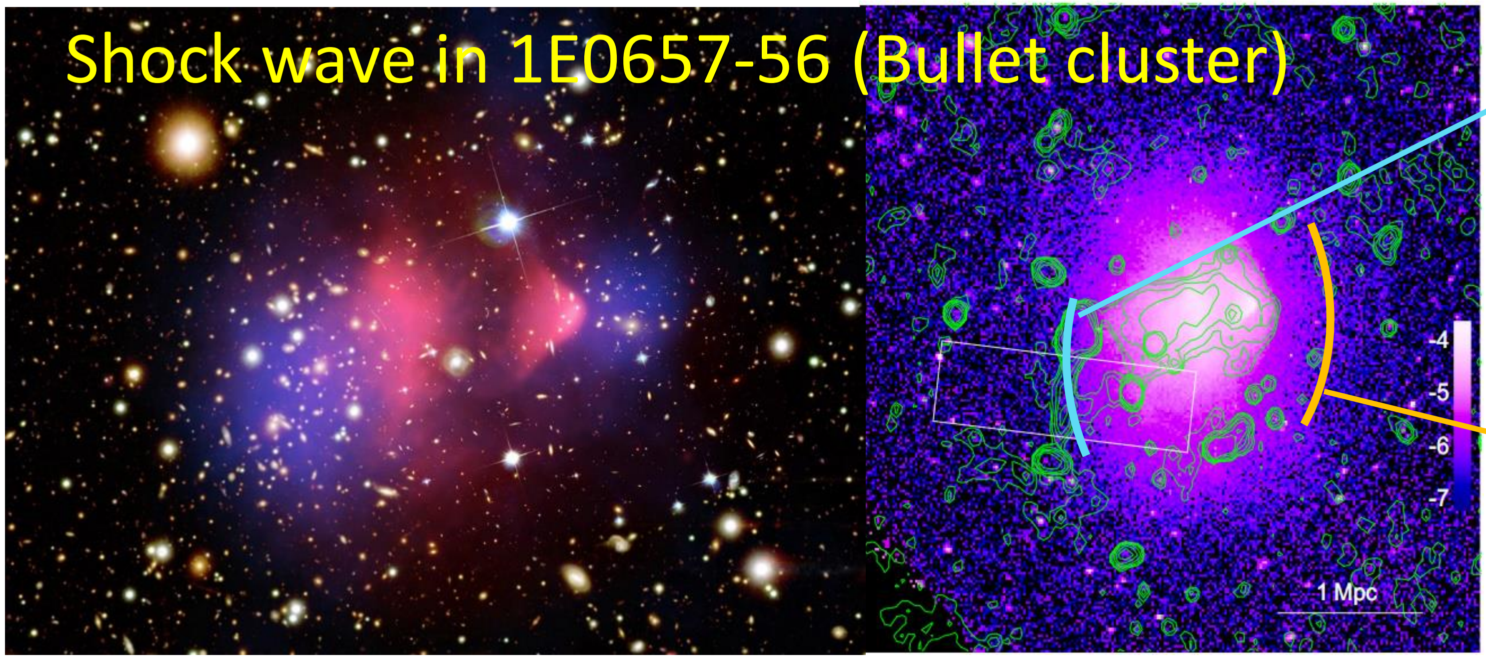








Observation of shocks in clusters



$M_X \approx 2.5$

Shimwell et al. 2015

$M_X \approx 3.0$

(no associated radio relic)

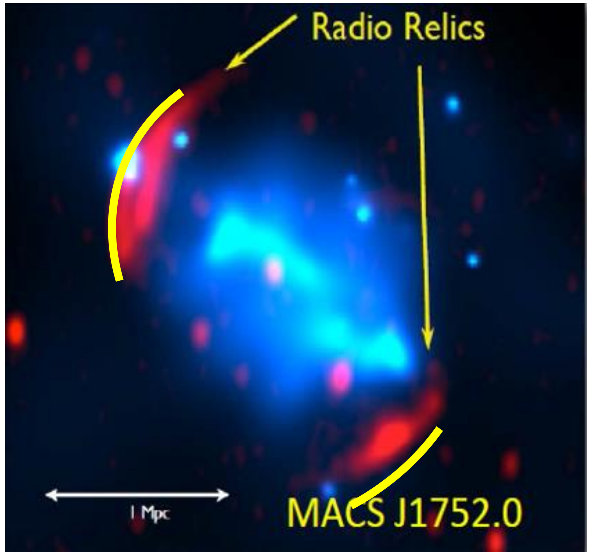
Markevitch 2006

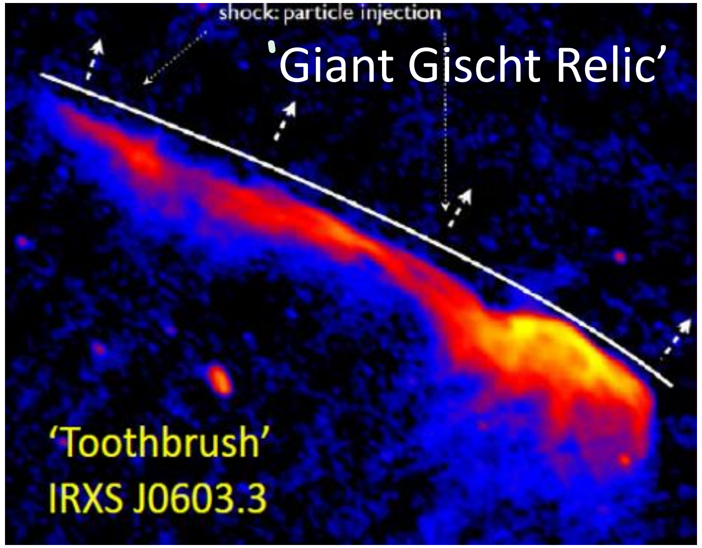
Mach number of "X-ray" shocks in ICMs:

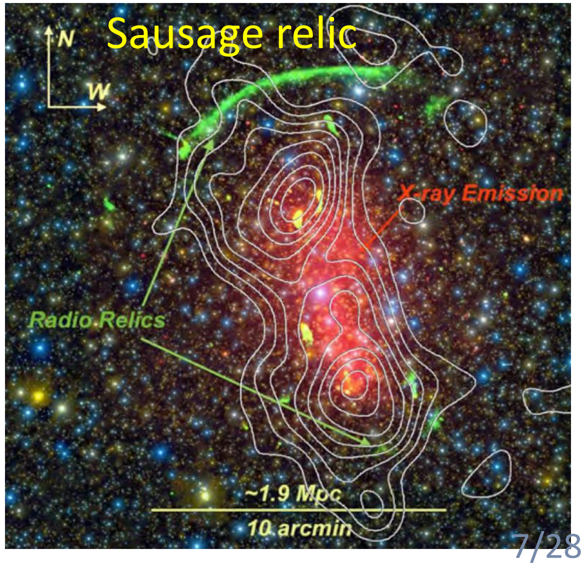
M_{shock} <~ a few

Mach number of "radio" shocks in ICMs:

M_{shock} <~ several



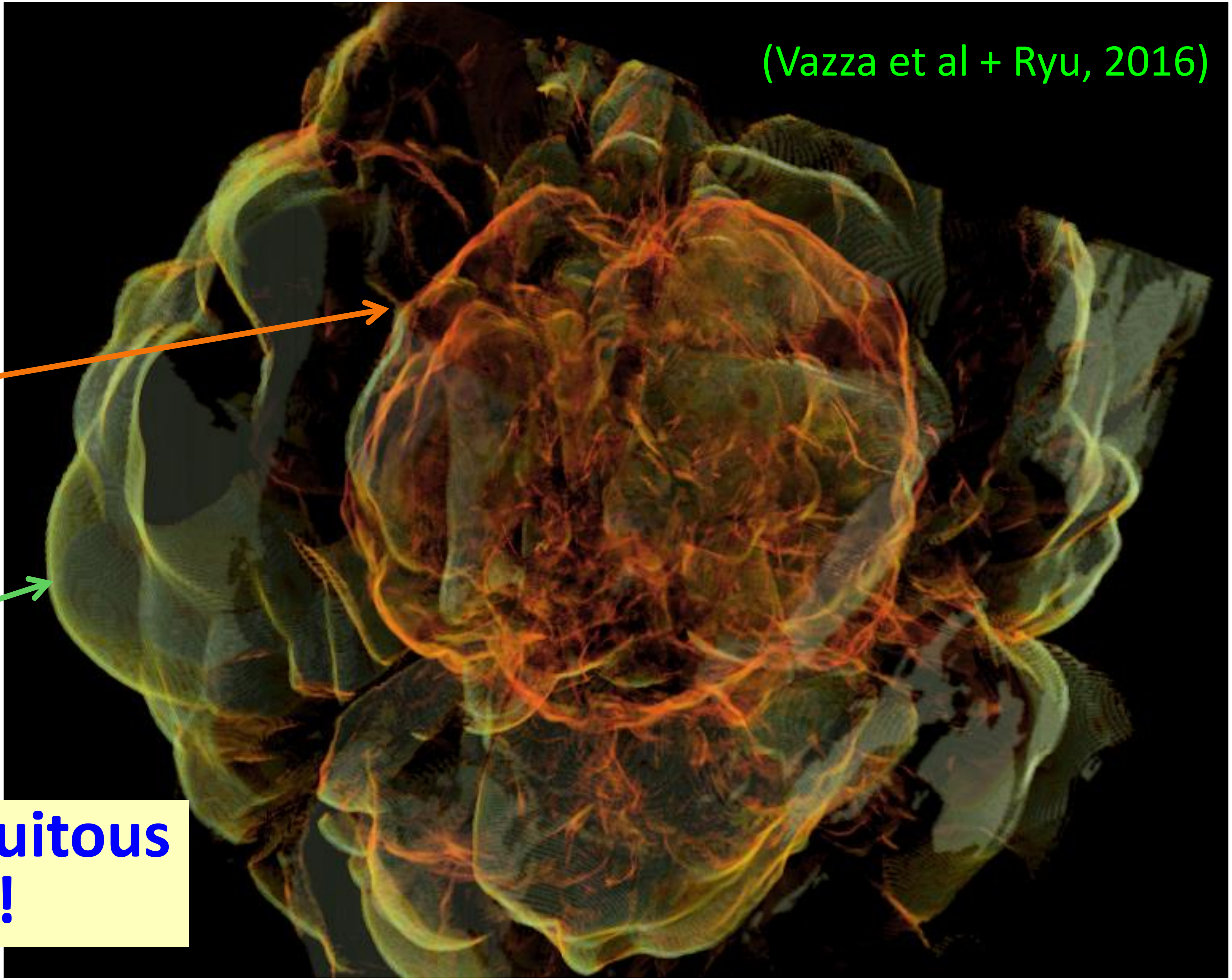




Shock waves in simulation

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

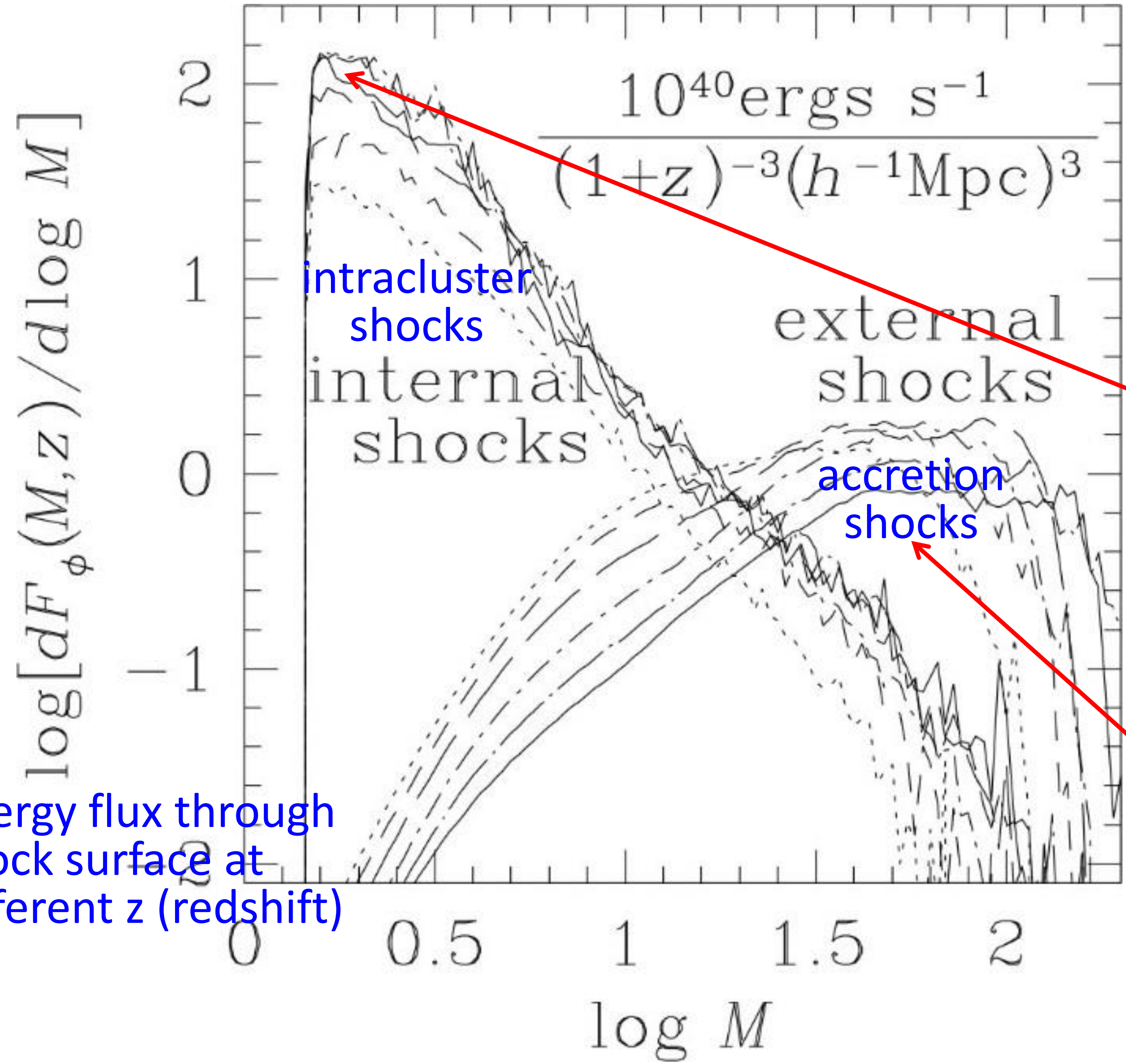
strong accretion shocks with M_s > ~10 (green)



Shocks are ubiquitous in the ICM!

Shock waves inside and around clusters

(Ryu et al. 2003)

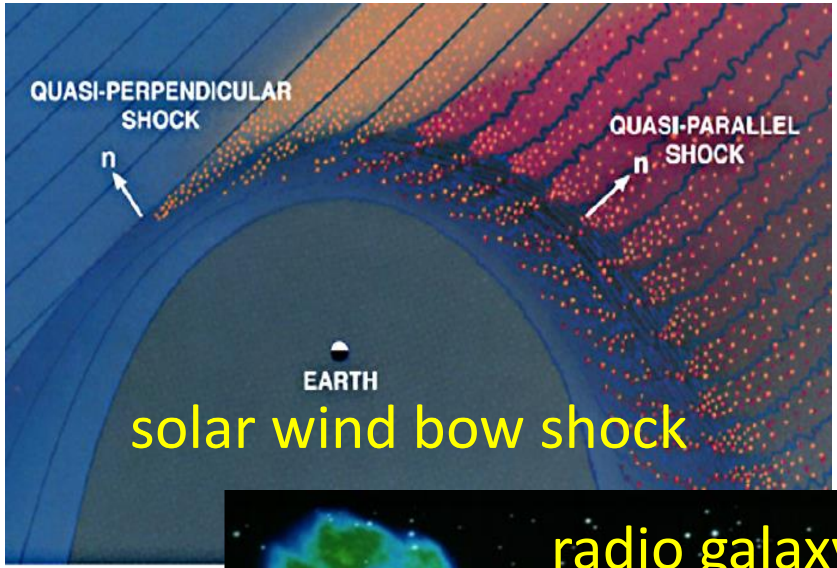


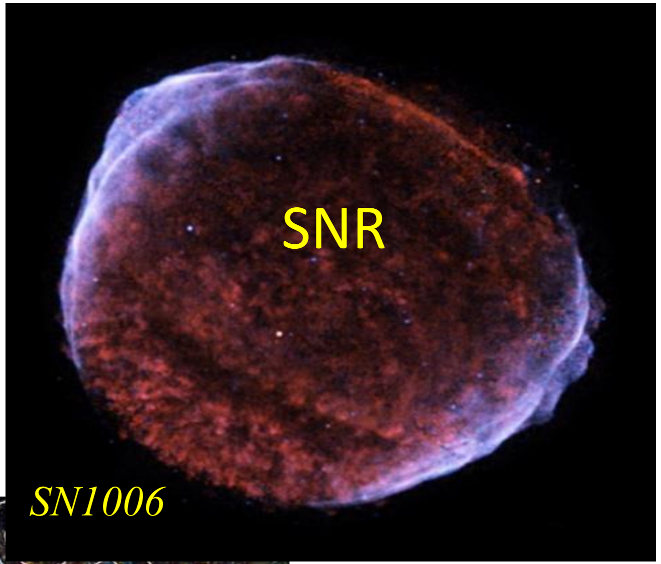
energy flux through shock surface at different z (redshift)

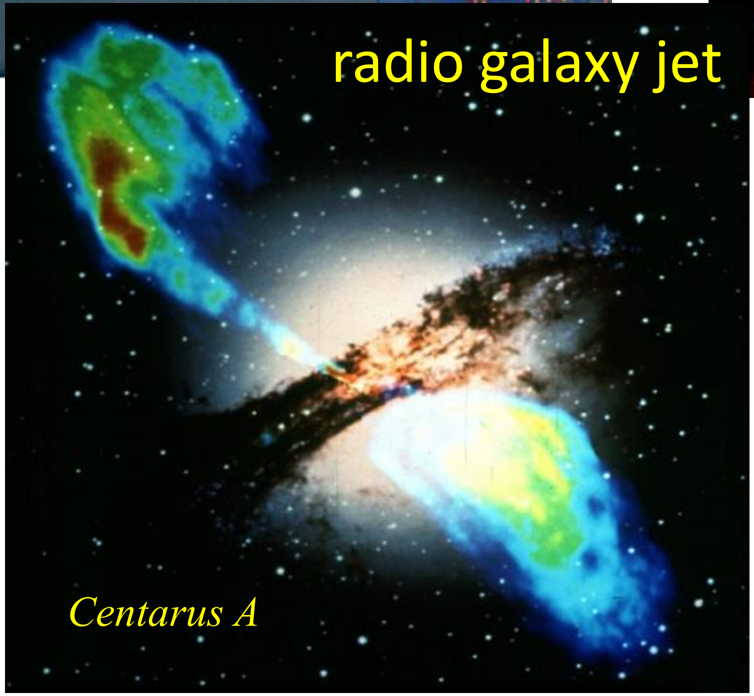
intracluster shocks are weak with M_s ~ a few, but energetically more important

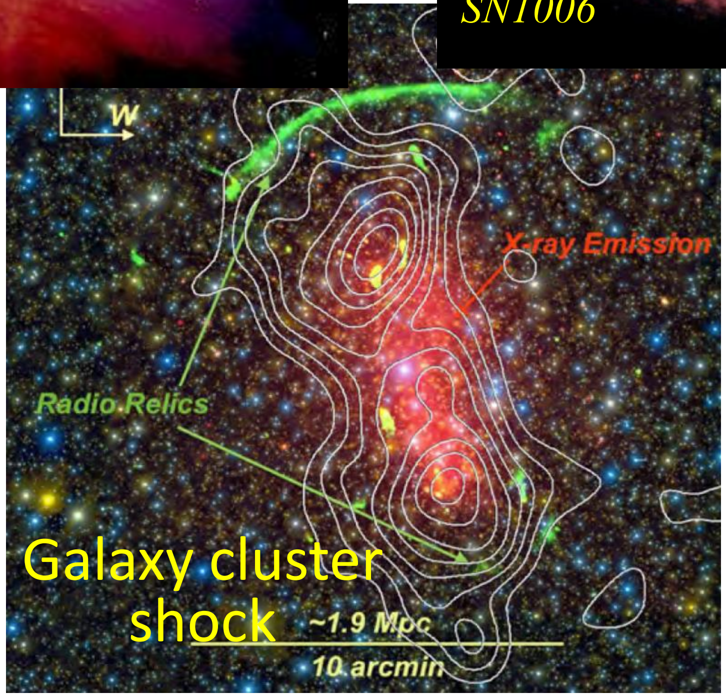
accretion shocks with are energetically less important, but strong with M_s ~ up to 100

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









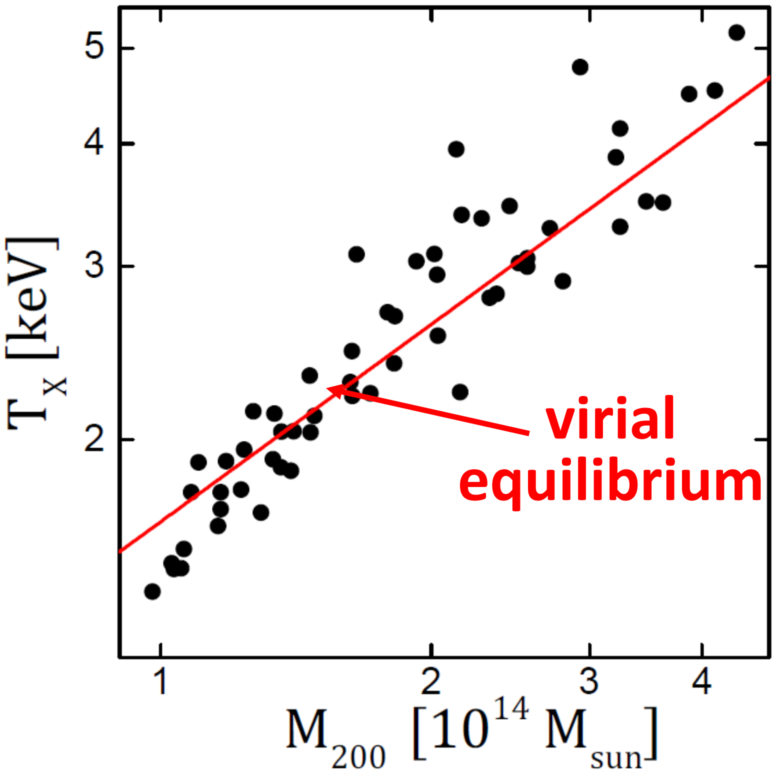
Neutrinos (& gamma-rays) from galaxy clusters

- due to CRs accelerated at intracluster shocks ?
- due to CRs accelerated at accretion shocks ?

Simulated galaxy clusters and intracluster/accretion shocks

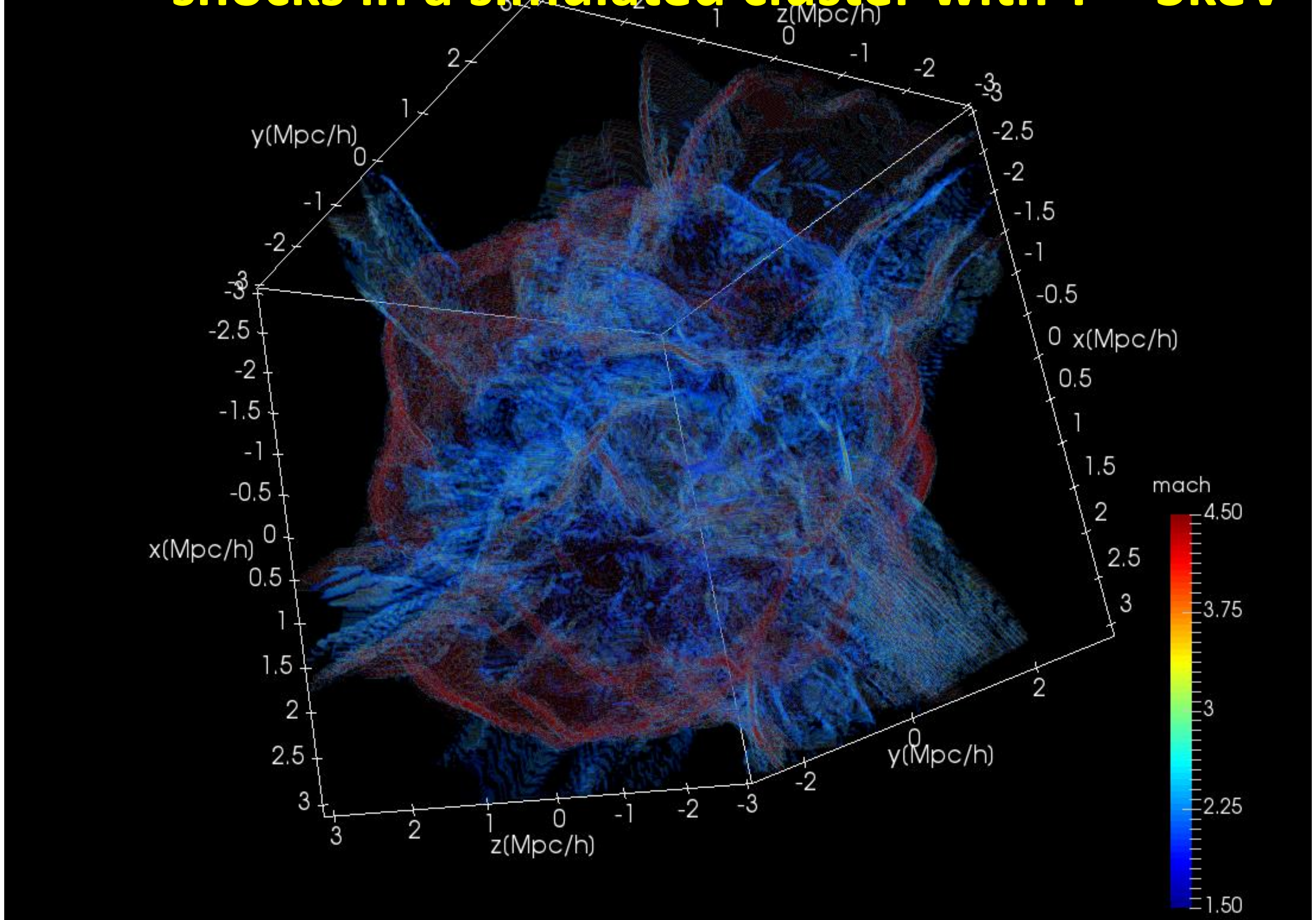
(Ha, Ryu, Kang, submitted)

four cosmological hydrodynamic simulations [L = 57 Mpc/h box (1650 cells)]



58 sample clusters identified

shocks in a simulated cluster with T ~ 3keV



Simulation of proton acceleration at quasi-parallel ICM shocks

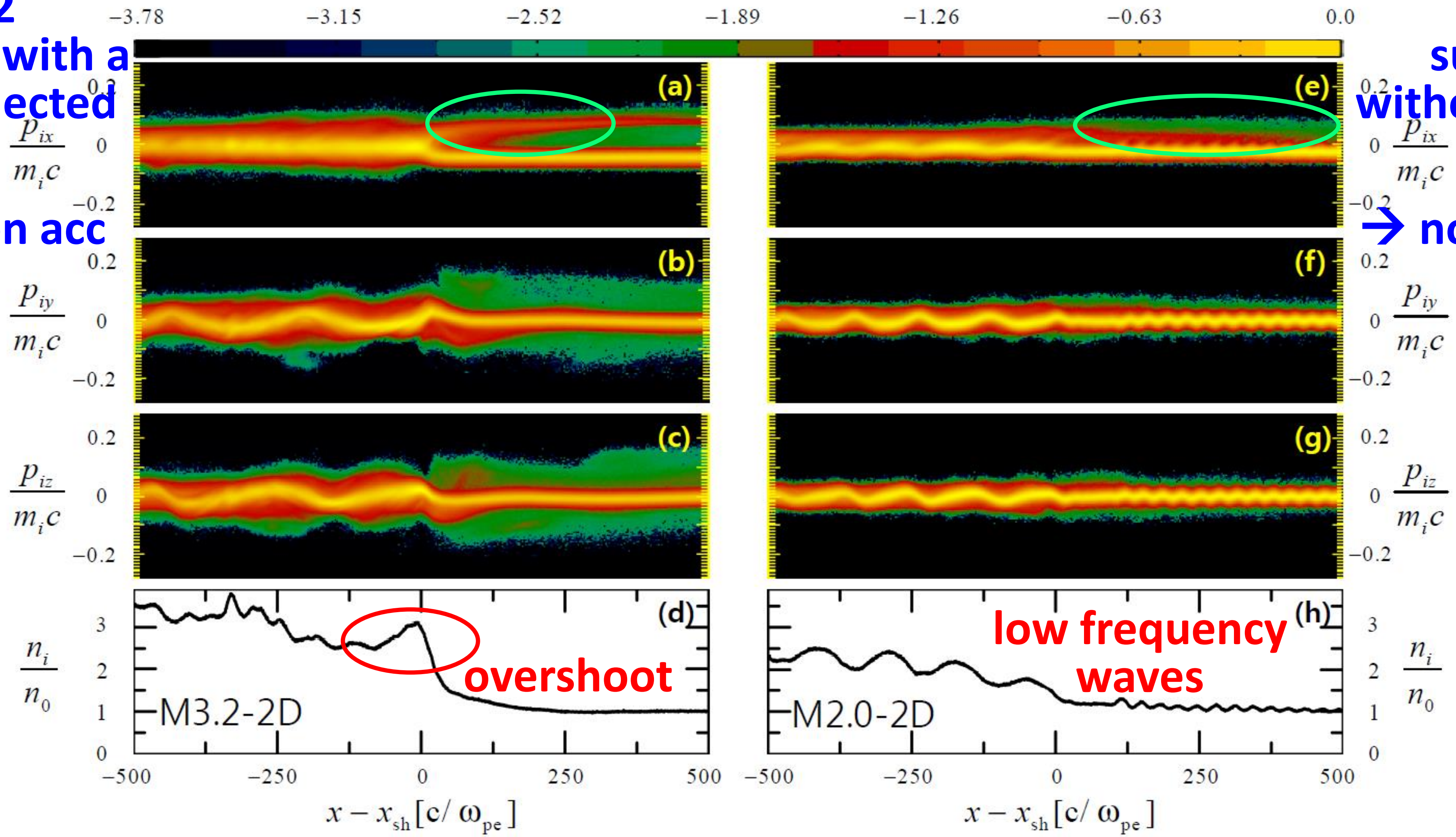
(Ha, Ryu, Kang, van Marle 2018)

M_s = 3.2
supercritical with a beam of reflected ions

→ CR proton acc

M_s = 2.0
subcritical without reflected ions

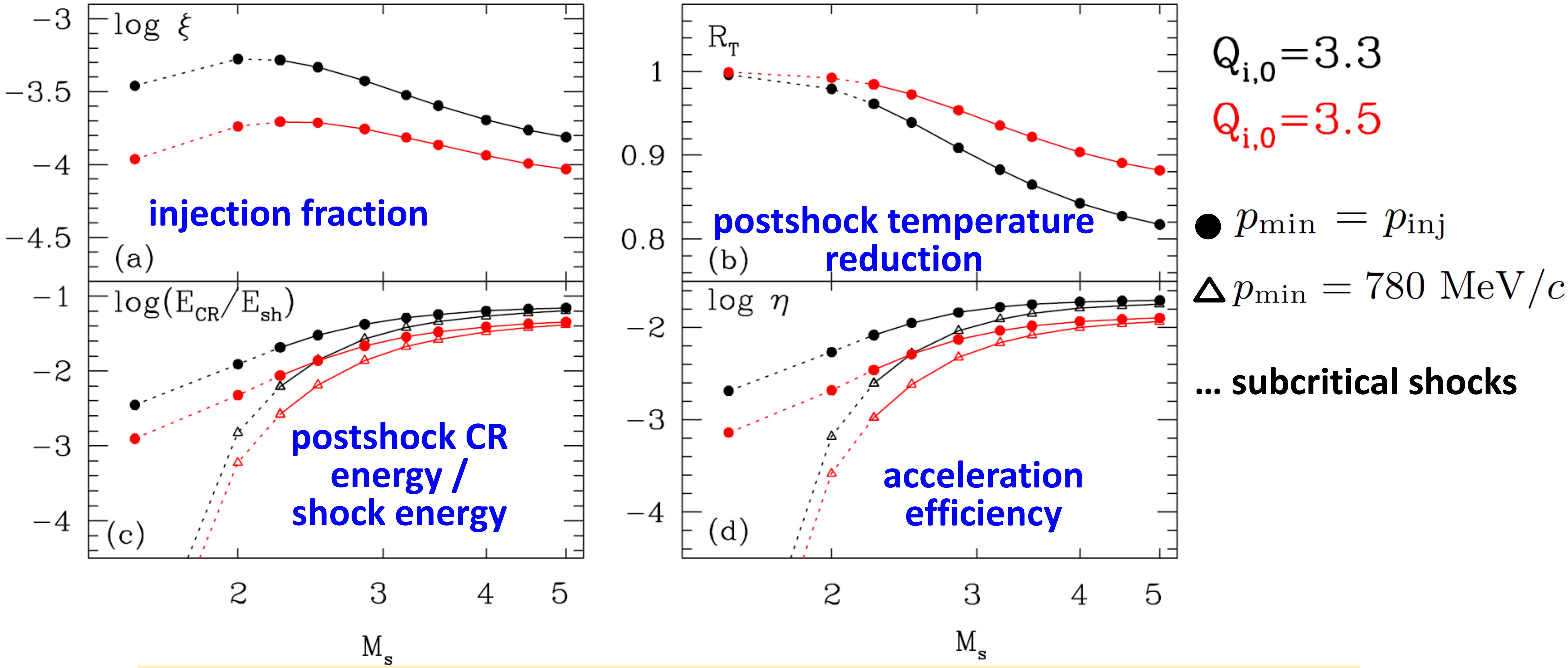
→ no accleration



PIC simulation $\theta_{Bn} = 13^\circ$ $r_{L,i} \equiv \frac{m_i v_0 c}{eB_0} = M_{A,0}\sqrt{\frac{m_i}{m_e}}\frac{c}{w_{pe}}$ ~ $200\,\frac{c}{w_{pe}}$

DSA parameters in the model

(Ryu, Kang, Ha 2019)



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

A model for reacceleration of CR protons in ICM shocks

(Ha, Ryu, Kang, submitted)

(1) ICM gas within virial radius passes through shocks "three" times on average
← estimated with cosmology simulation

(2) Reacceleration operates only at quasi-parallel, supercritical ($M_s \geq 2.25$) shocks
← because the generation of upstream waves is necessary

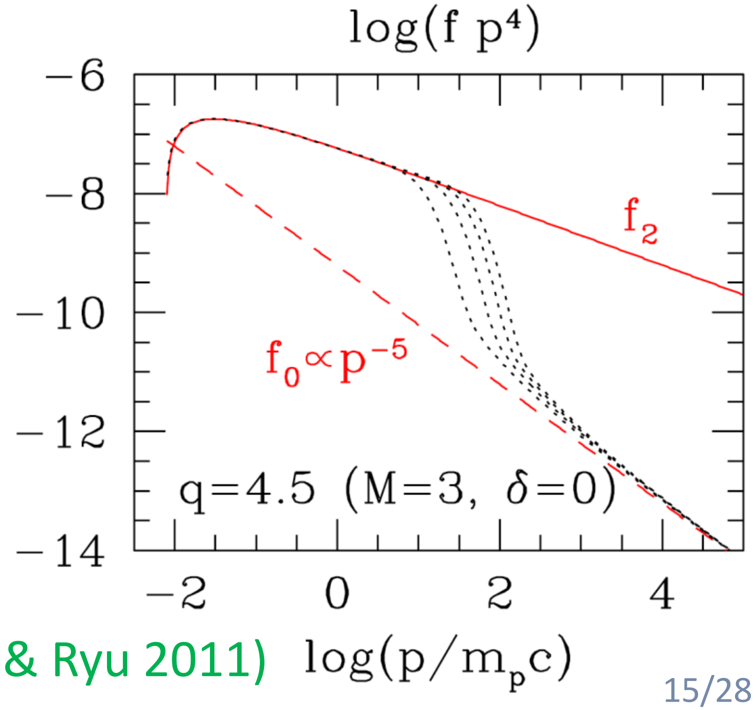
(3) DSA is in the test-particle regime, and reacceleration is described as

$$f^{(1)}_{\rm reacc}(p) = \begin{cases} [q/(q-s)][1-(p/p_{\rm inj})^{-q+s}]f_{\rm pre}(p), & \text{if } q \neq s \\ q\, ln(p/p_{\rm inj}) f_{\rm pre}(p), & \text{if } q = s. \end{cases}$$

s: the slope of the pre-existing CR proton spectrum

q: the slope of the test particle power-law spectrum

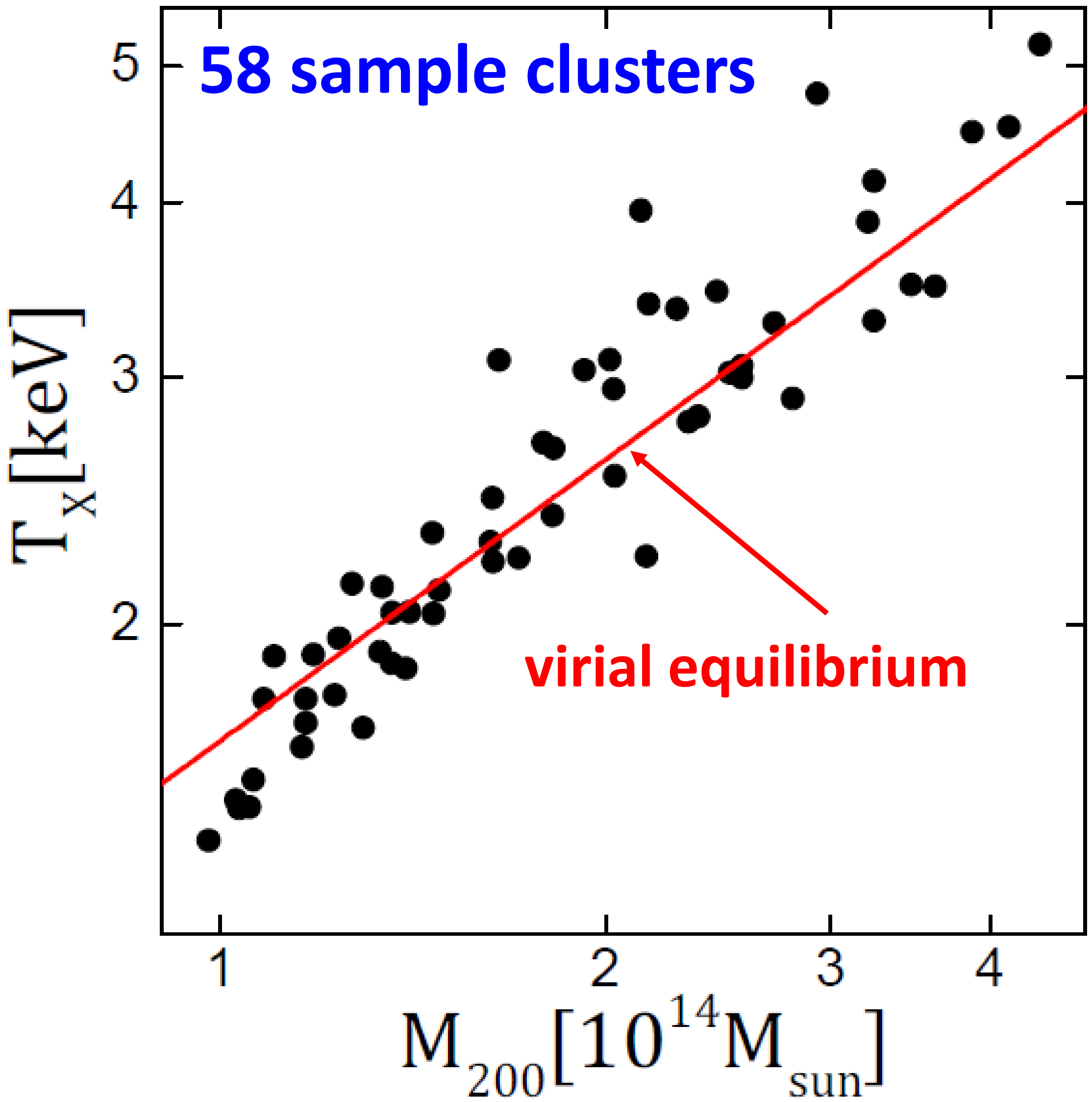
$q = 4 M_s^2/(M_s^2-1)$

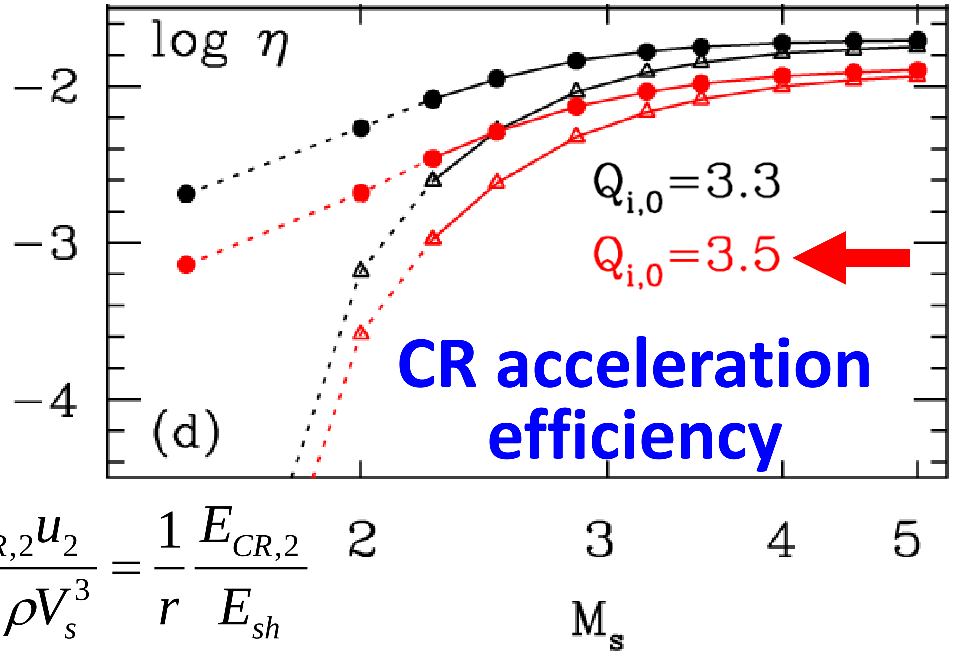


(Kang & Ryu 2011)

CR protons in simulated galaxy clusters

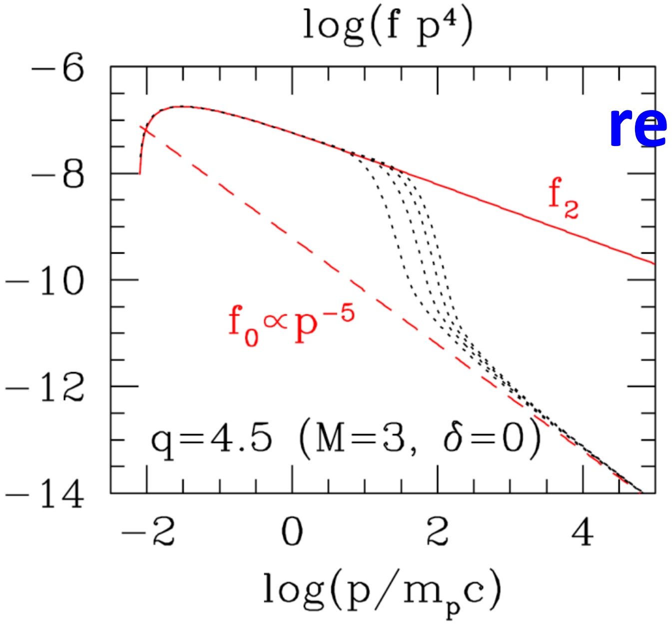
(Ha, Ryu, Kang, submitted)





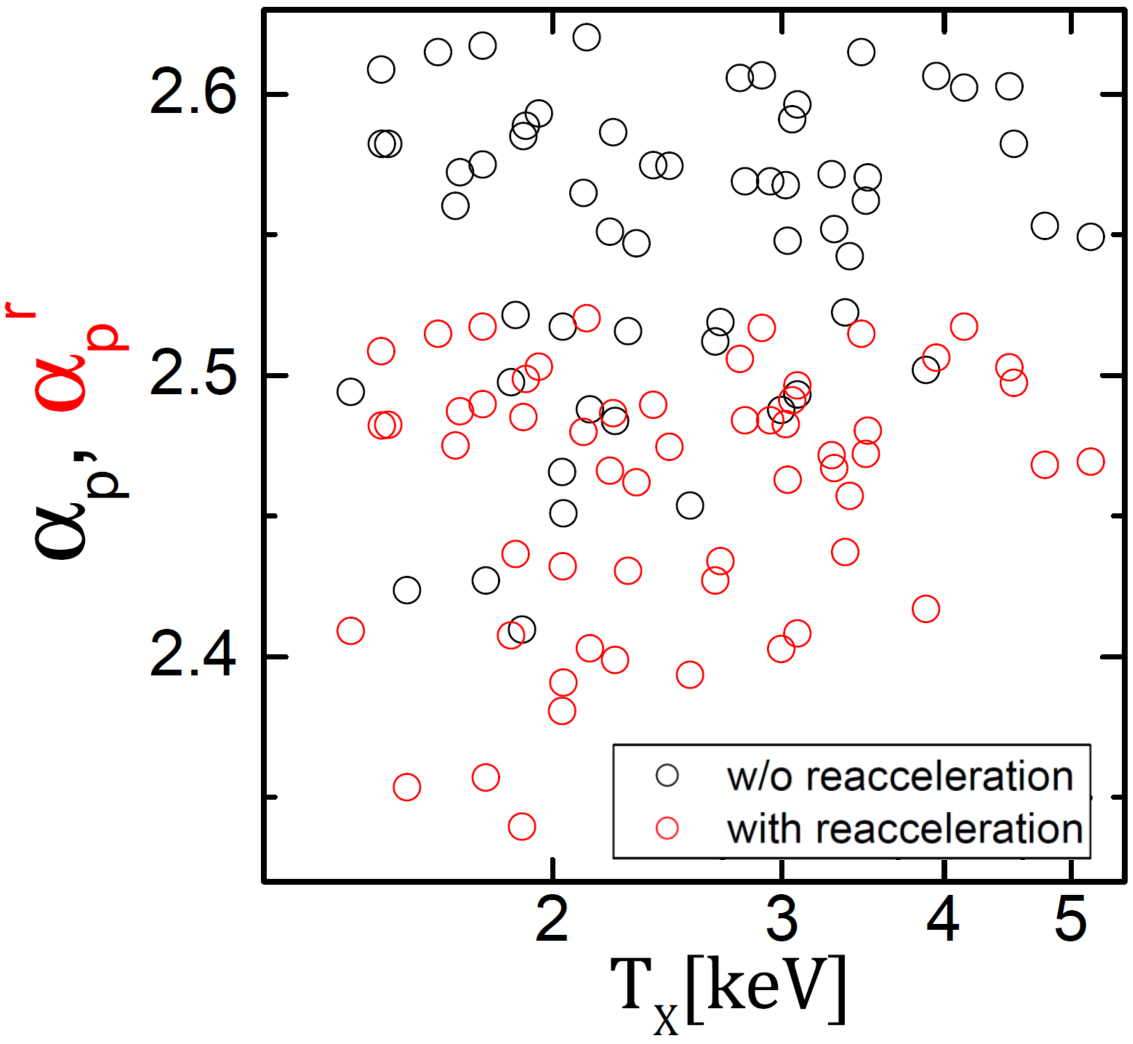
$$\eta \equiv \frac{E_{CR,2}u_2}{1/2\rho V_s^3} = \frac{1}{r}\frac{E_{CR,2}}{E_{sh}}$$

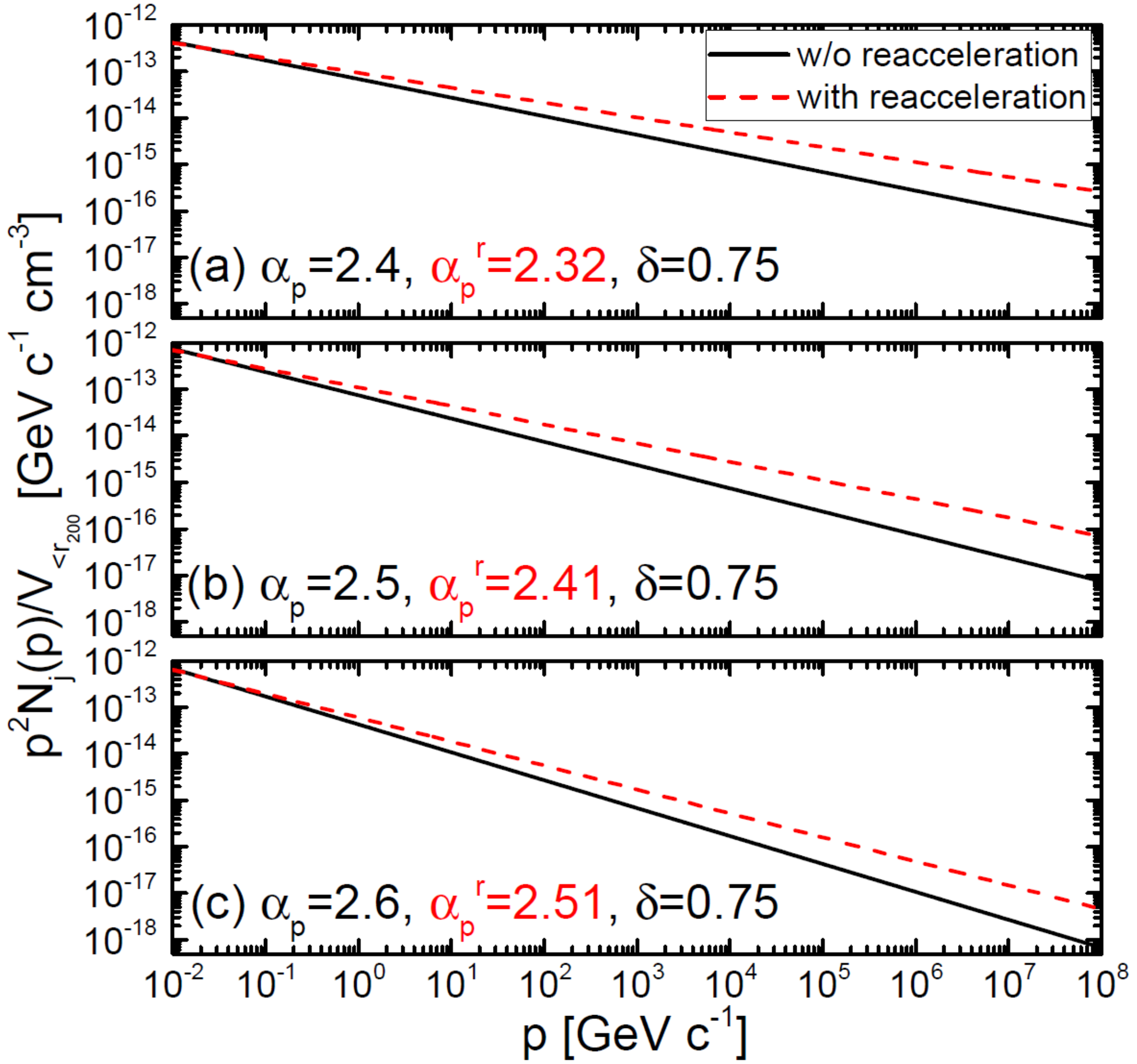
+



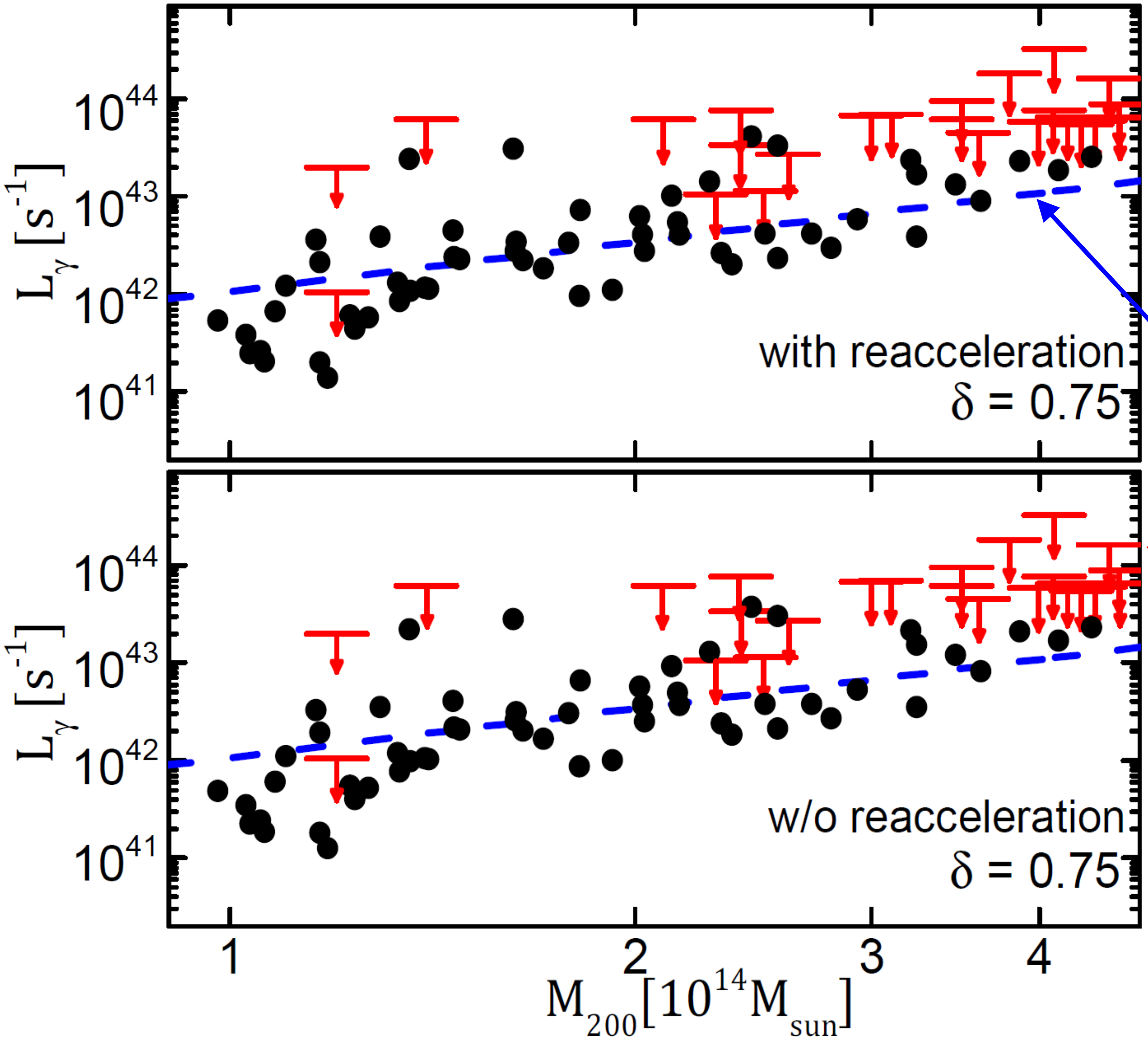
reacceleration

CR protons in simulated galaxy clusters





Gamma-ray luminosity of simulated galaxy clusters



$$\mathcal{L}_\gamma = \int_0^{r200} 4\pi r^2 dr \int_{E1}^{E2} q_\gamma(r, E_\gamma) dE_\gamma$$

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

using the source q_γ in Pfrommer & Ensslin (2004)

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

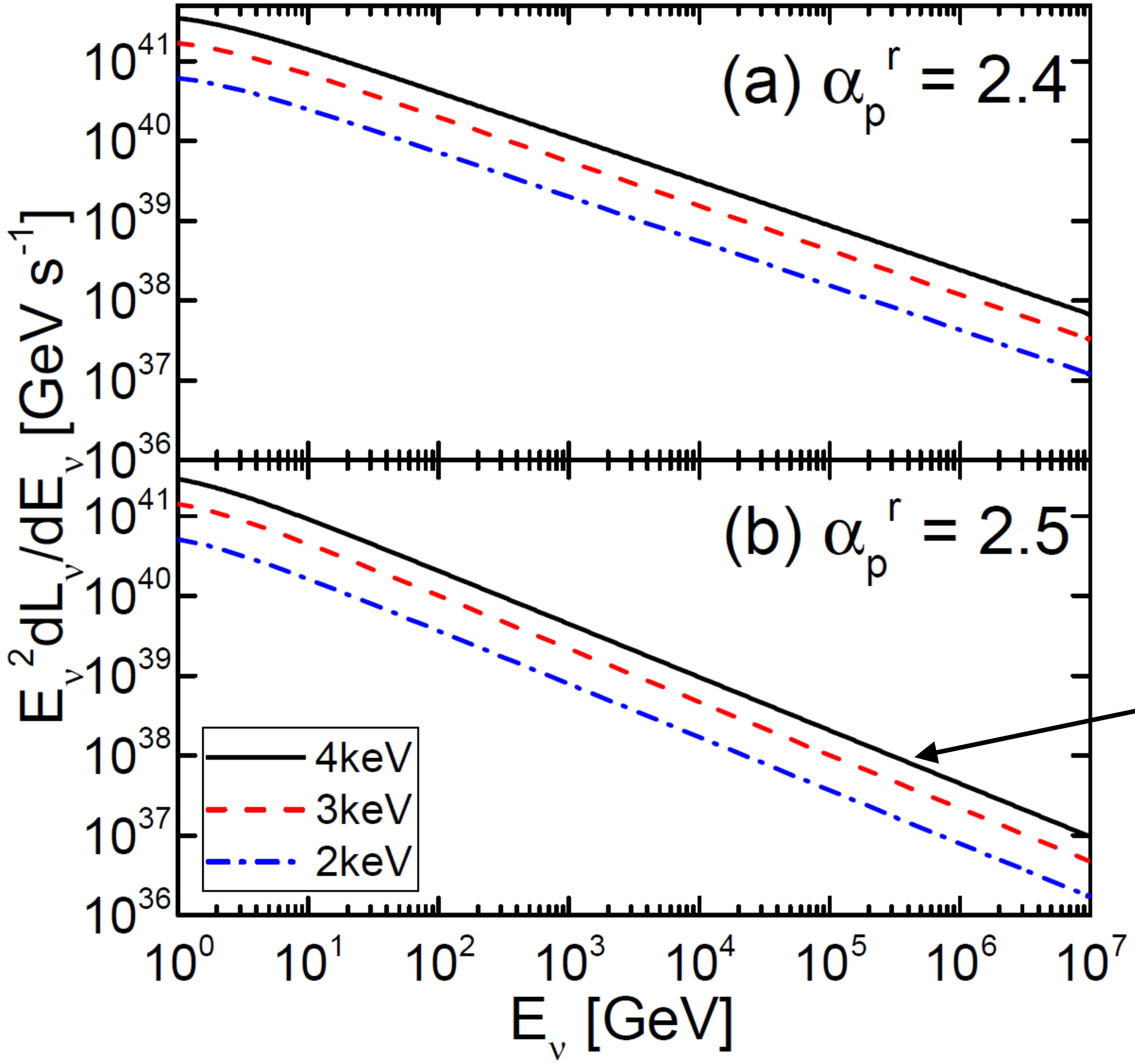
$$L_\gamma \propto M_{200}^{5/3}$$

Fermi LAT upper limit

● **simulated clusters**

The predicted gamma-ray flux is consistent with the Fermi LAT upper limit

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)

α_p :the slope of the momentum spectrum of volume-integrated CR protons

clusters of different temperatures

our N_ν is orders of magnitude or more smaller than, e.g., Zandanel et al (2015)

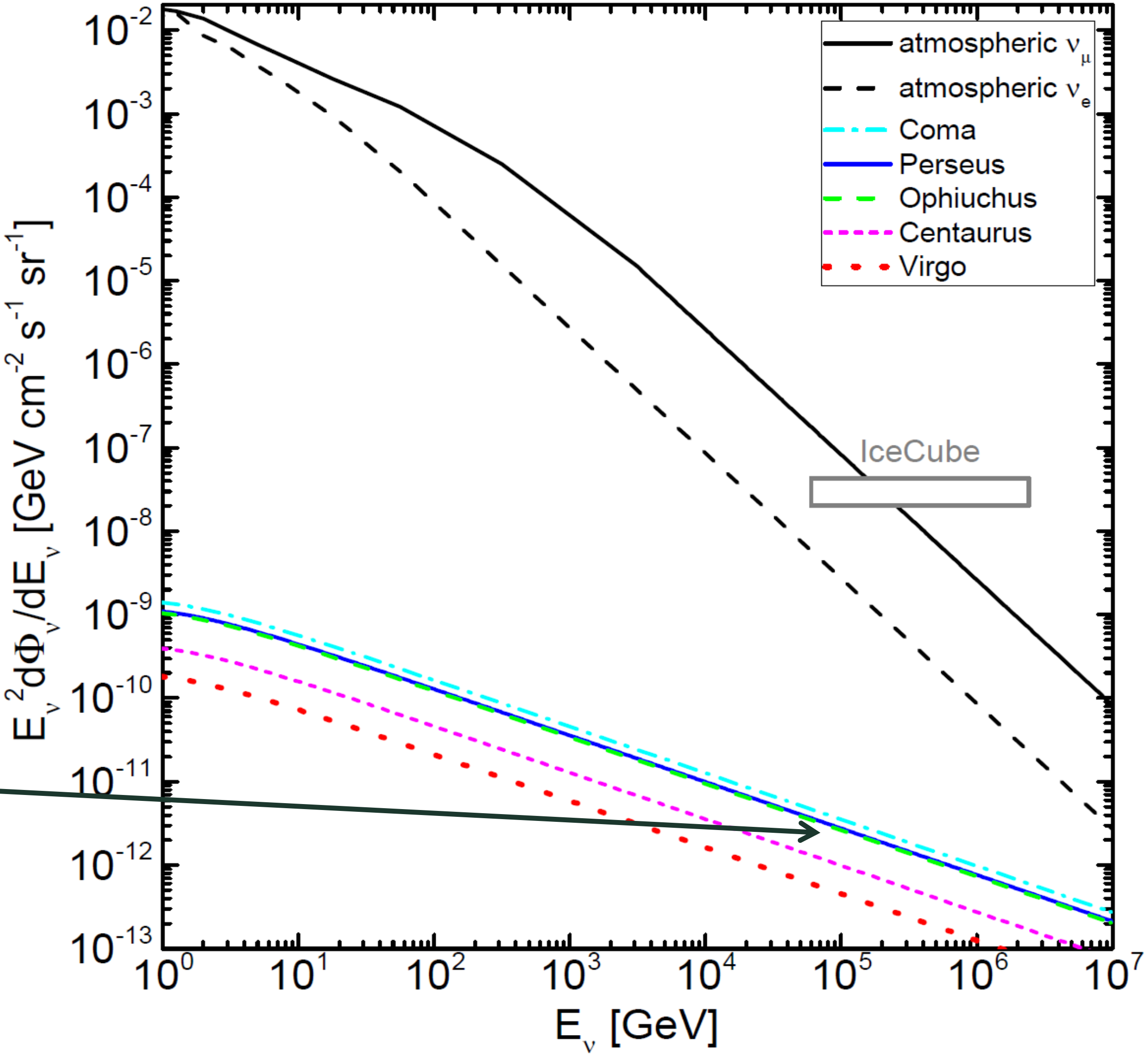
Estimation of neutrino fluxes from nearby clusters

Table 1. List of Nearby Clusters

Cluster	d [Mpc] [a]	T_X [keV] [b]	$R_{\rm vir}$ [Mpc] [b]
Virgo	16.5	2.3	1.08
Centaurus	41.3	3.69	1.32
Perseus	77.7	6.42	1.58
Coma	102	8.07	1.86
Ophiuchus	121	10.25	2.91

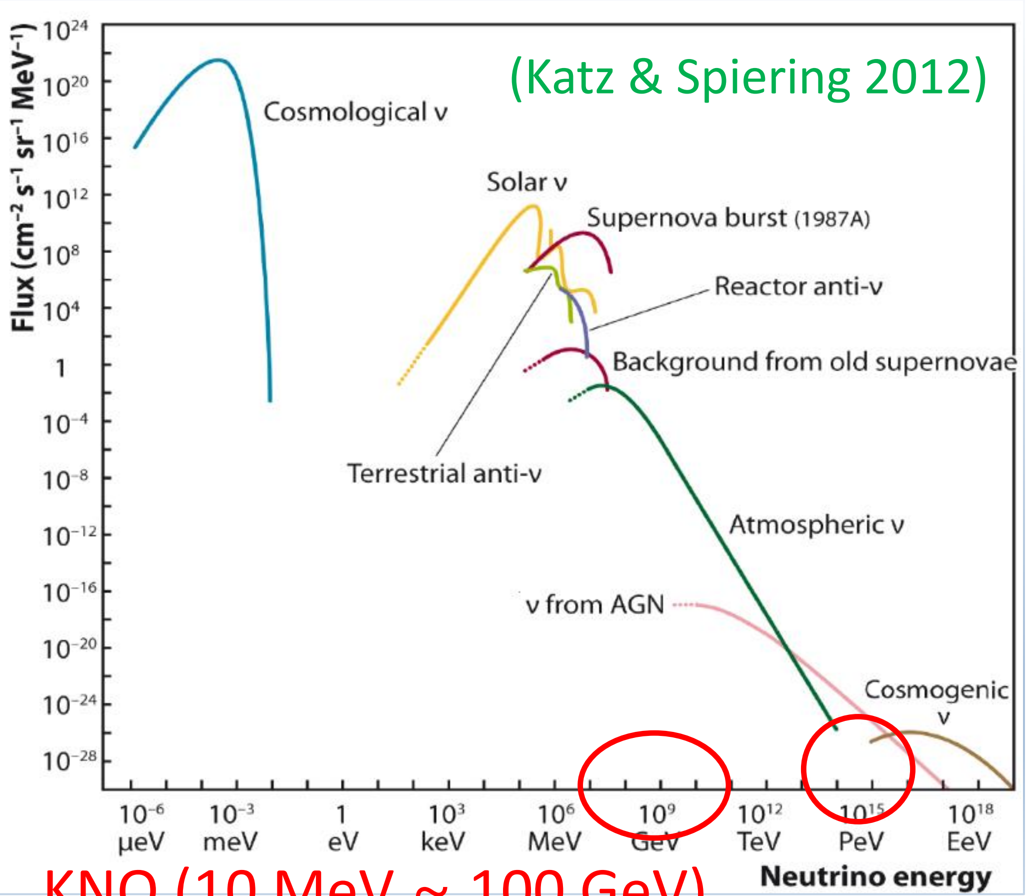
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi^2 R_{\rm vir}^2} \frac{dL_\nu}{dE_\nu}$$

predicted neutrino fluxes are ~ 10^{-4} x IceCube flux



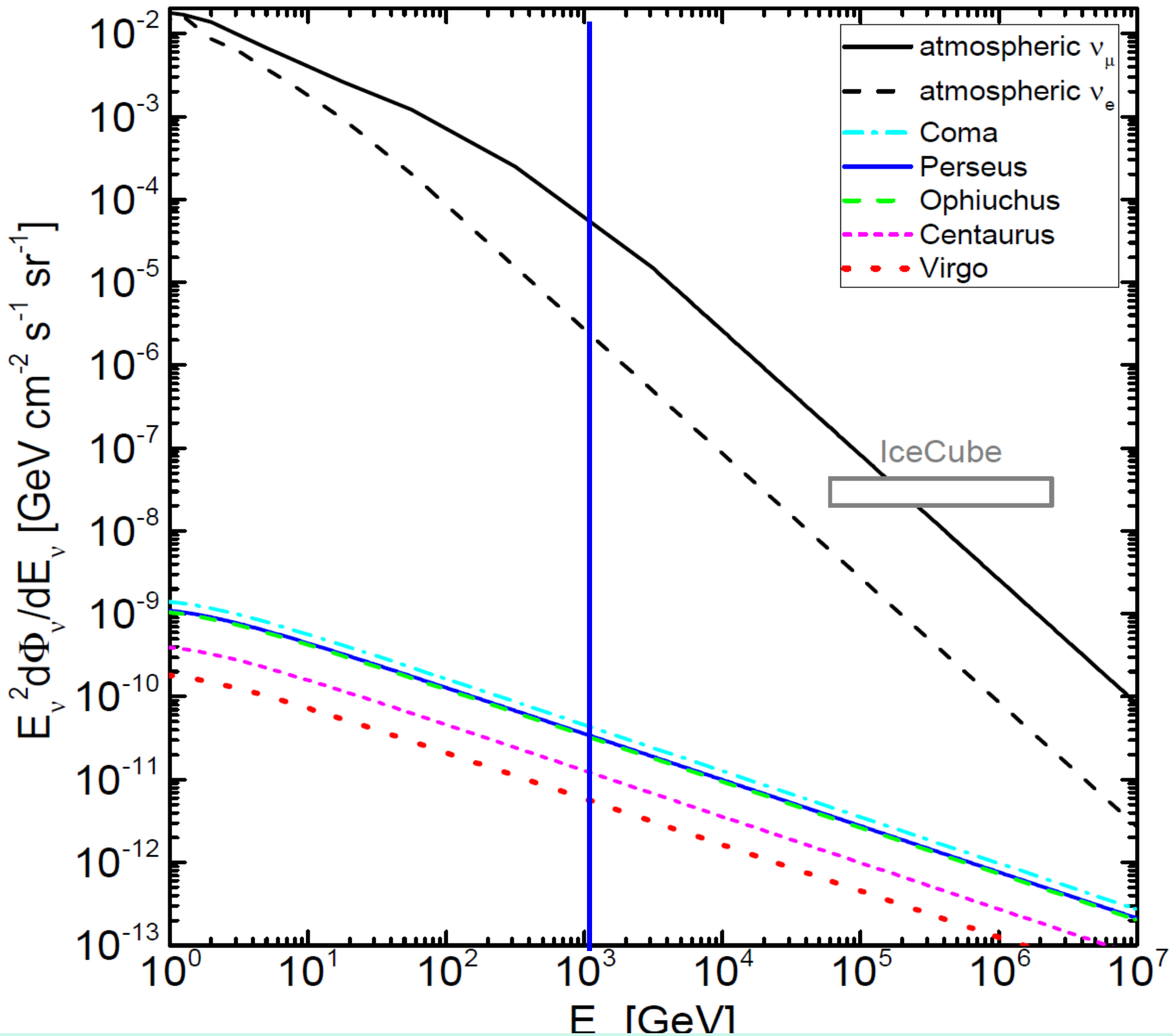
Can neutrinos from galaxy clusters be detected?

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



KNO (10 MeV ~ 100 GeV)

ICE-CUBE



the neutrino flux from nearby galaxy clusters is ~ 10^{-6} of that of atmospheric neutrino at 100 GeV !

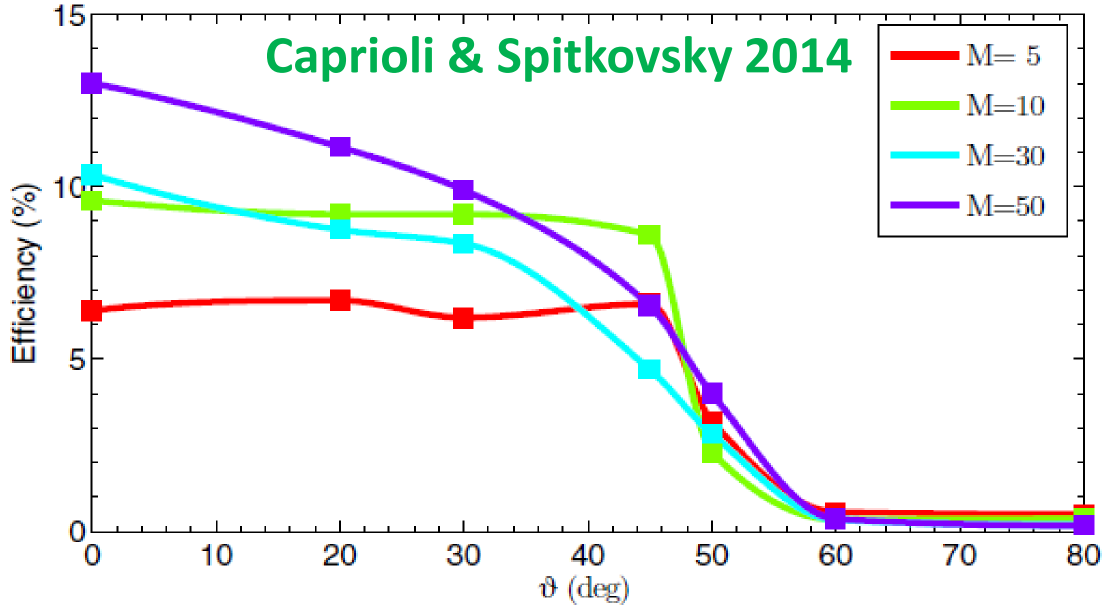
Neutrinos from accretion (external) shocks

Ha, Ryu, Kang (under progress)

External shocks

- form around clusters and filaments when the cool ($T \sim 10^4\ K$), tenuous gas with no or very weak magnetic fields (B) in voids accretes onto them.
- Strong shocks with the Mach number reaching up to M ~ 100

CR production at such shocks – not well understood!



Acceleration efficiency ($\varepsilon_{CR} = E_{CR,2}/(E_{CR,2} + E_{th,2})$)

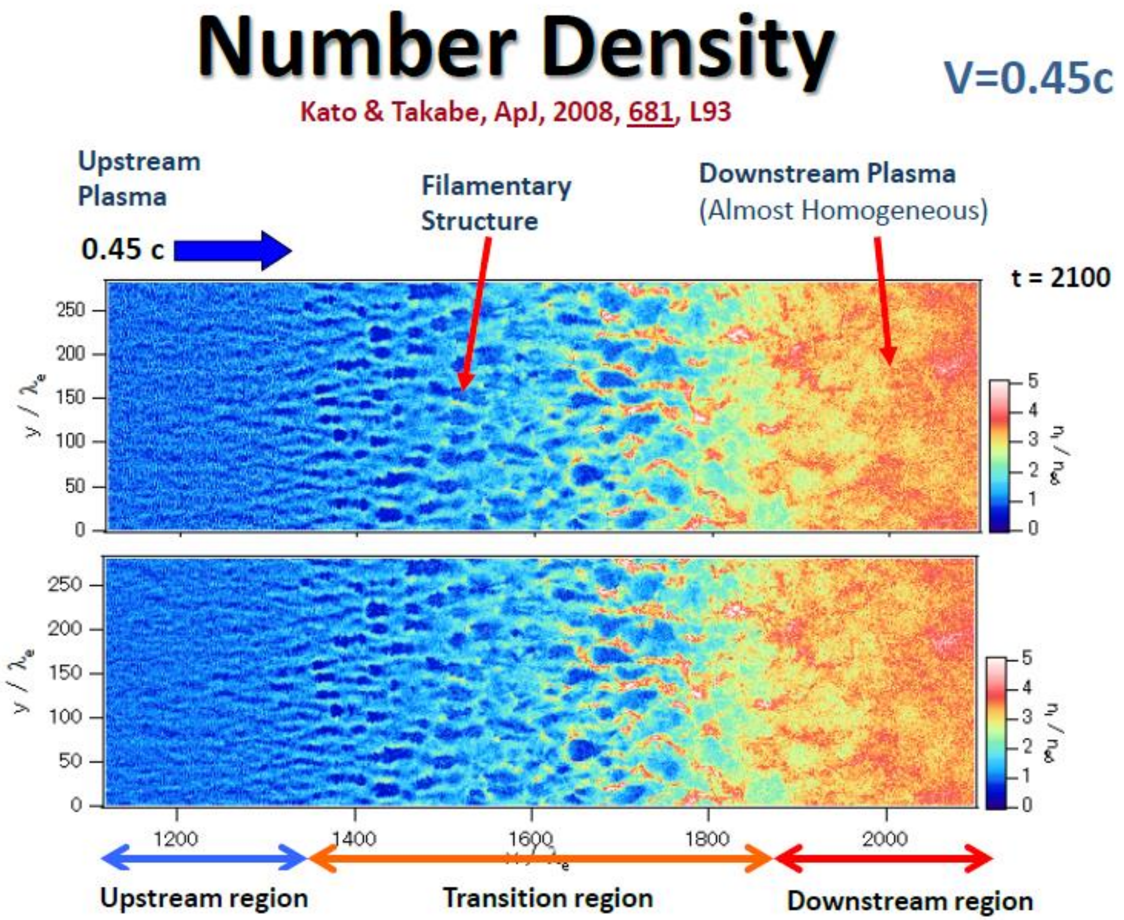
For ISM, $T = 10^4 K$, $\beta = 1$, $M < \sim 60$

(strong shocks, but with strong B fields)

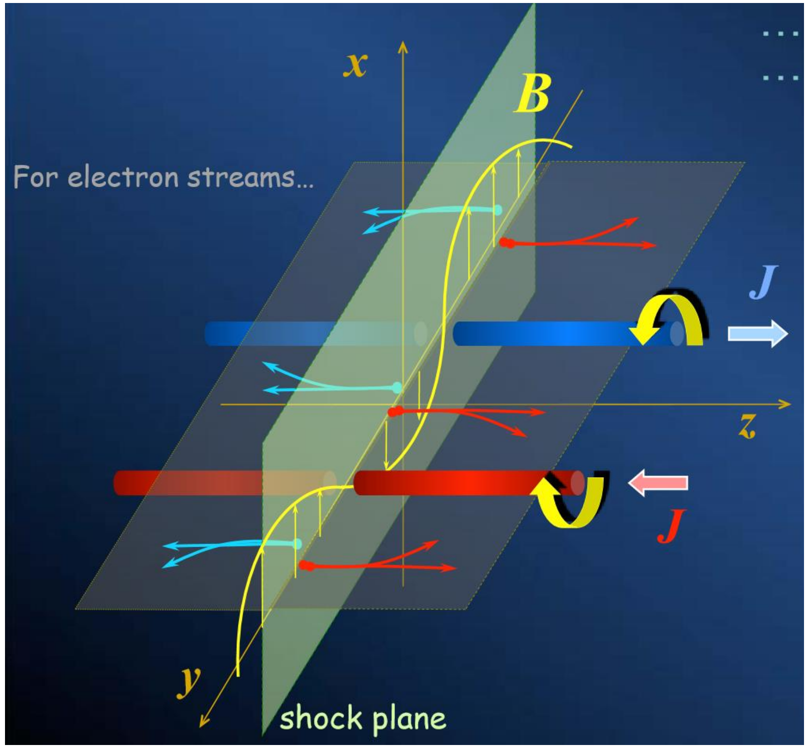
Strong collisionless shocks with weak B fields

→ Weibel-mediated shocks?

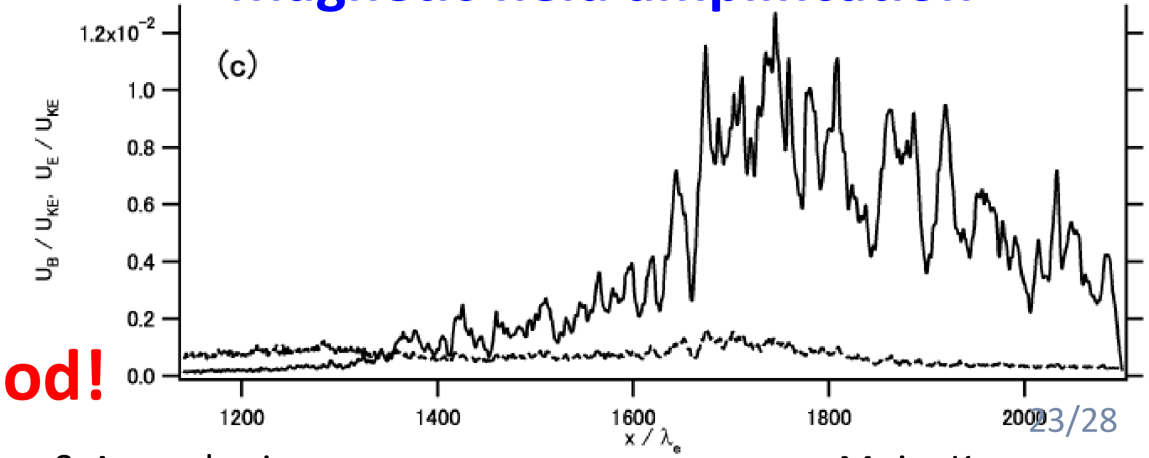
Kato & Takabe 2008



Weibel instability



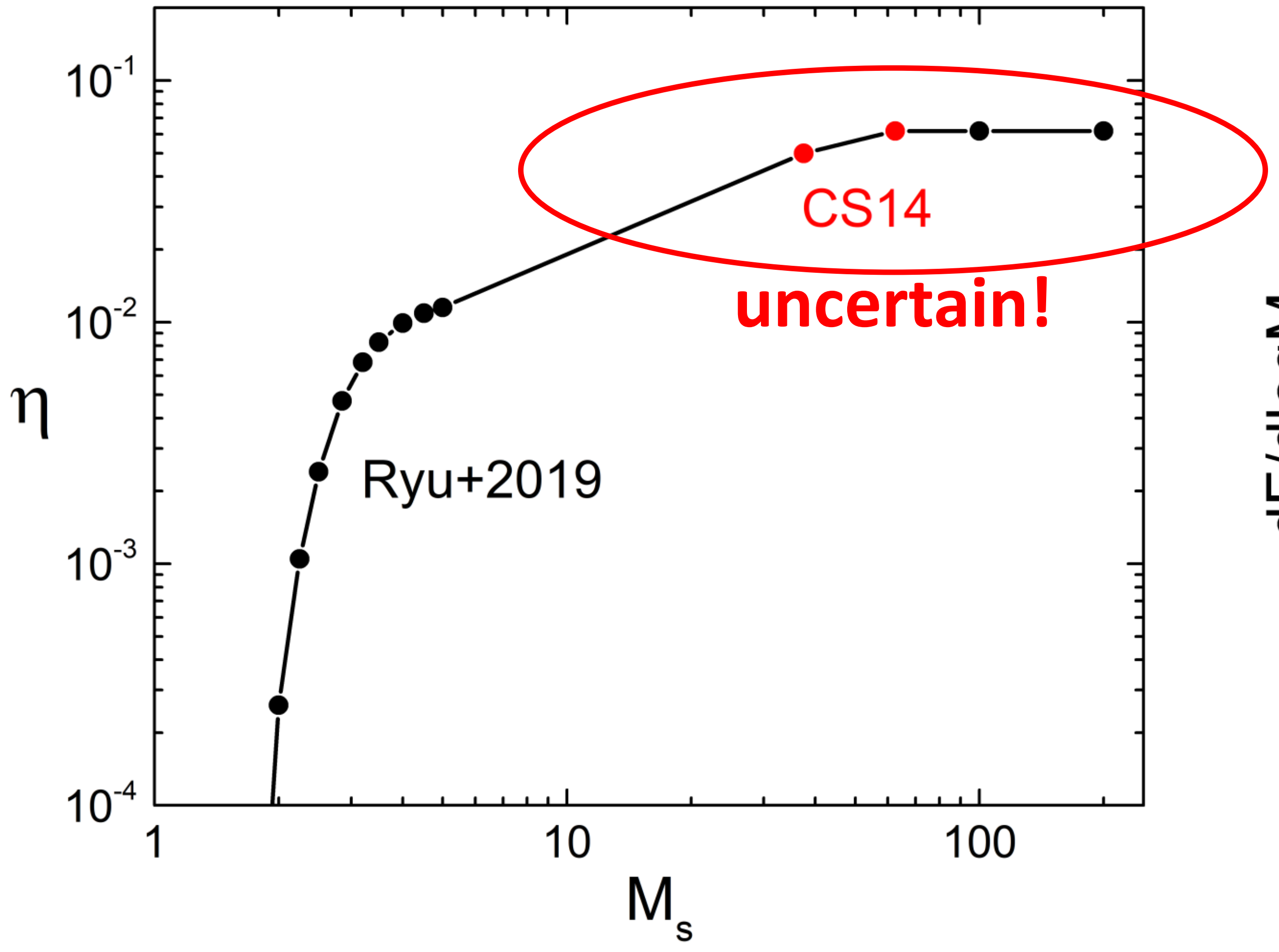
Magnetic field amplification



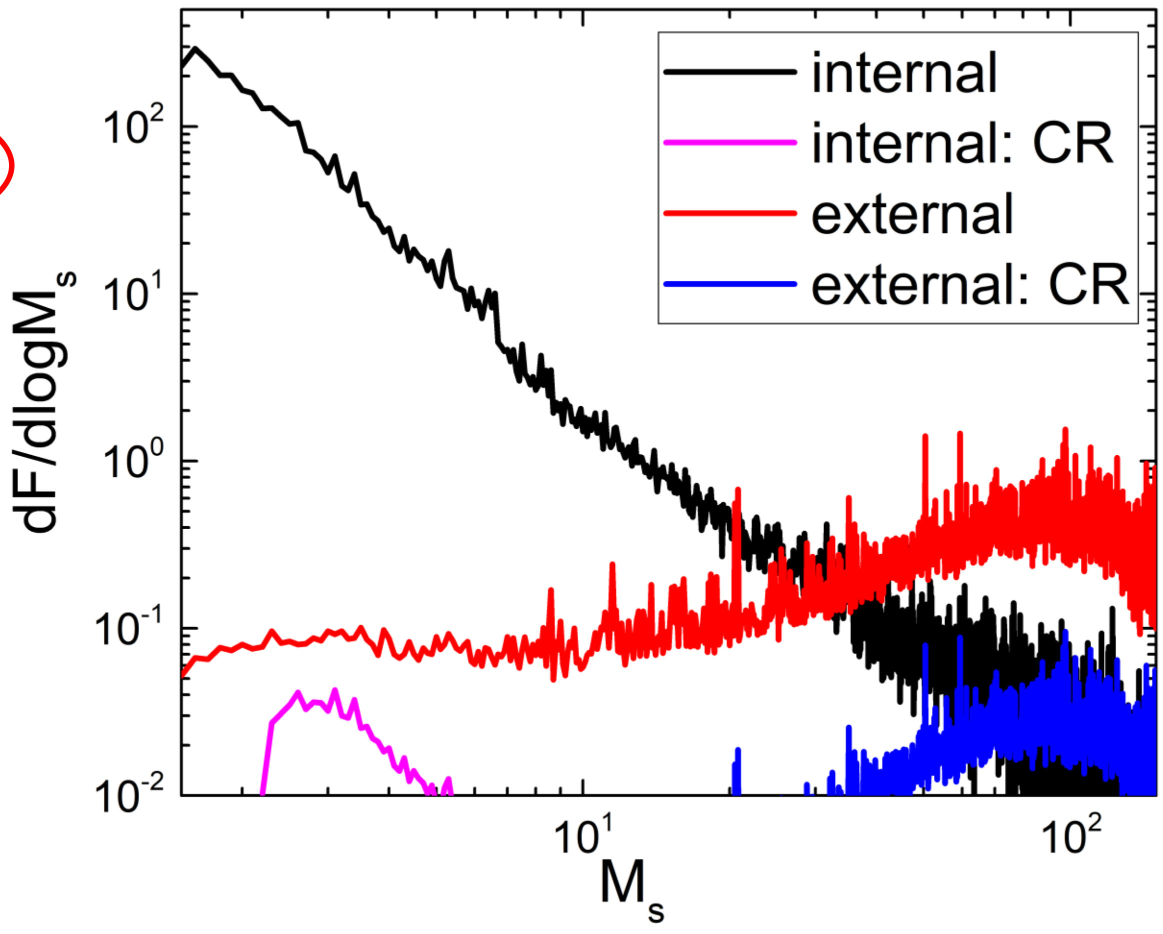
Acceleration of particles is not well understood!

A model for CR acceleration at accretion shocks

CR acceleration efficiency

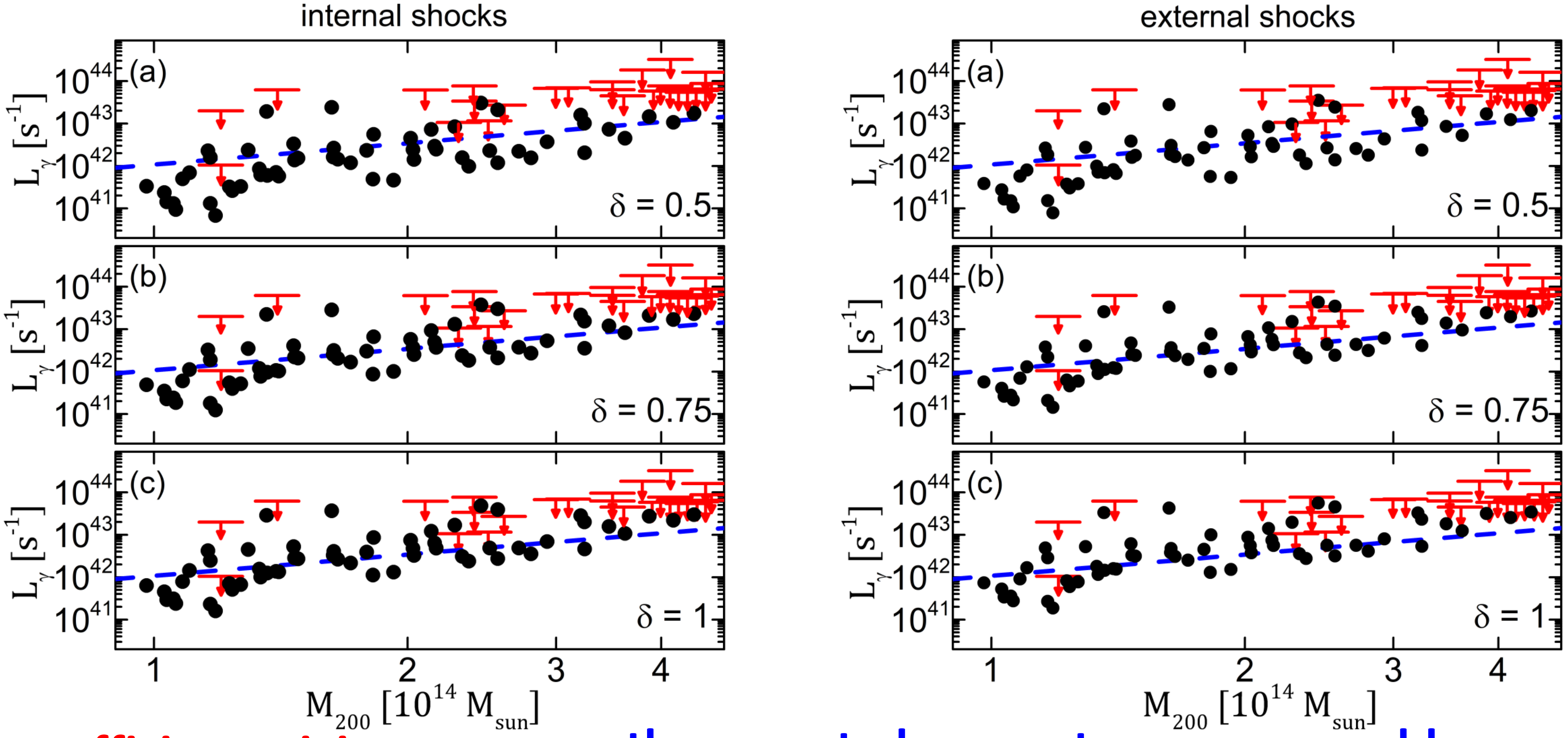


Kinetic & CR Energy fluxes



Gamma-ray emissions due to CRs from galaxy clusters

intracluster shocks | **accretion shocks**

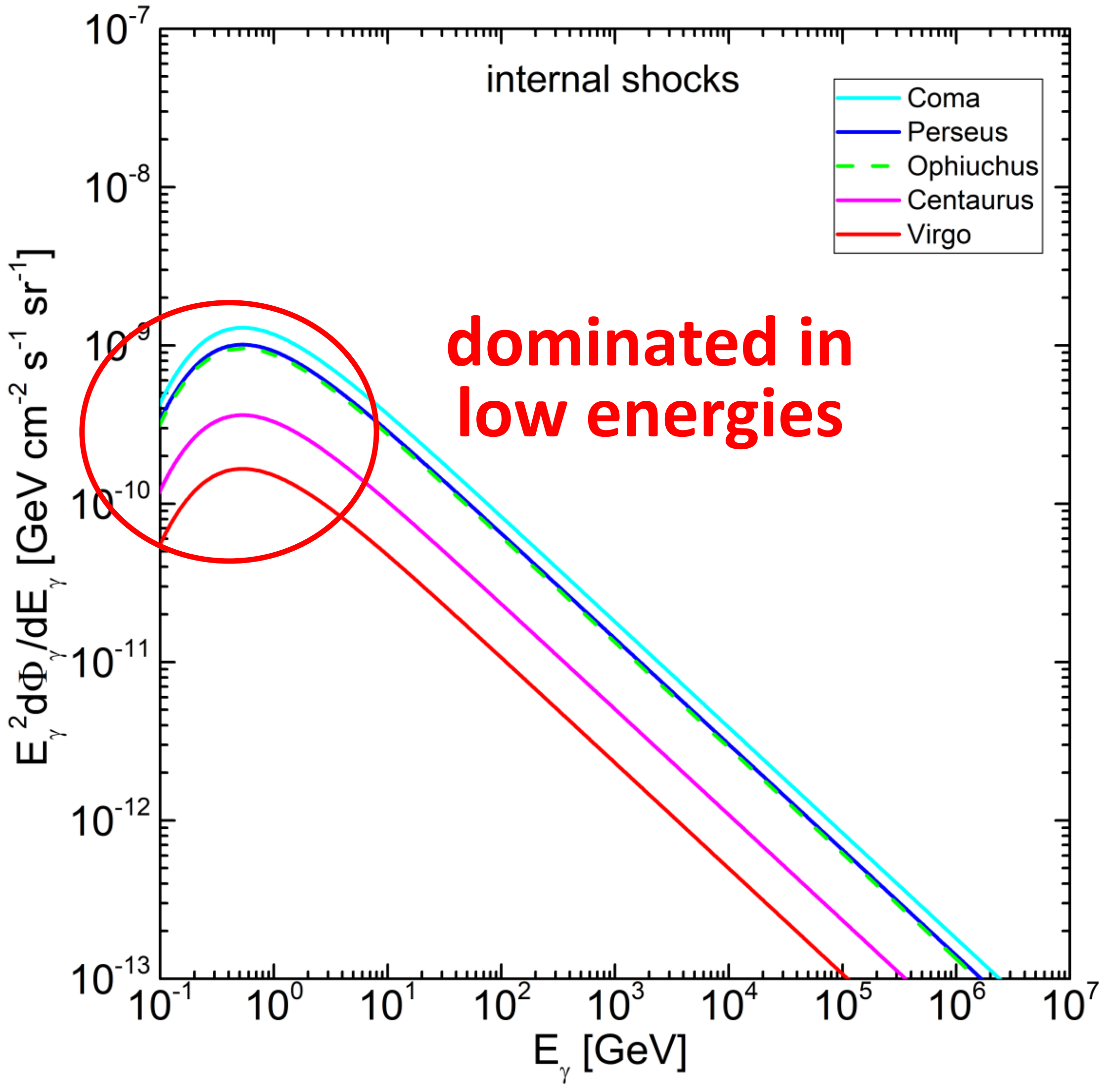


efficient mixing of CRs assumed!

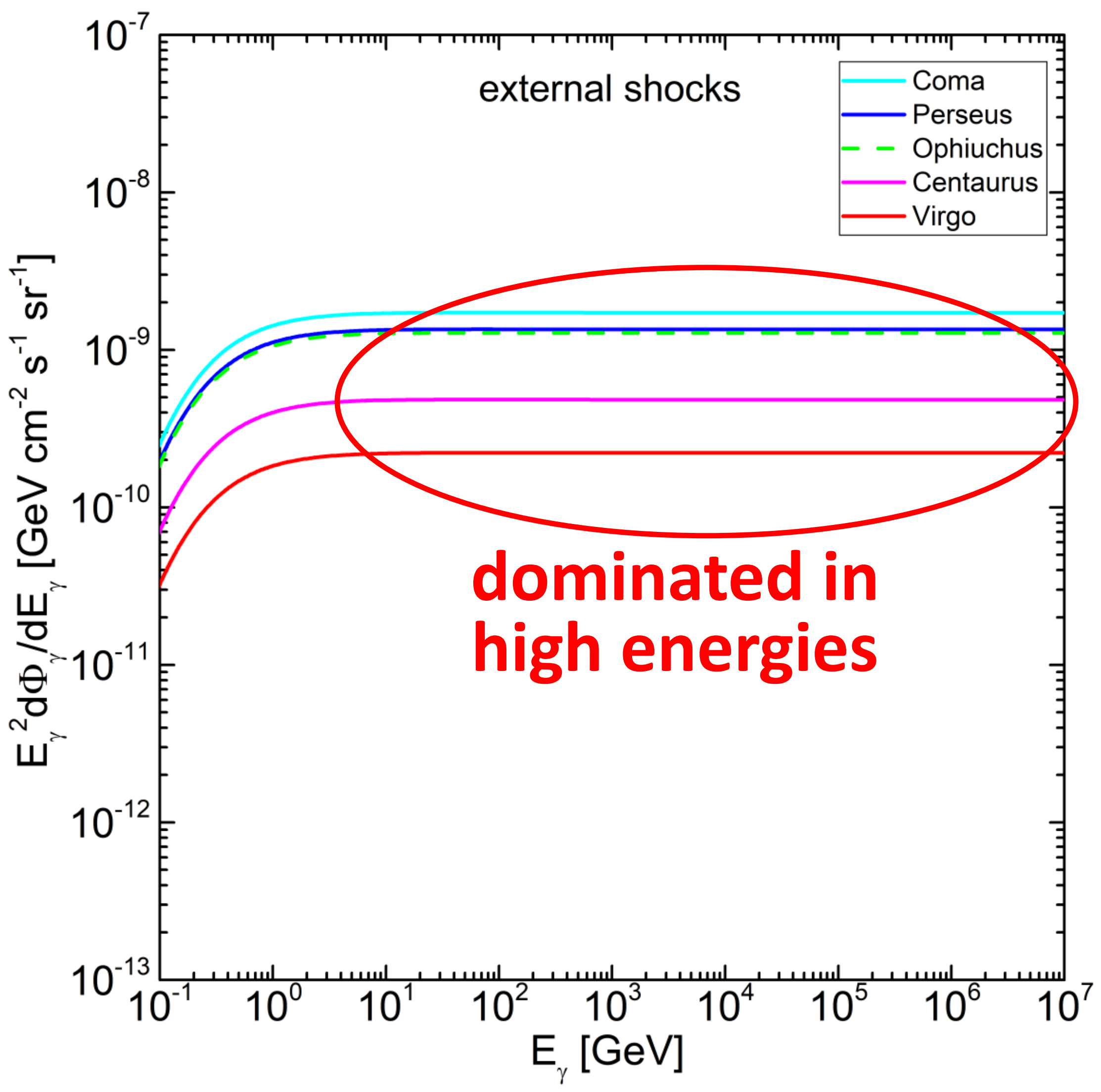
- **the expected amounts are comparable**
- **both are consistent with the Fermi-LAT constraint**

Predicted gamma-ray fluxes from nearby galaxy clusters

intracluster shocks

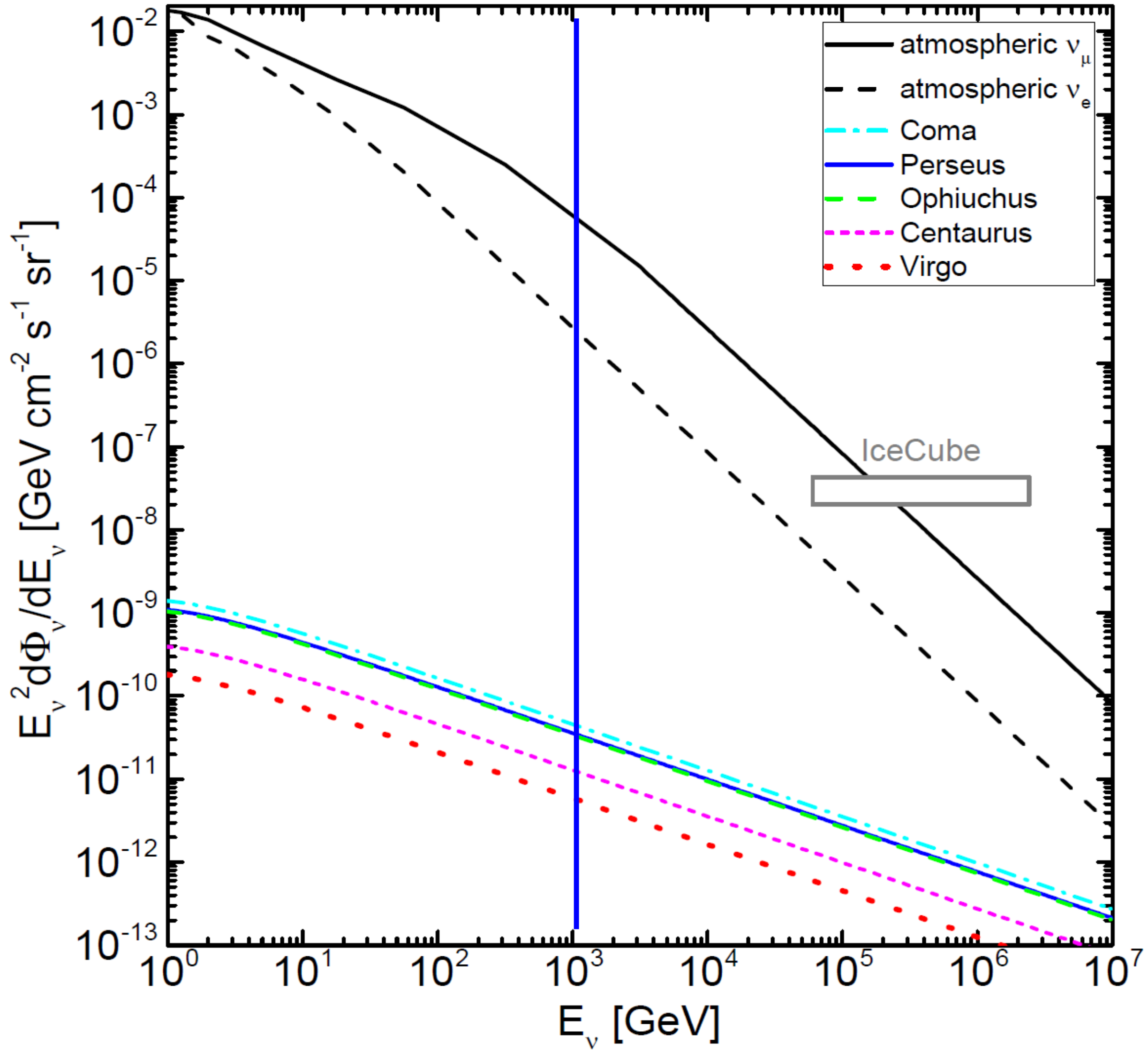


accretion shocks

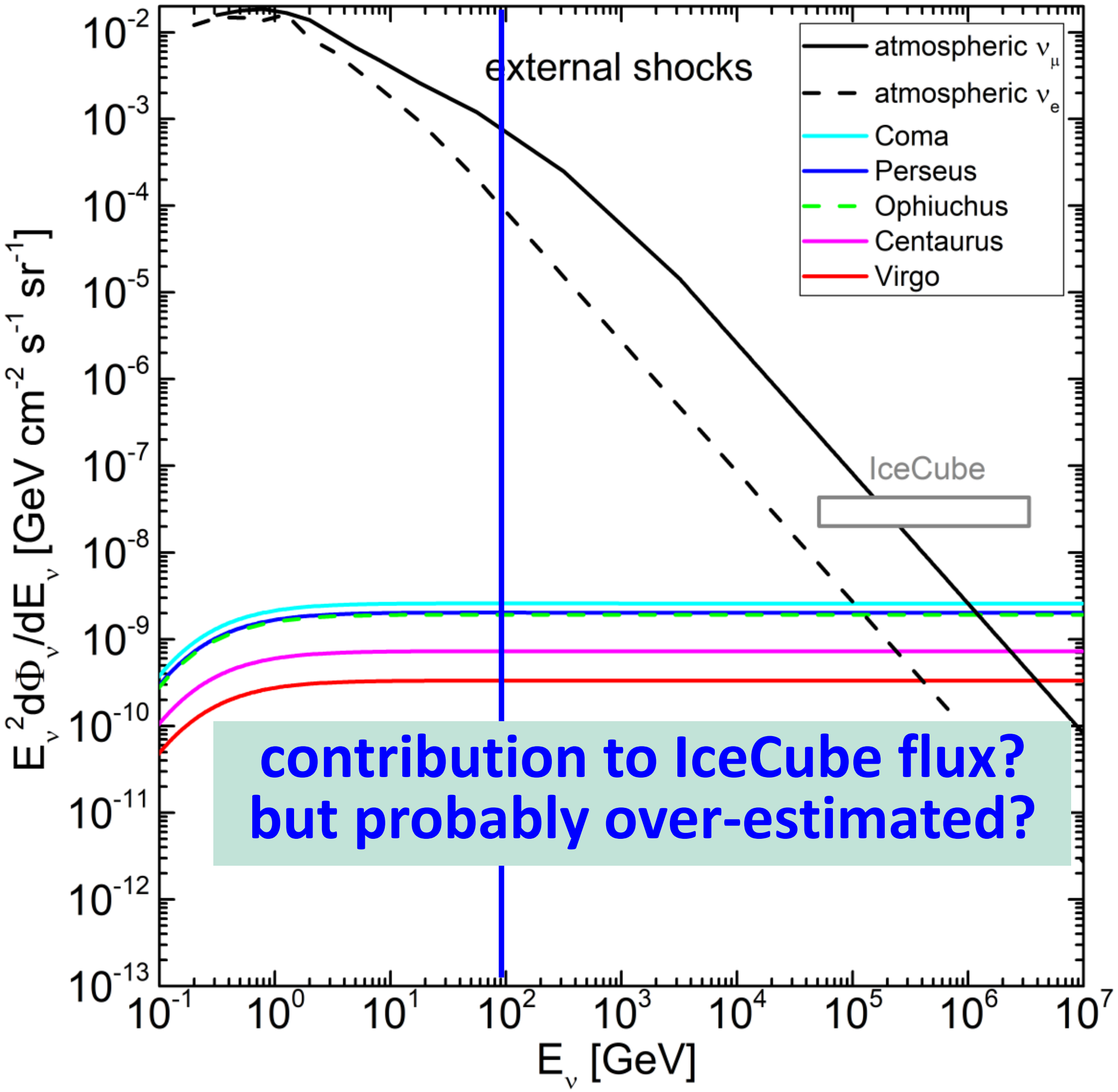


Predicted neutrino fluxes from nearby galaxy clusters

intracluster shocks



accretion shocks



Summary

1. Shocks are ubiquitous in galaxy clusters.
2. Shocks can accelerate cosmic ray protons through DSA.
3. Cosmic ray protons can produce gamma rays and neutrinos through p-p collisions.
4. The estimated gamma-ray flux is consistent with the Fermi-LAT upper limit.
5. The estimated neutrino flux from nearby galaxy clusters are much smaller than the IceCube flux.
6. It is unlikely to detect neutrinos from clusters of galaxies with KNO.