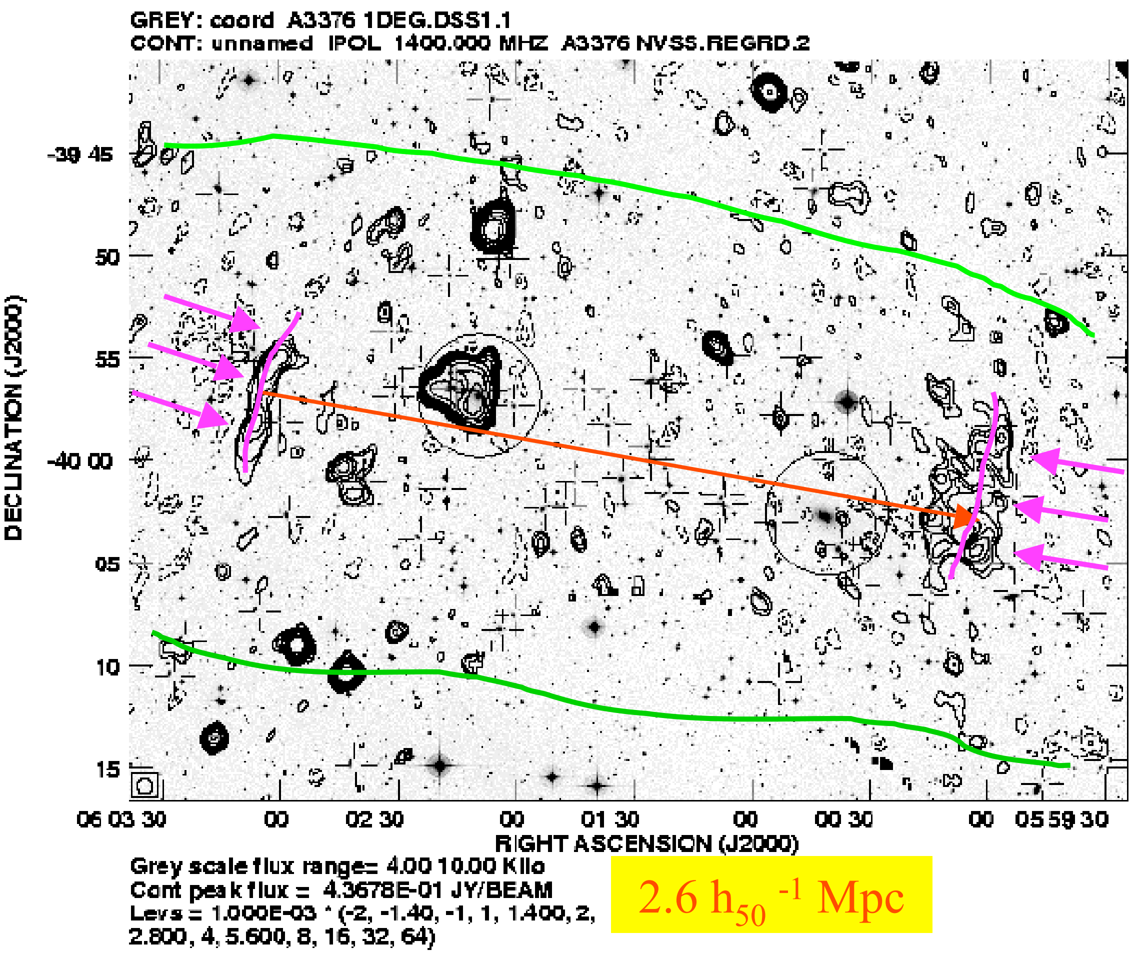
Shock Waves and Shock-Heated Gas in Cosmological Hydrodynamic Simulations

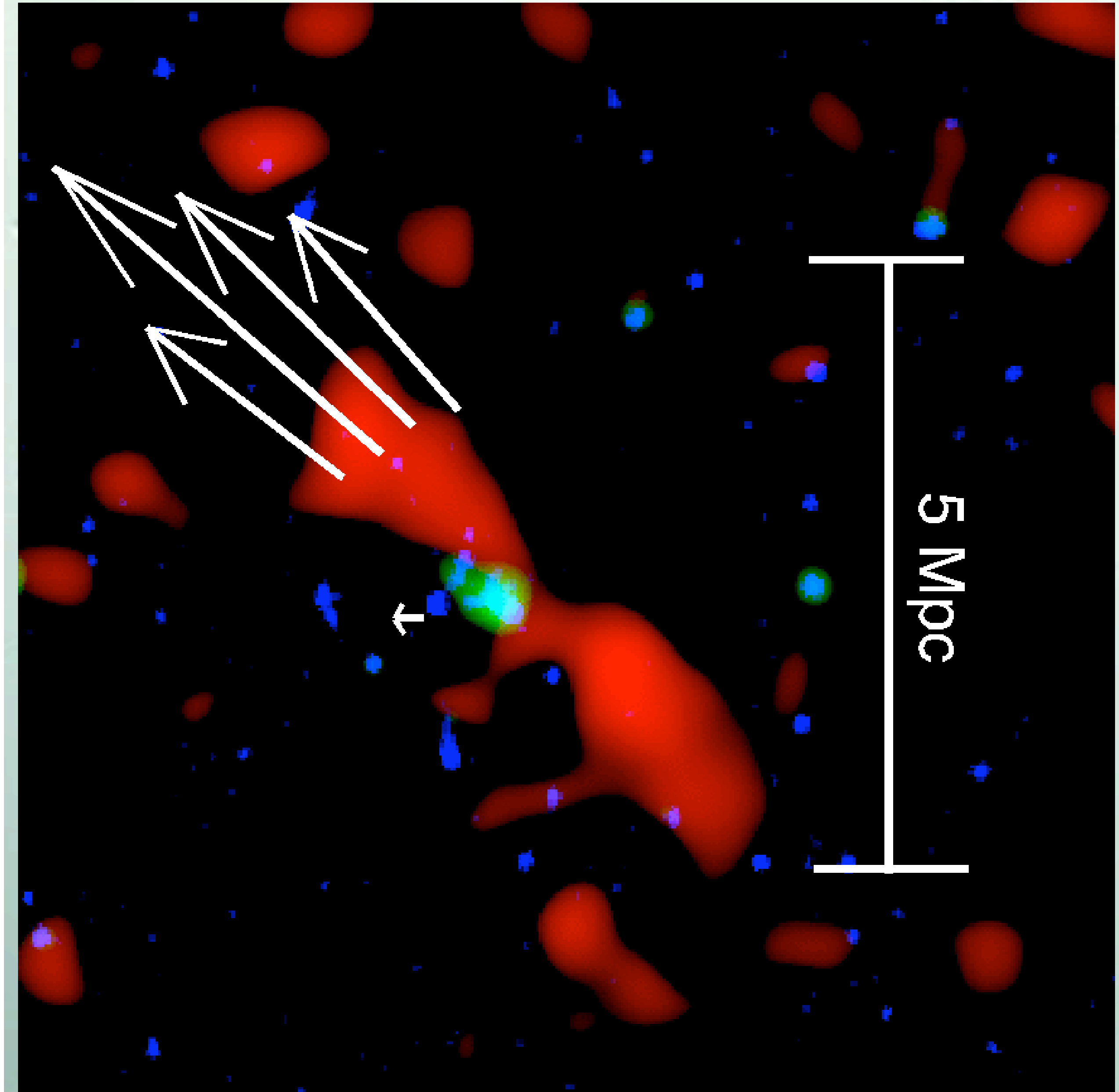
Dongsu Ryu (Chungnam National U, Korea)
Hyesung Kang (Pusan National U, Korea)

- Cosmological shock waves in LSS
  : distribution & properties
- Shock-heated gas (WHIM)
  : distribution & observations
- Cosmic rays accelerated at cosmological shocks

radio arcs in A3376 (Bagchi 2003)

observational evidence for accretion shocks or merger shocks ?





radio observation in large scale stru cture

green: known relic
blue: background source
red: new source

possible detection of diffuse radio emisson from filaments

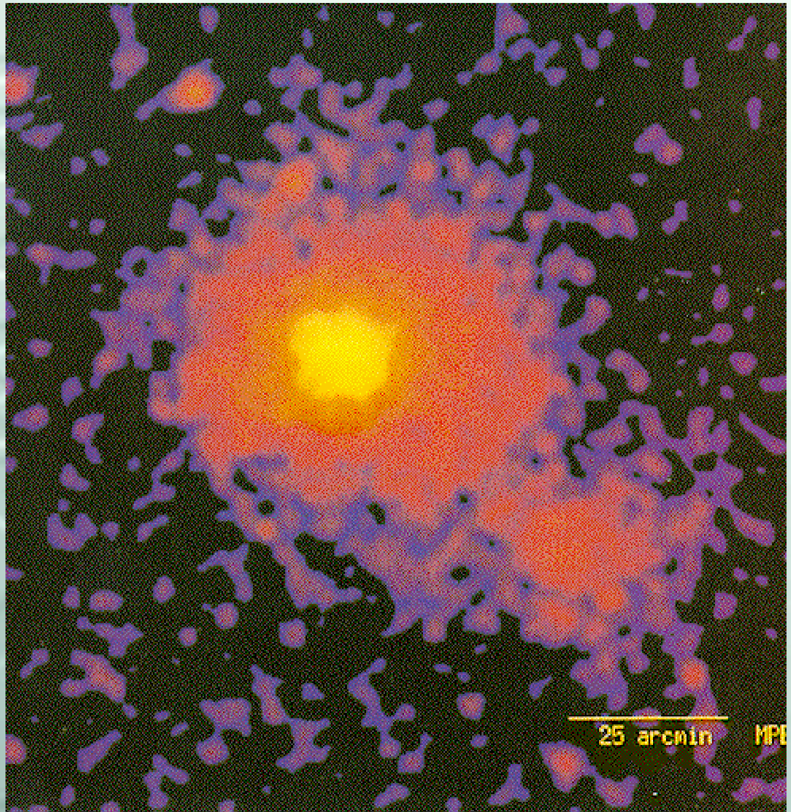
(Rudnick, preliminary)

diffuse raiod sources in clusters of galaxies

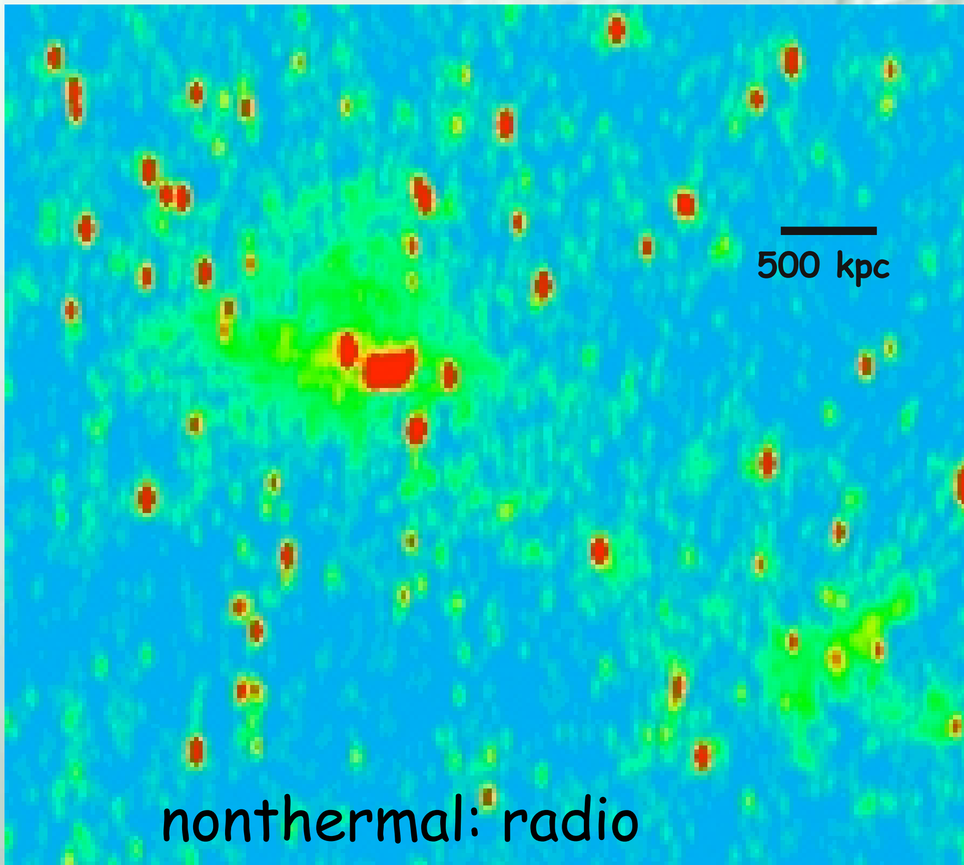
prove the existence of relativistic electrons of energy ~ GeV
and of magnetic fields ~ μG
on scales of Mpcs !!

Coma cluster

X-ray: ROSAT (White et al. 1993)

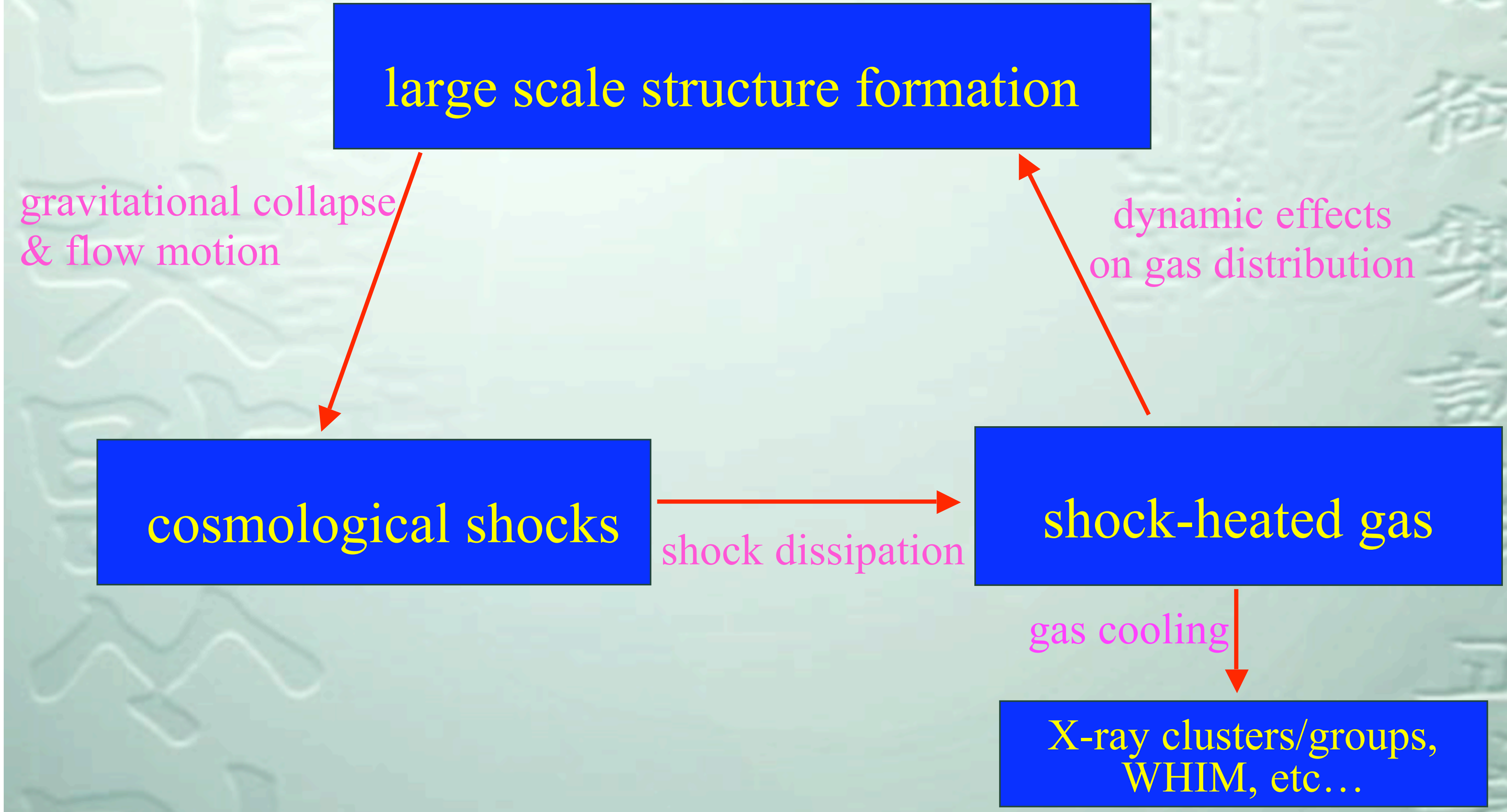


thermal: X-ray



RADIO: WSRT, 90 cm (Feretti et al.1998)

Shock waves & shock-heated gas in large scale structures



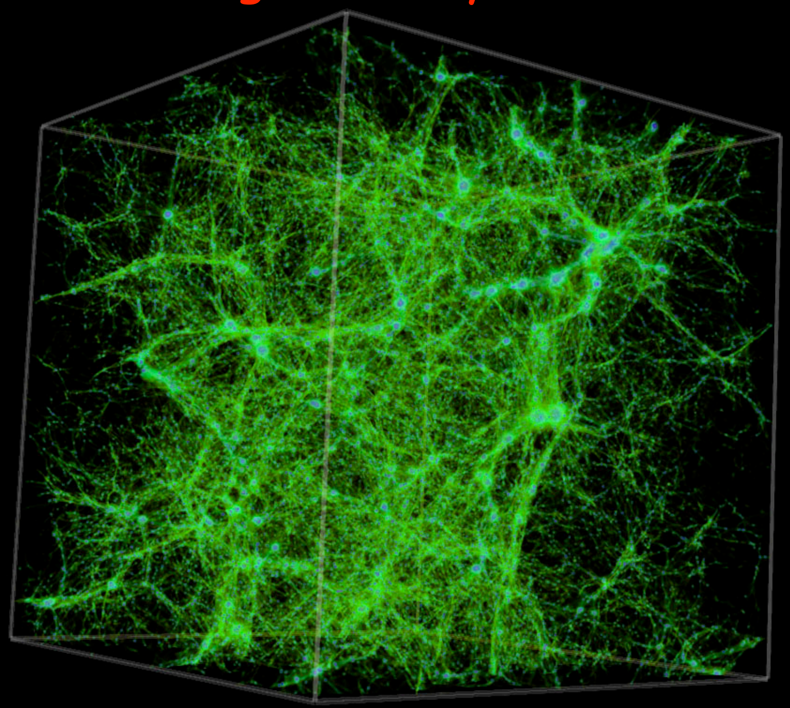
Shock waves in the large scale structure of the universe

(Ryu, Kang et al)

Numerical simulations

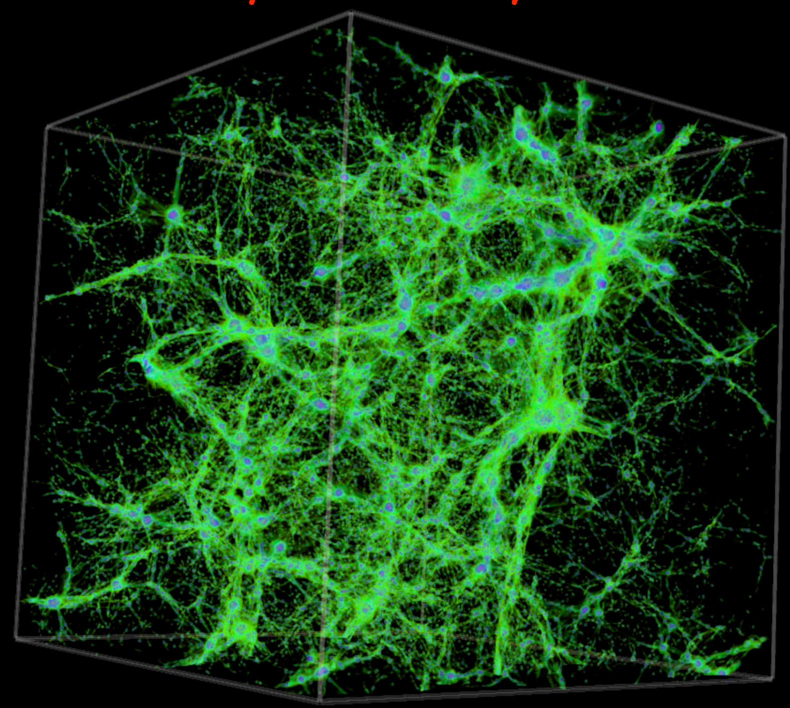
- Λ cold dark matter cosmology
  $\Omega_\Lambda = 0.73$, $\Omega_{DM} = 0.27$, $\Omega_{gas} = 0.043$, h=0.7, $n = 1$, $\sigma_8 = 0.8$
  without/with gas cooling
- computational box: $(100h^{-1}\ \mathrm{Mpc})^3$
  1024^3 cells for gas and gravity, 512^3 DM particles, $\Delta x = 97.7\ h^{-1}$Mpc

gas desity

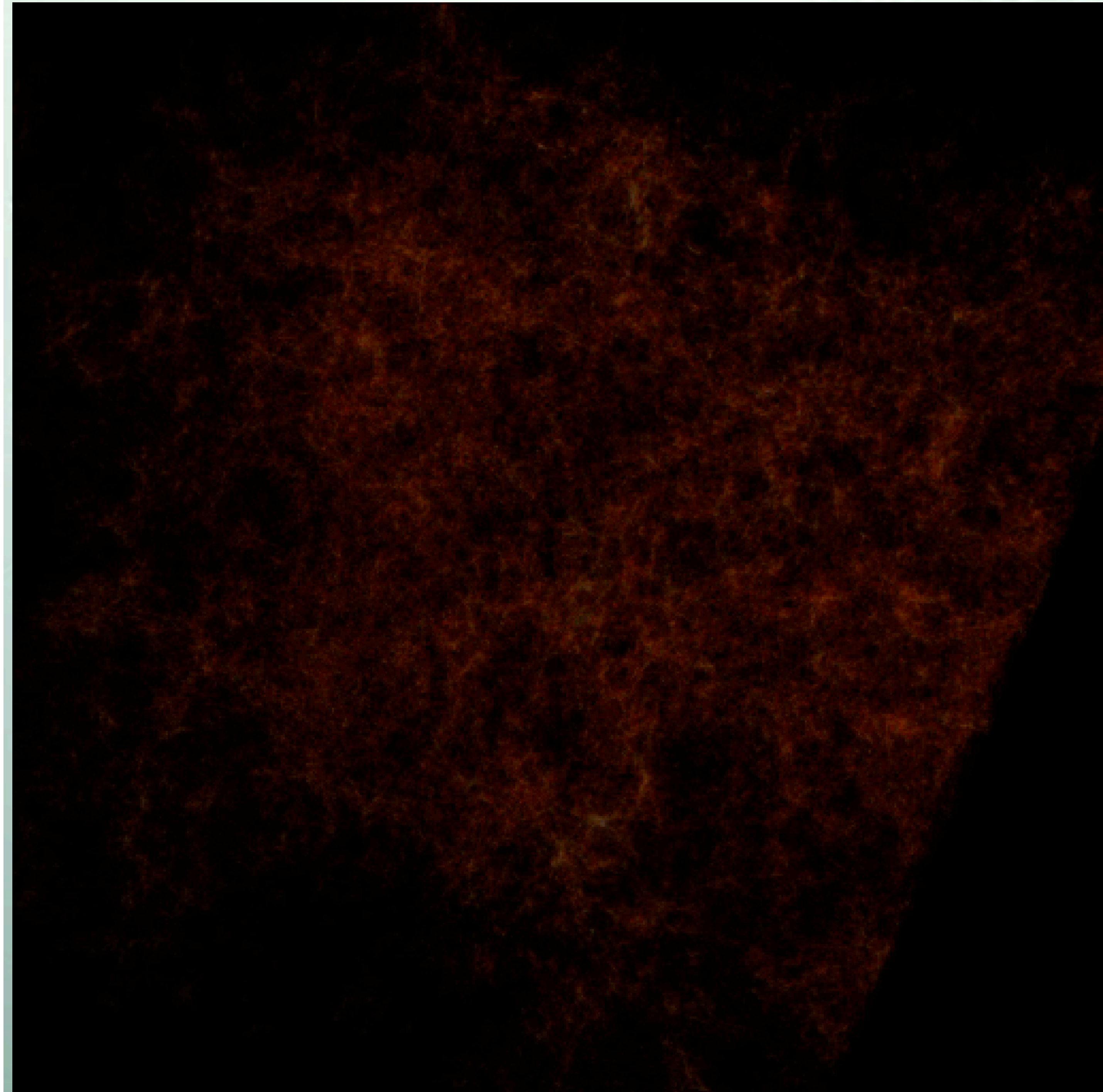


$\rho = 1 - 10^4 \langle\rho\rangle$ and higher

X-ray emissivity



$\varepsilon = 10^{-37} - 10^{-29}$ erg cm^{-3} s^{-1} and higher



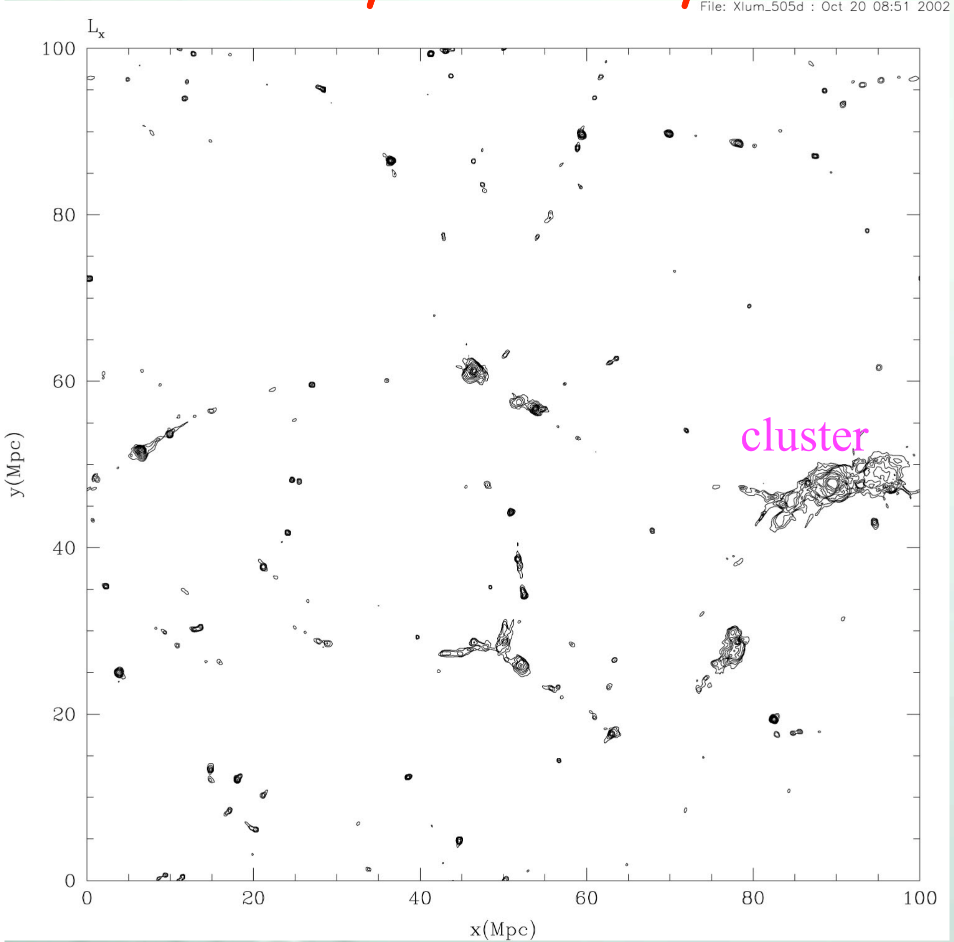
X-ray emissivity distribution: time evolution

(100 h^{-1} Mpc)^3

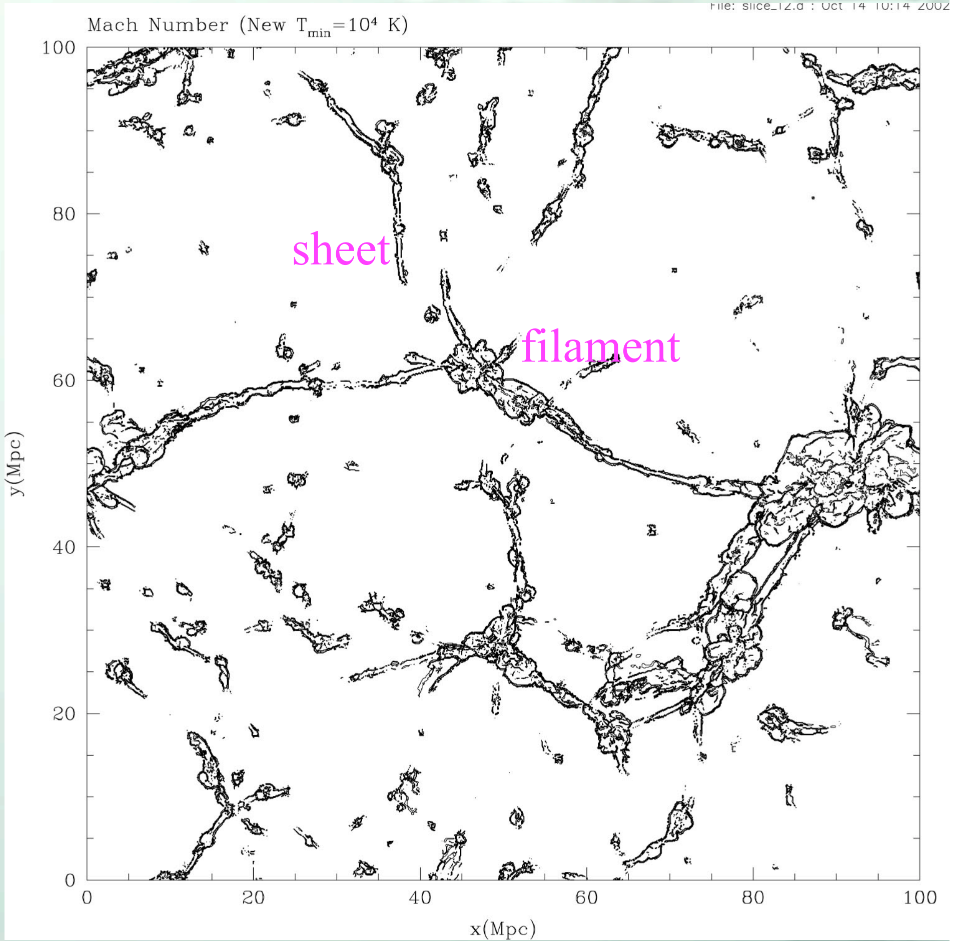
1024^3 cells

full box spinning

X-ray emissivity



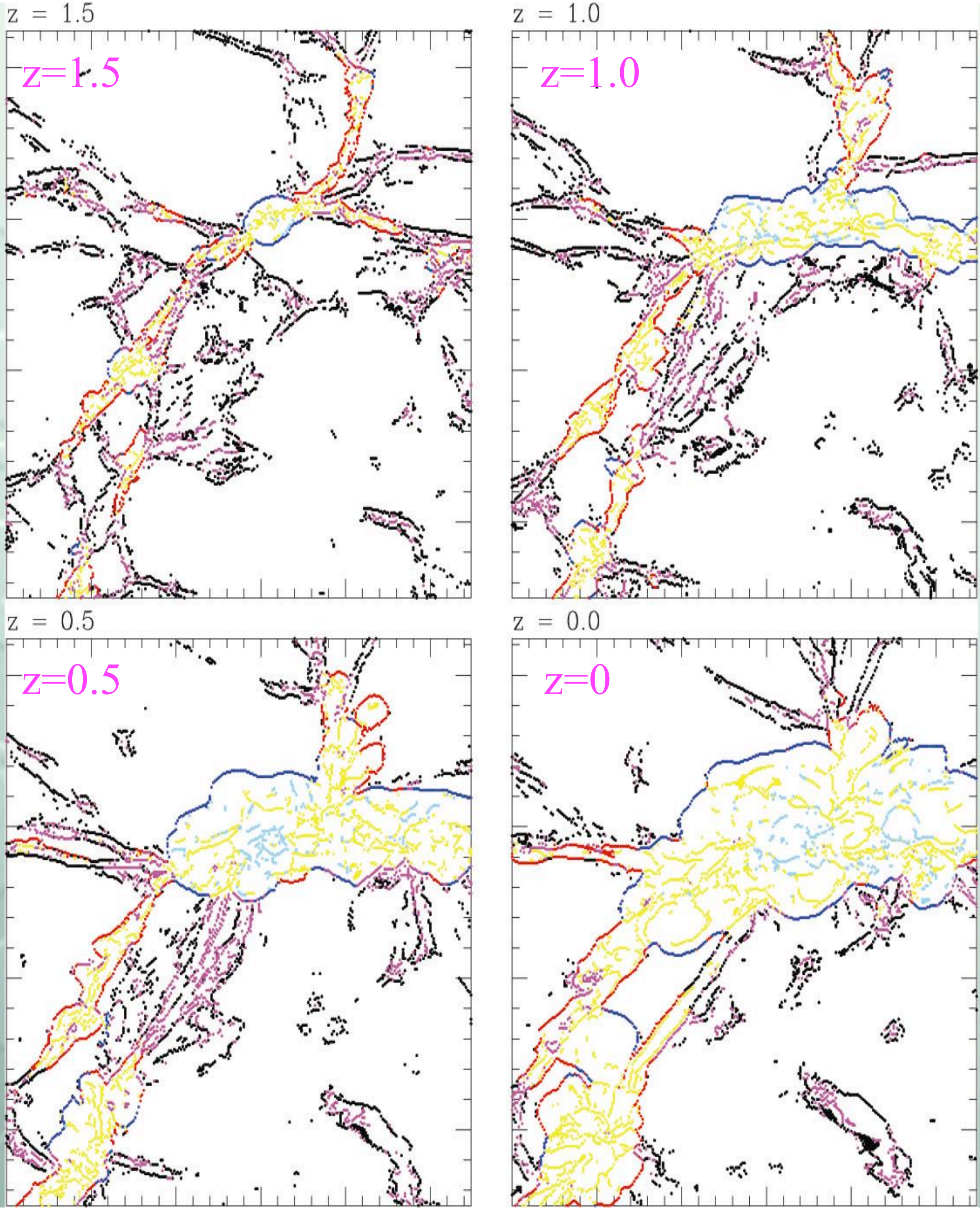
shock waves



(100 Mpc/*h*)^2 2D slice

rich, complex shock morphology:

shocks "reveal" filaments and sheets



time evolution of s
hocks around a clus
ter complex

28 x 37 (h^{-1} Mpc)^2 slice

external shocks

v_{sh}< 150 km/s

150 < v_{sh}< 700 km/s

v_{sh}> 700 km/s

internal shocks

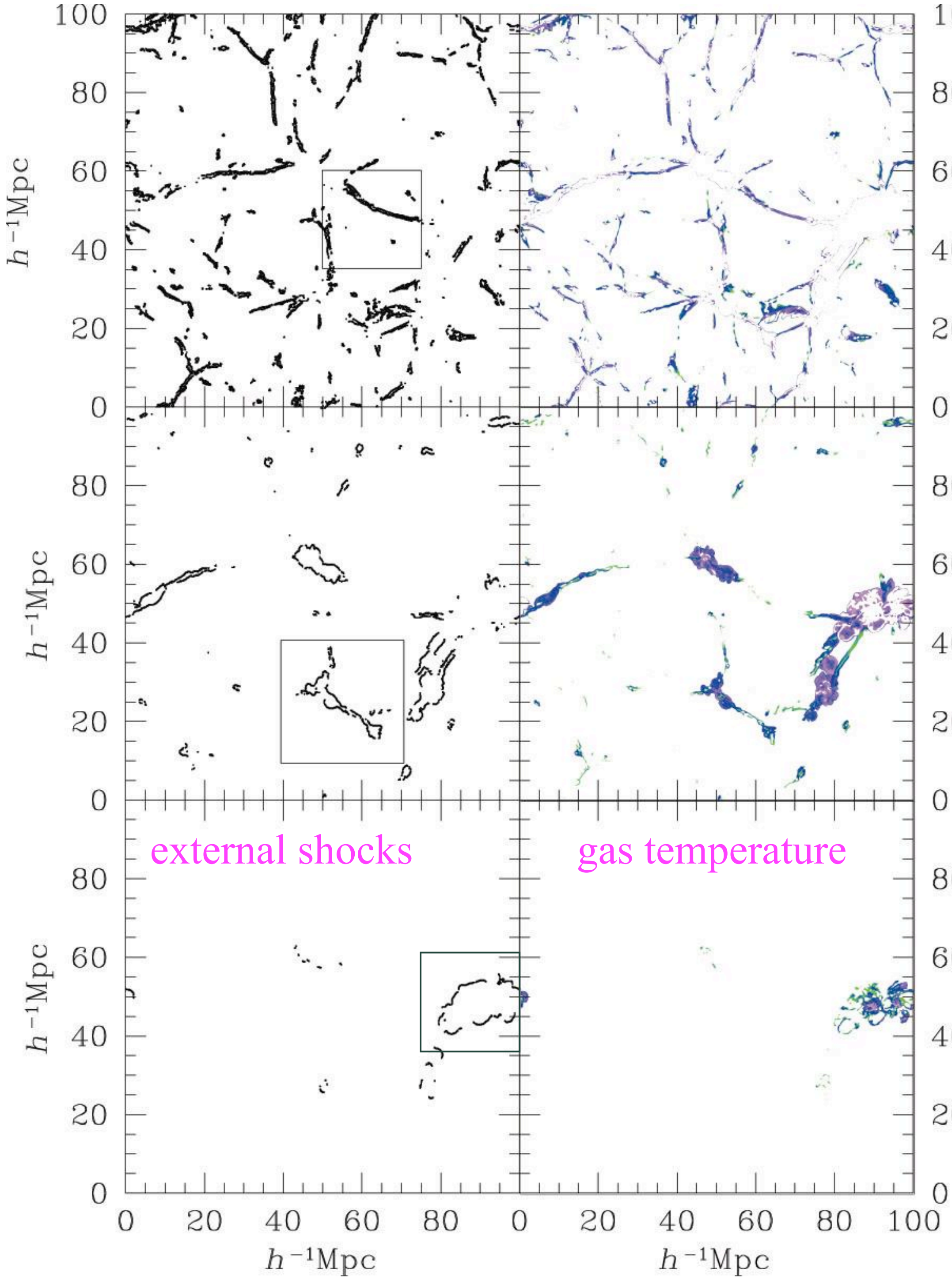
v_{sh}< 150 km/s

150 < v_{sh}< 700 km/s

v_{sh}> 700 km/s

external shocks: high Mach no.
outer surfaces of nonlinear struct.

internal shocks: low Mach no.
inside nonlinear structure



external shocks with

$v_{sh} < 150$ km/s

gas with $T_{gas} < 10^5$K (WHIM)

sheet-like structures

external shocks with

$150 < v_{sh} < 700$ km/s

gas with $10^5 < T_{gas} < 10^7$K (WHIM)

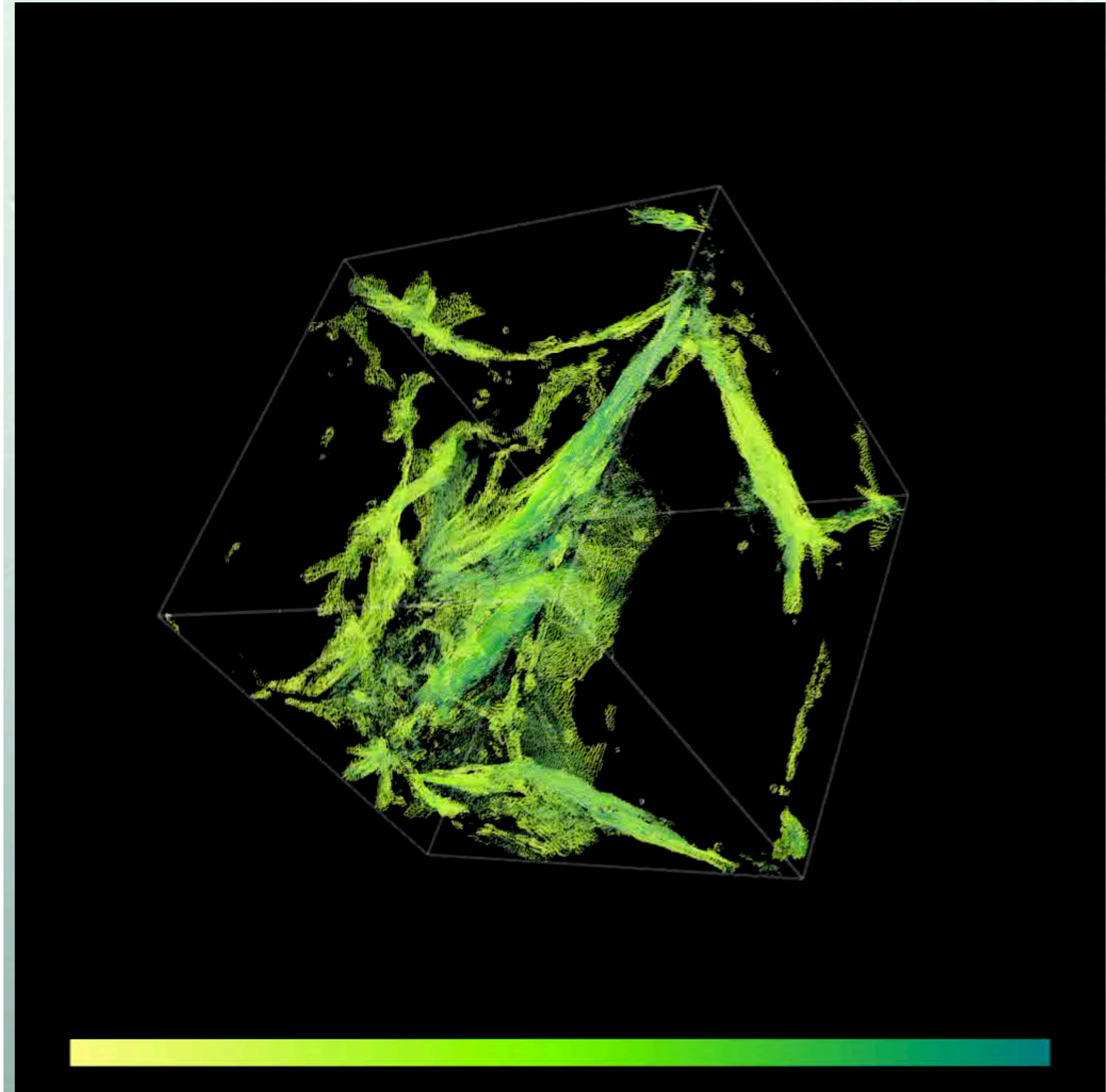
filamentary structures

external shocks with

$v_{sh} > 700$ km/s

gas with $T_{gas} > 10^7$K (hot)

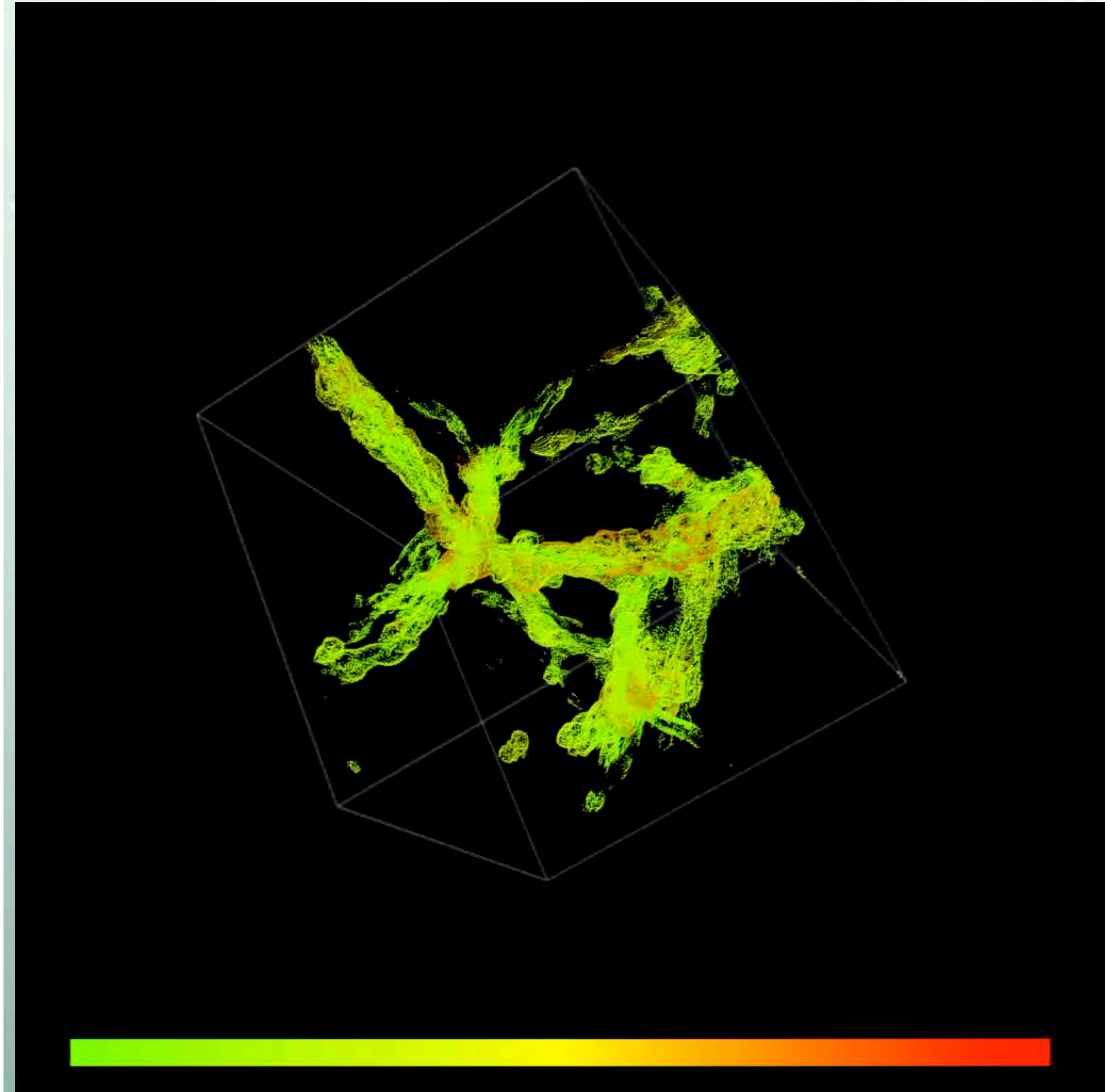
knot-like structures



distribution of shock waves with v_{sh}=15 – 150 km s^{-1}

°Ësheet-like structures

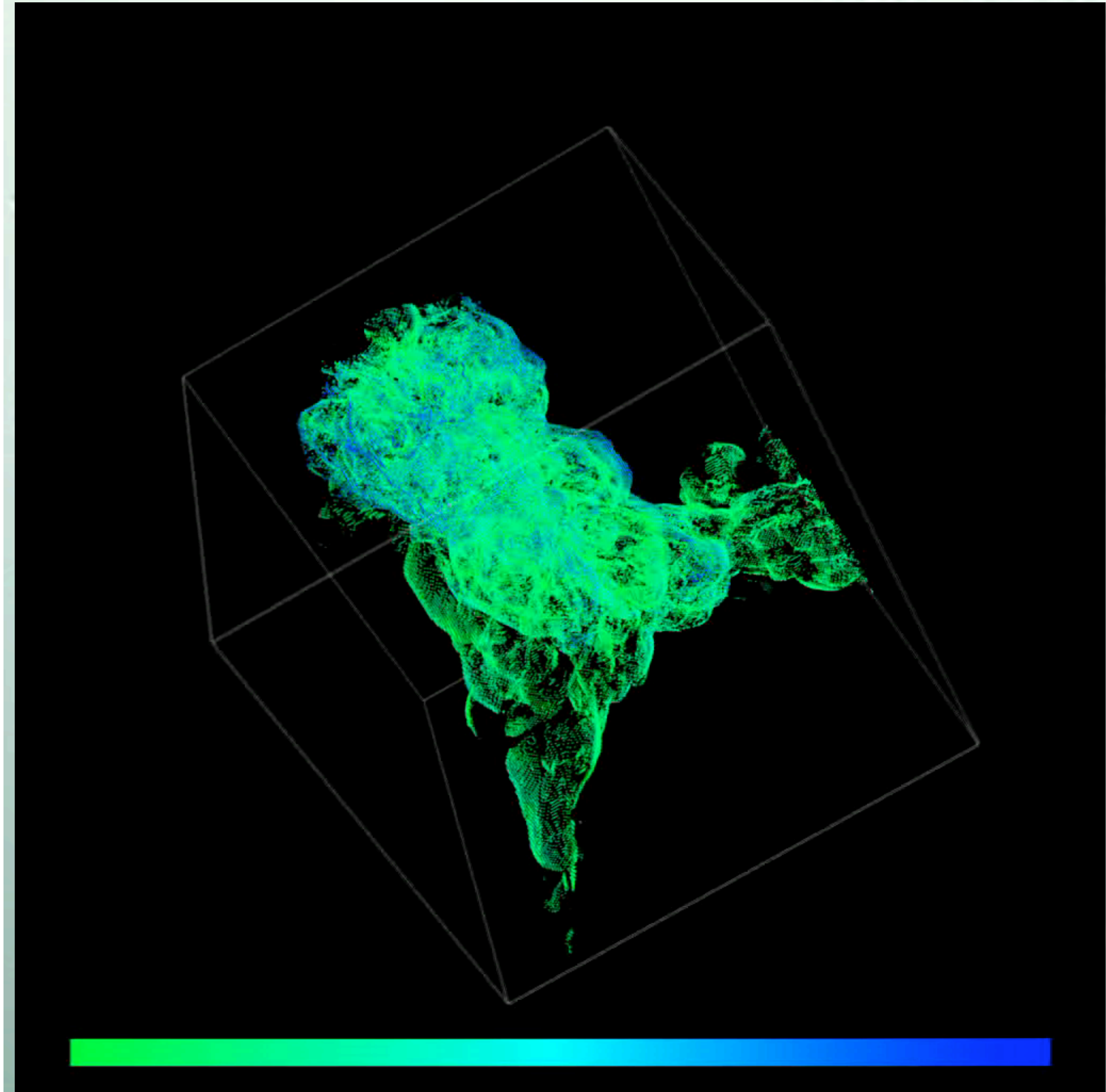
($25\ h^{-1}$ Mpc)^3 3D cube



distribution of shock waves with v_{sh} = 150 – 700 km s^{-1}

°ê filamentary structures

(31 h^{-1} Mpc)^3
3D cube

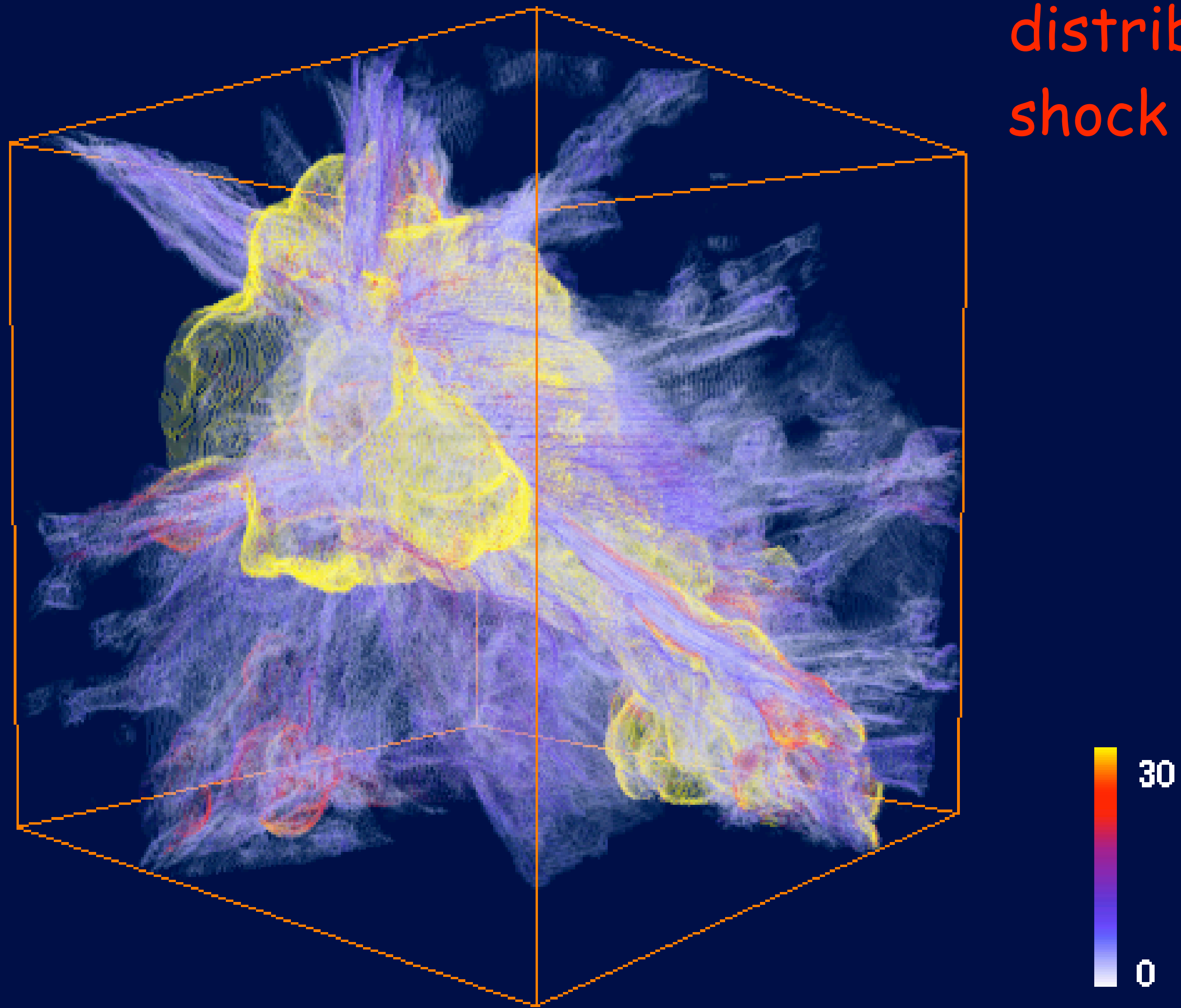


distribution of s
hock waves with v_{sh} > 700 km s^{-1}

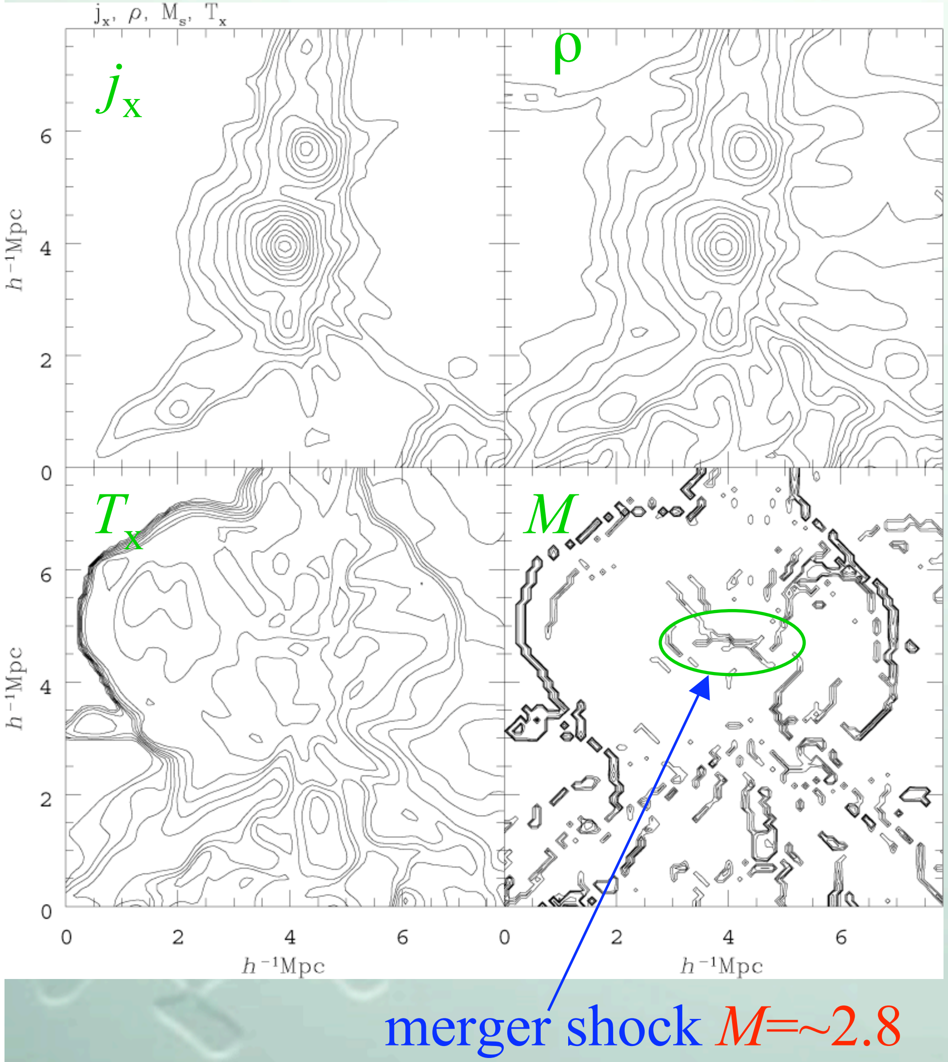
around a cluster complex

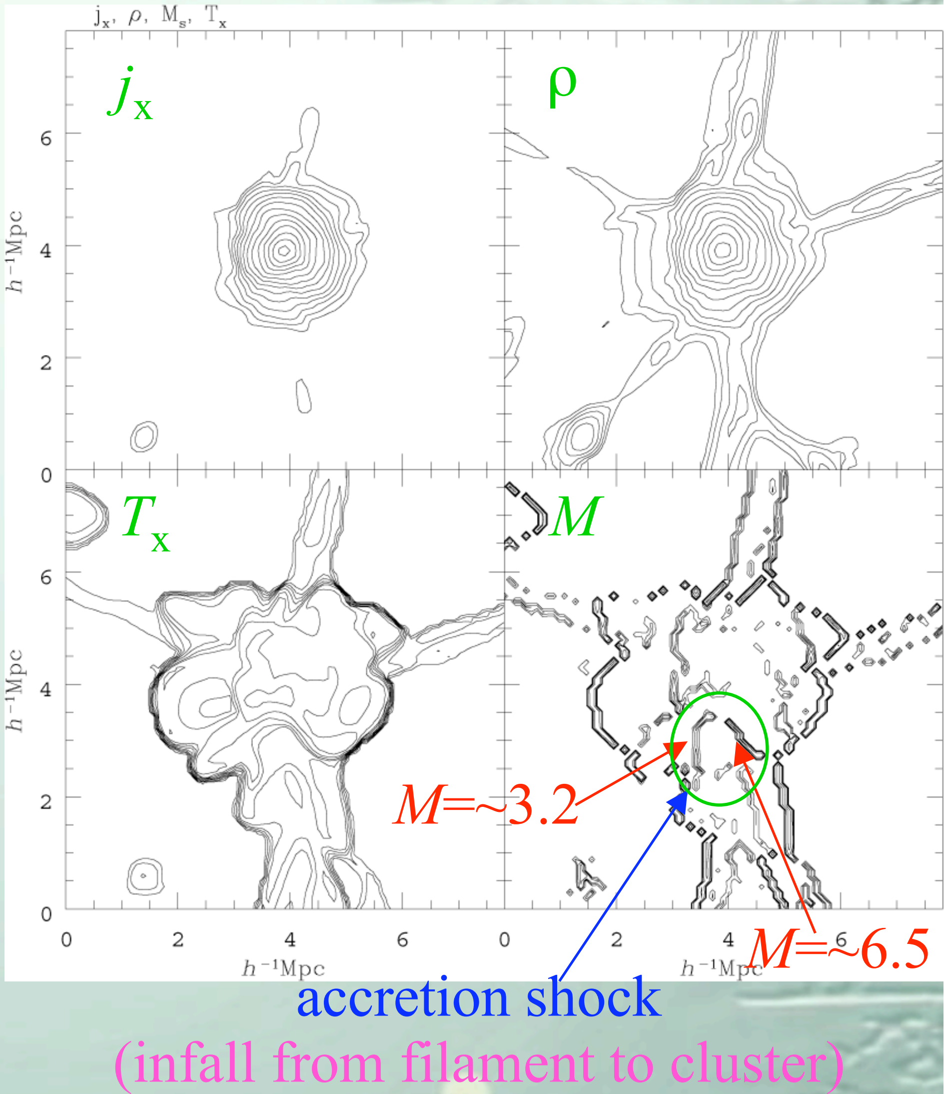
(25 h^{-1} Mpc)^3
3D cube

distribution of shock Mach no.

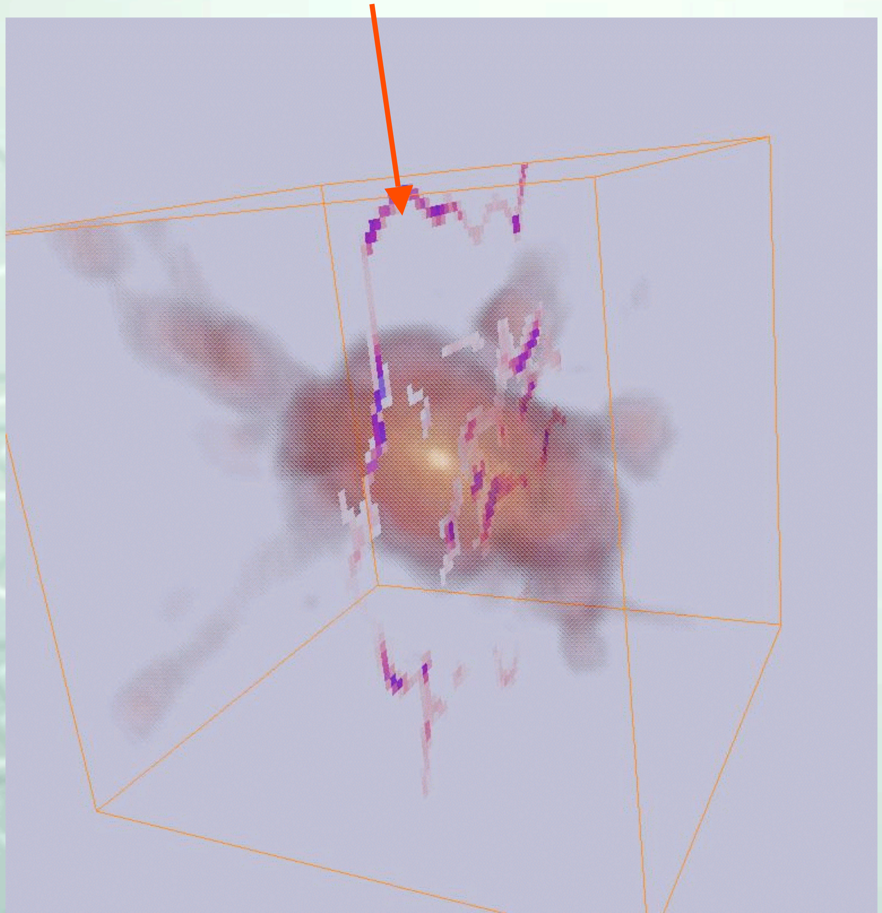


internal shocks inside/around clusters/groups



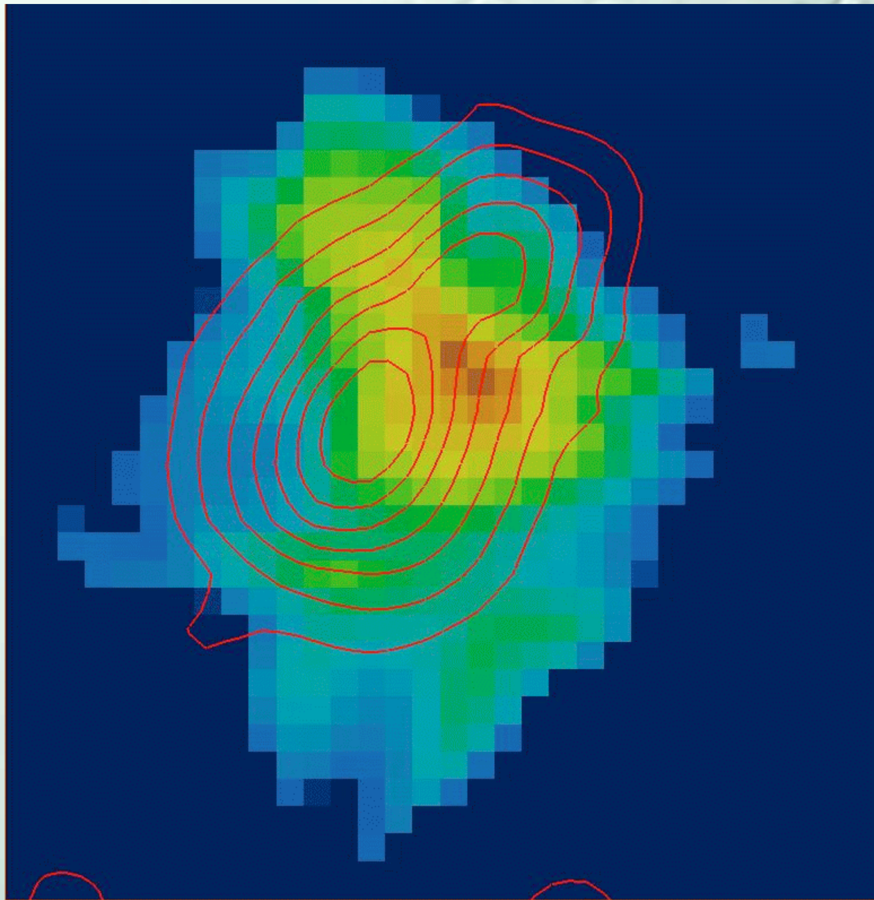


synthetic observation of merging clusters



X-ray emissivity & shock location

°ÊMach number = 1.7



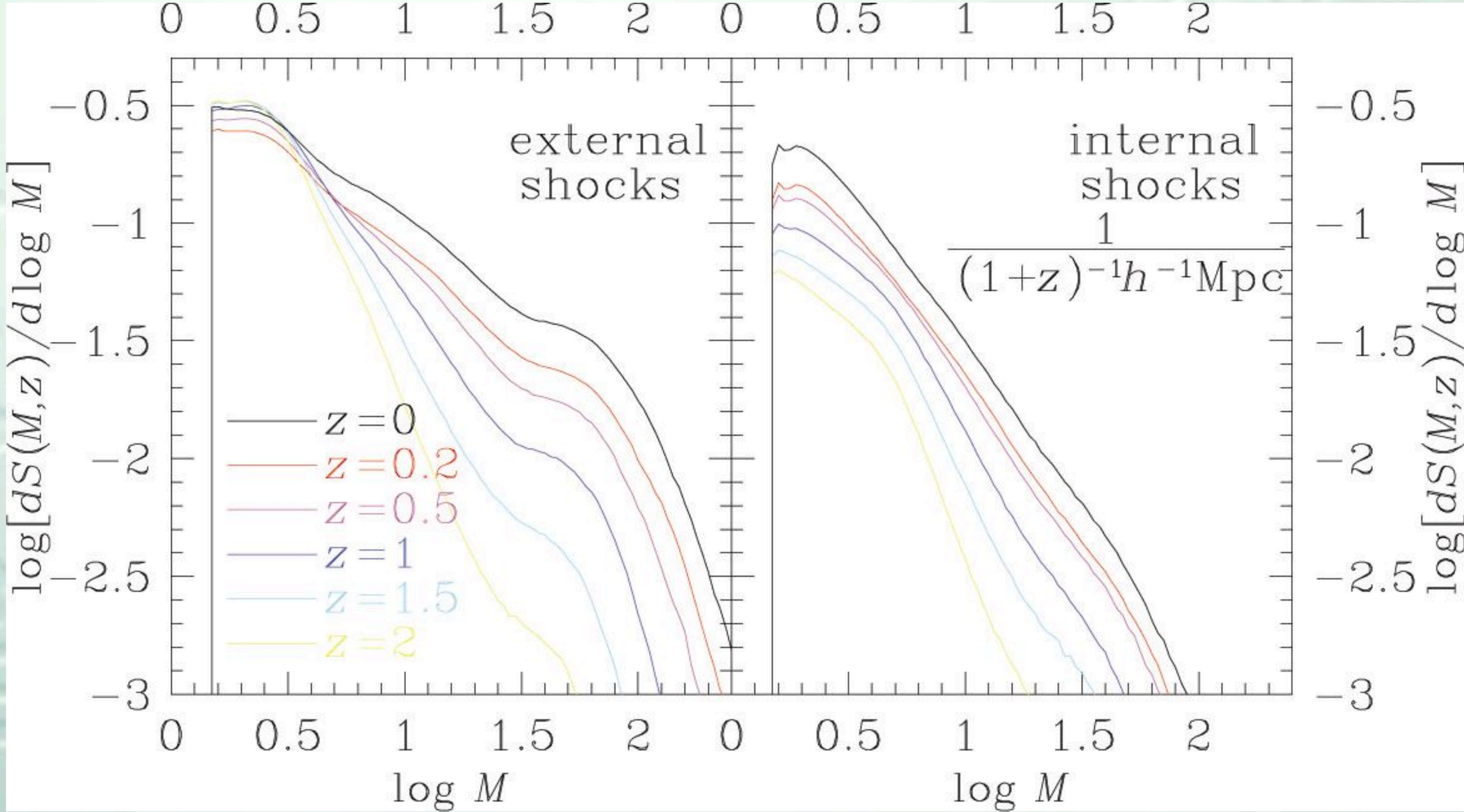
contour: surface brightness
color map: projected emission weighted *T*

°ÊMach number = 1.3

(Hallmann, private comm.)

statistics of Mach number distribution

($S \equiv S_{shock}/V$, $1/S \equiv$ mean comoving distance btw shock surfaces)



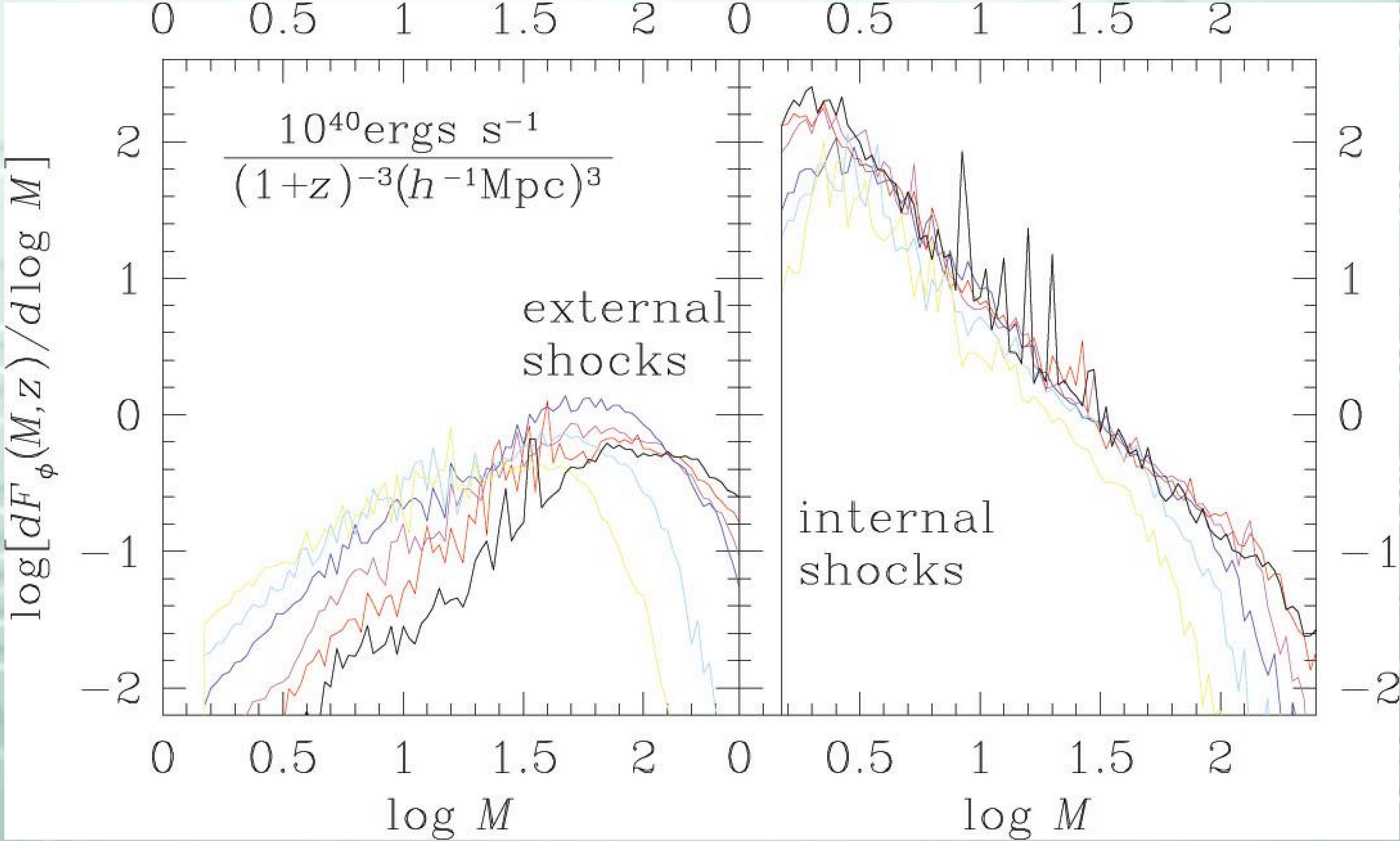
S (external) / S(internal) = ~2 at $z = 0$ and larger in the past

°Êexternal shocks are more common than internal shocks

$S = \sim 1/3\ h^{-1}$Mpc with $M > 1.5$ at $z = 0$

°Êaverage inverse comoving distance between shock surfaces

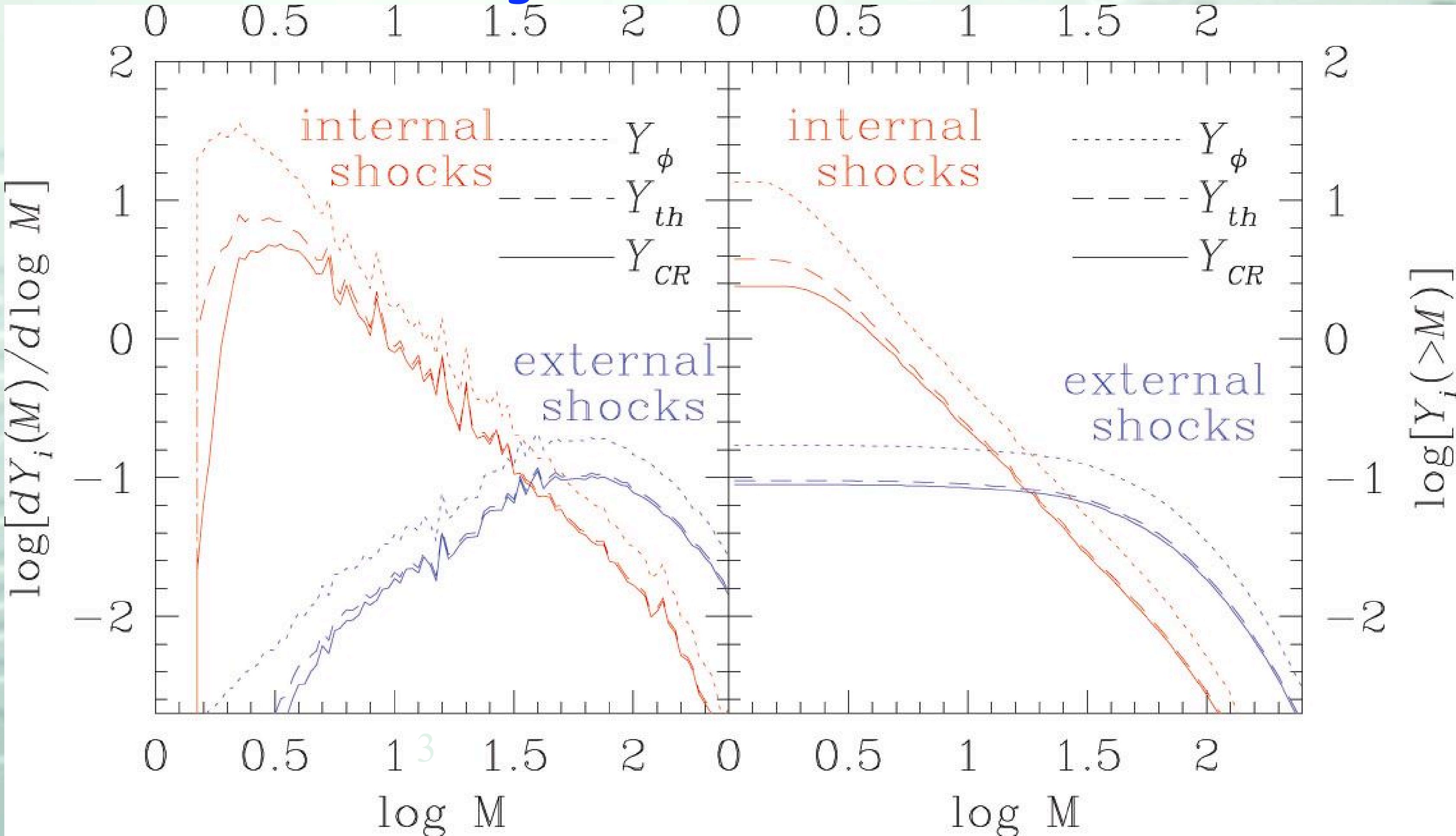
kinetic energy flux per unit comiving volume through s hock surfaces



internal shocks are energetically more important t han external shocks!

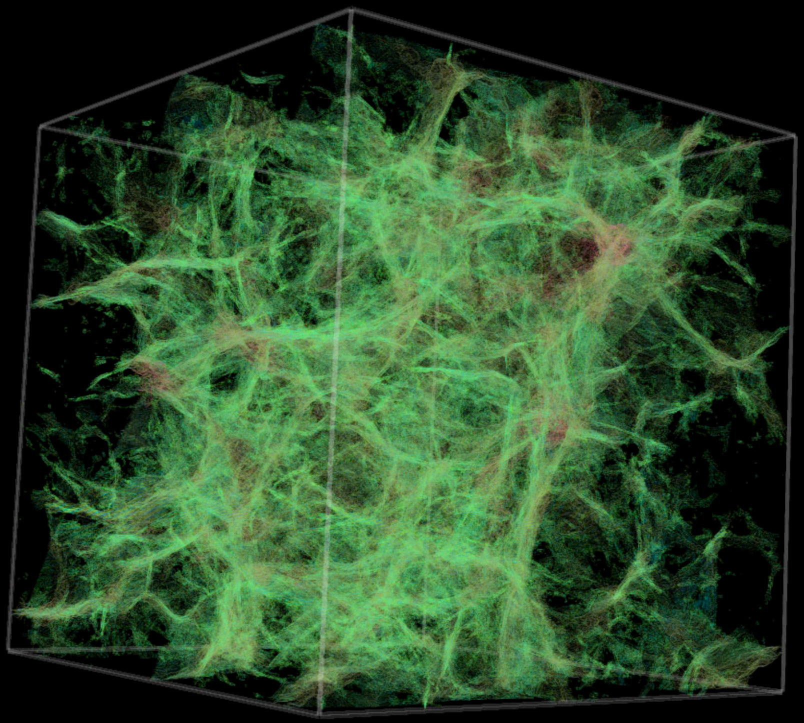
heating of gas at cosmological shock waves (dashed lines)

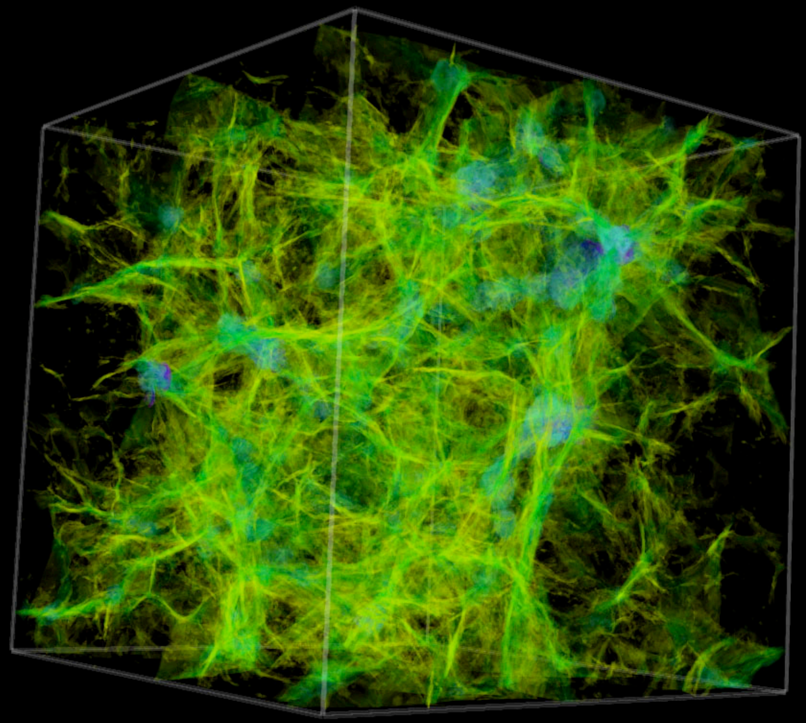
integrated from z = 2 to 0



gas heating ← internal shocks with M = 2~5 contribute most shock speed

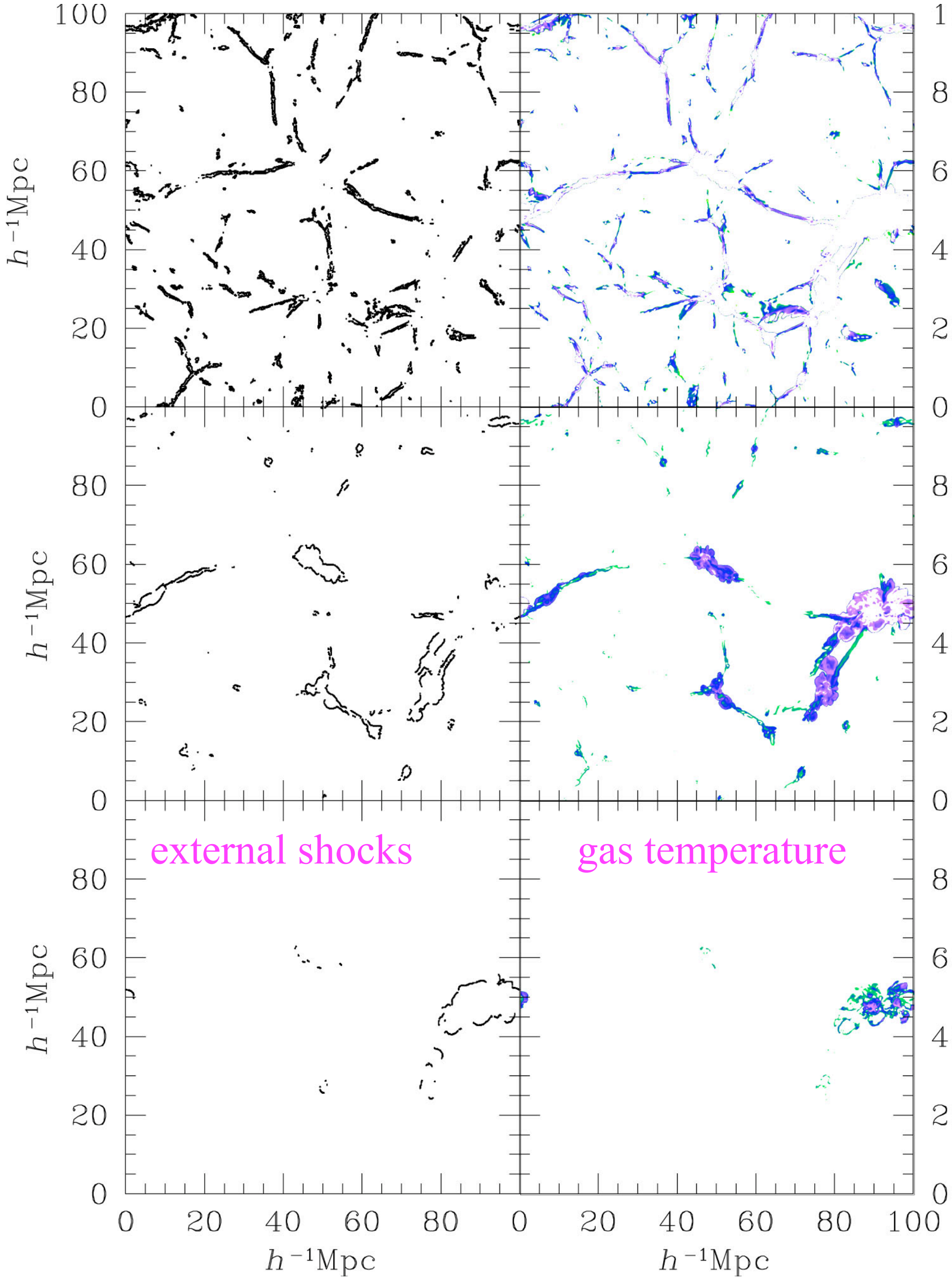
gas temperature





v_{sh} = 15 - 1500 km s^{-1} and higher

$T = 10^4 - 10^8$ K and higher



external shocks with $v_{sh} < 150$ km/s

gas with $T_{gas} < 10^5$K (LWIM)

sheet-like structures

external shocks with $150 < v_{sh} < 700$ km/s

gas with $10^5 < T_{gas} < 10^7$K (WHIM)

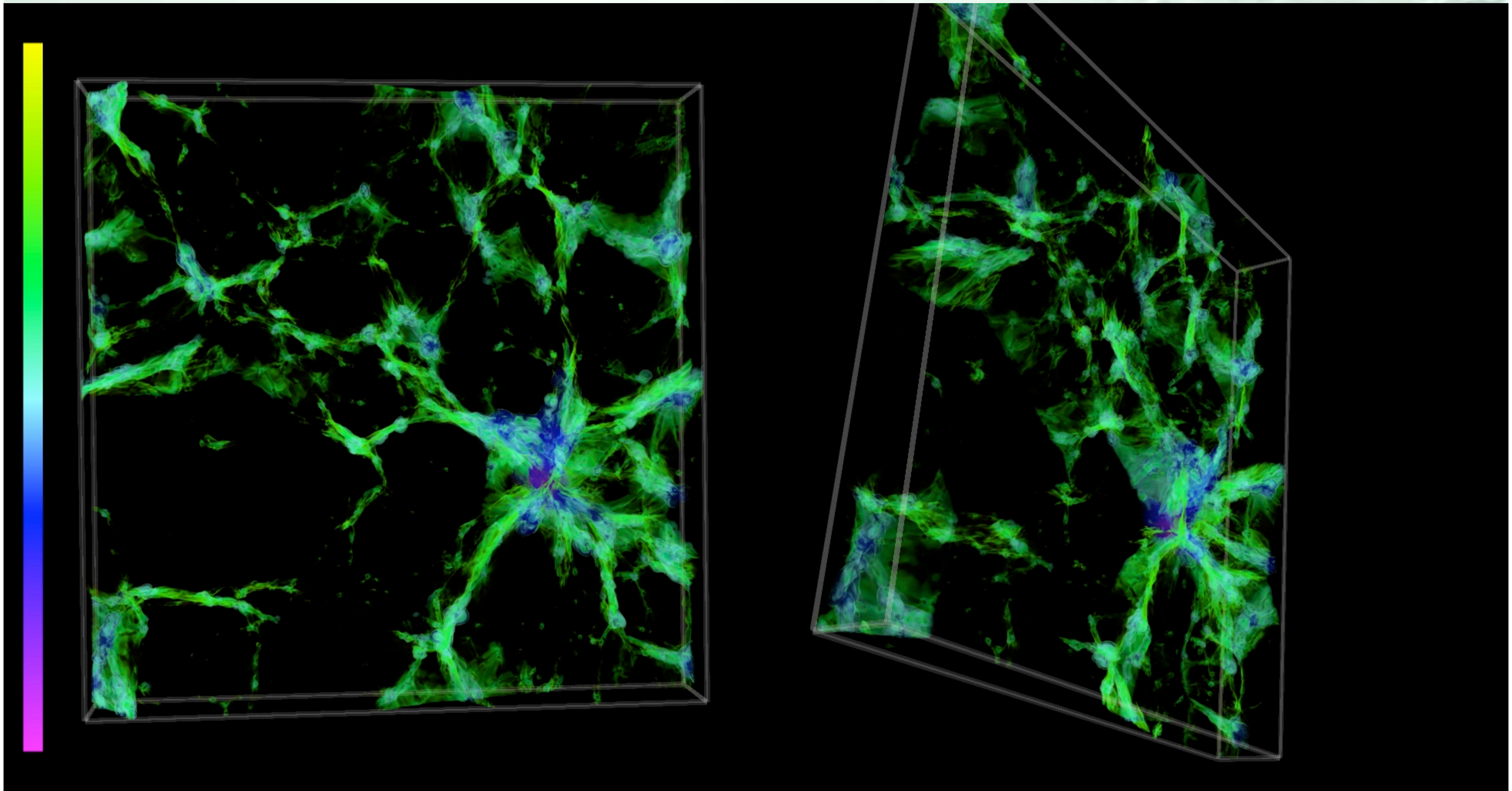
filamentary structures

external shocks with $v_{sh} > 700$ km/s

gas with $T_{gas} > 10^7$K (hot)

knot-like structures

gas temperature

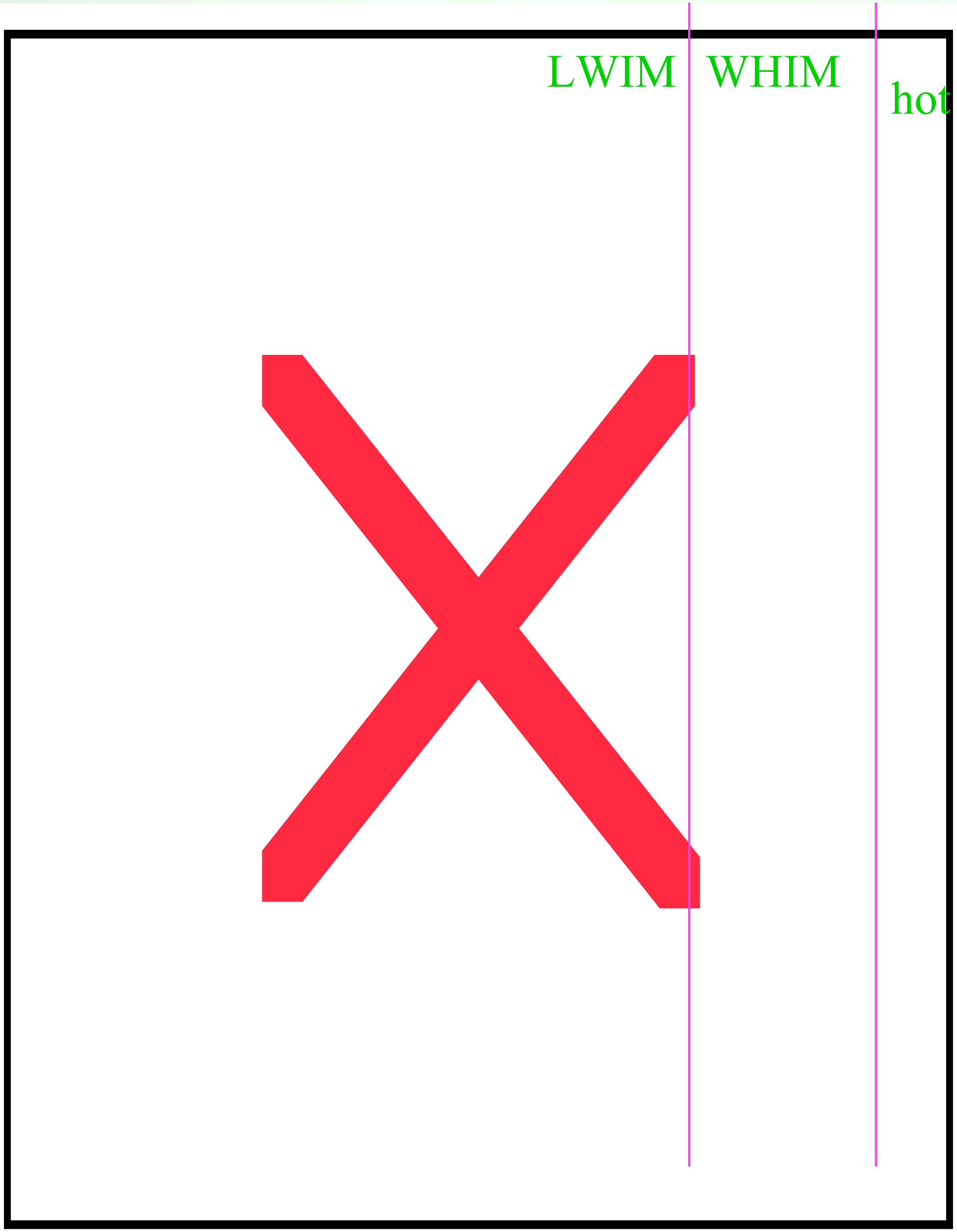


$T = 10^4$ - 10^8 K and higher

100 x 100 x 12.5 $(h^{-1}\ \mathrm{Mpc})^3$

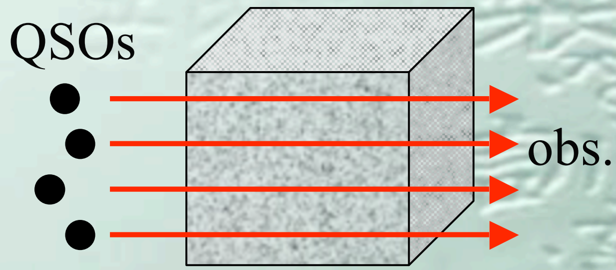
observations of shock-heated gas

- hot gas <= X-ray clusters/groups
- WHIM <= absorptions and emissions in soft X-ray and far UV
- LWIM <= absorptions and emissions in far UV and near UV



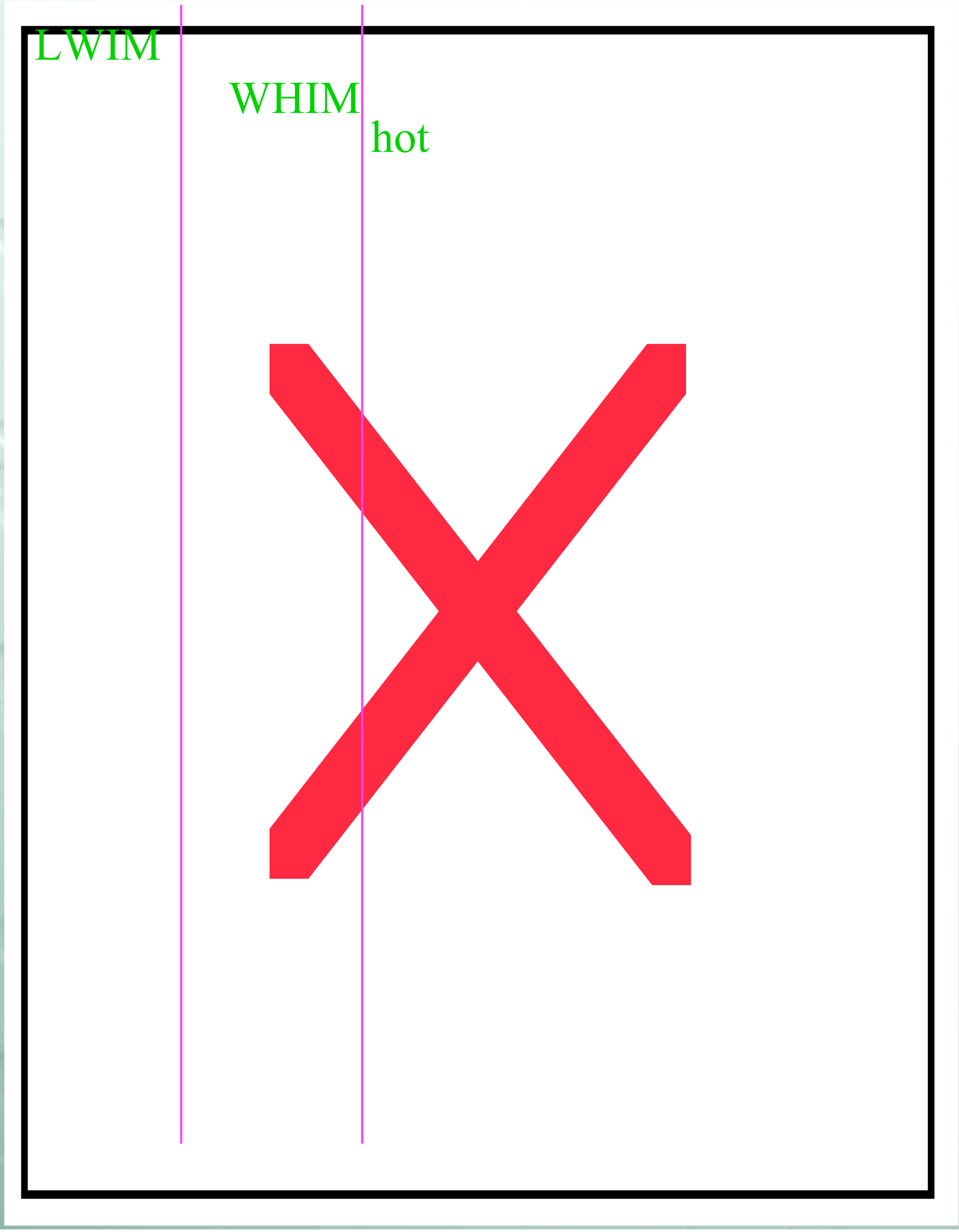
absorption systems
of "oxygen ions"

number of line paths pe
r unit redshift



(many references)

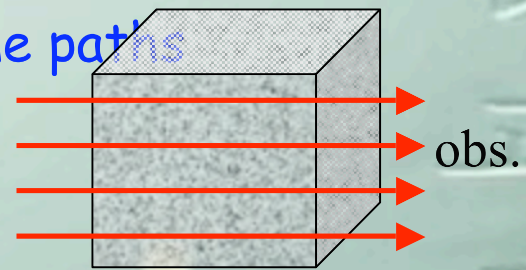
fraction of absorptions
as a function of temper
ature



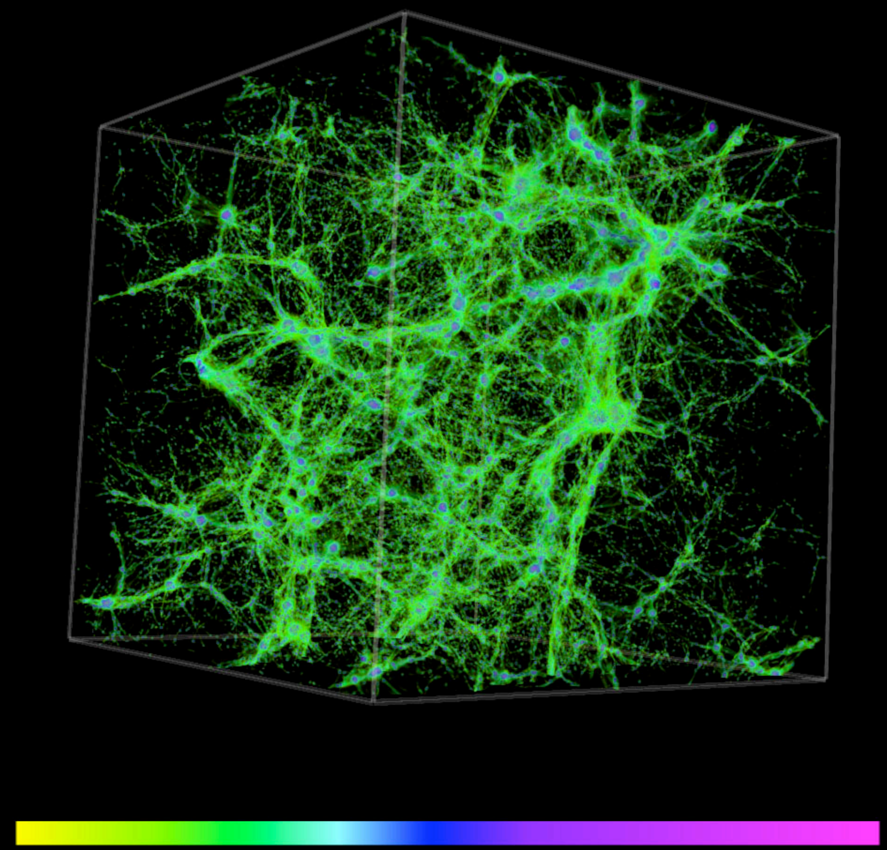
emissions from "oxygen ions"

fraction of emissions as a function of temperature

cumulative fraction of line paths

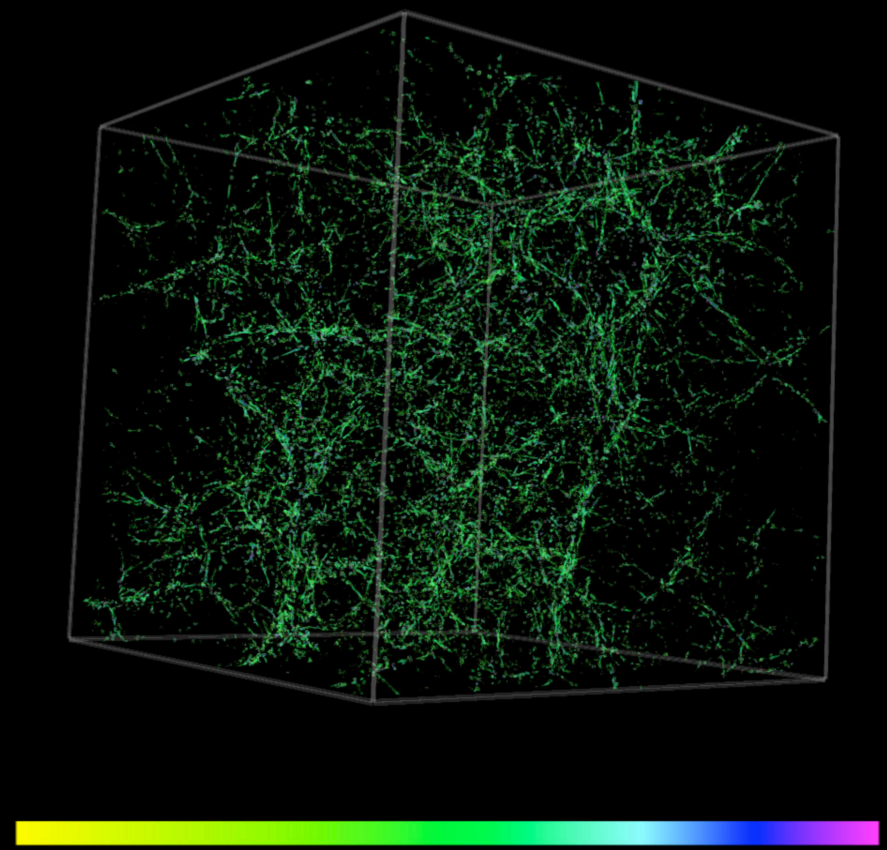


X-ray emissivity

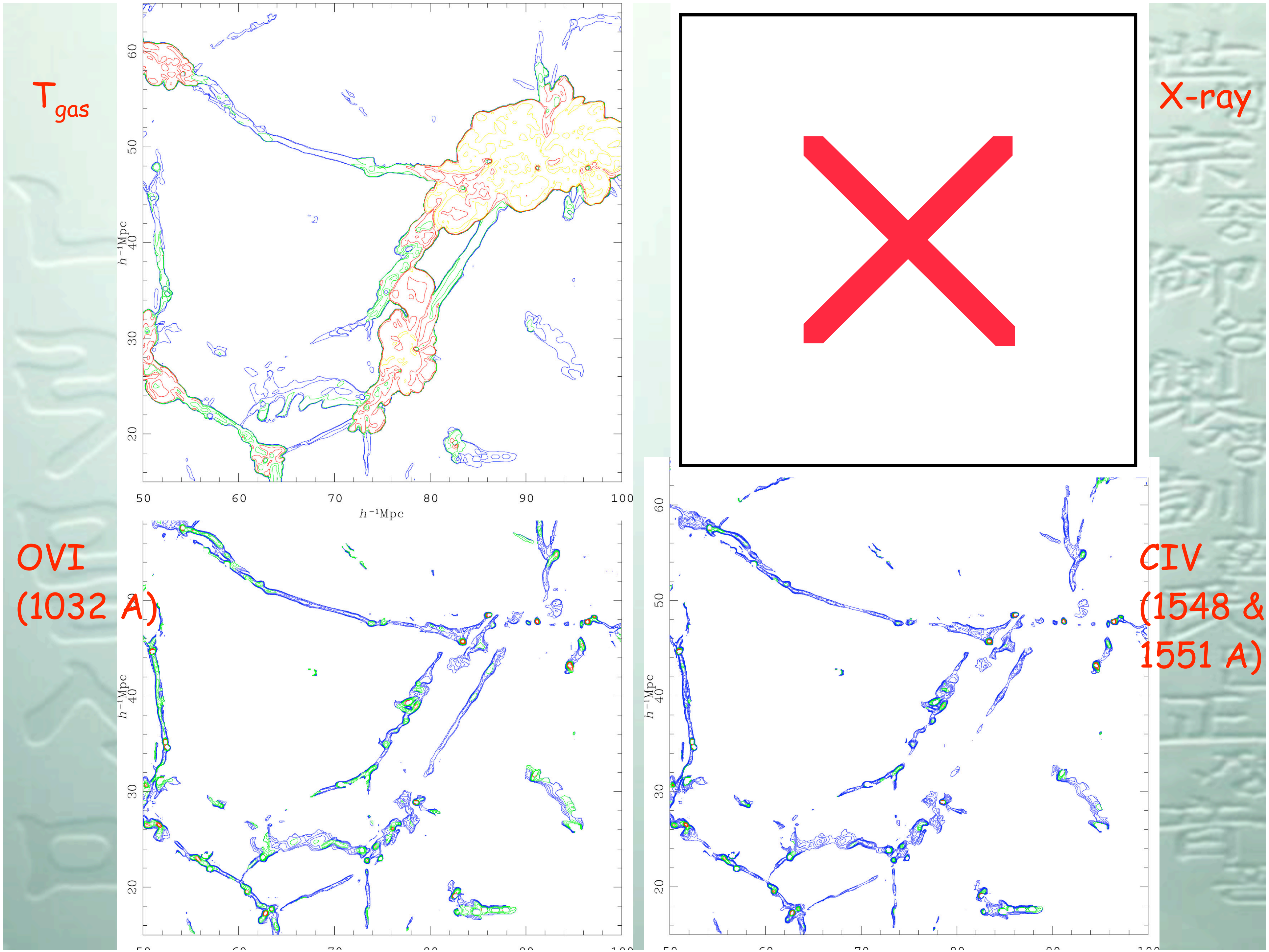


$\varepsilon = 10^{-37} - 10^{-29}$ erg cm^{-3} s^{-1} and higher

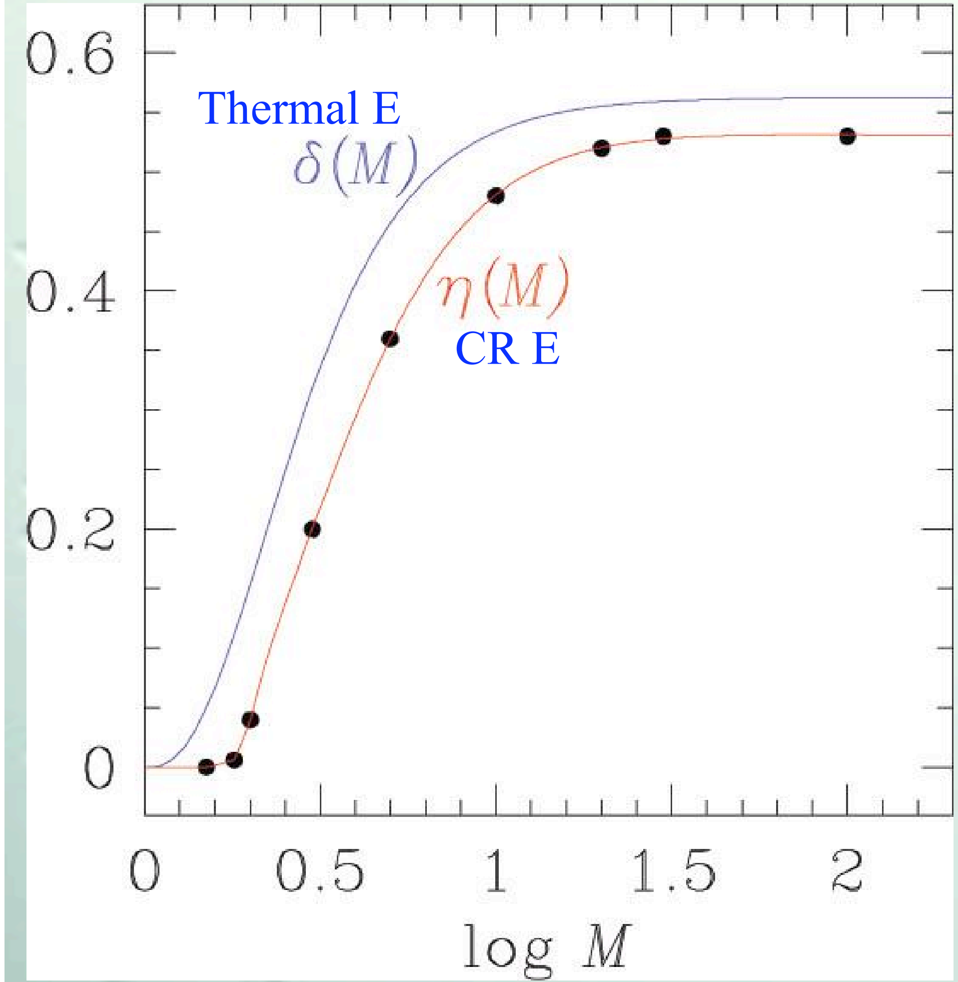
OVI (1032 A) emissivity



$\varepsilon = 10^{-35} - 10^{-33}$ erg cm^{-3} s^{-1} and higher



T_{gas}
X-ray
OVI
(1032 A)
CIV
(1548 &
1551 A)
h^{-1}Mpc



- kinetic energy flux through shocks

$F_k = (1/2)\rho_1 V_s^3$

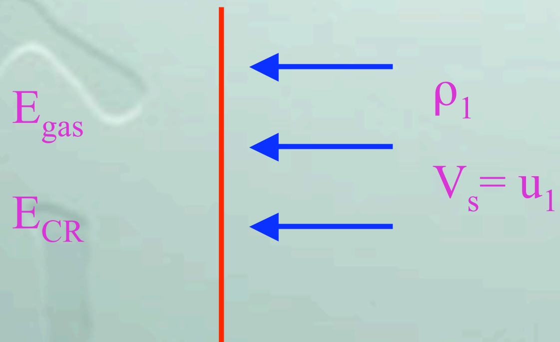
- net thermal energy flux generated at shocks

$F_{th} = (3/2)\,[P_2 - P_1(\rho_2/\rho_1)^\gamma]\,u_2$

$= \delta(M)\,F_k$

- CR energy flux emerged from shocks

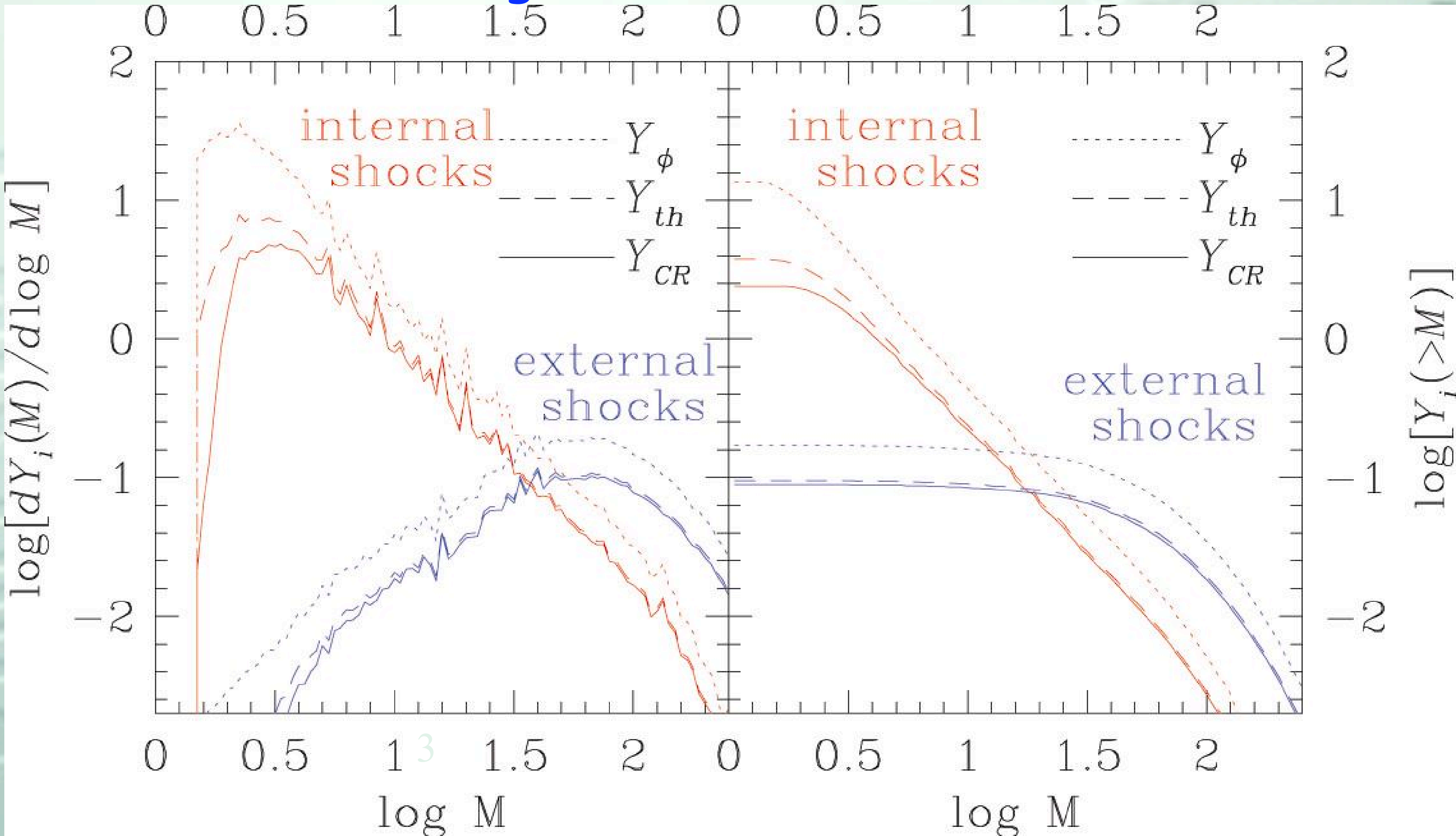
$F_{CR} = \eta(M)\,F_k$



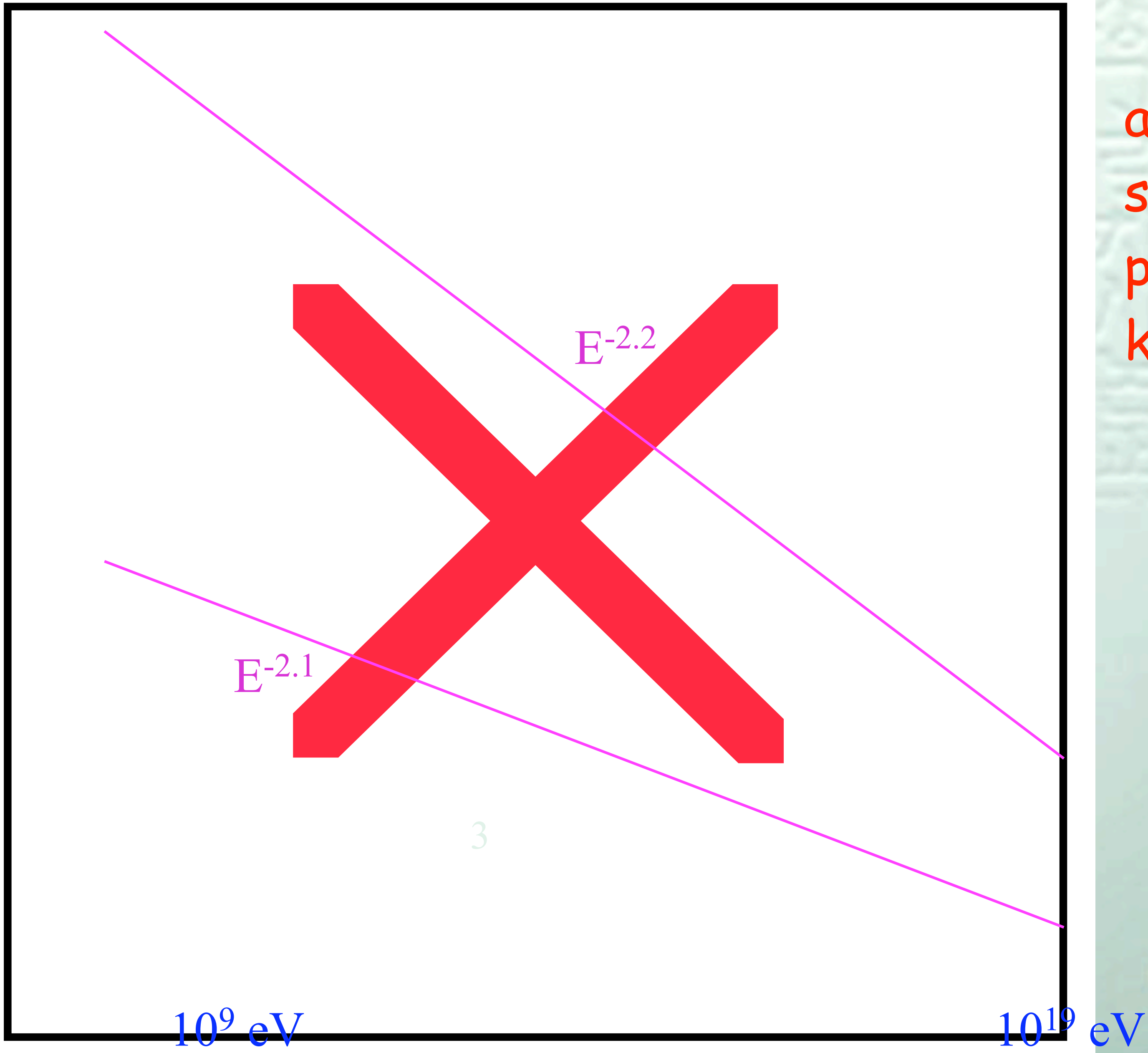
thermalization efficiency: $\delta(M)$

CR acceleration efficiency: $\eta(M)$

CRs accelerated at cosmological shock waves (solid lines) integrated from z = 2 to 0



- CR acceleration ← shocks with M = 2~5
- E_{CR} accelerated at shocks = ~1/2 × E_{th} generated at shocks
- E_{CR} ~ E_{th} at present (after gas cooling & adiabatic exp/comp)



averaged energy spectrum of CRs produced at shocks at z = 0

thermal leakage & test particle models adopted

Summary

- shock waves are common in the large scale structure of the Universe, which are consequences of structure formation

  V/S_{shock} = ~3h^{-1}Mpc with M >1.5 at z=0
  S(external)/S(internal) = ~2 at z=0 and larger in the past
  (V/S_{shock} = ~1h^{-1}Mpc with M >1.5 at z=0 inside structures)

- shocks with M = 2~4 heat gas most

- shock-heated gas in the intergalactic medium:

  the hot component with $T > 10^7$ K: ~5 % of gas, mostly in clusters/groups
  the WHIM component with $10^5 < T < 10^7$ K: ~25 % of gas, mostly in filaments
  the LWIM component with $T < 10^5$ K: ~15 % of gas, mostly in sheets

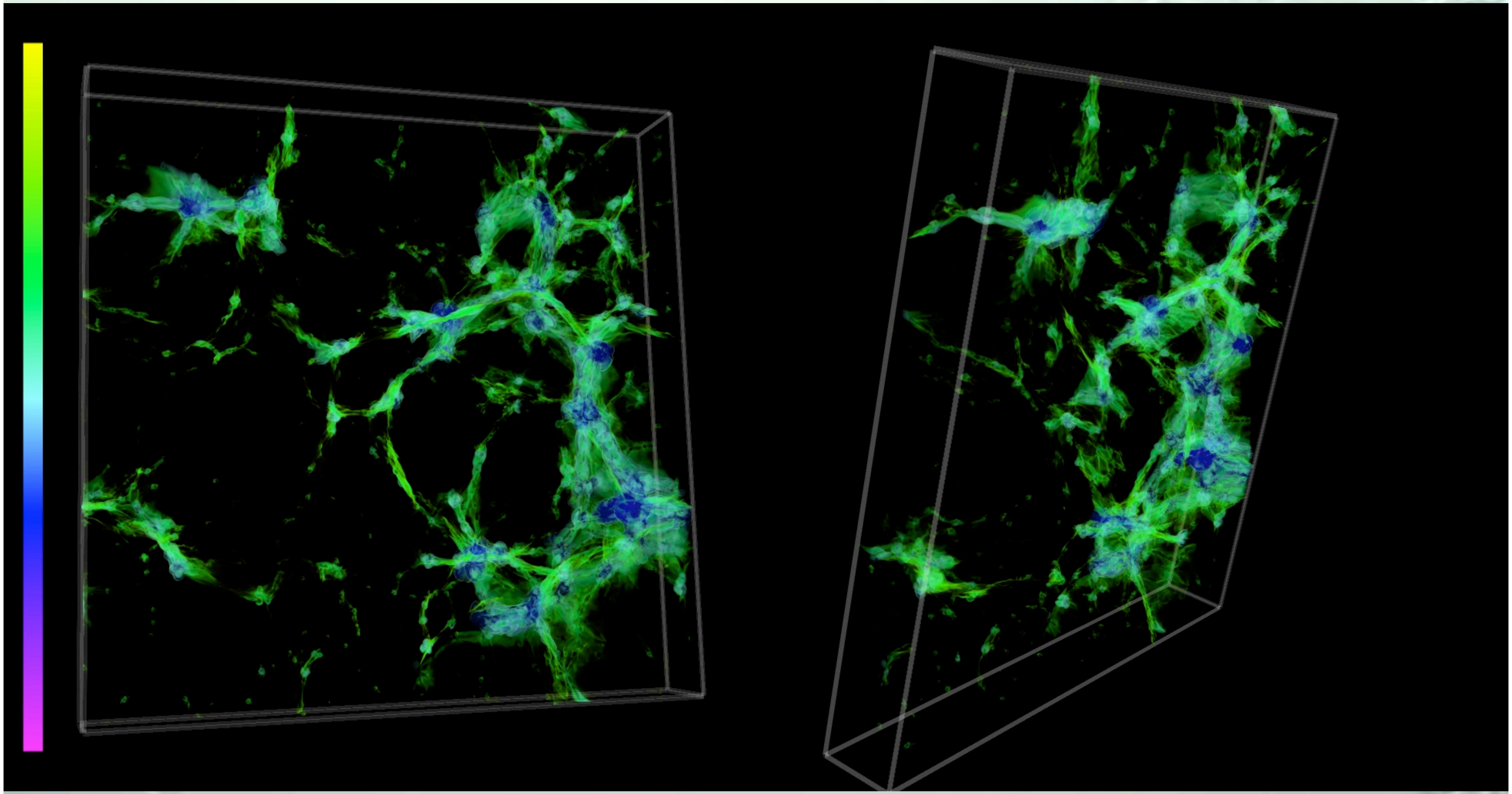
- observation of shock-heated gas

  through absorptions & emissions
  different ions can be used to explore shock-heated gas with different T & ρ
  observations would reveal filament and sheet structures (?)

- cosmic-ray particles are natural byproducts of the collisionless shock formation process: they are everywhere

Thank you !

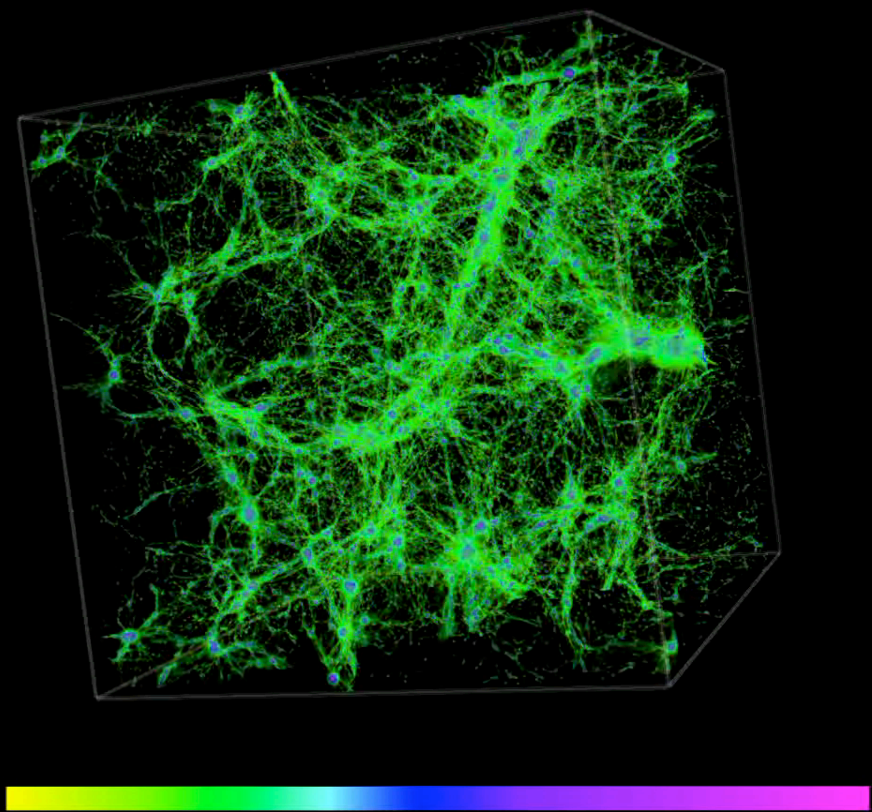
gas temperature



$T = 10^4$ - 10^8 K and higher

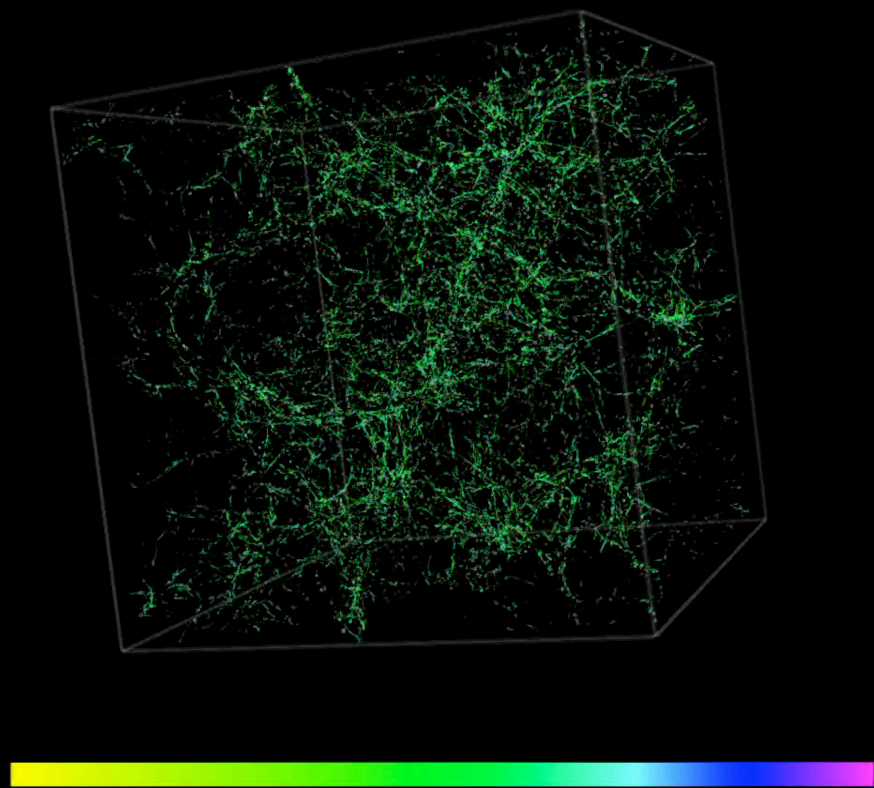
100 x 100 x 12.5 (h^{-1} Mpc)^3

X-ray emissivity



$\varepsilon = 10^{-37} - 10^{-29}$ erg cm^{-3} s^{-1} and higher

OVI (1032 A) emissivity



$\varepsilon = 10^{-35} - 10^{-33}$ erg cm^{-3} s^{-1} and higher