

# Elemental abundances in the hot intra-cluster medium

Pavel Medvedev, Sergey Sazonov and Marat Gilfanov

Space Research Institute, Moscow

# TALK STRUCTURE

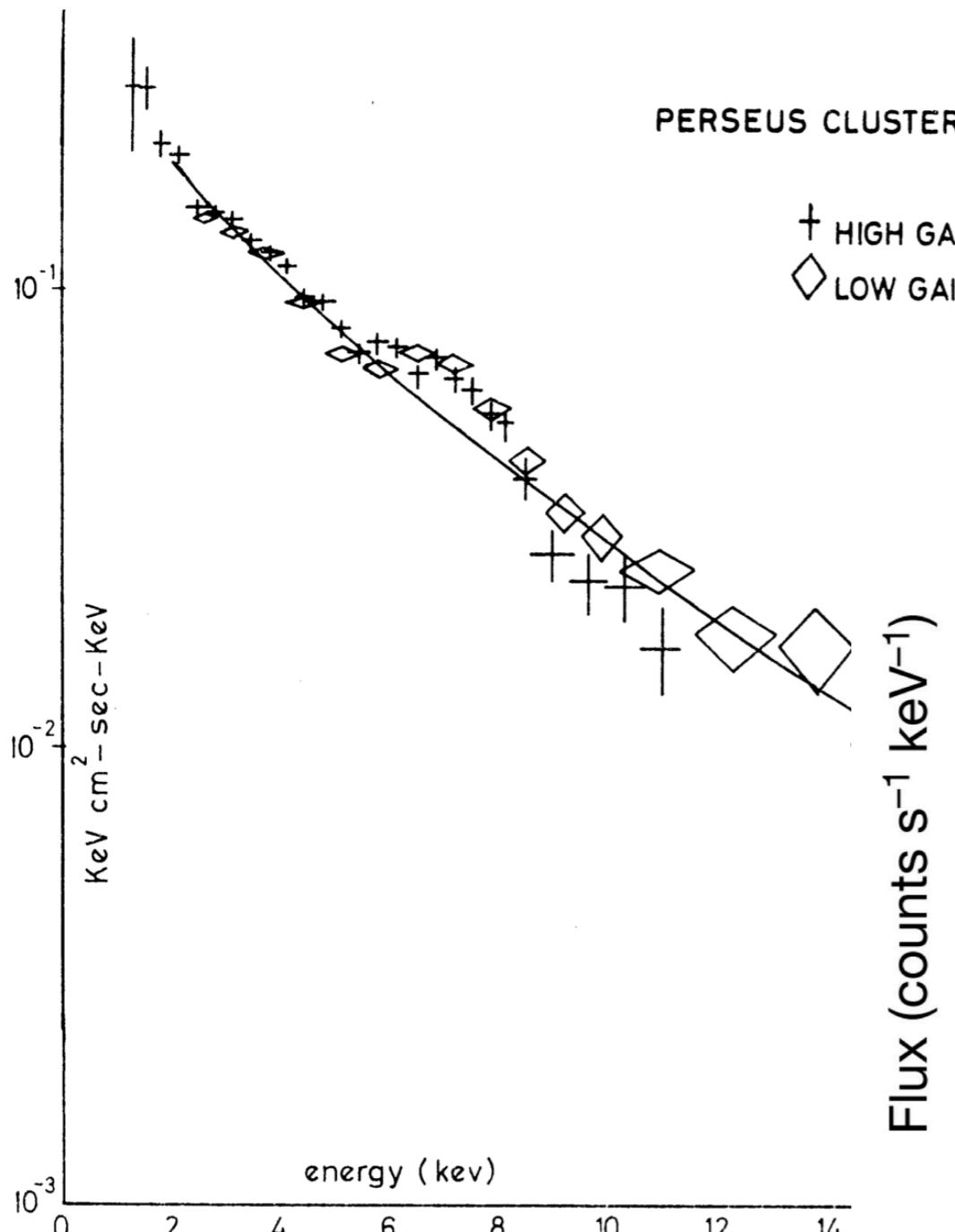
- I. Chemistry of the intracluster medium (ICM)
  - A. X-ray spectral lines
  - B. Abundance diagnostics
- 2. Element diffusion in the ICM
  - A. Sedimentation model
  - B. Calculation method and results
- 3. Bias in metal abundance measurements caused by helium diffusion.

# ABELL 1689

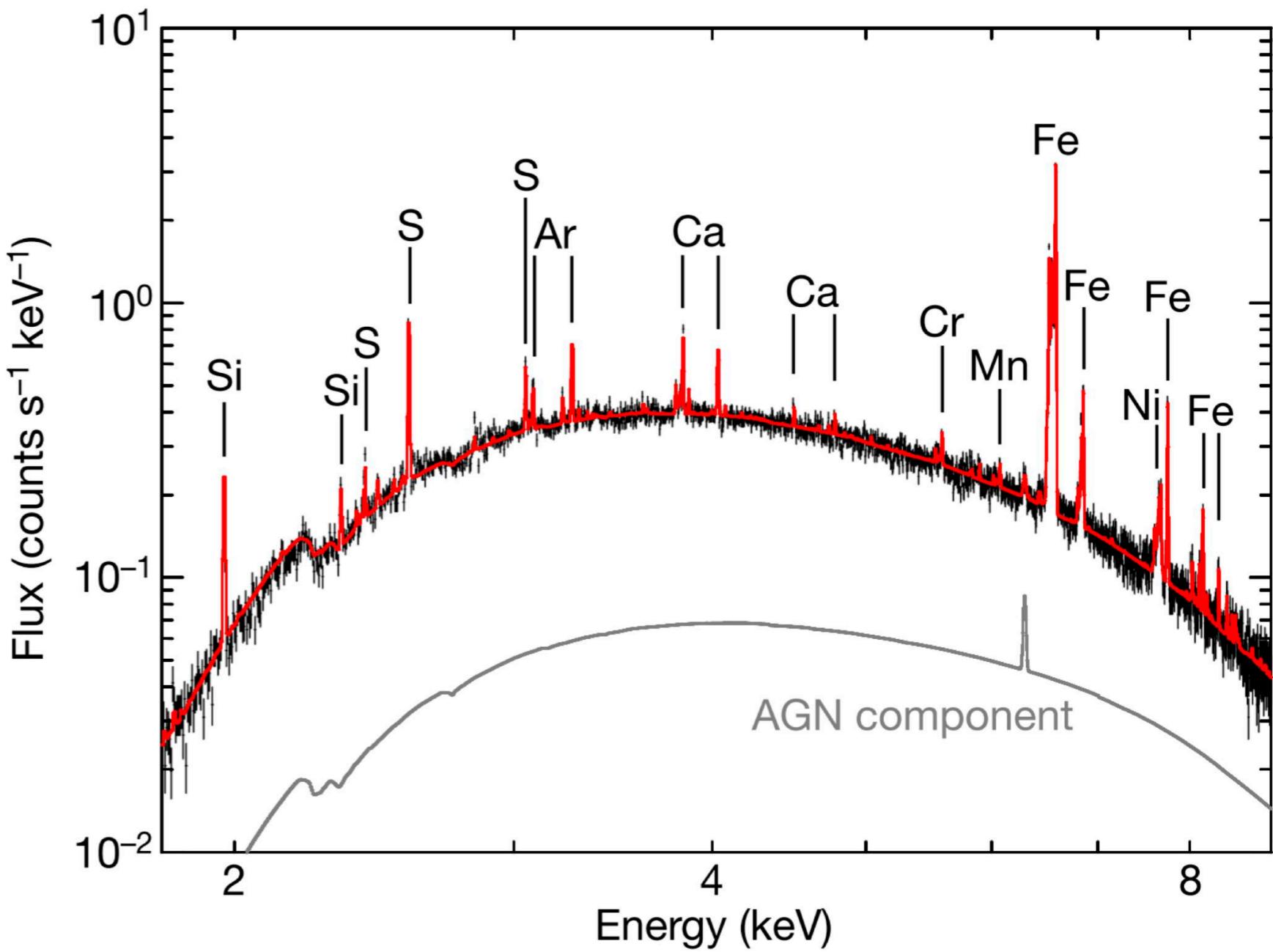


X-ray: NASA/CXC/MIT/E.-H Peng et al; Optical: NASA/STScI

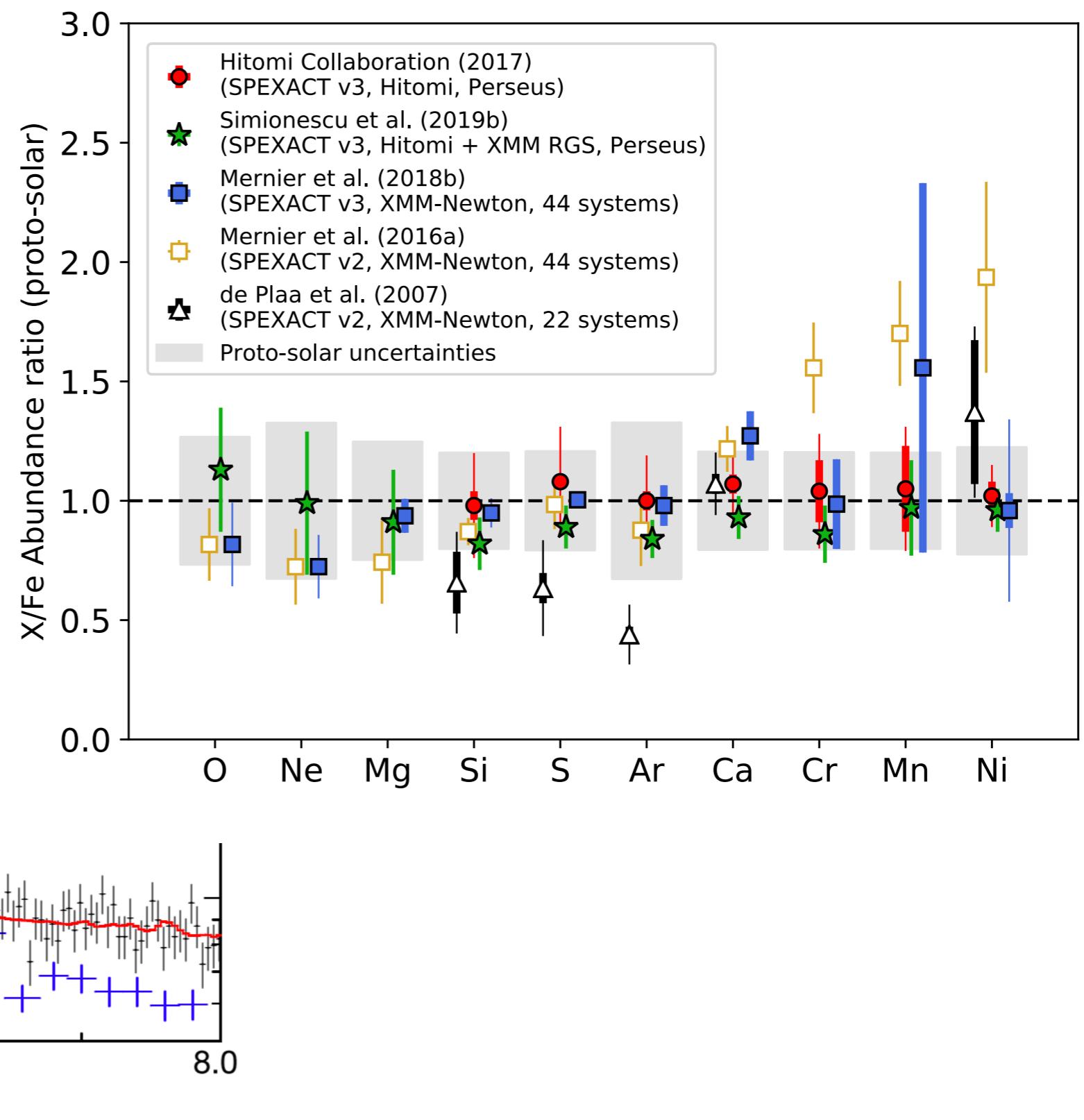
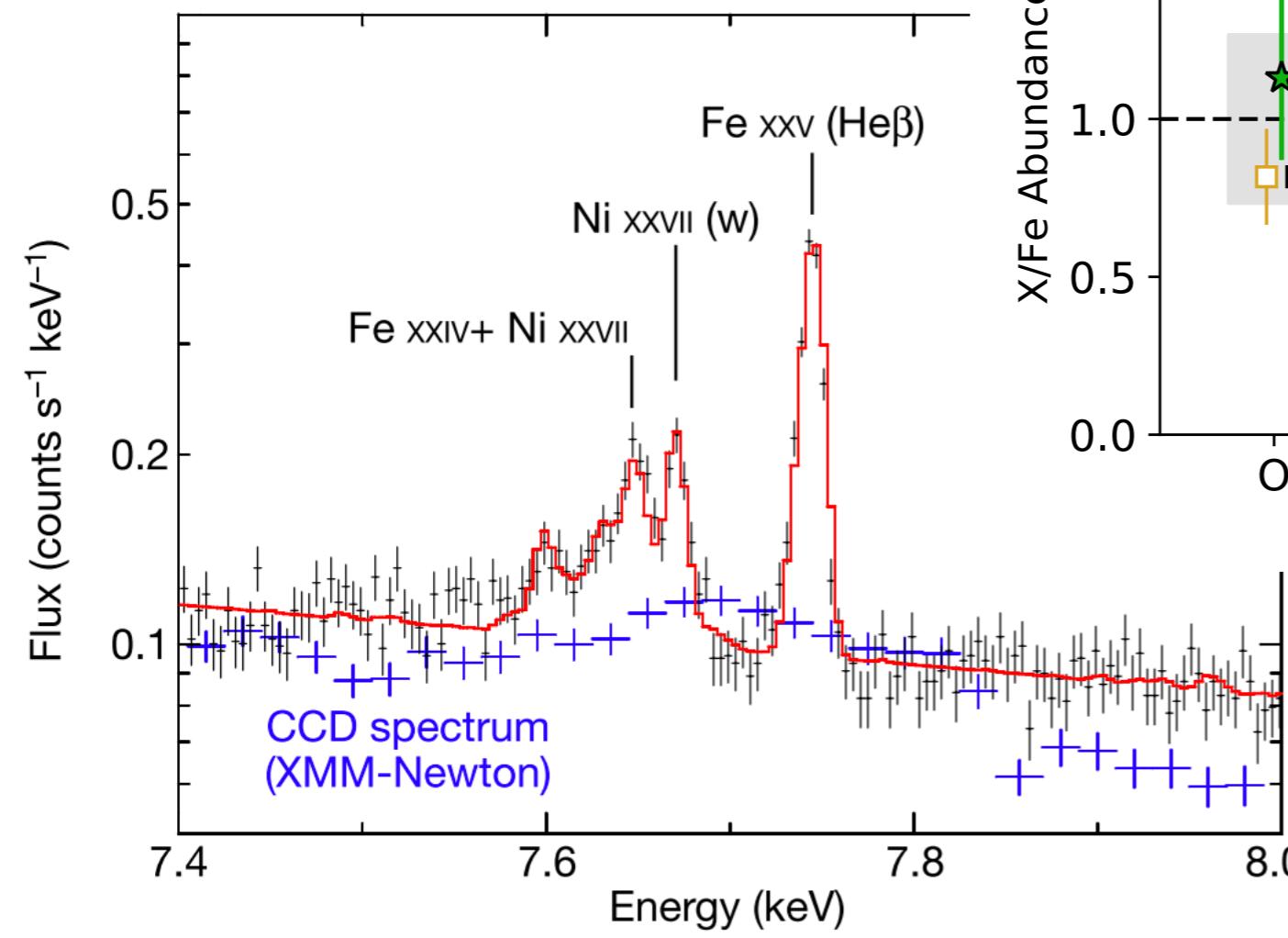
# METALS IN THE ICM



from Mitchell et al. 1976

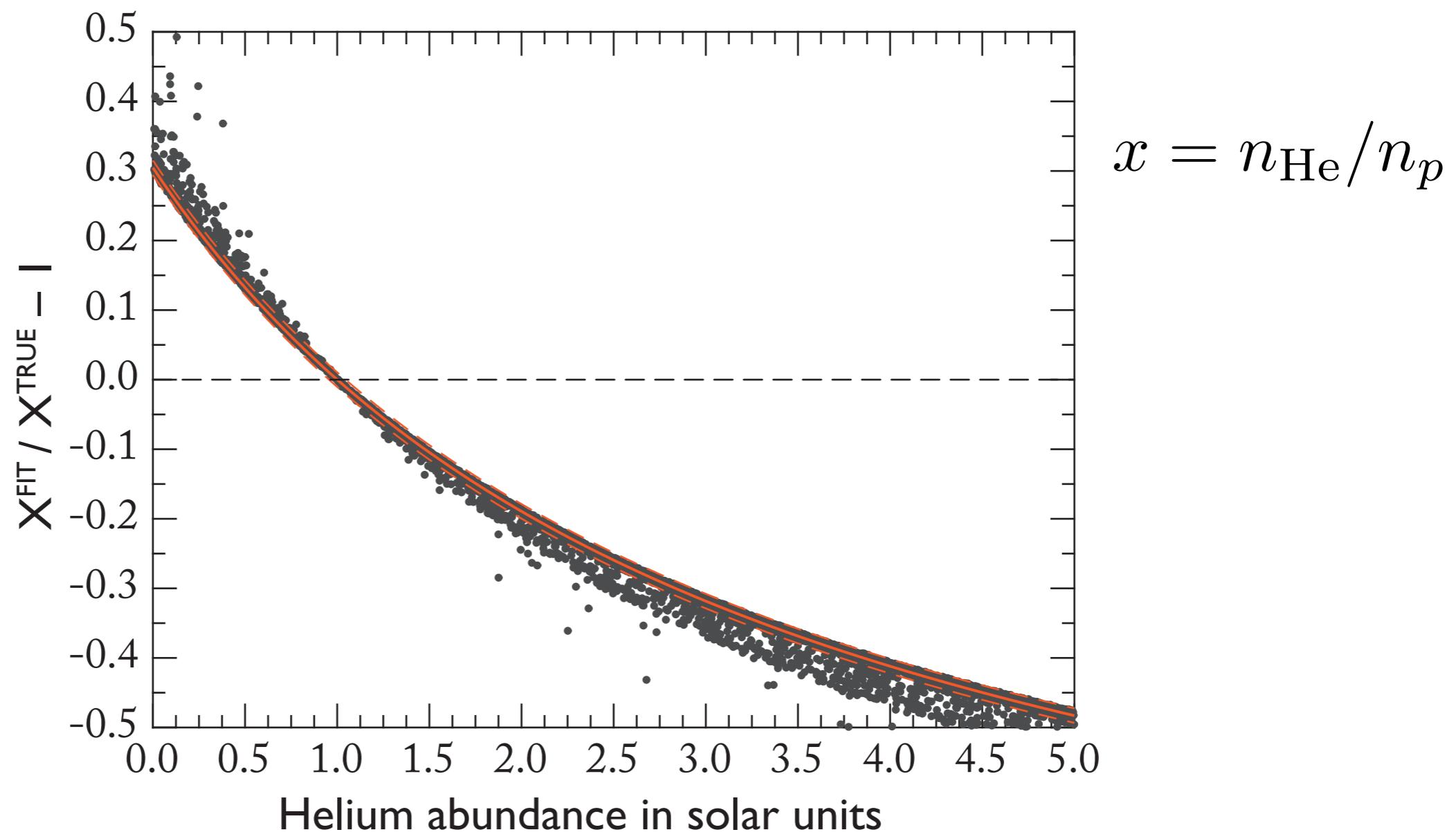


# ABUNDANCE DIAGNOSTICS



# EFFECT OF INCORRECTLY ASSUMED He/H RATIO ON ABUNDANCE MEASUREMENTS

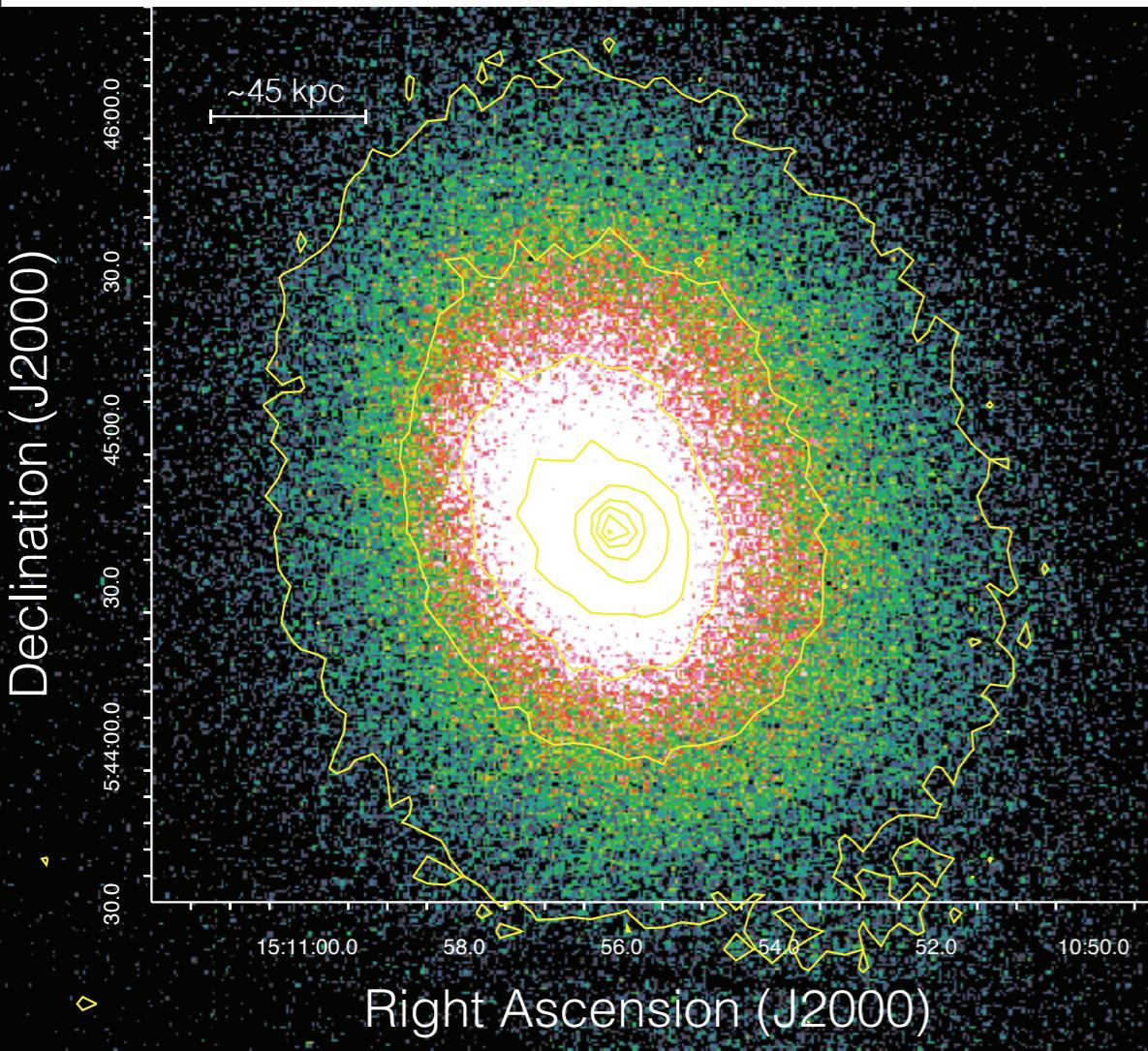
- I. The X-ray continuum of the ICM is dominated by thermal bremsstrahlung.
2. At temperatures  $> 1$  keV radiation from H and He dominates the whole X-ray range.
3. Bremsstrahlung emissivity:  $\epsilon_{ff} \propto n_e(n_p + Z_{\text{He}}^2 n_{\text{He}}) \approx n_p^2(1 + 2x)(1 + 4x)$
4. Dependence of derived abundance on assumed  $x$ :  $n_X/n_p \propto (1 + 4x)$



# DIFFUSION IN THE INTRACLUSTER MEDIUM OF GALAXY CLUSTERS

## THE ICM PROPERTIES

1. Dilute  $n \sim 10^{-2} - 10^{-3} \text{ cm}^{-3}$  and high temperature plasma  $T \sim 10^7 - 10^8 \text{ K}$
2.  $\approx$ Spherical symmetry (*relaxed cool-core clusters*)
3.  $\approx$ Hydrostatic equilibrium  
e.g. Vikhlinin et. al. 2006



Abell 2029, Chandra ACIS-S, obsID 4977, 79 ksec

## SEDIMENTATION VELOCITY

$$v_{drift} = gt_{coll} \quad \nu_{coll} = t_{coll}^{-1} \propto T^{-3/2} n$$

$$\lambda_{coll} \approx 20 \left( \frac{T}{10^8 \text{ K}} \right)^2 \left( \frac{n}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \text{ kpc}$$

$$v_{drift} \sim 1 - 100 \text{ km/s} \sim 1 - 100 \text{ kpc/Gyr}$$

Fabian & Pringle, 1977

Gilfanov & Sunyaev, 1984

# I-D ELEMENT SEDIMENTATIONAL MODEL WITH NO MAGNETIC FIELDS

Diffusion velocity:

$$\mathbf{u}_s = \int \mathbf{v} F_s d\mathbf{v} \quad \mathbf{u} = \frac{\sum_s \rho_s \mathbf{u}_s}{\rho} \quad \mathbf{w}_s = \mathbf{u}_s - \mathbf{u}$$

Momentum transfer equation:

Burgers 1969

$$\frac{d(n_s k_B T)}{dr} + n_s m_s g - n_s Z_s e E = \sum_{t \neq s} K_{st} [(w_t - w_s) + f(dT/dr)]$$

*Concentration gradient diffusion*

*Gravitational sedimentation*

$$n_s/n = \text{const}$$
$$n_s \propto e^{-m_s gh/kT}$$

# I-D ELEMENT SEDIMENTATIONAL MODEL WITH NO MAGNETIC FIELDS

Diffusion velocity:

$$\mathbf{u}_s = \int \mathbf{v} F_s d\mathbf{v} \quad \mathbf{u} = \frac{\sum_s \rho_s \mathbf{u}_s}{\rho} \quad \mathbf{w}_s = \mathbf{u}_s - \mathbf{u}$$

Momentum transfer equation:

Burgers 1969

$$\frac{d(n_s k_B T)}{dr} + n_s m_s g - n_s Z_s e E = \sum_{t \neq s} K_{st} [(w_t - w_s) + 0.6(x_{st} r_s - y_{st} r_t)]$$

**Concentration gradient diffusion**

**Gravitational sedimentation**

**Thermal diffusion**

Heat transfer equation:

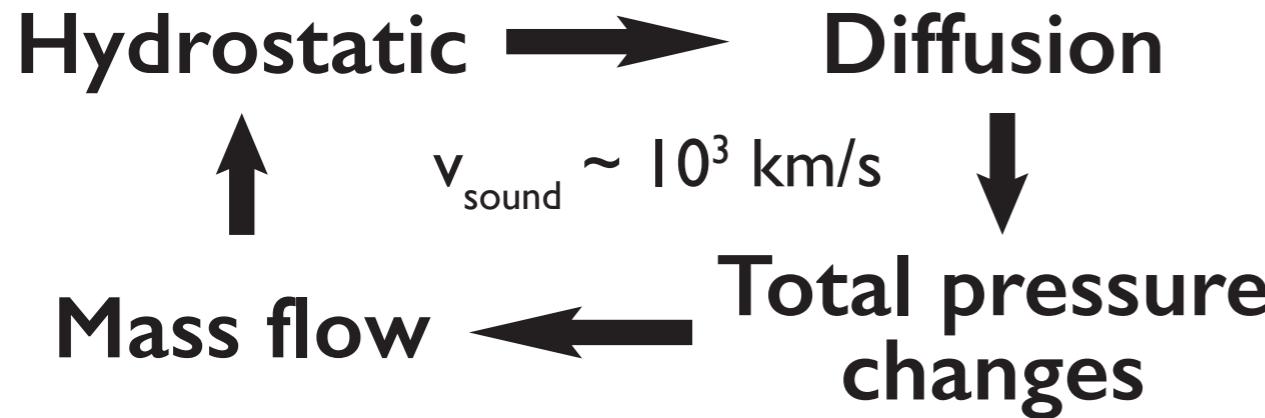
$$\frac{5}{2} n_s k_B \frac{dT}{dr} = \sum_{t \neq s} K_{st} \left\{ \frac{3}{2} x_{st} (w_s - w_t) - y_{st} \left[ 1.6 x_{st} (r_s + r_t) + Y_{st} r_s - 4.3 x_{st} r_t \right] \right\} - 0.8 K_{ss} r_s$$

Diffusion in the solar interior: *Thoul, Bahcall & Loeb 1994*

Diffusion in the ICM: *Peng & Nagai 2009, Shtykovskiy & Gilfanov 2010*

# NUMERICAL SOLUTION

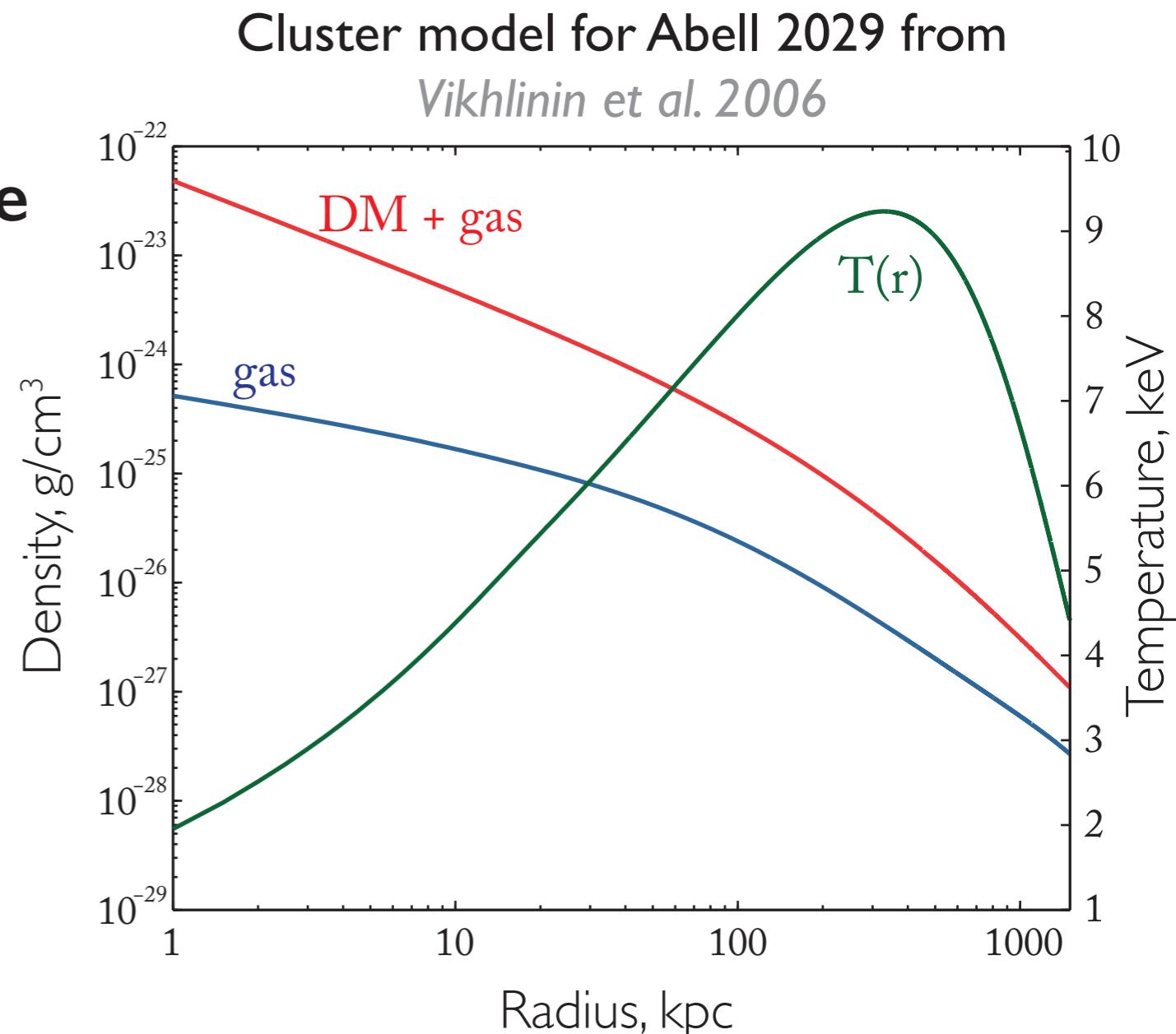
Calculation scheme



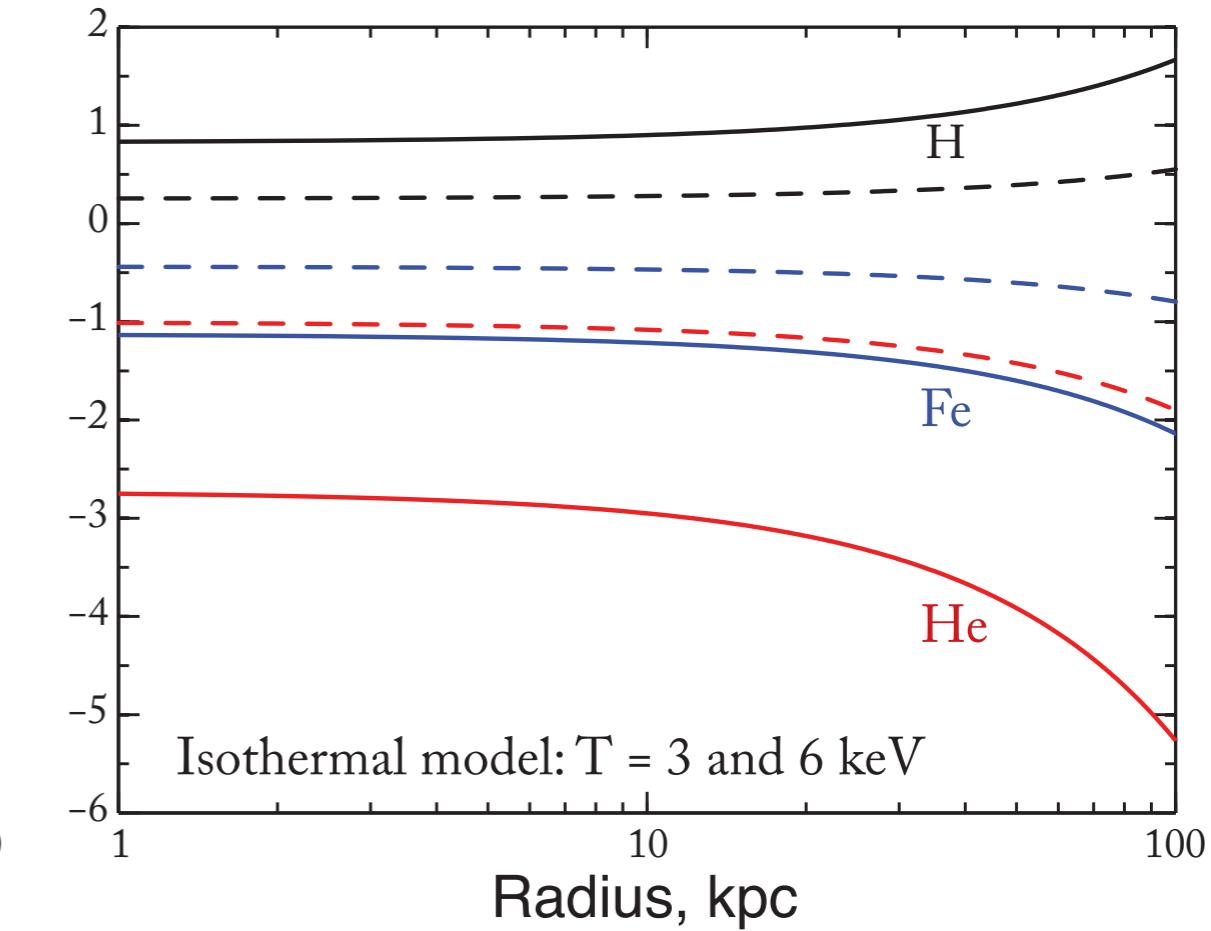
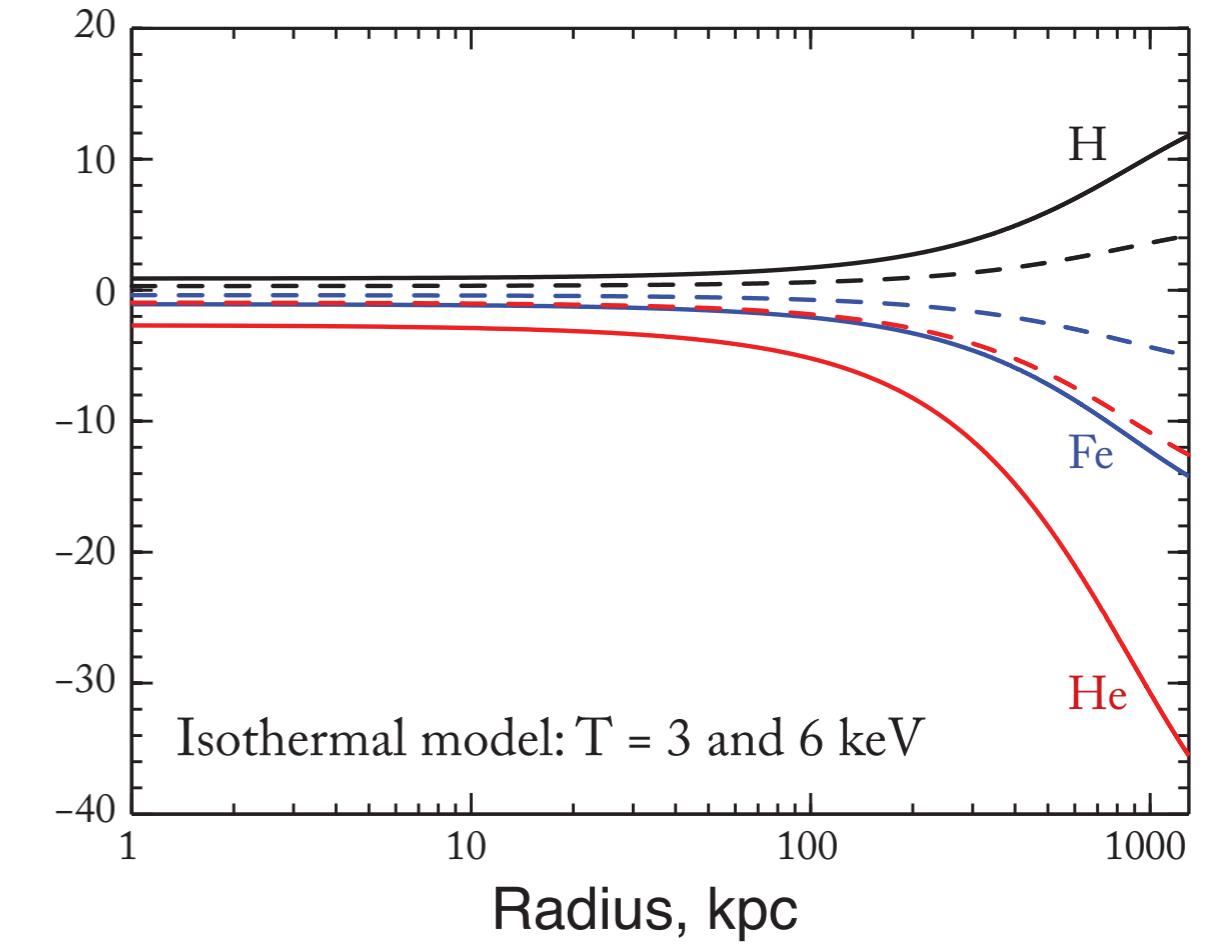
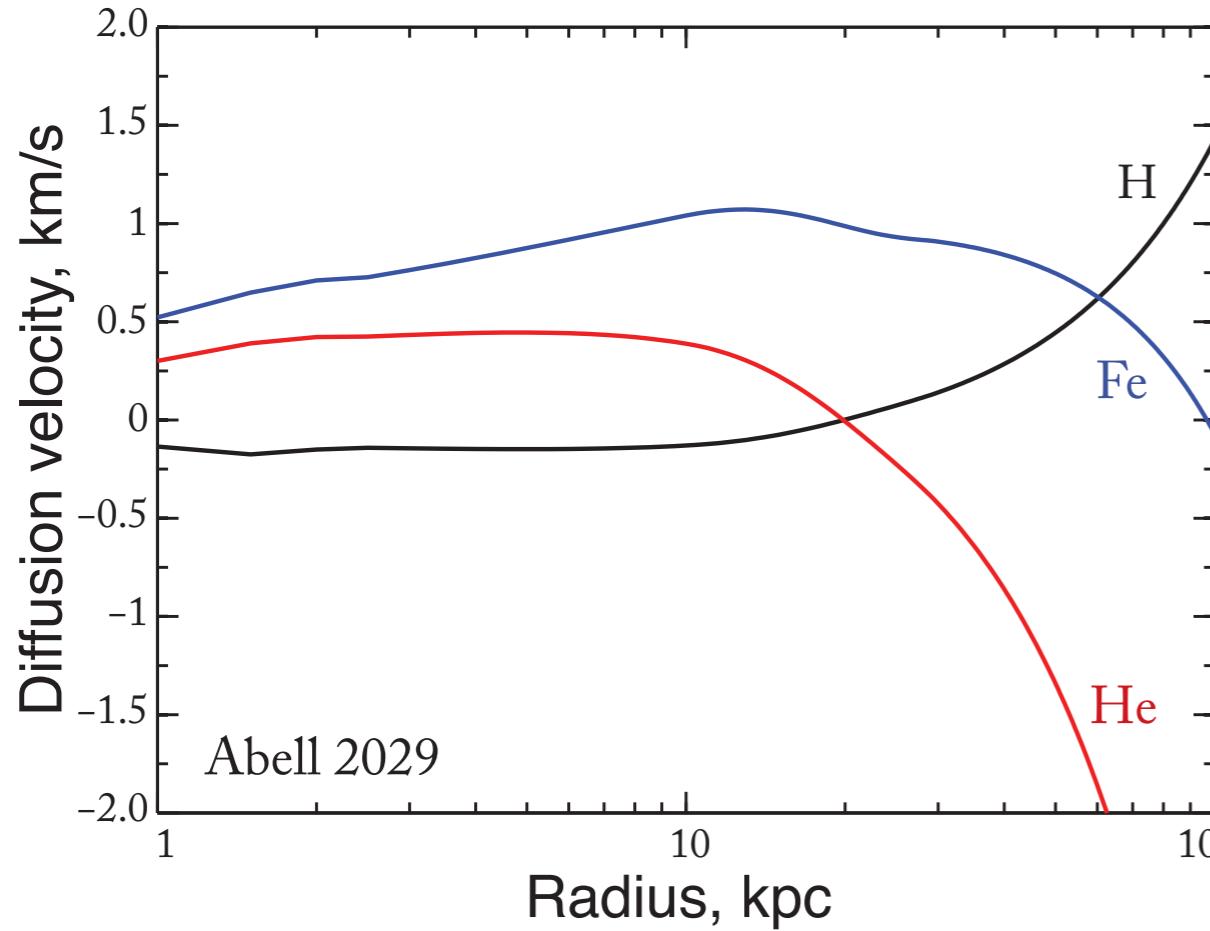
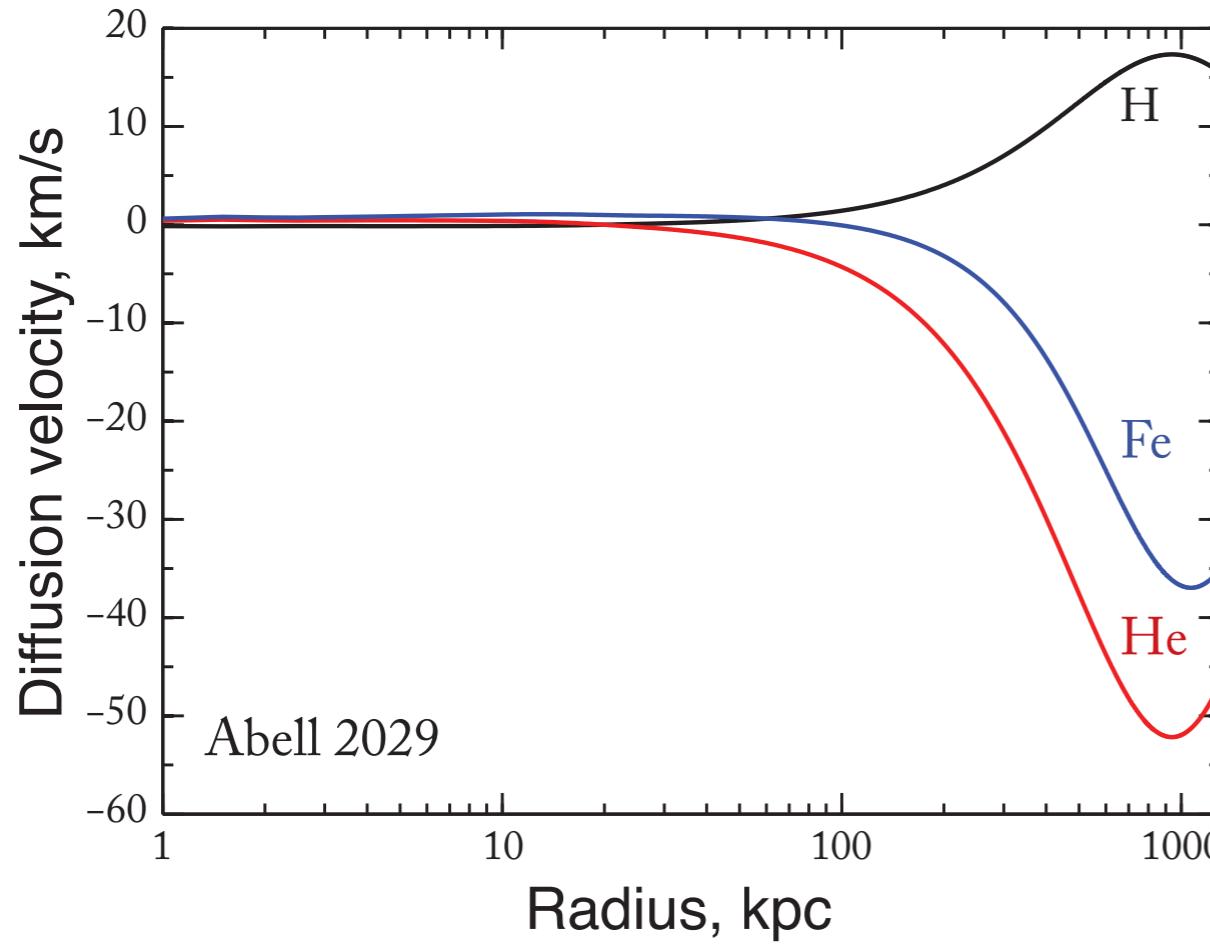
Simplifying assumptions:

- i) Outer boundary fixed:  $r_{\text{out}} = 1500 \text{ kpc}$
- ii) Cluster embedded in “infinite reservoir” of gas:  $n_s(r_{\text{out}}) = \text{const}$
- iii) No sink (or source) of gas at center:  $v_s(r=0) = 0$
- iv) Temperature profile fixed:  $T(r,t) = T(r,0)$

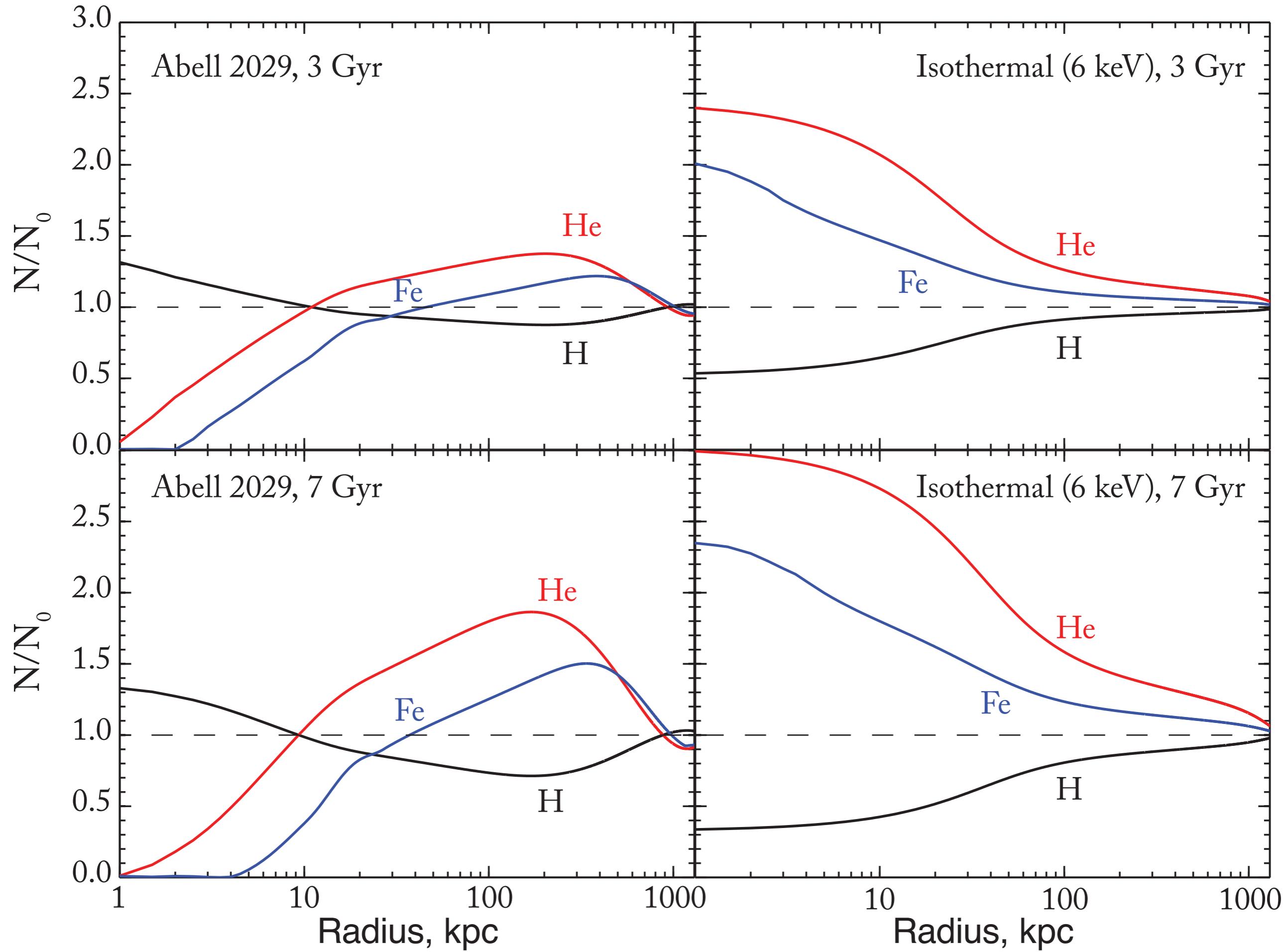
Implies ICM heating is balanced by radiative cooling, e.g. *Guo, Oh & Ruszkowski 2008*



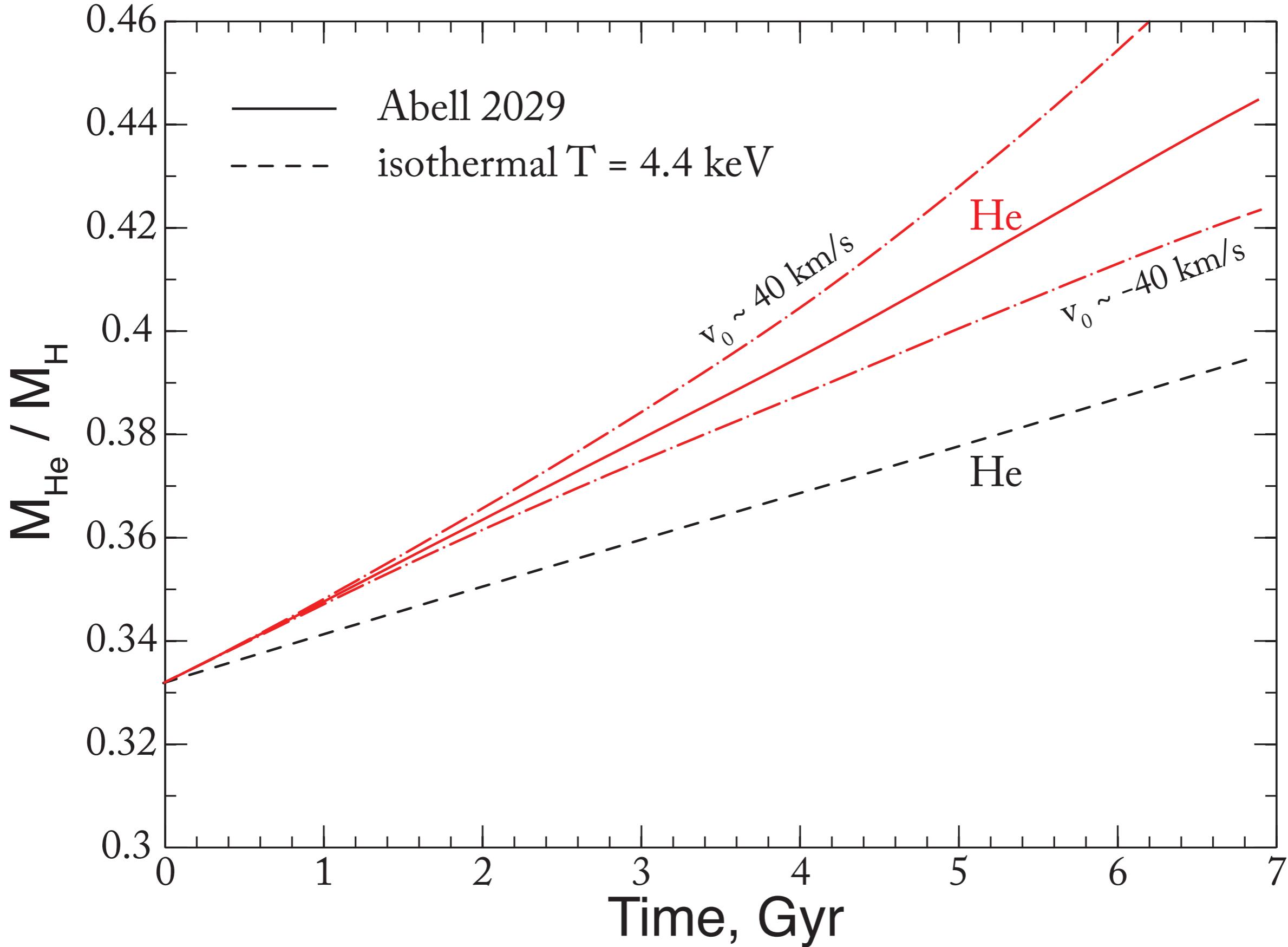
# DIFFUSION VELOCITY: THERMAL DIFFUSION VS. SEDIMENTATION



# ELEMENT DISTRIBUTION AFTER GYRS OF DIFFUSION

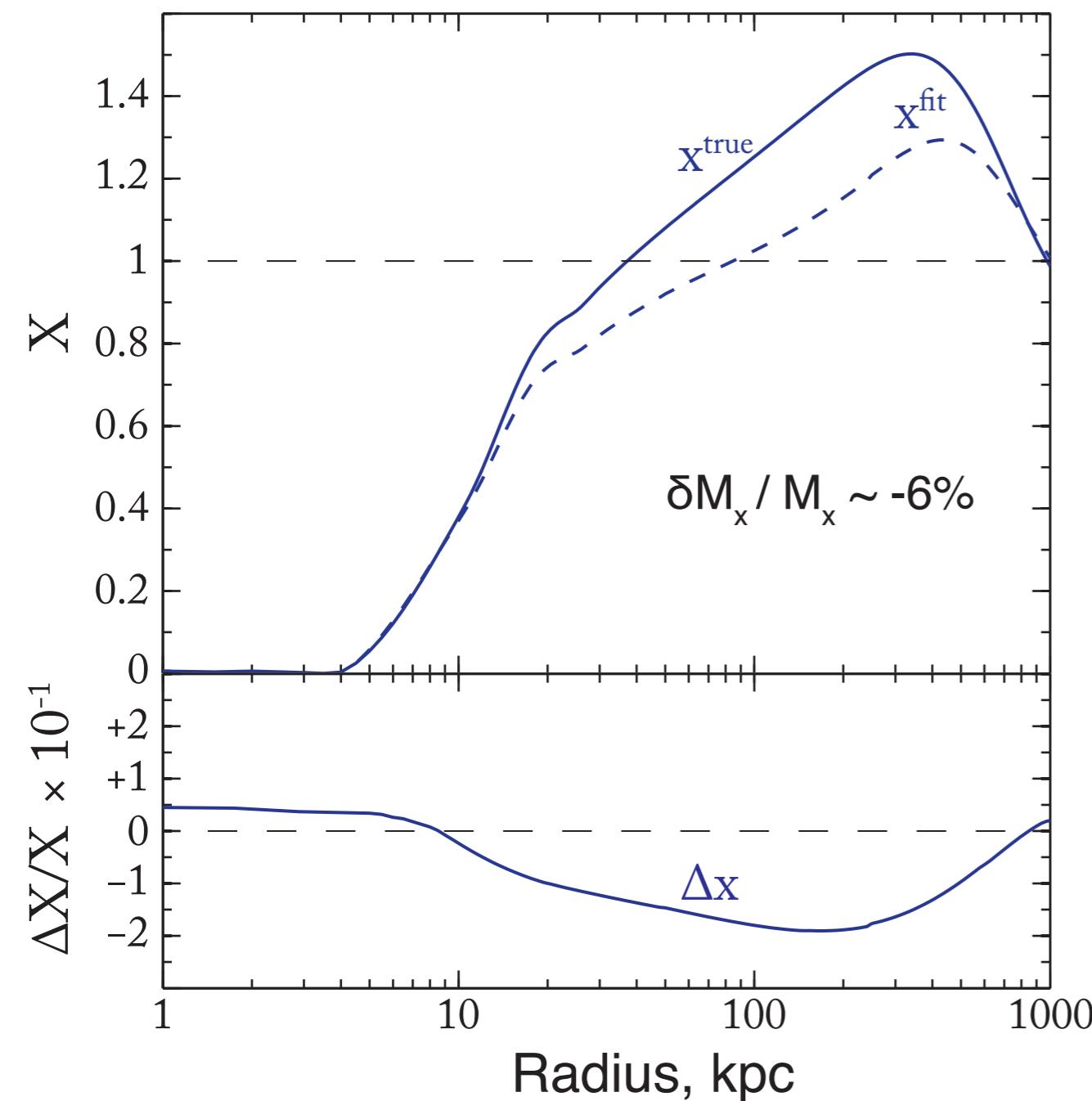


# EVOLUTION OF CLUSTER-AVERAGED ABUNDANCES

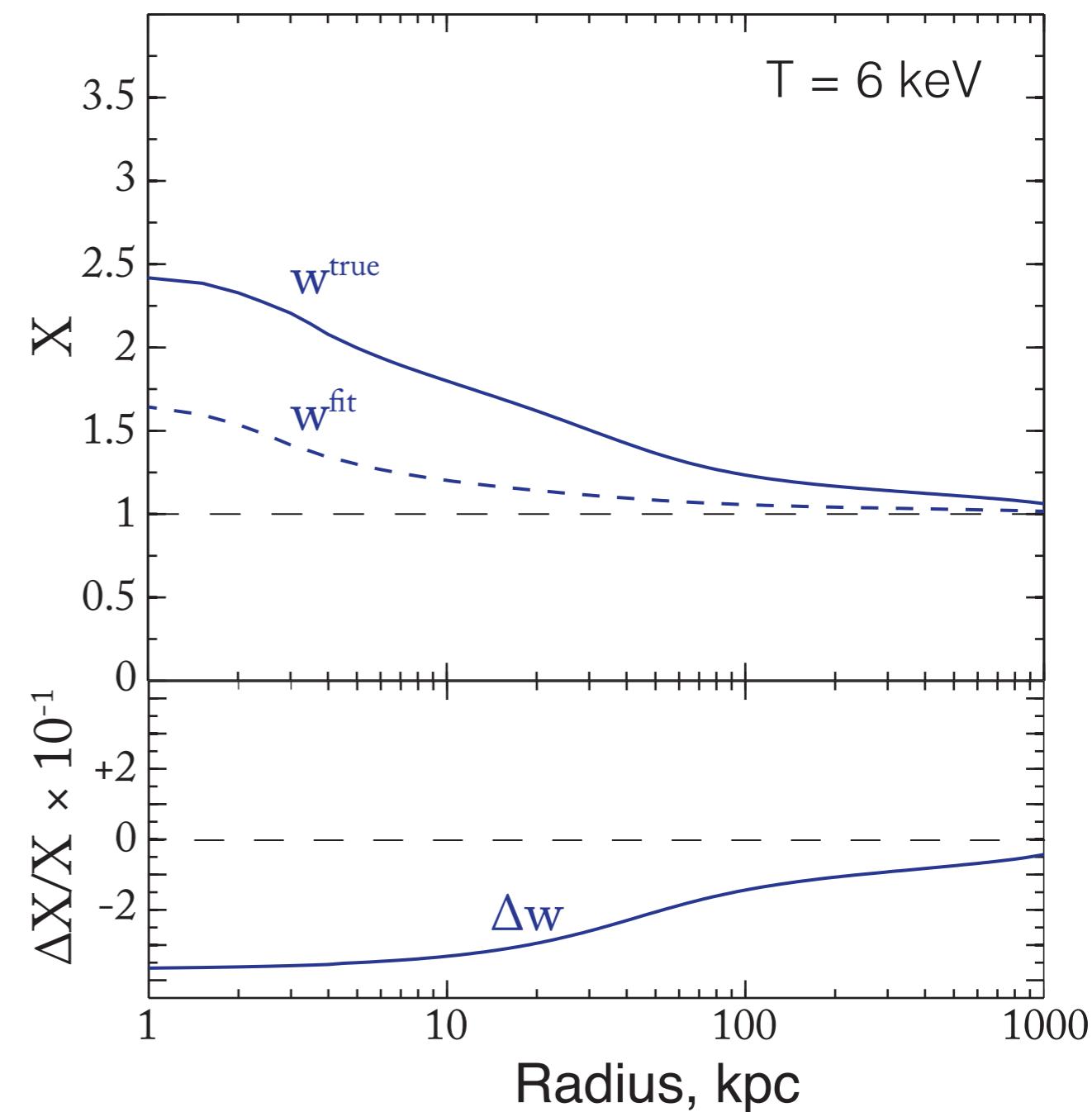


# BIAS IN METALS MEASUREMENTS CAUSED BY HELIUM SEDIMENTATION

After 7 Gyr of diffusion for Abell 2029



After 7 Gyr of diffusion for isothermal model



## SUMMARY

of element diffusion in shaping ICM abundance  
still unclear. The sedimentation effects can be  
led by magnetic fields and turbulent mixing

model with no magnetic fields, gravitational  
sedimentation can significantly increase cluster-  
abundance of helium at rate of ~5% per Gyr  
2029 cluster model

maximum bias in metal abundance measurements  
by helium sedimentation can reach ~40% in the  
the most massive galaxy clusters

Thanks for your attention!

# Back-up slides

# WEAKLY COLLISIONAL AND MAGNETIZED NATURE OF THE ICM

	Cool cores	Hot ICM
Temperature	$\sim 10^7$ K	$\sim 10^8$ K
Particle density	$\sim 10^{-2}$ cm <sup>-3</sup>	$\sim 10^{-3}$ cm <sup>-3</sup>
Mean free path $\lambda_{coll}$	0.02 kpc	23 kpc
Electron Larmor radius $\rho_e$	30 km	800 km
Ion Larmor radius $\rho_i$	1500 km	30000 km

I. No magnetic fields:  $\kappa_{Sp} = nD_{sp} \sim n\lambda_{coll}v_{th,e} \sim 10^{13} \left(\frac{T}{10^8 K}\right)^{5/2}$  ergs s<sup>-1</sup>cm<sup>-1</sup>K<sup>-1</sup>

2. Ordered magnetic fields:  $D_{\perp} \sim (\rho_i/\lambda_{coll})^2 D_{Sp} \sim 10^{-24} D_{Sp}$

3. Tangled magnetic fields:  $D \sim 0.2\text{--}0.3 \times D_{Sp}$  *Rechester & Rosenbluth, 1978  
Chandran & Cowley, 1998  
Narayan & Medvedev, 2001  
Chandran & Maron, 2004*

4. The role of plasma instabilities is still unclear:

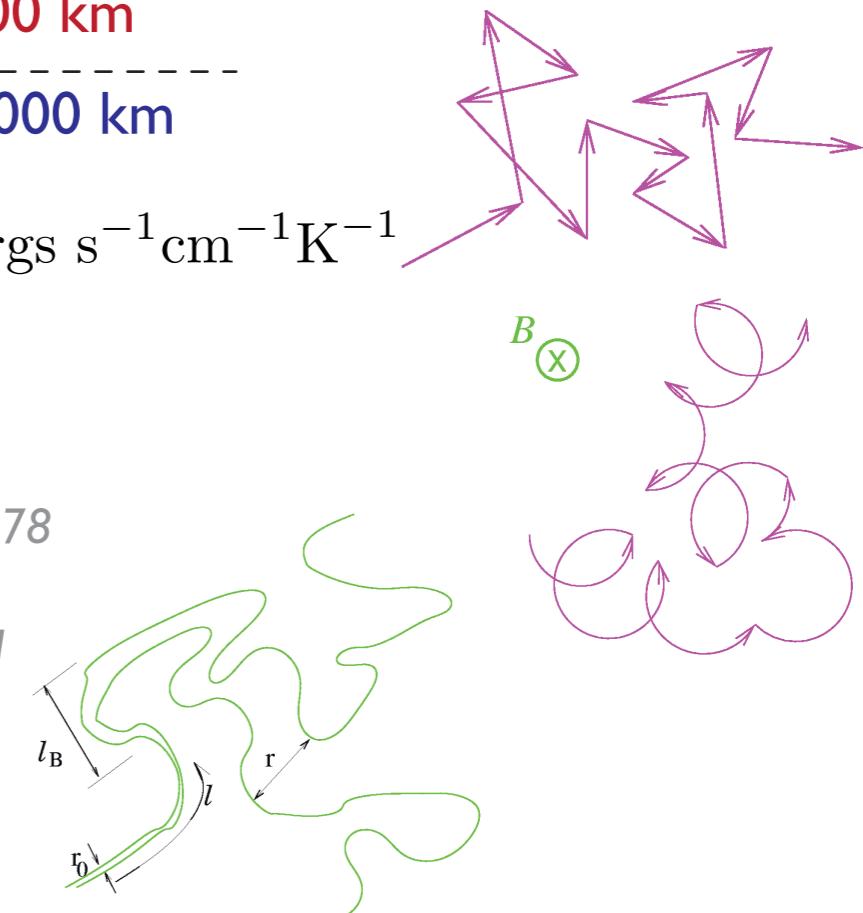
- a. Firehose instability. Suppression of ion diffusivity. *Kunz et al. 2014*
- b. Mirror instability.

Ions and electrons:  $\kappa_{\parallel} \sim \frac{1}{5} \kappa_{Sp}$  *Komarov et al. 2016*

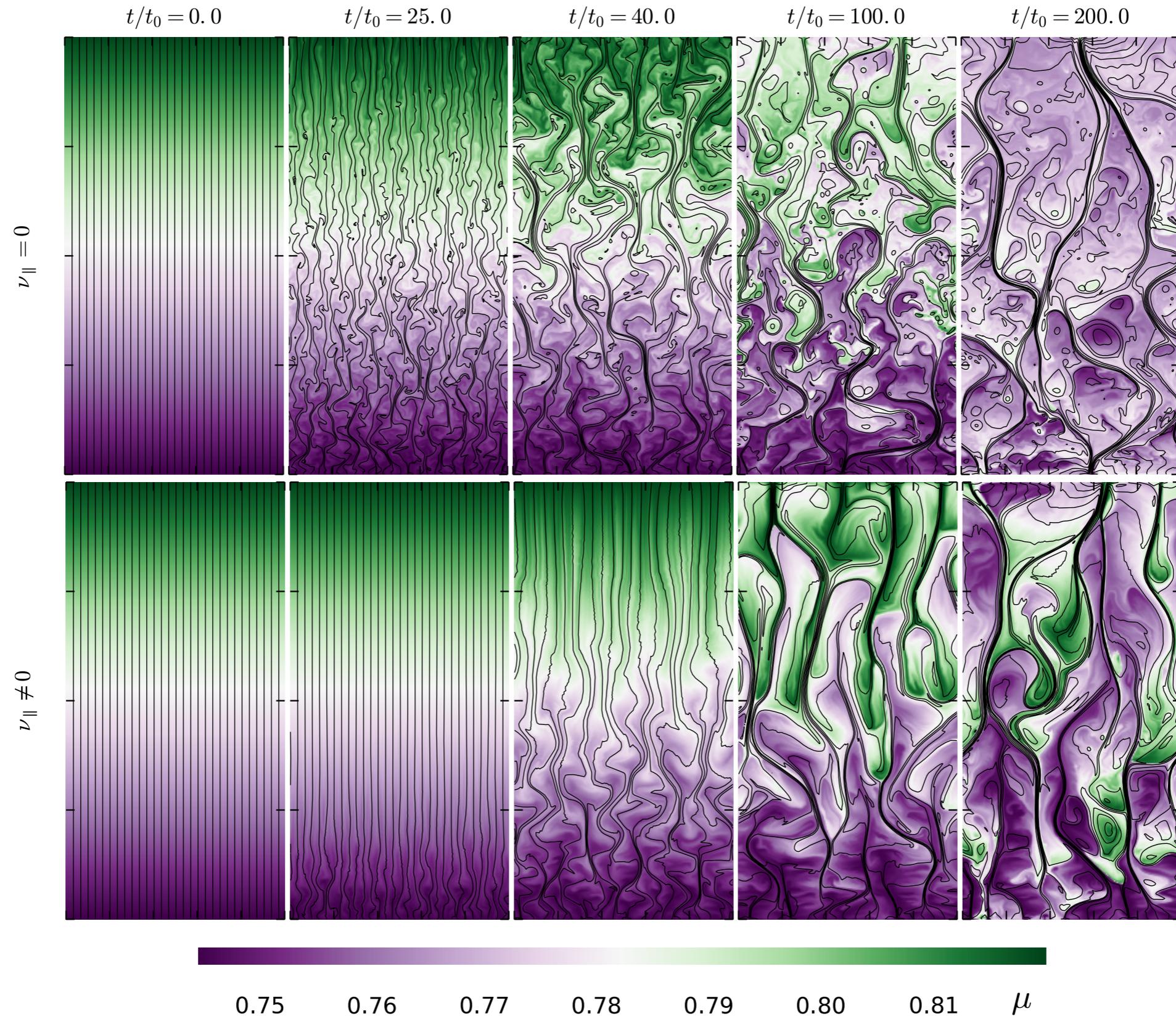
- c. Whistler instability.

Only electrons:  $\kappa_{\parallel} \sim \kappa_{Sp}/(10 \text{ max. at large } \nabla T)$

*Levinson & Eichler 1992; Pistinner et al. 1998  
Roberg-Clark et al. 2017; Komarov et al. in preparation*



Berlok & Pessah 2016



# TALK STRUCTURE

1. Element diffusion in the intracluster medium (ICM)
  - A. Calculation method and results
  - B. Possible observational evidences
  - C. Bias in X-ray and SZ derived quantities
2. Primordial elements diffusion during formation of first galaxies
  - A. Diffusion amplitude in growing halos before collapse
  - B. Estimations for subsequent stage of structure formation
  - C. Effect of gas preheating before the cosmic reionization

