

# X線天文の現在と未来

満田和久

宇宙航空研究開発機構・宇宙科学研究本部

# 概要

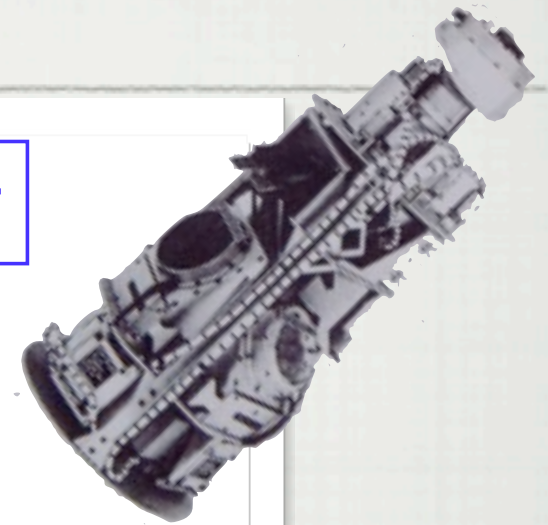
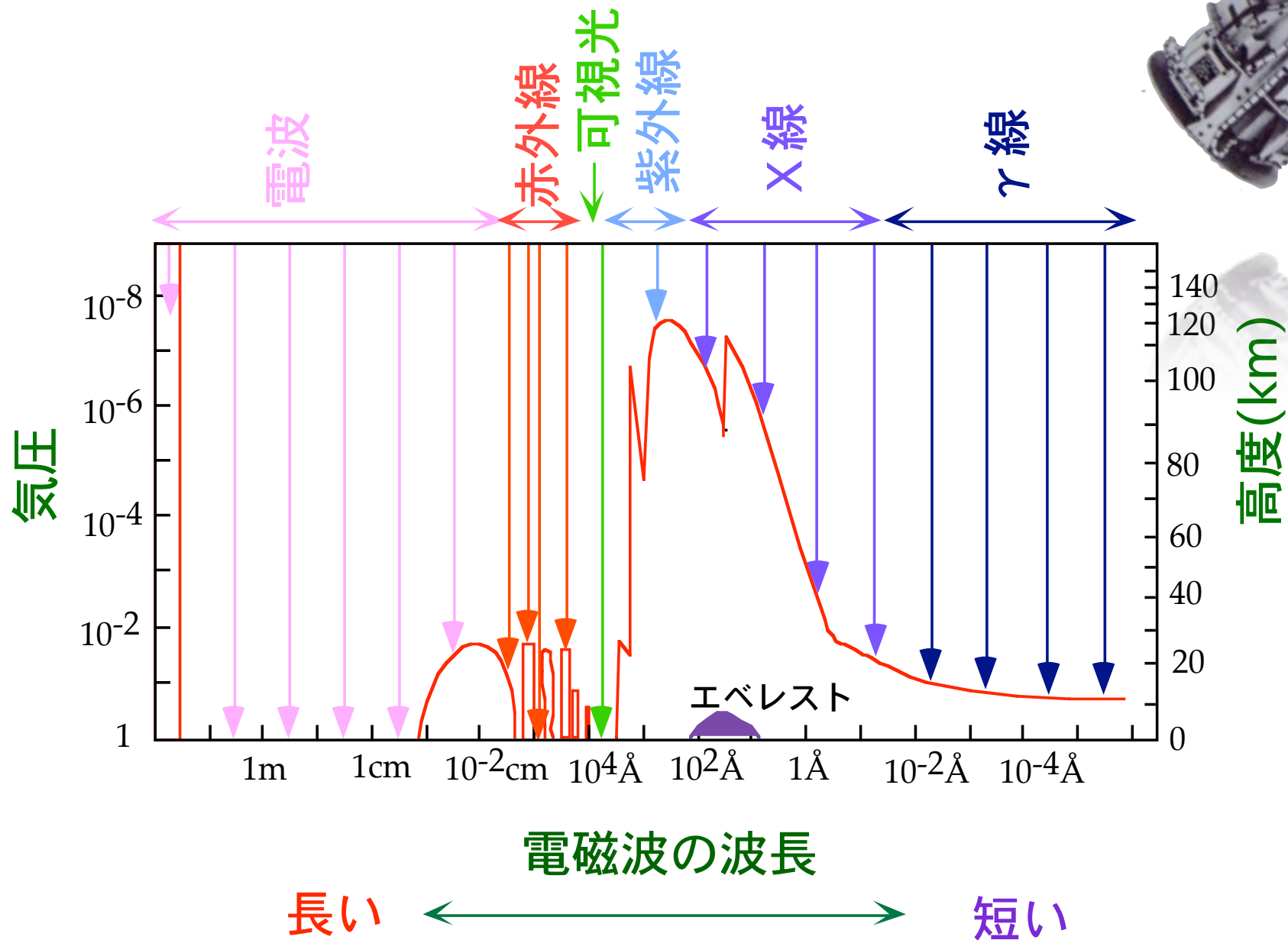
---

- 過去から現在
  - X線天文学がもたらした3つの驚き
- 現在から未来
  - 動物学と基礎科学
  - 宇宙最大の高エネルギー実験室
  - その向こう側と手前側



# X線天文学

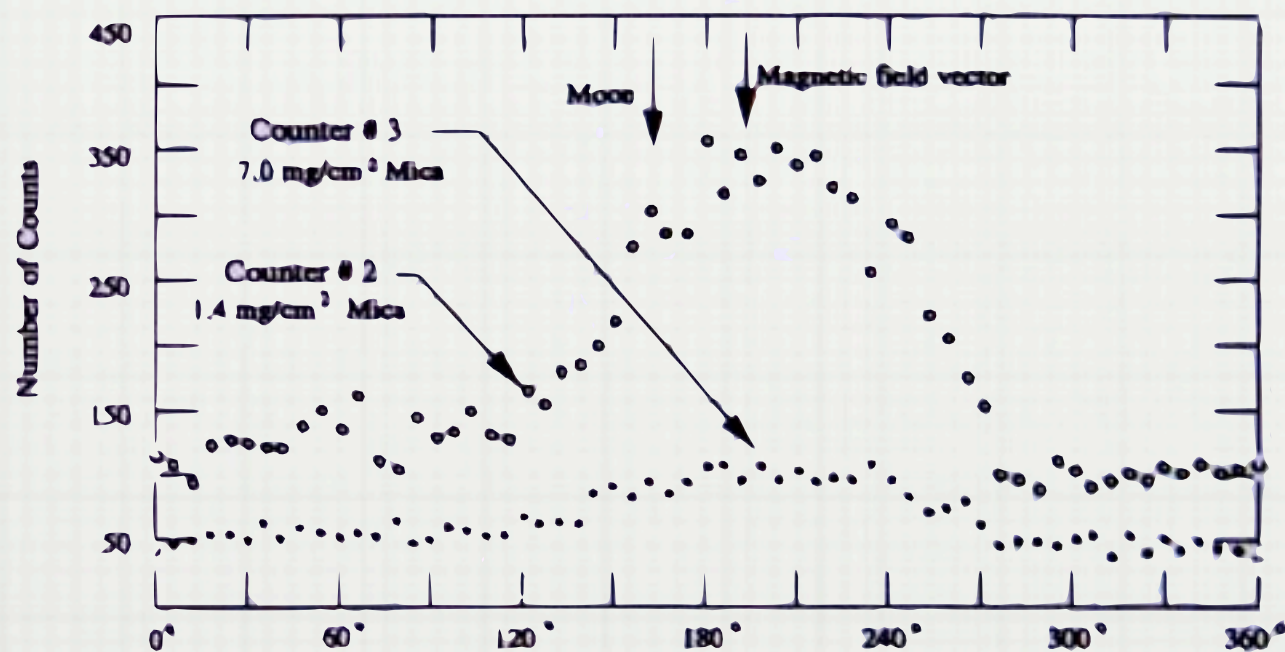
電磁波の種類と大気により吸収される様子





# X線天文学がもたらした3つの驚き：その1

- 質量降着の概念：天体のエネルギー源の重要な形態



$$L = \eta \dot{M} c^2$$

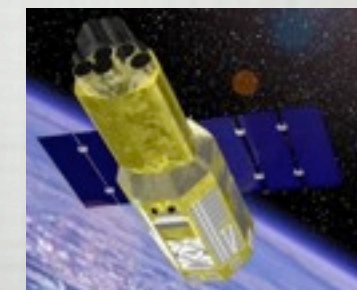
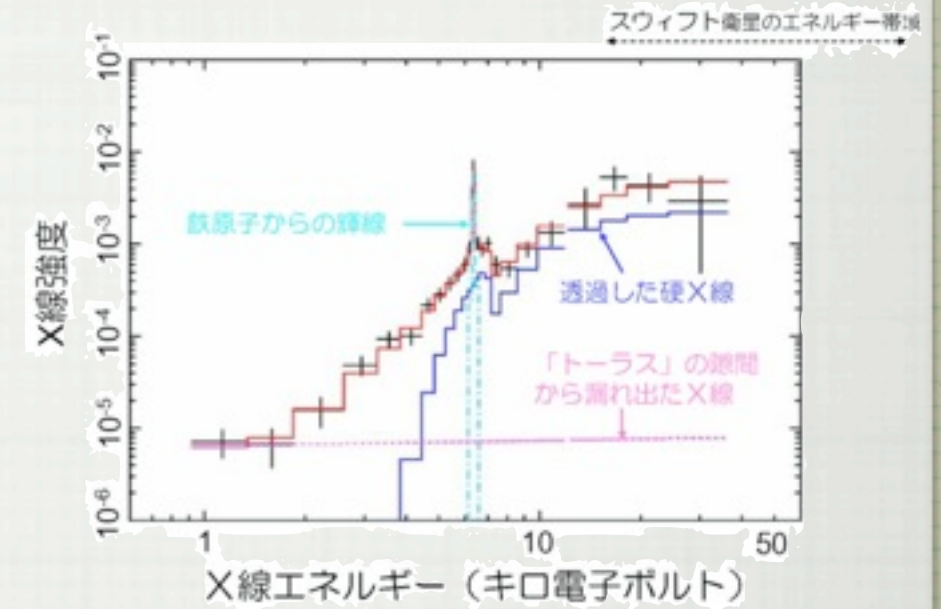
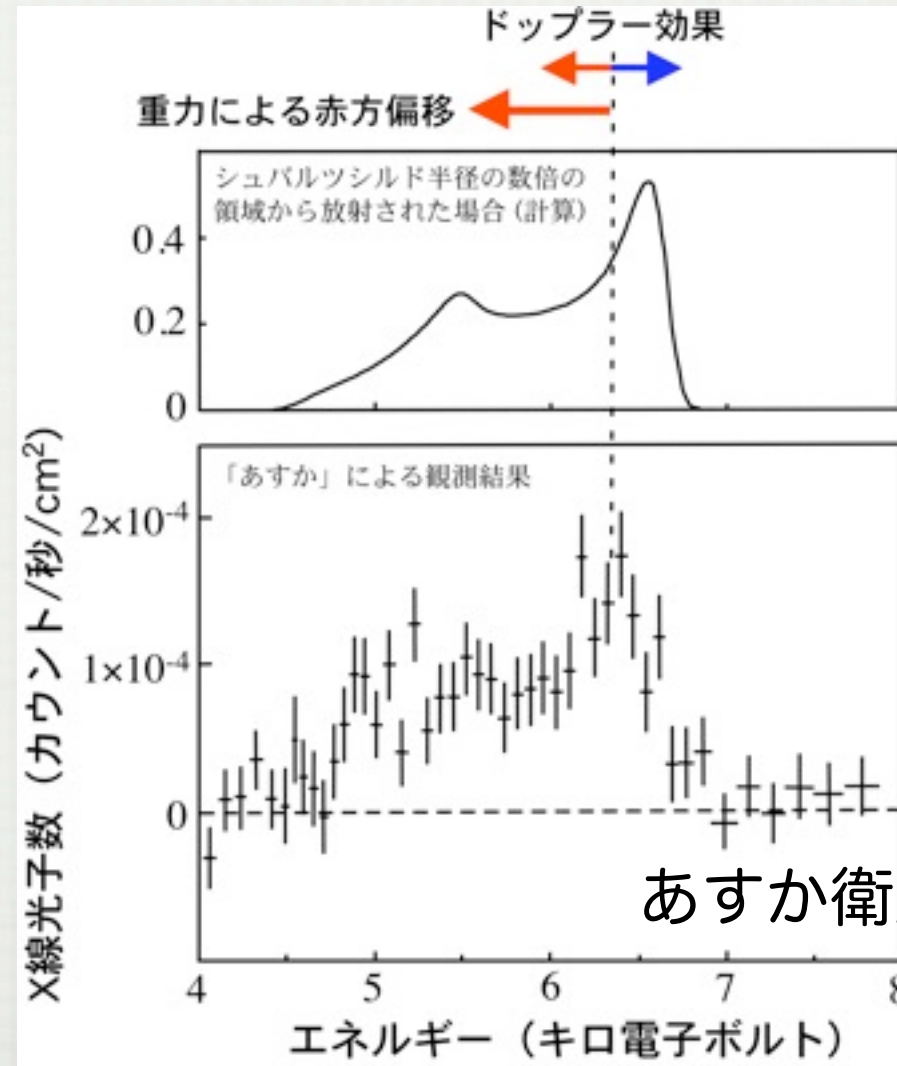
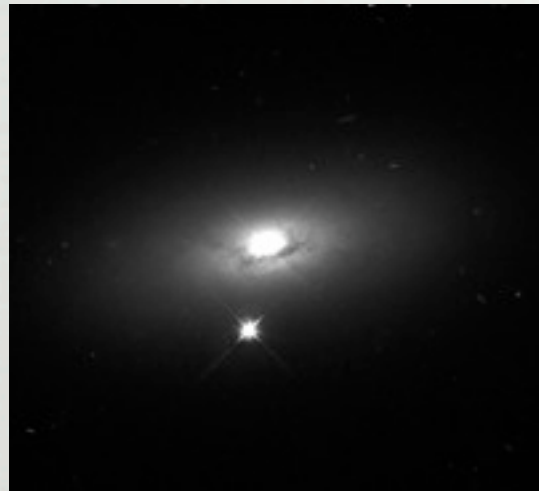
$$\eta \sim \frac{1}{6}$$



Ginga transients

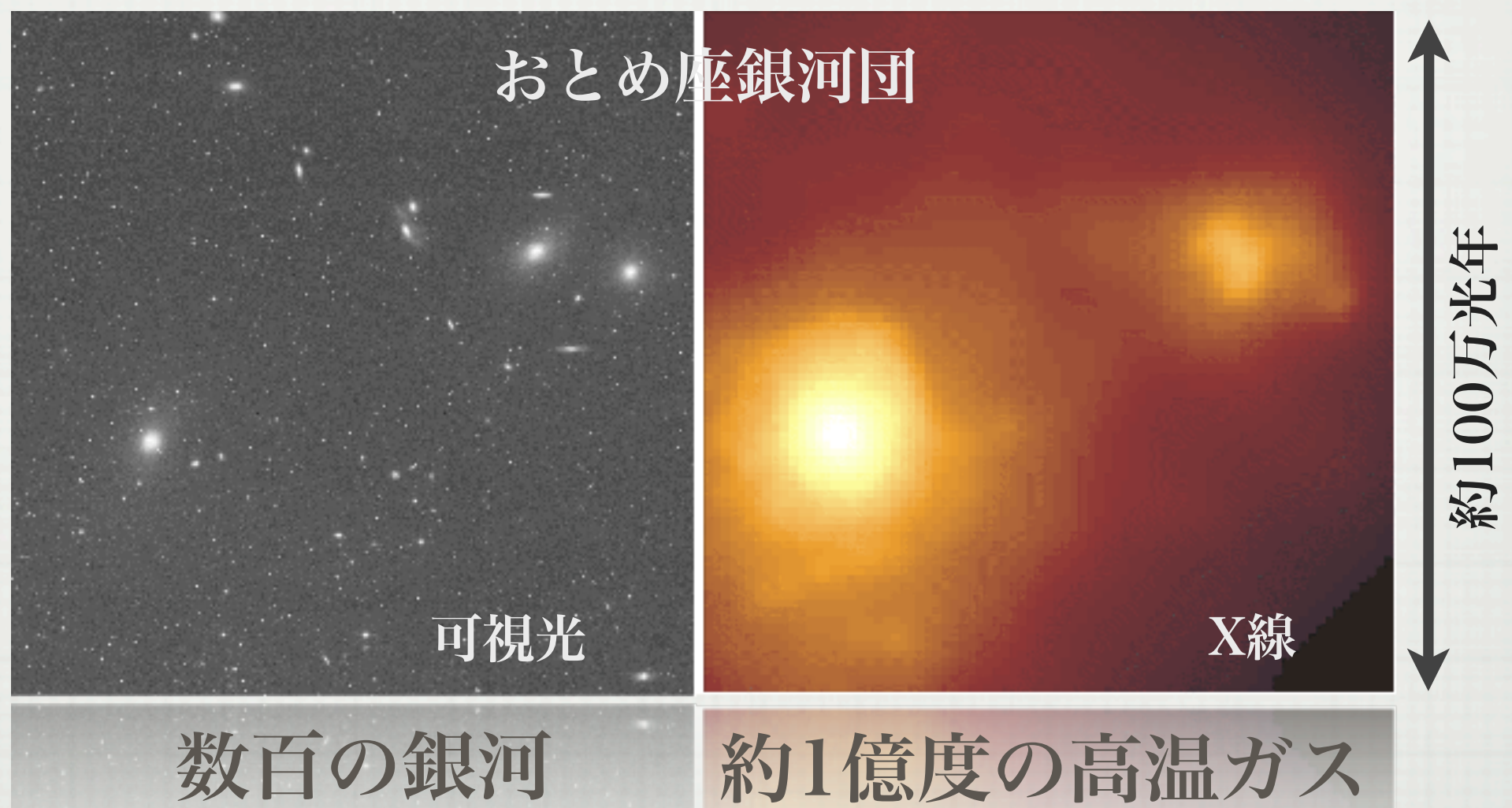


# 質量降着：活動銀河核





# X線天文学がもたらした3つの驚き：その2



Spectroscopy

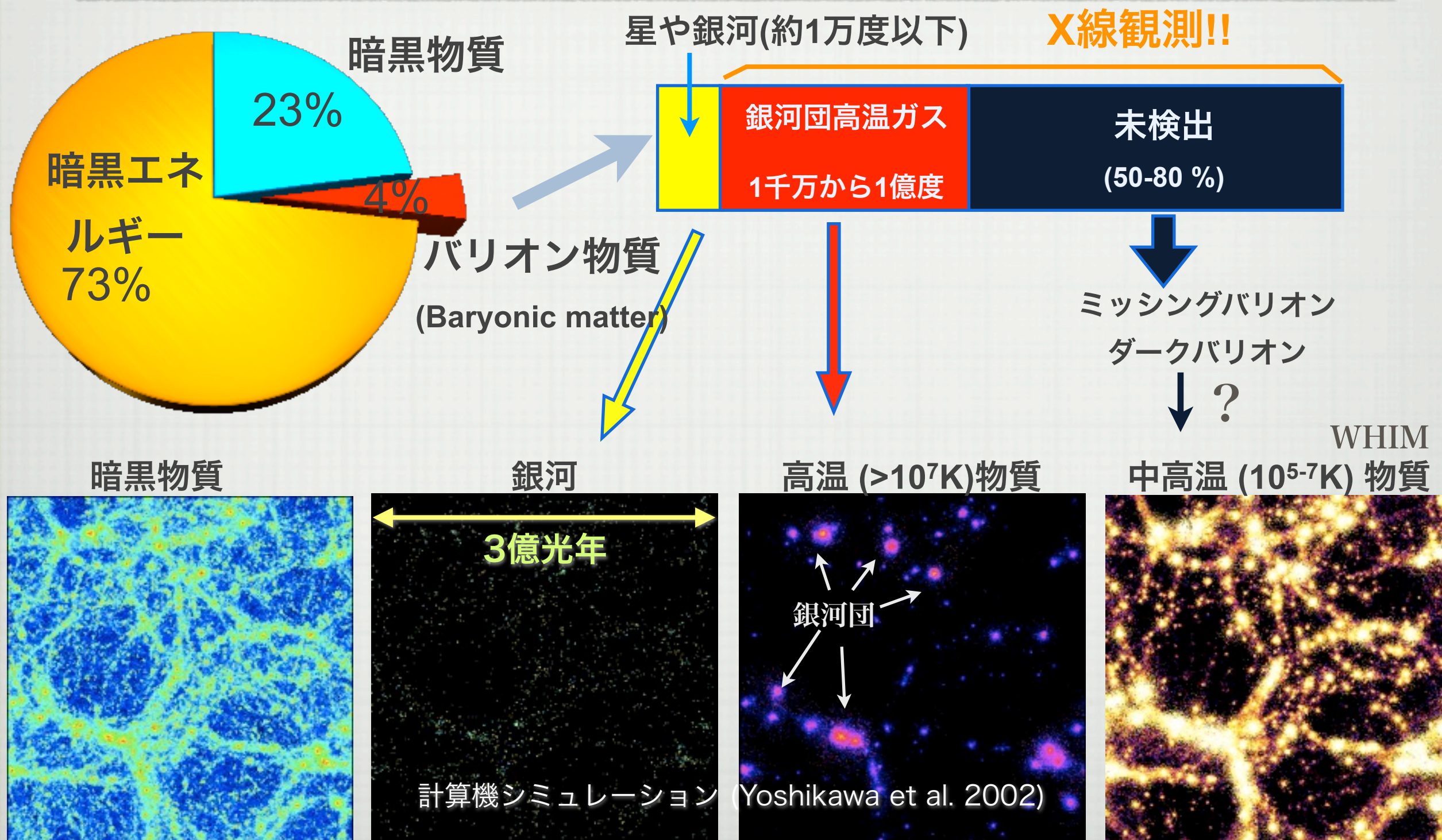
Ariel V





# 高温物質は宇宙の主要な構成要素

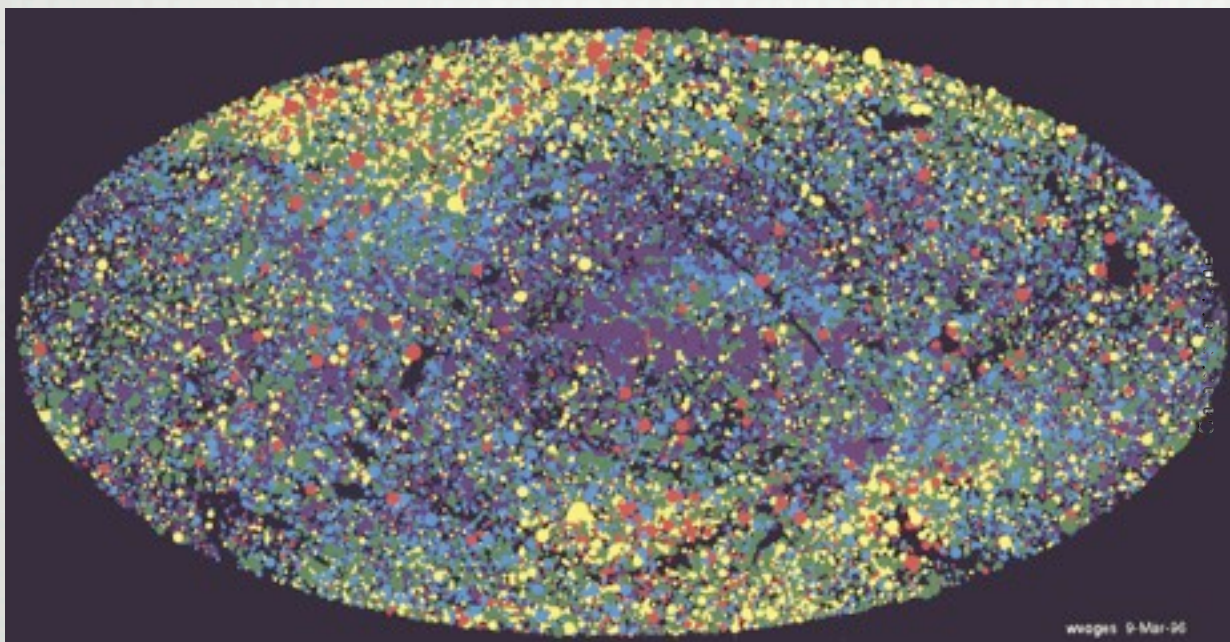
## 現在の宇宙 = 熱い宇宙



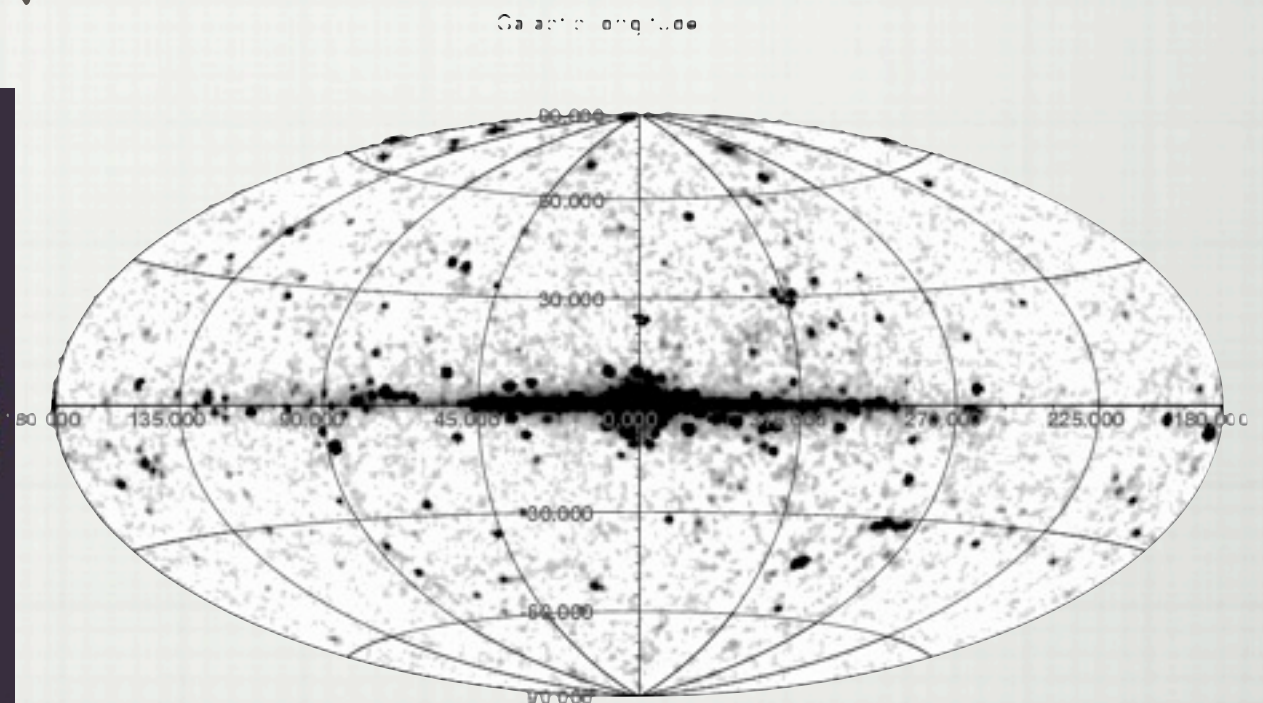


# X線天文学がもたらした3つの驚き：その3

- およそあらゆる天体がX線を放射する
  - 恒星、原始星、HII領域、、、

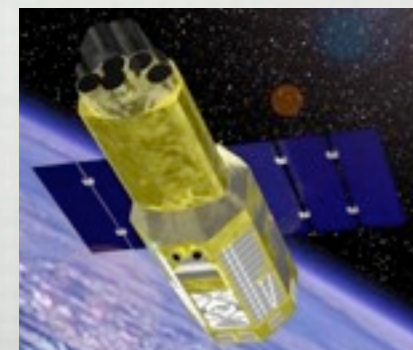


0.1 - 2.4 keV (ROSAT)



3 - 20 keV (RXTE)

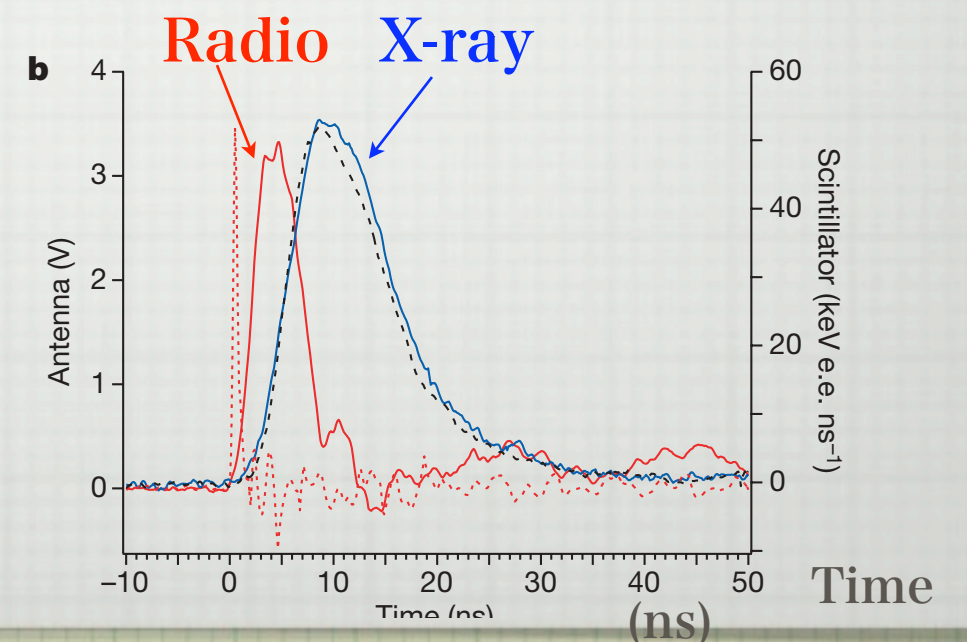
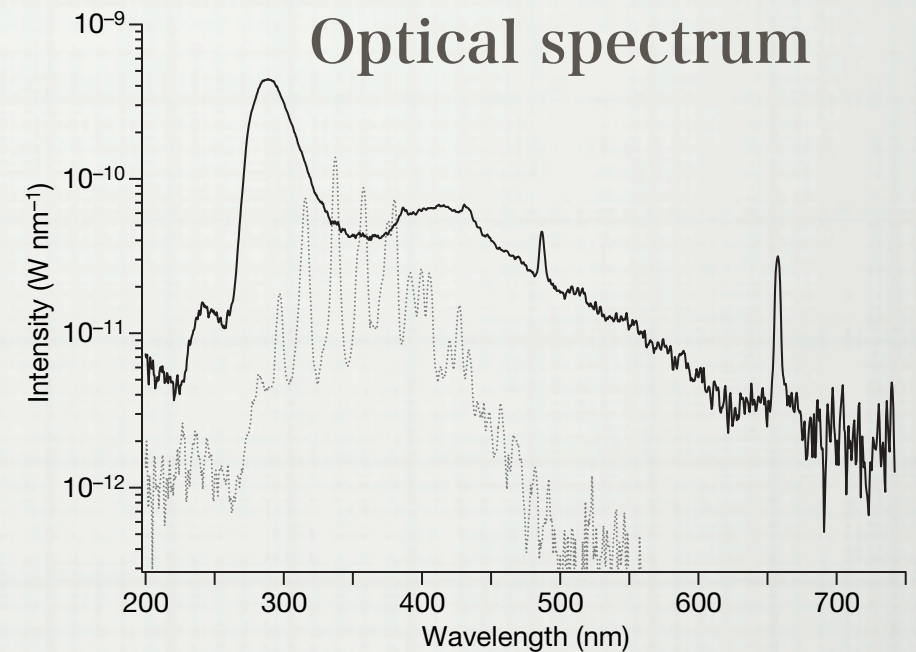
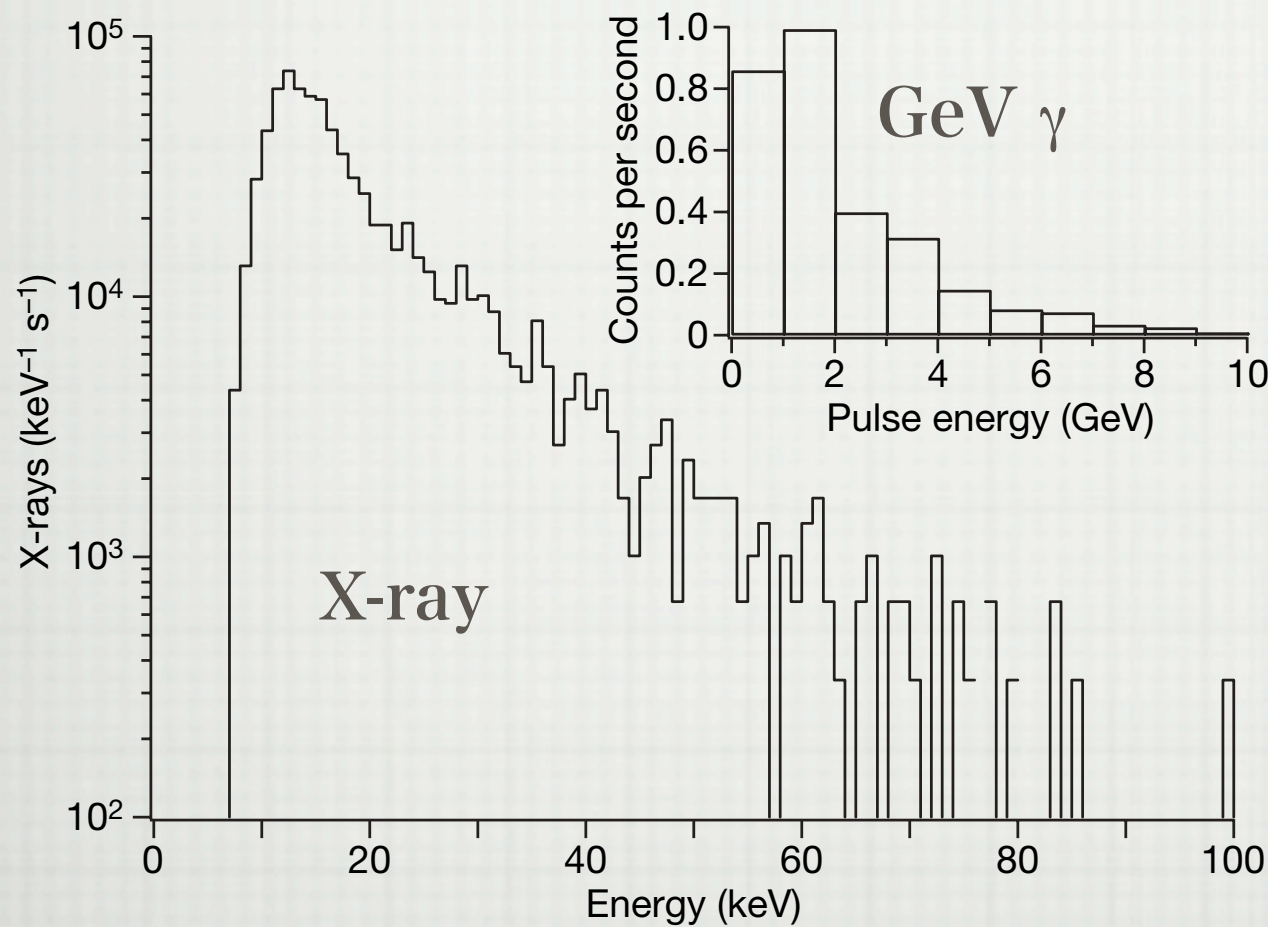
Einstein





# 様々なX線放射

“ある現象”に伴う電波からGeV ガンマまでの放射



(Camara+ 2008, Nature 455, 189)

# 様々なX線放射

---

## Triboluminescence

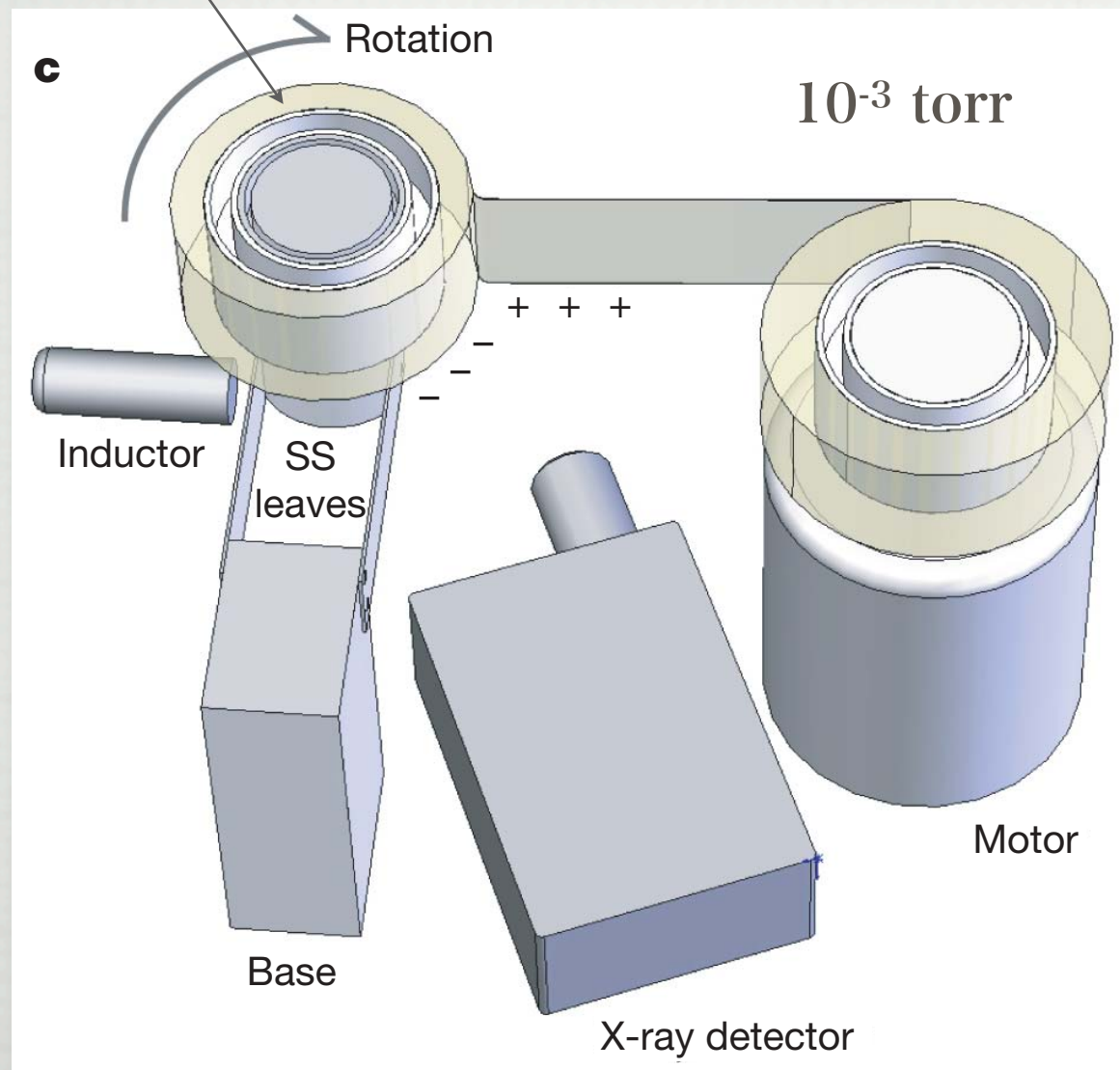
(Camara+ 2008, Nature 455, 189)



# 様々なX線放射

## Triboluminescence

スコッチテープ



(Camara+ 2008, Nature 455, 189)

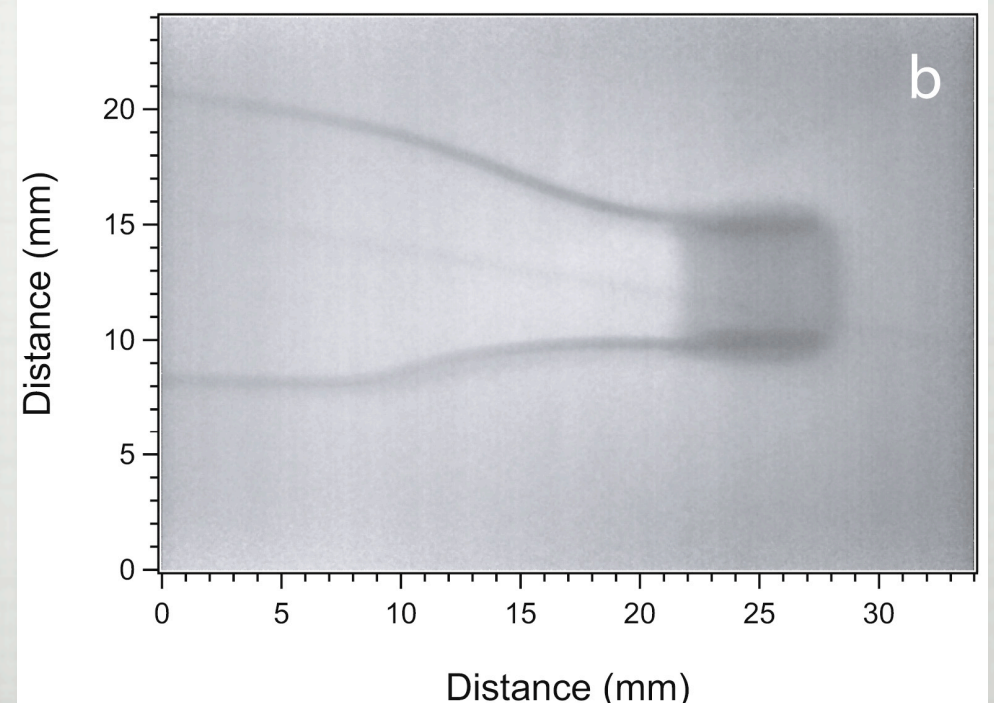
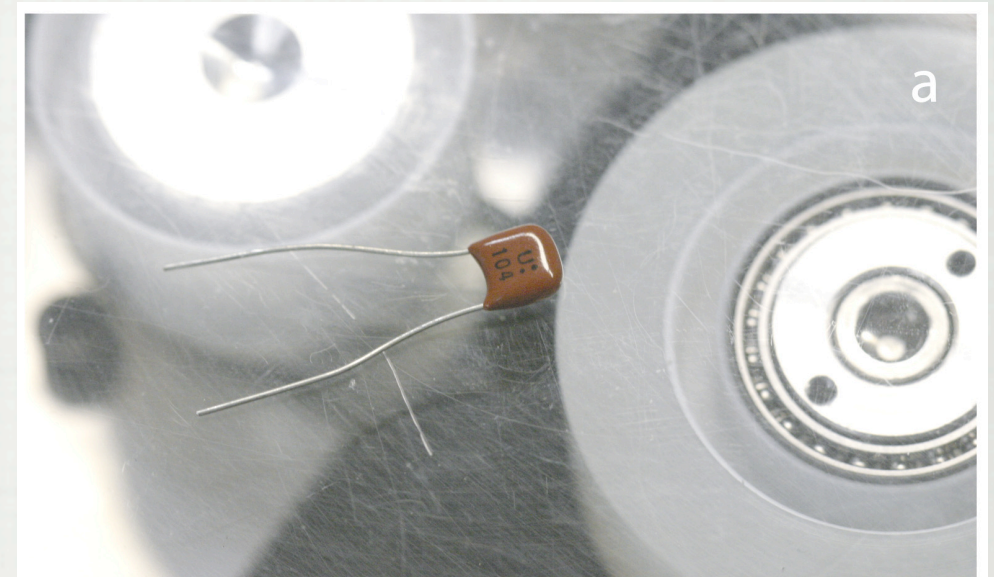
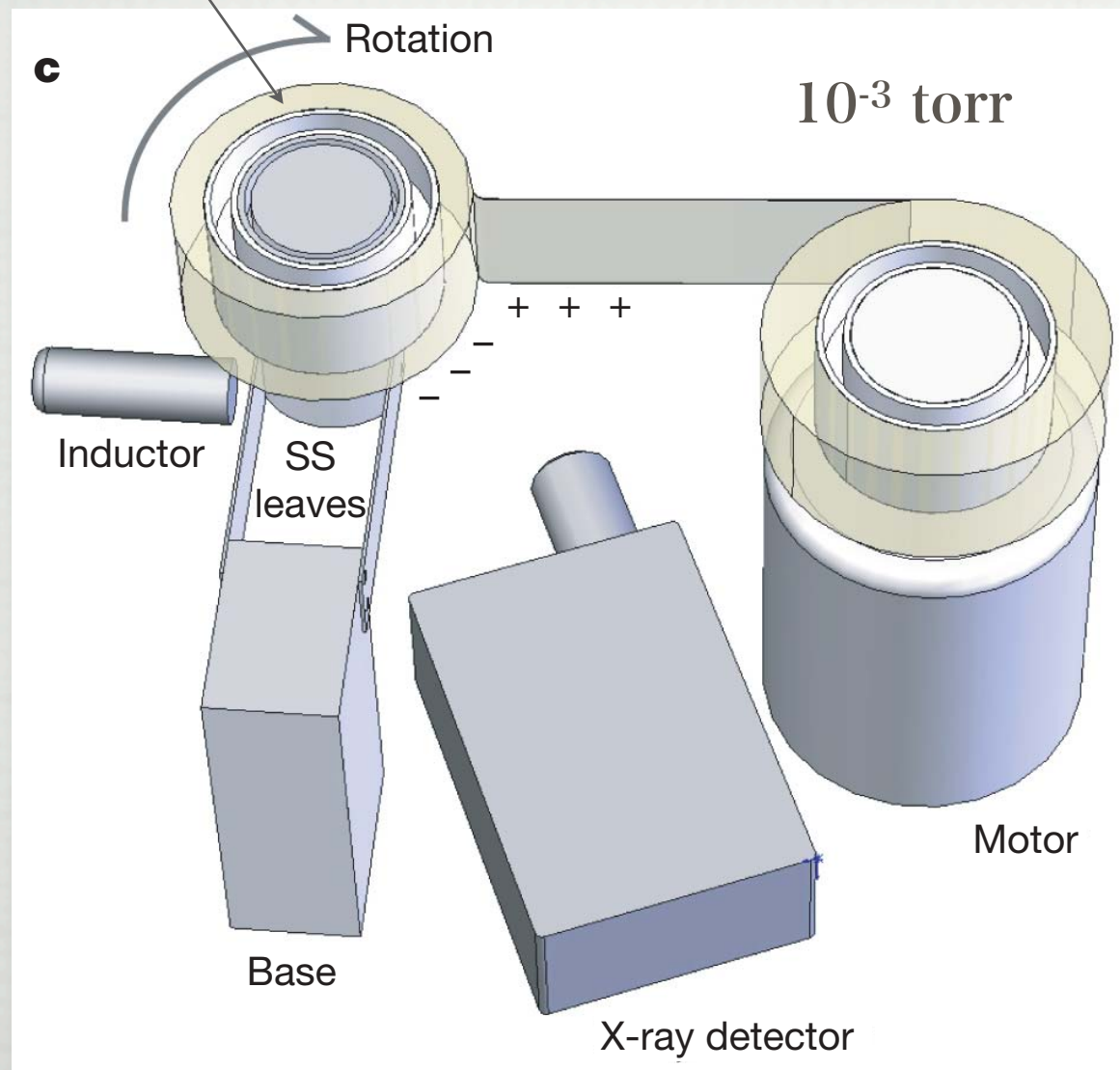


# 様々なX線放射

## Triboluminescence

## X-ray generator w/o high voltage

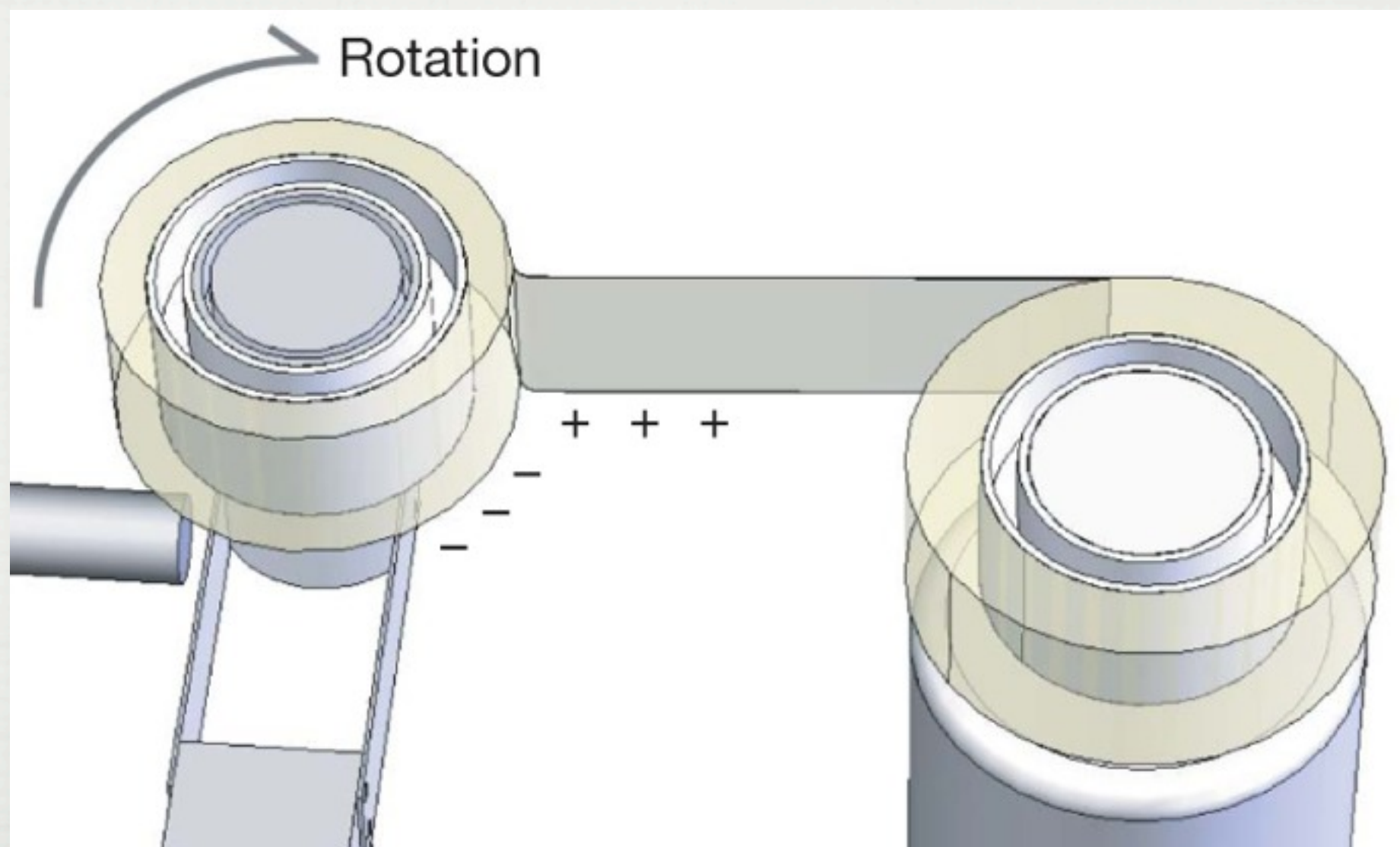
スコッチテープ



(Camara+ 2008, Nature 455, 189)

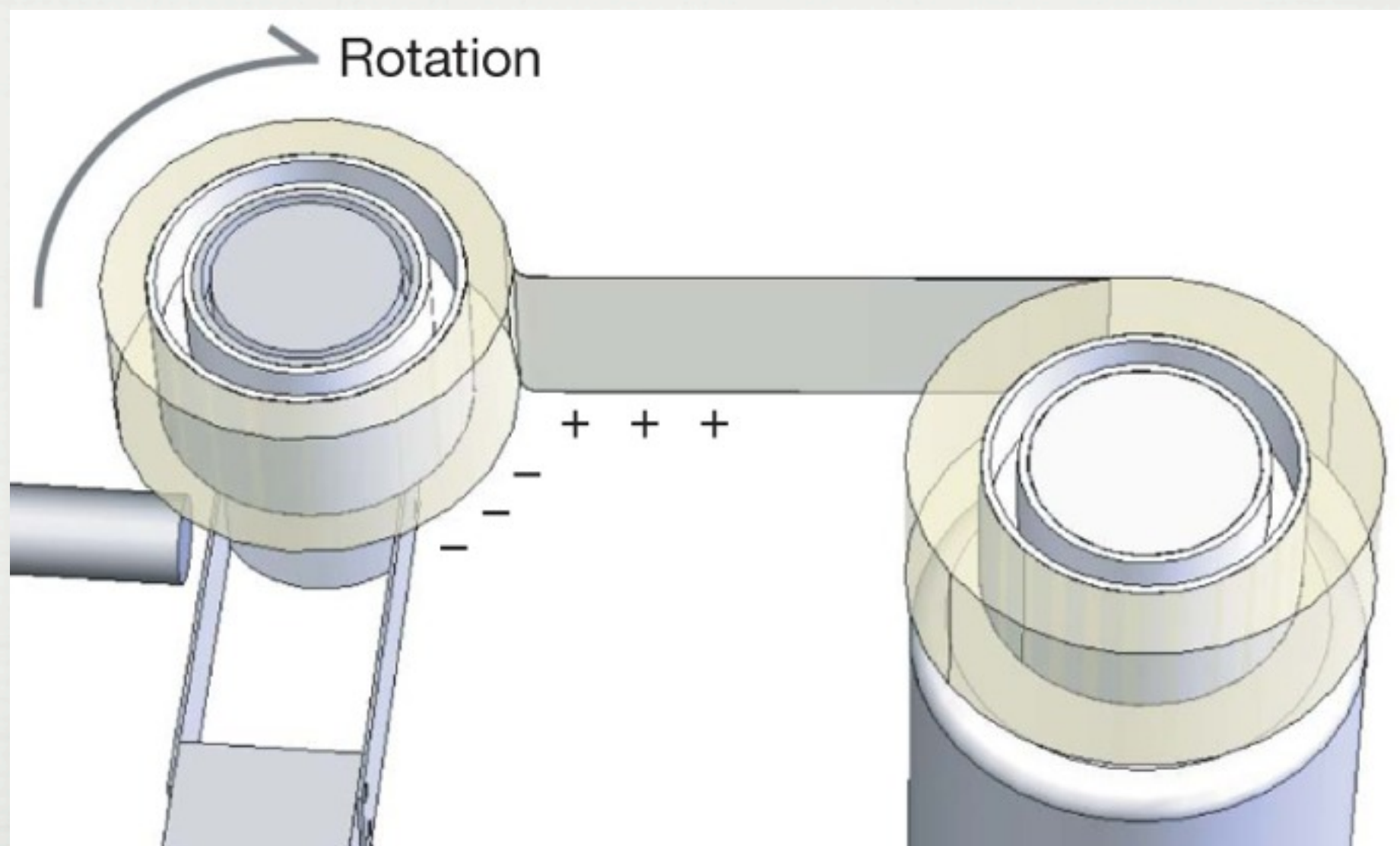


# Physics of scotch tape





# Physics of scotch tape

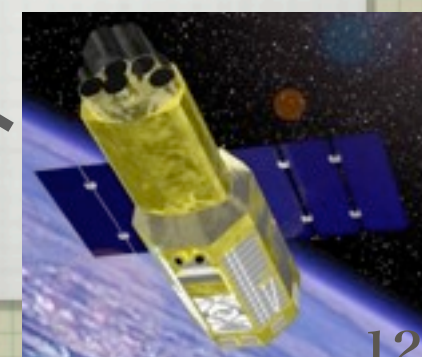
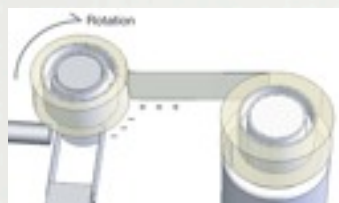


## Zoology



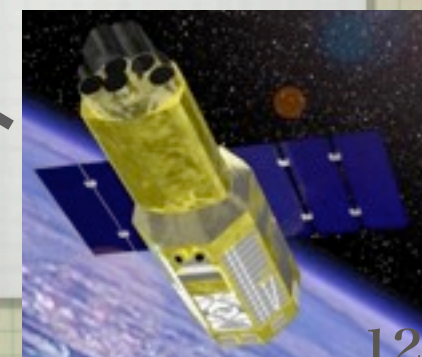
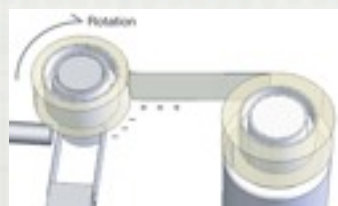
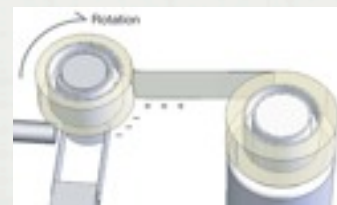
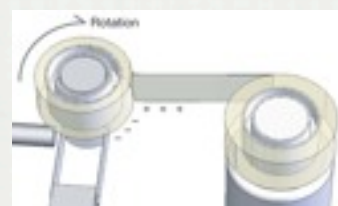
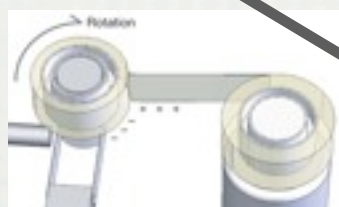
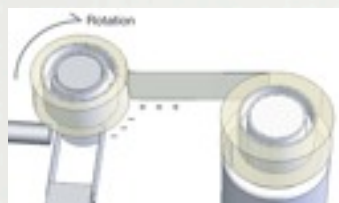
# Scotch tapes as standard candles

---



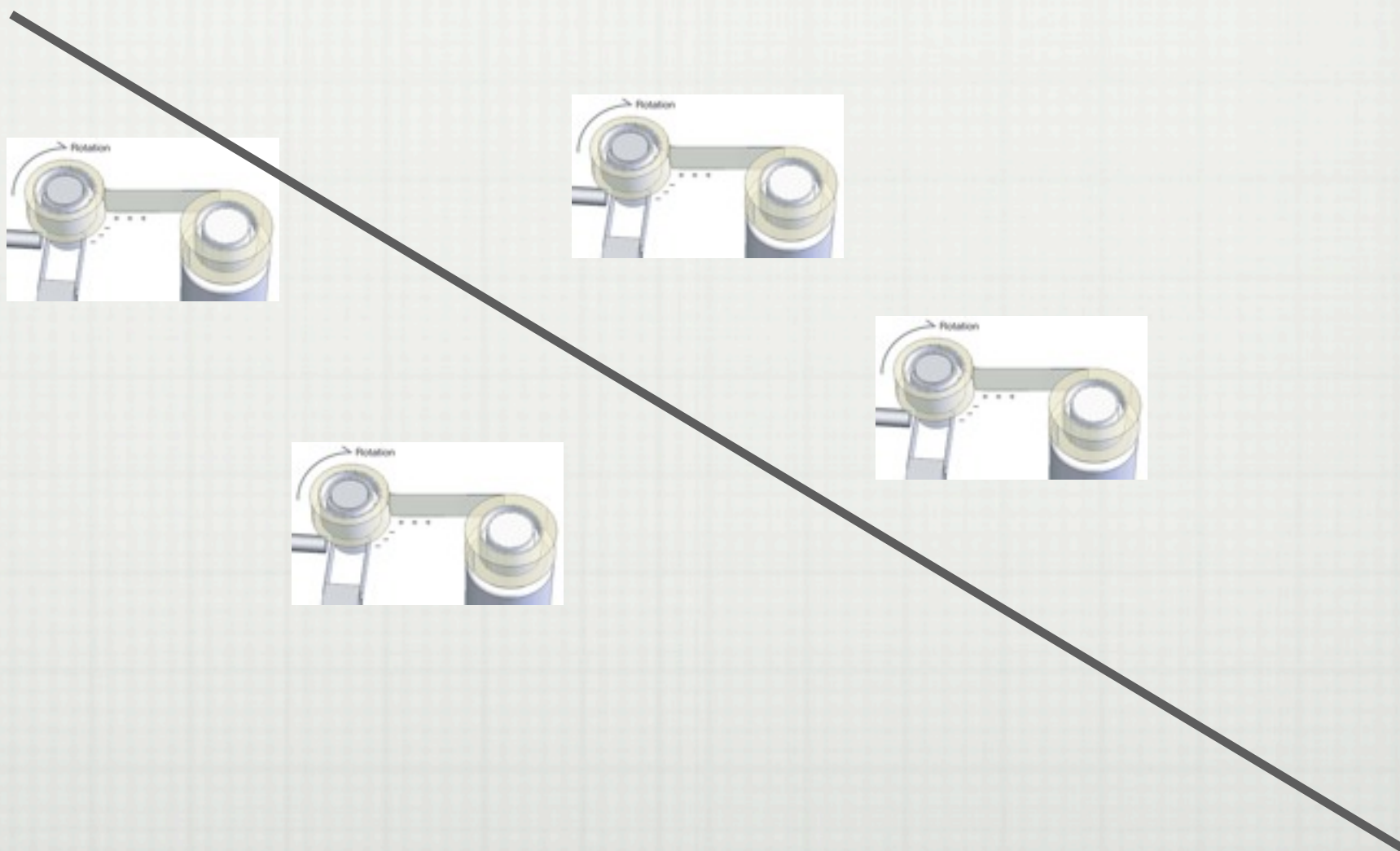
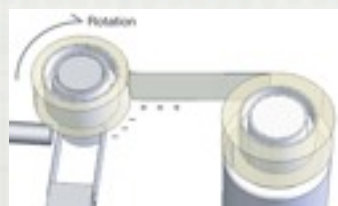
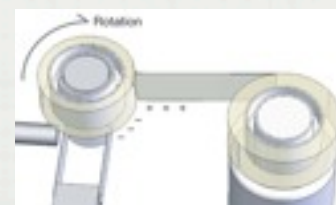
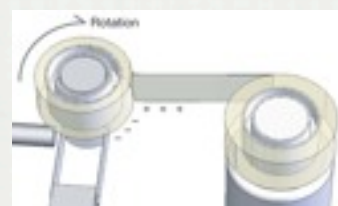
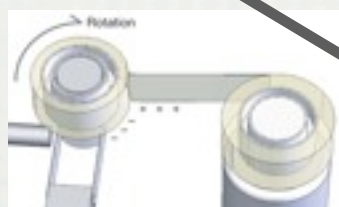
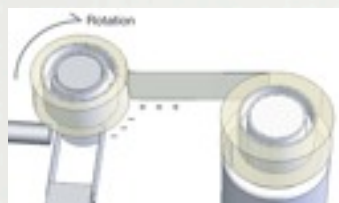


# Scotch tapes as standard candles





# Scotch tapes as standard candles



## Fundamental physics





# Clusters of galaxies

---

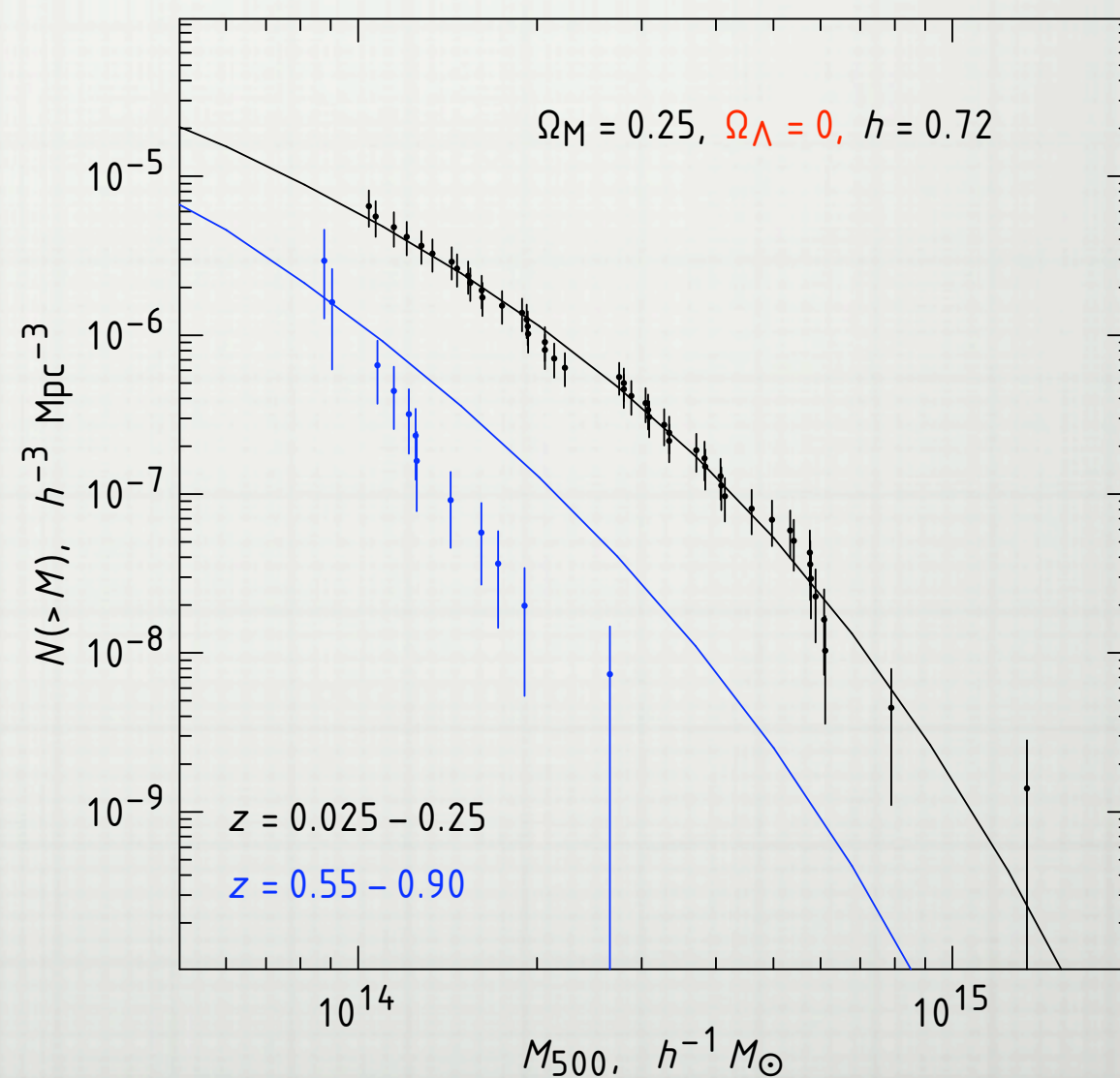
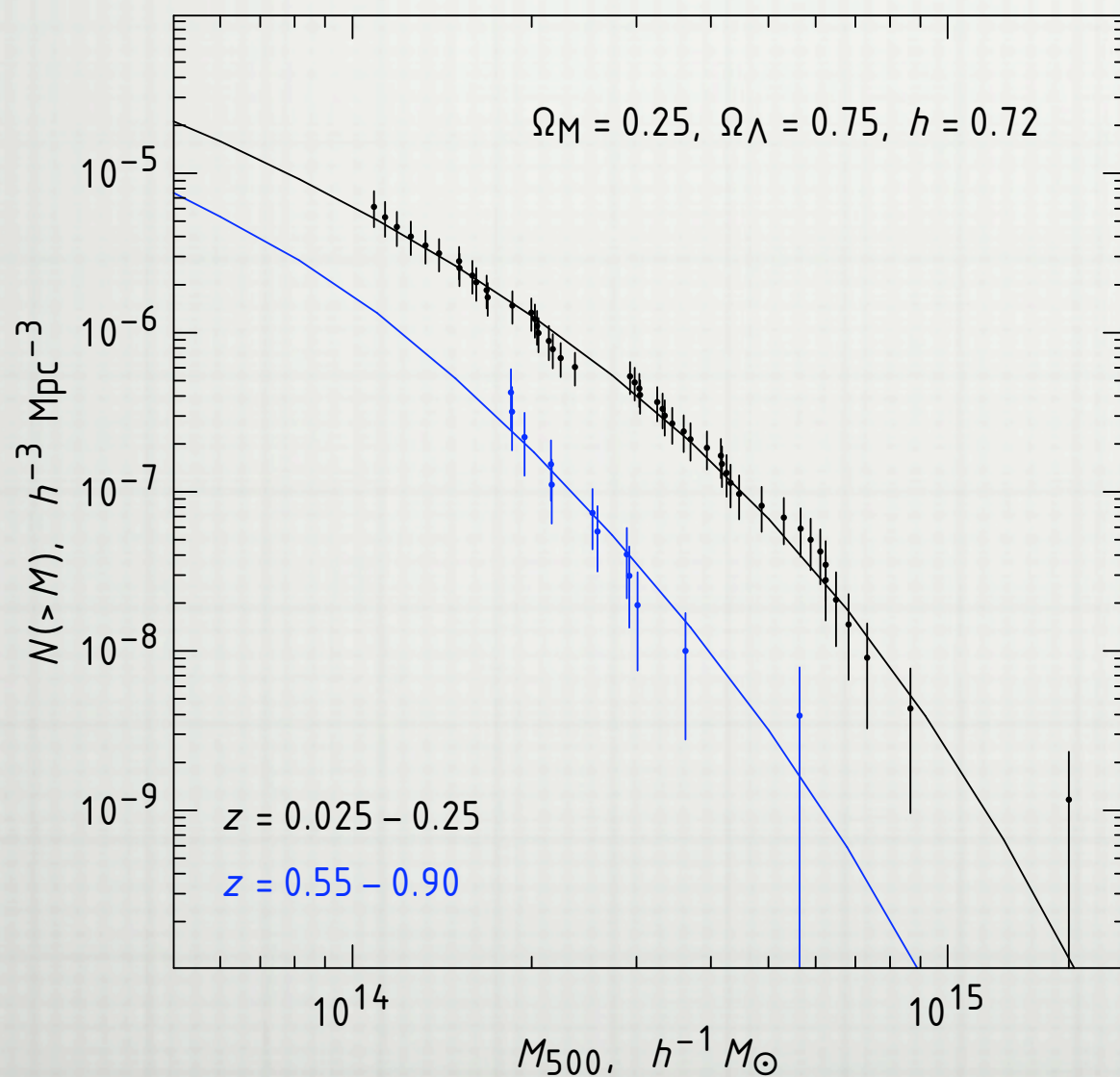
- 重力的に束縛された系としては、宇宙最大の天体
  - 重力：宇宙の大構造のノード
    - $z < 2$  の宇宙の大構造形成史
- Baryonic matter interactions：高エネルギー実験室
  - 高温ICM: thermal energy, kinetic energy
  - 高エネルギー電子、宇宙線(陽子)、磁場
  - Dark matter annihilation (?)



# Clusters of galaxies as a probe of structure formation of the universe

## Cluster mass function

Vikhlinin+ 2009

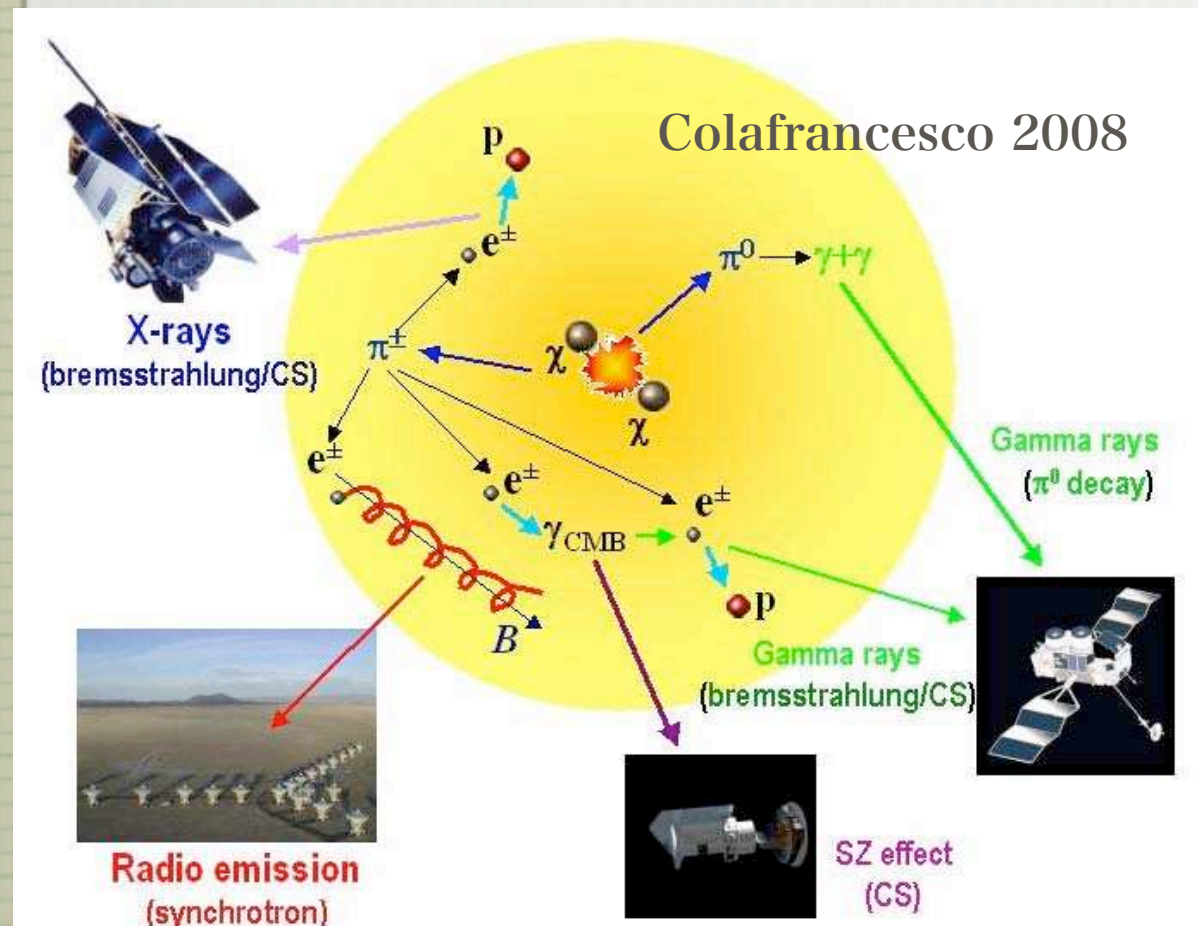


$\omega_8$  のみを free parameter として fit

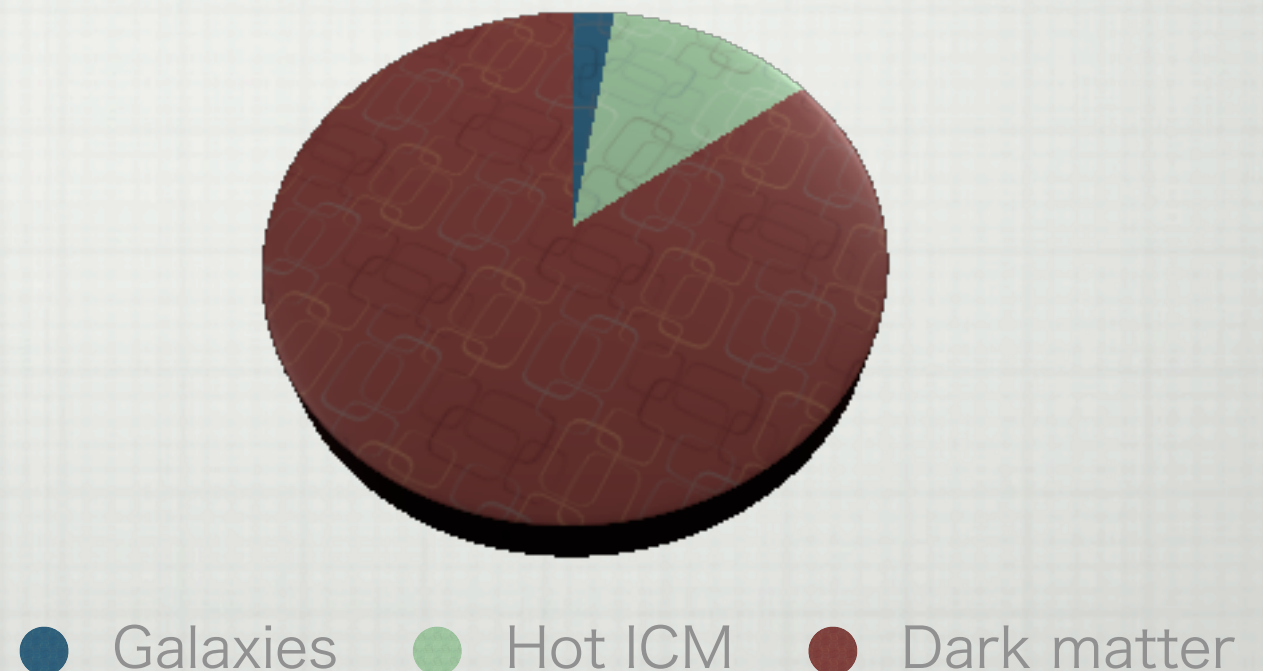


# Clusters of galaxies as the largest laboratory for high energy astrophysics

- 重力：Dark matterが支配。
- Baryonic matter: 高エネルギー粒子（AGN、accretion shock, merger shock、dark matter annihilation(?)）や磁場を含めた複雑な系
- 宇宙最大の高エネルギー物理の Zoo

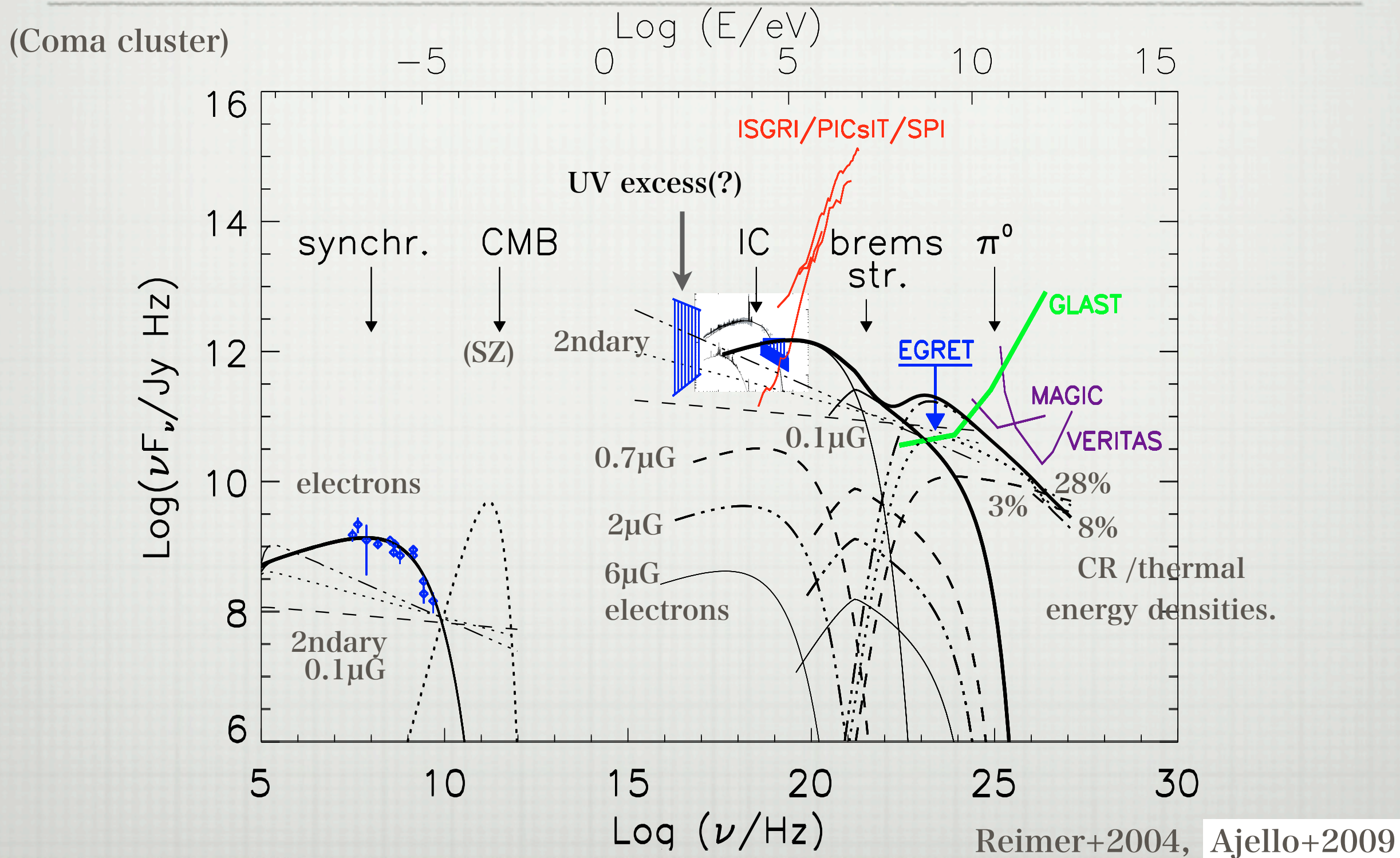


Cluster mass budget





# Multi-wavelength view of a cluster





# Energy densities

---

	ICM thermal	ICM kinetic	GeV electrons	Magnetic field	Cosmic rays
eV/cm <sup>3</sup>	1.3	0.30	6.7E-05	6.2E-03	0.11

Crude, but maybe present best estimate

Energy density  $\propto$  Pressure



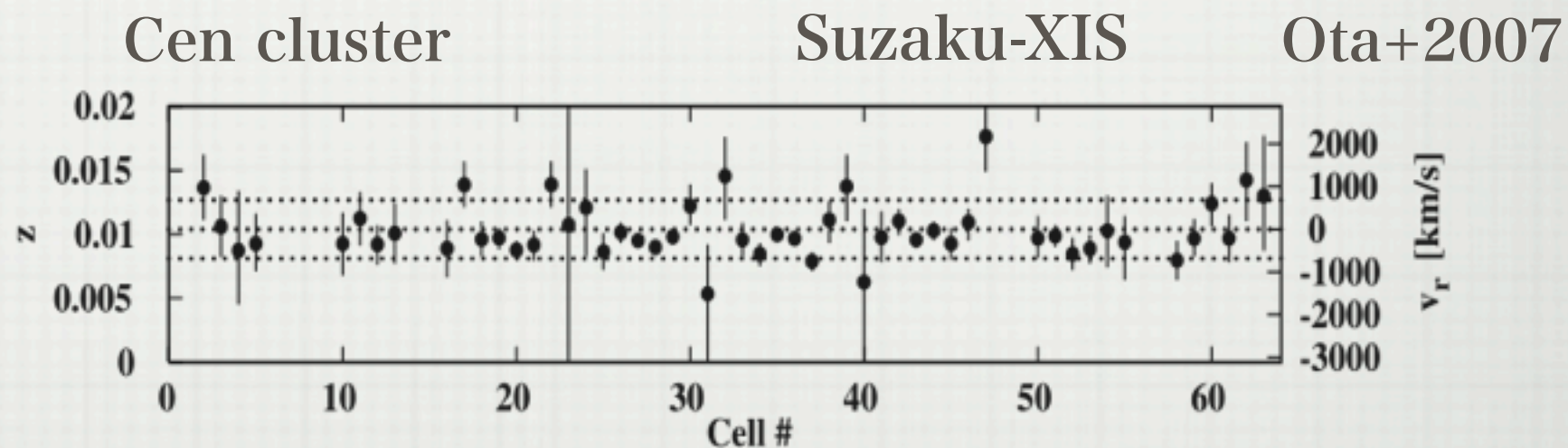
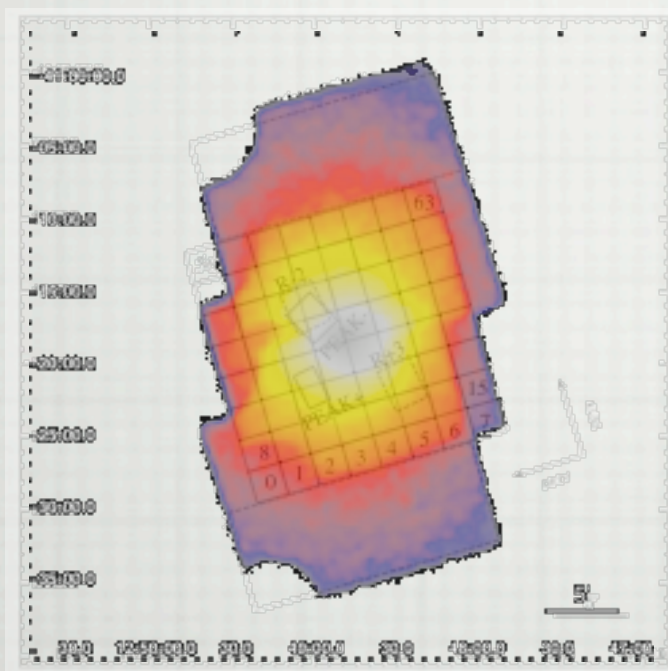
# Energy density estimation (1)

## ICM thermal energy

$$\bar{n} = 500 \rho_{cr} \Omega_b / (m_H \mu) = 1.1 \times 10^{-4} \text{ cm}^{-3}$$

$$kT = 8 \text{ keV}$$

## ICM kinetic energy



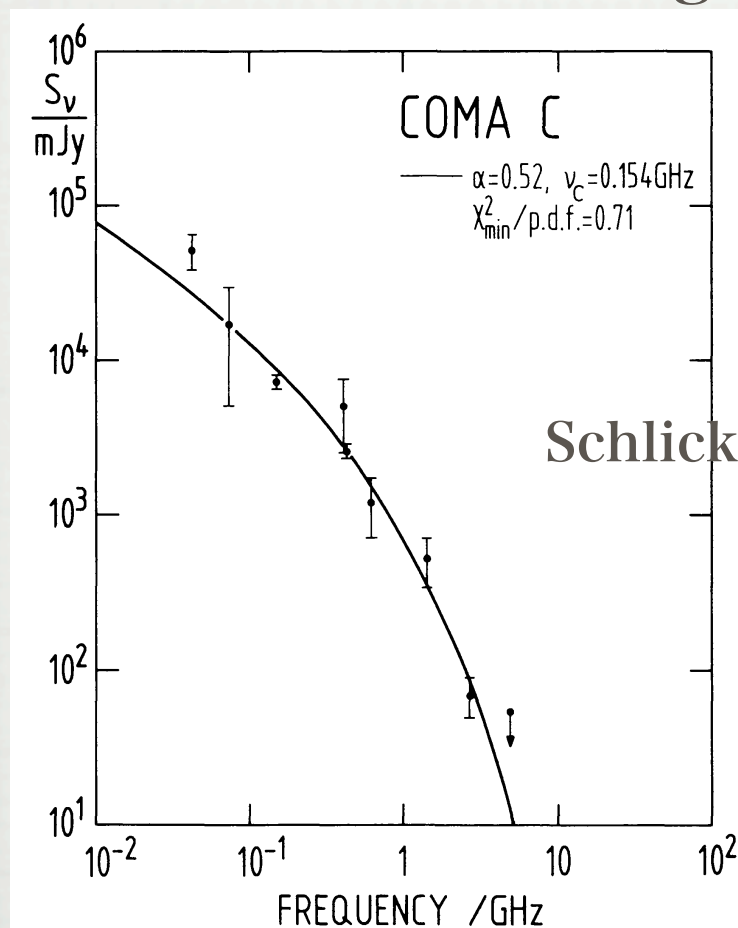
$$\sqrt{v_r^2} < 1300 \text{ km/s}$$

➔  $\sqrt{v_r^2} = 500 \text{ km/s}$  を仮定

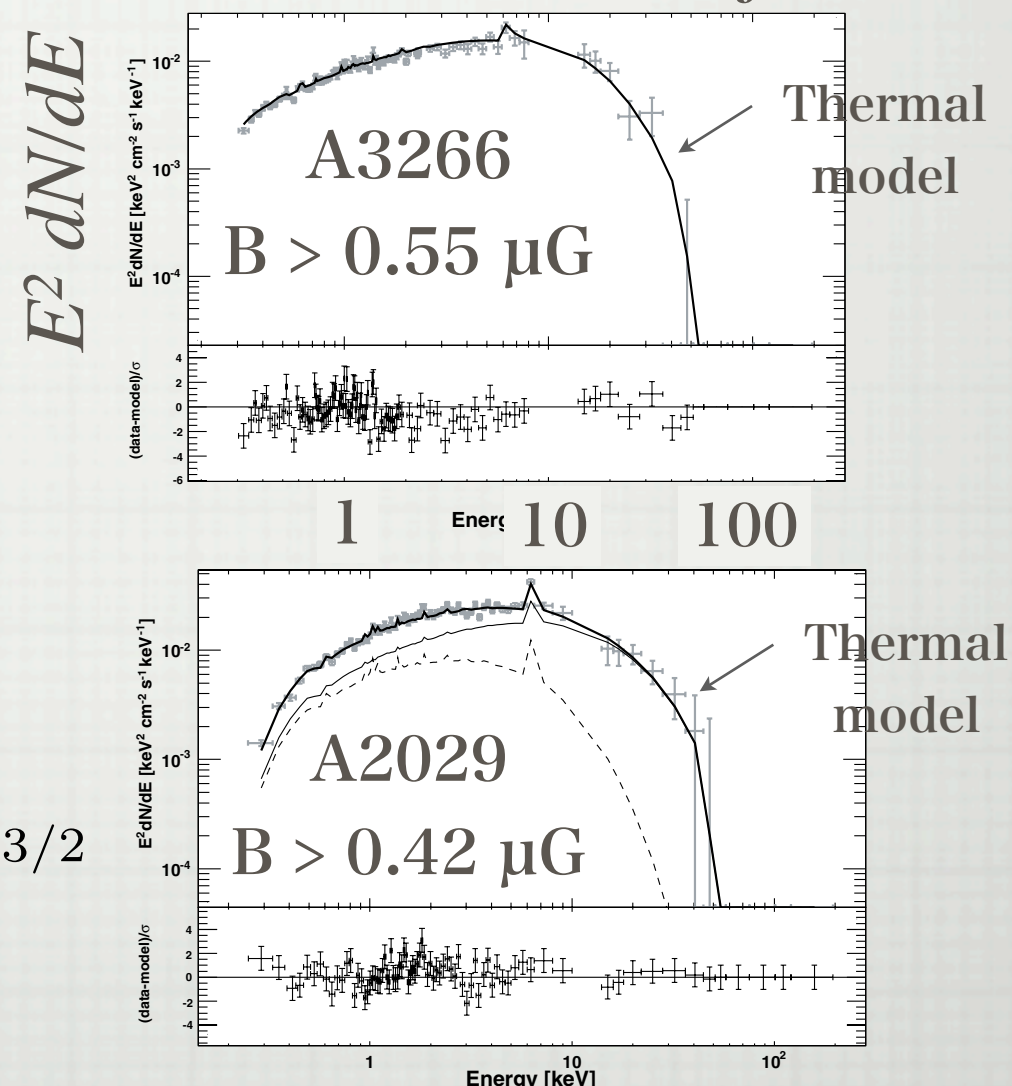


# Energy density estimation (2)

## GeV electrons and magnetic field



Swift-BAT + XMM/Swift-XRT  
Ajello+2009



$$E_e = 8.3 \times 10^{69} \text{ eV} \left( \frac{J_{2.6 \text{ GHz}}}{70 \text{ mJy}} \right) \left( \frac{B}{0.5 \mu\text{gauss}} \right)^{-3/2}$$

( $\nu_0$ に対応するエネルギーの10%以上のエネルギーの電子を積分)

$R = 1 \text{ Mpc}$  を仮定



$B = 0.5 \mu\text{ gauss}$  を仮定



# Energy density estimation (3)

## Cosmic rays

Colafrancesco & Blasi 1998

Diffusion time  $\tau \sim 7 \times 10^{21} \text{ s} \left( \frac{r}{1 \text{ Mpc}} \right)^2 \left( \frac{E}{1 \text{ eV}} \right)^{-1/3} \left( \frac{B}{1 \mu\text{G}} \right)^{1/3}$

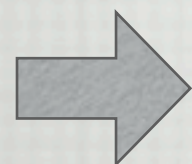
<  $4 \times 10^5 \text{ GeV}$  のproton は宇宙年齢以上閉じ込められる

## CR sources

$$L_{\text{CR}} = L_{\text{galaxy}} + L_{\text{AGN}} + L_{\text{shock}}$$

$\sim 10^{42} \text{ erg/s} \quad \sim 10^{44} \text{ erg/s} \quad \sim 10^{44} \text{ erg/s}$

cluster内でのlossは  $L_{\text{CR}}$  に比べて小さい



$$E_{\text{CR}} \sim L_{\text{CR}} t_{\text{age}} / 2 \sim 1.4 \times 10^{73} \text{ eV}$$



# Energy densities

---

	ICM thermal	ICM kinetic	GeV electrons	Magnetic field	Cosmic rays
eV/cm <sup>3</sup>	1.3	0.30	6.7E-05	6.2E-03	0.11

Crude, but maybe present best estimate

Energy density  $\propto$  Pressure



# Energy densities

	ICM thermal	ICM kinetic	GeV electrons	Magnetic field	Cosmic rays
eV/cm <sup>3</sup>	1.3	0.30	6.7E-05	6.2E-03	0.11

Crude, but maybe present best estimate

Energy density  $\propto$  Pressure



# Energy densities

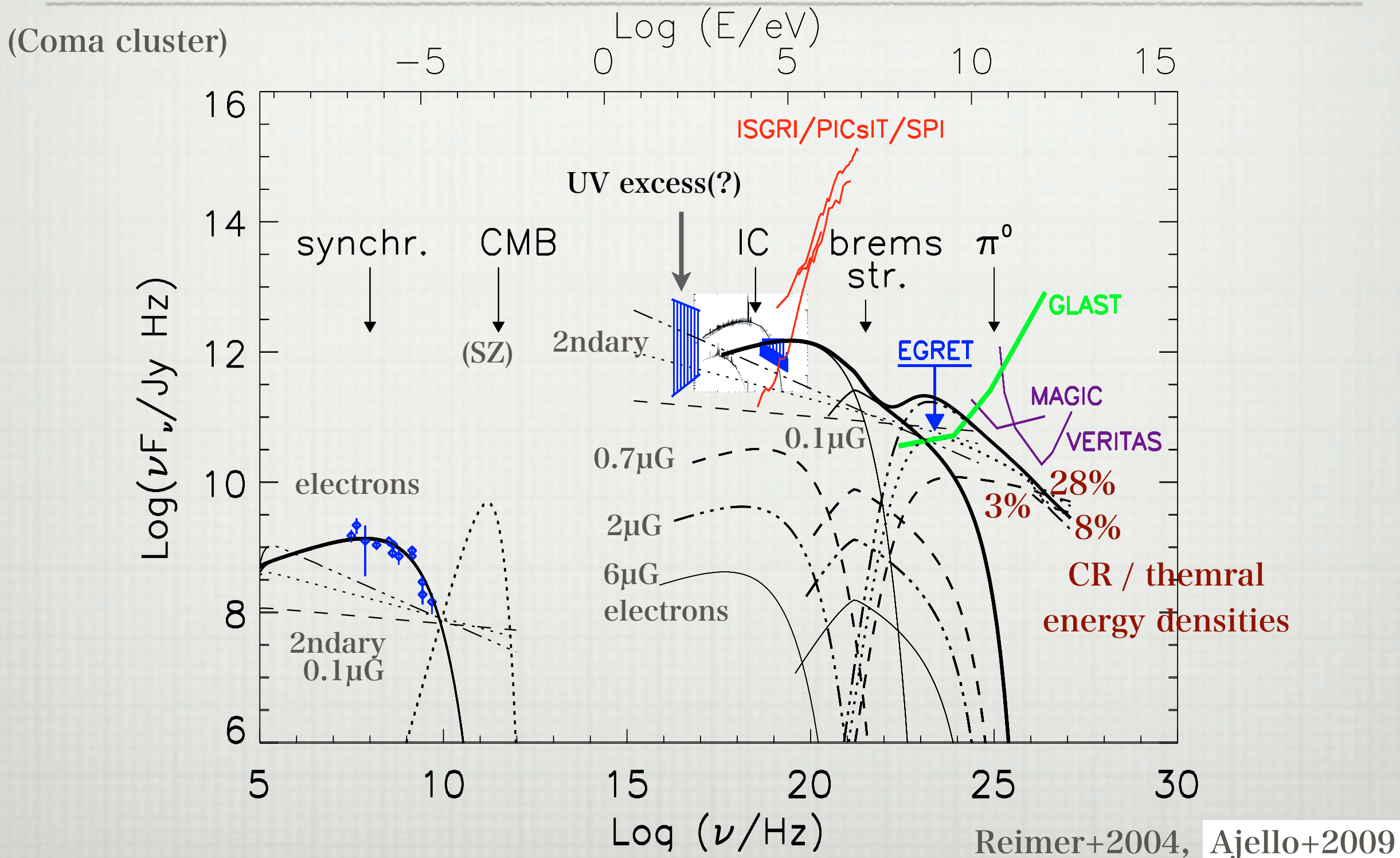
	ICM thermal	ICM kinetic	GeV electrons	Magnetic field	Cosmic rays
eV/cm <sup>3</sup>	1.3	0.30	6.7E-05	6.2E-03	0.11

Crude, but maybe present best estimate

Energy density  $\propto$  Pressure



# Multi-wavelength view of a cluster





# Astro-Hへの期待

New exploration X-ray Telescope

Japanese

## ASTRO-H



### Main features:

**Hard X-ray imaging Spectroscopy (2-80 keV)**

**Soft X-ray high-resolution Spectroscopy (FWHM  $\leq$  7eV)**

### Main objectives:

**Evolution of super massive black holes**

**Evolution of clusters of galaxies**

**Accelerations in clusters and SNRs**

**Vicinity of black holes**



# Astro-Hへの期待

- Kinetic energy of ICM
  - Direct measurement by SXS ( $\mu$  calorimeter)
- Cosmic ray
  - A window in EUV to soft X-ray
  - Soft X-ray excessはあるのか、ないのか？
  - Emission lines (WHIM)なのか、continuum (IC of CR secondary  $e^+e^-$ ) なのか？
  - Combined analysis with Fermi
- Magnetic field
  - Hard X-ray excess by HXI

$\mu$  calorimeterの分解能と  
< 0.3 keVの感度が重要

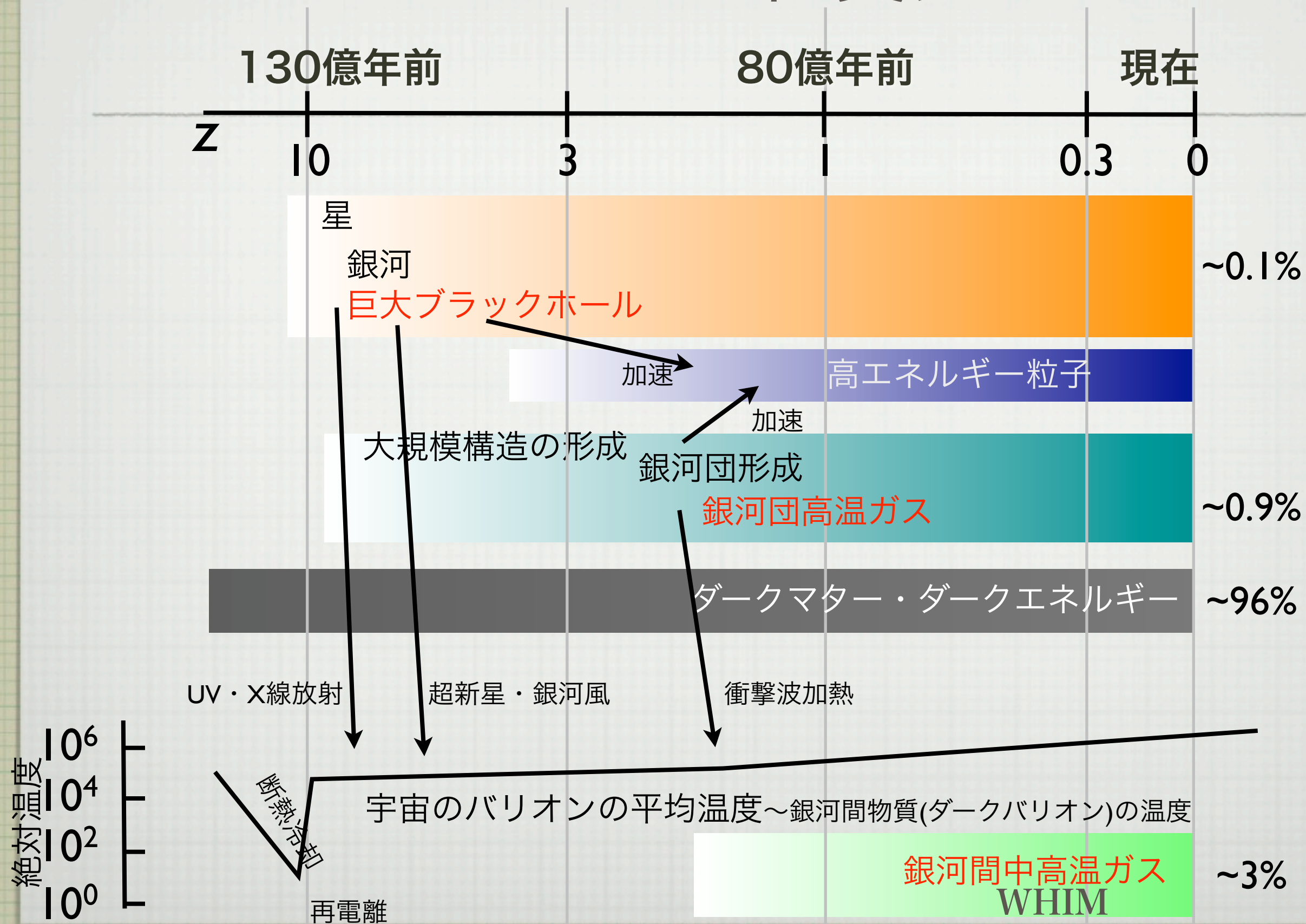


銀河団 Energy budget の理解

宇宙の大構造進化とバリオン物質史の理解へ

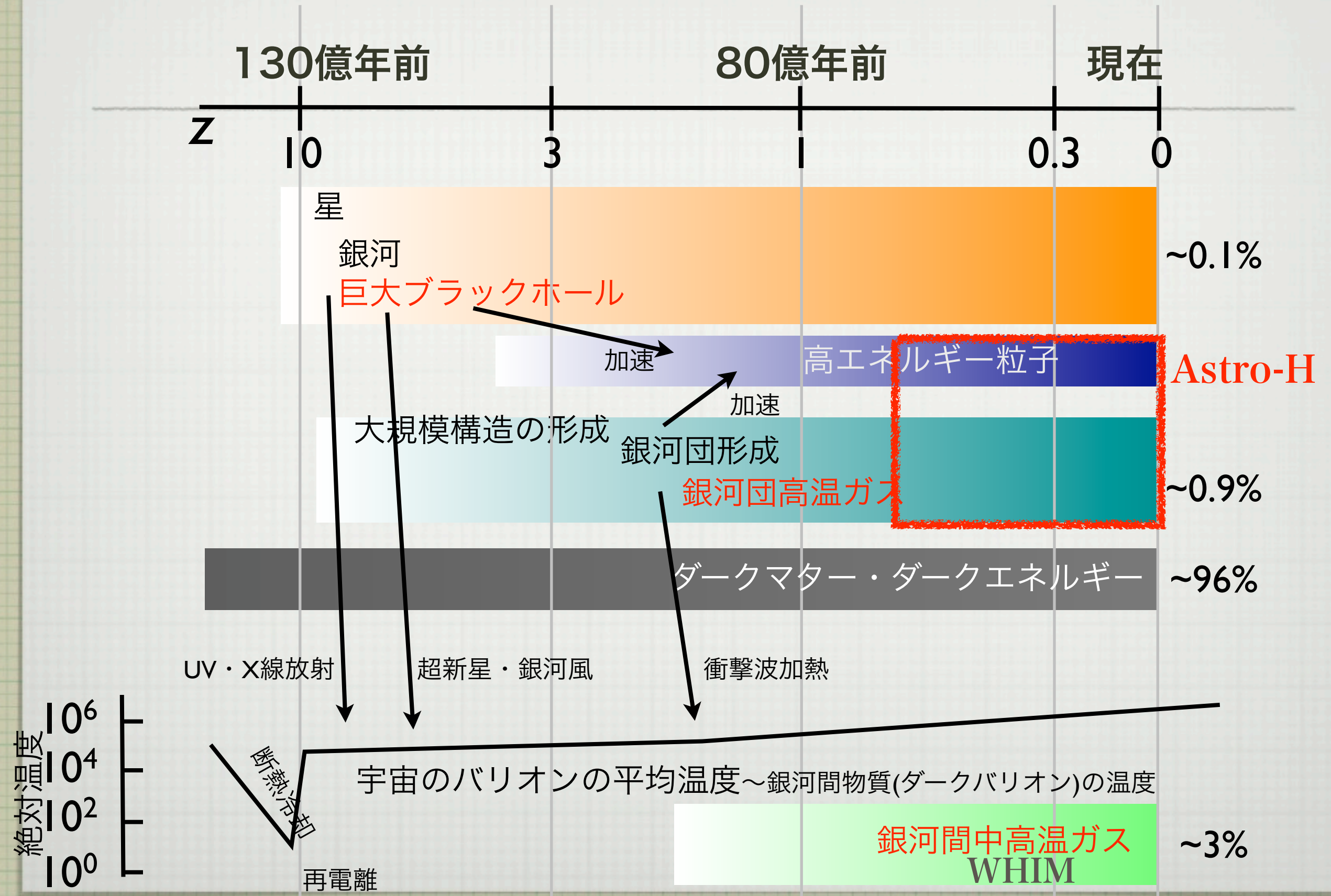


# バリオン物質史



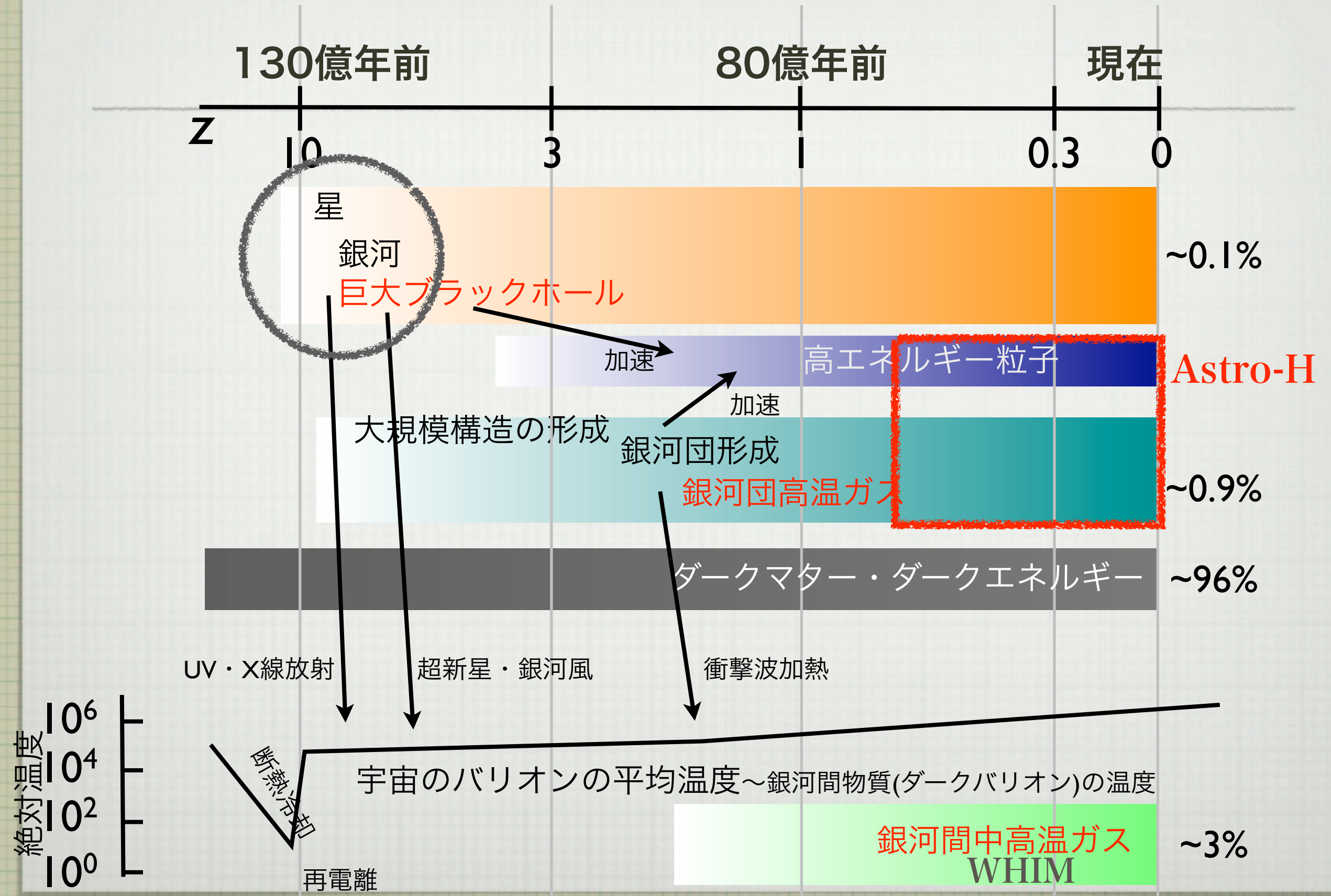


# バリオン物質史



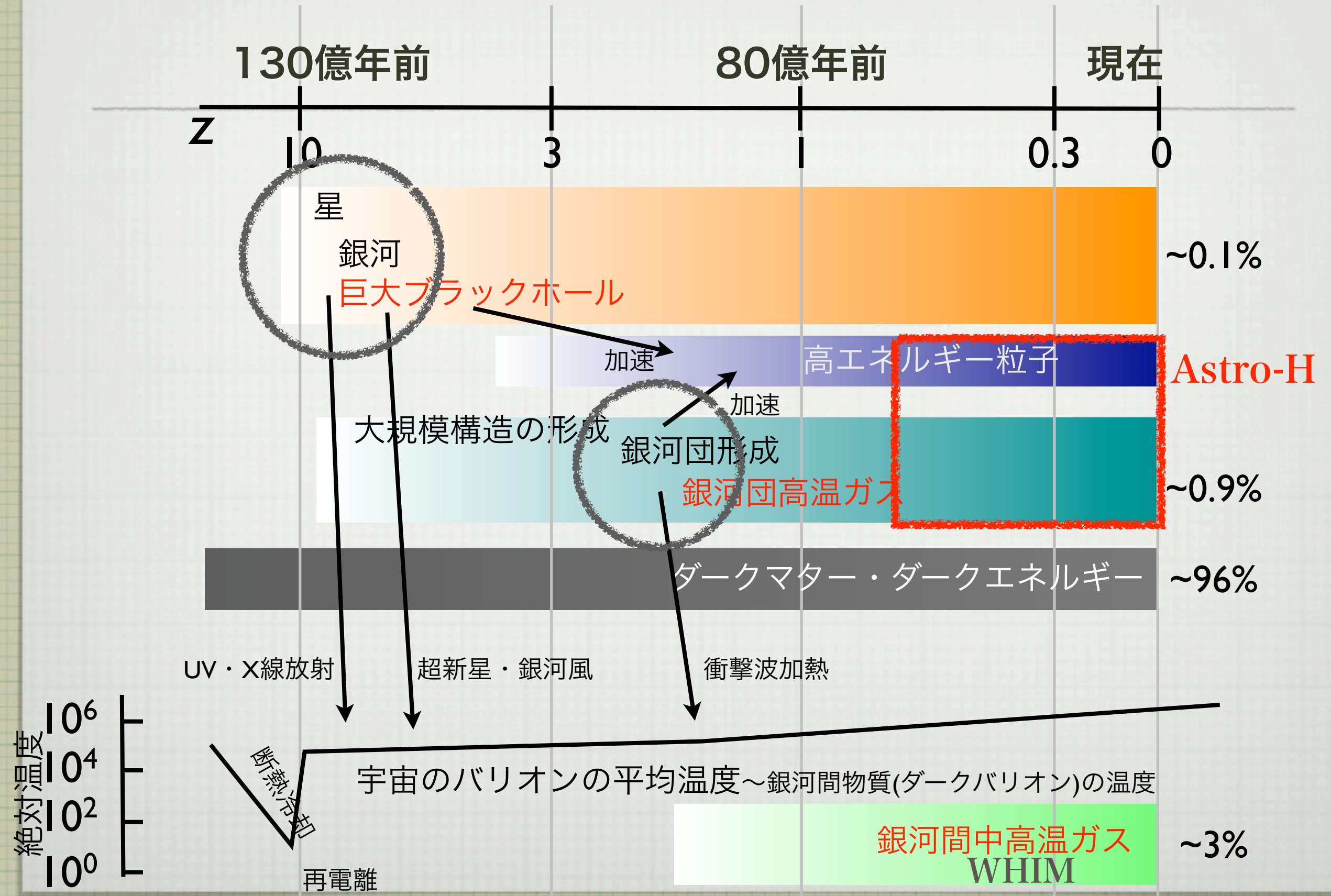


# バリオン物質史



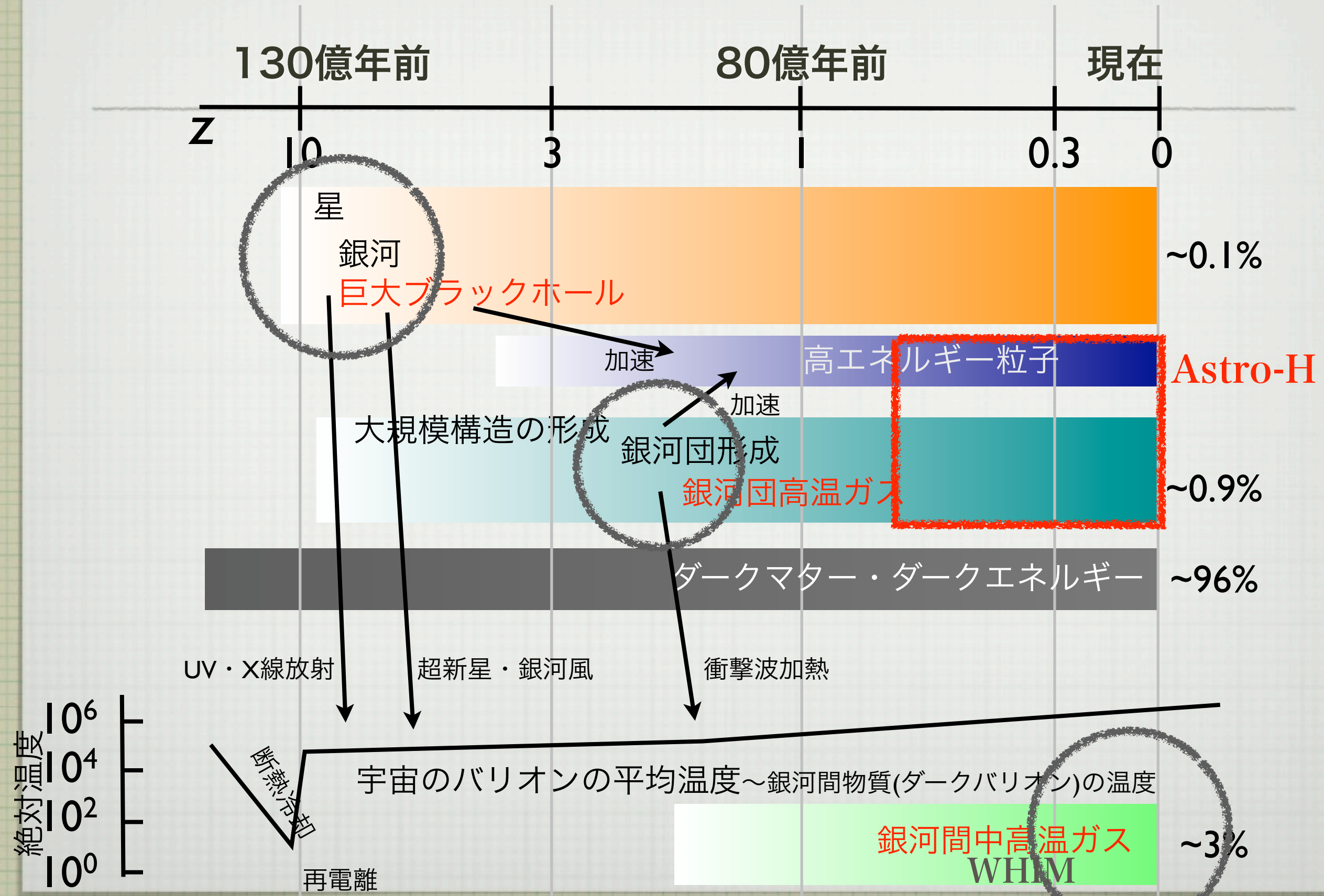


# バリオン物質史



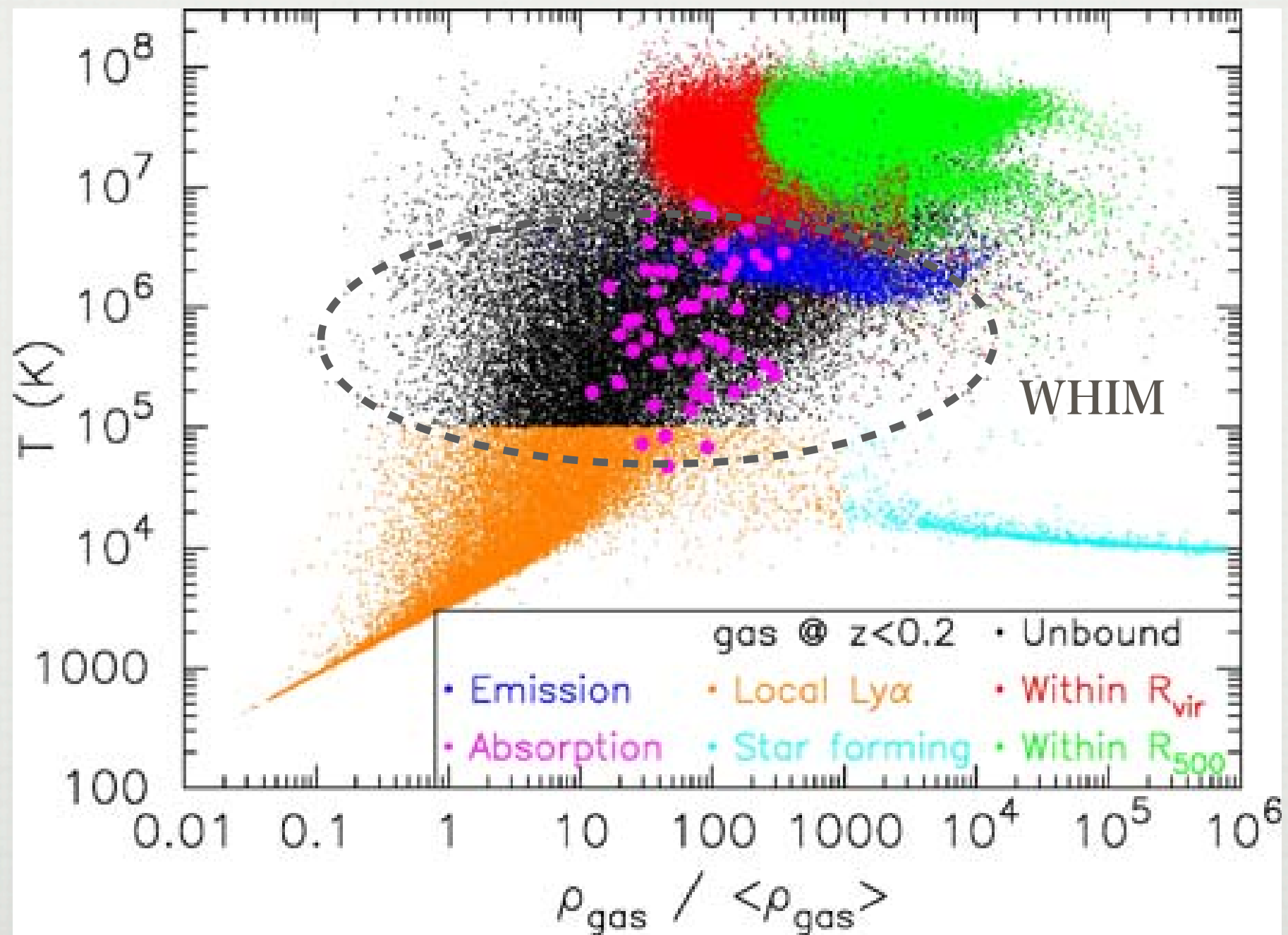


# バリオン物質史





# Baryonic matter in present universe



Piro+ 2009 (simulation by Branchini)



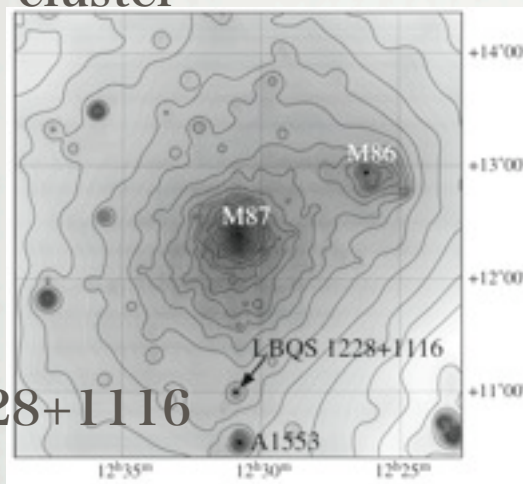
# WHIMの尻尾

Searches for IGM at a known  $z > 0$  with  $T > 10^6\text{K}$

Absorption

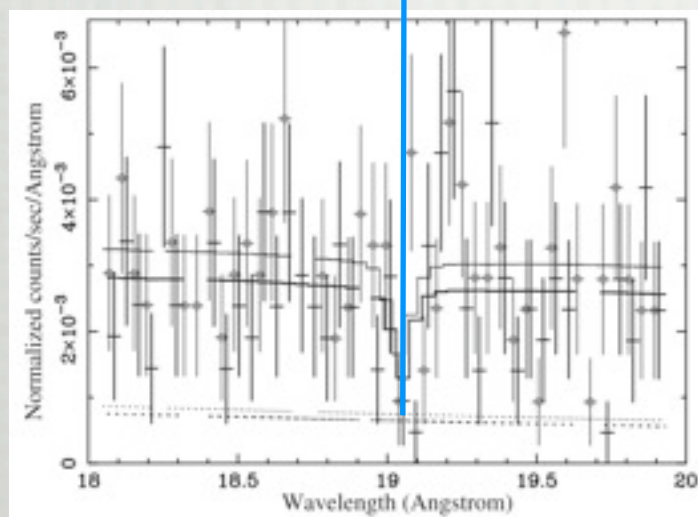
Emission

Virgo cluster



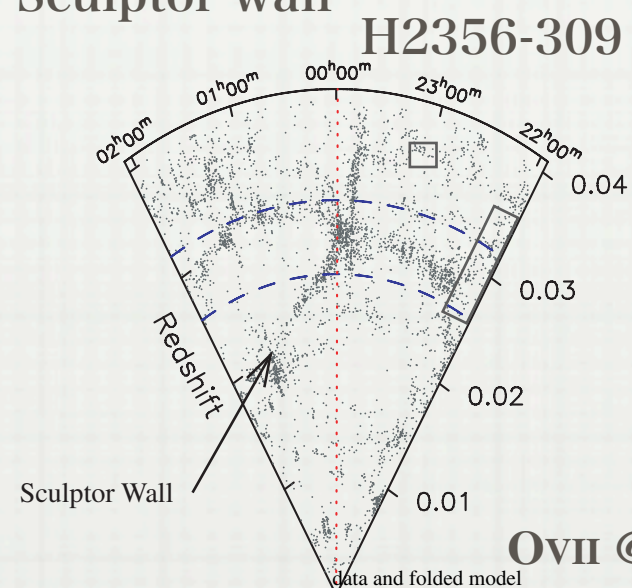
LBQS1228+1116

O VII @  $z = 0.004$

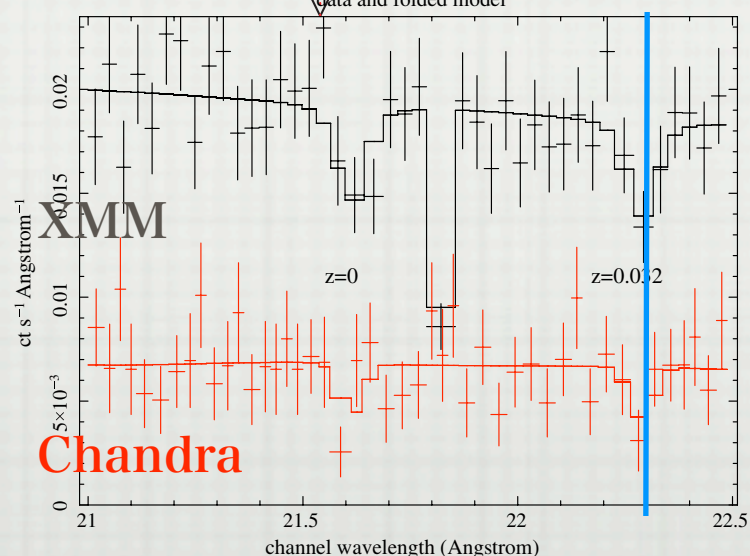


2.8- $\sigma$  with XMM  
Fujimoto+2004

Sculptor wall

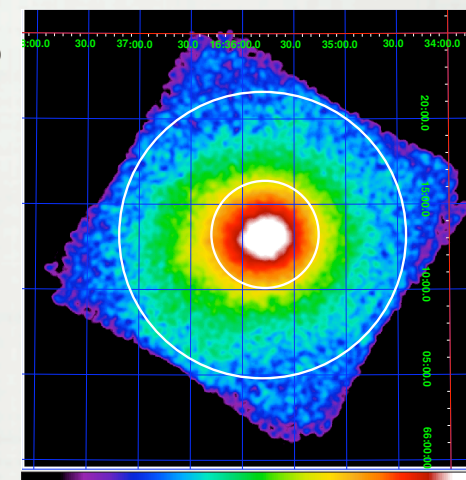


O VII @  $z = 0.032$

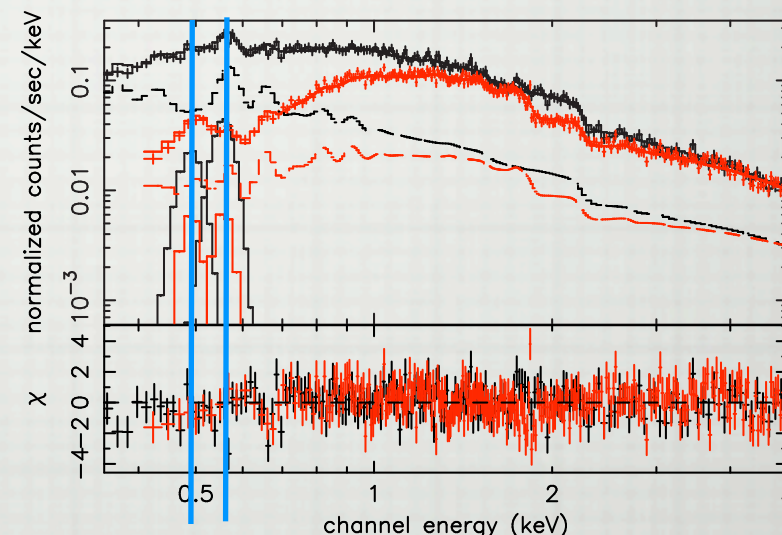


3- $\sigma$  with XMM + chandra  
Buote+2009

A2218



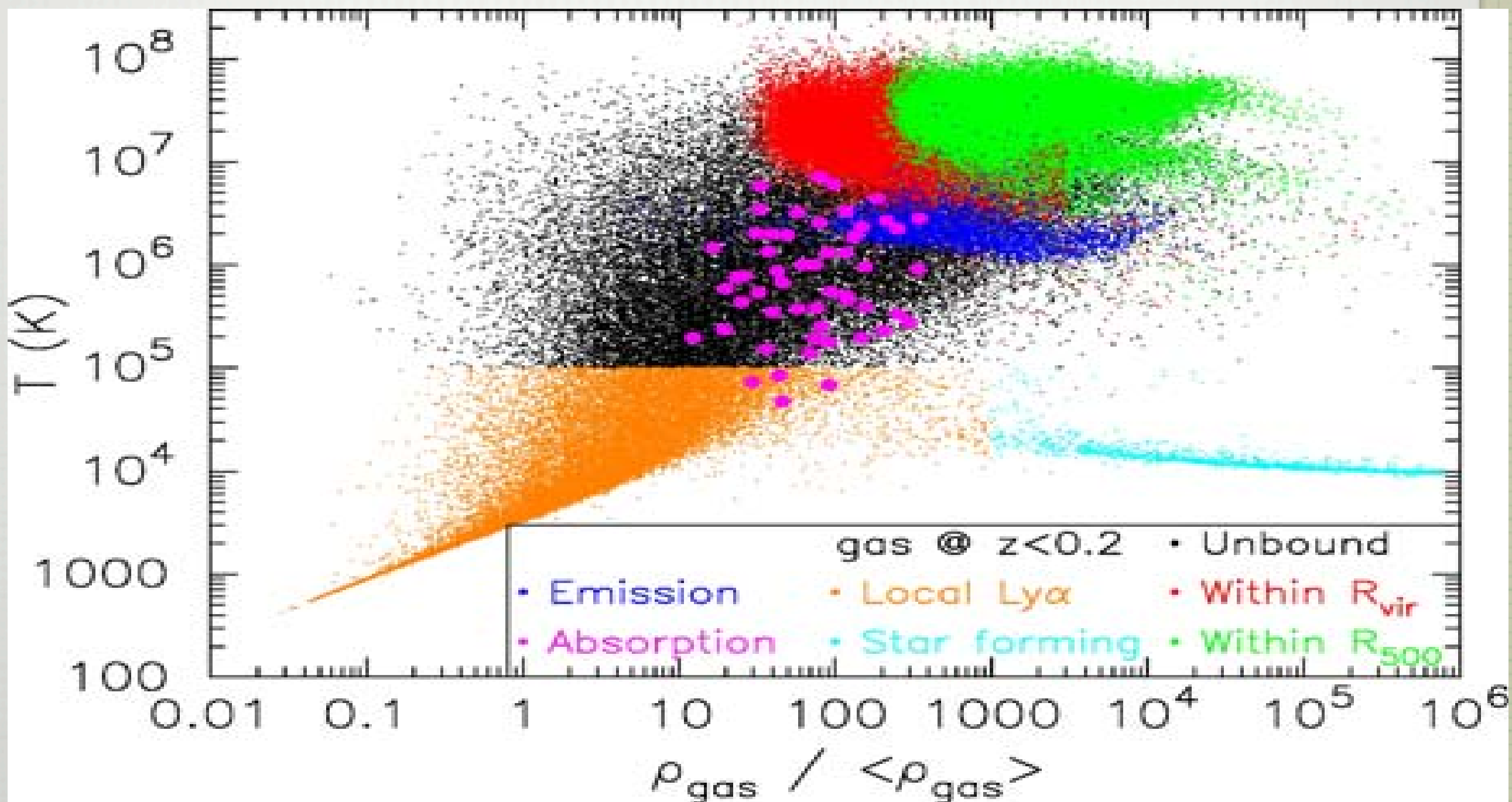
O VII & O VIII @  $z = 0.18$



Suzaku upper limit  
Takei+ 2007

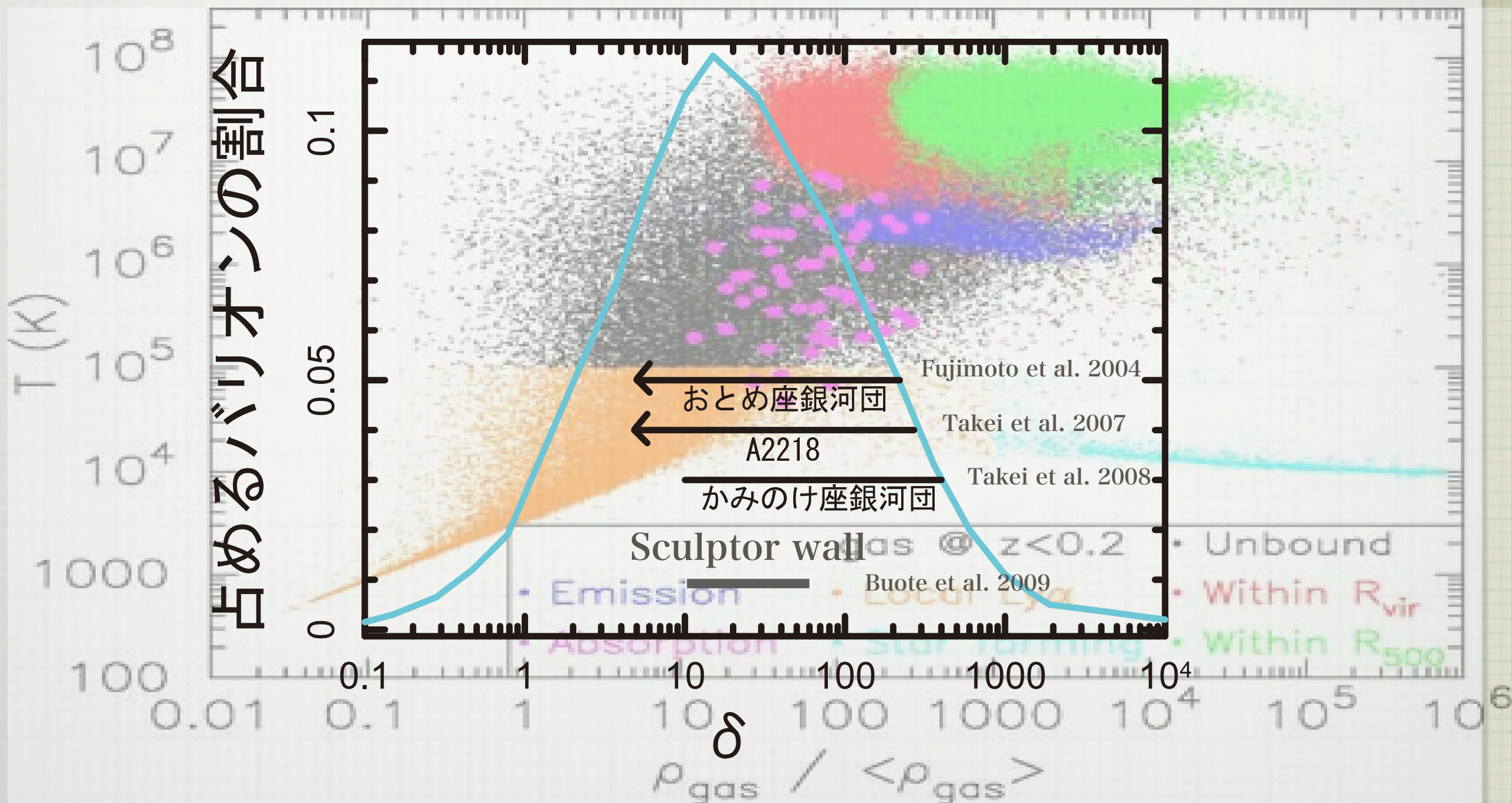


# WHIMの密度



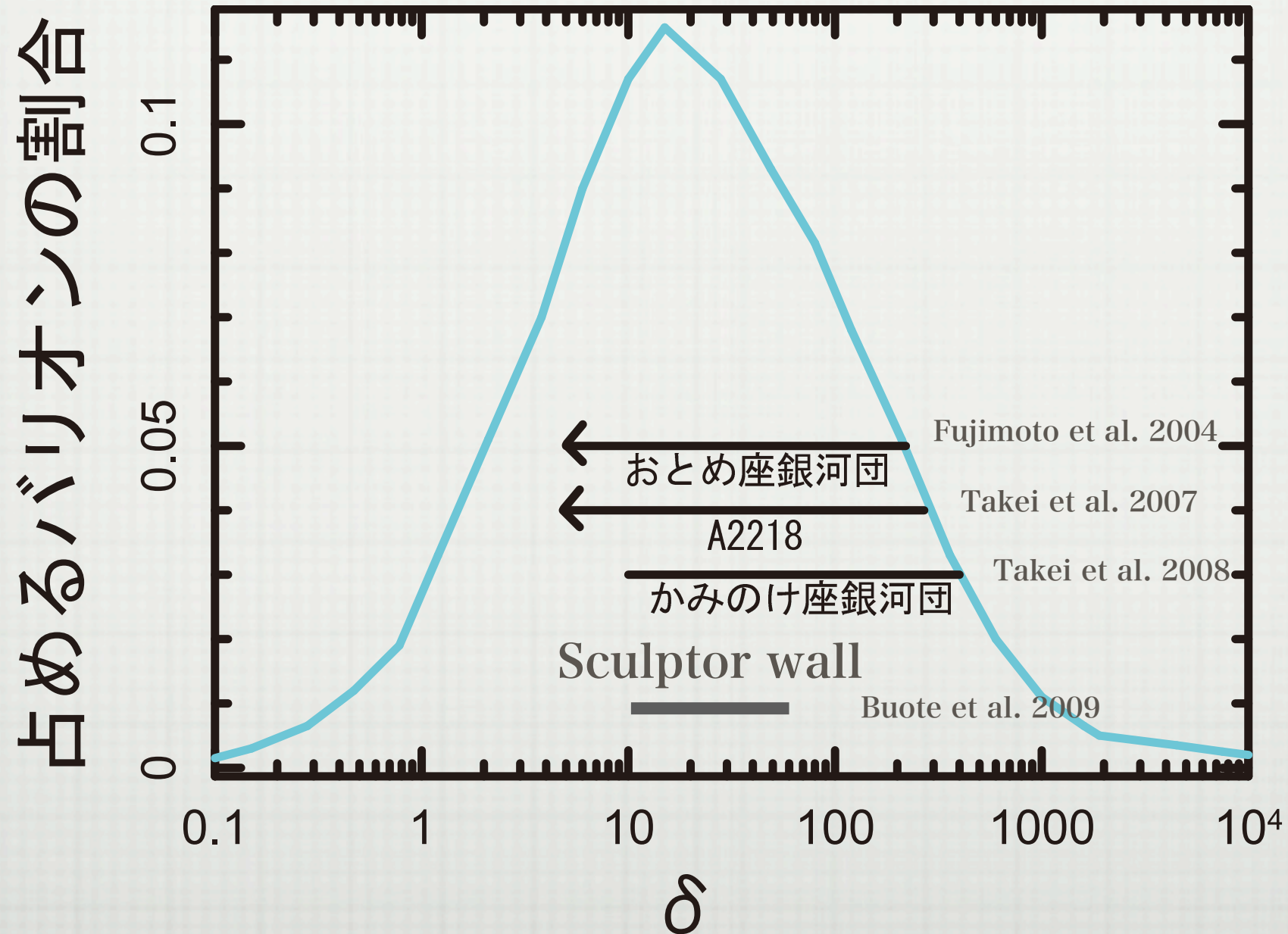


# WHIMの密度





# WHIMの密度





# Future high-resolution spectroscopy

## DIOS

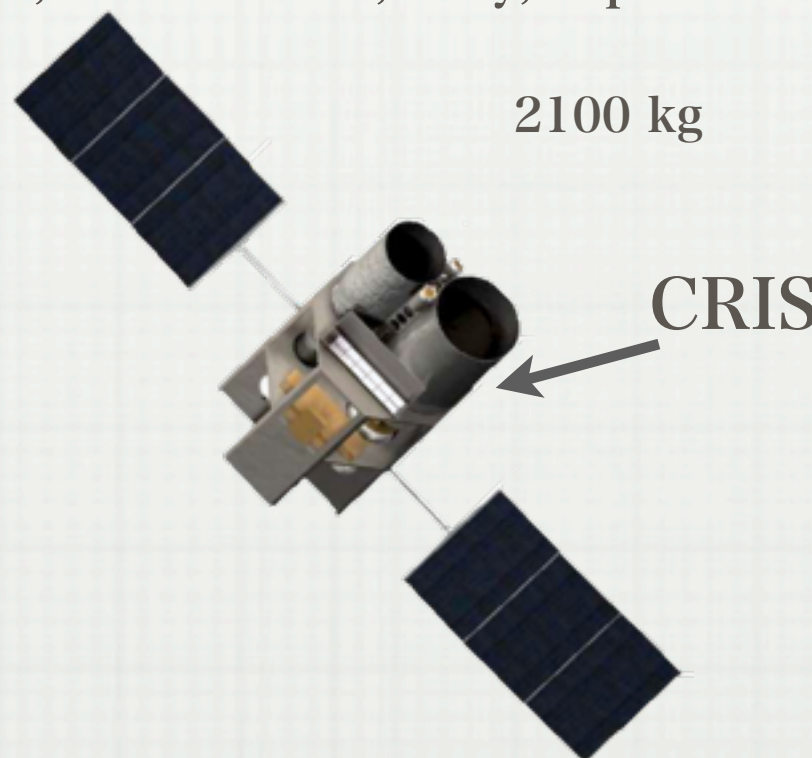
Japan



400 kg

## Xenia

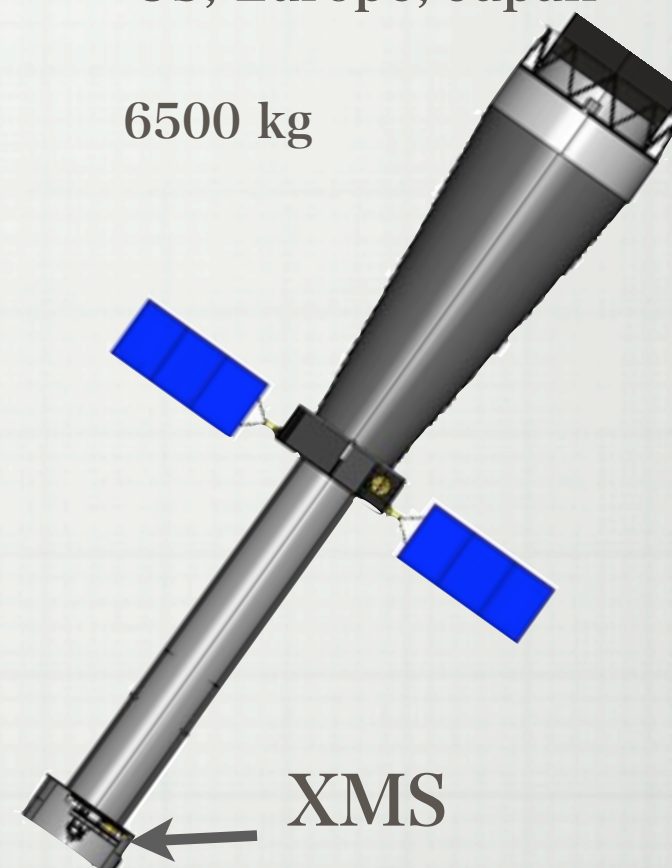
US, Netherlands, Italy, Japan



2100 kg

## IXO

US, Europe, Japan

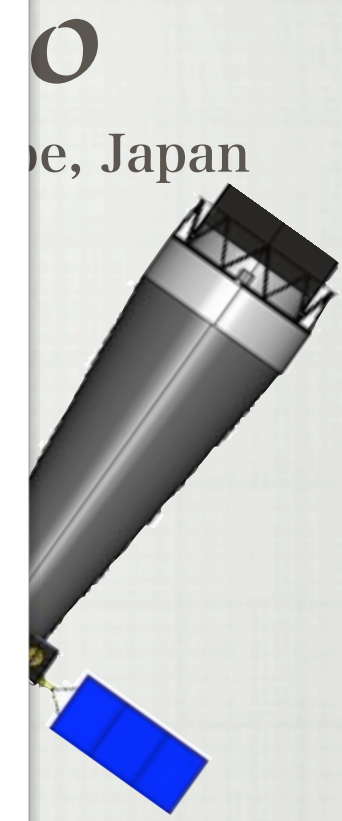
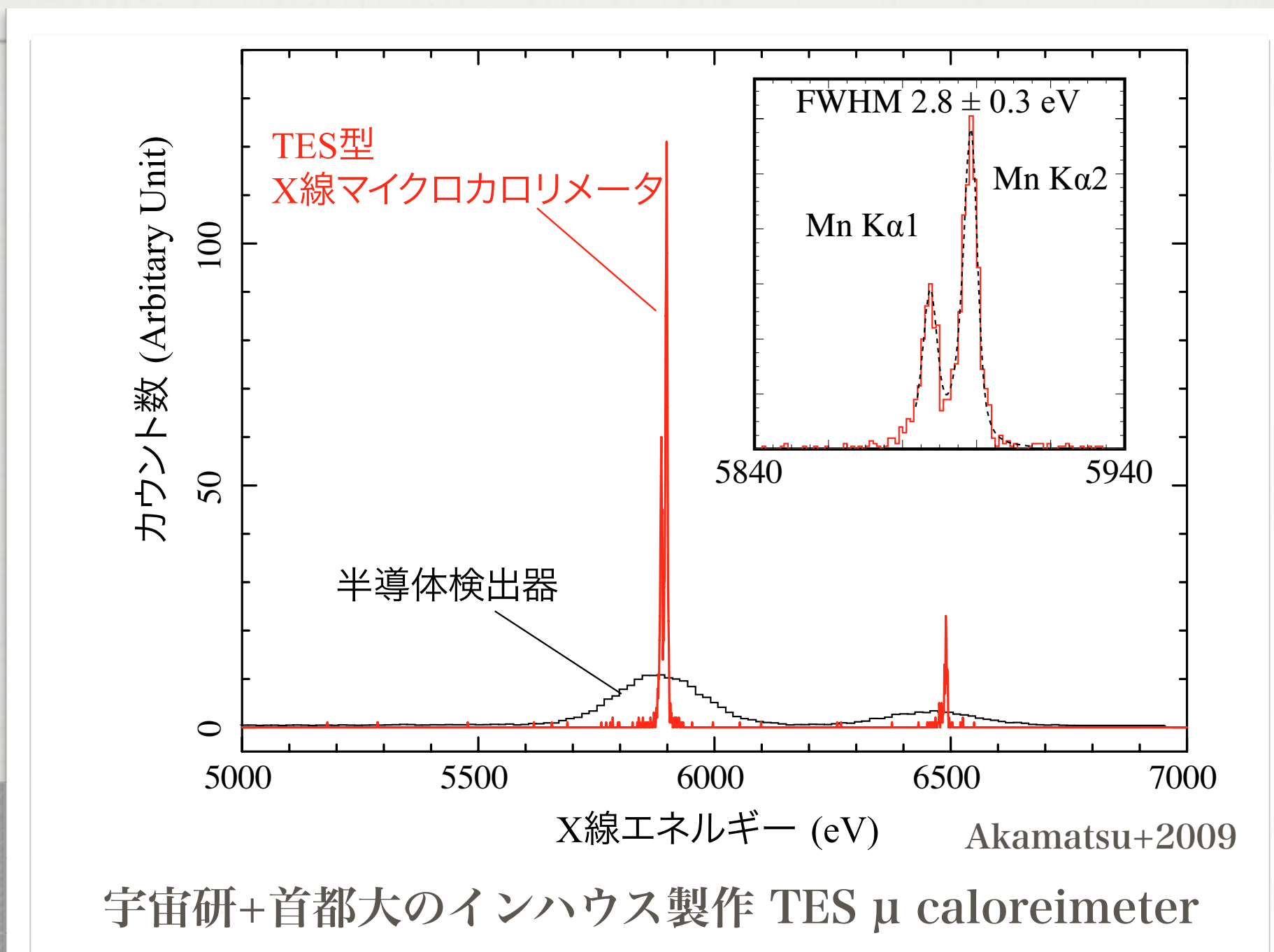


6500 kg

Mirrors	four reflection	four reflection	Si pore / slumped glass
	200 cm <sup>2</sup>	1300 cm <sup>2</sup>	3 m <sup>2</sup>
Detector	TES $\mu$ calorimeter	TES $\mu$ calorimeter	TES $\mu$ calorimeter
	2eV, $\geq 16 \times 16$	2.5 eV, $\geq 32 \times 32$	2.5eV, 40x40 + 18x18x4



# Future high-resolution spectroscopy



Mirrors

Detector

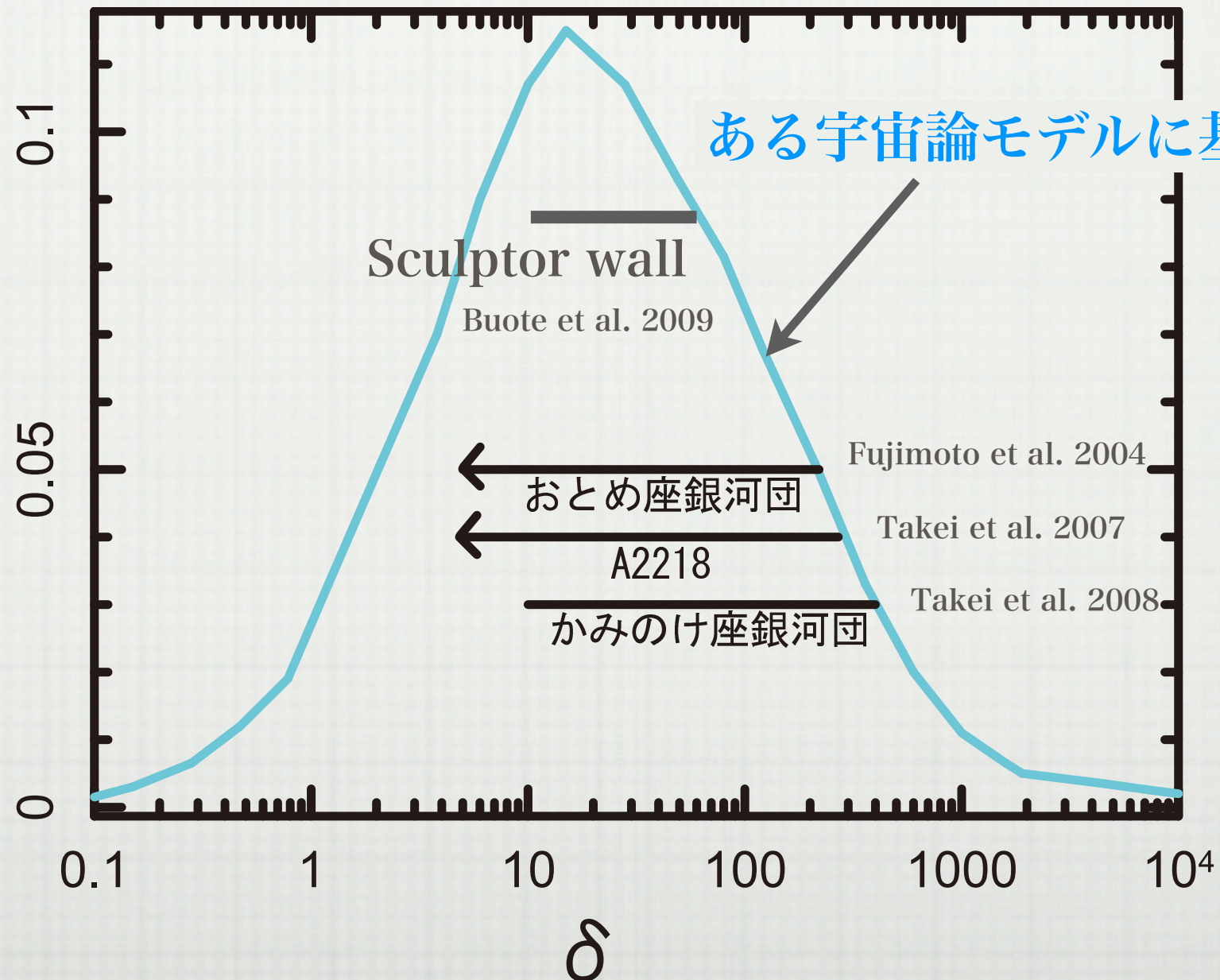
TES $\mu$ calorimeter	TES $\mu$ calorimeter	TES $\mu$ calorimeter
2eV, $\geq 16 \times 16$	2.5 eV, $\geq 32 \times 32$	2.5eV, $40 \times 40 + 18 \times 18 \times 4$



# バリオン物質の密度分布

銀河団質量関数の低密度側への拡張

占めるバリオンの割合

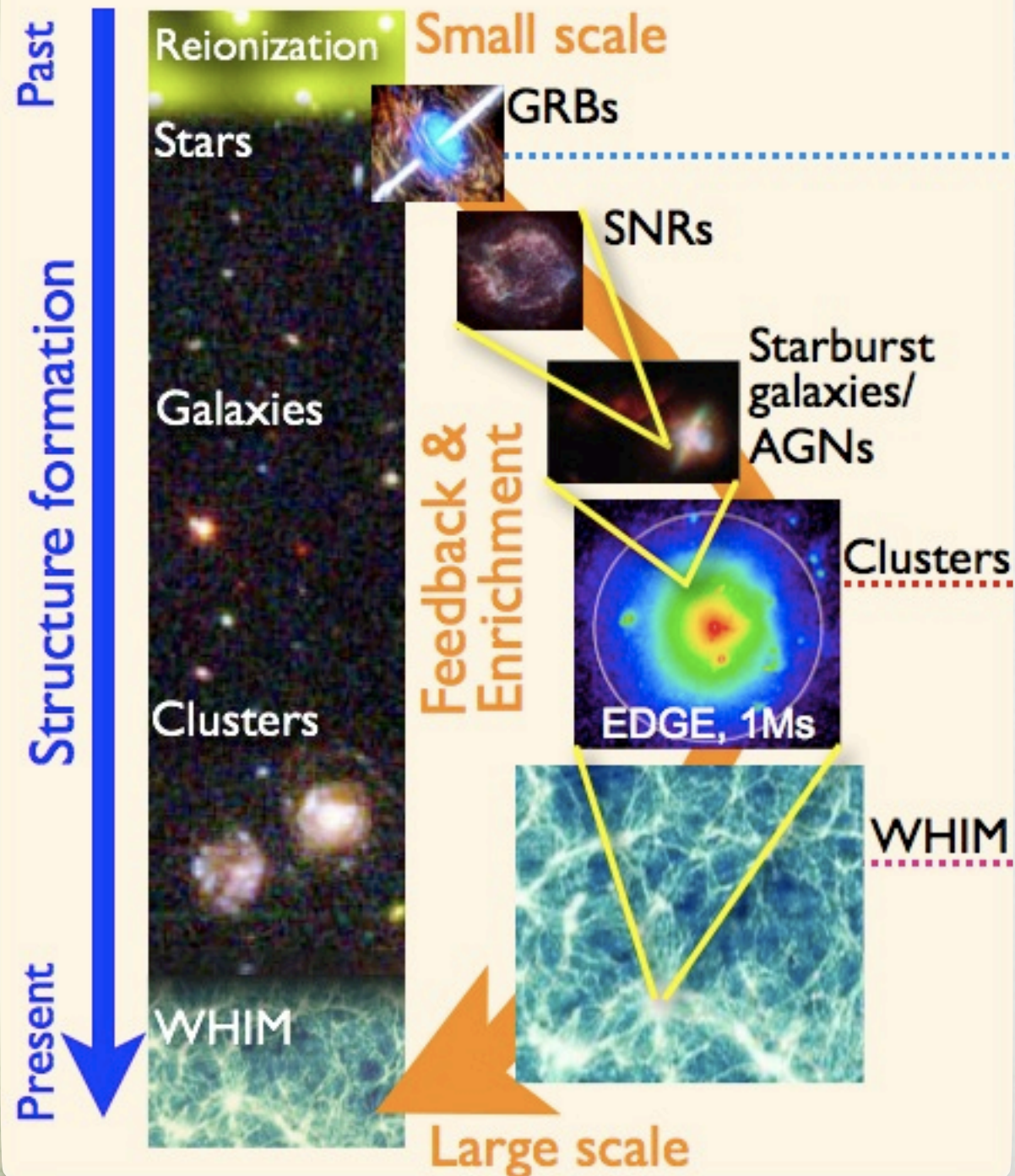


Takei 2007 より (Sculptor を除く)

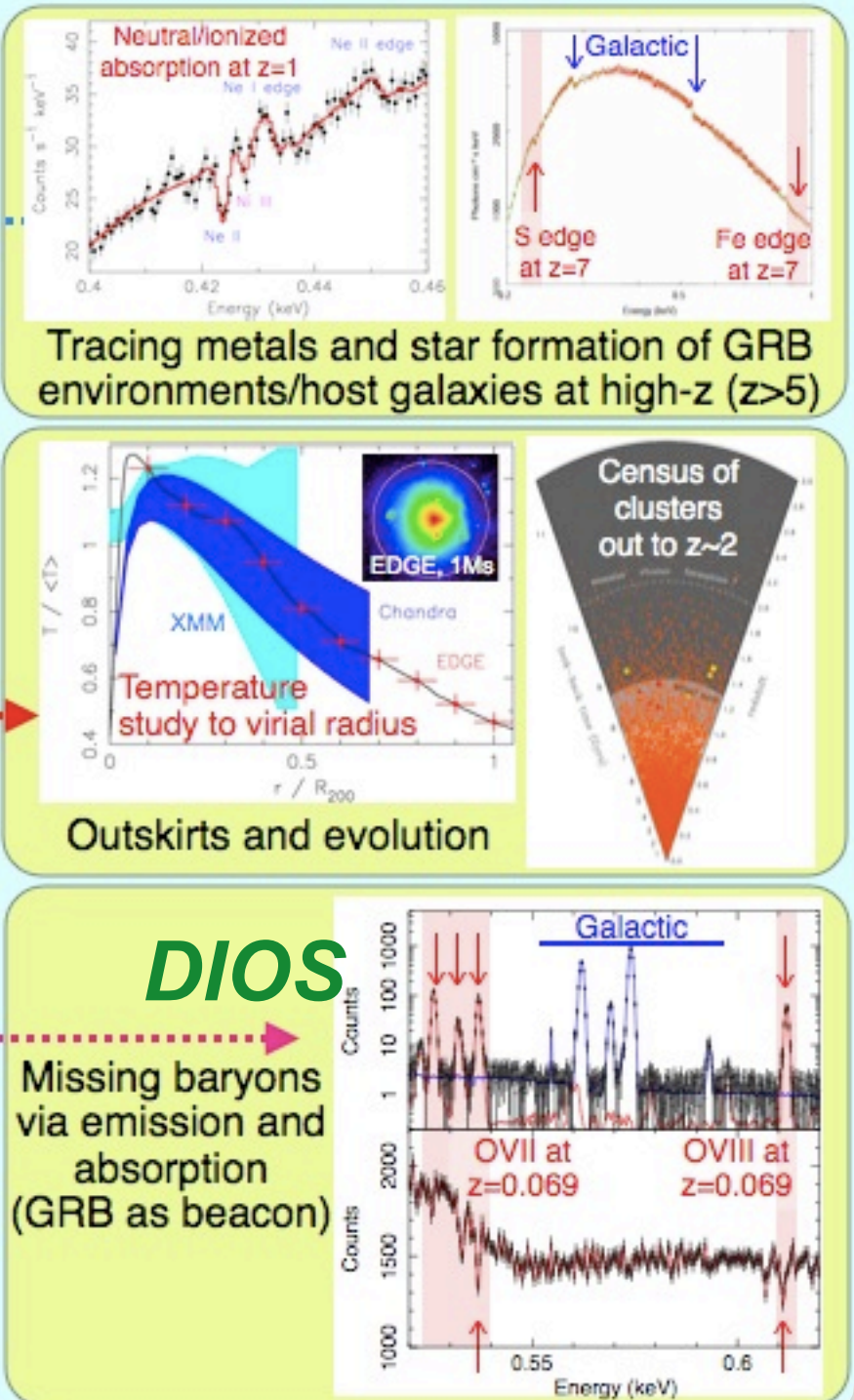


# From dark age to present

## Evolution of the Universe



## EDGE/Xenia



最初の天体形成時期の環境

構造形成と星・銀河からのfeedback

現在の宇宙3D構造

暗黒時代直後から現在に至る高エネルギー宇宙史、暗黒エネルギー



# まとめ

---

- 過去から現在
  - X線天文学がもたらした3つの驚き
    - 質量降着をエネルギー源とする天体
    - バリオン物質の多数を占める高温物質
    - ほとんど全ての天体がX線源
- 現在から未来
  - 動物学と基礎科学
    - 天文学による基礎科学のためには、動物学が必須
  - 宇宙最大の高エネルギー実験室
    - 銀河団：バリオン物質のzoo
  - その向こう側と手前側：Dark age から現在
    - 最初の天体形成期の環境、現在の宇宙の3D地図