# Science results from Hitomi

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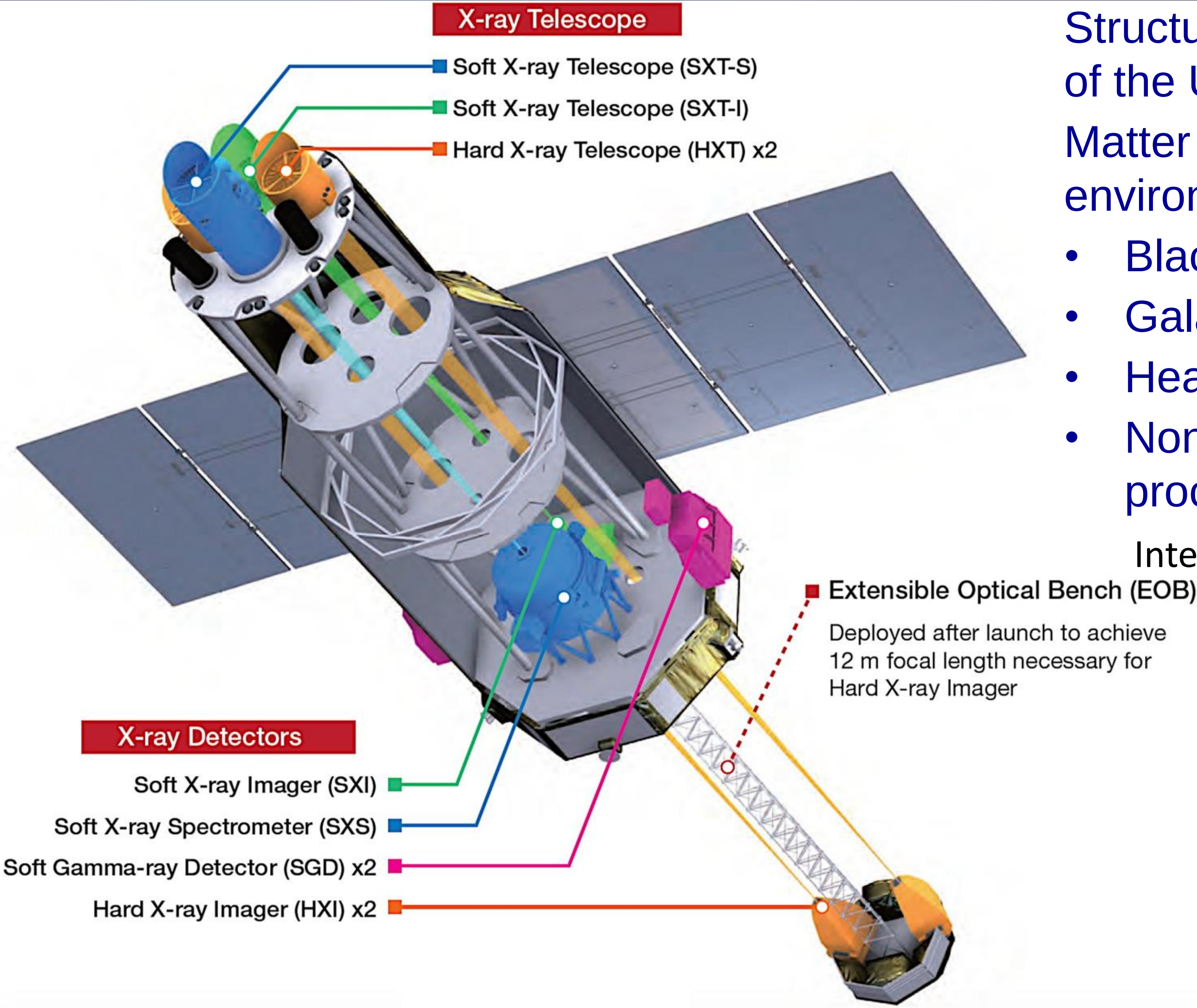
# *Hitomi* – “Eye” to the Universe




Structure and evolution of the Universe

Matter in extreme environments

- Black holes
- Galaxies
- Heavy elements
- Non-thermal processes

International collaboration

| |
|---|
| **NASA**<br>Micro Calorimeter Array/ADR<br>Two soft X-ray Telescopes<br>Eight Science Advisors<br>Pipeline Analysis |
| **SRON & U. of Geneva**<br>Filter Wheel/MXS for SXS<br>**CEA/DSM/IRFU**<br>Contribution to BGO Shield/ASIC test<br>**ESA**<br>Three Science Advisors<br>Contribution to mission instruments (SXS/HXI/SGD/HXT)<br>User support in Europe |
| **CSA**<br>Metrology System |

# Launch on February 17, 17:45 JST, 2016


Orbital parameters

| | Result | Planned |
|---|---|---|
| Apogee (km) | 576.52 | (575.00) |
| Perigee (km) | 574.42 | (575.00) |
| Inclination (˚) | 31.00 | (31.00) |

# Science papers (I)

| Target | Title | |
|---|---|---|
| Perseus | The quiescent intracluster medium in the core of the Perseus cluster | Nature 2016 |
| Perseus | Hitomi Constraints on the 3.5 keV Line in the Perseus Galaxy Cluster | ApJ Lett 2017 |
| Perseus | Solar abundance ratios of the iron-peak elements in the Perseus cluster | Nature 2017 |
| Perseus | Atmospheric gas dynamics in the Perseus cluster observed with Hitomi | PASJ 2018 |
| Perseus | Measurements of resonant scattering in the Perseus Cluster core with Hitomi SXS | PASJ 2018 |
| Perseus | Temperature structure in the Perseus cluster core observed with Hitomi | PASJ 2018 |
| Perseus | Atomic data and spectral modeling constraints from high-resolution X-ray observations of the Perseus cluster with Hitomi | PASJ 2018 |
| Perseus | Hitomi observation of radio galaxy NGC 1275: the first X-ray microcalorimeter spectroscopy of Fe-K$\alpha$ line emission from an active galactic nucleus | PASJ 2018 |

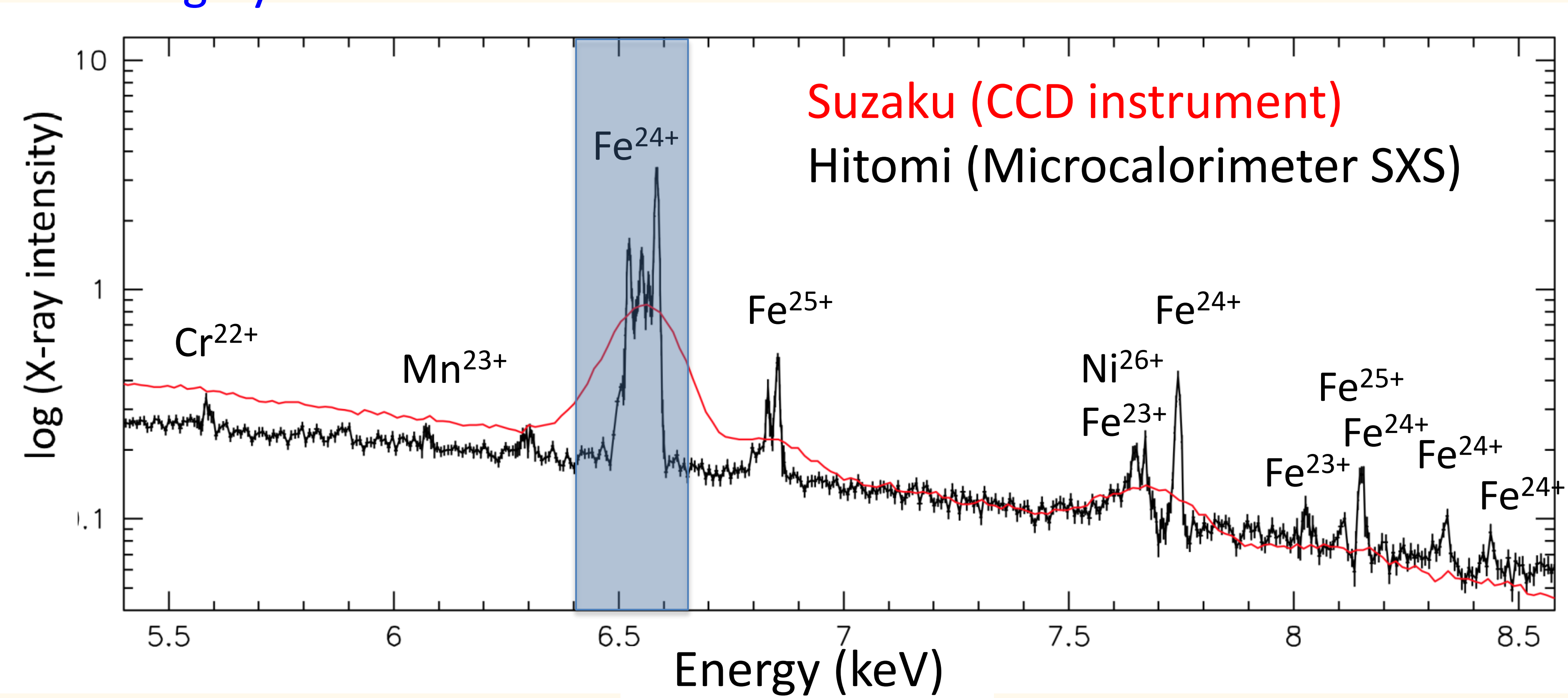
# Science papers (II)

| Target | Title | |
|---|---|---|
| N132D | Hitomi observations of the LMC SNR N132D: highly redshifted X-ray emission from iron ejecta | PASJ 2018 |
| G21.5-0.9 | Hitomi X-ray observation of the pulsar wind nebula G21.5-0.9 | PASJ 2018 |
| IGR J 16318-4848 | Glimpse of the highly obscured HMXB IGR J16318-4848 with Hitomi | PASJ 2018 |
| Crab | Search for thermal X-ray features from the Crab nebula with Hitomi soft X-ray spectrometer | PASJ 2018 |
| Crab | Hitomi X-ray studies of giant radio pulses from the Crab pulsar | PASJ 2018 |
| Crab | Detection of polarized gamma-ray emission from the Crab nebula with Hitomi Soft Gamma-ray Detector | PASJ submit |
| Perseus | Constraints on the Chemical Enrichment History of the Perseus Cluster of Galaxies from High-Resolution X-ray Spectroscopy | MN submit |
| Perseus | An X-ray spectroscopic search for dark matter and unidentified line signatures in the Perseus cluster with Hitomi | PASJ submit |

Hitomi papers in PASJ special issue are open access till September 30

# Energy spectrum of the Perseus cluster

Thermal emission from a plasma of $4 \times 10^7$ K ⇒ Lines from highly ionized ions



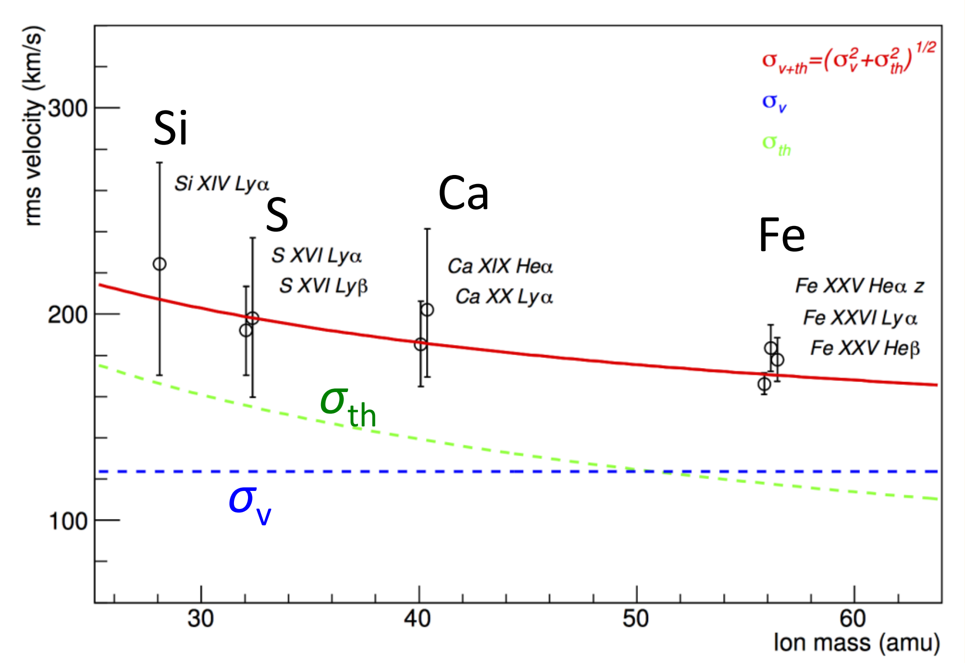

Energy resolution of < 5 eV enables gas velocity measurement at ∼10 km/s accuracy.

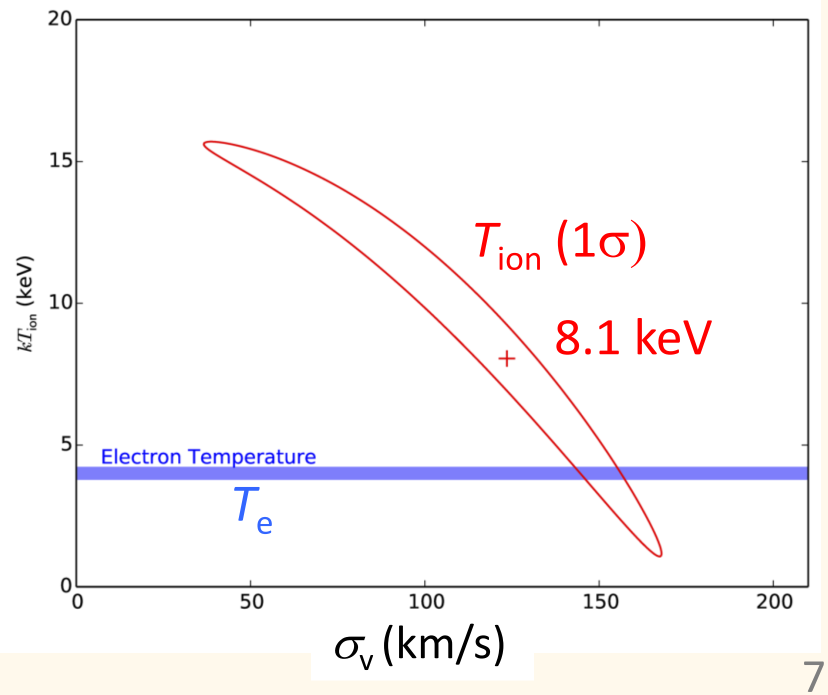
# Constraint on ion temperature

- Ion temperature is estimated from systematic variation of line width for different elements

$$s^2 = s_v^2 + s_{\mathrm{th}}^2;\quad s_{\mathrm{th}}^2 = kT_{\mathrm{ion}} / m_{\mathrm{ion}}$$

- Line width is obtained by fitting with continuum + gaussians
- $\sigma_v$ = 123+31-45 km/s, $kT_{\mathrm{ion}}$ = 8.1+5.0-4.7 keV – large error
- $T_{\mathrm{ion}}$ is consistent with $T_e$ (4.0 keV) from the continuum spectrum



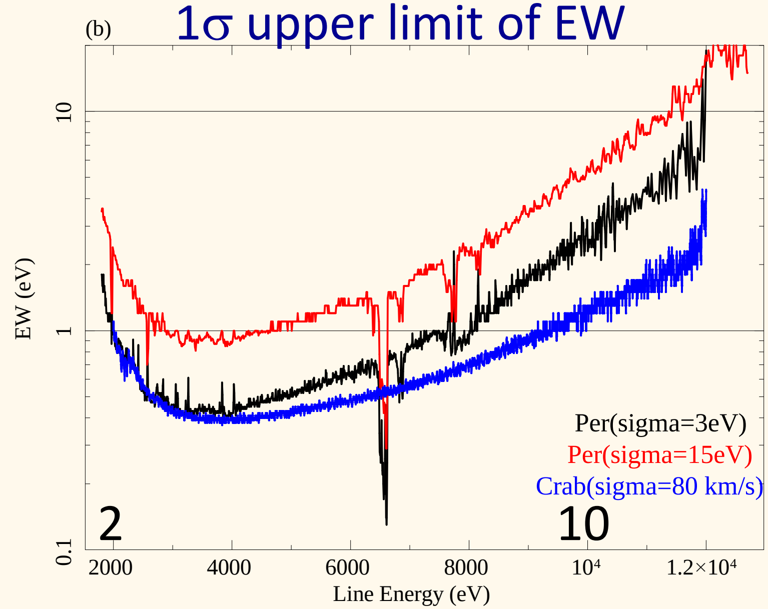
# Search for unidentified lines

T. Tamura et al. 2018, submitted to PASJ

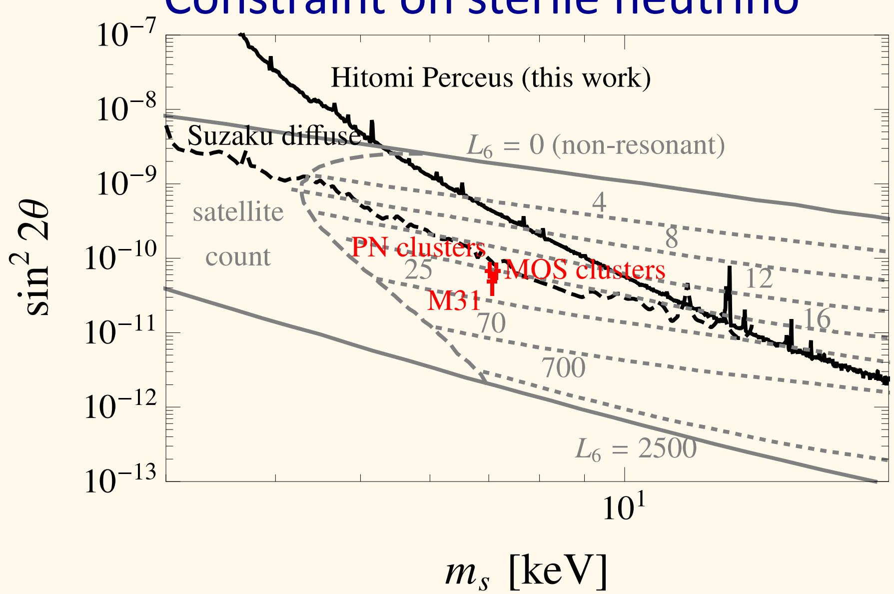
Perseus cluster spectrum:

- Blind search of new lines is performed in 5 or 10 eV step.
- No significant new line is detected, considering the “look elsewhere” factor of 1600
- Decay rate of sterile neutrino is constrained with fine mass resolution in 4 – 24 keV.
- Possible atomic lines, not well modeled (such as CX), are marginally (2.5-3σ) detected.

1σ upper limit of EW



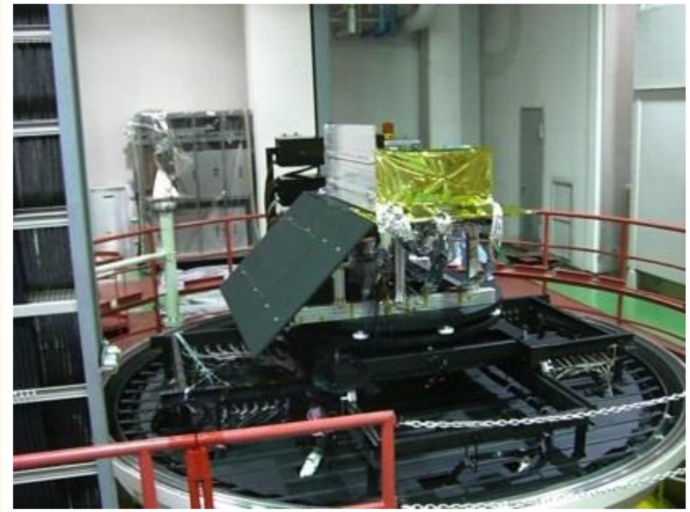

Constraint on sterile neutrino

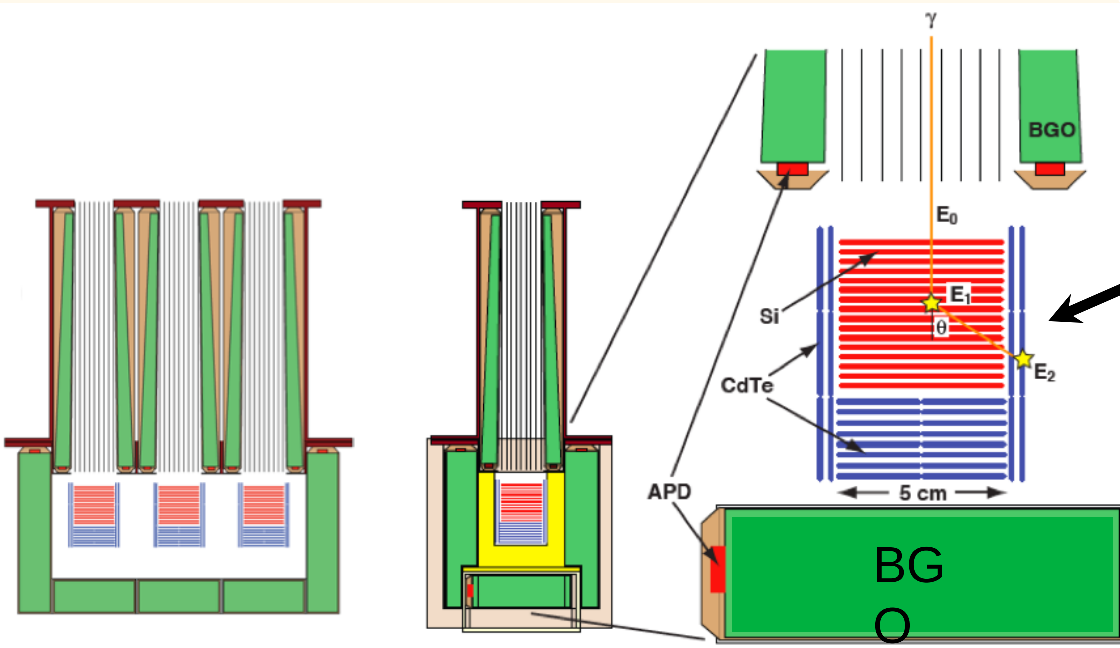


# Soft Gamma-ray detector

- Si/CdTe Compton Gamma Camera and Well-type shield to achieve ultimately low background. (40 - 600 keV)
- The Compton Camera enables us to measure polarization > 60 keV.
- GRB Monitoring using BGO shield.

SGD Thermal Balance Test






Si/CdTe Compton Camera (only select gamma-rays from the FOV)

Compton Kinematics

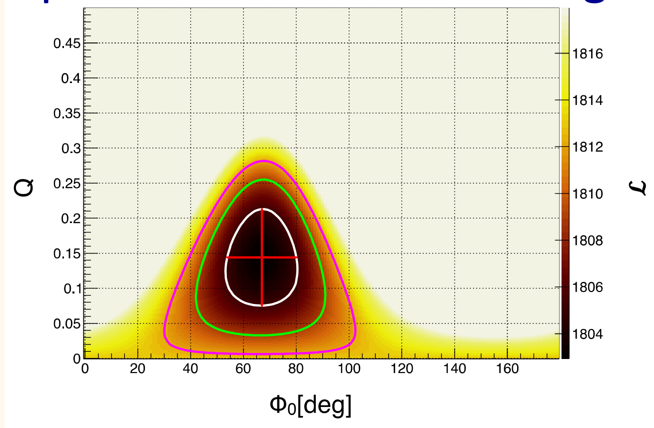
$$\cos\theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

$$E_{\rm in} = E_1 + E_2$$

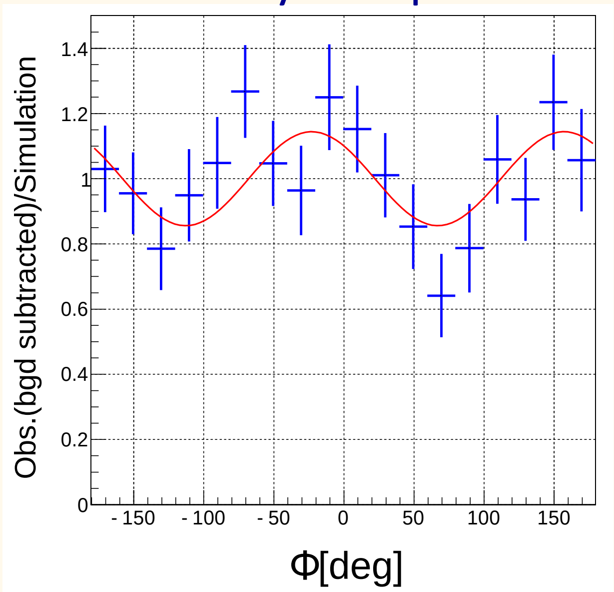
# Polarization study with SGD

- 5 ksec exposure on Crab Nebula
- Detector properties reproduced by GEANT4 simulation
- Polarization detected at 99.3% confidence
- Position angle 110.7 ± 13 deg, polarization fraction 22.1 ± 10.6%, consistent with previous results

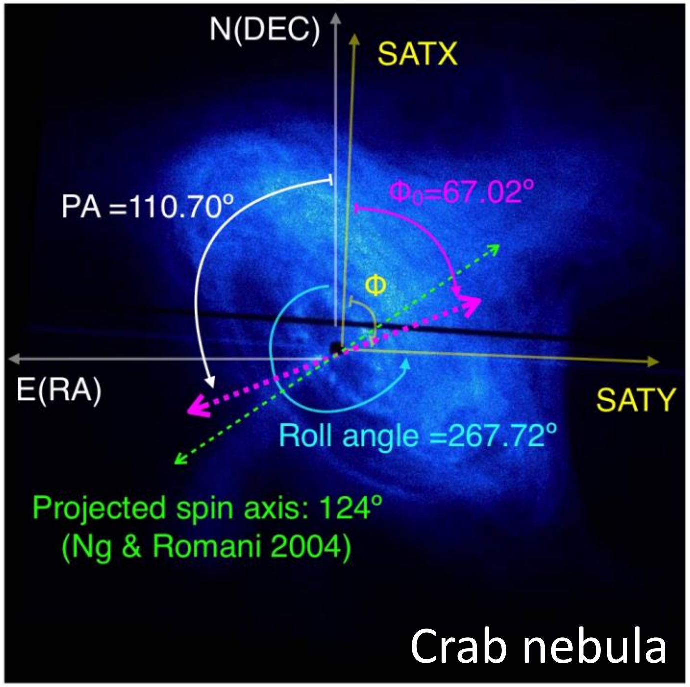
Amplitude vs Polarization angle




Data divided by non-polari simulation




Sine wave



# Summary

- Hitomi has really opened the door to new science with high resolution X-ray spectroscopy
- We should be proud of the good function of all the instruments on-board Hitomi
- Even the mission itself has a short life, long international collaboration on the spacecraft production and discussion on science have made a strong team
- XRISM will fulfill the spectroscopy science of Hitomi, which will be ultimately expanded with Athena
- Sensitive Hard X-ray mission will also be desirable to provide another view of the dynamically evolving universe

# Hitomi collaboration


Professor
Yasuo Tanaka
1931 - 2018

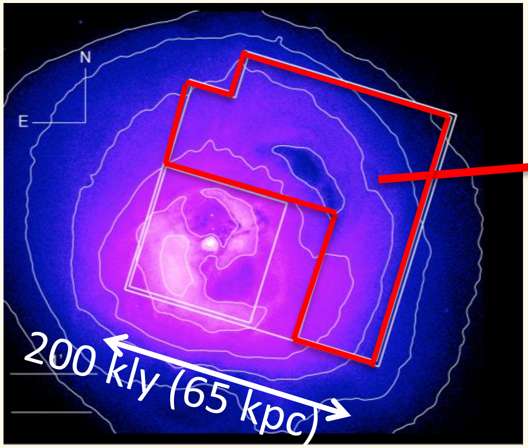
# END

# The Hitomi mission

- Study of dynamical evolution of the universe
  - With high resolution spectroscopy (microcalorimeters)
  - and with wide-band spectral coverage (multilayer supermirror with hard X-ray imager and Compton camera)
- Direct measurement of gas velocity
- Sensitive probing of non-thermal processes
- Complementary to high-resolution images (with Chandra and XMM-Newton)
- Establish key technologies for future missions

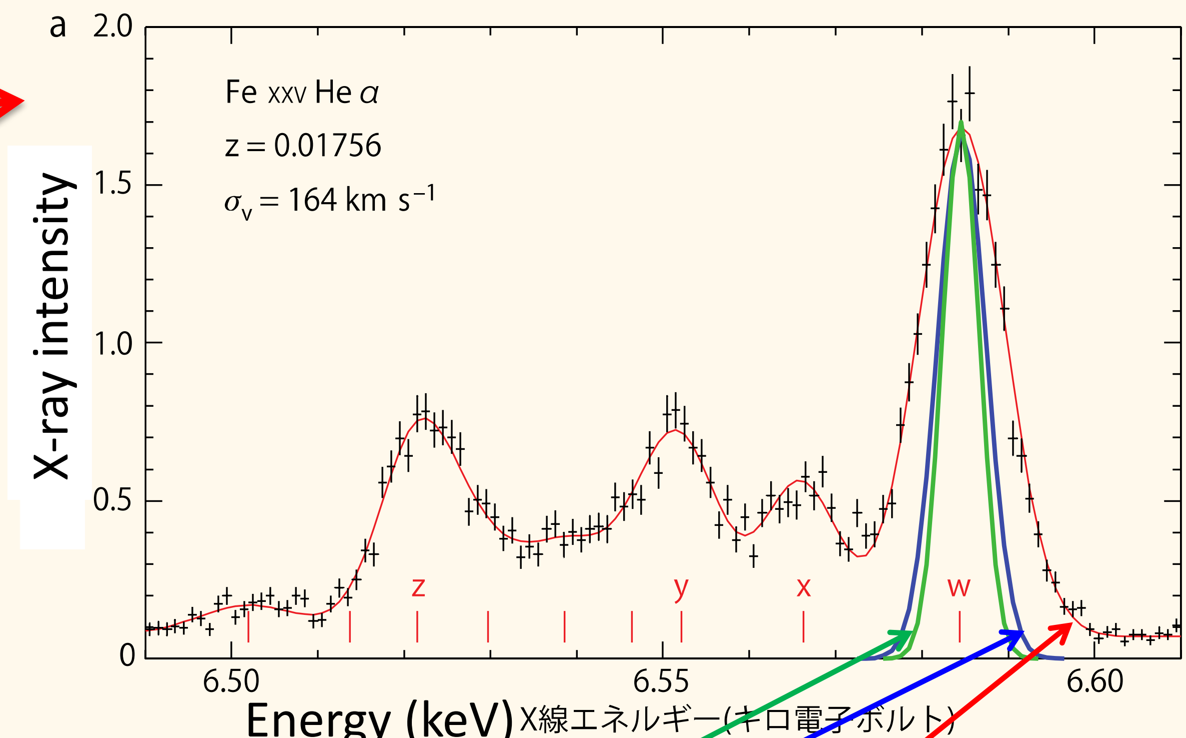
Length: about 14 m in orbit
Weight: about 2700 kg

# Width of He-like Fe K lines




SXS field of view on Chandra image

Energy spectrum excluding the AGN region




Stationary gas (SXS energy resolution)

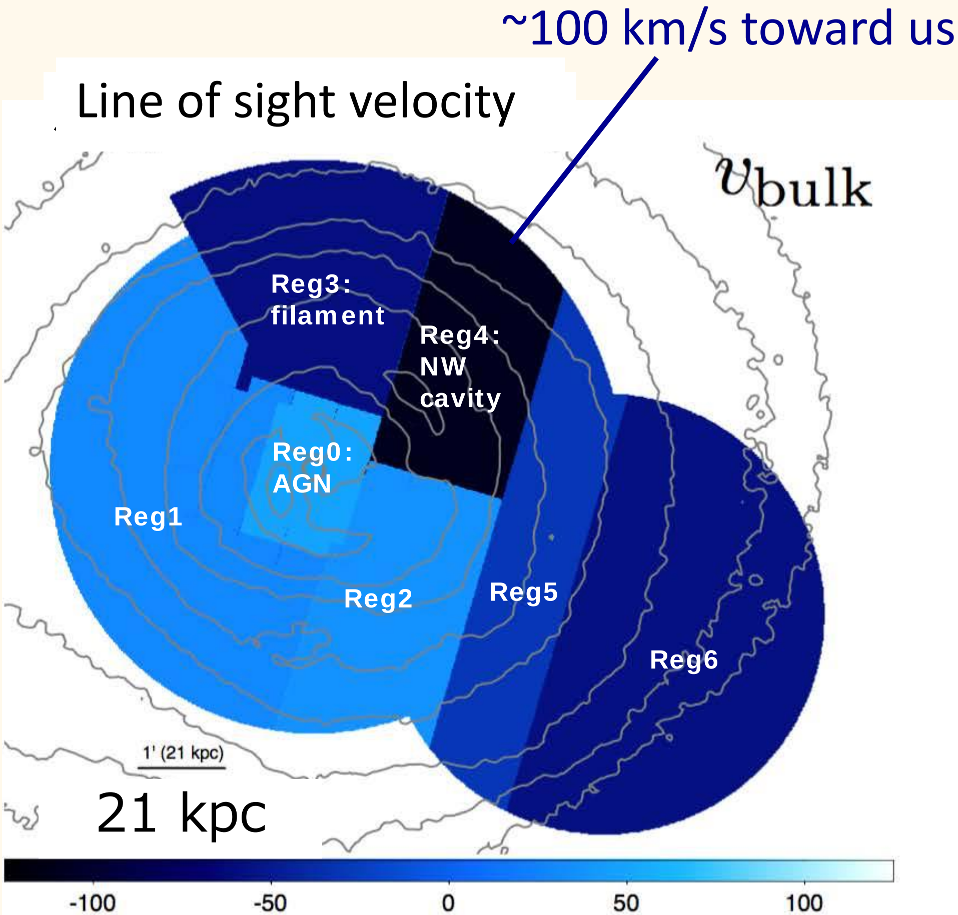
Thermal motion of Fe ion (80 km/s)

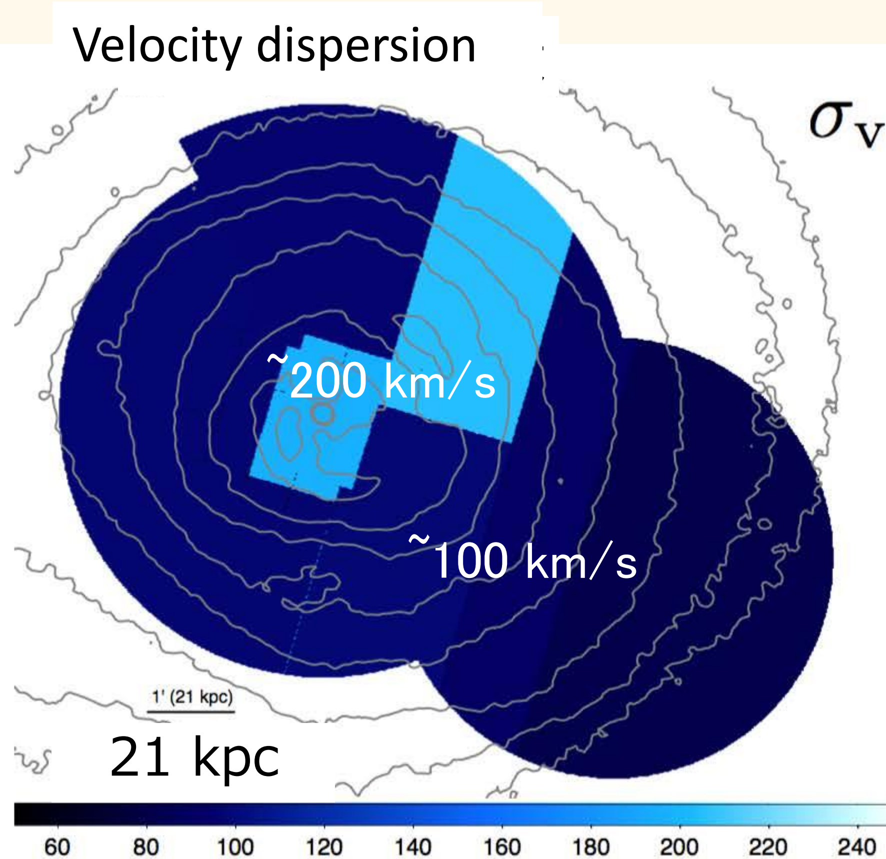
Thermal (80 km/s)＋Turbulence(164 km/s)

(Velocity is along the line of sight. Isotropic 3-dim velocity is 1.73 times higher)

Hitomi collaboration 2016, Nature, 535, 117

# Velocity structure

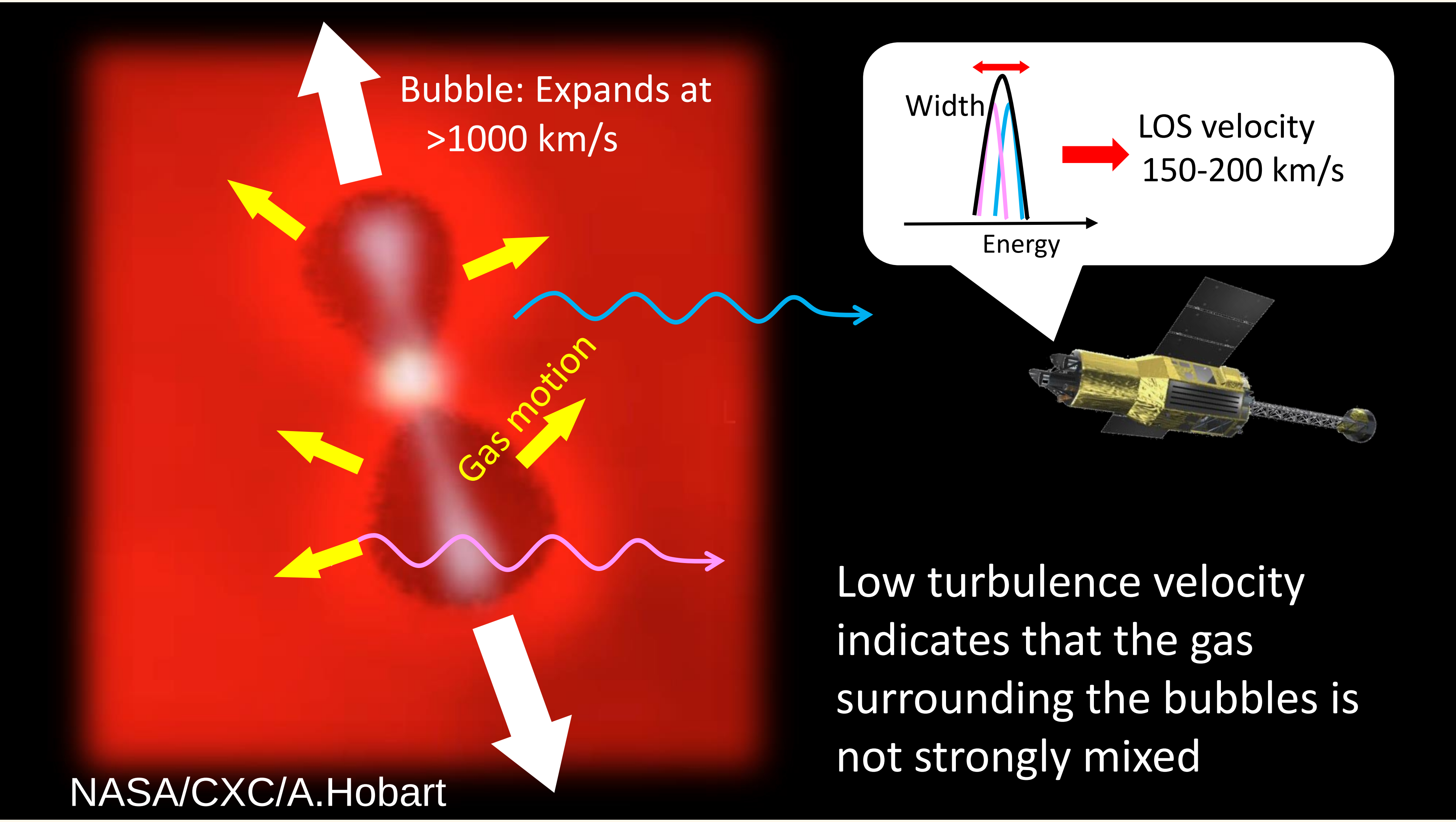



- Velocity shear exists in the central 100 kpc region of the cluster
- Velocity dispersion (100 – 200 km/s in LoS) is much smaller than the sound velocity (~ 1000 km/s).

Hitomi collaboration 2017, arXiv: 1711.00240

# Turbulence seems weak in the center

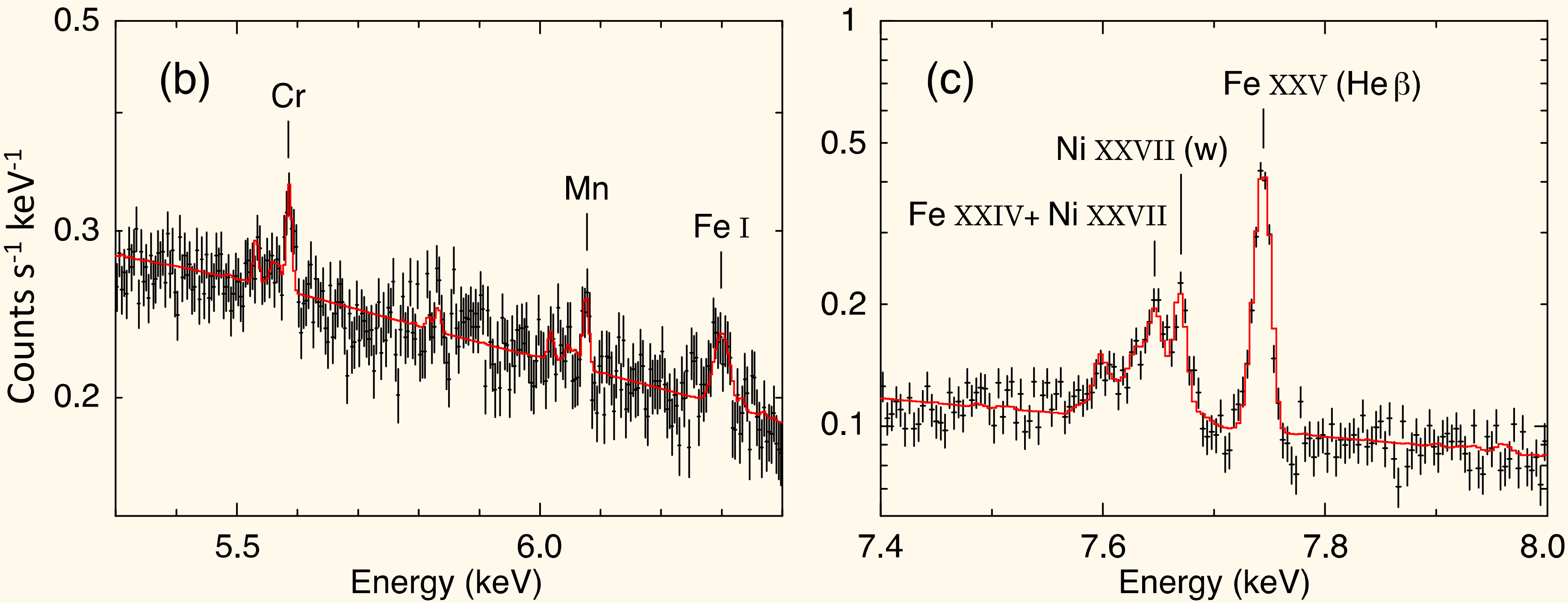



Low turbulence velocity indicates that the gas surrounding the bubbles is not strongly mixed

- Turbulent pressure is about 4% of the thermal gas pressure
- It is not clear how the cluster gas is heated and maintained for a long time

# Measuring low abundance elements

- Ni and Mn abundances have key information to tell how type Ia supenova explosions, involving white dwarfs, occur.
- Cr, Mn, and Ni lines were very difficult to measure, due to low intensity and contamination with Fe lines.
- Hitomi SXS enables clear measurement of these lines.

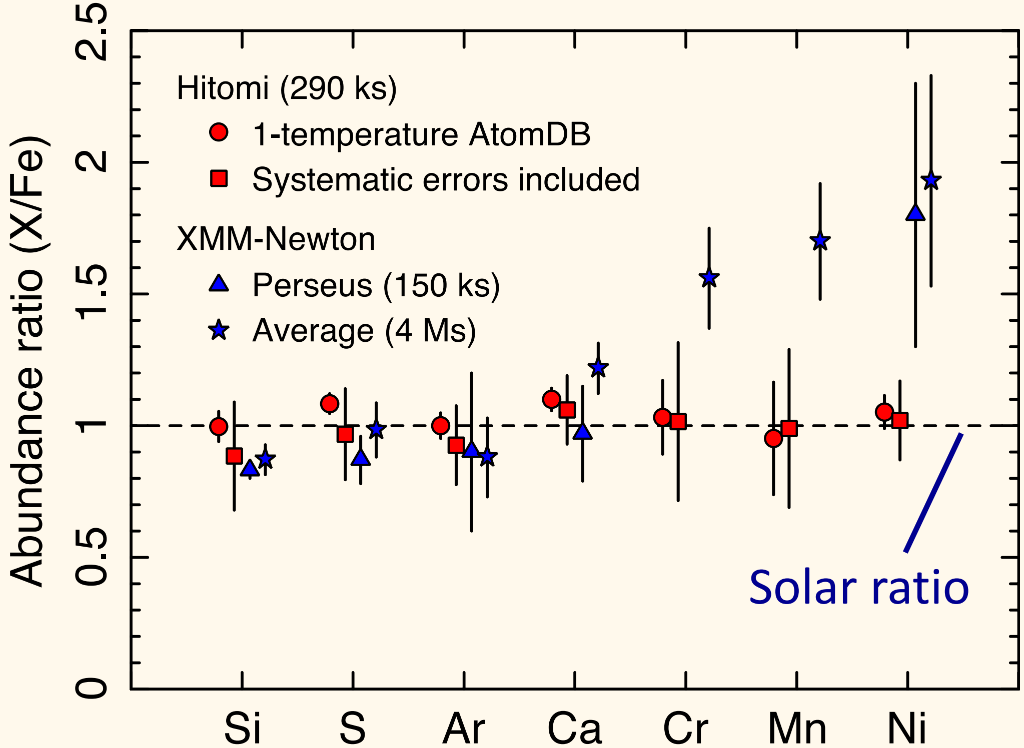



Hitomi collaboration 2017, Nature, 551, 478

# Metal abundances

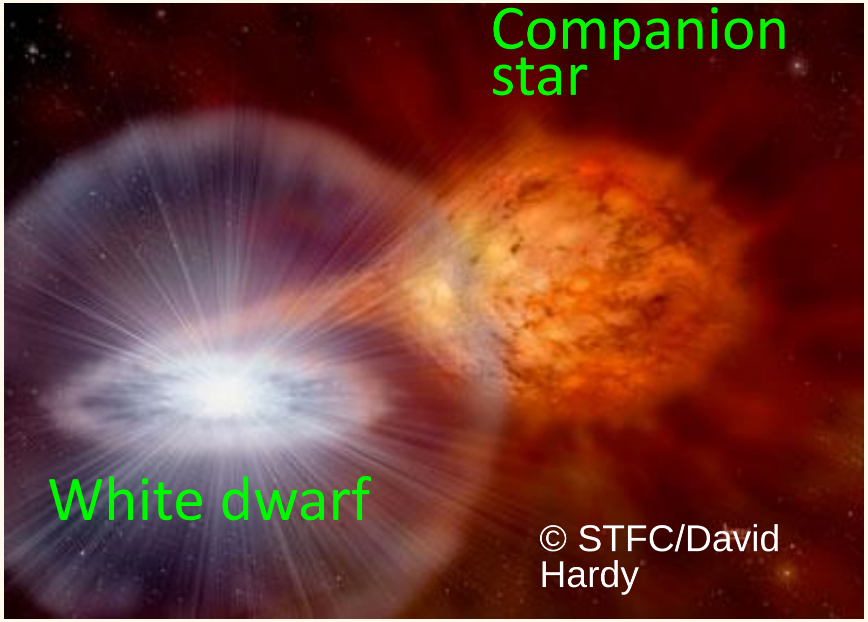
- Uncertainty in modeling (two temperatures, e.g.) gives abundance difference of < 20% for Si and S, and < 5% for other elements.
- All the elements show relative ratios close to the solar abundance, including Cr, Mn and Ni.
- XMM-Newton reported higher abundances for Cr, Mn and Ni: due to possible contamination from other lines.

Cluster (mainly elliptical galaxies) and the Milky Way (spiral) indicate very similar metal composition: Supernova process is not sensitive to galaxy types.



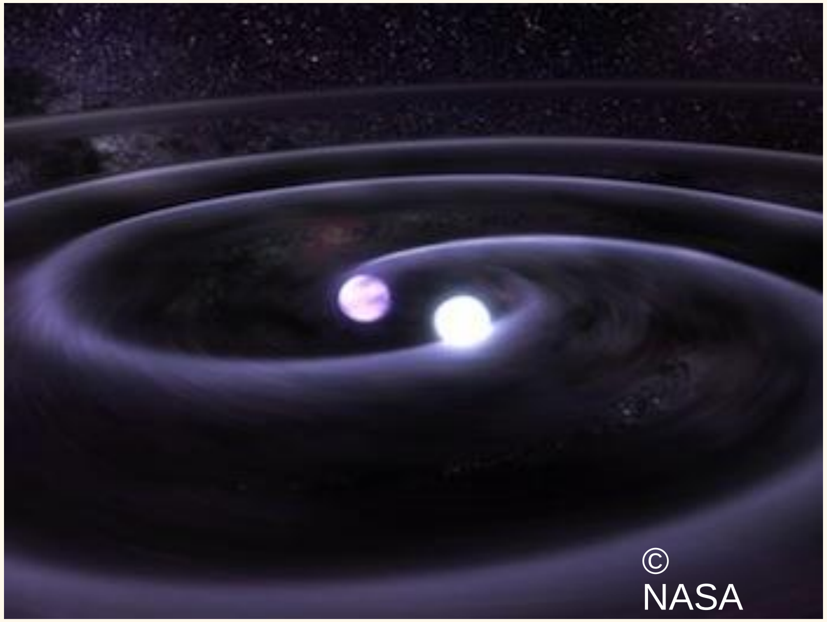

Relative abundance for 1-temperature plasma. Errors are 1σ statistical.

# Origin of Type Ia supernova




**Explosion at Chandrasekhar mass**

➔Super-solar metallicity




**Merger: explosion mass is less than the limit**

➔Lower metallicity

Both scenarios need to work to explain the observed solar abundance of elements.

# Hitomi Collaboration

- > 200 members, not including students, from > 70 institutes.
- Collaboration meeting was held twice every year.
- Science activities were carried out to prepare for the mission: PV target selection and target team formation, white papers for 16 subjects, summer schools for young members etc.

Cambridge, UK, 2012 ($8^{th}$)

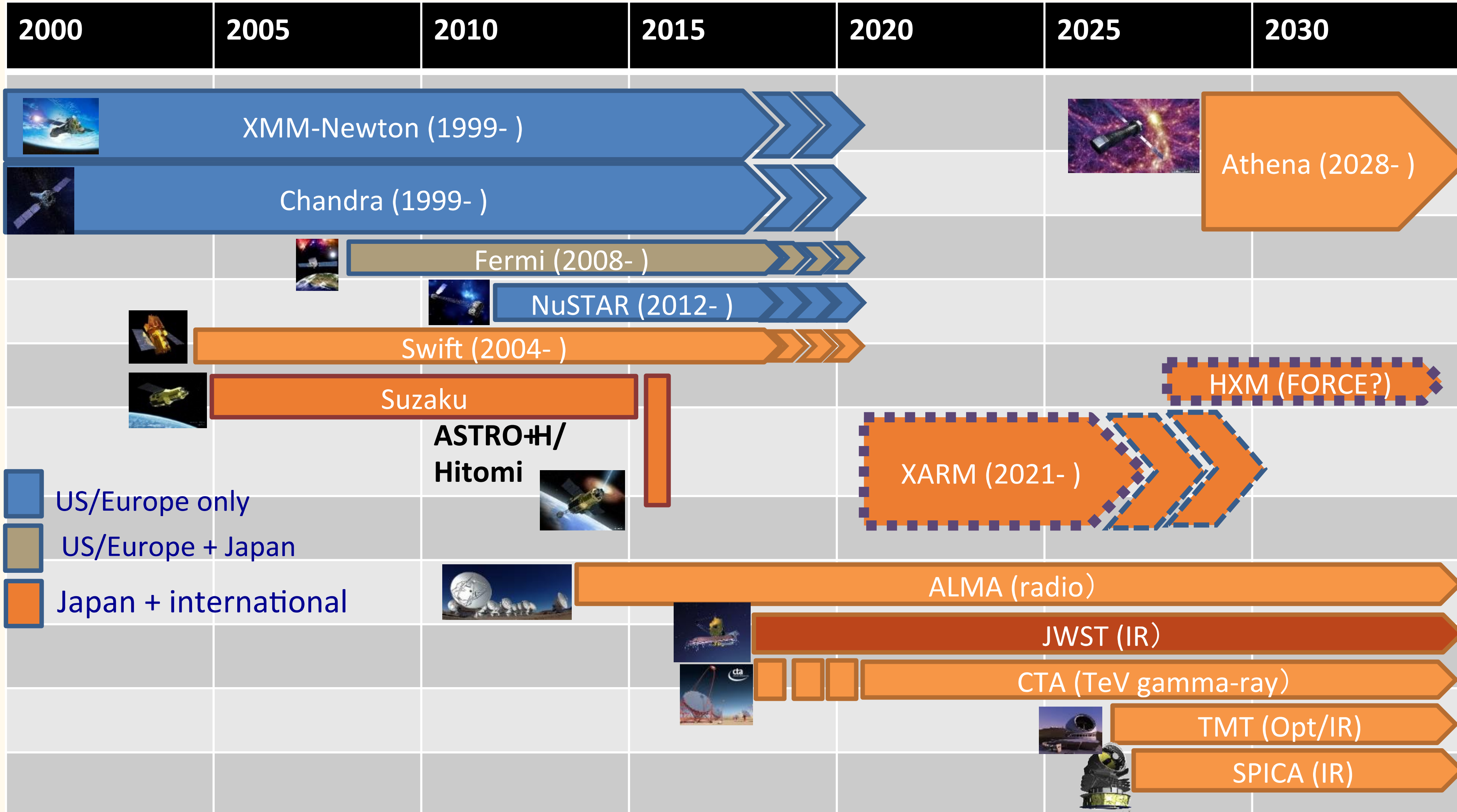
Tokyo Metropolitan U, 2015 ($14^{th}$)

# Recovery of the Hitomi science

X-ray Astronomy Recovery Mission (XARM)

- We aim the launch of XARM to be around 2021.
- The mission will carry microcalorimeters and CCD instrument.
- The mission will be carried out by JAXA and NASA, with contribution from ESA
- After the delay of ~ 5 years, we expect a substantial advance in the spectroscopy of cosmic plasmas by measuring all categories of X-ray objects.

# Time Frame of XARM



# Anomalous event of Hitomi

The Hitomi spacecraft lost its ground contact on March 26, 2016, and later the recovery operation by JAXA was discontinued.

The following page gives more information:□
http://global.jaxa.jp/projects/sat/astro_h/topics.html□

# Targets in the start-up phase

Perseus cluster
N132D (SNR)
IGR J 16318-4848 (Obscured HMXB)
G21.5-0.9 (SNR)
RXJ 1856.5-3754 (Isolated NS)
Crab Nebula

SXS, SXI | HXI | SGD

All detectors are confirmed to function properly

- All sources were observed for 2-4 days, but some sources had short exposures (due to attitude parameter tuning).
- N132D and IGR J 16318 have very limited SXS data, and RXJ1856 was absorbed by SXS gate valve.

# Hot gas heating by SMBH

- The mechanical pressure of “bubbles” exceeds the thermal gas pressure.
- However, observed weak turbulence (4% of thermal pressure) can heat only very close region from the bubble.
- The turbulence energy will be exhausted in $10^8$ years
- Continuous generation of turbulence is needed or heating occurs without involving the turbulence.
- Cluster mass estimated from the hydrostatic equilibrium does not need significant revision.

# Shock fronts in clusters

- Temperature jumps are confirmed in the radio relic regions
  - Clear evidence of shock fronts
  - Only Suzaku could measure pre-shock temperature, because of the low background (better than Chandra and XMM-Newton)
- Temperature jump → Rankine-Hugoniot relation → Mach number $M_X$ to be about 3

$$\frac{T_2}{T_1} = \frac{5M^4 + 14M^2 - 3}{16M^2}$$

- Radio data also give Mach numbers from spectral indices ($M_R$)
- $M_X \approx M_R$ is confirmed for about 5 clusters