



ASTRO-H計画と その目指すサイエンス



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国分 紀秀

ASTRO-H チーム

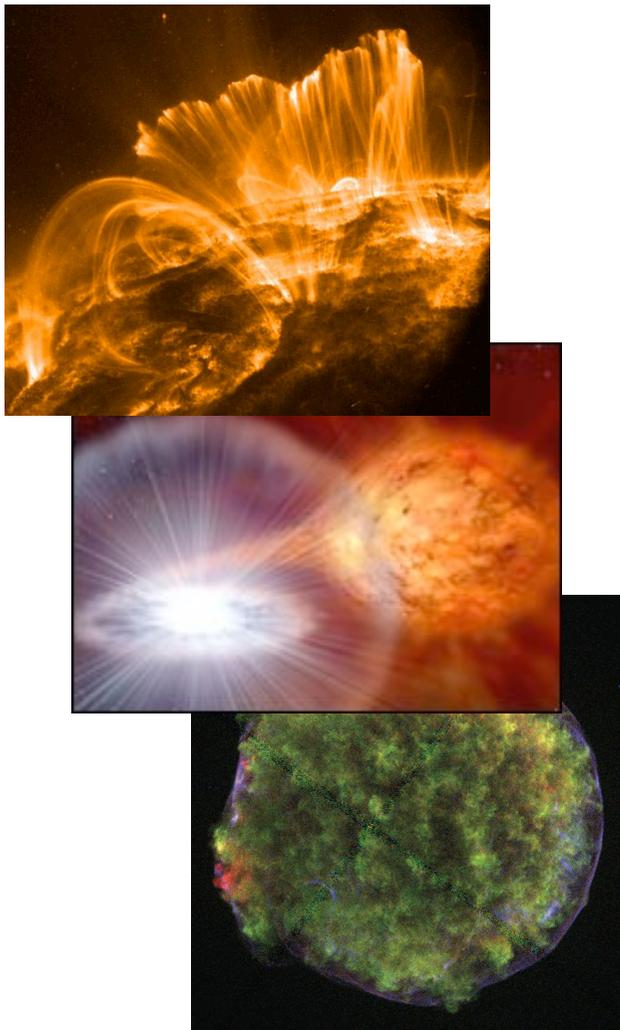


A handwritten signature in black ink is located in the bottom right corner of the slide. The signature is cursive and appears to read 'S. Kusuhira'.

科学的意義 - X線で探る宇宙 -



宇宙で我々が観測できる物質の80パーセントはX線でしか観測できない高温状態にあるとされている (Fukugita & Peebles 2004, Read & Trentham 2005)。宇宙の全貌を知る上で、X線観測は地上からの光学・電波観測などと並び不可欠の手段である。



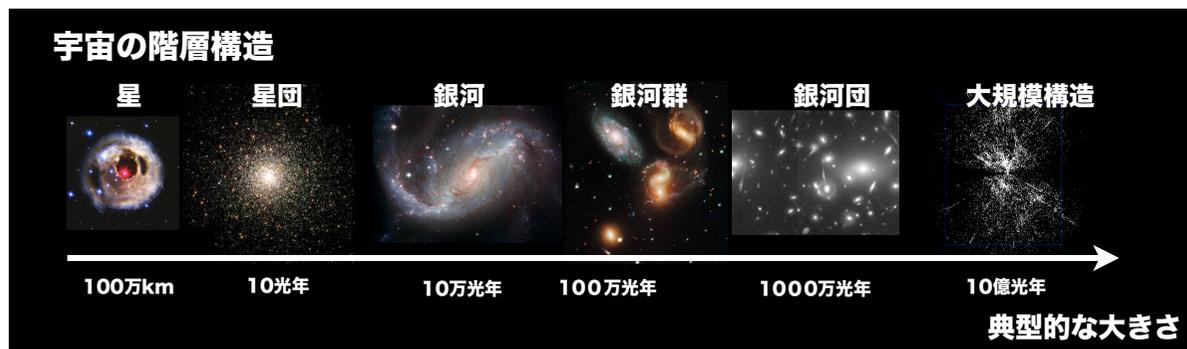
- ◆ Gas at temperatures of 1 - 100 million degrees.
- ◆ Remnants of exploded stars
- ◆ Matter falling into black holes and neutron stars
- ◆ Stellar coronae
- ◆ Winds from star-forming galaxies
- ◆ Electrons accelerated in strong magnetic fields ($\sim 10^{12} - 10^{14}$ Gauss)
- ◆ Electronic transitions in partially ionized atoms of atomic number greater than or equal to 4 (Be)

とりわけシンクロトロン放射によるX線放射の観測は、 10^{12} eVにも達するような巨大な宇宙の加速現象を探索することにつながる。得られる情報は加速された電子についてのみならず、対生成された $e^{+/-}$ によるシンクロトロン放射を介して、高エネルギー粒子と周辺物質との衝突過程を探ることにつながる。特に非熱的放射が卓越する硬X線バンドが重要となる。

世界最高のエネルギー分解能を持ち、X線からガンマ線までの広大なエネルギー範囲を観測する衛星「ASTRO-H」による研究は、宇宙のダイナミックな進化と非熱的物質を含めたエネルギー集中過程の解明を目指すものである。高温ガスの運動を捉え、宇宙の進化をリアルタイムの映像として明らかにし、超広帯域の観測とも合わせることで、ダイナミックな宇宙の進化の真の姿が初めて明らかにされる。それにより、現在の宇宙論における大きな謎である、宇宙を満たす“暗黒エネルギー”の本質の追求にもつなげることをめざす。

ASTRO-H衛星の目的

宇宙の進化における
エネルギー集中と
宇宙の階層形成の解明





○ 「宇宙の大規模構造と、その進化の解明」のため

1. 銀河団という宇宙最大の天体における熱、銀河団物質の運動エネルギー、非熱的エネルギーの全体像を明らかにし、**ダイナミックな銀河団の成長を直接観測**する。

○ 「宇宙の極限状態の理解」のため

2. 厚い周辺物質に隠された**遠方(過去)の巨大ブラックホール**を「すざく」の約100倍の感度で観測し、**その進化と銀河形成に果たす役割を解明**する。

○ 「多様性にとんだ非熱的エネルギー宇宙の探求」のため

3. **ブラックホールの極近傍の物質の運動を測定**することで重力のゆがみを把握し、**相対論的時空の構造を明らかに**する。

4. 宇宙に存在する高エネルギー粒子(宇宙線)がエネルギーを獲得する現場の物理状態を測定し、**重力や衝突・爆発のエネルギーが宇宙線を生み出す過程を解明**する。

○ 「ダークマター・暗黒エネルギーの探求」のため

5. 距離(年齢)の異なる銀河団内のダークマターの分布と総質量を測定し、**銀河団の進化に果たすダークマターと暗黒エネルギーの役割を探求**する。

軌道上で稼働中のX線衛星たち

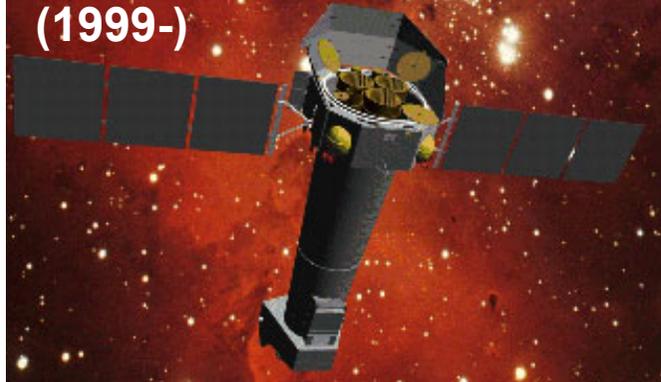


XMM 0.3-12 keV
(1999-)



Largest collecting area

CXO 0.07-10 keV
(1999-)



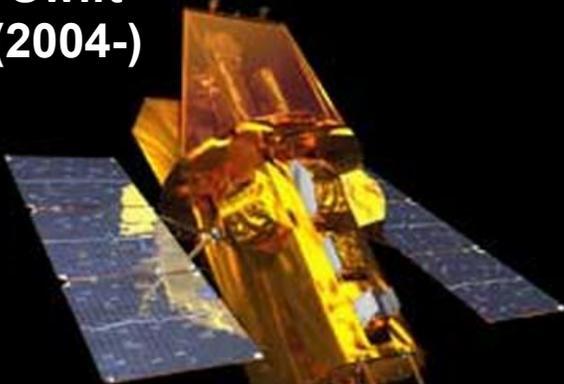
Excellent Imaging

Suzaku 0.2-600 keV
(2005-)



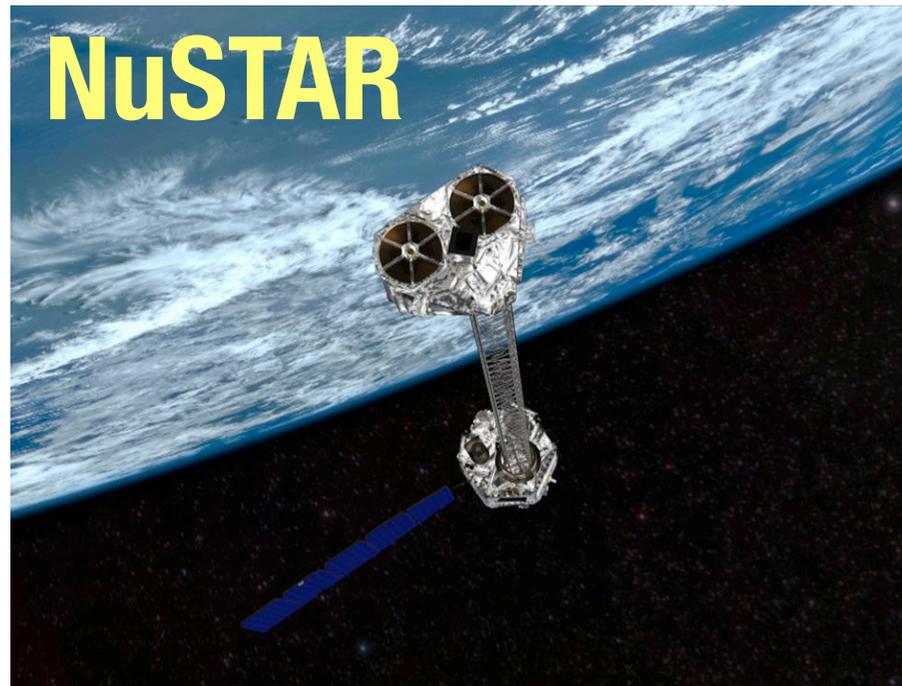
Broadband coverage

Swift 0.2-150 keV
(2004-)



Dedicated to GRBs
(fast repointing)

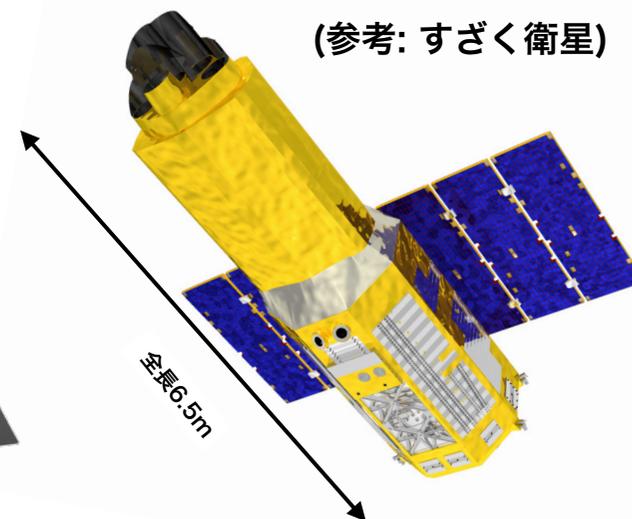
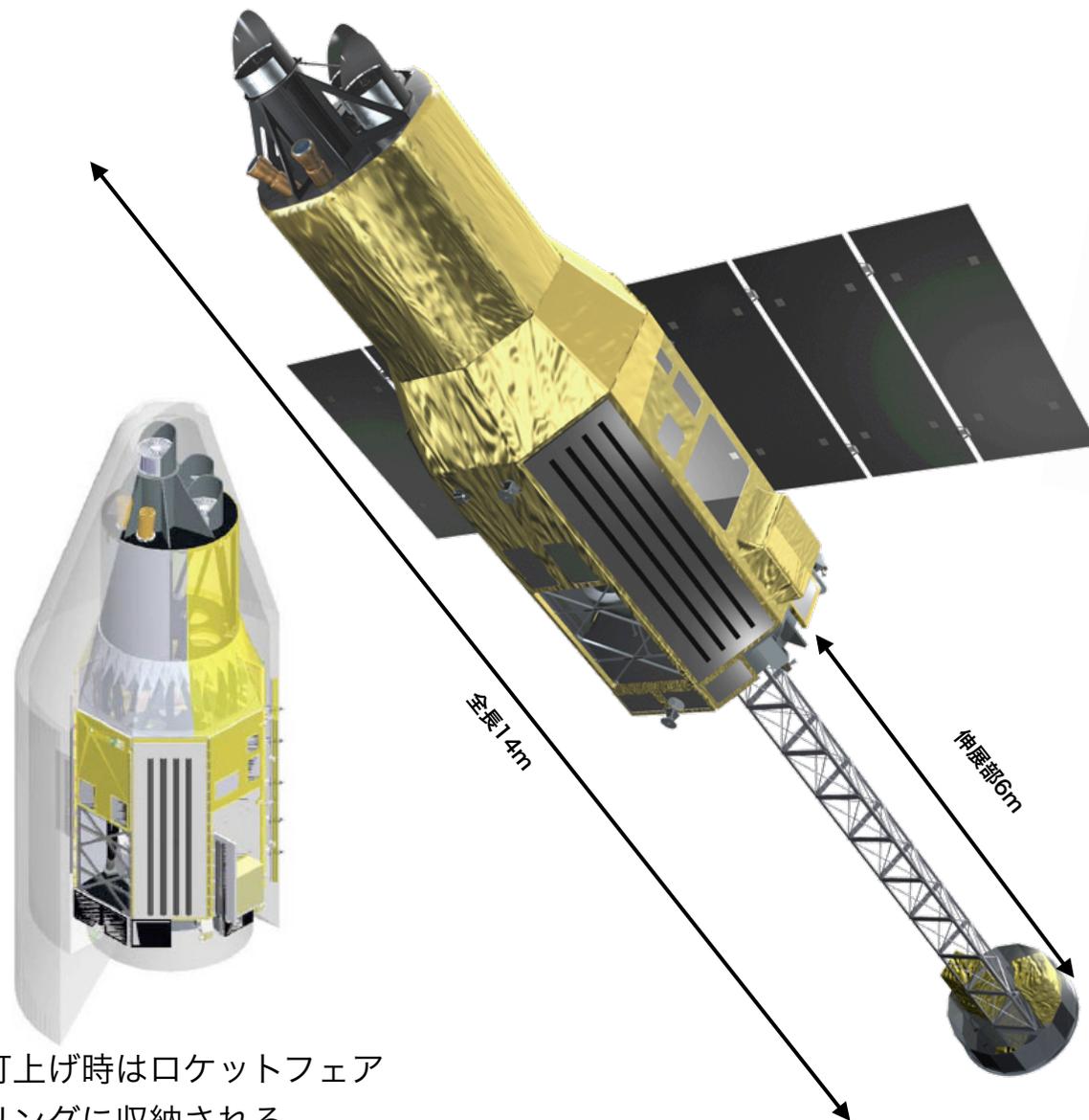
NuSTAR





ASTRO-H衛星

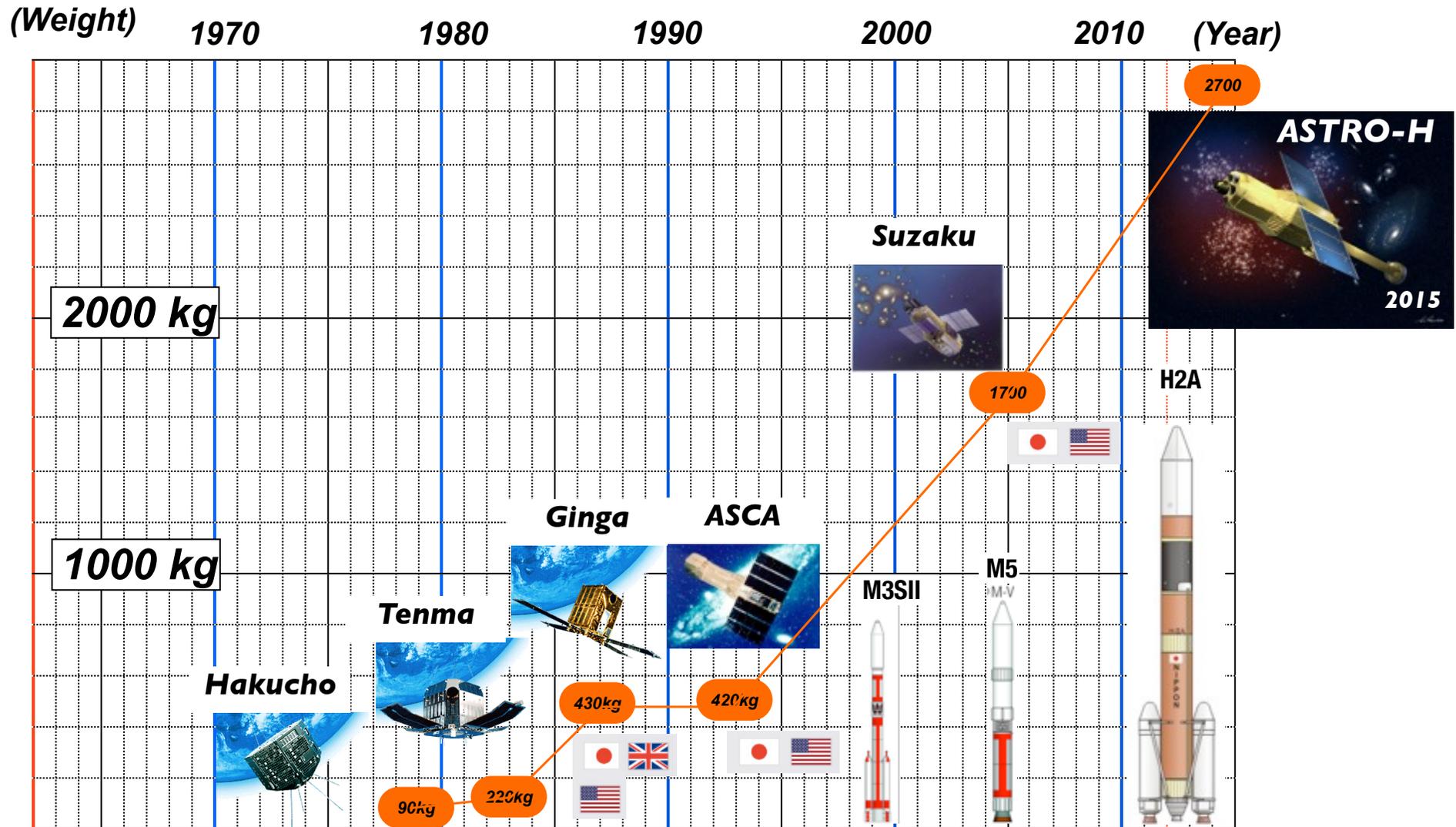
ASTRO-H衛星主要緒元



打上げ時はロケットフェアリングに収納される

- 全長: 14 メートル
- 重量: 約2.7 トン
- 電力: 3500 W (@EOL)

過去の日本のX線衛星との比較



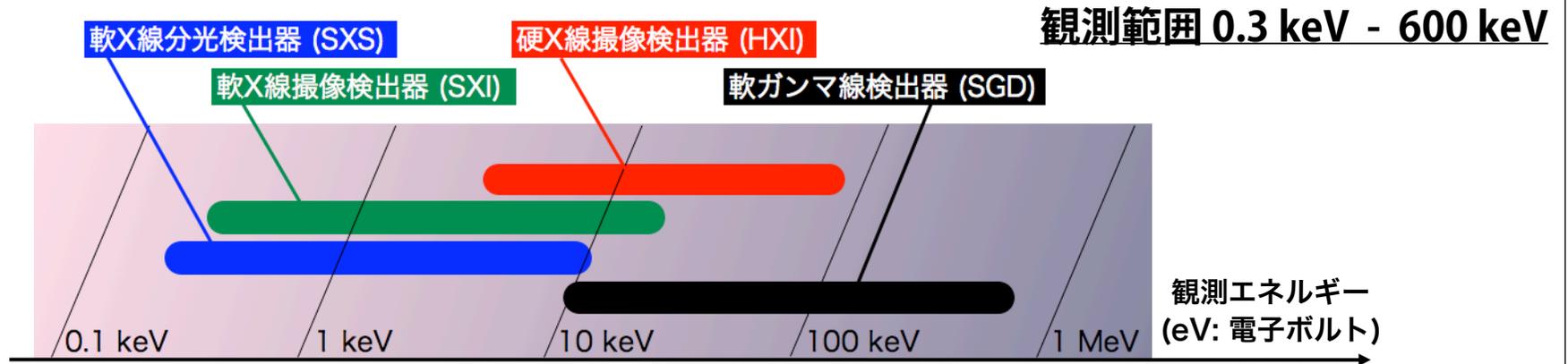
衛星試験中のASTRO-H衛星 (熱バランス・熱変形)



衛星試験中のASTRO-H衛星 (音響試験)



ASTRO-H - 搭載観測装置の構成 -



硬X線撮像システム

HXT
(望遠鏡)

HXI

国産ナノ技術を駆使し、世界に先駆けて開発した硬X線望遠鏡と、ASTRO-Hをめざして開発した新しい高効率CdTe半導体素子に基づく硬X線撮像検出器を組み合わせ、硬X線帯で初めての集光撮像を実現し、飛躍的な高感度を実現。

軟X線分光システム

SXT-S
(望遠鏡)

SXS

大面積かつ軽量の軟X線望遠鏡と、50ミリ度という極低温技術によって超高分解能分光を実現する軟X線分光検出器を組み合わせ、超精密X線分光を実現

軟X線撮像システム

SXT-I
(望遠鏡)

SXI

軟X線望遠鏡と、大面積低雑音X線CCD素子を用いた軟X線撮像検出器を組み合わせ、広い視野を持ち観測の基本となるX線撮像を実現。

軟ガンマ線検出器

SGD

独自のアイデアである狭視野半導体コンプトンカメラに基づいた超低雑音軟ガンマ線検出器により、一桁以上の感度の向上と、ガンマ線偏光観測能力を実現。

これら4種類の観測システムが同時に機能することで、3桁にもおよぶ広帯域において、「すざく」より10倍から100倍高感度の観測を実現して、最大限の科学的成果を引き出すことが可能となる。

ASTRO-H - 搭載観測装置の構成 -

Cutting-edge Instruments



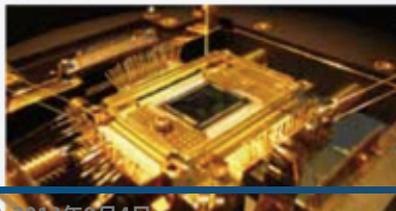
Close-up view of the aperture.

Reflecting X-ray Telescopes (SXT/HXT)

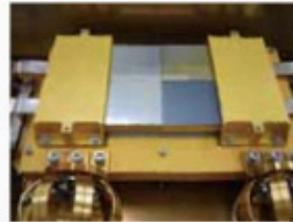
This instrument focuses X-rays from celestial objects onto the detectors. Unlike the single lenses and mirrors usually used for visible light, this X-ray reflecting telescope is made up of over one thousand reflector-coated aluminum foils stacked into concentric circles.

Soft X-ray Spectrometer (SXS)

Specialized detector elements are cooled down to near absolute zero (-273 degrees Celsius) using a series of refrigeration units. When an X-ray hits a detector element, its temperature slightly rises. This increase in "heat" is measured, and from this the energy of the incident X-ray can be estimated to a higher degree of accuracy than any achieved to date. Researchers from around the world have great expectations for this instrument, the centerpiece of ASTRO-H.



Close-up view of the main sensor part.



Soft X-ray Imager (SXI)

This is a wide field-of-view X-ray camera using an array of four large-format X-ray CCD chips. It provide simultaneous imaging and spectroscopic data in the energy range of 0.5 keV to 12 keV. The detector will be placed in the main body of the satellite.



Soft Gamma-ray Detector (SGD)

Many layers of semiconductor sensors are stacked to optimize the sensitivity of the gamma-ray spectrometer. Since gamma-rays have a higher penetrating power than X-rays, this instrument plays an important role investigating astronomical objects surrounded by dense gas.



X-ray sensor and signal-processing electronics

Hard X-ray Imager (HXI)

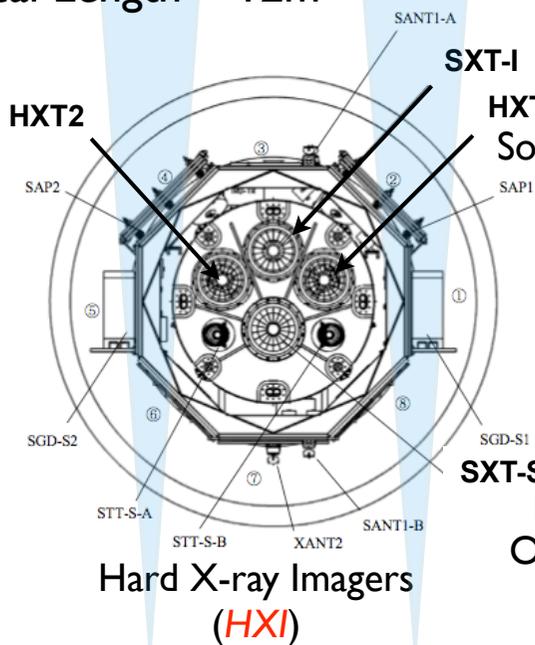
This produces images of objects in the hard X-rays above 5 keV using a combination of silicon and cadmium telluride semi-conductors. Since this imaging telescope has a 12-meter focal length, this sensor will be placed at the end of a boom which will be extended in orbit.

ASTRO-H - 搭載観測装置の構成 -

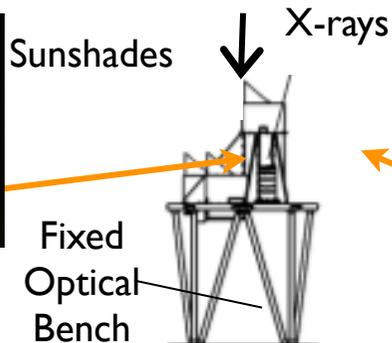
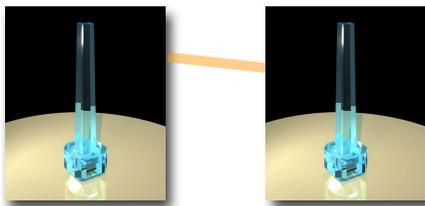


Hard X-ray Telescopes
(HXT)

Focal Length = 12m



Hard X-ray Imagers
(HXI)



Sunshades

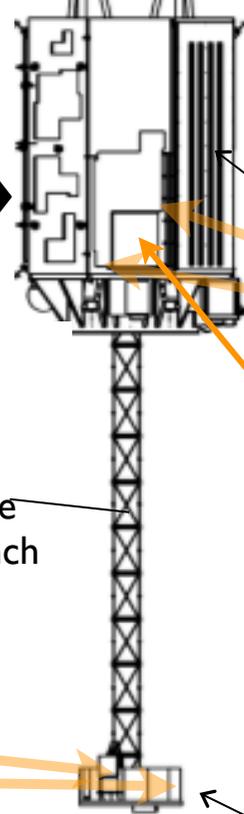
X-rays

Fixed
Optical
Bench



Soft X-ray Telescopes
(SXT-S, SXT-I)

Focal Length = 5.6 m

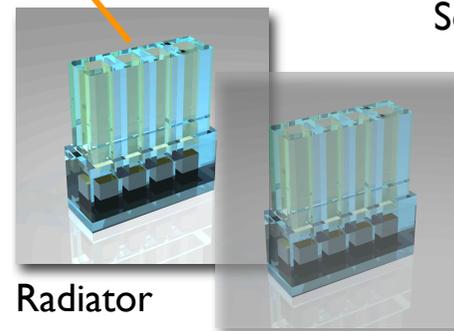
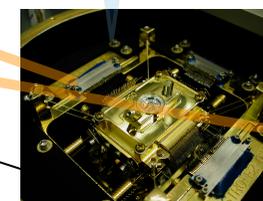


Deployable
Optical Bench

Radiator

Microcalorimeter
(SXS)

X-ray CCD
(SXI)



Soft γ -ray detectors
(SGD)



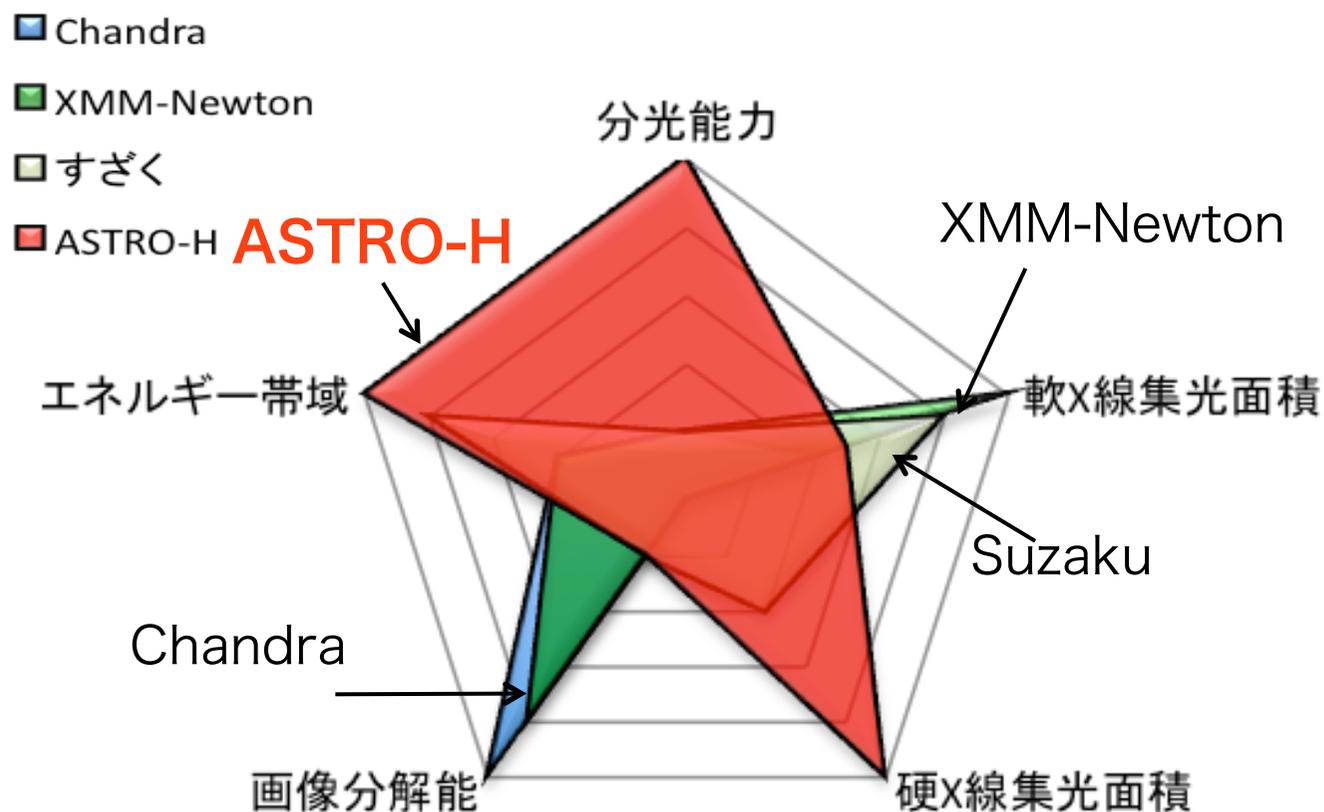
TABLE 2. Key parameters of the ASTRO-H payload

Parameter	Hard X-ray Imager (HXI)	Soft X-ray Spectrometer (SXS)	Soft X-ray Imager (SXI)	Soft γ -ray Detector (SGD)
Detector technology	Si/CdTe cross-strips	micro calorimeter	X-ray CCD	Si/CdTe Compton Camera
Focal length	12 m	5.6 m	5.6 m	–
Effective area	300 cm ² @30 keV	210 cm ² @6 keV 160 cm ² @ 1 keV	360 cm ² @6 keV	>20 cm ² @100 keV Compton Mode
Energy range	5 –80 keV	0.3 – 12 keV	0.5 – 12 keV	40 – 600 keV
Energy resolution (FWHM)	2 keV (@60 keV)	< 7 eV	150 eV (@6 keV)	4 keV (@40 keV)
Angular resolution	<1.7 arcmin	<1.3 arcmin	<1.3 arcmin	–
Effective Field of View	~ 9 × 9 arcmin ²	~ 3 × 3 arcmin ²	~ 35 × 35 arcmin ²	0.6 × 0.6 deg ² (< 150 keV)
Time resolution	several 10 μ s	several 10 μ s	4 sec	several 10 μ s
Operating temperature	–20°C	50 mK	–120°C	–20°C

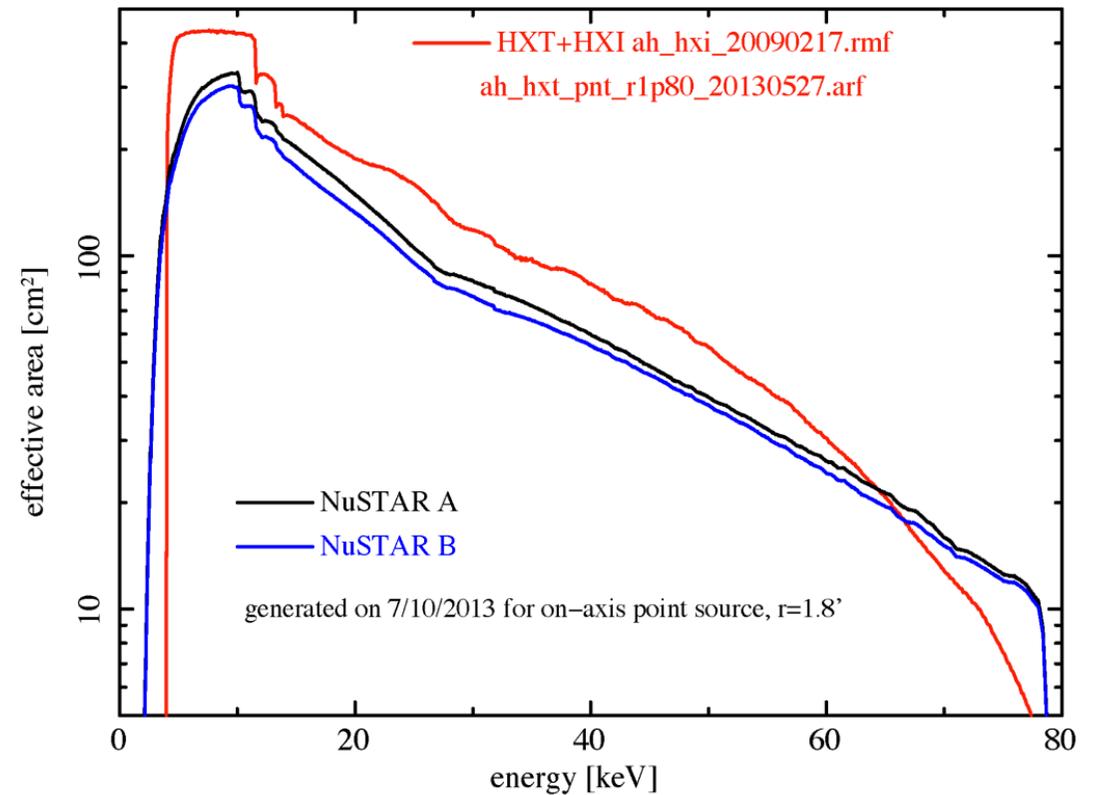
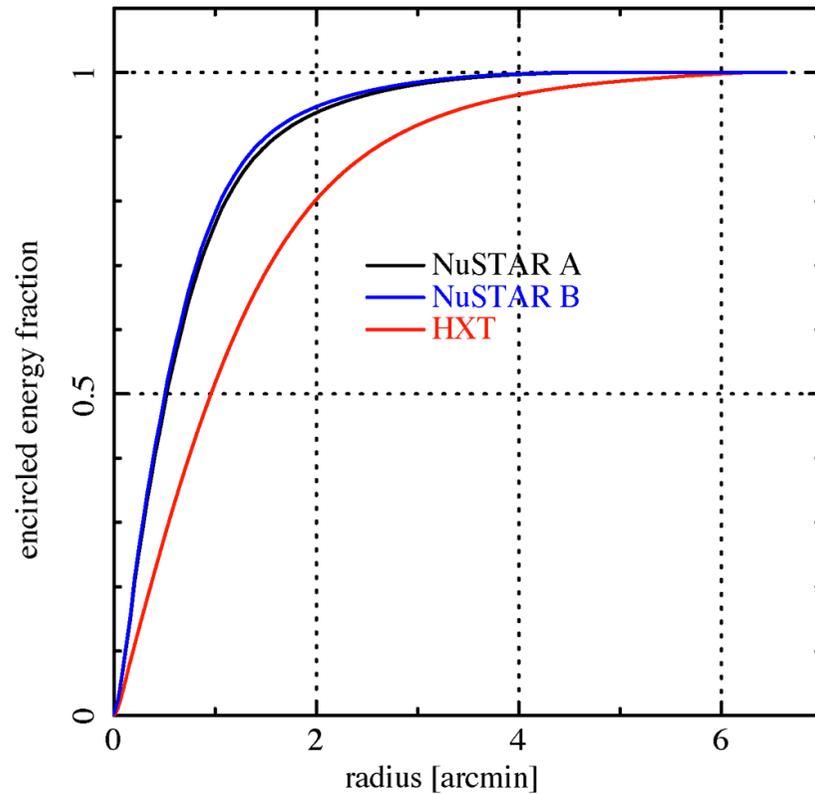
ASTRO-H 搭載観測装置と他衛星の性能比較



ASTRO-Hは、従来より一桁以上も高い分光能力を持つマイクロカロリメータと3桁にわたる広い帯域にわたって高い感度を持つX線・ガンマ線検出器を**同時に**備えている。



NuSTARとの比較



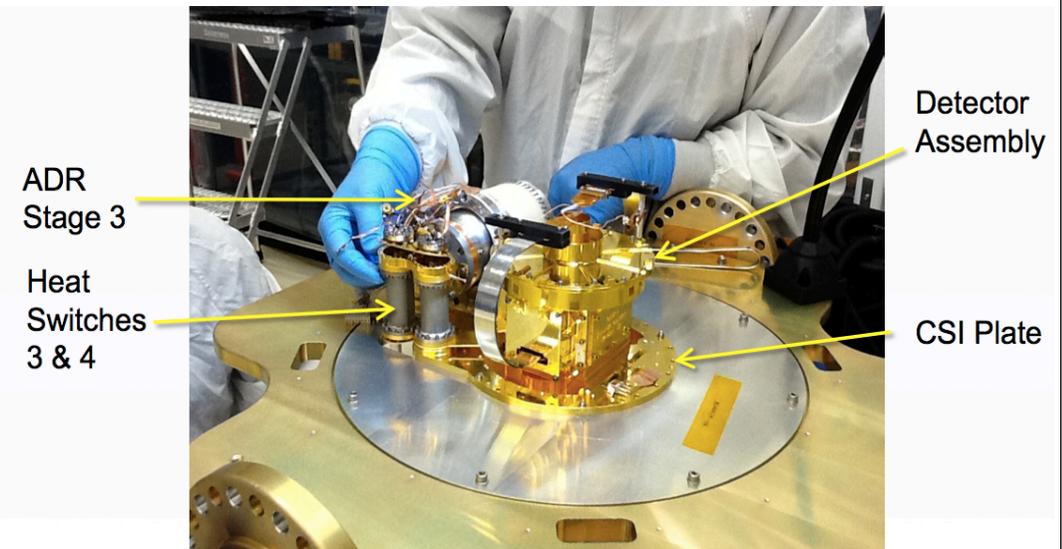
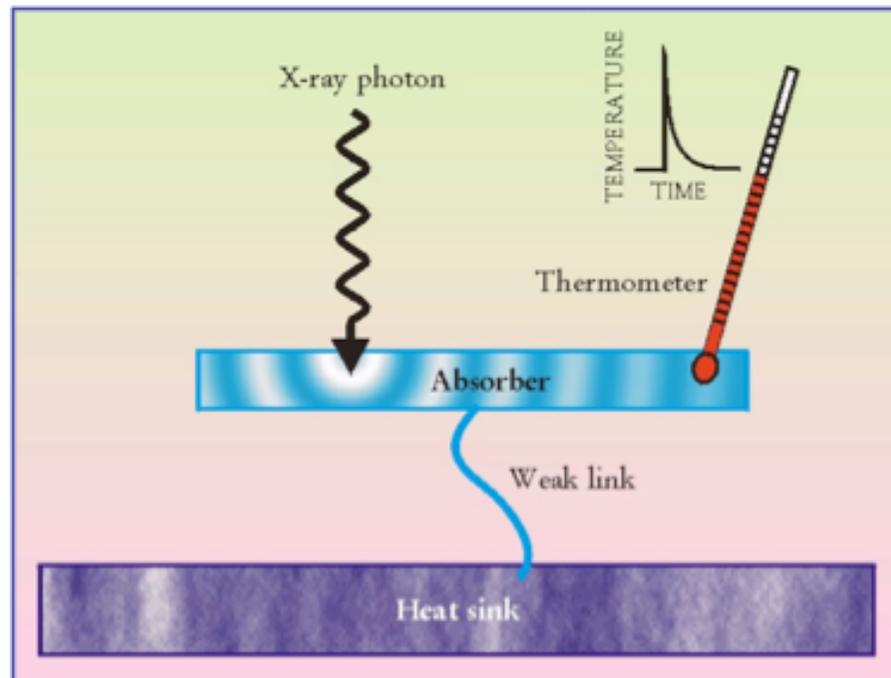
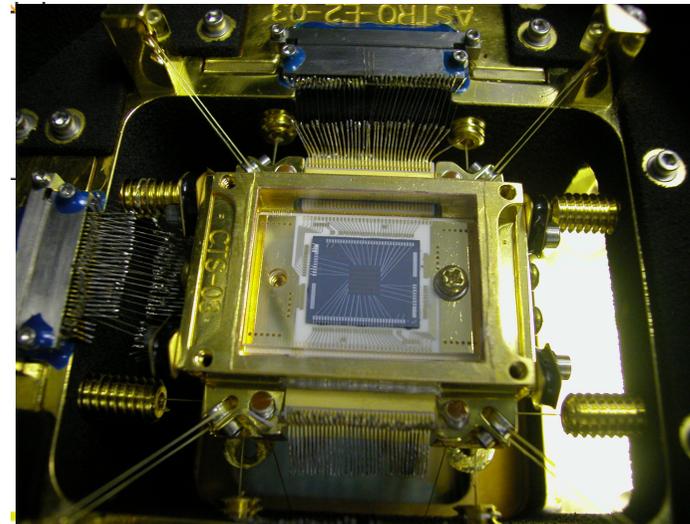
- Astro-H: Data from HXT-I.
- NuSTAR:
 - CALDB to be updated soon.
 - Integration region: $r < 1$ arcmin (HXT: $r < 1.8$ arcmin)



ASTRO-Hの搭載観測装置 : SXS

軟X線分光検出器(SXS/XCS) : X線マイクロカロリメーター

マイクロカロリメーターは、エネルギーを熱に変えて温度上昇を精密に測定する。そのために、センサー部を50ミリ度という極低温にまで冷却することが必要である。ASTRO-Hでは日米協力により、これらの高い技術的要求を満たして、従来より一桁以上も良い分光性能を実現して、高温ガスの運動が初めて測定可能となる。

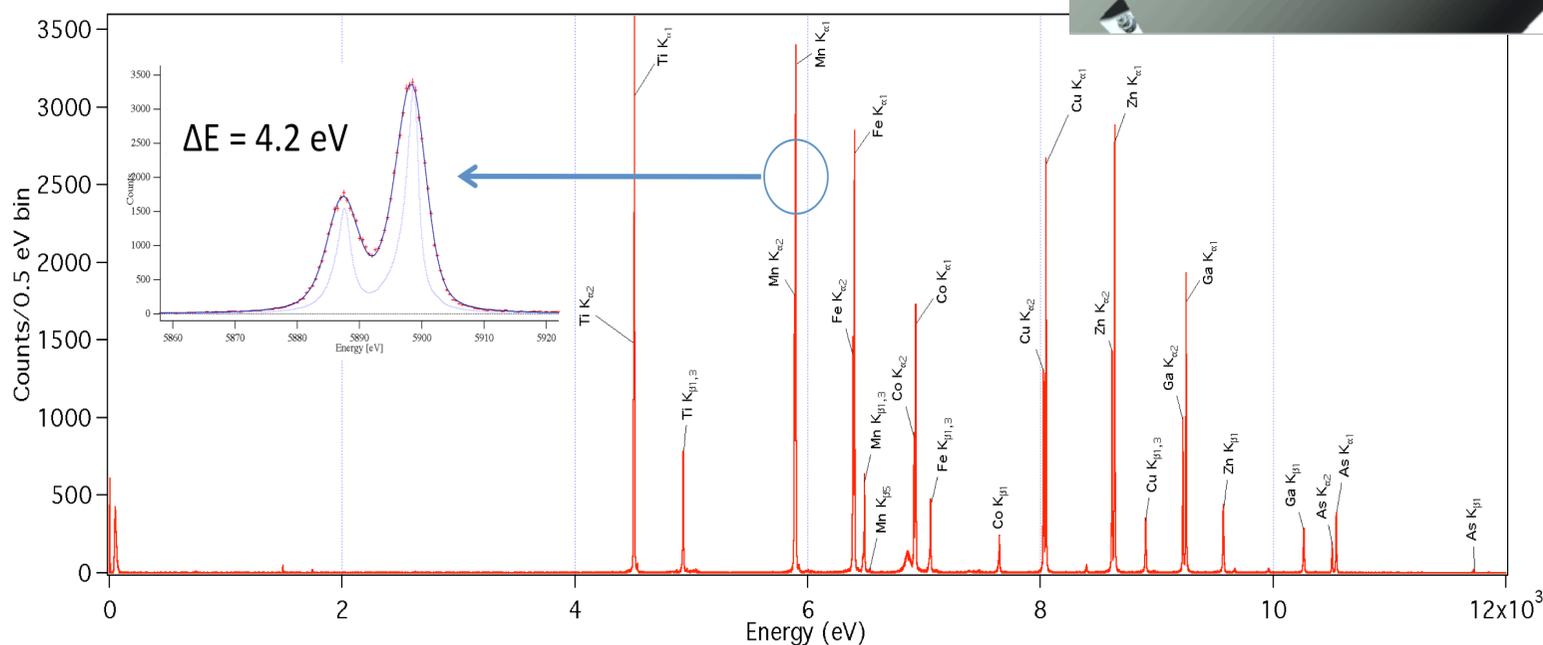
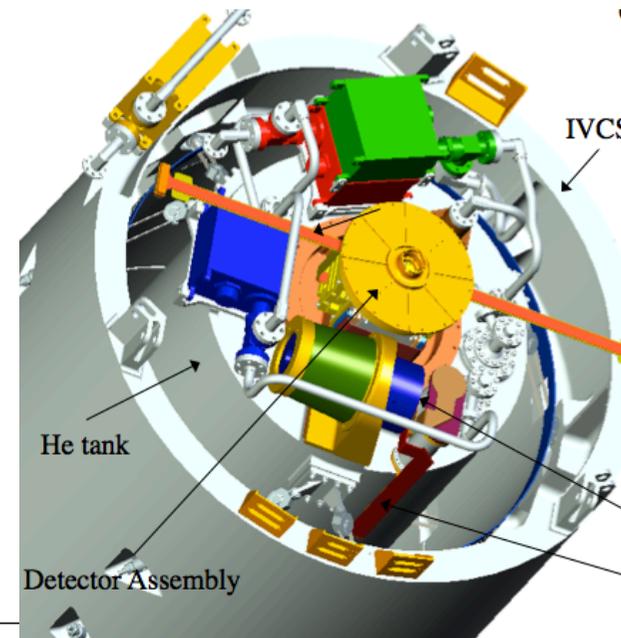


ASTRO-Hの搭載観測装置 : SXS



軟X線分光検出器(SXS/XCS) : 極低温デュワー

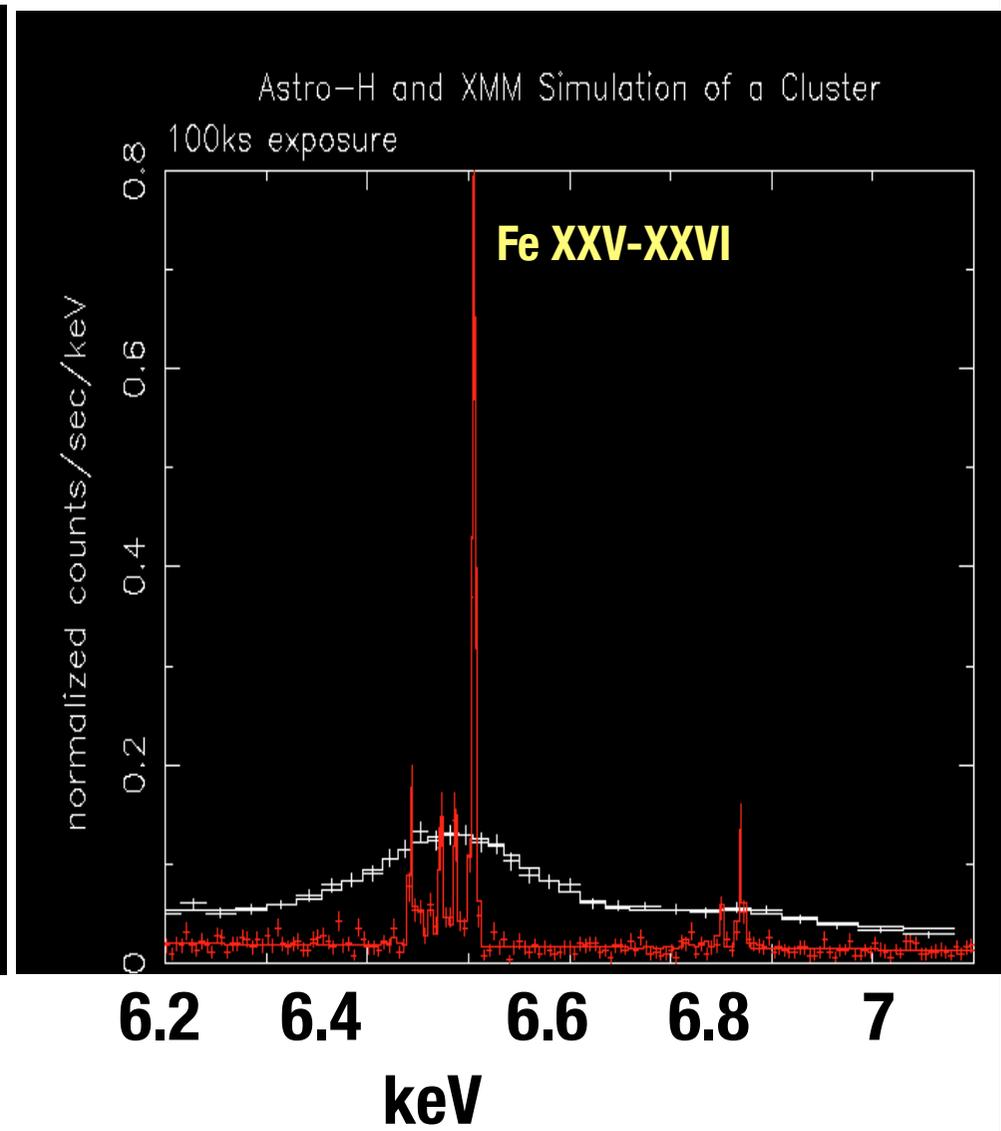
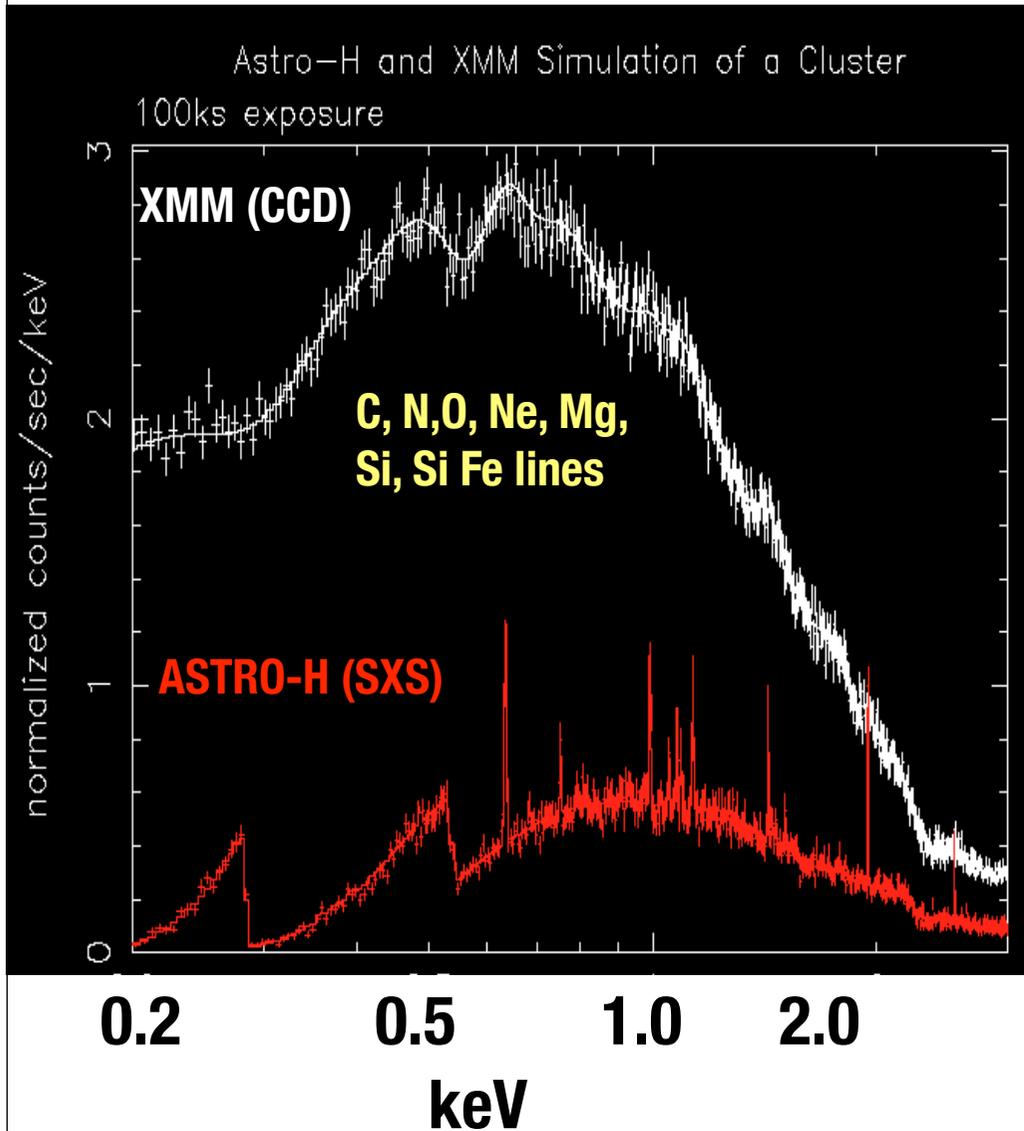
打ち上げの機械環境に耐えつつ、30リットルの液体ヘリウムを3年以上持たせるために、ヘリウムタンクへの侵入熱を数100マイクロW以下に抑えることが要求される。



ASTRO-H/SXSがもたらすブレークスルー



R. Mushotzky (2013)

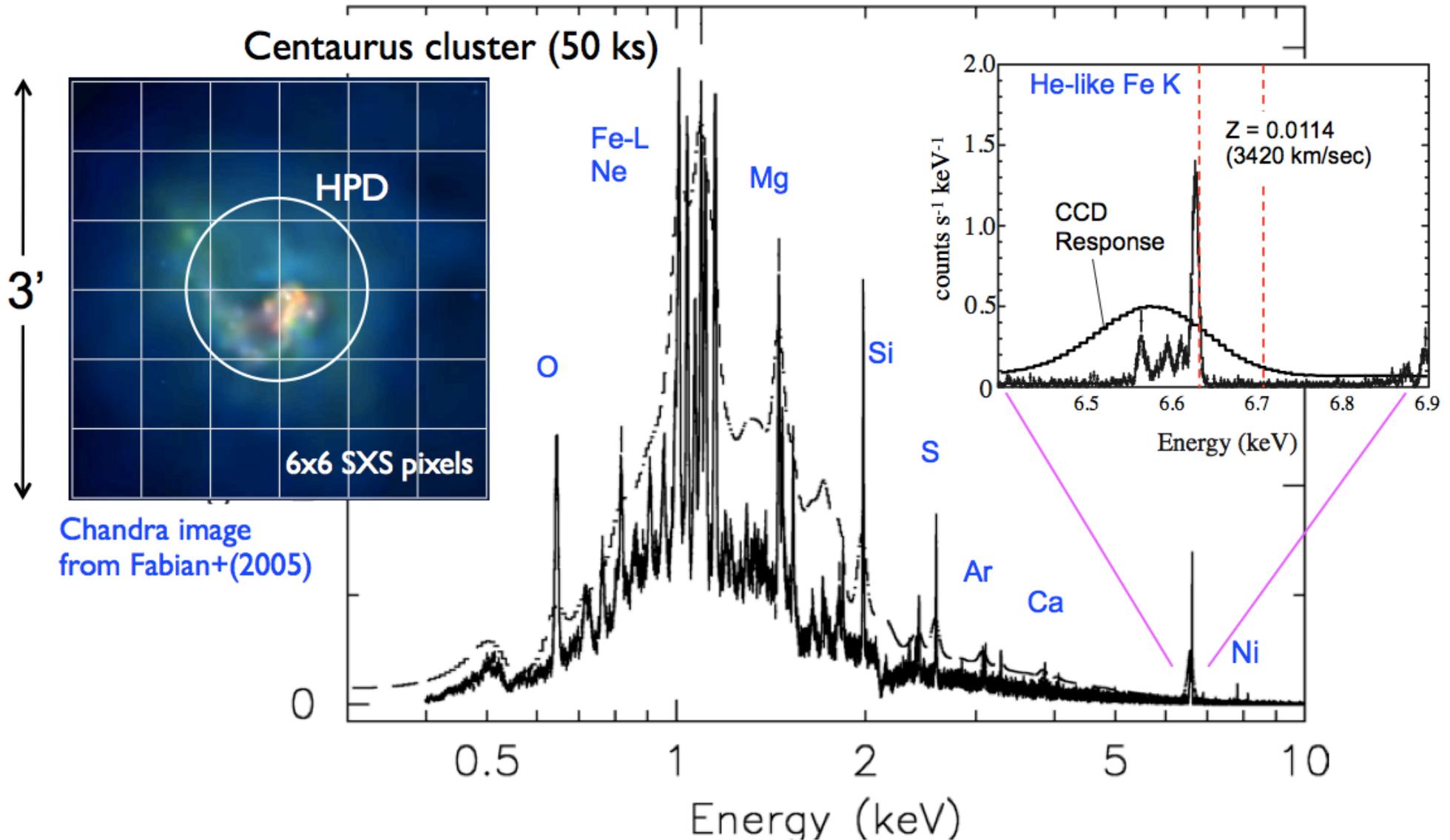


2. ASTRO-H Features --- High Resolution Spectroscopy ---



High Resolution Spectroscopy by a micro-calorimeter array

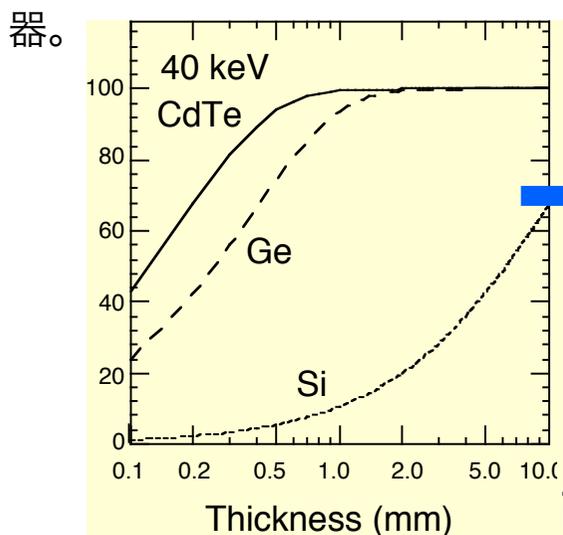
<7 eV (FWHM) @ 6 keV



11. ASTRO-H 搭載観測装置 - Core Technology -

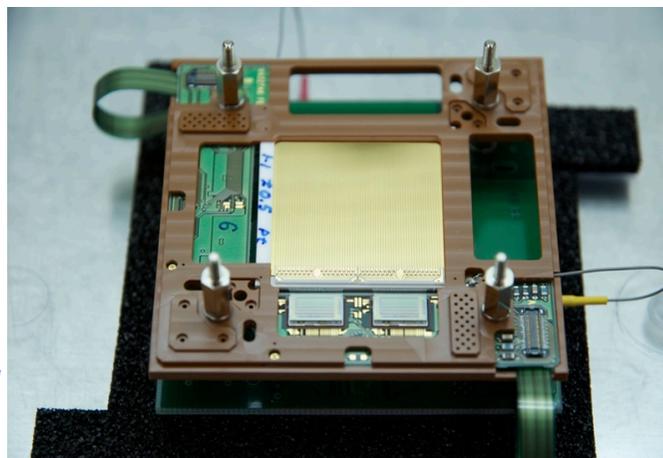
X. 硬X線撮像検出器

高エネルギーのX線やガンマ線の撮像を可能にするものとして開発した、テルル化カドミウム (CdTe) 半導体素子を用いた日本独自の新型検出器。

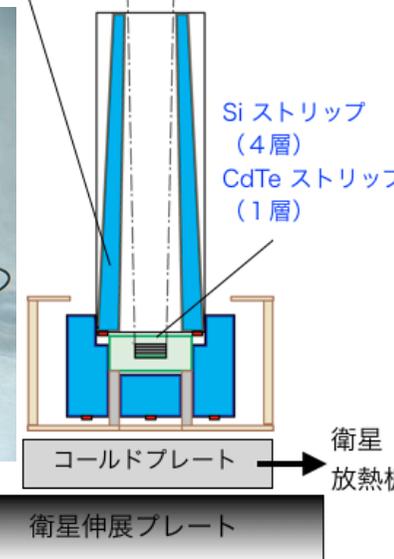


高効率

高エネルギー分解能

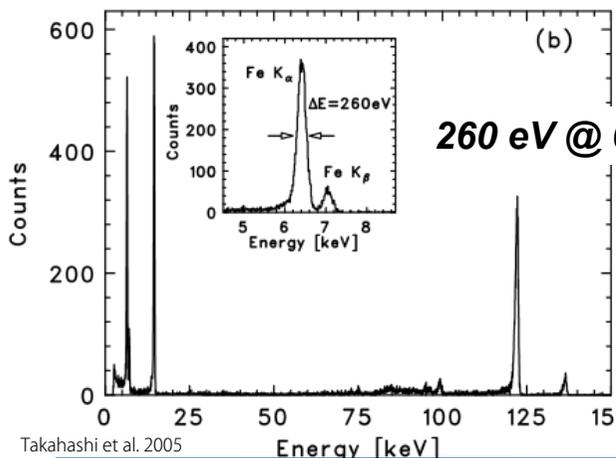


BGO結晶
+アパランシェ
フォトダイオード



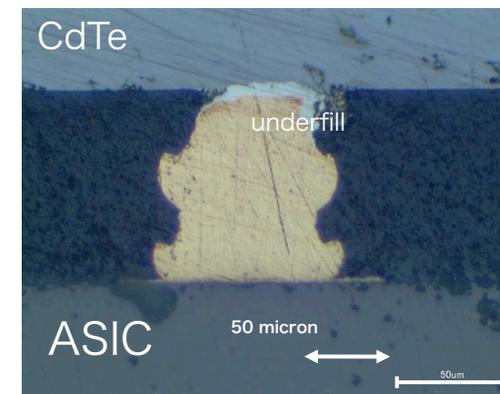
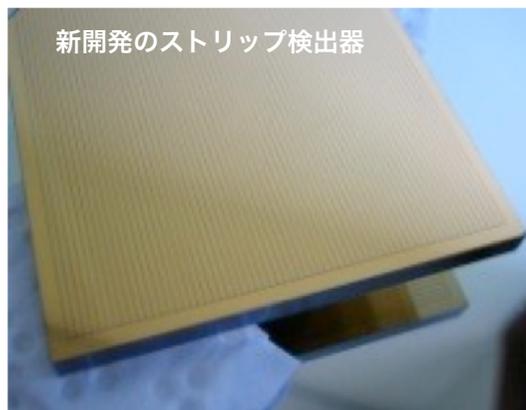
34 mm x 34 mm
0.75 mm thick
250 μm strip pitch

高位置分解能 (ピクセル/ストリップ化)



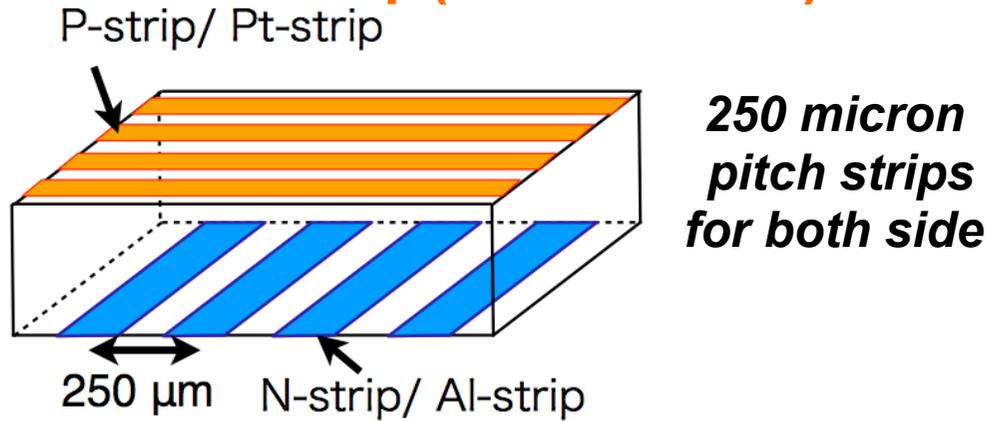
ISAS/東大/
早稲田/埼玉/
Stanford/
広島/CEA他

Takahashi et al. 2005



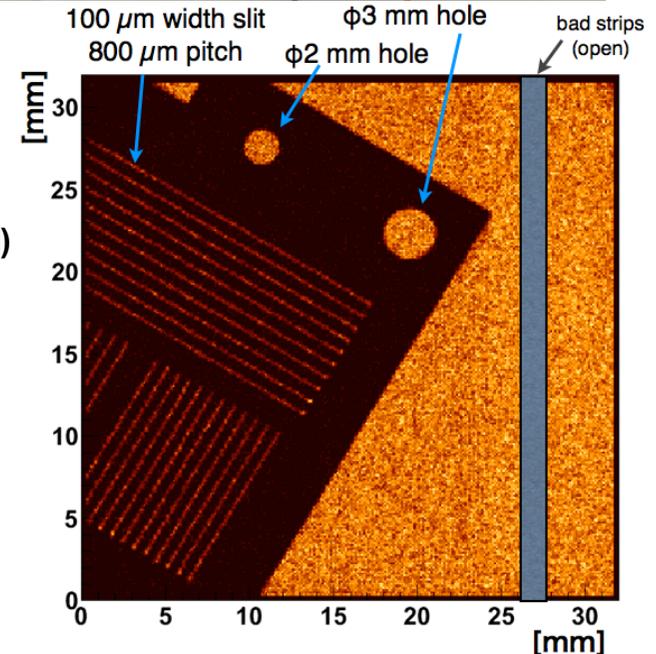
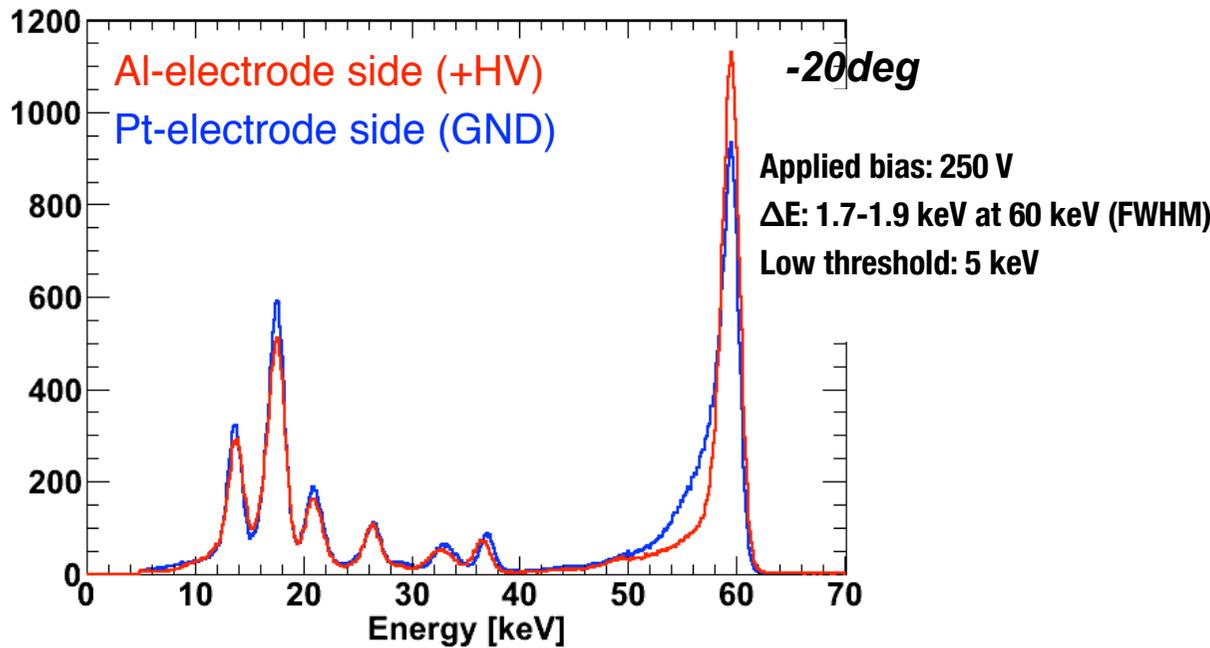
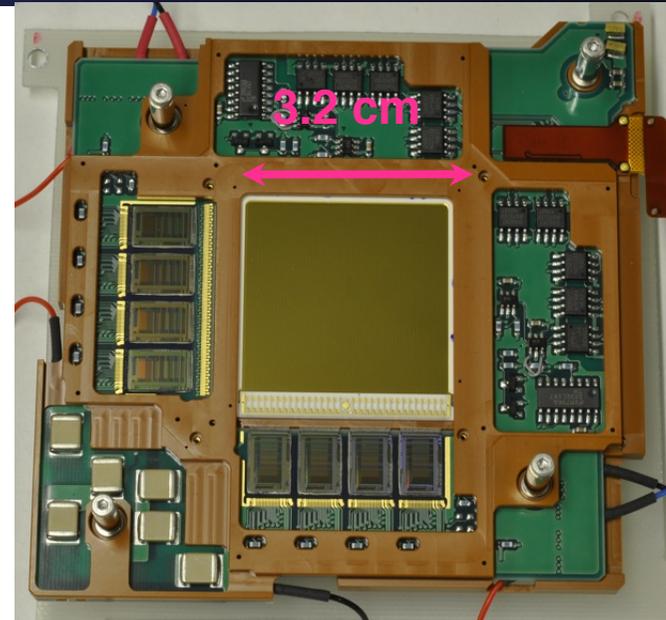
6. Hard X-ray Imager (HXI)

CdTe double side strip (3.2cm x 3.2 cm)



Al-strip (+)
(Schottky barrier)

$2 \times 128 = 256$ channels
($\ll 128 \times 128 = 16,384$)



Watanabe et al., 2011

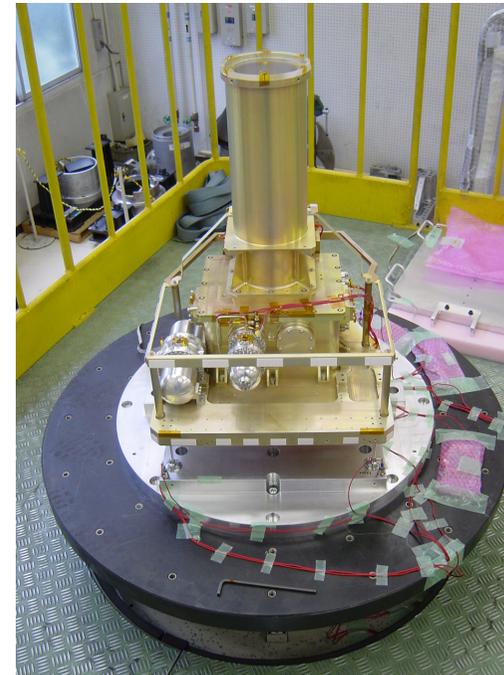
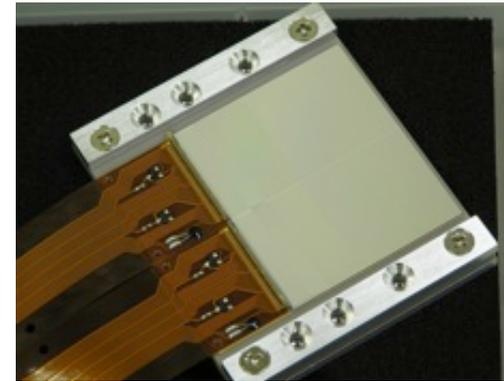
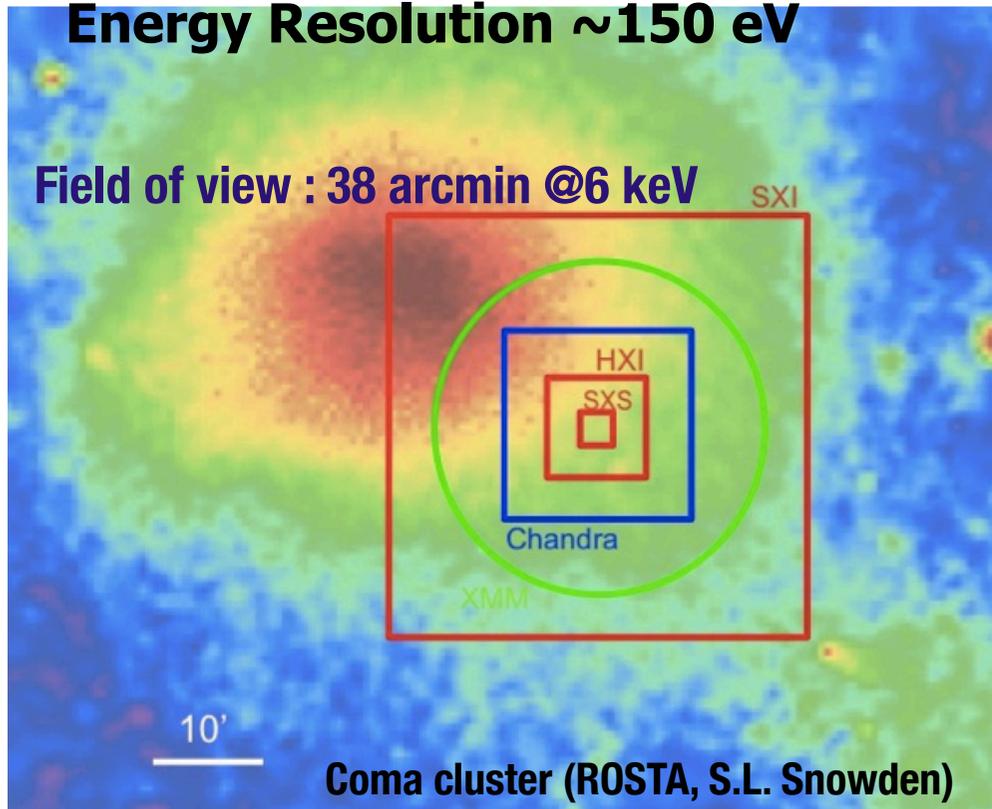
ASTRO-Hの搭載観測装置 : SXI



Large FOV X-ray CCD (F.L. 5.6 m)

4CCD chips/62x62mm²/38arcmin²

Energy Resolution ~150 eV

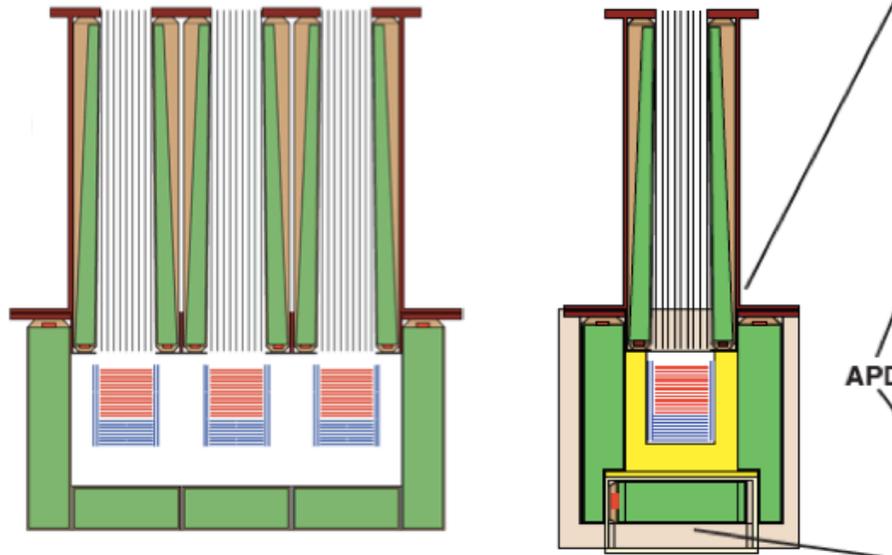


これまでのX線衛星の中で最大の視野を誇る。日本で開発したX線画像取得専用CCD。宇宙での長期間動作に対応。

ASTRO-Hの搭載観測装置 : SGD

X. 軟ガンマ線検出器

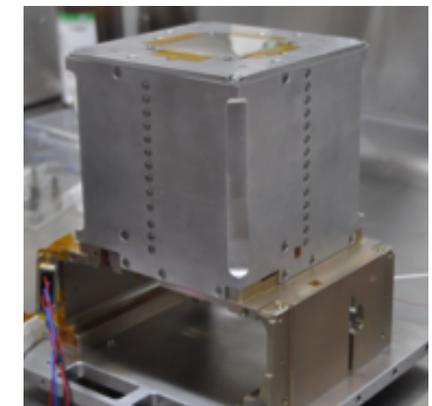
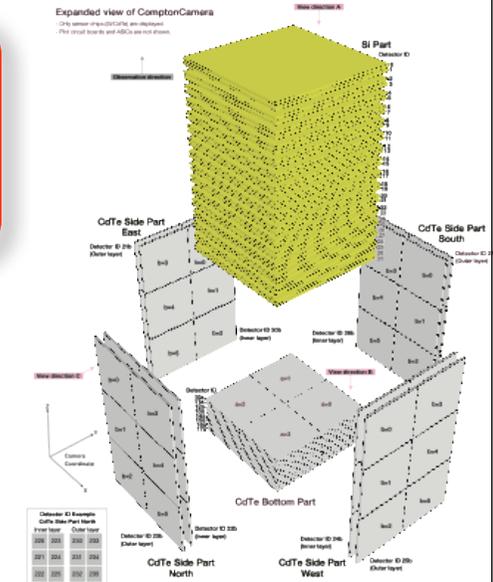
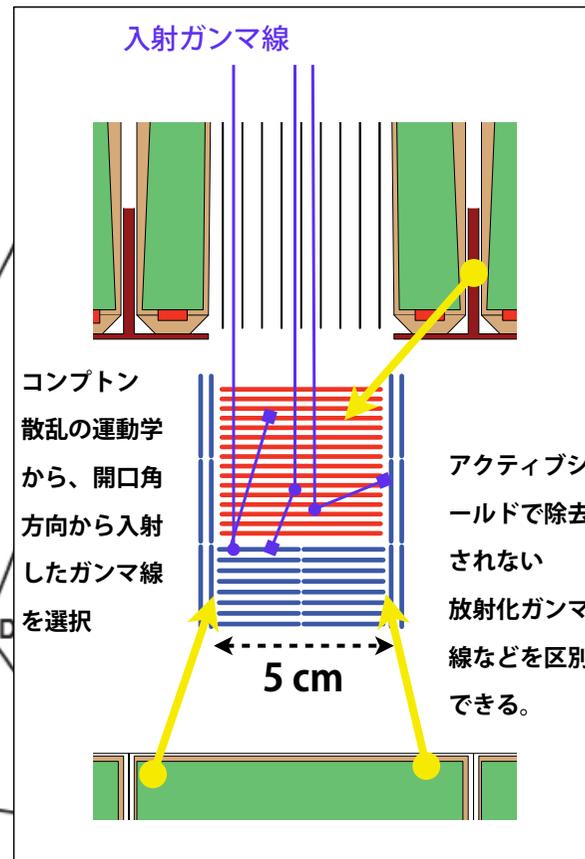
ASTRO-Hの為に発明された「狭視野Si/CdTe半導体コンプトンカメラ」を用いて軟ガンマ線領域での世界最高感度観測を実現するとともに、コンプトン散乱を用いた偏光観測を行う。



Compton Kinematics

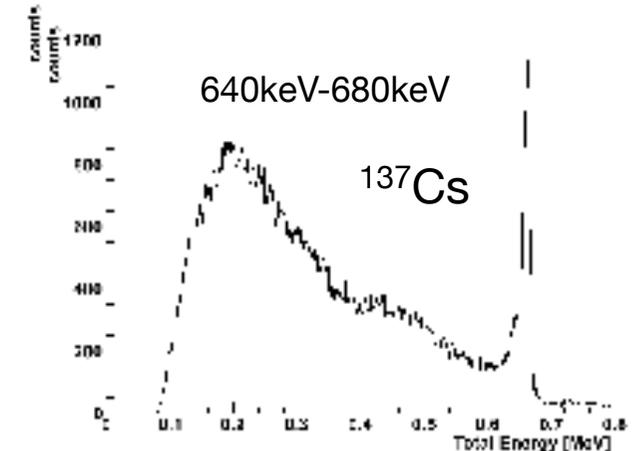
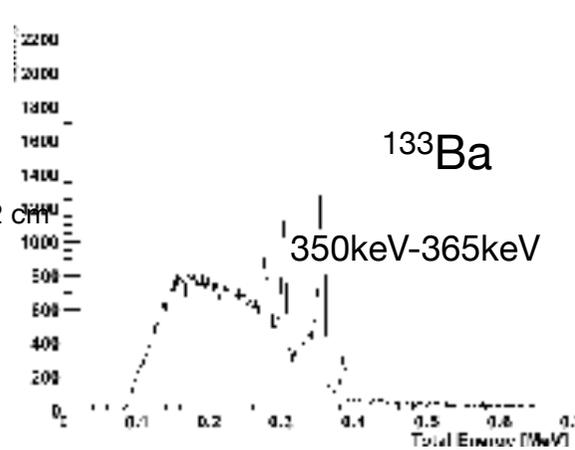
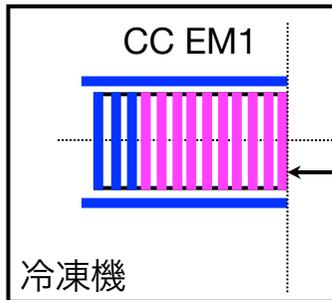
$$\cos \theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

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

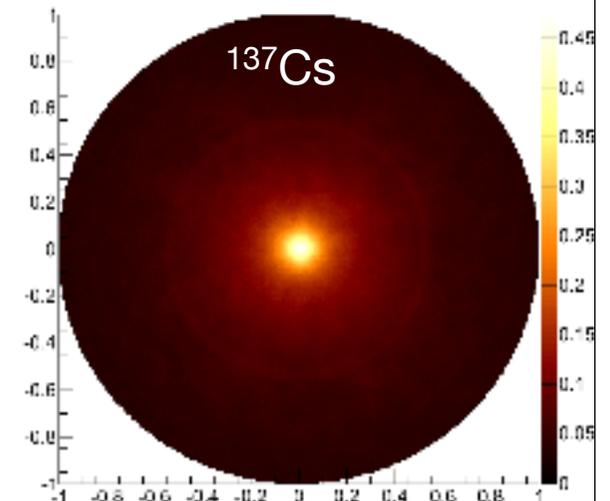
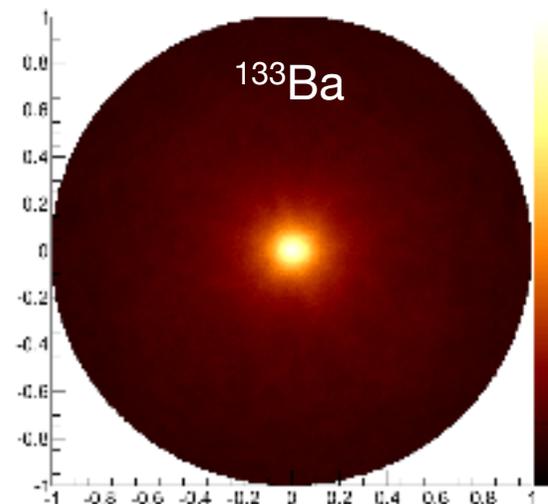
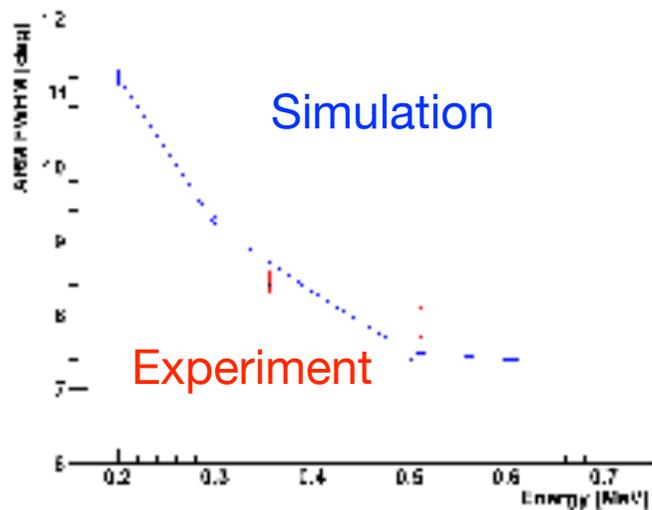


Spectrum and Energy Dependence

- 102cm, ^{133}Ba , ^{137}Cs
- Compton Imaging using the 356keV peak and 662keV peak



Angular Resolution



**energy becomes higher, angular resolution becomes better
(experimental results and simulation results are consistent)**

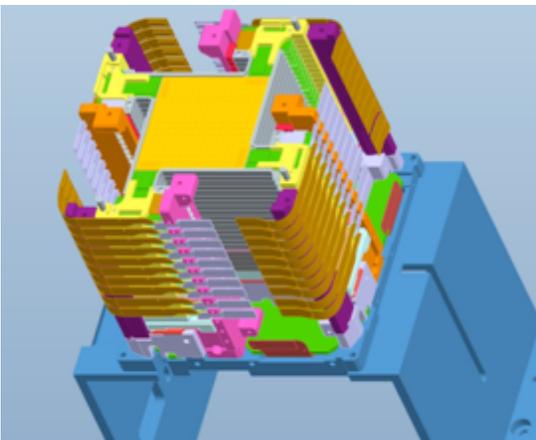
5. ASTRO-H Features --- Wide Band Observation---



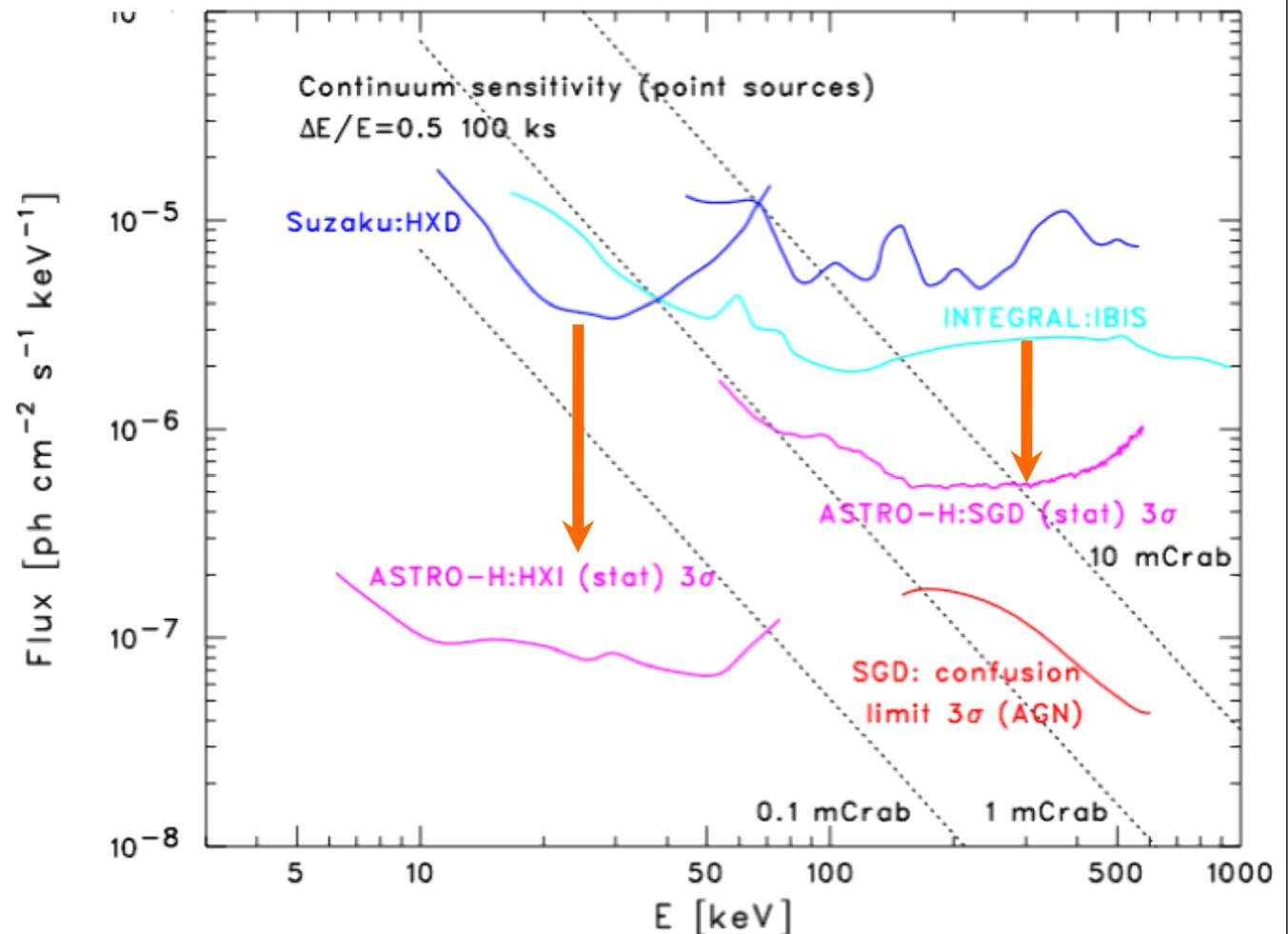
●Pt/C depth-graded multilayer Hard X-ray telescope + Imager



●Si/CdTe Compton Camera (upto 0.6 MeV)



Vast Improvements of the sensitivity in the energy window from 10 keV to 600 keV





ASTRO-H衛星によるサイエンス

ASTRO-Hがもたらす科学成果



銀河団の観測

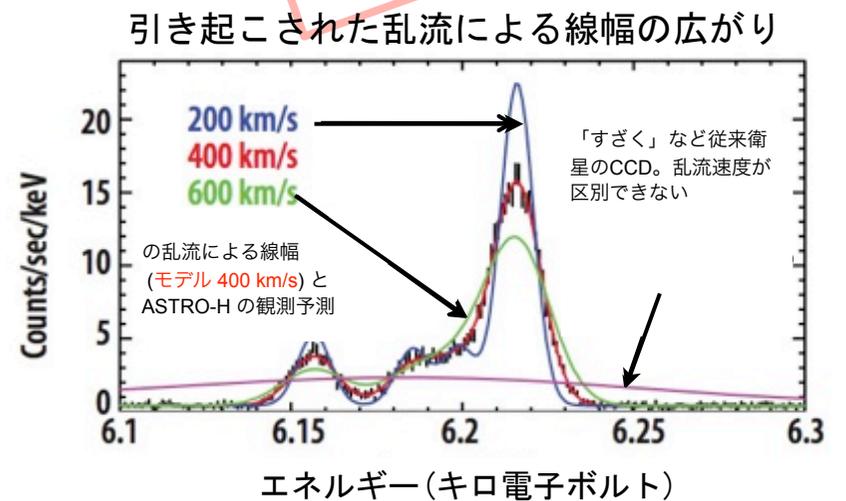
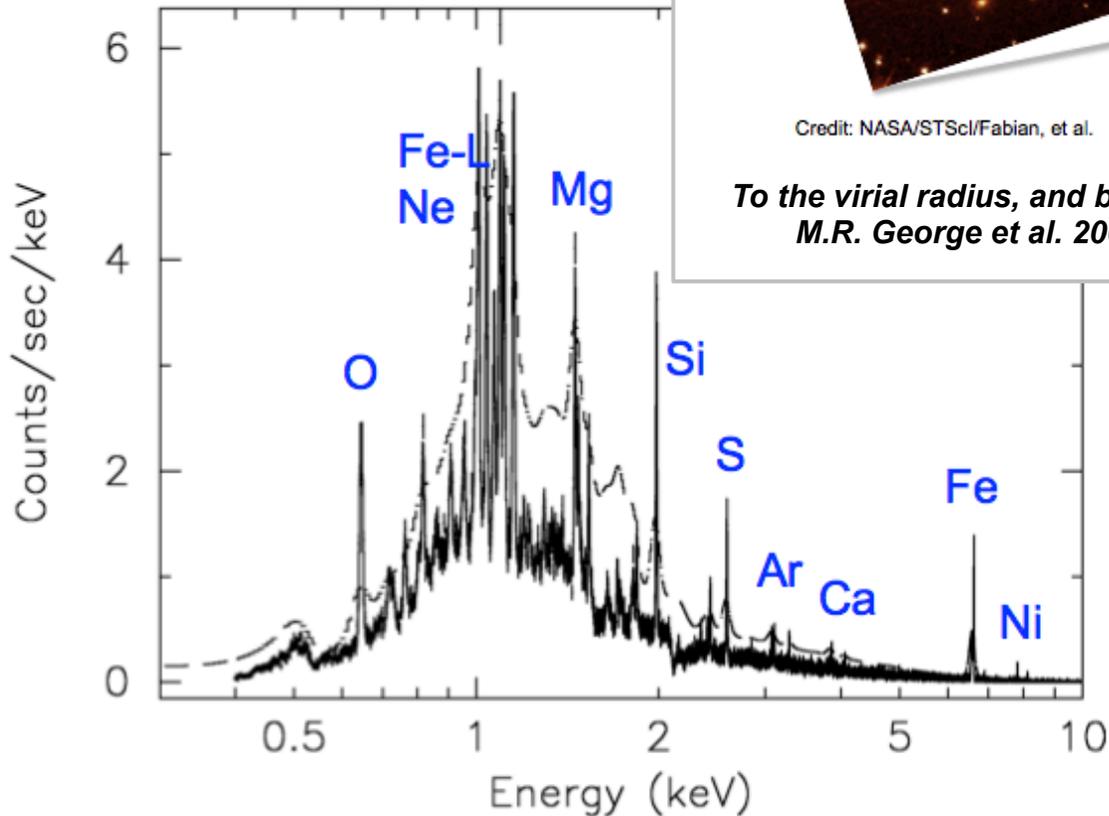
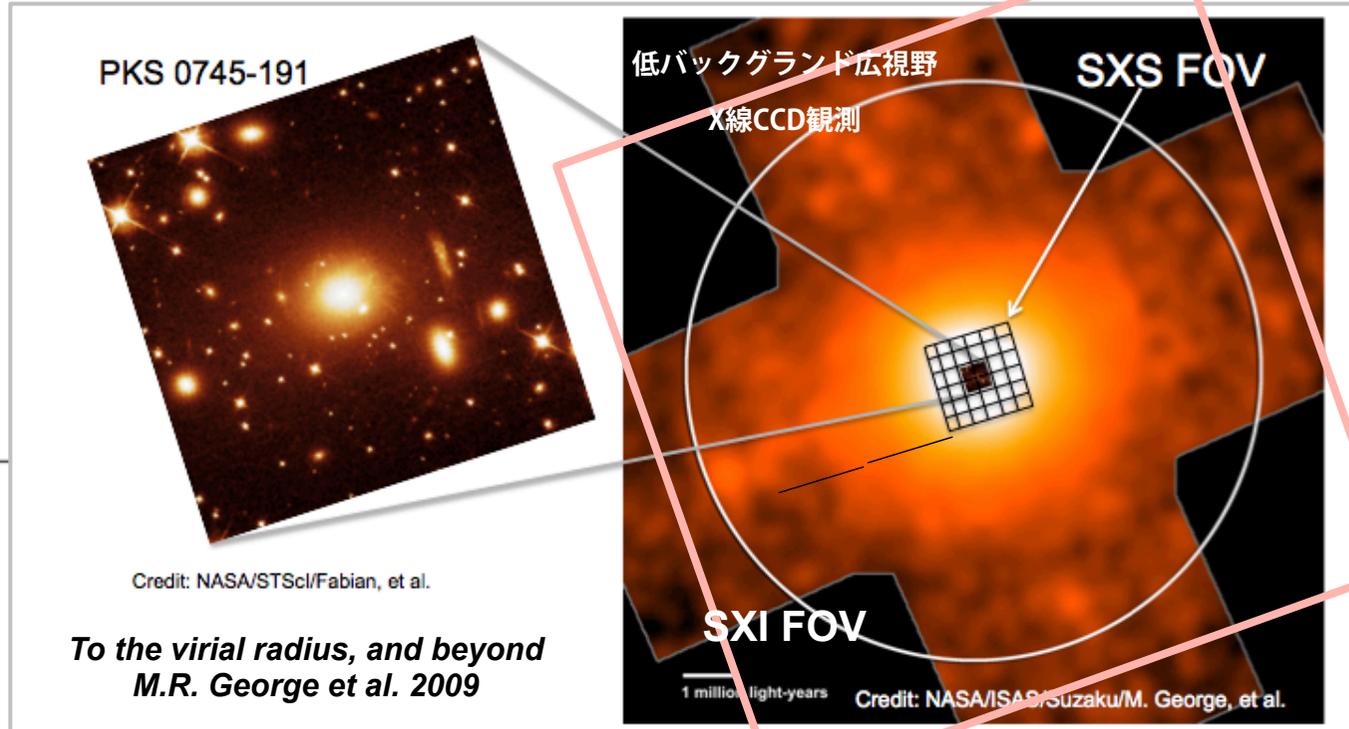
銀河団ダイナミクス

(乱流、衝突)

非熱的放射

外縁部の放射 (構造形成の現場)

重元素分布 / 温度分布





obtain dynamical information about the ICM from line shifts, widths. First ever probe of:

- **plasma viscosity**
- **turbulent pressure support**
- **merger dynamics**
- **motions induced by AGN feedback**

measure metal abundances

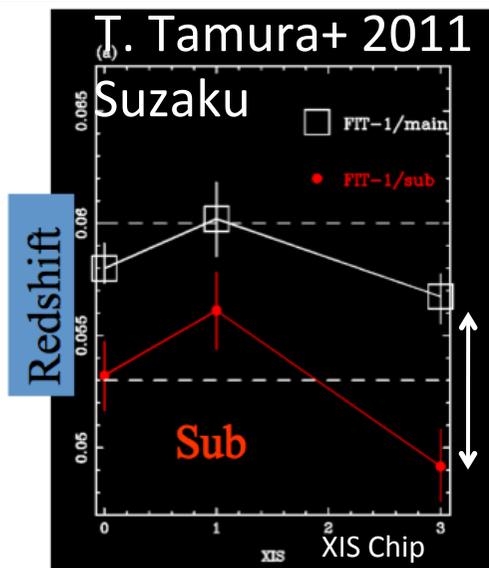
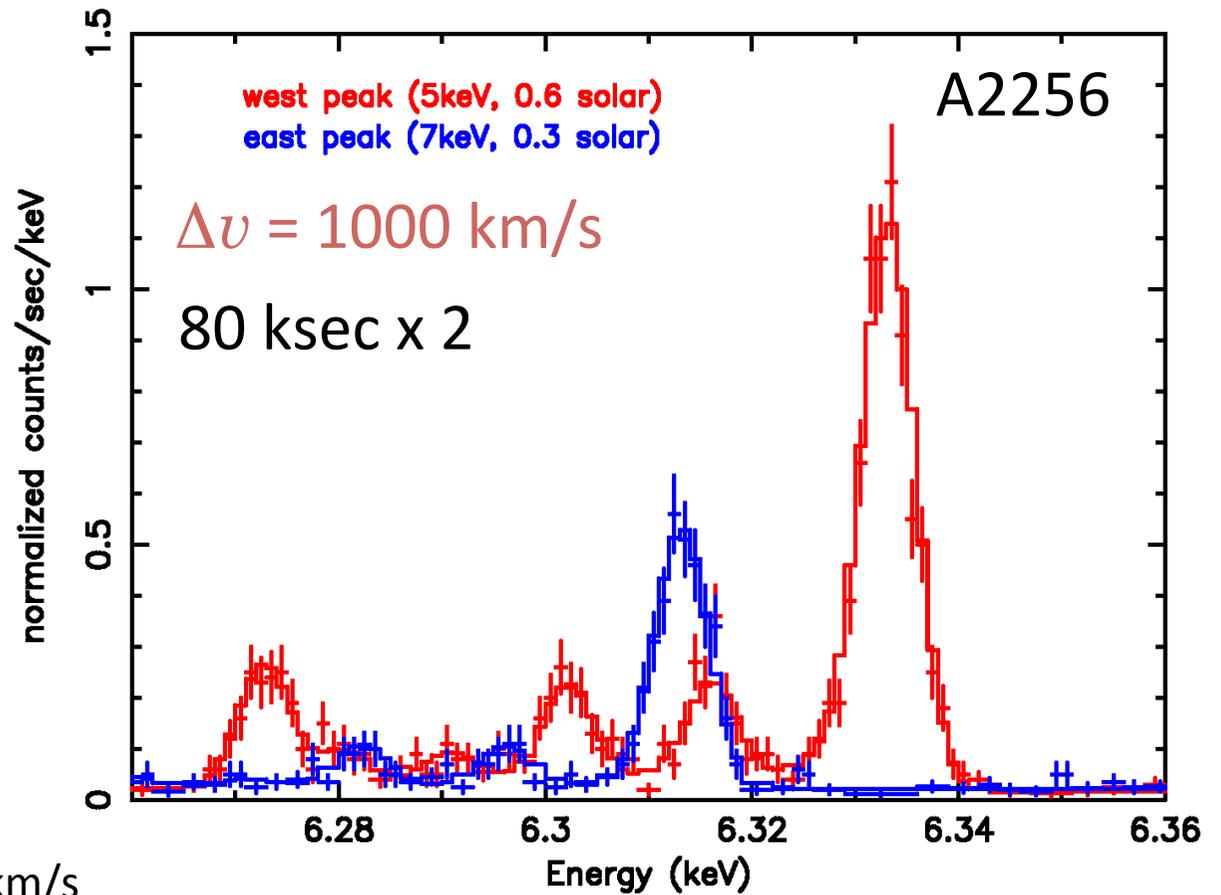
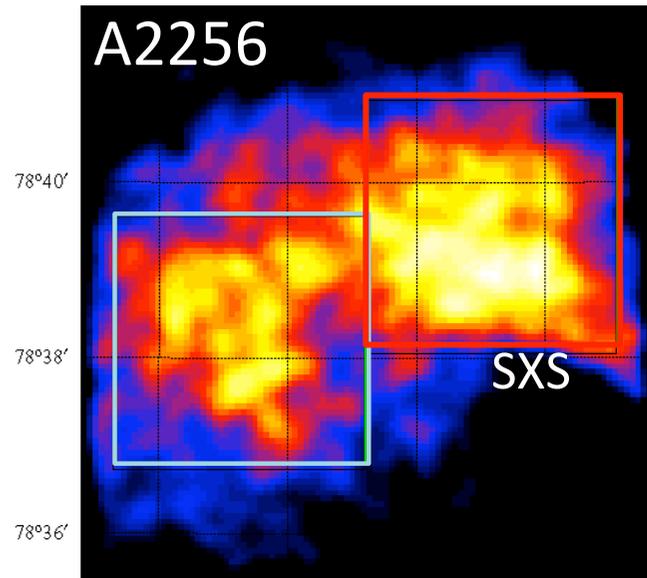
**→ determine integrated chemical enrichment history;
constrain SN yields**

Power of ASTRO-H : Cluster dynamics: Gas bulk motion



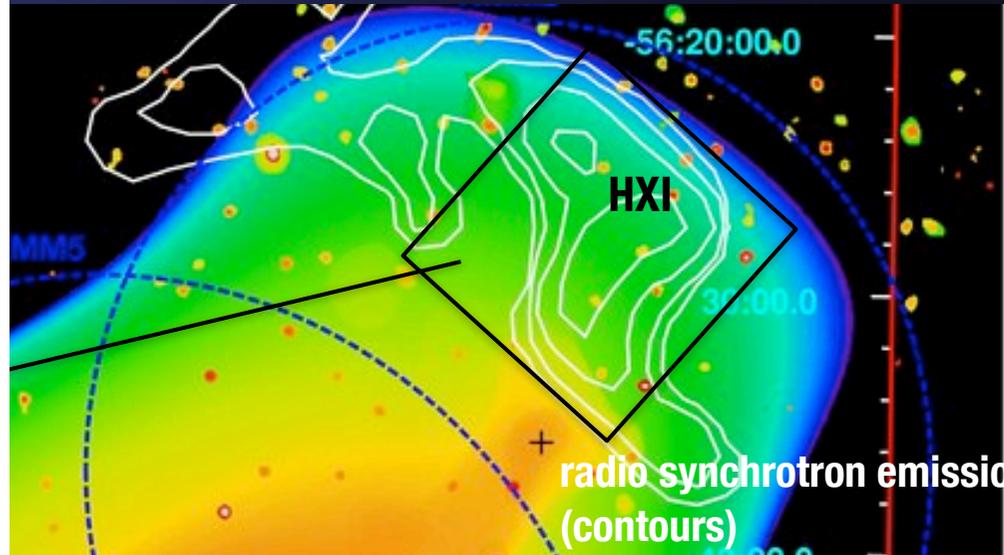
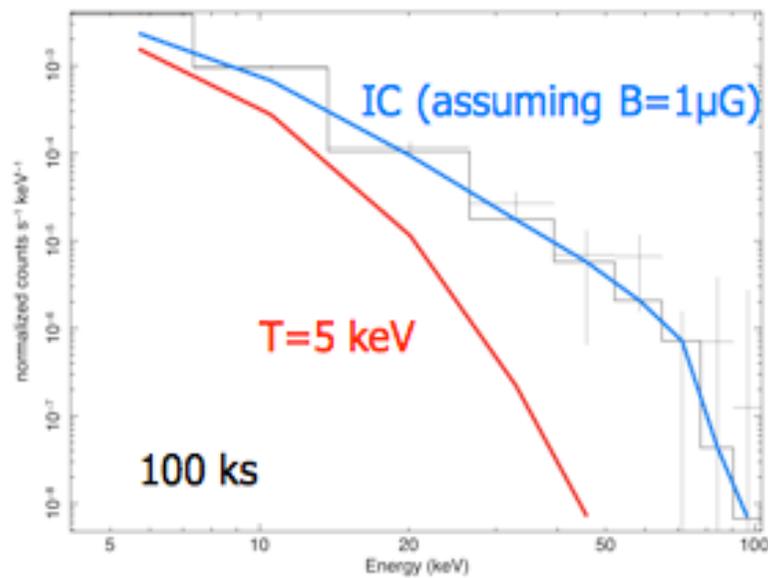
- With high-resolution spectroscopy, the velocity of matter can be derived from the energy shift and width of emission lines

+78°42' 17^h04^m30^s 17^h04^m 17^h03^m30^s 17^h03^m



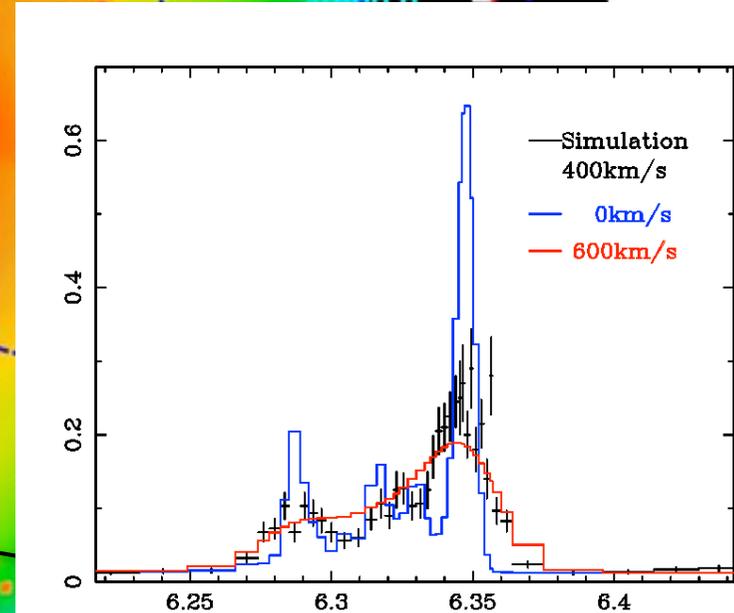
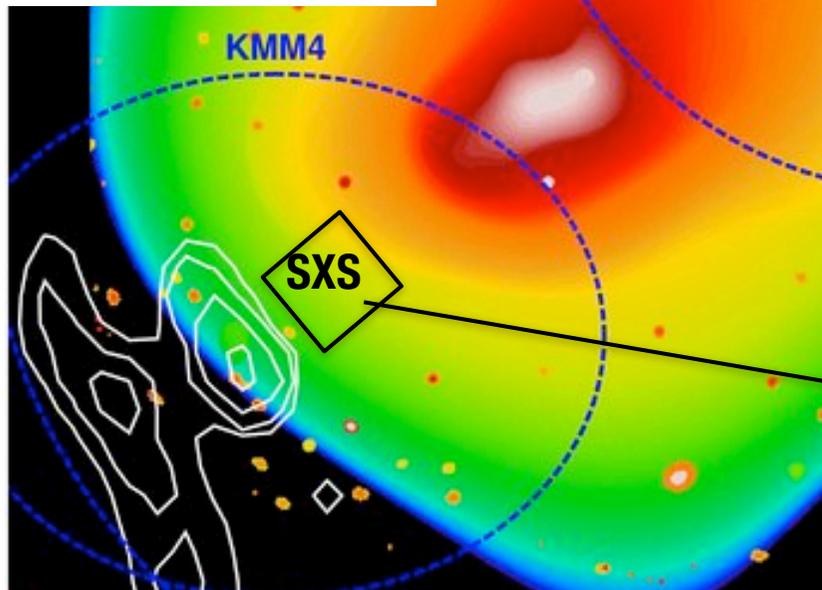
SXS spectra of a merging cluster A2256 assuming 1000 km/s difference in the line-of-sight velocity

Power of ASTRO-H : Cluster dynamics: Non-thermal emission



Non-thermal hard X-ray emission from relativistic particles

A3667
z=0.05



Line broadening due to turbulent gas motion

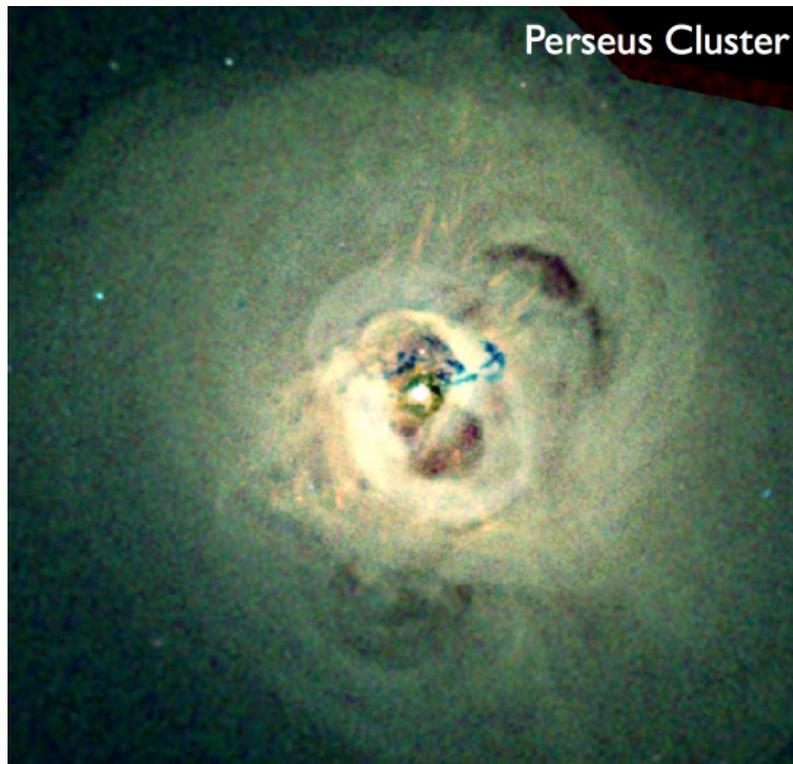
XMM (color)
Finoguenov+10

Markevitch, Akamatsu, and the ASTRO-H Cluster STF

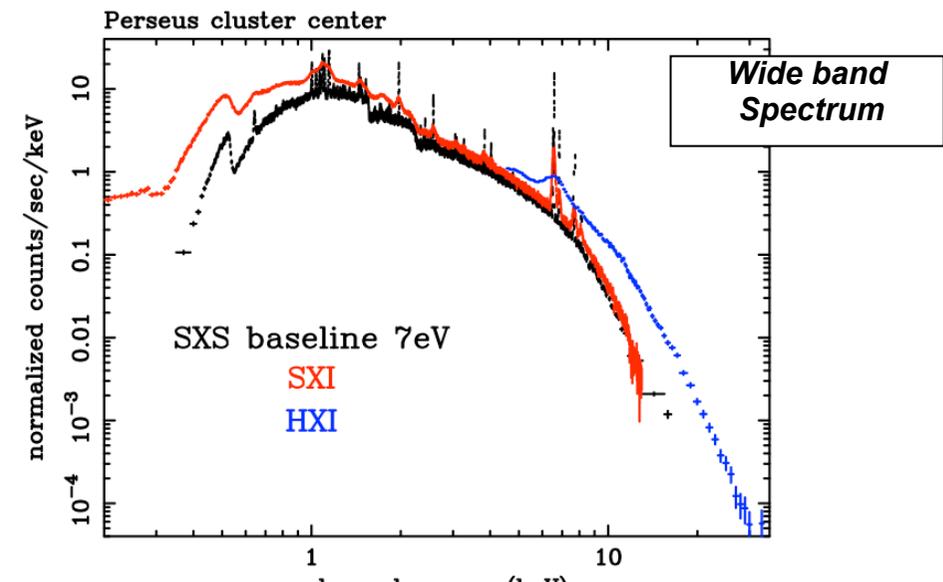
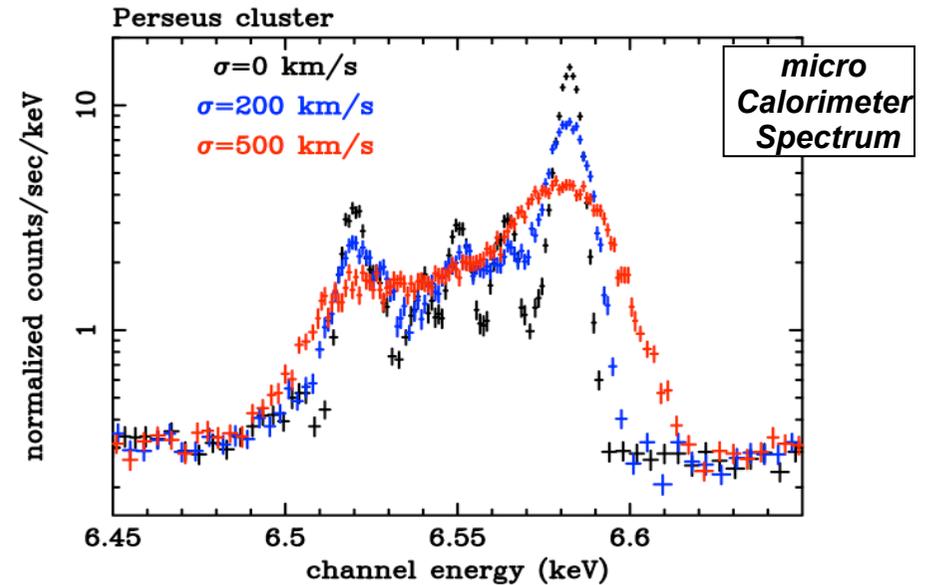
Power of ASTRO-H : Cluster dynamics



The Perseus Cluster, the brightest extragalactic extended X-ray sky in the sky, is a massive, relatively relaxed system at a distance of 68 Mpc ($z = 0.0179$)

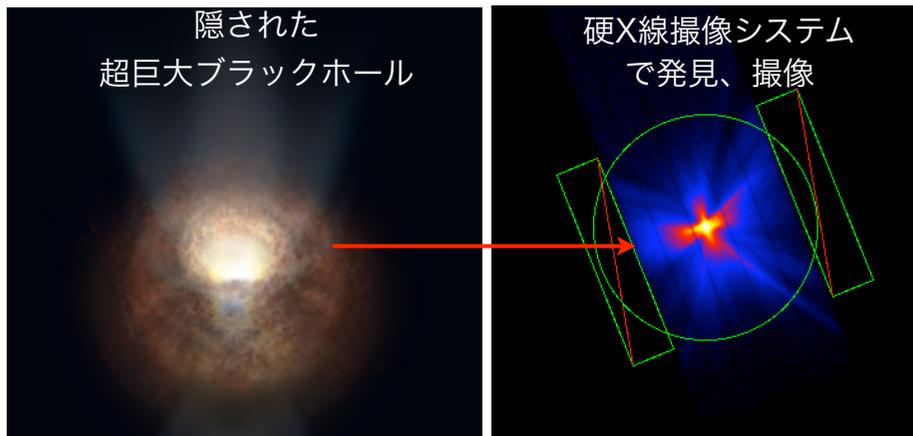


Perseus cluster ($r < 2'$, 100ks)
vapec 3T (0.6keV, 2.6keV, 6.1keV)

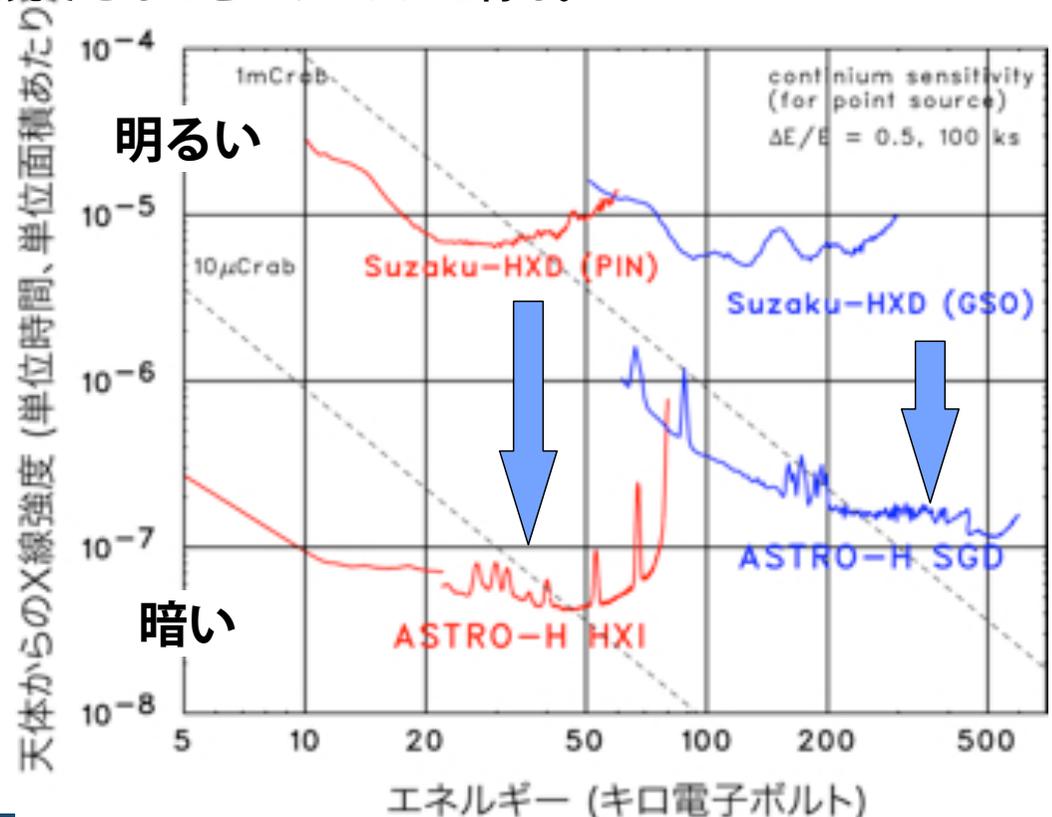


巨大ブラックホールの観測

- ・ 透過力の高い硬X線放射 (10 キロ電子ボルト以上) の集光、撮像により、個々の天体の微弱な放射を切り出すことが可能とする。
- ・ 10-50 keVで「すざく」の硬X線検出器 (HXD) の100倍もの感度向上。最高で80keVまでの撮像能力
- ・ これまでのX線衛星では不可能だった、厚い周辺物質によって隠された巨大ブラックホールからの放射を検出。その進化と銀河形成における役割を研究できるほどのサンプルを得る。



- ・ 明るい活動銀河核については、数100 keVまでの正確なスペクトルを取得

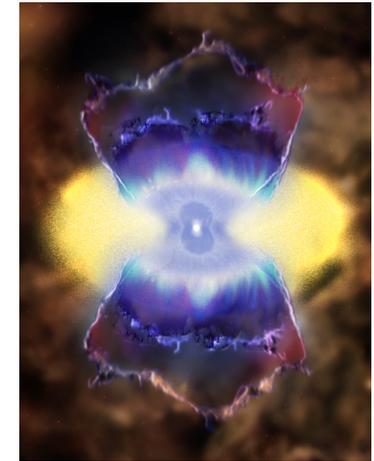


Power of ASTRO-H --- Outflow---

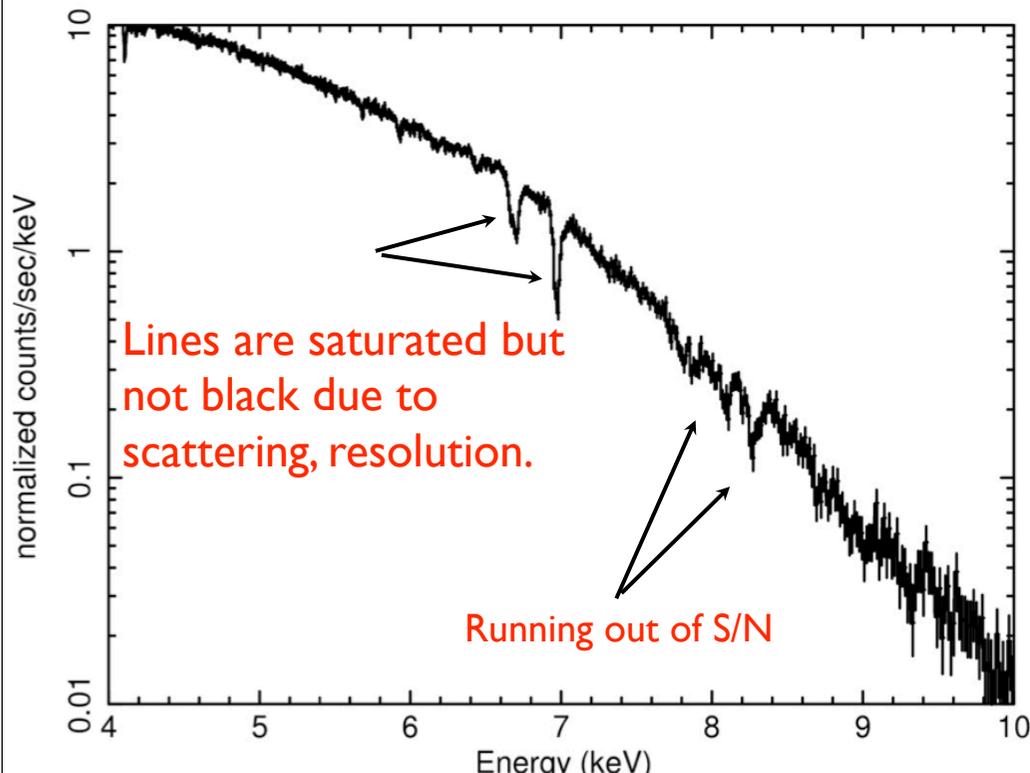


GRO J1655-40 (Black Hole)

The superior resolution of SXS in the Fe K band enables the unambiguous detection of weak and narrow lines from a wind.

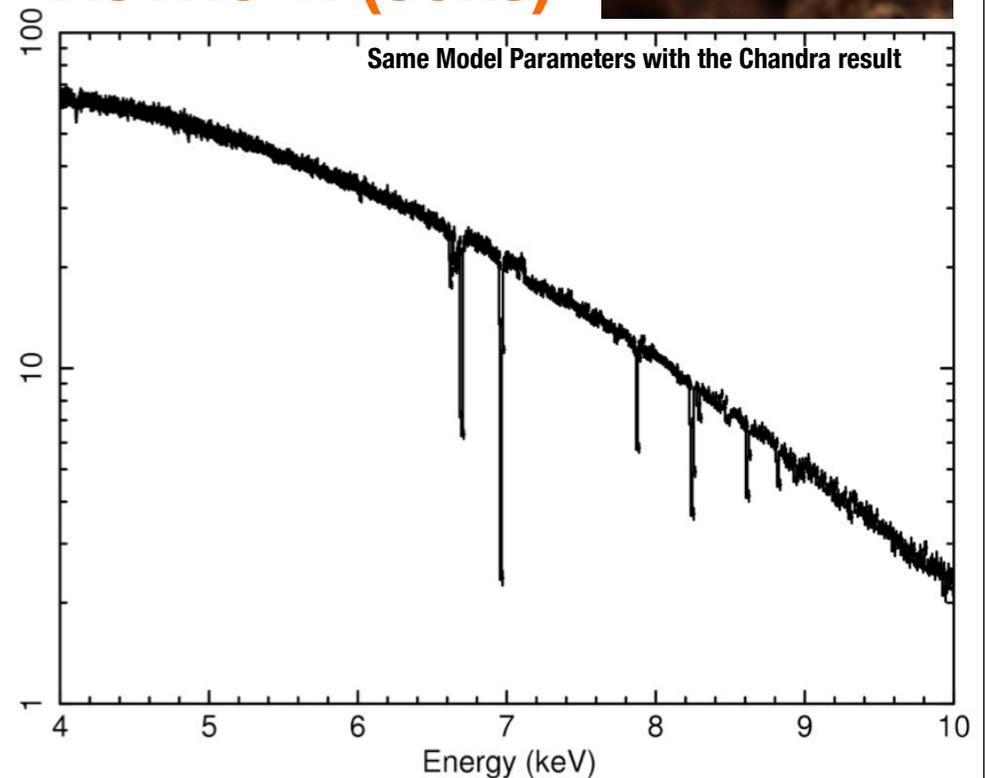


Chandra



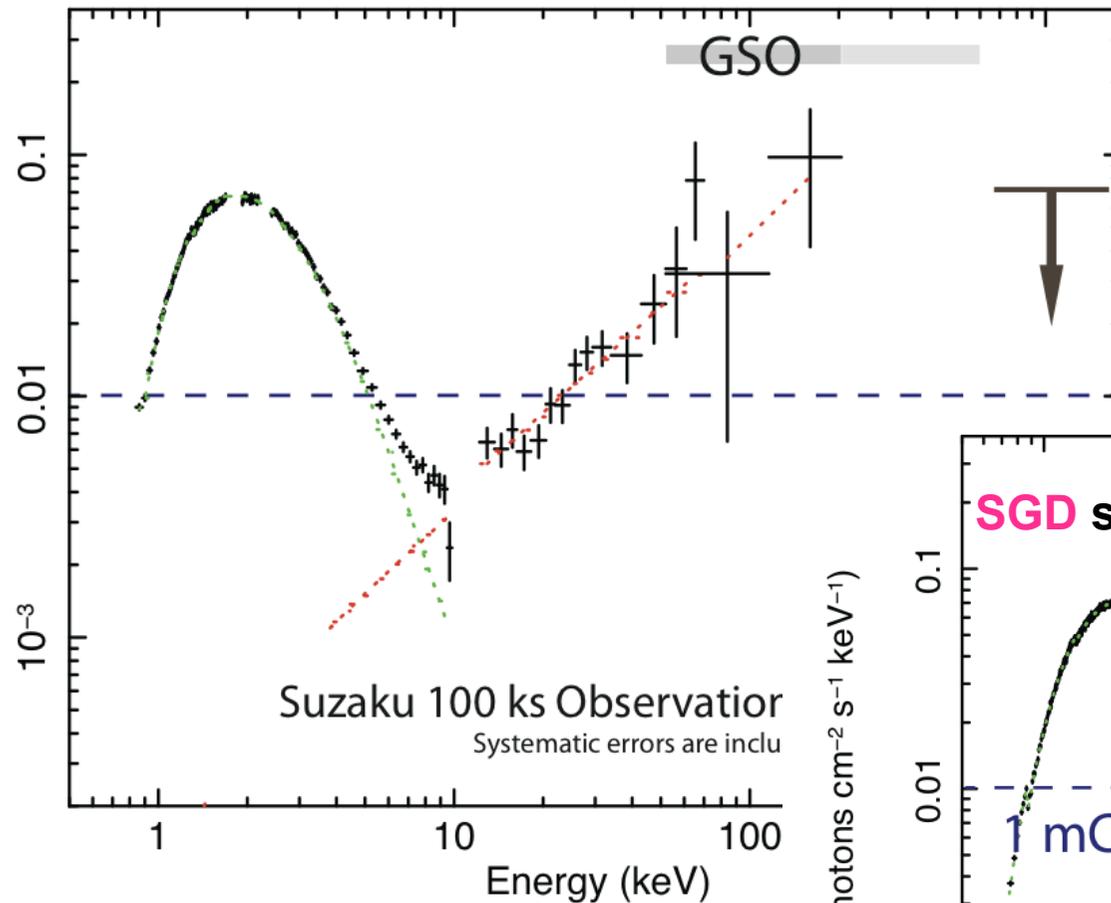
(Simulation by J. Miller)

ASTRO-H (50ks)

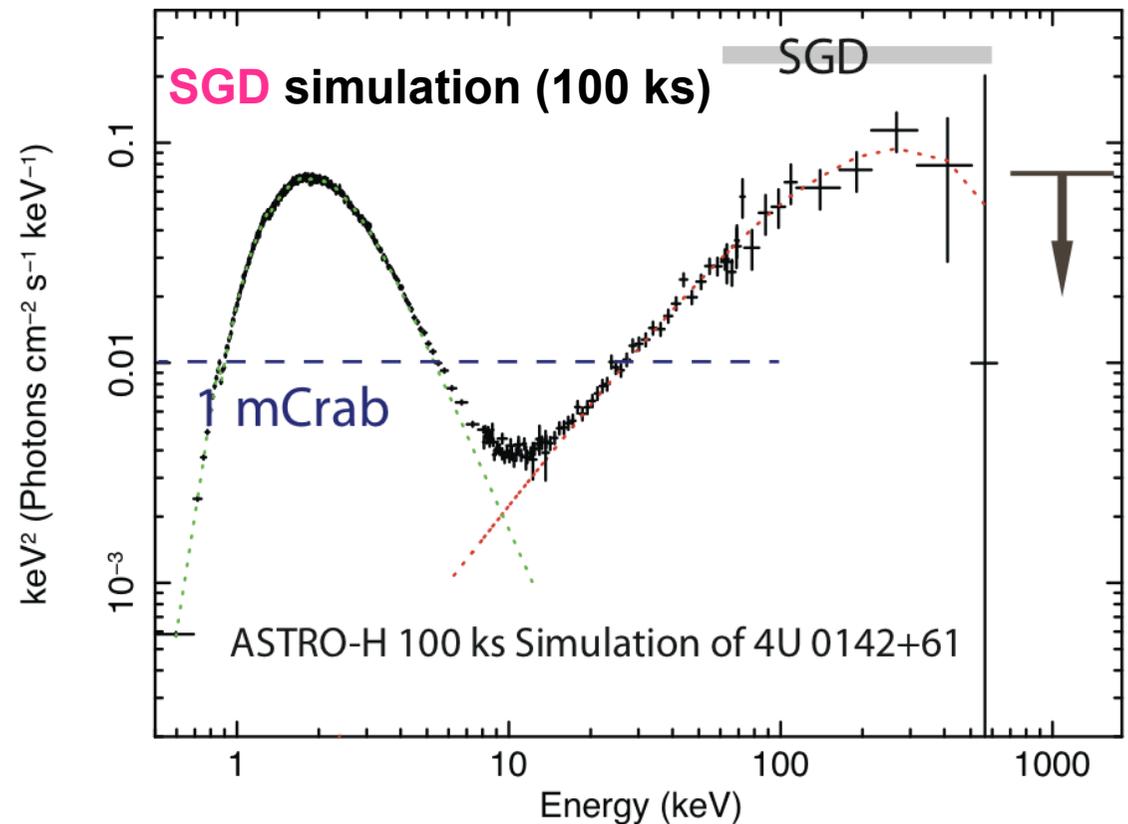


ASTRO-H SXS can handle 250 cts/s

SGD Performance - Magnetar 4U 0142+61



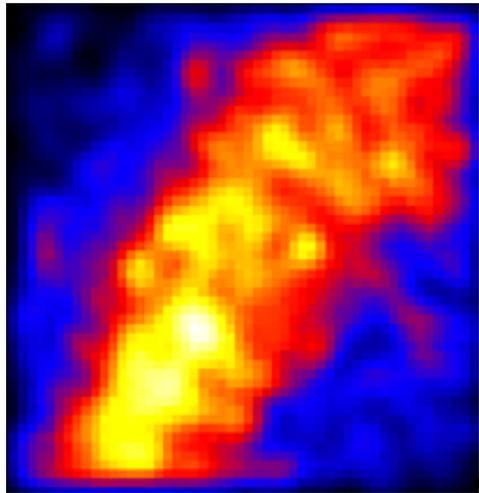
SGD will be able to measure spectra up to 600 keV with higher quality, and will constrain the nature of the hard component.



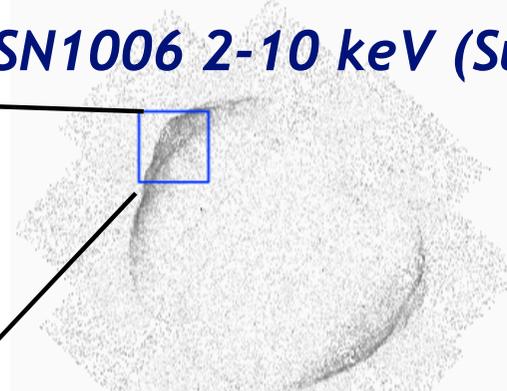
(Simulation by T. Enoto)

超新星残骸の観測

ASTRO-H 10-40 keV (100ks)

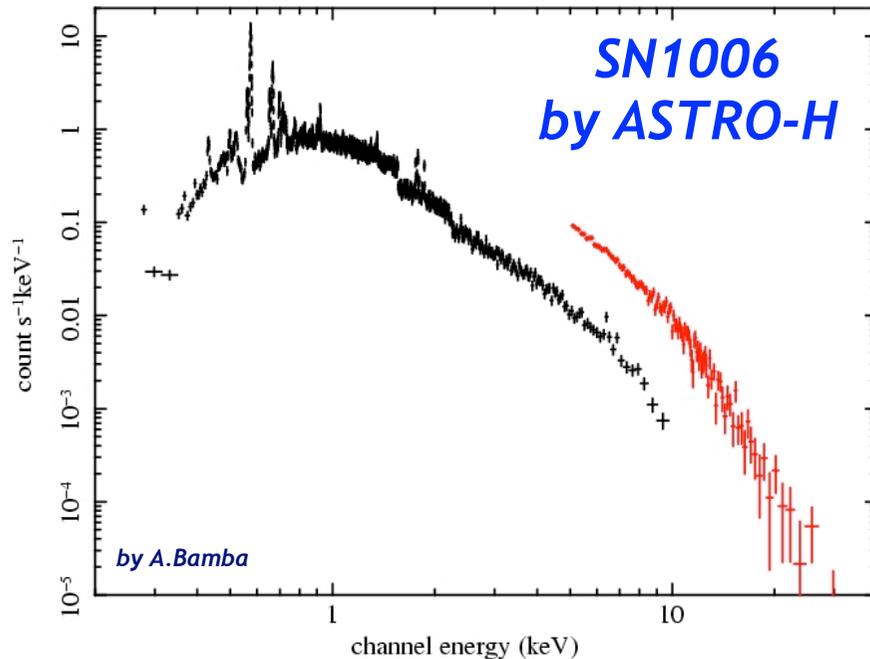


SN1006 2-10 keV (Suzaku)

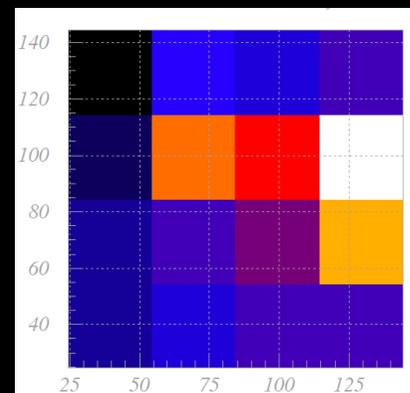


最大エネルギー宇宙線の加速現場
 E_{max} にいたるまでのスペクトル

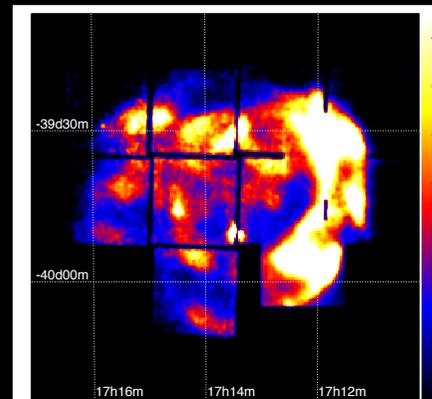
超新星残骸で、最大エネルギー宇宙線の加速現場の撮像観測を行い、熱的放射と非熱的放射を同時観測することで高エネルギー粒子(宇宙線)がエネルギーを獲得する現場の物理状態を解明する。



RXJ1713
Suzaku at 40 keV



ASTRO-H at 40 keV



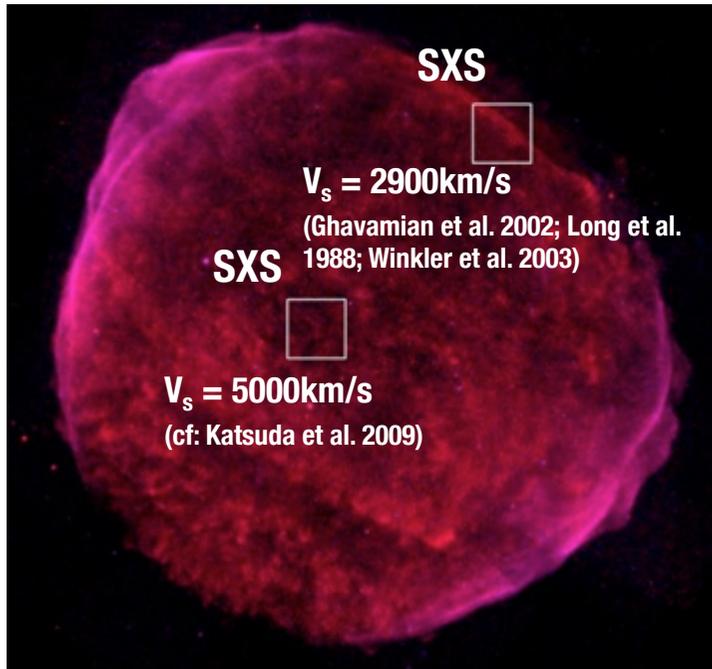
Power of ASTRO-H : SNR



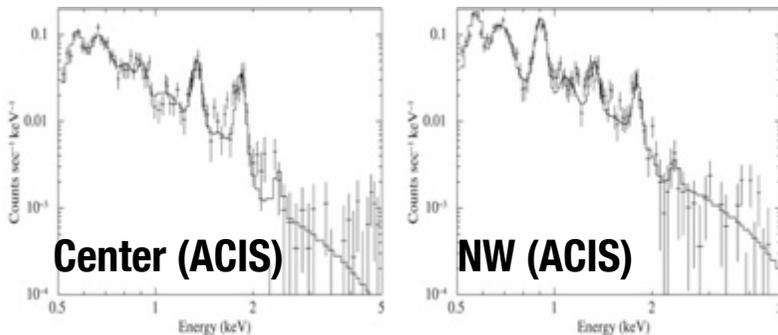
Line shift (V_s) and broadening (T_{ion}) clearly seen

Simulation by S. Katsuda

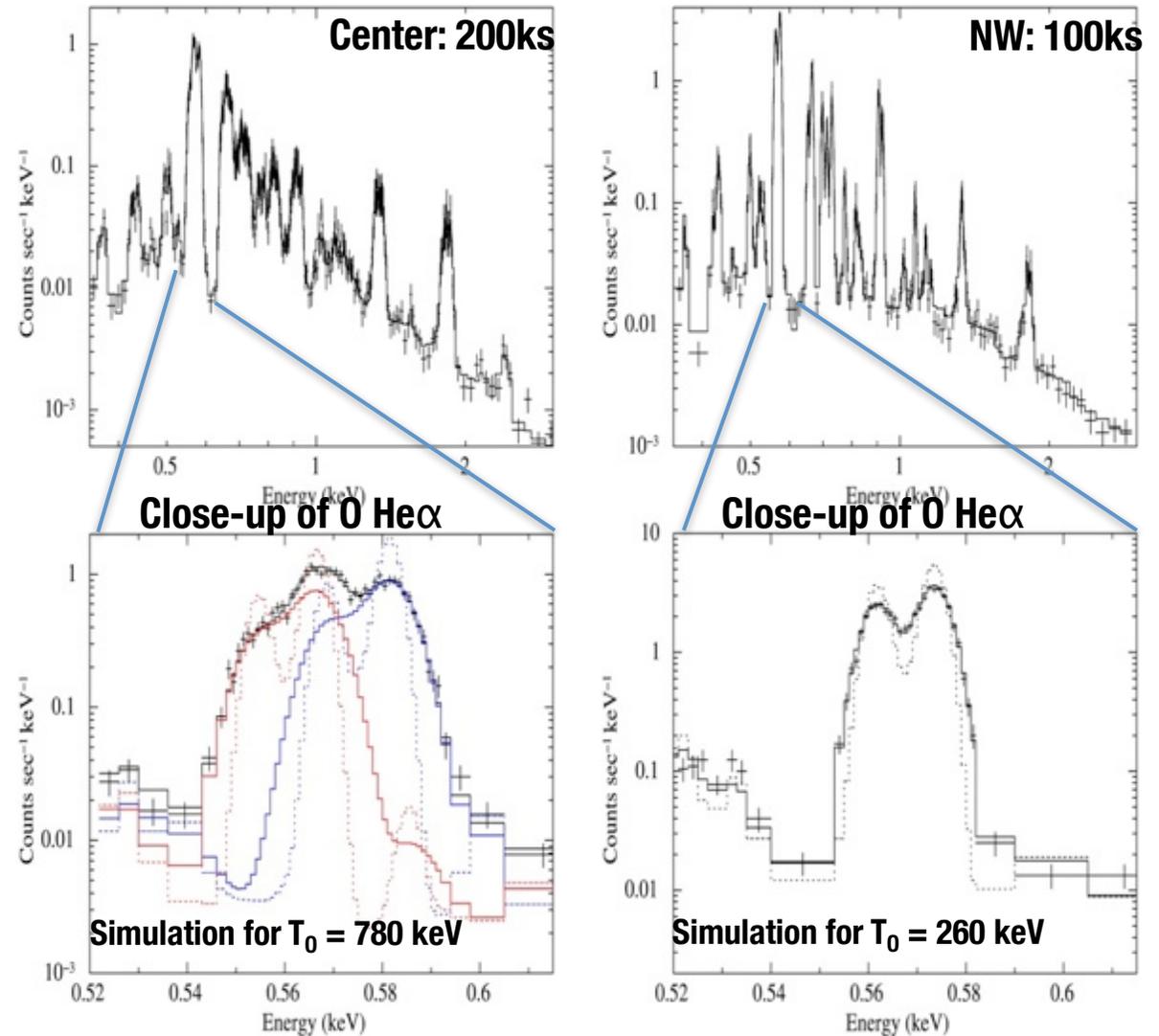
SN1006



Expansion is measured with Chandra

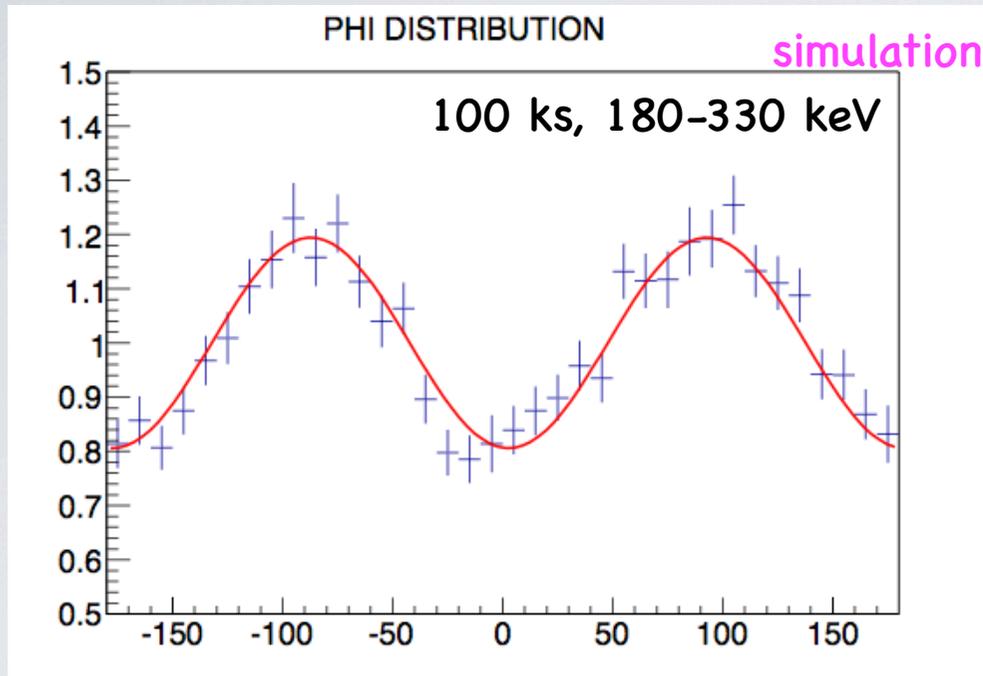


ASTRO-H SXS spectra



Dotted lines are for $T_0 = T_e$ (1.4 and 1.7 keV).

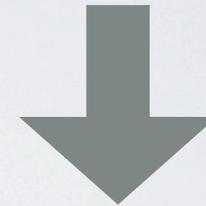
Power of ASTRO-H --- Polarization by SGD --- Crab Pulsar & Nebula



Assumption for simulation

Polarization fraction = 50%

Polarization angle = 0°



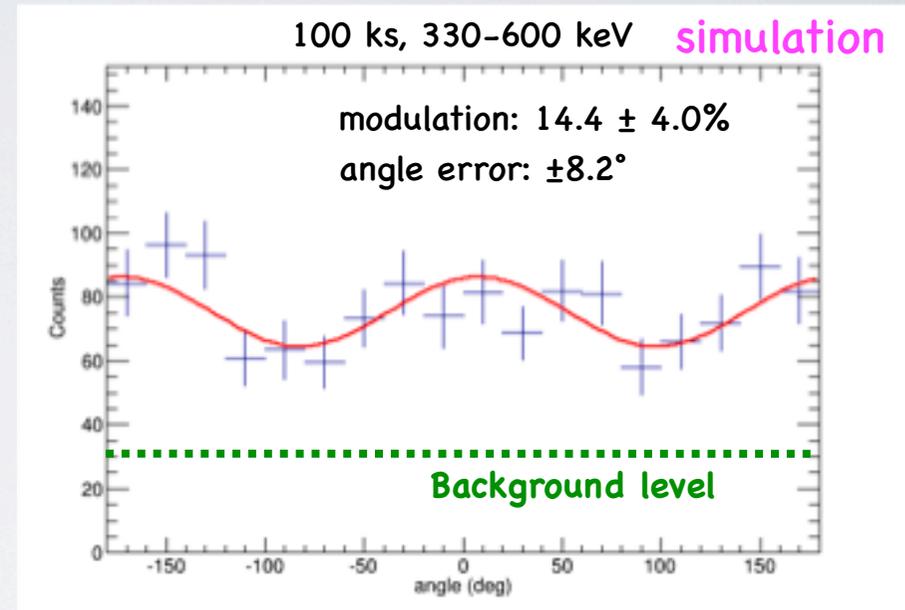
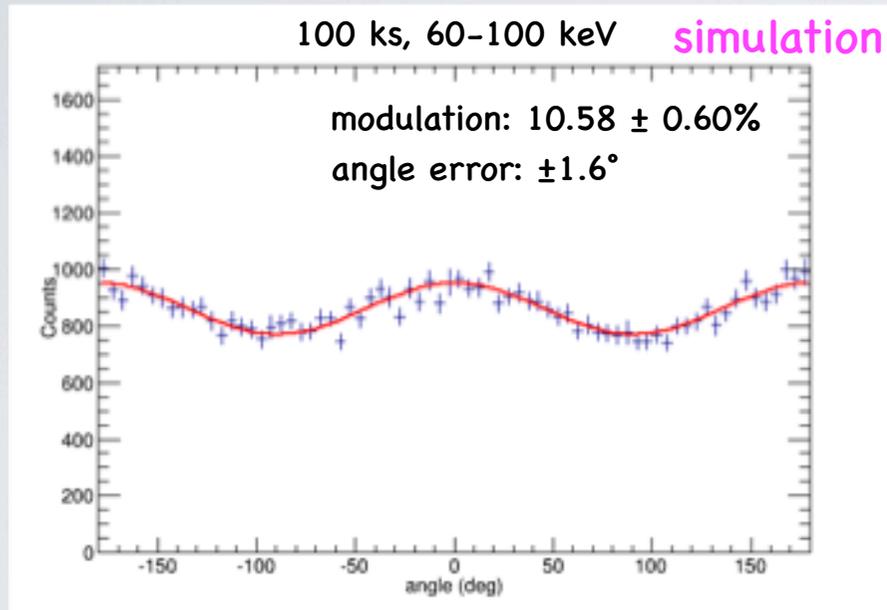
Fit values of the simulation data

Polarization fraction = $48 \pm 3\%$ (stat.)

Polarization angle = $2.7^\circ \pm 1.6^\circ$ (stat.)

The SGD will be able to measure polarization of Crab in an energy range between 50 keV and 500 keV with high precision!

Power of ASTRO-H --- Polarization by SGD --- Microquasar: Cygnus X-1



higher energies => to confirm the INTEGRAL results about the jet radiation
lower energies => precise measurement of coronal emission & disk reflection

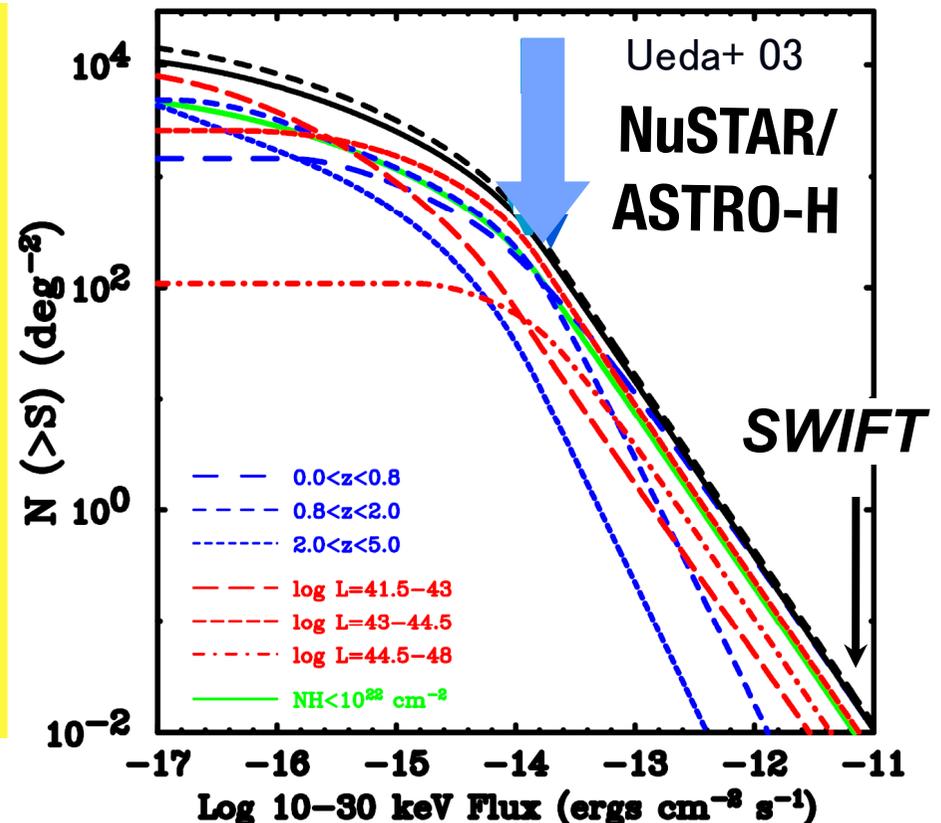
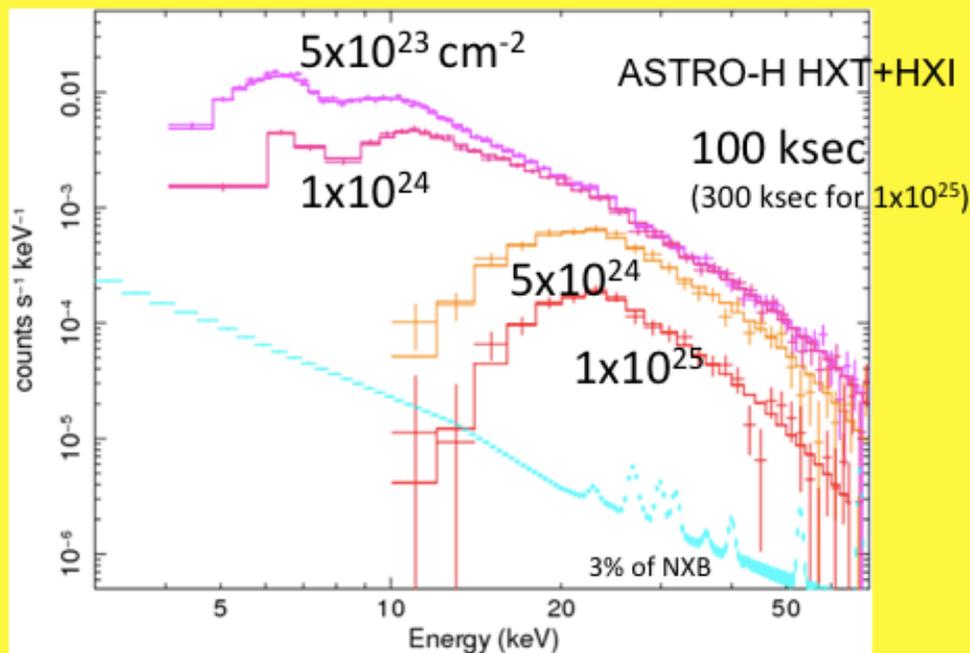
Power of ASTRO-H : CXB



Imaging with hard X-ray optics will enable us to observe at x100 times higher sensitivity than Suzaku. 30-50% of the cosmic X-ray background will be resolved into hidden super-massive black holes.

NuSTAR already starts showing the importance of the hard X-ray observation

30-50% of Hard XRB will be resolved



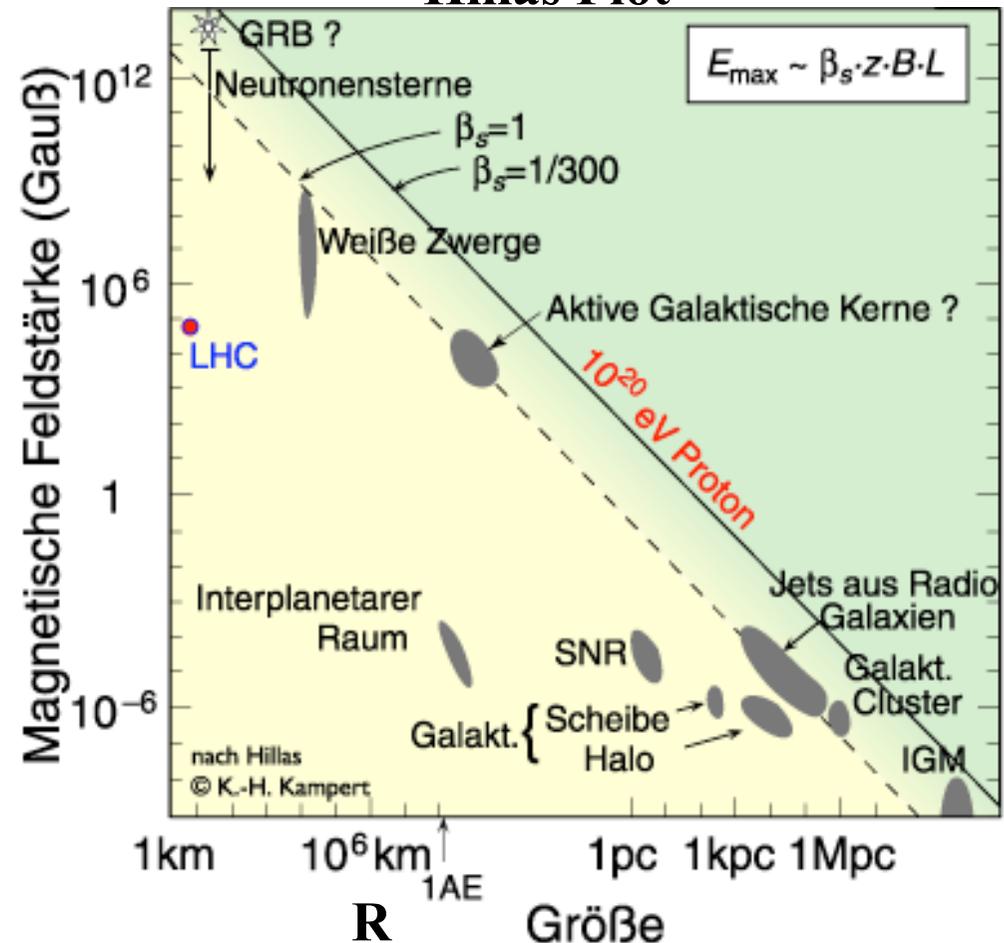
Non-thermal X-ray Astronomy ⇒ Study of Cosmic Accelerators

Pulsar wind nebula
Supernova Remnant
Microquasar
AGN jet
Cluster of Galaxies
(and probably more)

Important ingredients
magnetic field, velocities
& size/age

B

Hillas Plot



$$E_{\max} = 460 \left(\frac{V}{10^4 \text{ km/s}} \right) \left(\frac{B}{10 \mu\text{G}} \right) \left(\frac{R}{10 \text{ pc}} \right) \eta^{-1} \text{ TeV}$$

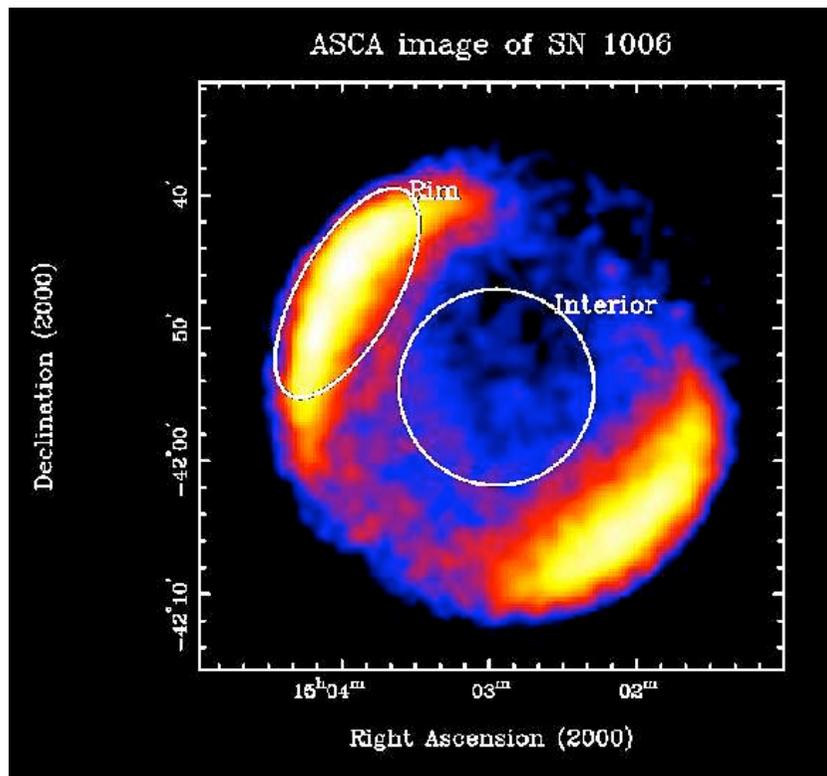
$$\eta \equiv \left(\frac{\delta B}{B} \right)^2$$

“gyro-factor”

X-ray Observation is

- Very sensitive to the existence of the distribution of high energy electrons (particle accelerators)

ASCA



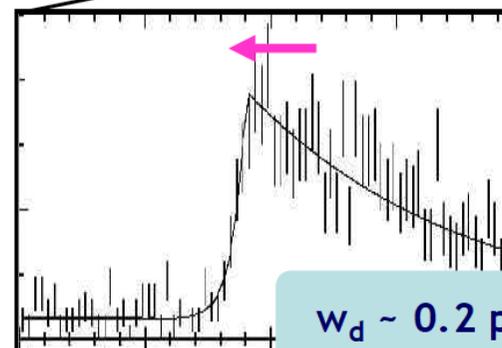
Cooling time of X-ray emitting electrons is much shorter than radio ones

$$h\nu_{\text{synch}} = 5.3 E_{100\text{TeV}}^2 B_{10\mu\text{G}} \text{ [keV]}$$

2.3. Our knowledge on electron acceleration

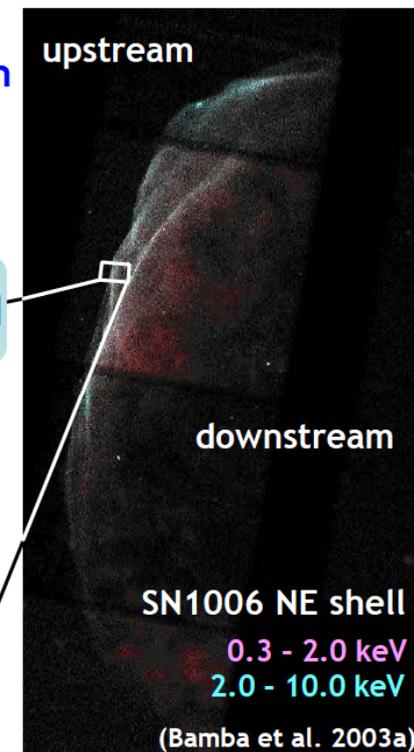
thermal plasma = extended
sync. X-rays = thin filaments

Acceleration sites are localized



$w_d \sim 0.2 \text{ pc}$

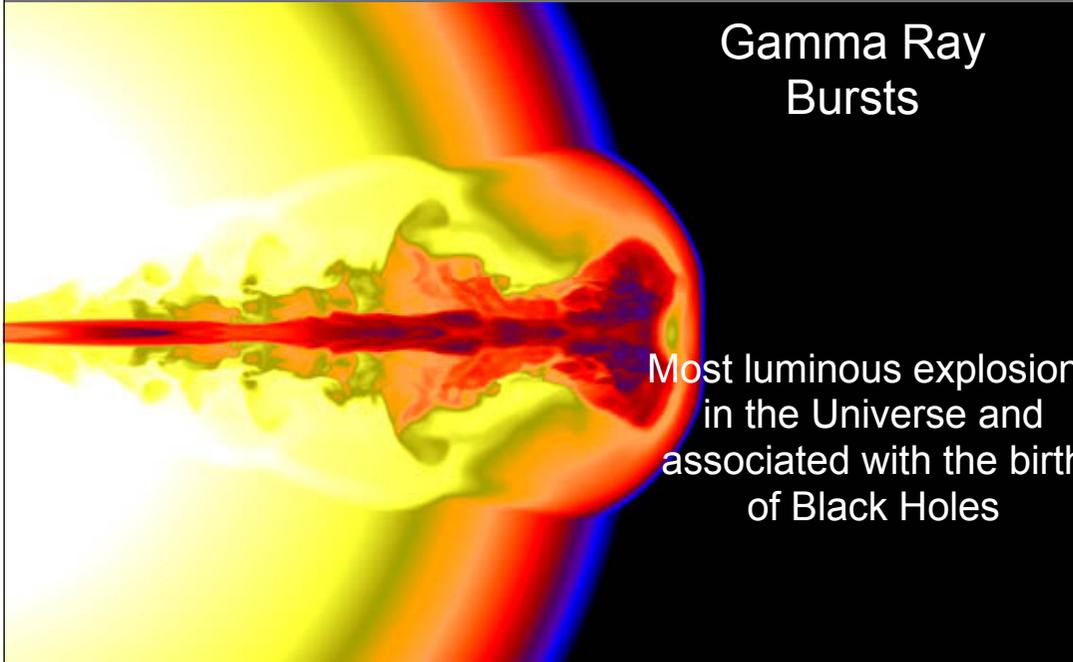
Chandra



Relativistic Outflows

TIPP09, March 12, 2009

(propagation, acceleration, particle content, emitted radiation)

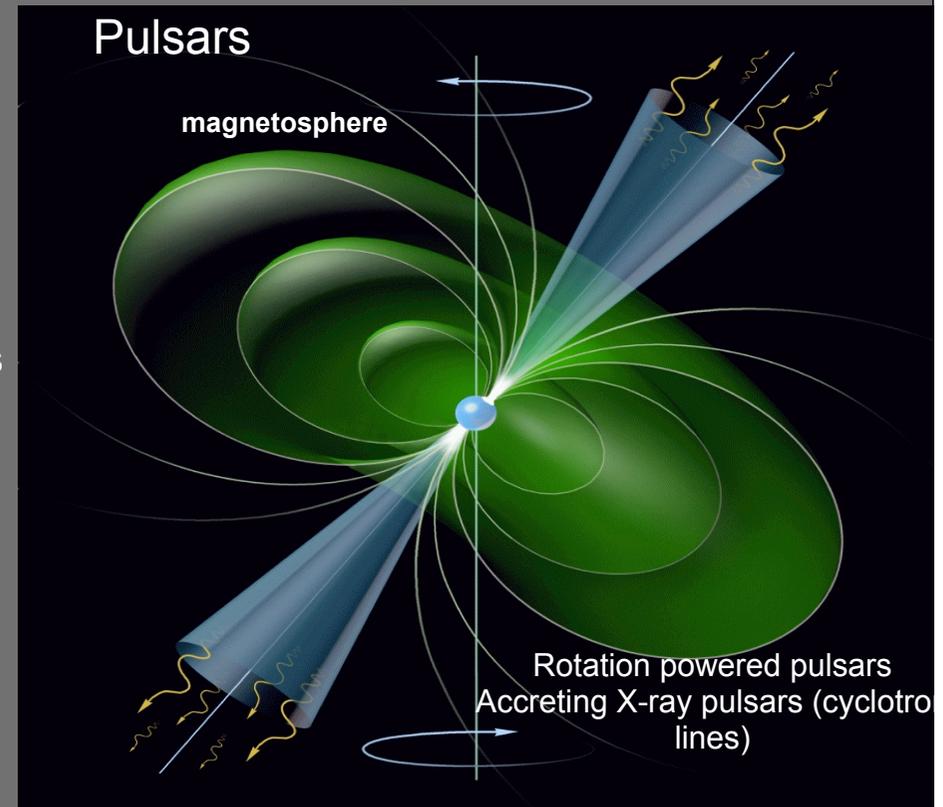


Gamma Ray Bursts

Most luminous explosions in the Universe and associated with the birth of Black Holes



Supermassive Black holes in active galactic nuclei (jets)



Pulsars

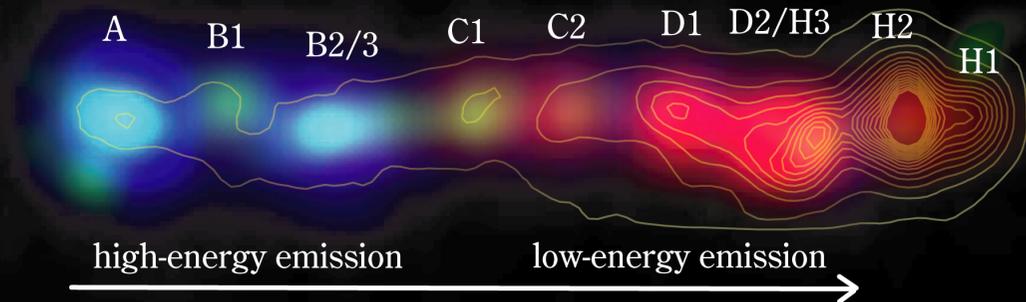
magnetosphere

Rotation powered pulsars
Accreting X-ray pulsars (cyclotron lines)

3C 273 jet VLA Spitzer* Hubble Chandra

Uchiyama, Y. et al. 2006, ApJ v.648, 910
(* deconvolved)

quasar



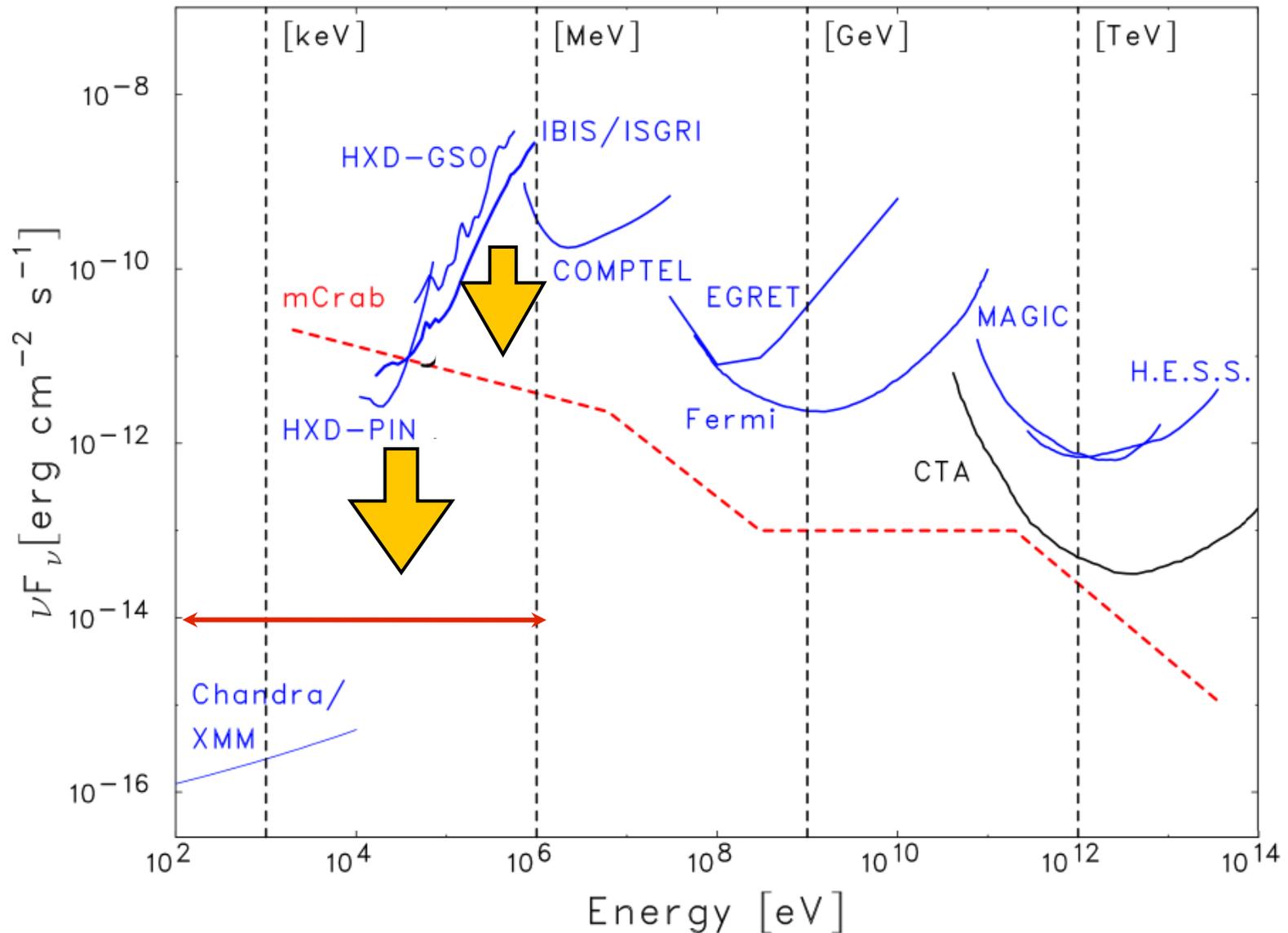
1"

high-energy emission

low-energy emission

Radio
Optical
IR
+
GeV
TeV
+

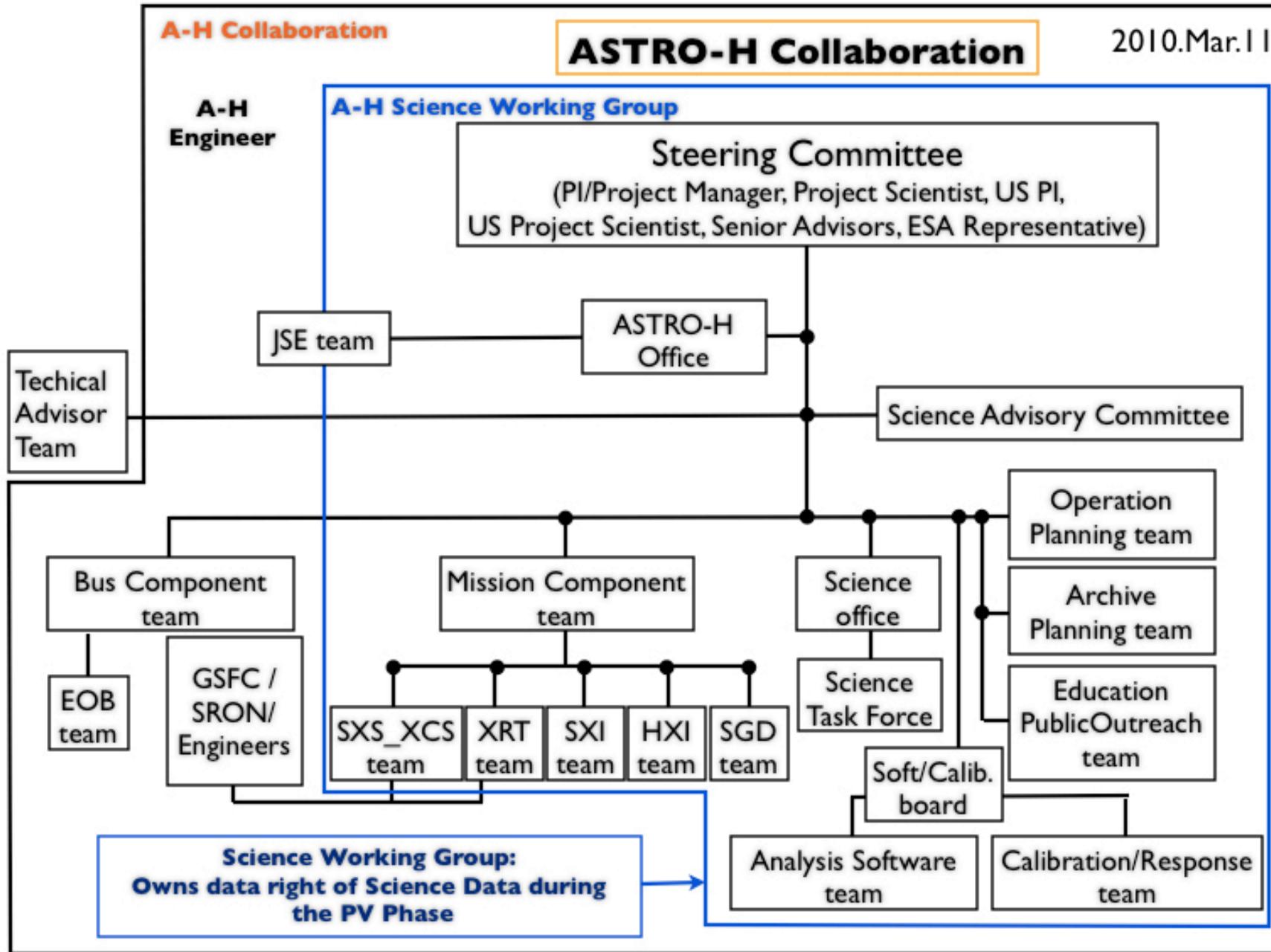
Need Multi Wave Length <Wide Coverage>



ASTRO-H 開発チーム (国際協力)



ASTRO-H衛星の開発体制



ASTRO-H の観測公募(予定)



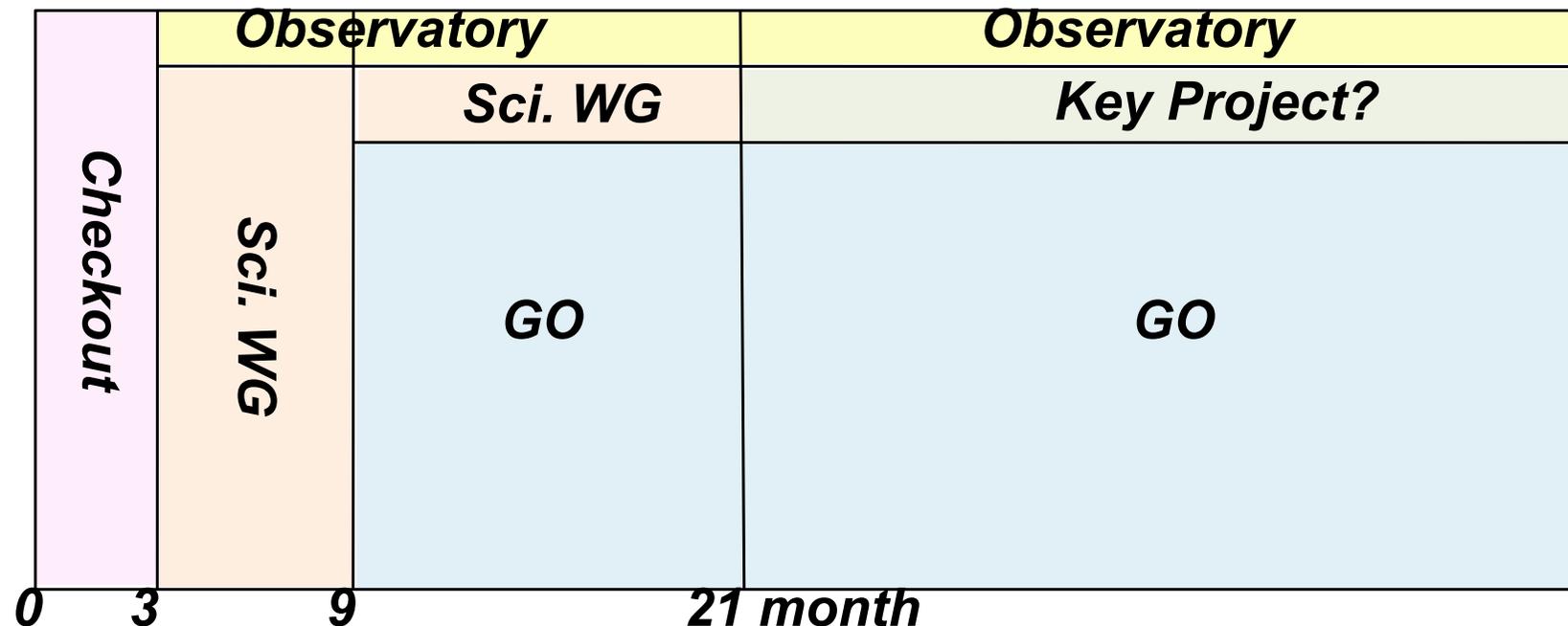
Phase 0 : 3 Months : Satellite/Instruments Check out (including Calibration))

Phase 1 : 6 Months : SWG 90 % (PV Phase) Observatory 10 %

Phase 2 : 12 Months : SWG Carry Over 15 %, GO 75 %, Observatory 10 %

Phase 3 : Rest of the mission : KeyProject 15 % (TBD) , GO 75 %, Observatory 10 %

Observatory 10 % = Calibration + T00 + Director's Time



Data policy among J/Europe/US in the GO time, would be similar to the Suzaku case. But we are planning to introduce key-project type and/or early-data-released type observations from early phase of the mission.