Gamma2012
9-13 July 2012

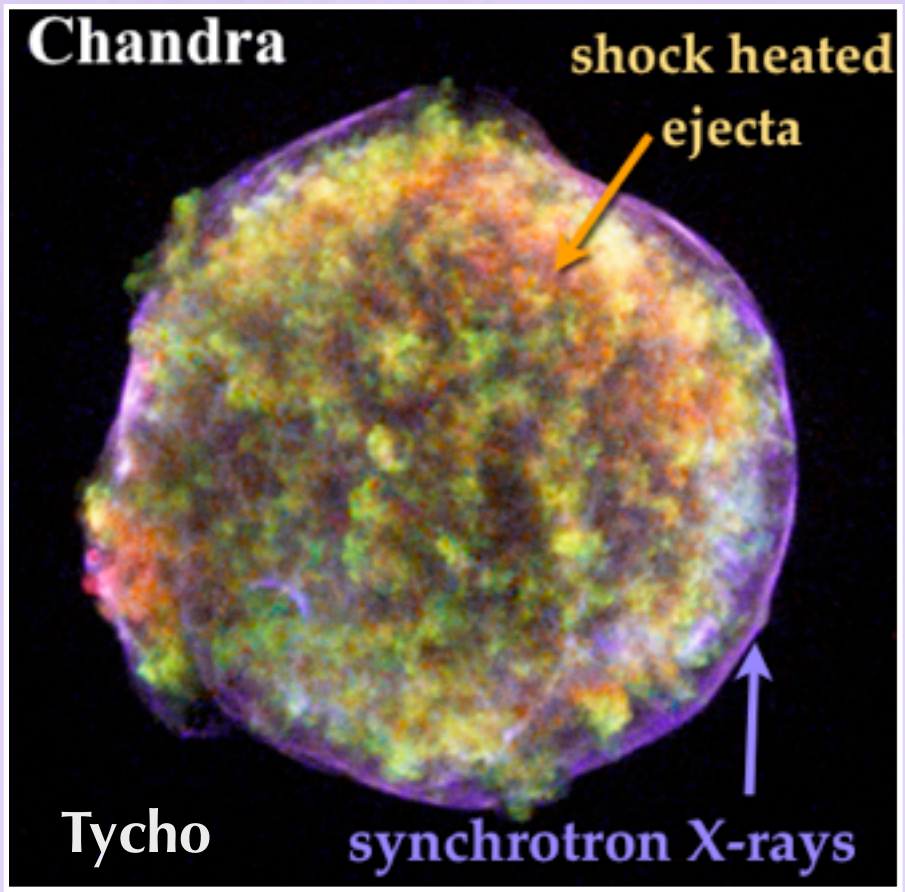
Non-thermal X-ray Astronomy

Yasunobu Uchiyama
(SLAC, Stanford)

50th Anniversary of X-ray Astronomy

Supernova Remnants

The best laboratory to test DSA theory



Nonthermal X-ray (synchrotron):

- Shock-accelerated CR electrons with energies of 10-100 TeV emit synchrotron X-rays in B=10-100 μG.
- Synchrotron cut-off frequency indicates acceleration at the Bohm limit.
- Chandra images (sharp filaments and their variability) tell us about magnetic field amplification.

Thermal X-ray (lines, bremsstrahlung):

- Shock-heated ISM, ejecta
- Dynamics (velocity, temperature etc)
- Environment (density etc)

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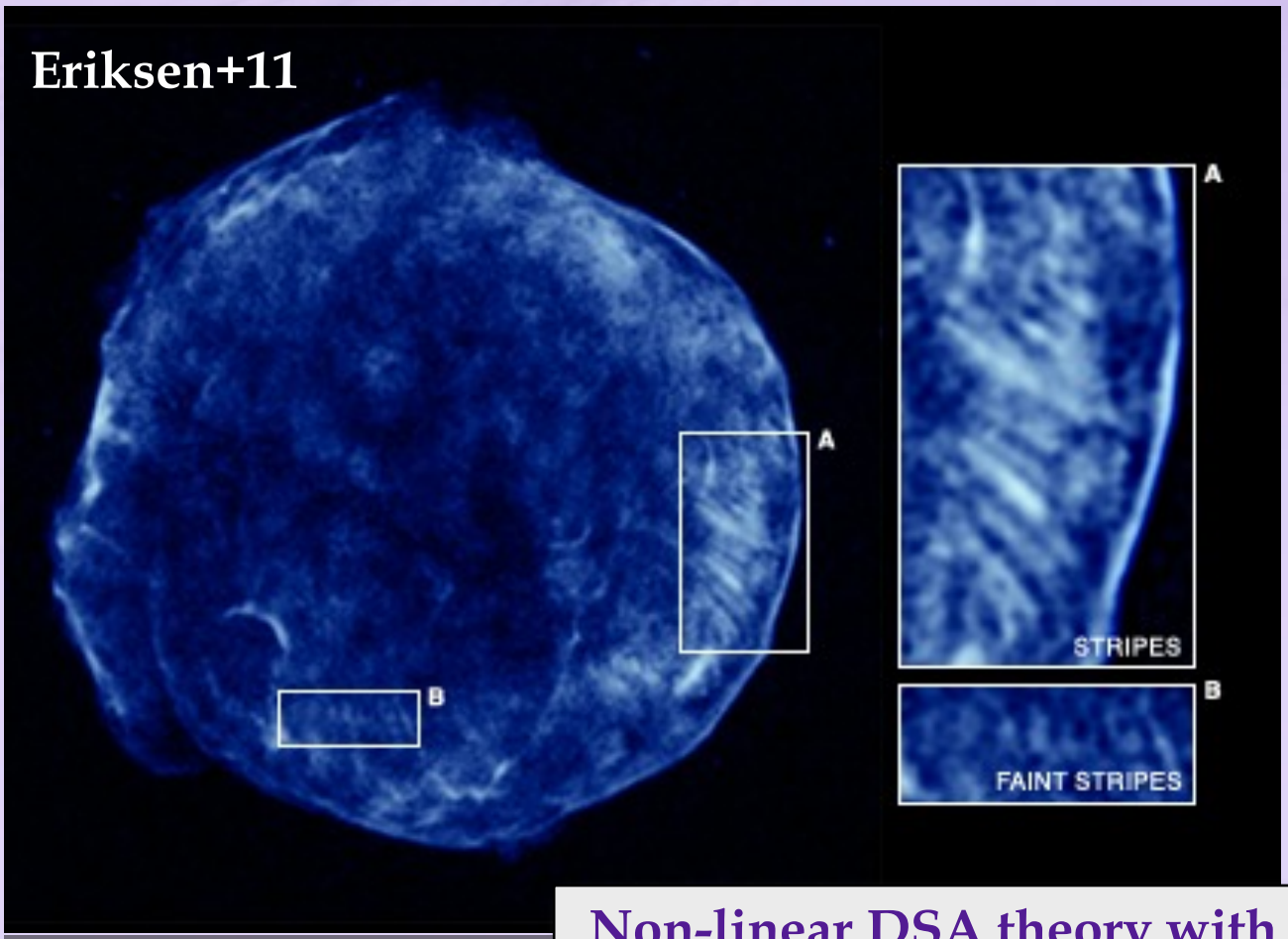
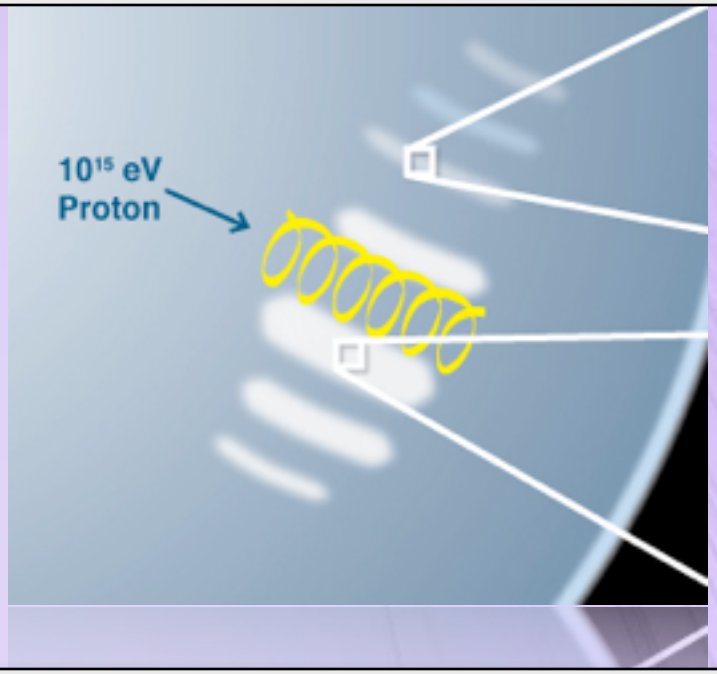
Recent Results (1): Stripes in Tycho's SNR



Separation of stripes:

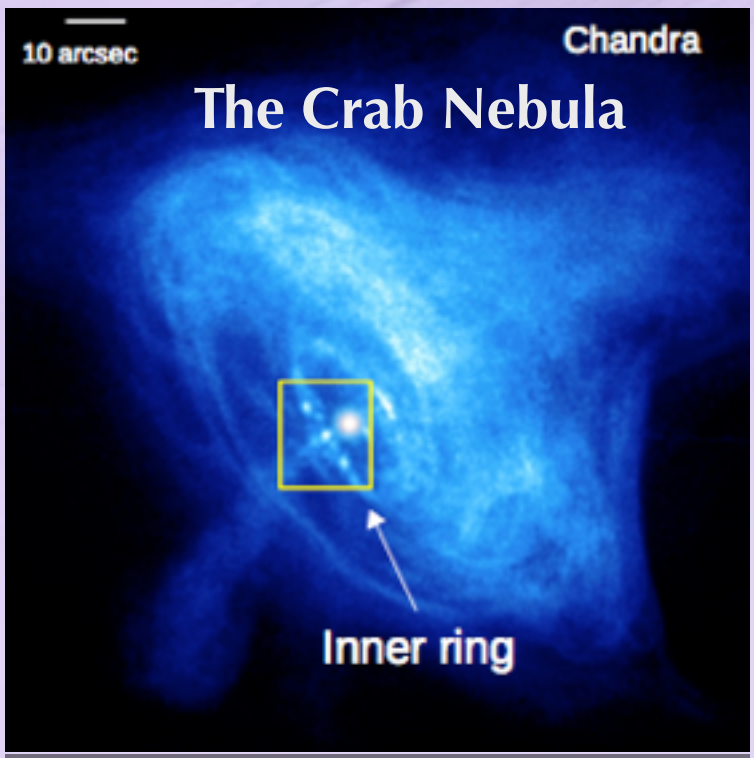
Gyroradius of highest energy protons (~10^{15} eV)

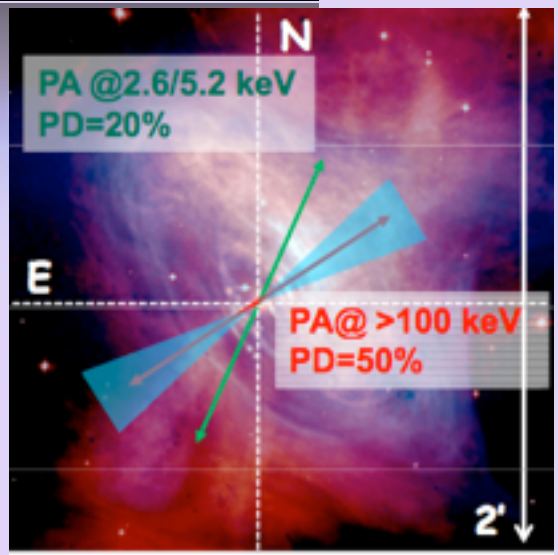


Non-linear DSA theory with magnetic field amplification due to CR current driven instability can explain the stripes (Bykov+11):

- magnetic turbulence wave spectrum may have a peak, if turbulence cascading along the mean field is suppressed (Vladimirov+09)

Pulsar Wind Nebulae





Nonthermal X-ray (synchrotron):

- CR electrons/positrons with energies of 10-100 TeV emit synchrotron X-rays in B=1-100 μG.
- Chandra images suggest particle acceleration at termination shock.
- Synchrotron spectrum extends to 100 MeV during Crab's flares, which challenges models of e-/e+ acceleration.
- Polarization has been detected from the Crab Nebula:
  - π=20% PA=156° (2.6/5.2 keV) OSO-8 (Weisskopf+78)
  - π=50% PA=124° (>100 keV) INTEGRAL-SPI (Dean+08)

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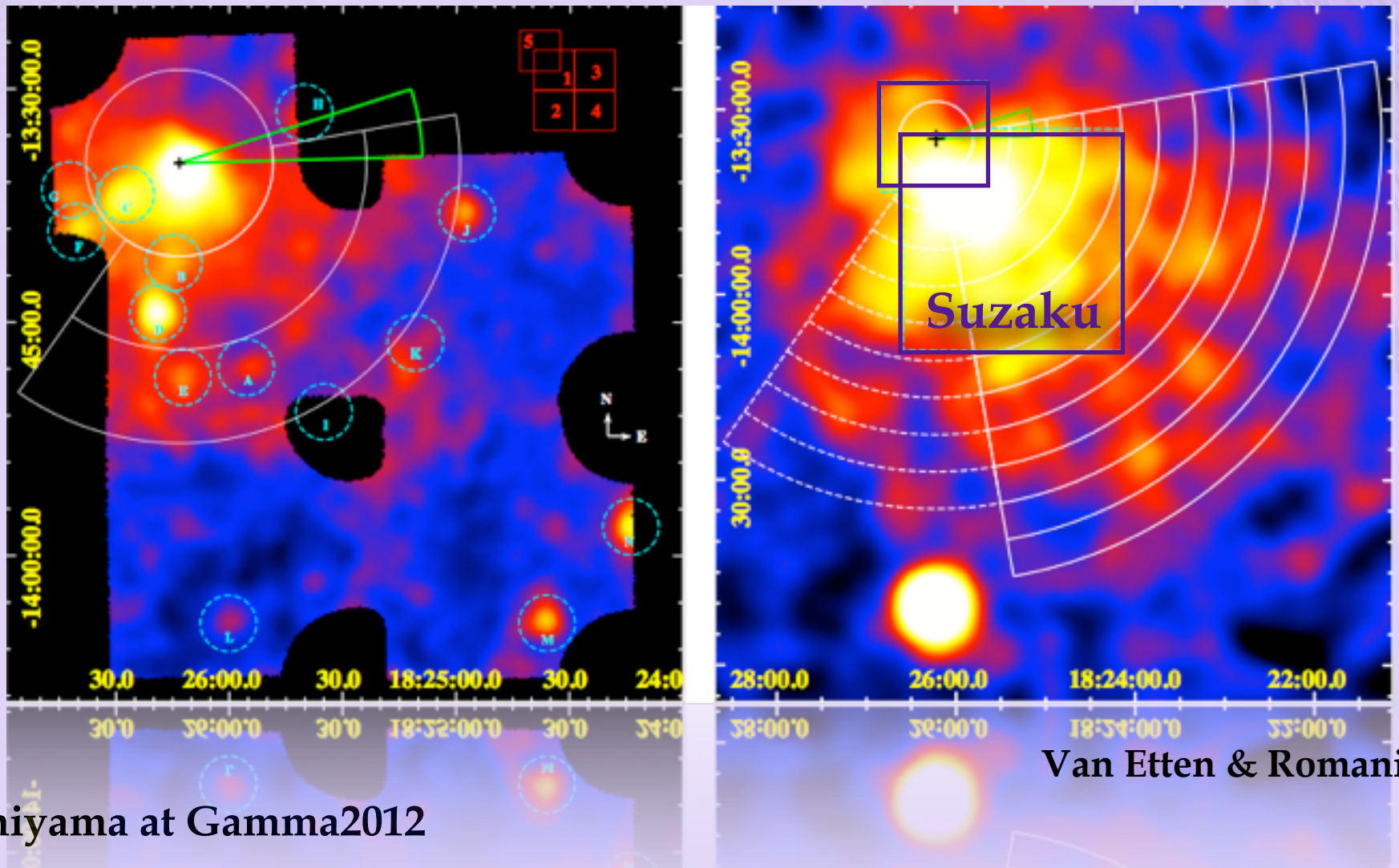
Recent Results (2): HESS J1825-137

- PWN powered by PSR B1823-13 (spindown age of 21 kyr)
- HESS revealed energy-dependent TeV morphology, likely due to synchrotron cooling (Aharonian+2006)

Suzaku XIS (1-8 keV)

HESS



Van Etten & Romani (2011)

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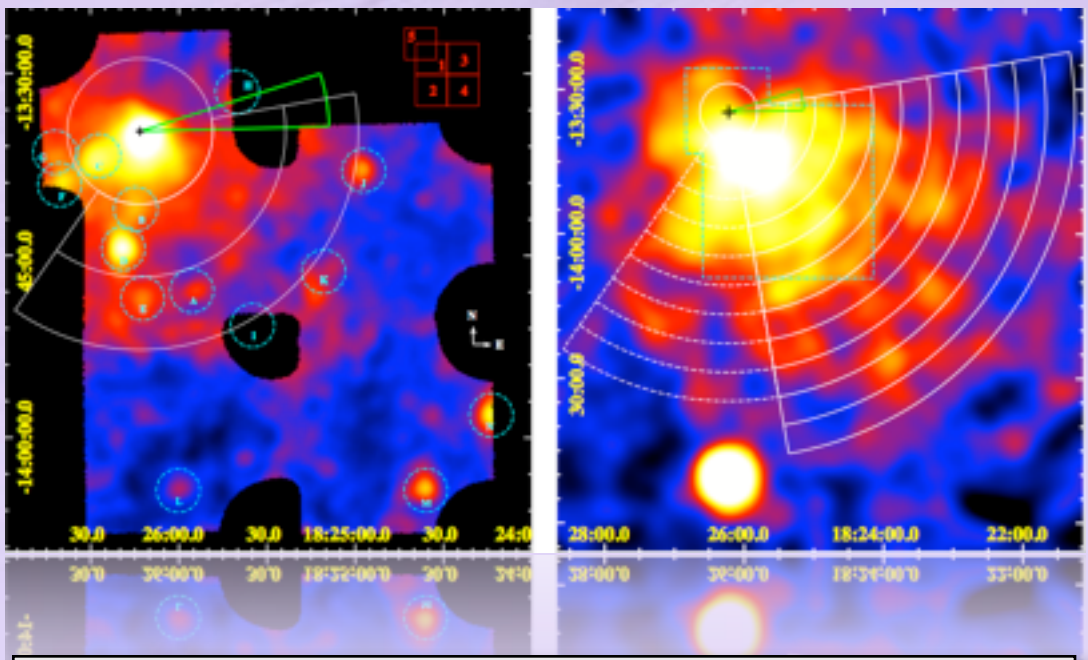
Recent Results (2): HESS J1825-137



- spin period 13 ms, age = 40 kyr
- velocity profile: $v(r) \propto r^{-0.5}$
- $B(r, t) \propto r^{-0.7} L_{sd}(t)^{0.5}$

  12μG (zone 1) → 1.7μG (zone 12)
- fast diffusion:

  $\tau \approx 90\ (R/10pc)^2\ (E/100\ TeV)^{-1}\ yr$

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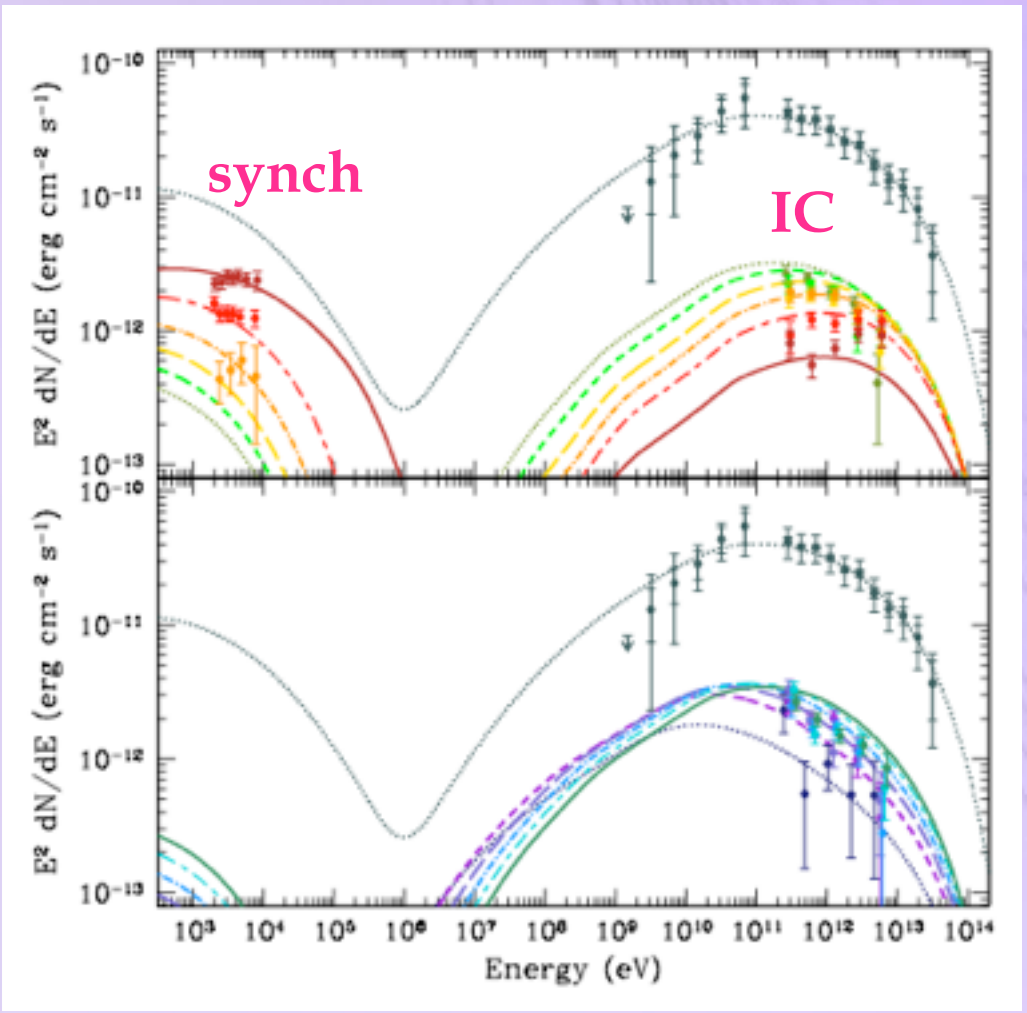
X-ray-Gamma-ray SED as a function of distance



Van Etten & Romani (2011)

Gamma-ray Binaries

- GeV/TeV emission was detected from a few high mass X-ray binaries
- Now, some unID GeV/TeV sources are being identified as X-ray (γ-ray) binaries.

- **PSR B1259-63** (pulsar's spin-down) T_{orb} = 3.4 years
  - TeV (HESS) & GeV (Fermi-LAT)
- **LS 5039** (unknown source of power) T_{orb} = 3.9 days
  - TeV (HESS) & GeV (Fermi-LAT)
- **LS I +61° 303** (unknown source of power) T_{orb} = 26 days
  - TeV (MAGIC/VERITAS) & GeV (Fermi-LAT)
- **HESS J0632+057** (unknown source of power) T_{orb} = 320 days
  - TeV (HESS/MAGIC/VERITAS)
- **1FGL J1018.6-5856** (unknown source of power) T_{orb} = 16.6 days
  - GeV (Fermi-LAT)
- **Cyg X-3** (accretion onto BH/NS) T_{orb} = 4.8 hours
  - GeV (Fermi-LAT/AGILE) : **transient**

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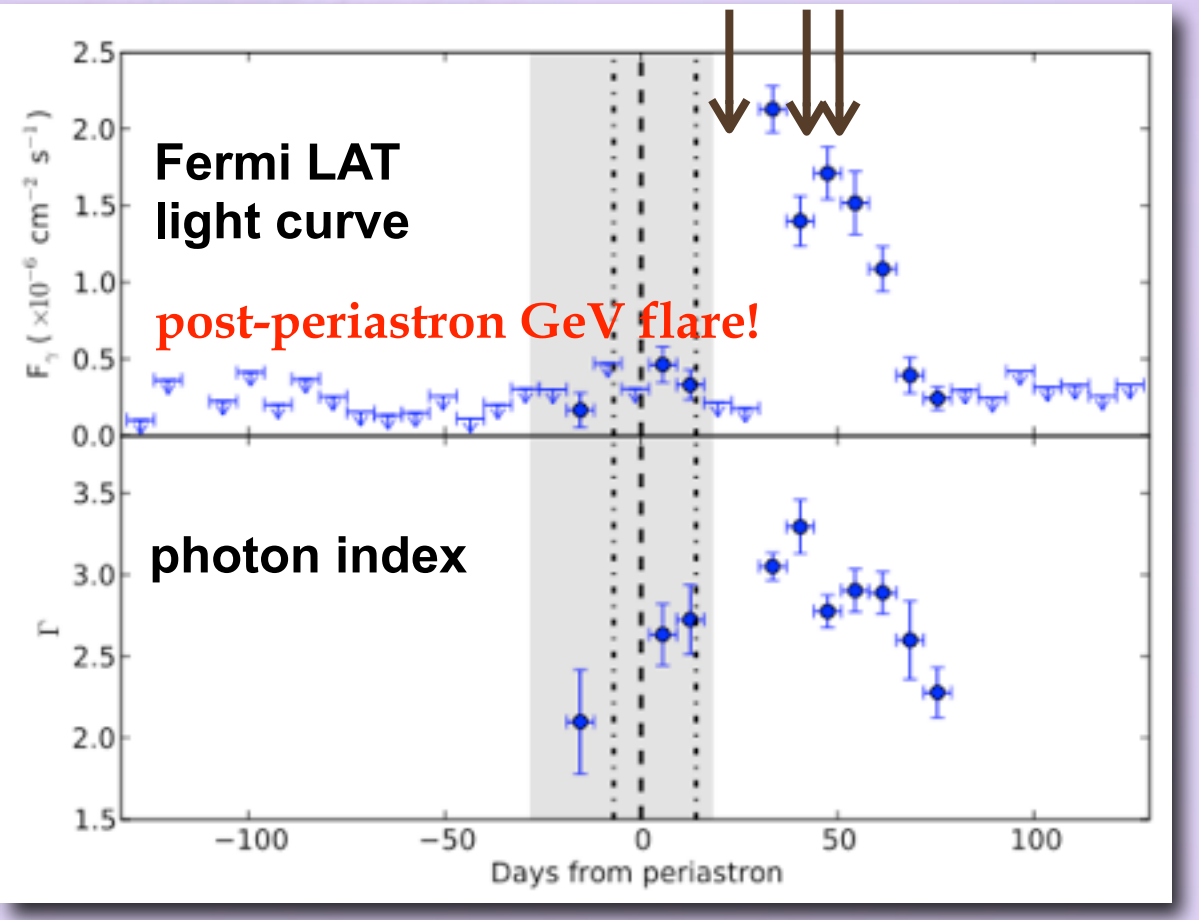
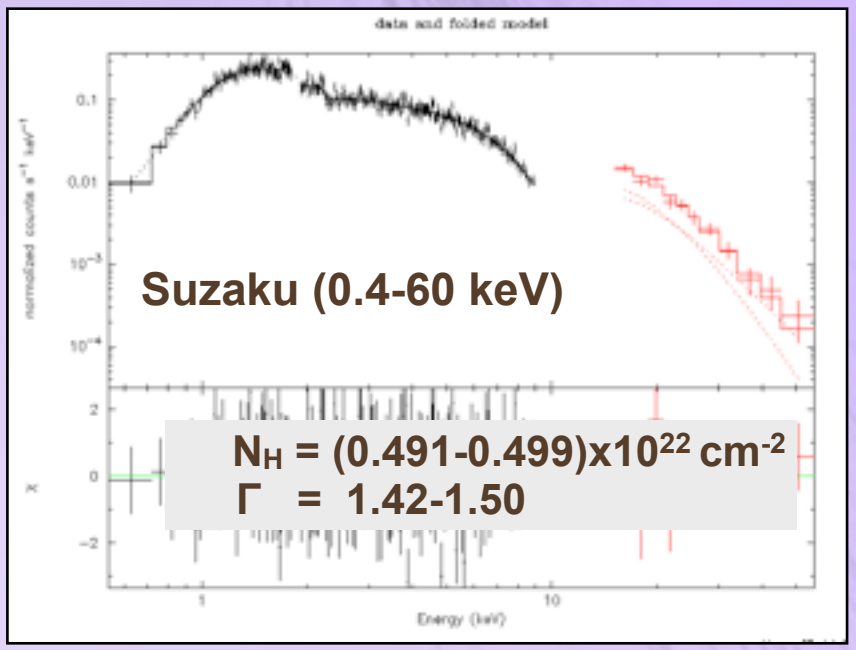
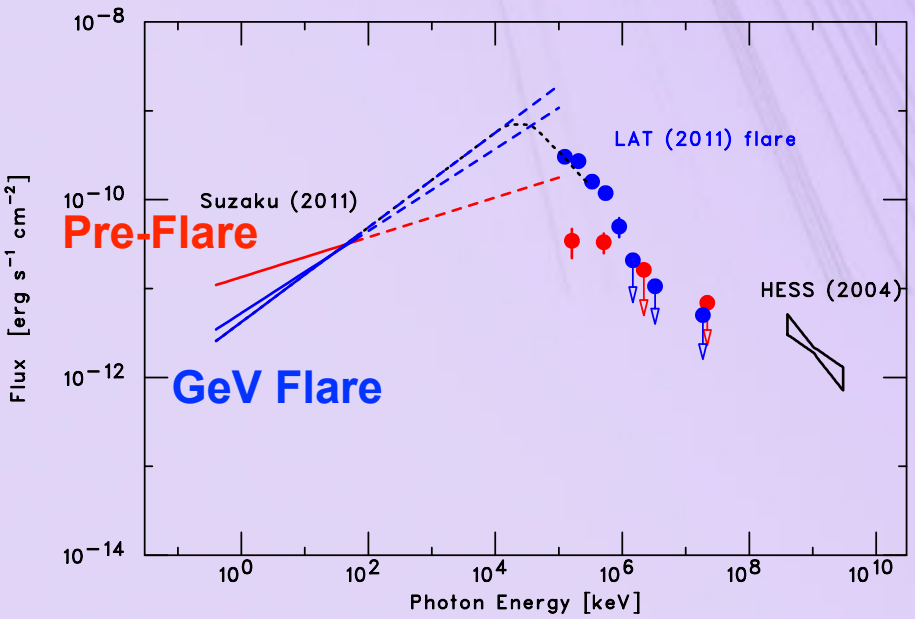
Recent Results (3): PSR B1259-63

- Orbital period of 3.4 yr (e~0.87), spindown power of 8×10^{35} erg/s

Suzaku Observations (PI: Uchiyama)
80 ks, 40 ks, 20 ks







GeV flare may be "bulk Compton" by a cold relativistic wind (Khangulyan+12)

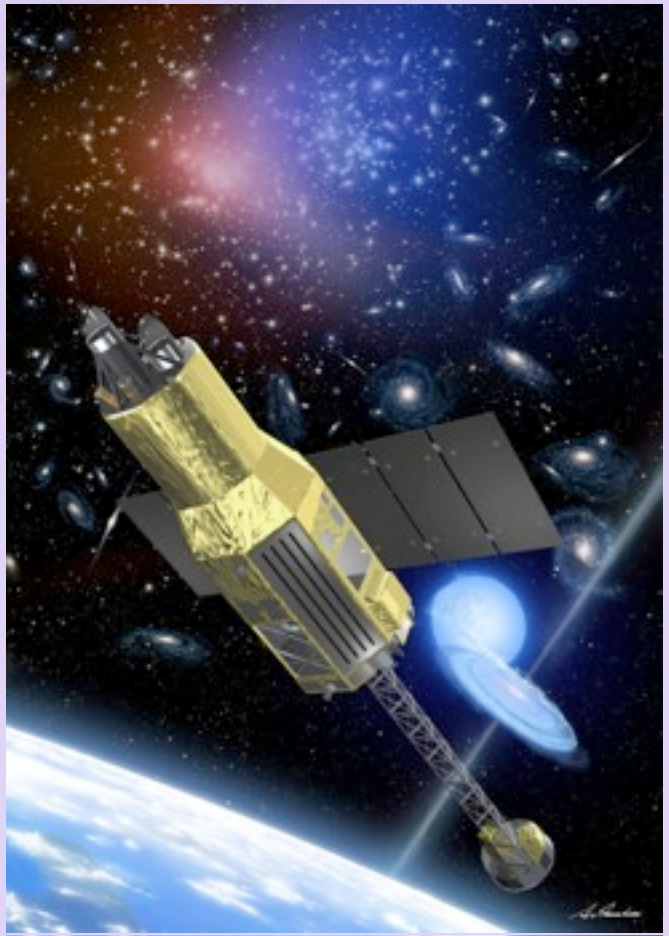
Y. Uchiyama at Gamma2012

New X-ray Satellites

ASTRO-H (2014-)

"Observatory"

micro-calorimeter, hard X-ray mirror, large CCD, soft-gamma-ray detector



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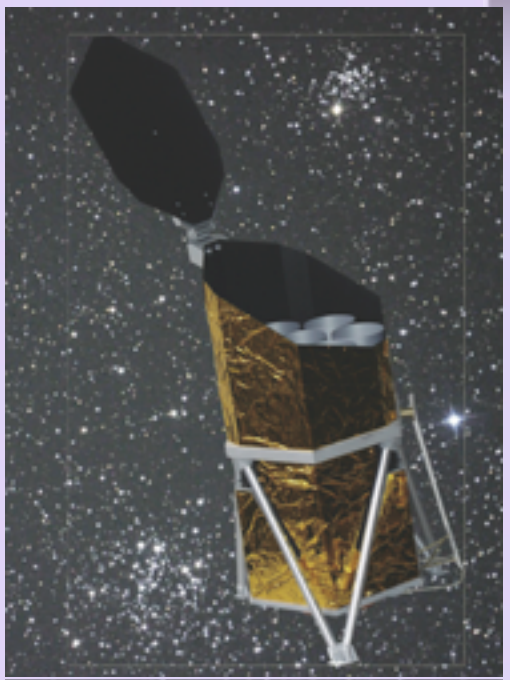
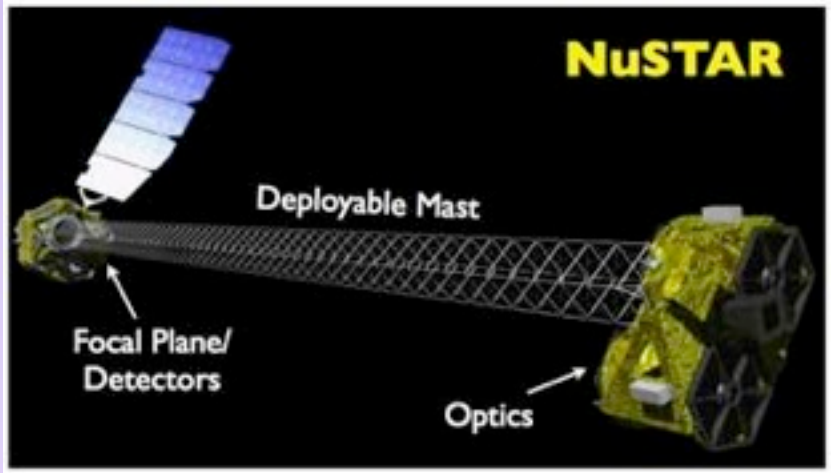
GEMS?



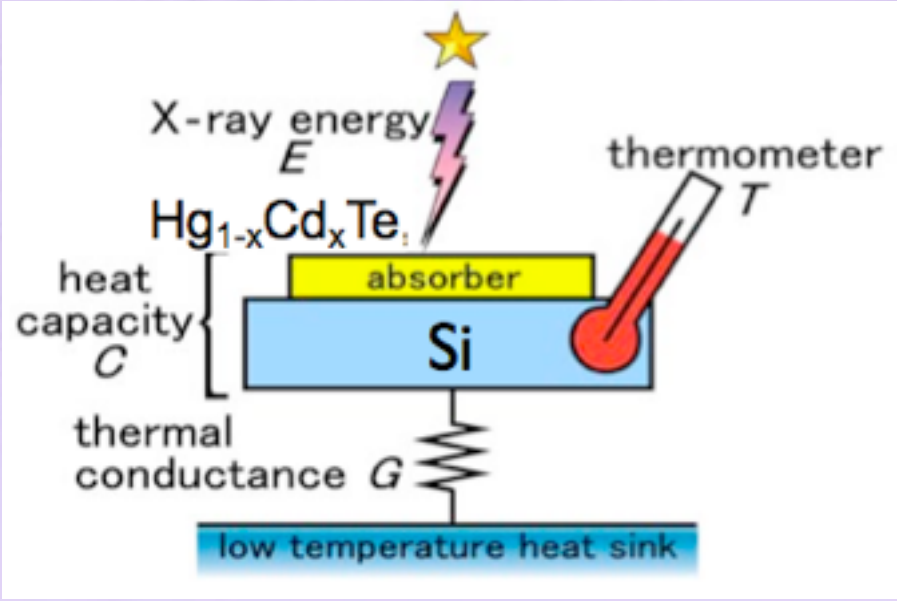
NuSTAR (2012-) Hard X-ray mirror

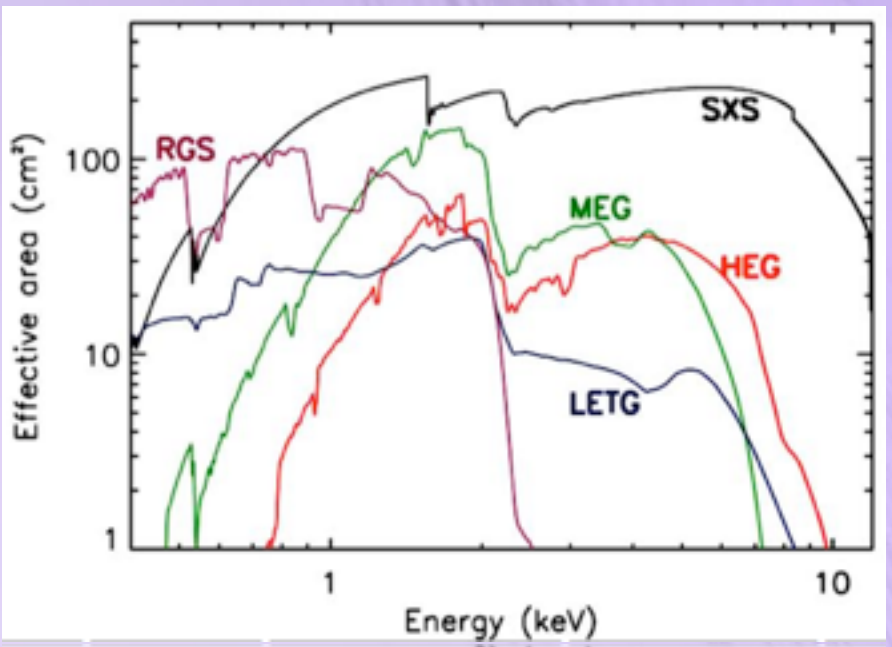


eROSITA & ART-XC onboard SRG (2013-)

eROSITA:
- all sky survey
30 times deeper than ROSAT
- will find >10,000 clusters of galaxies

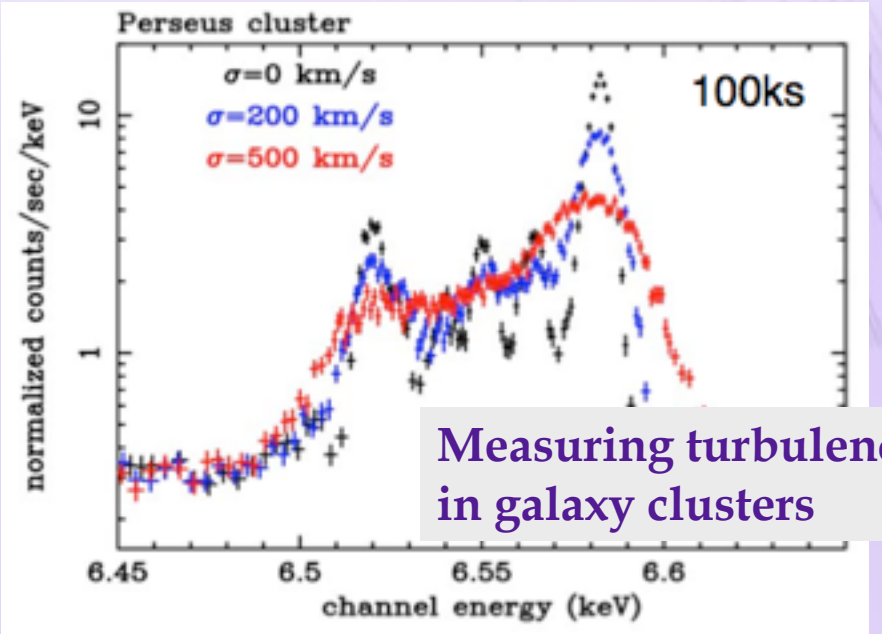
Micro-Calorimeter (SXS onboard ASTRO-H)





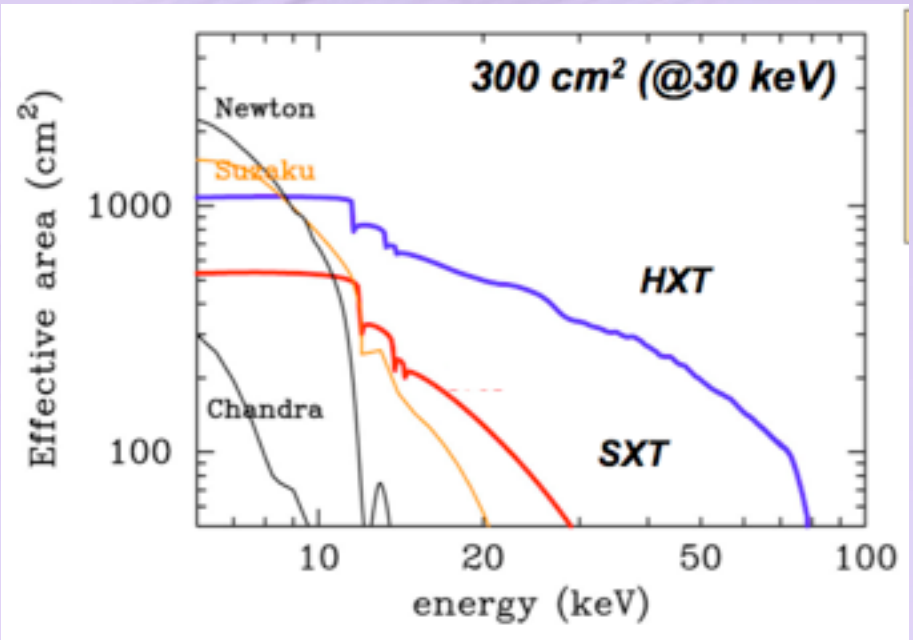
Micro-calorimeter onboard ASTRO-H

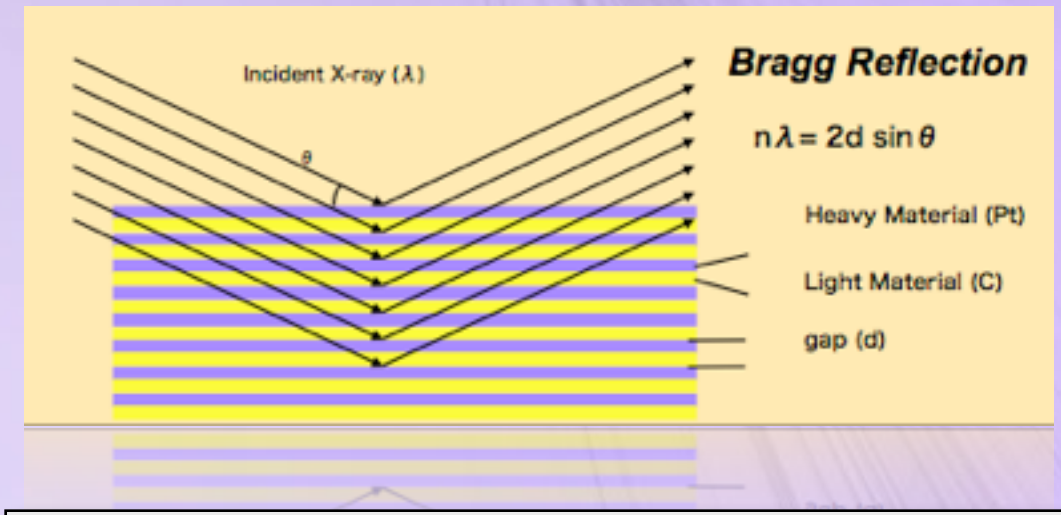
- Energy resolution: 5 eV (FWHM)
  - cf. CCD: 150-200 eV
- Effective area: 210 cm² @ 6keV
- PSF: 1.7 arcmin (HPD)
- FoV: 3 arcmin (6x6 array)
- Suited for extended sources

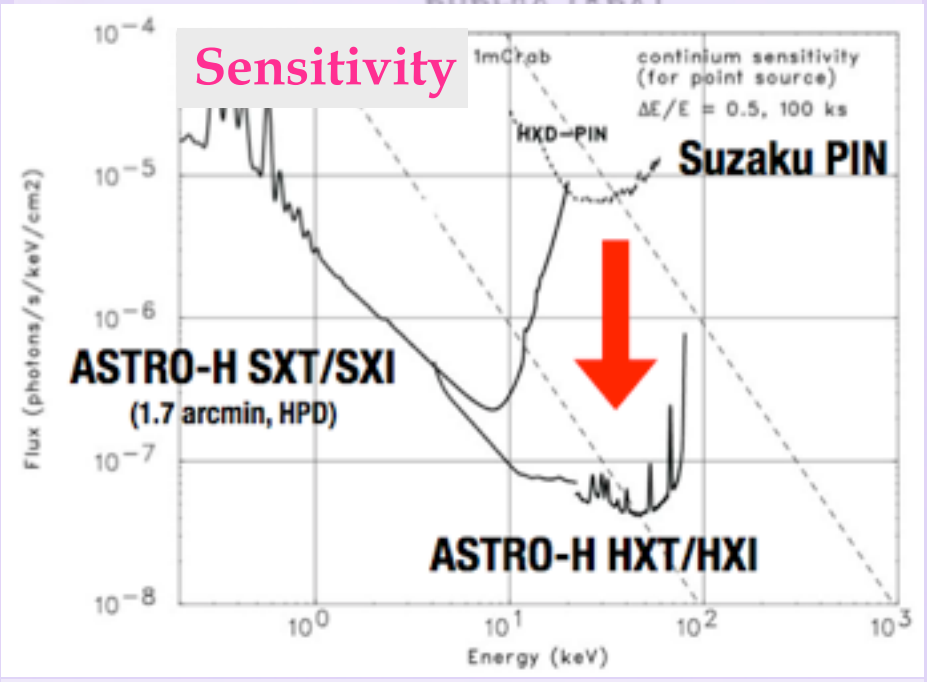


Measuring turbulence in galaxy clusters

Hard X-ray Mirror (NuSTAR, ASTRO-H)







Hard X-ray Mirror (< 80 keV)

- "Depth-graded multilayers"
  - ASTRO-H: Pt/C
  - NuSTAR: Pt/SiC, W/Si
- Focal plane detector:
  - Si/CdTe (AH), CZT (NuS)
- Imaging spectroscopy at Hard X-rays
- 100 times better sensitivity than Suzaku

Some examples of
"Nonthermal X-ray Astronomy"
to be made with
micro-calorimeter and hard X-ray mirror

(SNRs are highlighted)

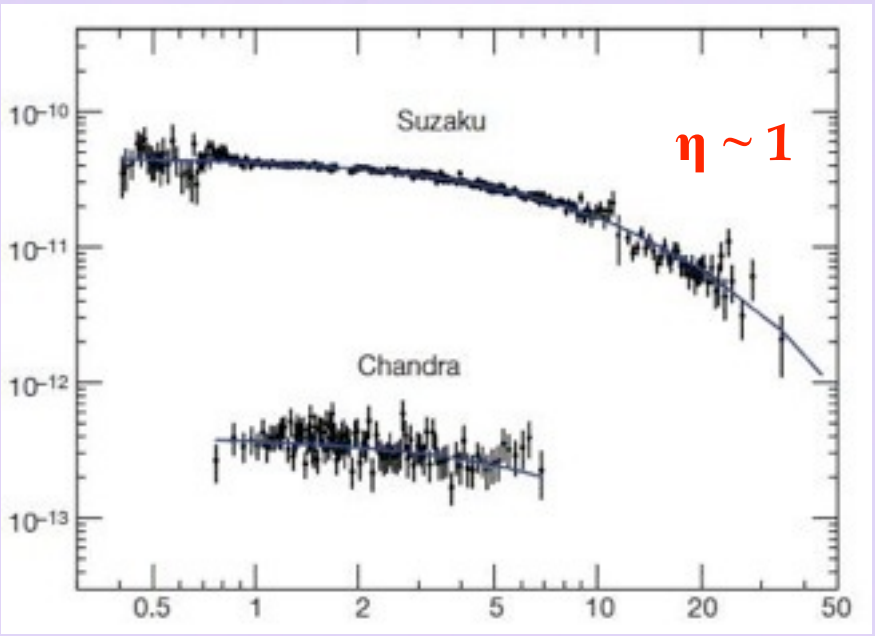
Precise Measurement of Synchrotron X-ray Spectra in SNRs

Synchrotron spectrum from electrons whose acceleration (Bohm regime) is limited by synchrotron cooling is given by (Zirakashvili & Aharonian 2007):

$$F_\nu \propto \nu^{-1}\left[1+0.46\left(\frac{\nu}{\nu_0}\right)^{0.6}\right]^{2.29}\exp\left[-\left(\frac{\nu}{\nu_0}\right)^{0.5}\right]$$

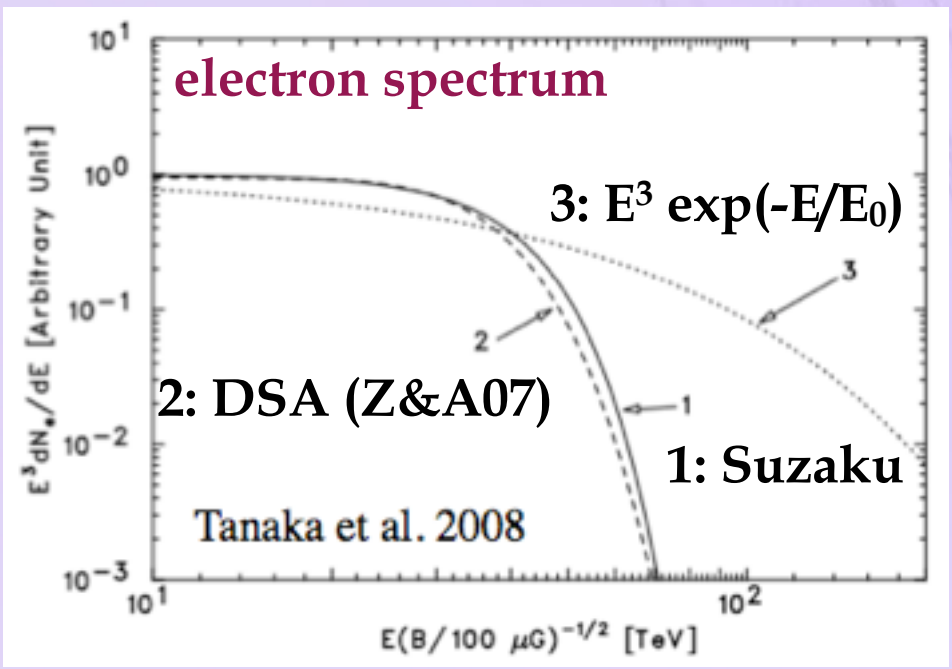
turbulent B-field

$$h\nu_0 \simeq 1\left(\frac{V_s}{3000\ \mathrm{km\ s^{-1}}}\right)^2 \eta^{-1}\ \mathrm{keV}$$



RXJ1713.7-3947 (XIS+HXD)

ASTRO-H broadband measurement
➔ determination of electron spectrum, (testing DSA prediction), B-field turbulence



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turbulent B-field

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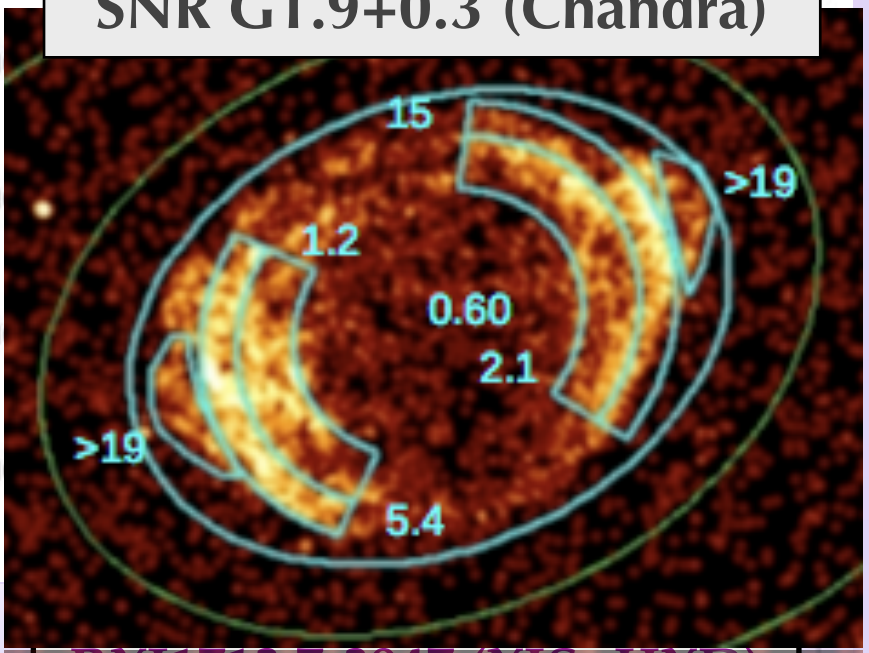
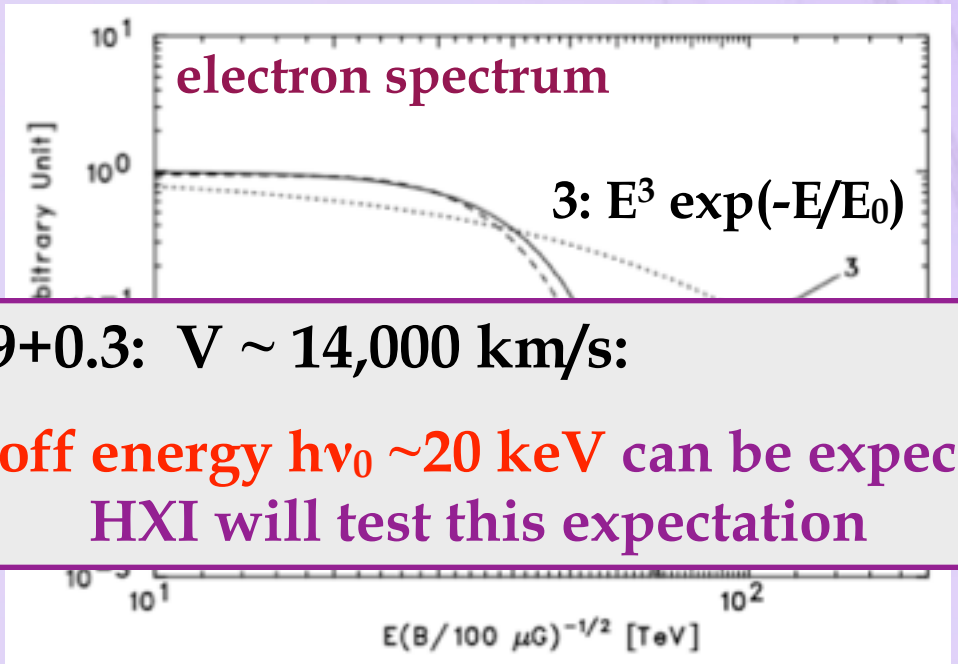
SNR G1.9+0.3 (Chandra)



RXJ1713.7-3947 (XIS+HXD)

ASTRO-H broadband measurement
➔ determination of electron spectrum, (testing DSA prediction), B-field turbulence



G1.9+0.3: V ~ 14,000 km/s:

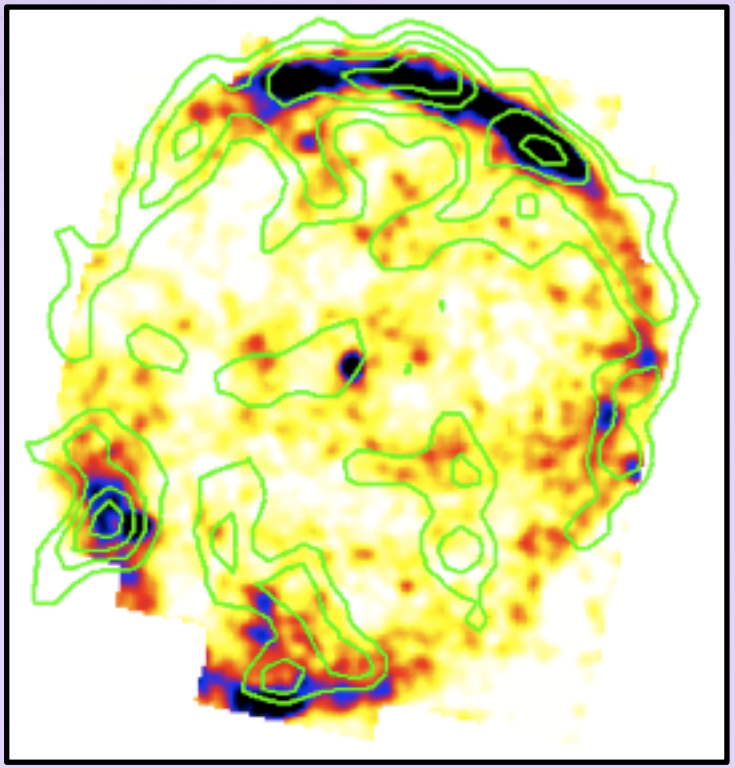
Cutoff energy $h\nu_0$ ~20 keV can be expected.
HXI will test this expectation

Search for thermal emission in synchrotron-dominated SNRs

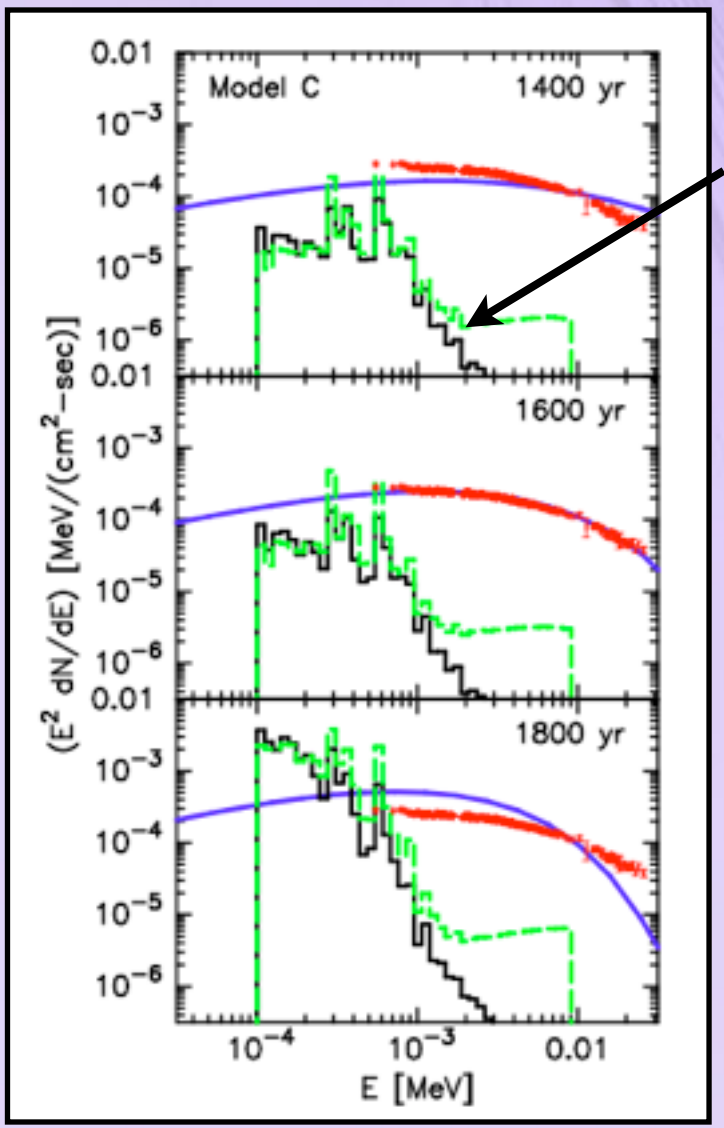
Possible targets:

RX J1713.7-3946,
Vela Jr,
HESS J1731-347

Vela Jr.: Suzaku (sync) vs HESS



RX J1713 (Ellison+12)



Coulomb heating only

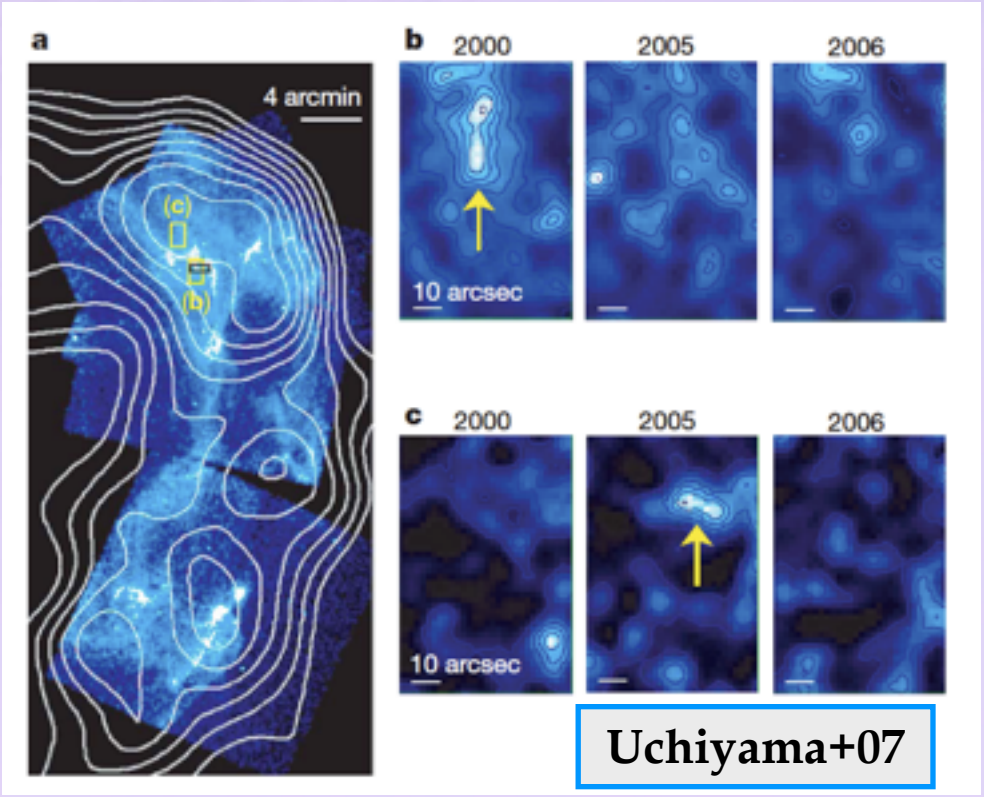
Non-detections of thermal X-rays have been used to argue against hadronic origin of gamma-rays.

<u>SXS will shed new light.</u>

HXI Observations of RX J1713.7-3946

Synchrotron X-ray variability (year-scale) found in this SNR

➜ Probe of DSA (acceleration) and MFA (B-field amplification)



Uchiyama+07

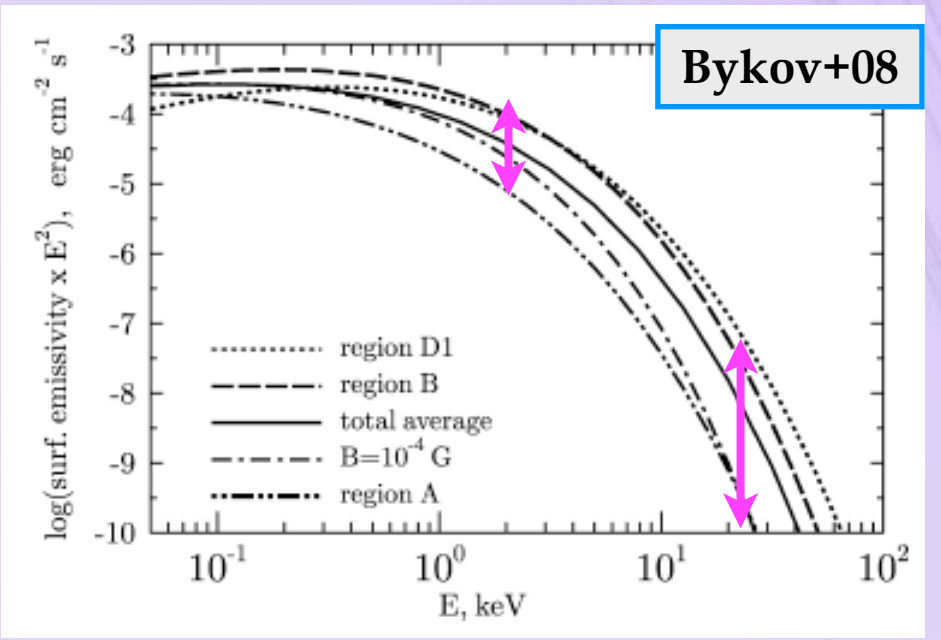
Chandra X-rays (color)

H.E.S.S. TeV γ-rays (contours)

Year-scale variability:

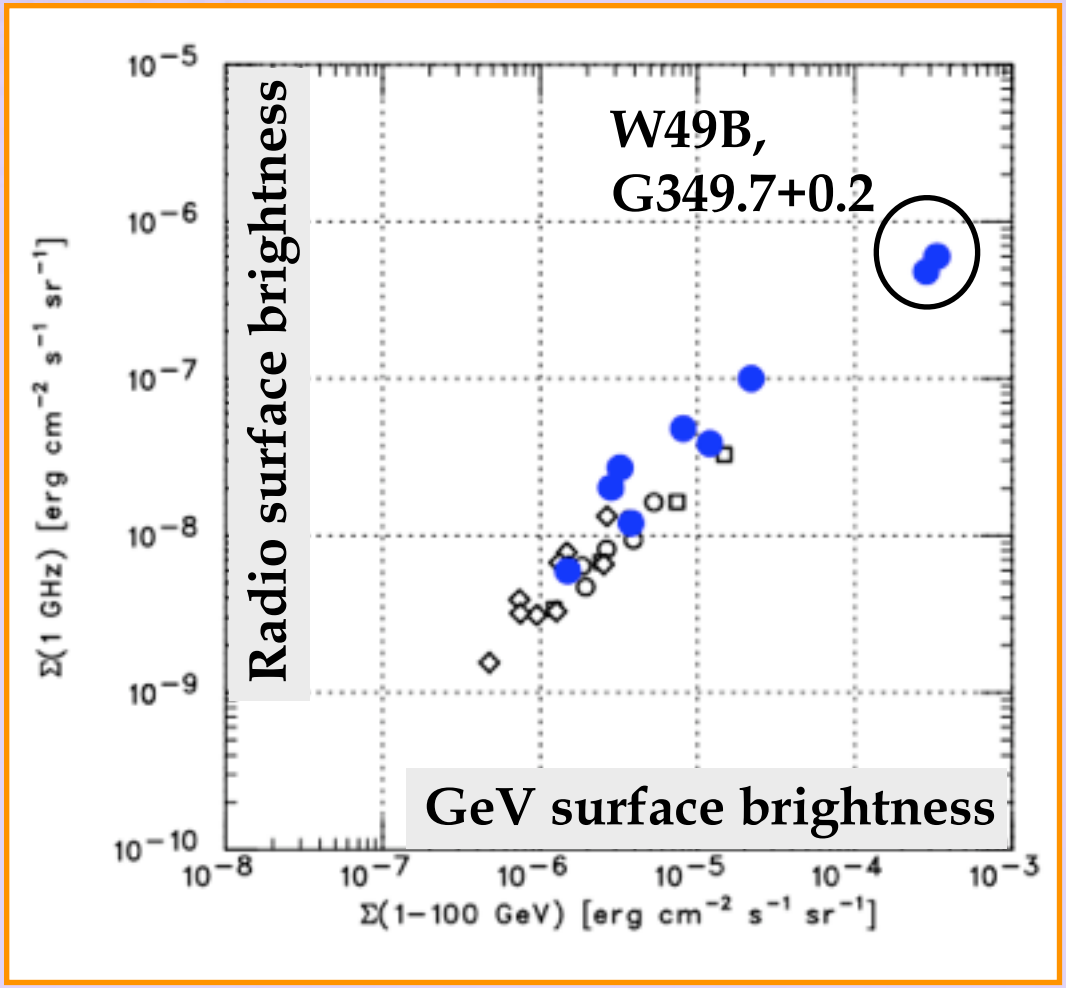
- **Acceleration/cooling of TeV electrons within a year**
- **B-field flickering**

Variability in the hard X-ray band should be more significant.



Non-thermal Bremsstrahlung and Associated Fe lines in SNRs

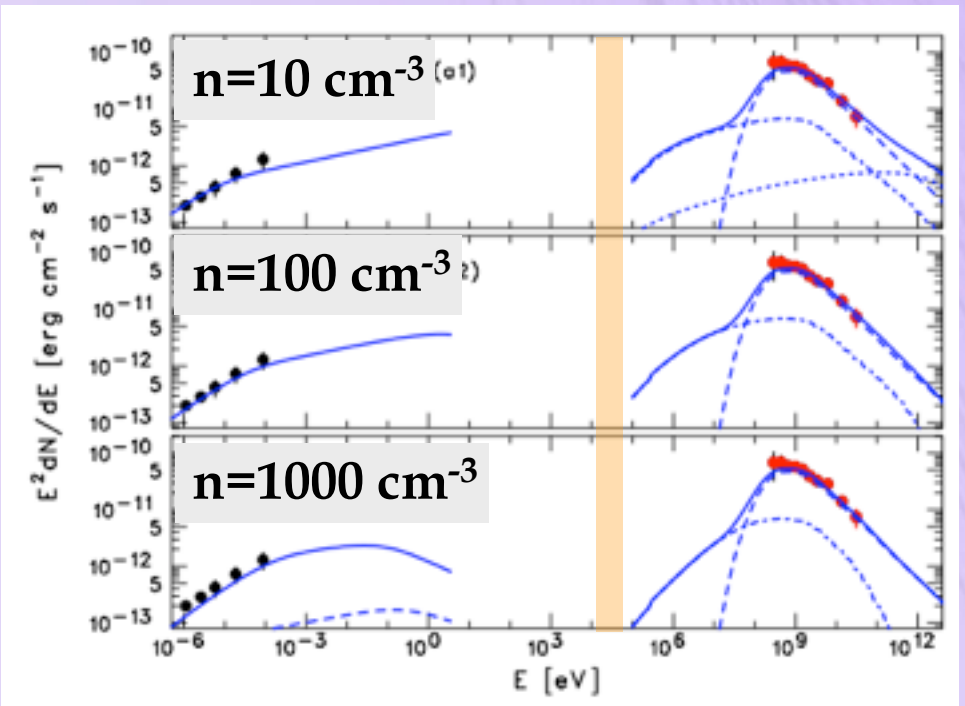
Nonthermal Bremsstrahlung is not efficient (only ~10^{-5} of the kinetic energy can be converted to X-rays, and the rest goes to Coulomb heating / ionization). Yet, it would be detectable with HXI in some GeV-bright SNRs.



Uchiyama (Texas symposium 2010)

~10^{-12} erg cm^{-2} s^{-1} @HXI

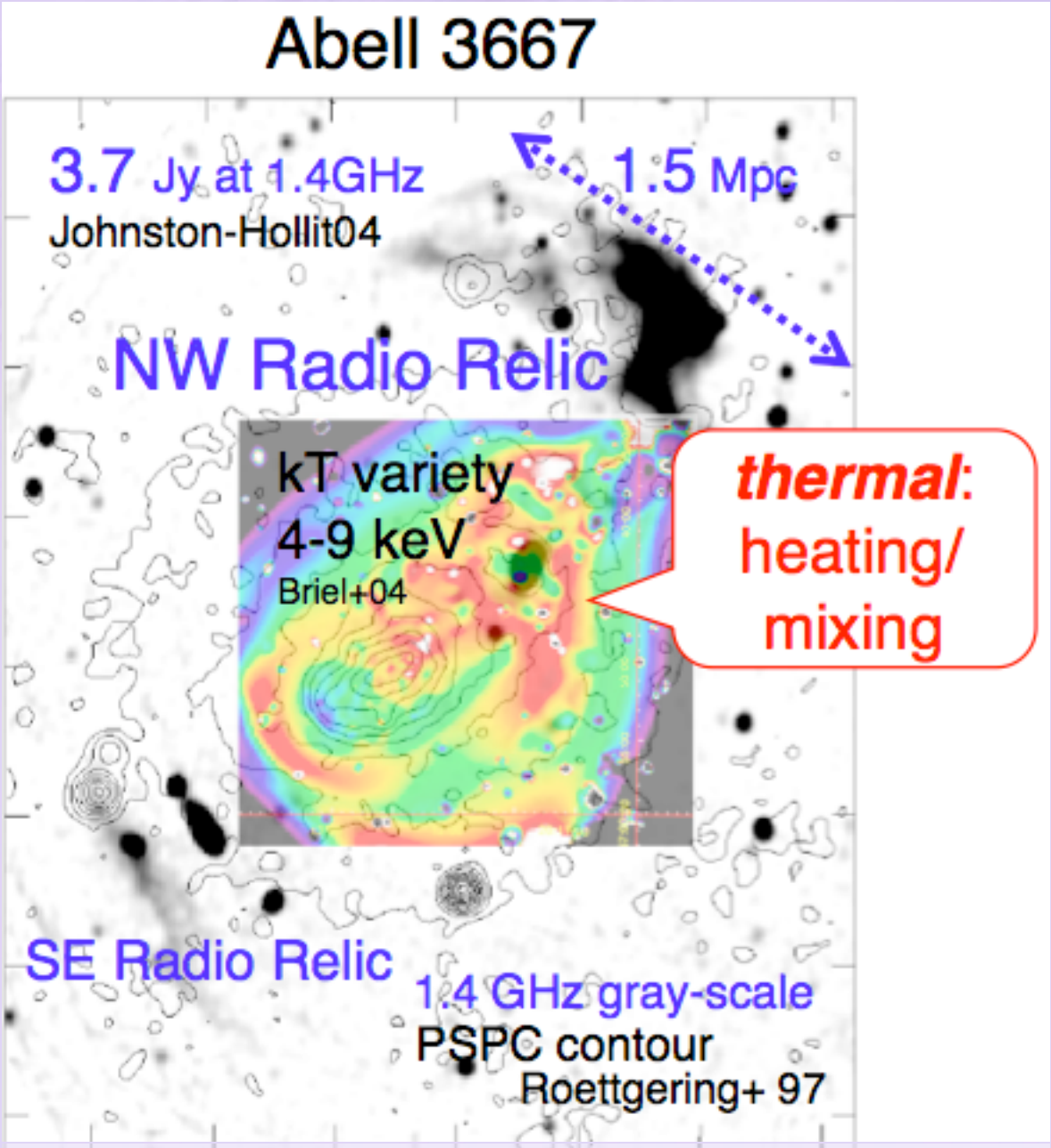
W49B (Katsuta+)



ASTRO-H SXS:

Fe lines due to CR electrons and ions.

IC Hard X-rays from Galaxy Clusters



Nakazawa (X-ray Astronomy 2009)

Particle acceleration at accretion shocks or merger shocks:

a major merger : ~10^{64} erg

➔ CRs and B-field

So far, only radio emission has been firmly detected.

Hard X-ray observations of clusters have been controversial....

Suzaku UL of A3667 (Nakazawa+):

➔ B > 2.2 μG

Pressure around NW relic

ICM: 1.2 eV/cm^3

B-field: >0.1 eV/cm^3

CR e (GeV): <0.1 eV/cm^3

Hard X-rays as "Hadronic" Messengers

cf Aharonian (2004)

Synchrotron radiation by secondary e-/e+ produced at interactions of PeV-EeV protons with ambient gas or photons.

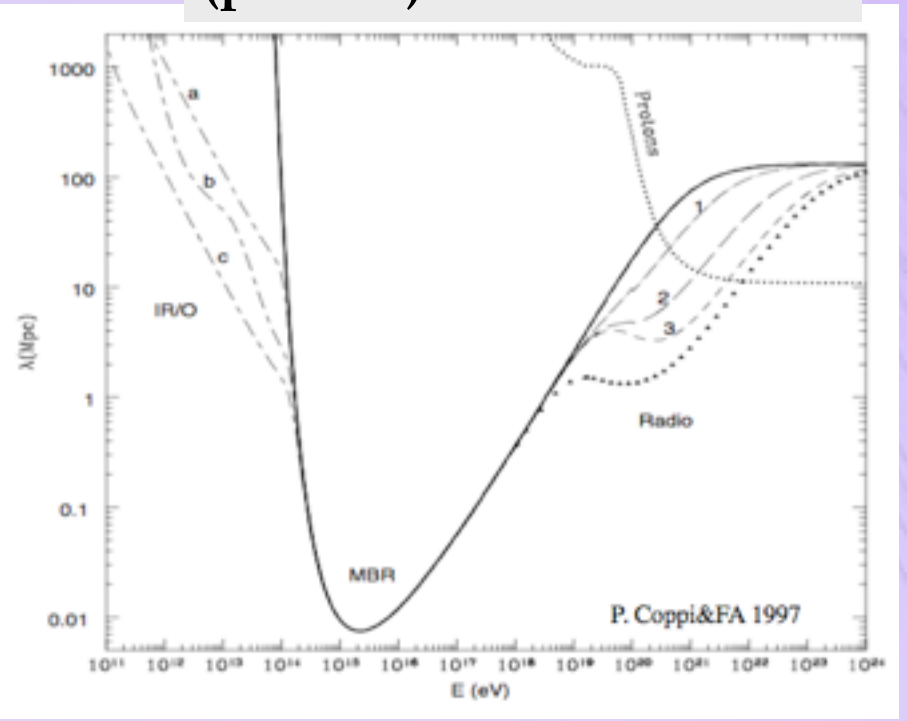
$$p + p\,(\gamma) \rightarrow \pi \rightarrow \mu \rightarrow e \xrightarrow[B]{} \gamma \text{ (hard X-ray)}$$

$$p + \gamma \rightarrow e\text{-}e+ \xrightarrow[B]{} \gamma \text{ (hard X-ray)}$$

Sensitive hard X-ray observations with HXI can probe the highest energy CR protons in SNRs and galaxy clusters.

A better probe than VHE γ-rays and neutrinos.

Transparency of γ-rays (protons) in the Universe

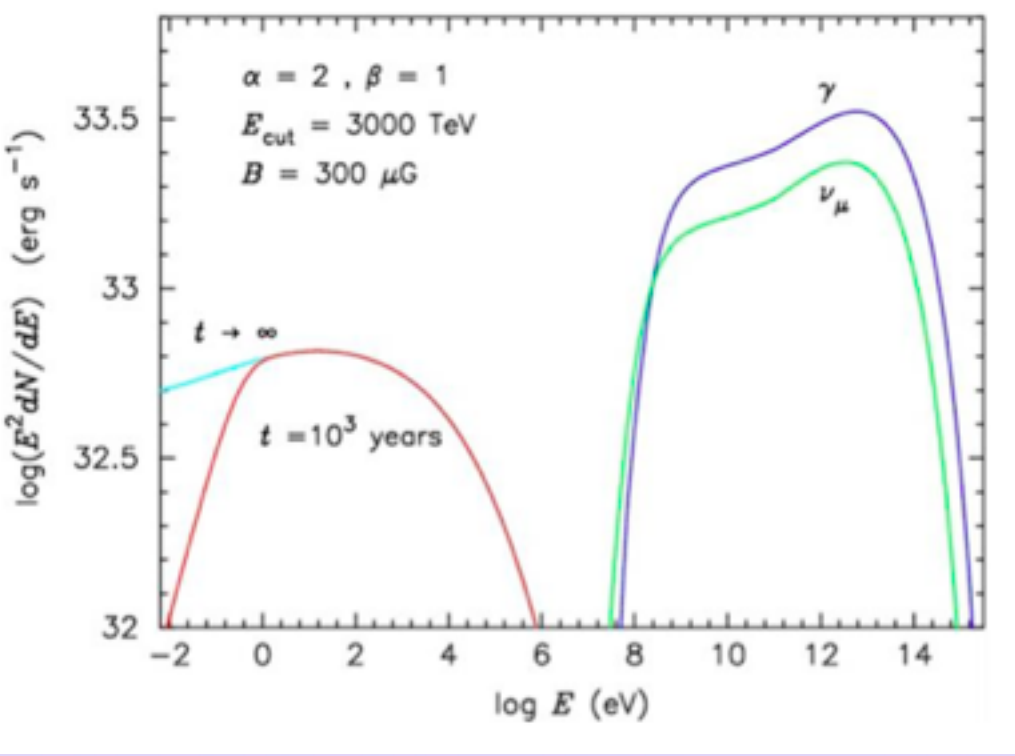


Coppi & Aharonian (1997)

PeV protons in SNRs
& >EeV protons in Galaxy Clusters

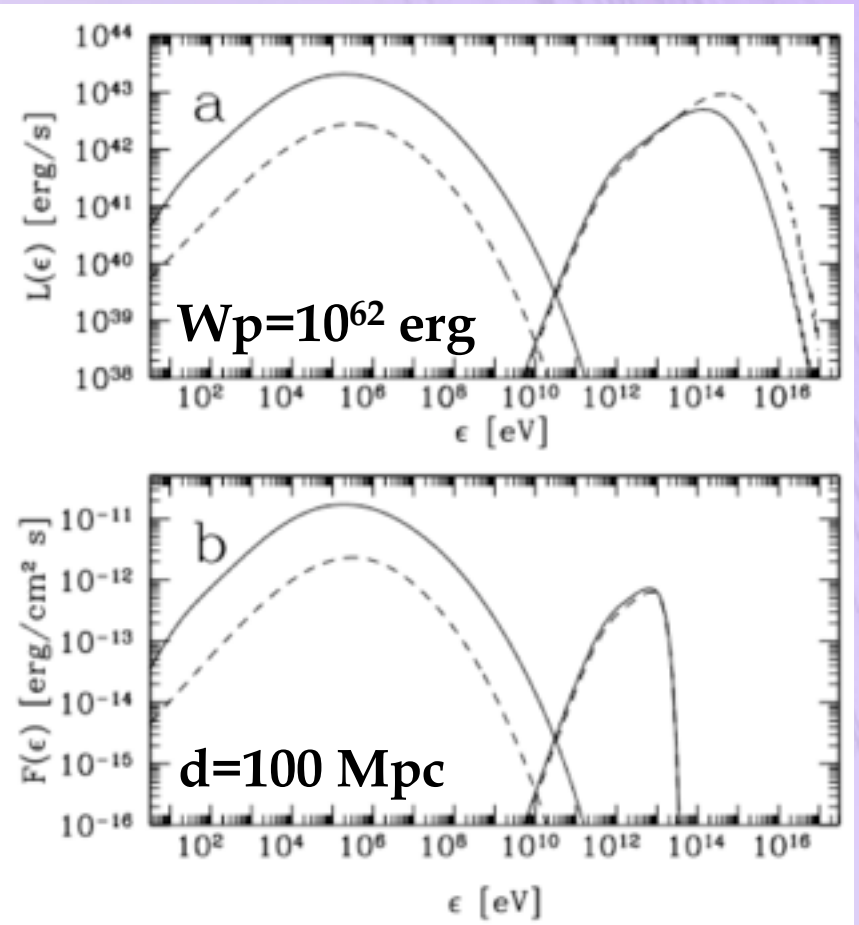
Young SNRs with 3 PeV protons:

Radiation from secondaries



NOTE: synchrotron by primary electrons has a cutoff of $h\nu_0 \sim 1$ keV.

Galaxy Clusters with strong accretion shocks

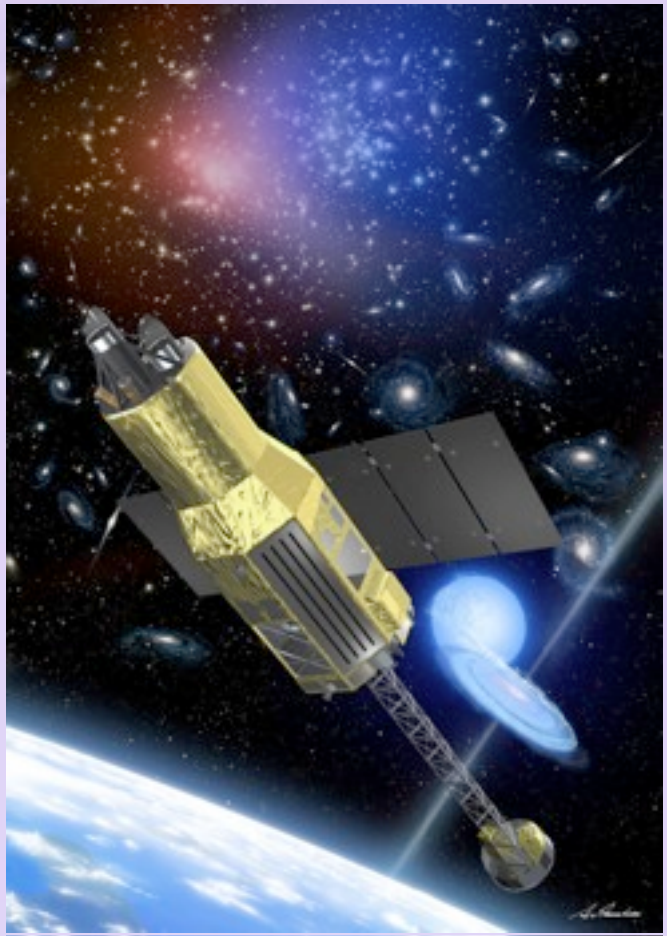


Vannoni+2011

ASTRO-H (2014-)

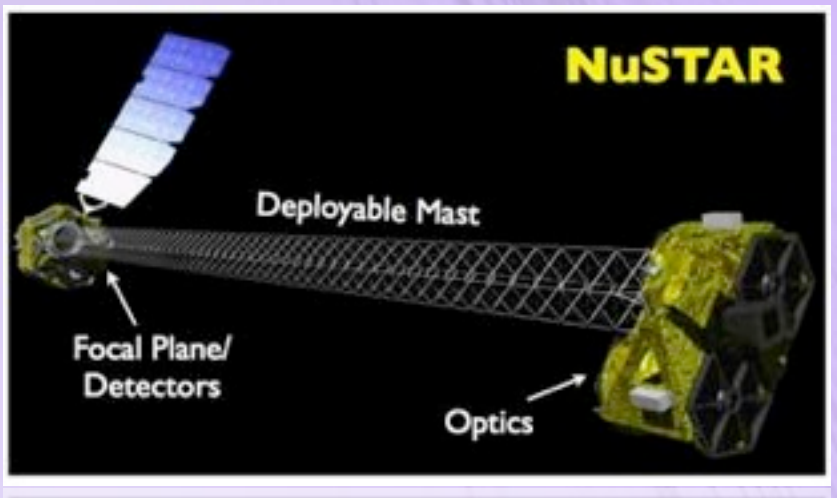
"Observatory"

micro-calorimeter, hard X-ray imager, CCD, soft-gamma-ray detector



NuSTAR (2012-)

Hard X-ray mirror



Stay Tuned!

Y. Uchiyama at Gamma2012