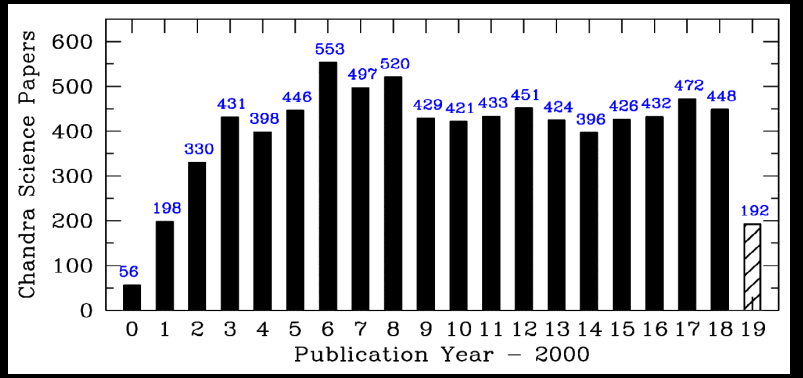
NASA's Chandra X-ray Observatory
Celebrating 20 years

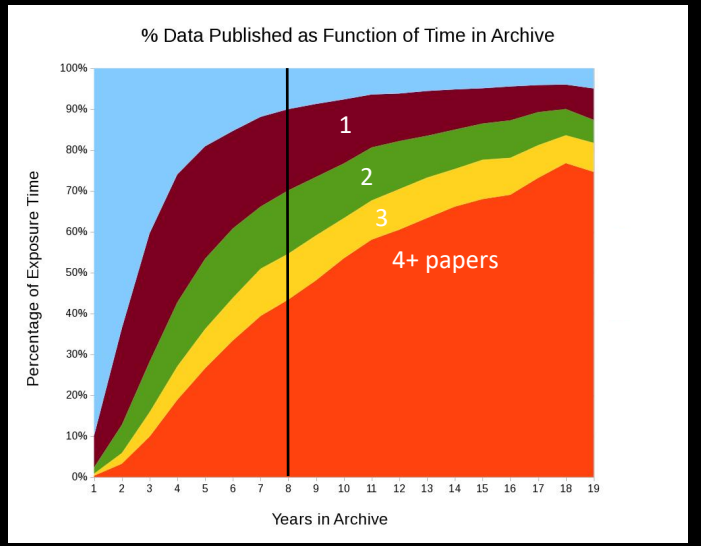
20 years of Chandra
3-6 Dec 2019

Belinda Wilkes
Director, Chandra X-ray Center

NASA's Chandra X-ray Observatory

- Lifetime: ~9 +/- ?? **more** of operation
- High Impact on Astrophysics:
  - Science Papers: >8000
  - ~480 papers/yr
  - Citations/paper: >35 after 6 years
  - >4300 PIs&CoIs, ~150 new/yr (distinct)
  - Proposal oversubscription ~ 5.5
  - >90% data published
- High Impact on Public via Press, website, social media etc.





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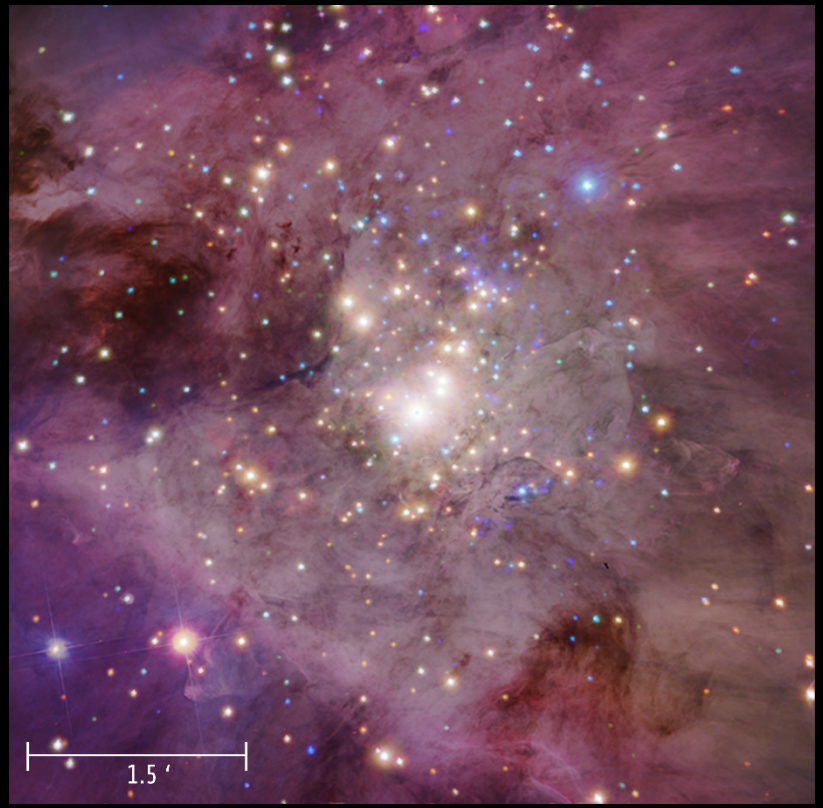
Star Forming Regions: Orion Nebula

- ROSAT: **~250 sources** *(Gagne et al.)*
- *Chandra* (840 ks): **~1400 sources**
- *Chandra's* sensitivity and resolution was a game-changer for pinpointing young stars

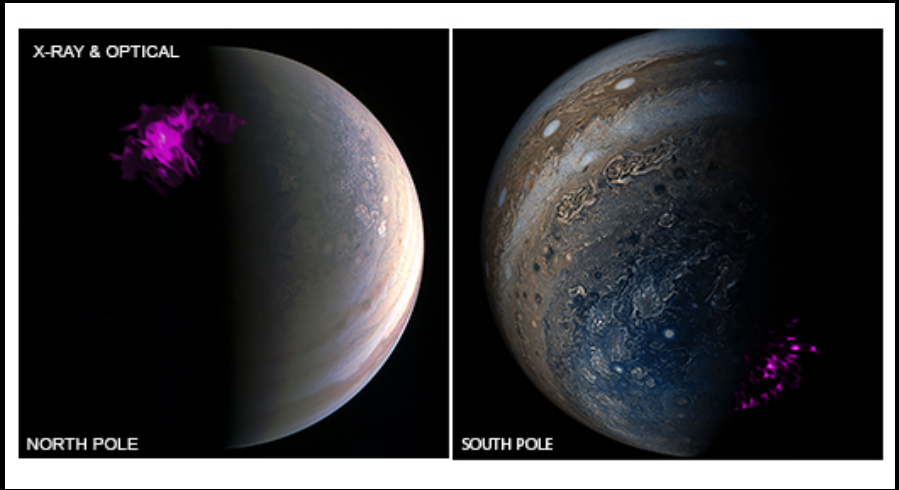


Chandra
Garmire, Feigelson, Townsley ++

Solar System Objects

- X-ray emission
  - due to charge-exchange with solar wind ions
  - seen from comets, Venus, Mars, and Pluto (during New Horizon's Flyby)

- Jupiter
  - Aurorae at north and south poles
  - Triggered by magnetic unloading from Jupiter's equatorial plasma sheet
  - Observations during Juno mission, timed to investigate this interaction



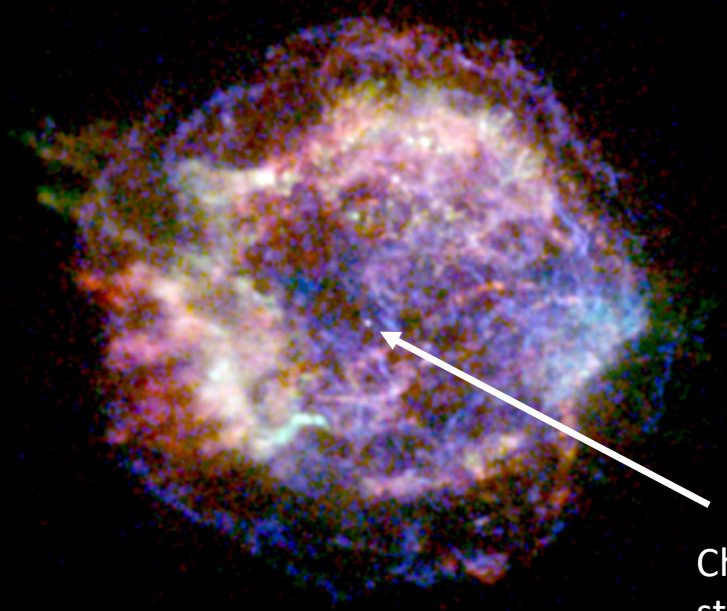
Dunn et al. 2017

Official First Light (Aug 1999)

Supernova Remnant: Cassiopeia A

Age: 340 years

Size: 29 lyrs



1 Msec Deep Image (12 days)

Chandra-discovered stellar remnant

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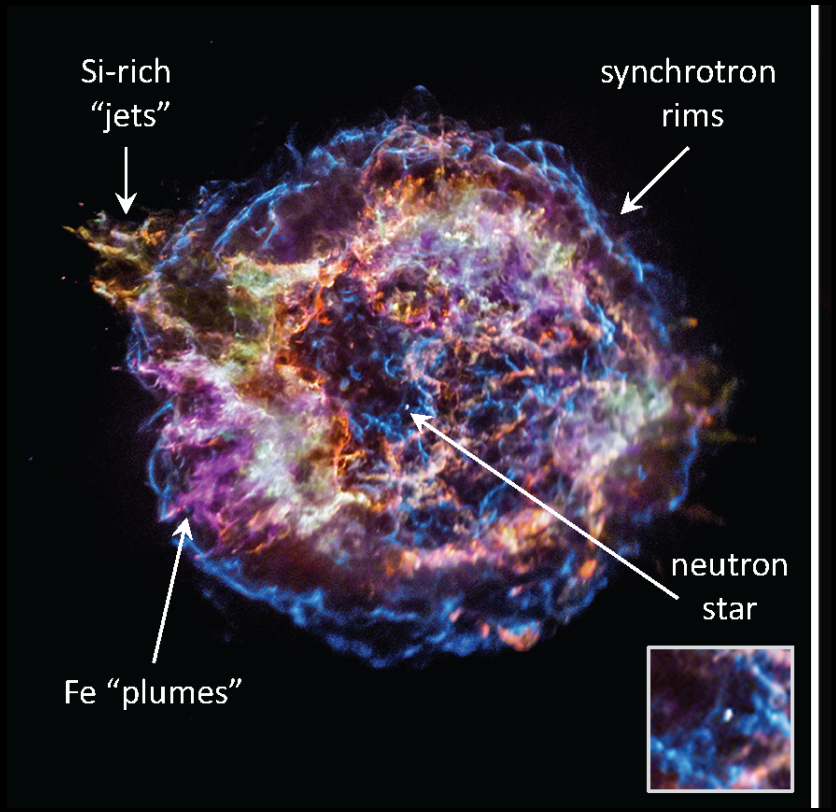
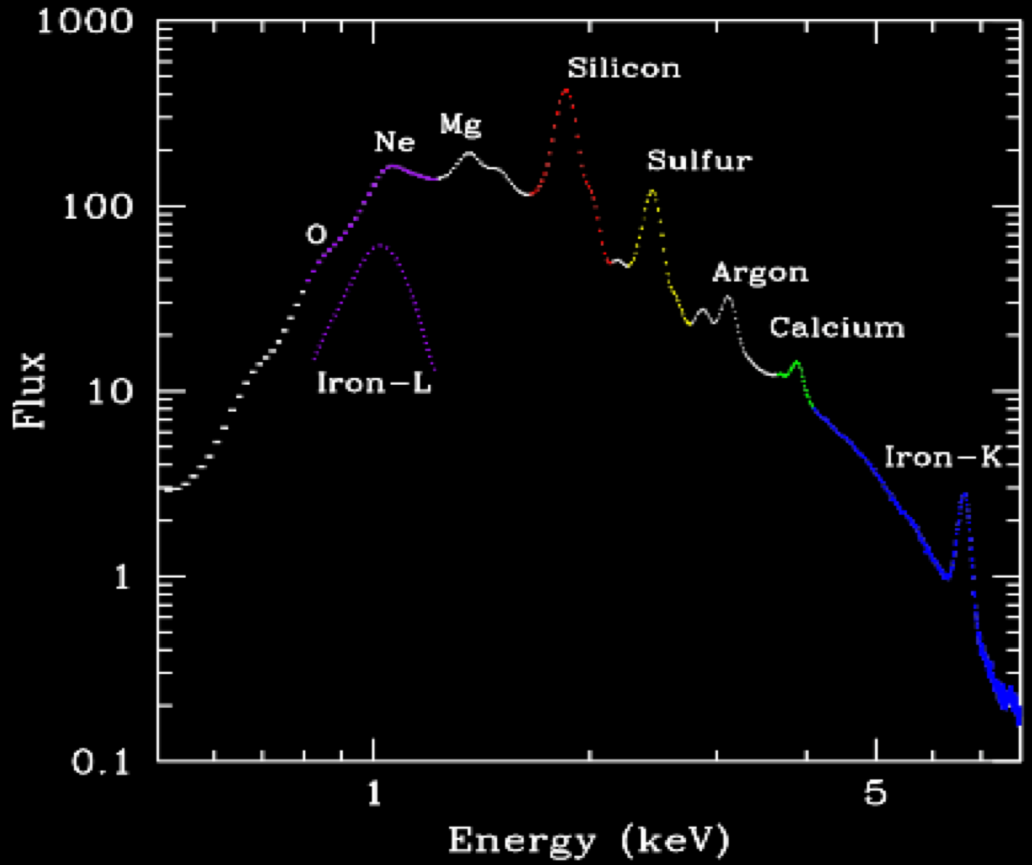
Cas A (continued)





Hwang, Laming, Slane, Patnaude ++

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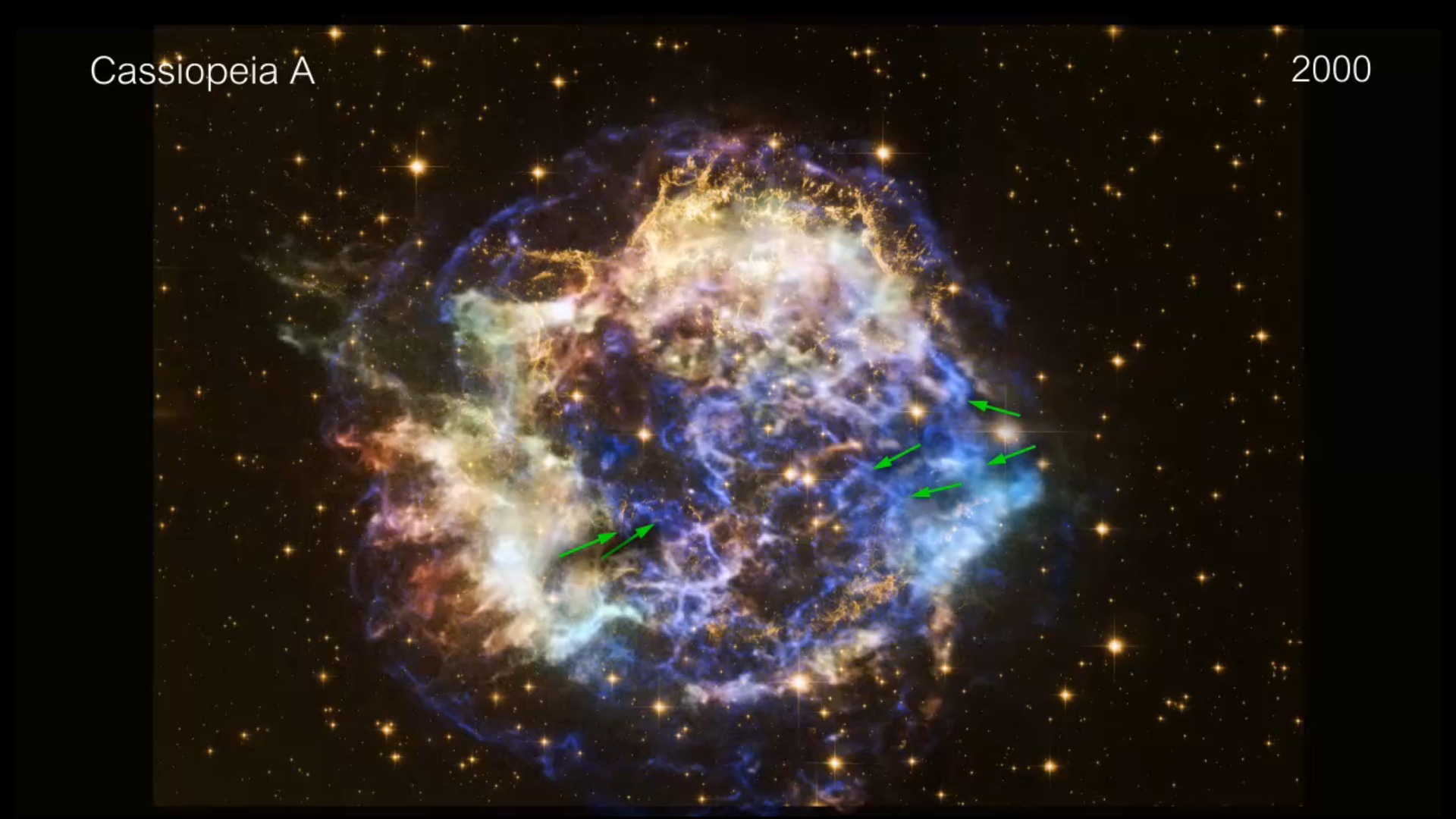
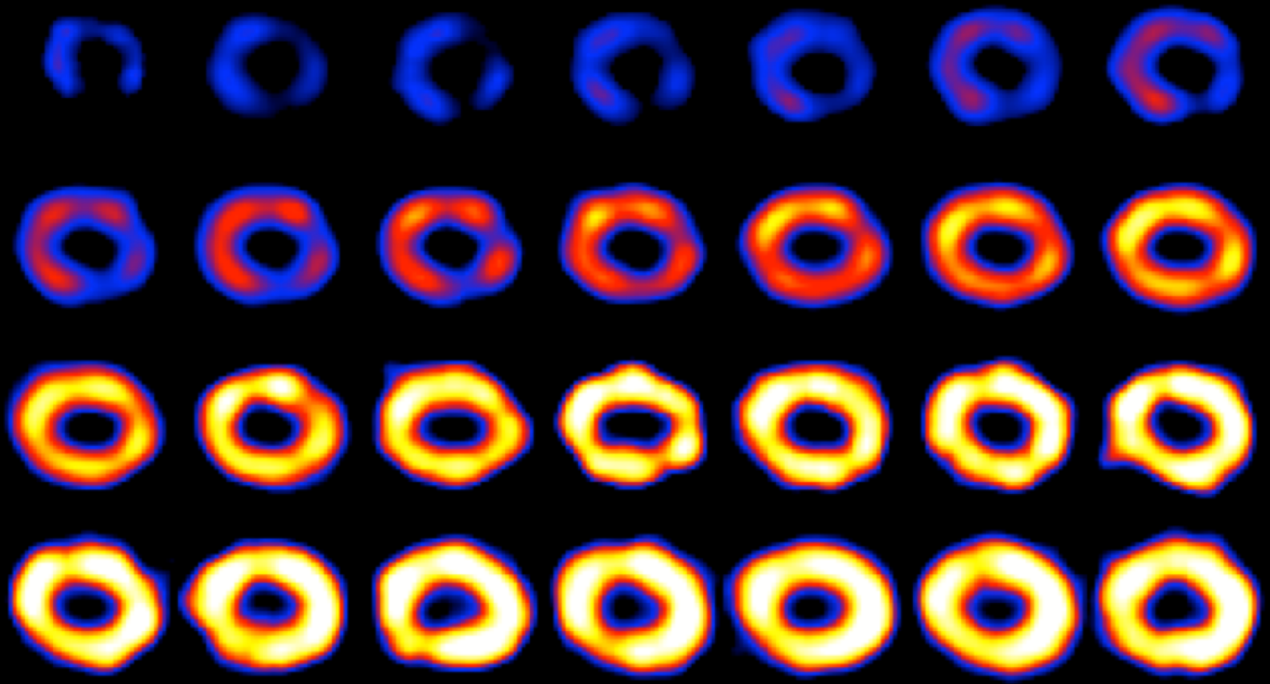

Cassiopeia A
2000

SN1987A: Extended Long-term Monitoring

- 1999-2015
- X-rays increase as forward shock interacts with circumstellar material
- >10,000 days, X-rays fading, forward shock moving beyond equatorial ring

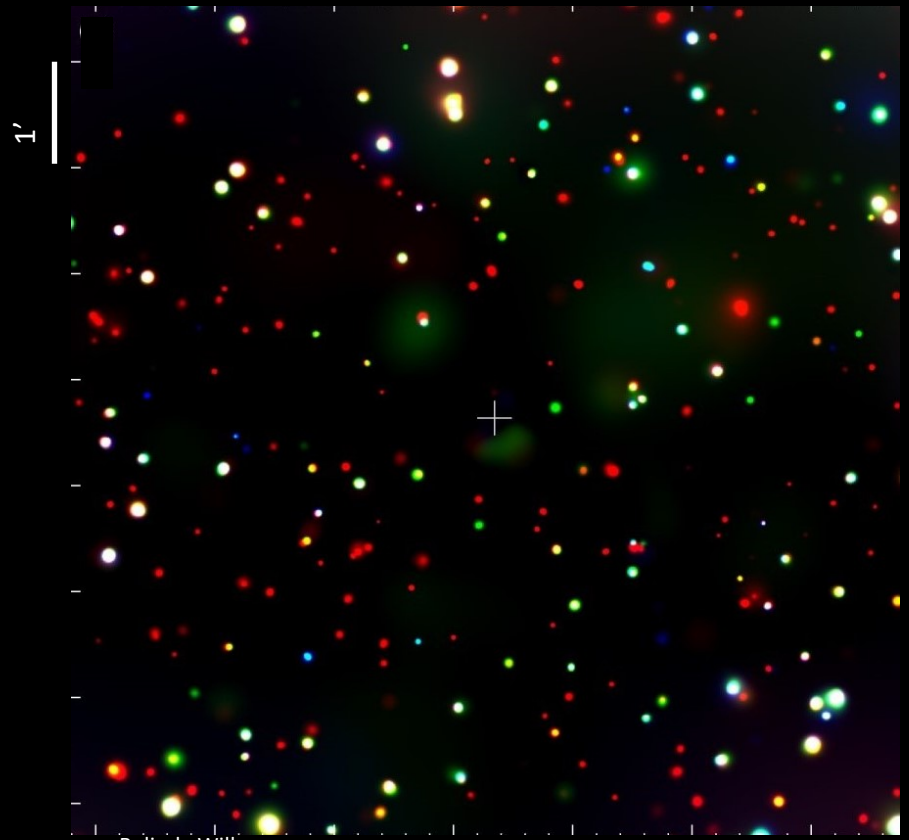


Frank, Burrows et al. 2016

Deep Fields: Cosmic X-ray Background

Primary *Chandra* Science Goal

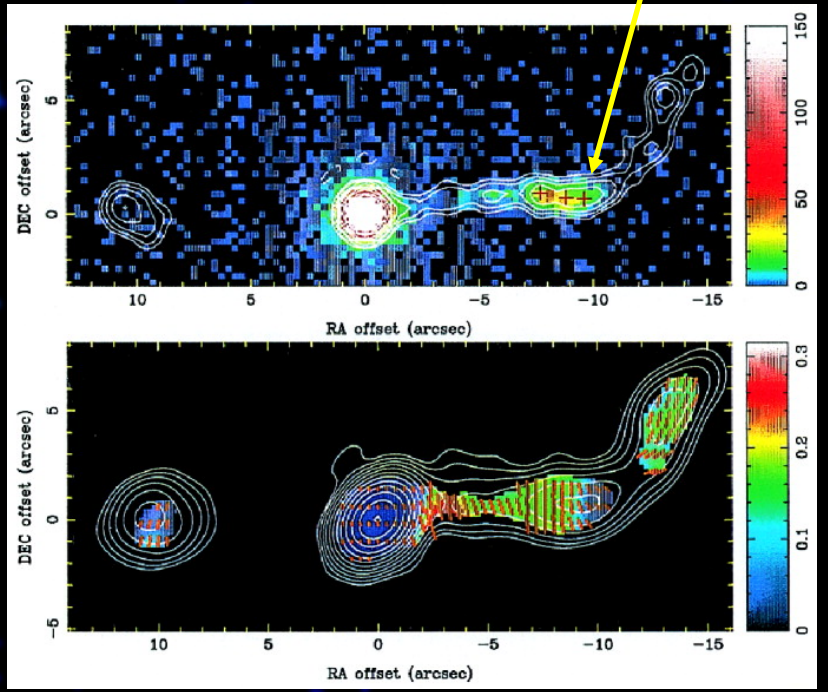
- Resolve CXRB, observed to be ubiquitous in previous X-ray missions
- Fully resolved to ~9 keV: Chandra Deep Field South (CDFS, 7 Ms)
- 1000 sources, mostly Super Massive Black Holes
- Look back ~12-13 Gyrs, ~10% current age of Universe
- Detects log L_X~42 at z>4
- Hardness: wide range, including highly obscured sources



Luo, Brandt et al. 2017

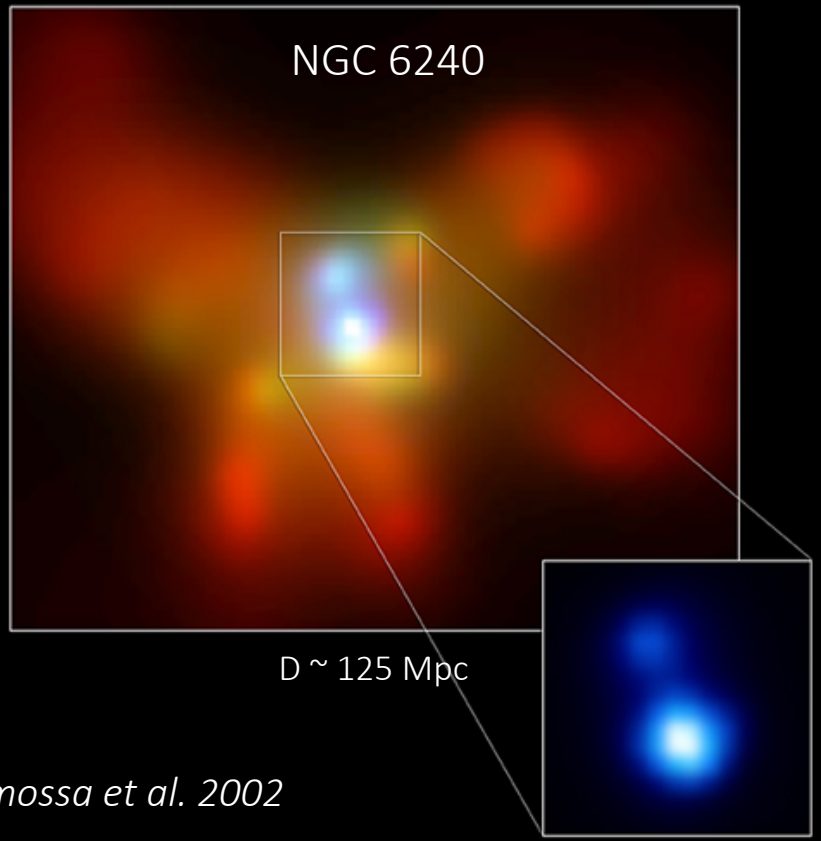
First Targeted Source
Quasar: PKS 0637-75

- Point Source to focus: Quasar, z=0.66
- X-ray Jet visible: 9” long, (100 kpc)
- Jet L~$10^{44.6}$ erg s^{-1}
- No X-rays beyond the jet bend
- Radiation mechanisms:
  - Inverse-Compton/CMB, mildly relativistic *(Tavecchio et al. 2000)*
  - **BUT**
  - Ruled out by lack of Fermi GeV γ-ray emission *(Meyer et al. 2015)*
  - →Synchrotron emission from 2nd electron population
- The birth of multi-λ studies of jets



Schwartz et al. 2000

Binary Supermassive Black Holes

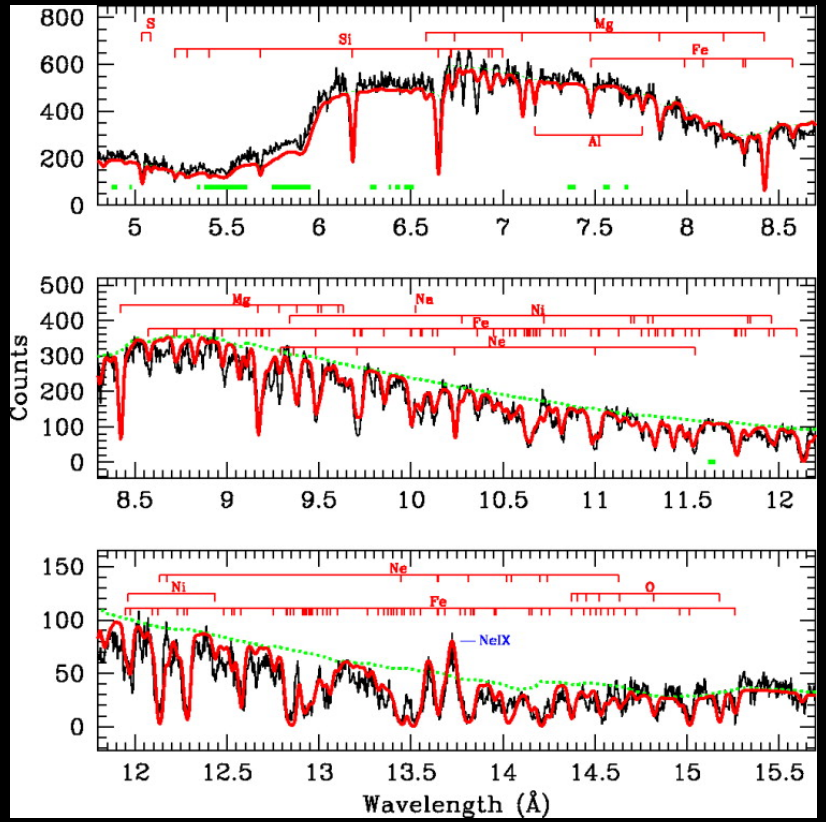


Komossa et al. 2002

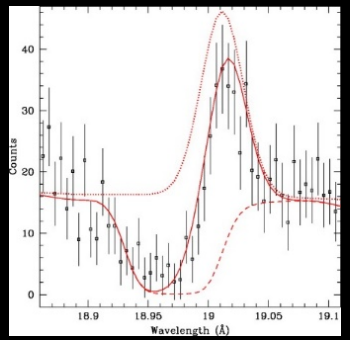
- Merging galaxies (optical: red)
- Binary SMBHs (*Chandra* : blue)
- SMBHs: 1 kpc apart, will merge in ~10-100 Myrs
- Binary AGN in ~10% galaxies *(Koss et al.)*
- Numbers vs separation → Galaxy merger rate & binary SMBH merger rate *(Comerford et al.)*
- Triple System: SDSS J084905.51+111447.2 *(Pfeifle et al. 2019)*

Grating Spectroscopy: NGC 3783

- 900 ks HETG Spectrum, z~0.01 Type 1 active galaxy
- 2-phase clumpy absorber, high and low ionization, pressure equilibrium
- Outflow, v~750 km s^{-1}
- Dynamical agreement with UV absorber
- Variability → ~6 pc from SMBH
- Mass outflow rate 0.2-4 M_{sun} yr^{-1}
- Blended absorption and emission components: OVIII λ18.969



Krongold et al. 2003,2005



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Perseus Cluster: Optical and X-ray

Credit: Paul Nandra, ESA Athena

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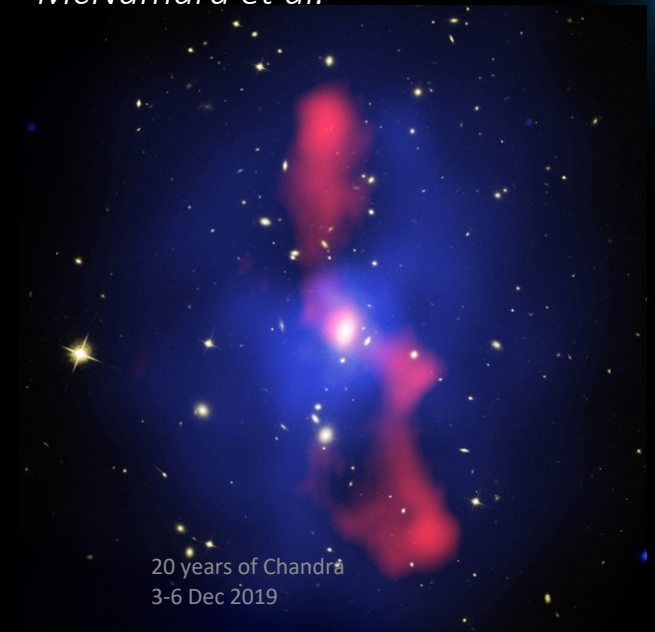
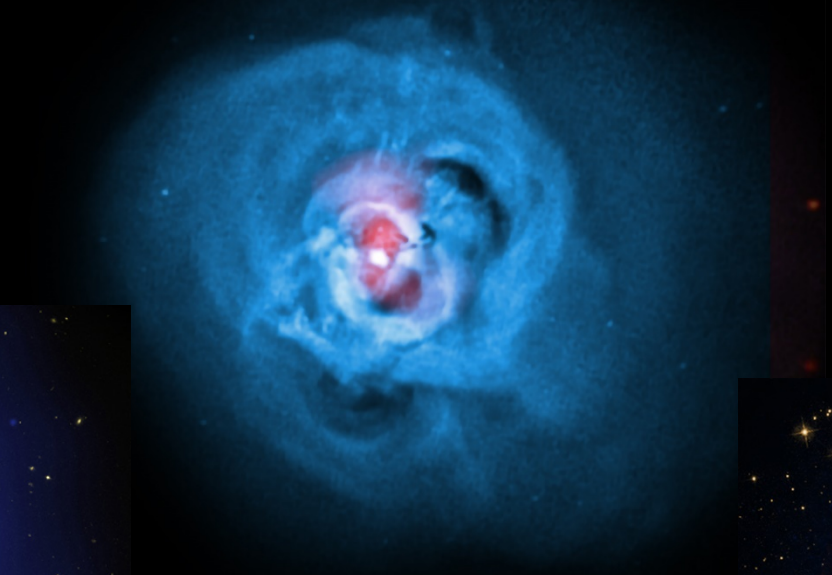
X-ray and Radio emission from SMBHs in Clusters

MS 0735.6+7421
McNamara et al.





Perseus
Fabian et al.

Cygnus A:
Wise, Nulsen et al.

A luminous, nearby

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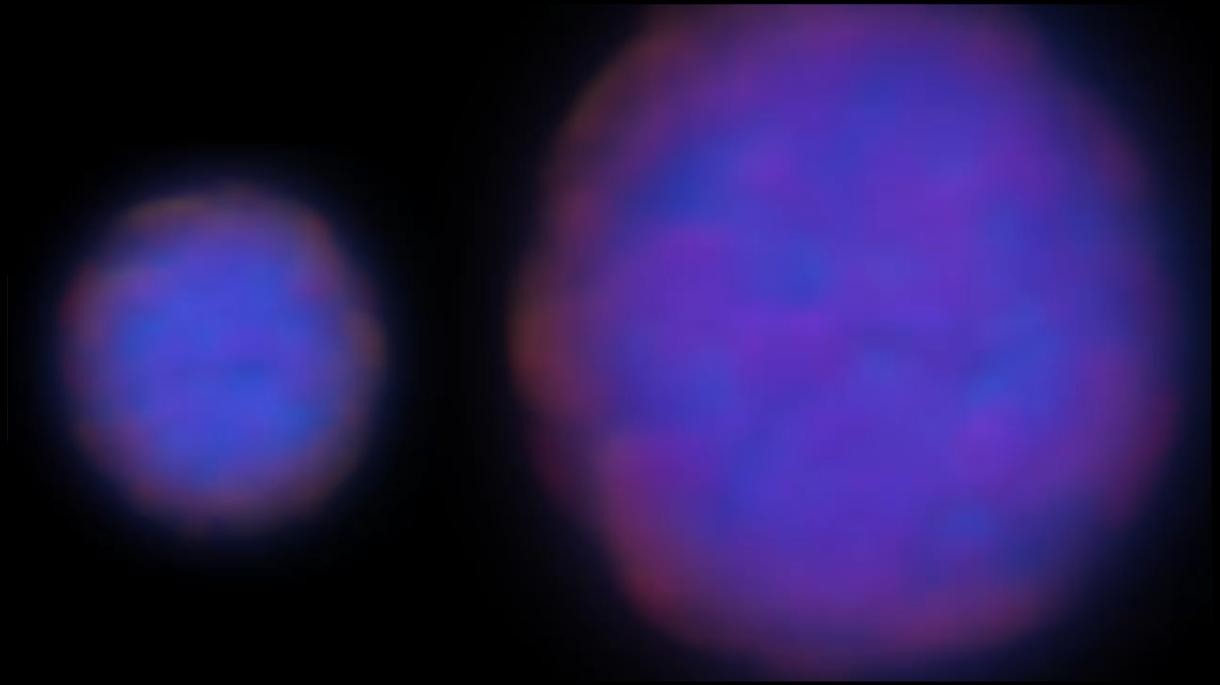
Dark Matter: Direct Visualization

Bullet cluster

- **Colliding Galaxy Clusters:**
  - *Chandra:* hot X-ray-emitting gas
  - Dark Matter (inferred from gravitational lensing, ESO WFI)
  - *HST,Magellan (white):* galaxies
- Interpretation:
  - Drag on gas
  - No drag on stars/dark matter
  - Gravity due to dark matter clearly separated from baryons
- Dark Matter:
  - weak self-interaction cross-section, $\sigma/m < 0.7\ cm^2 g^{-1}$

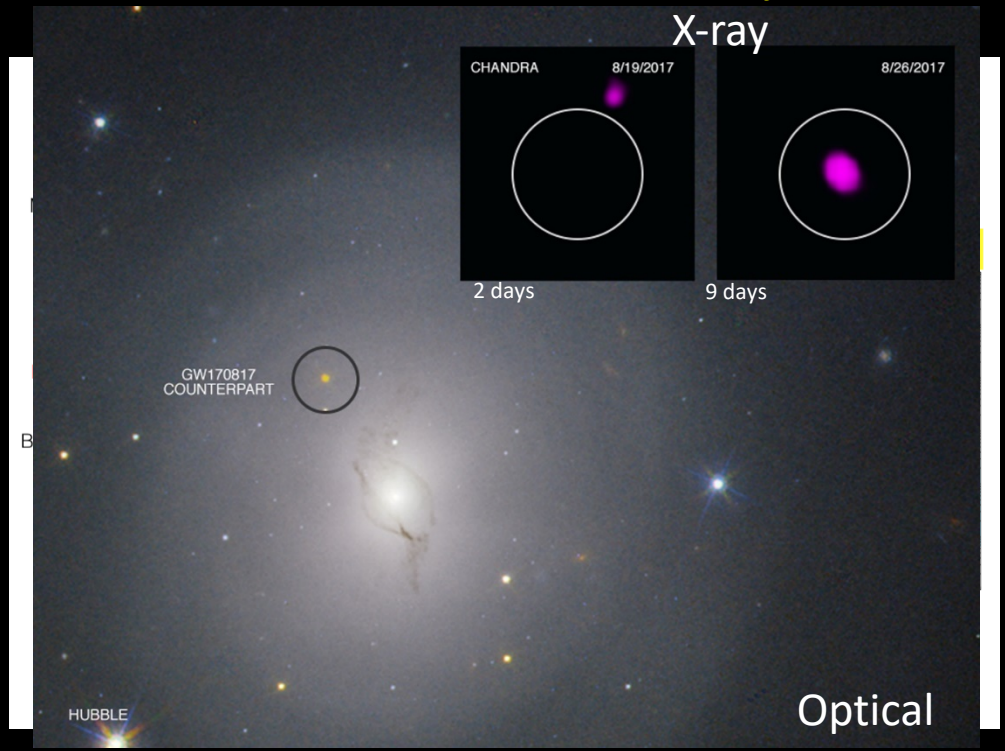


Clowe et al. 2007, Randall et al. 2008

Merging Neutron Stars, LIGO/Virgo: GW170817

- Fermi, Integral: Faint, short gamma-ray burst ~2s >LIGO/Virgo
- Optical counterpart found, tracked, faded and reddened over ~2 weeks (kilonova → r-process elements)
- X-ray & γ-ray jet viewed off-axis
- Source behind the sun – no X-ray observations until December
- X-ray tracked radio, peaked ~160 days, then faded α^{-2} → 30° off-axis jet
- *Chandra* monitoring continues
- Awaiting next NS-NS or NS-BH GW trigger!

First EM detection of GW source!!



Fong, Haggard, Margutti, Troja

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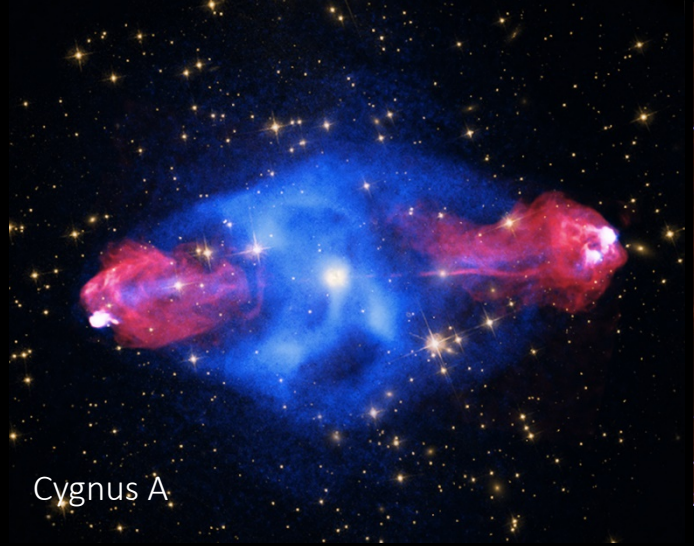
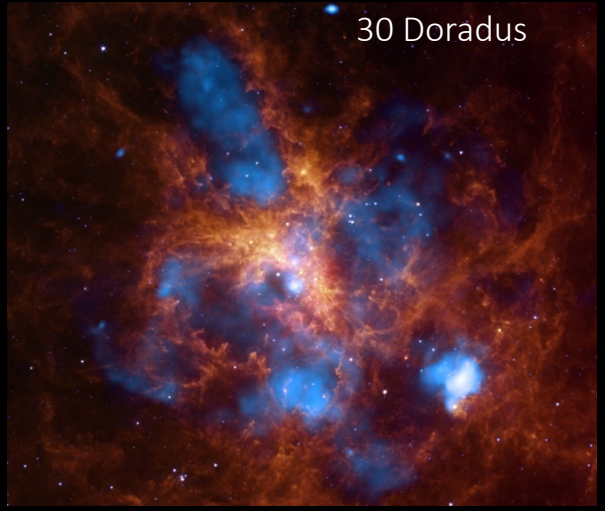


Cygnus A



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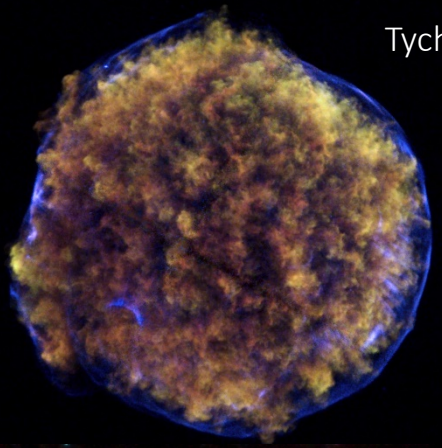
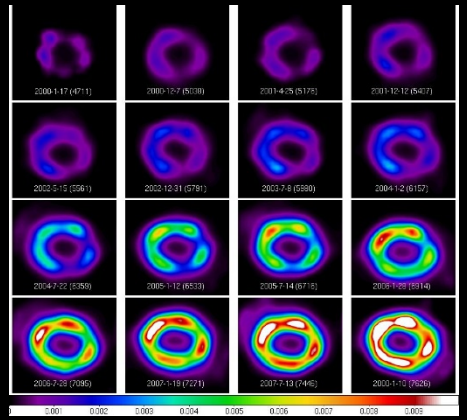
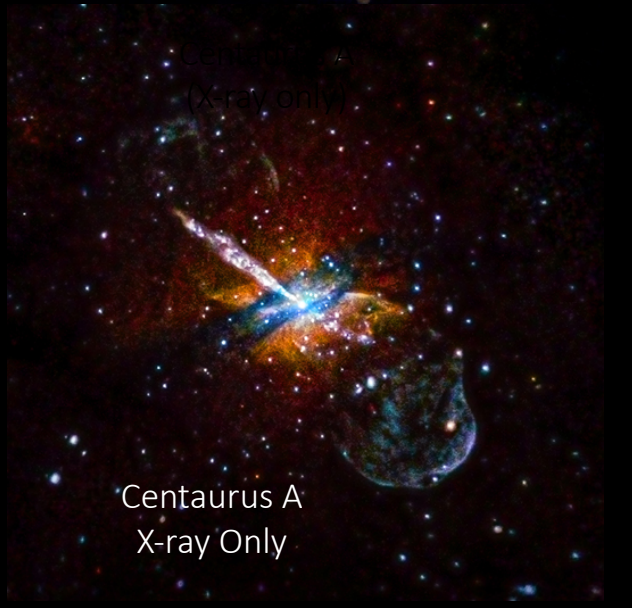


Tycho

Bullet Cluster

SN 1987A over time





Centaurus A
X-ray Only

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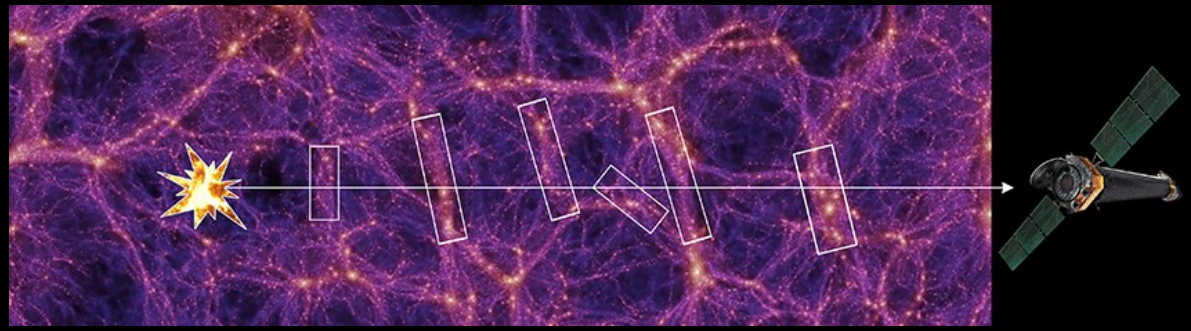
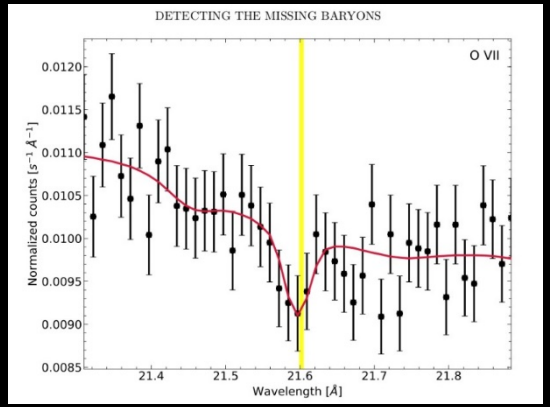
Missing Baryons (WHIM) detected

Quasar: H 1821+643, z=0.297



The missing baryonic mass at z<2 (1/3rd cf. high-z estimates)
(WHIM, T< & > 10^5 K)

- Updated a technique: concentrate on OVII
- 17 UV absorption line systems in HST data
- Stacked *Chandra*/HETG spectrum, blue-shifted to UV redshifts
- Effective exposure ~8 Ms (470 ks observation)
- Significant (3.3σ) OVII λ21.6 absorption line, EW~4.1 mA
- N_{OVII}~$1.4*10^{15}$ cm^{-2}, Ω_b(OVII)~0.0023 /[Z/Z_{sun} f_{OVII}]
- Consistent with WHIM expectations for this los
- Cycle 21 VLP to confirm this detection to >5σ *(PI Bogdan)*



Kovacs et al. 2019