The Chandra X-ray Observatory

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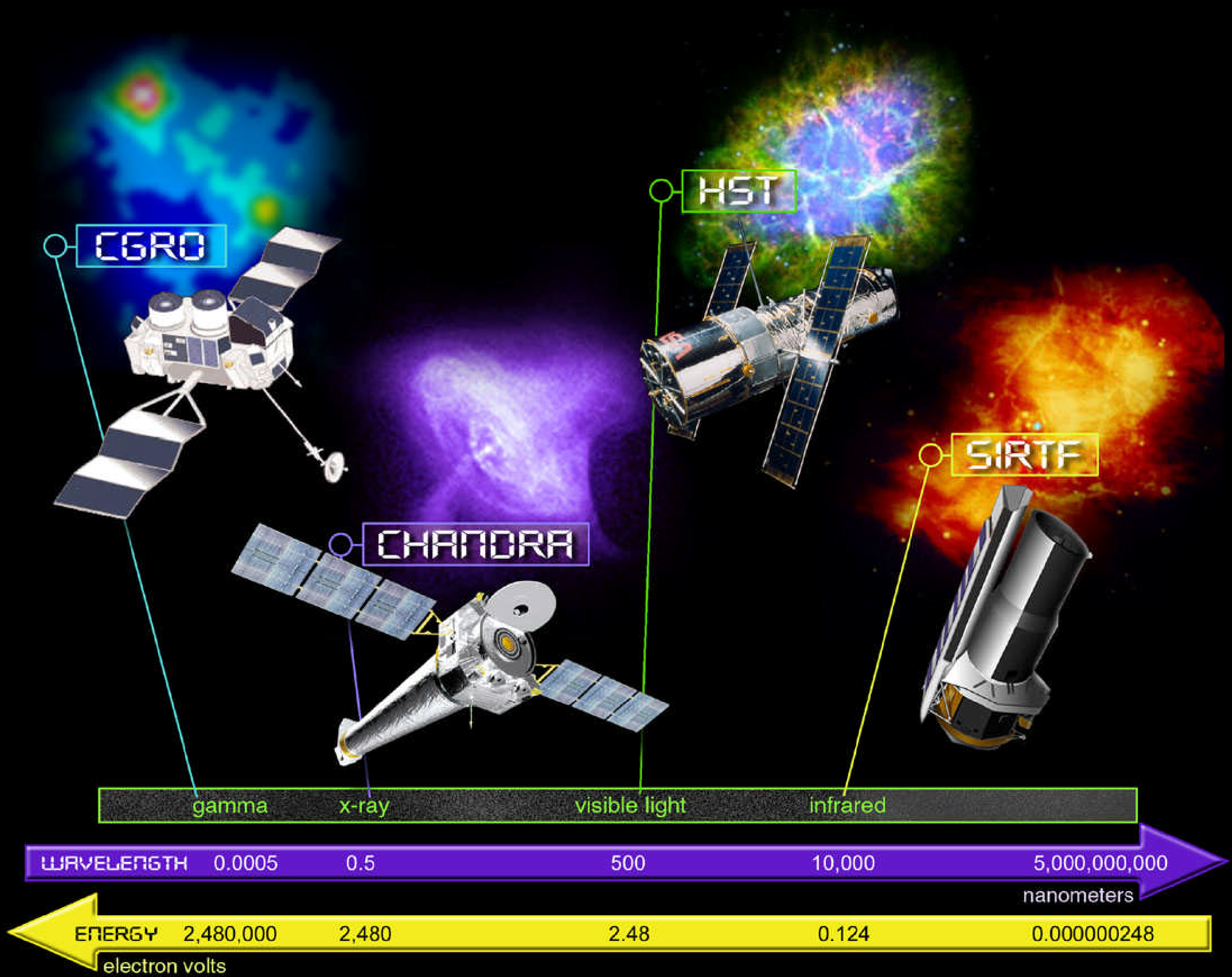
NASA's Great Observatories

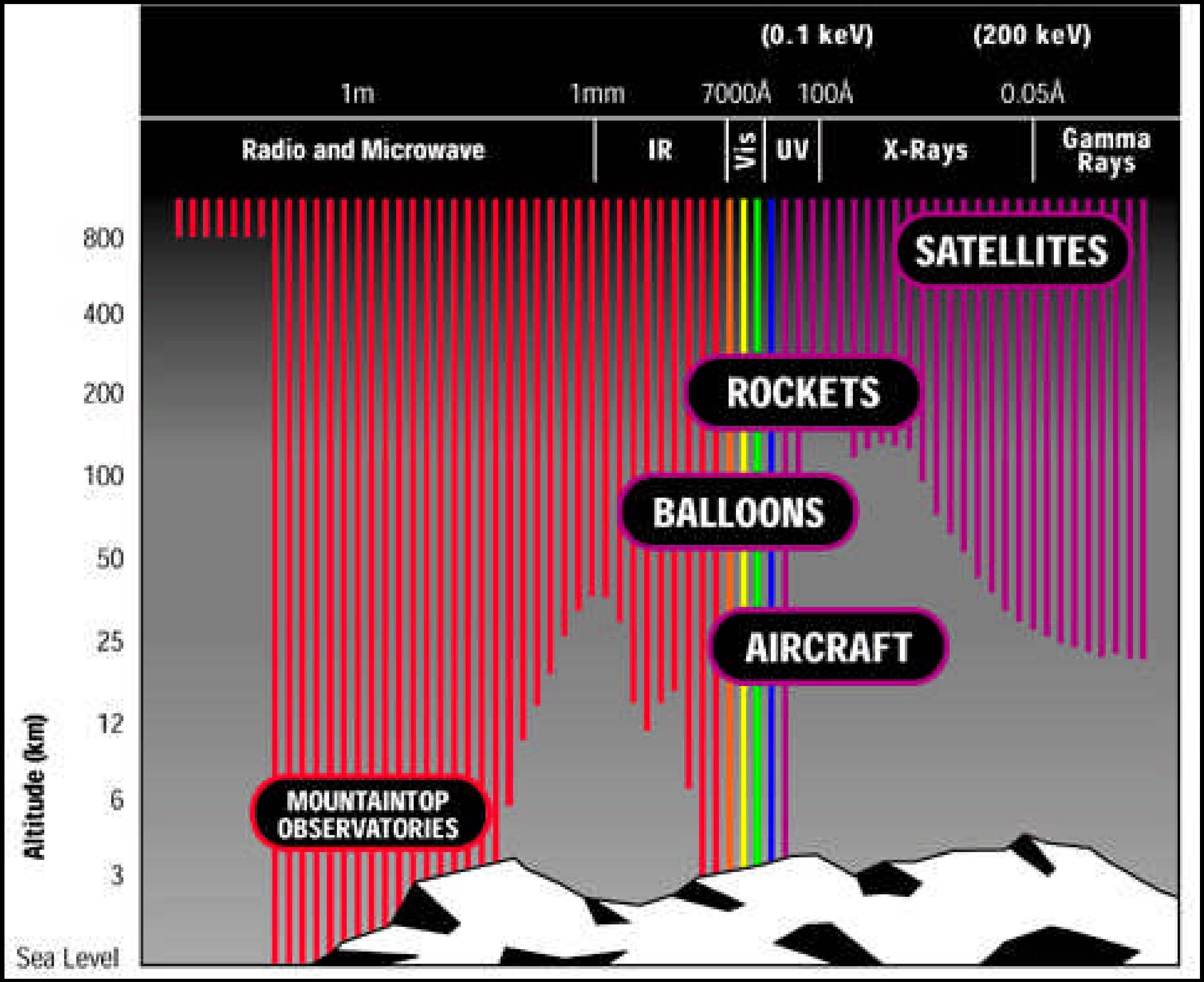


Some Chandra Facts

- The only X-ray observatory amongst those currently flying (and planned) that features sub-arcsecond angular resolution
- 2979 distinct PIs and CoIs in cycles 1-11
  - ~200 new PIs and Co-Is per year
- Involved more than 1350 students and postdocs
- After initial buildup now averaging over ~500 papers per year
- Has had a major impact (Trimble & Ceja 2008)

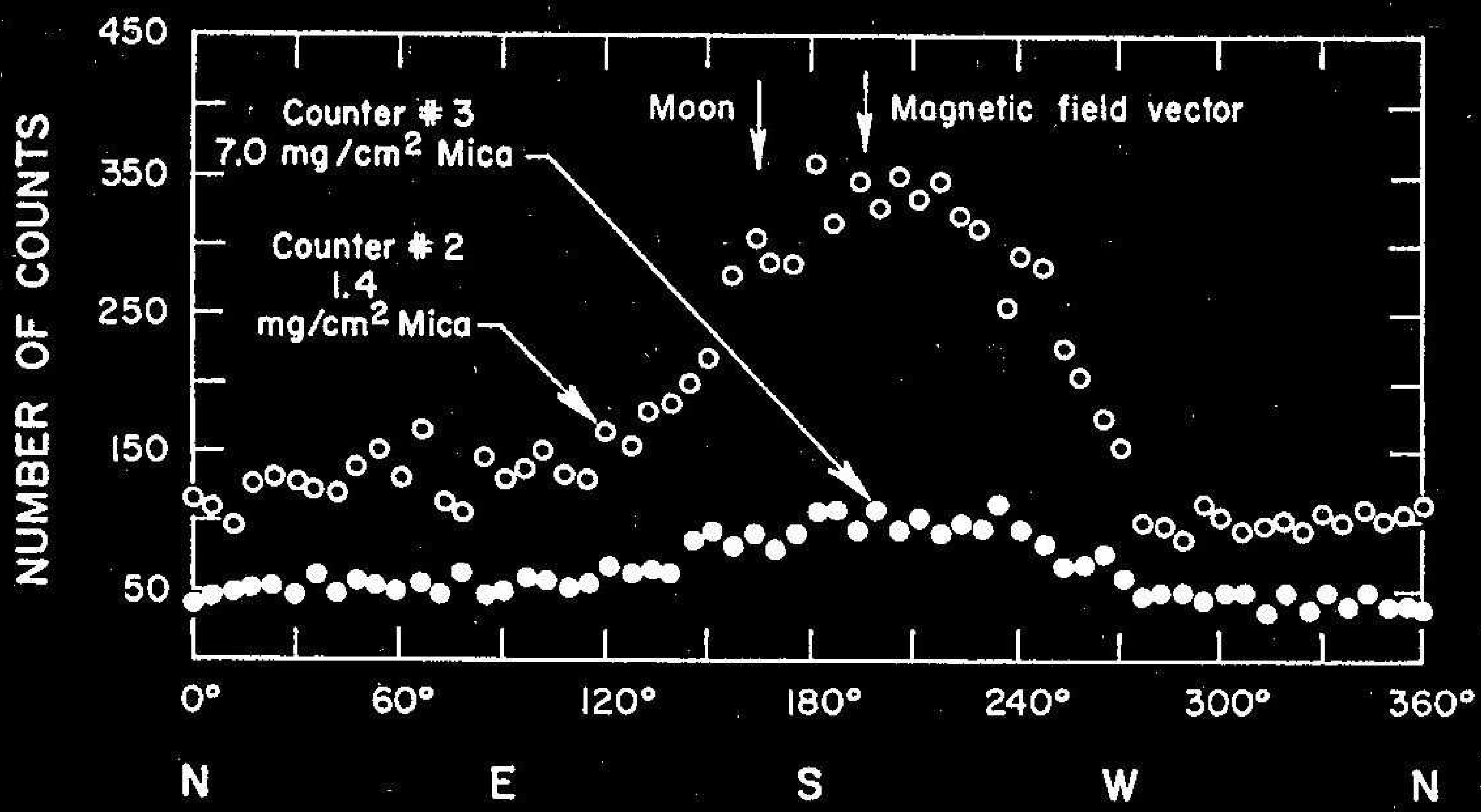
Telescope	Citations	Papers	Cites/paper
Chandra	16936	723.5	23.41
HST	15390	1063.1	14.48
VLA	8478	582.2	14.60
Keck	8122	356.6	23.33
XMM-Newton	7993	332.0	24.08
VLT	5696	345.5	16.49
AAT	4592	170.2	26.98

The atmosphere poses problems

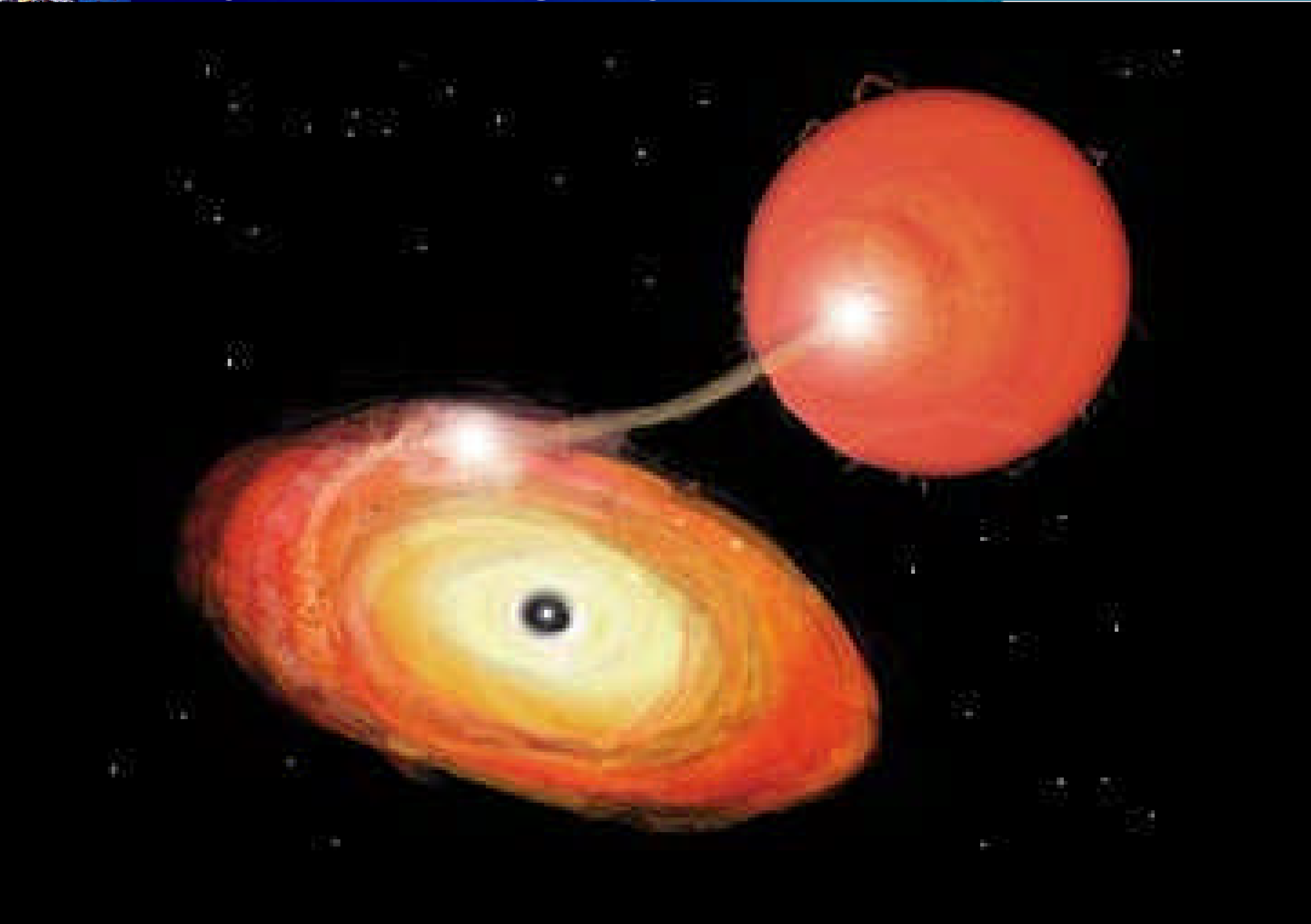


The early history

- Solar Studies in late 40's
- Discovery of first extra-solar source in 1962



Binary sources and gravity

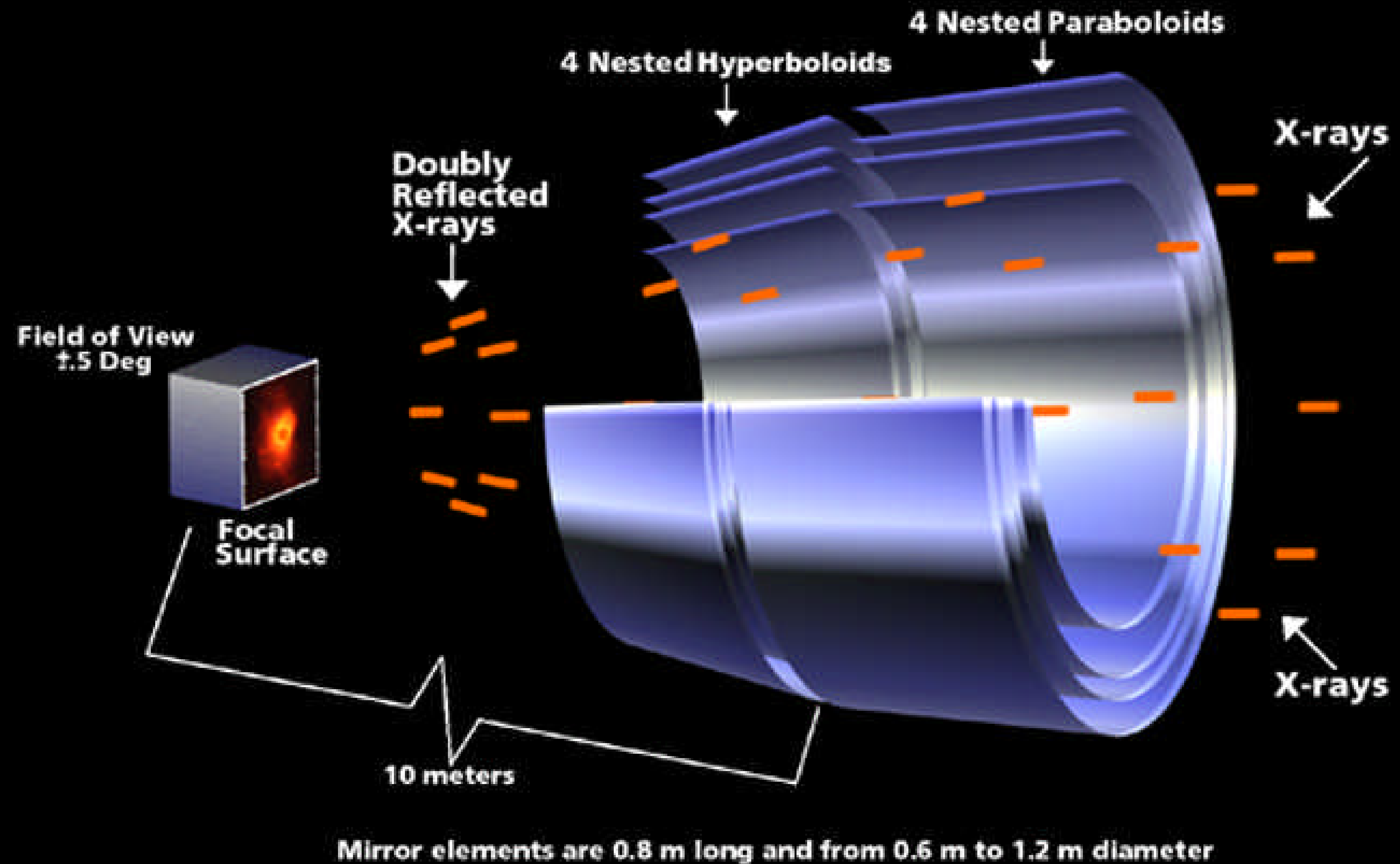


Where is the beef?

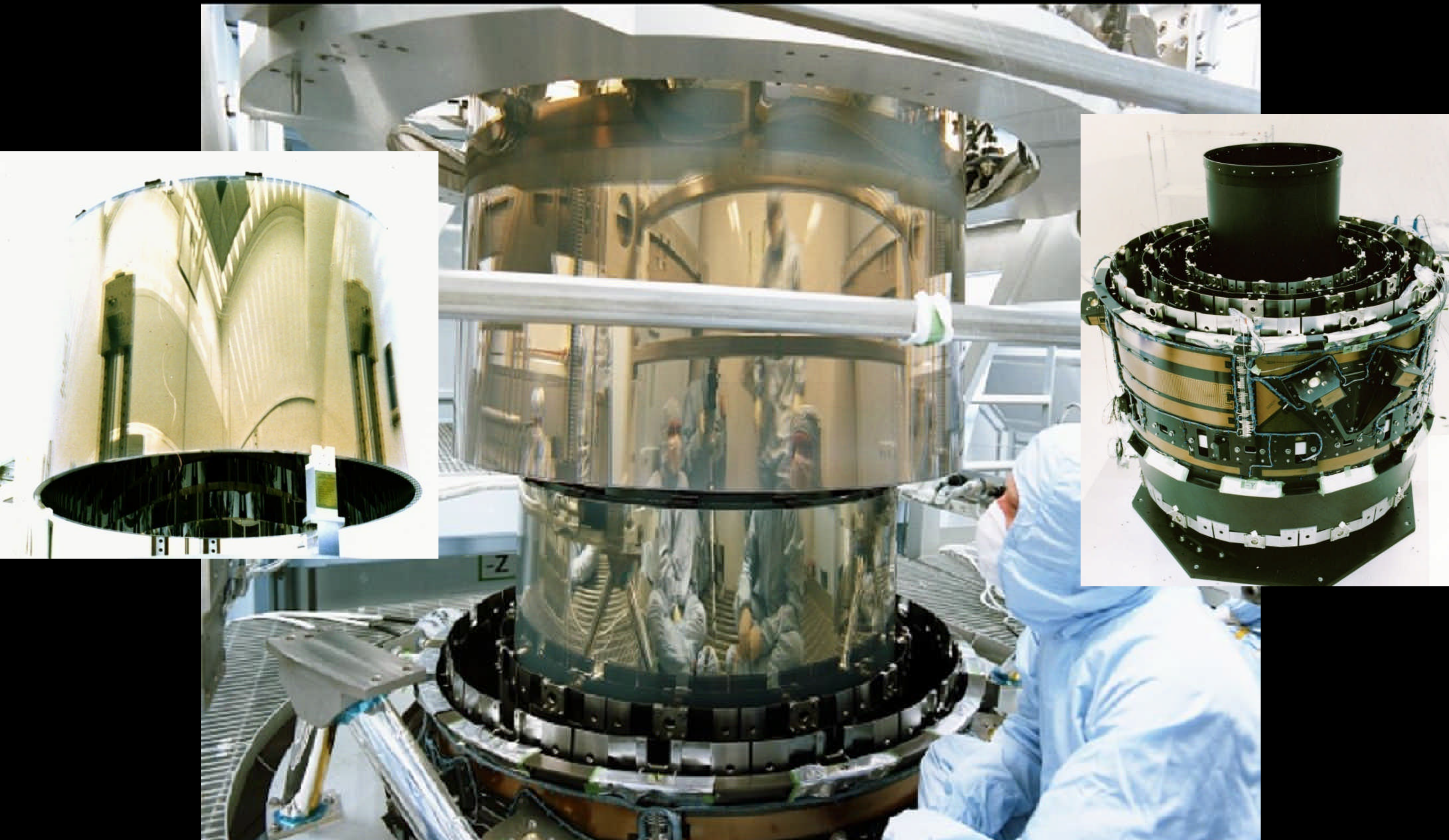
We know now that most of the matter that we “see” is from its X-ray emission

The bulk of this matter is the hot X-ray-emitting gas in the great galaxy clusters

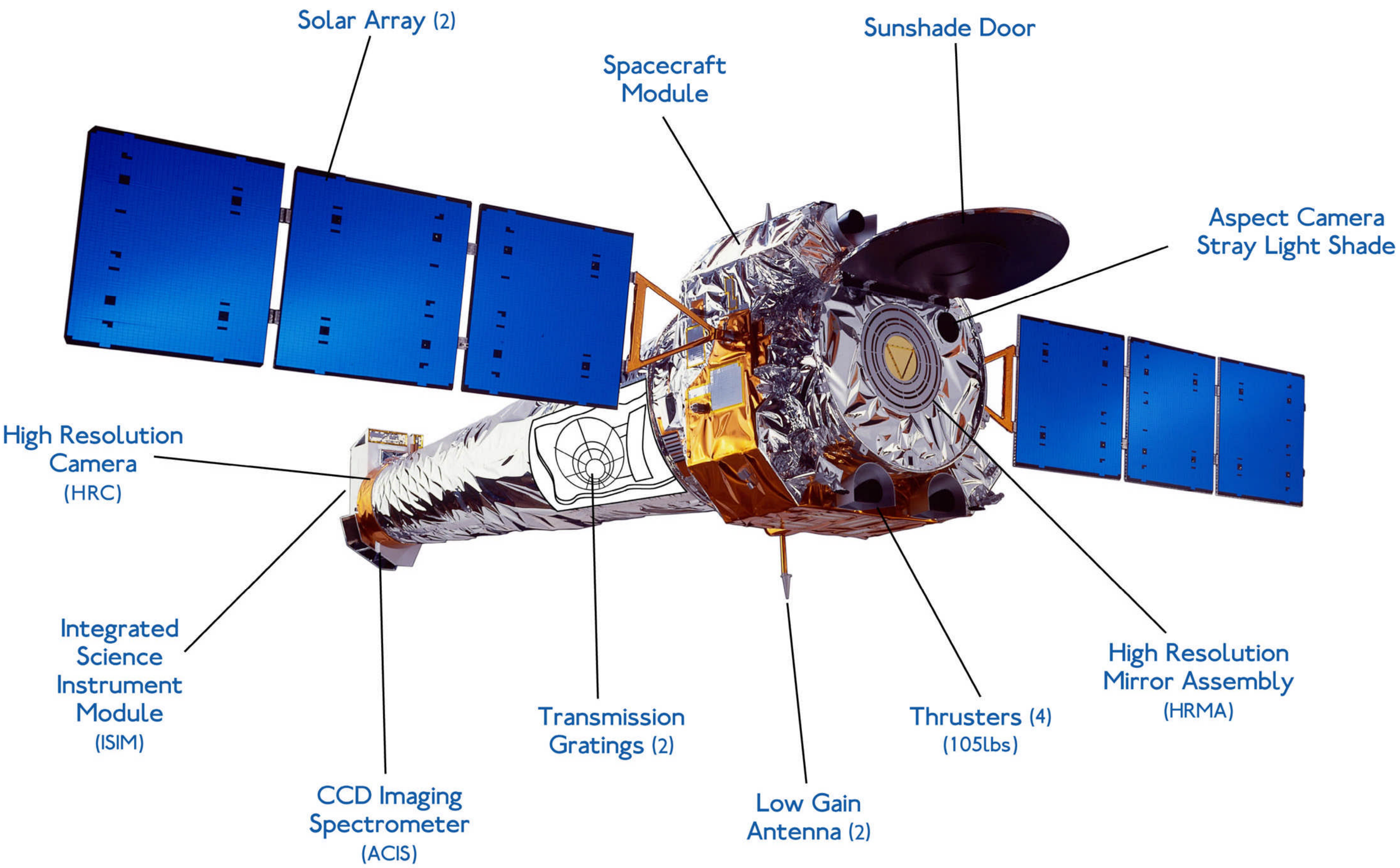
How the optics work



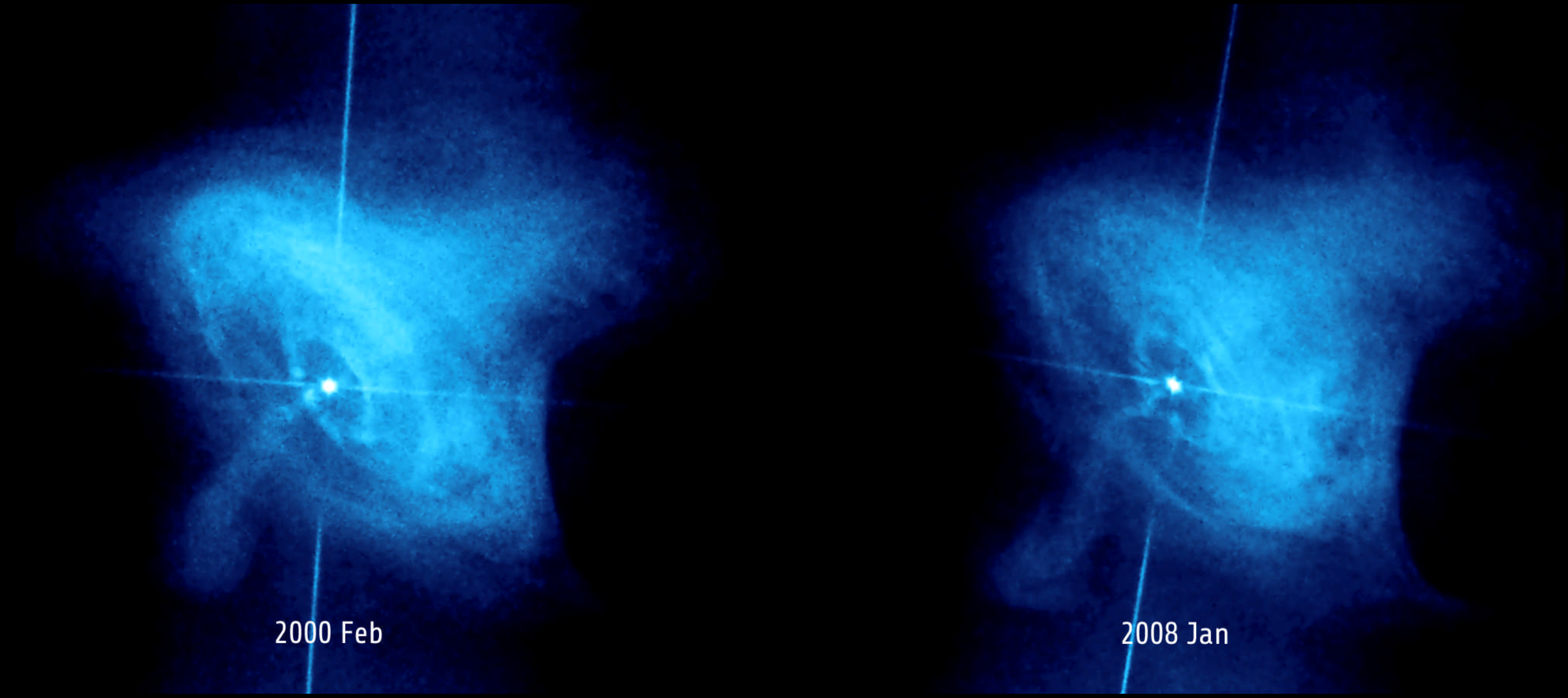
How the optics look



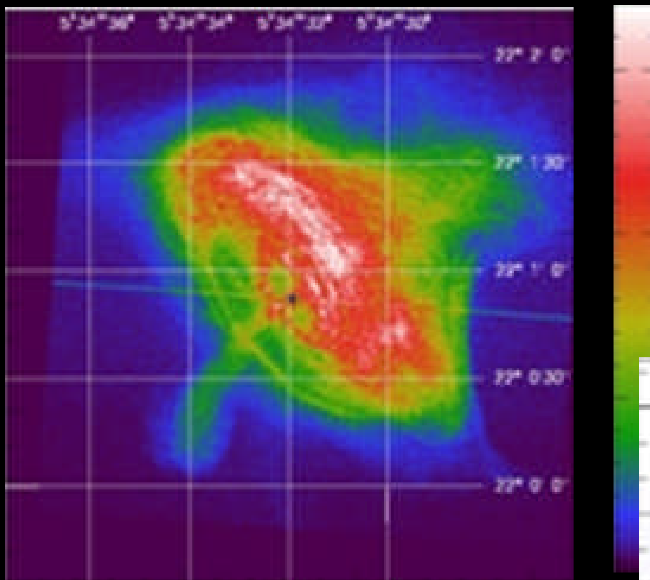
The Observatory

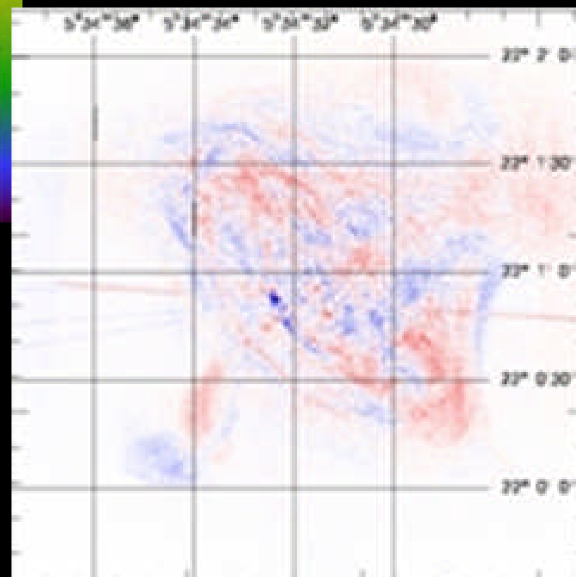


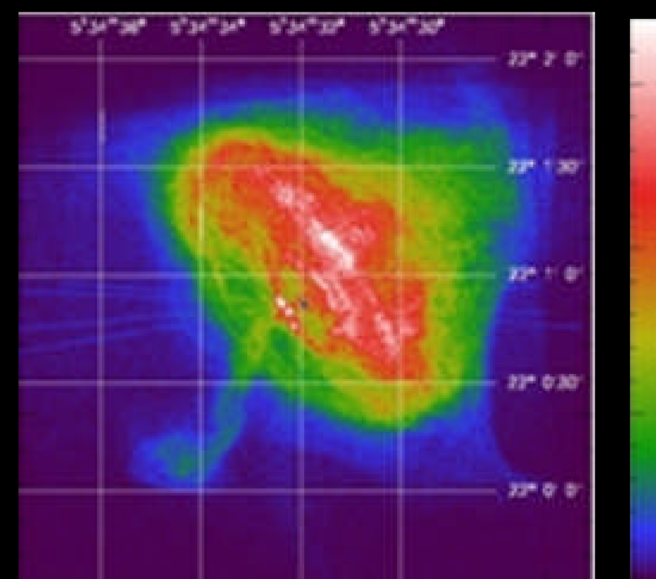
The Crab never ceases to give us new insights!



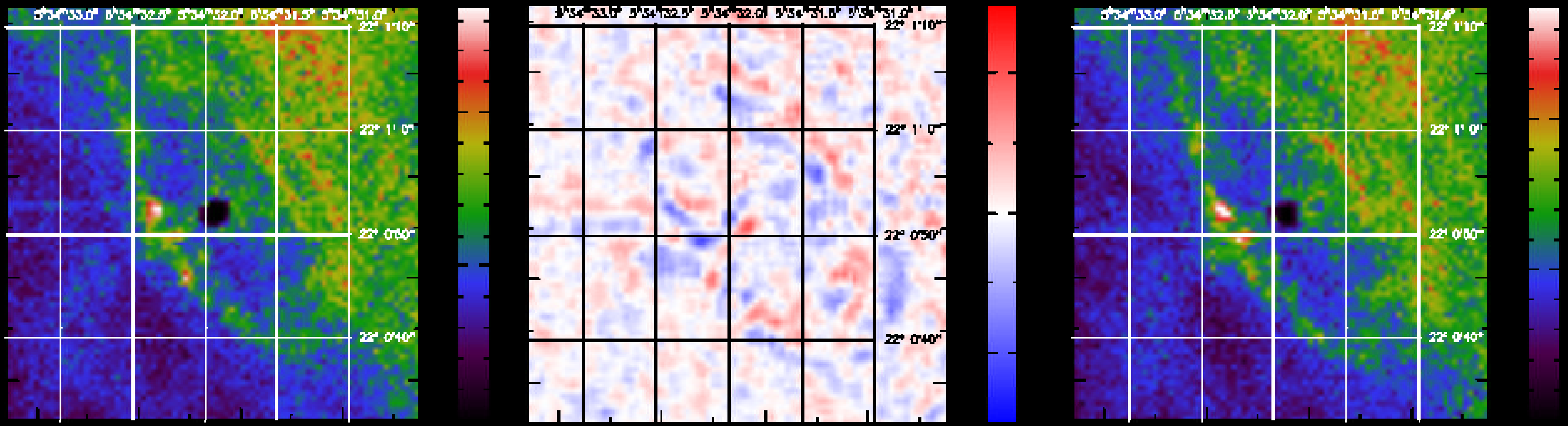
The Crab never ceases to surprise!



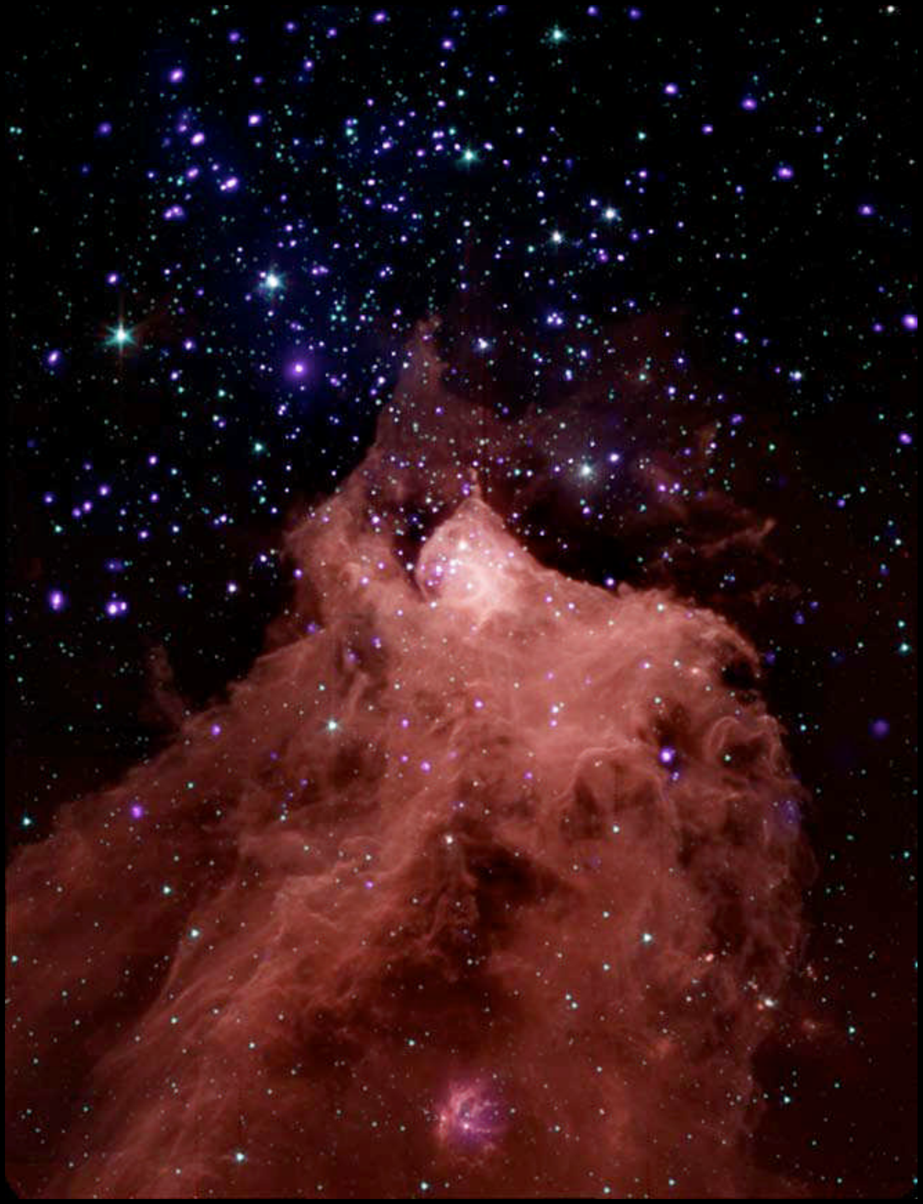




The hunt for the site of the gamma-ray flare!

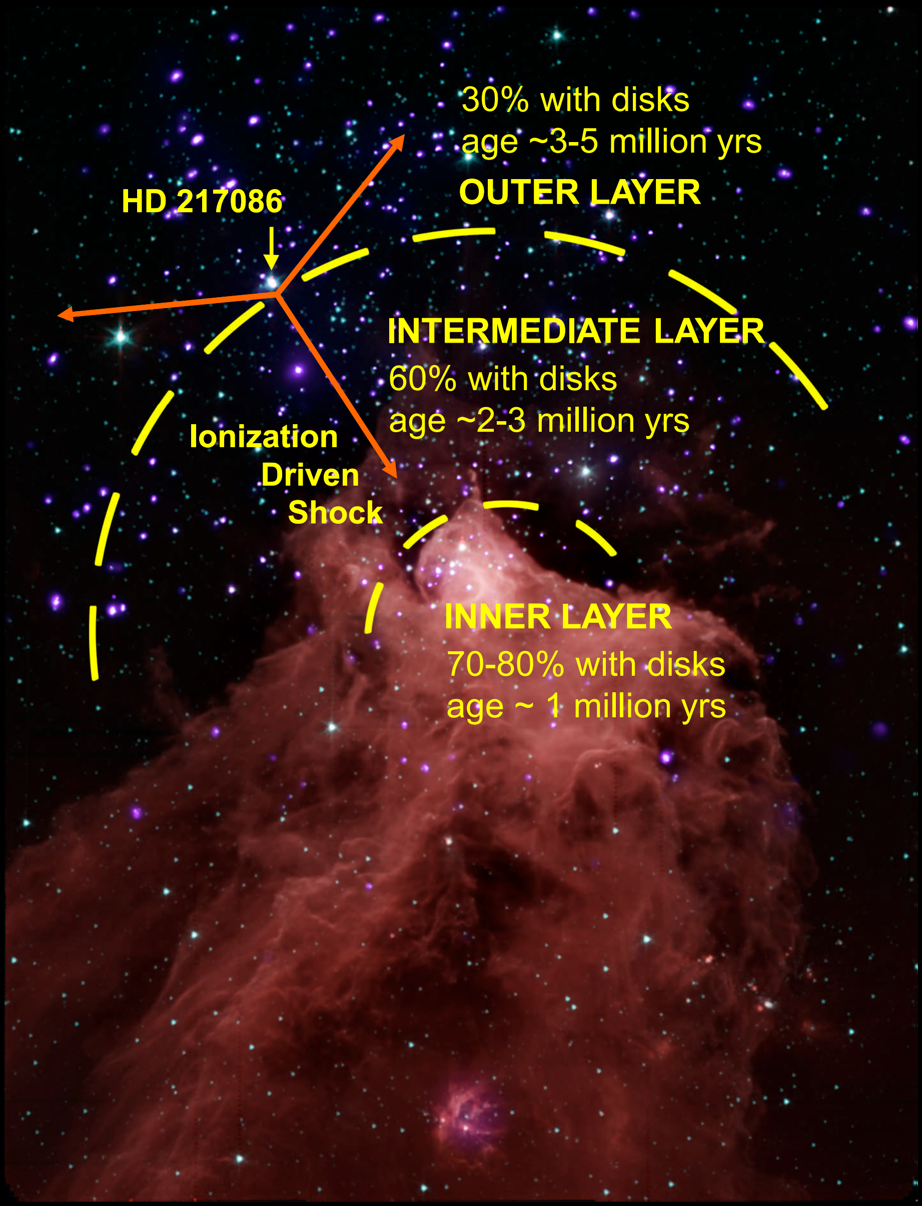


Chandra& Spitzer show radiation-driven implosion triggers star formation



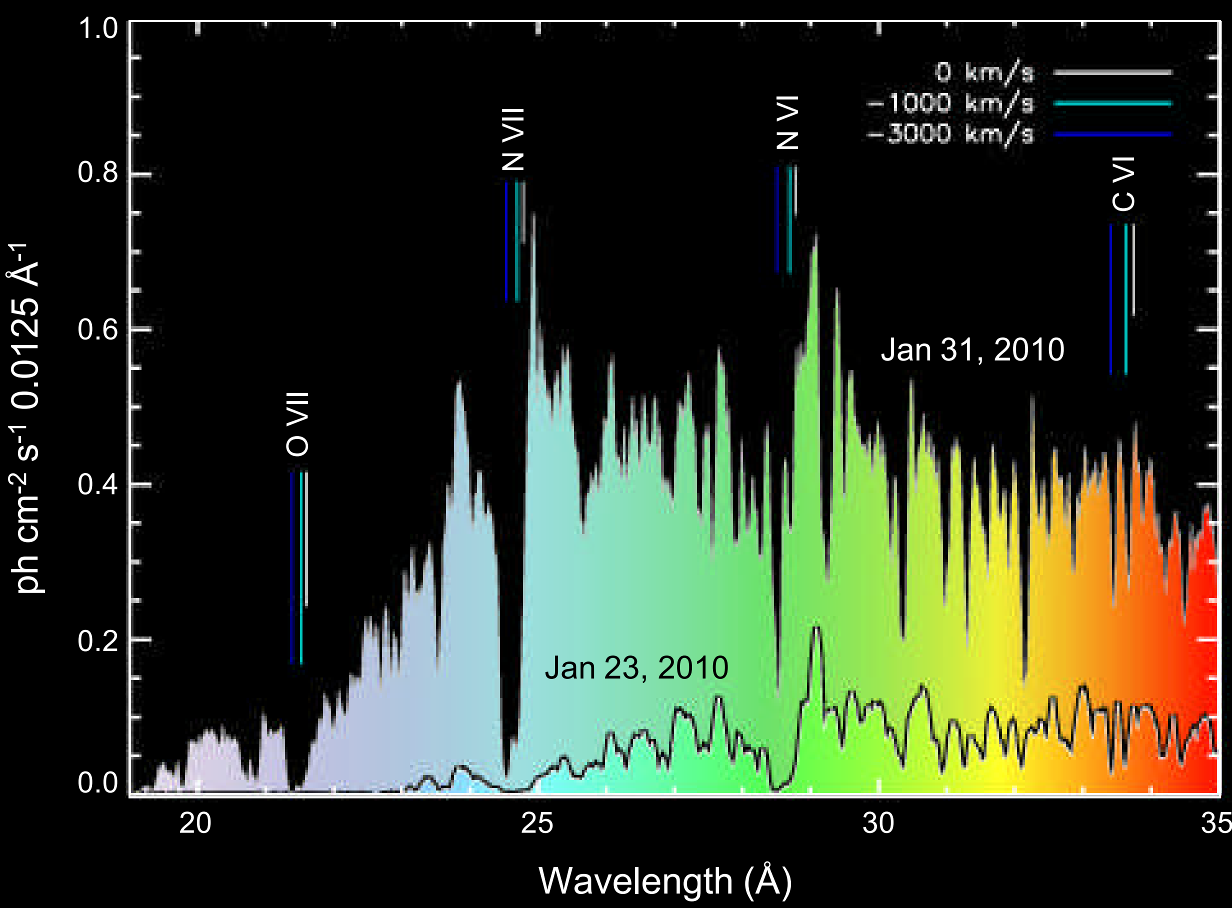
- Gravitational collapse of cold gas common driver for star formation
- Collisions, tidal forces, supernova explosions, jets, and radiation from massive stars also trigger star formation.
- Can radiation trigger rich star formation?
- Cepheus B molecular cloud at 750pc
- Spitzer (red) detects diffuse emission and hundreds of stars
- Chandra (violet and white) selects young stars based on x-ray brightness
- IRAC and 2MASS colors identify young stars with proto-planetary disks

Getman et al (2008)



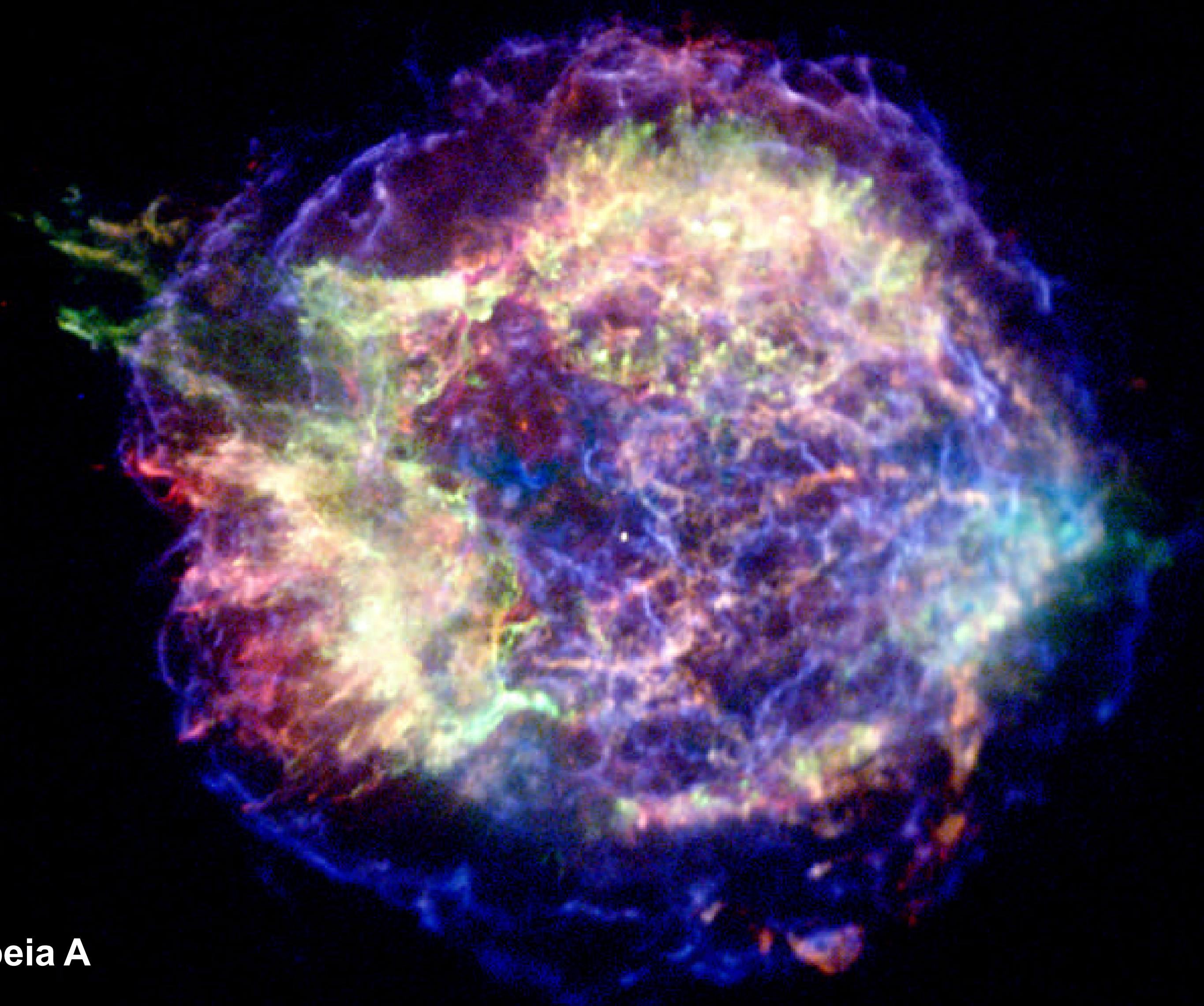
Getman et al (2008)

Chandra LETG spectra of Nova KT Eri explore nucleosynthesis under extreme conditions



- Nucleosynthesis in stellar interiors normally hidden
- Classical nova explosion due to thermonuclear runaway with T ~ 10^8
- Ejecta expand and thin with time revealing deeper layers, while photosphere evolves to lower R and higher T
- C, N, and O absorption features provide abundances
- N abundances several times C - reversal of usual ratio
- Data are fingerprints for TNR, testing models based on lab cross-sections
- High res spectra map complex velocity structures and inhomogeneities in outflow

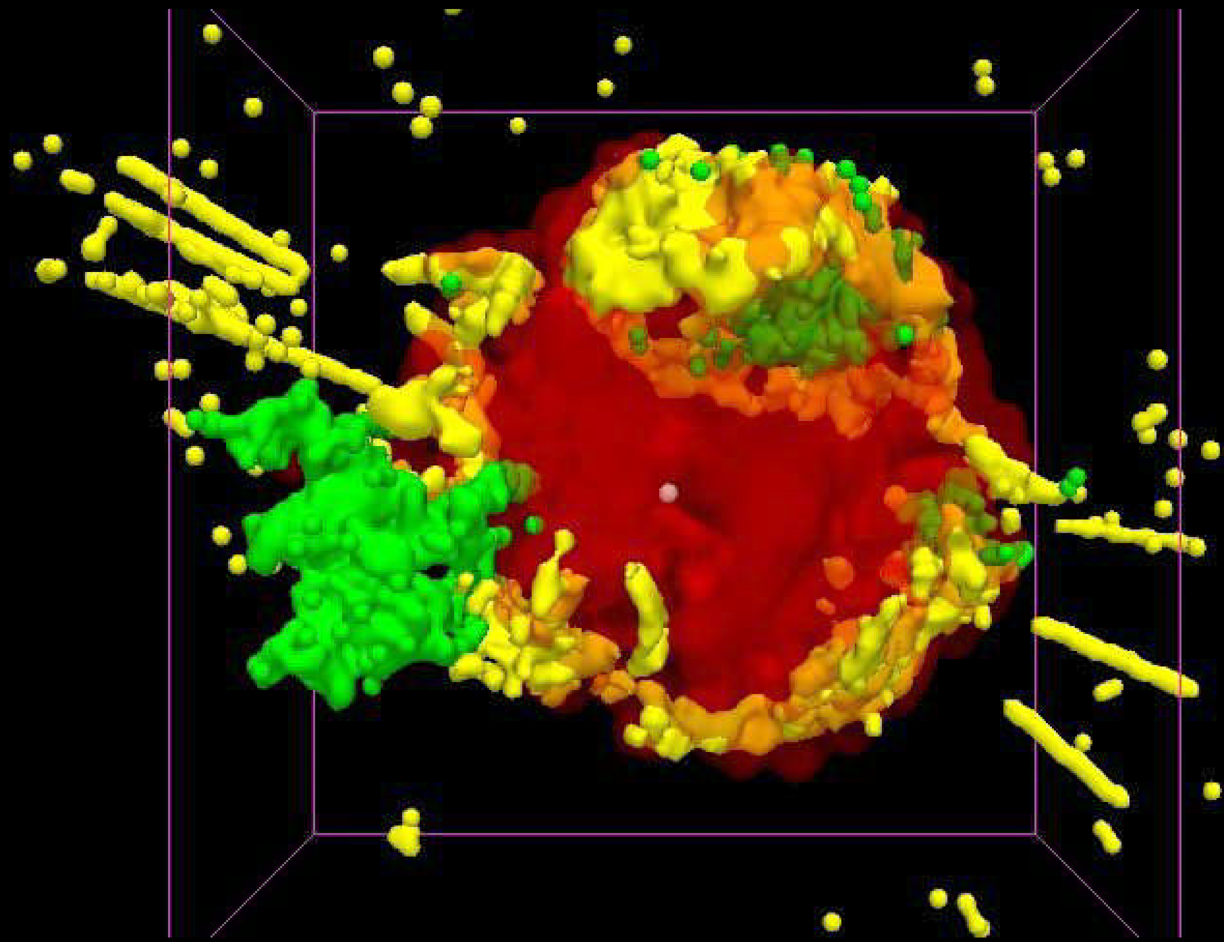
Drake and Ness (2010)



Cassiopeia A

Hwang et al (2004)

3-D reconstruction using Chandra, Spitzer, and optical telescopes indicates that asymmetries are intrinsic to explosion



- Assume ejecta freely expanding from single point
- Distance proportional to velocity
- 3-D positions of features seen from different viewing angles
- See spherical component, torus-like tilted thick disk, and jets/pistons
- Asymmetries intrinsic to explosion

Delaney et al (2010)

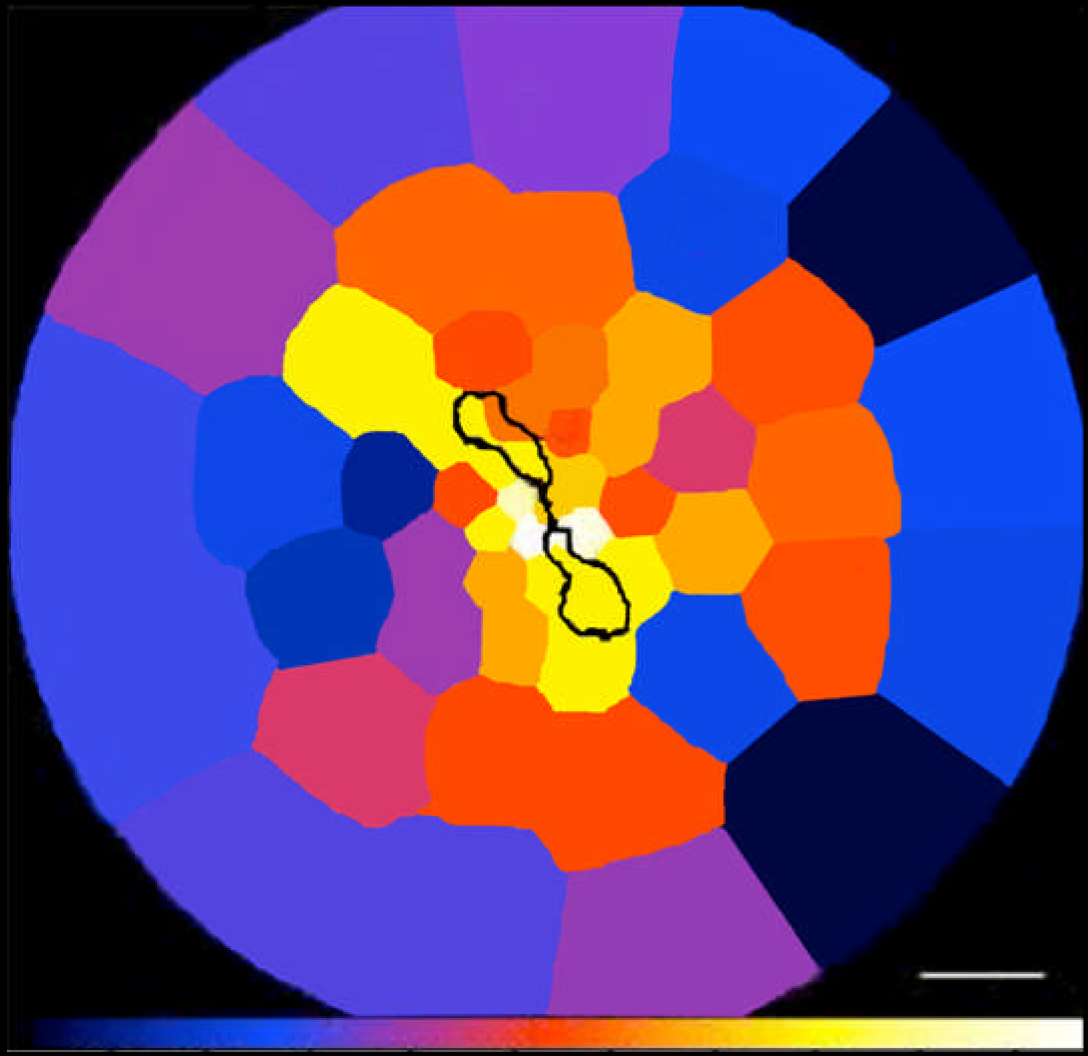
Chandra and SOAR/Gemini data show that ram pressure stripping of ESO 137-001 in Cluster A3627 transforms galaxy and leads to star formation in the ICM

- Galaxy ISM stripped via ram pressure
- X-ray tails (blue) extend ~80kpc, L_X~10^{41}, M_{gas}~10^9, T~0.8 keV
- Outer layers of tails heated by 6 keV cluster gas via conduction, mixing, etc
- Stripping slows star formation in galaxy
- Follow-up Hα (pink) and GMOS show star formation in tails/ICM

Sun et al (2010)

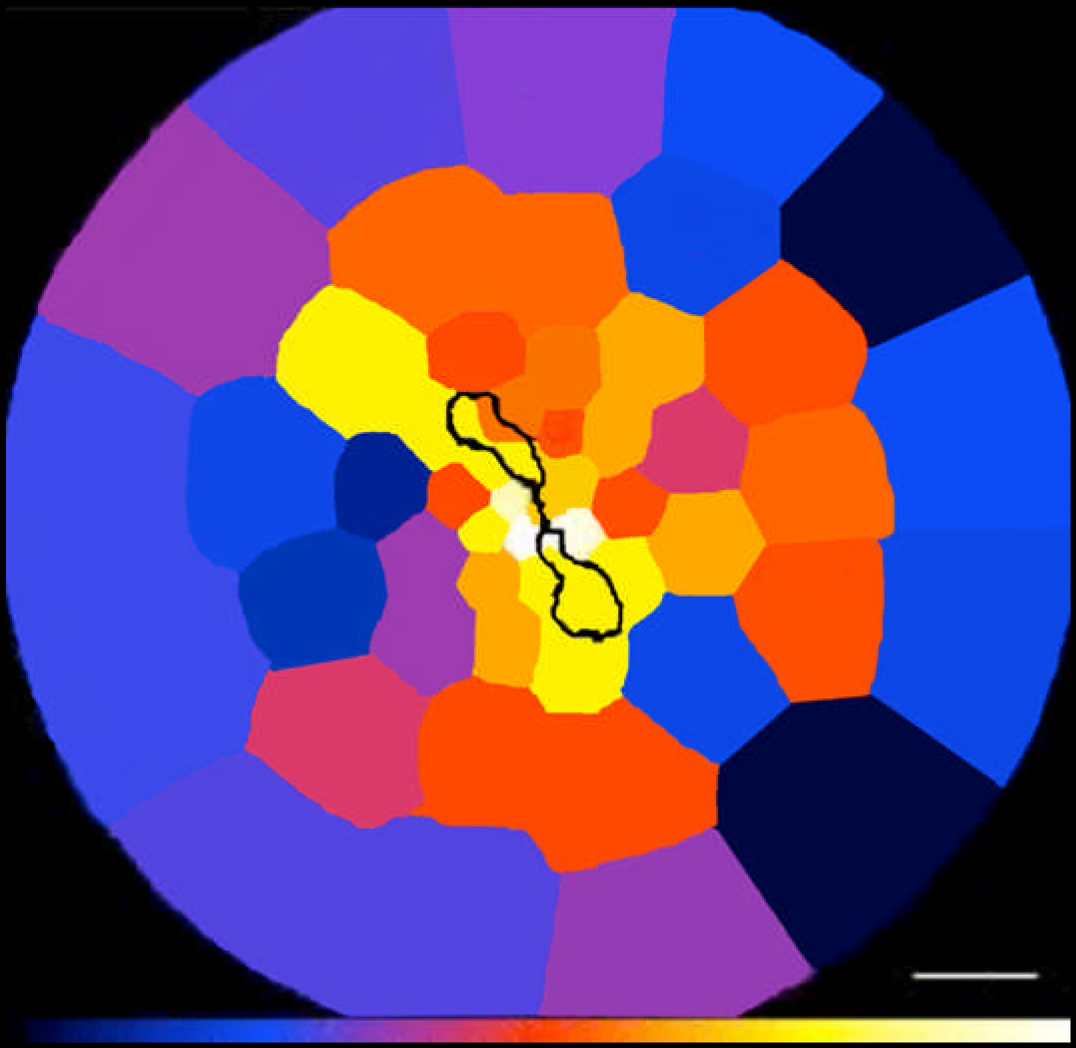
Jets filling X-ray cavities

Jet enriches ICM with Fe from central galaxy



Kirkpatrick et al (2009)

Jet enriches ICM with Fe from central galaxy



Metallicity enhanced by ~60% along direction of radio jets and lobes extending from ~20-120 kpc

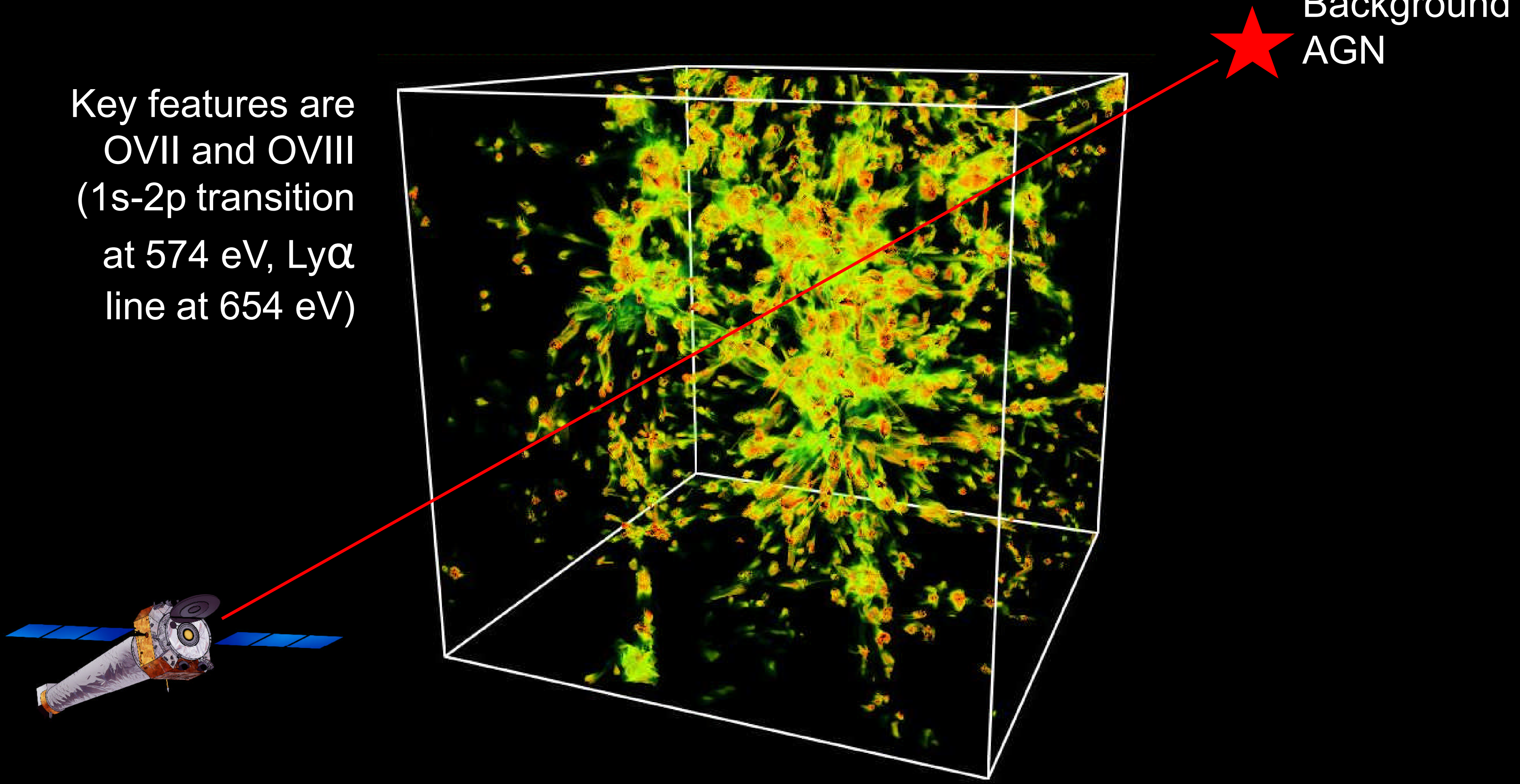
20% ±10% of Fe transported from central galaxy to ICM (2-7 10^7 $M_\odot$)

Energy required to lift gas is 1~5% of AGN output

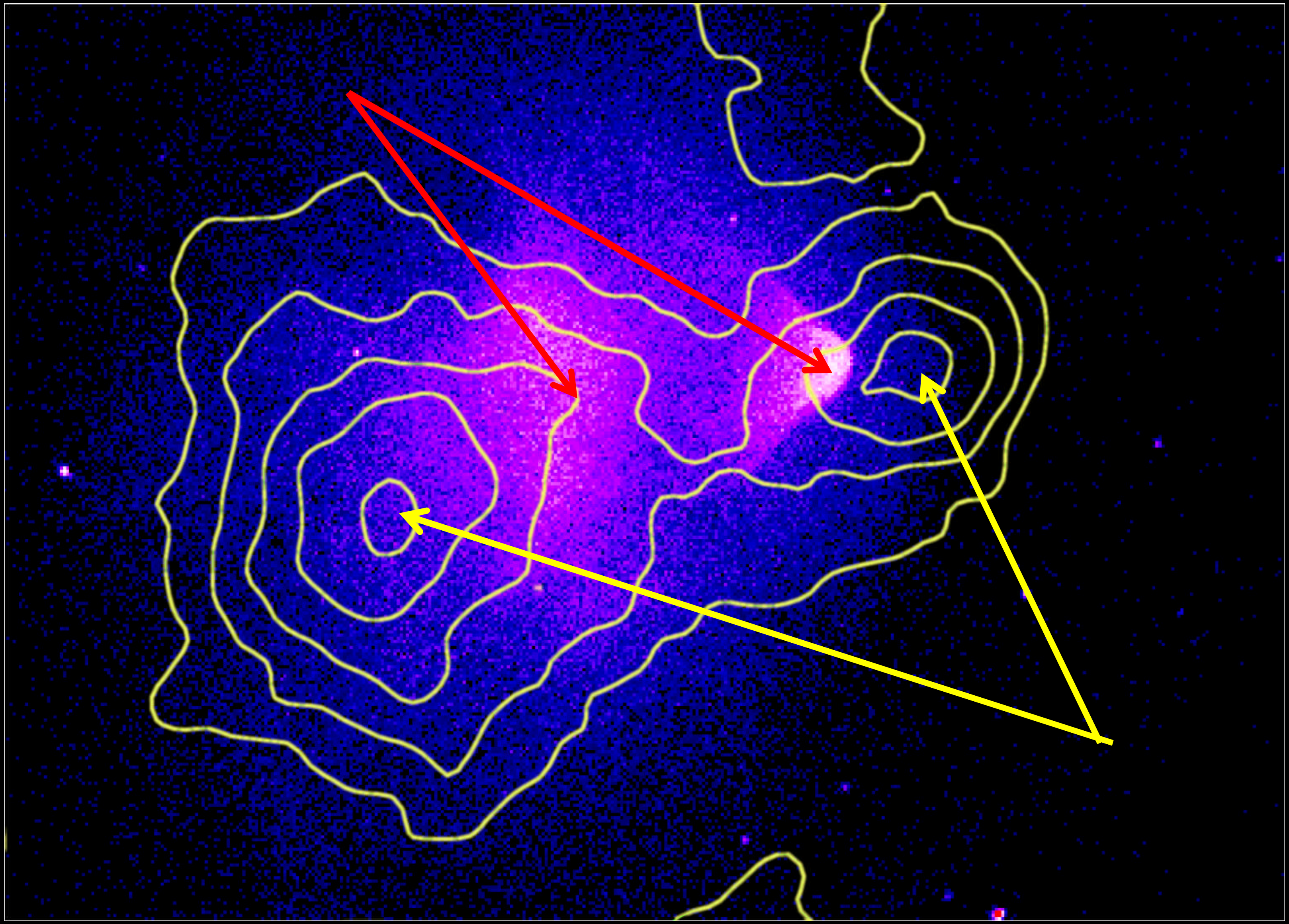
AGN outbursts can enrich ICM

Kirkpatrick et al (2009)

Key features are OVII and OVIII (1s-2p transition at 574 eV, Lyα line at 654 eV)

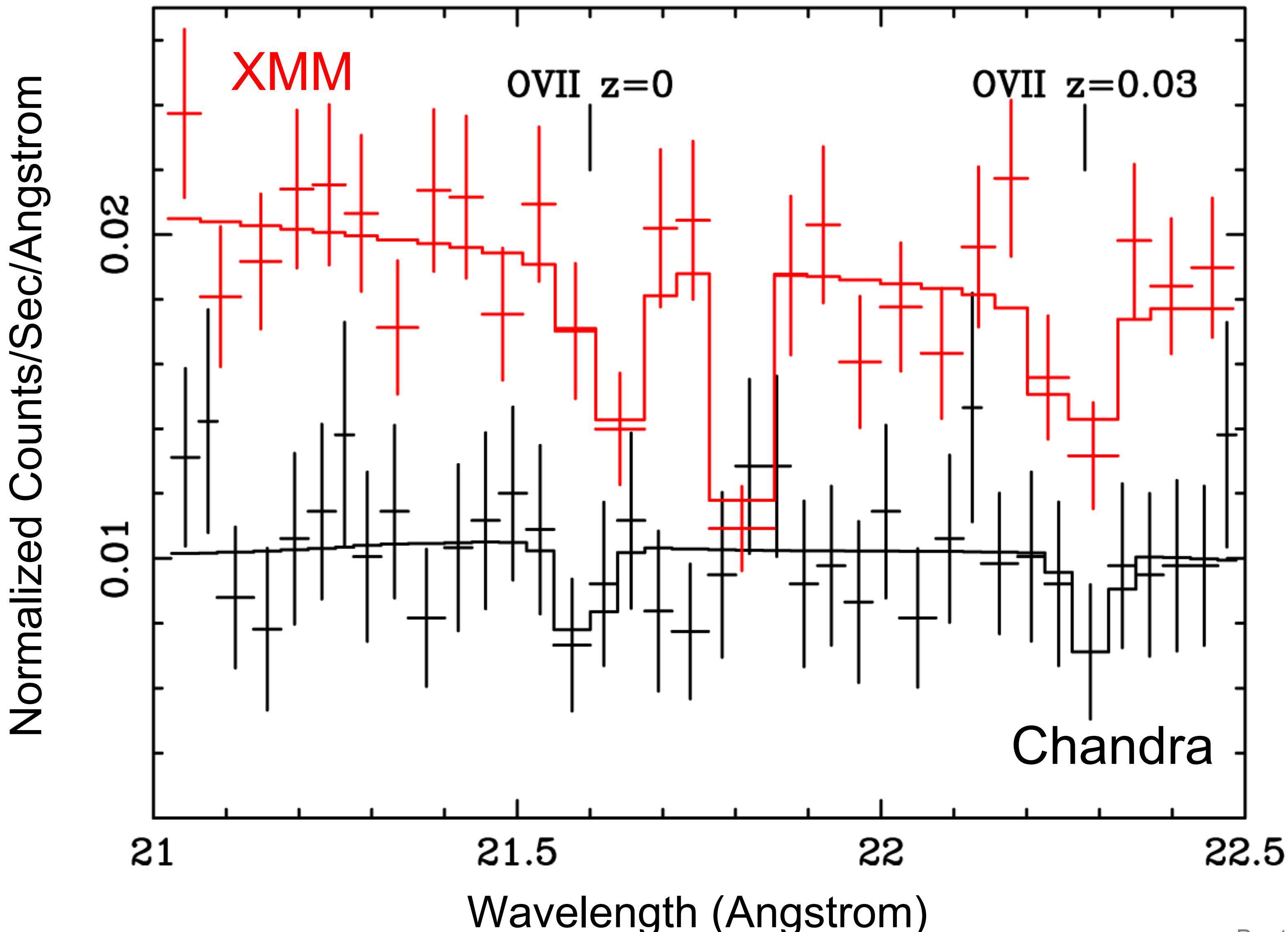


Demonstration of non-interacting dark matter



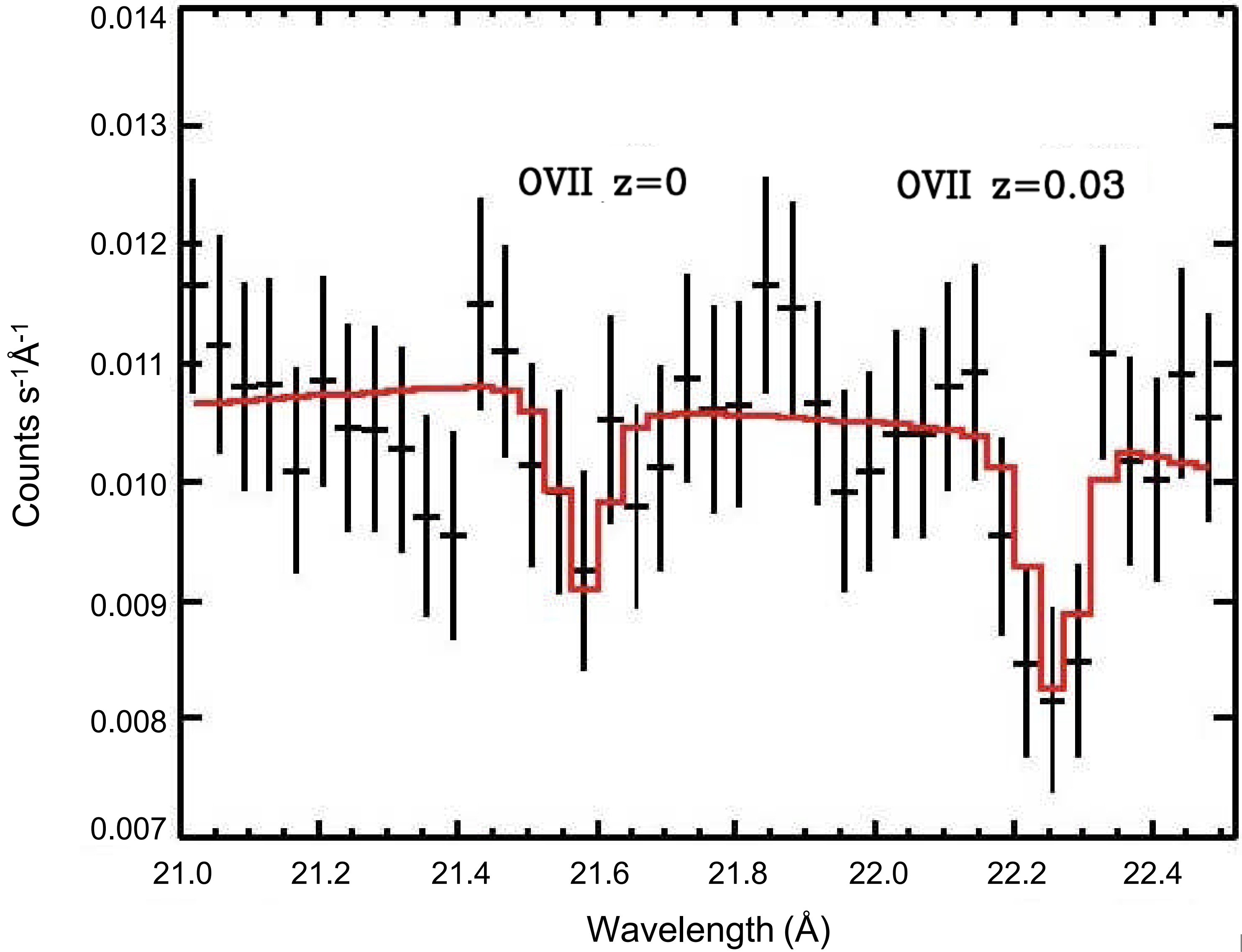
Clowe, Gonzalez, & Markevitch(2004)

Previous Chandra and XMM observations produced marginal WHIM detection



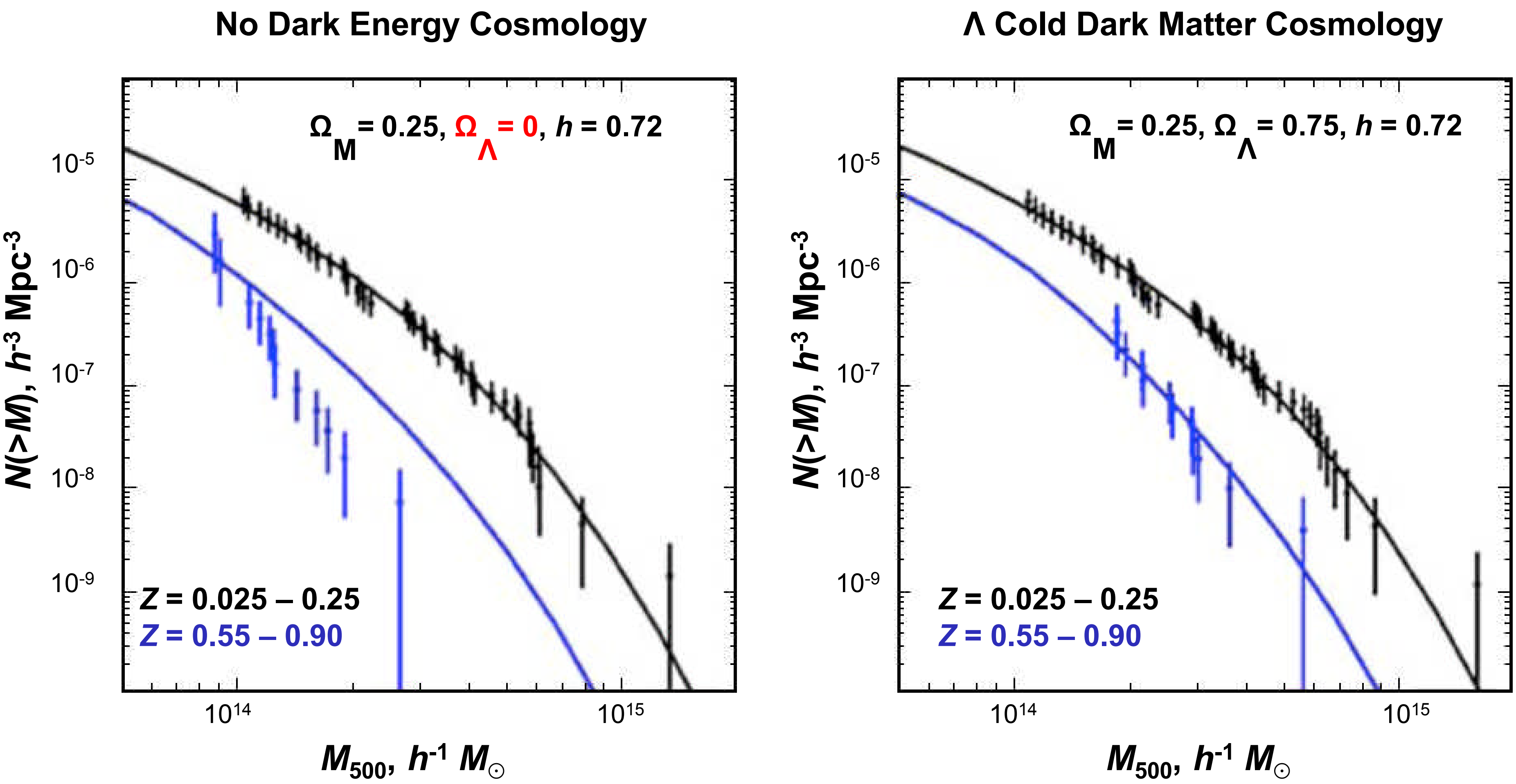
Buote et al (2009)

Deeper Chandra exposure provides firm detection of WHIM hot component (OVII)



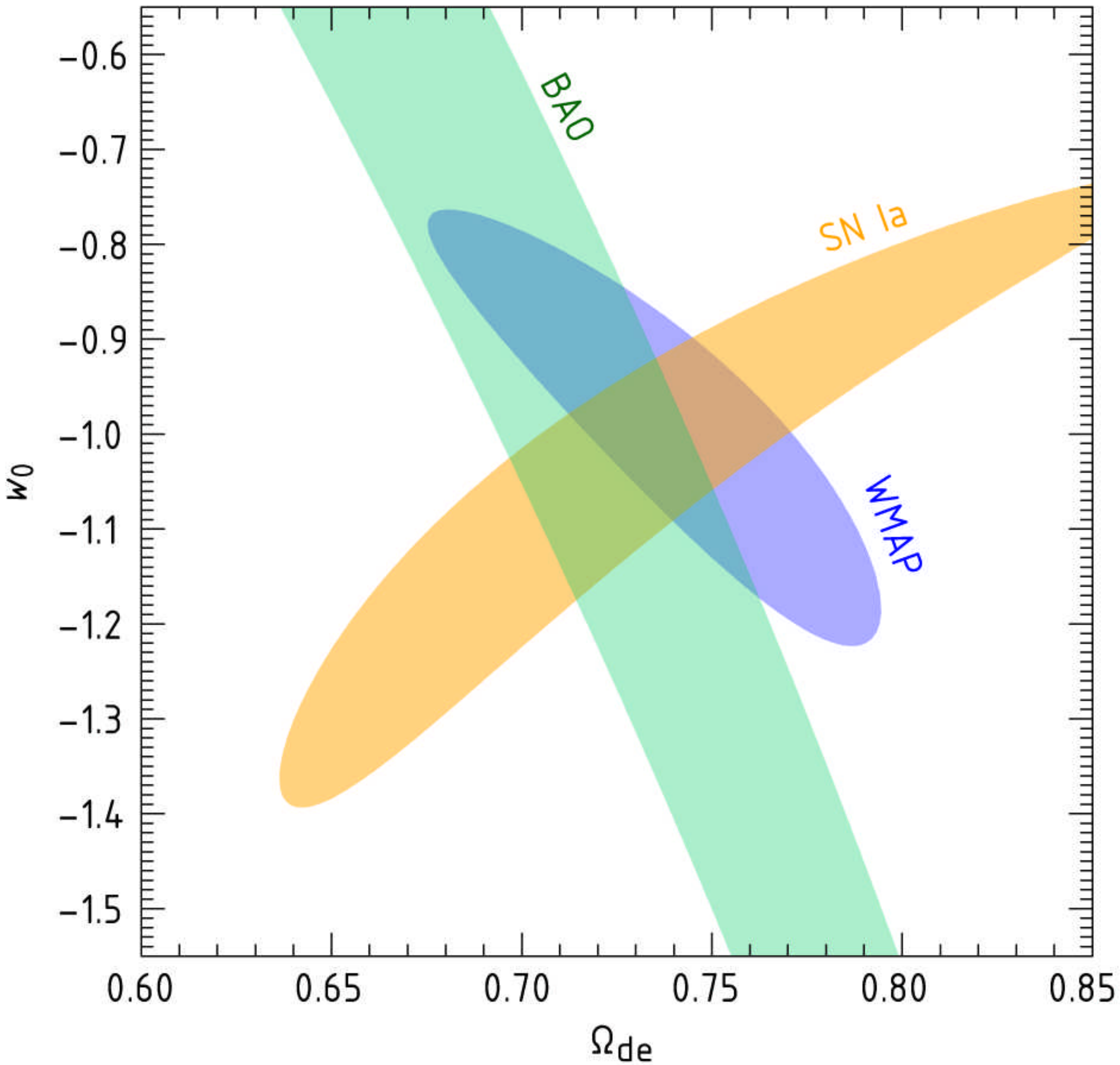
Fang et al (2010)

Chandra measures the cluster mass function demonstrating the impact of dark energy on the growth of structure



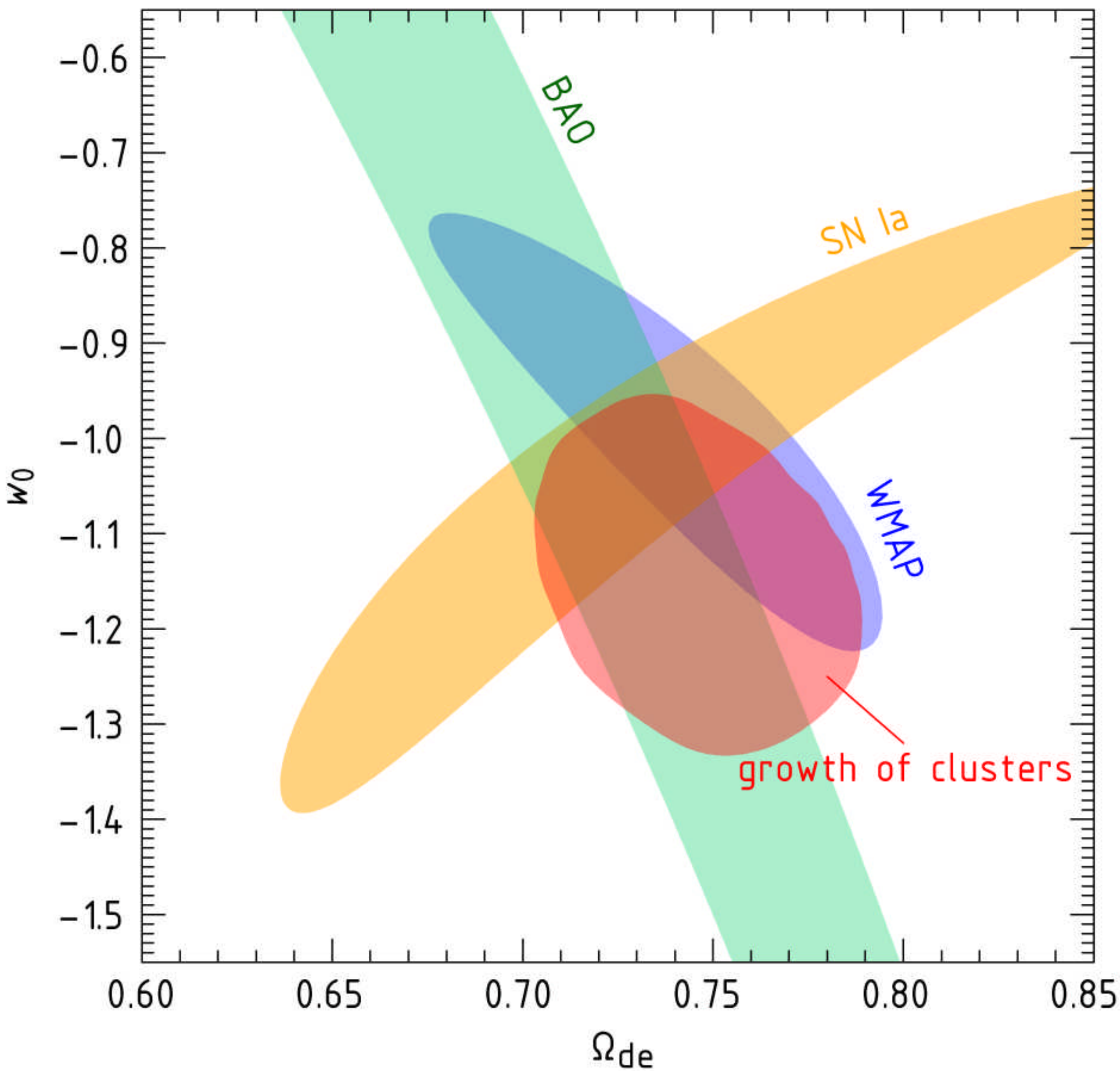
Vikhlinin et al (2009)

Chandra measurements of cluster mass function to constrain cosmological parameters



Vikhlinin et al (2009)

Chandra measurements of cluster mass function to constrain cosmological parameters



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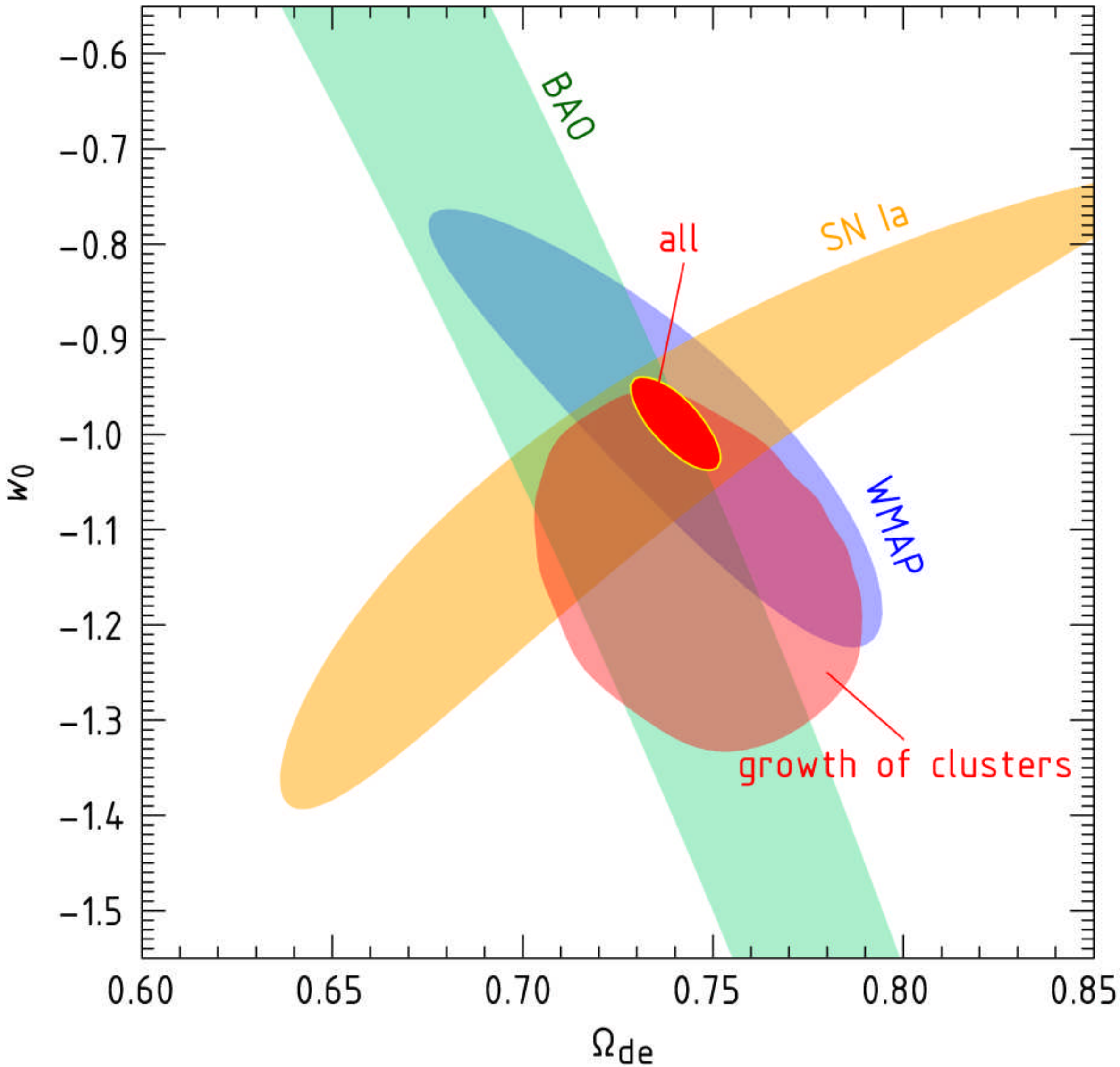


- Combining all data sets yields w = -0.991 ±4.5% (stat) ±4% (sys)
- For alternative gravity model f(R) range of "fifth force" reduced by factor of ~100 to scales ≲ 40 Mpc
- Limits summed mass of light neutrinos to ≲ 0.33 eV

Vikhlinin et al (2009)

Riccardo Giacconi receives Nobel Prize 2002

In Sept 1963 laid out a proposal calling for, amongst other things 10m-focal length, ~arcsec angular resolution telescope of area > 400 cm^2

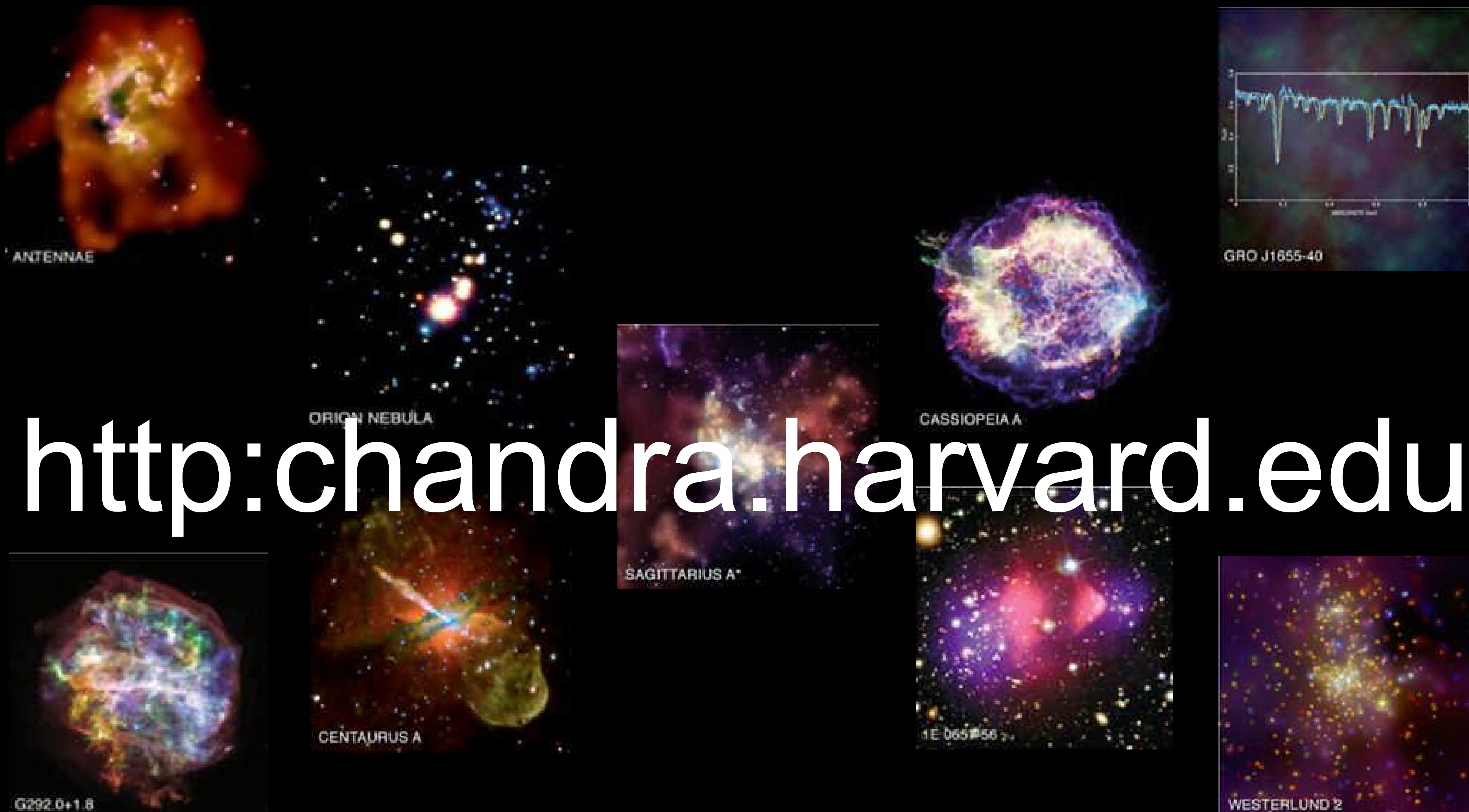
Possible future products

Science	Goal	Observations
Dark Energy	Measure the expansion history of the universe for 0.5<z<1	Take X-ray images & spectra for massive clusters selected using SPT, ACT, and Planck Surveys
Dark Matter Decay	Search for evidence of decaying dark matter particles	Take X-ray images and spectra of galaxy clusters to test the evolution of f_{gas} to z~1.2
Missing Baryons	Measure WHIM features to constrain the baryon overdensity	Obtain high-resolution spectra of quiescent blazars along lines of sight selected using COS and other instruments.
AGN Feedback	Determine how AGN feedback operates in galaxies and clusters of galaxies	Obtain deeper images of both galaxies and clusters as well as high-resolution spectra of selected bright AGN
Accreting SMBHs, AGN unification, and the Cosmic X-ray Background	Measure the luminosity and evolution functions for obscured and unobscured AGN	Extend the CDFS survey from 2 to 4 Mseconds to extend the survey to lower luminosities and higher z.
Metal Enrichement in Starburst Galaxies	Trace evolution of temperature, density pressure and velocity of shocked material in very young SNR	Obtain deep images and spectra of a number of starburst galaxies to trace the metals and hot gas
Evolution of Young Supernova rRmnants	Measure mass and radius for bursting neutron stars	Take grating spectra of X-ray binaries in outburst
Equation of state for Ultra-Dense Matter	Extend mass and radius measurements for a number of neutron stars	Perform high-resolution spectroscopy to determine distances with burst data from other satellites
Formation of Protoplanetary disks	Determine the lifetimes of the disks	Make simultaneous Chandra and ALMA observations of young star clusters

Observatory status

- Spacecraft is in excellent health – almost in the 13th year
  - No safe-modes since first year of operations
- All redundant systems are available except one pair of gyro rotors that has been swapped to a backup.
  - One of the switched gyro rotors is fully healthy and the second has reserve life. Chandra can operate with one rotor from each set.
- Thermal insulation has slowly degraded
  - Some systems are warming
  - Requires increased pitch restrictions and limits on constrained observations
  - Focused mission planning effort has managed impacts
- There will (no doubt) be new challenges as Chandra ages
- However, overall observatory performance remains superb
- No known limitations to > 20-yr mission

The Future



http:chandra.harvard.edu

The opportunity for exploration and discovery with Chandra remains as high as it was at launch