# 25 Years of Chandra Observations of SS 433

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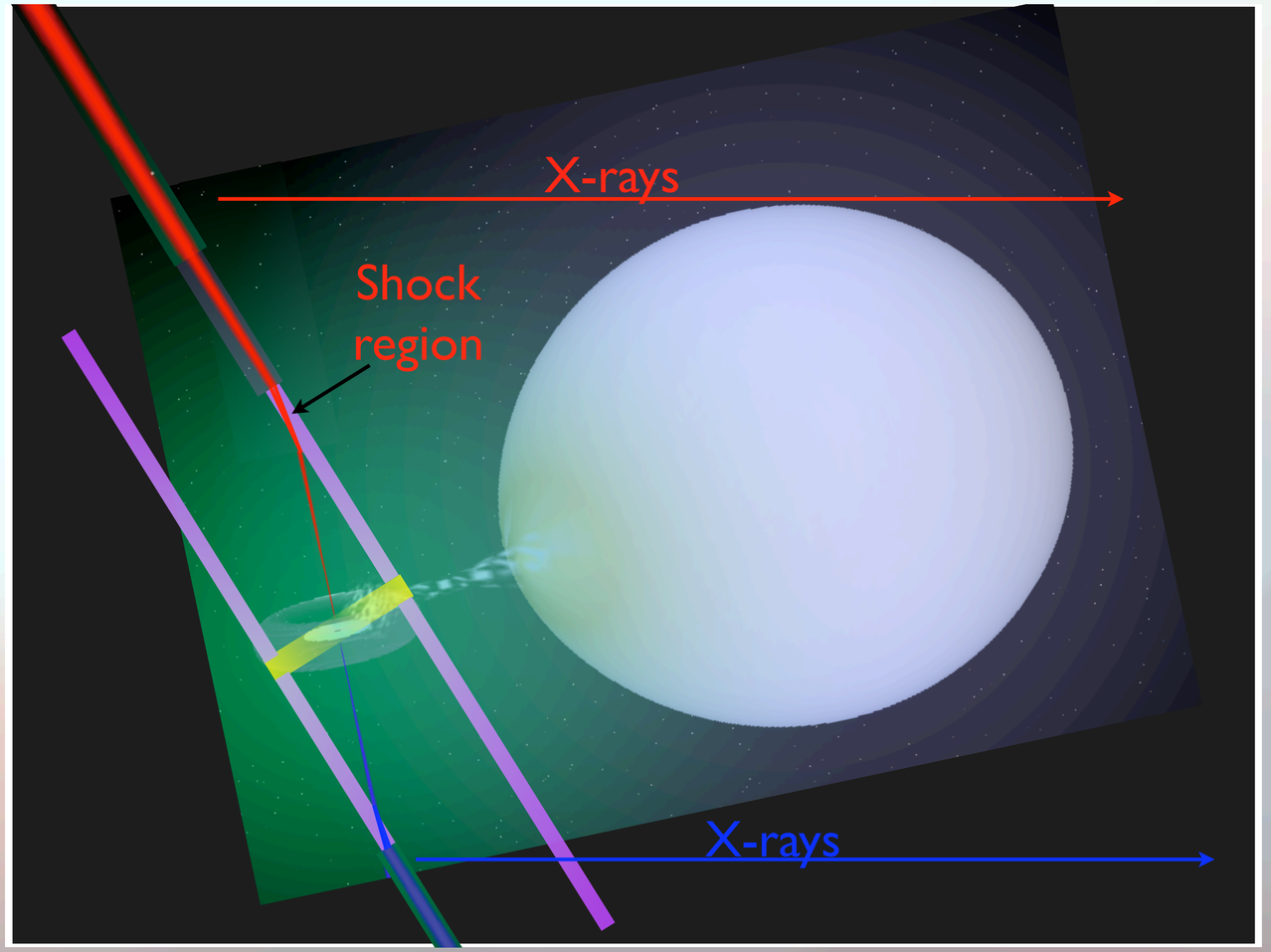
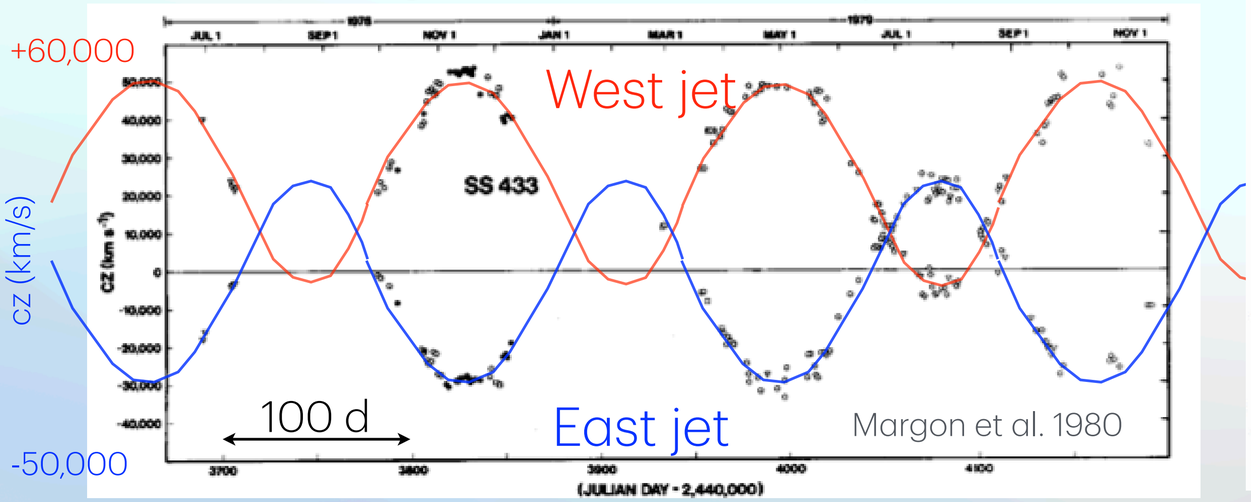
(MIT Kavli Institute)

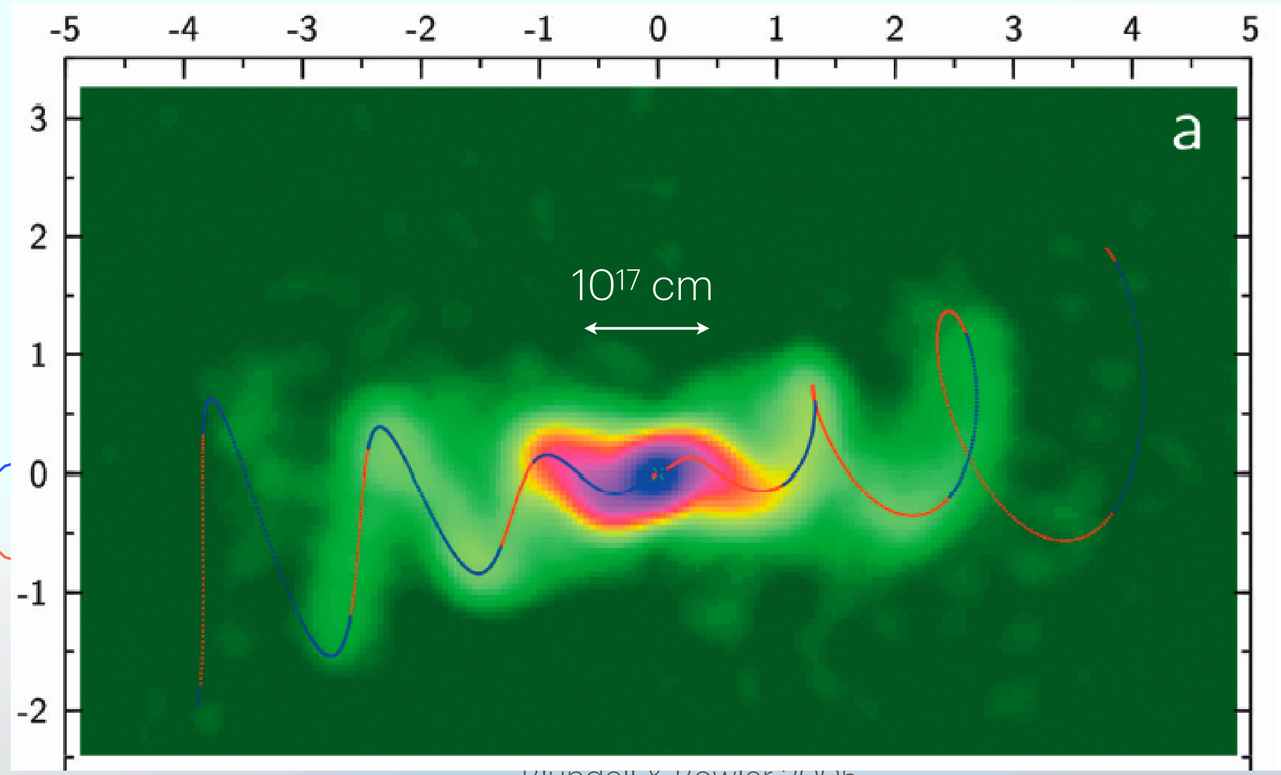


# SS 433 Background (0-20 years B.C.)

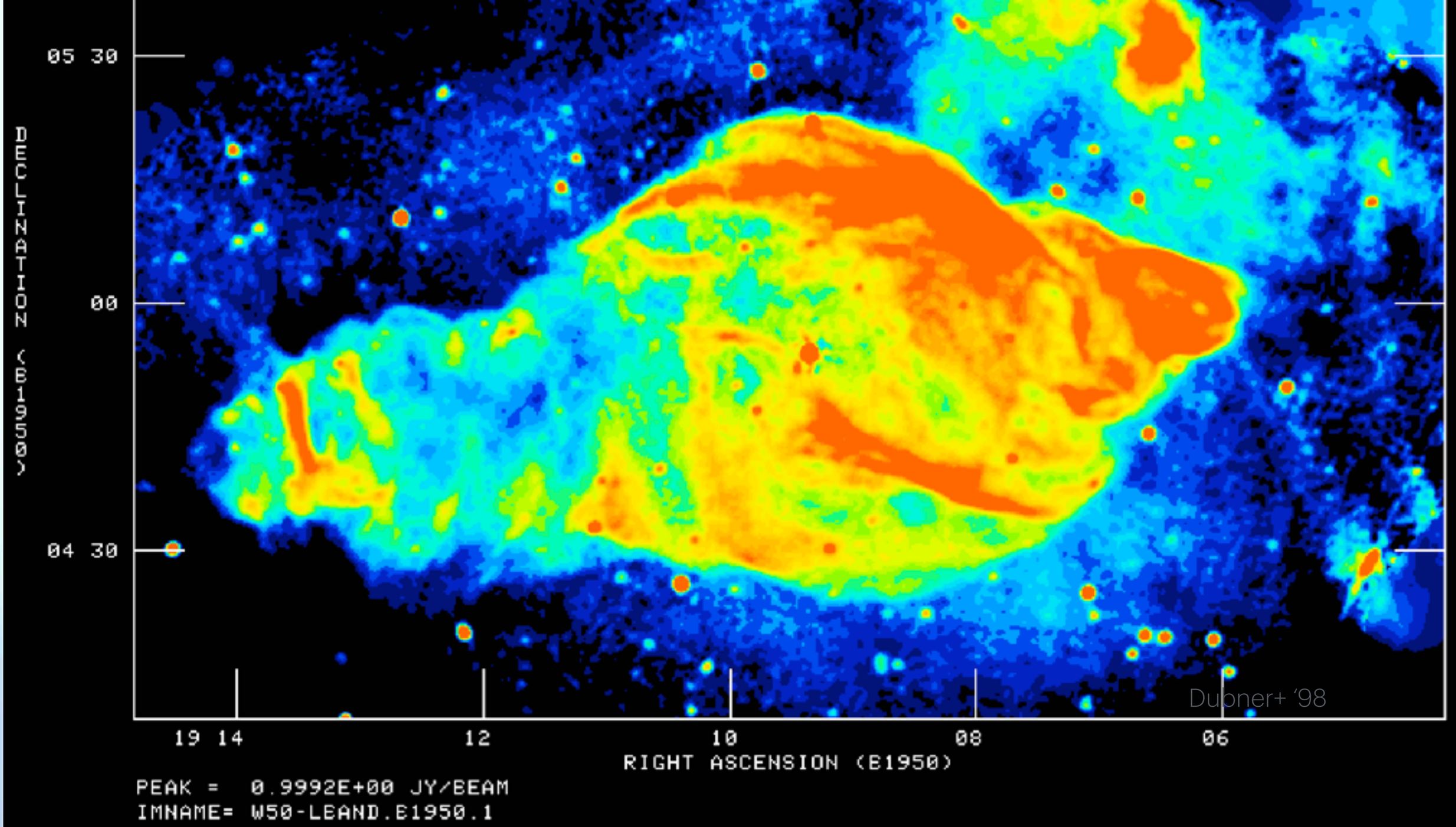
- Periodically Doppler shifting Ha HeI and H β
- Model: oppositely directed jets at 0.26 c
  - Precession period: 162 days
  - Orbital period: 13.08 days
- Radio: verifies model and sets orientation
- Only jet known to contain baryons
- Optical & radio: discrete, ballistic blobs
- X-rays: higher Z elements in jets

$$\frac{\lambda}{\lambda_0} = 1 + z = \gamma(1 \pm \beta \cos\alpha)$$




Blundell & Bowler 2005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DECLINATION (B1950)
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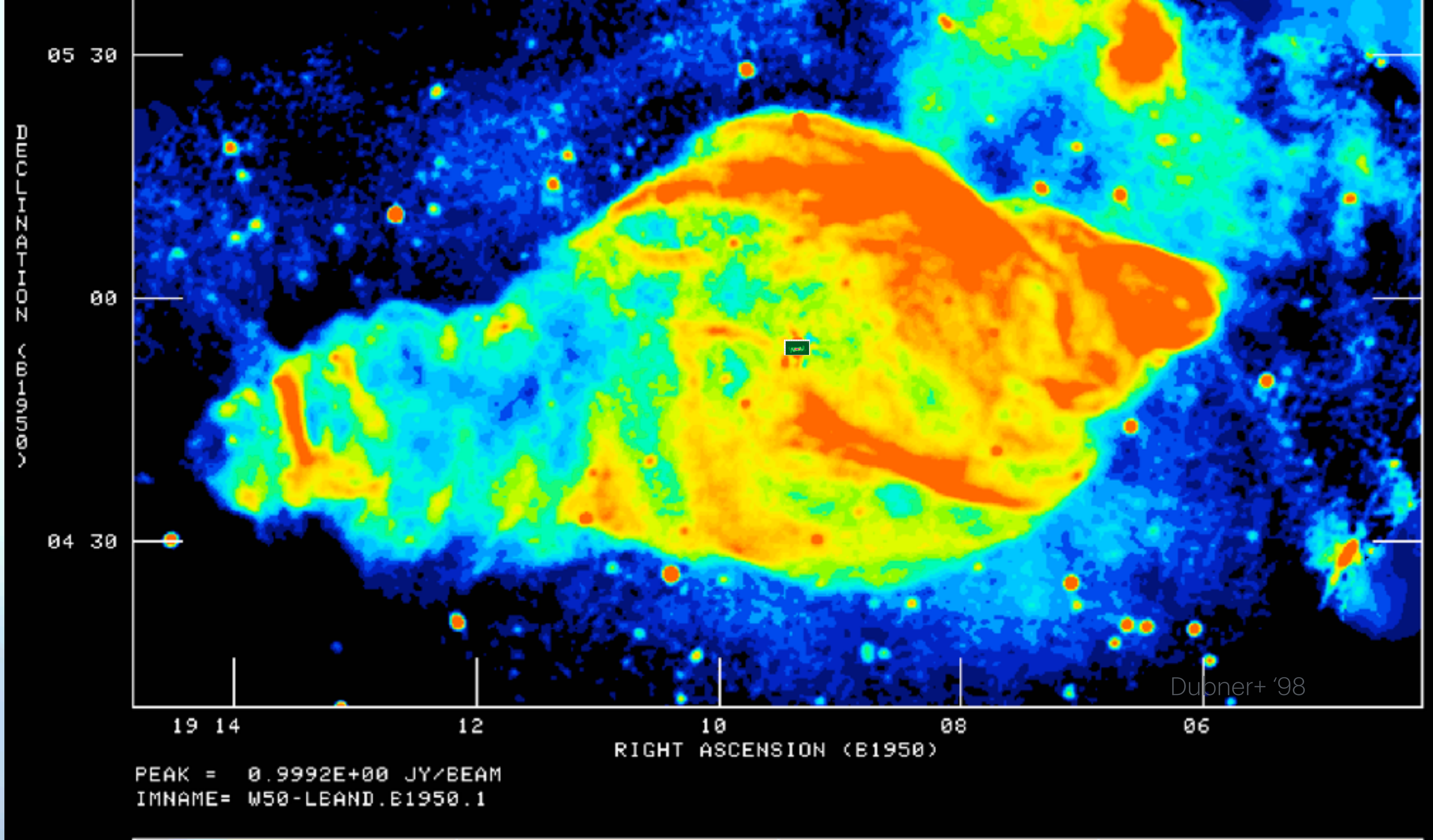
RIGHT ASCENSION (B1950)
PEAK = 0.9992E+00 JY/BEAM
IMNAME= W50-LEAND.B1950.1

Dubner+ '98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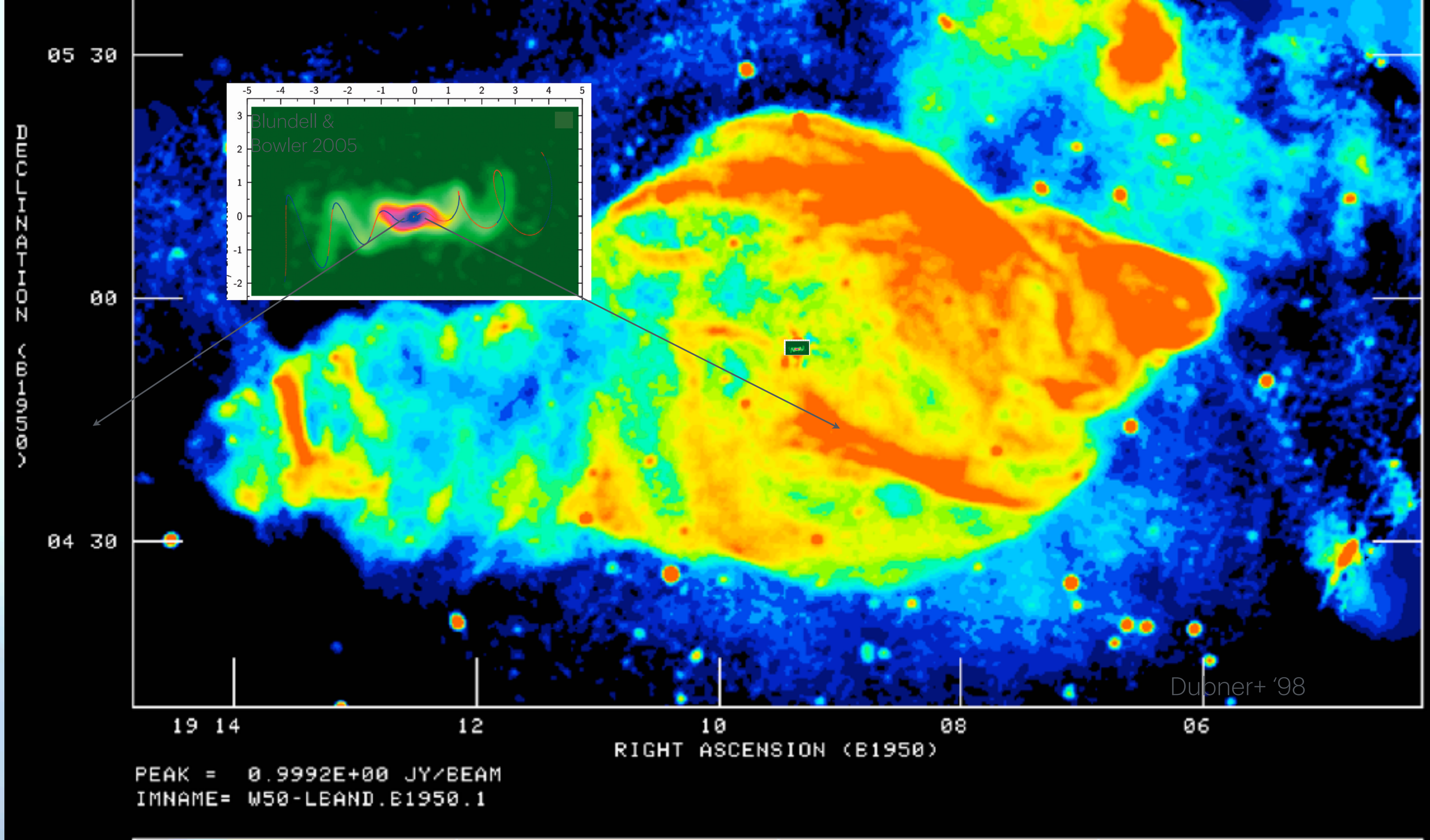
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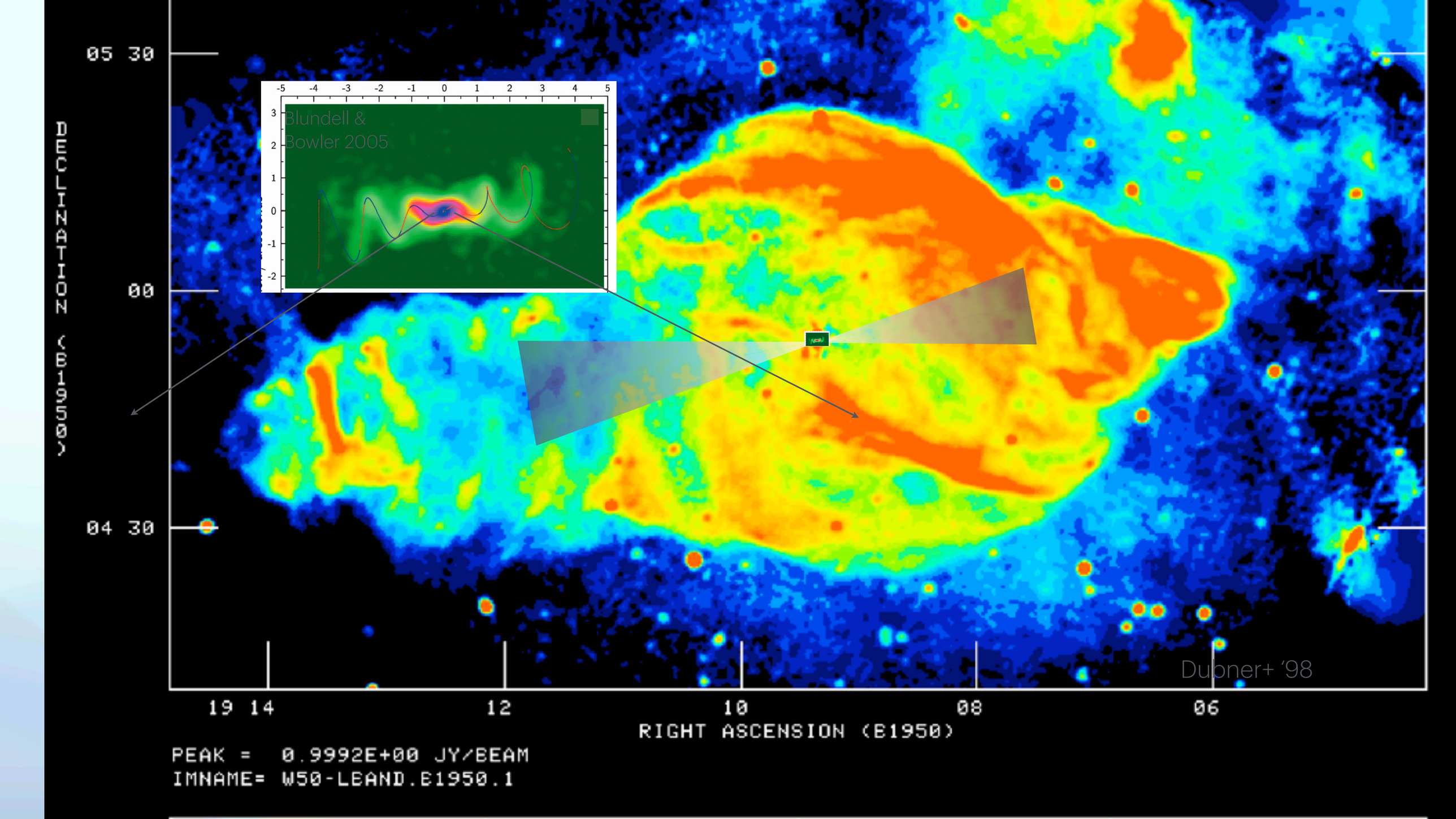
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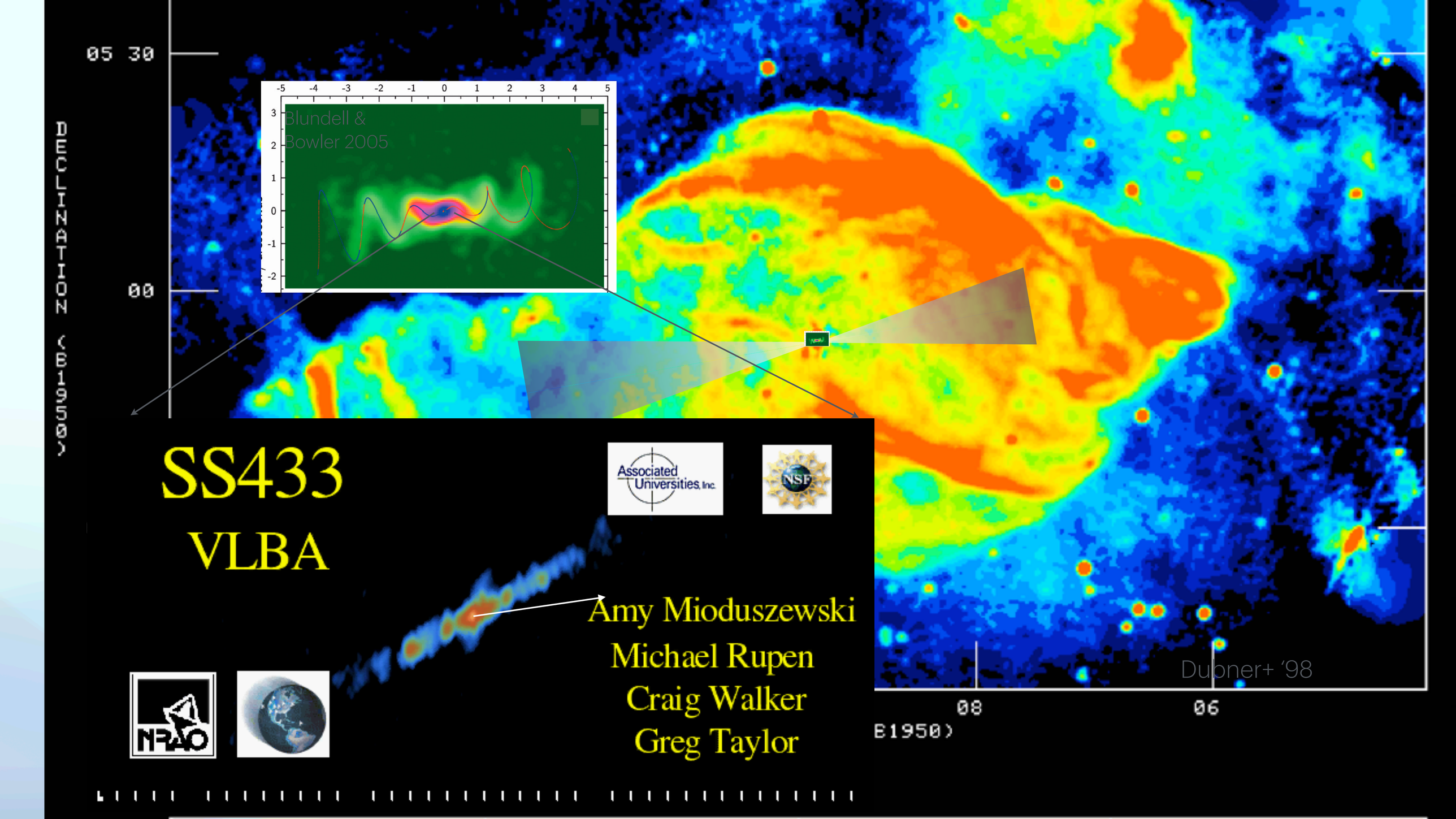
SS433
VLBA
Amy Mioduszewski
Michael Rupen
Craig Walker
Greg Taylor
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NRAO
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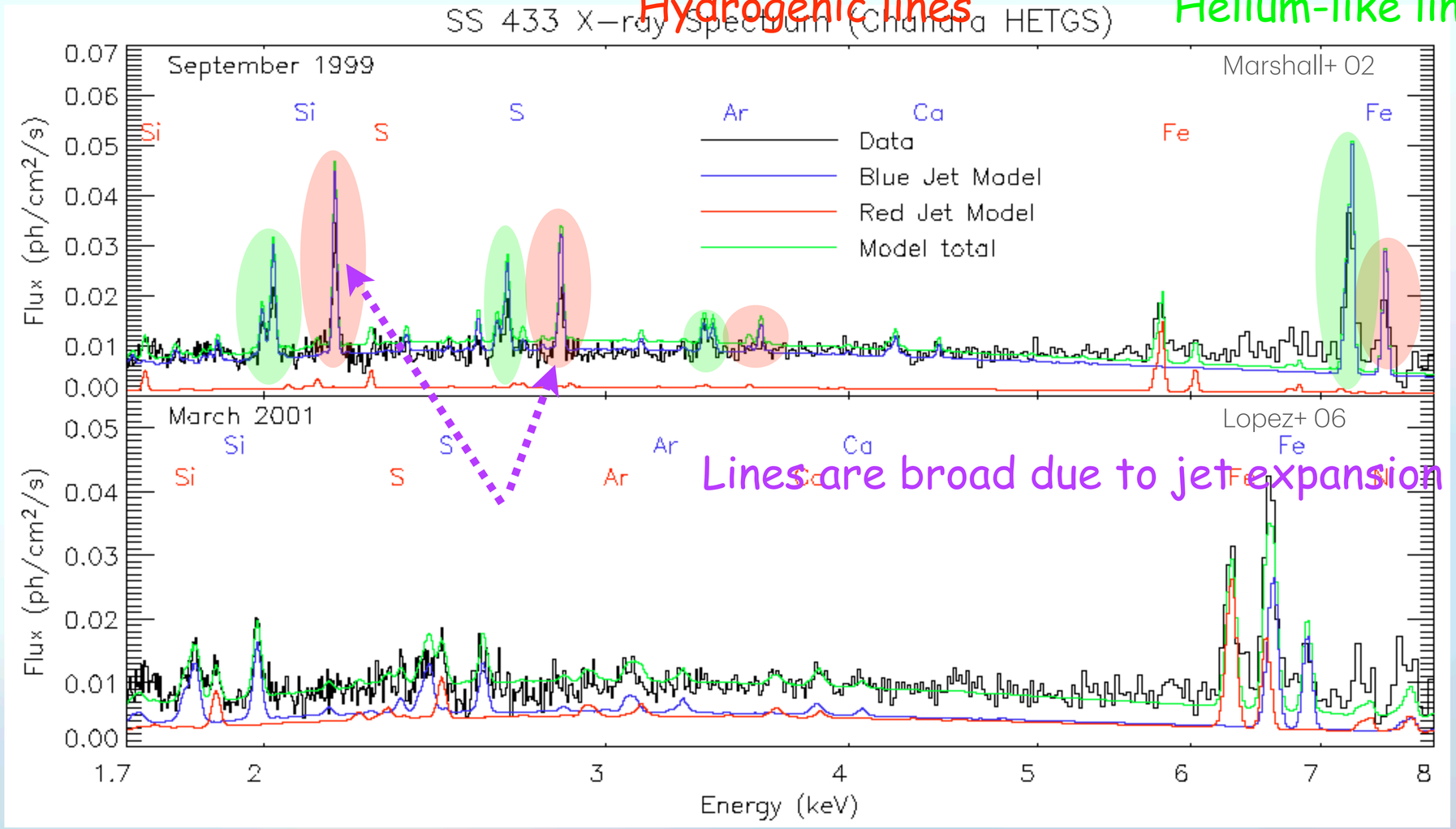
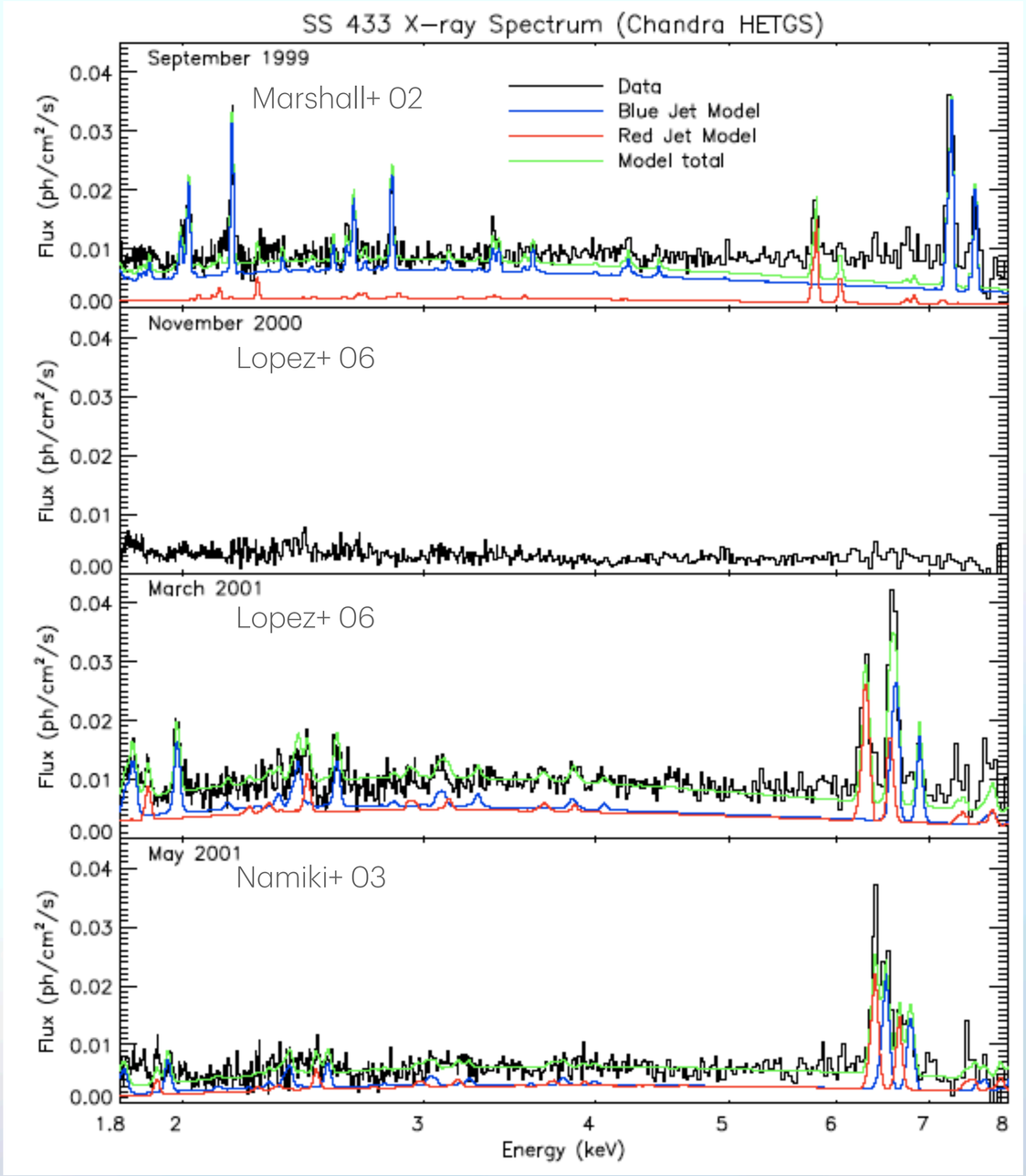
# Early HETGS Spectra

- Lines from many ions at $10^7$ K < T < $10^8$ K
- Red jet is weak in 1999 but strong in 2001
- $L_j \sim 10^{40}\mathrm{erg/s}$
- $L_j \gg L_X$ (ULX?)



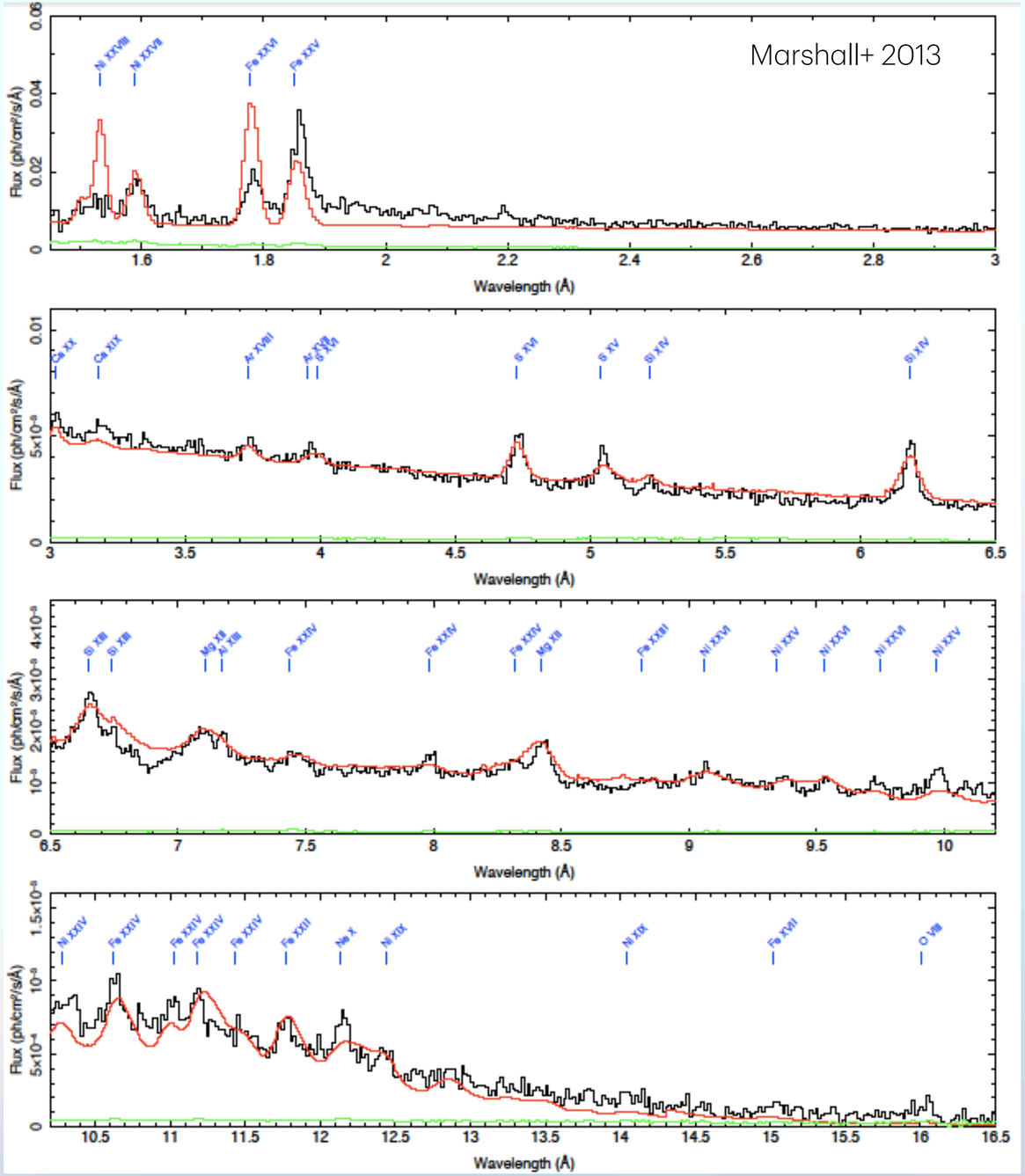
# More HETGS

- Sept. ’99: mostly blue-shifted jet, basic model
  - cooling gas, constant speed ($n_e \propto r^{-2}$)
  - conical outflow 1.5° opening angle
  - directly obtain emission measure $\int n_e^2 dV \sim \Omega r^3 n_e^2 = f(T)$
  - can estimate jet power: ~1e40 erg/s >> Lx
- Nov. ’00: no lines
- Jet eclipse: estimate companion R (Lopez+ 06)
- Aug. ’05
  - cooling time < 5000 s —> jet < 4e13 cm long
  - E and W jet directions aren’t anti-parallel
  - fast jet direction changes —> blob ejection?
  - overabundant metals, Ni

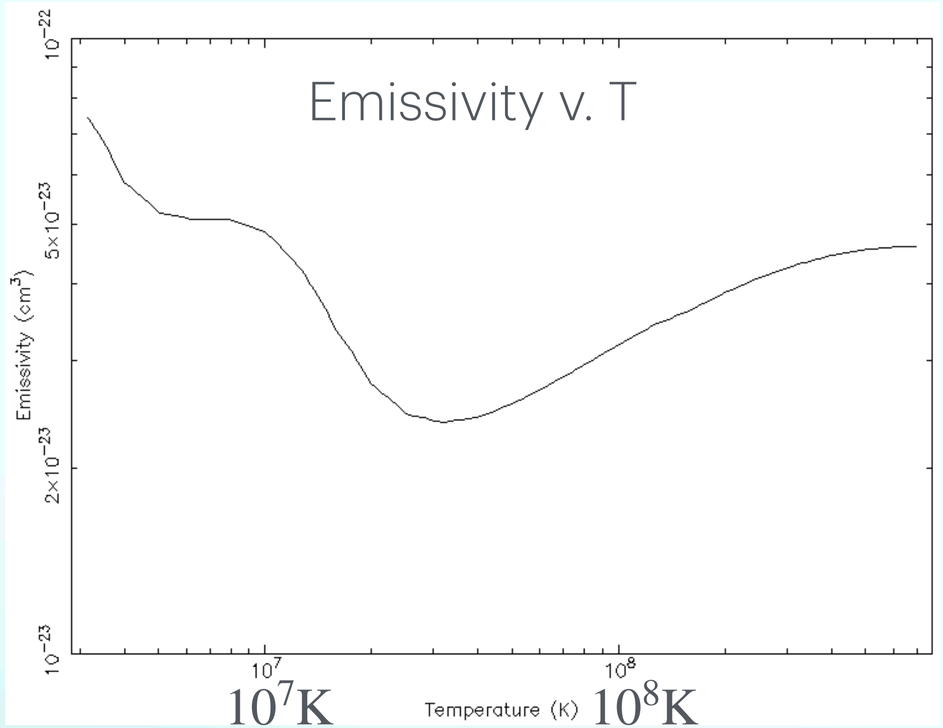


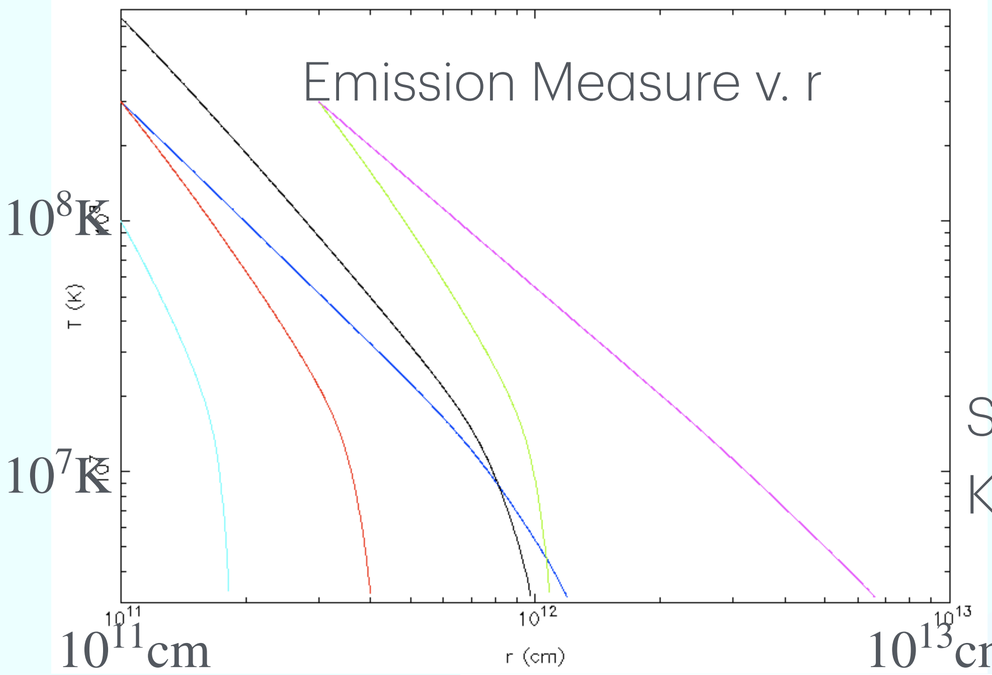
# Jet X-ray Spectrum

- Adjust for time-varying Doppler shift
- Combine spectra
- Ignore red-shifted lines
- Fit in isis to 4T model
  - Basis of adiabatically cooling model
  - High T cutoff needed
  - Similar to (broadened) $\theta^1$ Ori C
- Ni: x10 overabundant

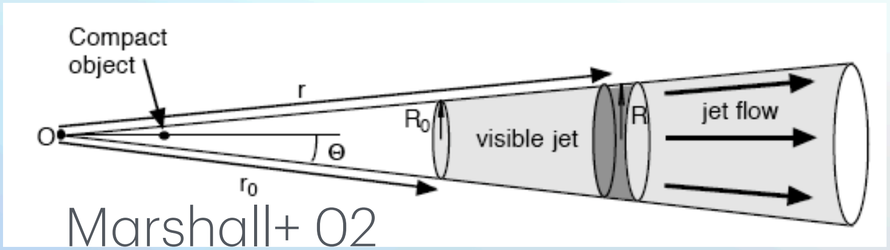


# Jet Cooling Model

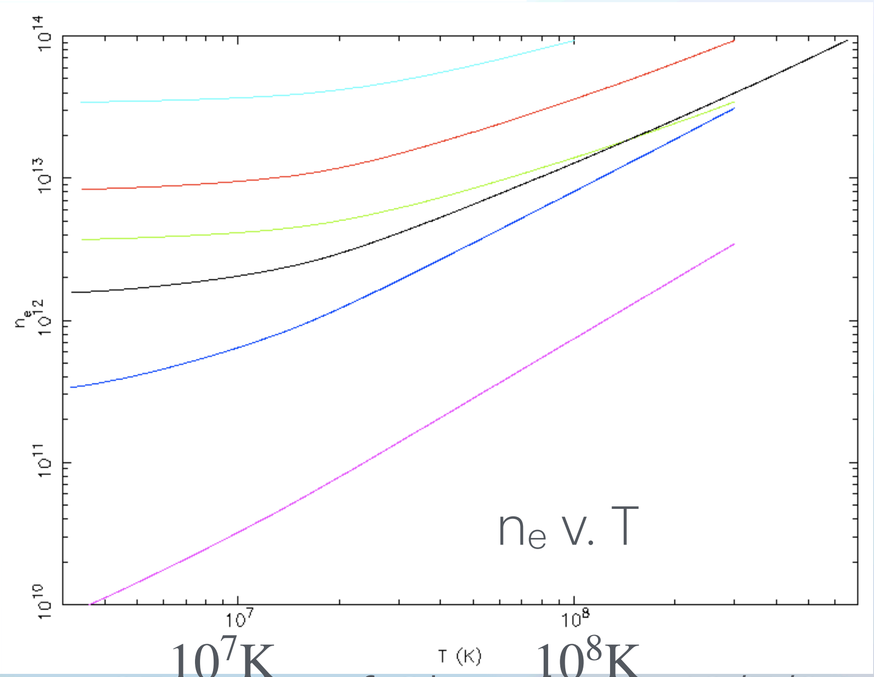



See also:
Khabibullin+ ‘16

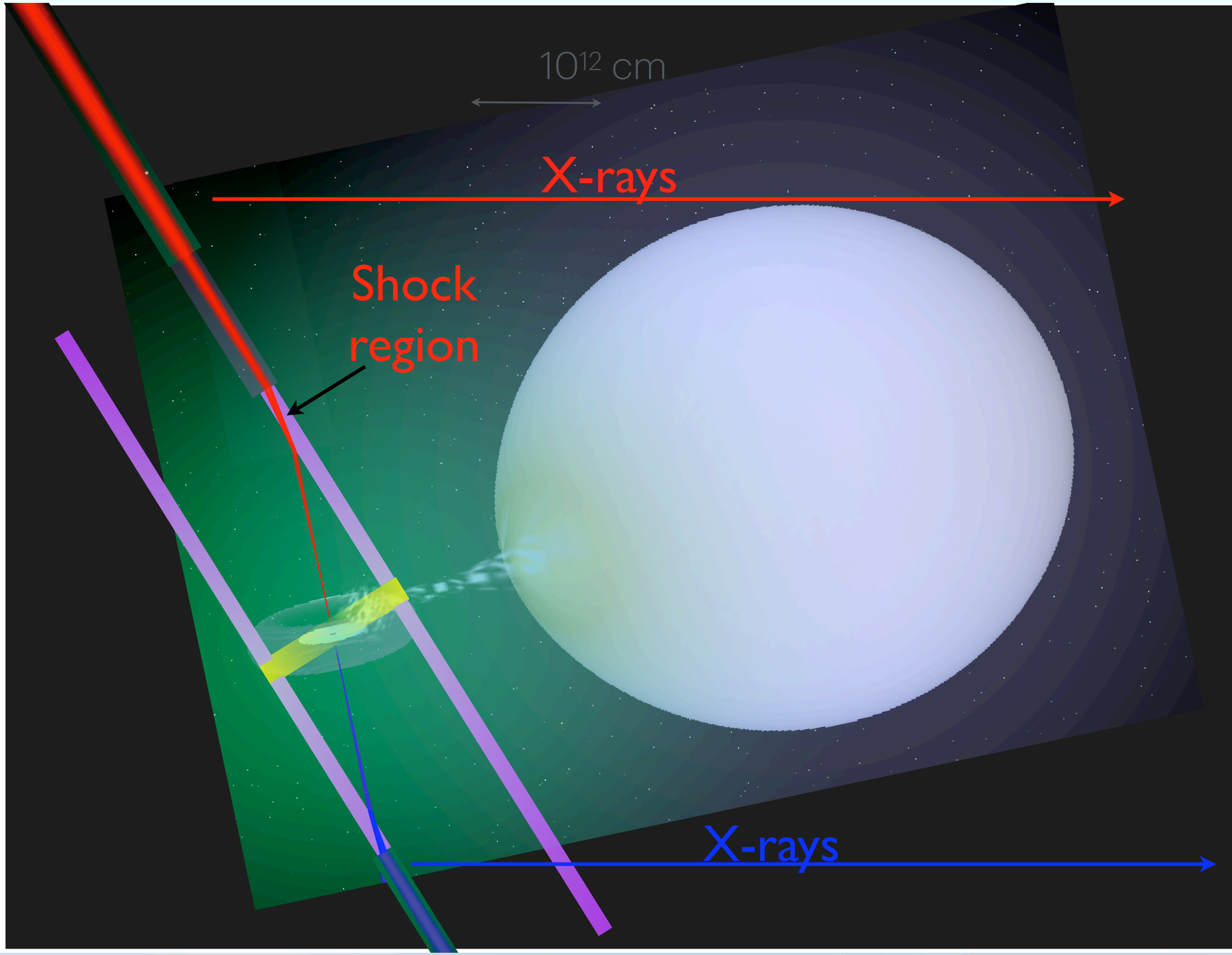



Marshall+ 02



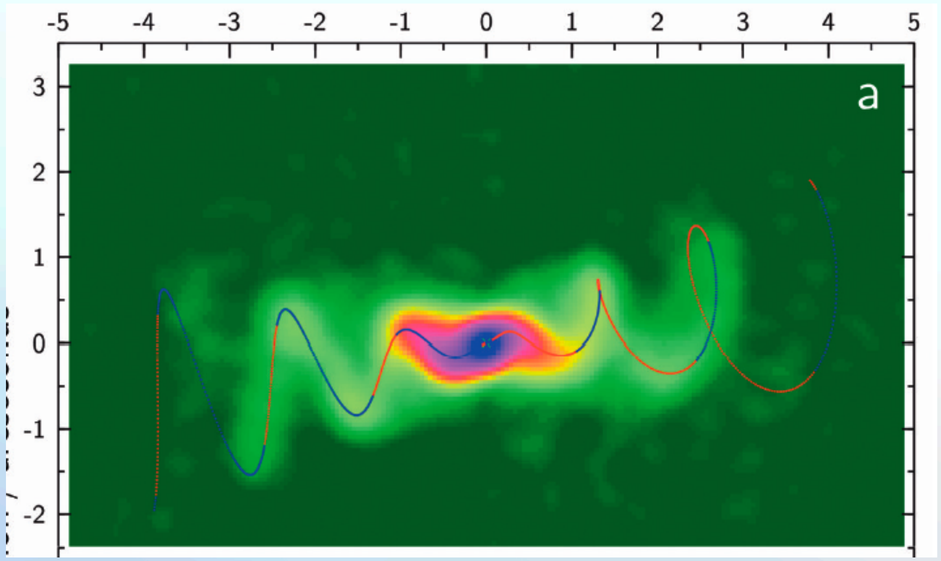
# A Model

- Jet direction from inner disk about BH
- Wind from warped outer disk
- Wind bends jet gently
- Direction of jet varies as warp wobbles
- Jet can start leptonic and entrain metals at shocks
- Red jet's shock hidden during eclipse



# Chandra Imaging

- Extended flux at 2-5” scale
- Found in first HETGS observation
- Aligns with extended radio flux
- Confirmed in later observations



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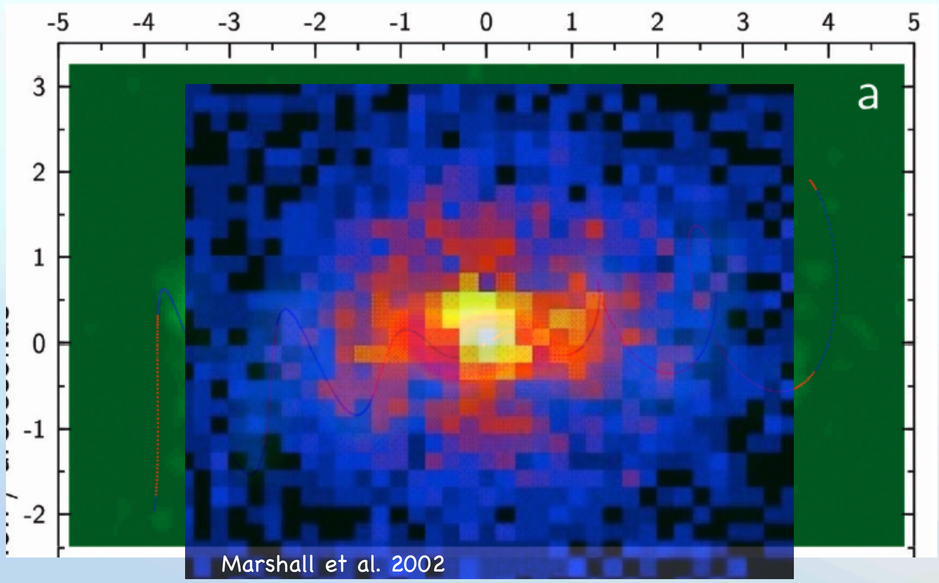


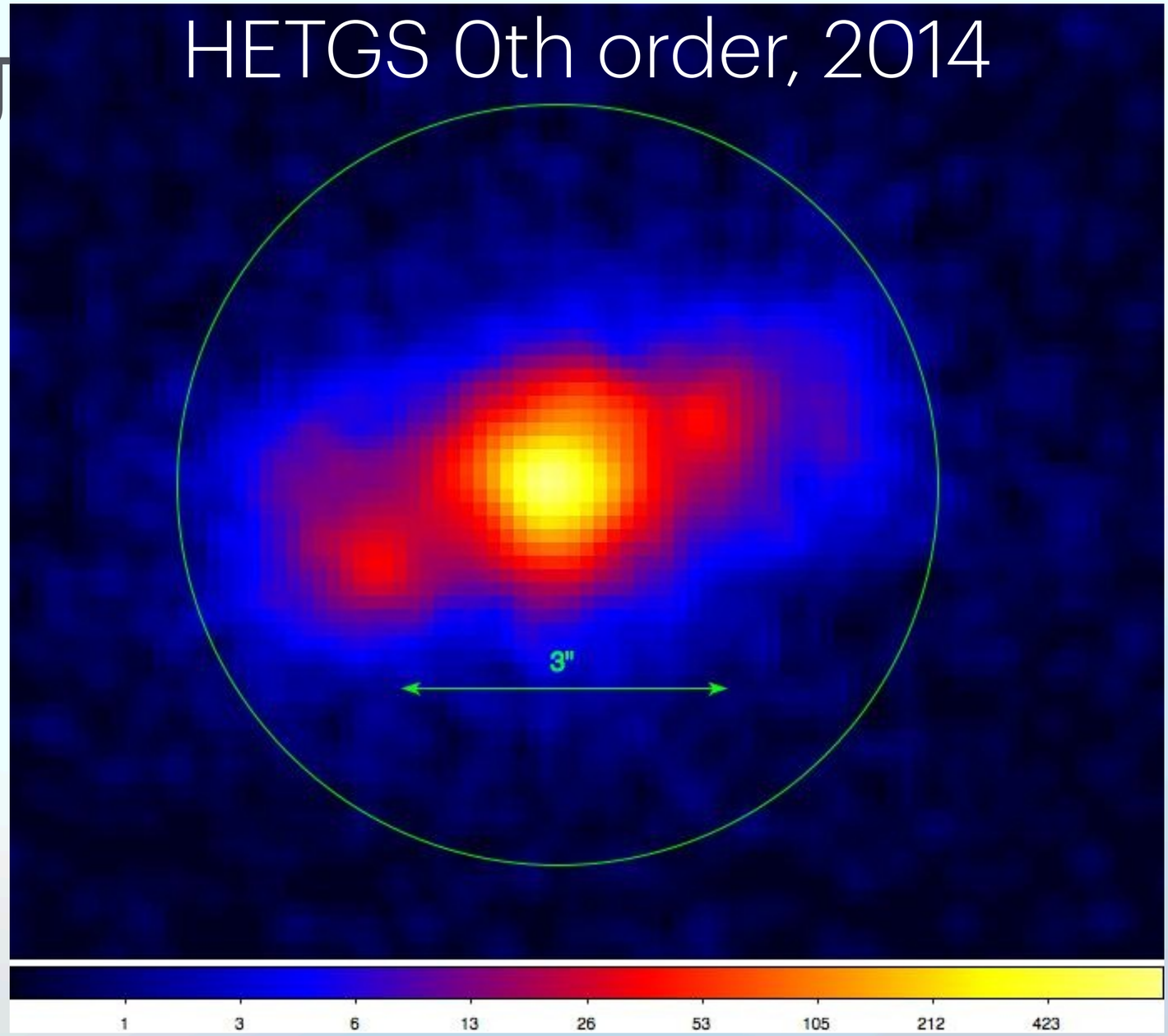

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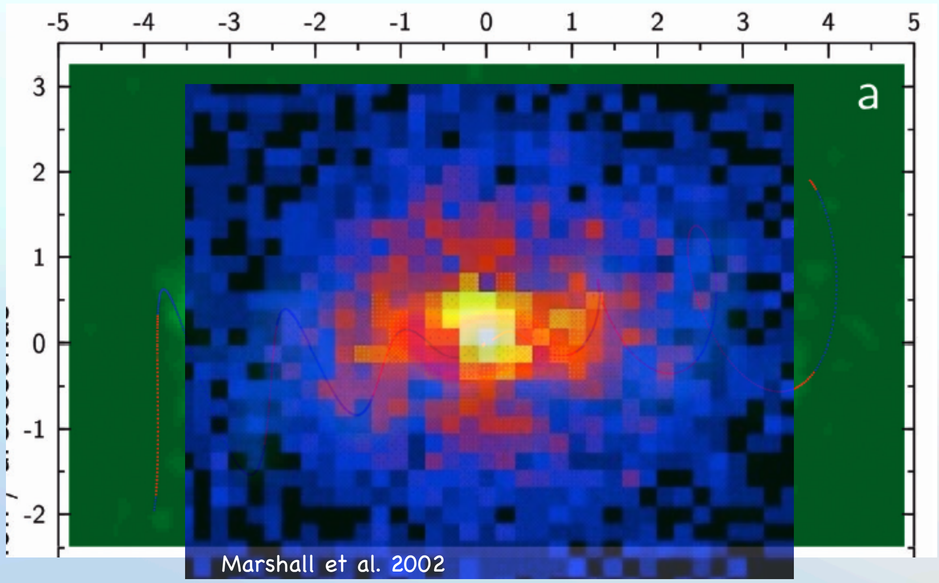
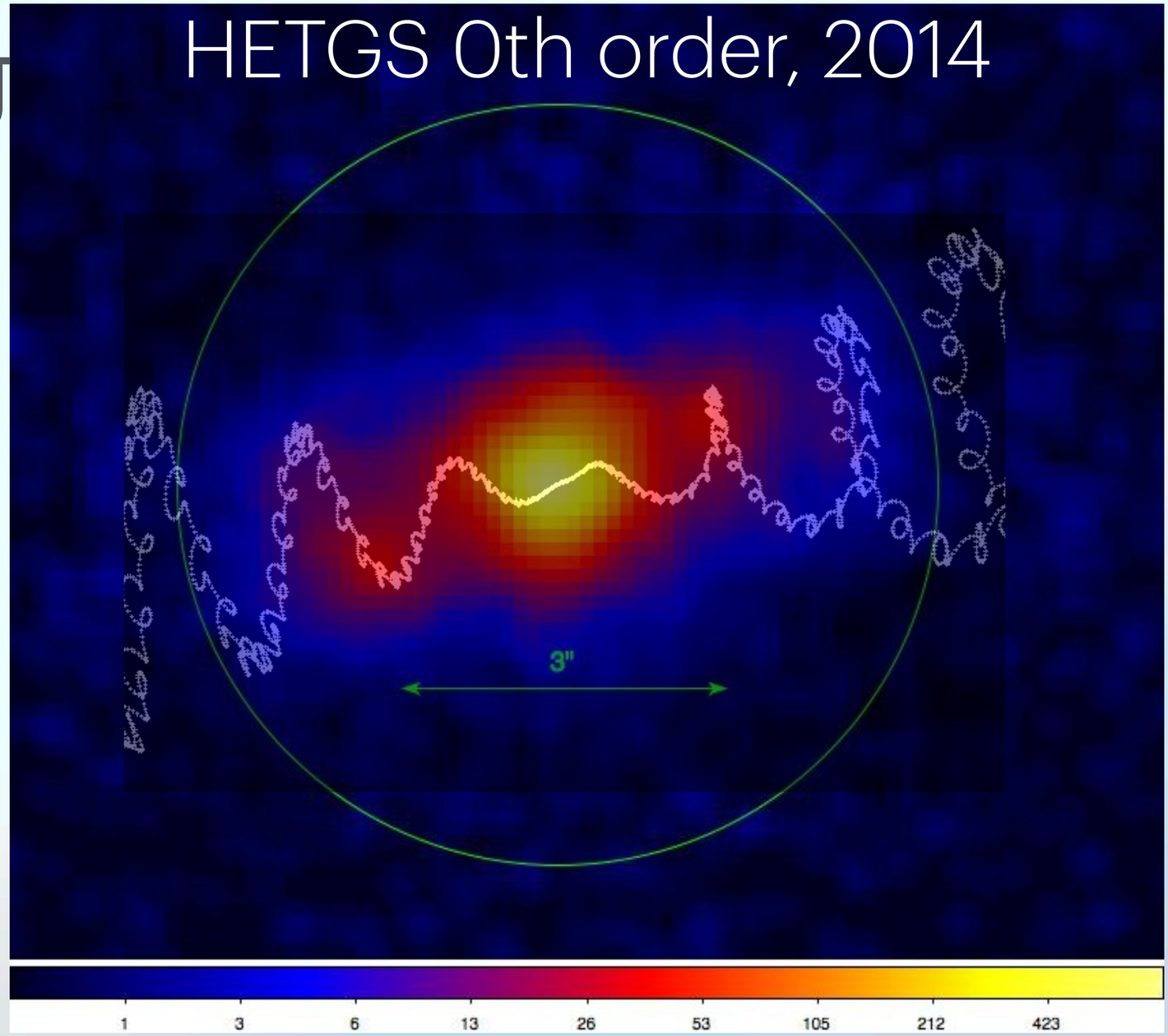
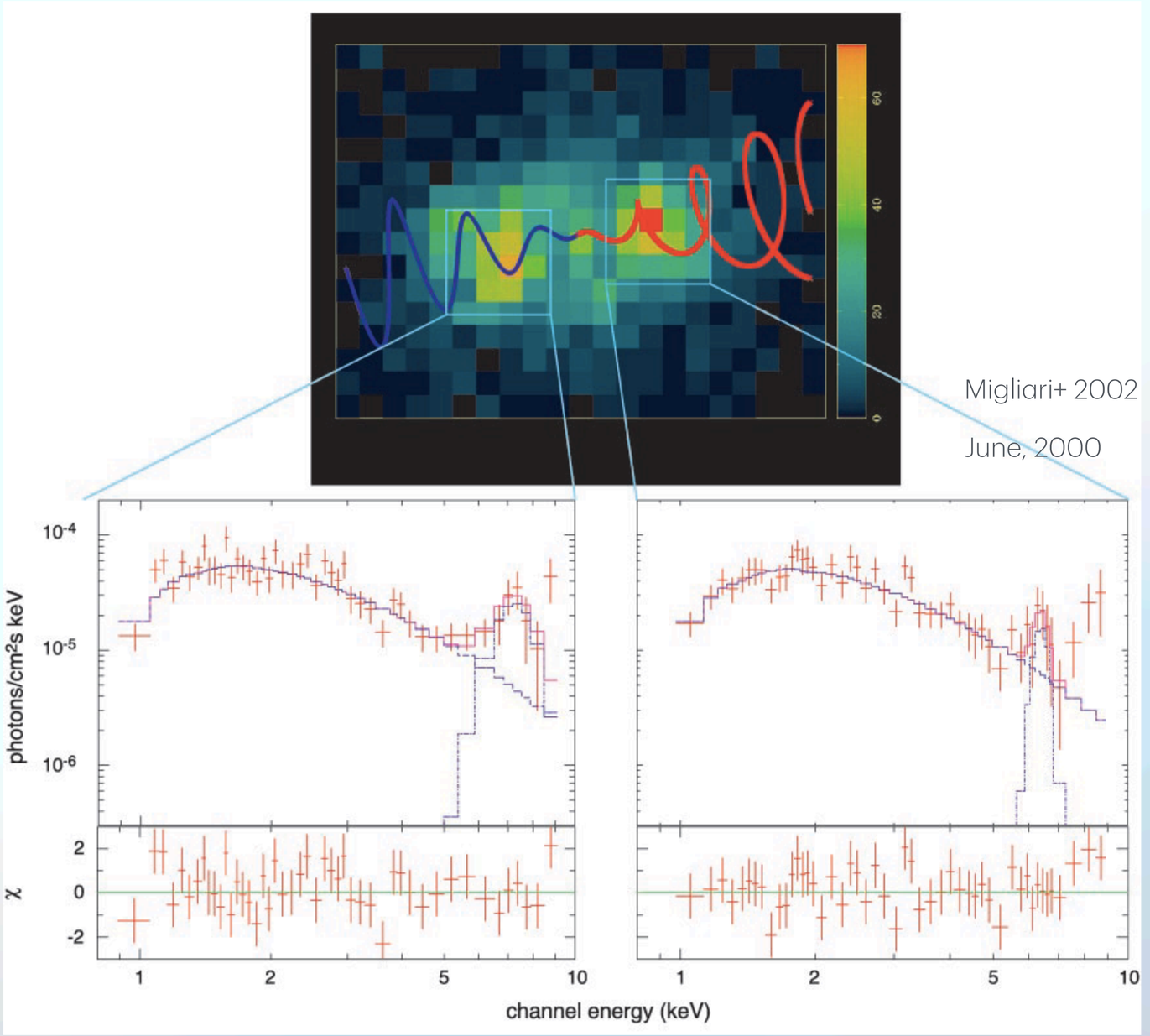


# Chandra Imaging

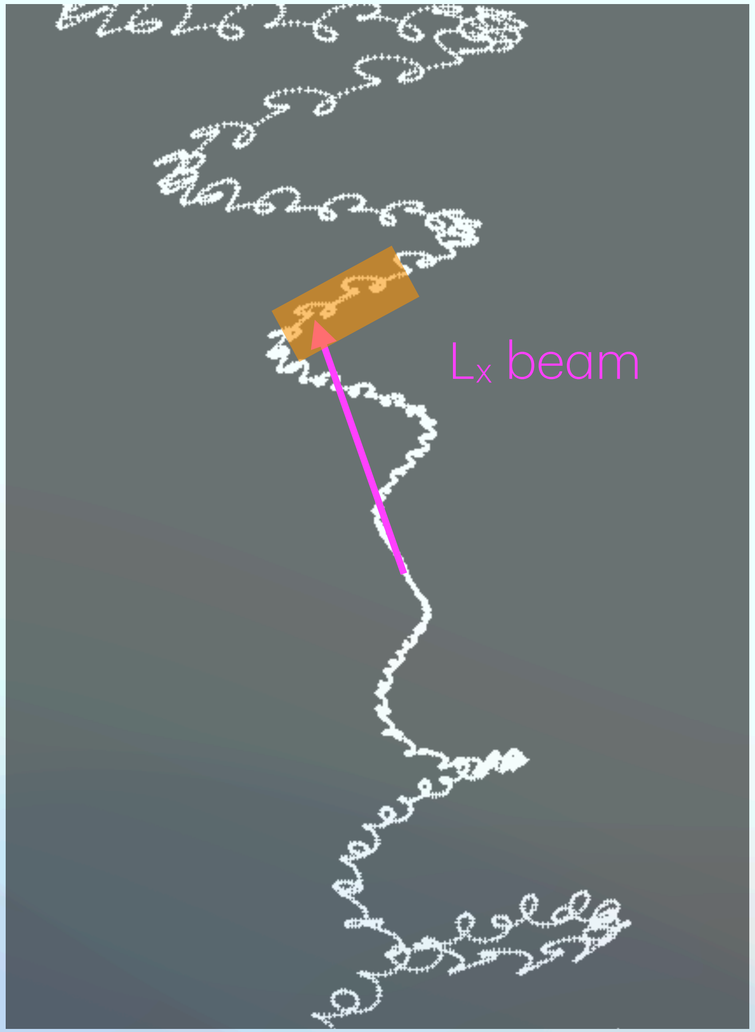
- ACIS spectra show Fe lines at $10^{17}$ cm from core
- Jet has recombined by $10^{15}$ cm
- Migliari+ ‘02: gas is reheated via shocks in jet
- Migliari+ ‘05: extended emission varies on hours to days
  - Second, faster outflow?
  - Propagating shock wave?




Migliari+ 2002

June, 2000

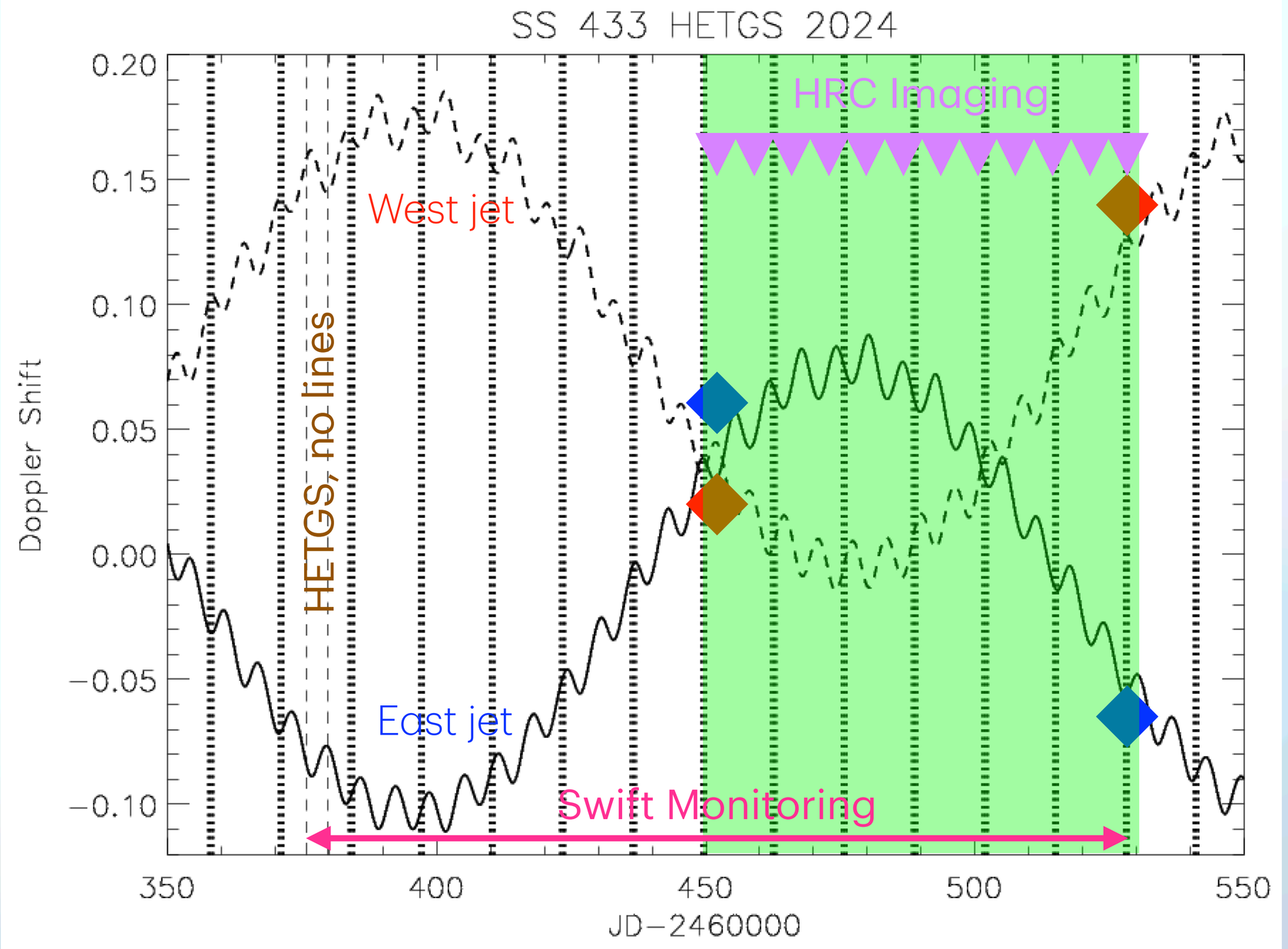
# A ULX model — Reflection from Jet Knots




- $L_{ext}$ ~ 2e33 erg/s = 0.5% of $L_{jX}$ (3e35 erg/s)
- $P_j = \dot{m}v_j^2/2$ = 5e39 erg/s, infer beamed $L_X \sim P_j$
- Electron scattering?
  - Density ~ $1/r^2$ —> n = 20 $cm^{-3}$ at 2e17 cm (3" @ 5 kpc)
  - Pathlength ~ 3 days of propagation: 0.7 l-d = 2e15 cm
  - t = 3e-8 —> Lscat ~ 1.5e32 erg/s along 1.5° portion
  - Beam half-angle = 20° = 13 beams —> 2e33 erg/s
- Note: x = $L_X/(nr^2)$ ~ 5000 —> ionized @ 1e17 cm
  - $t_{ion,H}$ ~ 4000 s, $t_{recomb,H}$ ~ 1e11 s —> H doesn't recombine
  - But, $t_{ion,fe}$ ~ 5e8 s >> $t_{cross}$ —> Fe is not ionized to Fe XXV
- Experiment (completed Aug. 24):
  - track HRC images, measure extended flux
  - monitor X-ray flux with Swift
  - check that jet is "operating" with HETGS

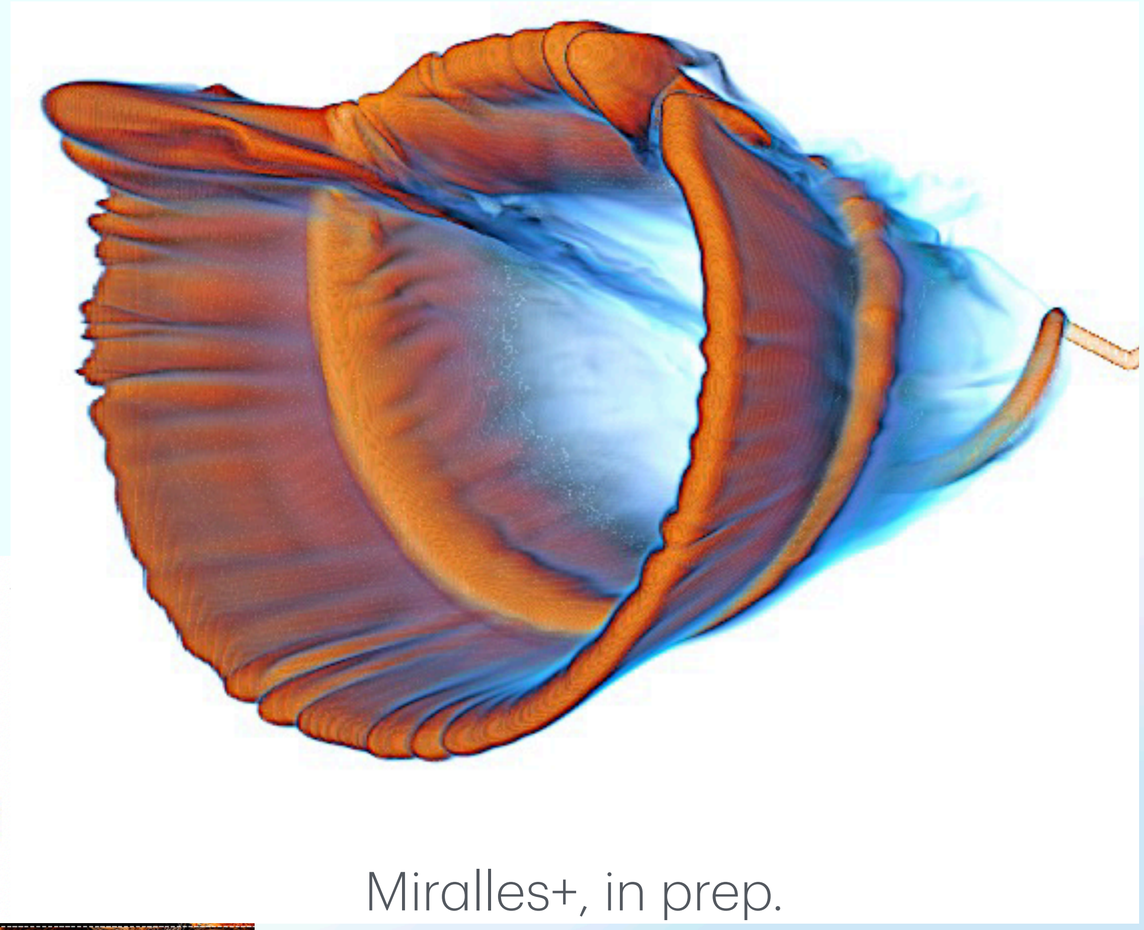
# ULX Test

- Data have been obtained
- Swift monitoring
  - Every 3 days
  - Started MJD 60375
  - Timing mode to avoid pileup
  - Lightcurve formed
- HETGS analysis:
  - No strong lines in 1st epoch
  - Good spectral fits to others
  - Doppler shifts match model
- HRC imaging in process
  - Extent is clear
  - Some variation observed
  - New, unexpected feature!

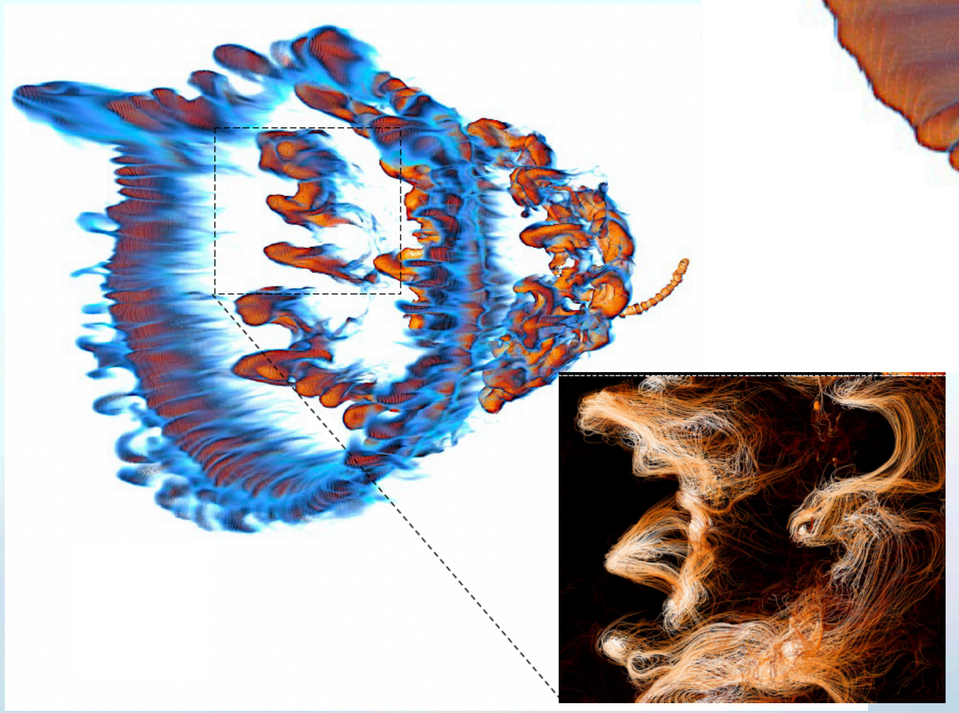


# Simulations!

- MHD simulations are improving!
- Including blob interactions
- Features depend on how knotty the jets become
- Magnetic fields can be very tangled



Miralles+, in prep.



# Summary

- Before Chandra (B.C.):
  - Clumps move ~ ballistically over x1000 in r
  - Jet is clumped > $10^{15}$ cm, radio-dominated > $10^{16}$ cm
  - Atomic H, He recombination emission at $10^{15}$ cm
  - X-ray emission from recombining metal ions
- With Chandra Spectroscopy
  - Jet cools from kT > 30 keV (shocks!), cooling time < 5000 s
  - Jet contains common metals, overabundant Ni
  - Jet has constant speed, constant opening angle
  - Jet is continuous over $10^{12\text{-}14}$ cm, discretizes after cooling
  - Direction is separately set for opposite jets
  - Radiative cooling limits jet X-ray emission length
  - Shock model 1: jet intercepts disk funnel
  - Shock model 2: jet bent by wind from outer disk
- With Chandra Imaging
  - Extended flux was not expected — reheating due to knot velocity variations?
  - Test of ULX hypothesis: flux may just reflecting the core power — in progress


Thanks for your attention!