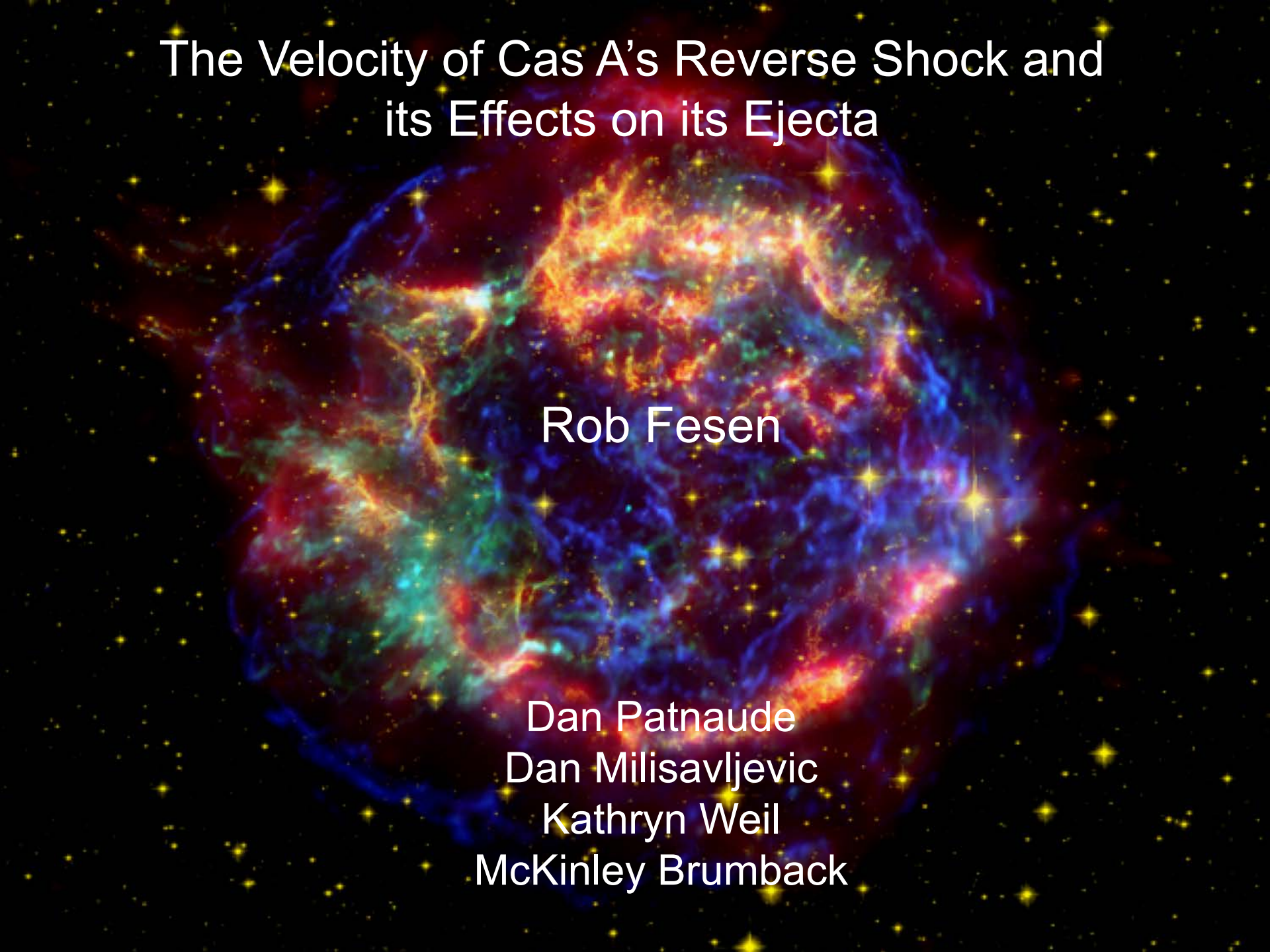
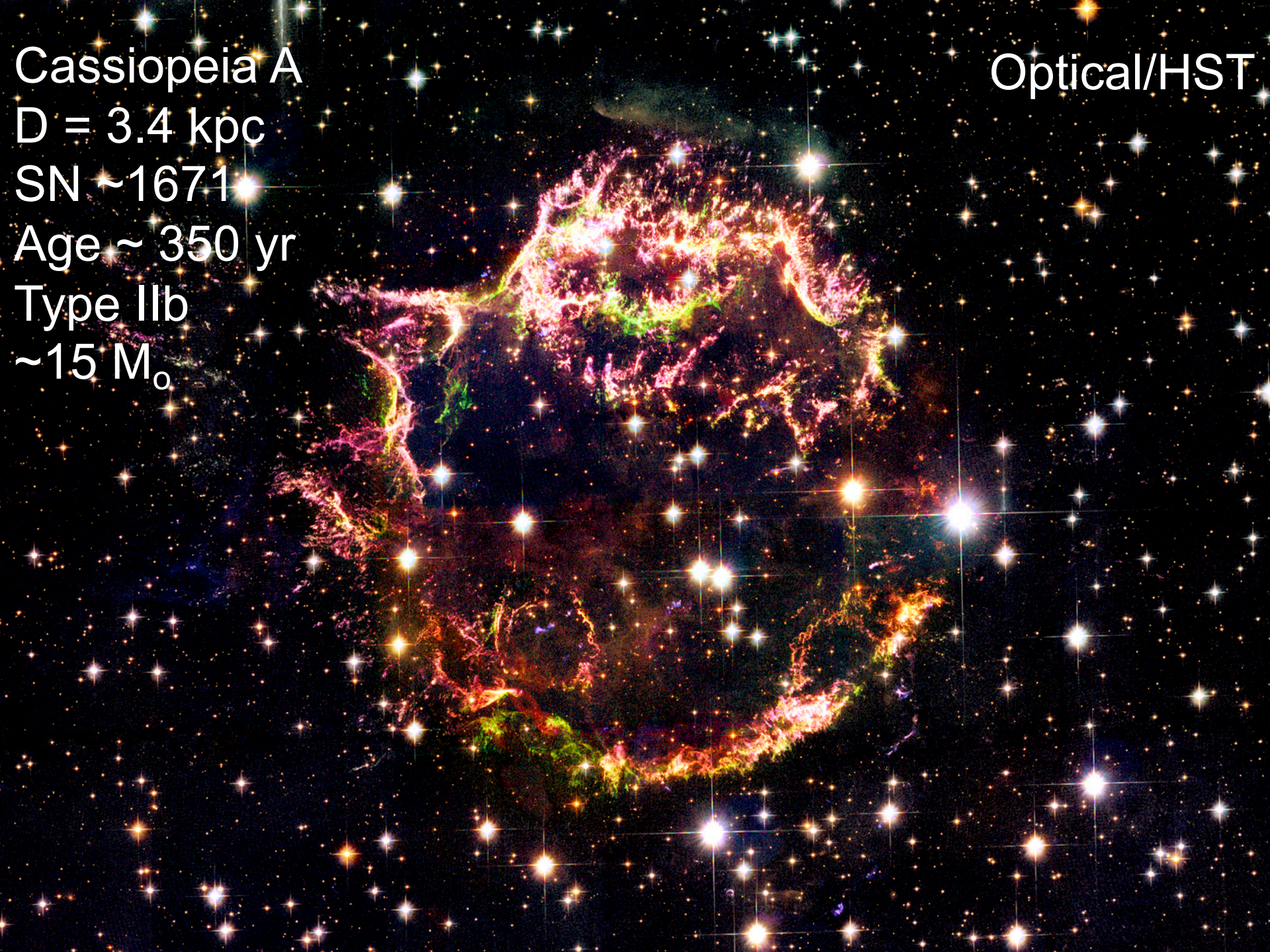
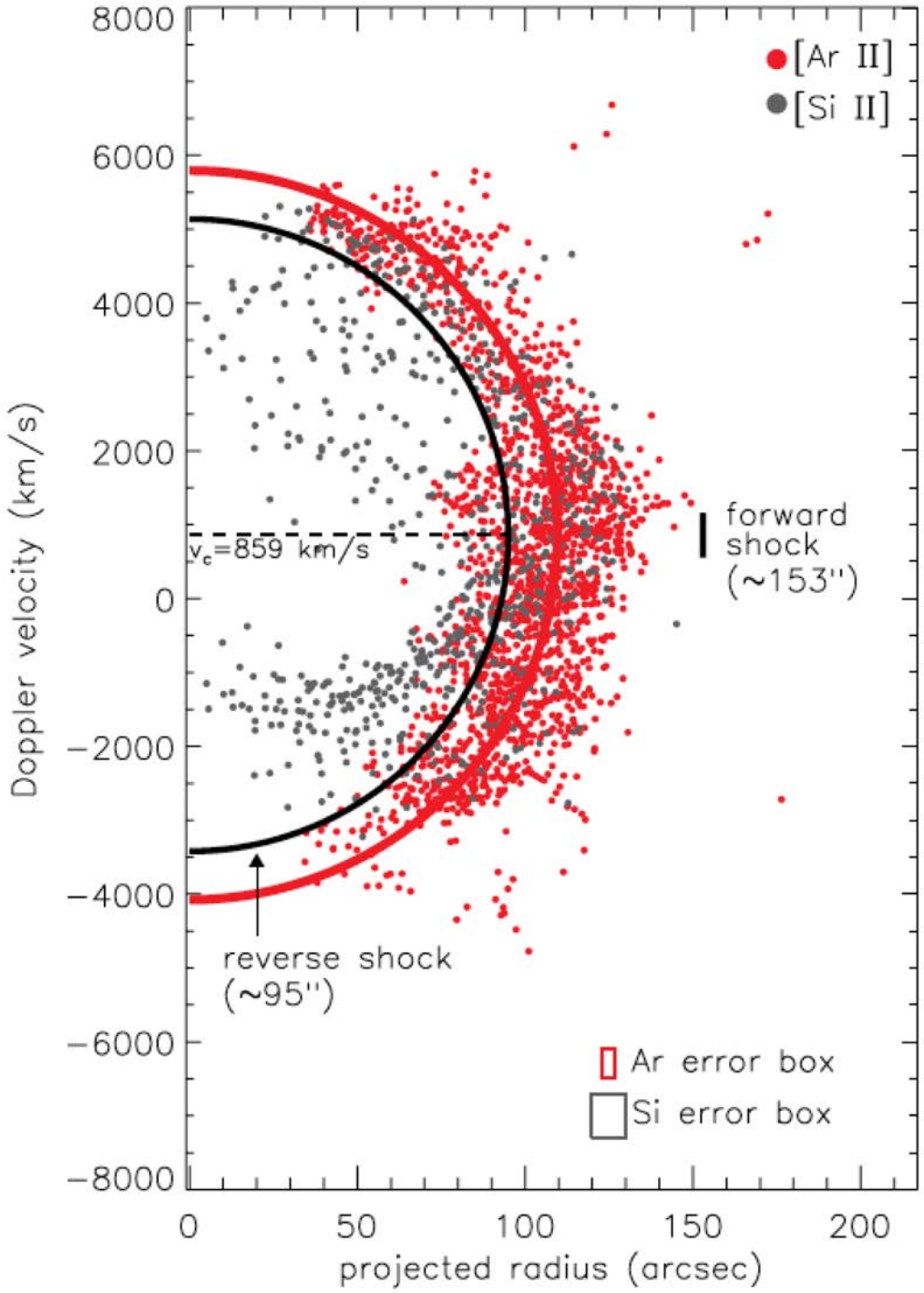
The Velocity of Cas A's Reverse Shock and its Effects on its Ejecta



Rob Fesen

Dan Patnaude
Dan Milisavljevic
Kathryn Weil
McKinley Brumback


Cassiopeia A
D = 3.4 kpc
SN ~1671
Age ~ 350 yr
Type IIb
~15 M_o
Optical/HST

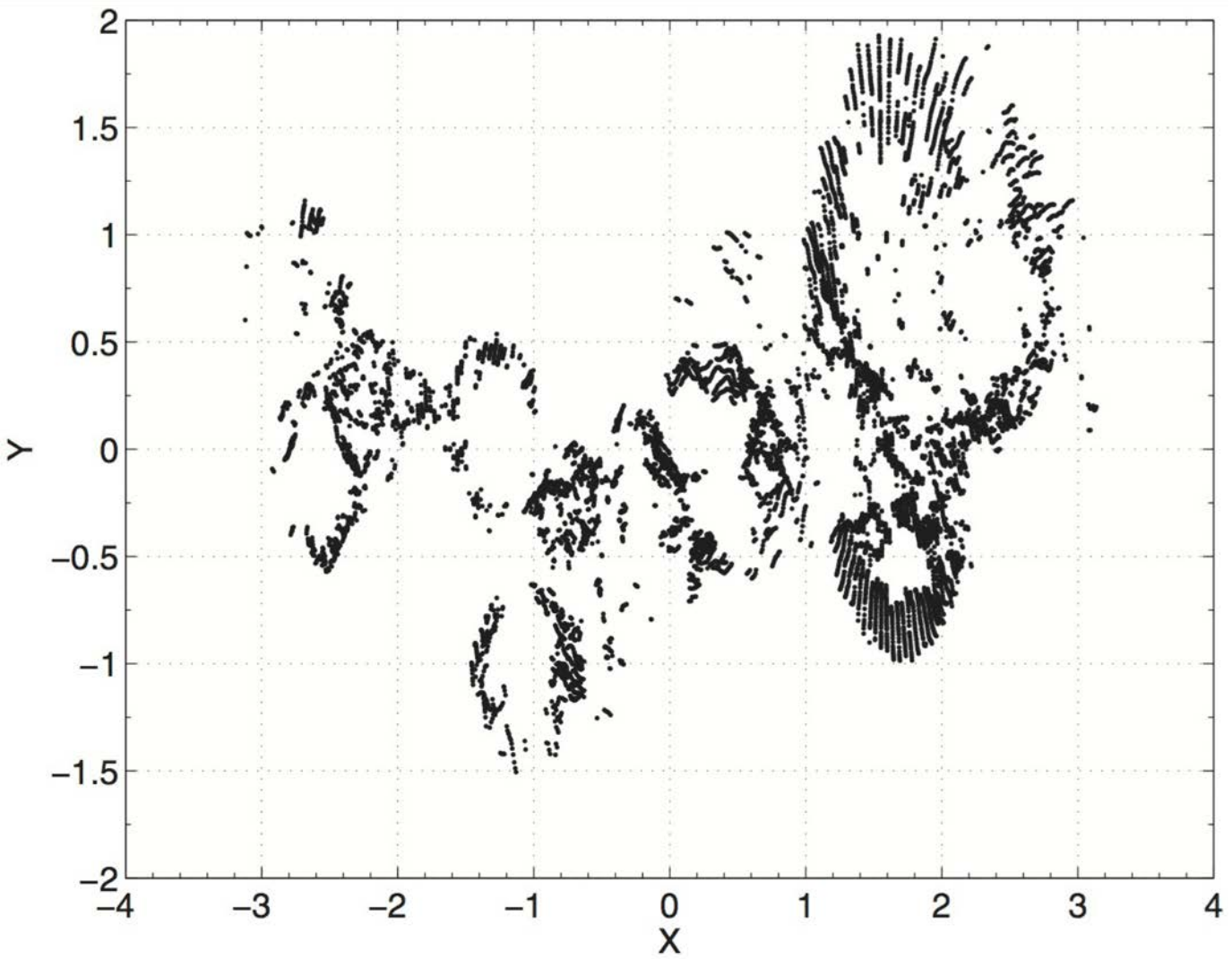


Ejecta Velocities:

-4000 to +6000 km/s

DeLaney et al. 2010

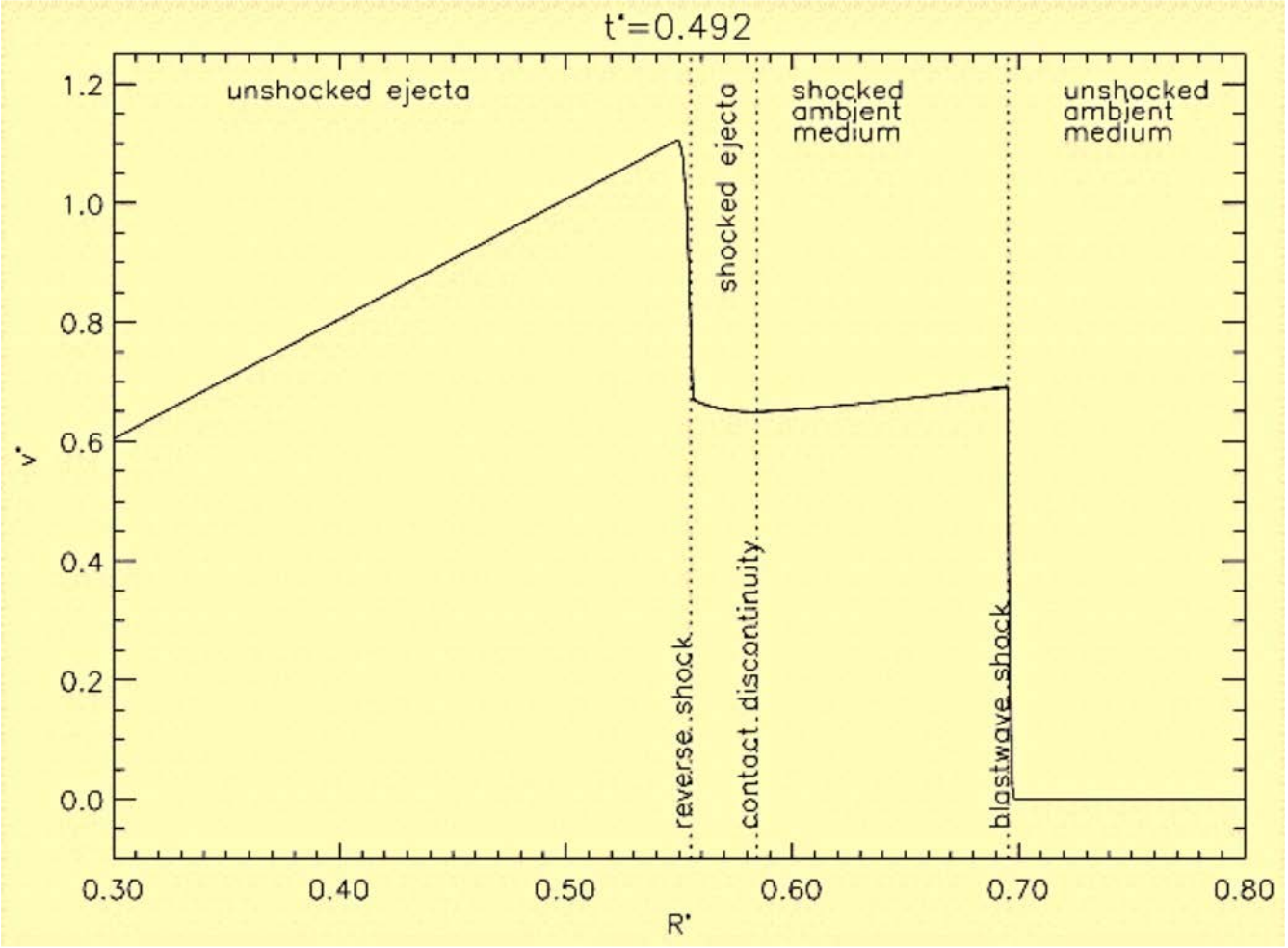
Cas A's ejecta are arranged in large "rings", marking the cross-sections of ejecta bubbles encountering the reverse shock front.



A Mercator map of Cas A's main shell emission.

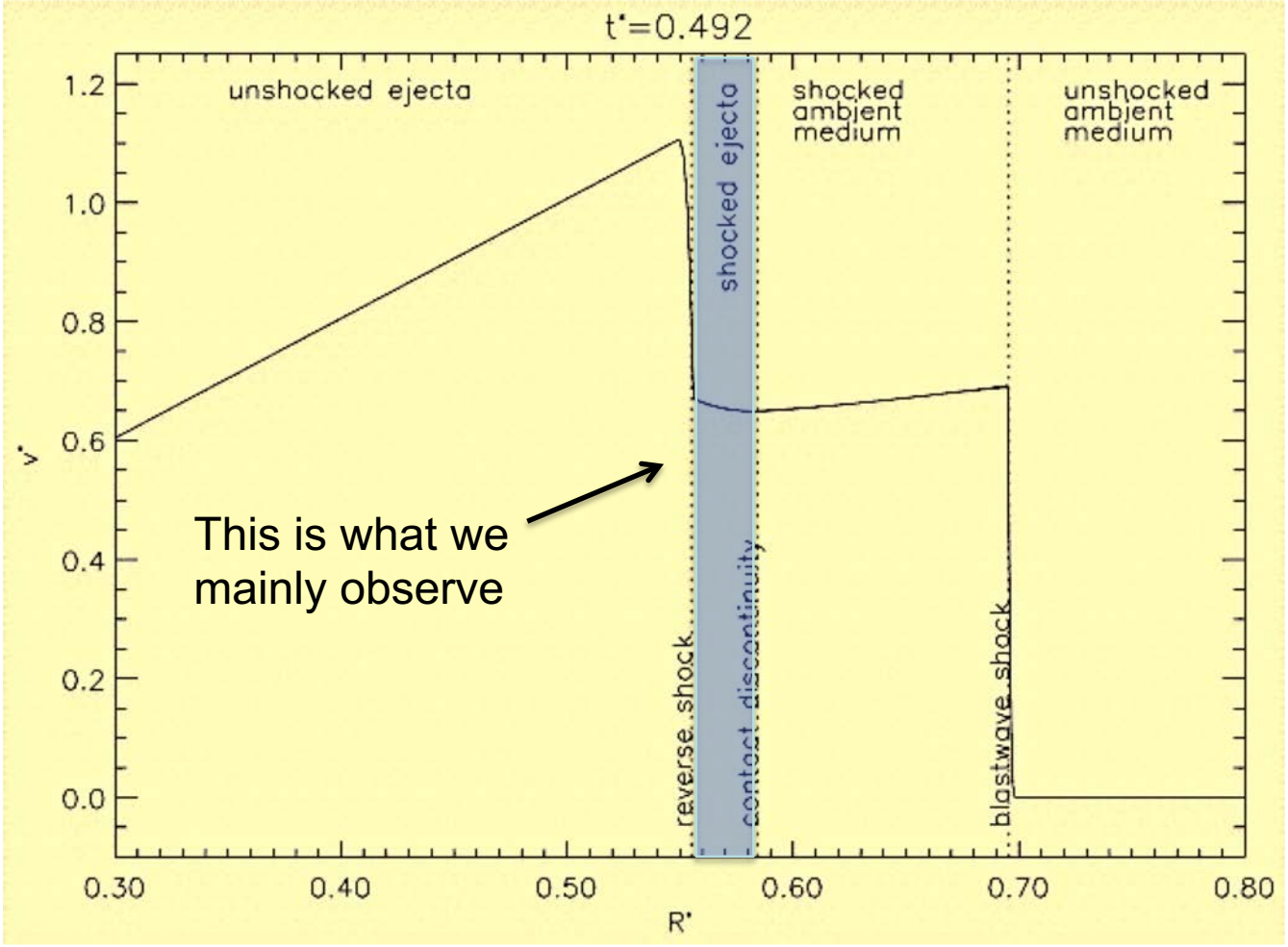
Milisavljevic & Fesen

Below illustrates the basic structure of an idealized, spherically symmetric remnant: unshocked ejecta, reverse shock, shocked ejecta, contact discontinuity, shocked ambient gas, and unshocked ambient gas. This figure is taken from a simulation of uniform ejecta expanding into a uniform ambient medium.

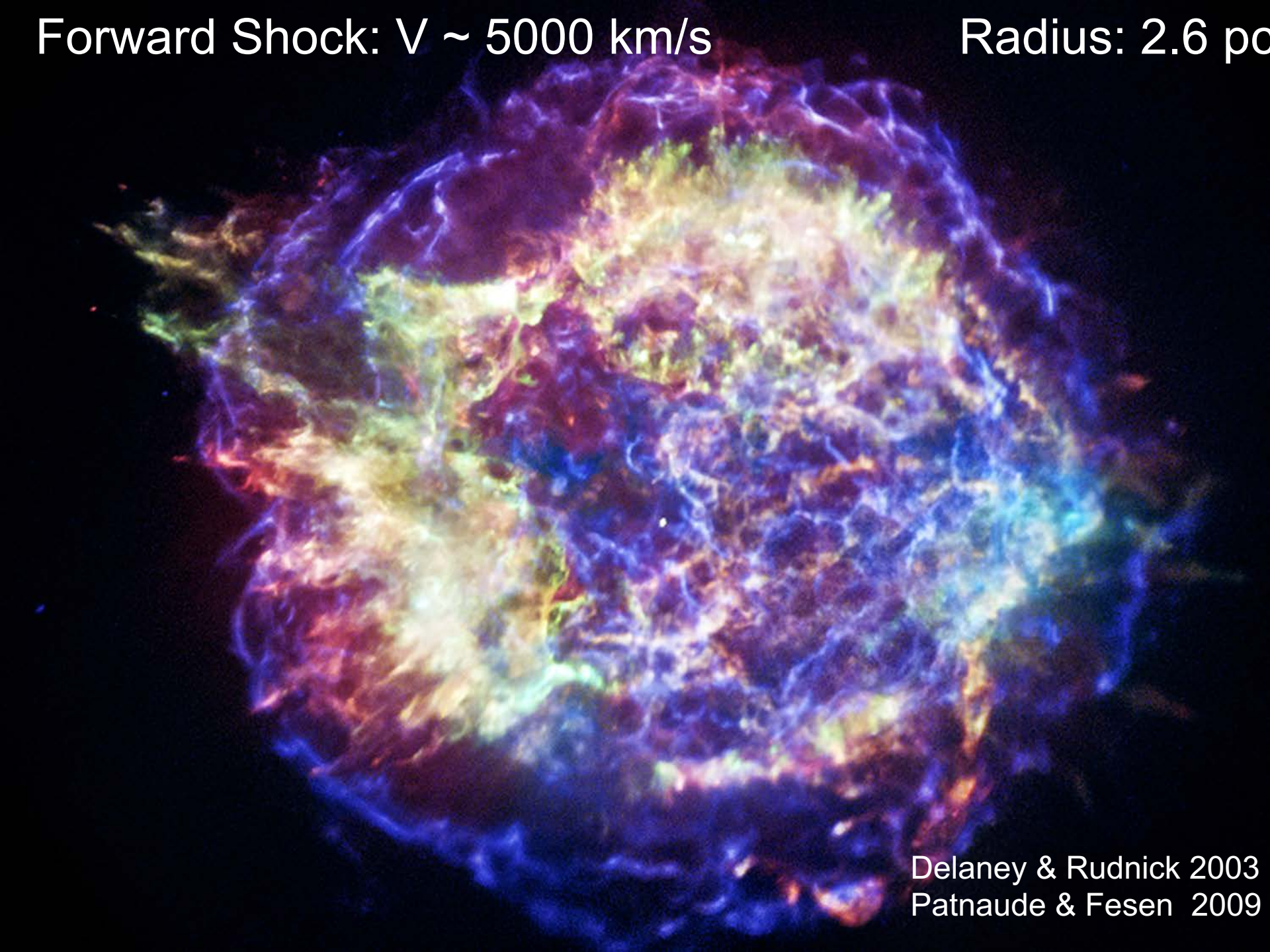


Truelove & McKee 1999

Below illustrates the basic structure of an idealized, spherically symmetric remnant: unshocked ejecta, reverse shock, shocked ejecta, contact discontinuity, shocked ambient gas, and unshocked ambient gas. This figure is taken from a simulation of uniform ejecta expanding into a uniform ambient medium.

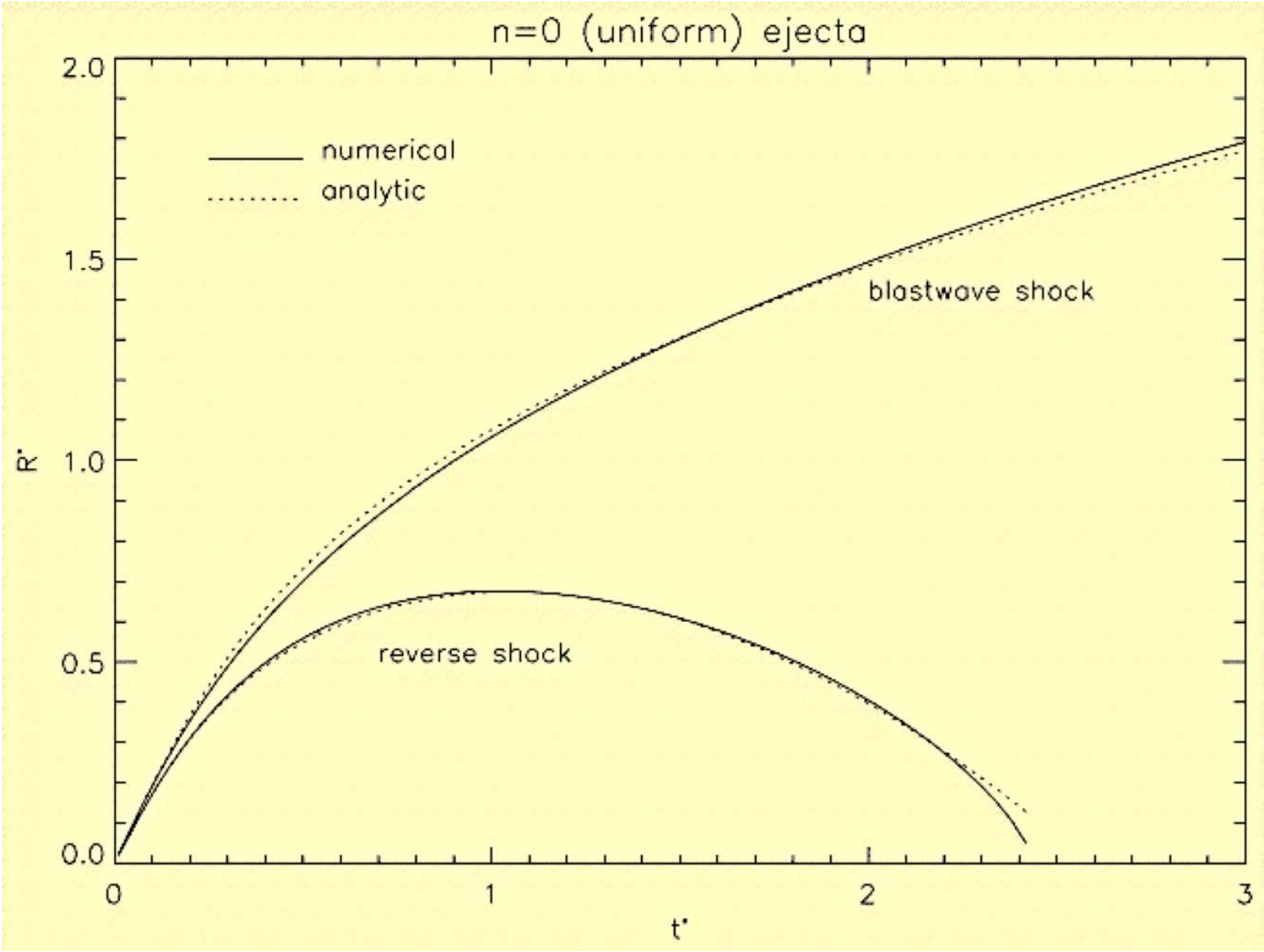


Truelove & McKee 1999

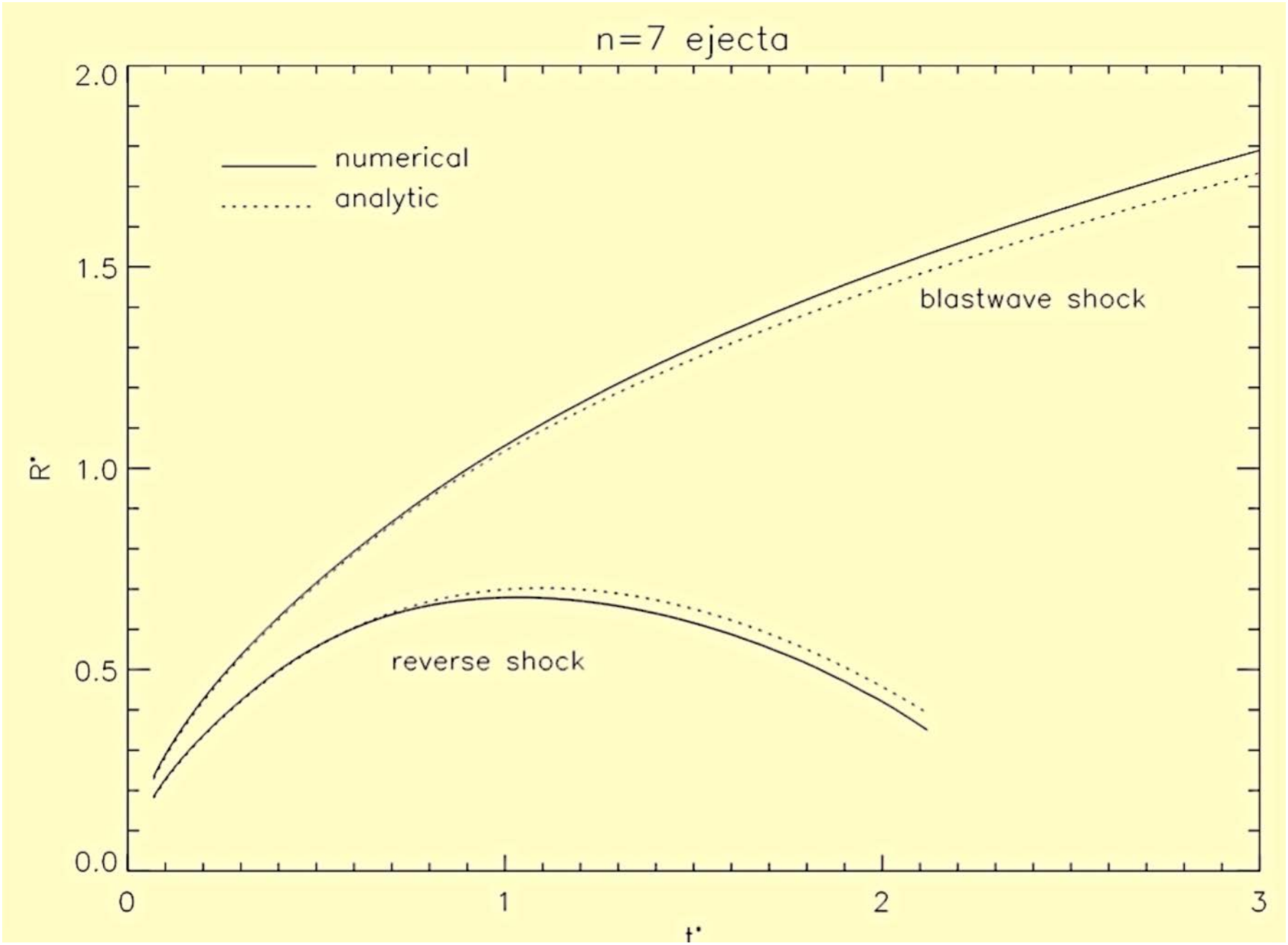

Forward Shock: V ~ 5000 km/s
Radius: 2.6 pc
Delaney & Rudnick 2003
Patnaude & Fesen 2009

What about the velocity of the reverse shock?


Well…that's where things get interesting.



Truelove & McKee 1999



Truelove & McKee 1999

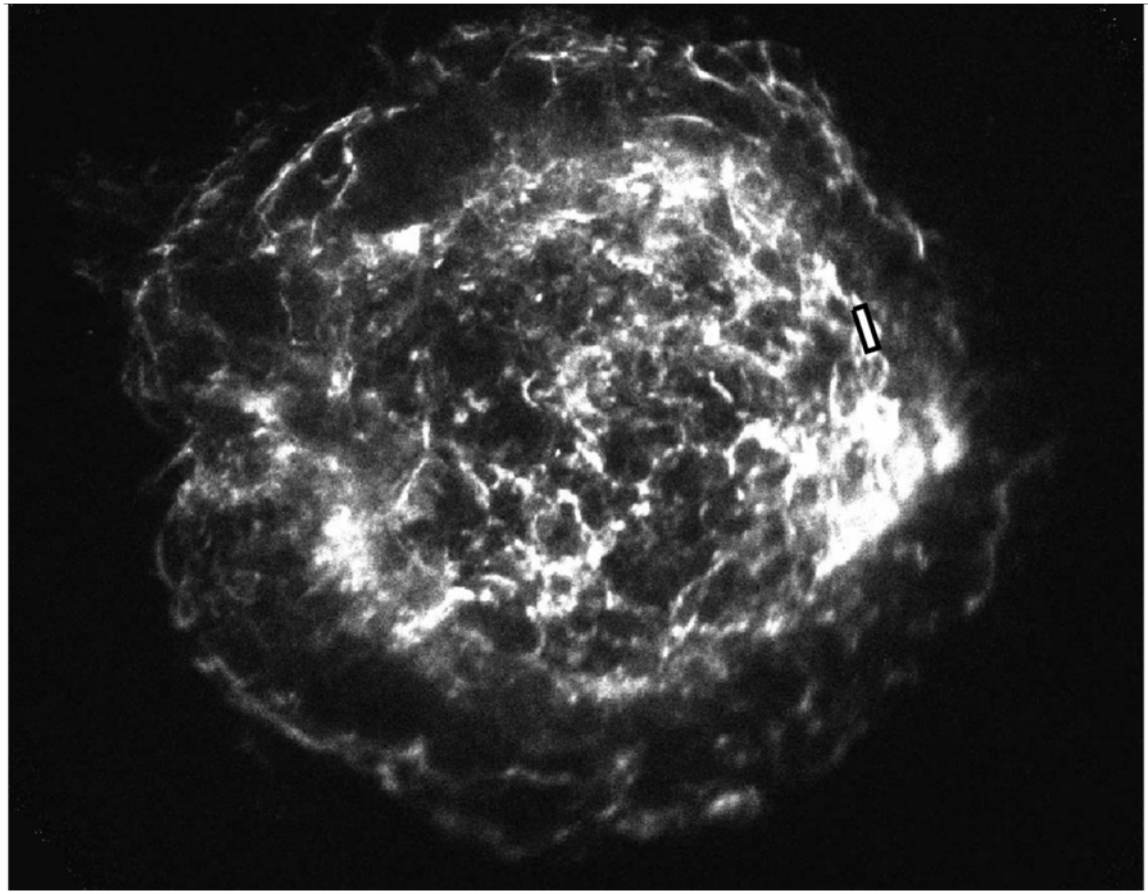
$$V_{RS\ ejecta} = V_{ejecta} - V_{RS\ sky}$$

Helder & Vink (2008) found for a small western limb region:

$V_{RS\ sky}$ = -970 km/s

Meaning the reverse shock is moving back toward remnant center.

if V_{ejecta} = 5000 km/s, the ejecta contacts the RS with a velocity of $V_{RS\ ejecta}$ = 6000 km/s



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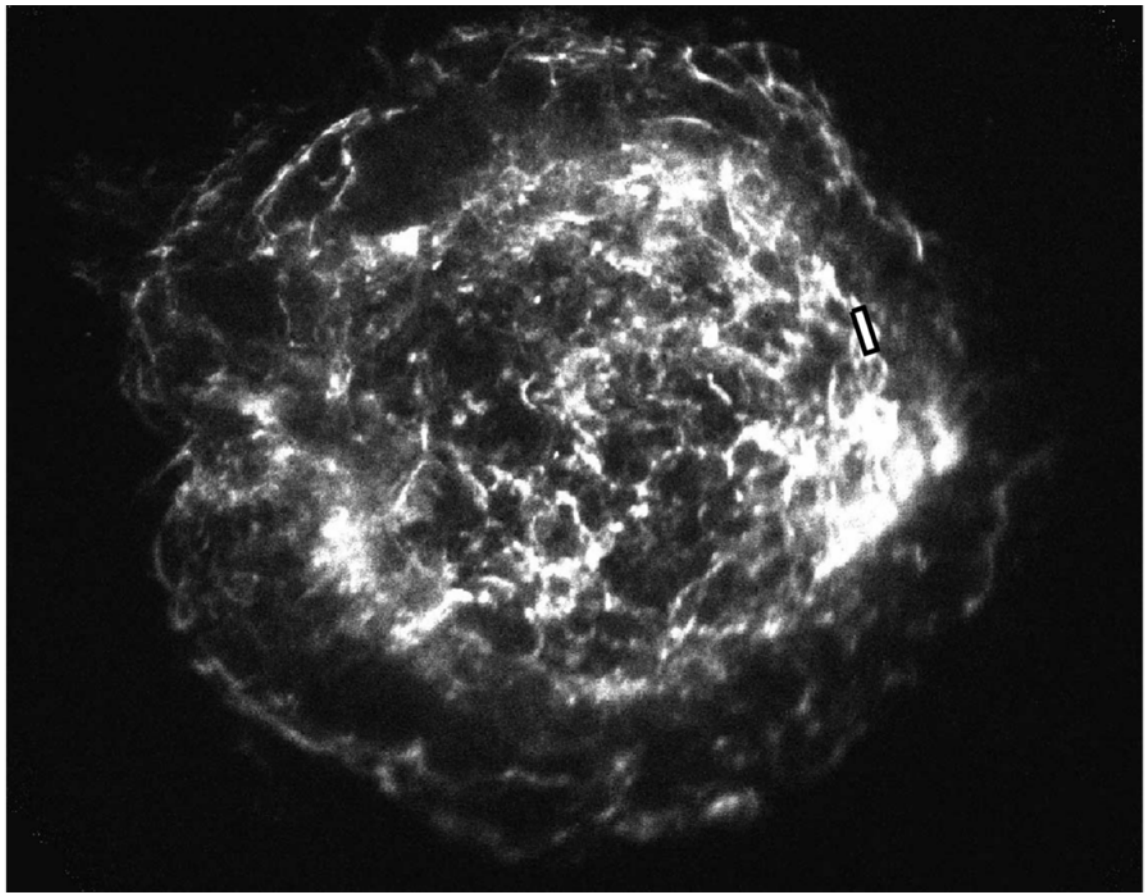
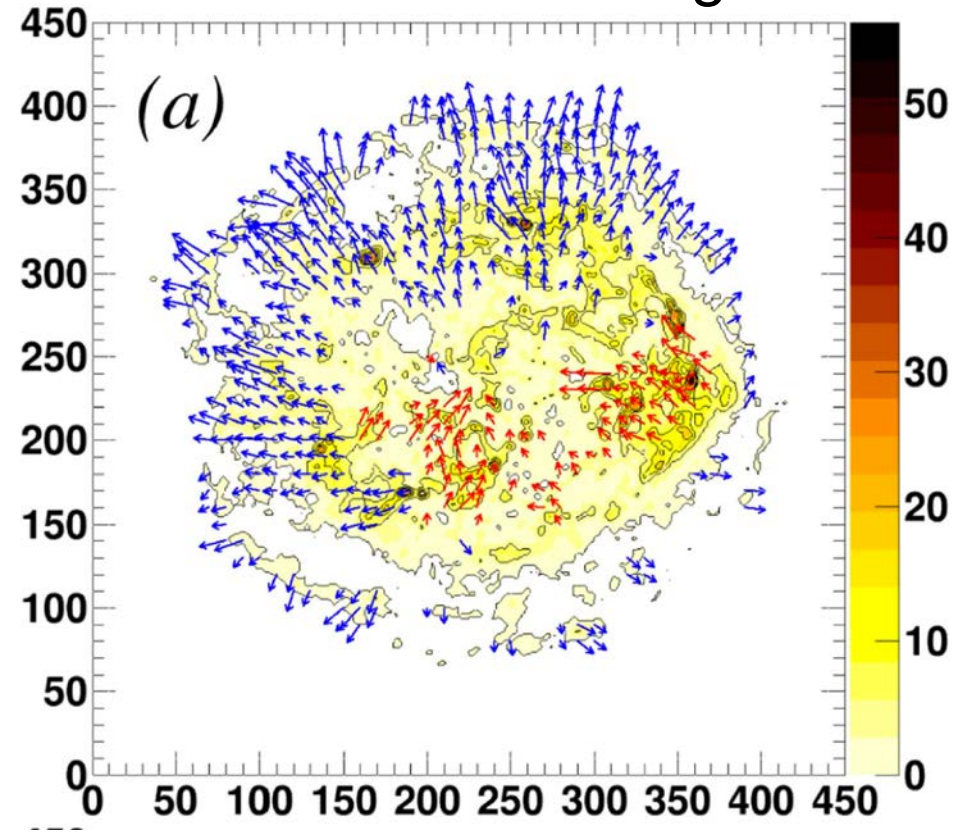
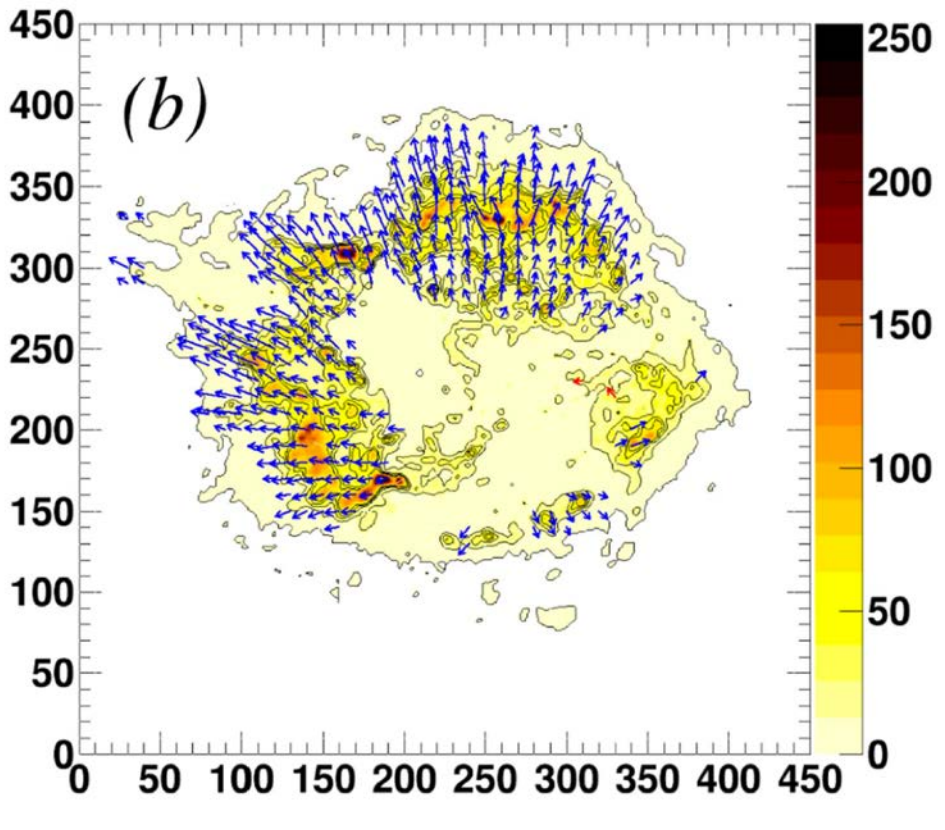


However, elsewhere (i.e., northern and eastern regions) $V_{RS\ sky}$ ~ +2000 km/s; meaning it moves outward wrt sky frame

Larger transverse proper motions have been reported across central and western regions for Cas A's nonthermal filaments.



a) Continuum band of 4.1–6.3 keV



b) a Si–K band of 1.7–2.1 keV

Vector length is proportional to the actual shifting value. Blue and red show outward and inward motions, respectively.

Inward transverse velocities: -2100 to -3800 km/s (!)

Sato+ 2018

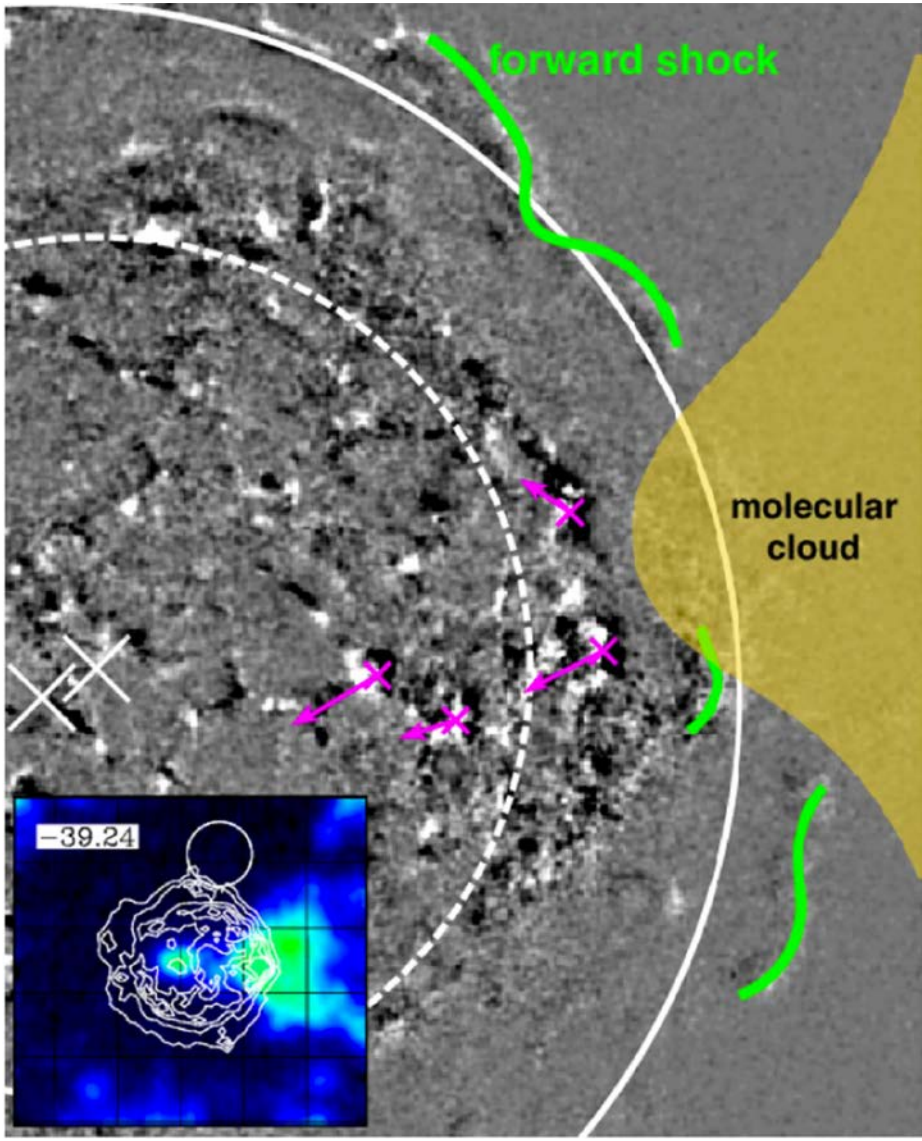
Consequently, they claim:

$V_{RS\ ejecta}$ = 5100 – 8700 km/s

which is nearly 3000 km/s faster than the ISM/CSM sees the forward shock.

Sato et al. discount possible inward motions as reverse shocks (in the observer's reference frame) for an evolutional phase that describes a 350 yr old Cassiopeia A…because the reverse shock should be expanding outward.

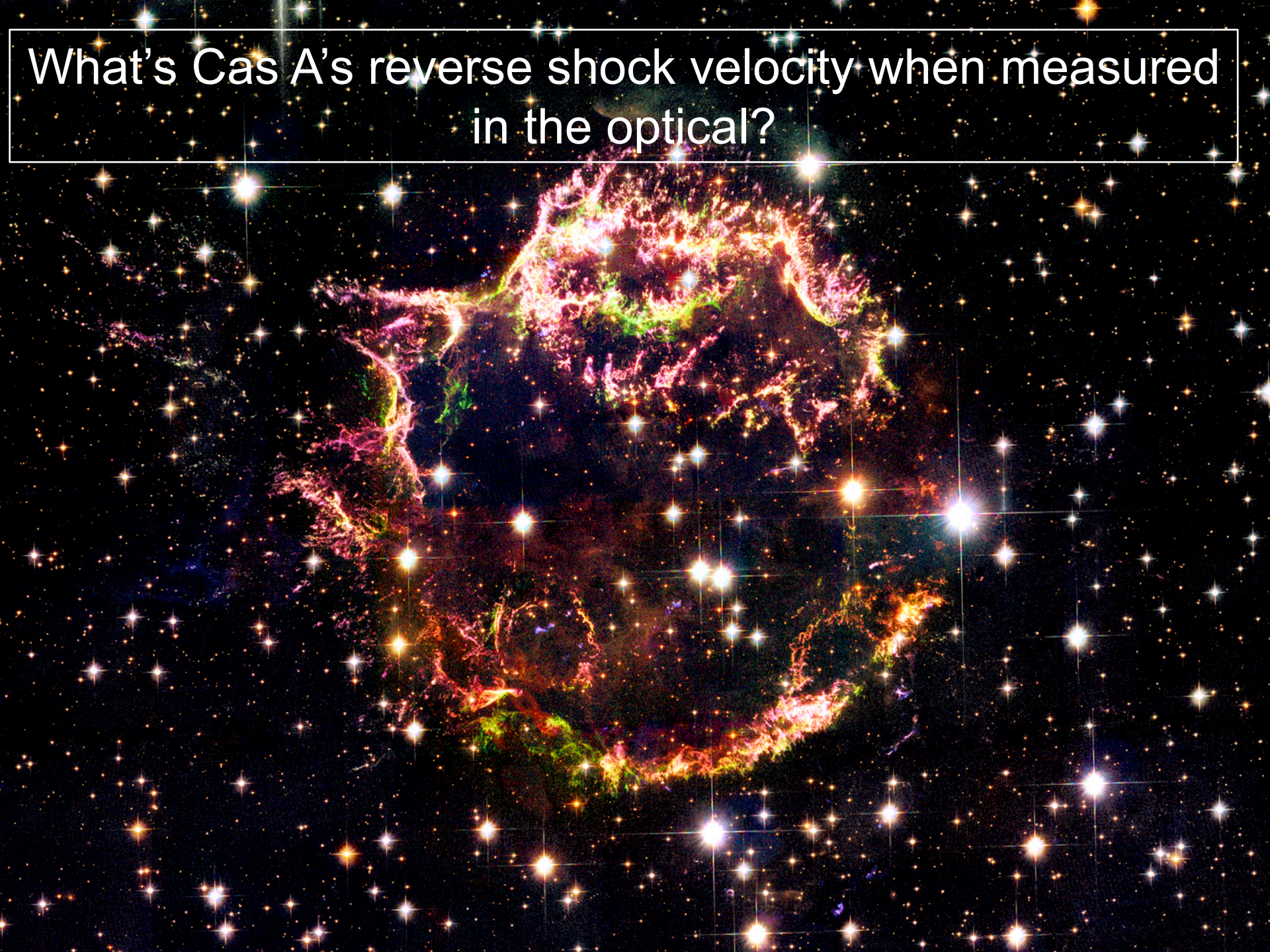
Instead, they proposed the inward shock was a "reflection shock" produced by the forward shock interacting with a density jump in the ambient medium.



Kilpatrick+ 2014

But see poster Zhou+ S10.21

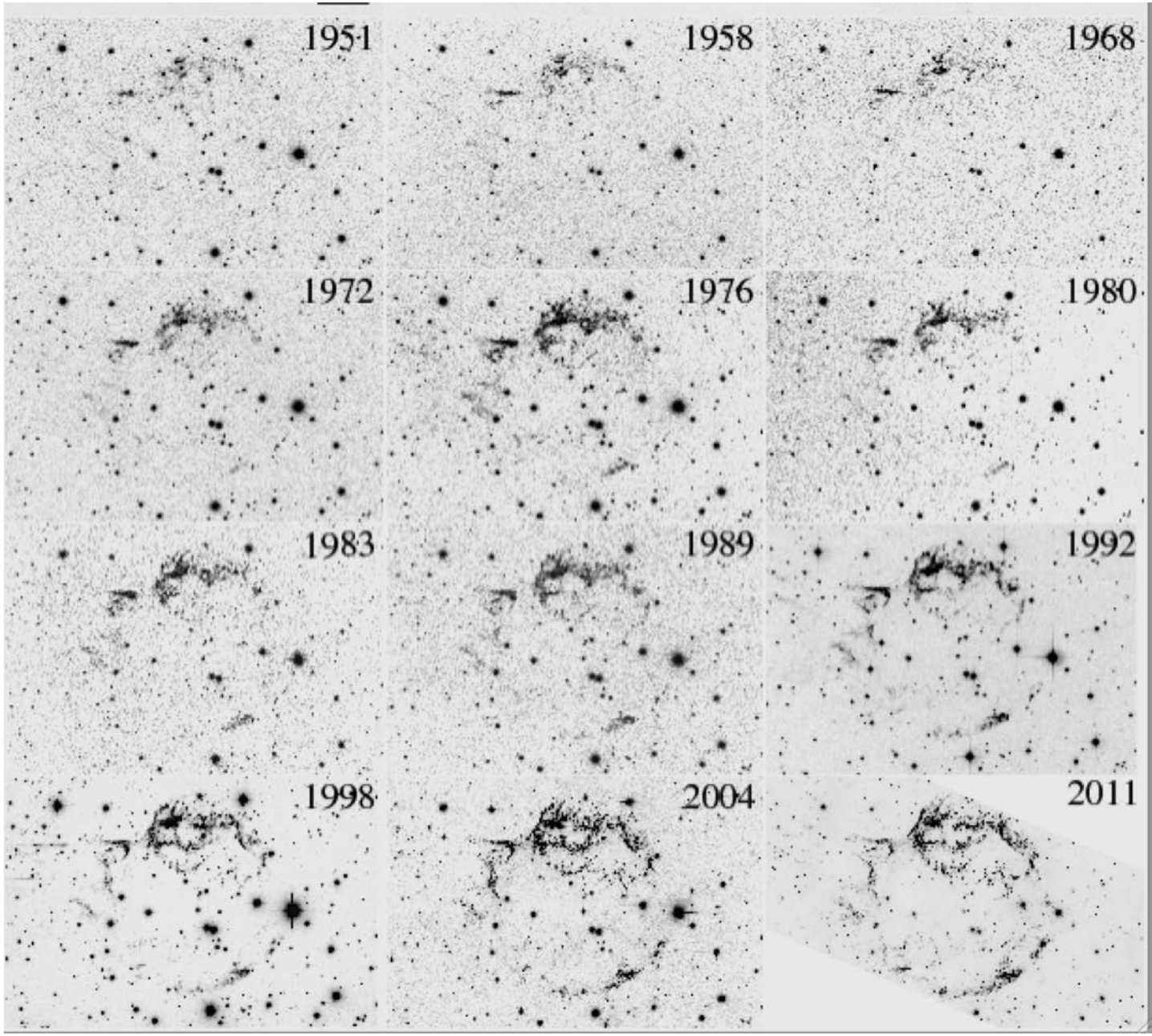
What's Cas A's reverse shock velocity when measured in the optical?



Well…
its not so simple

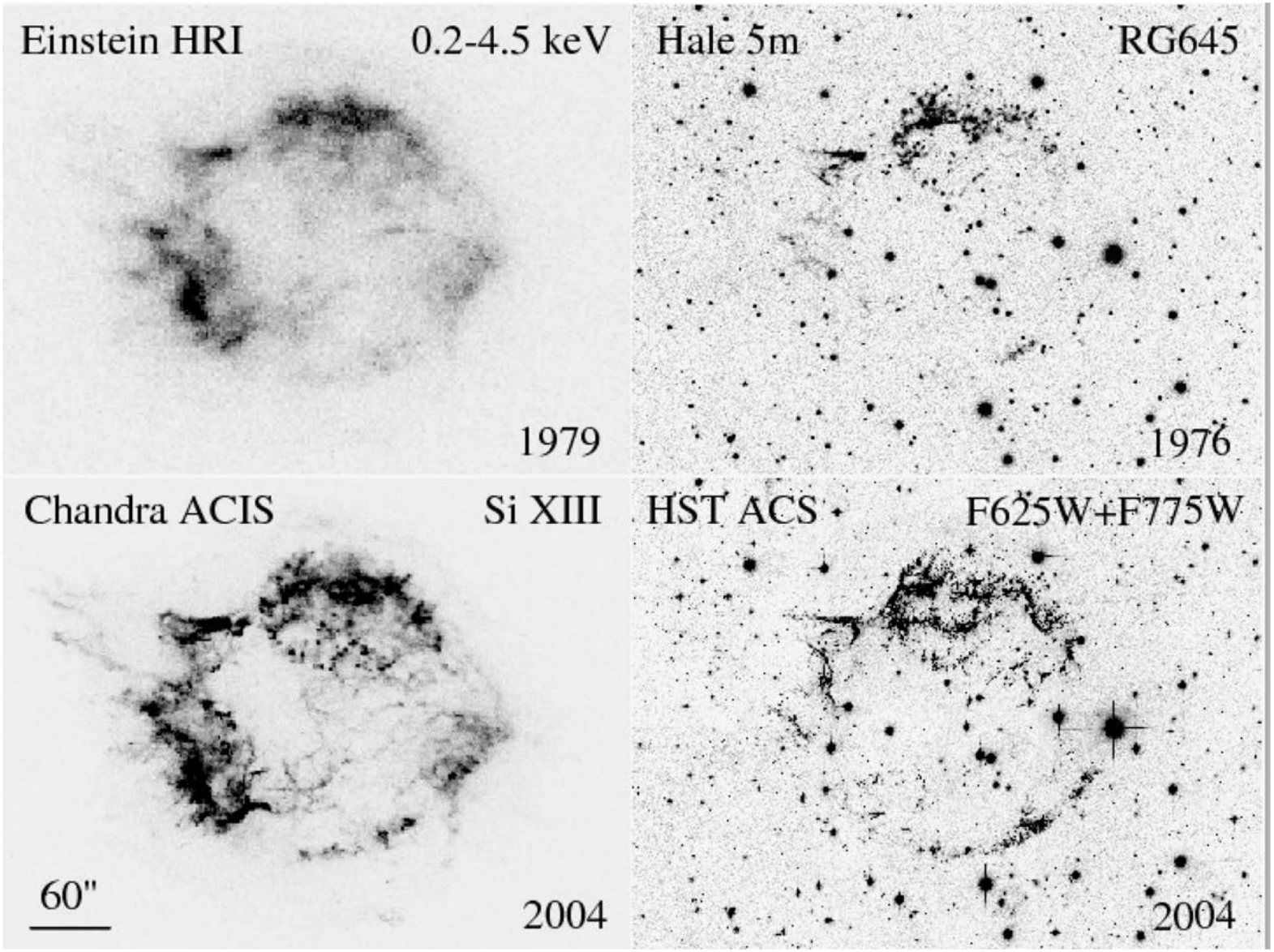
There has been significant changes in Cas A's optical appearance over the last 60 yrs.

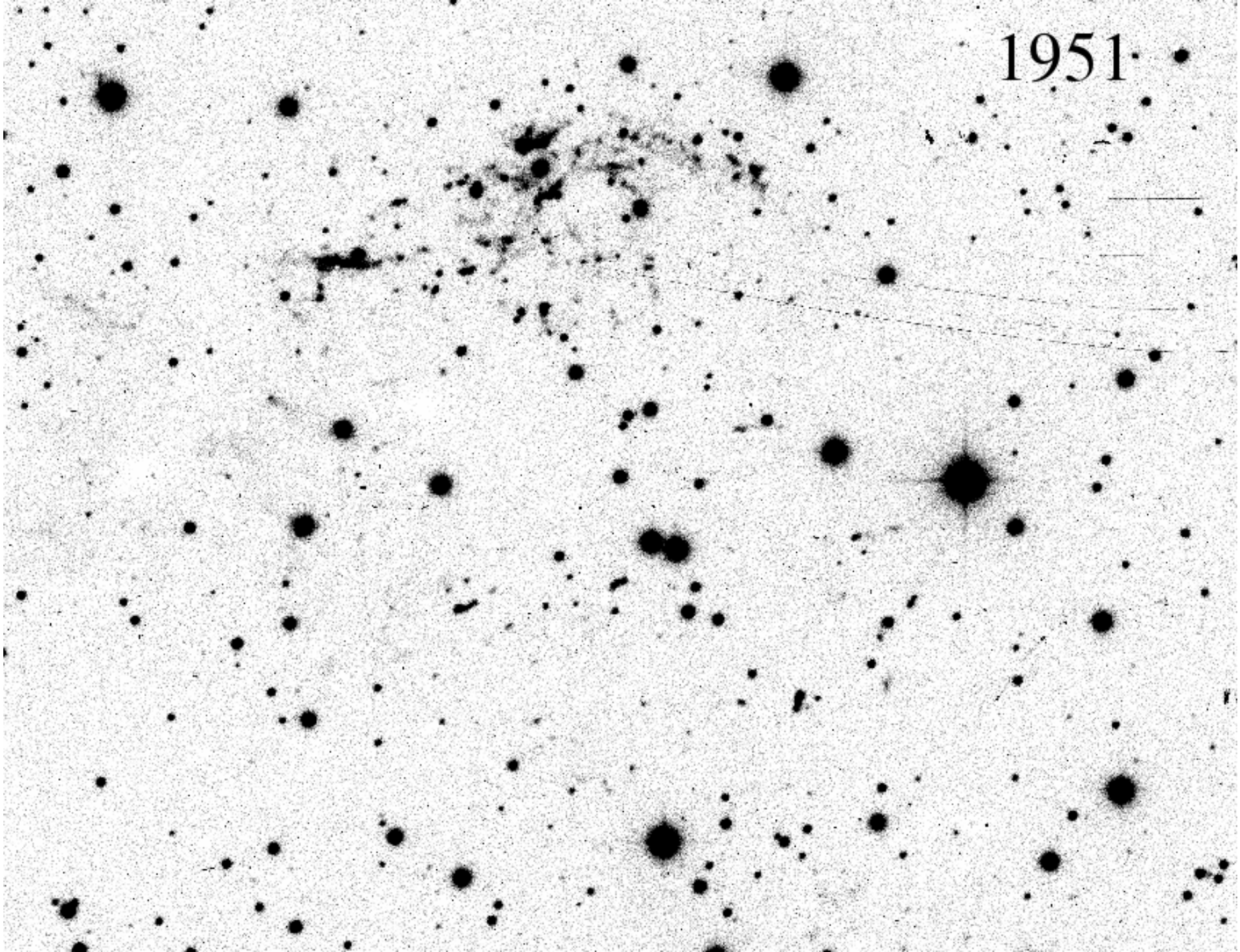
Due to the advancement of the reverse shock into the expanding ejecta cloud.

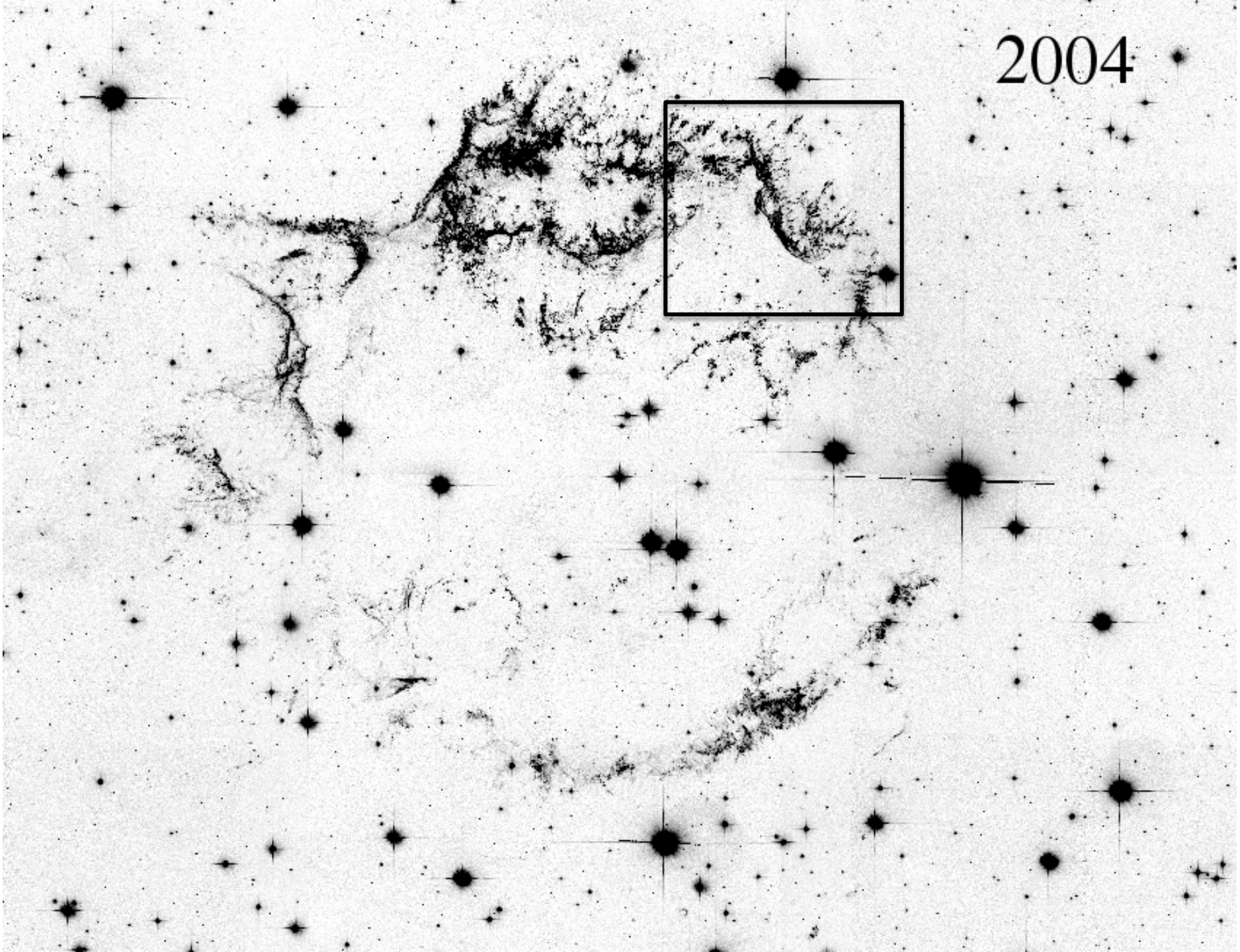


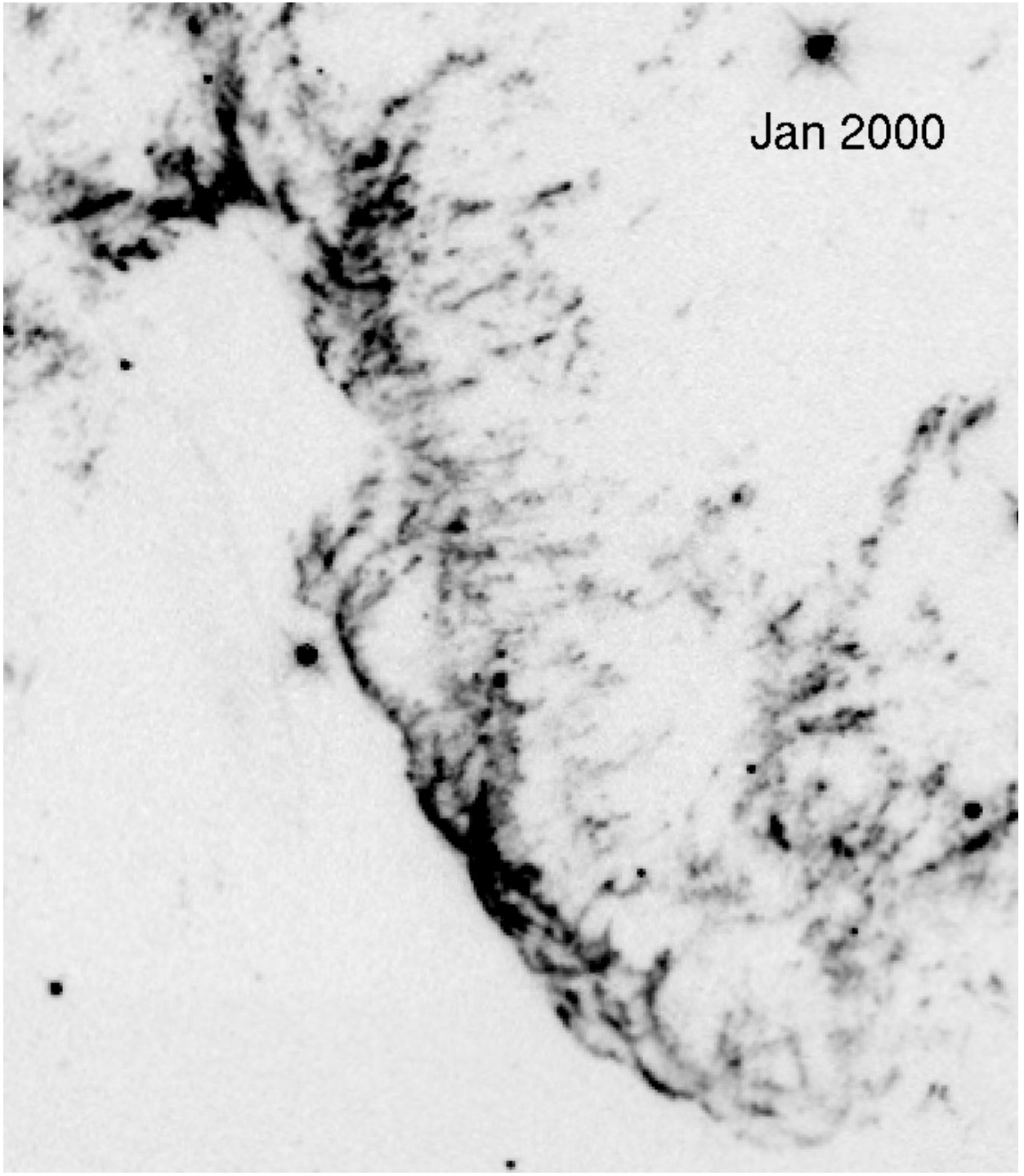
Patnaude & Fesen 2012

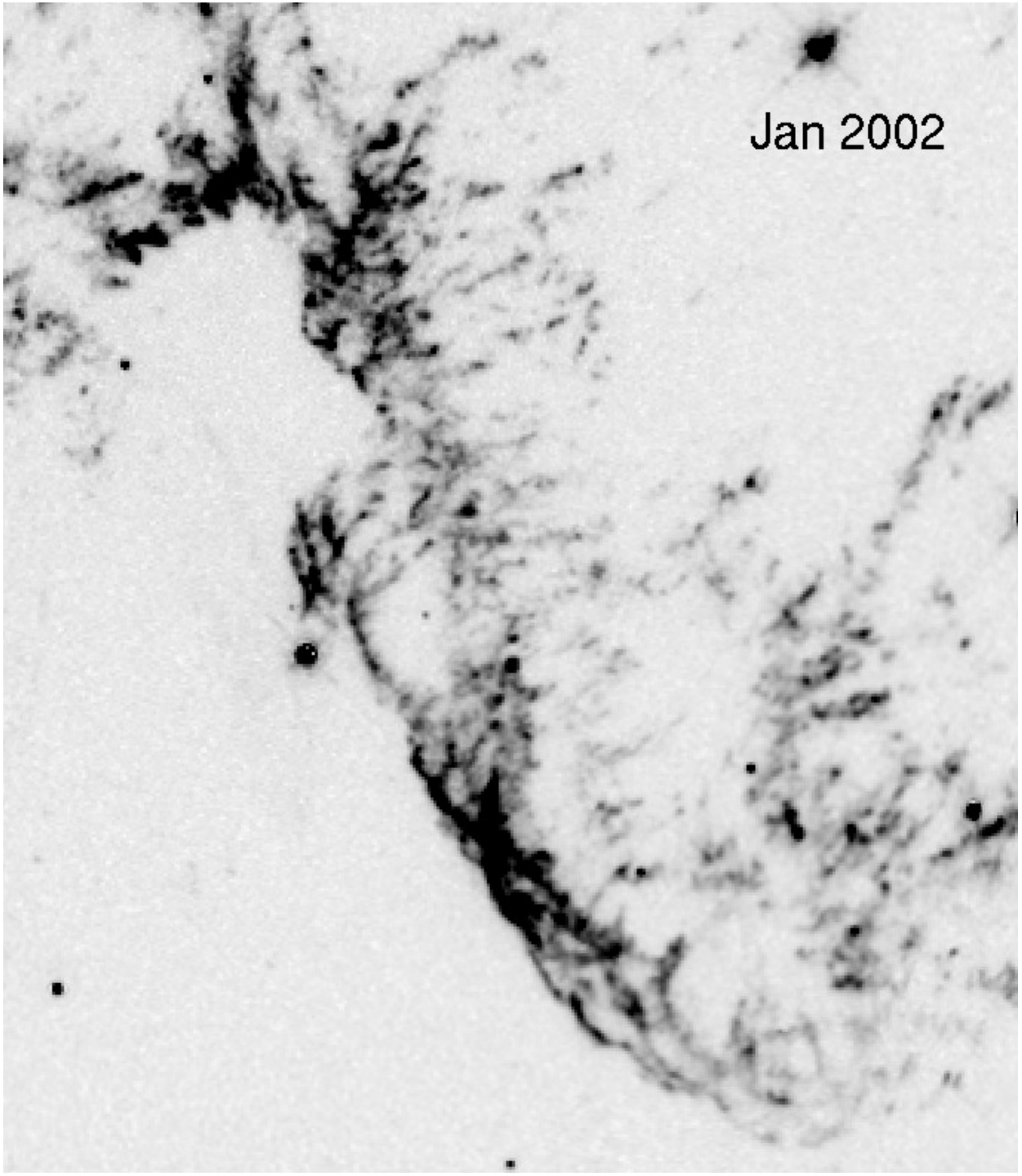
Changes in Cas A with time

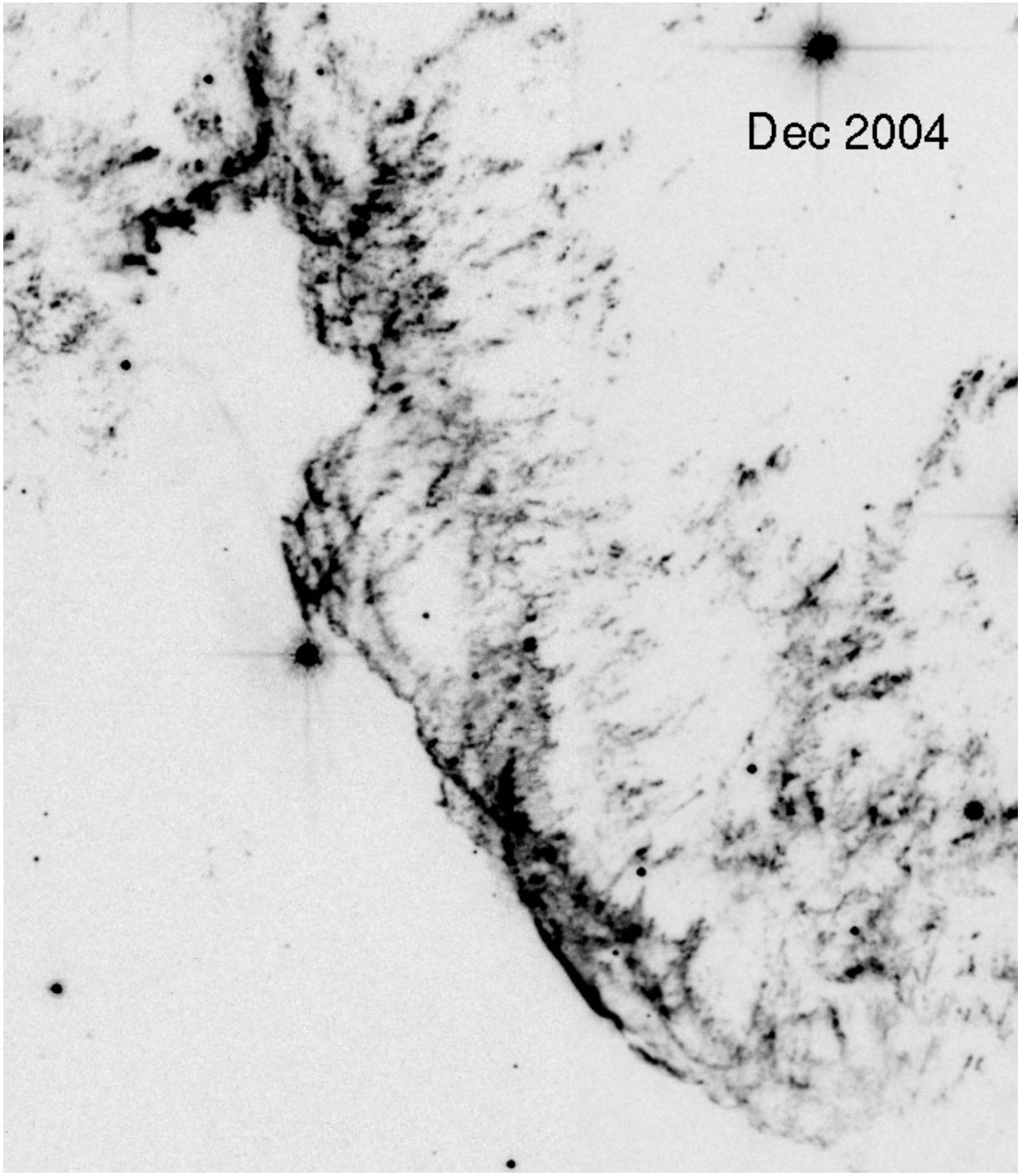


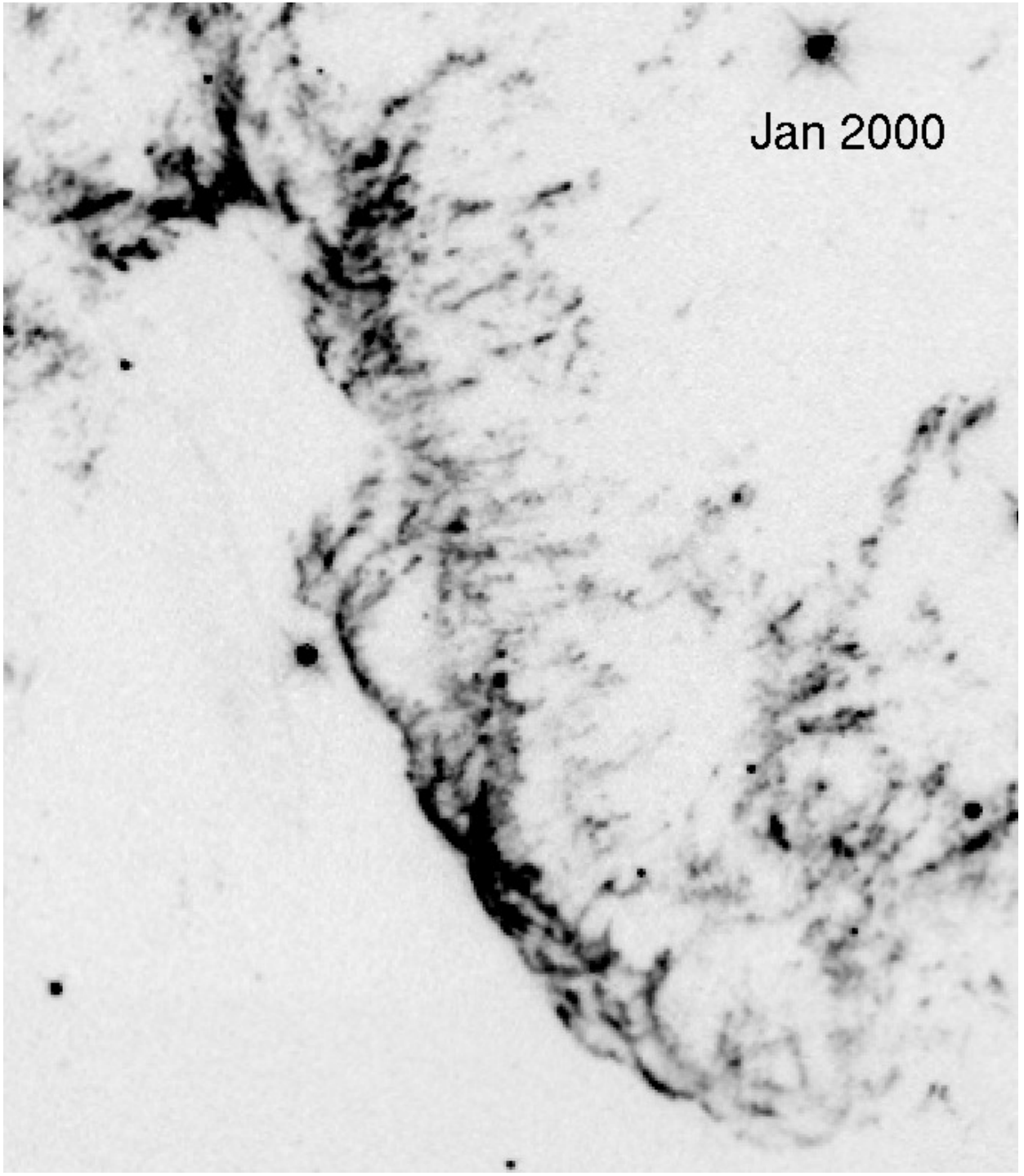

1951

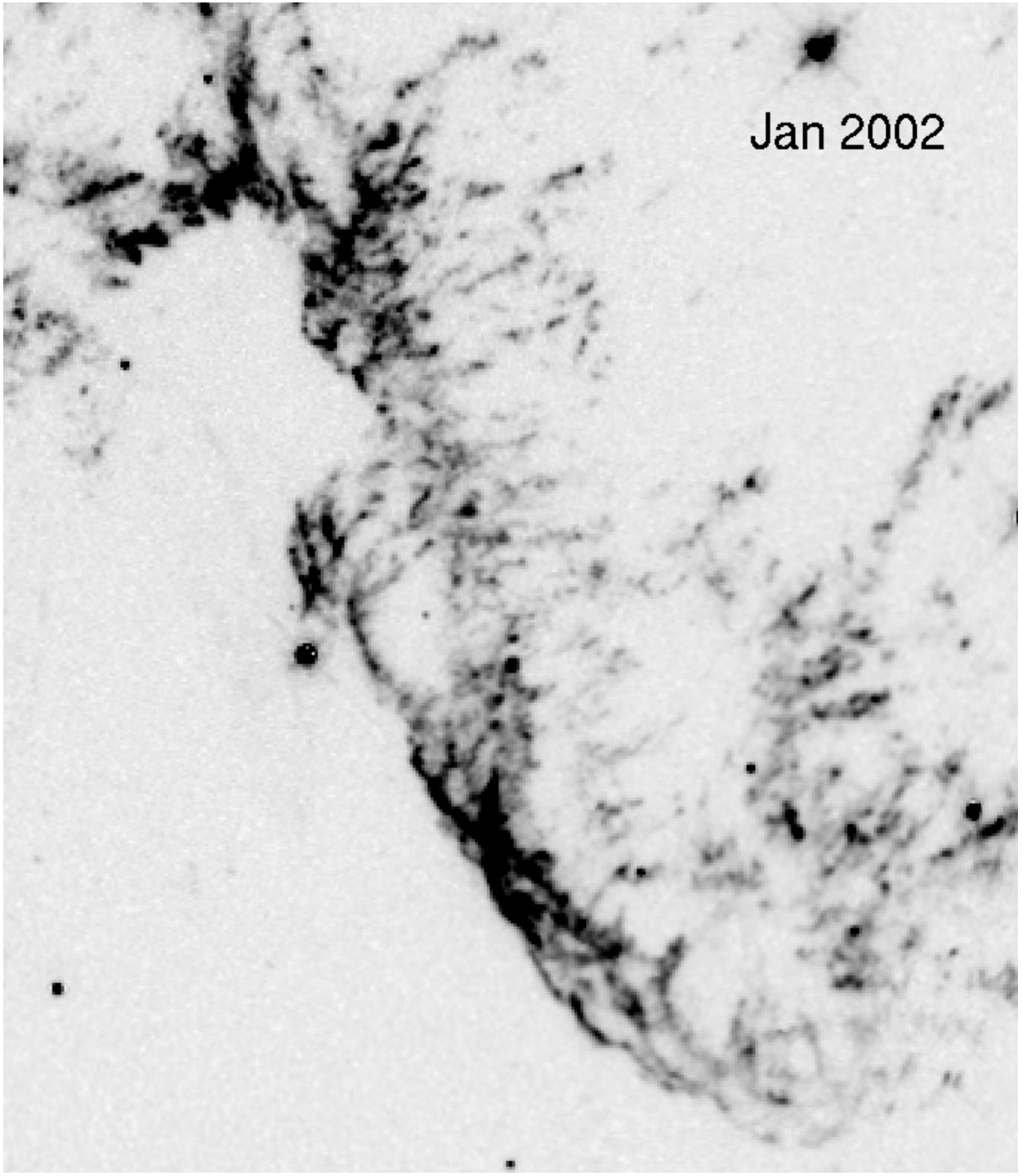

2004

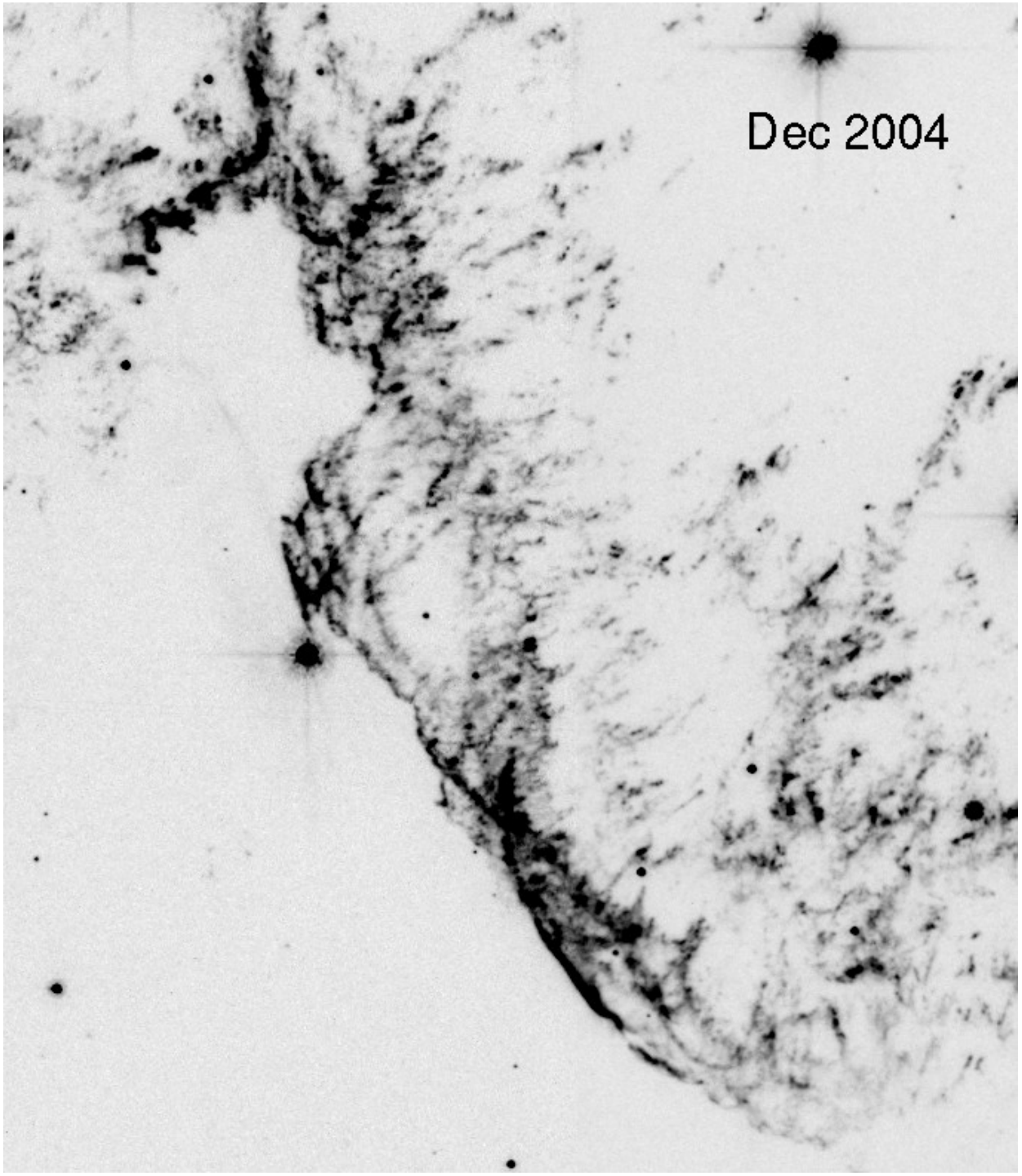

Jan 2000

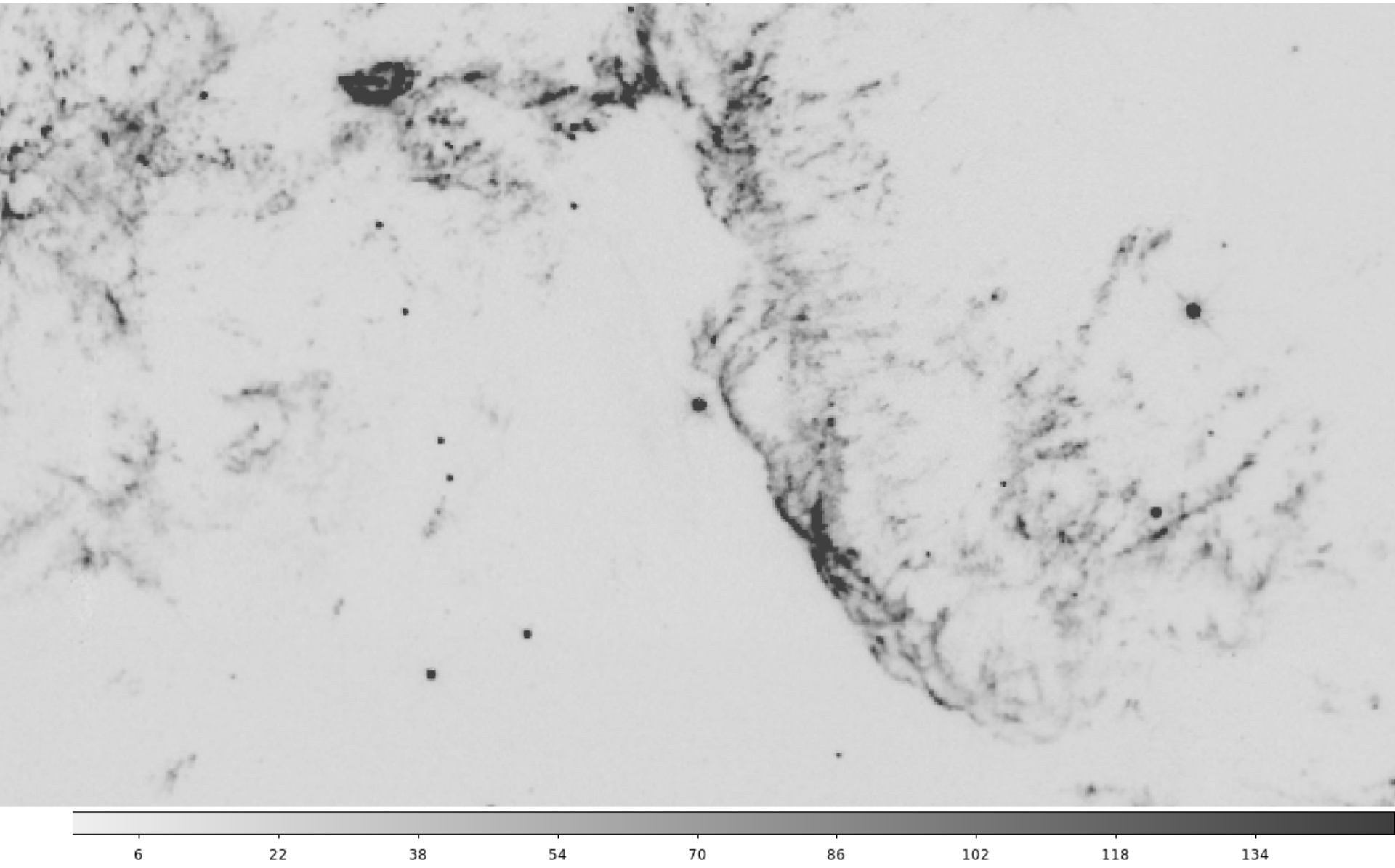

Jan 2002

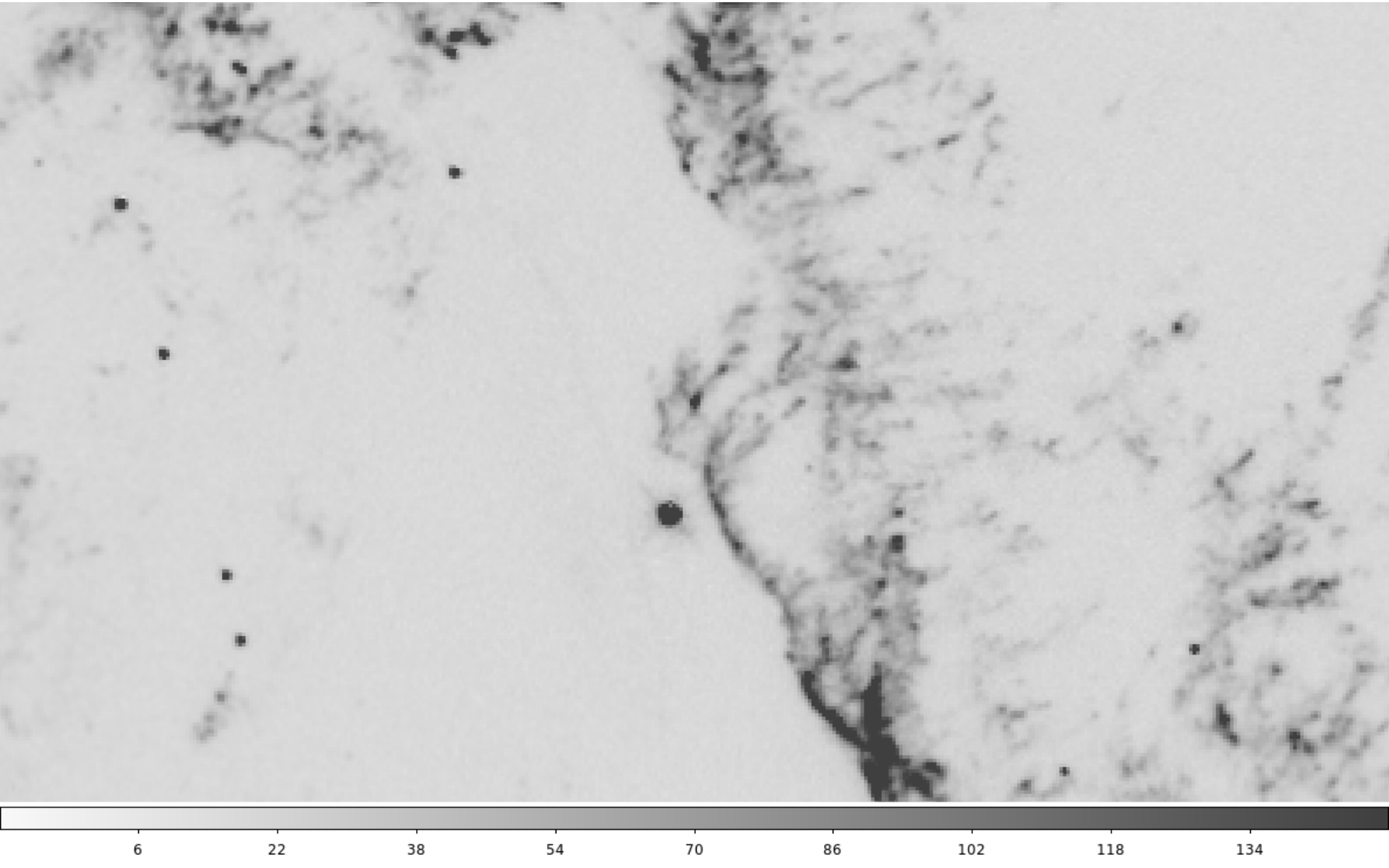

Dec 2004


Jan 2000


Jan 2002


Dec 2004


6
22
38
54
70
86
102
118
134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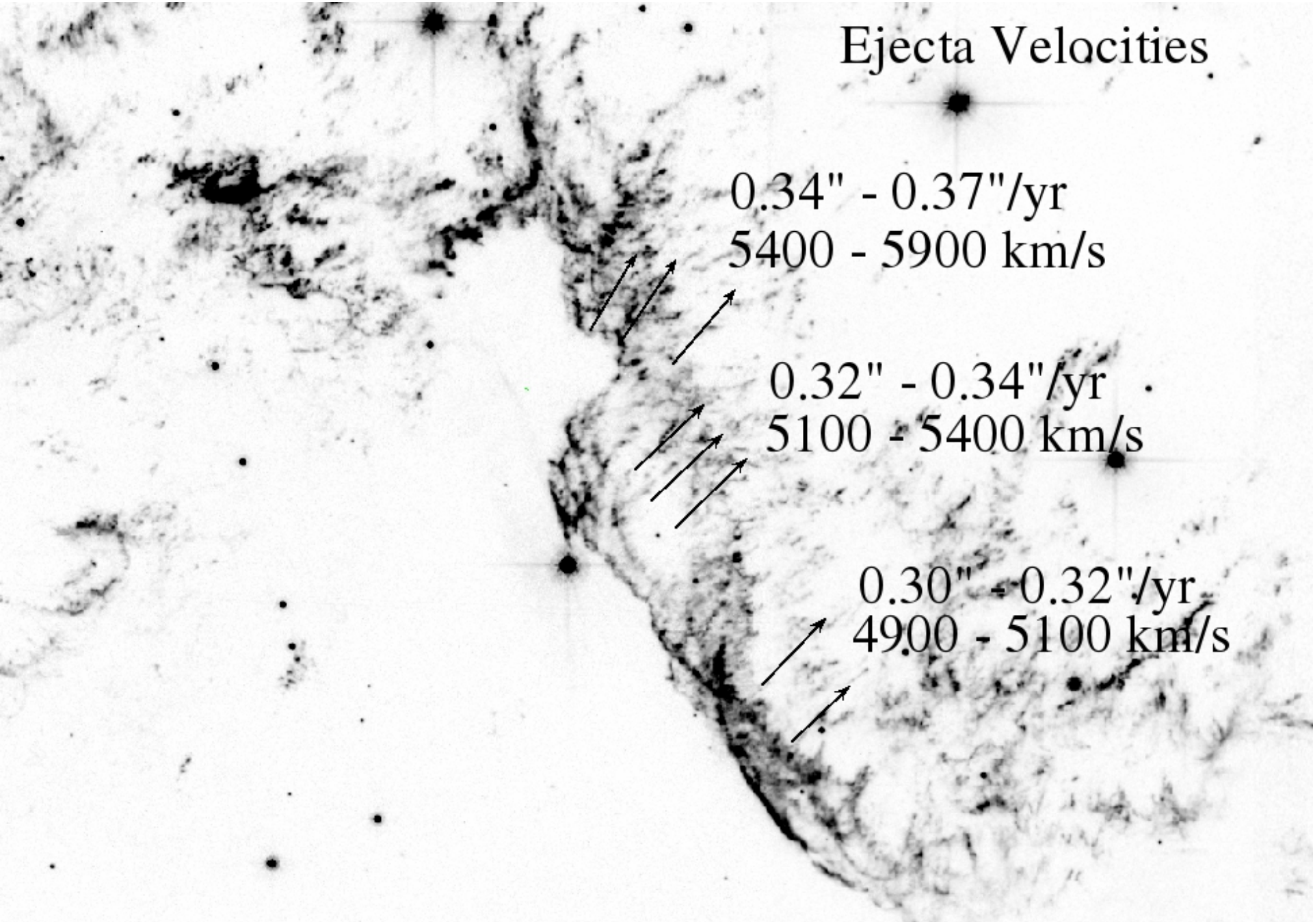
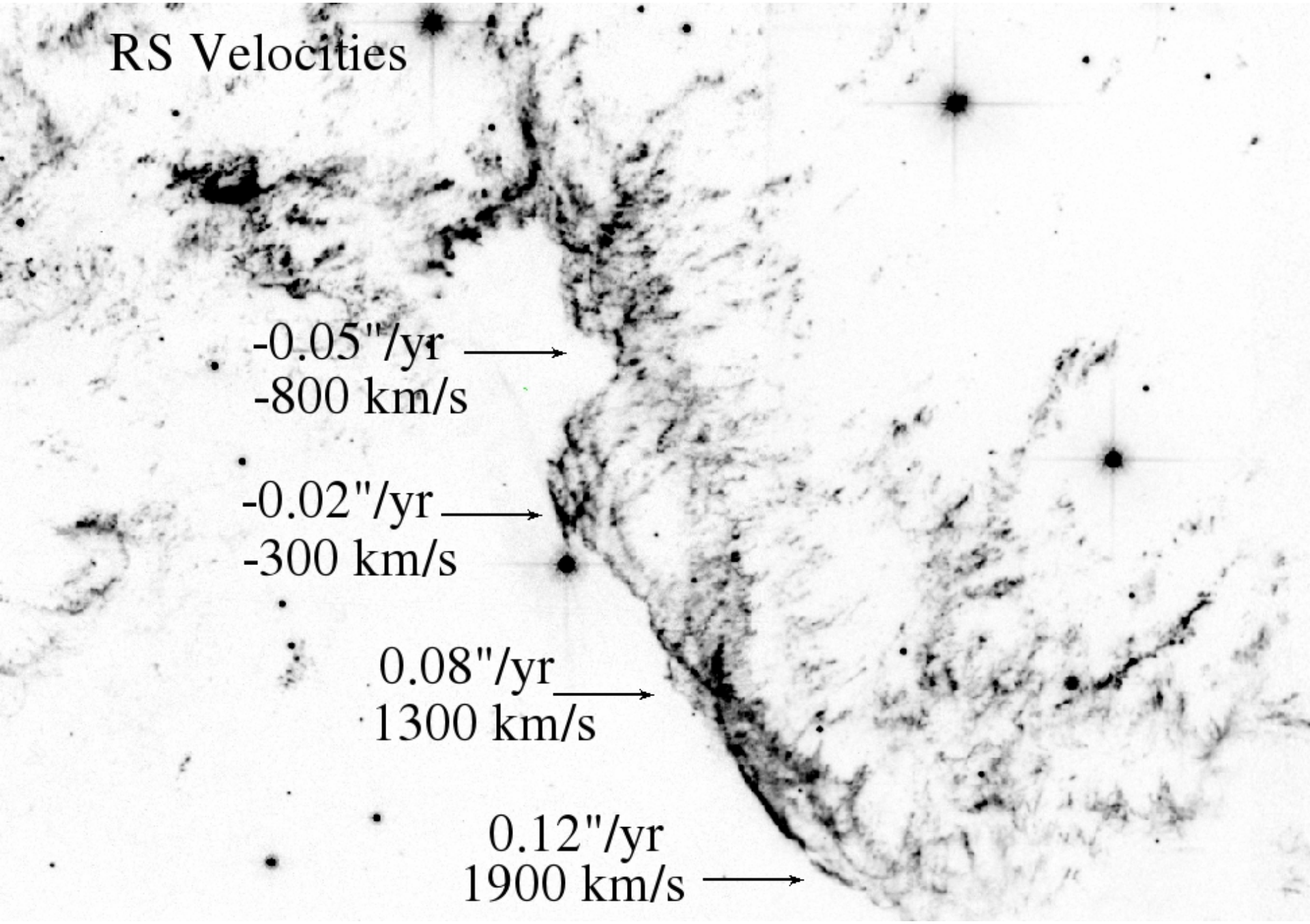
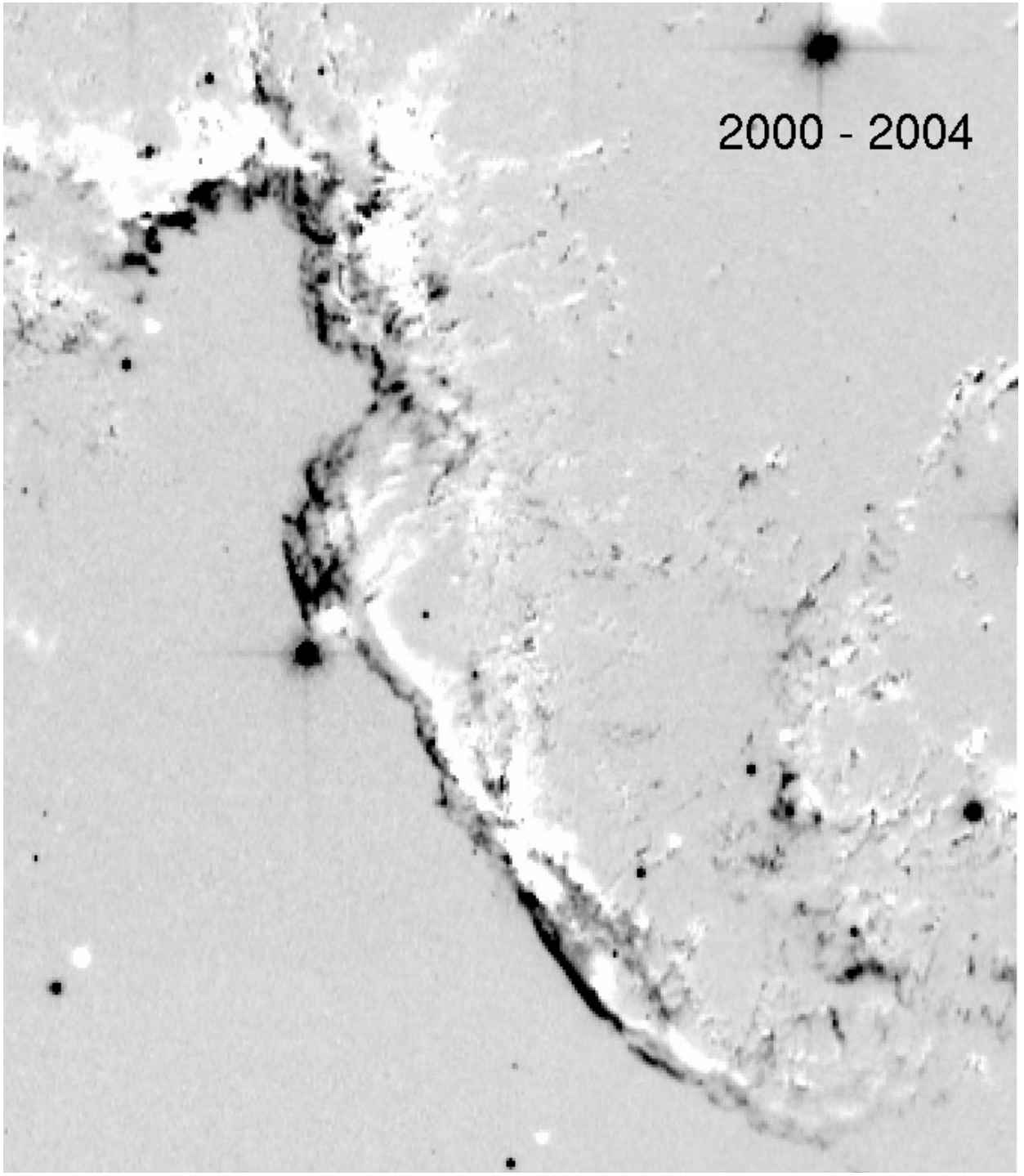
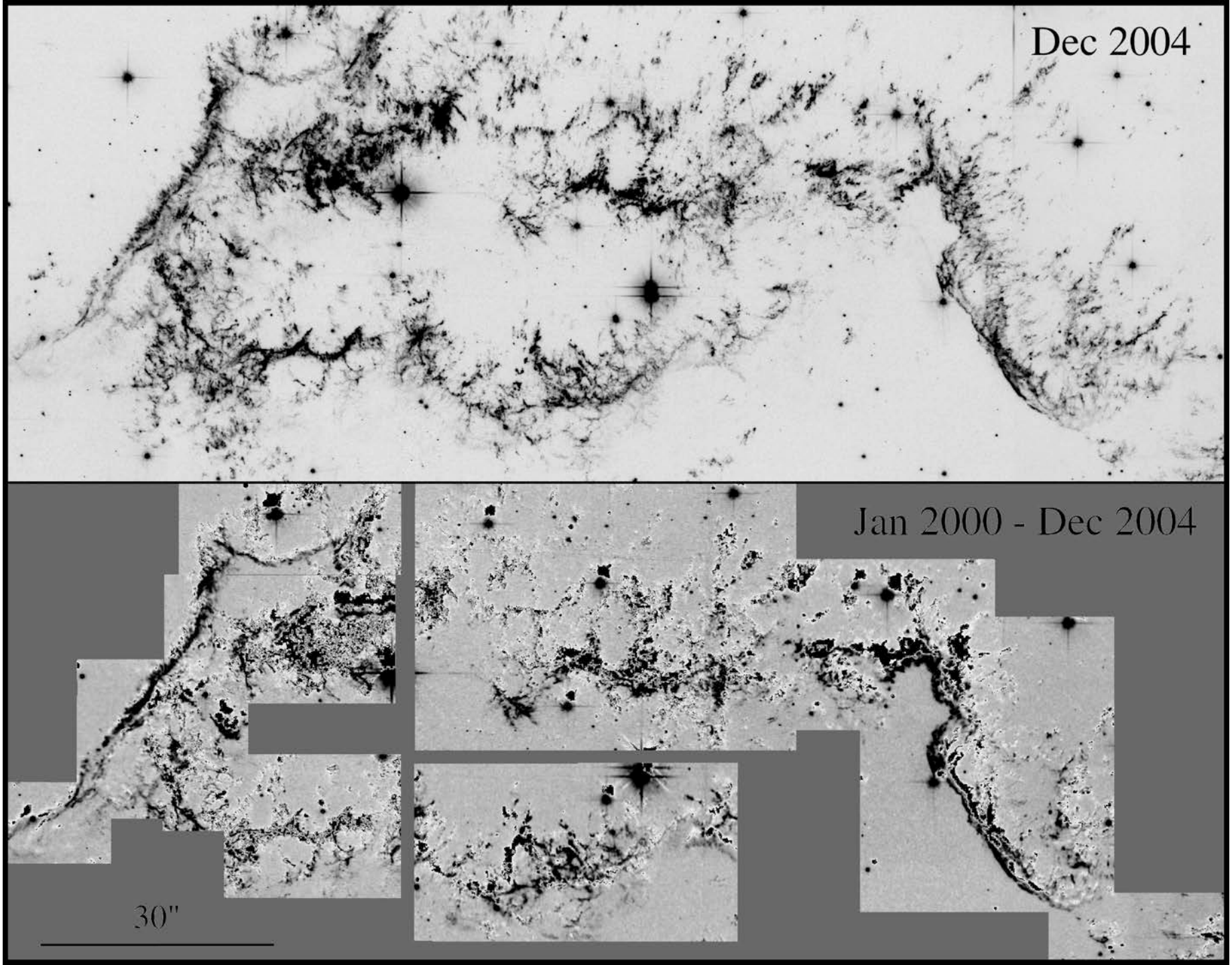
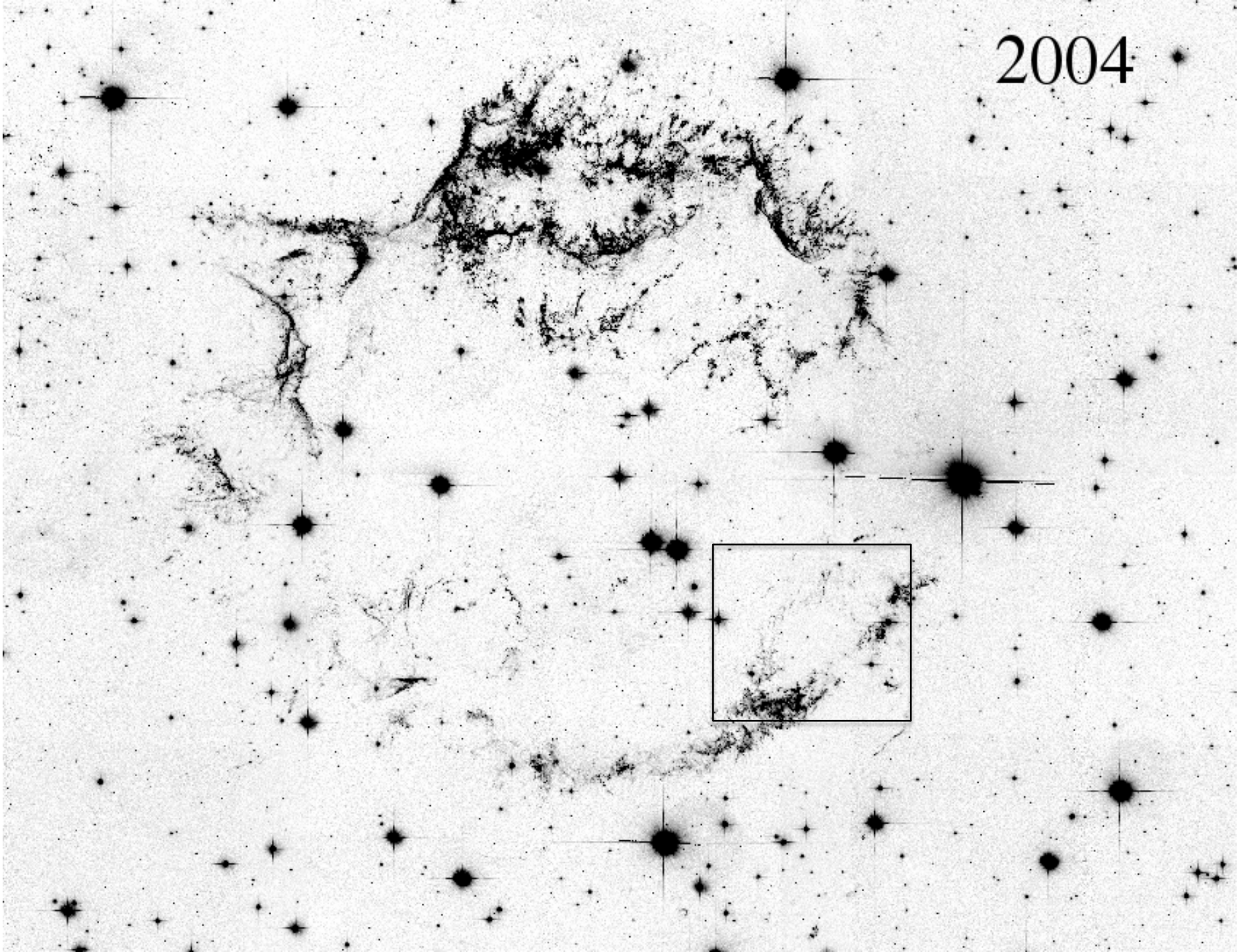
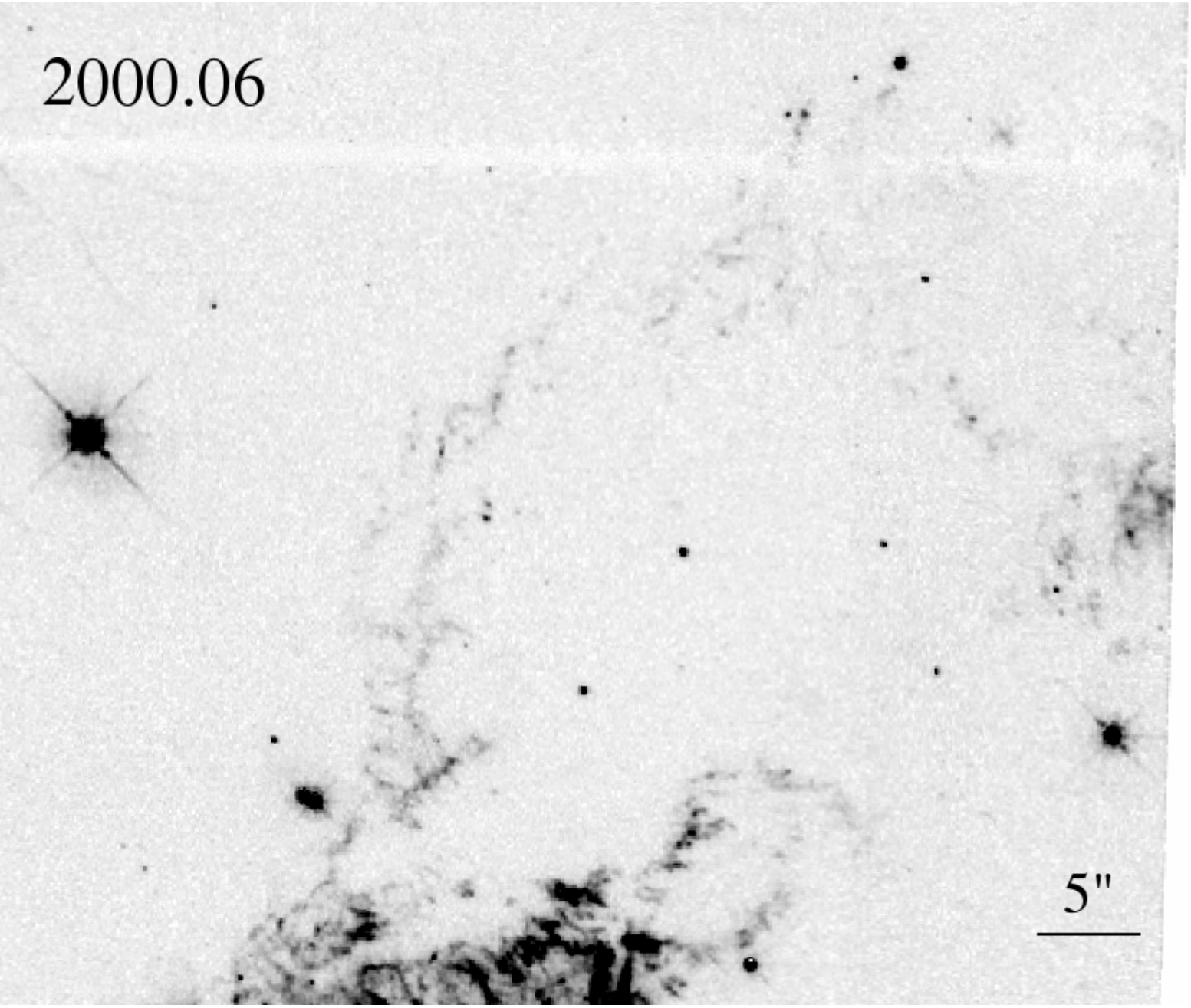

Ejecta Velocities
0.34" - 0.37"/yr
5400 - 5900 km/s
0.32" - 0.34"/yr
5100 - 5400 km/s
0.30" - 0.32"/yr
4900 - 5100 km/s

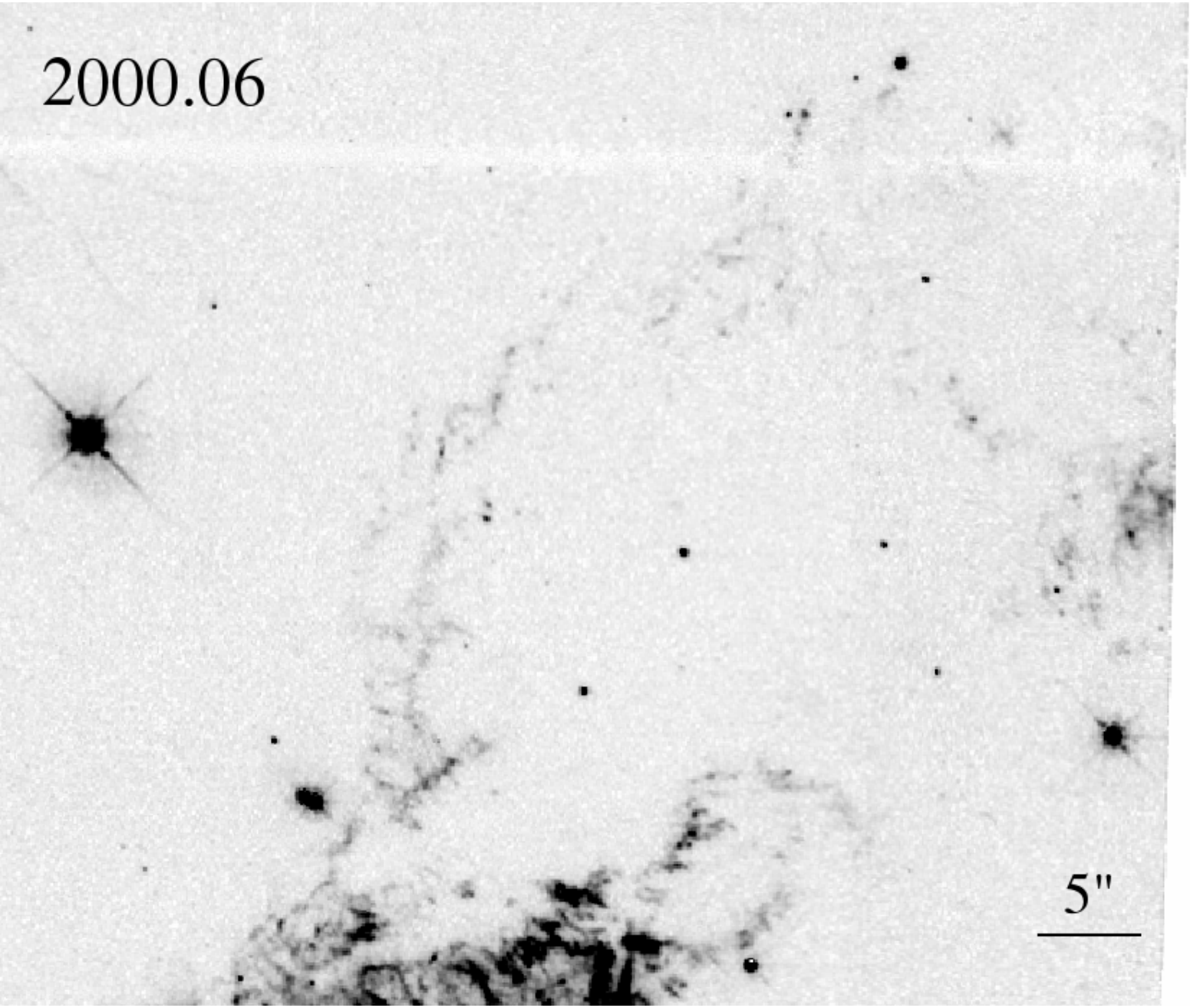

RS Velocities
-0.05"/yr
-800 km/s
-0.02"/yr
-300 km/s
0.08"/yr
1300 km/s
0.12"/yr
1900 km/s

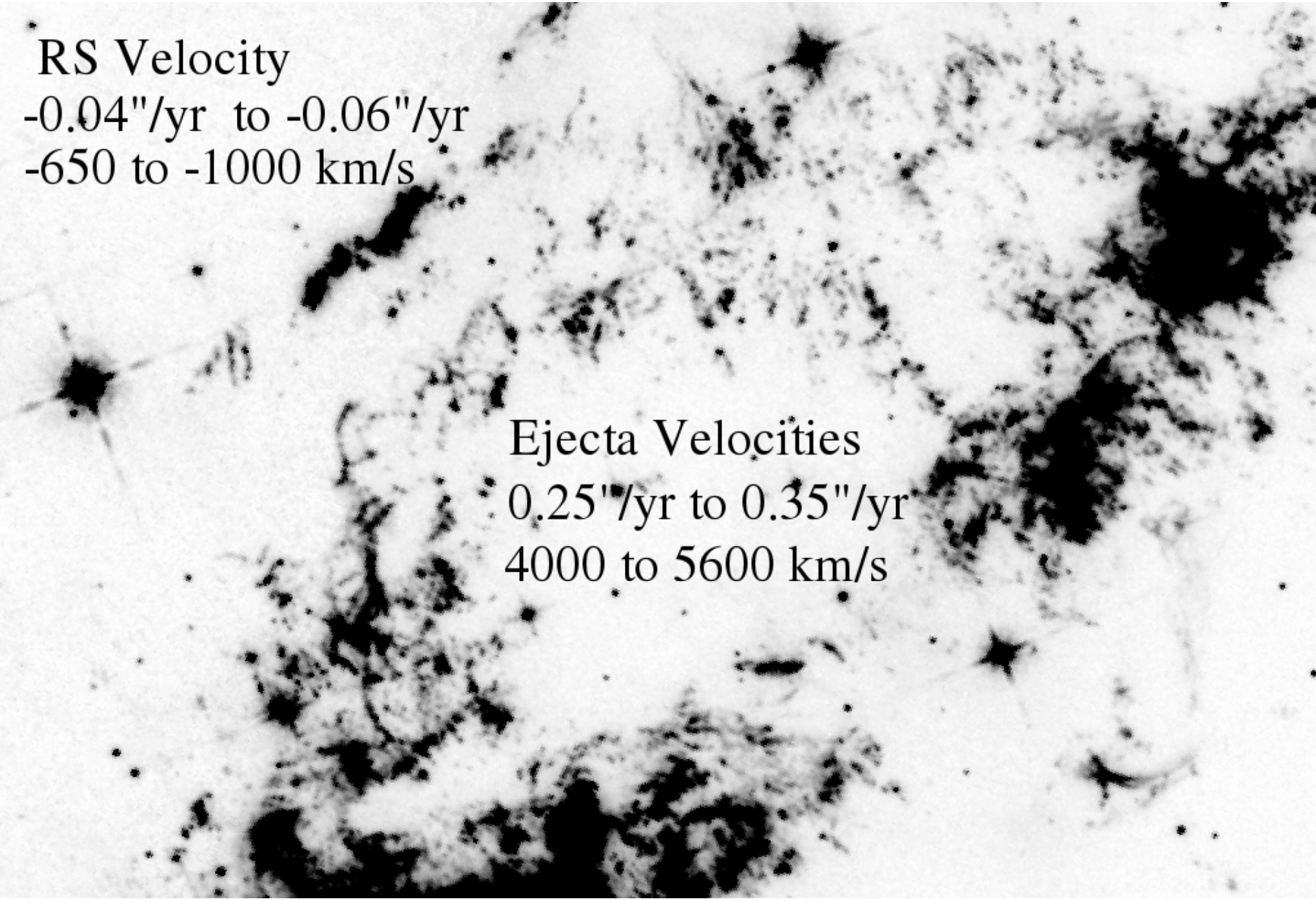

2000 - 2004

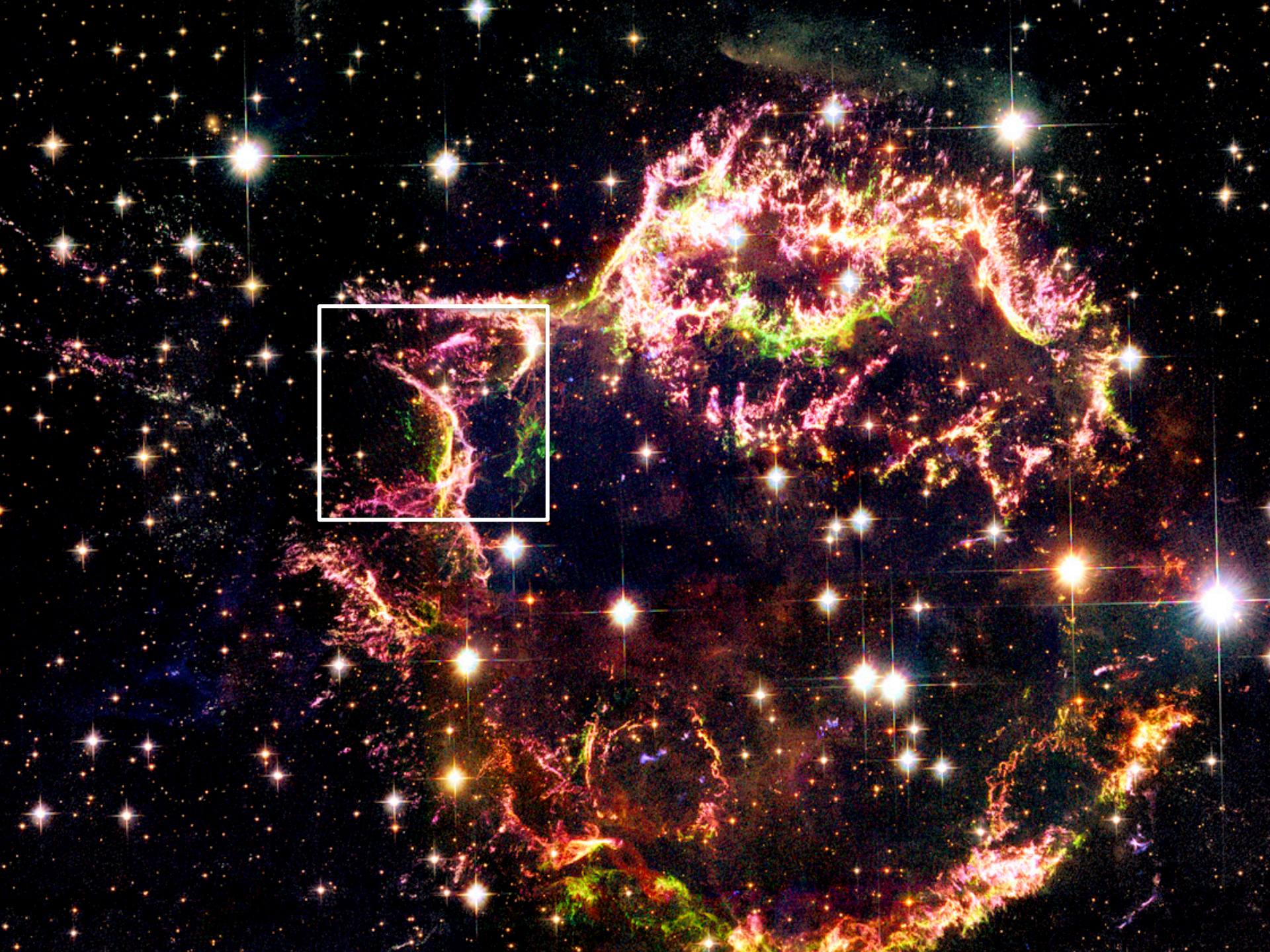

Dec 2004
Jan 2000 - Dec 2004
30"

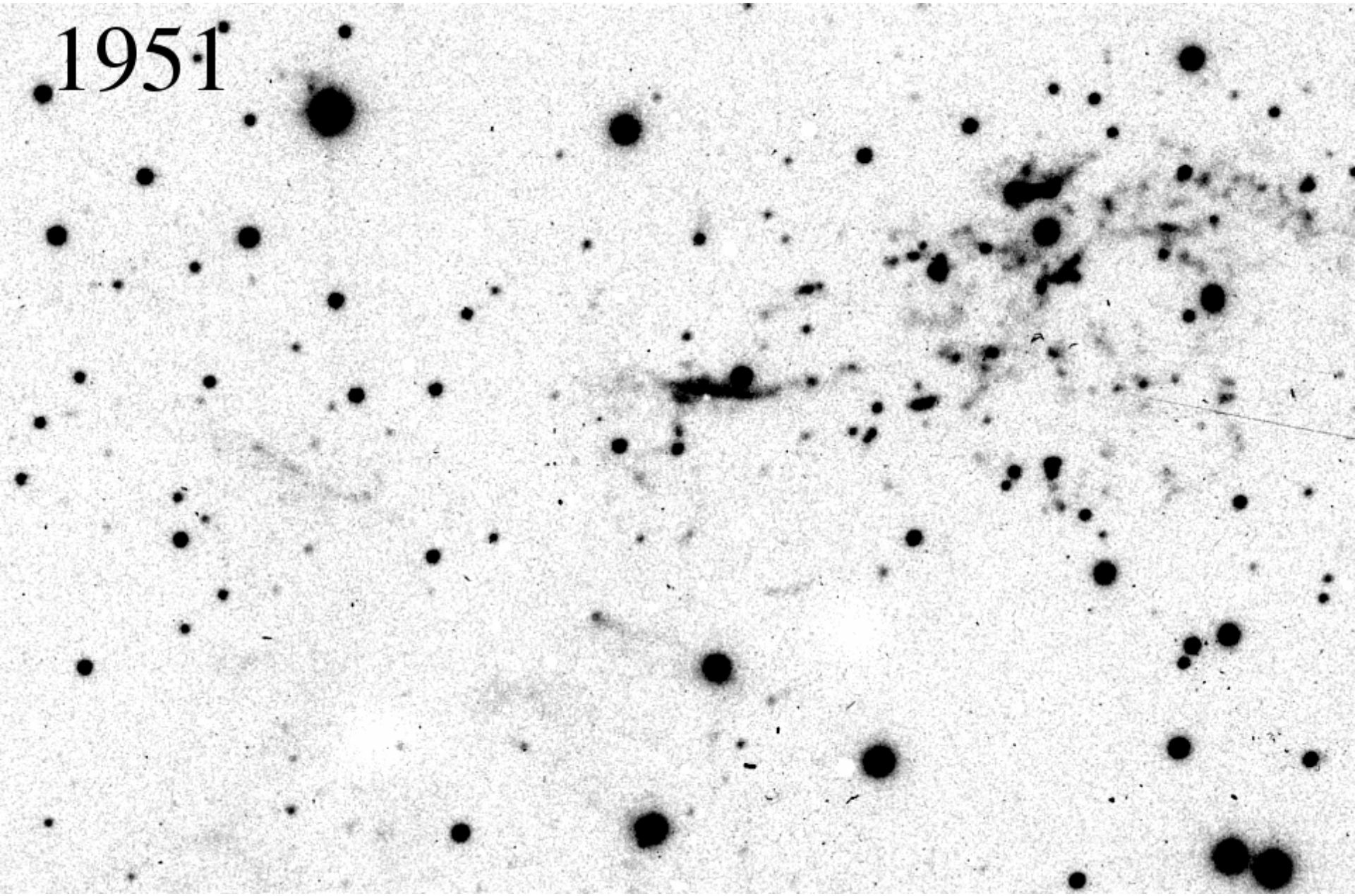

2004

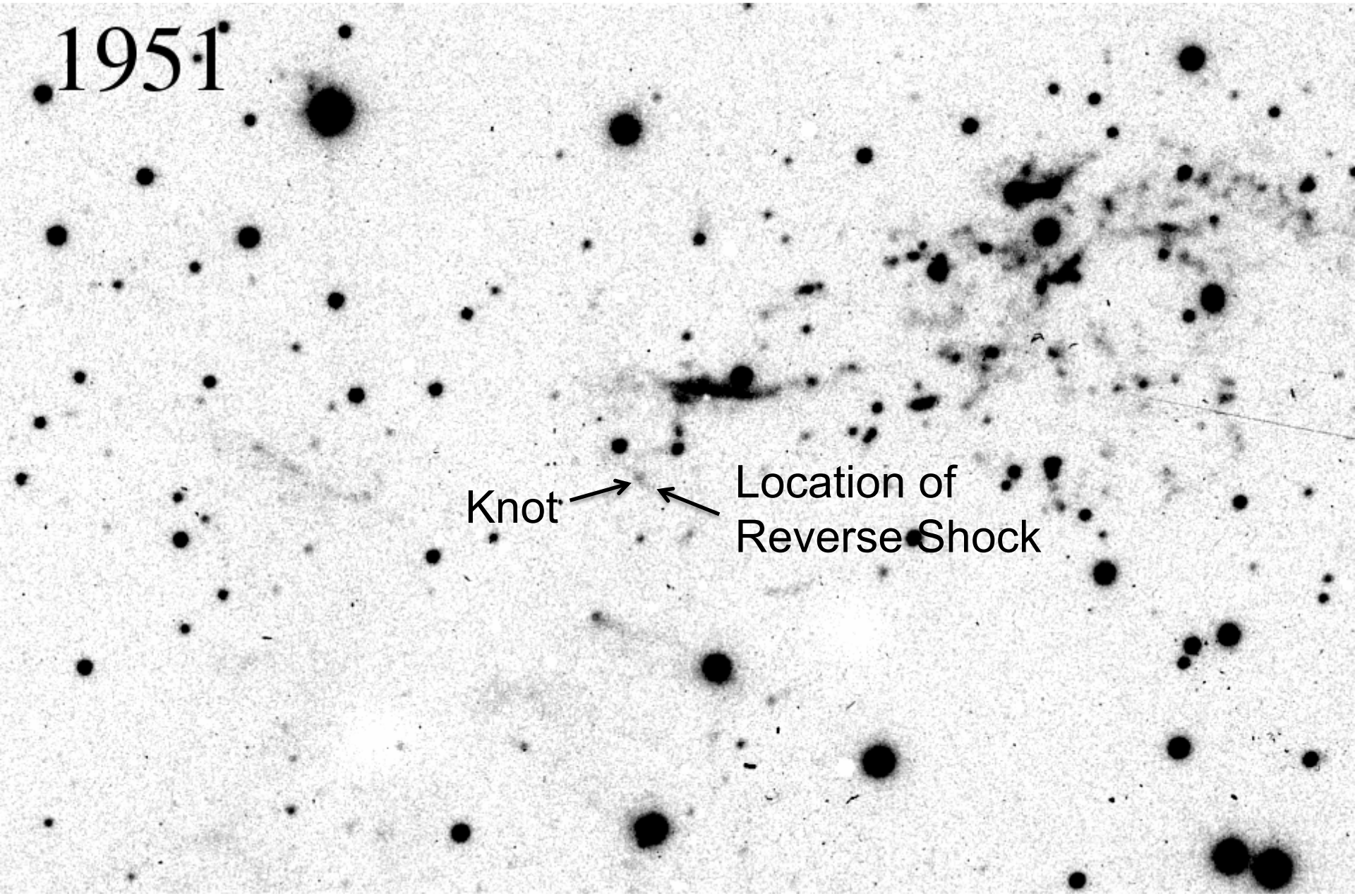

2000.06
5"

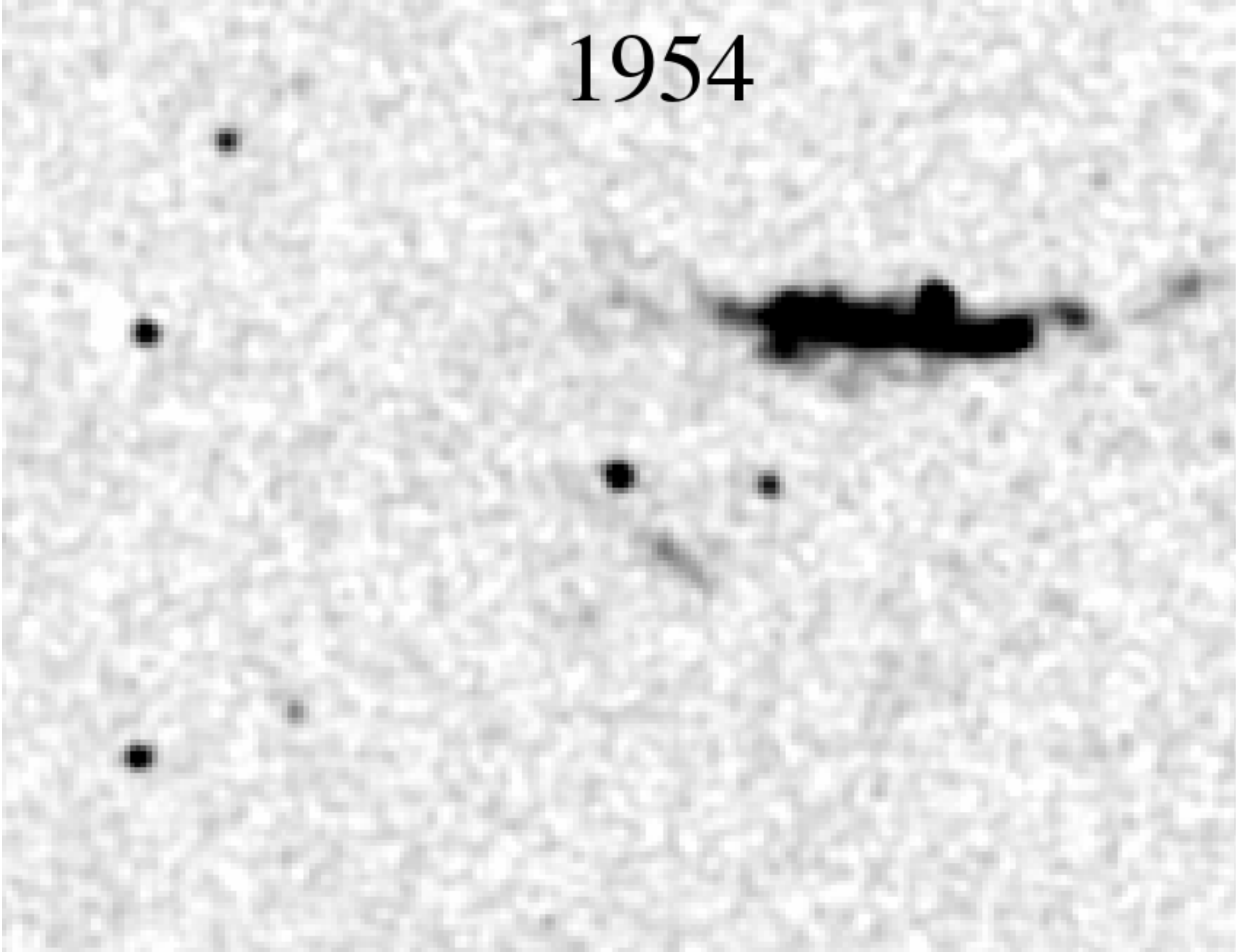

2000.06
5"

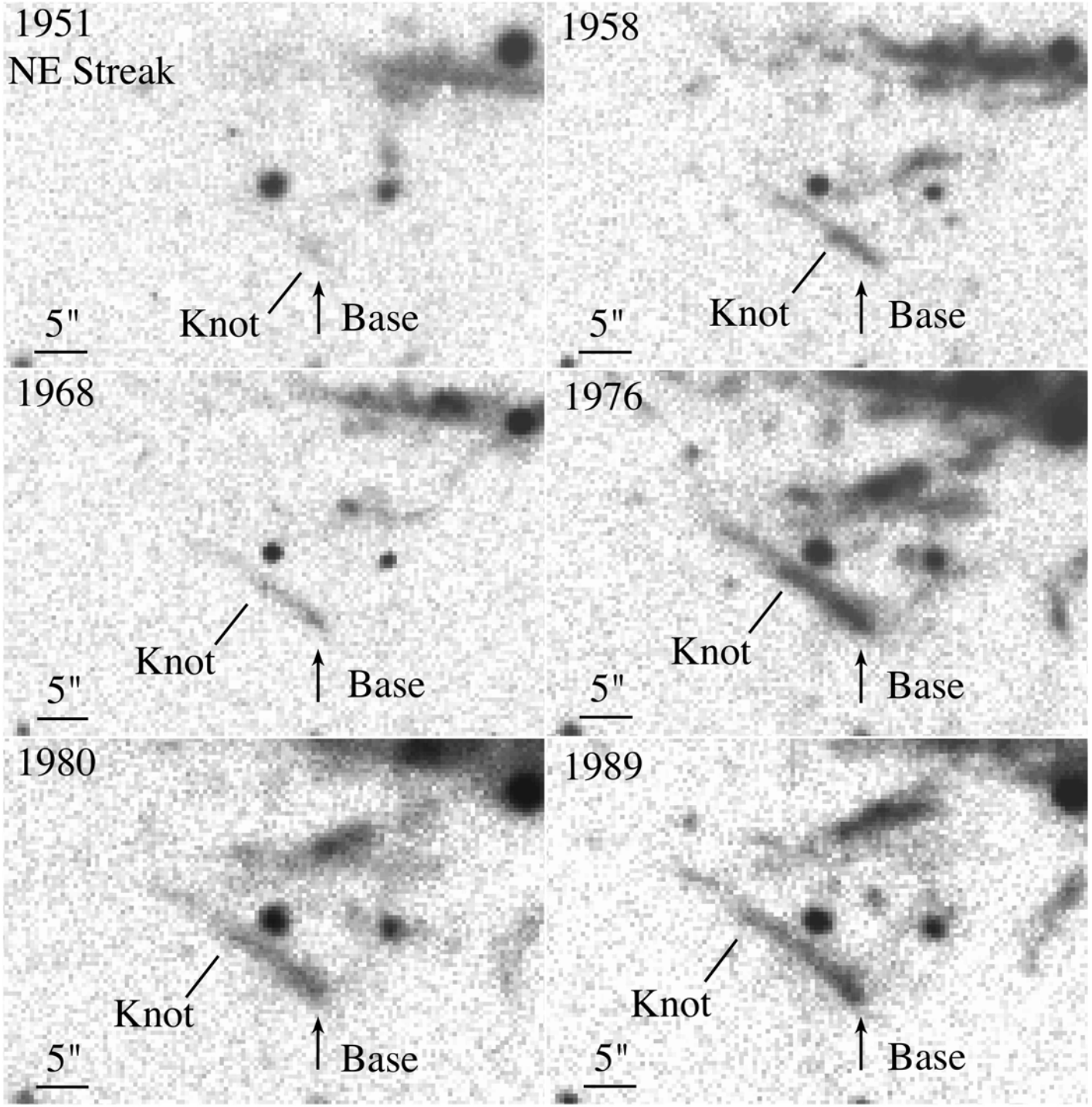

RS Velocity
-0.04"/yr to -0.06"/yr
-650 to -1000 km/s
Ejecta Velocities
0.25"/yr to 0.35"/yr
4000 to 5600 km/s




1951

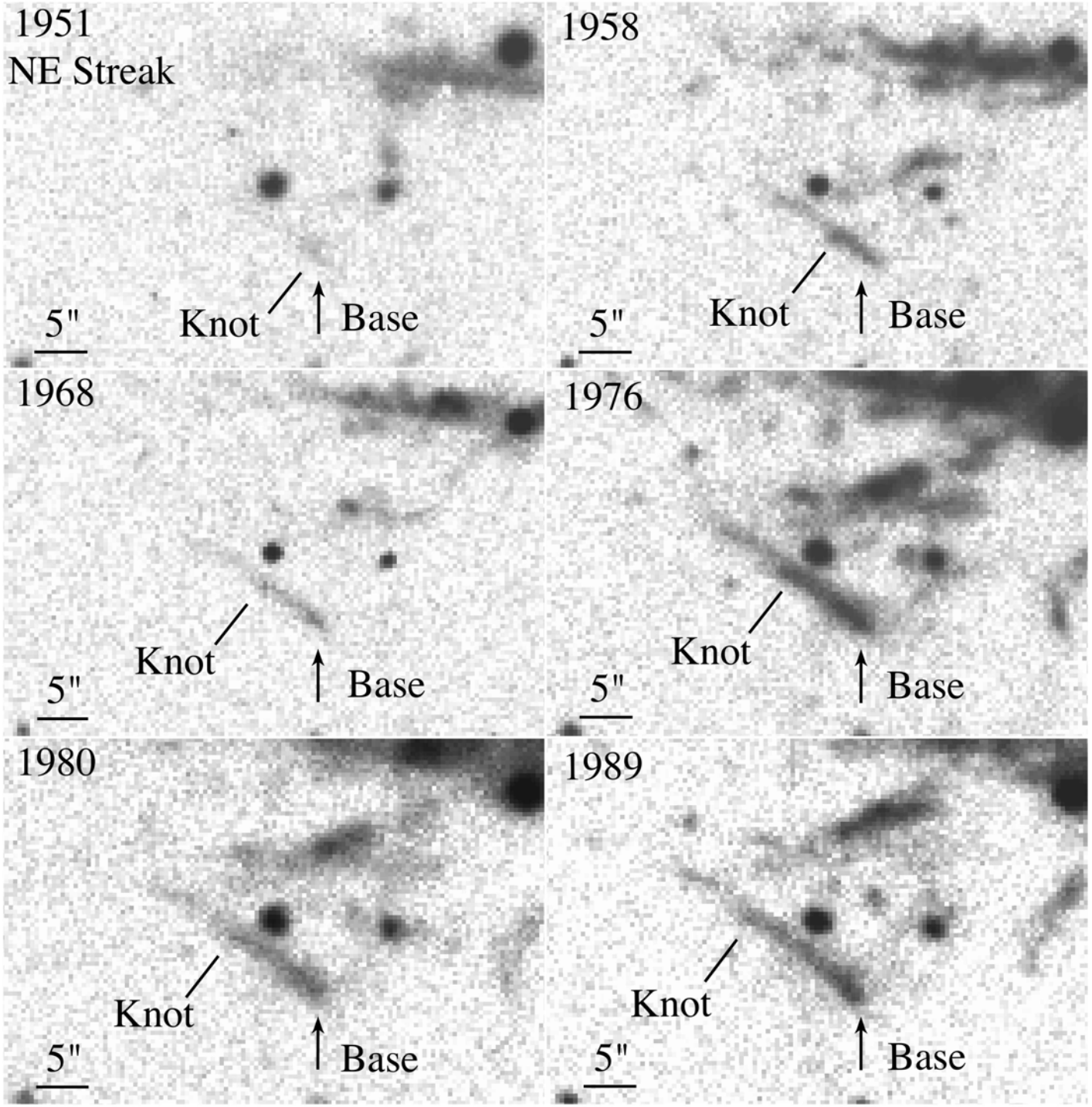

1951
Knot
Location of
Reverse Shock


1954



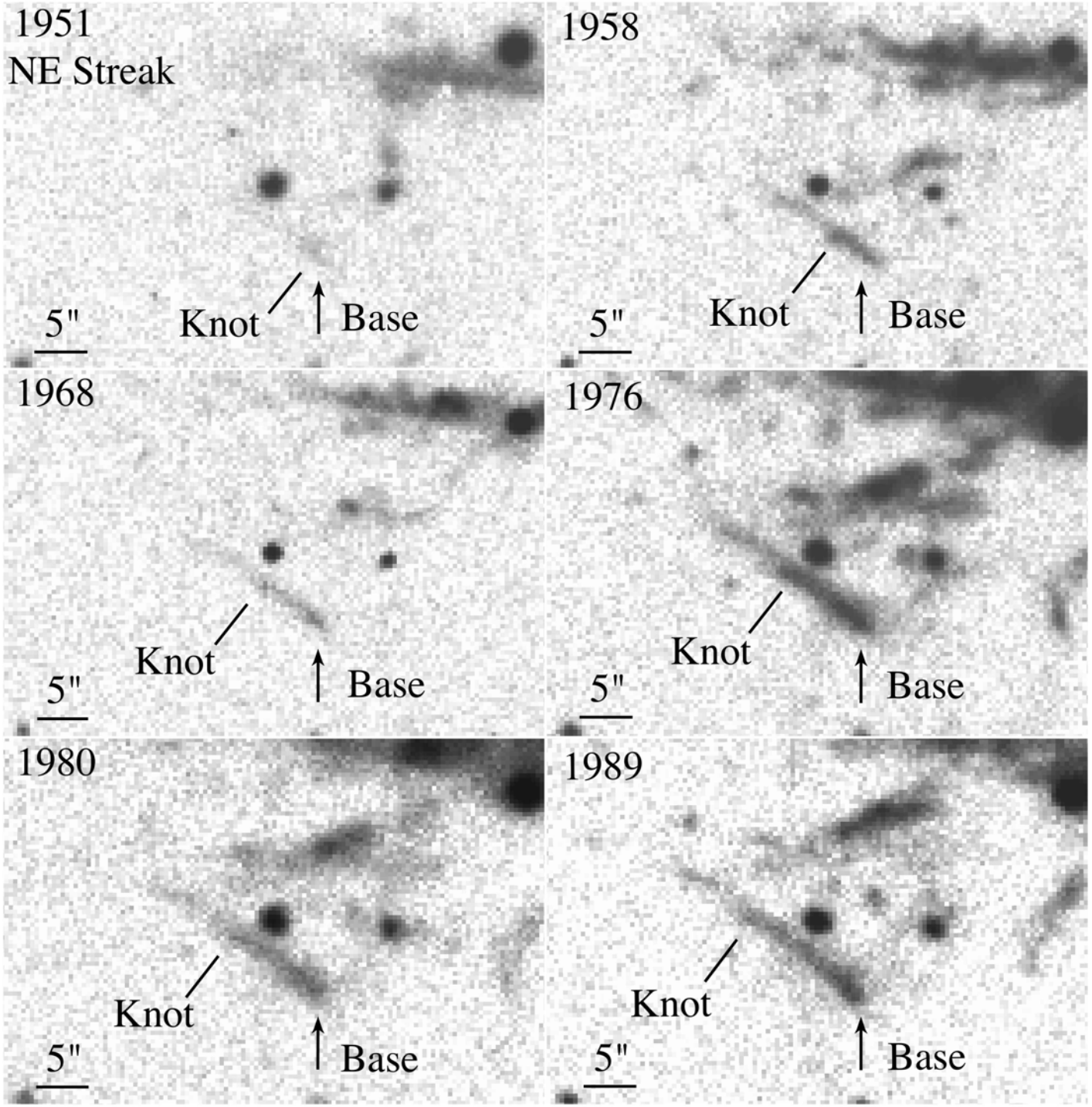
Knot Velocity:

0.32”/yr = 5150 km/s



Knot Velocity:
0.32”/yr =
5150 km/s

RS Velocity (Base)
0.0”/yr =
0 km/s



Knot Velocity:

0.32”/yr = 5150 km/s

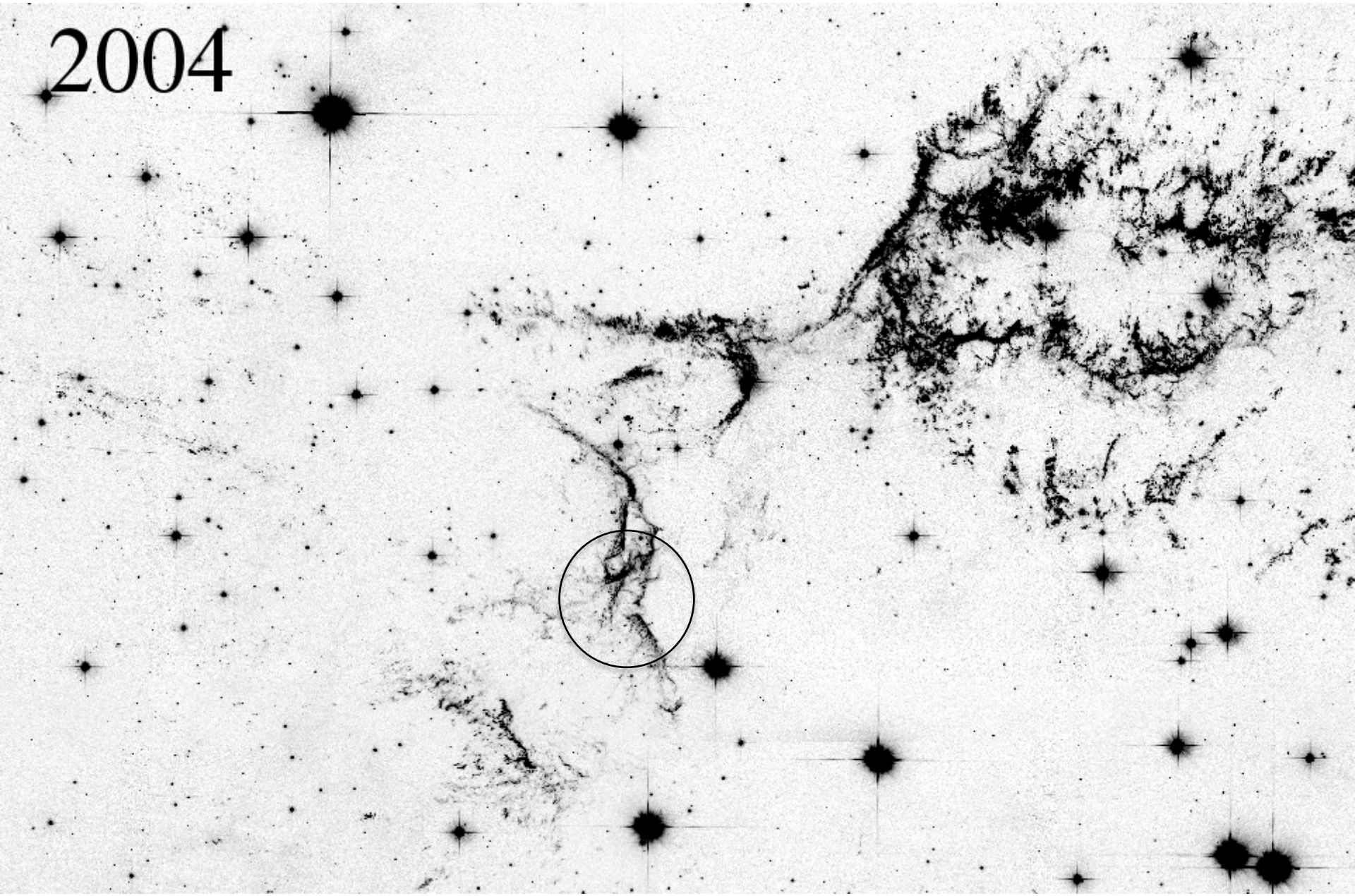
RS Velocity (Base)

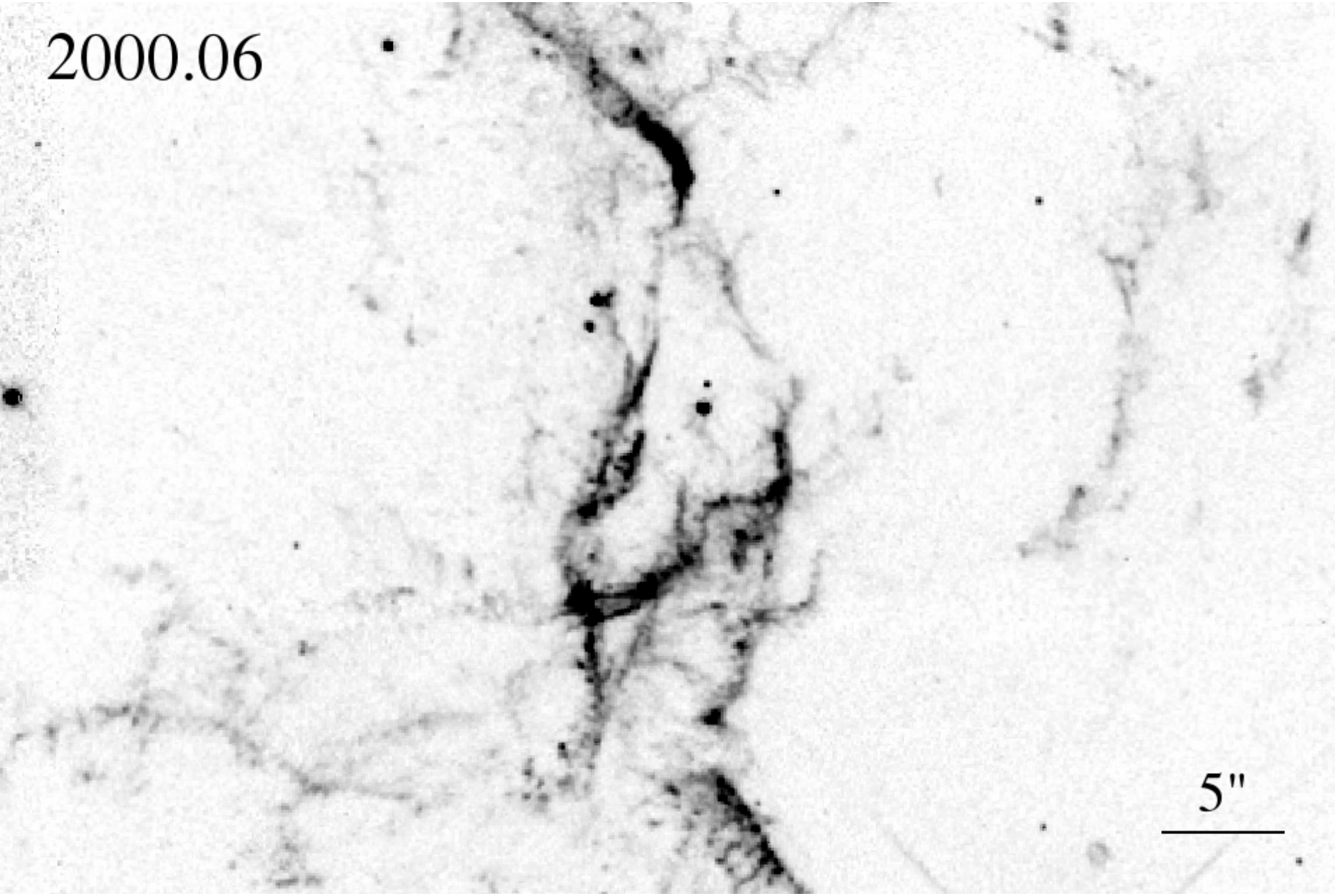
0.0”/yr = 0 km/s

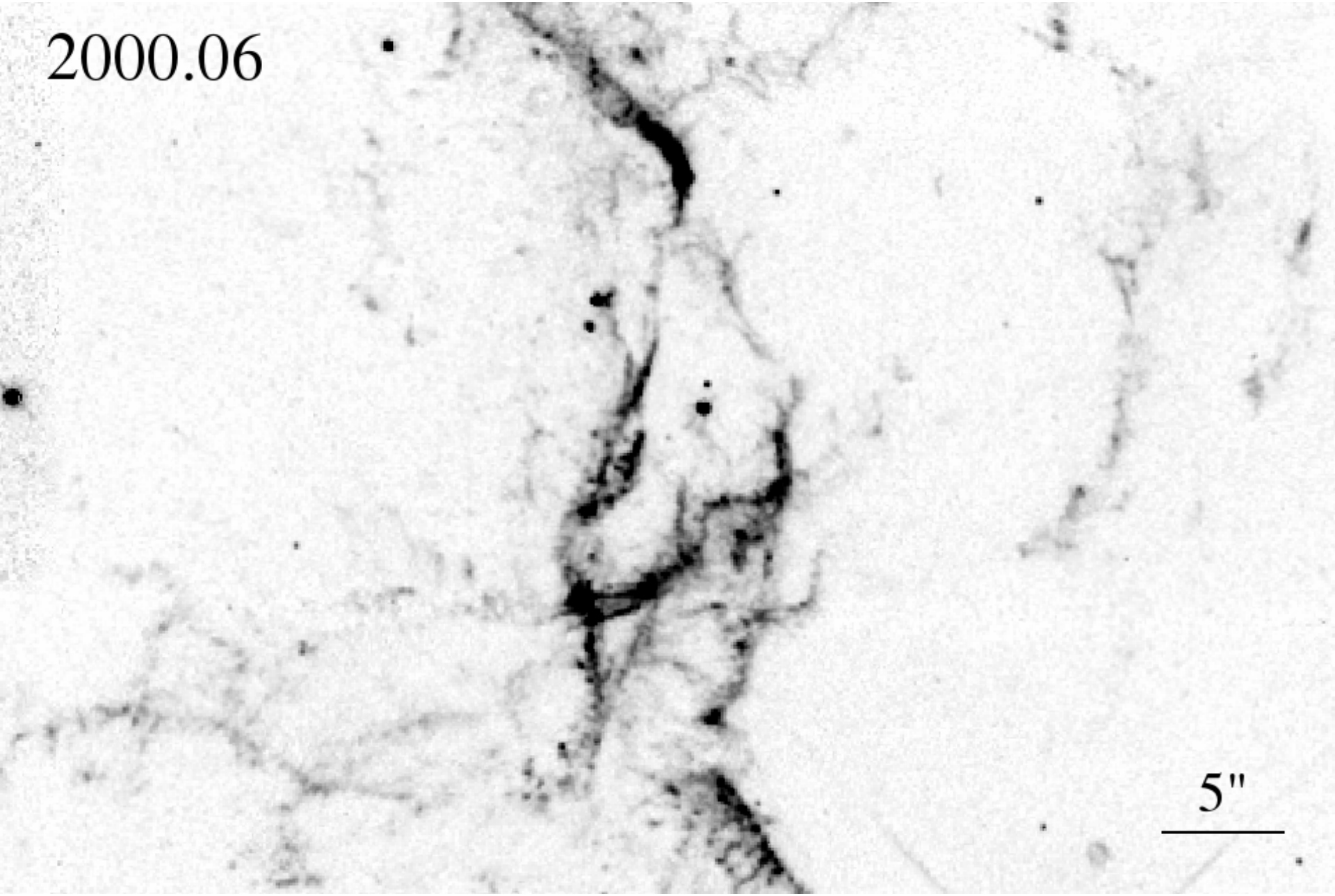
So:

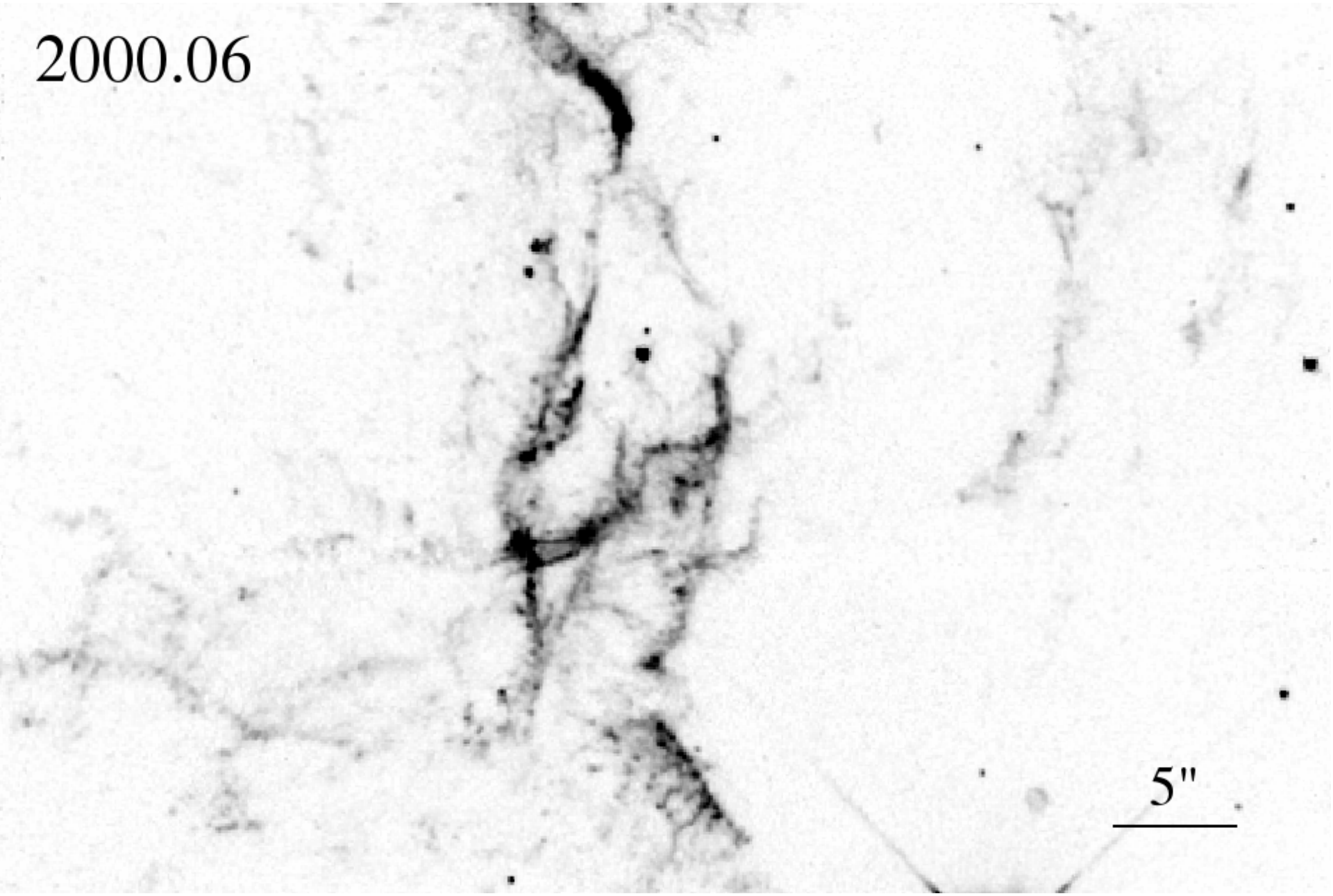
$V_{RS\ ejecta}$ = 5150 km/s

(projected velocity)


2004


2000.06
5"


2000.06
5"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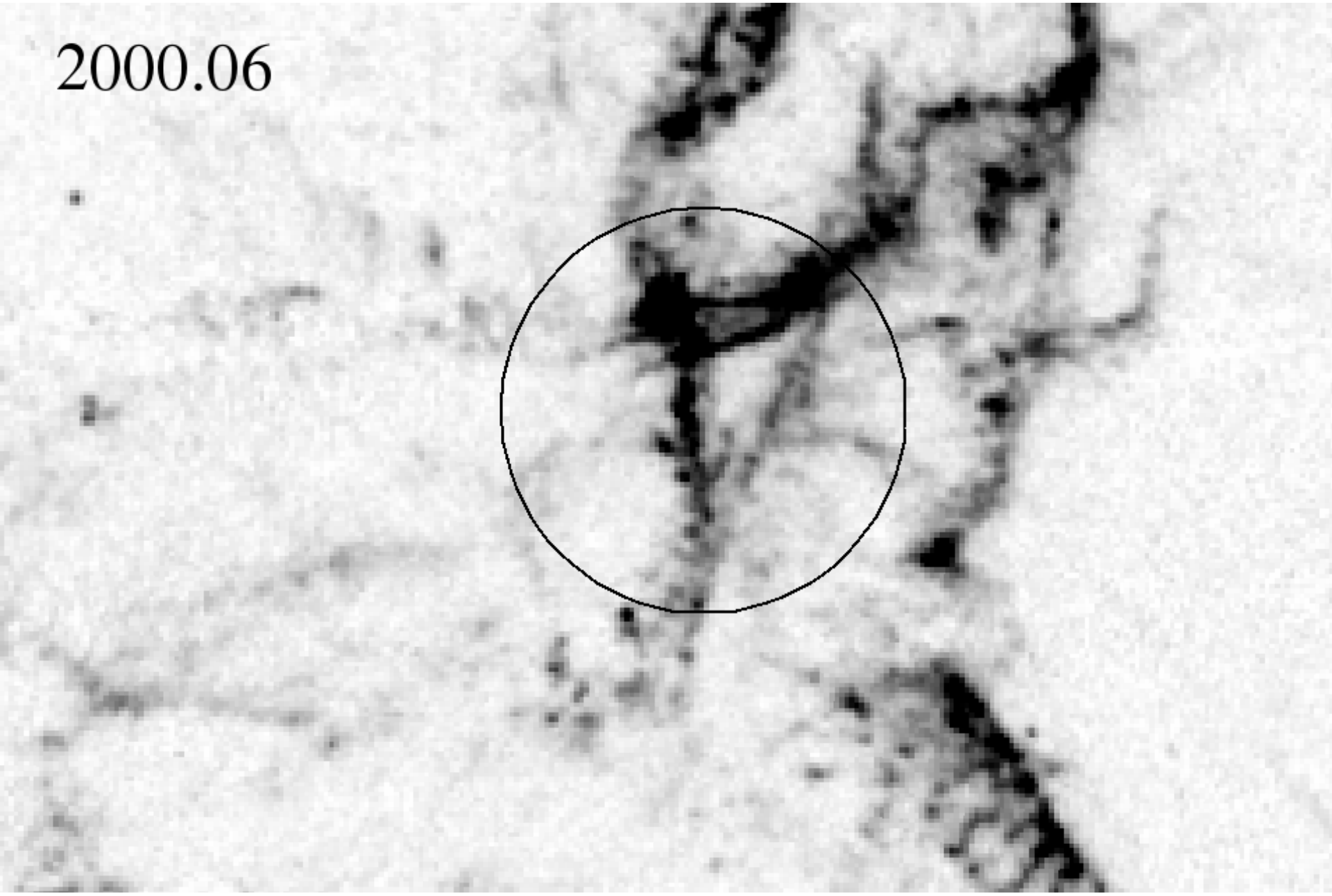
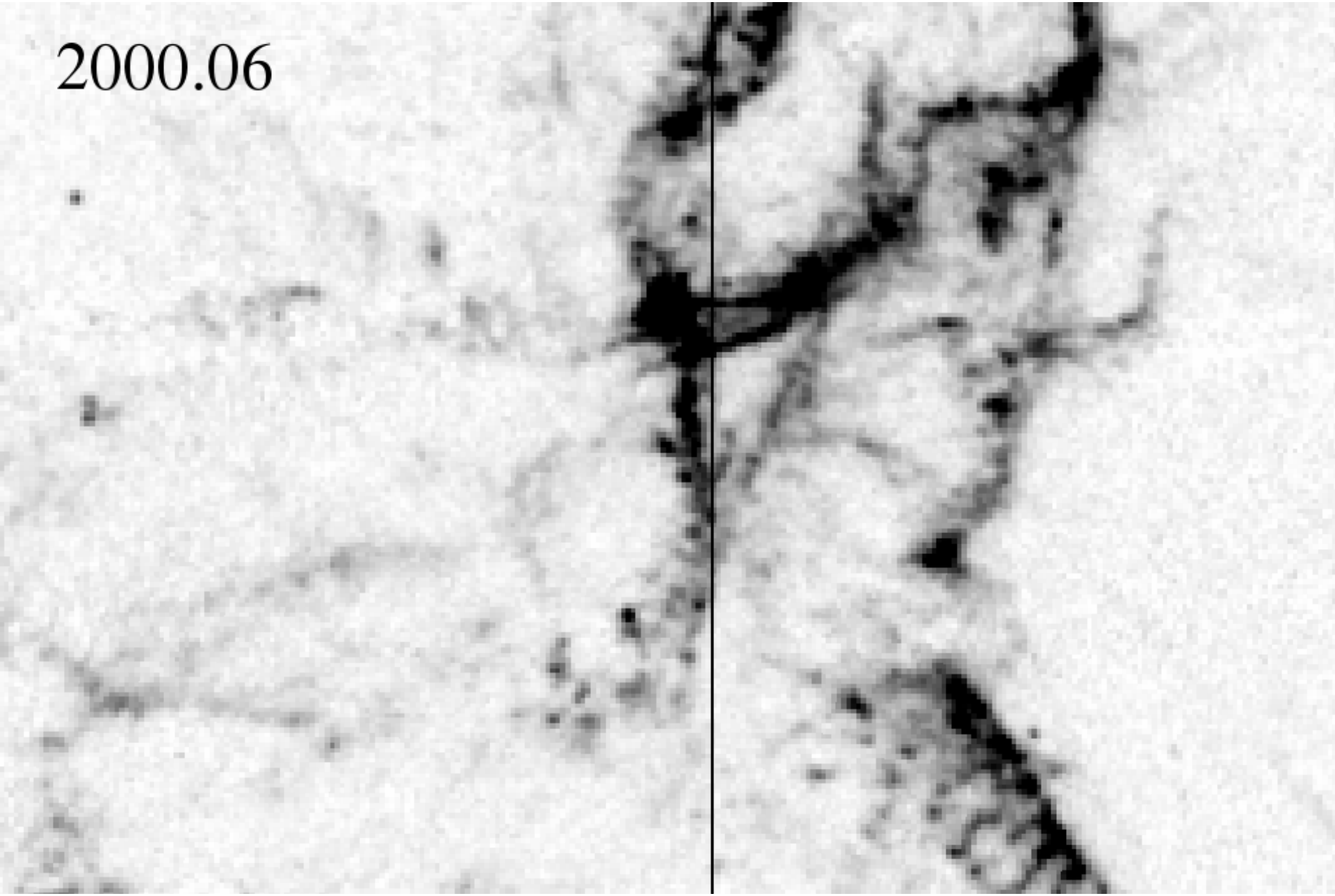
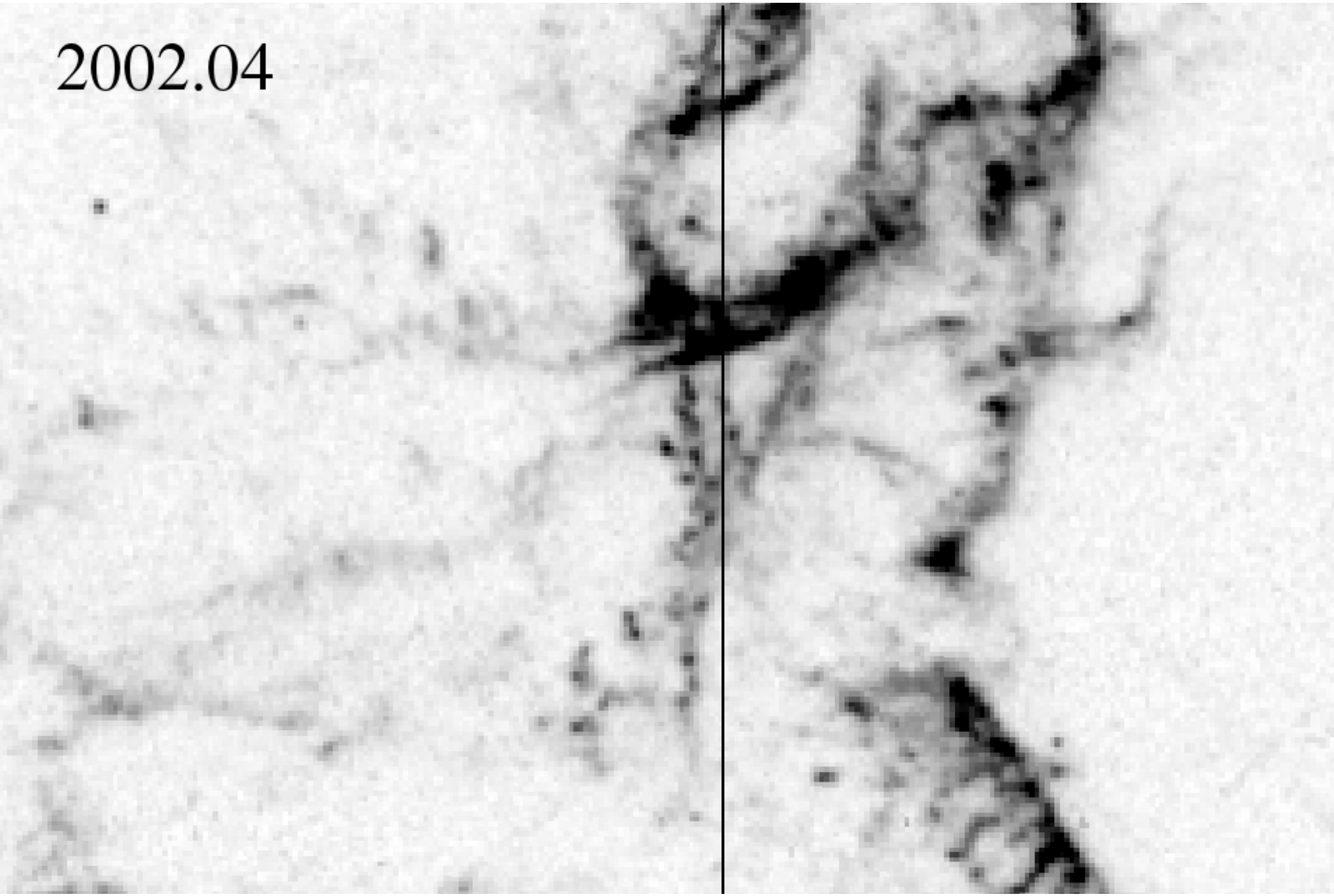
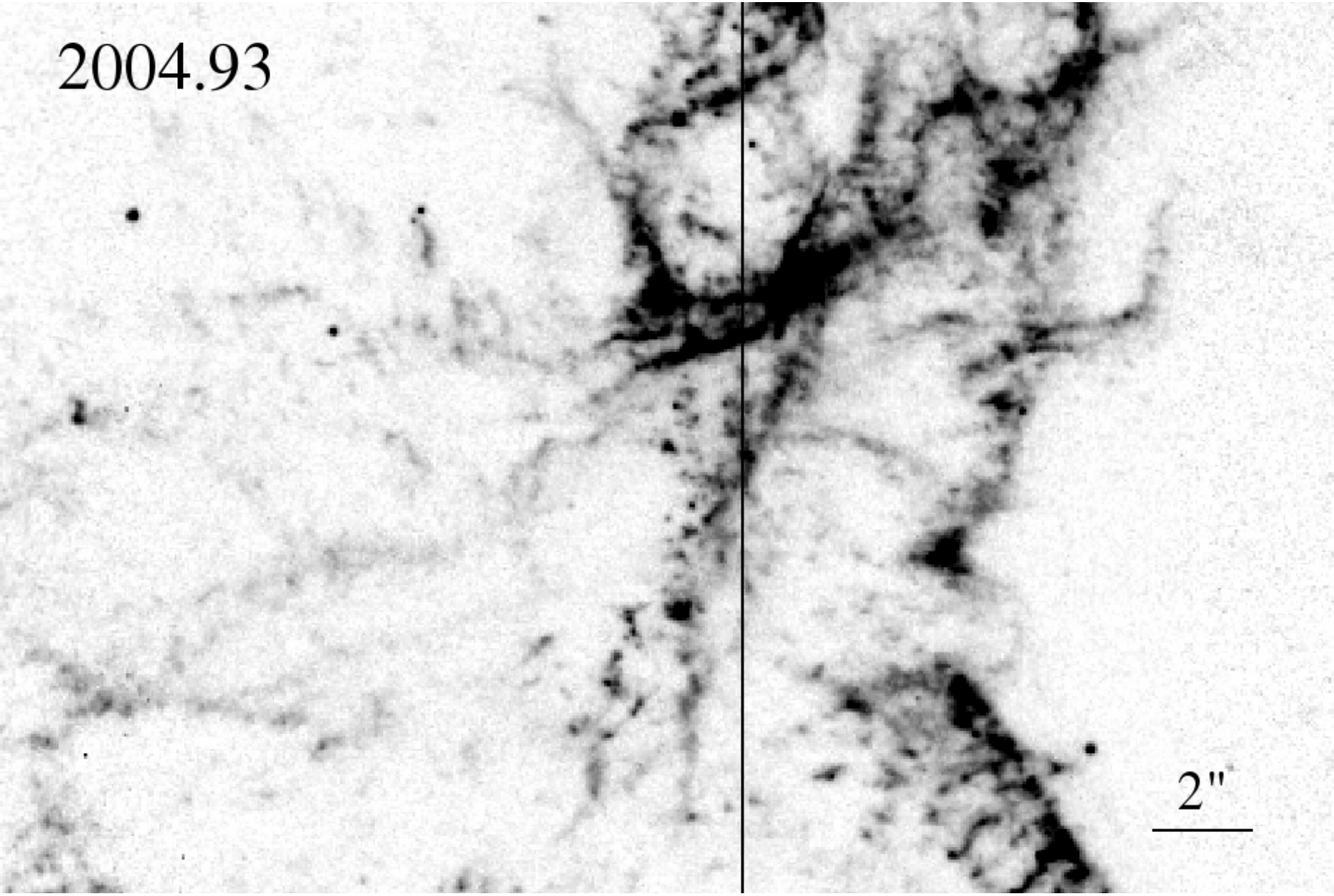
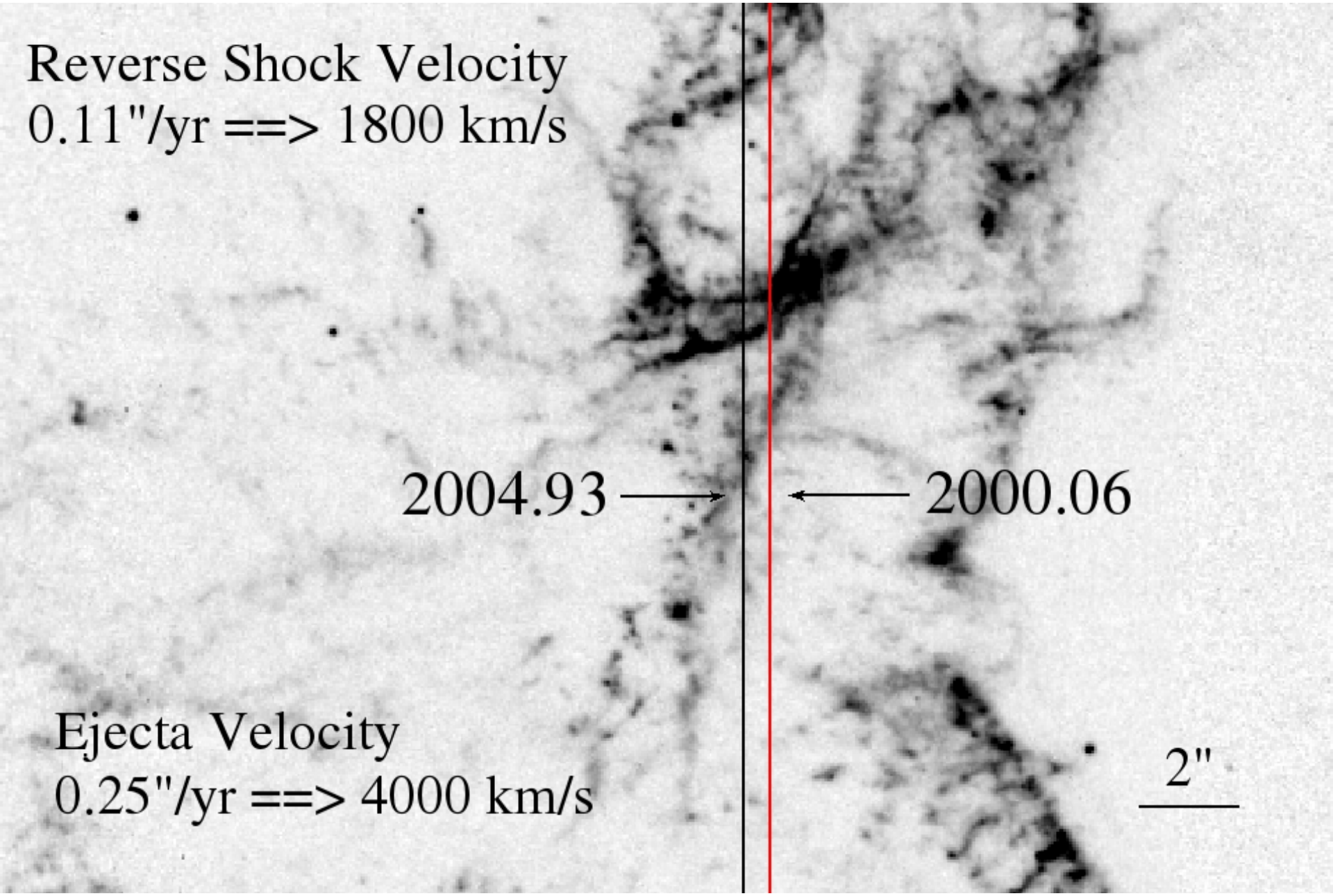
5"


2000.06

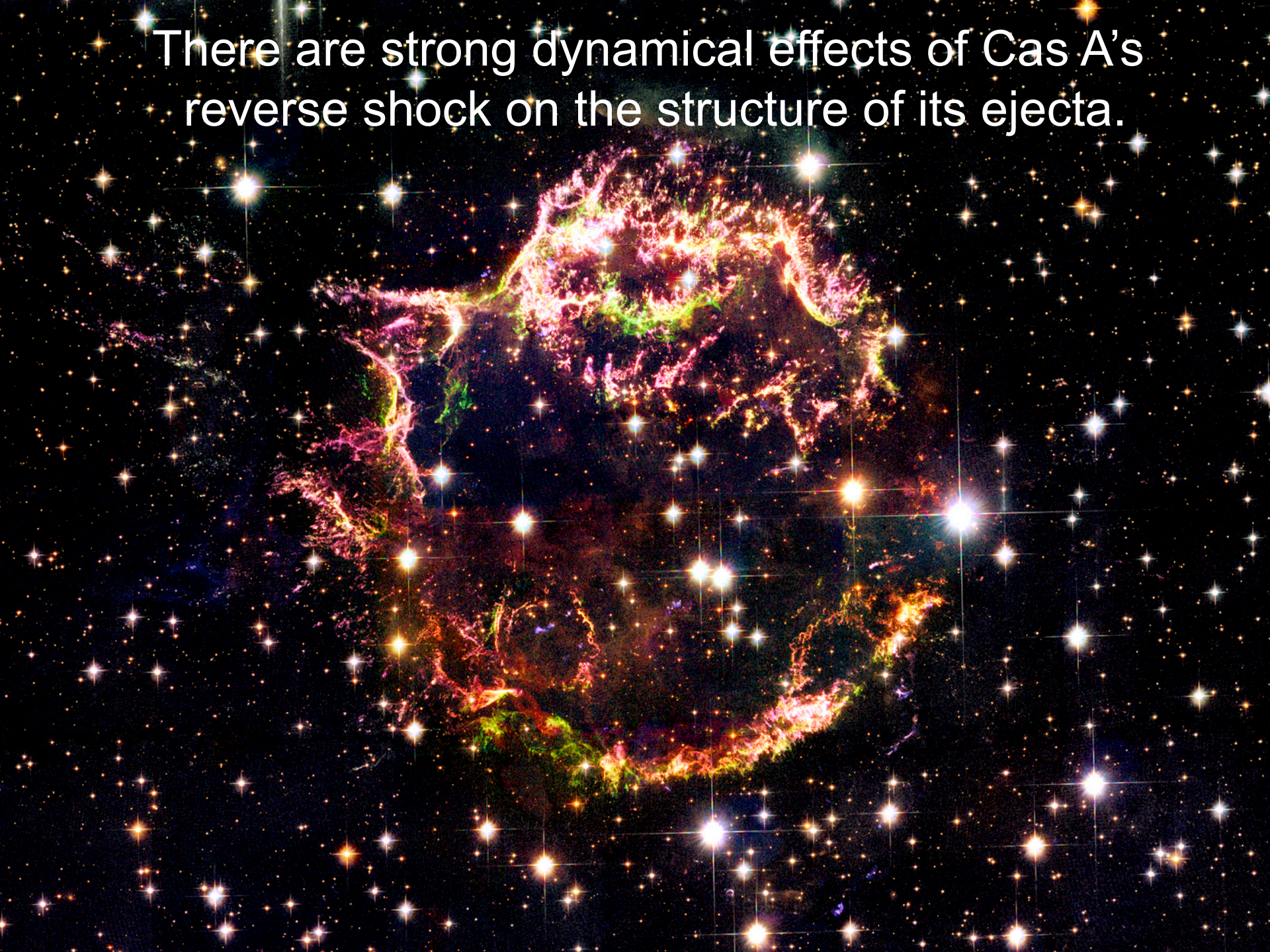

2000.06

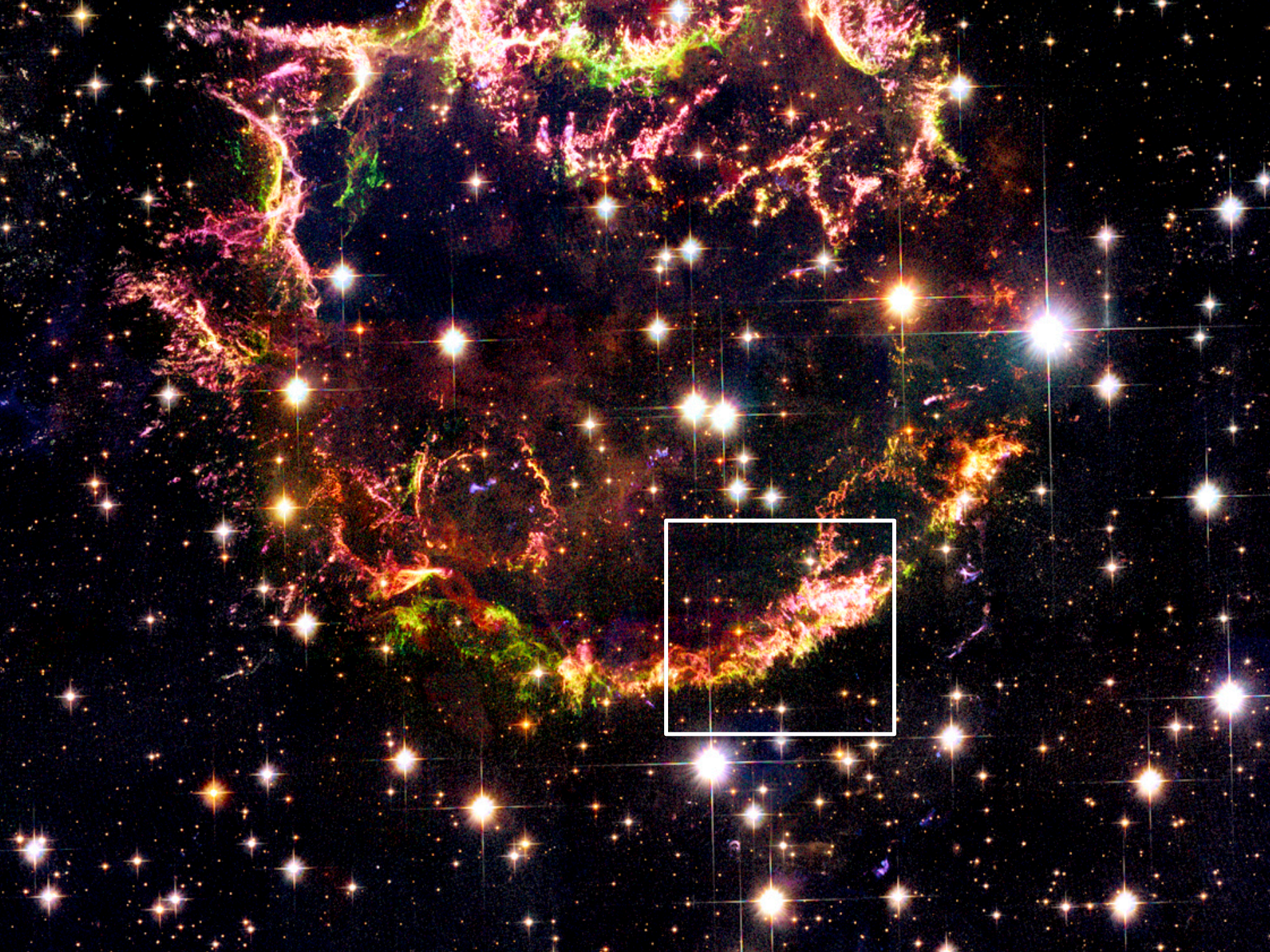

2002.04

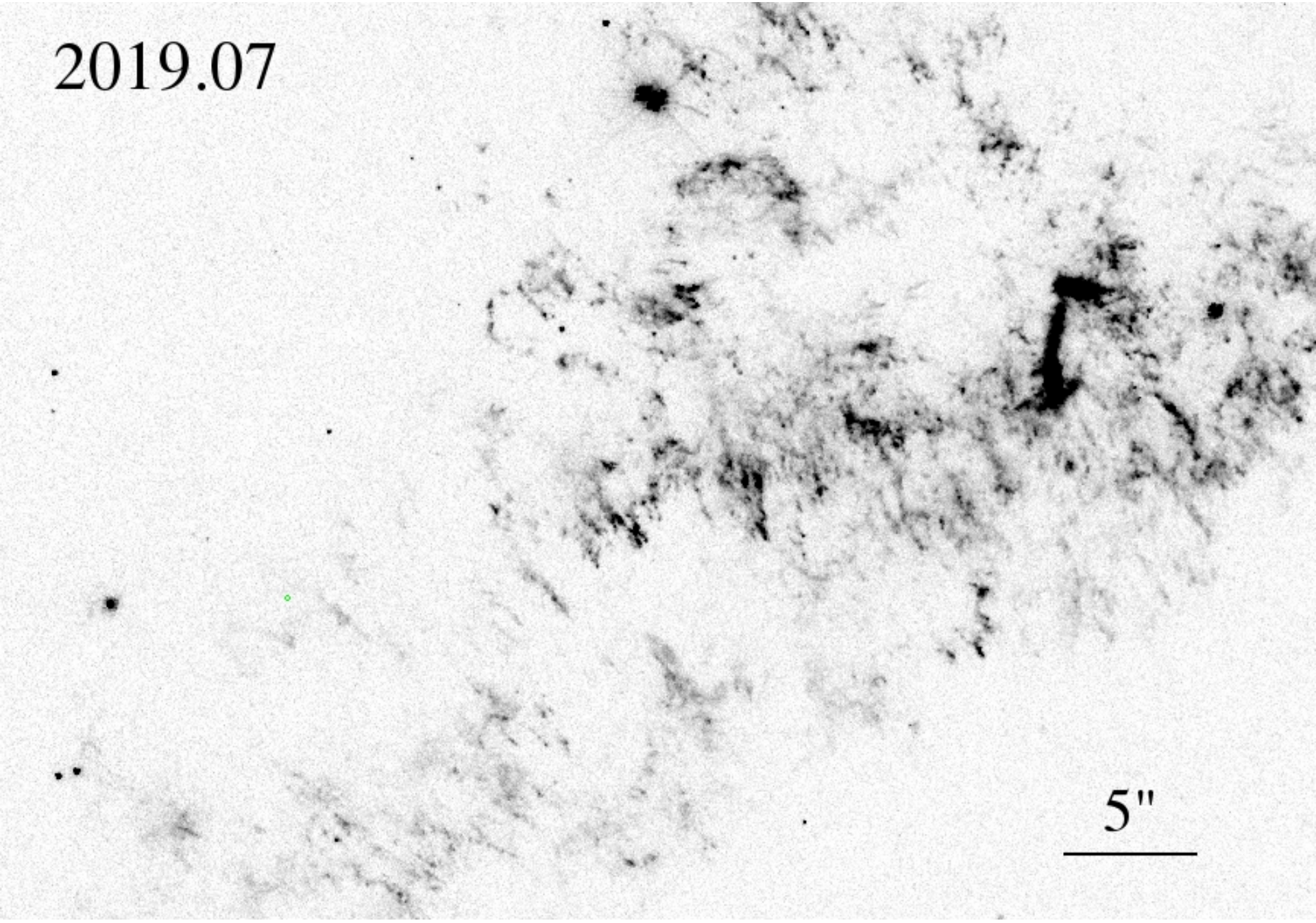

2004.93
2"

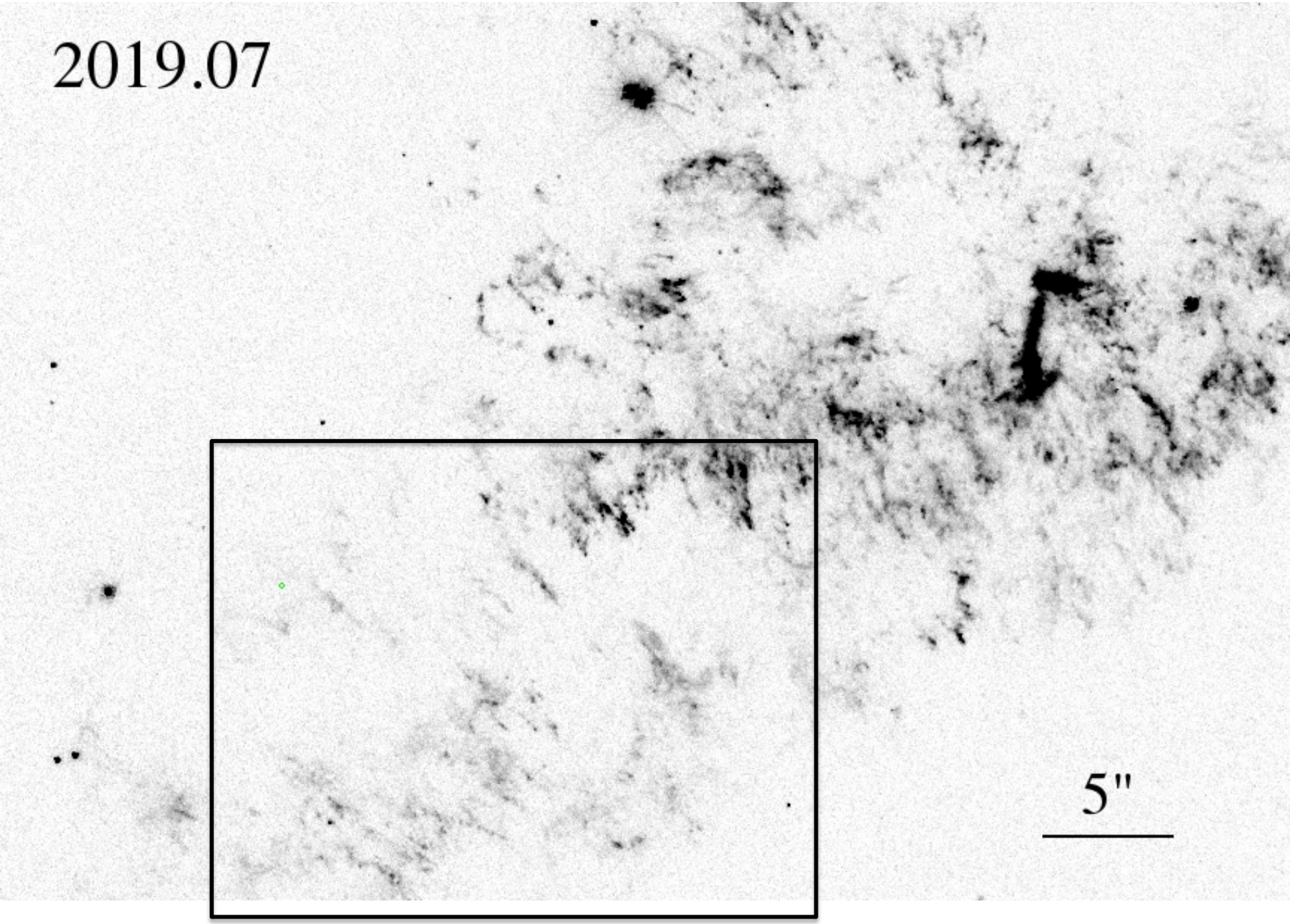

Reverse Shock Velocity
0.11"/yr ==> 1800 km/s
2004.93
2000.06
Ejecta Velocity
0.25"/yr ==> 4000 km/s
2"

There are strong dynamical effects of Cas A's reverse shock on the structure of its ejecta.






2019.07
5"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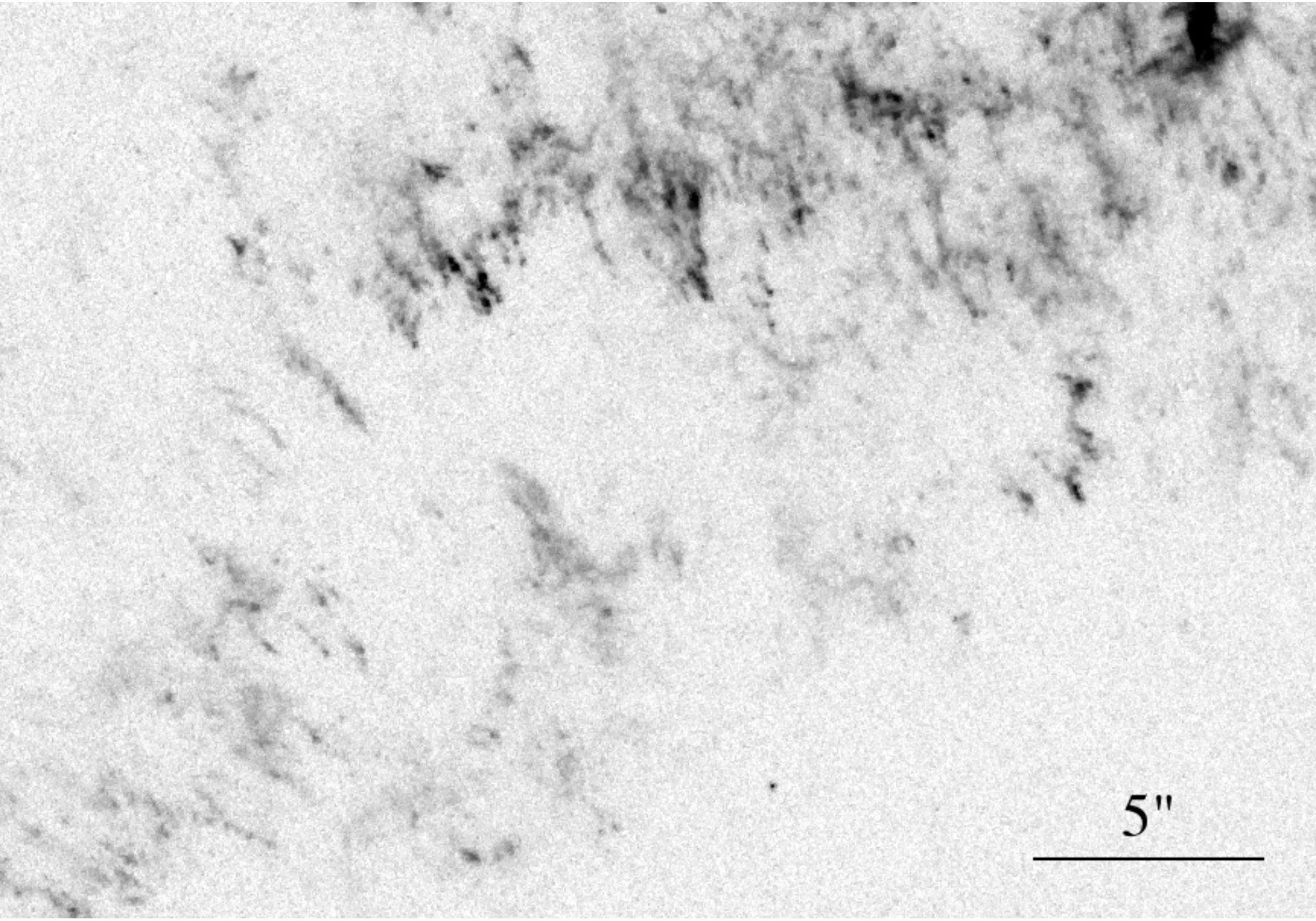
5"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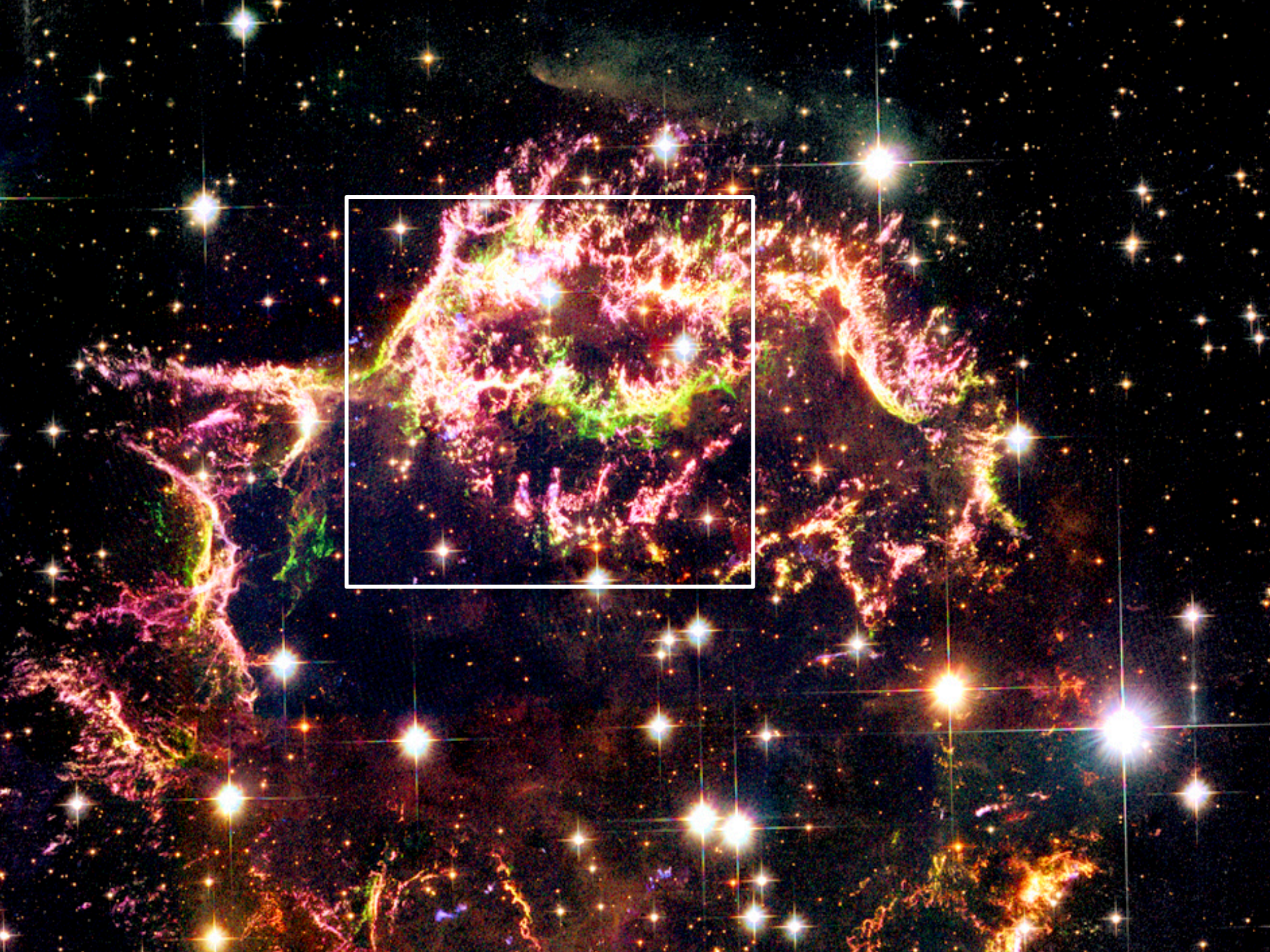

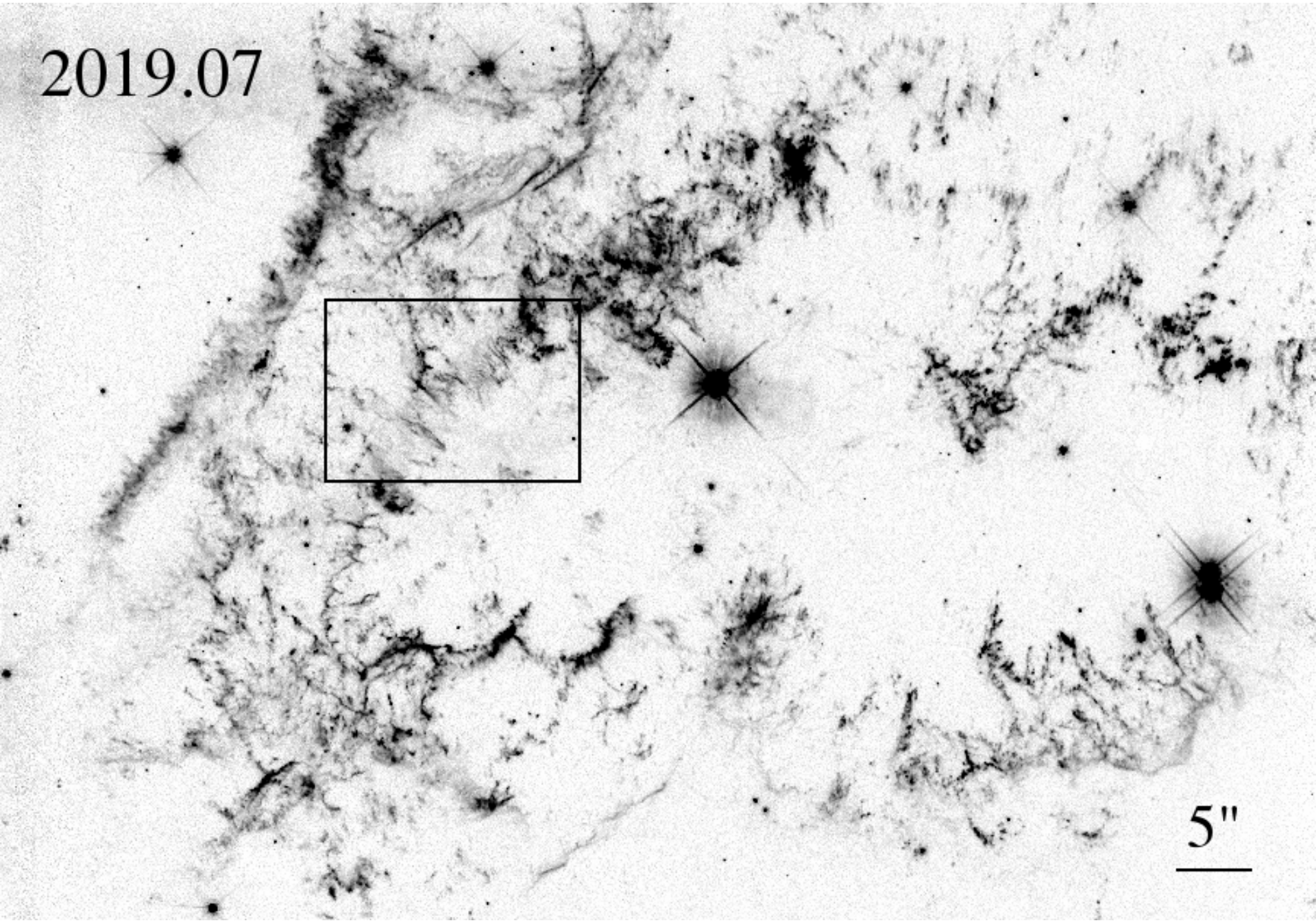
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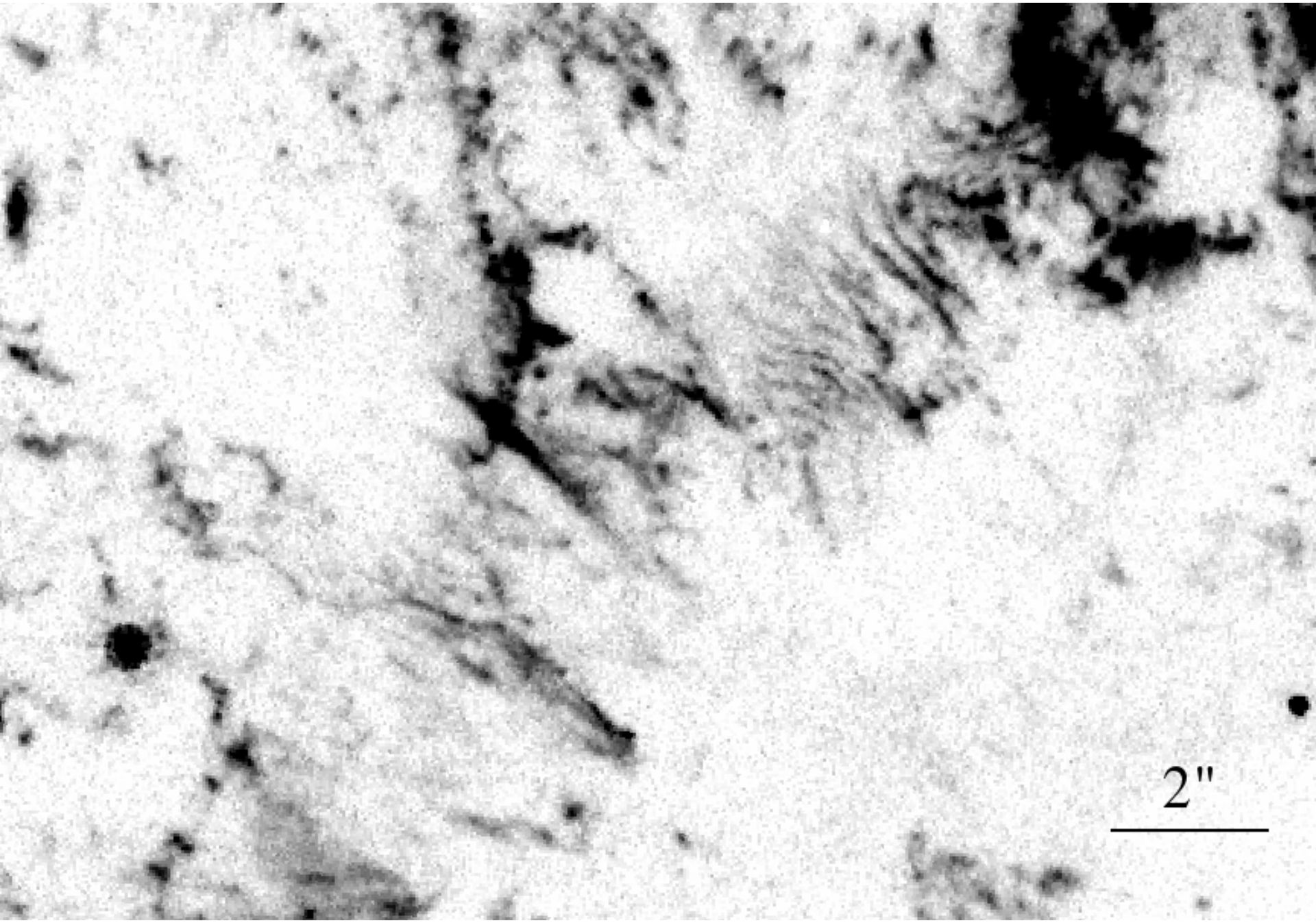
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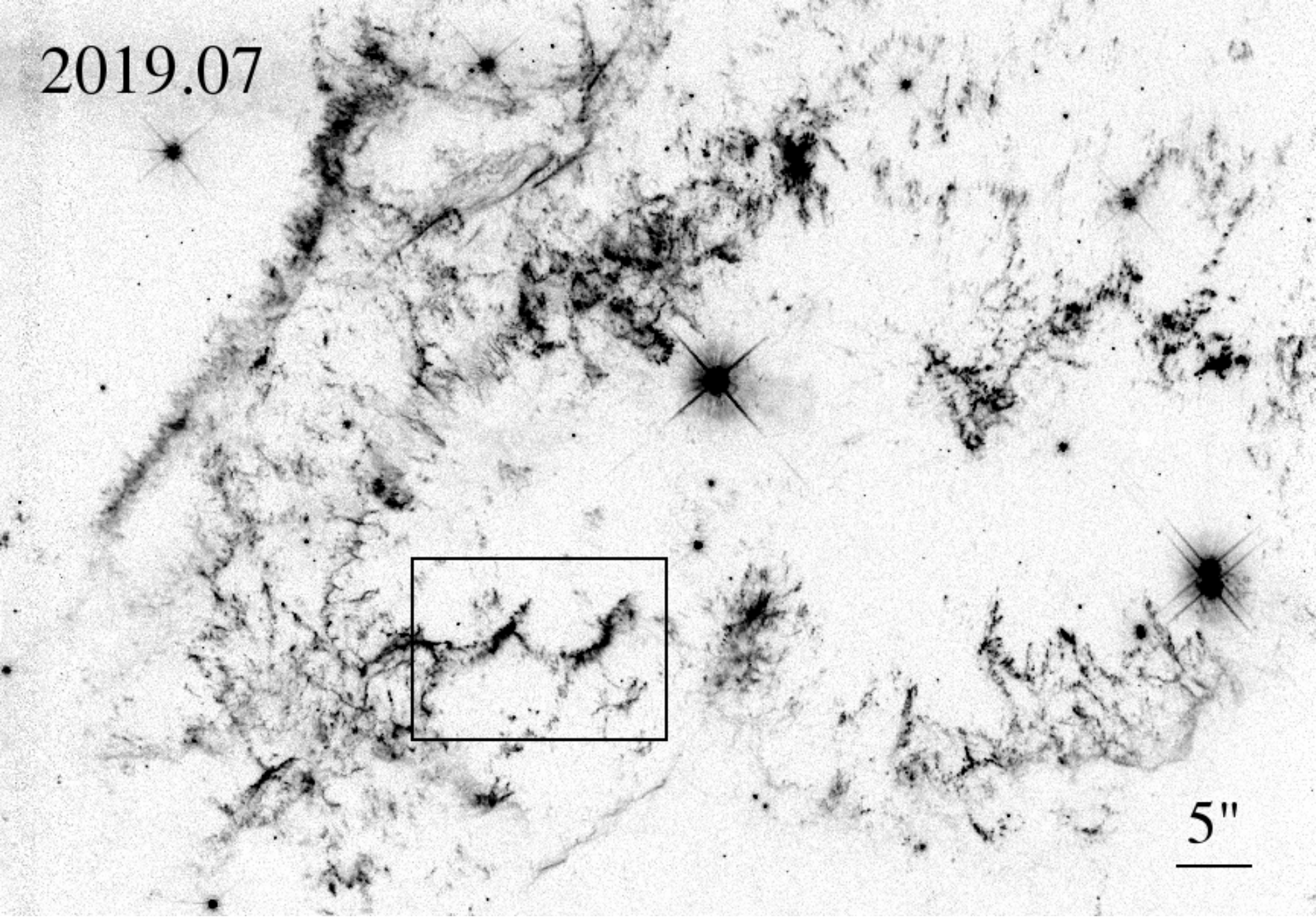
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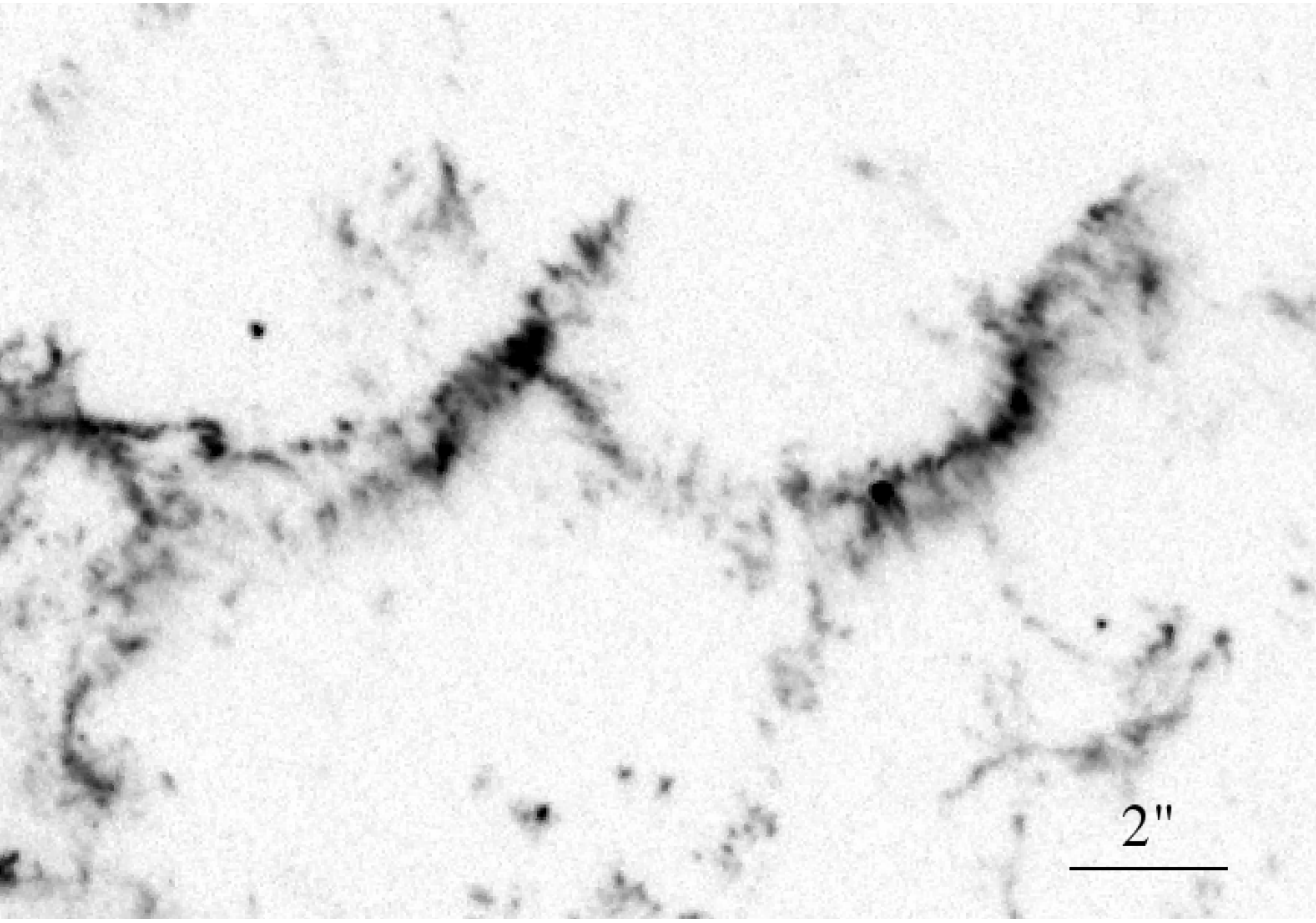
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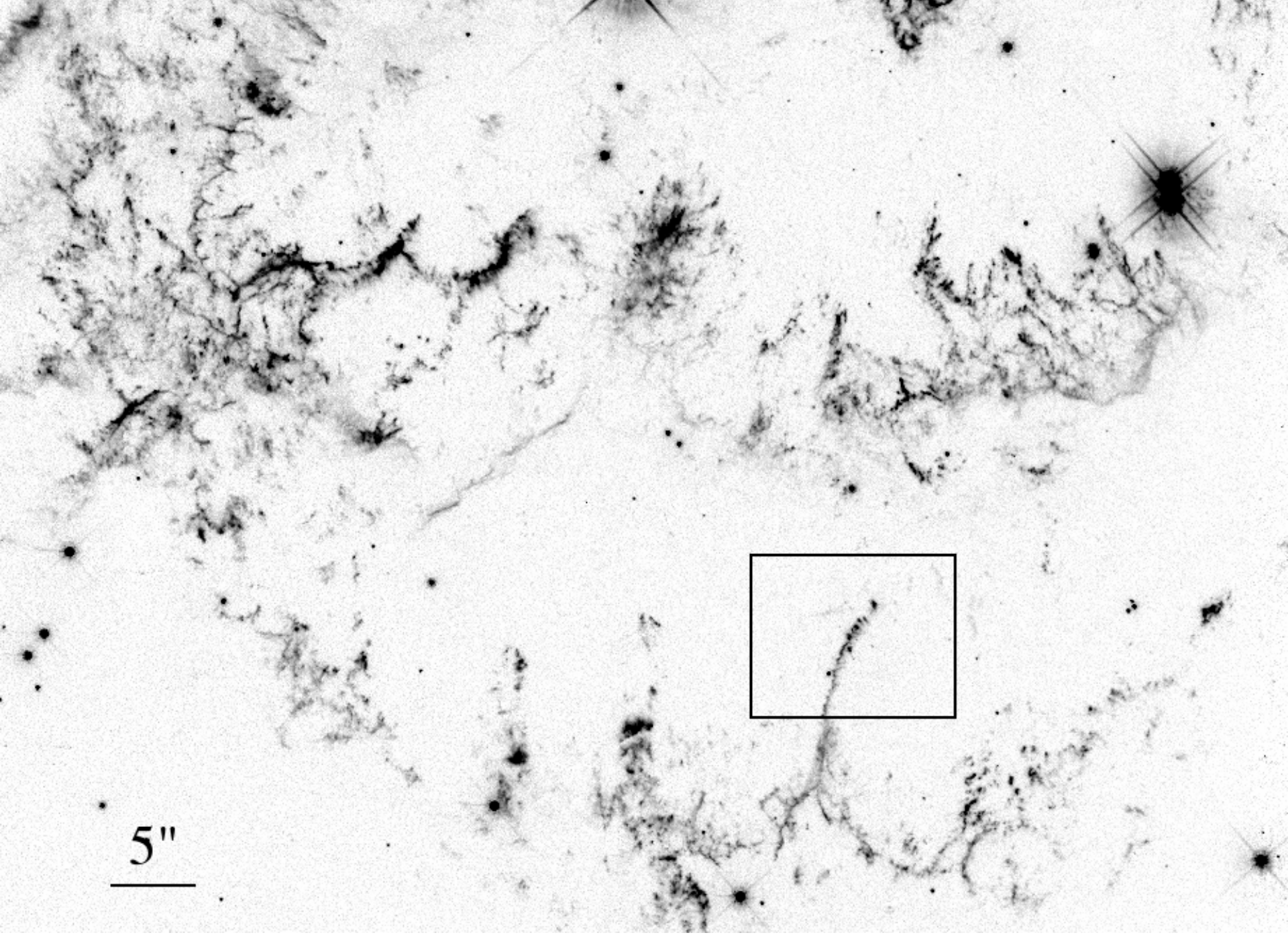
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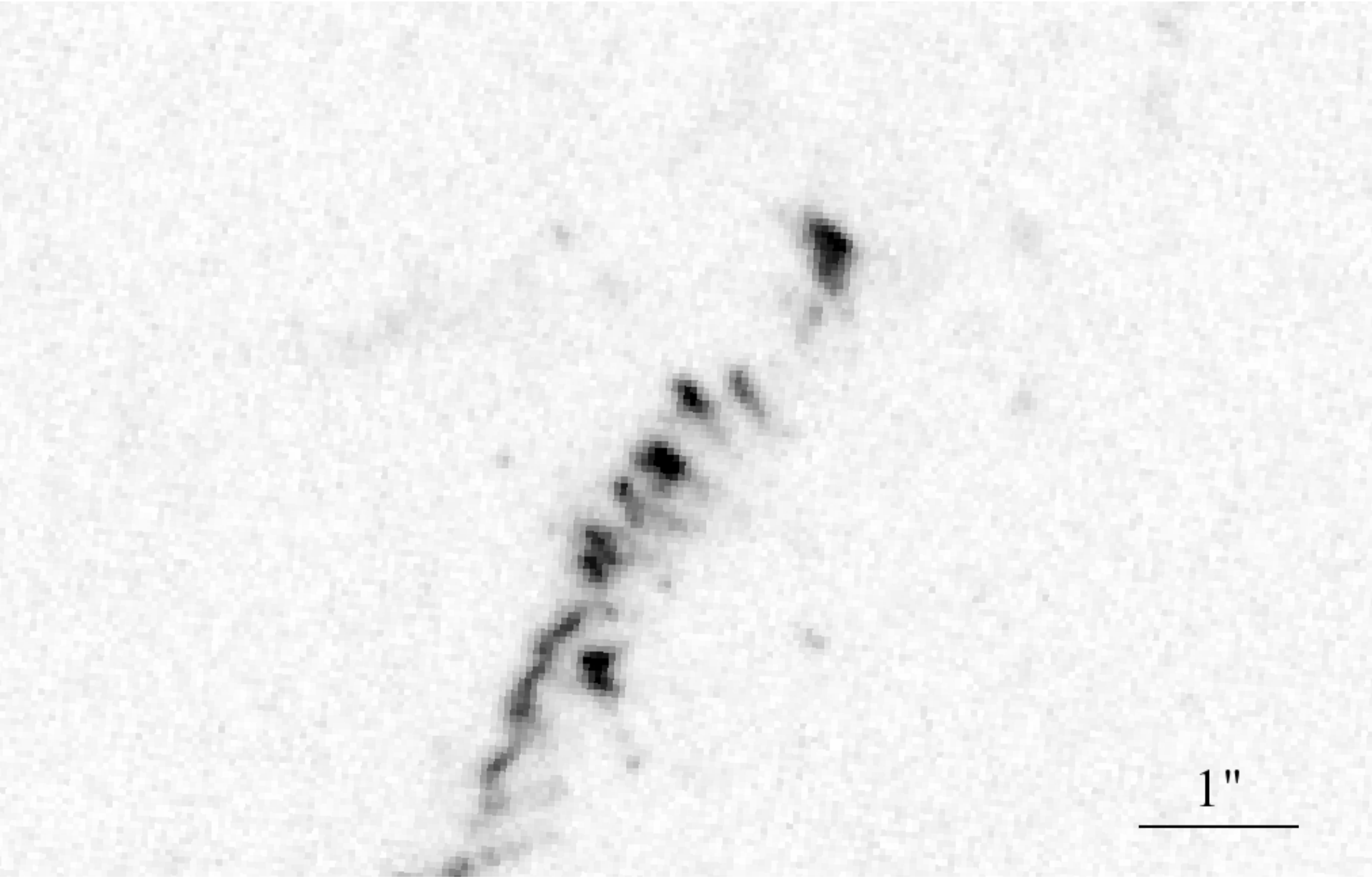
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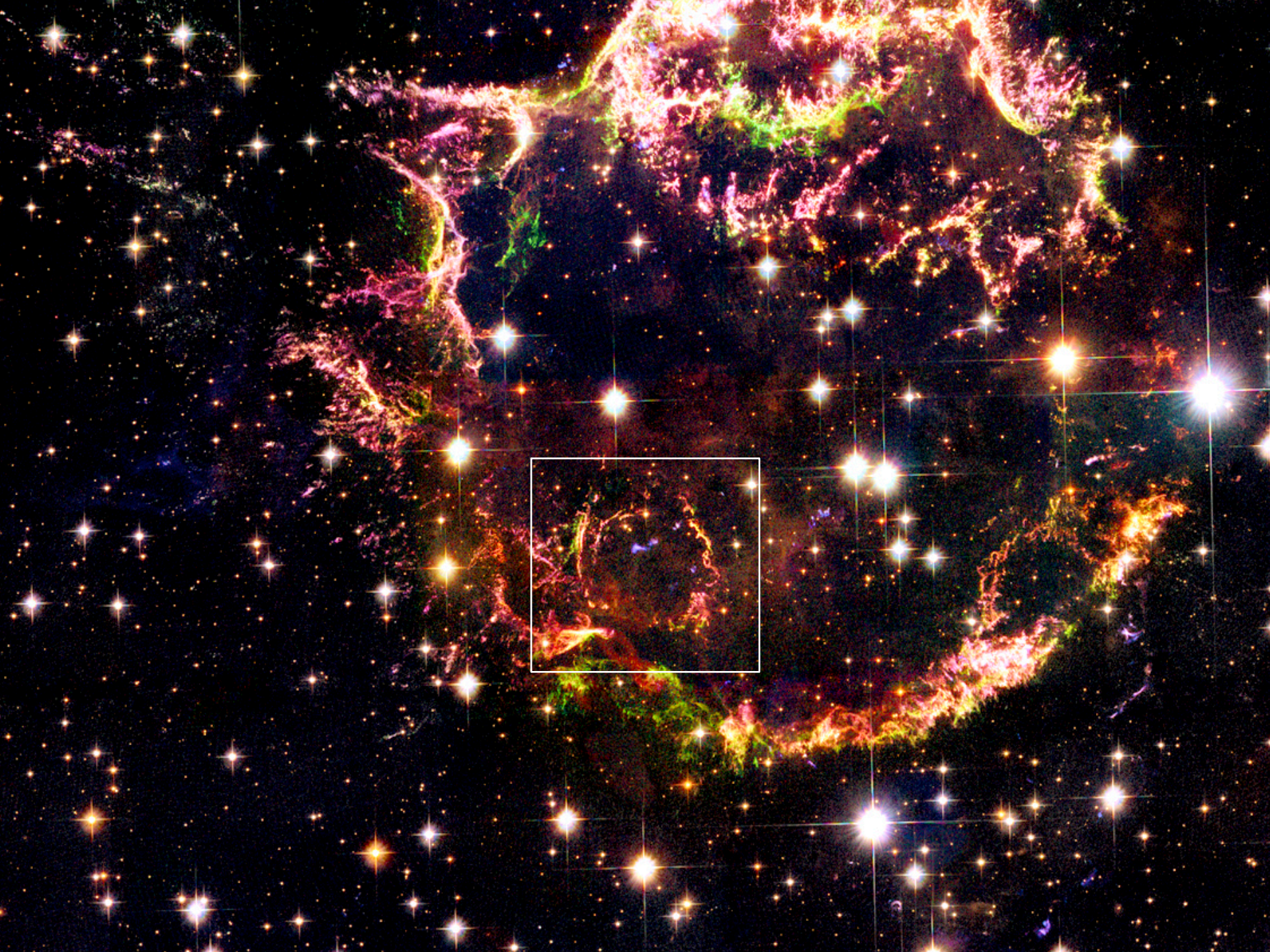
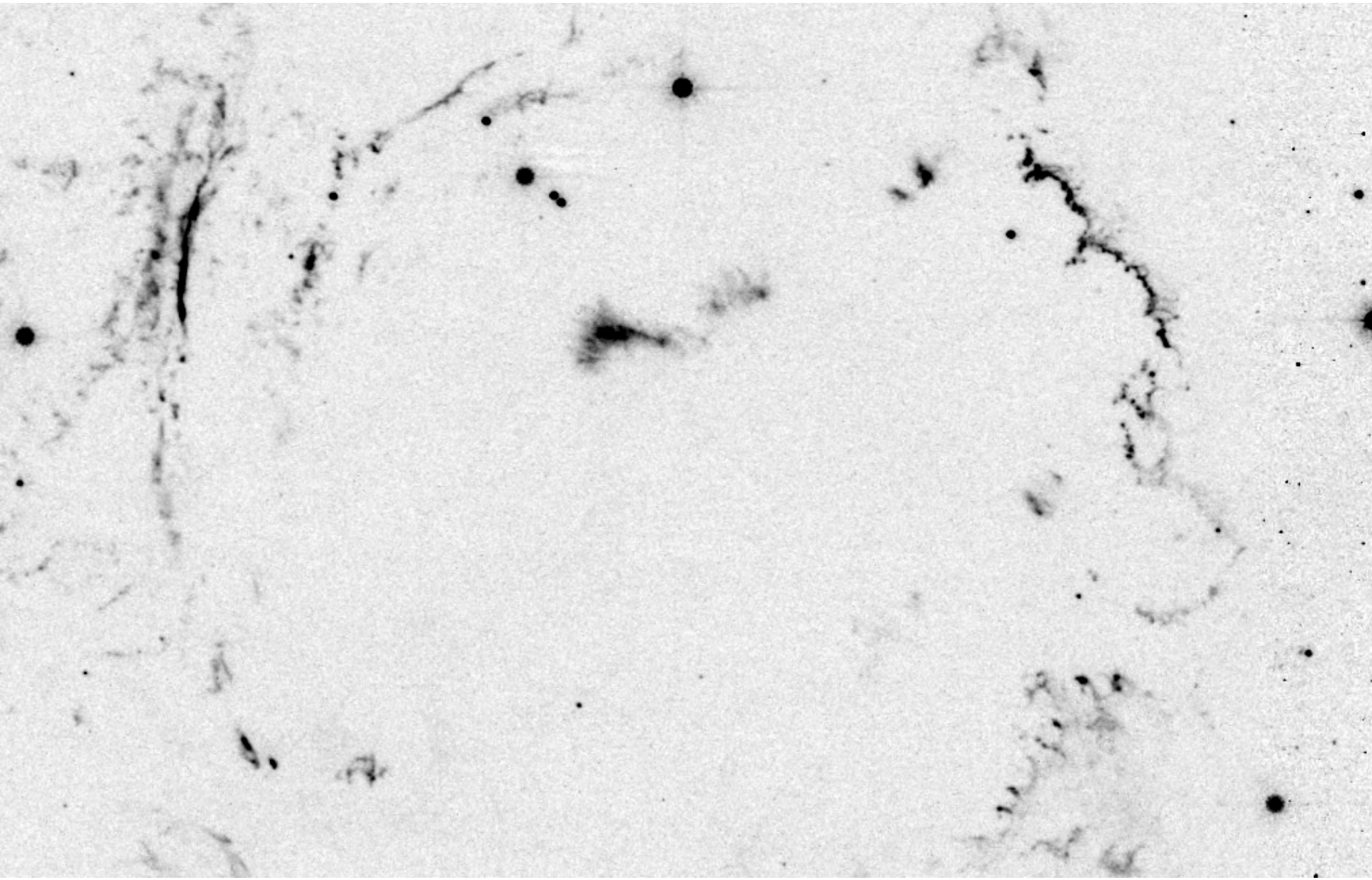
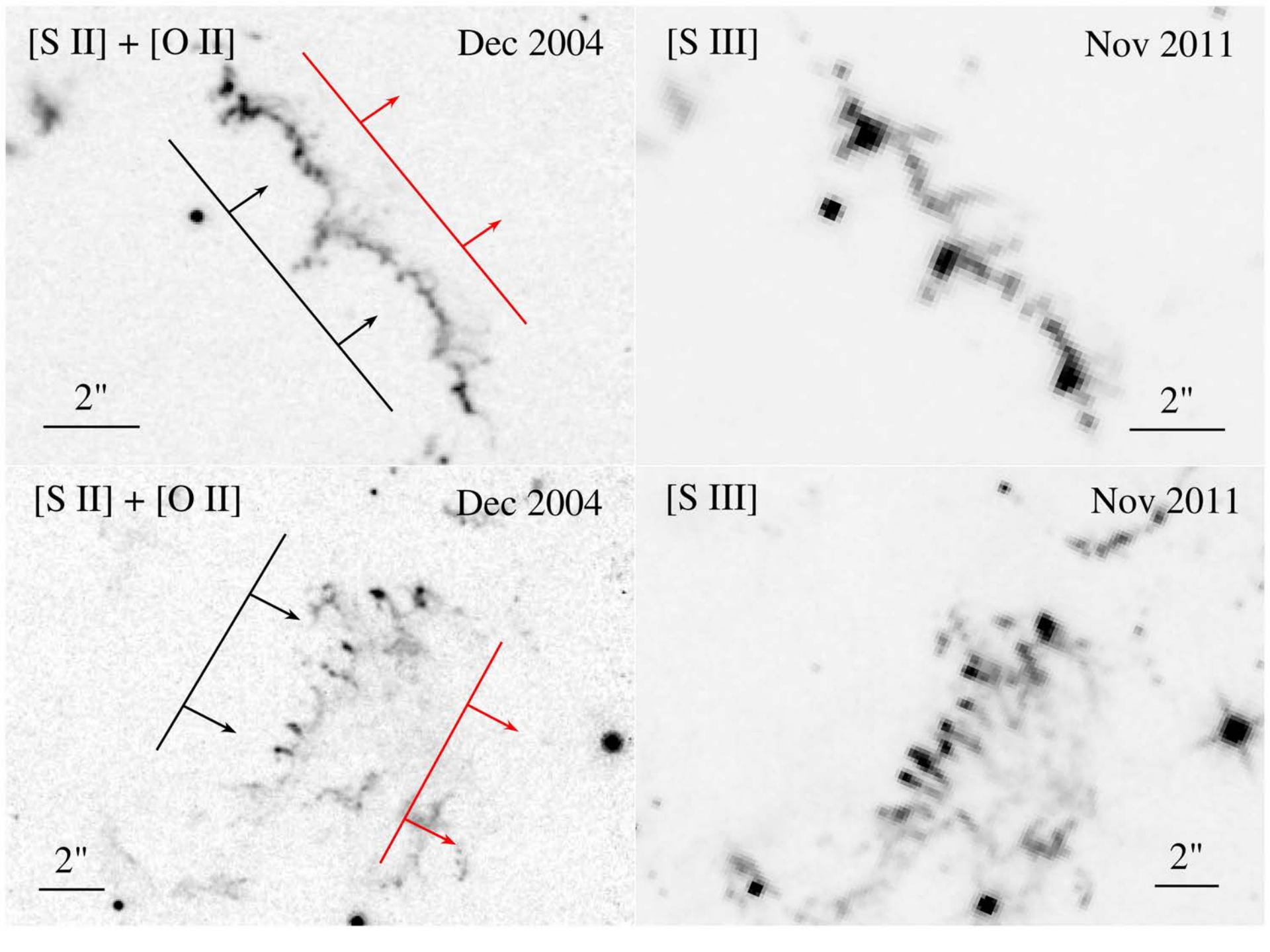
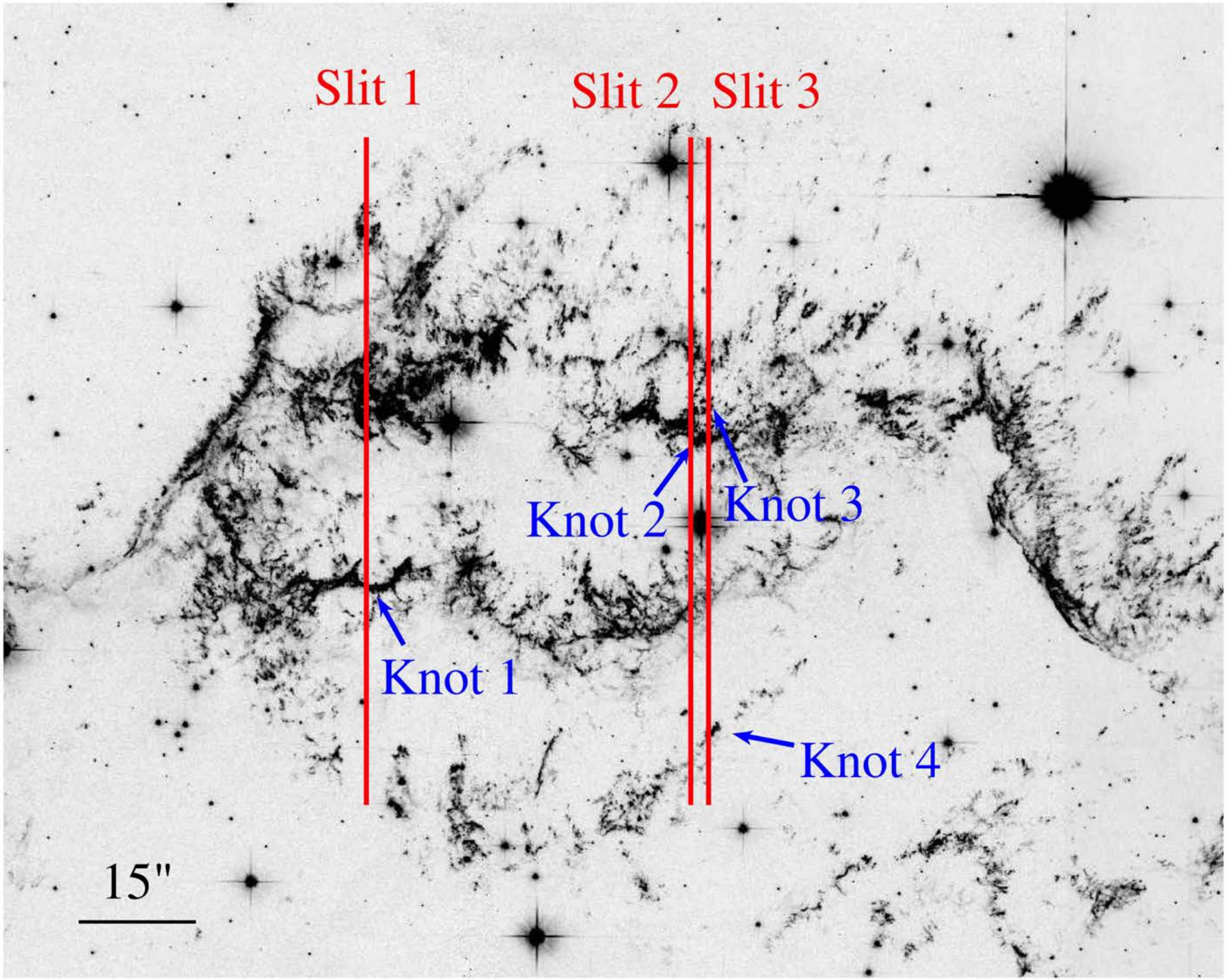
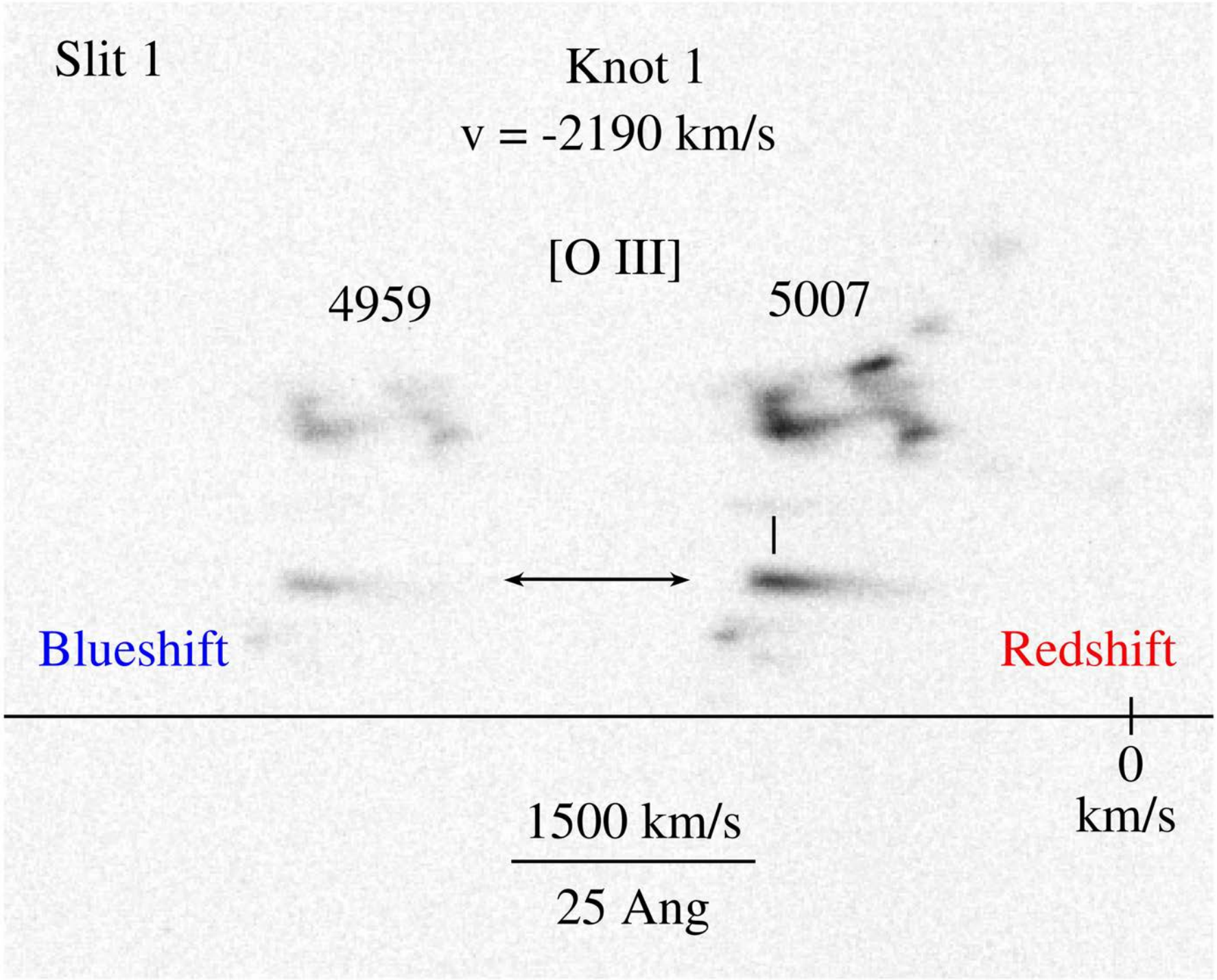
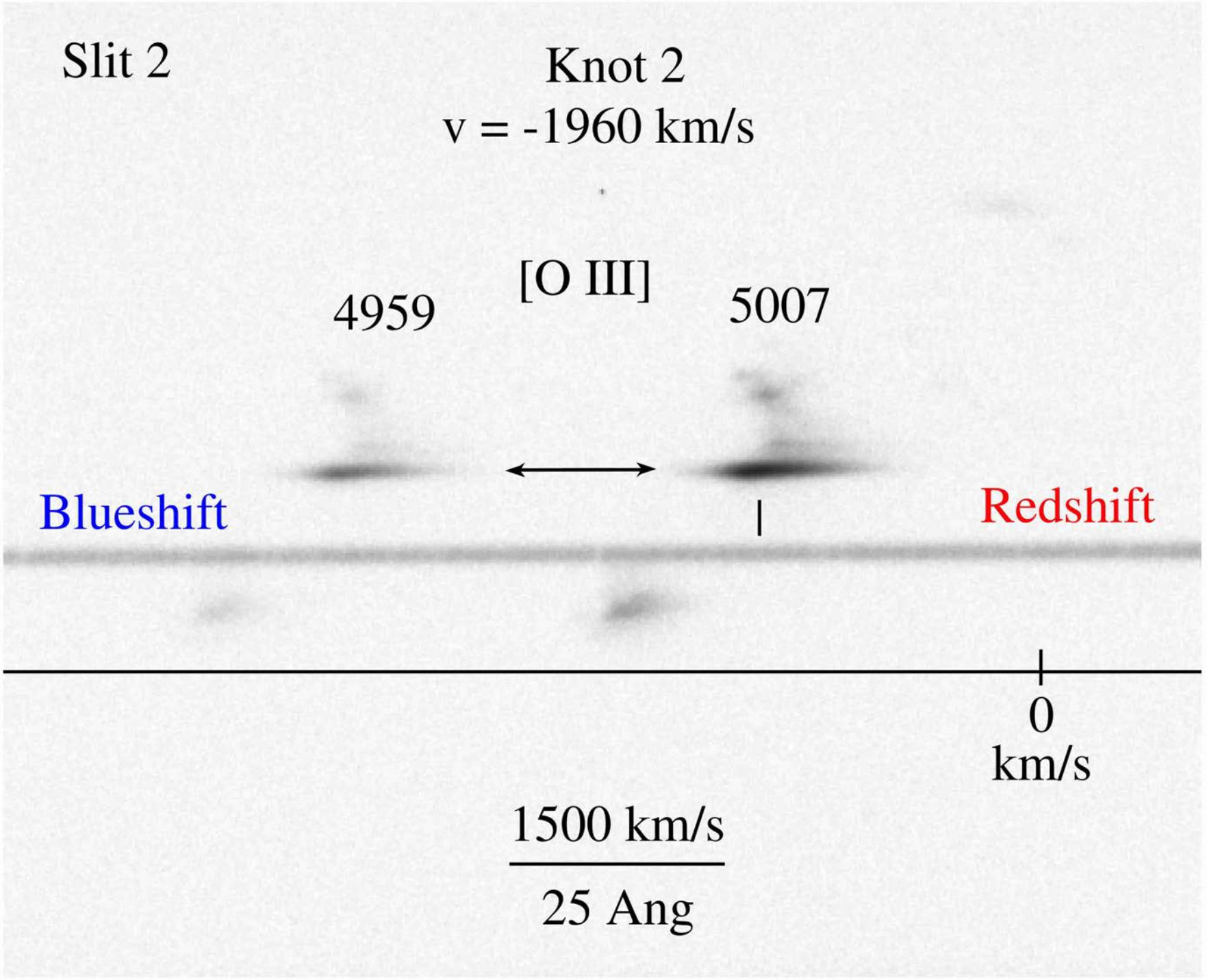





[S II] + [O II]
Dec 2004
2"
[S III]
Nov 2011
2"
[S II] + [O II]
Dec 2004
2"
[S III]
Nov 2011
2"


Slit 1
Slit 2
Slit 3
Knot 2
Knot 3
Knot 1
Knot 4
15"


Slit 1
Knot 1
v = -2190 km/s
[O III]
4959
5007
Blueshift
Redshift
0
km/s
1500 km/s
25 Ang


Slit 2
Knot 2
v = -1960 km/s
[O III]
4959
5007
Blueshift
Redshift
0
km/s
1500 km/s
25 Ang

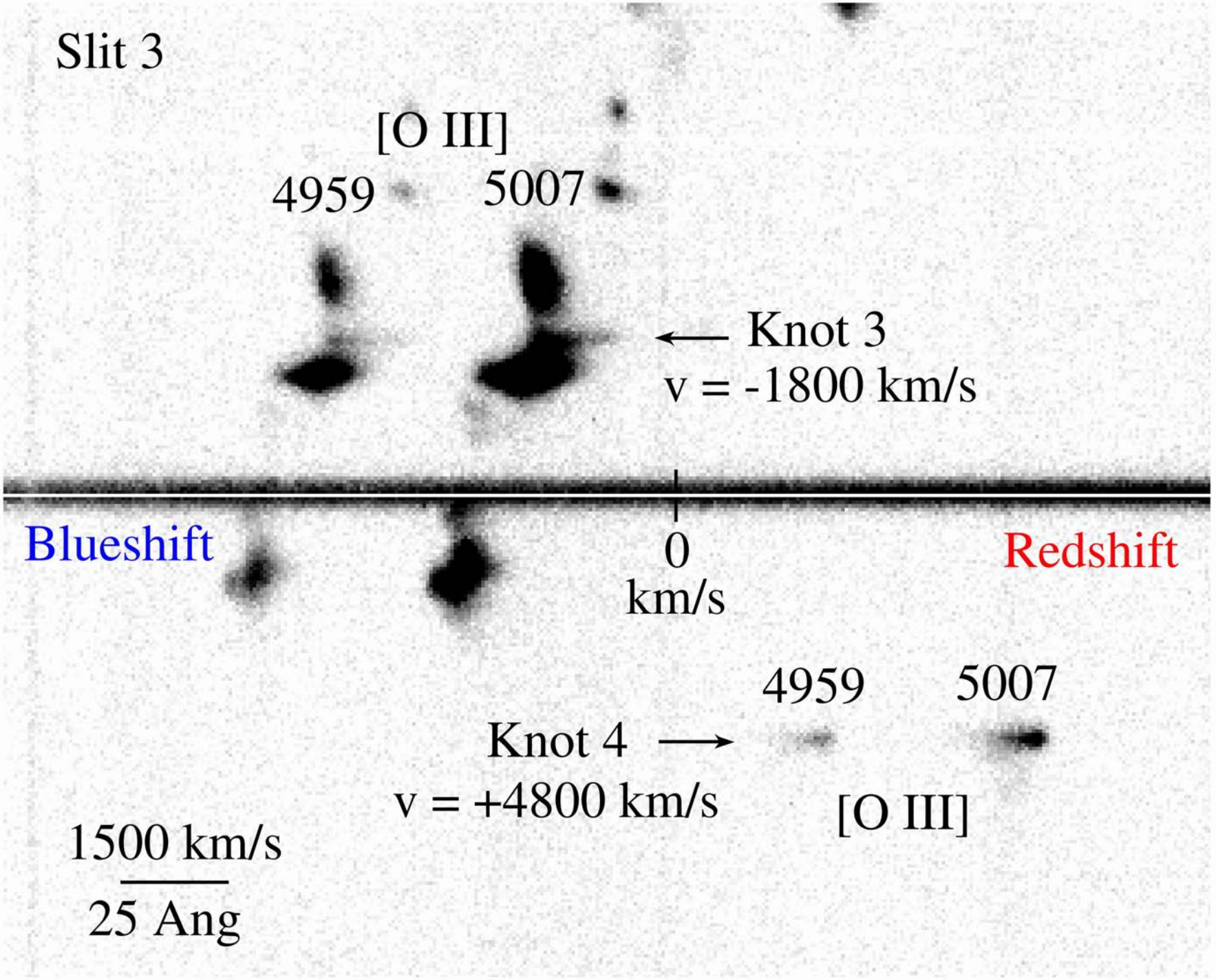
Take Aways

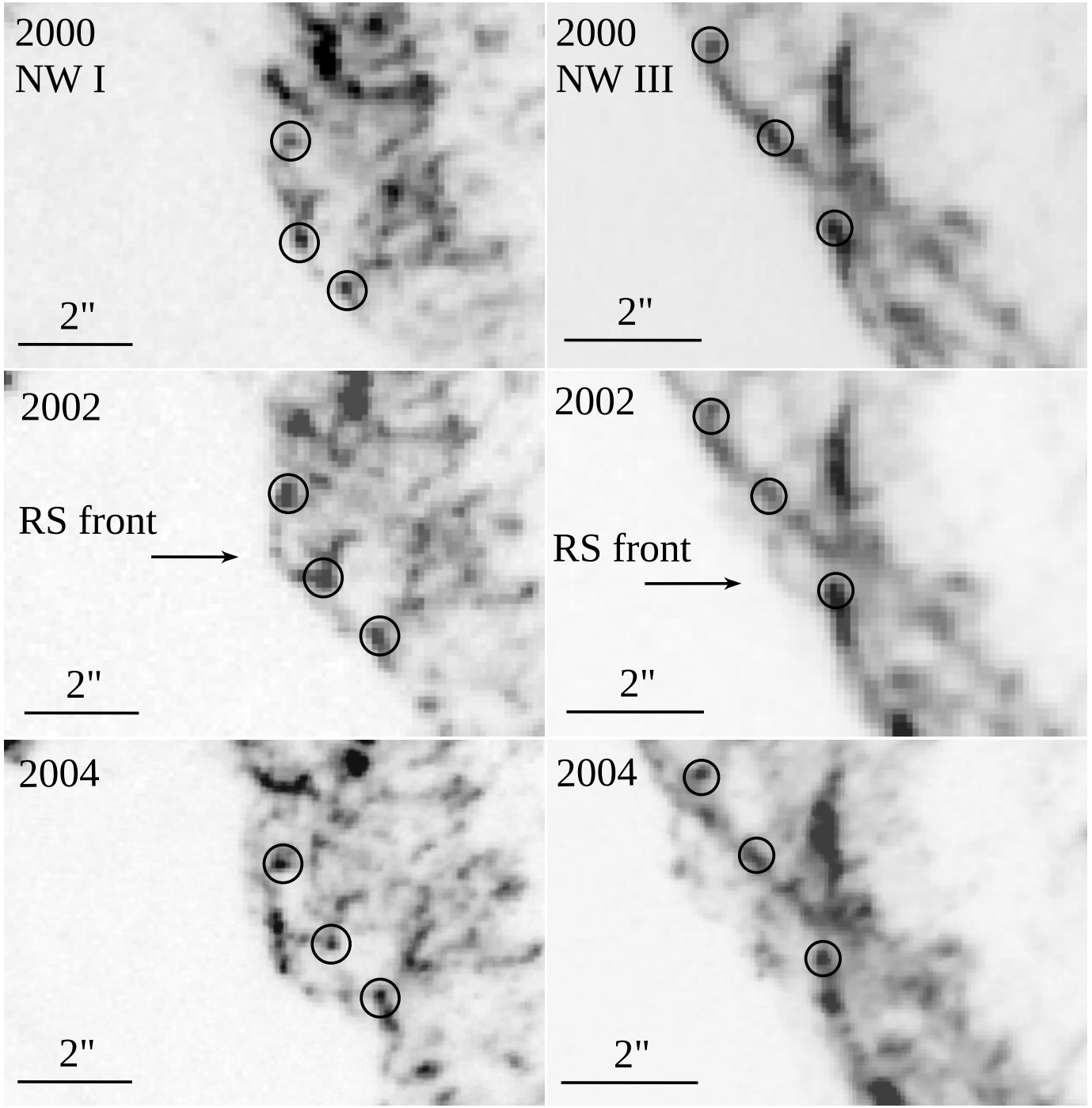
1) The velocity of Cas A's reverse shock seems to depend on the density of ejecta knots it is moving around and through.
-- ejecta dense regions $V_{RS\ ejecta}$ = 1000 – 3000 km/s
-- lower density regions $V_{RS\ ejecta}$ = 5000 – 6000 km/s

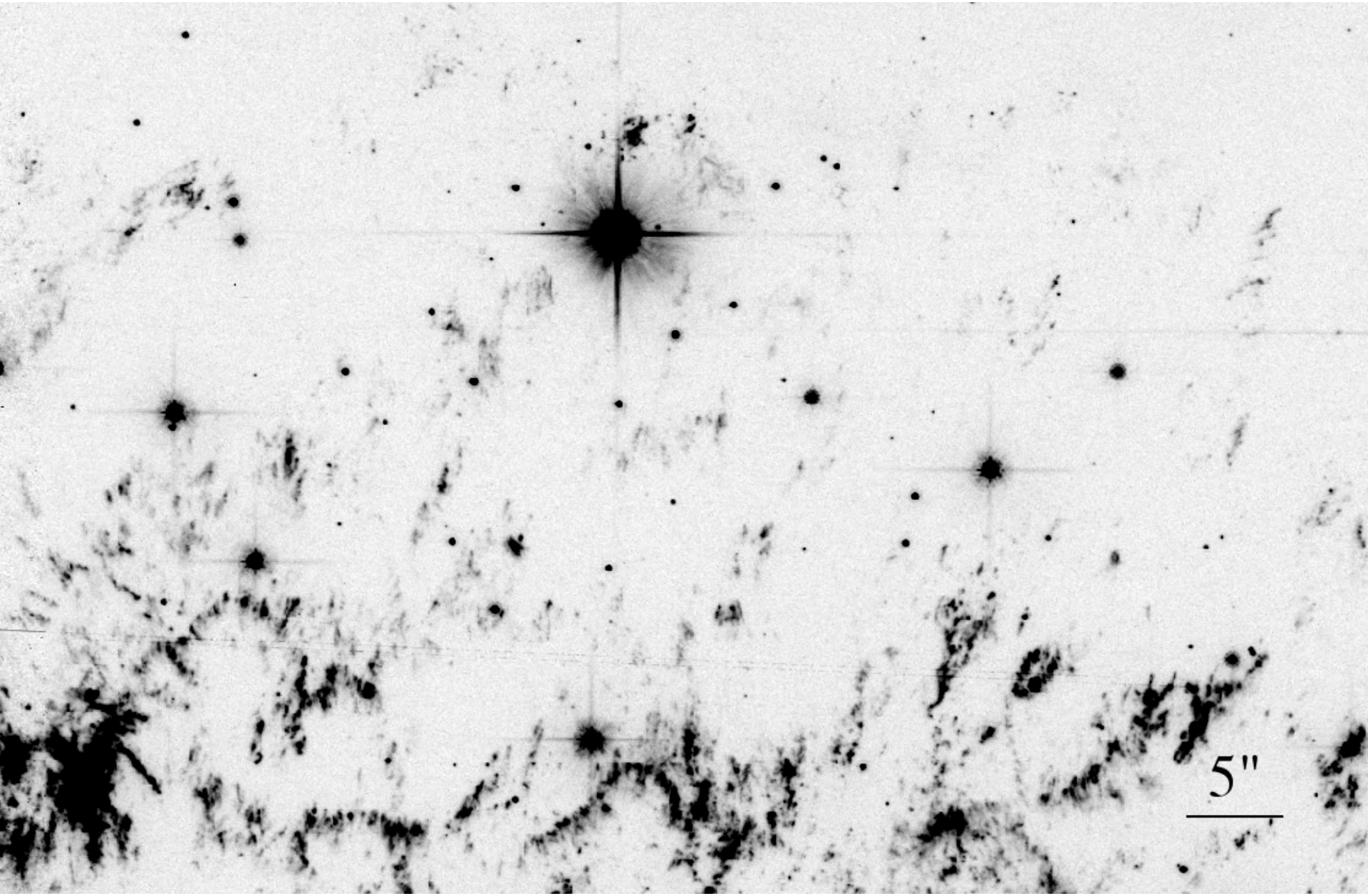
RS radius wrt COE: 1.4 pc – 1.8 pc

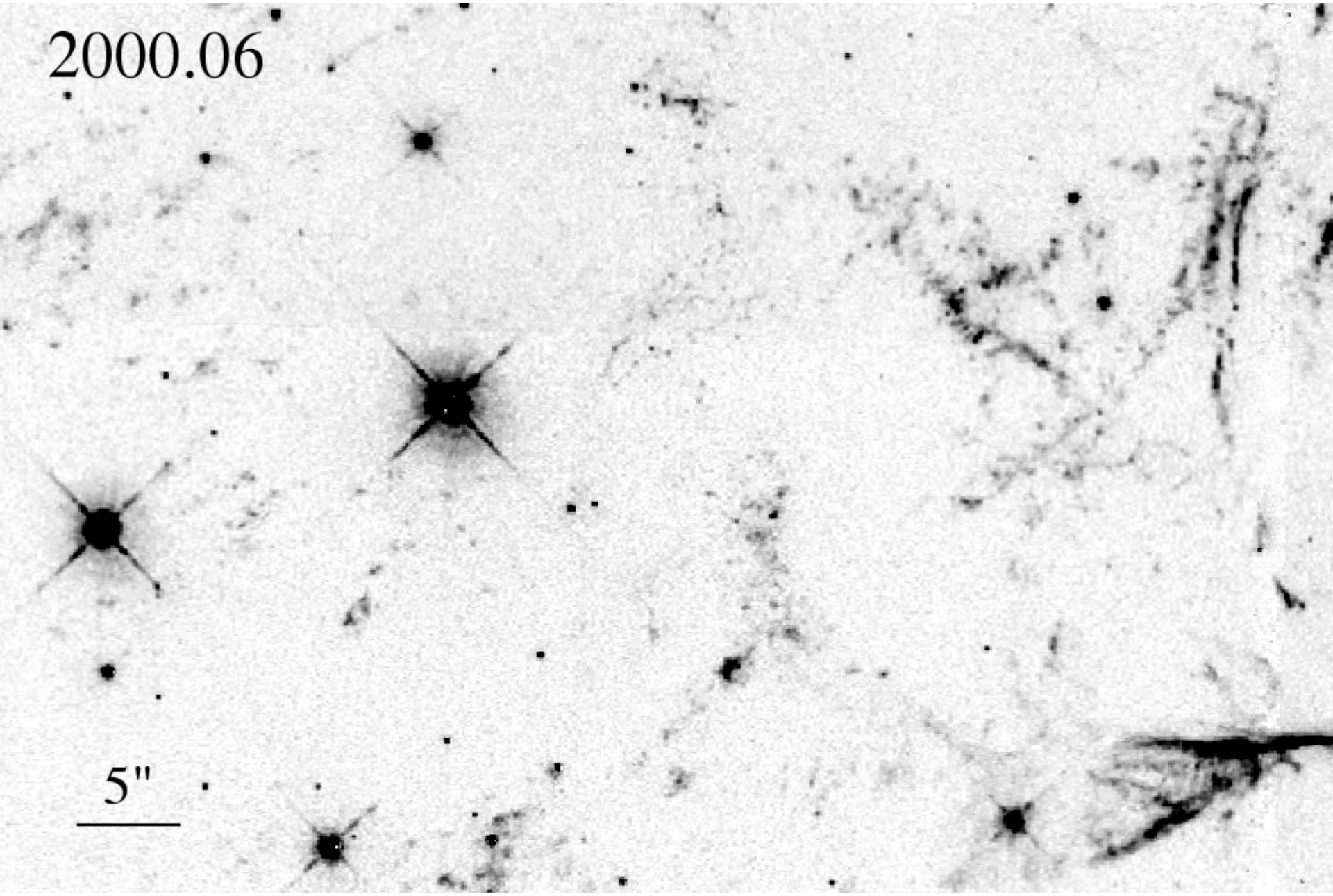
Why is the reverse shock velocity so high? Unclear.
Interaction of the forward shock with dense CSM clouds, along with varying ejecta density profiles (n=7 to ?) may play a role in increasing Cas A's reverse shock velocity.

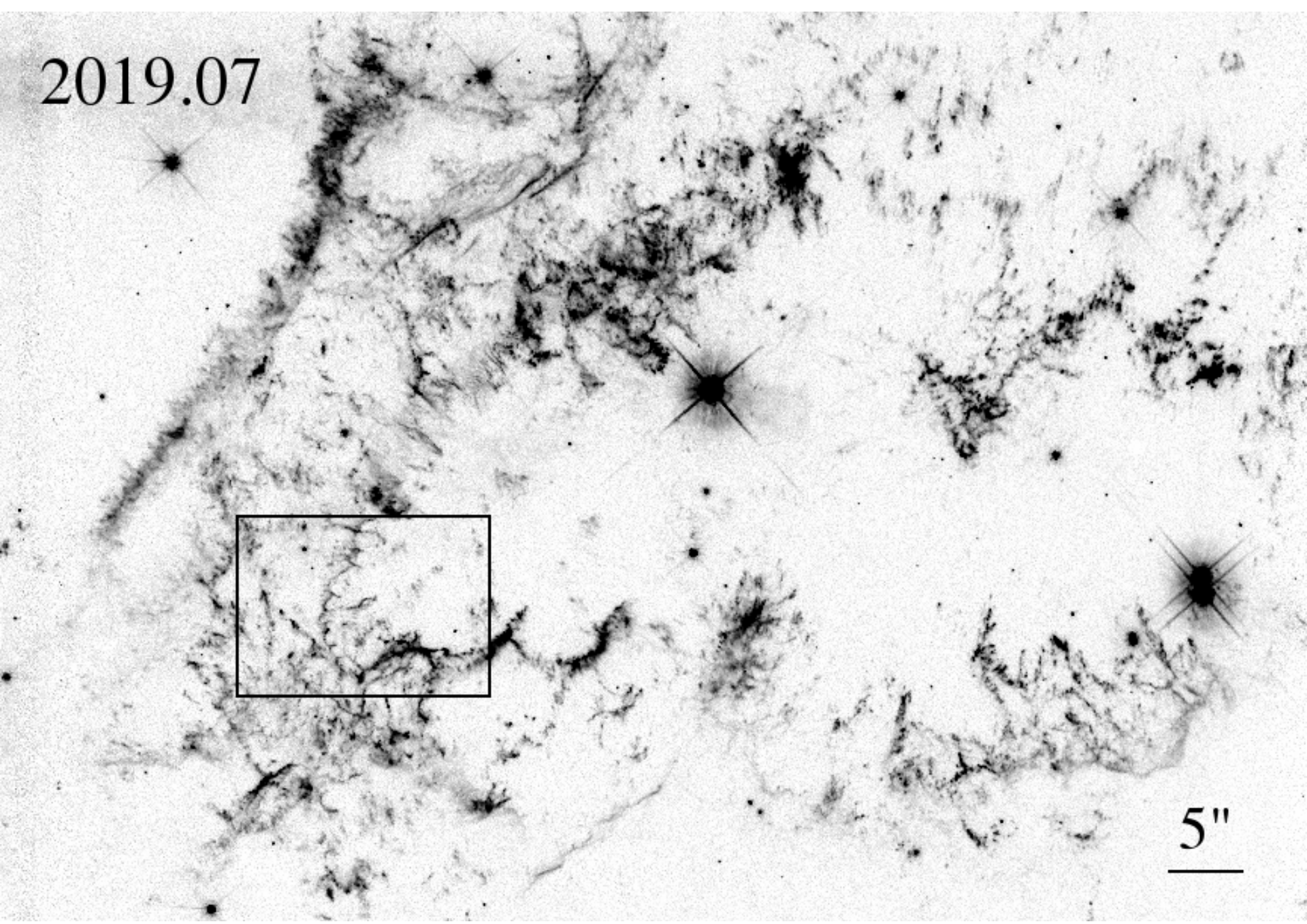
2) Cas A's reverse shock front strips the outer layers of small dense ejecta knots creating long, contrail-like streams (~0.008 pc long and slower (500 – 1000 km/s) of higher ionized material.

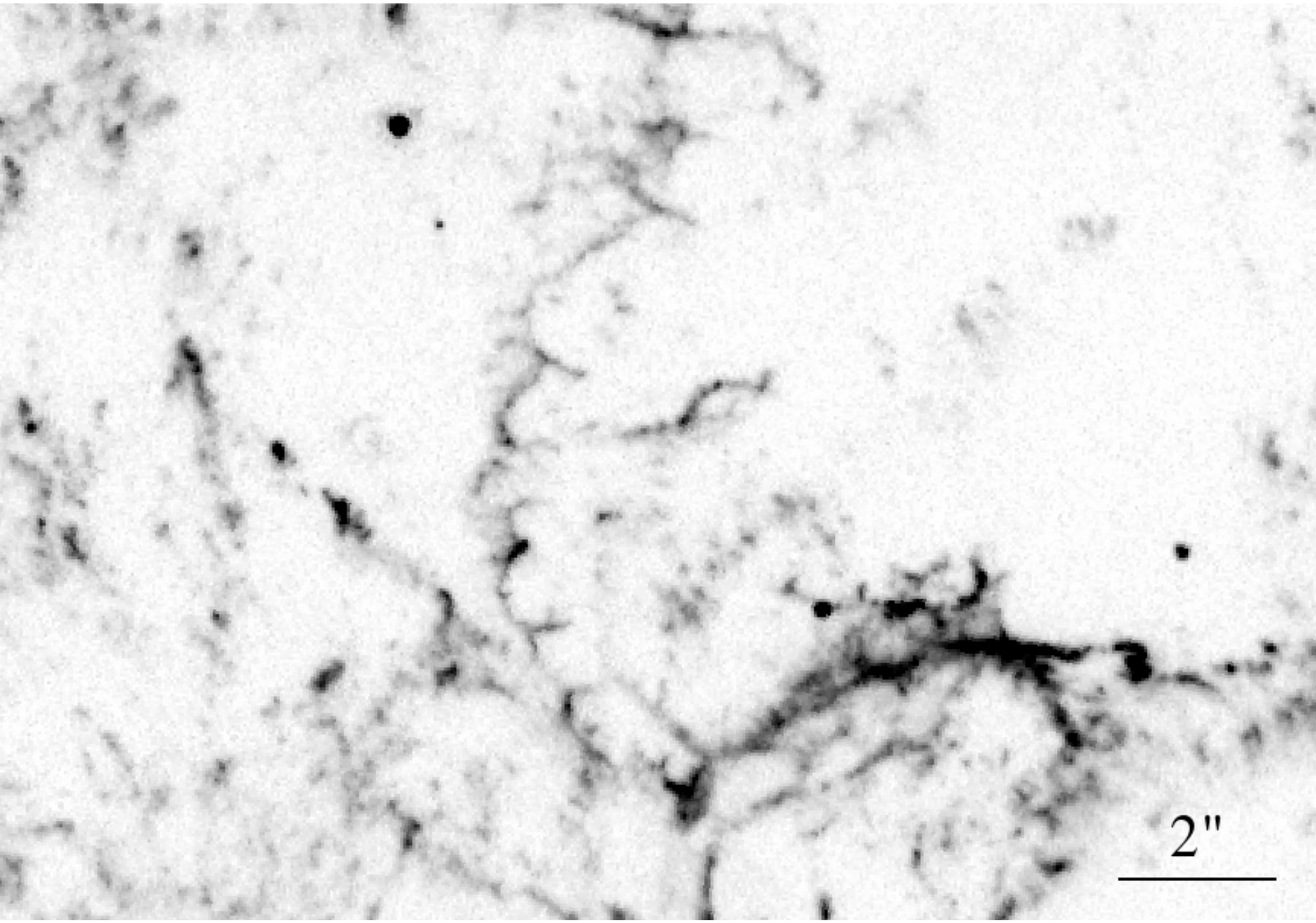

Slit 3
[O III]
4959
5007
← Knot 3
v = -1800 km/s
Blueshift
0
km/s
Redshift
4959
5007
Knot 4 →
v = +4800 km/s
[O III]
1500 km/s
25 Ang


2000
NW I
2"
2000
NW III
2"
2002
RS front
2"
2002
RS front
2"
2004
2"
2004
2"


5"


2000.06
5"


2019.07
5"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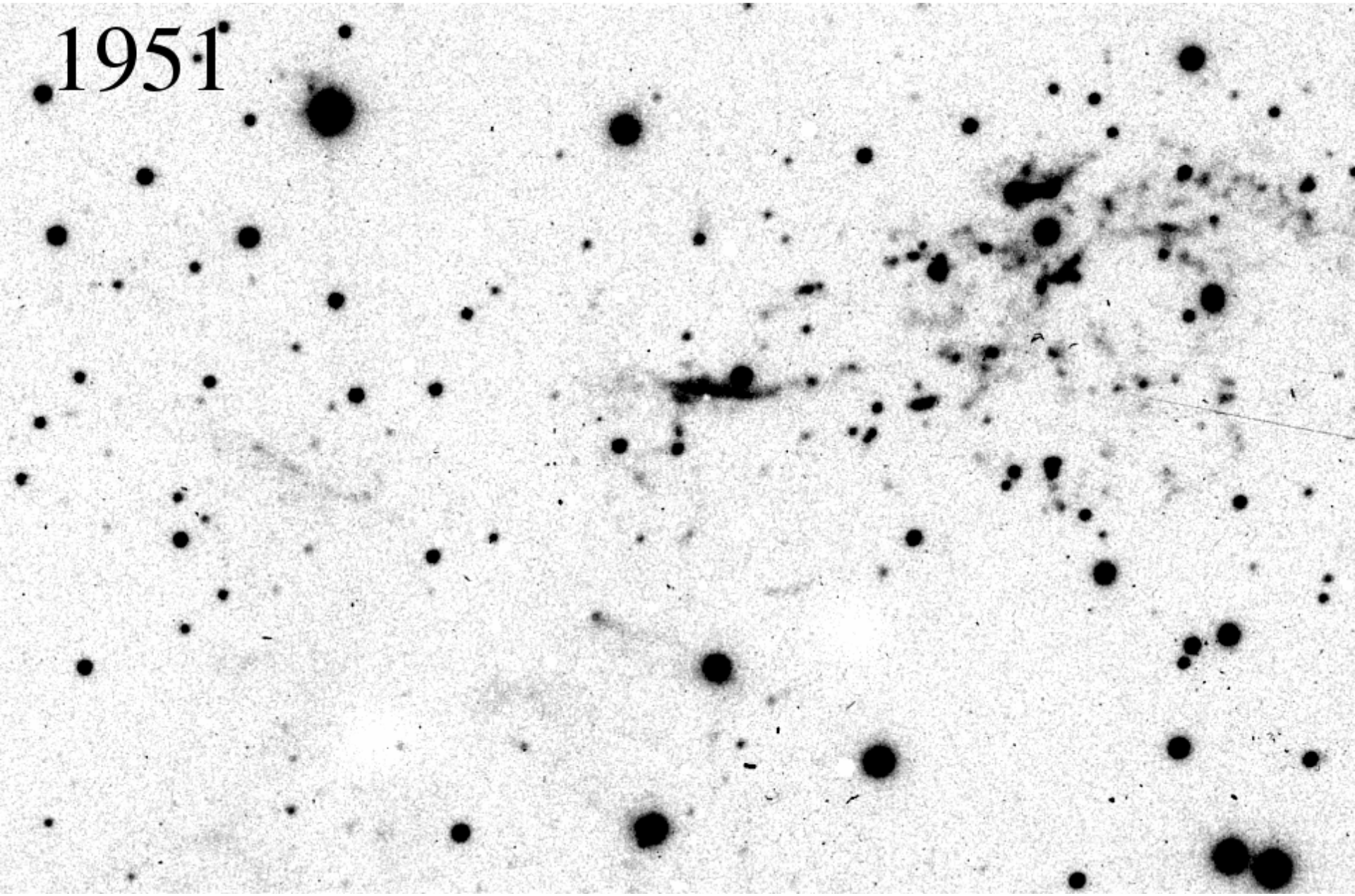

1951

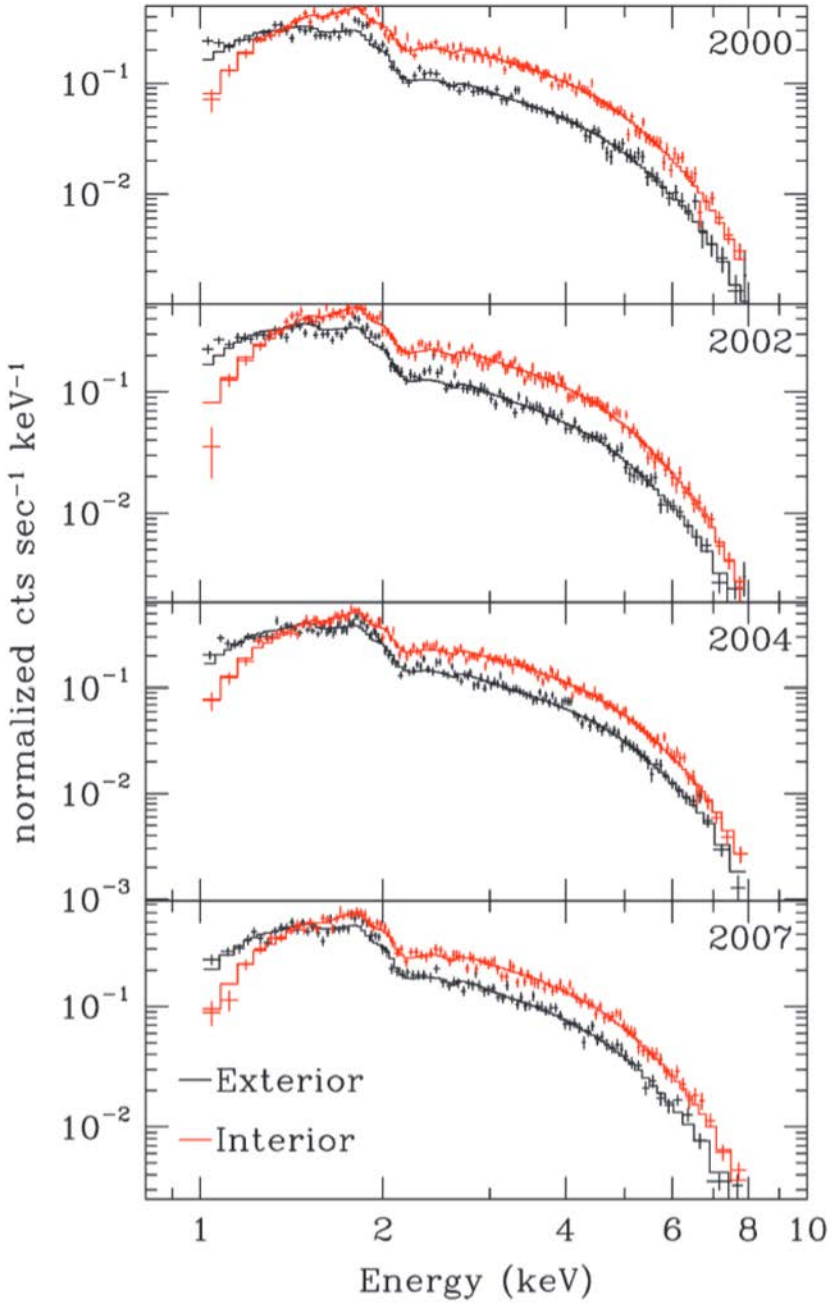
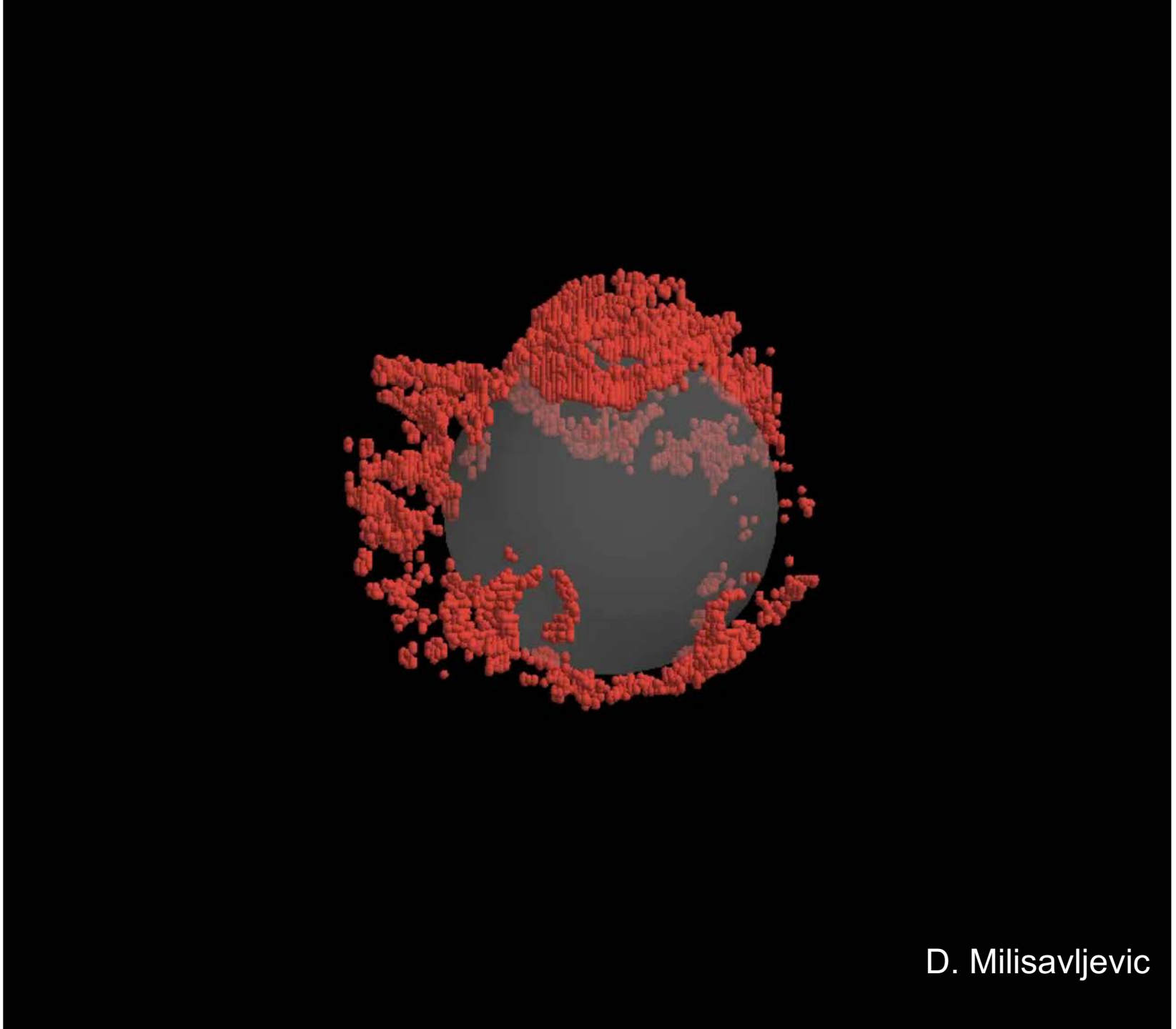
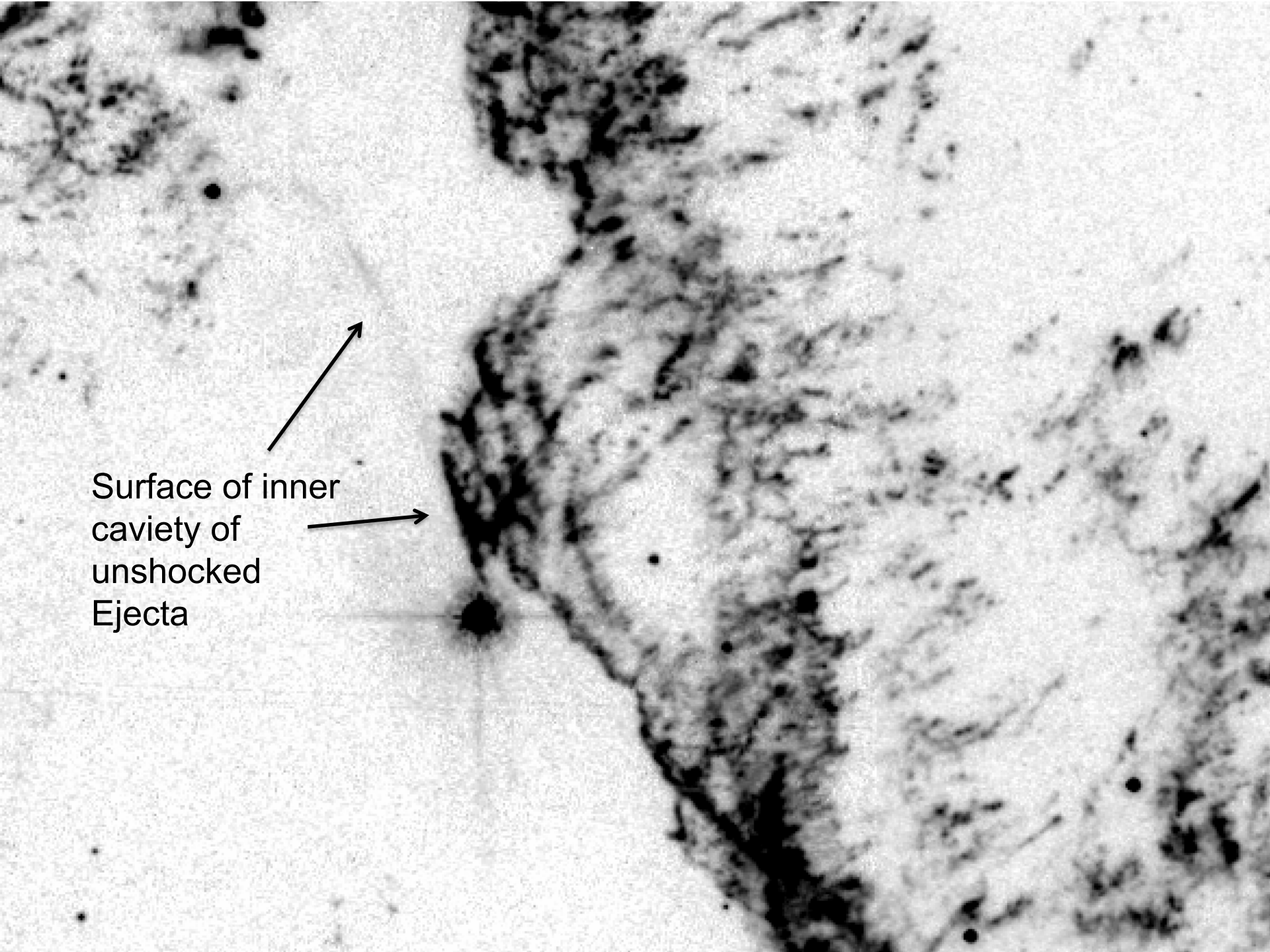
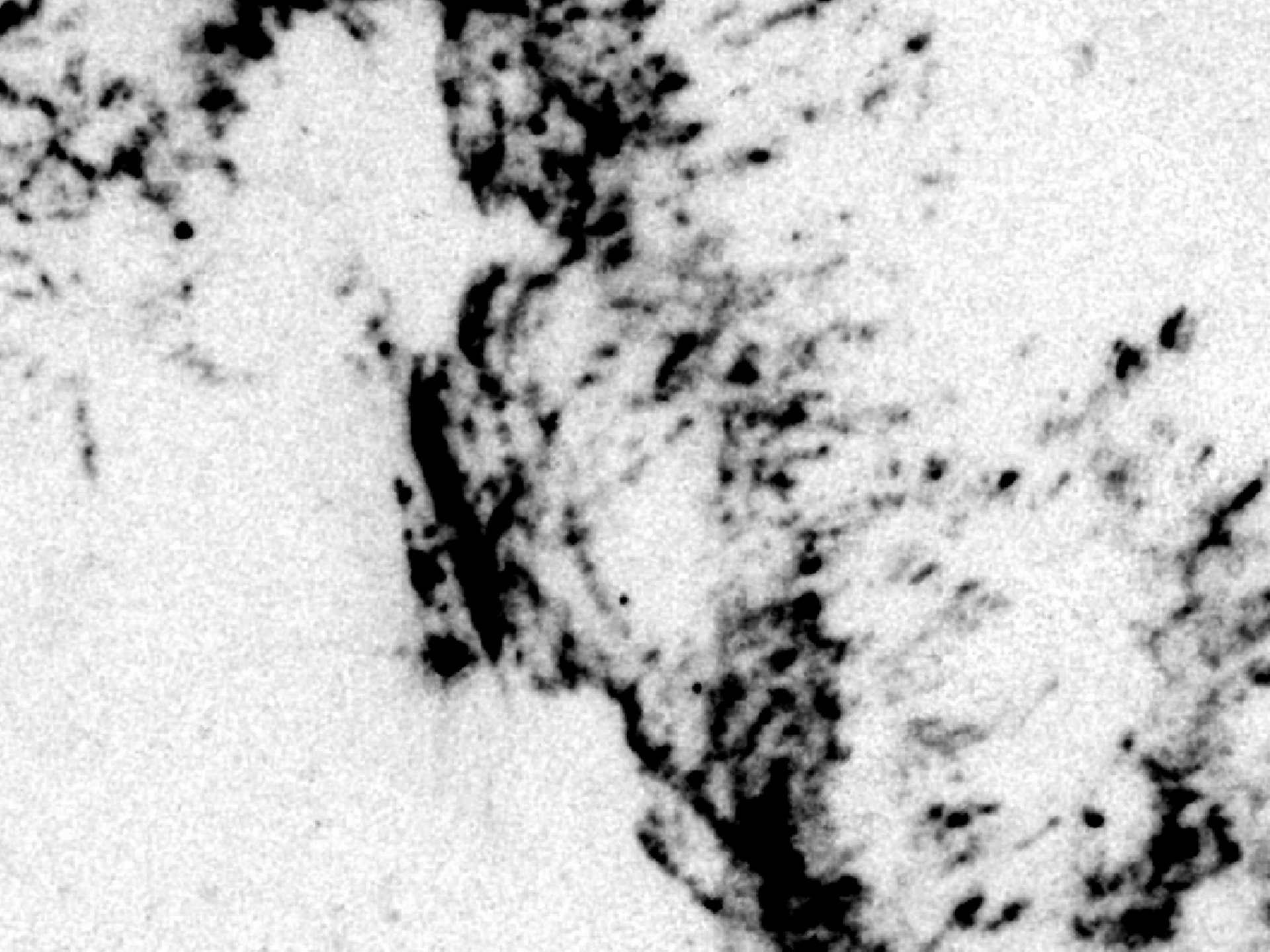
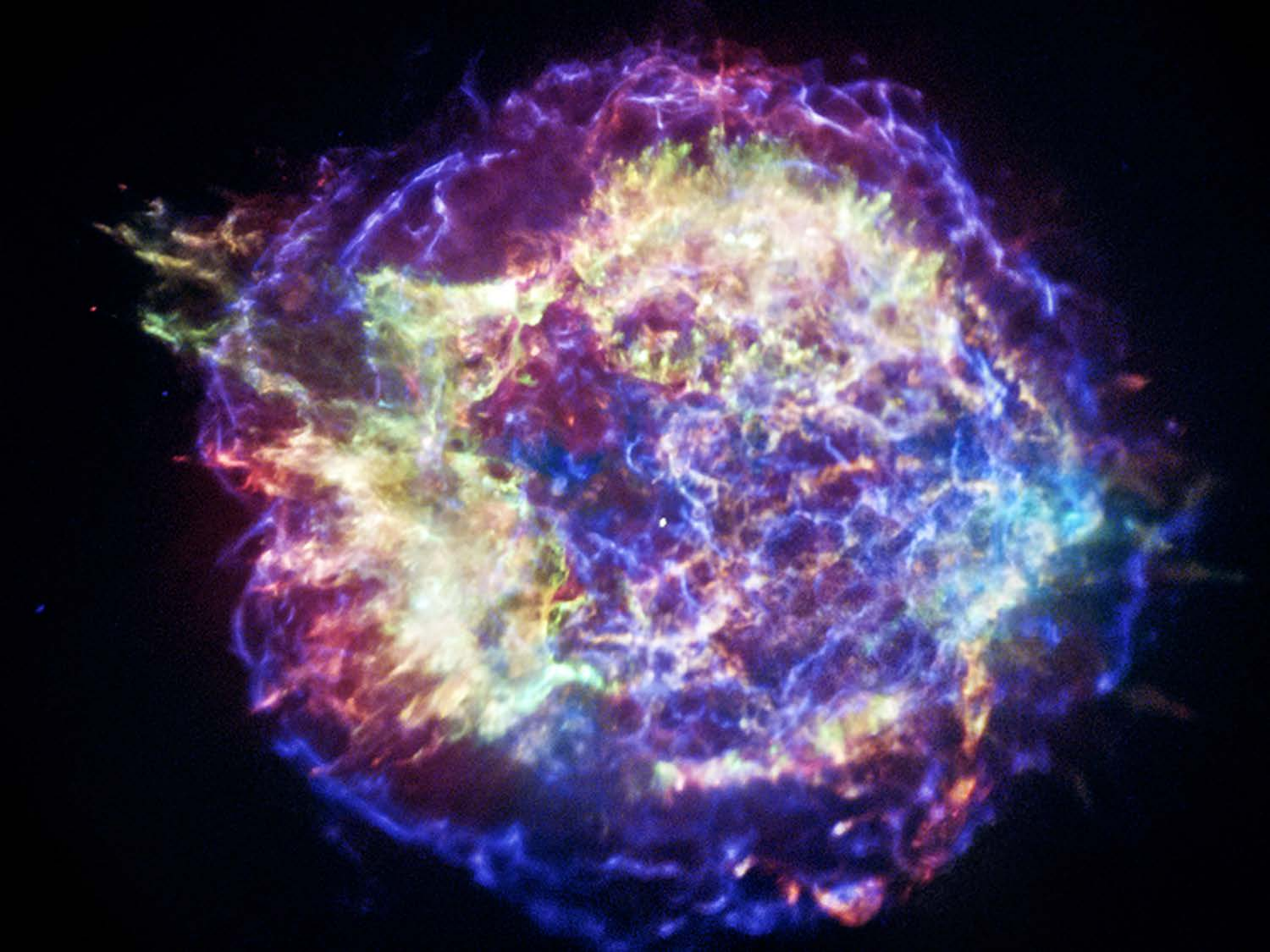


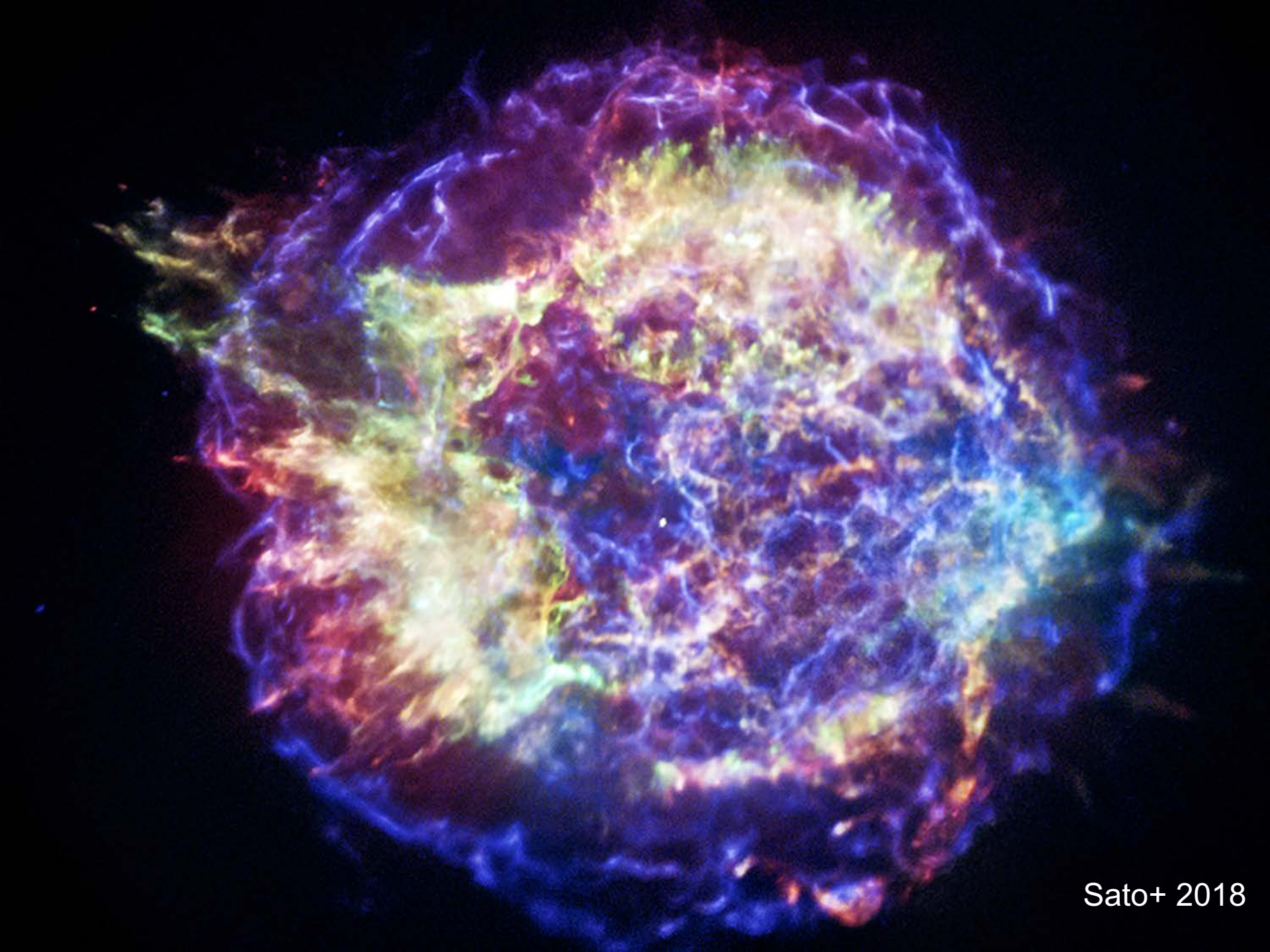
Figure 6. Extracted spectra for forward shock and interior nonthermal filaments.


D. Milisavljevic


Surface of inner
caviety of
unshocked
Ejecta






Sato+ 2018

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