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The strange behavior of the reverse shock of Cassiopeia A

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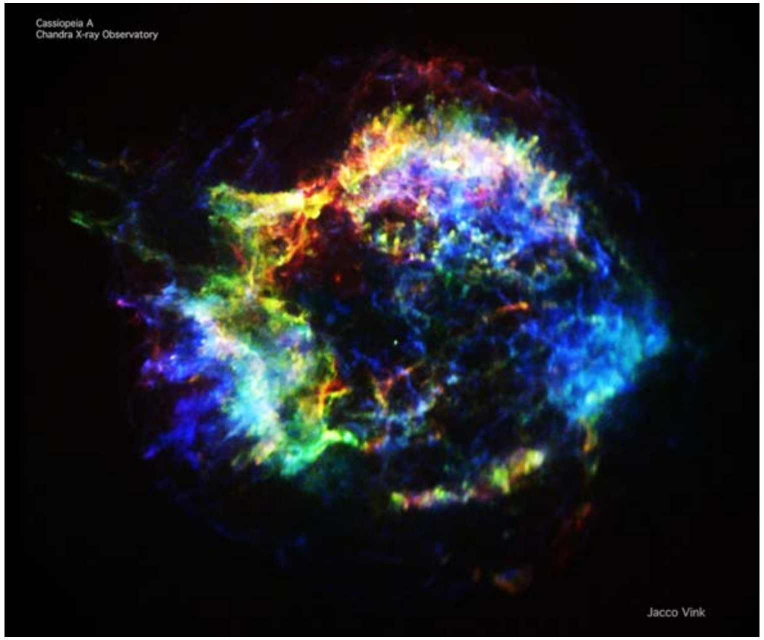
Chandra observations of Cassiopeia A



- First light image: 1999
- 1Ms (VLP): 2004 (PI: U. Hwang)
- Since 2008: monitoring of Cas A (PI: Patnaude)

- Work presented here:
  - Expansion measurements of Cas A in *4.2-6 keV* band (*continuum*)
  - Collaborators: JV, D. Castro, R. Fesen, M. Laming,..
  - Work in progress

Velocity needed for X-ray synchrotron

- Synchrotron loss-time

$$\tau_{\rm syn} = \frac{E}{dE/dt} = 12.5 \left(\frac{E}{100\ {\rm TeV}}\right)^{-1} \left(\frac{B_{\rm eff}}{100\mu{\rm G}}\right)^{-2}\ {\rm yr.}$$

- Diffusive acceleration time (depends on diffusion coeff. D, compression X)

$$\tau_{\rm acc} \approx 1.83 \frac{D_2}{V_{\rm s}^2} \frac{3\chi^2}{\chi - 1} = 124\eta B_{-4}^{-1} \left(\frac{V_{\rm s}}{5000\ {\rm km\,s^{-1}}}\right)^{-2} \left(\frac{E}{100\,{\rm TeV}}\right) \frac{\chi_4^2}{\chi_4 - \frac{1}{4}}\ {\rm yr,}$$

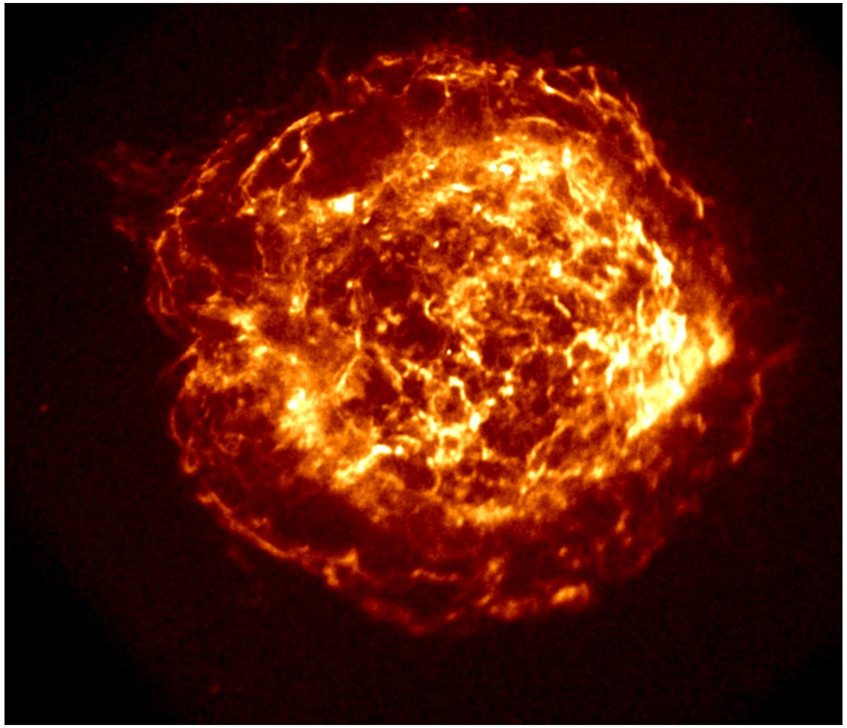
- Equating gives expected cut-off for loss-limited case

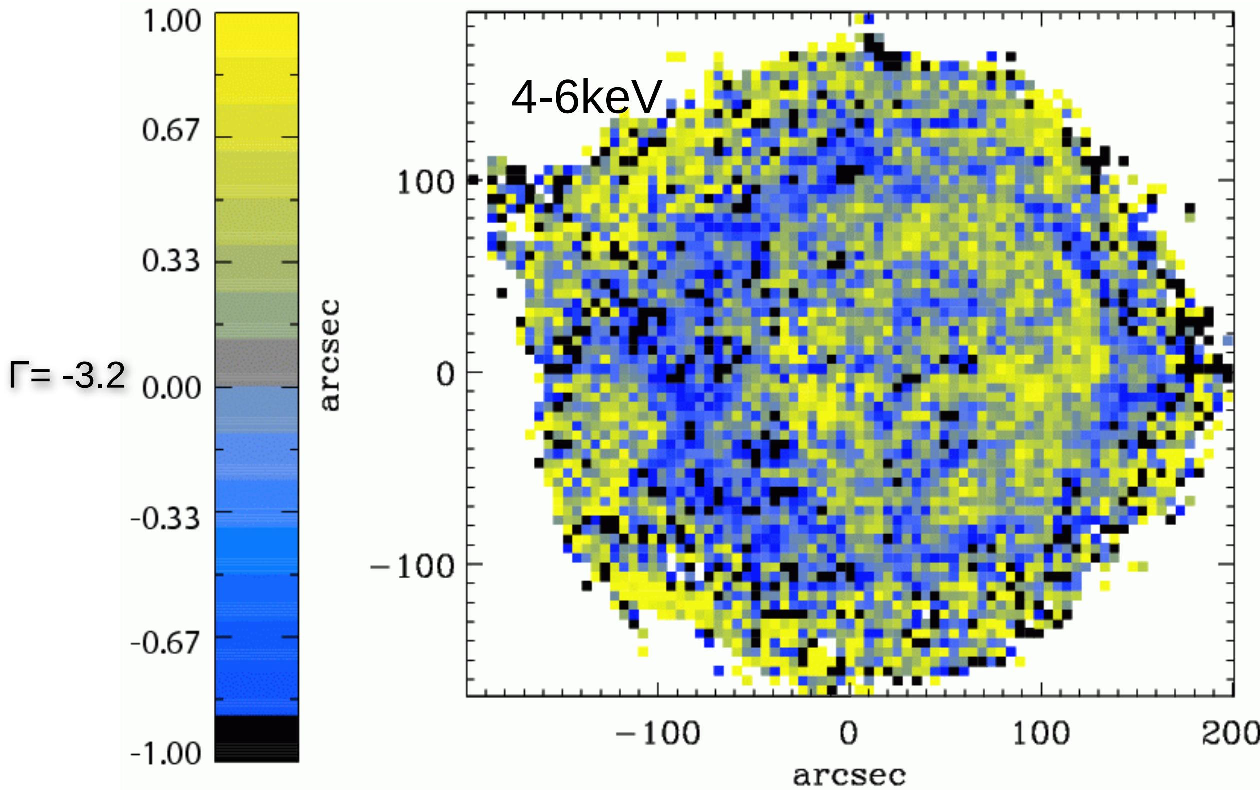
$$\boxed{h\nu_{\rm cut-off} = 1.4\eta^{-1} \left(\frac{\chi_4 - \frac{1}{4}}{\chi_4^2}\right) \left(\frac{V_s}{5000\ {\rm km\,s^{-1}}}\right)^2\ {\rm keV}}$$

- Photon energy cut-off independent of B, but depends on V_s and B-turbulence!!

Non-thermal emission

Helder& Vink 2008

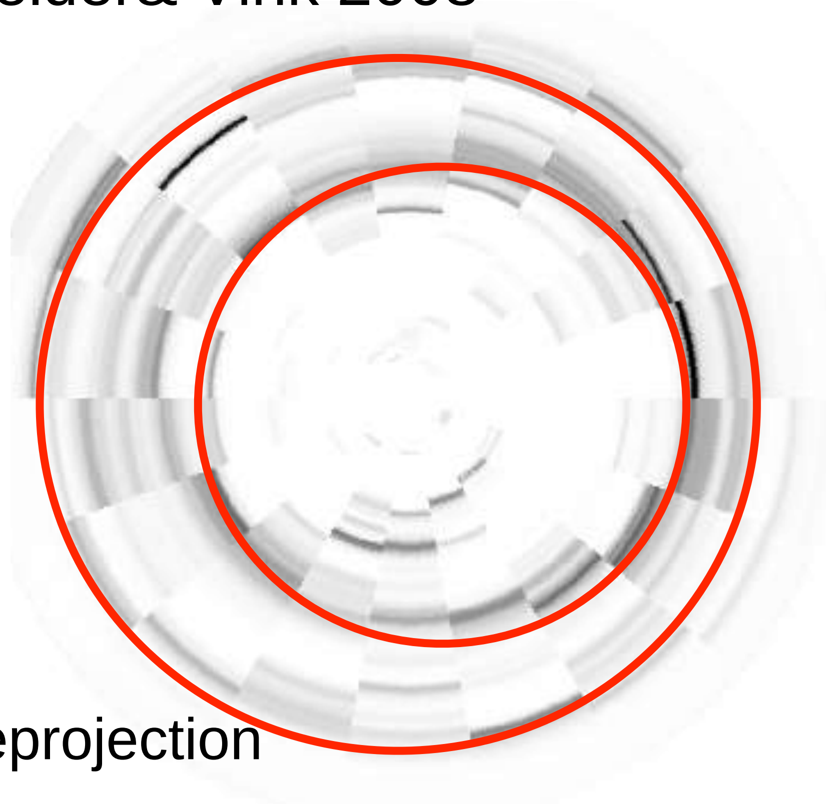




- Cas A unique (?) among young SNRs:
  - forward *and reverse shock* emit X-ray synchrotron radiation
  - reverse shock synchrotron confined to central and *western part*
  - gives outline of reverse shock in west
  - not all continuum is synchrotron (yellow)

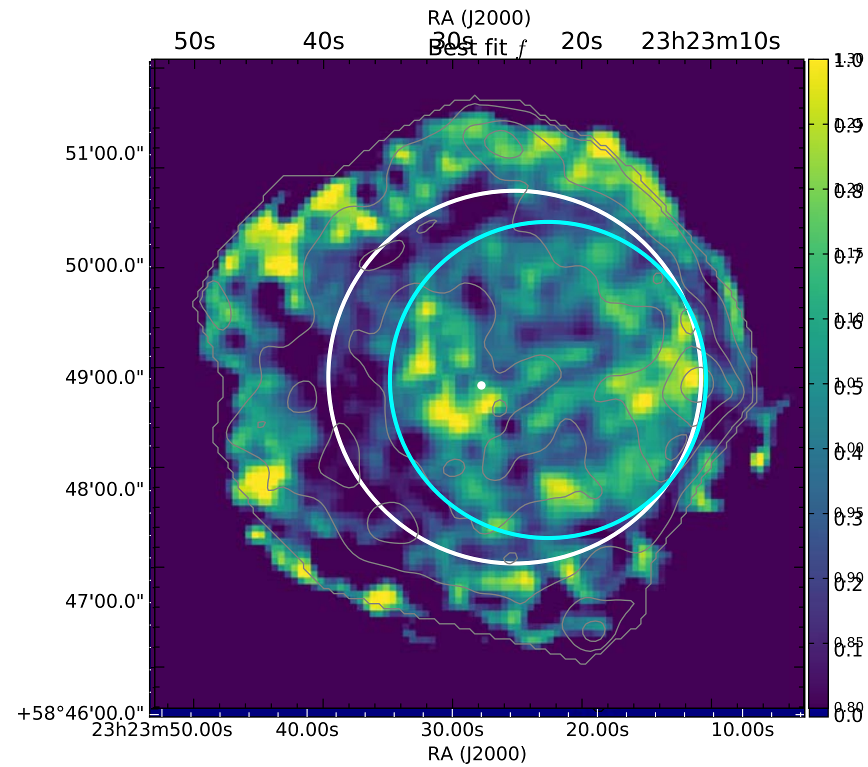
The location of the reverse shock

Helder& Vink 2008



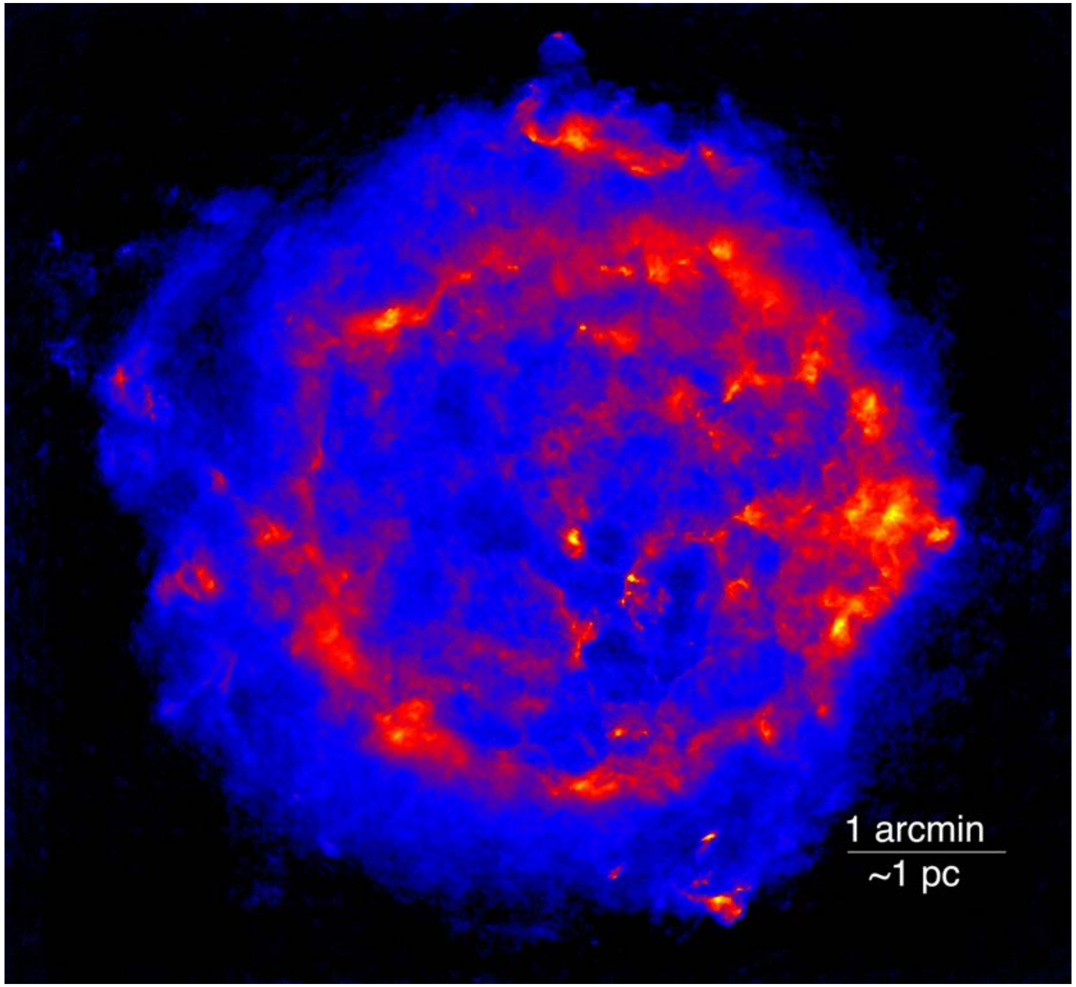
Deprojection

Arias et al 2018



- Radio absorption (LOFAR, talk by Maria Arias):
  - reverse shock larger than indicated by X-ray synchrotron
- West: forward and reverse shock close together
- What is different in the West?

Cas A in the radio



- Ring likely also electrons accelerated by reverse shock!

Previous expansion results

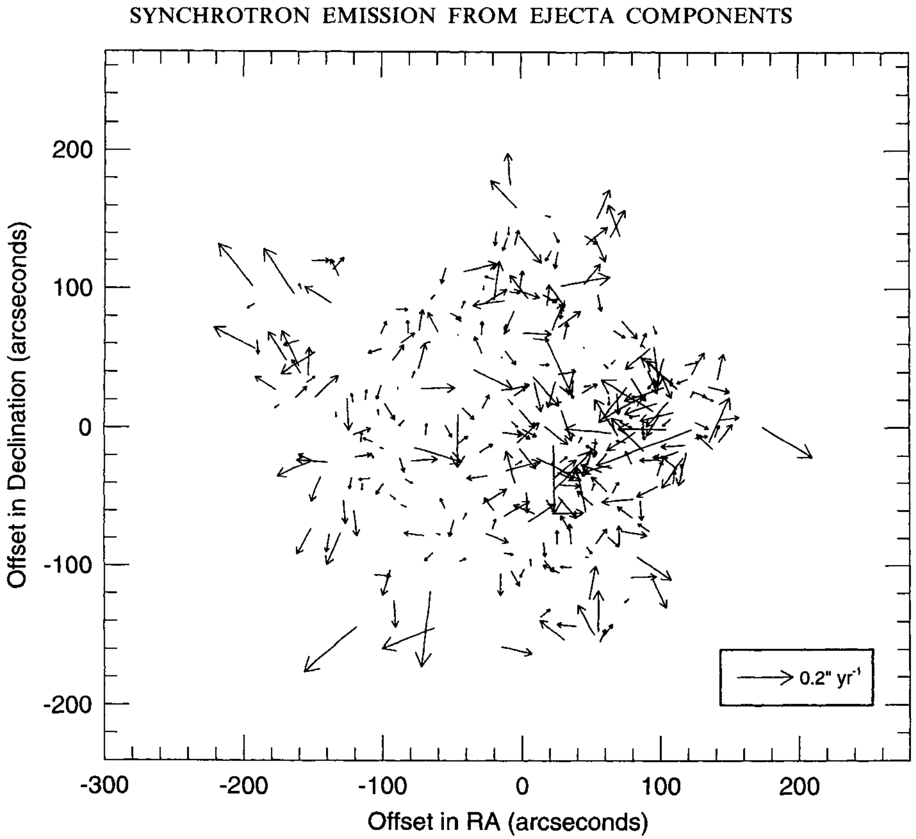
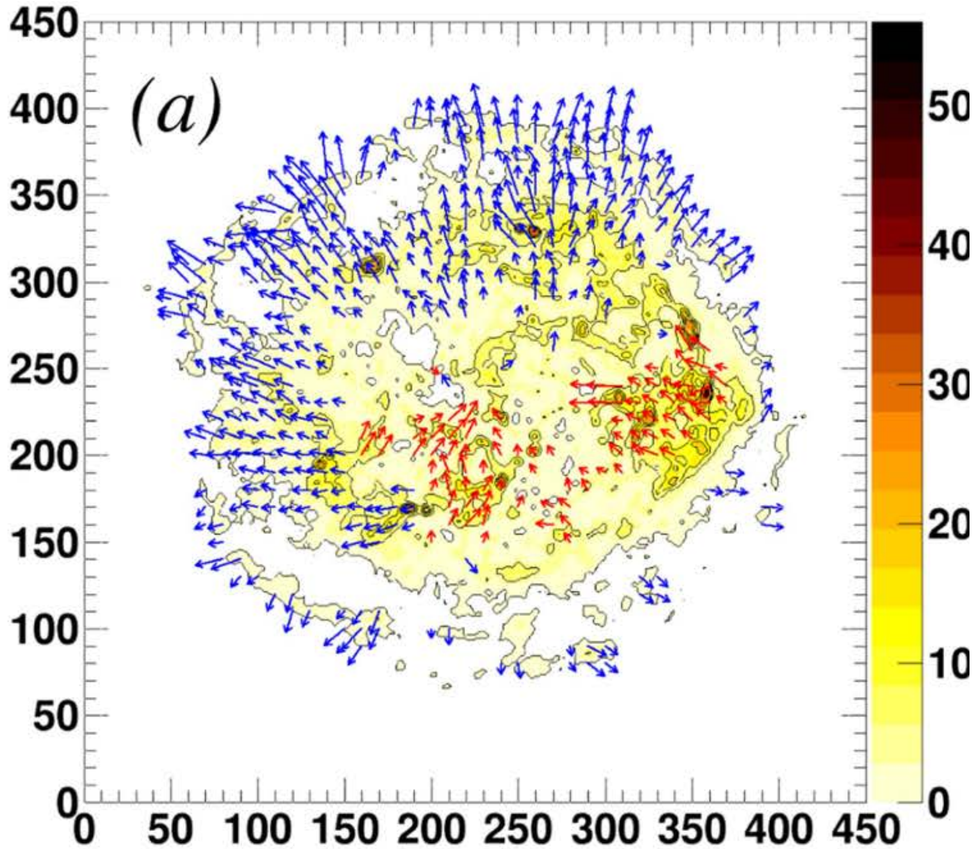


FIG. 6.—Residual velocity vectors representing the vector difference between knot proper motions and a linear expansion model



Anderson & Rudnick ’95:

- Radio: deviations from radial outflow
- Expansion slow: 800 yr time scale
- Hindsight: knots assoc. with rev. shock

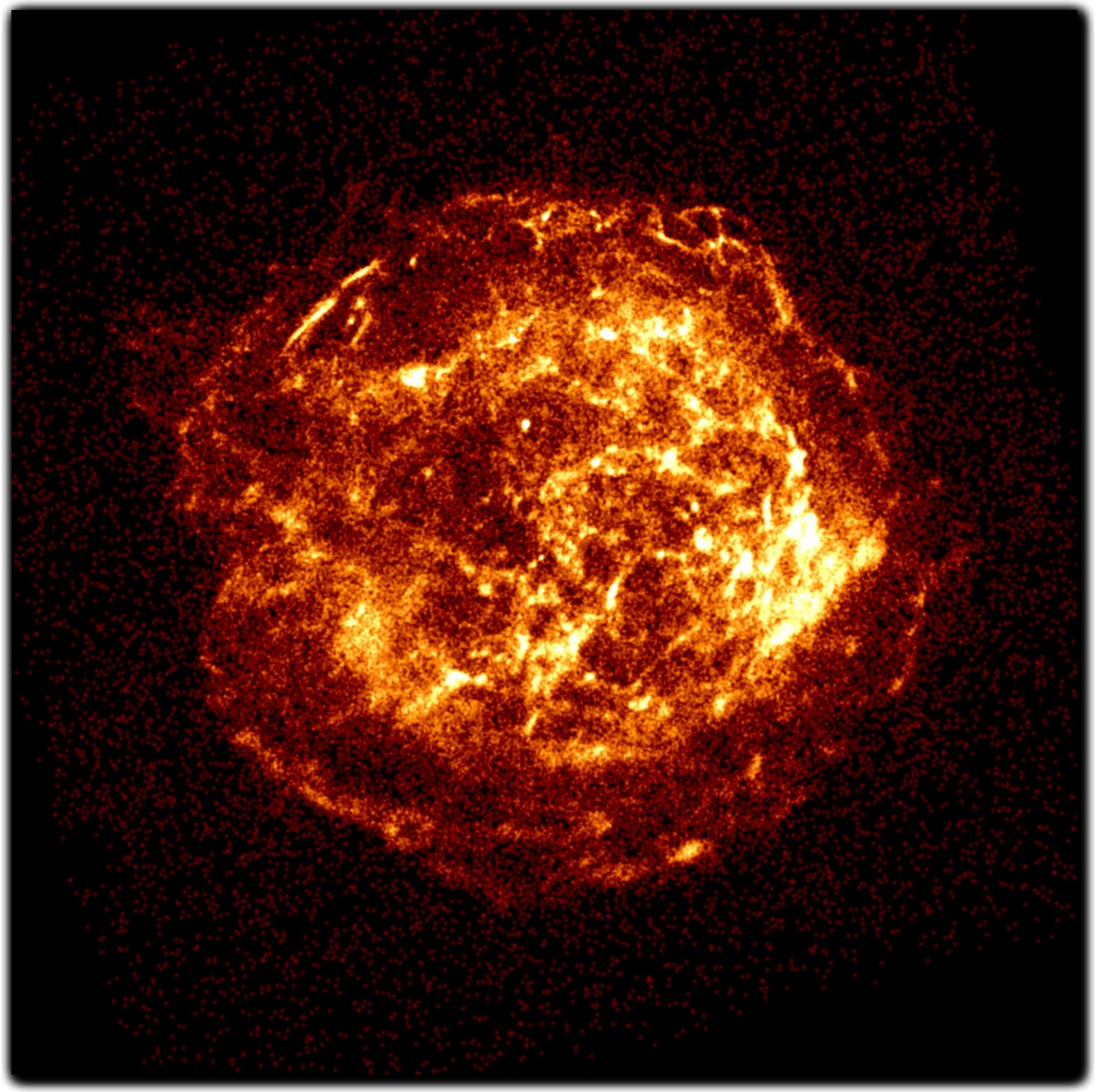
Sato+ 2018:

“Optical flow model” X-rays:

Inward motions West & SE

+ isolated regions measurements

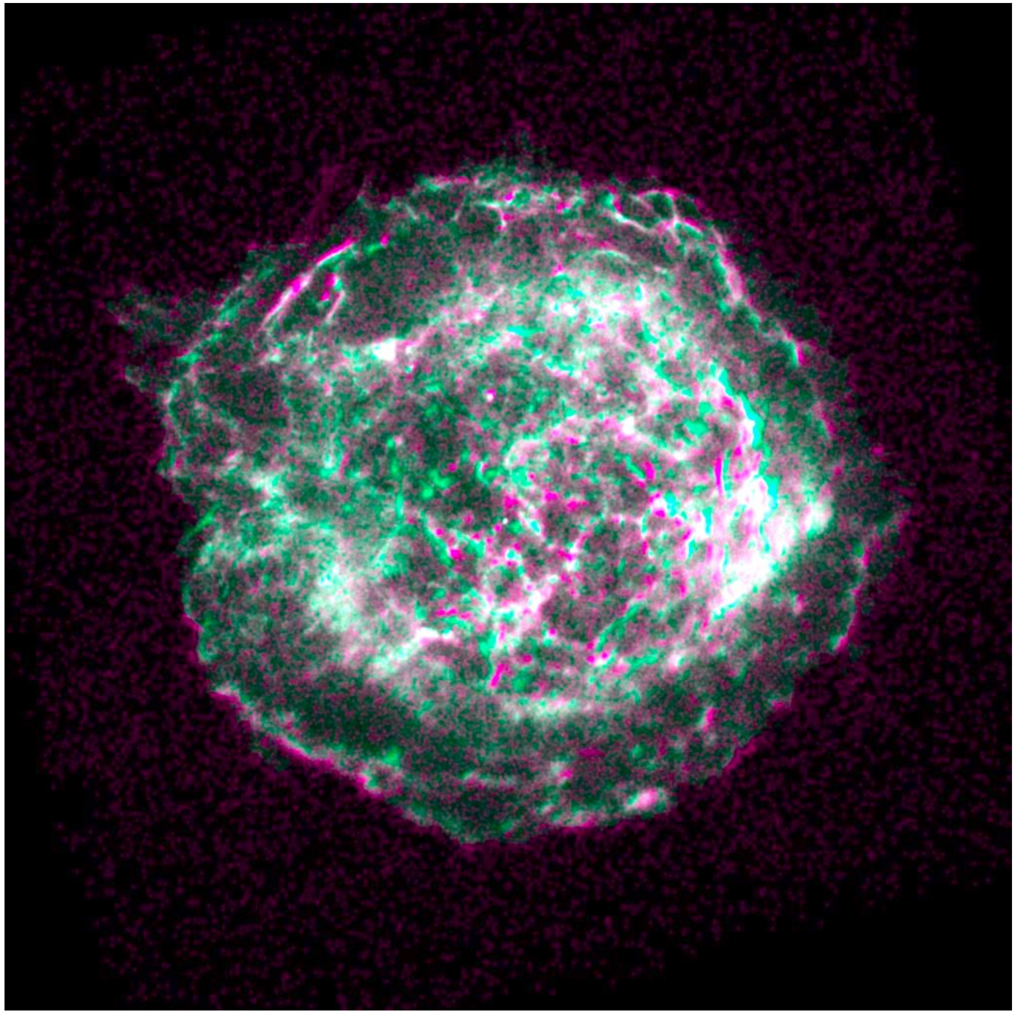
Changes 2004-2018



Expansion measurements method

- Reference (“model”) image: 2004 image (850 ks)
- Stretch image/optimise using C-statistic (Poisson maximum likelihood)
  - Extension of codes used in Vink+ 1998, Vink 2008
- Select arbitrary regions
- *New*:
  - Fit multiple images simultaneously
  - Improves statistics (expansion ages with 1 yr errors!)
  - Here: obs. 1999, (2004), 2009, 2012, 2013, 2014, 2015, 2017,2018
- Difficulty: registering the images (no point source but NS)
- Solution (for now): fit dx,dy for each image, for rev. shock/forw. region

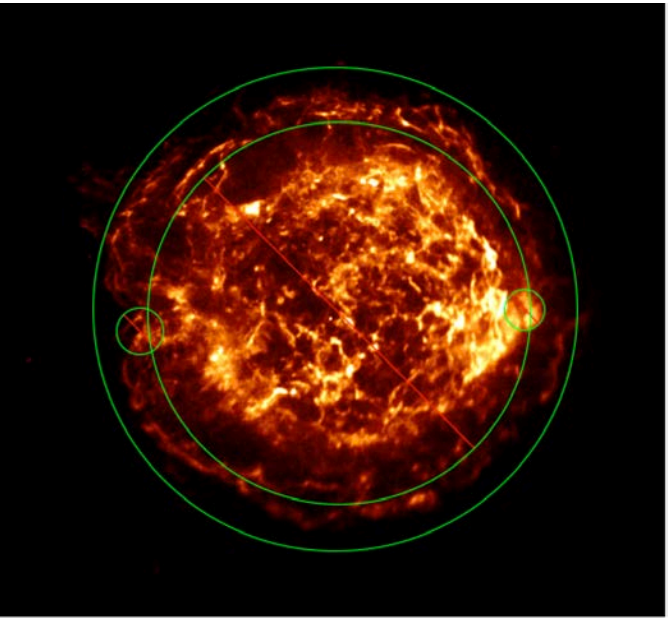
2004-2018: mean expansion corrected



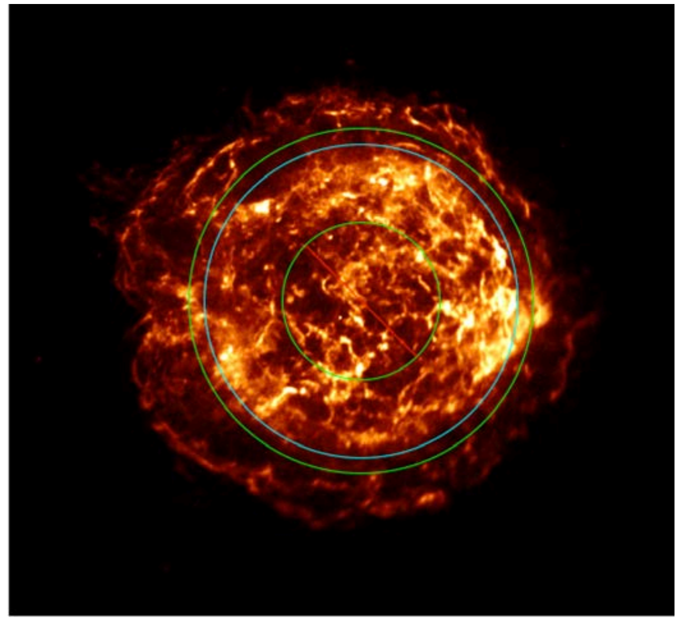
- Red: original 2018 image
- Green: 2004 image expanded to 2018 (mean expansion)
- Motion: green/red aligned filaments
- Changes in brightness: isolated colours

Fit regions

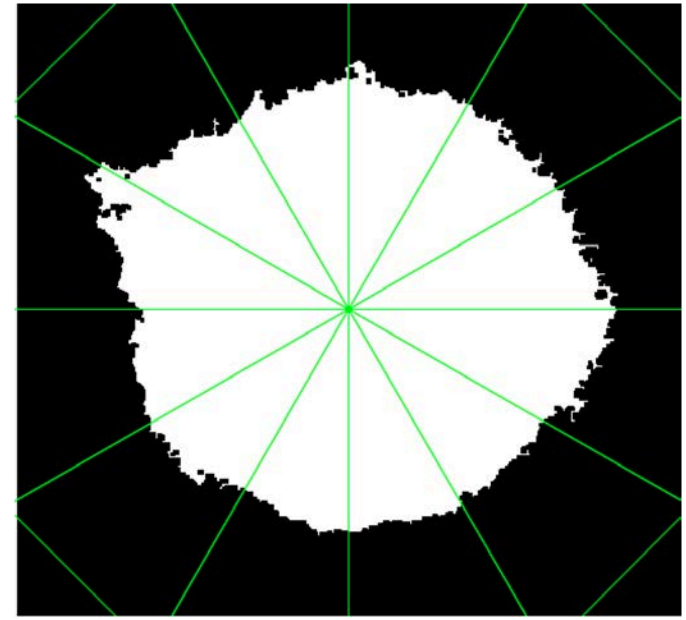
Forward shock region



Reverse shock region

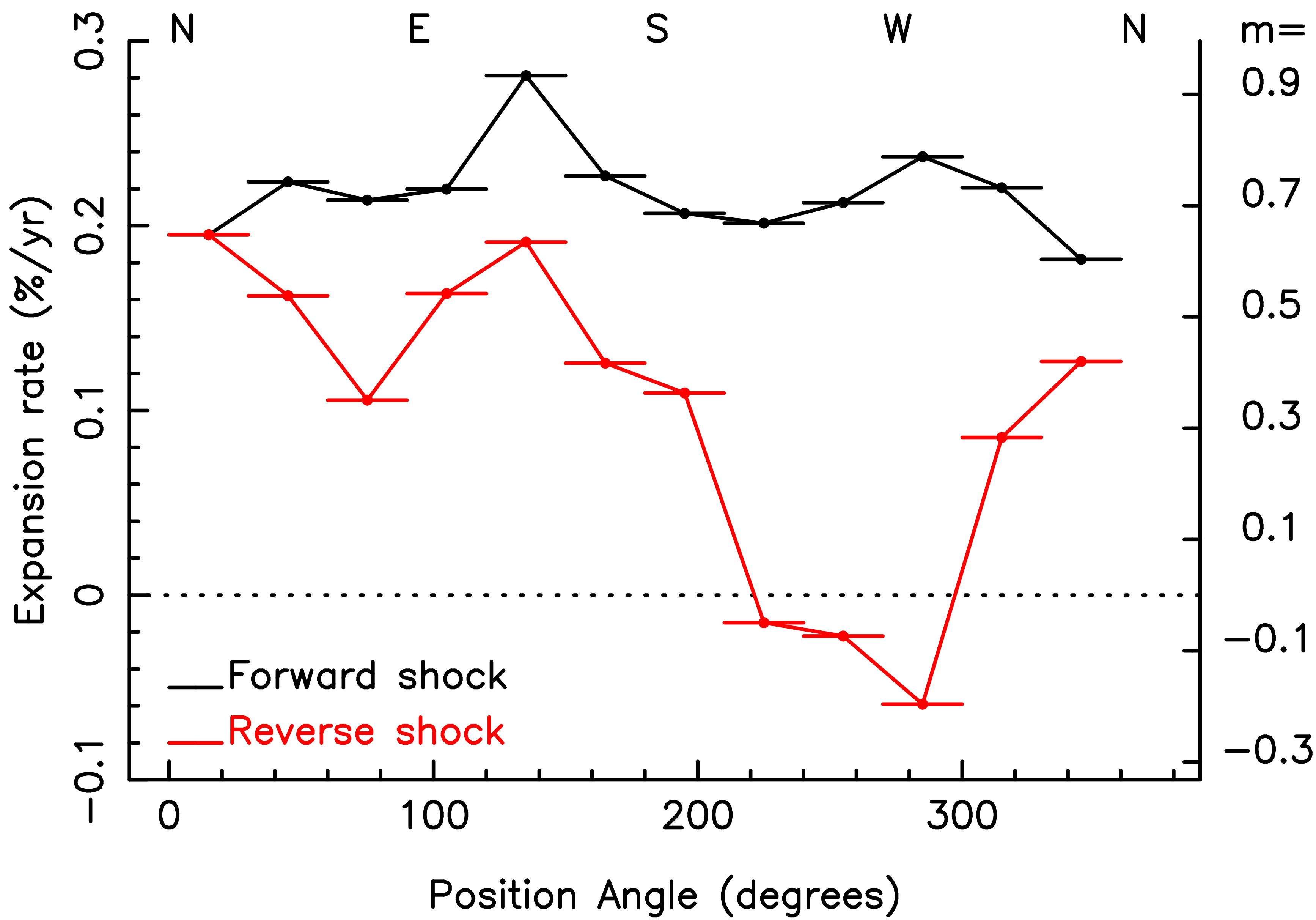


Mask/30° sectors

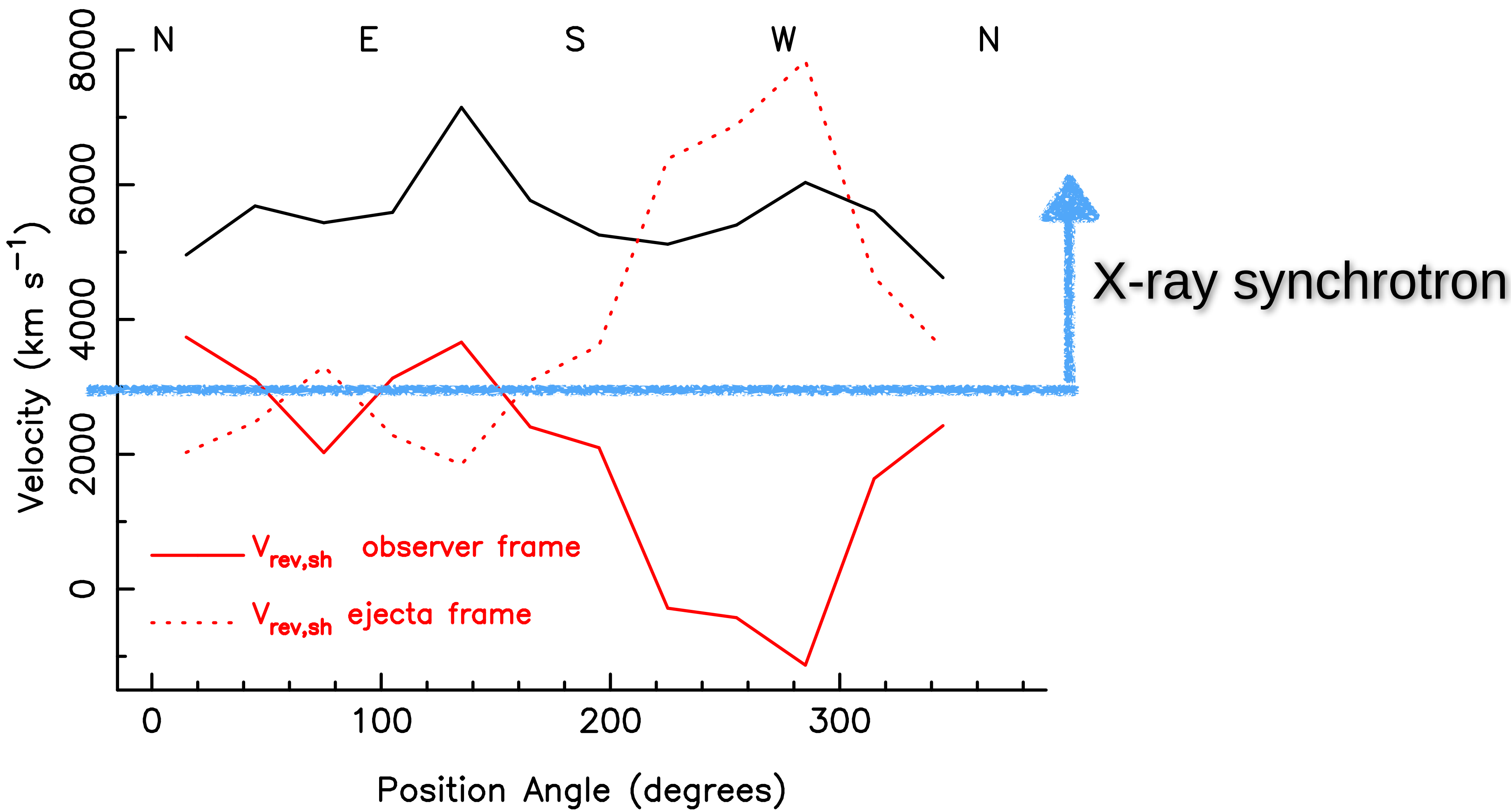


- General mask: minimum #counts in 2004 map
- Forward shock: annulus (two knots removed)
- Reverse shock: broad annulus with R_{in} < R_{lofar} <R_{out} (< $R_{in,forw}$)
- Central region left out: unclear what it is/projection effects
- Angular division in 30 degrees sectors

Fitting result

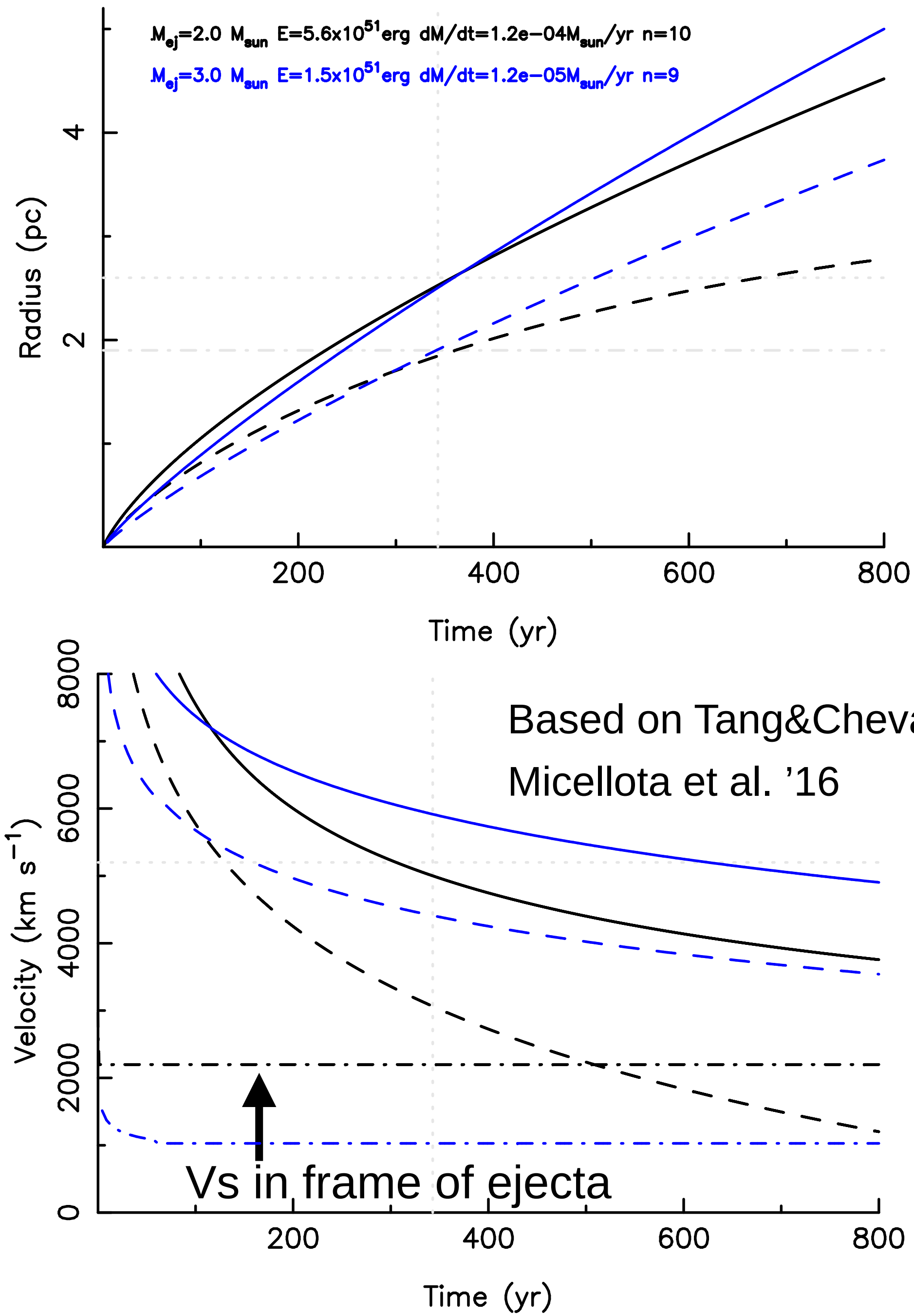


Implied shock velocities



- Shock in ejecta frame: use shifted center of rev. shock
  - $R_{rs,west} > R_{rs,east} \rightarrow$ free expansion in West is higher!
- In the Western region: rev. shock in ejecta frame: ~8000 km/s!!
- Forward shock in West also fast

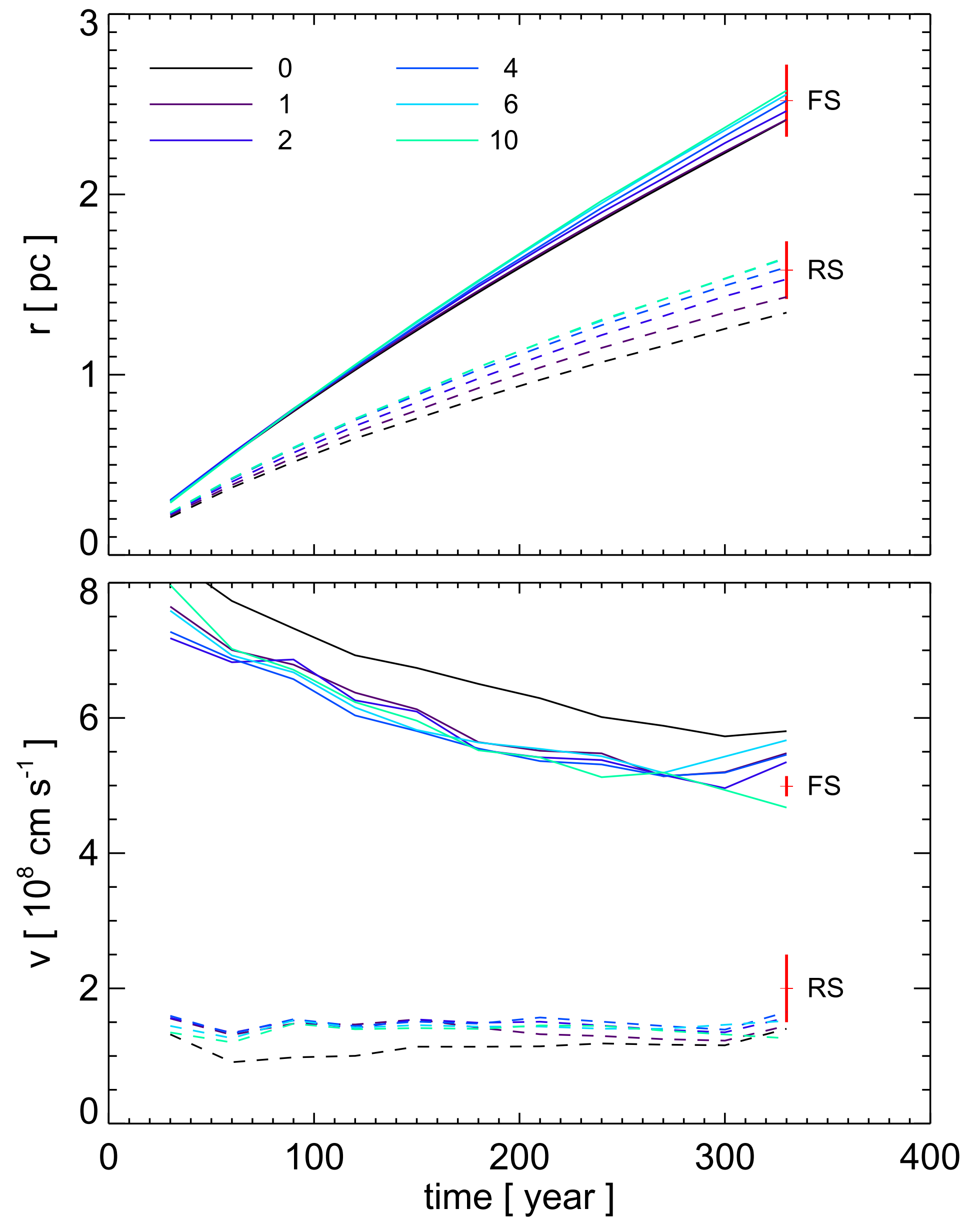
Comparison with models



Based on Tang&Chevalier '17

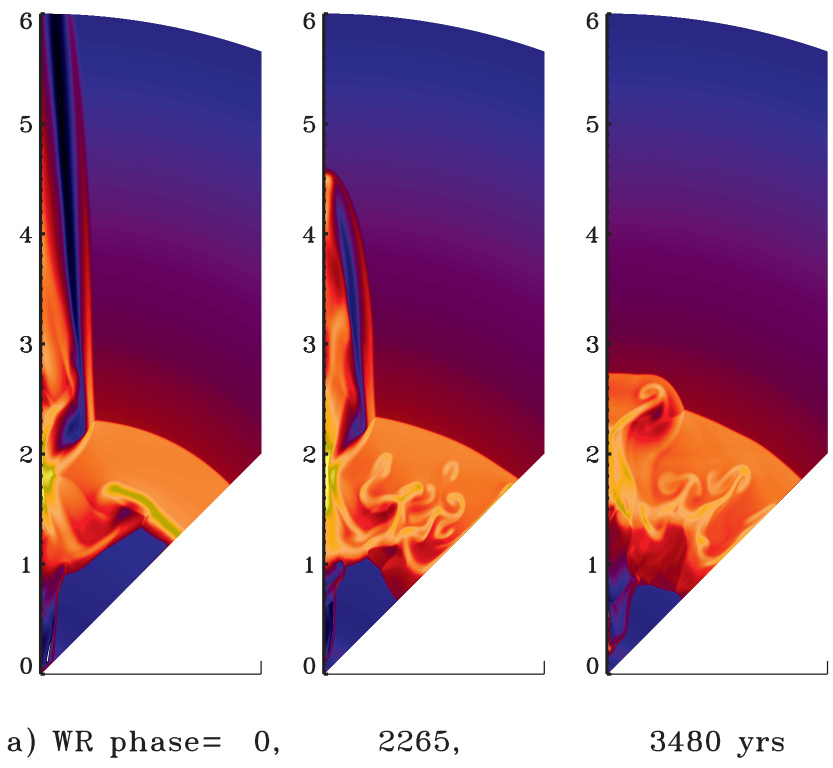
Micellota et al. '16

Orlando et al 2016



Comparison with models

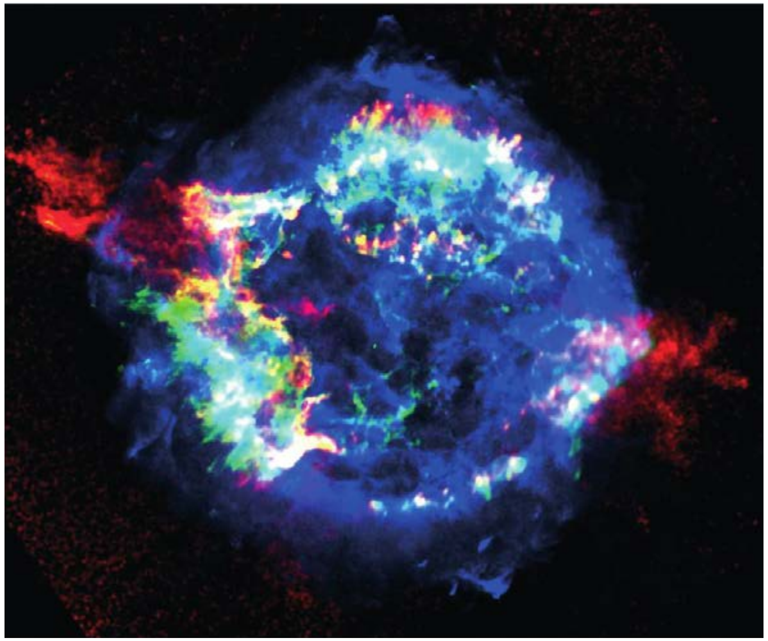
Schure + ‘08

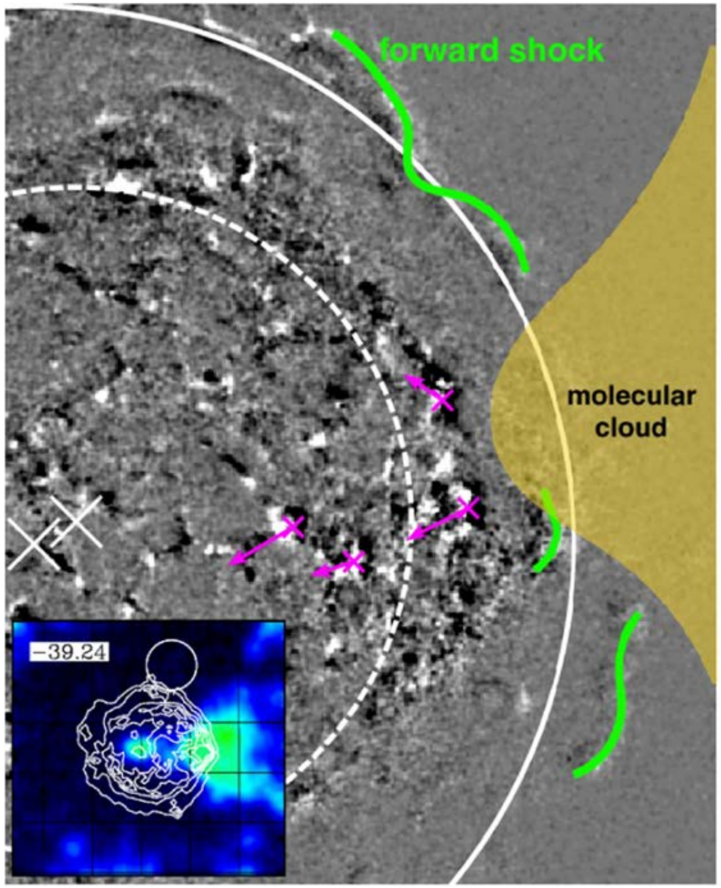


- Numerical/semi-analytical models: $V_{rev} > 0$!
  - Simple stellar wind CSM + uniform ejecta + power law is incorrect!
  - Western region encountering dense CSM?
    - No: forward shock is fast/no CO evidence
    - Perhaps: past encounter dense CSM, but evidence destroyed
    - Perhaps: low density ejecta behind the jet → triggering strong rev. sh.
- If simple models are incorrect: what model to focus on?
  - density high @ 2.6 pc: long wind duration: $t=R/v_w \approx 250\ (v_w/10\text{km/s})$kyr
  - extensive low density cavity/dense shells ruled out (Schure+ 2008)

Problem with Molecular Cloud

Sato+ 2018





- Western jet looks disturbed
- But:
  - no enhanced thermal emission
  - no evidence for interaction from CO data: Zhou+ 2018 (see poster)

Caveats

Technical/method:

- Lack of point sources:
  - difficult to disentangle non-uniform expansion from registration errors
- Selection of optimum regions
- Filaments brighten and decay: not all changes due to motions
- Method assumes radial expansion: may not be correct!
  - Use more advanced methods? (optical flow? what about statistics?)

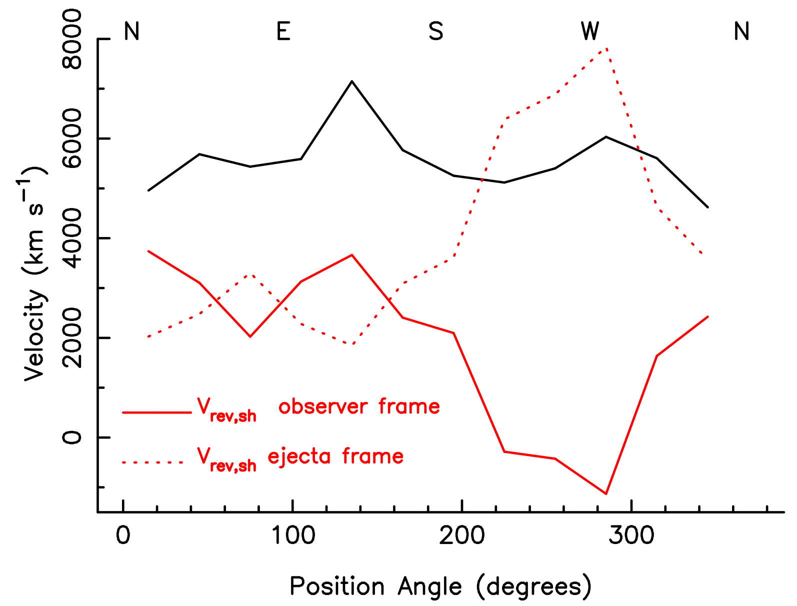
Physics:

- Difference synchrotron vs bremsstrahlung
  - synchrotron: follows filaments = reverse shock velocity
  - bremsstrahlung: follow plasma ≠ reverse shock velocity:

$$V_{\rm plasma} = \frac{3}{4} V_{\rm rev,sh} + \frac{1}{4} \frac{R_{\rm rev,sh}}{t}$$

$$V_{\rm rev,sh} = 0 \rightarrow V_{\rm plasma} = \frac{1}{4} \frac{R_{\rm rev,sh}}{t} \approx 1800 \text{ km s}^{-1}$$

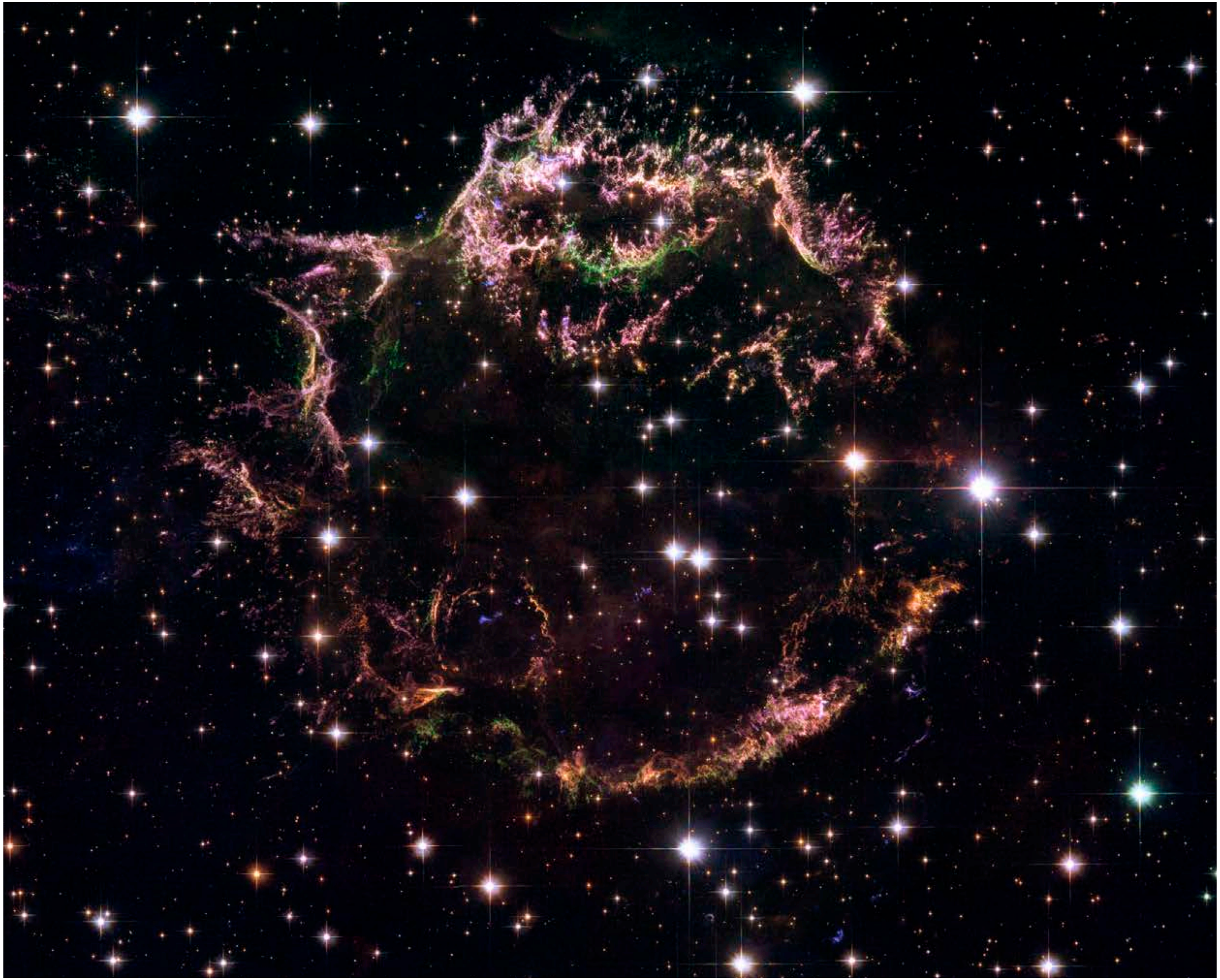
Summary/conclusions



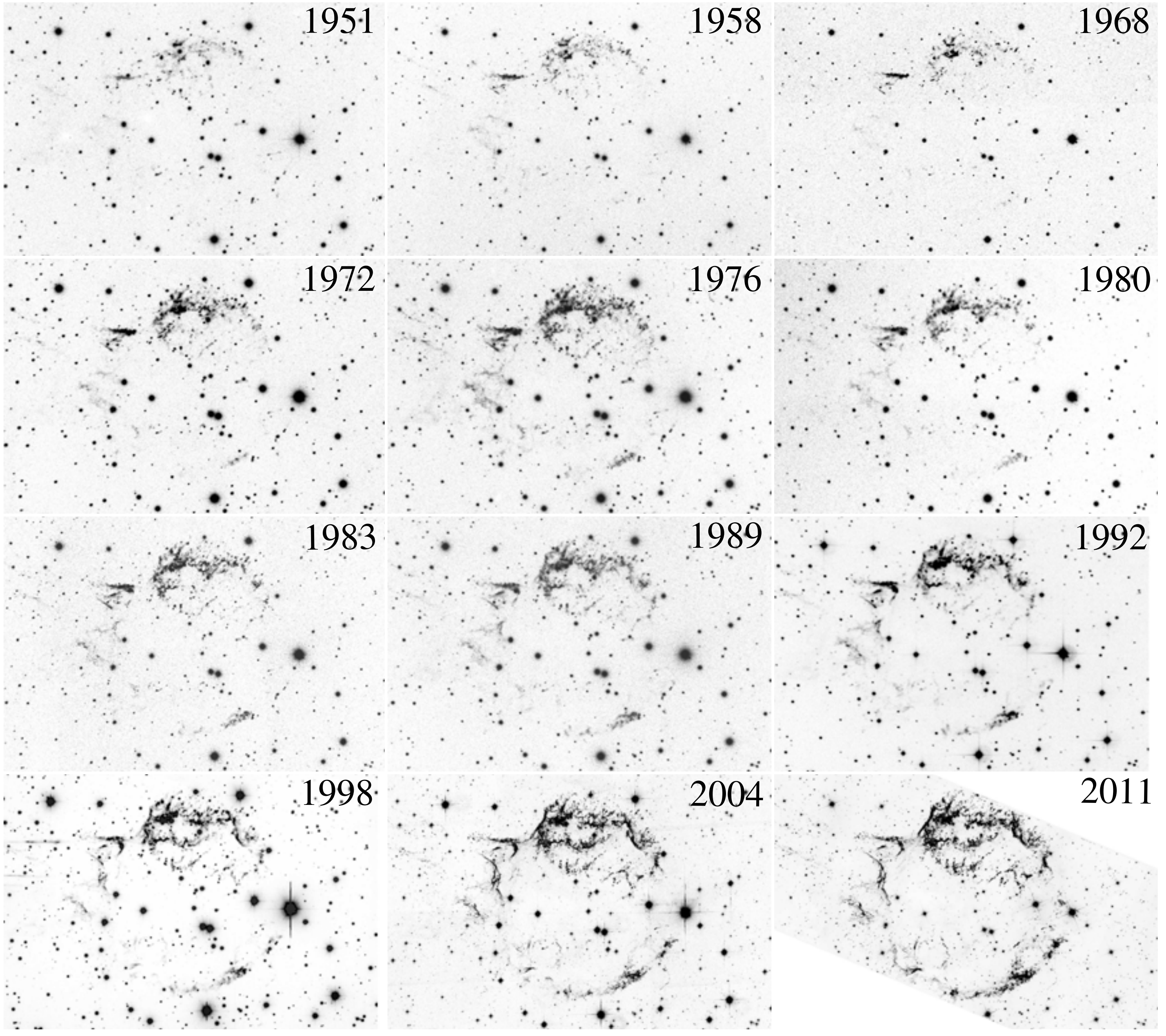
- Measurements of $V_{sh,forw}/V_{sh,rev}$ in 30° sectors
- Results:
  - Reverse shock moves backward in South and West (200°<PA<300°)
  - In West shock velocity (ejecta frame): close to 8000 km/s
  - Rest: $V_{rev,sh}$ ≈2000 - 4000 km/s outward
  - Not reproduced by semi-analytical/numerical models

- Fast rev. shock (>3000 - 8000 km/s): explains X-ray synchrotron at rev. shock!
- Outward shock in East and North: different from optical (Fesen talk)
- Possible solutions:
  - Measure plasma (not shock) velocity? → why no X-ray synchrotron in East?
  - Projection effects
  - Optically active shocks have different properties than X-ray active shocks?

Optical image



Optical evolution



Back up slides

Results

Table 1: Expansion of Cas A, forward shock.

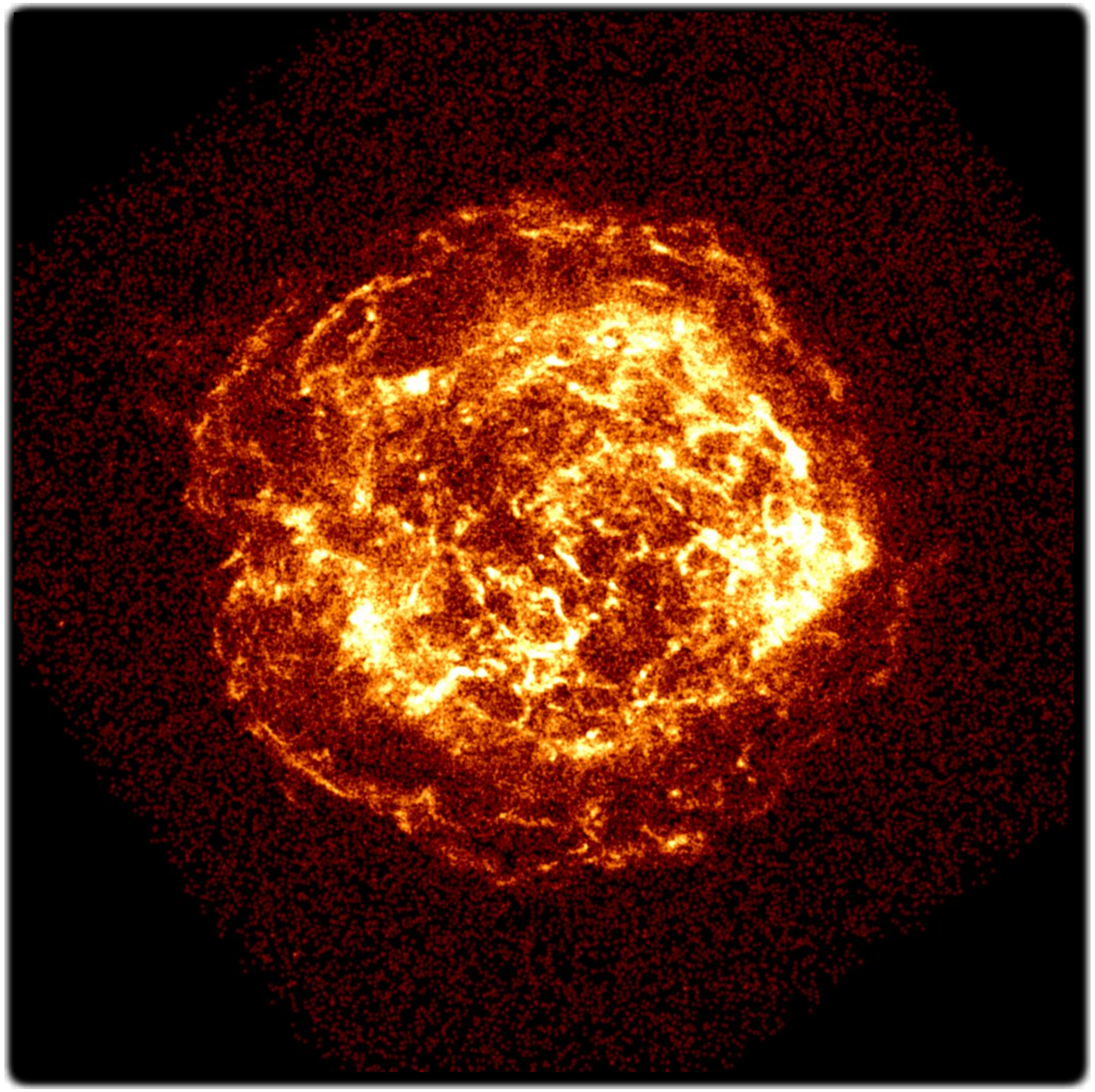
PA (°)	Exp. rate (% yr^{-1})	Exp. age (yr)	m
15	$0.19504^{+0.00001}_{-0.00000}$	$512.70^{+0.01}_{-0.02}$	0.65
45	$0.22366^{+0.00009}_{-0.00037}$	$447.11^{+0.75}_{-0.18}$	0.74
75	$0.21380^{+0.00041}_{-0.00021}$	$467.73^{+0.46}_{-0.89}$	0.71
105	$0.21985^{+0.00061}_{-0.00083}$	$454.86^{+1.72}_{-1.26}$	0.73
135	$0.28122^{+0.00025}_{-0.00016}$	$355.59^{+0.20}_{-0.32}$	0.93
165	$0.22691^{+0.00018}_{-0.00020}$	$440.71^{+0.39}_{-0.35}$	0.75
195	$0.20667^{+0.00045}_{-0.00017}$	$483.86^{+0.41}_{-1.05}$	0.69
225	$0.20133^{+0.00046}_{-0.00024}$	$496.71^{+0.58}_{-1.14}$	0.67
255	$0.21249^{+0.00014}_{-0.00019}$	$470.62^{+0.41}_{-0.32}$	0.71
285	$0.23732^{+0.00010}_{-0.00012}$	$421.37^{+0.20}_{-0.18}$	0.79
315	$0.22049^{+0.00025}_{-0.00015}$	$453.53^{+0.32}_{-0.51}$	0.73
345	$0.18177^{+0.00015}_{-0.00012}$	$550.13^{+0.37}_{-0.45}$	0.60
Average:	0.2184 ± 0.0248	457.92 ± 52.1	0.73

Table 2: Expansion of Cas A, reverse shock.

PA (°)	Exp. rate (% yr^{-1})	Exp. age (yr)	m
15	$0.1951^{+0.0000}_{-0.0000}$	$512.58^{+0.01}_{-0.00}$	0.65
45	$0.1620^{+0.0005}_{-0.0011}$	$617.13^{+4.11}_{-2.06}$	0.54
75	$0.1056^{+0.0008}_{-0.0018}$	$947.39^{+16.75}_{-7.24}$	0.35
105	$0.1633^{+0.0017}_{-0.0006}$	$612.55^{+2.08}_{-6.31}$	0.54
135	$0.1911^{+0.0010}_{-0.0009}$	$523.19^{+2.60}_{-2.72}$	0.63
165	$0.1256^{+0.0014}_{-0.0005}$	$796.31^{+3.05}_{-8.97}$	0.42
195	$0.1094^{+0.0006}_{-0.0013}$	$914.04^{+10.72}_{-5.09}$	0.36
225	$-0.0149^{+0.0004}_{-0.0004}$	$-6715.01^{+188.88}_{-171.56}$	-0.05
255	$-0.0222^{+0.0008}_{-0.0010}$	$-4501.06^{+194.24}_{-160.95}$	-0.07
285	$-0.0590^{+0.0004}_{-0.0006}$	$-1694.37^{+15.78}_{-11.53}$	-0.20
315	$0.0854^{+0.0010}_{-0.0006}$	$1171.04^{+8.97}_{-13.10}$	0.28
345	$0.1265^{+0.0004}_{-0.0005}$	$790.53^{+3.28}_{-2.50}$	0.42
Average:	0.0973 ± 0.0854	1027.56 ± 901.7	0.32

- Forward shock: consistent with earlier results
  (Vink+ ’98, Koralesky+ ’98, Delaney+ ’04, Patnaude+ ’08, Sato+ ’18,…)
- Reverse shock:
  - large excursions
  - $\langle m \rangle = 0.32 \rightarrow \langle V_{\mathrm{rev\,sh}} \rangle \approx 1880$ km/s

Changes from 1999-2018



Fitting result