IAKKO VINK
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GRAPPA
GRavitation AstroParticle Physics Amsterdam

SVPERNOVA REMNANTS
AN ODYSSEY IN SPACE AFTER DEATH

WHERE DO WE STAND TODAY
AND WHAT WILL THE FUTURE BRING?

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MY BIG FAT GREEK CONFERENCE

THE ODYSSEE: AN APT NAME

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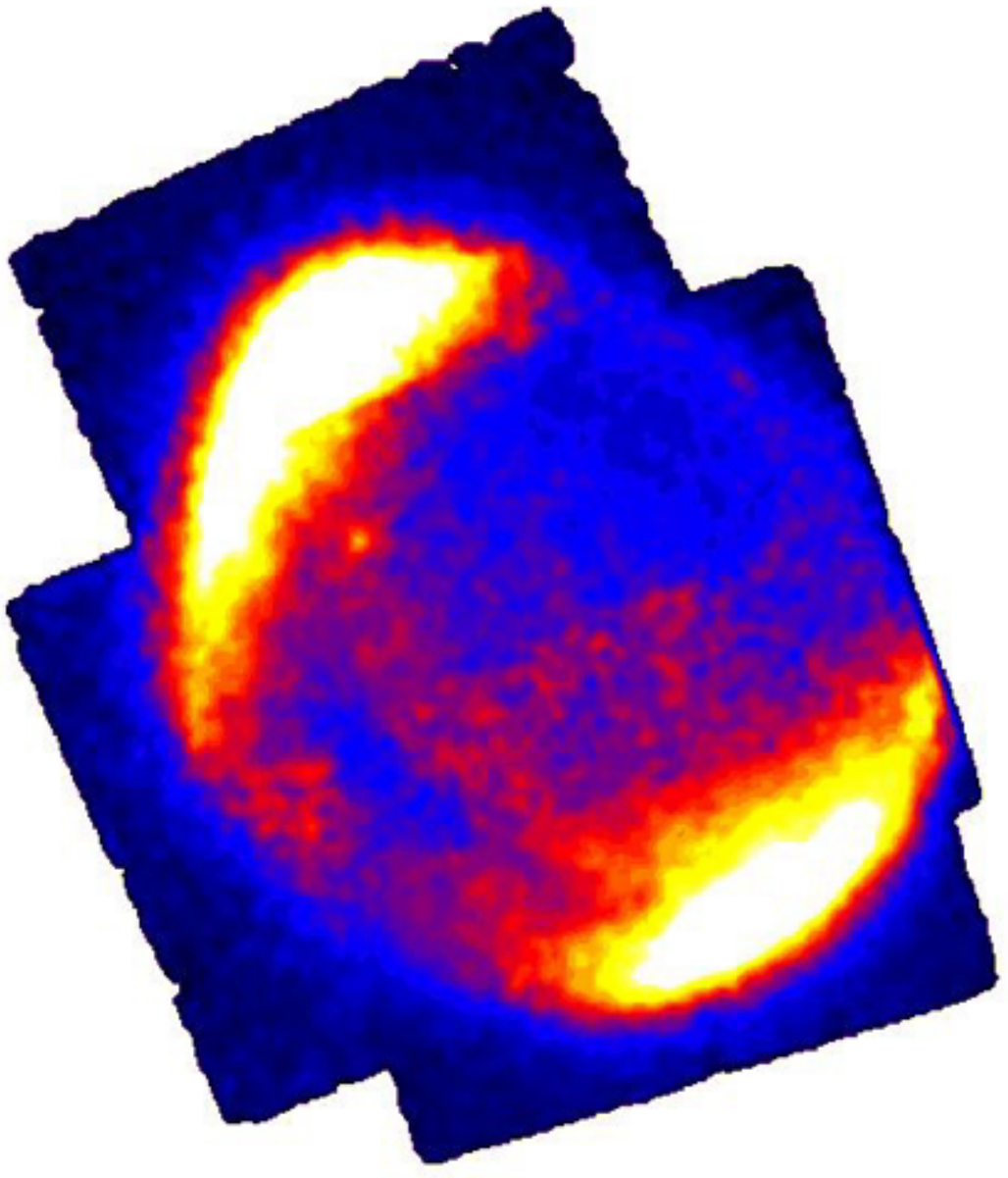
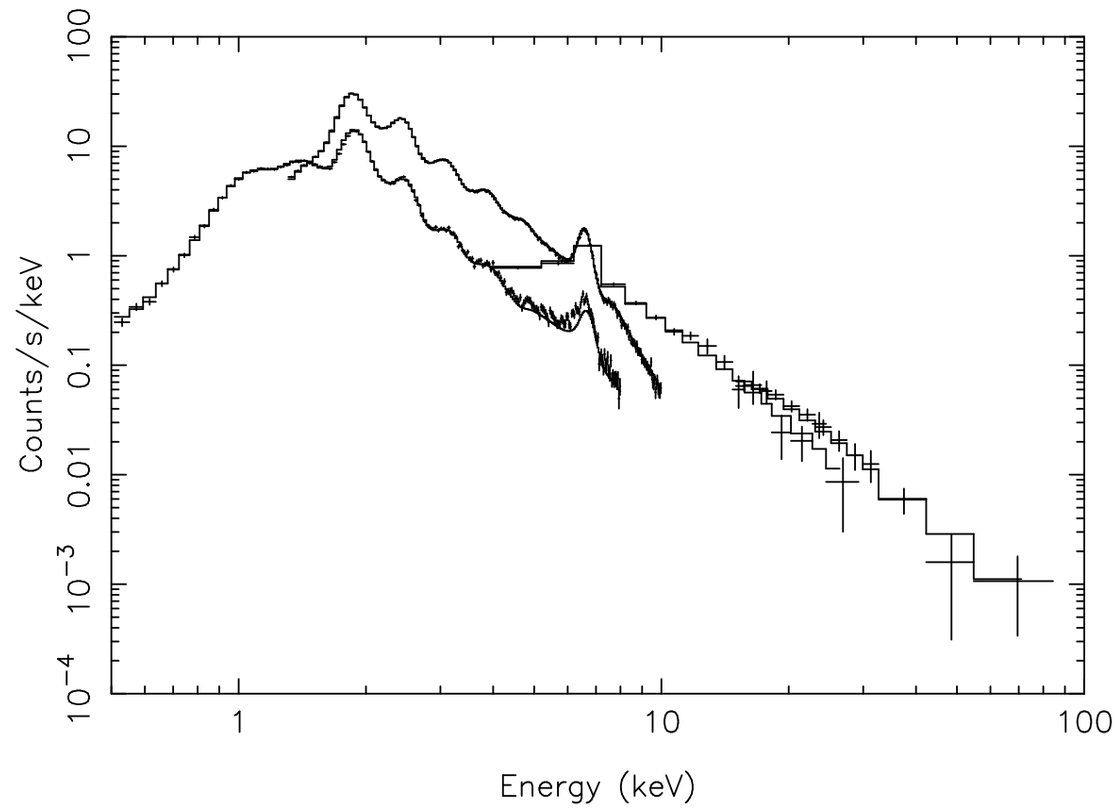
- Returns home just in time before wife gets another husband
- The odyssey lasted 20 yr

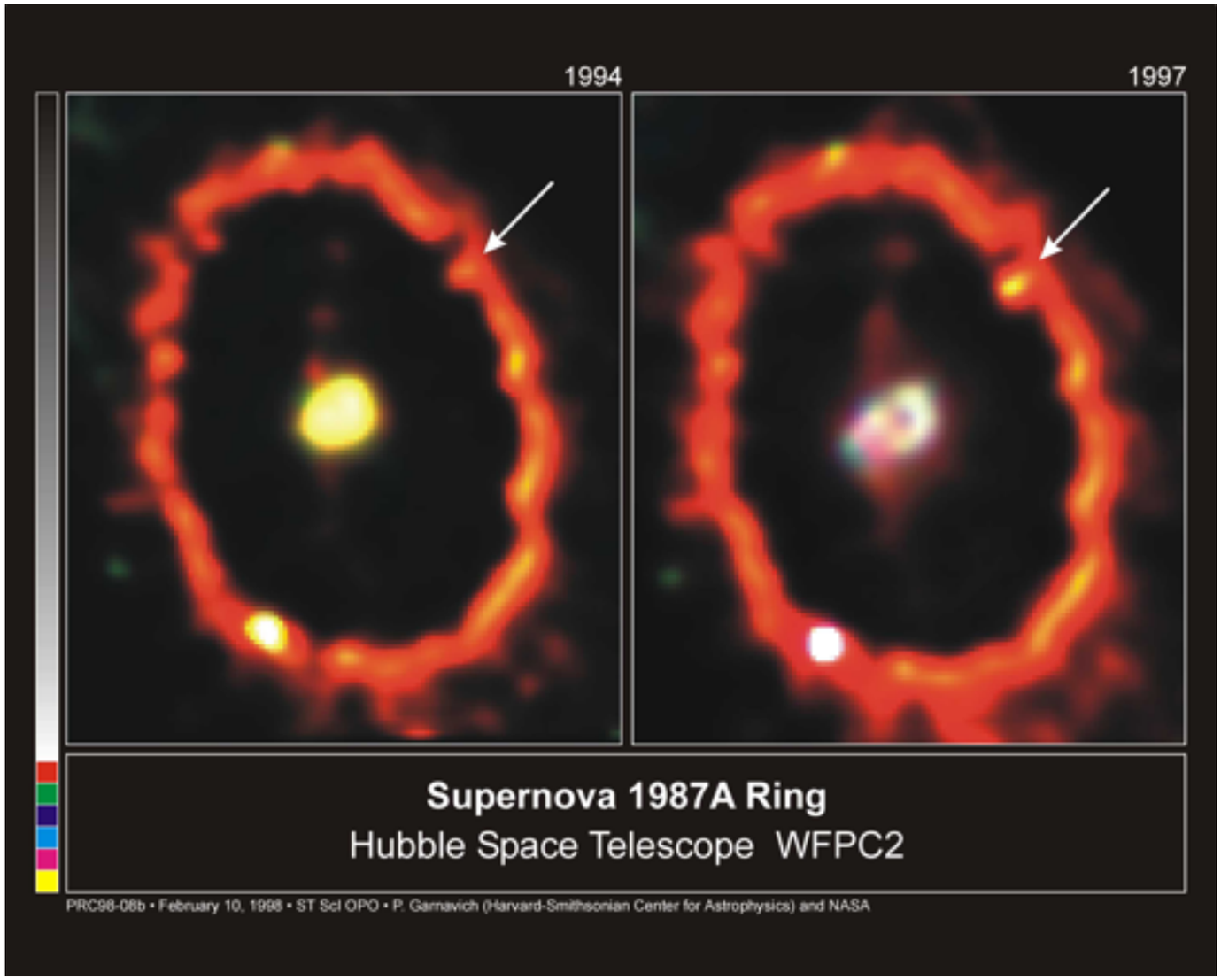
WHERE WERE WE IN 1996?
X-RAY SYNCHROTRON EMISSION JUST DISCOVERED





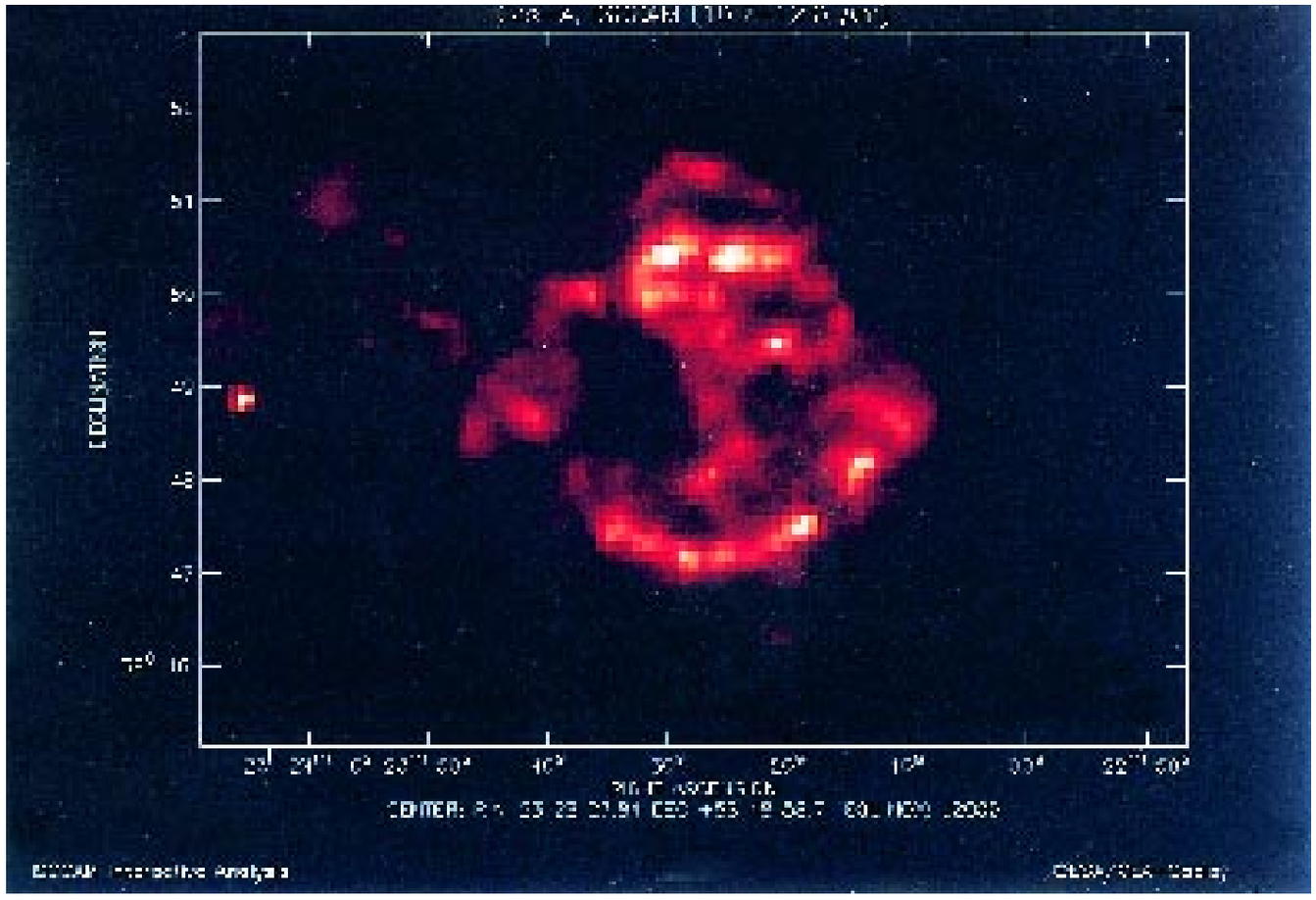
- Discovery of X-ray synchrotron SN1006 by Koyama+ 1999
- Hard X-ray emission Cas A (The+ 95, Allen+ ’96, Favata+ 96)
  - Discussions: non-thermal bremsstrahlung or synchrotron?

WHERE WERE WE IN 1996?
SN1987A WAS NOT YET 10 YR OLD



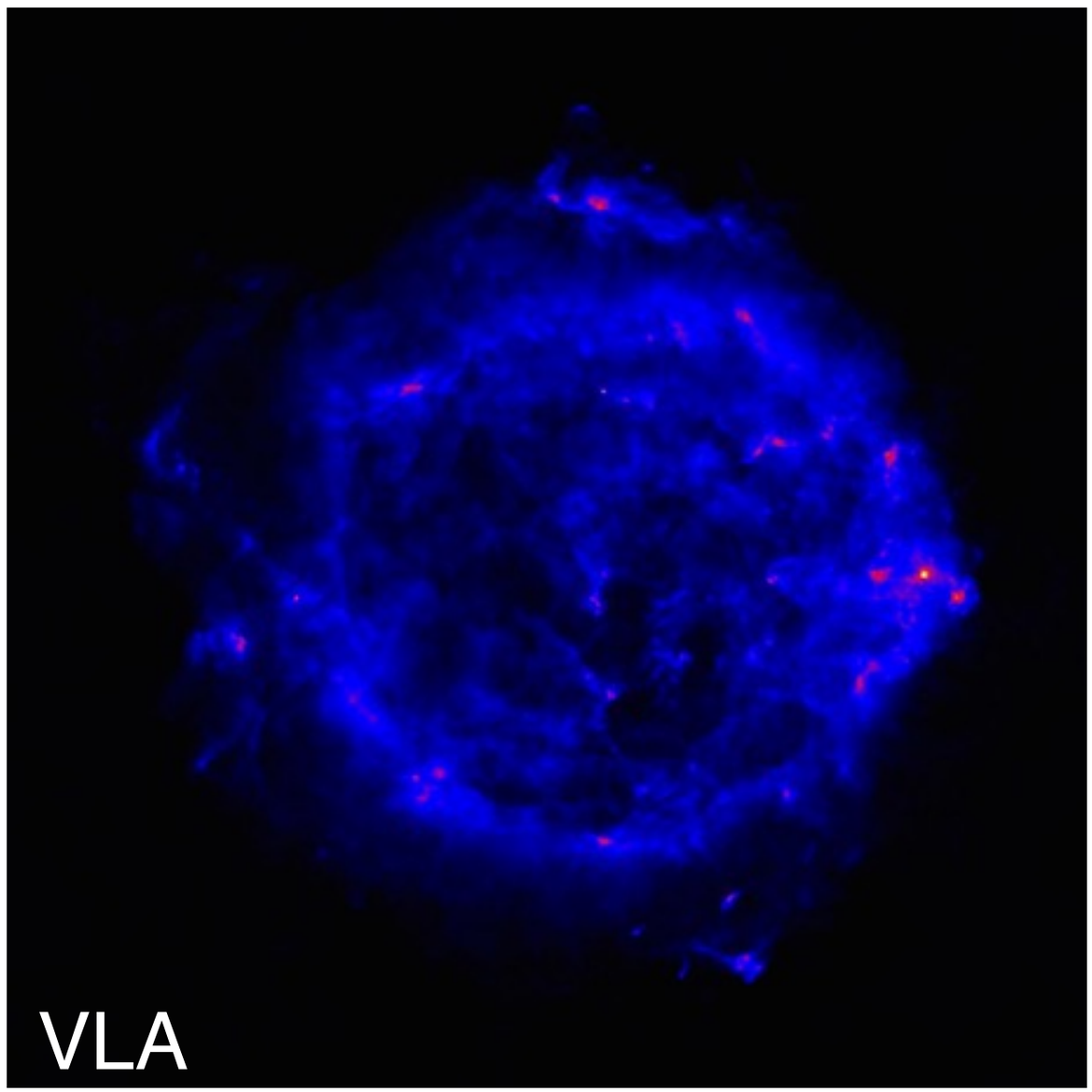
SN1987A just starts interacting with the interior part of ring

WHERE WERE WE IN 1996?
DISCOVERY DUST IN CAS A FROM EJECTA



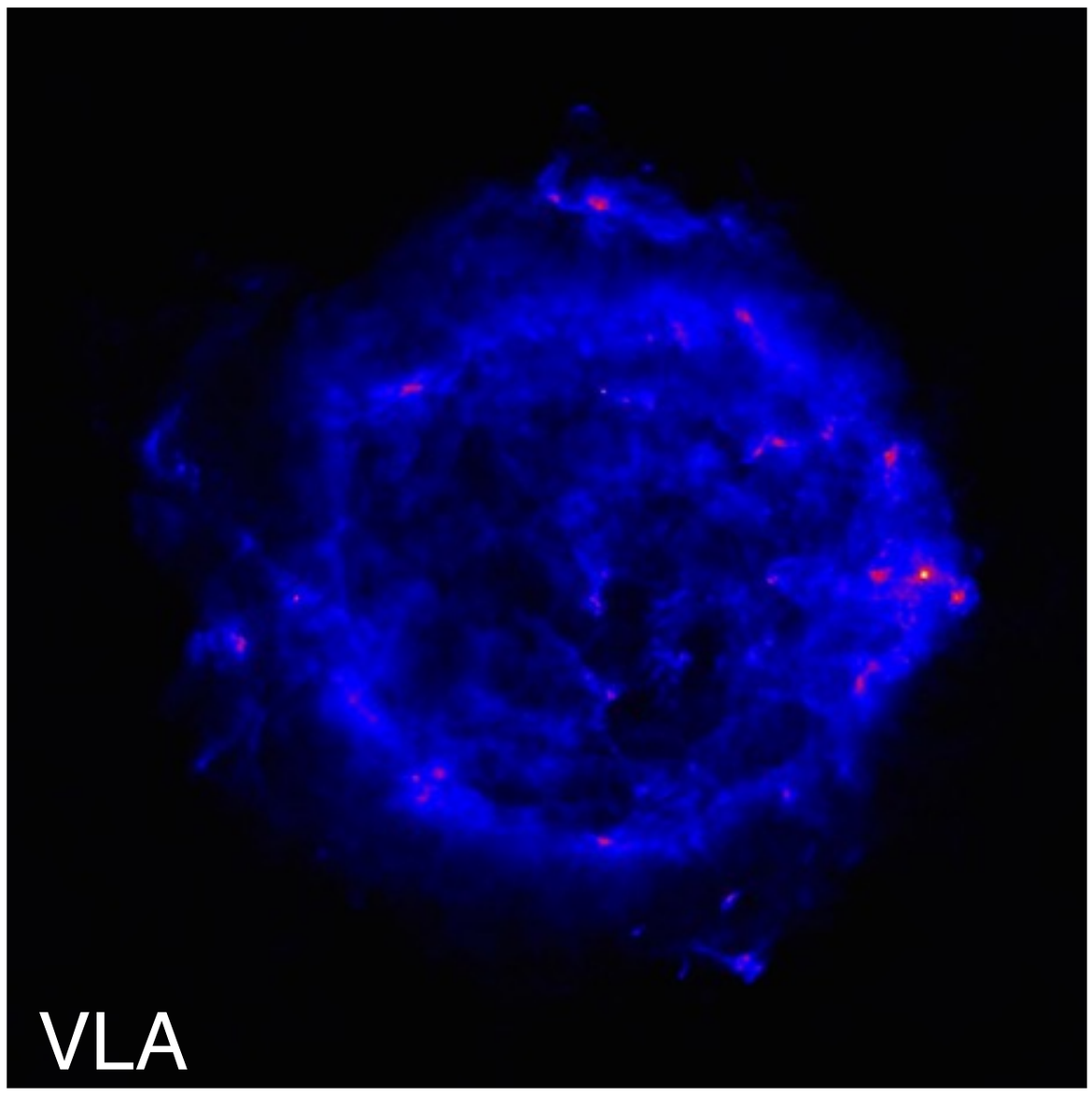
Cas A ISO-CAM (Lagage+ 1996)

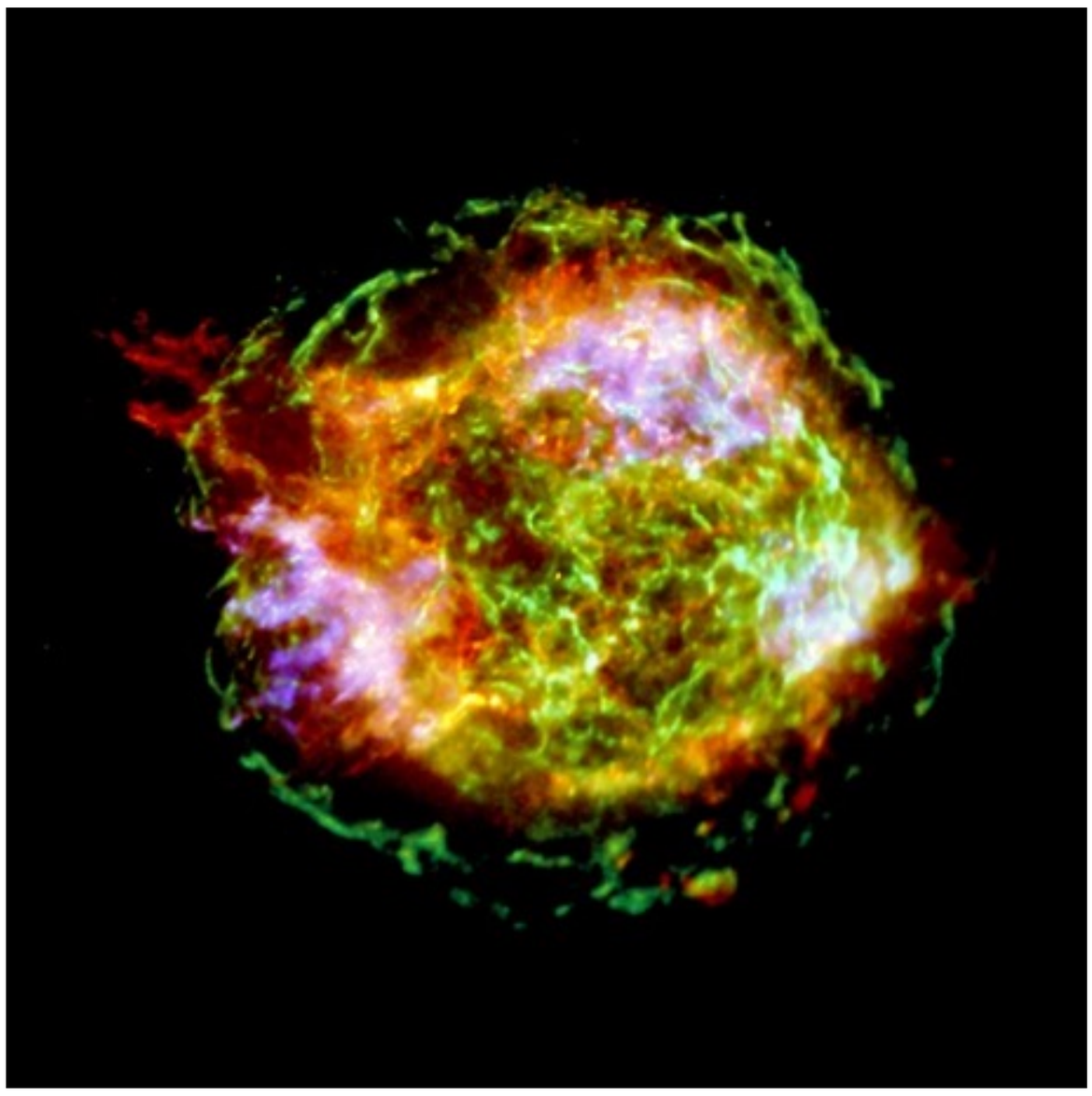
WHERE WERE WE IN 1996?



Discussion in 1998 (Rudnick):
Where is the shock?

WHERE WERE WE IN 1996?





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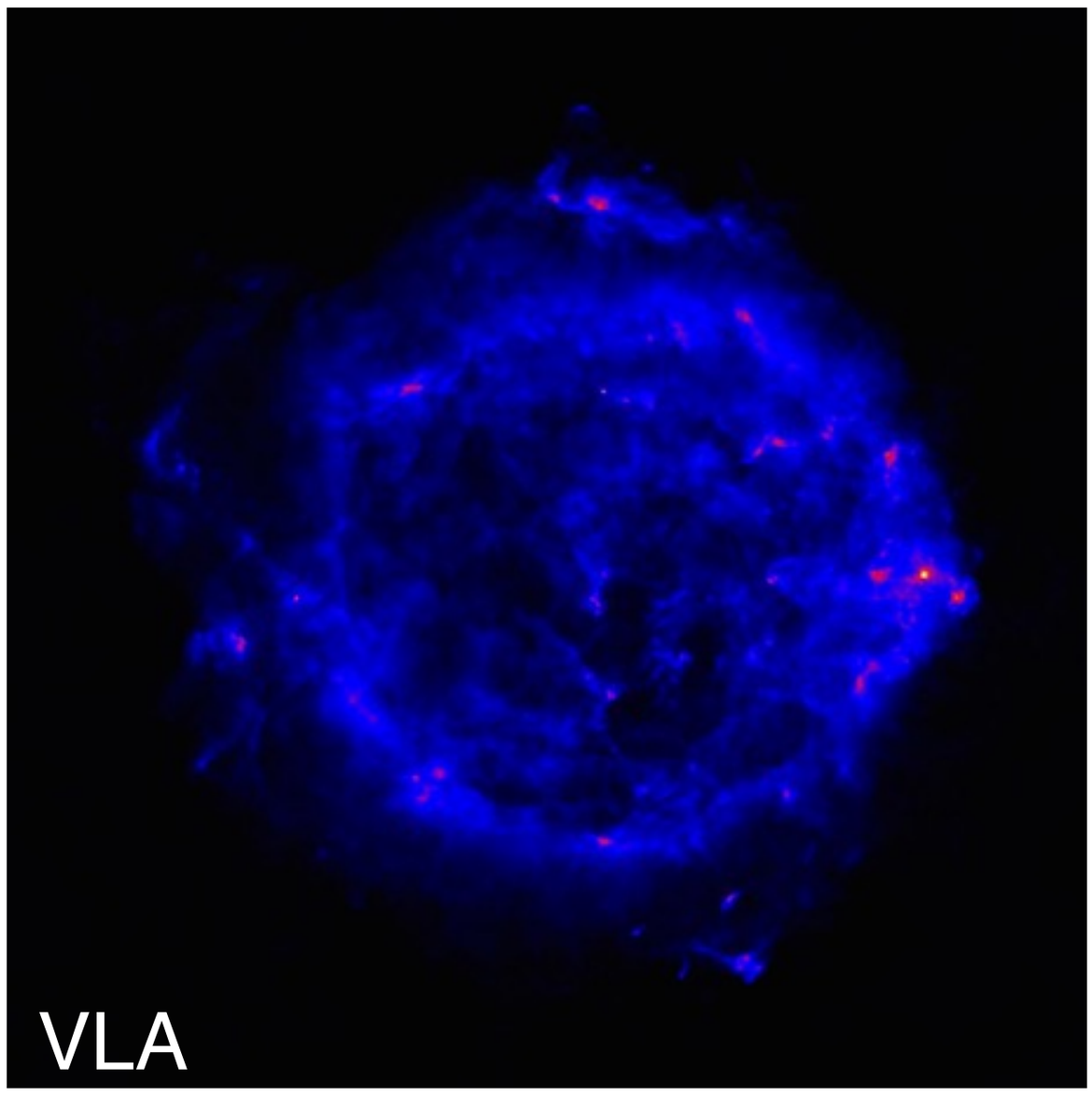

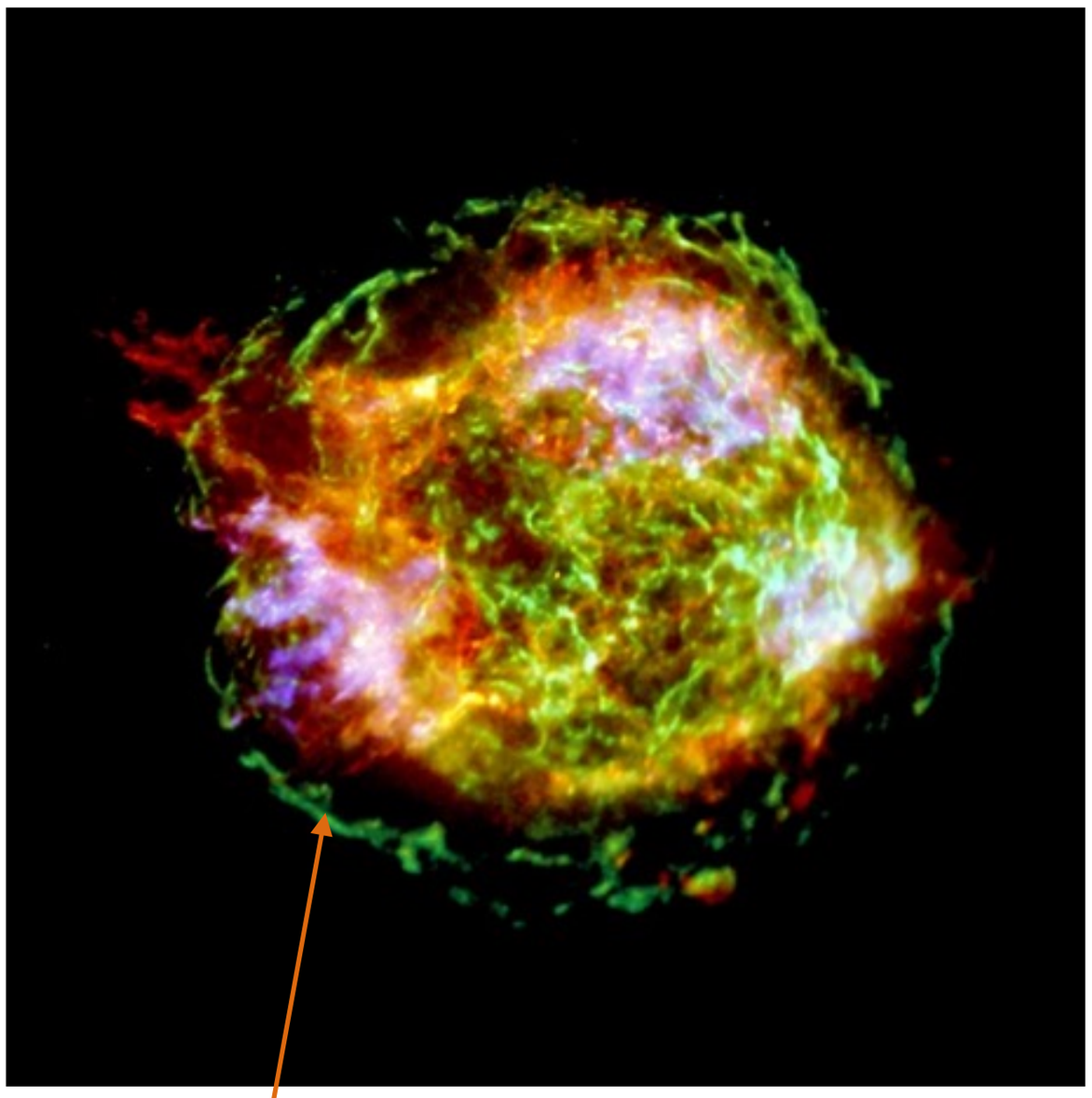

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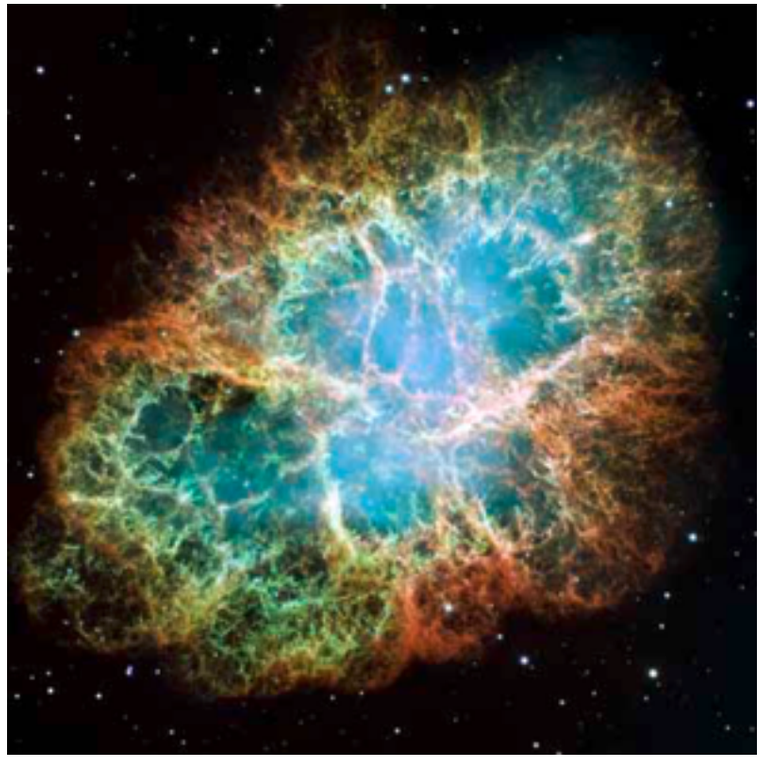
Where is the shock?

Chandra (1999+)
Here is the shock!!

HOT DISCUSSION IN 1997: DOES THE CRAB HAVE A SHELL?



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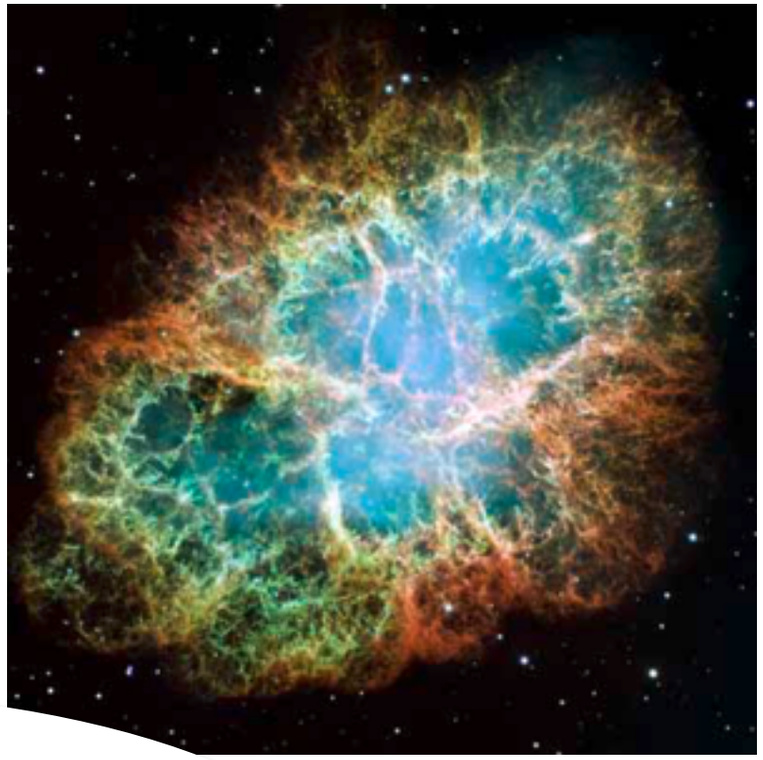

There is a big SNR shell!
Filaments are RT instabilities
from PWN pushing against ejecta

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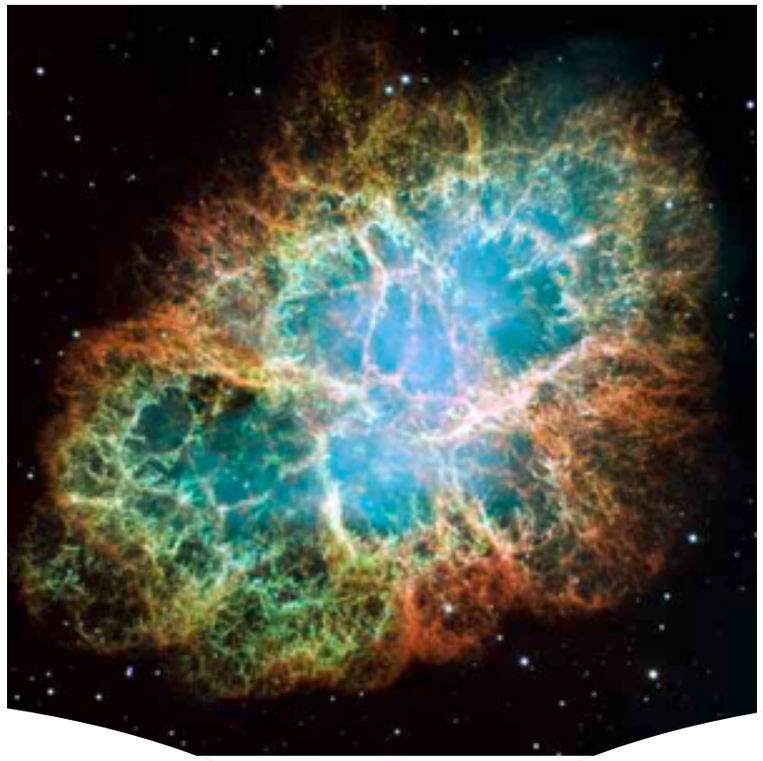

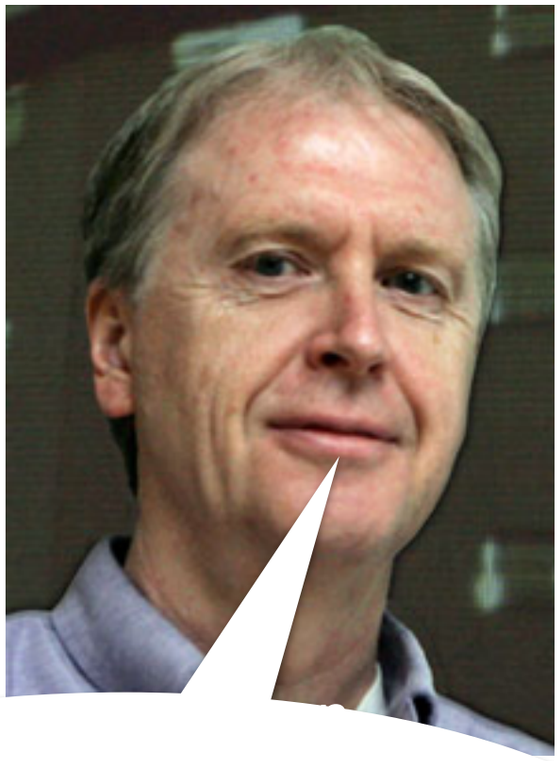

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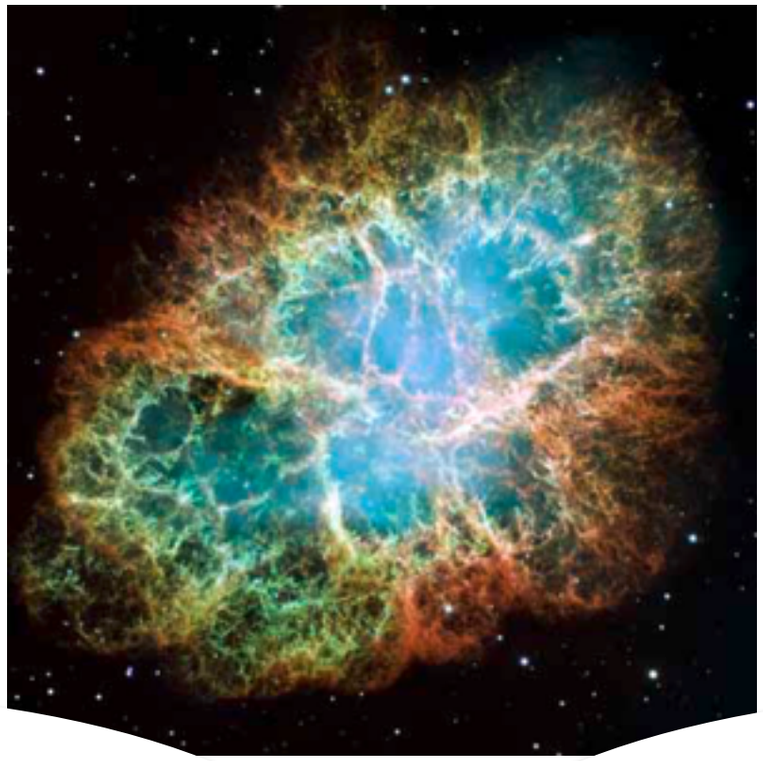

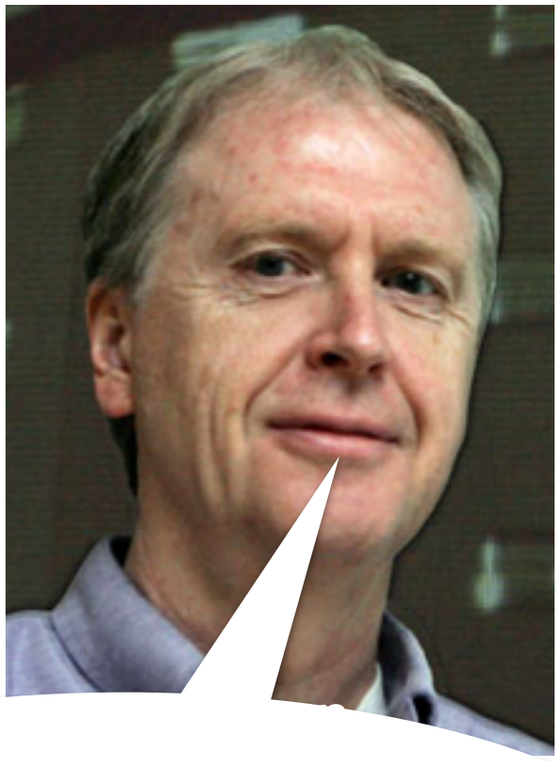

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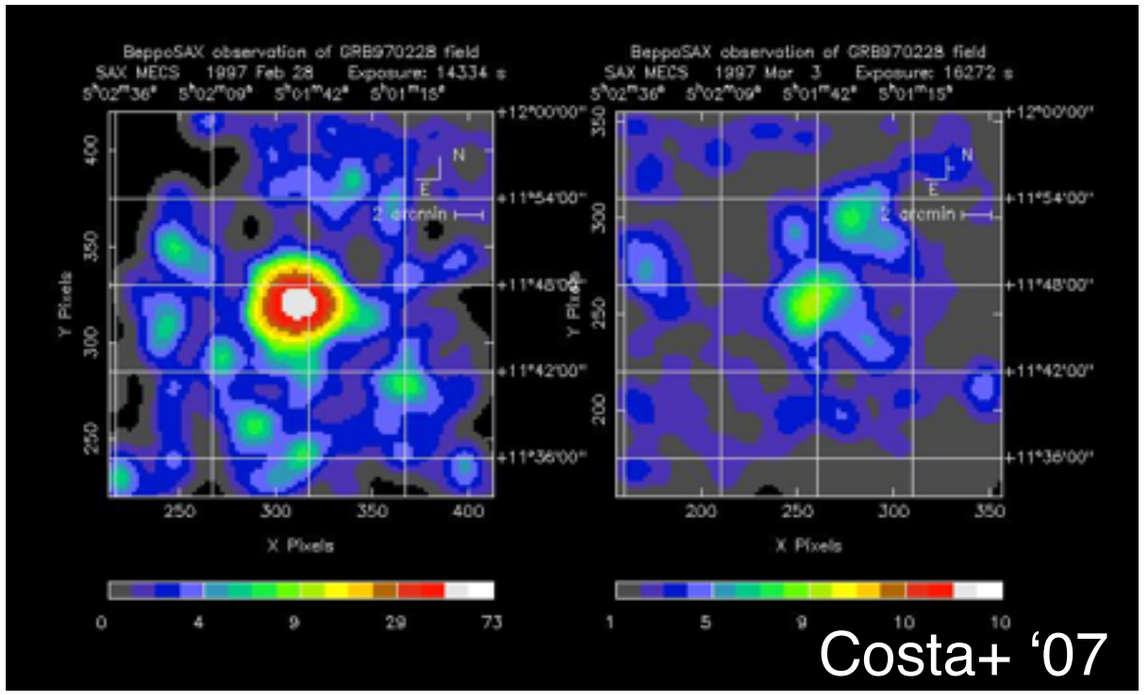
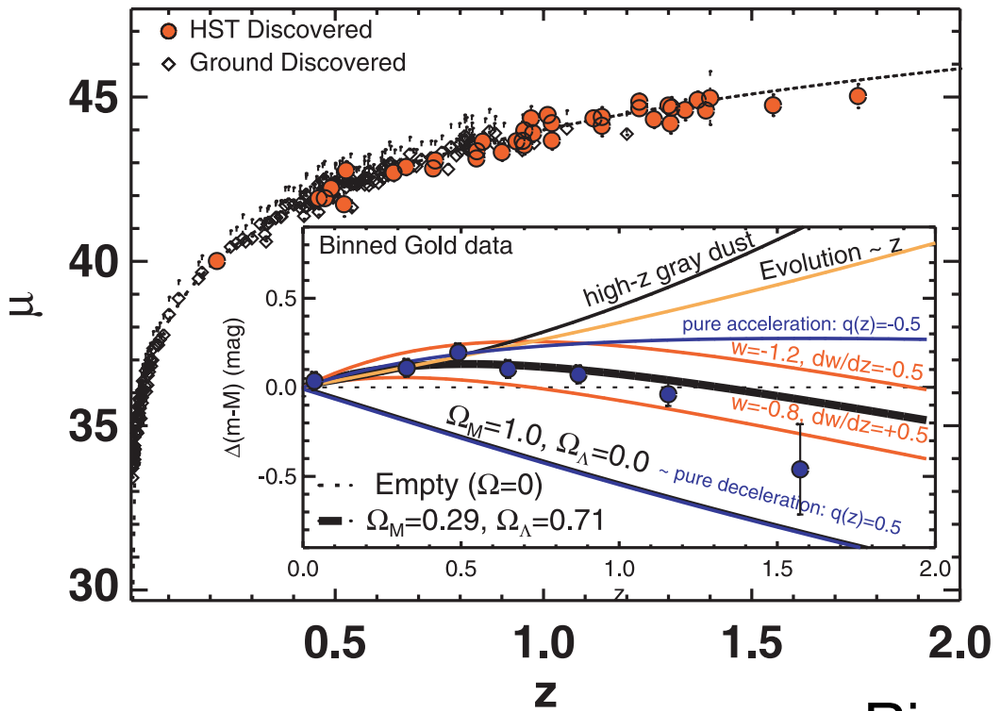
- Michael Bietenholz this week: the supernova was sub energetic and the filaments are RT instabilities

OTHER EVENTS AROUND 1996 INFLUENCING OUR CURRENT VIEWS





- Discovery of gamma-ray burst afterglows
  - GRBs are extra-galactic
  - SN1998bw-GRB connection:
    - SNe can have jets!!
    - Not all SNe have 10^{51} erg of energy
- SNe Ia and the accelerated expansion of the Universe (1998)
  - Created more interest in SNe Ia: do we understand them?
  - Increased effort in hunting for SNe in general

What happened since 1996: New instruments

- Radio: EVLA, LOFAR
- SubMM: ALMA
- Infrared: Spitzer,Herschel,MSX,WISE,…
- Optical: Hubble (with renewed instruments), VLT, Subaru, Magellan,….
- X-rays (99+): Chandra, XMM, Suzaku, NuStar,…

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- GeV gamma-rays (2007+): Fermi-LAT, AGILE
- TeV gamma-rays/stereoscopic arrays: H.E.S.S., MAGIC, Veritas

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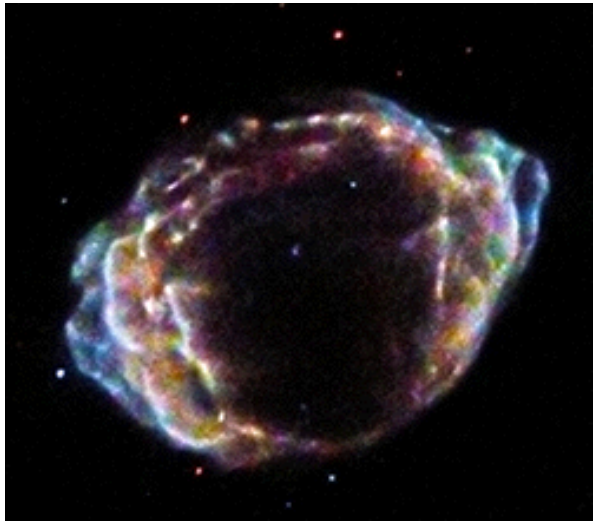
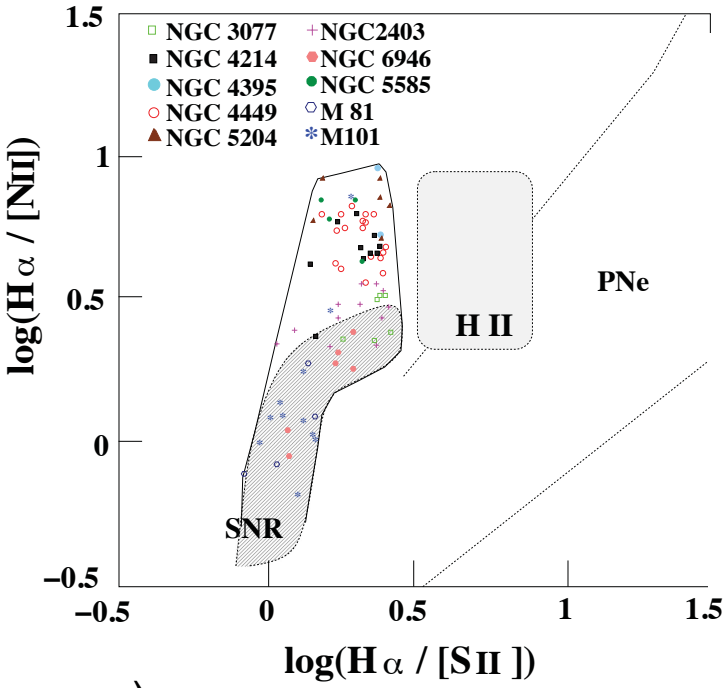
- Larger computers!

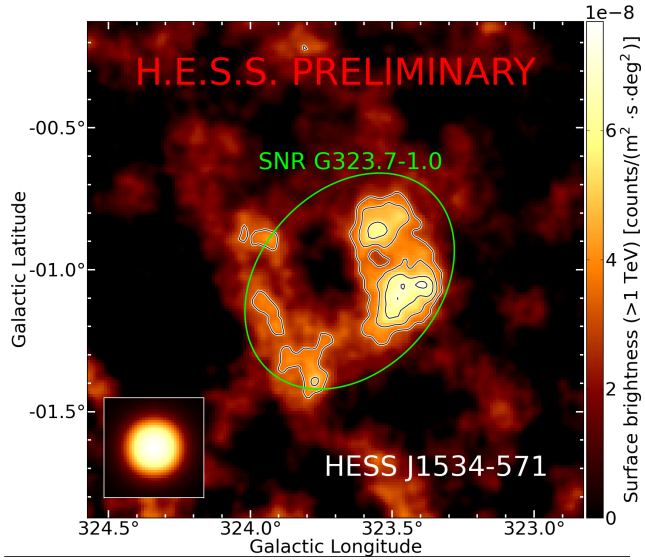
What did it bring us?
New SNRs



G1.9+0.3
(Reynolds, Borkowski, Green c.s.)



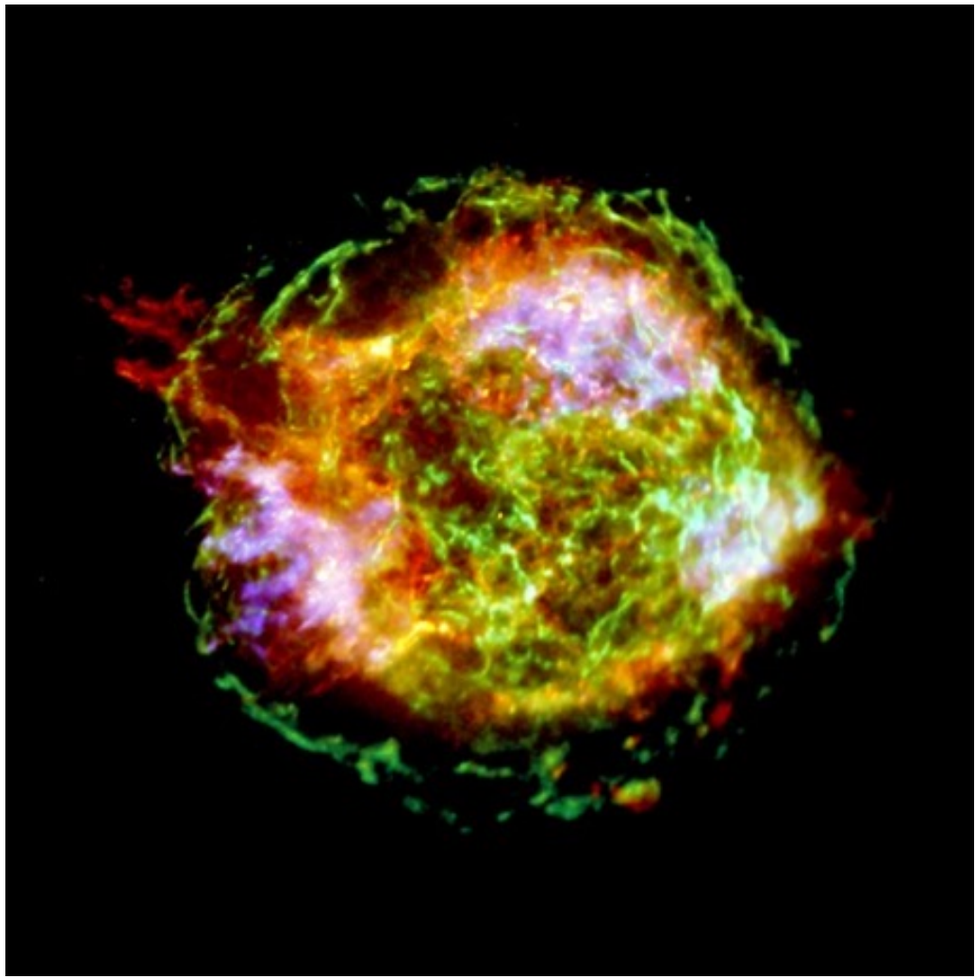
Extra-galactic
Leonidakis+ 2013

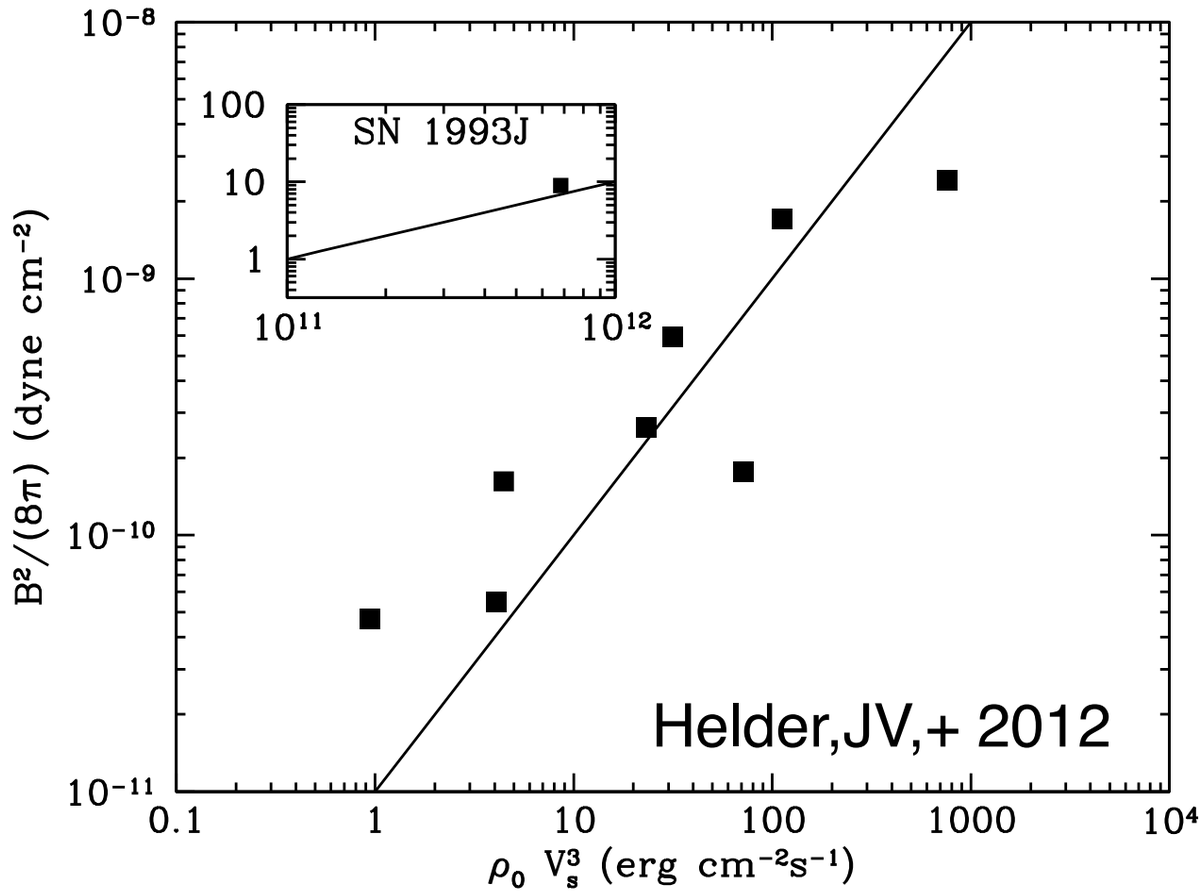


H.E.S.S. collab.
talk by Ryan Chaves

- radio, optical (extra-galactic!), and TeV!
- LMC/SMC (e.g. MCELS, Maggi+): better ideas about SNR populations
- extra-galactic population studies

WHAT DID IT BRING US?
PARTICLE ACCELERATION: AMPLIFIED B-FIELDS



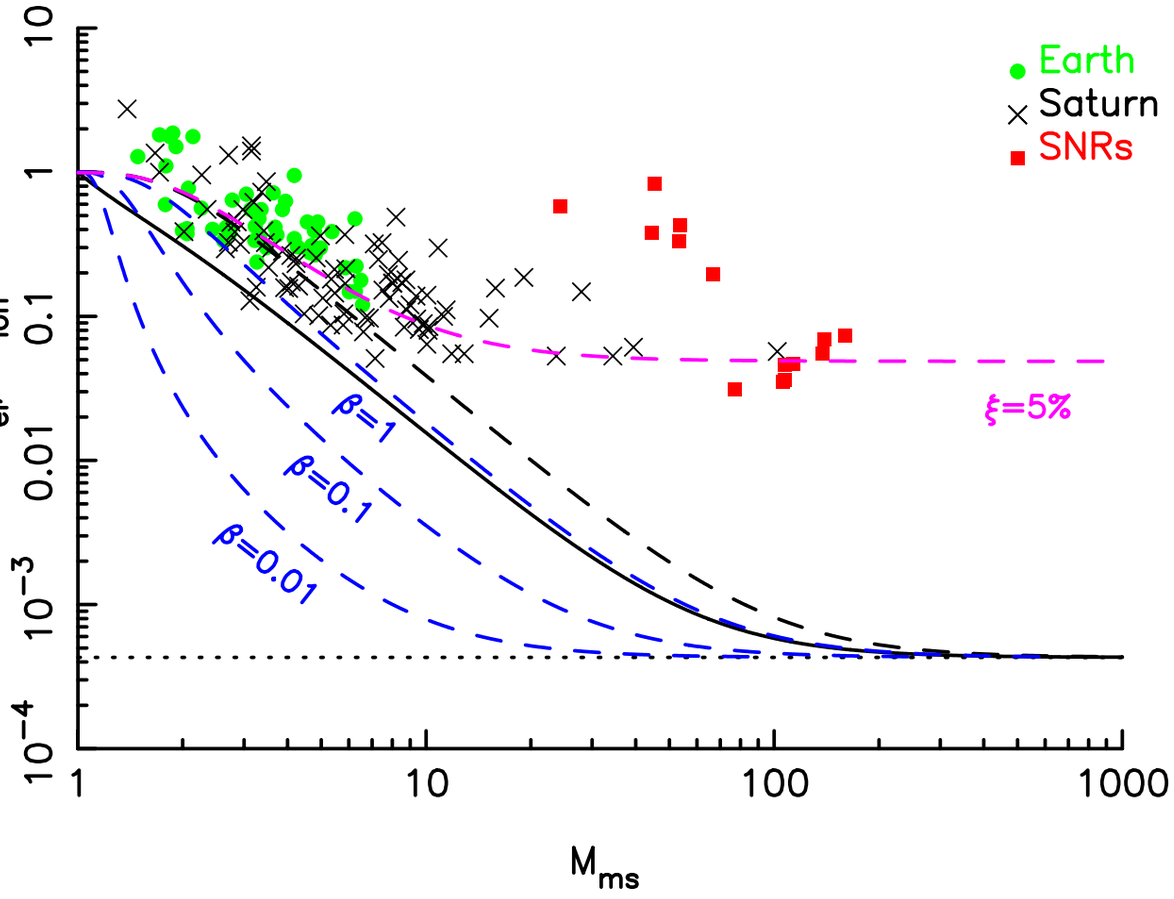


- X-ray synchrotron common in young SNRs!
- X-ray synchrotron needs high magnetic turbulence (η≈1)

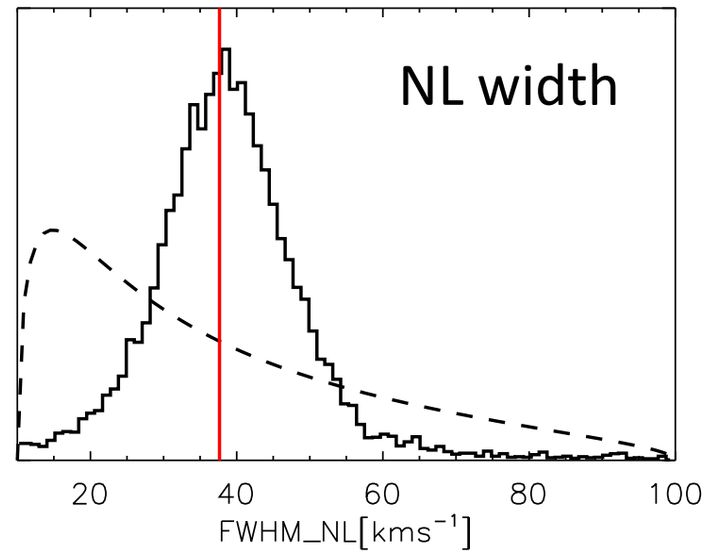
$$h\nu_{\text{cut-off}} = 1.4\eta_g^{-1}\left(\frac{r_4 - \frac{1}{4}}{r_4^2}\right)\left(\frac{V_s}{5000\ \text{km s}^{-1}}\right)^2 \text{keV}$$

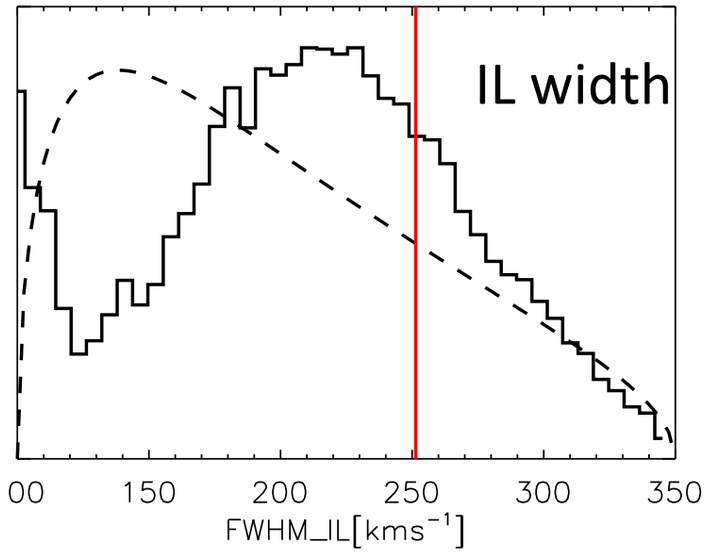
- Narrow filaments -> high losses -> high magnetic fields (50-500 μG)
- Need magnetic field amplification (e.g. Bell's cosmic-ray driven instability)

WHAT DID IT BRING US? COLLISIONLESS SHOCK HEATING



Data: P. Ghavamian+ 2013
Model: Vink+ 2015

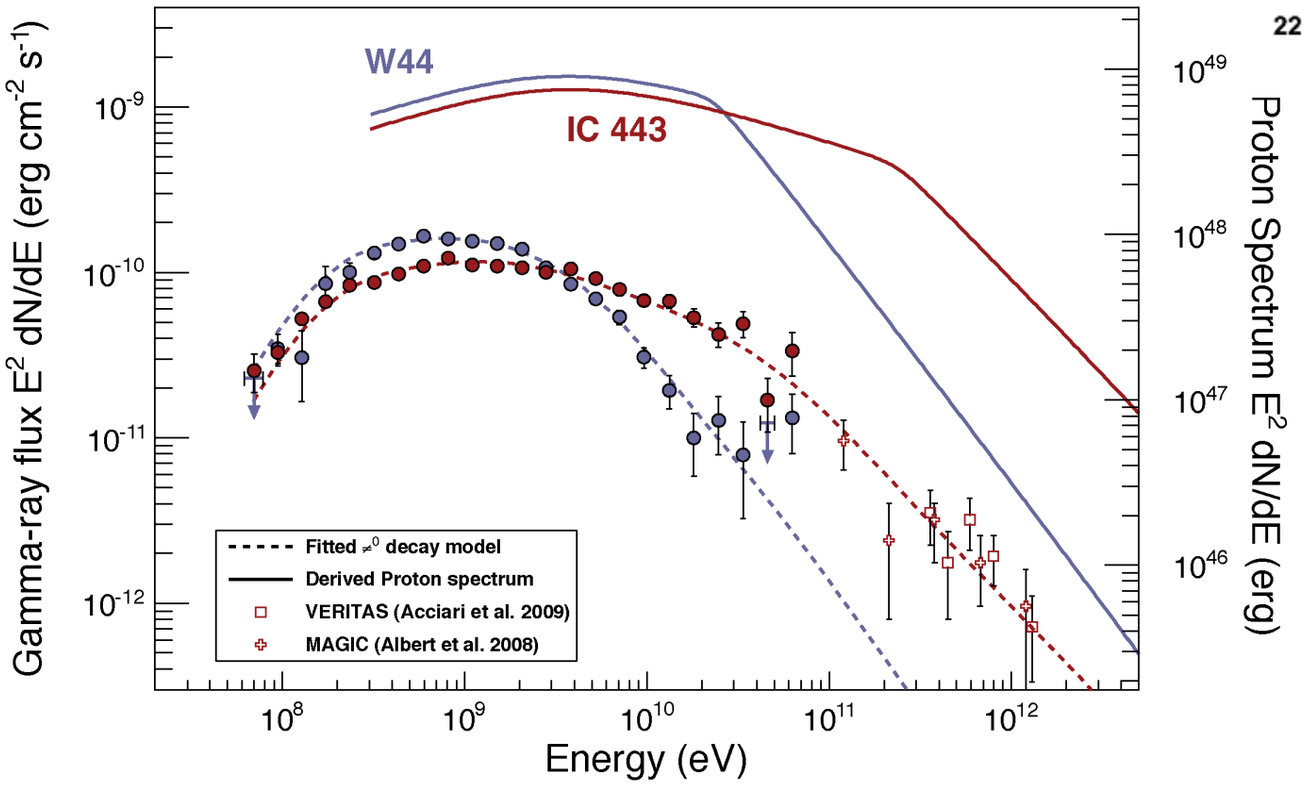


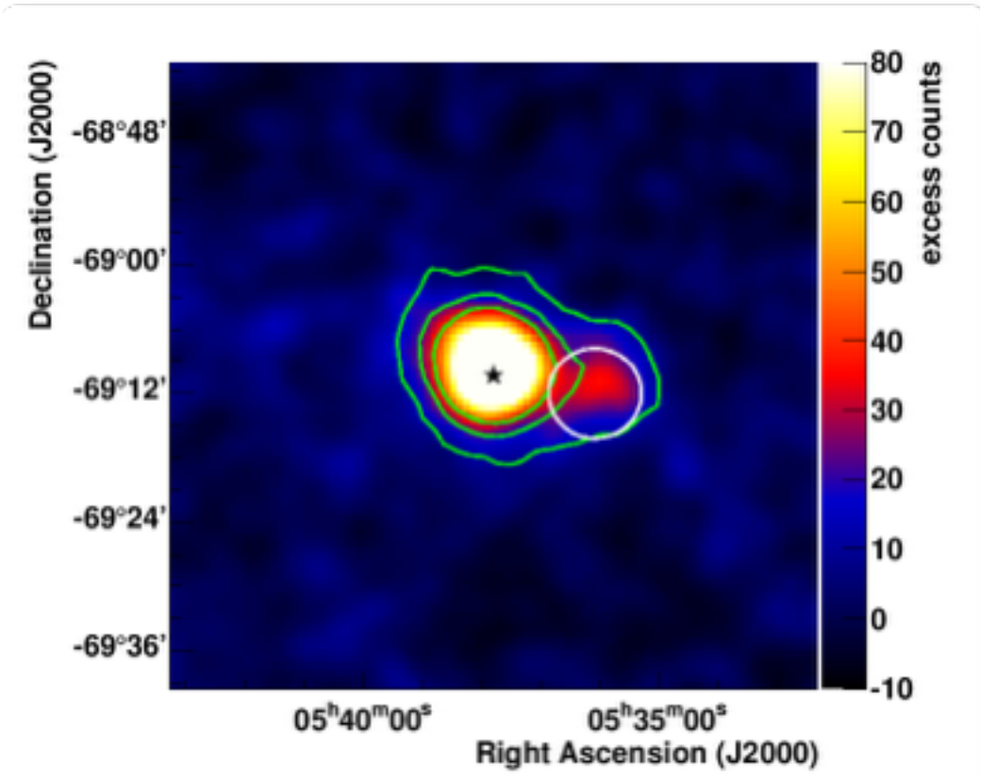


Talk S. Knevevic:
Tycho evidence for intermediate velocity comp.

- Long debate: are electron-ions equilibrated?
- Measurements: partially equilibrated $1/v^2$ dependence (Ghavamian+)
- CR theory/neutral kinetics (Blasi cs/Raymond): pre-shock heating
- This conference (Knevevic): evidence for intermediate component

WHAT DID IT BRING US?
PARTICLE ACCELERATION: GAMMA-RAYS

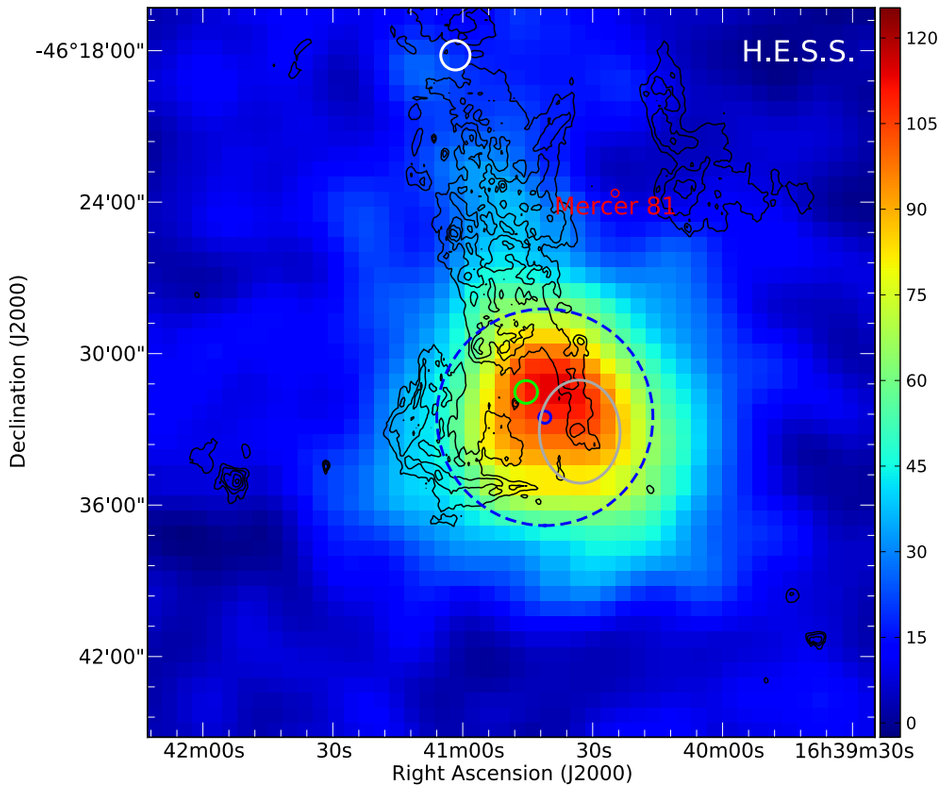


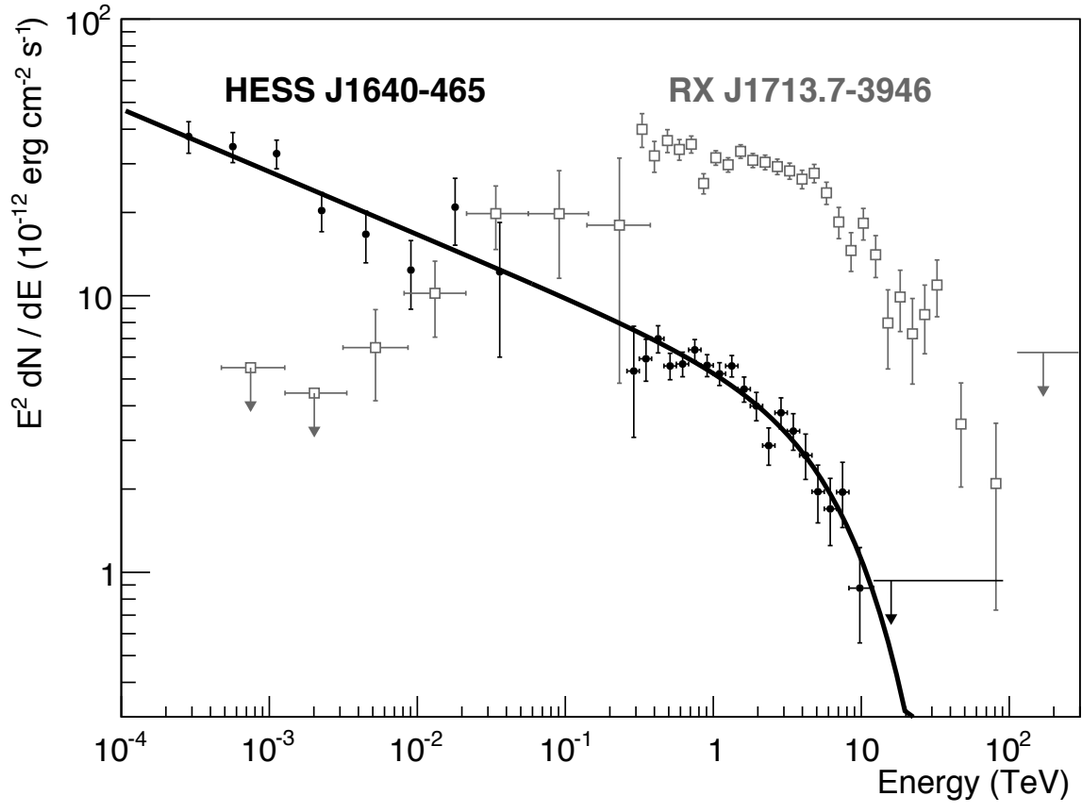


H.E.S.S. collab.
talk by Kavanach on X-ray

- Fermi-LAT & AGILE:
  - First firm evidence for accelerated protons!
  - Many SNRs detected
- TeV gamma-rays:
  - young shells & mature interactions
  - extended PWNe
  - debate over leptonic vs hadronic cosmic rays
  - first detection of a superbubble (in LMC)

WHAT DID IT BRING US?
PARTICLE ACCELERATION: GAMMA-RAYS

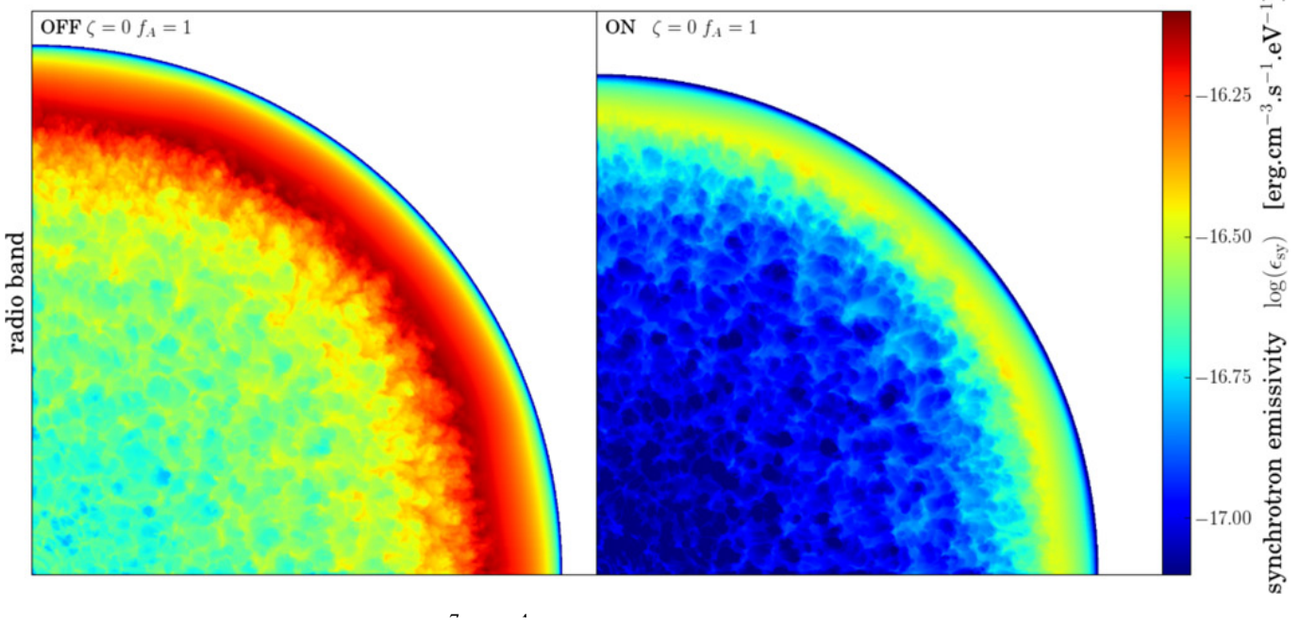




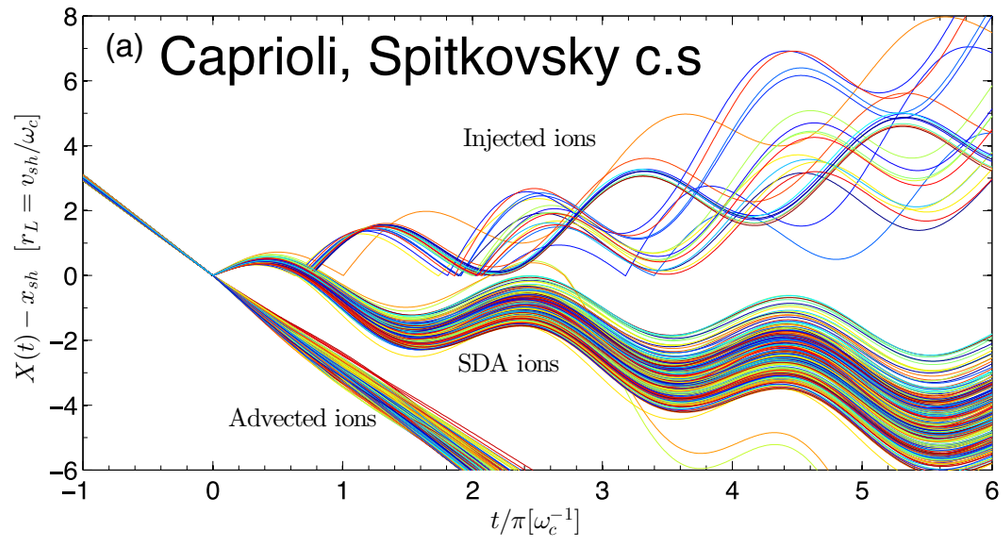
HESS J1640-465
H.E.S.S. collab. 2014 (A&A)

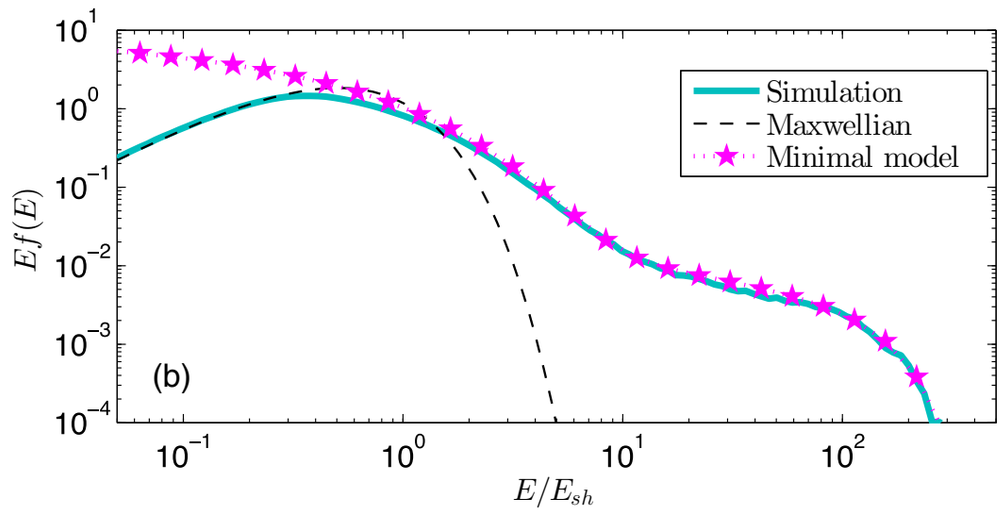
- TeV gamma-rays of HESS J1640:
  - Much softer than RX J1713
  - Seems good case for pion decay
  - Pion decay confirmed by Fermi-Lat (Lemoine-Goumard+ 2015)
  - Need non-standard scenario to explain:
    - SNR in cavity, cosmic-ray interaction with cavity wall

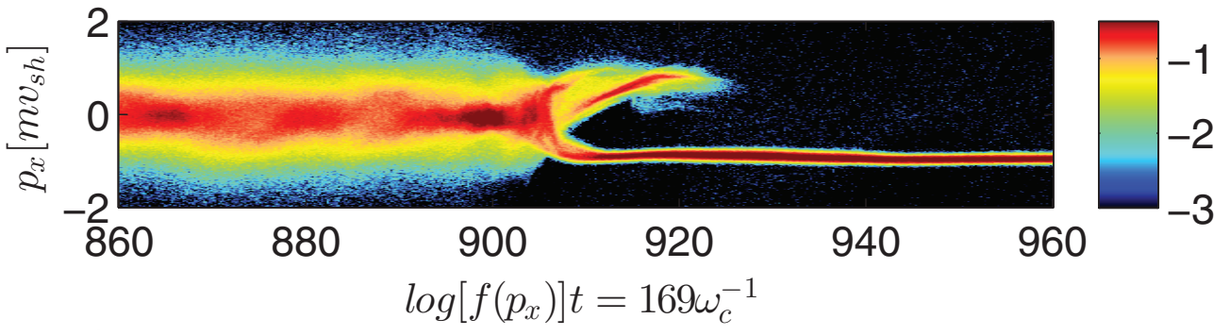
WHAT DID IT BRING US? COMPUTING



Ferrand+ 2014

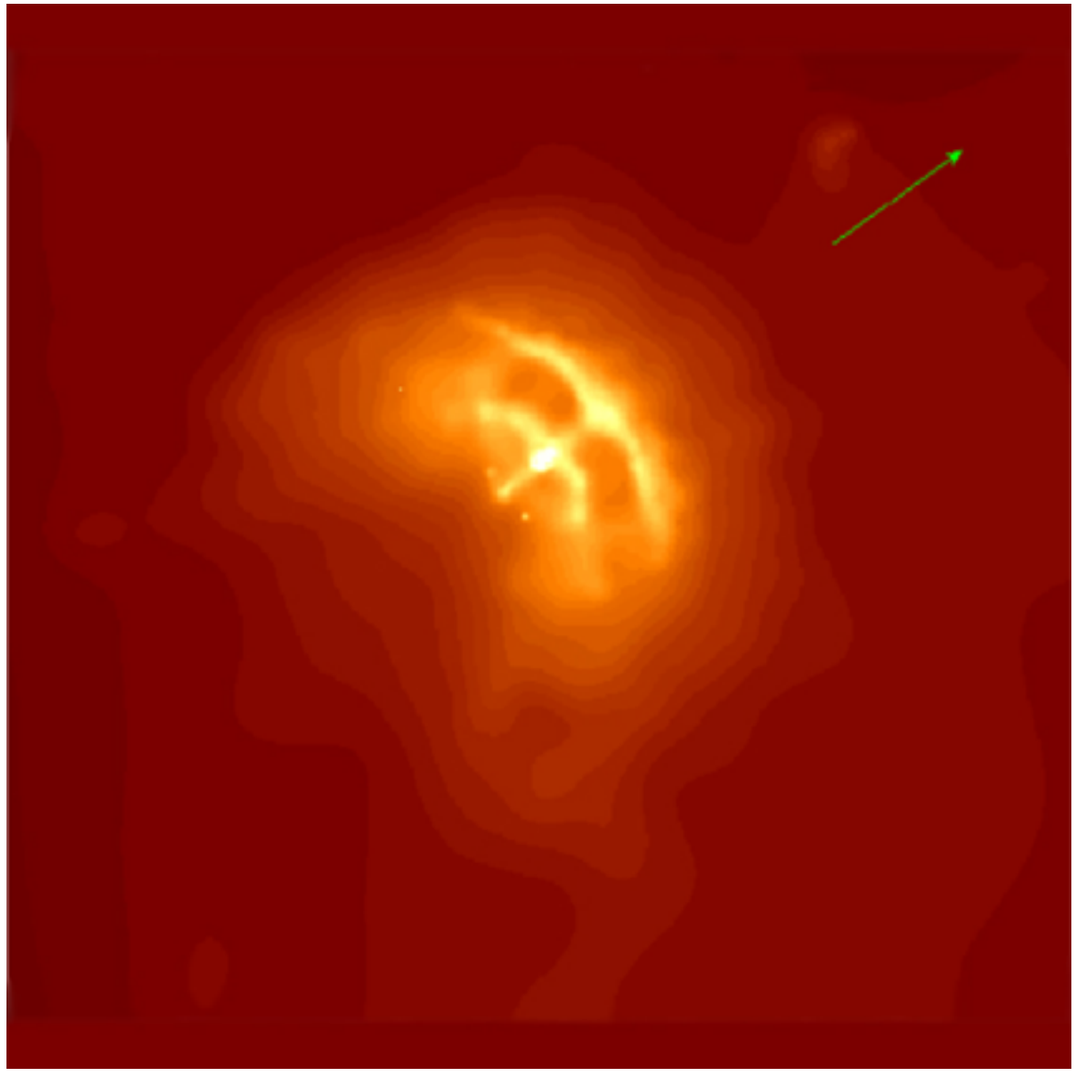




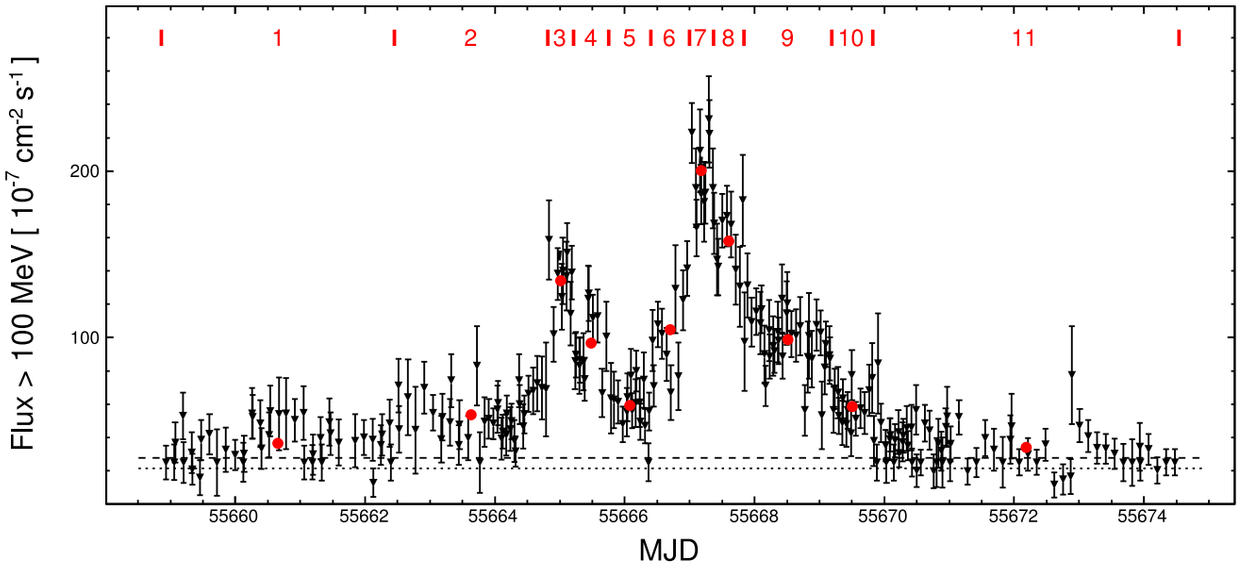


- Computing:
  - details of shock-heating and acceleration (PIC/Hybrid simulations)
  - 3D simulations of SNRs including cosmic-ray back pressure

WHAT DID IT BRING US?
PULSARS/PULSAR WIND NEBULAE



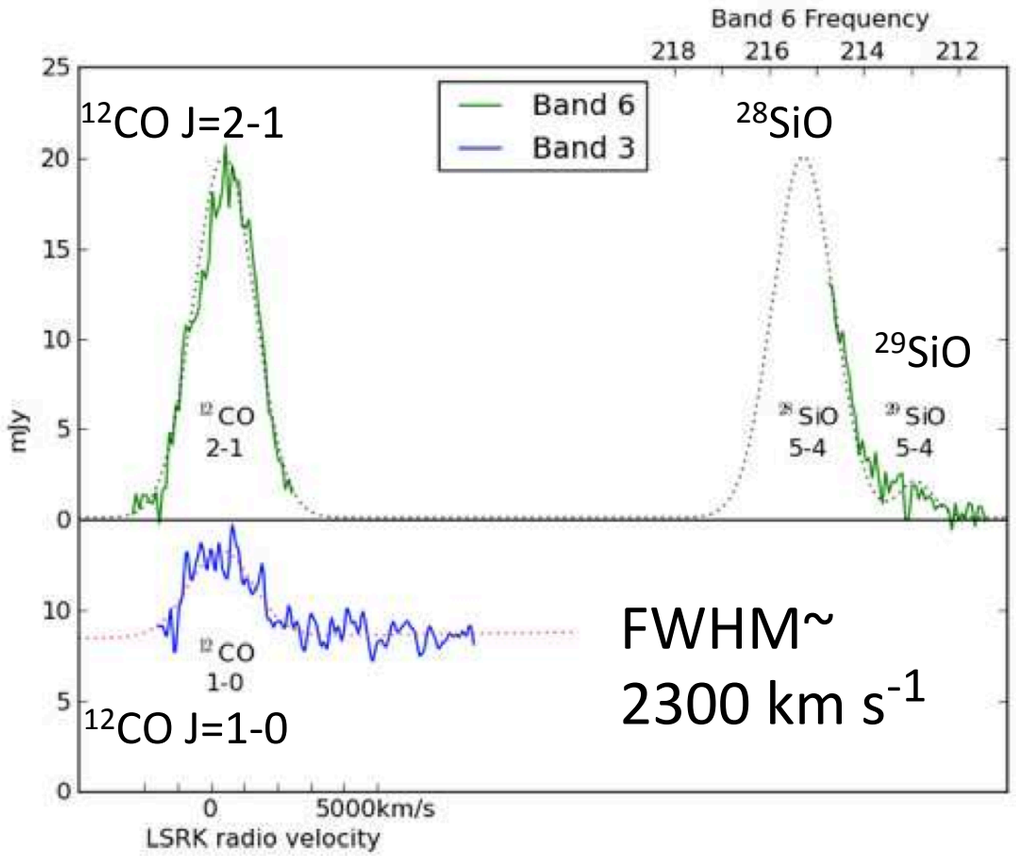
Chandra
see S. Safi-Harb's talk



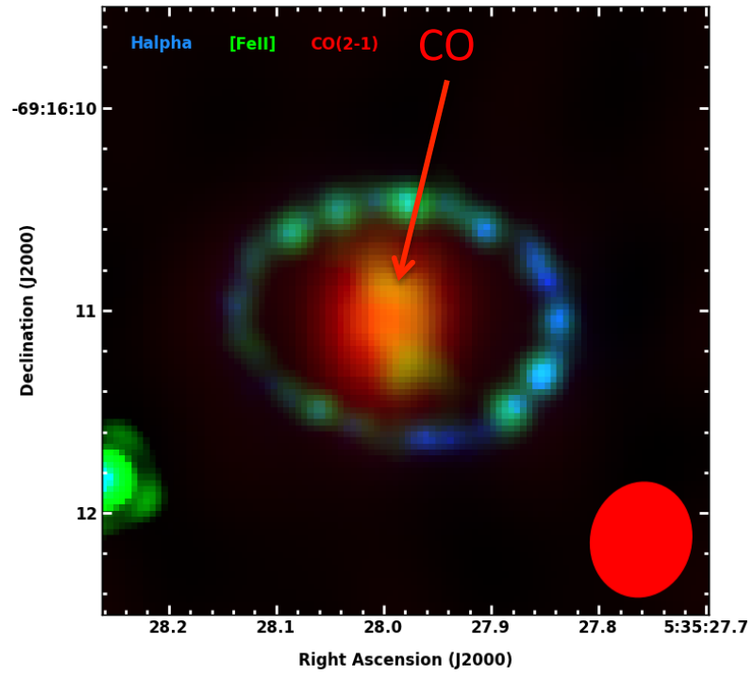
Fermi-LAT
Taken from Buehler+ '13

- Many PWNe have jet + torus morphology
- The Crab has flares GeV flares!
- Larger variety of neutron stars: magnetars, CCOs (anti-magnetar?)

WHAT DID IT BRING US?
DUST MASS MEASUREMENTS AND MOLECULES



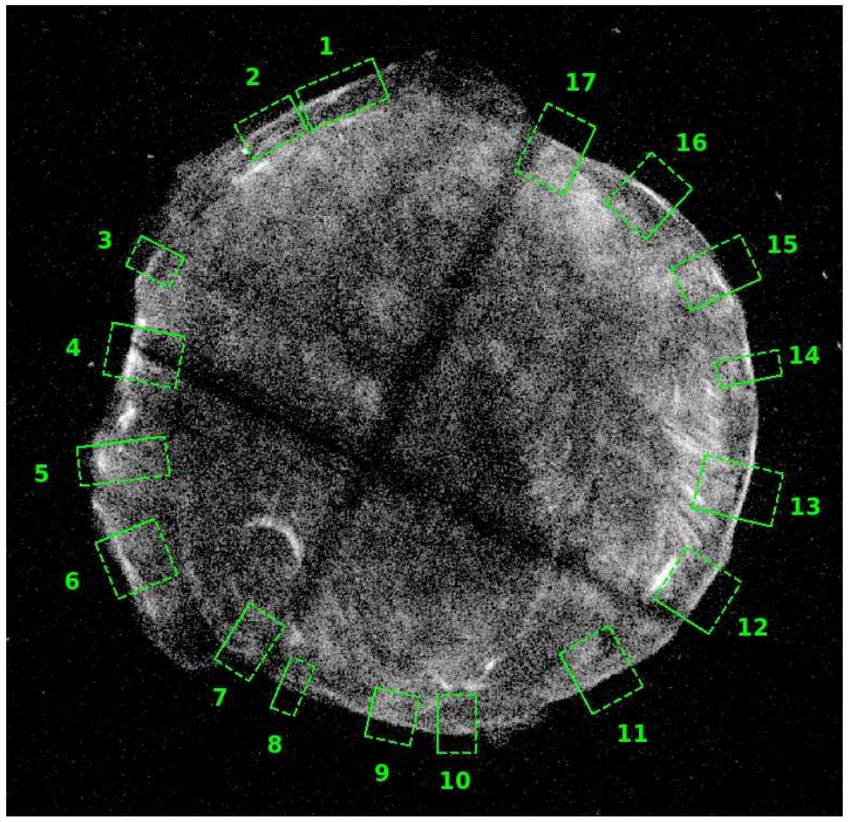
talk by M. Matsuura

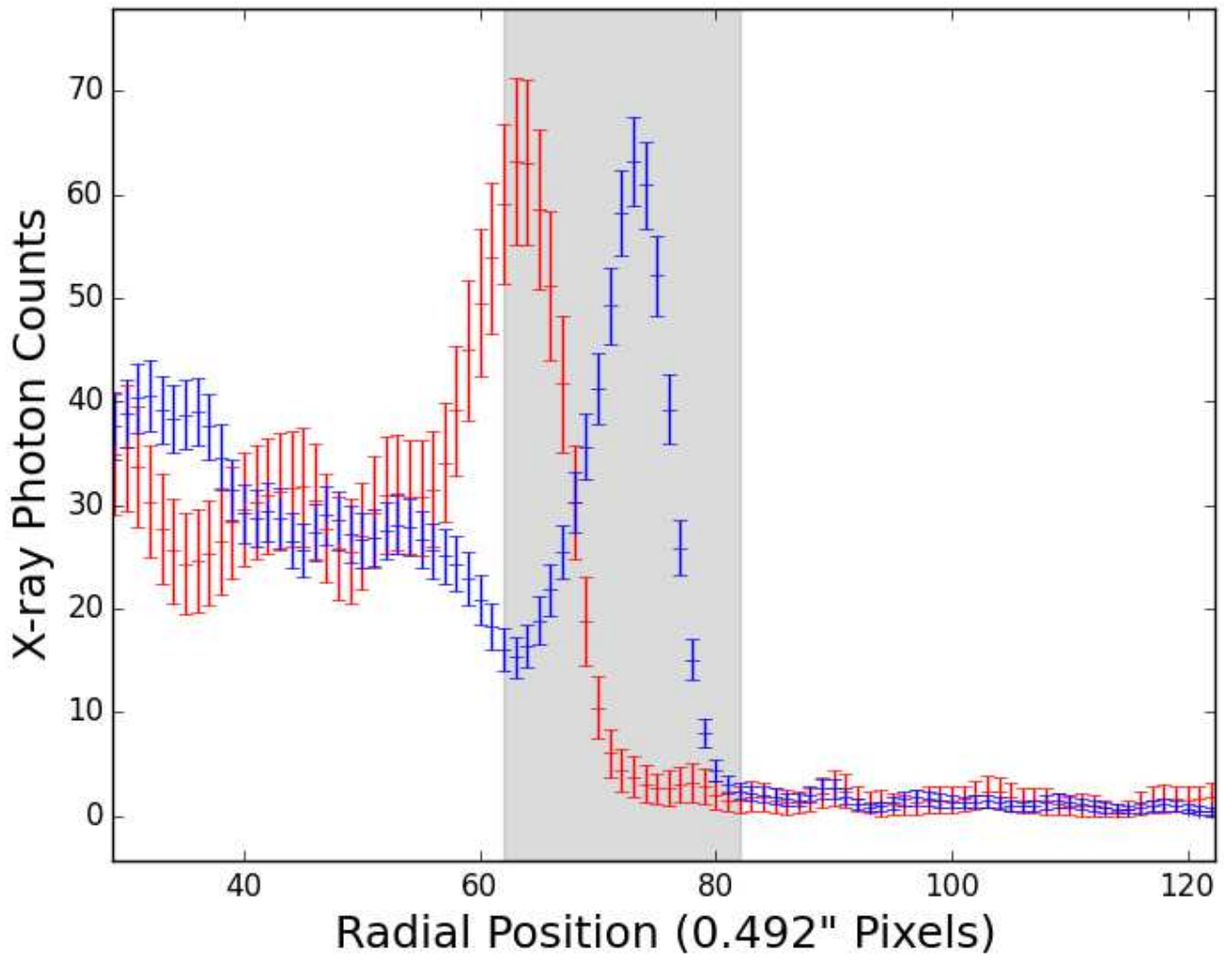


(Kamenetzky et al. 2013)

- SN1987A:
  - Surprisingly large dust mass (~0.1Msun)
  - Measurement of CO lines, including isotopic abundances!
  - Dust destruction at work (talk by Dwek)
- Other SNRs:
  - Some dust in ejecta (Cas A), sometimes CSM (SNIa: Kepler, Tycho)

WHAT DID IT BRING US?
PROPER MOTIONS & DOPPLER SHIFTS

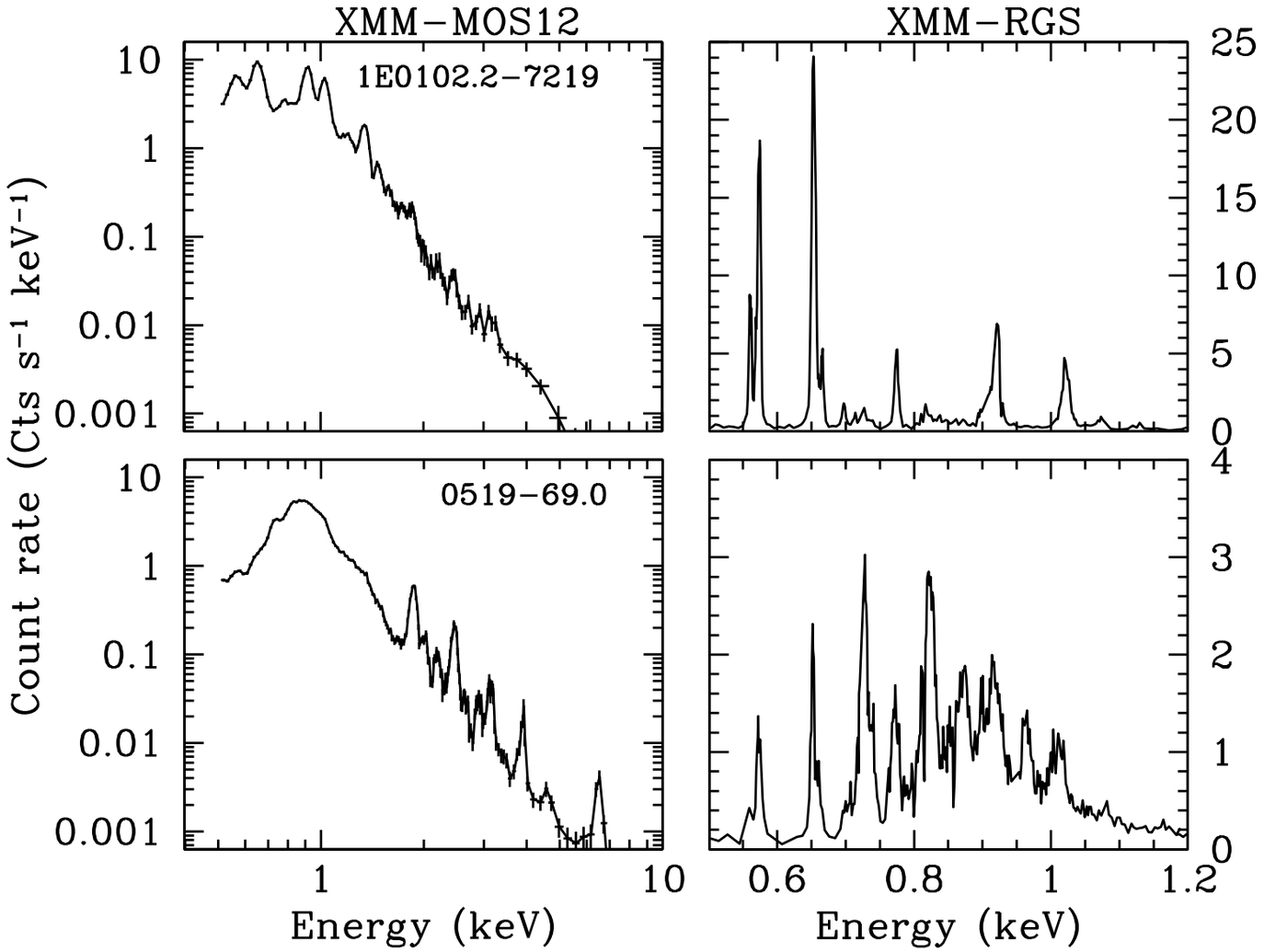




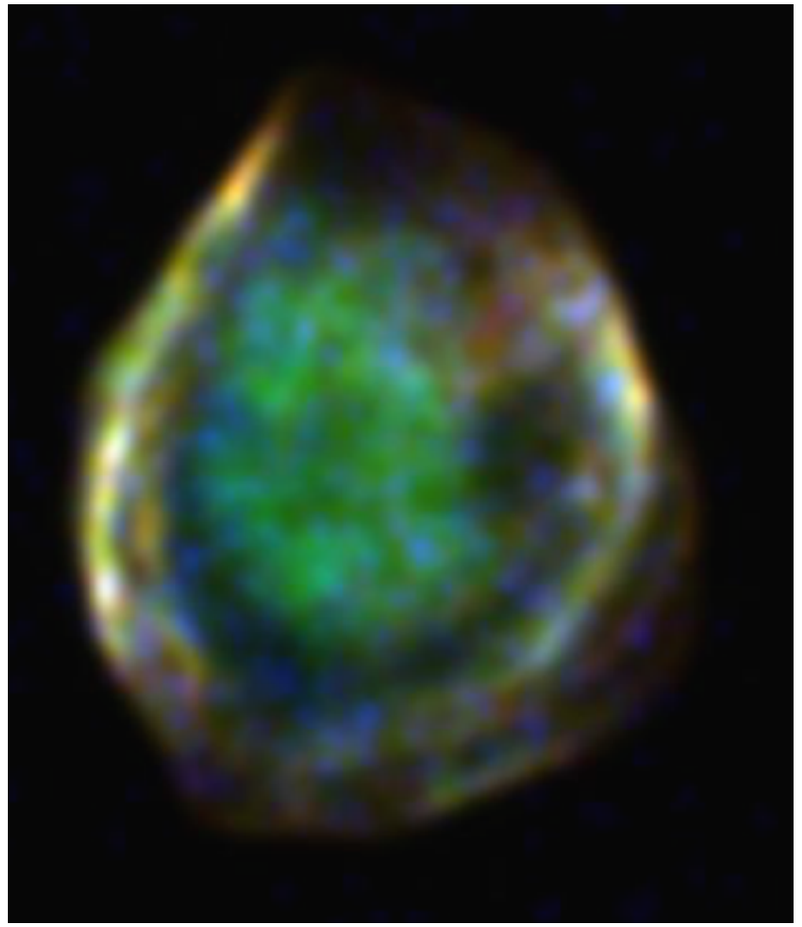
Brian Williams (2016)/talk

- Chandra resolution (also XMM): proper motions in X-rays
  - Tycho, Kepler, Cas A, RCW 86, RX J1713 (Acero talk), Vela Jr,….
- Longer tradition of radio proper motion measurements
- NB: Tycho & Kepler match John Dickel's measurements!
- Doppler mapping: Cas A (various authors), Tycho -> Jack Hughes talk

WHAT DID IT BRING US?
THE SUPERNOVA - SNR CONNECTION



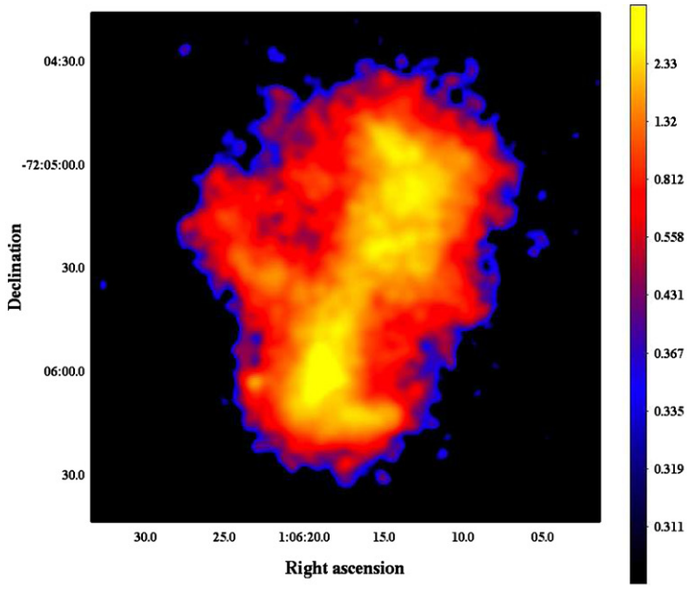
Vink 12 review (see also Hughes 95)

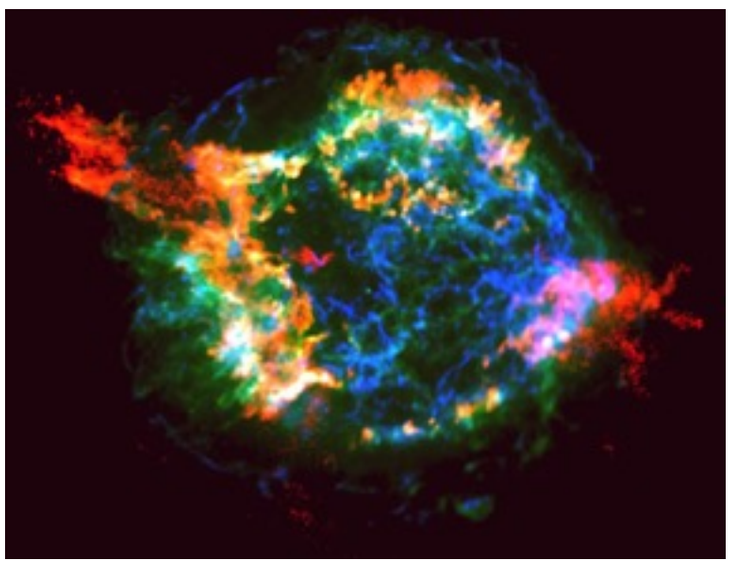


Glow of Fe-L in inside DEM L71

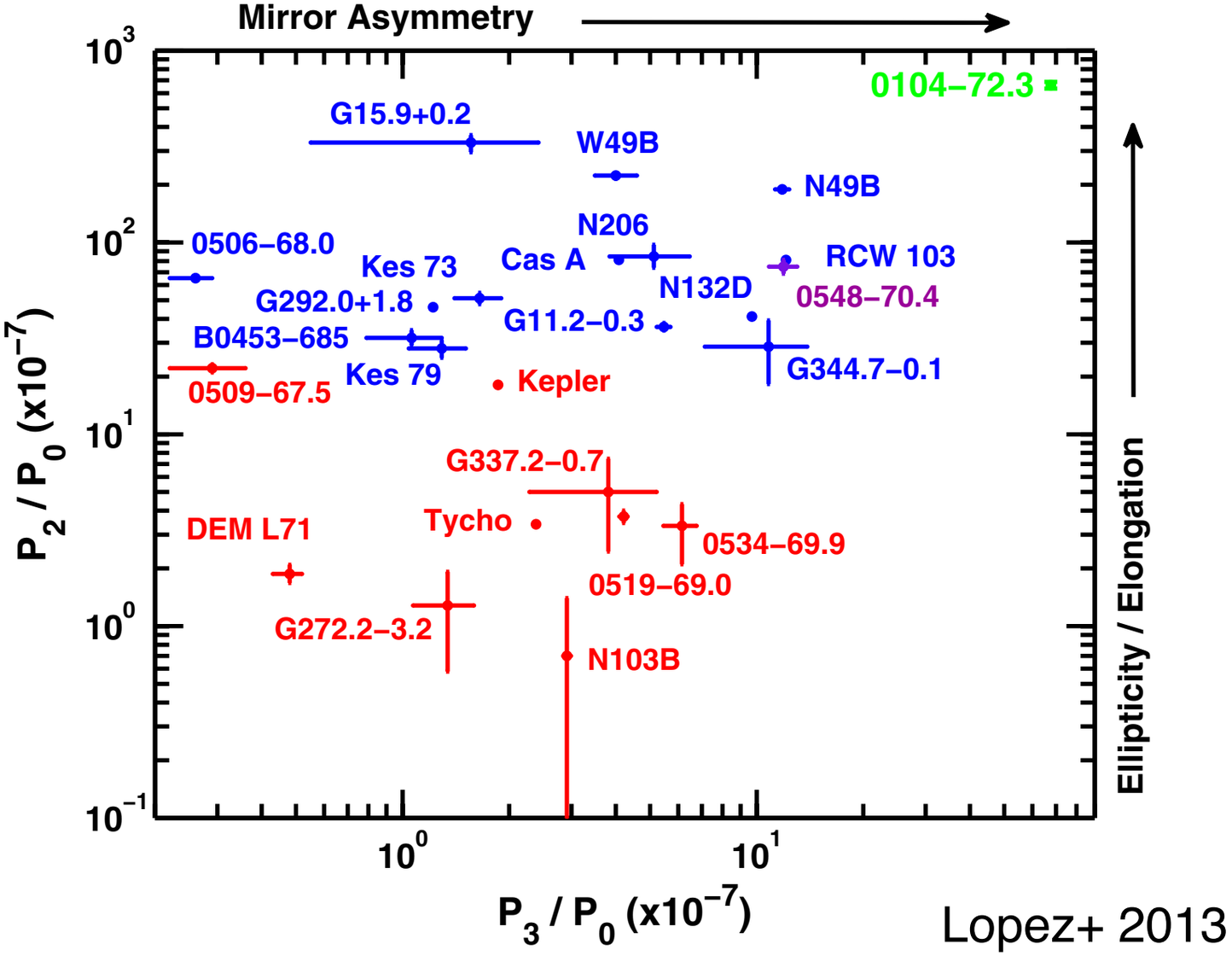
- X-ray imaging spectroscopy: Fe-L rich SN Ia spectra

WHAT DID IT BRING US? SYMMETRIES AND JETS





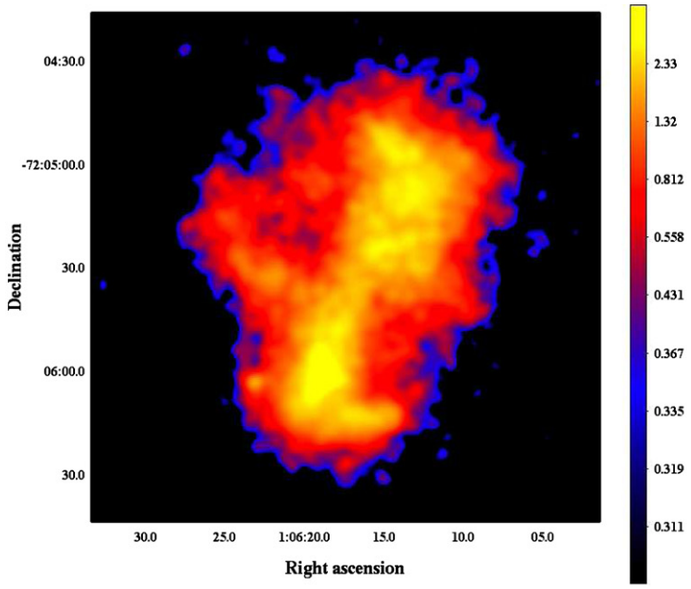
Fesen

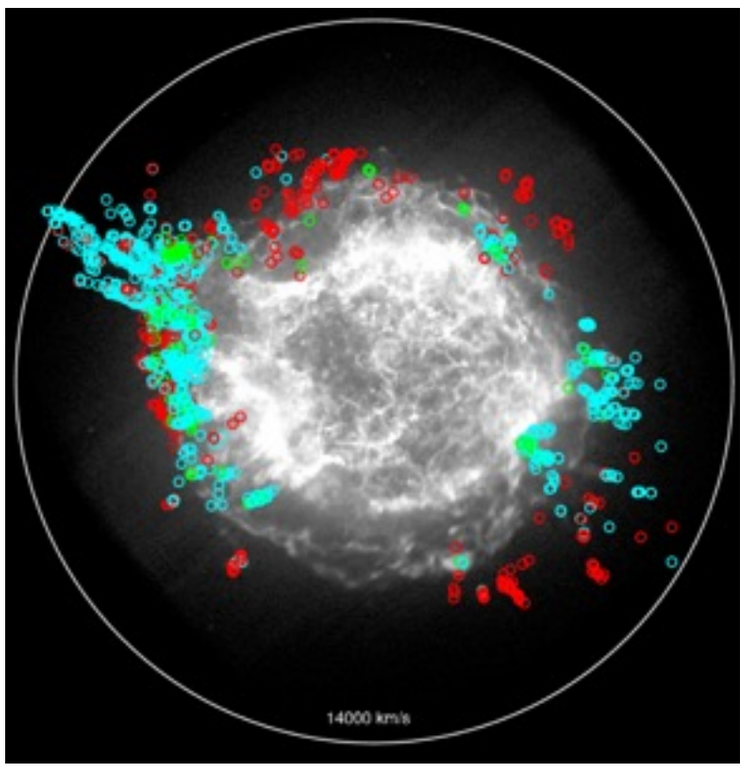


Lopez+ 2013

- Explosion or CSM?
  - CC SNe (Cas A, G292,..): explosion!!
  - Type Ia: no complex CSM to mess it up!
  - Why not always Fe-jets?

WHAT DID IT BRING US? SYMMETRIES AND JETS





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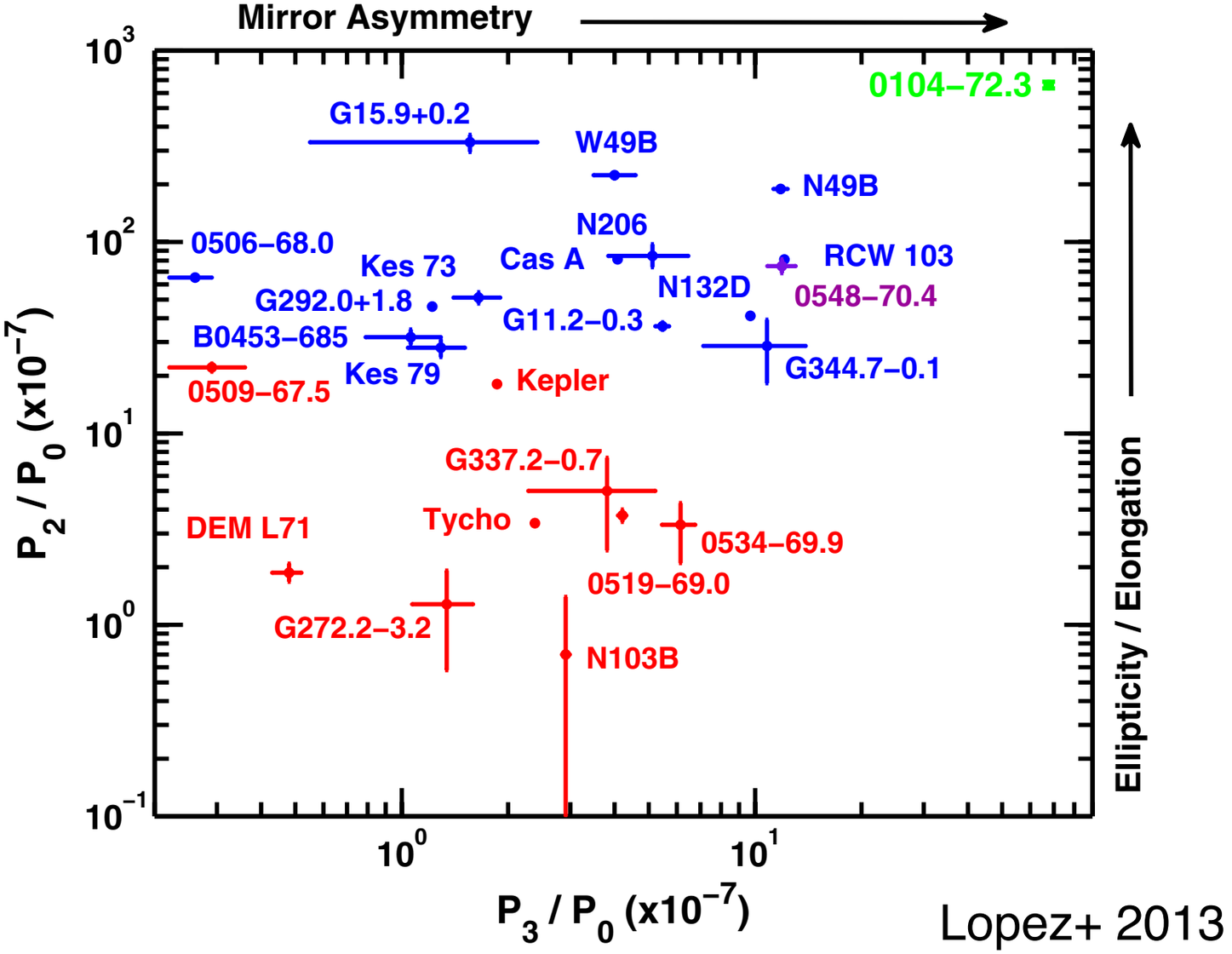

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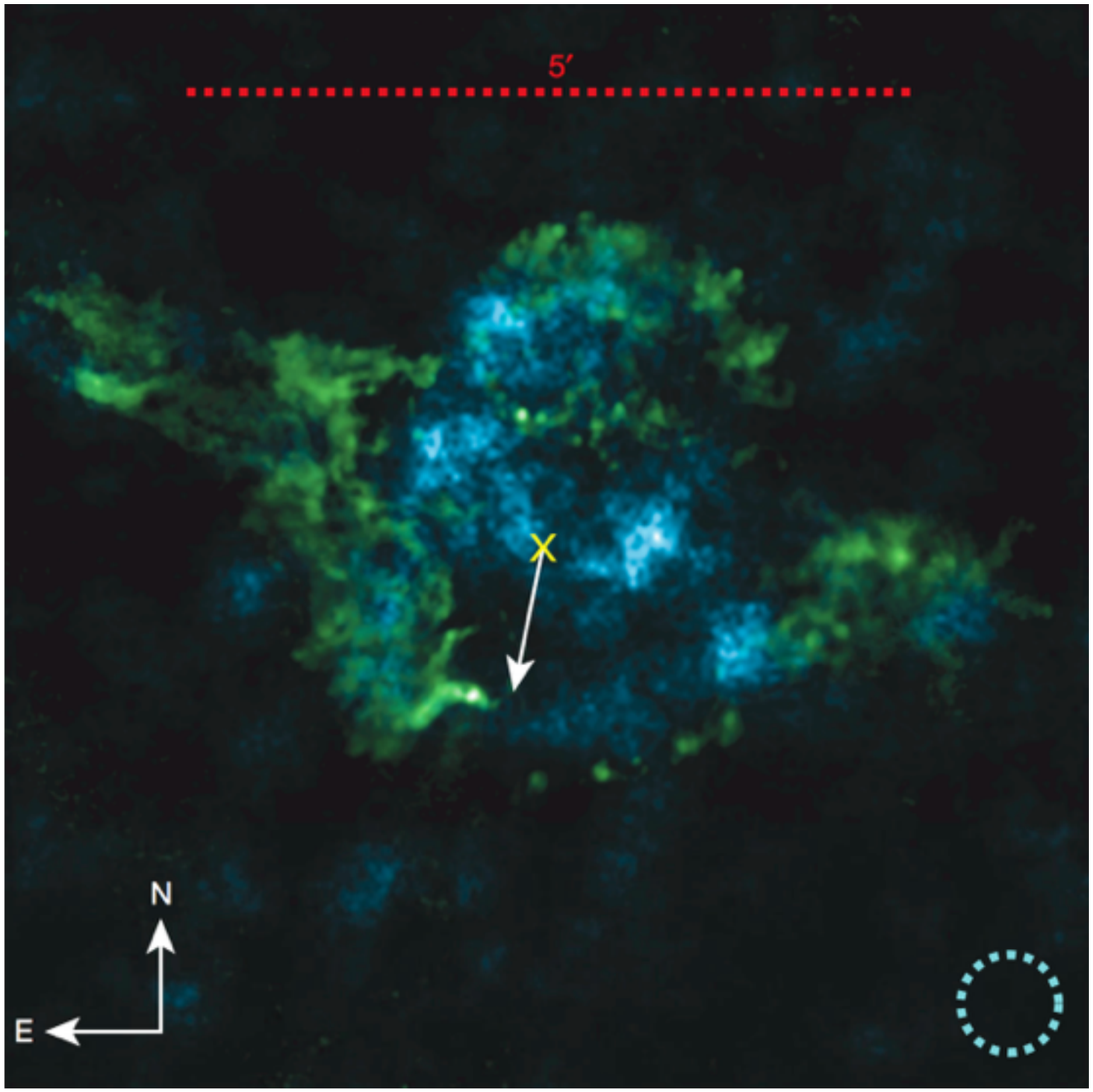
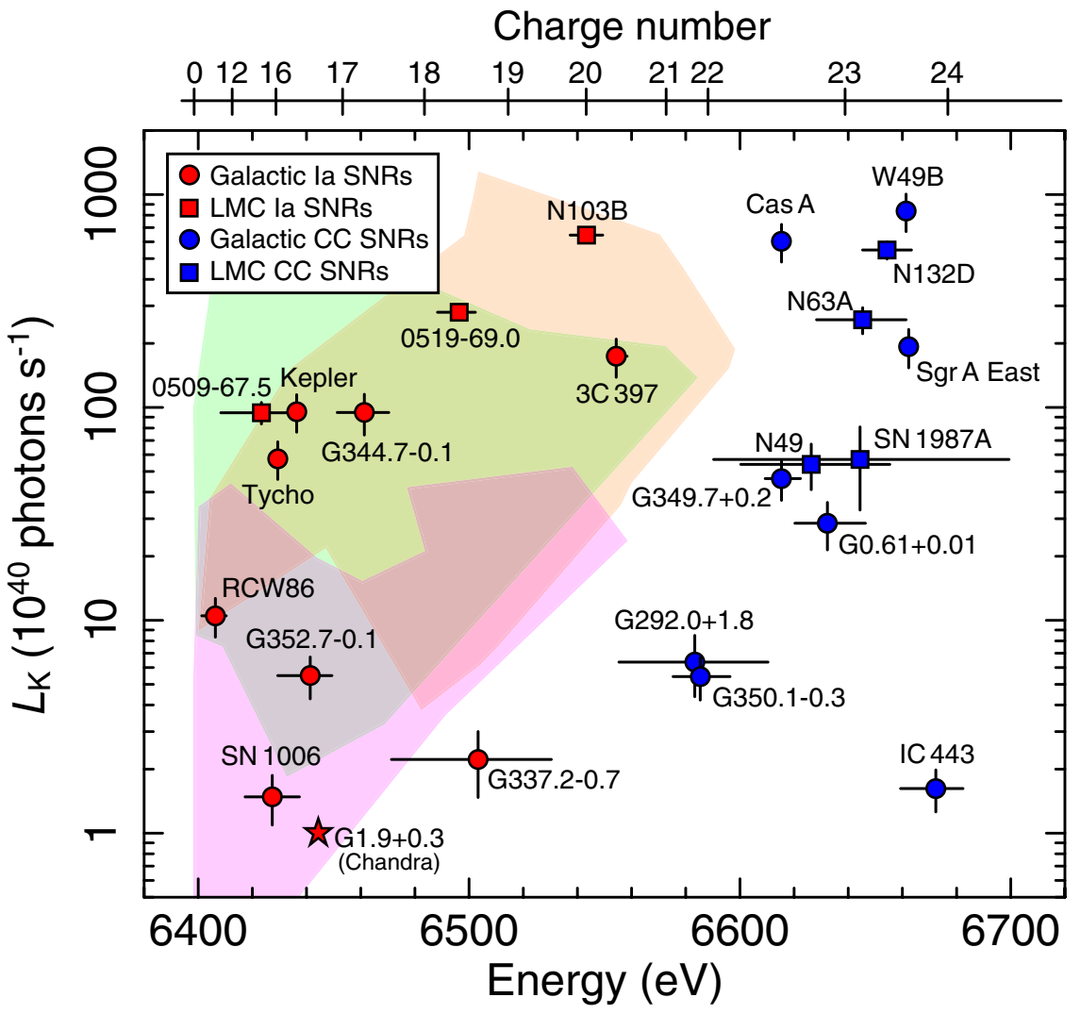
WHAT DID IT BRING US?
IMAGING RADIOACTIVE MATERIAL (^{44}Ti)



Grefenstette+ 2014

WHAT DID IT BRING US?
NEW X-RAY LINE DIAGNOSTICS



LFe vs Fe-K energy dichotomy
(Yamaguchi+ 13)

- Origin:
  - Type Ia more iron, but less dense CMS? (Yamaguchi+)

THEORY


ZEER INDRUKWEKKEND, COLLEGA....
MAAR WERKT HET OOK IN THEORIE?
dVRGnT

THEORY

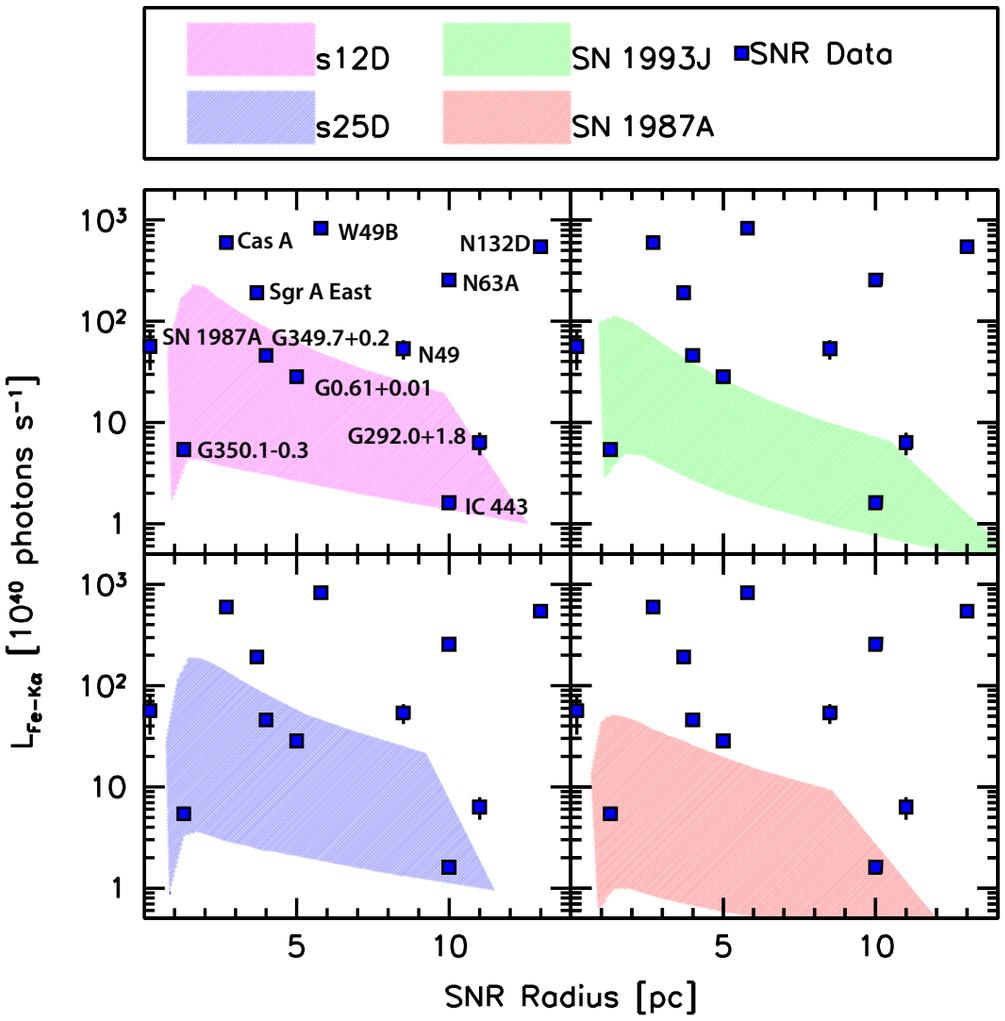
Very impressive colleague…

THEORY

Very impressive colleague…

But does it also work in theory?

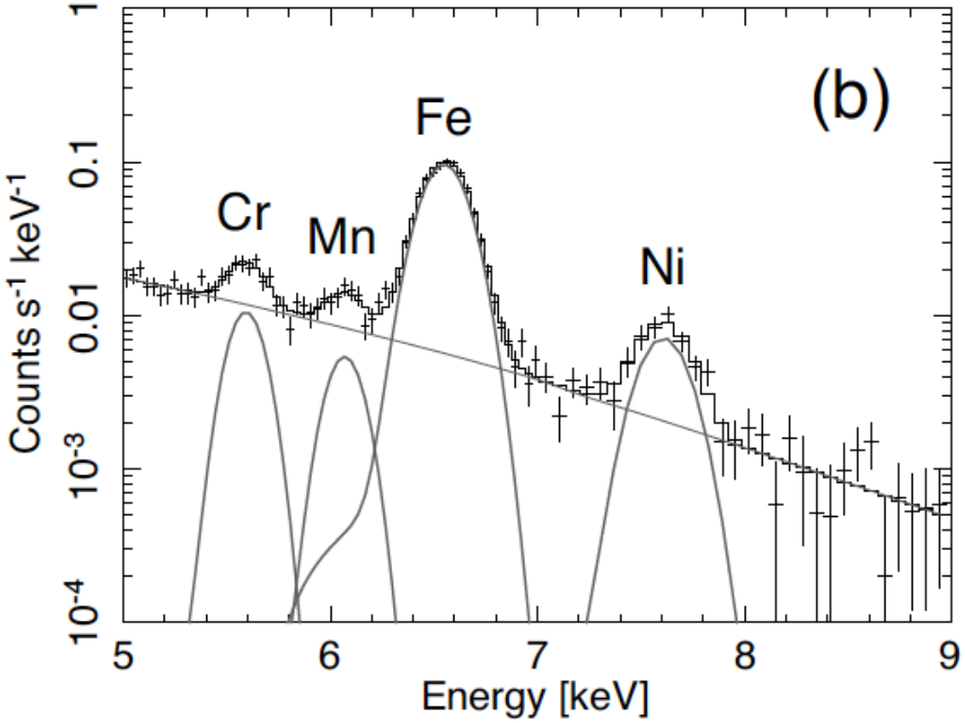
WHAT DID IT BRING US?
NEW X-RAY LINE DIAGNOSTICS

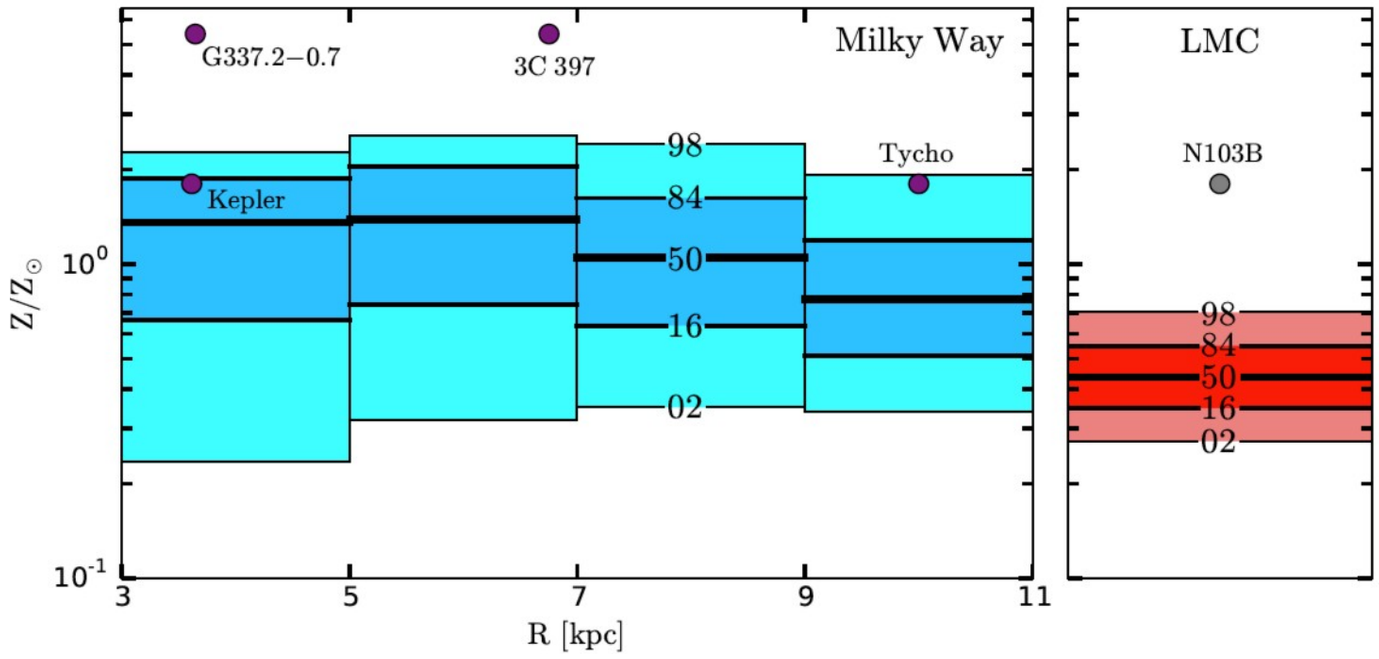


Talk D. Patnaude

- Concerns:
  - how much variation is there in SN Ia/CC environments?
  - role of clumping (CC ejecta more clumped)?

WHAT DID IT BRING US?
EVIDENCE FOR SIMMERING PRE SNIA PHASE?





- Carles Badenes talk:
  - Odd elements preserve memory of progenitor metallicity
  - Cr, Ni, Ca: SNIa remnants were (super)solar
  - Cannot be for LMC! -> Need simmering phase

What did it bring us?
The quest for surviving donor stars (SNIa)

Talks by Kerzendorf and Hovey

- No clear evidence for (bright) surviving donor stars!
- Suggest none is there !?

RESISTING TEMPTATIONS

RESISTING TEMPTATIONS

Siren Schaefer/Kerzendorf

RESISTING TEMPTATIONS

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RESISTING TEMPTATIONS

Siren Schaefer/Kerzendorf

Noam Soker

RESISTING TEMPTATIONS

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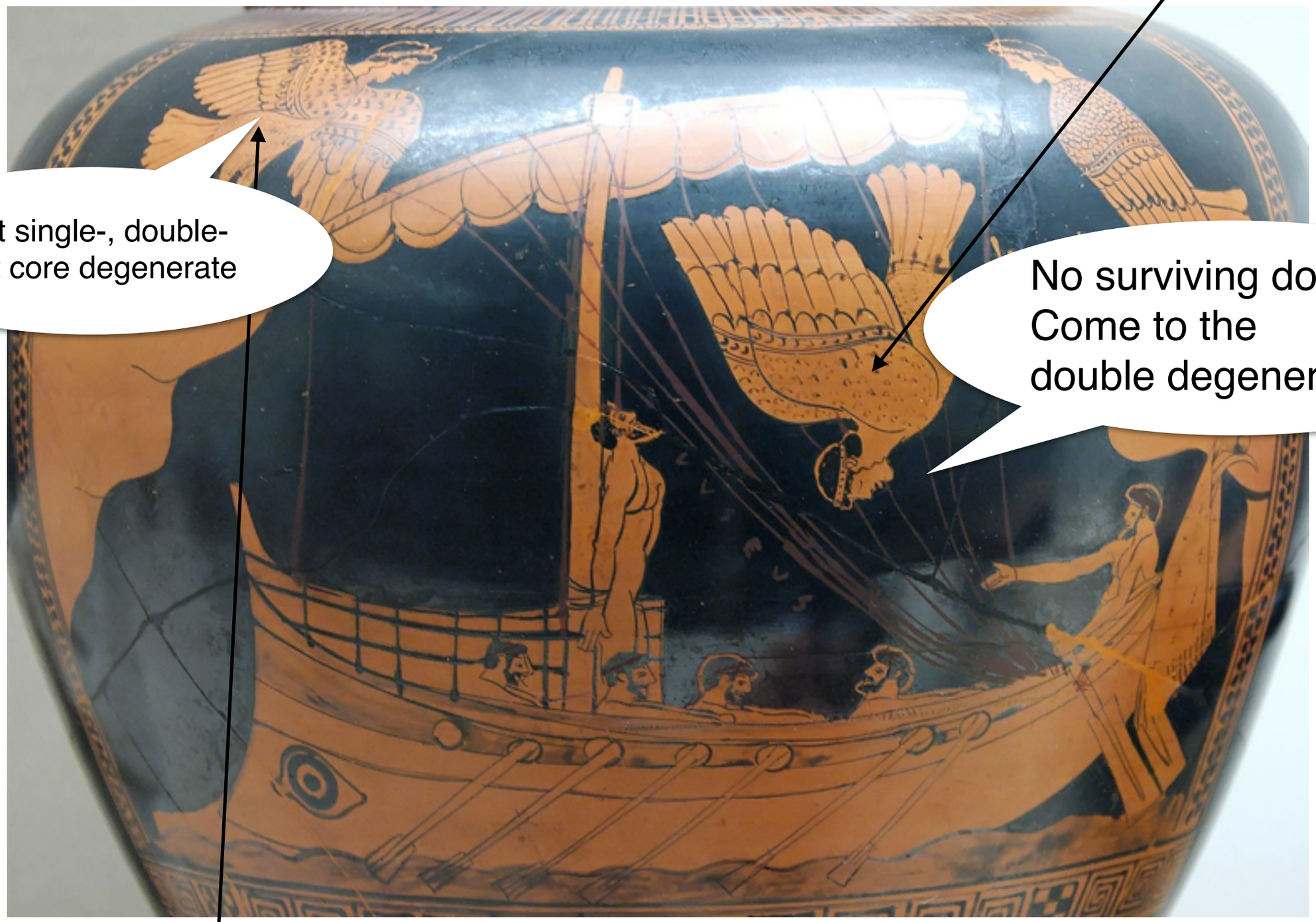
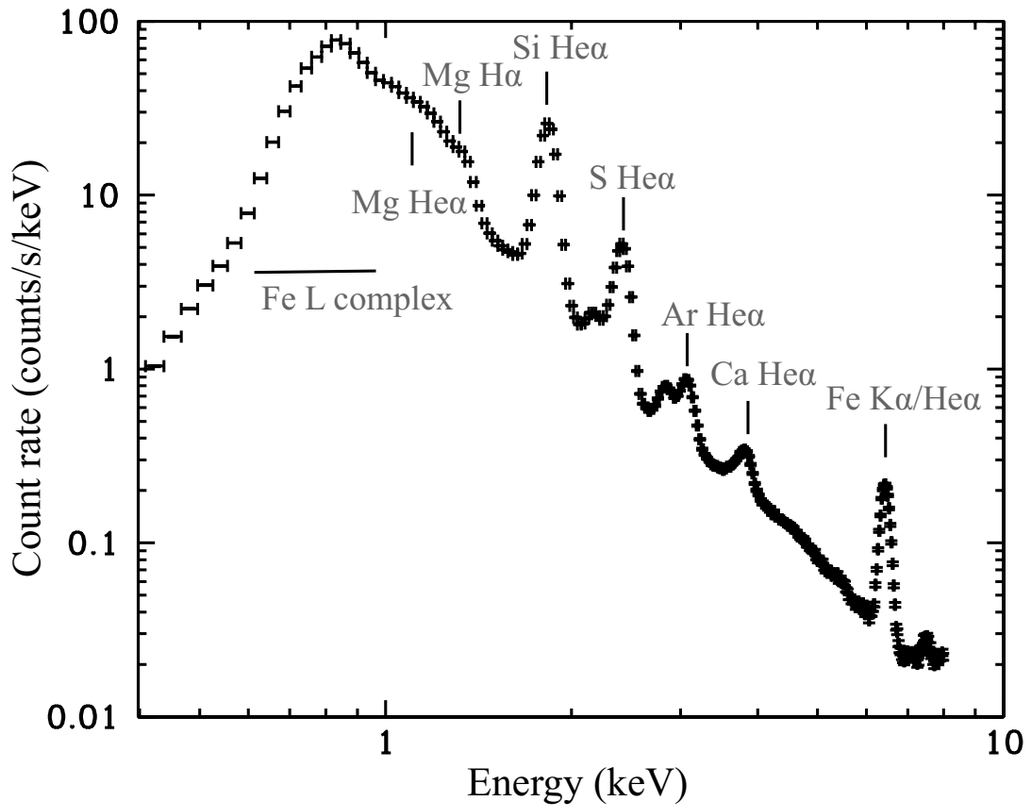


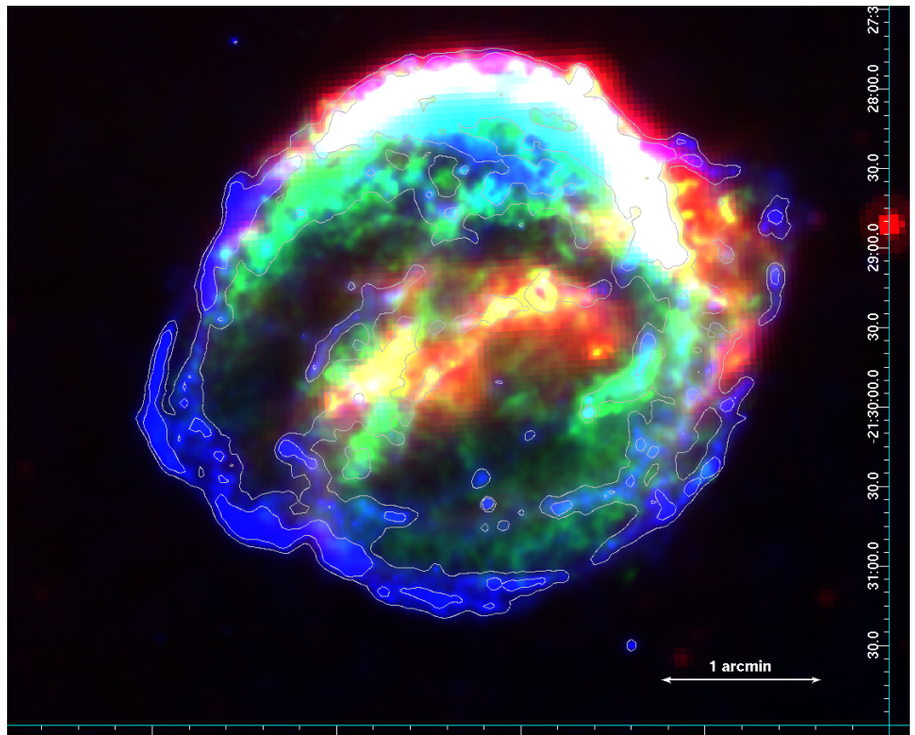
Not single-, double-
but core degenerate

No surviving donors!
Come to the
double degenerate side

Noam Soker

PERSONAL NOTES ABOUT KEPLER'S SNR

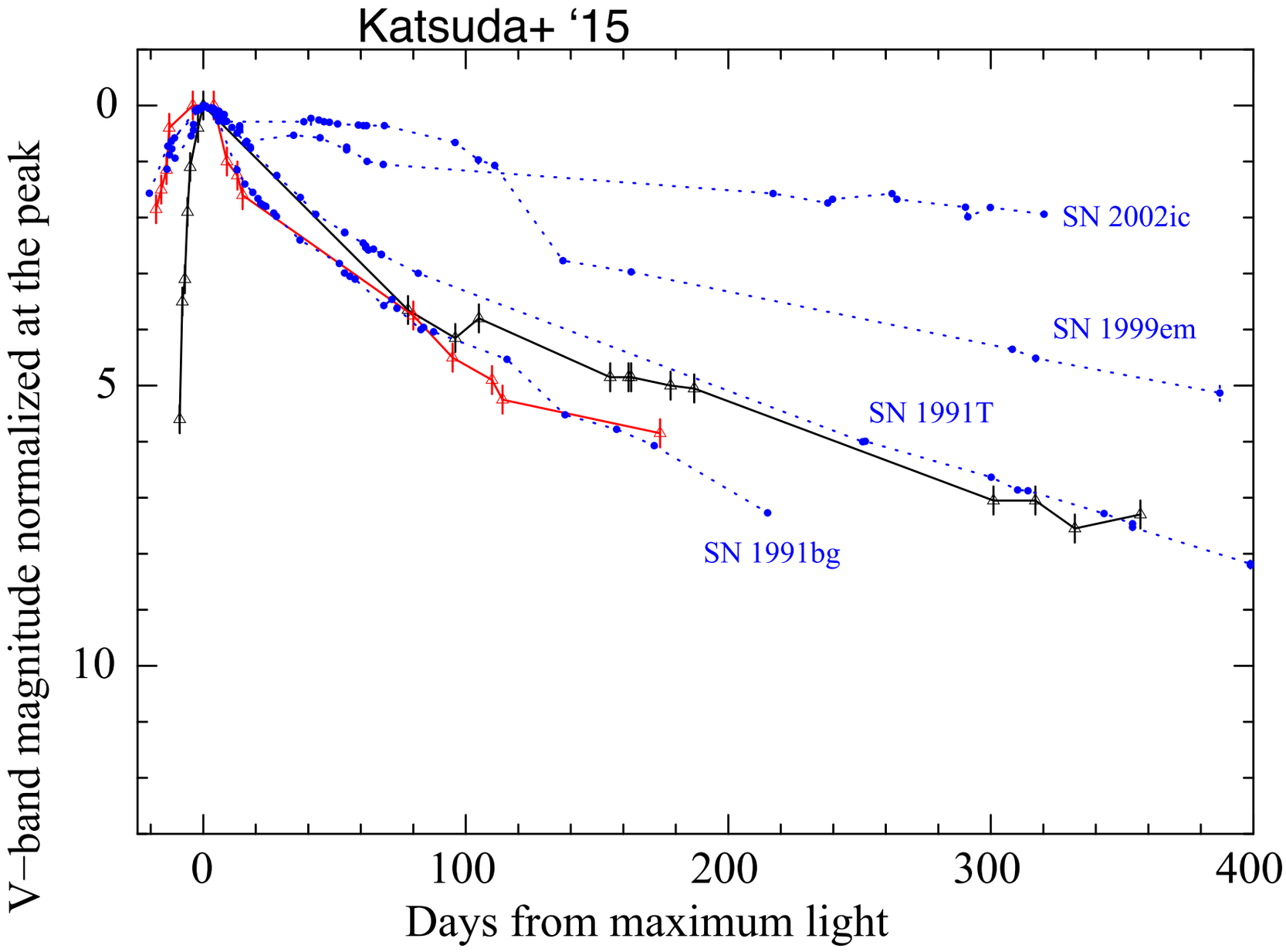




Vink 17 in Handbook of Supernovae
Talk by Chiotellis

- SN1604/Kepler clearly Type Ia (Katsuda+ 96,Reynolds+ 97)
- Also clear evidence for proper motion of system (~250 km/s)
- In north: bounces into dense bowshock-shaped wind material
- Clear need for progenitor wind: AGB star donor, single degenerate?
- No surviving donor (Kerzendorf): double degenerate?
- What is going on? -> Core degenerate model (Noam Soker)?
- Problem 2: How to eject *binary* out of MW with >200 km/s?

A FEW WORDS ABOUT KEEPER'S SNR
WAS IT A SN1991T TYPE (BRIGHT)?



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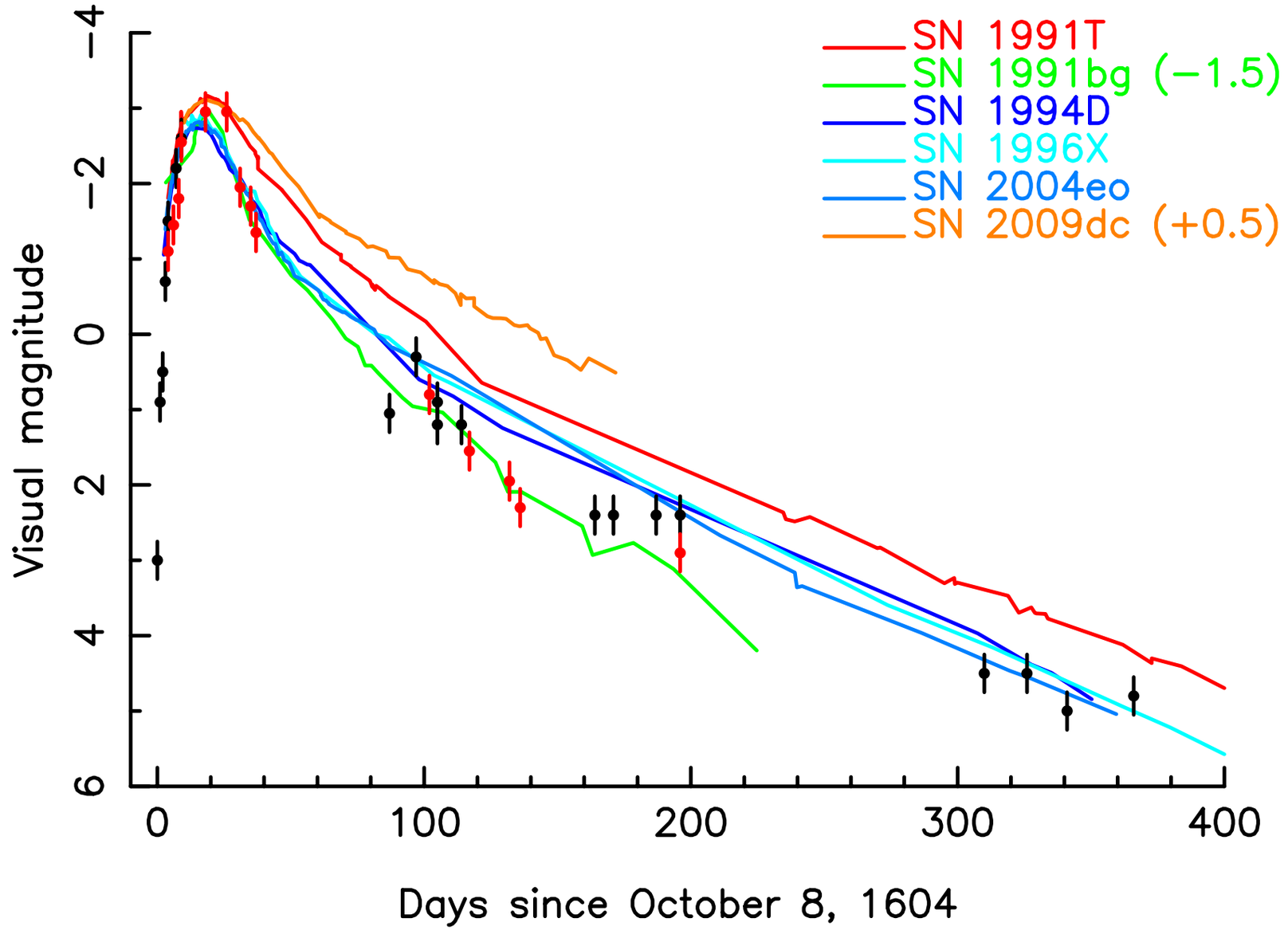

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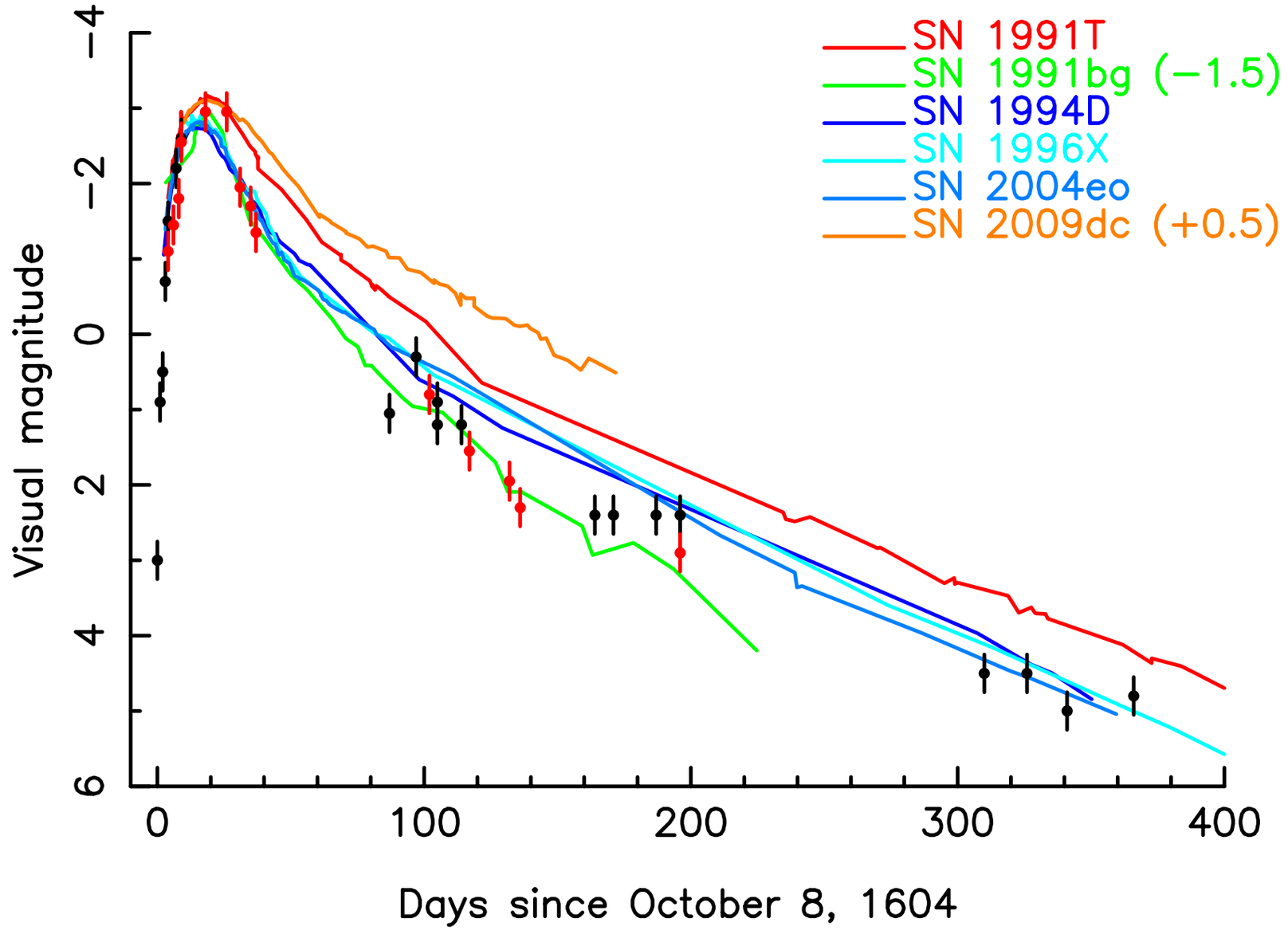
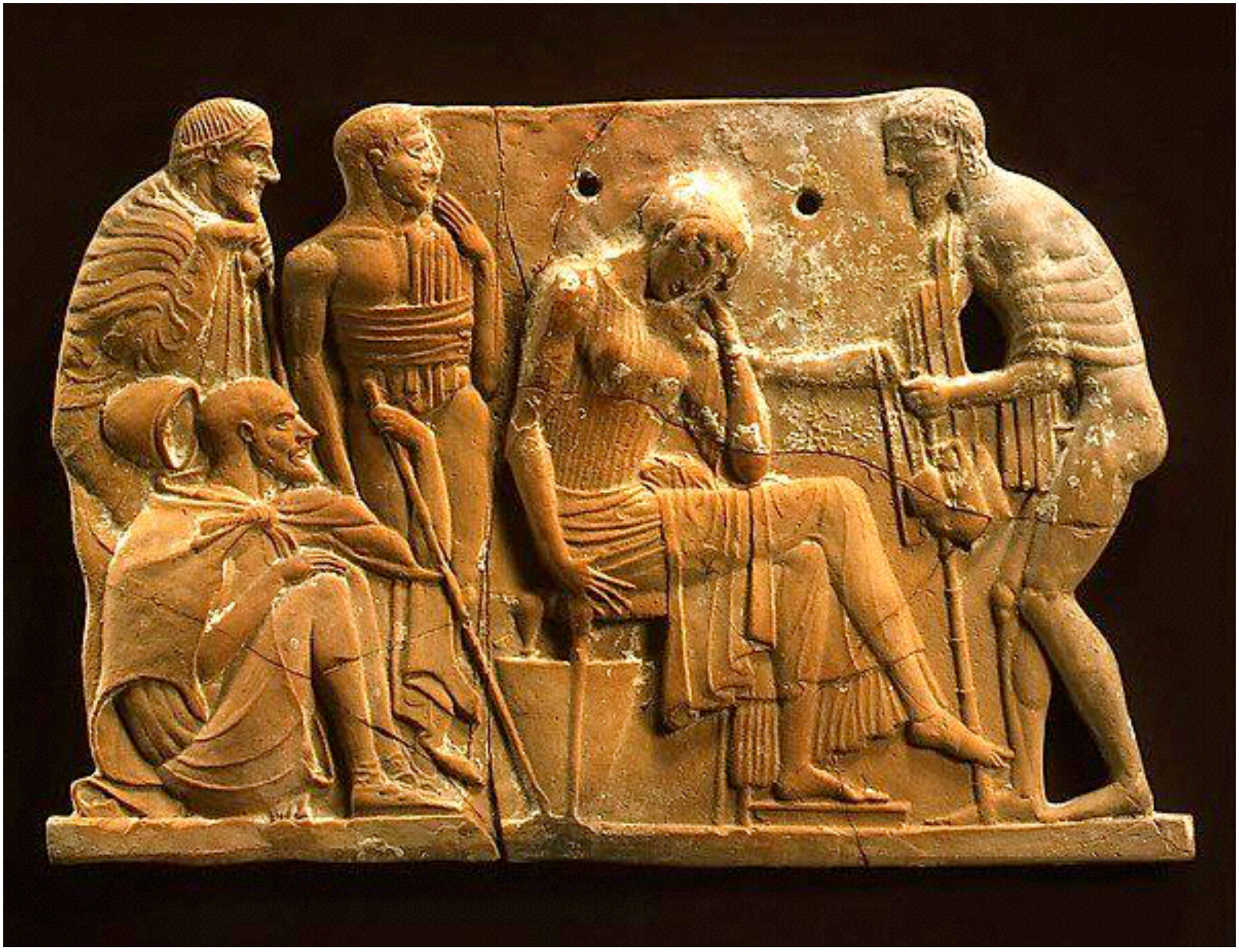


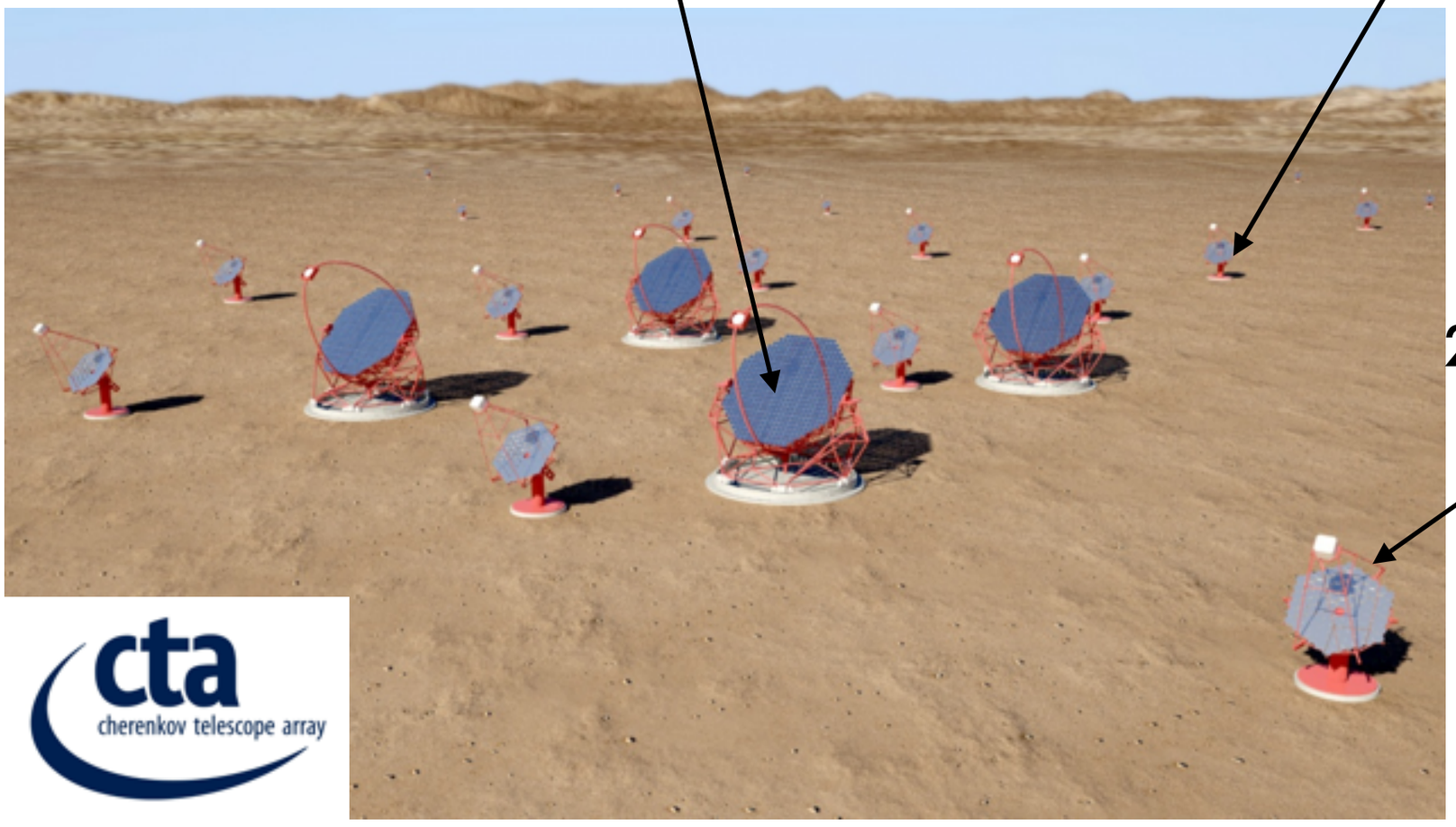
- Kepler's and Korean data
- Kepler: rich in Fe -> SN 1991T?
- Historical light curve: normal Type Ia not perfect, but work best

(To be published in Handbook of Supernovae)

What will the future bring?

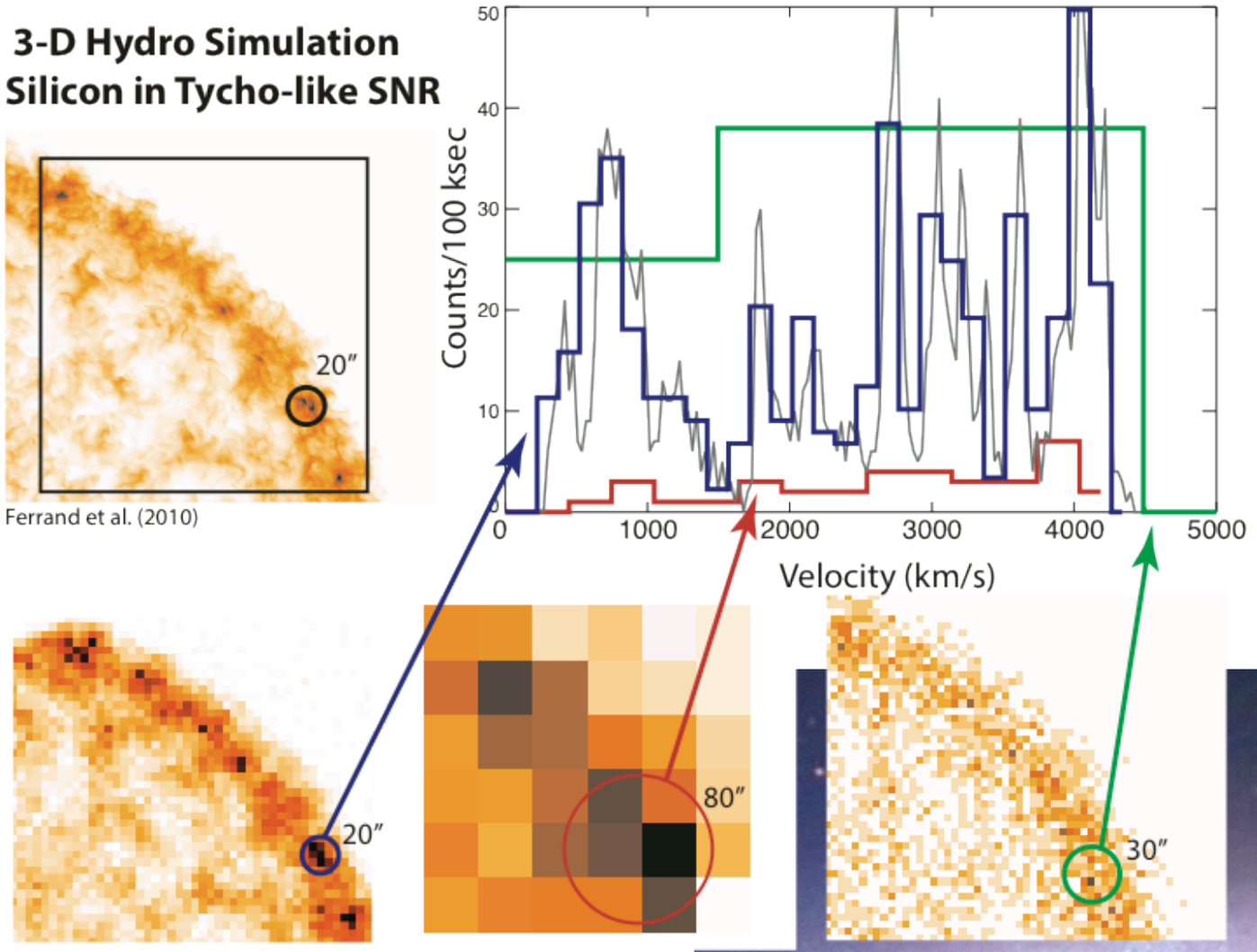


CHERENKOV TELESCOPE ARRAY (CTA)



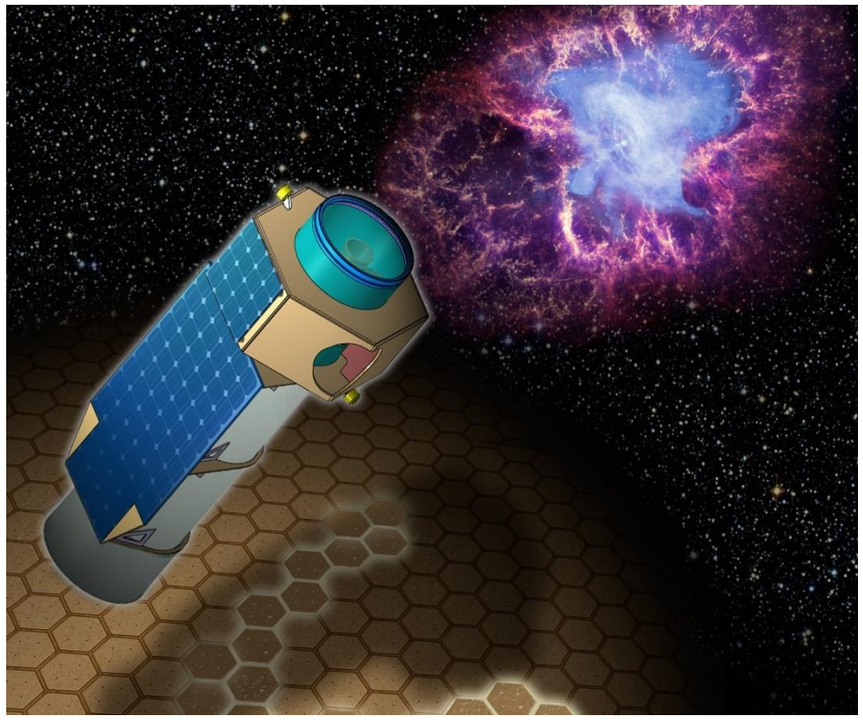
- power-law spectra: many low energy gamma-rays, few high energy gamma-rays
- low energy gamma-rays: faint showers ⇒ big telescopes
- high energy gamma-rays: bright showers ⇒smaller telescopes, many needed
- SNR research: Are there supernova/SNR PeVatrons (talk Dwarkadas)?
- More TeV SNRs and PWNe

ATHENA



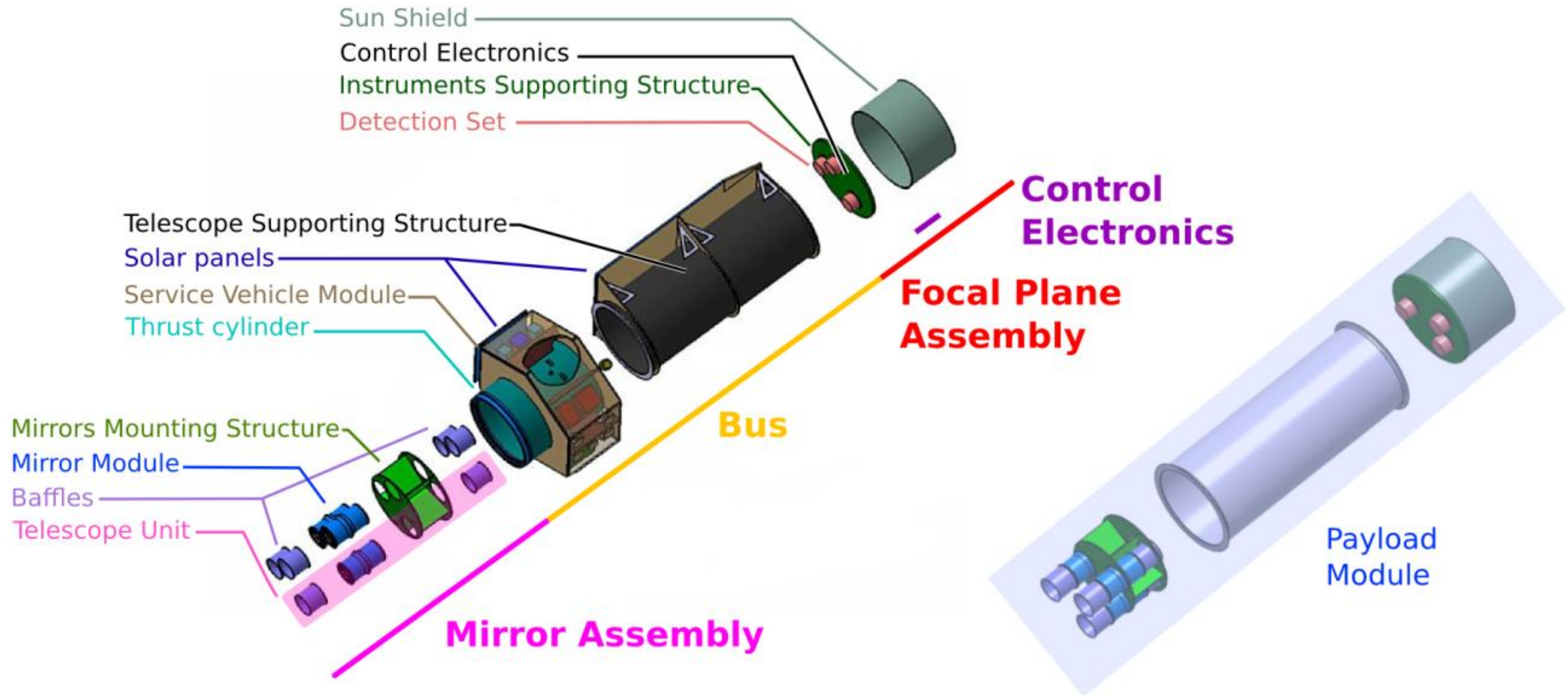
- ESA L2 Mission
- to be launched in 2028
- Instruments
  - Wide field imager
  - TES/Calorimeter
  - 5” resolution

XIPE: ESA M4 CANDIDATE
(IXPE: NASA SMEX CANDIDATE)



- XIPE=X-ray Imaging Polarimetry Explorer
  - Also: Aztec god for agriculture
- Selected candidate for M4
- Potential launch date: 2025
- ESA budget: 450 Meuro
- Competitors:
  - Ariel (exo-planetary atmosphere spectroscopy)
  - Thor (turbulence of space plasmas)

XIPE SPACECRAFT



- X-ray mirrors: XMM heritage:
  - Three mirror modules
  - XMM replication technique
  - Similar angular resolution (HEW 15")

GAS PIXEL DETECTOR (GPD)

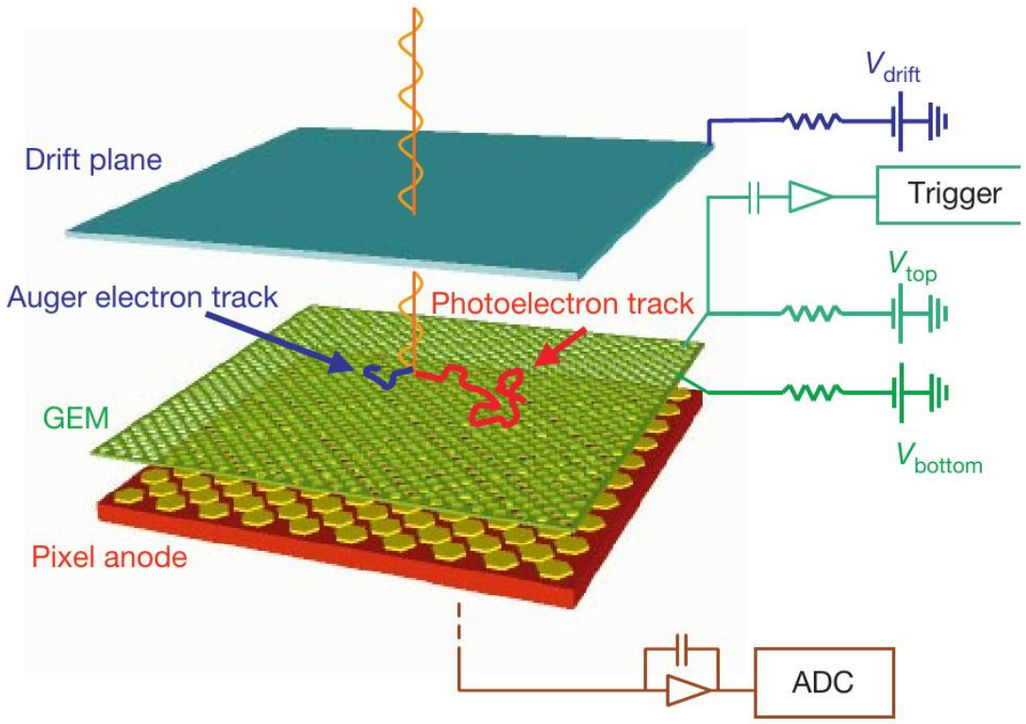


Figure 17 Principle of operation of the GPD (Costa et al. 2001).

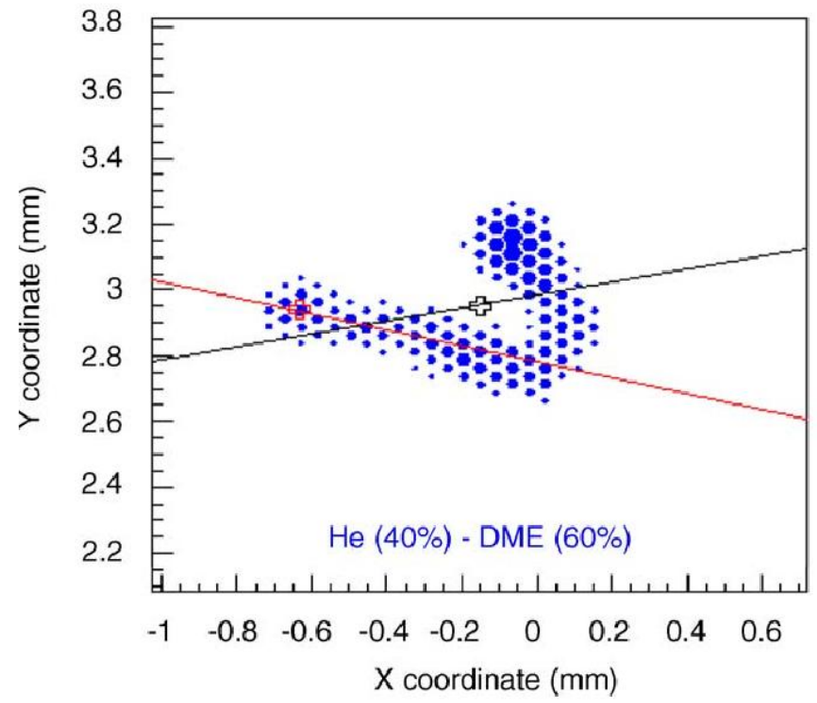
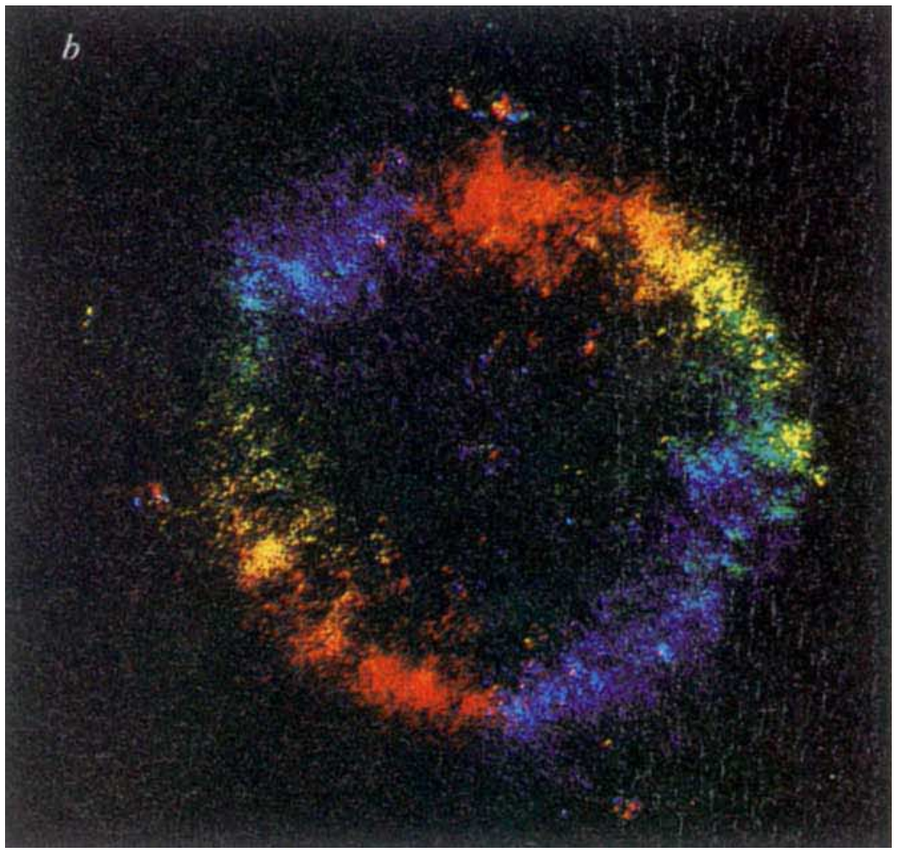


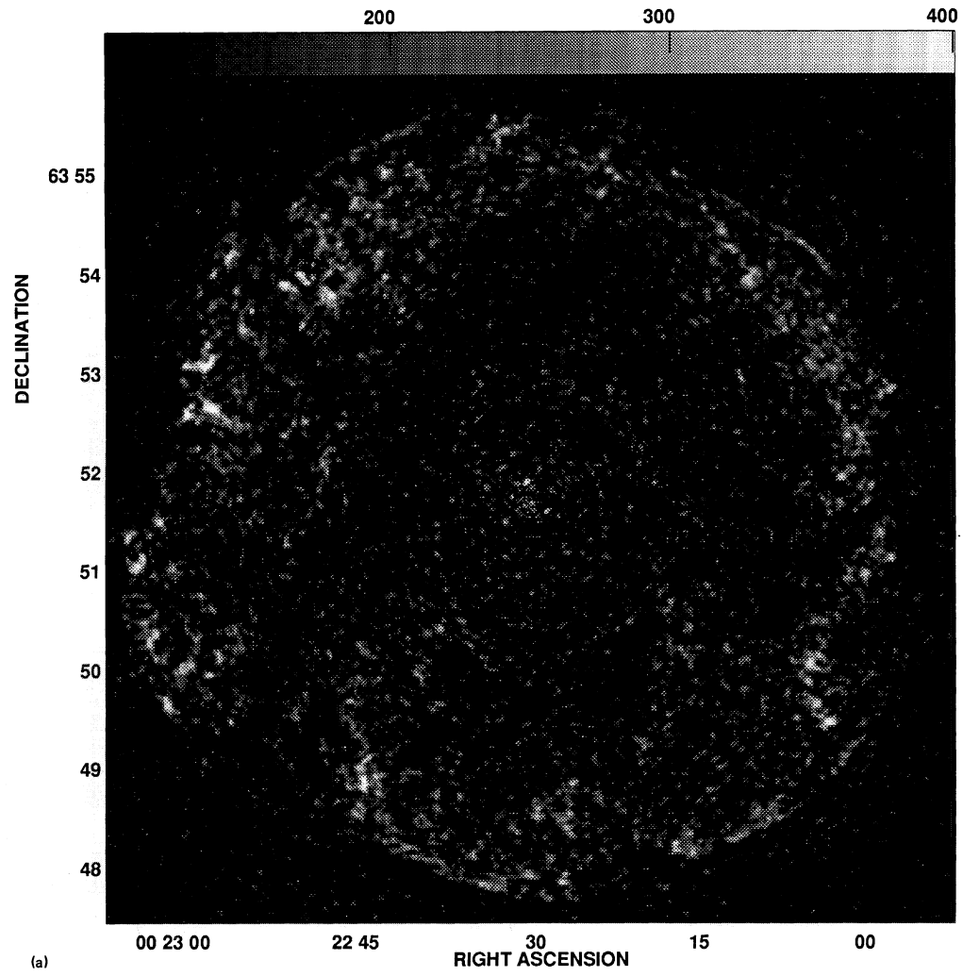
Figure 19 An example of a real photoelectron track at 5.9 keV (Bellazzini et al. 2006).

- Polarisation detection principle:
  - X-ray photon ionises atom in gas
  - Ionisation results in electron cloud
  - Electron cloud is imaged
  - #electrons → energy, direction of cloud → E-vector X-ray

MEASURED POLARISATION FRACTION YOUNG SNRS (SEE ALSO DUBNER'S TALK)



Braun, Gull, Perley, Nat. 1987



Tycho's SNR, Dickel+ 91

Object	Typical Π	Peak Π	Orientation B	λ	Remarks	References
RCW 86	8%	15%	radial	22 cm	some regions Π < 3%	Dickel et al. (2001)
SN 1006	17%	60%	mostly radial	20 cm	peak not in X-ray rims	Reynoso et al. (2013)
SN 1572	7%	25%	radial/fine structured (4″)	6 cm	peak at limbs	Dickel et al. (1991)
SN 1604	6%	12% (?)	radial/fine structured (20″)	6 cm		DeLaney et al. (2002)
Cas A	5%	~20%	radial	6 cm	outer plateau Π ≈ 9%	Braun et al. (1987); Anderson et al. (1995)
G1.9+0.3	6%	17 ± 3%	radial	6 cm	Faraday rotation affected?	De Horta et al. (2014)

SUPERNOVA REMNANTS

Lower surface brightness/Larger/Older

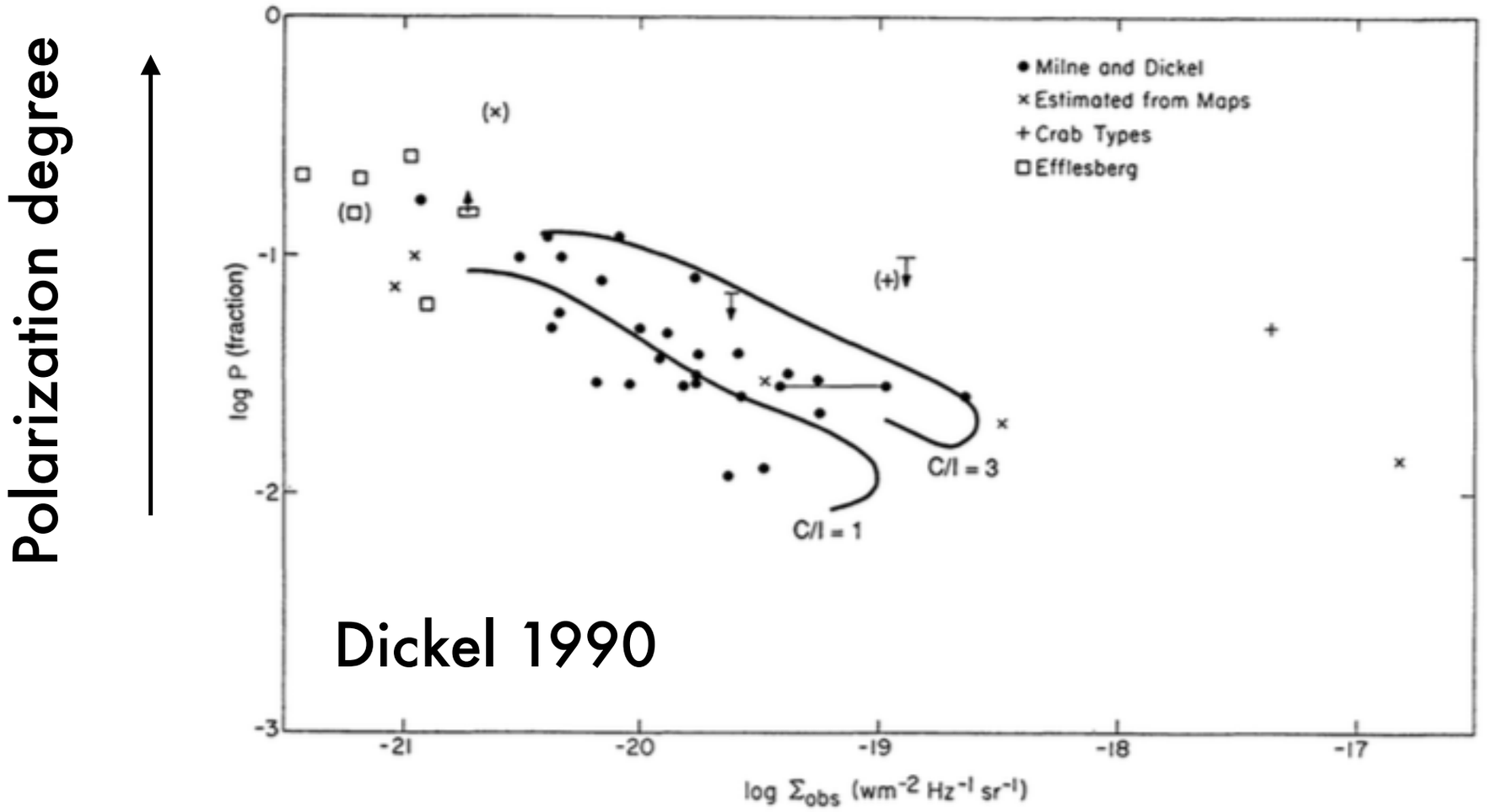


Fig. 1. Fractional polarization at 5 GHz as a function of 1 GHz surface brightness. Surface brightness decreases with age.

- Younger SNRs have lower polarisation degree:
  - Magnetic fields are more turbulent!

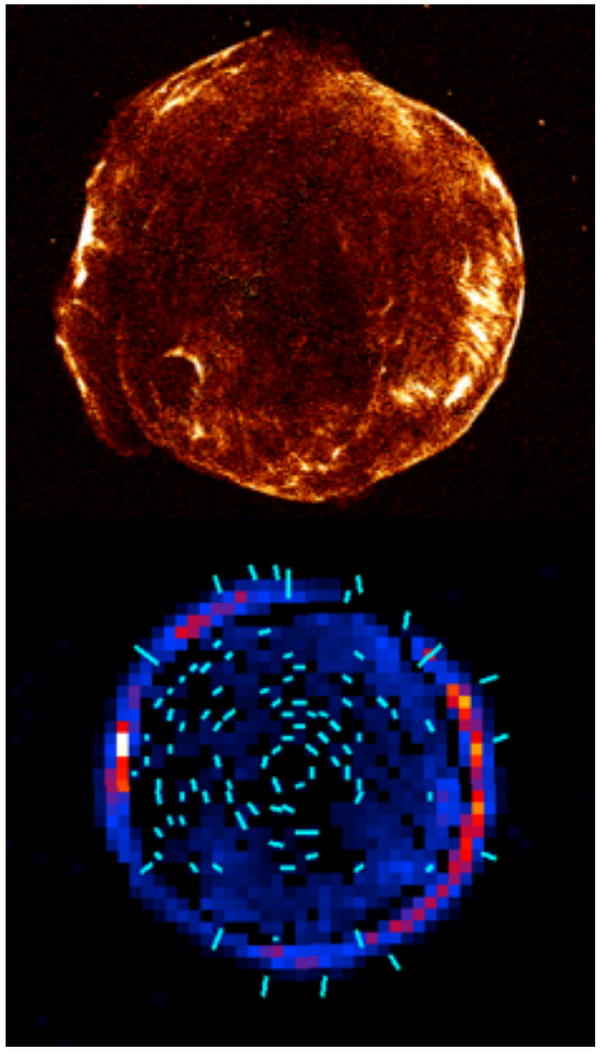
SNR X-RAY POLARISATION VS RADIO

- Expect higher X-ray polarisation:
  - X-ray synchrotron from smaller volumes
    -fewer line of sight effects (depolarisation)
  - Spectral index steeper: higher maximum polarisation
  - Enhanced due to B-field fluctuations: larger polarisation

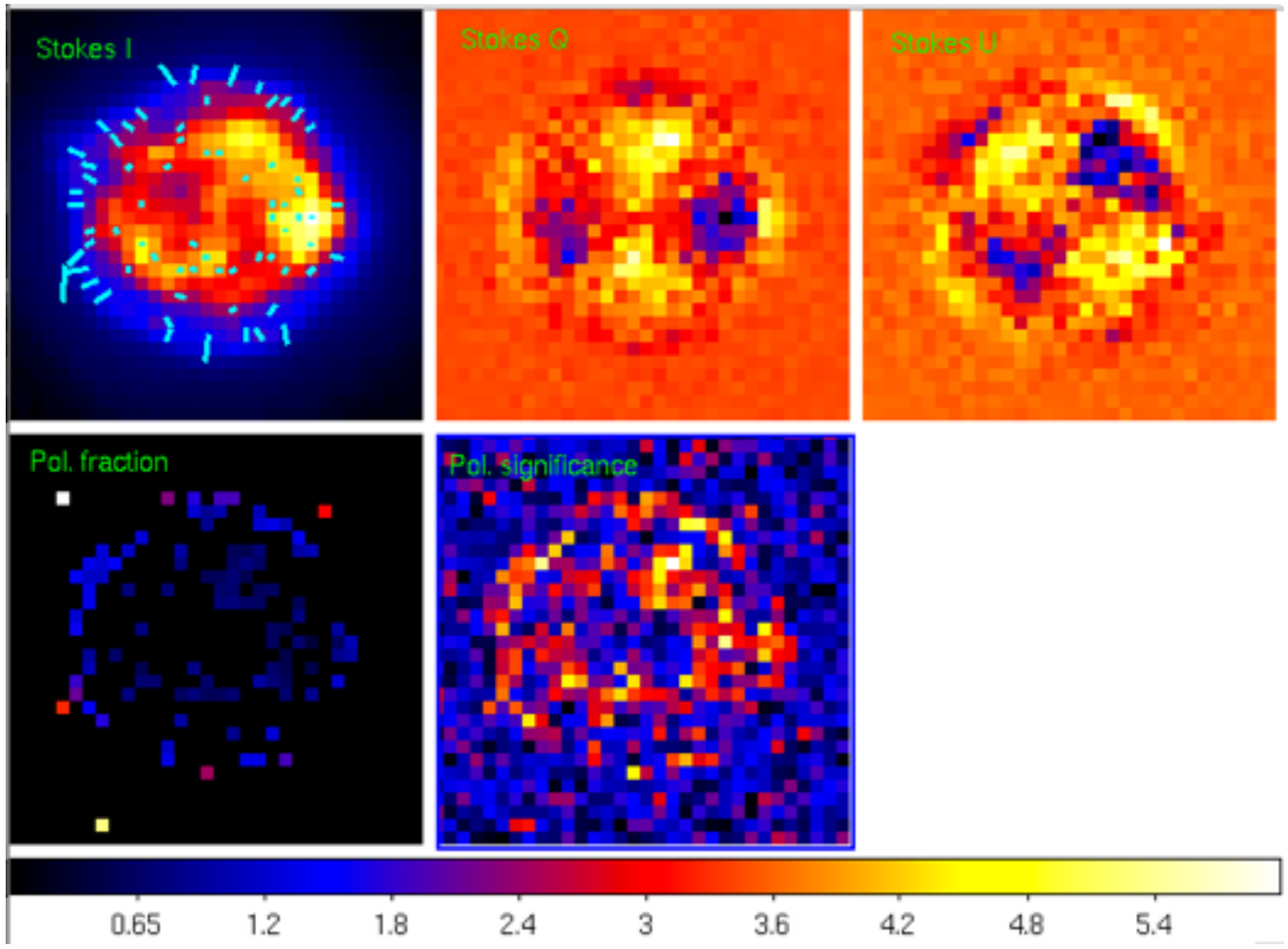
- Small polarisation in X-rays vs radio
  - Originates from close to the shock:
    higher local turbulence of magnetic field

- Complication for SNR: for most young SNRs only use 4-6 keV band

What polarisation from SNRs may reveal



Tycho: Polarized intensity



Cas A: Monte-Carlo images XIPE

- The polarisation fraction will tell us the turbulence level & perhaps spectrum
- Are the magnetic fields *close* to shock already radially stretched?
- Are the Tycho stripes indeed a coherent magnetic structure?

PRIZES FOR TALKS

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- Best conference location: Crete!

CLOSING REMARKS

- During my own 20 year Odyssee covering SNRs”
  - revolution in instrumentation (10^7-10^{24} Hz!)
  - better typing of SNRs (SNe Ia vs CC)
  - evidence for jets
  - large progress in understanding particle acceleration
    - gamma-rays -> acceleration properties, proton acc.
    - narrow X-ray filaments -> B-fields and turbulence
- Imaging of dust of different temperatures
- longer baselines/sharper images: propert motions!

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- Finally
  - Thank you Panos and the LOC/SOC for a great Odyssee/BFGC!