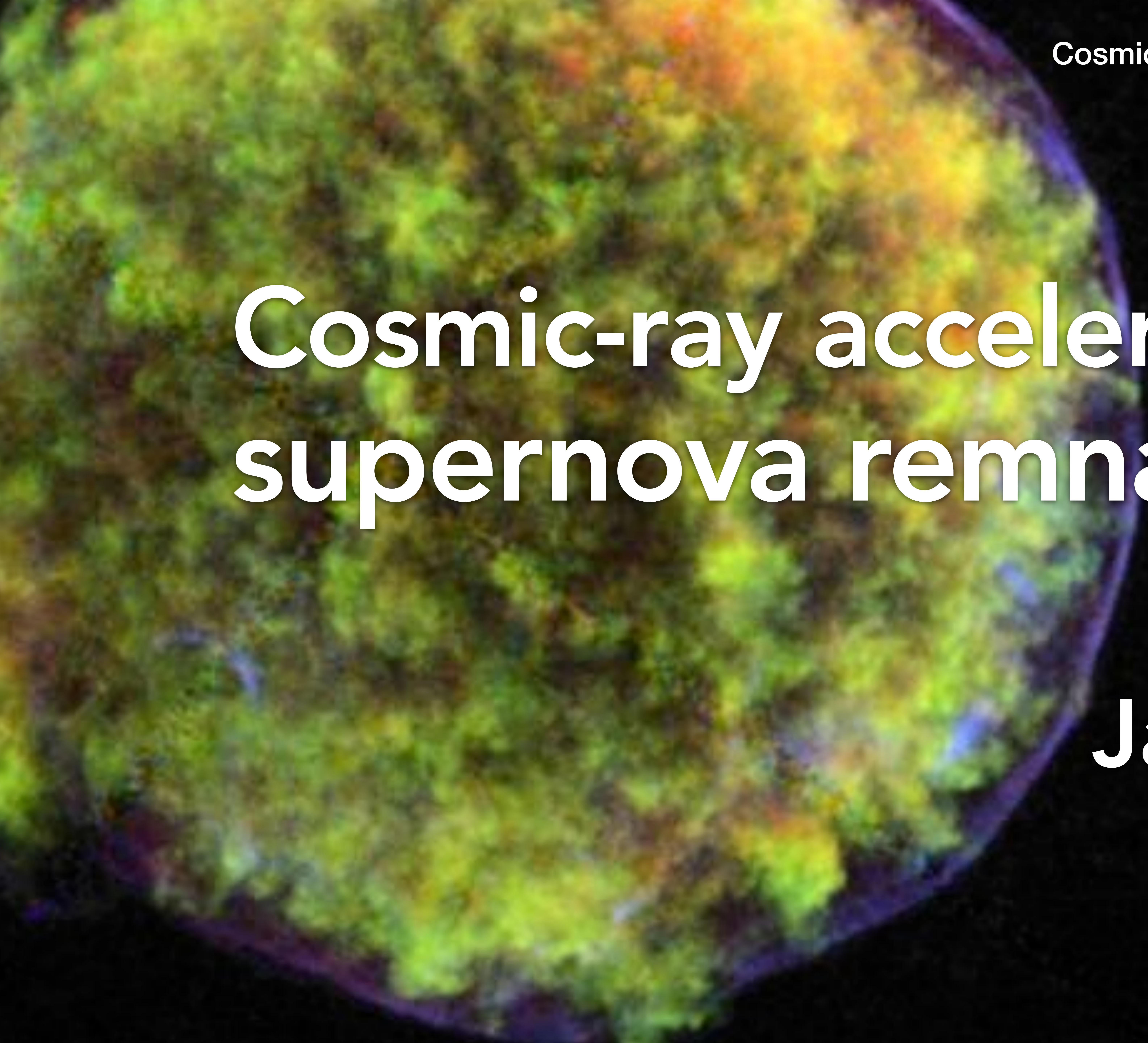
Cosmic Rays and Neutrinos in the Multi-Messenger Era
APC, 9-13 December 2024



Cosmic-ray acceleration by supernova remnants

Jacco Vink

GRAPPA
GRavitation AstroParticle Physics Amsterdam

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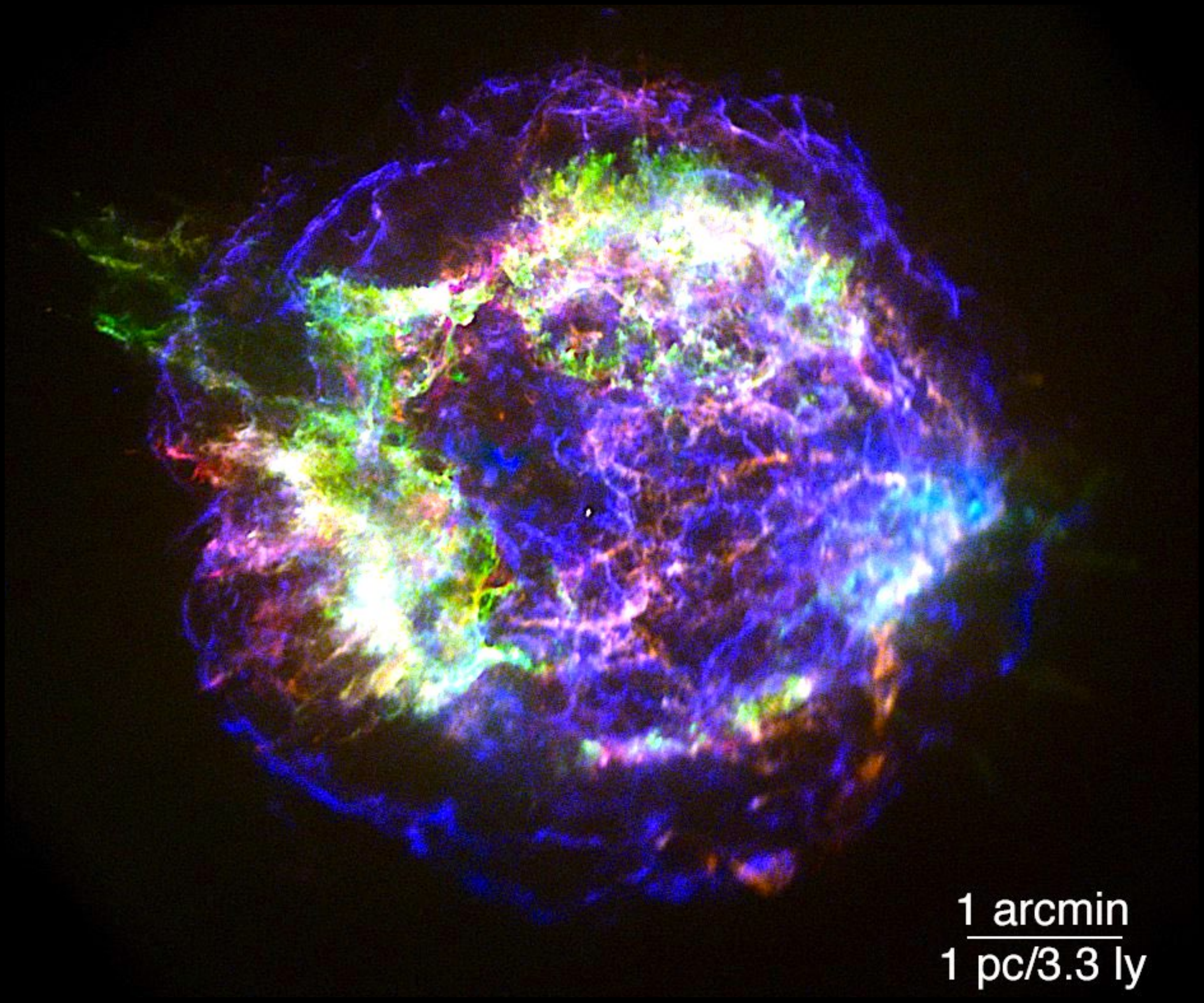
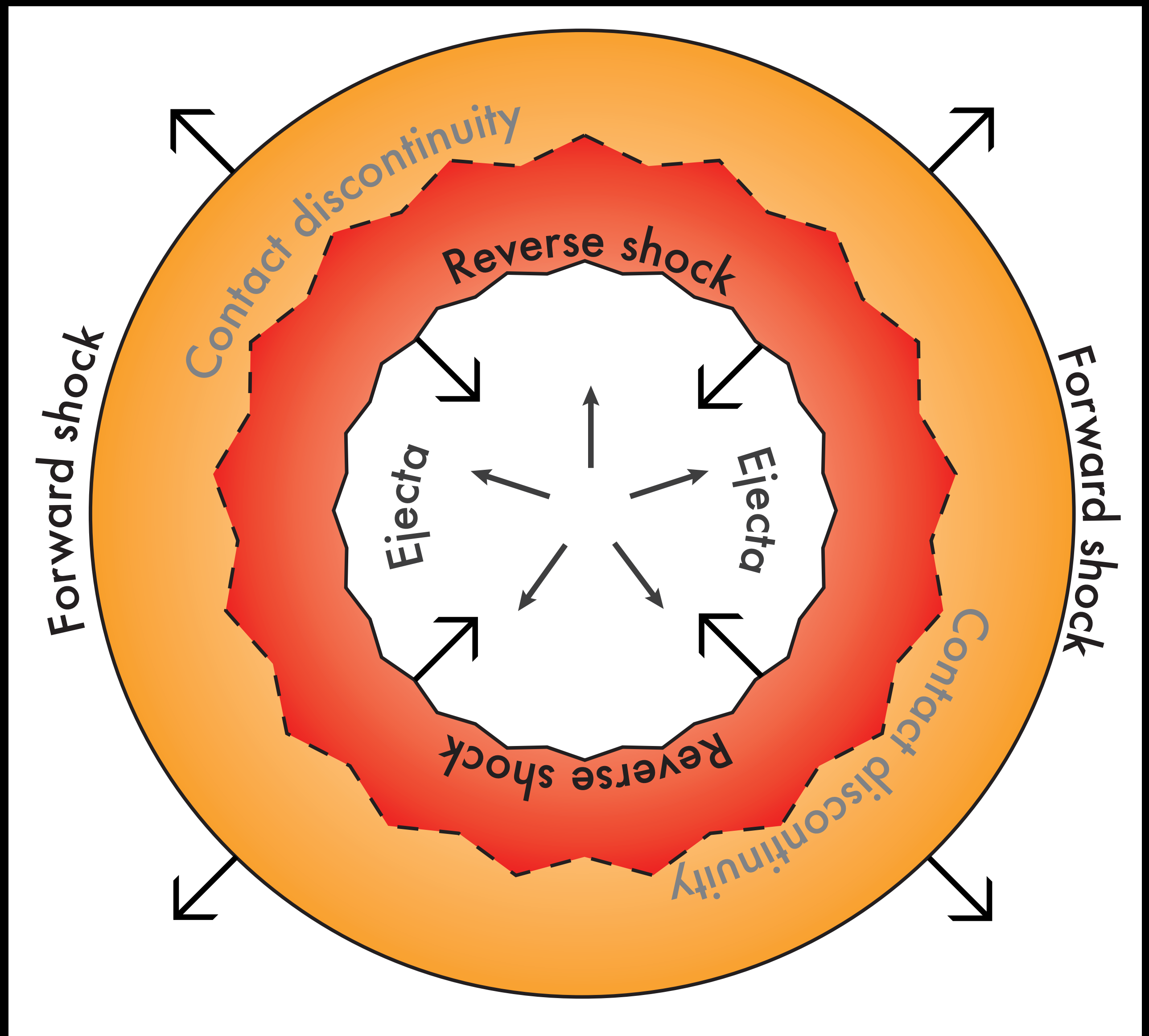
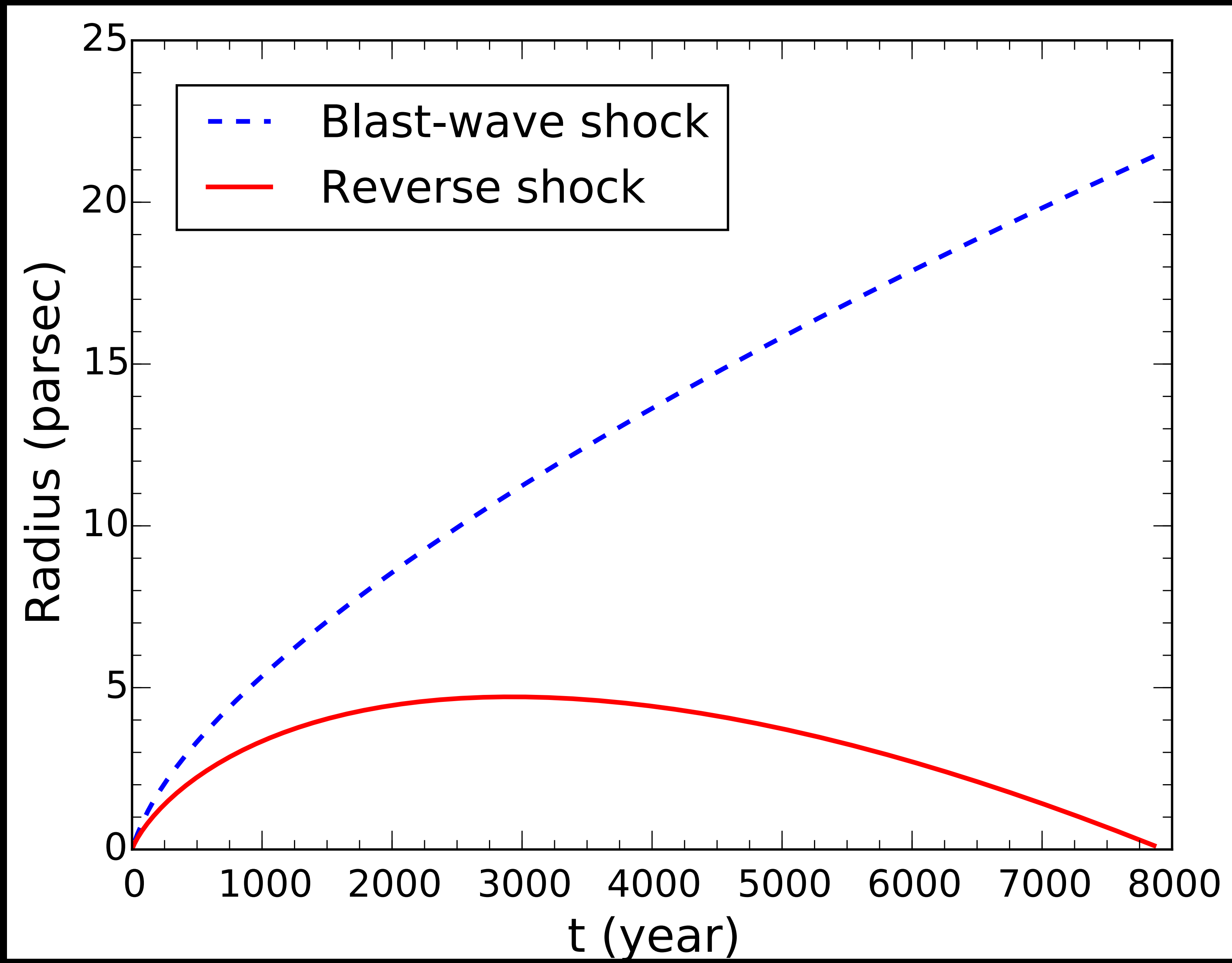
Supernovae & supernova remnants

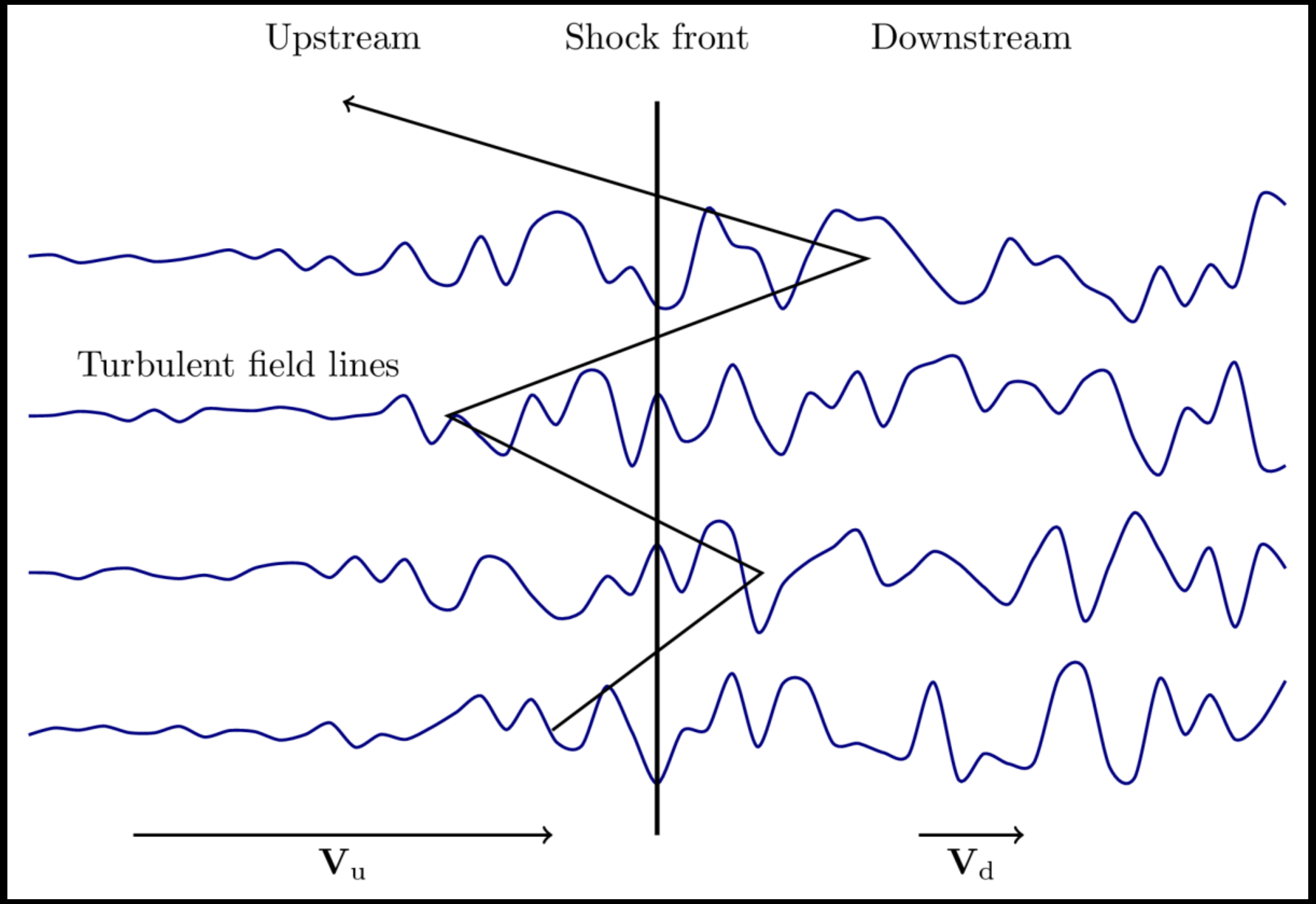






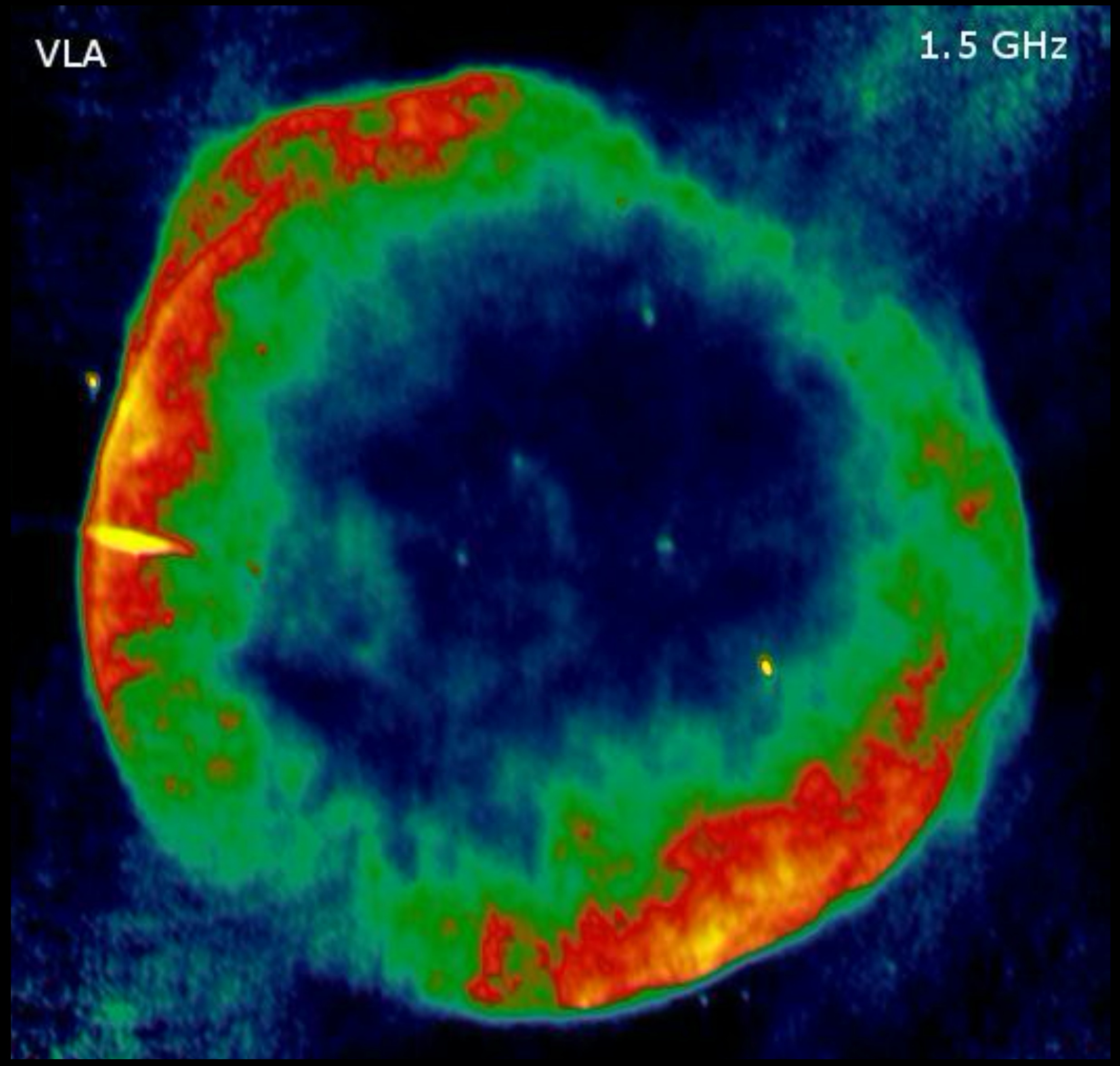
- 2-3 SNe/century ($\overline{\Delta t} \approx 40$ yr), E=10^{51} erg
- $\frac{dE}{dt} \approx \frac{E}{\overline{\Delta t}} \approx 8 \times 10^{41}$ erg s$^{-1} \approx 5\% - 10\,\%\, \dot{E}_{\rm cr}$
- Power sufficient, but can they accelerate to the "knee"?
- Mechanism: diffusive shock acceleration mostly by forward shock

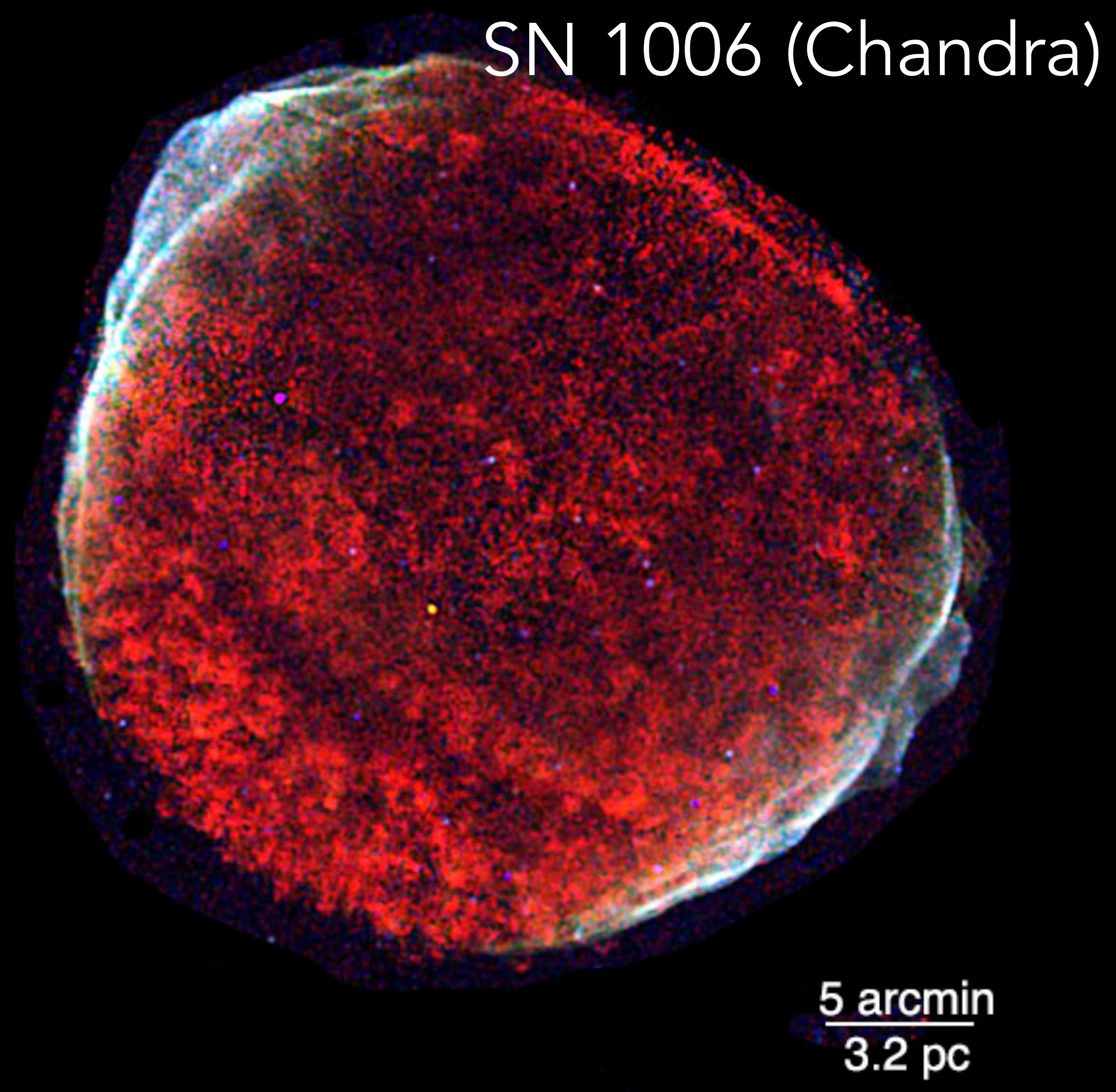
Diffusive shock acceleration

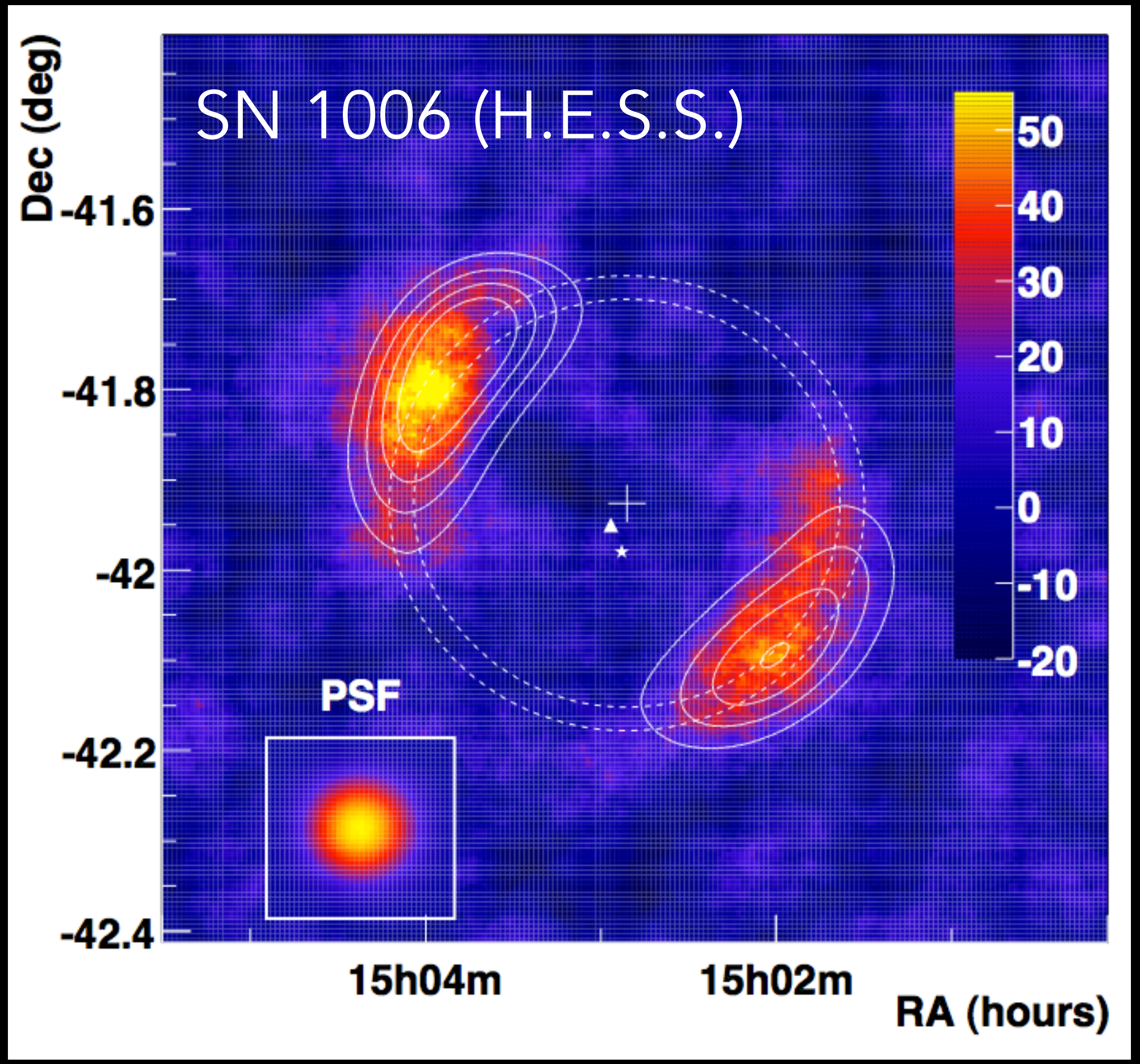


- Particles interact w. plasma thru magnetic fields
- Particles gain energy by crossing shock:
- ΔV_{plasma} → Lorentz boost of $\dfrac{\Delta E}{E} \approx \dfrac{\Delta V}{c}$
- Diffusion: particles can cross shock $D = \dfrac{1}{3} c\lambda_{\rm mfp} = \dfrac{1}{3}\eta r_{\rm g} = \dfrac{1}{3}\eta\dfrac{cE}{eB}$
- Acceleration time: $\tau_{\rm acc} \approx \dfrac{8D_0}{V_{\rm s}^2}$ → $E_{\rm max} \propto \eta^{-1} B V_{\rm s}^2 t \propto \eta^{-1} B t^{2m-1}$
  - $R \propto t^m$, E_{max} increases for m>0.5 (Sedov m=0.4)
- Higher energy: keep V_s for long time (t), strong, turbulent B ($\eta \approx \left\langle (\delta B/B)^2 \right\rangle^{-1} \approx 1$)

Evidence for cosmic-ray acc. by SNRs

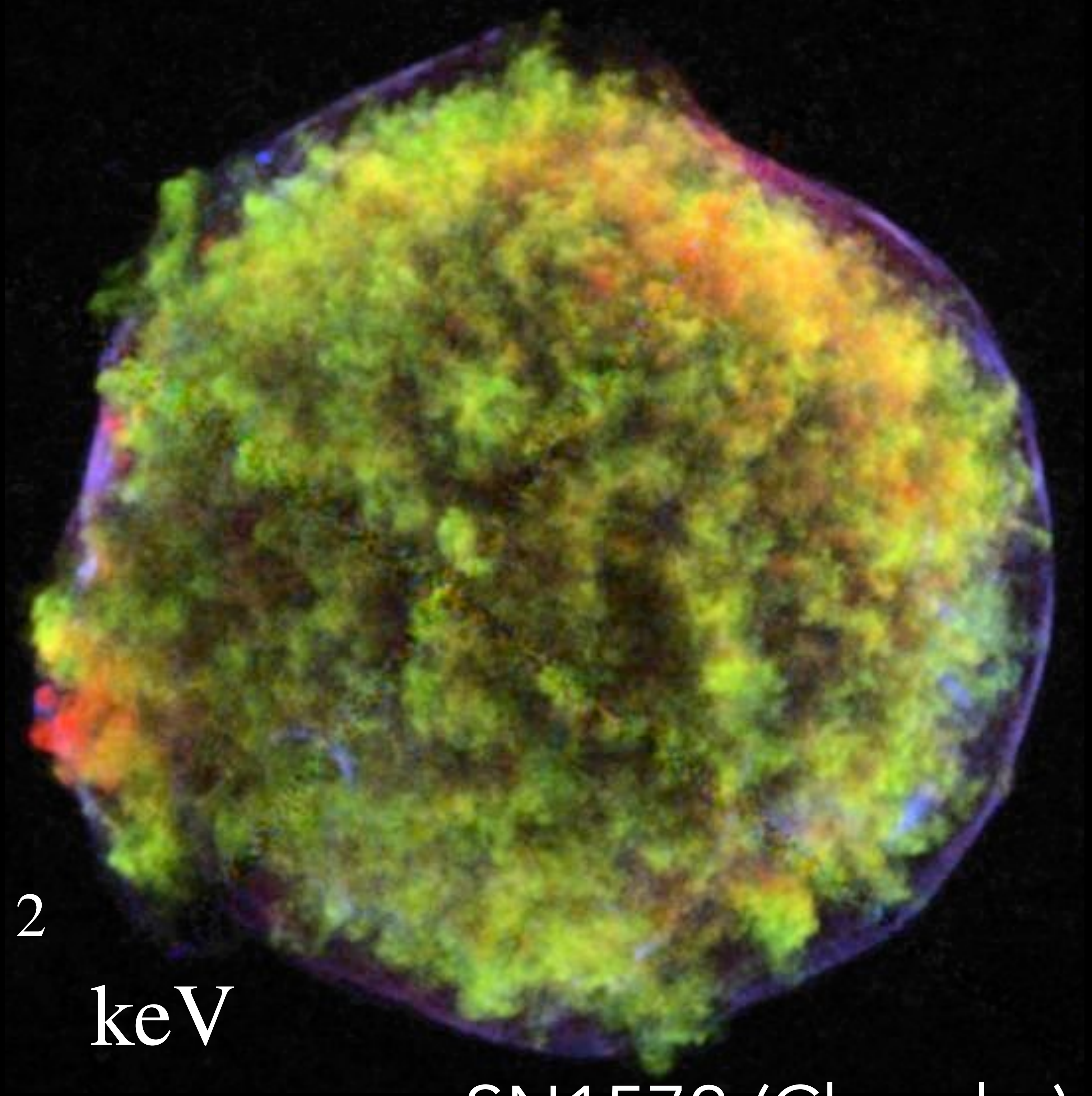






- Earliest evidence (50s): radio synchrotron emission (GeV electrons)
- 1990s (Koyama+95): X-ray synchrotron (10-100 TeV electrons)
- 2000s: gamma-ray emission (Fermi, IACTs)
  - pion-production and decay → cosmic-ray ions ($h\nu \sim 0.1 E_{\rm p}$)
  - inverse Compton scattering → electrons
  - bremsstrahlung → electrons (subdominant)

X-ray synchrotron radiation



SN1572 (Chandra)

- Requires >10 TeV electrons: $h\nu \approx 19 \left(\frac{B}{100\ \mu\text{G}}\right)\left(\frac{E}{100\ \text{TeV}}\right)^2\ \text{keV}$
- Electrons cool fast: $\tau_{\text{cool}} \approx 12.5 \left(\frac{B}{100\ \mu\text{G}}\right)^{-2}\left(\frac{E}{100\ \text{teV}}\right)^{-1}\ \text{yr}$
  - Acceleration needs to be fast
  - Electrons "out of contact with shock" will not emit X-rays →Narrow X-ray filaments
- Combining acceleration & cooling ($\tau_{\text{acc}} \approx \tau_{\text{cool}}$): $h\nu_{\text{cutoff}} \approx 1.4\eta^{-1}\left(\frac{V_{\text{sh}}}{5000\ \text{km/s}}\right)^2\ \text{keV}$

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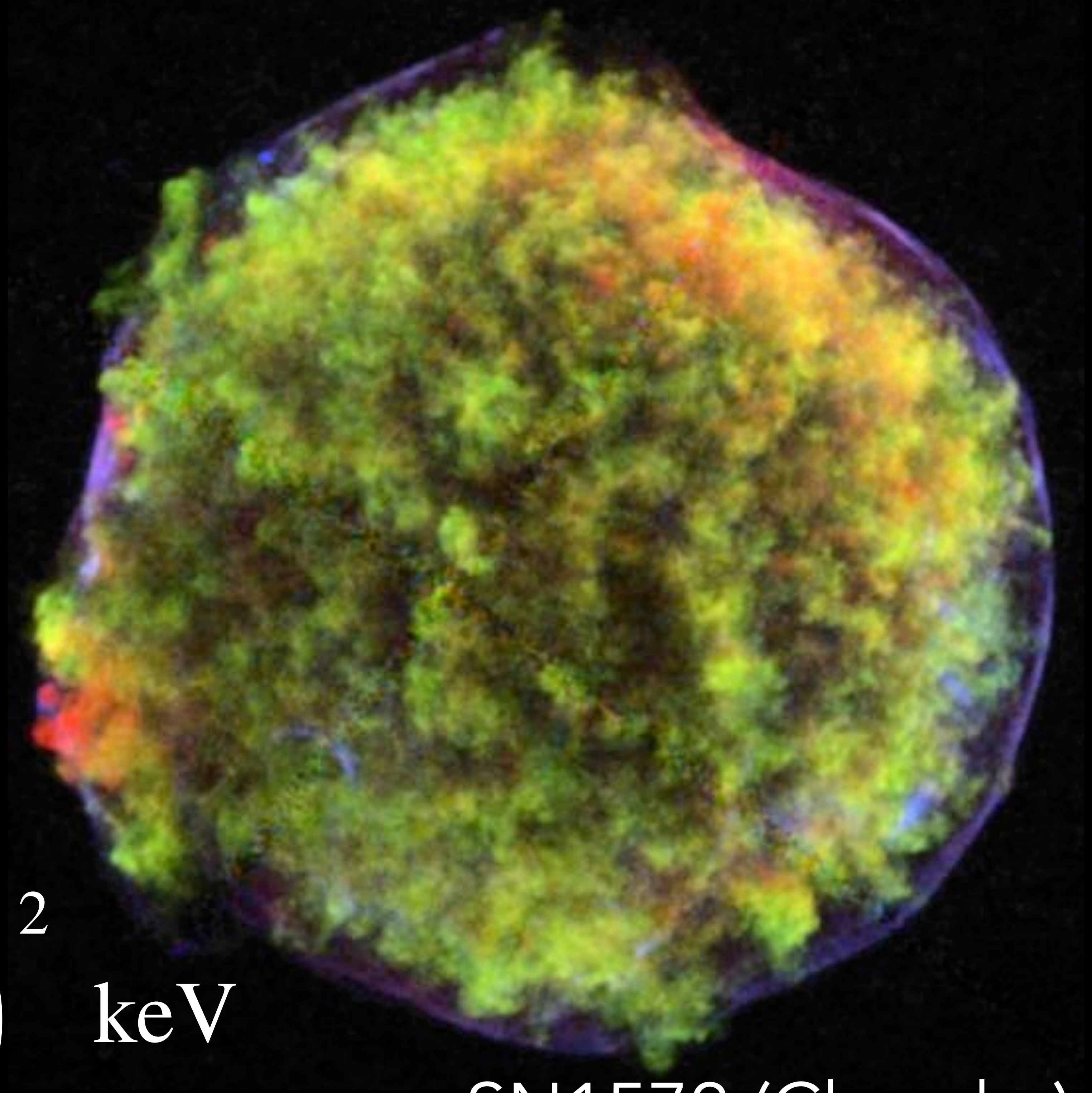

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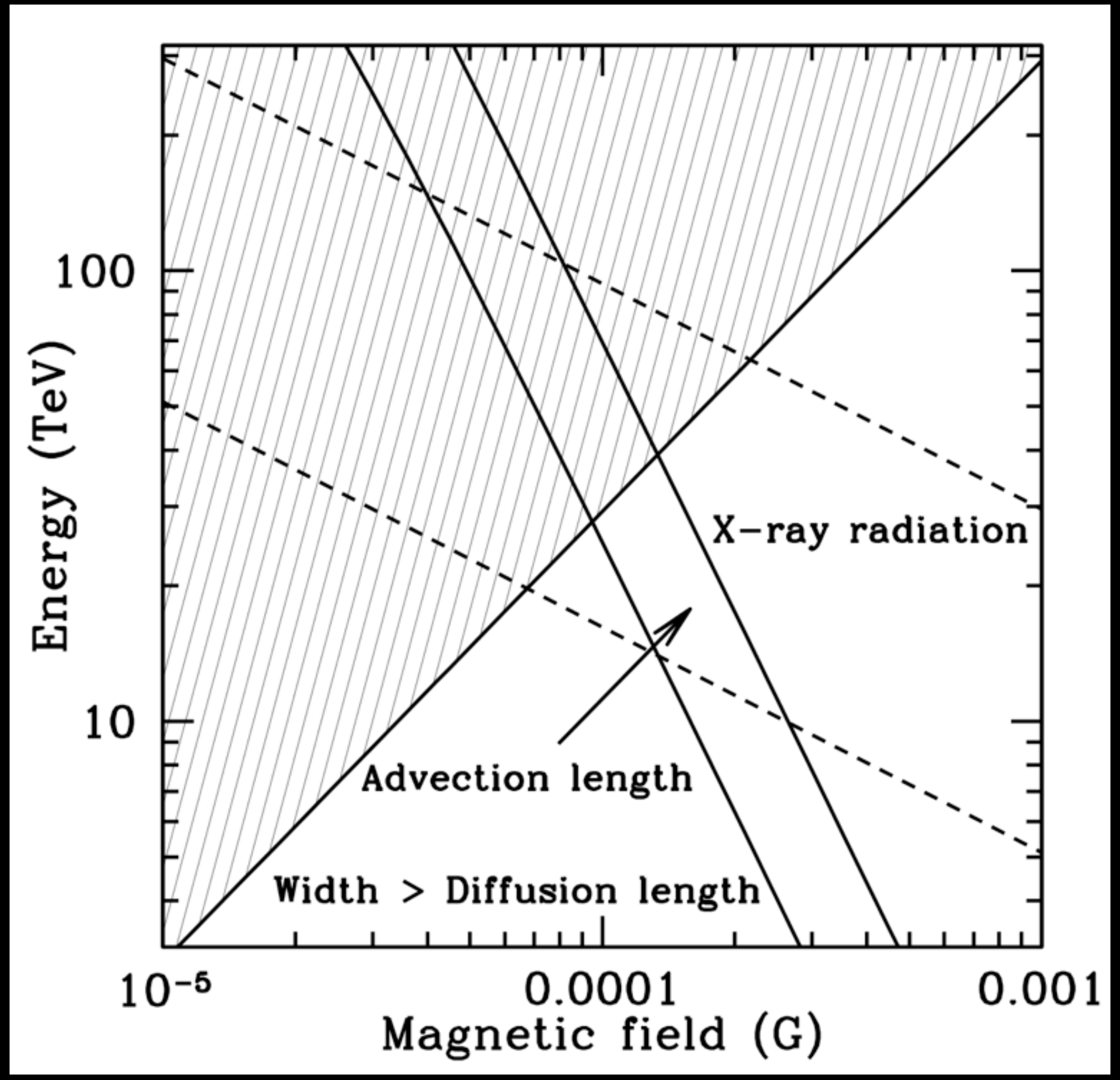
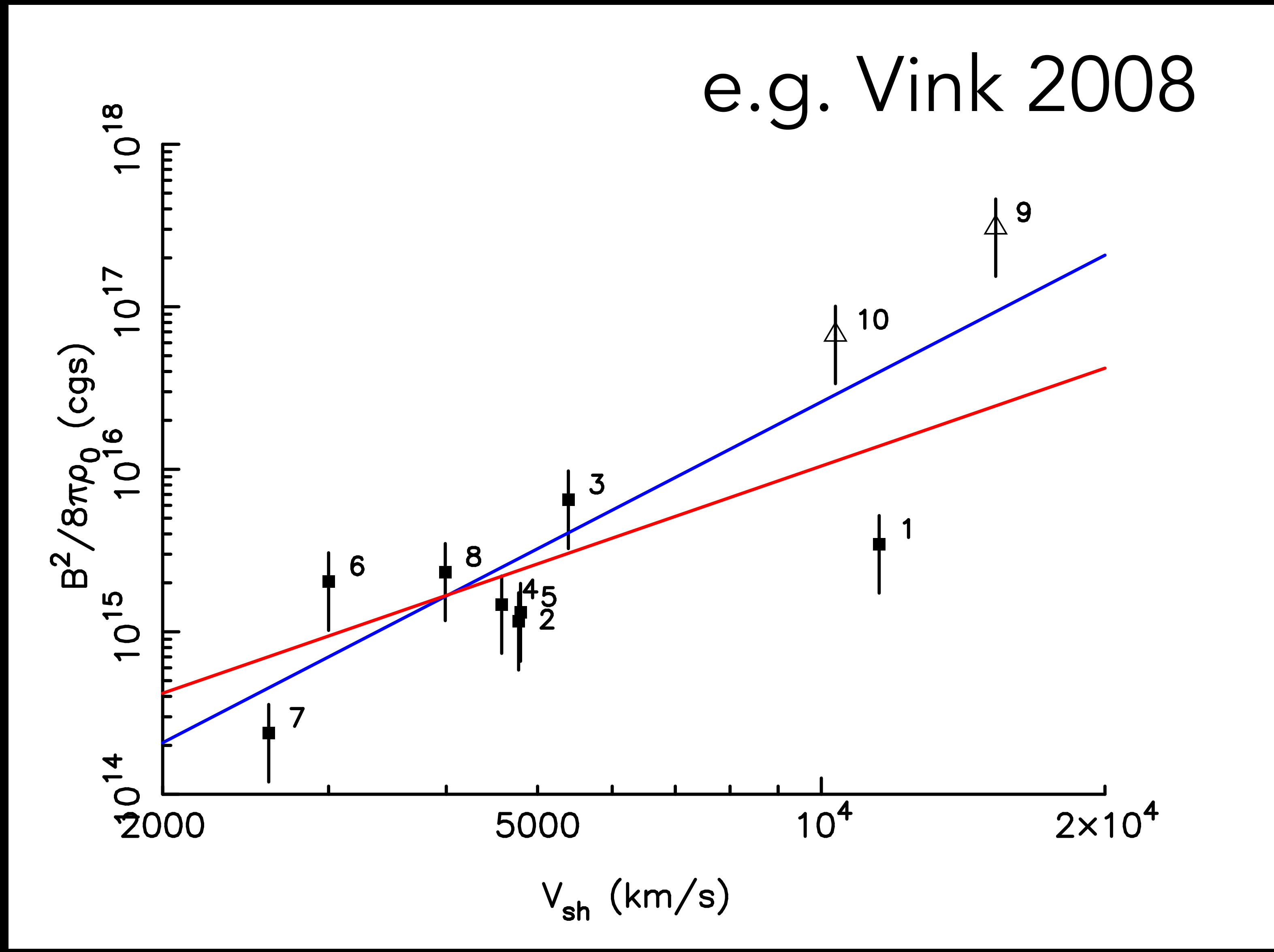
- **X-ray synchrotron: requires $\eta \approx 1$ and $V_{\mathrm{sh}} \gtrsim 3000\ \mathrm{km/s}$**

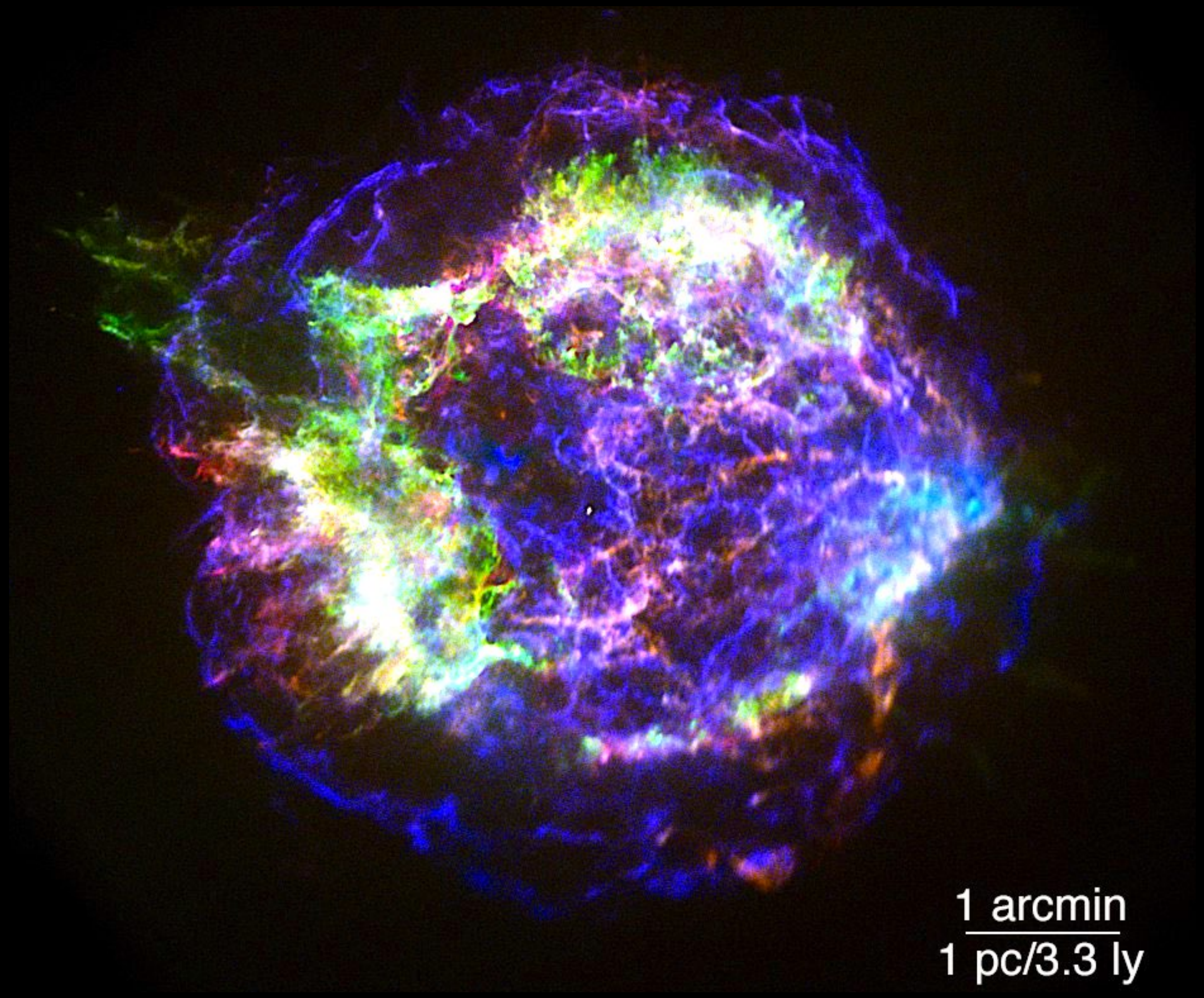
Turbulent, amplified magnetic fields





- All young (<2000 yr) SNRs show evidence for X-ray synchrotron
- Width limitations due to synchrotron cooling: $B_2 \approx 110\eta^{1/3}\left(\frac{\Delta r}{10^{17}\ \mathrm{cm}}\right)^{-2/3}\ \mu\mathrm{G}$
  - $B_2 \sim 20 - 500\ \mu\mathrm{G}$
- Prediction Bell (2004) instability $U_B = \frac{B^2}{8\pi} \propto \rho_0 V^{-3}$
- Very early on in stellar wind interaction: B~50 Gauss
  - e.g SN1993J, Fransson&Björnson ‘98

X-ray synchrotron radiation from reverse shock



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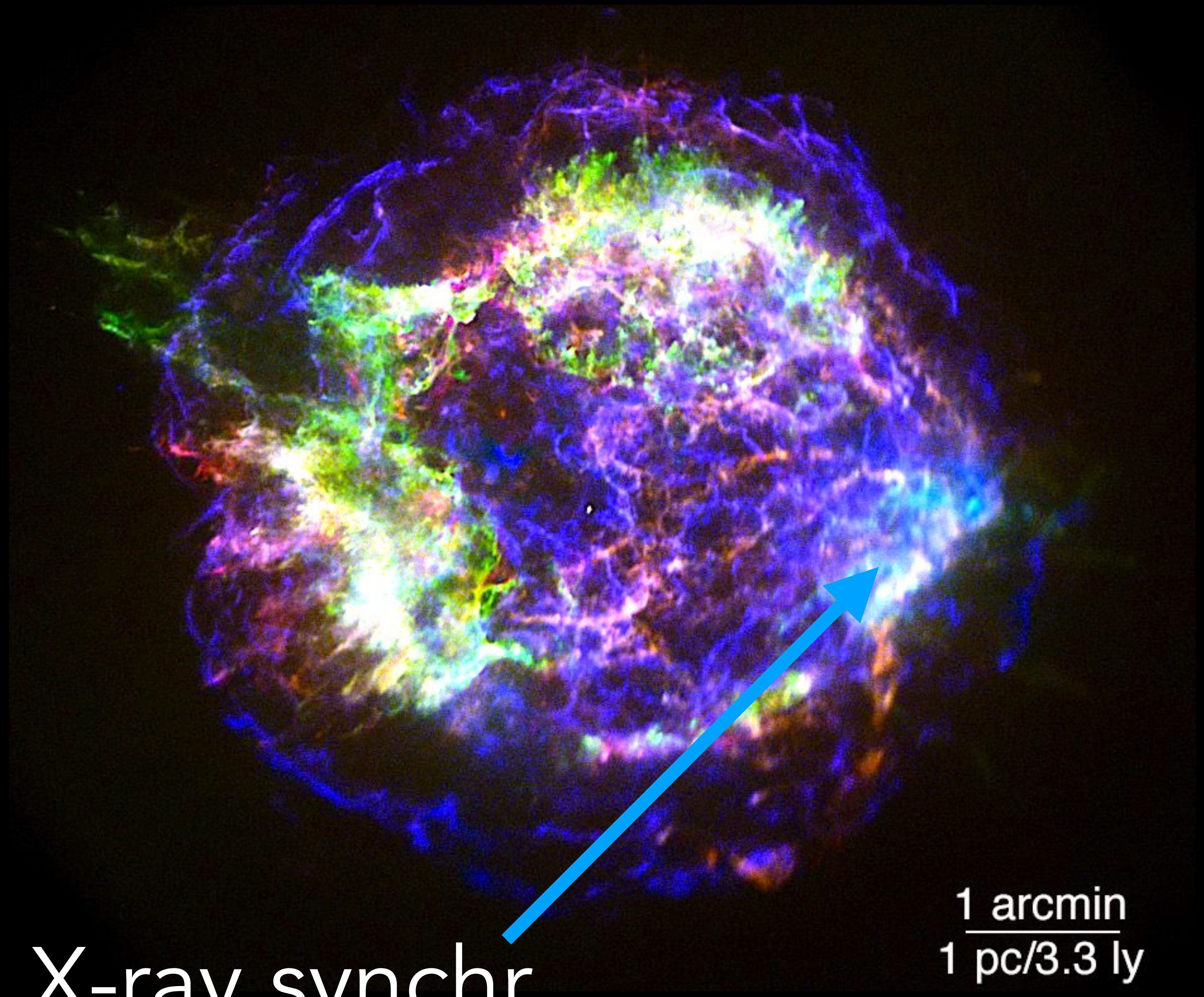

X-ray synchr.
reverse shock

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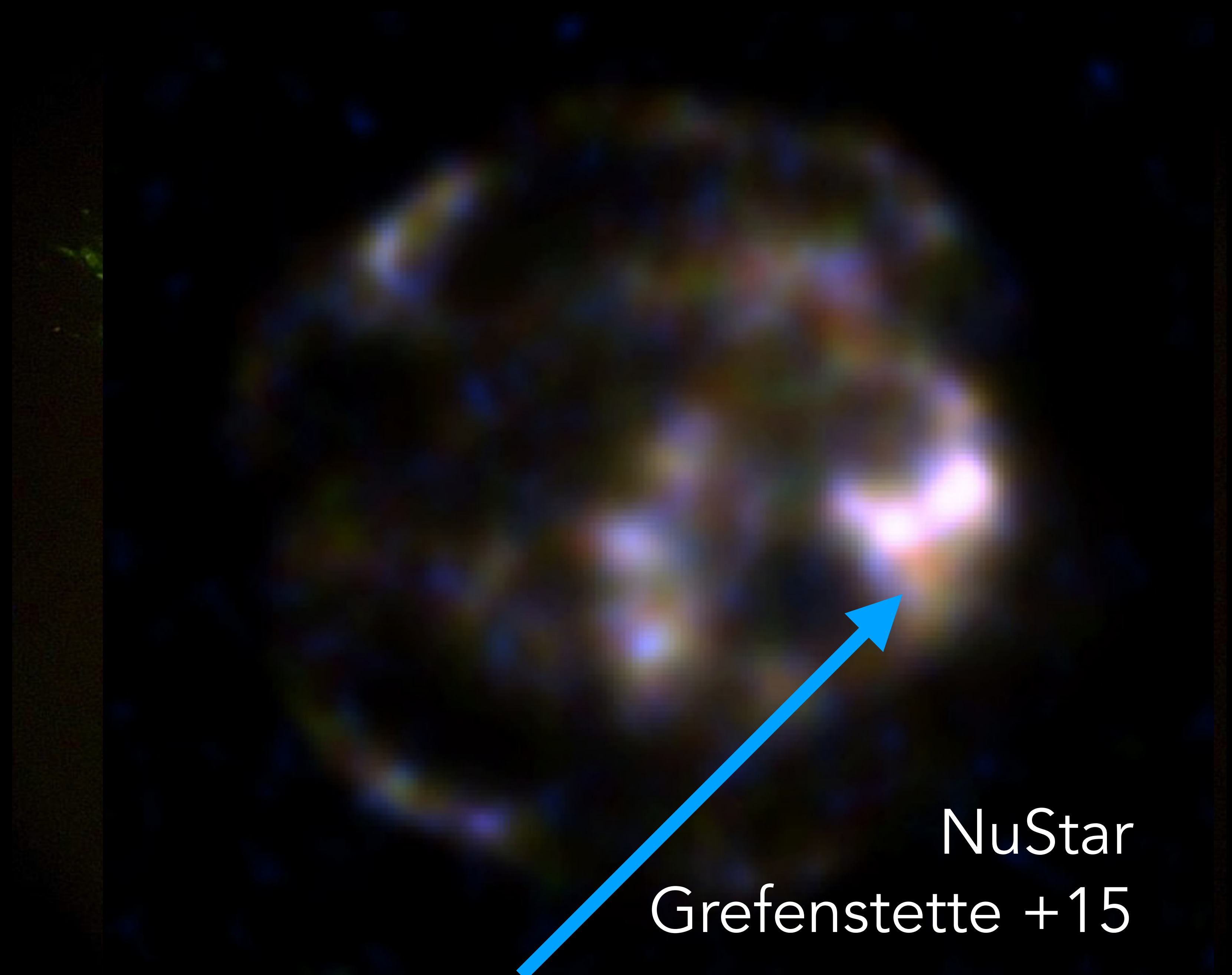

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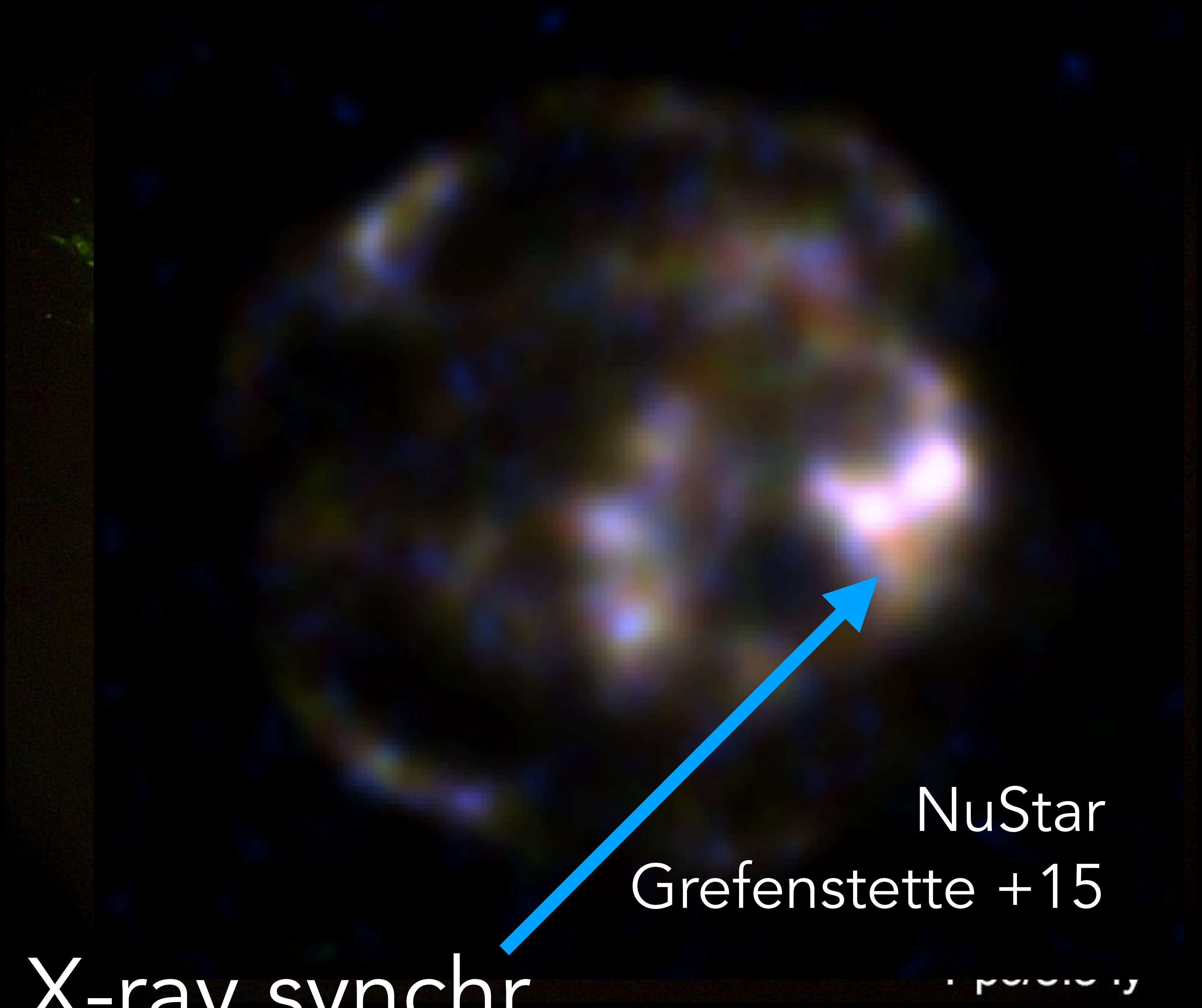

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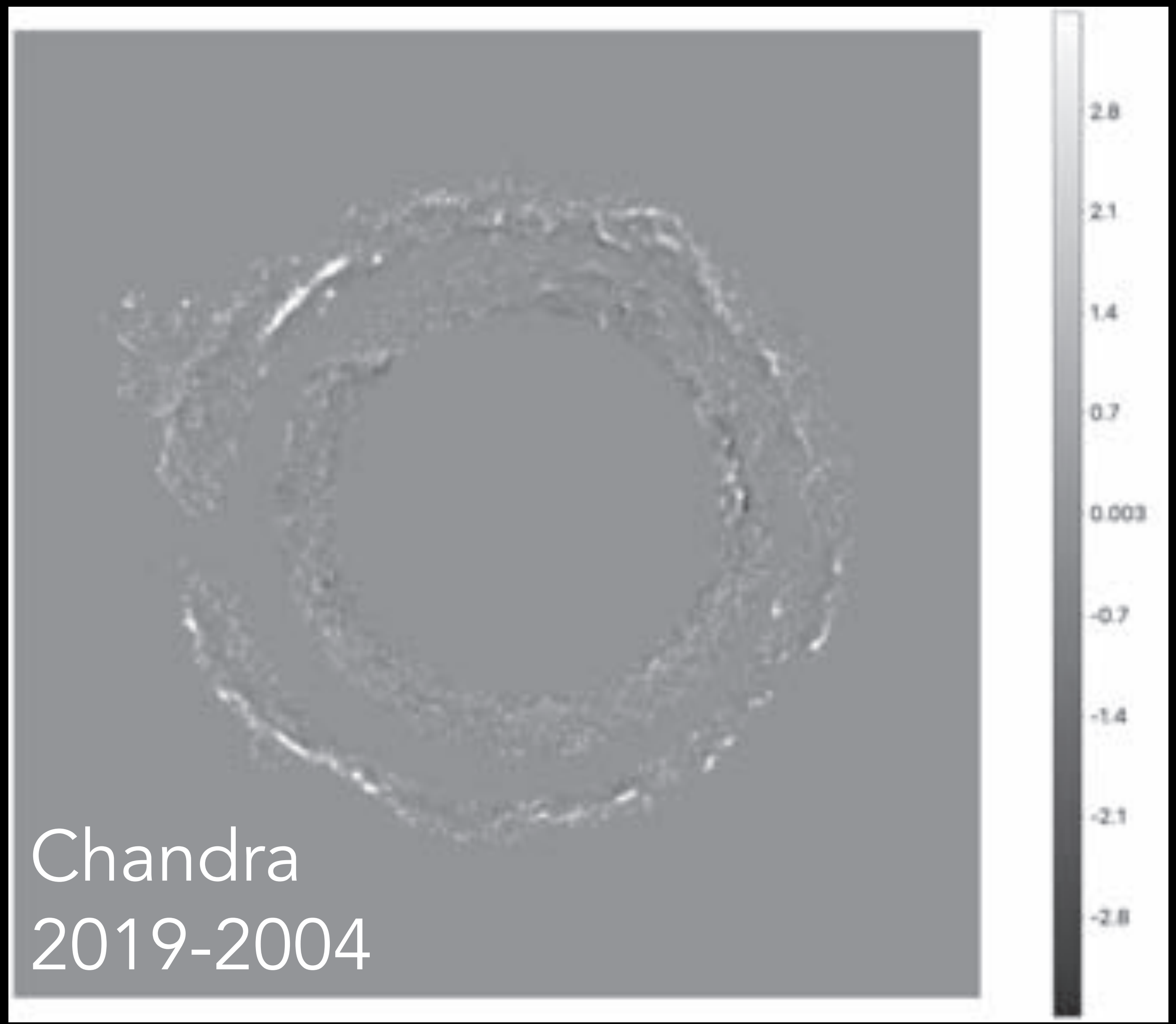

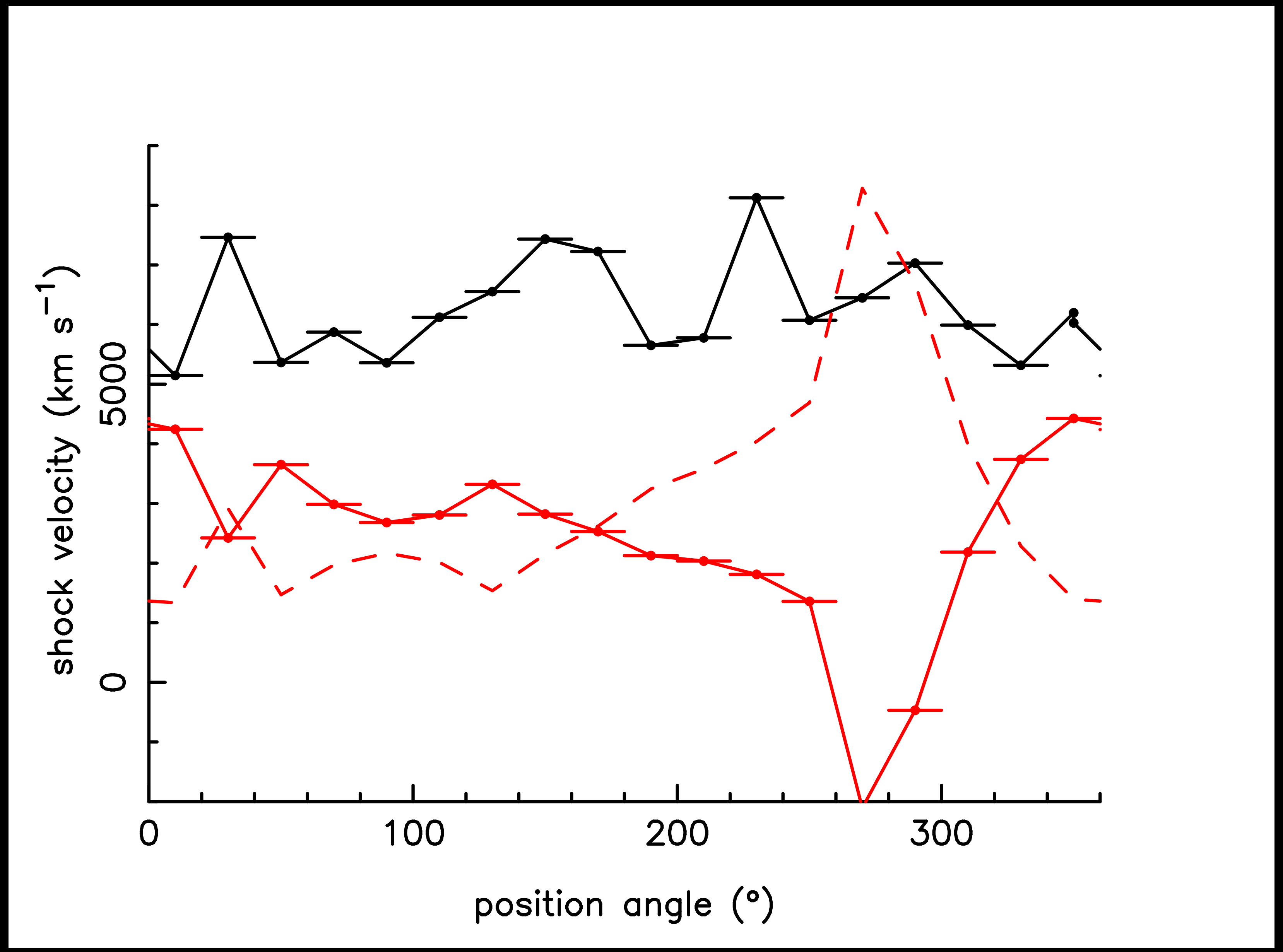

Vink+ 2022

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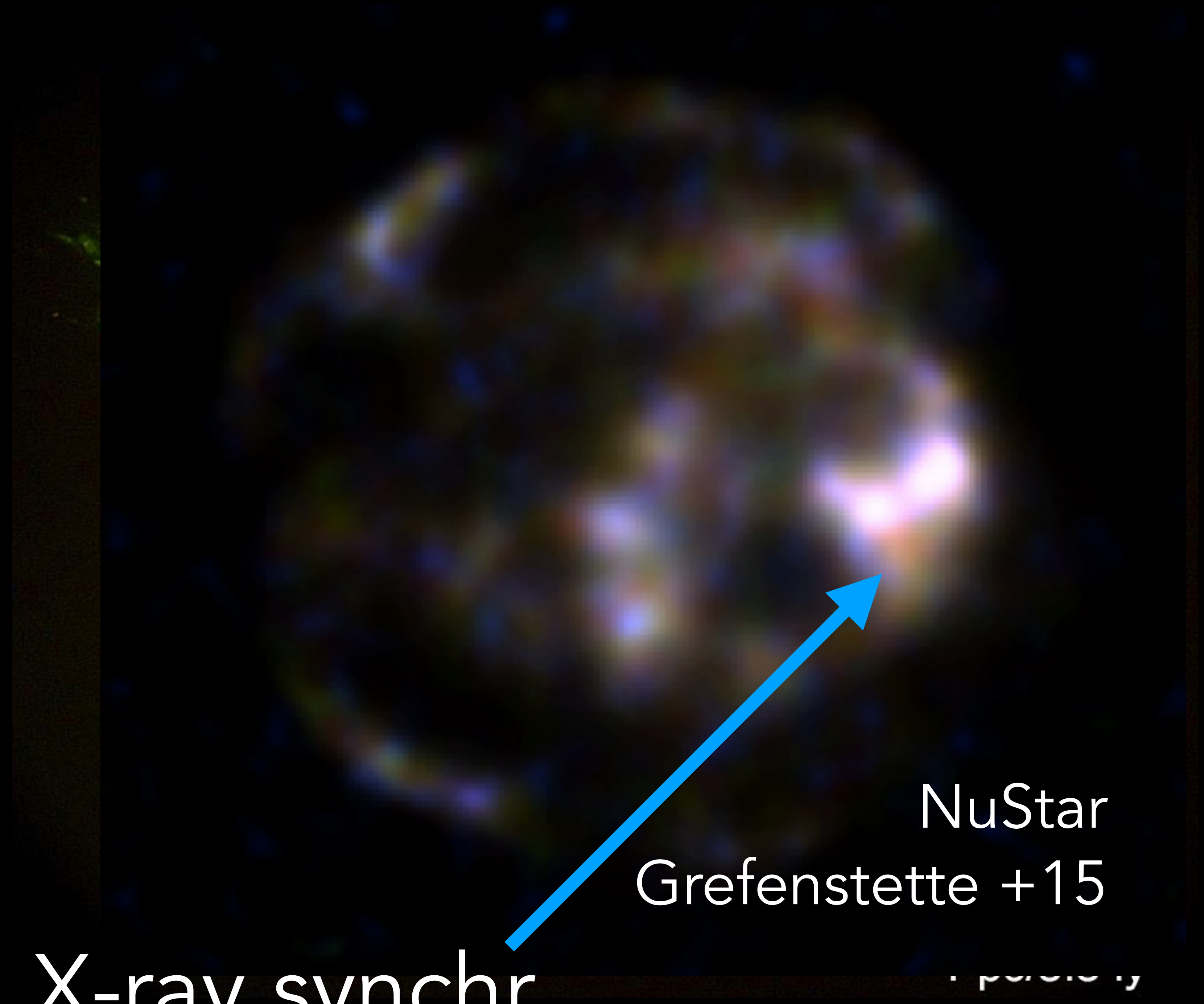

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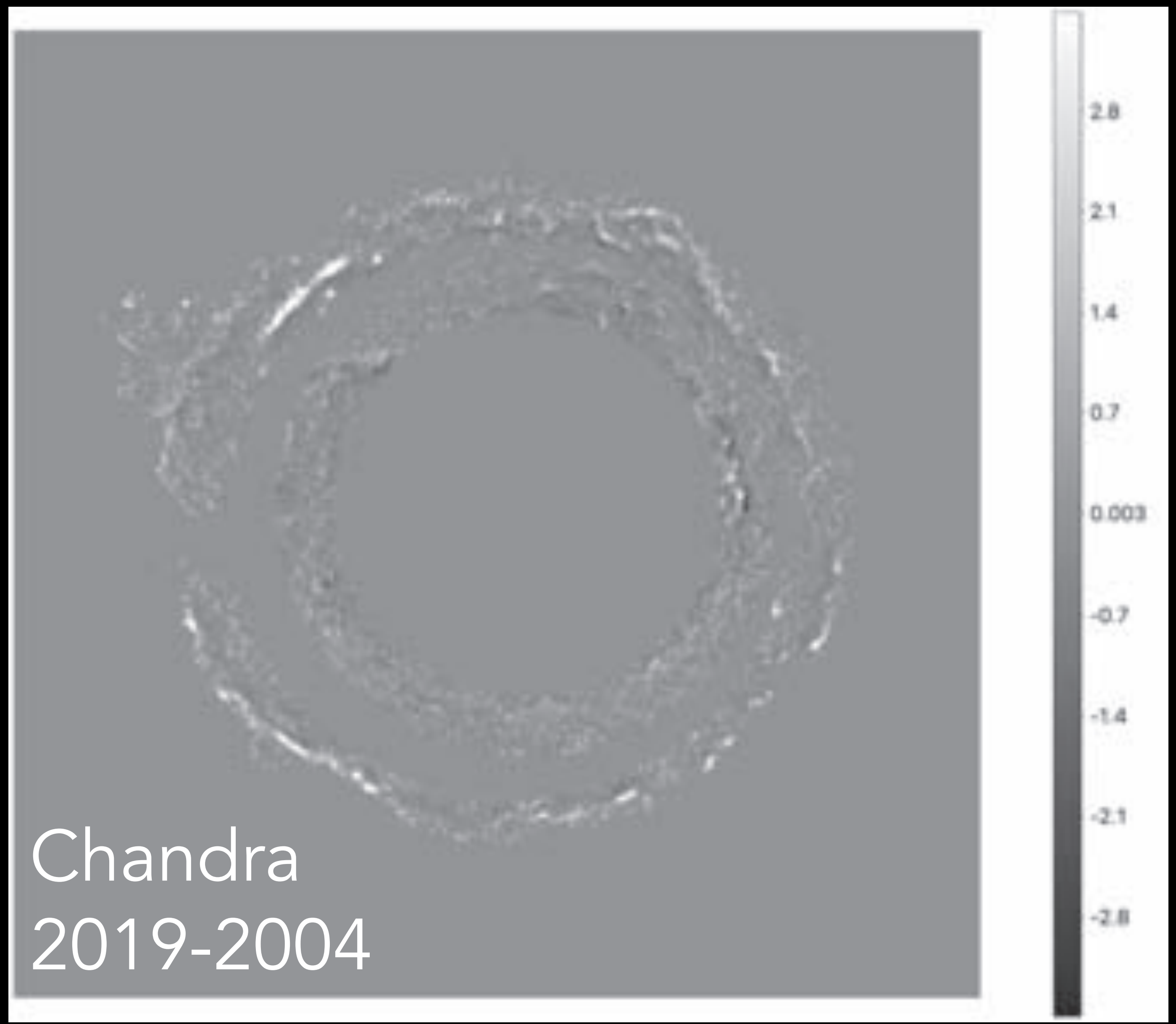

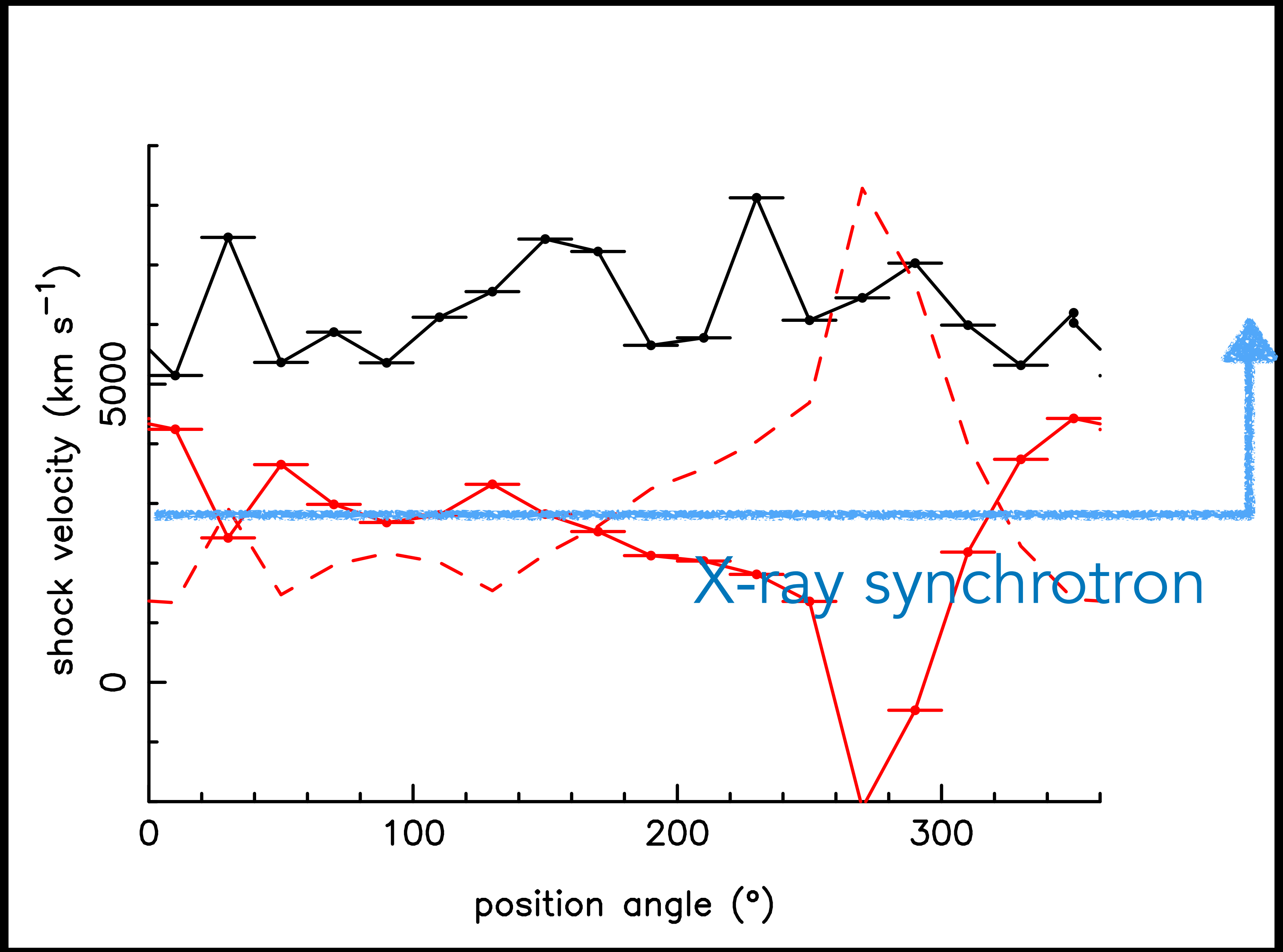

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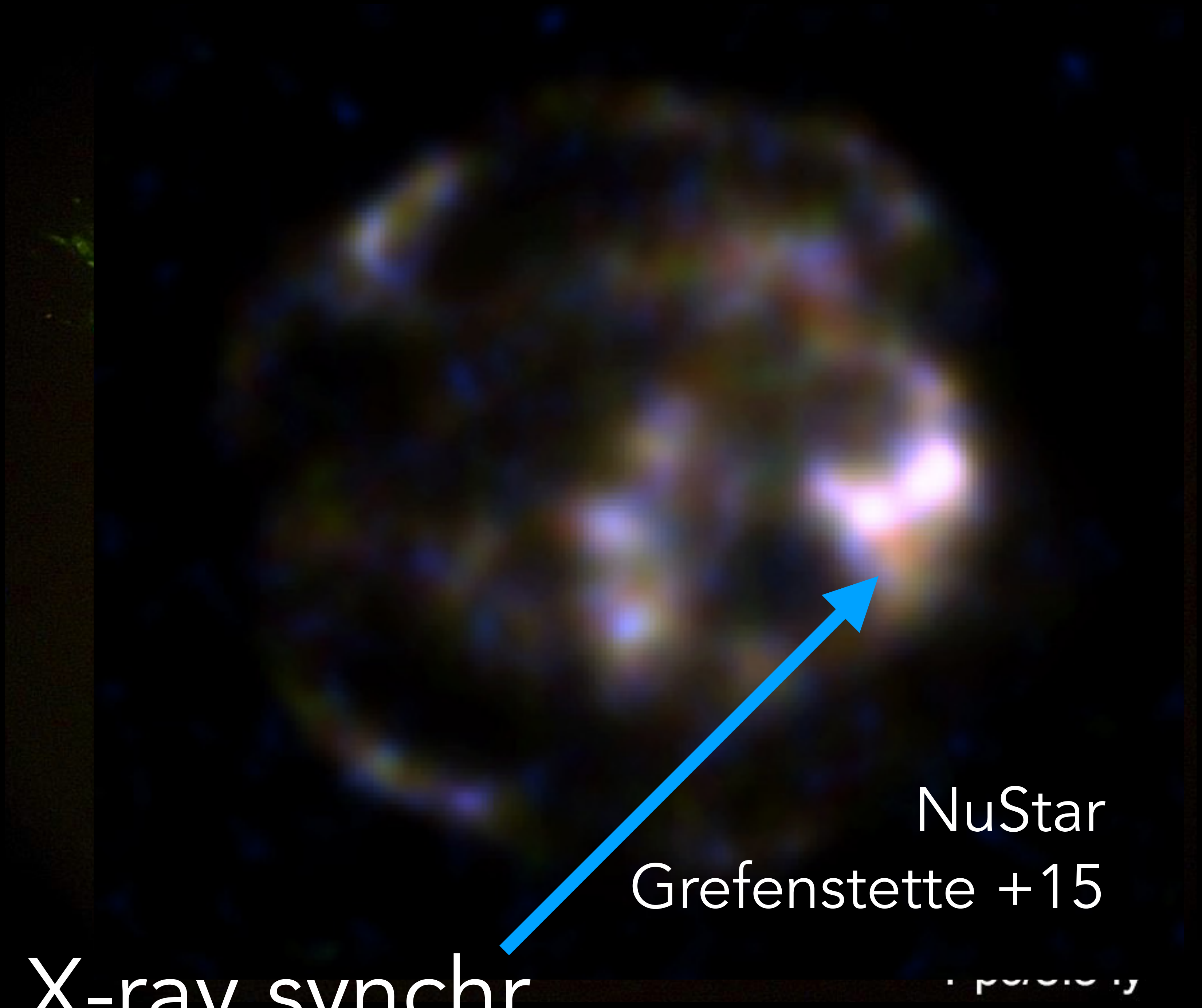
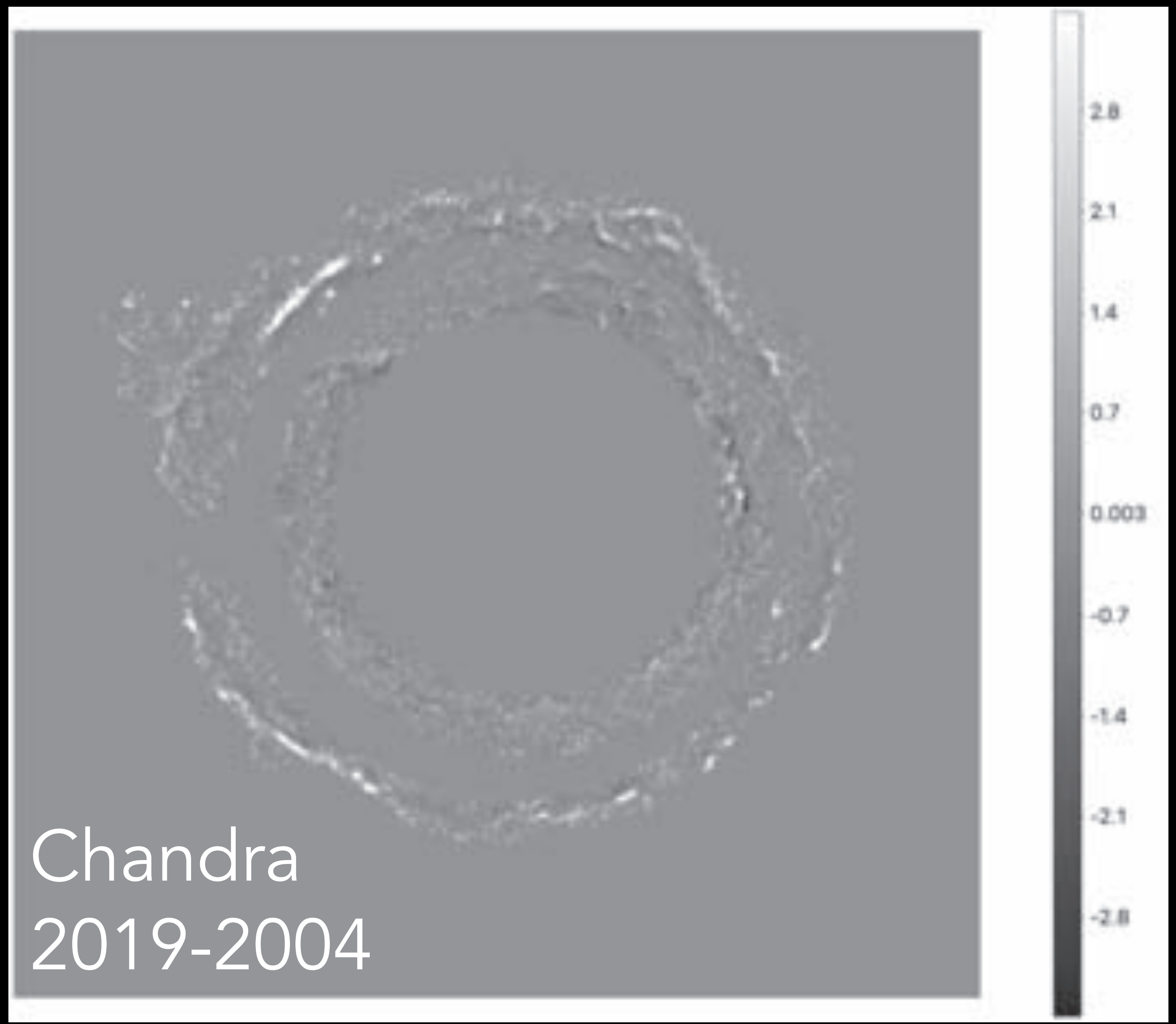
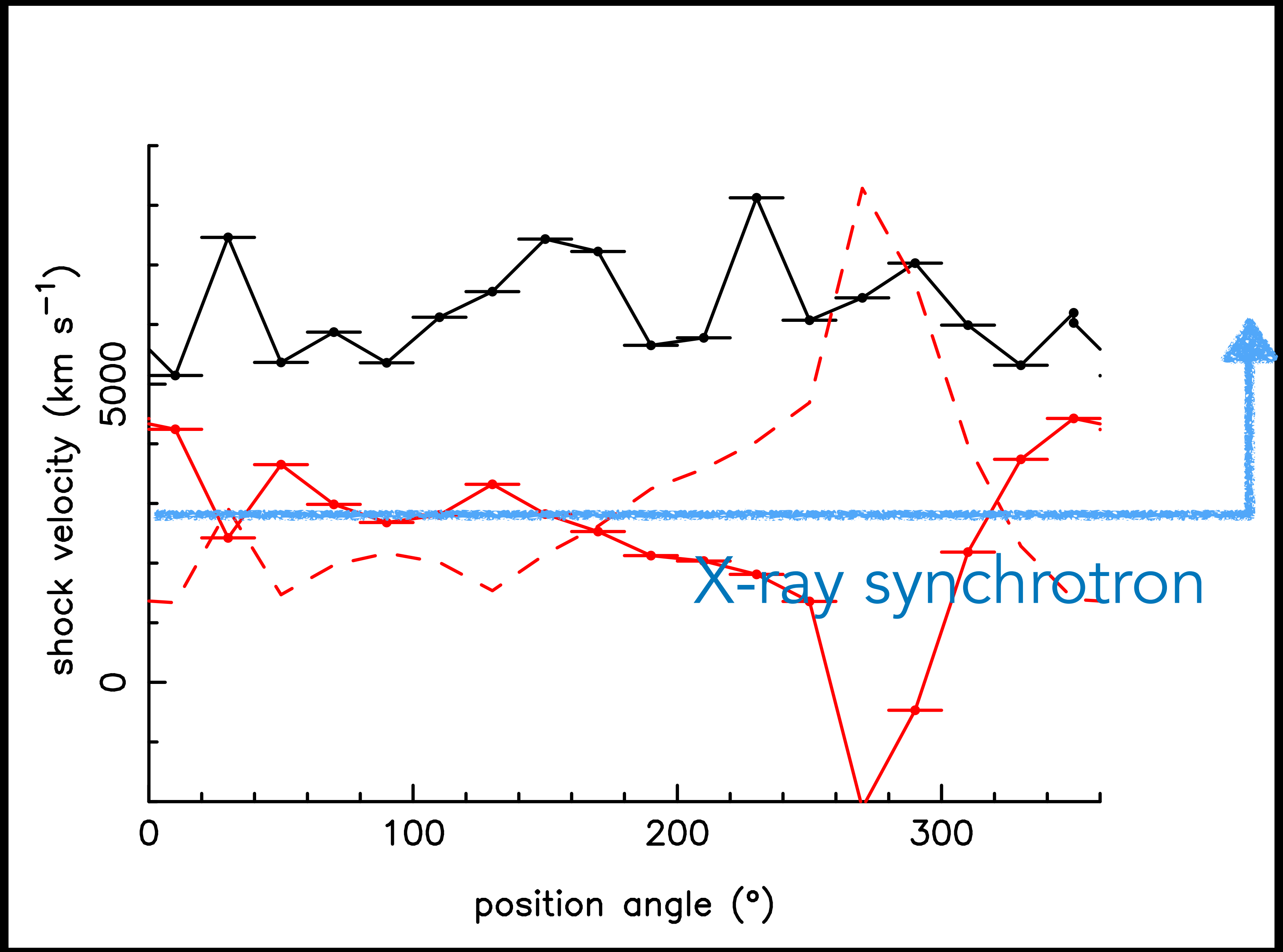




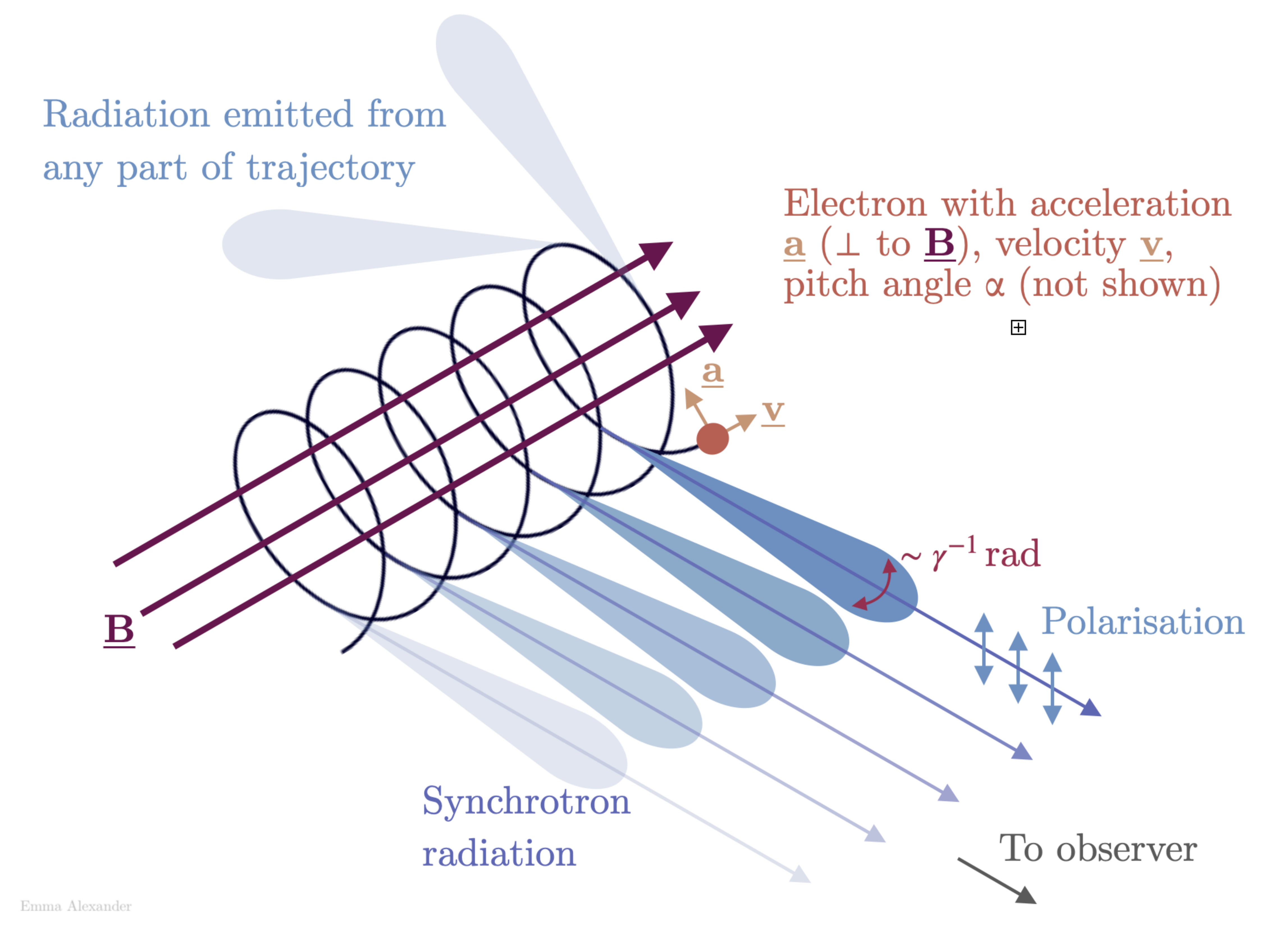


X-ray synchr.
reverse shock

Vink+ 2022

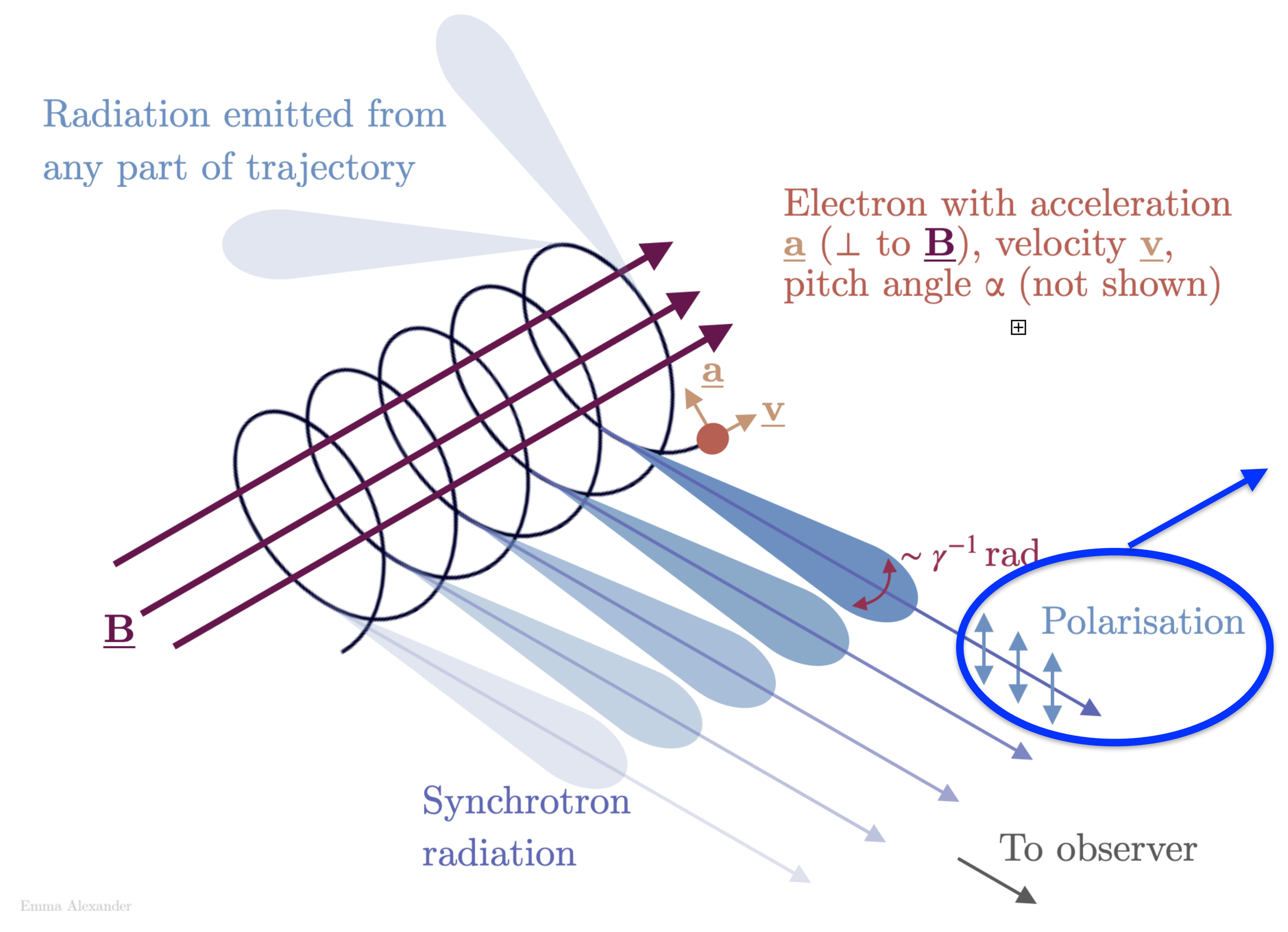
- Reverse shocks moves back in western part
  - Rev. shock velocities peak there: 7000-8000 km/s
- Rev. has high B-field despite low ejecta field -> very efficient amplification
- Rev. shock may be important for accelerating dust or high metal plasmas

Synchrotron radiation polarization



- Synchrotron radiation intrinsically polarized
- B-orientation perpendicular to EM E-vector

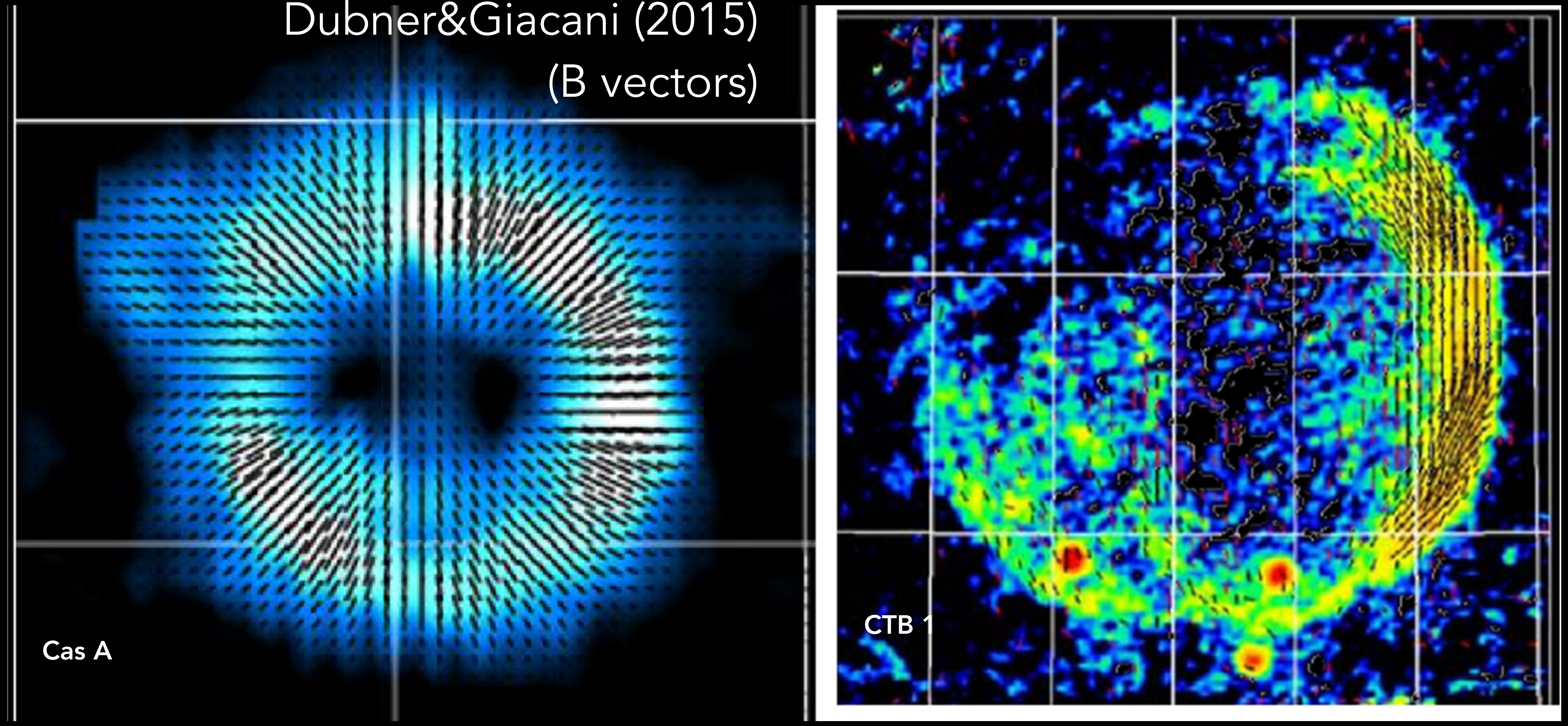
Synchrotron radiation polarization

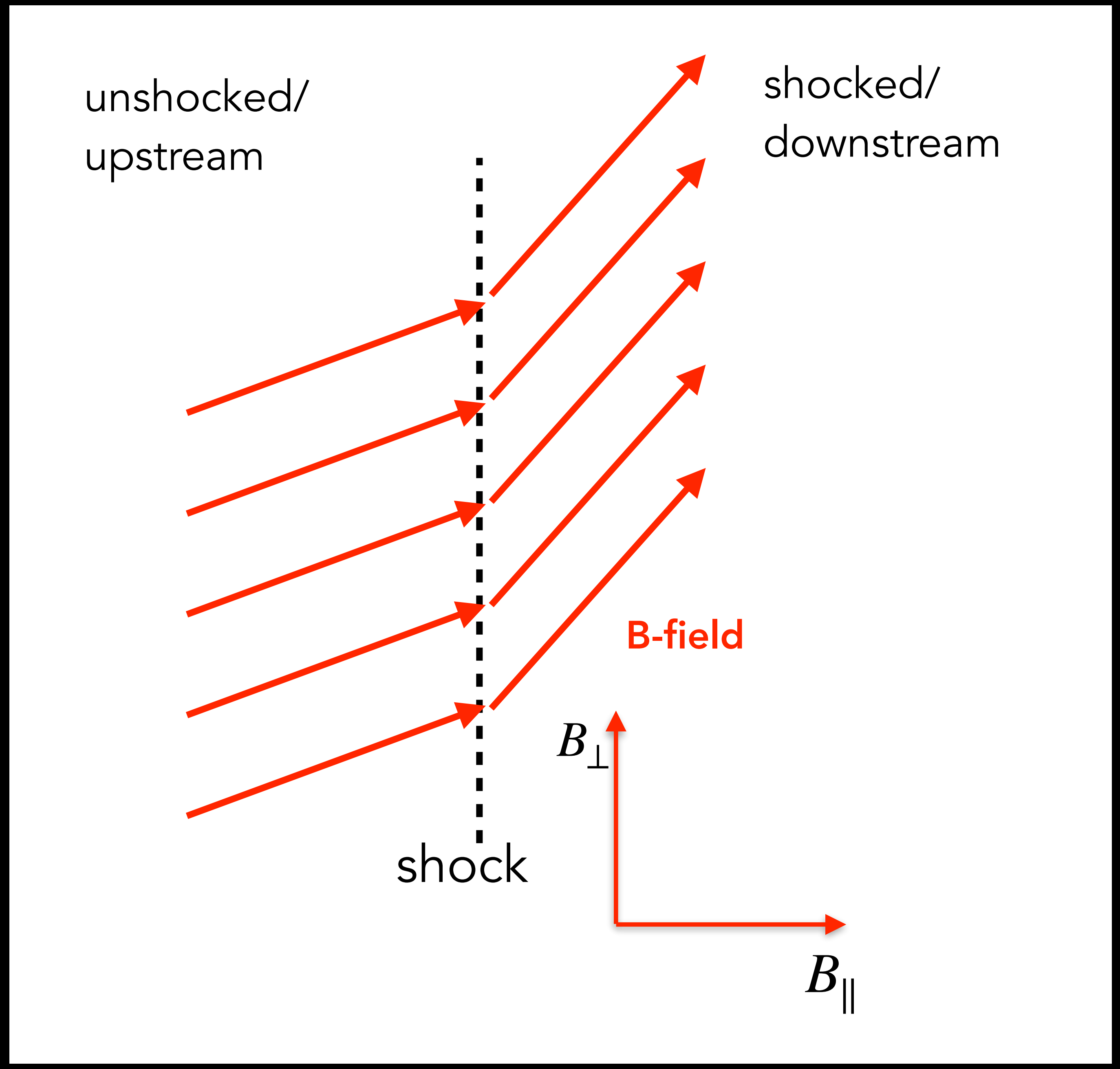


intrinsically ~70% polarized

- Synchrotron radiation intrinsically polarized
- B-orientation perpendicular to EM E-vector

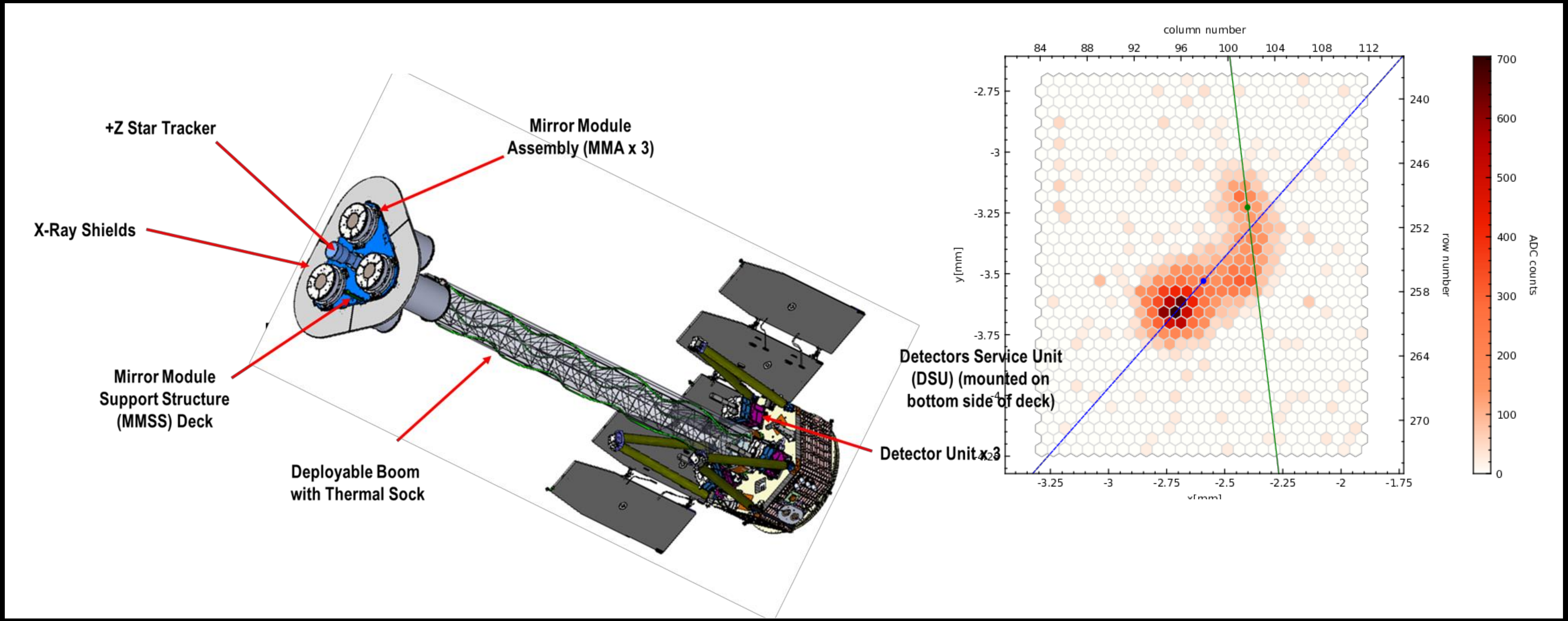
Magnetic field configuration

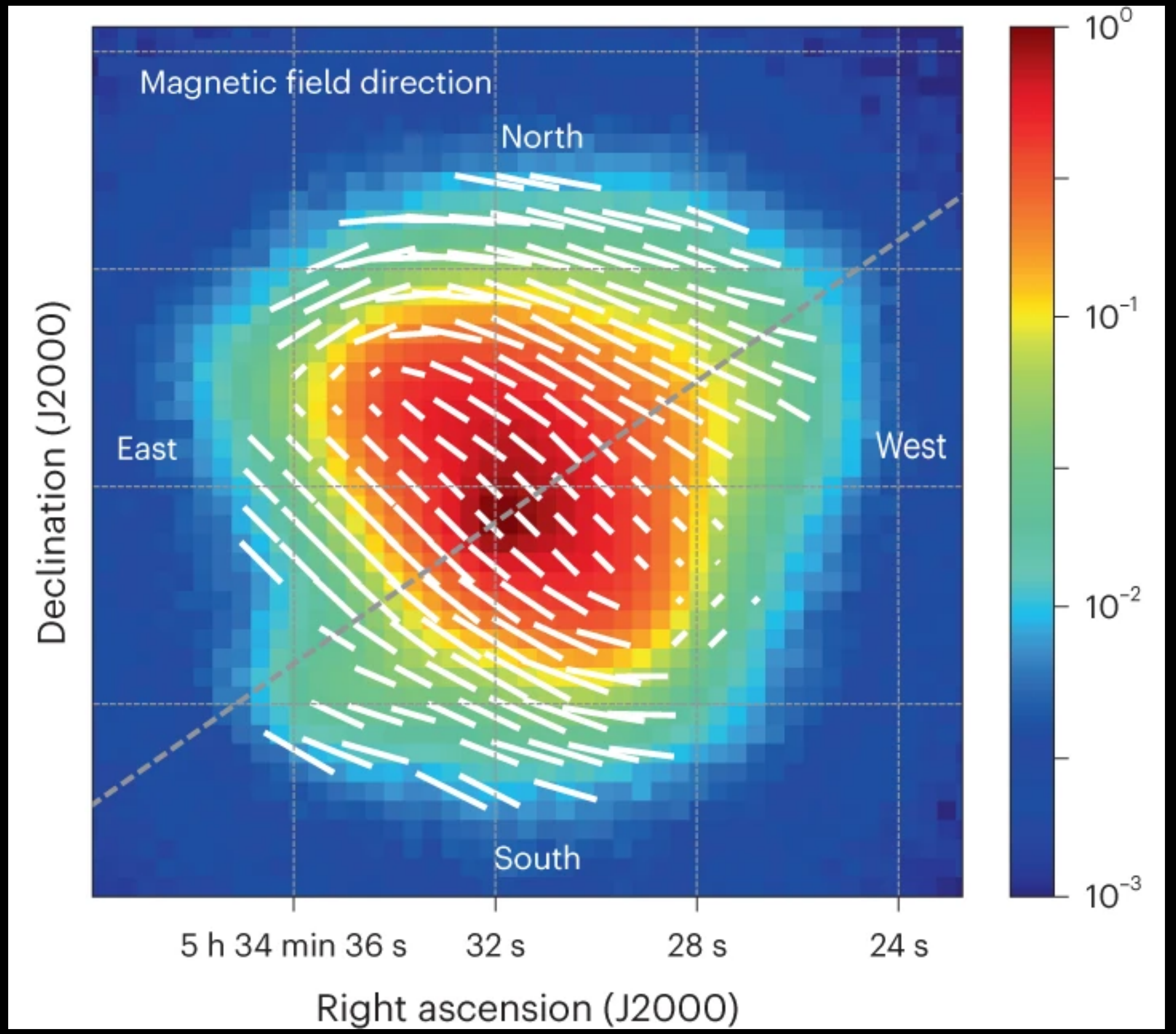




- X-ray synchrotron → requires turbulent magnetic fields!
  - Theory: CR resonant perturbations + Bell (2004) instability (upstream)
  - Isotropic B (?)
- Downstream: expect tangential field
- Radio observations: young SNRs have radial B-fields, old SNRs tangential
  - Magnetic fields radially stretched in young SNRs, but where?

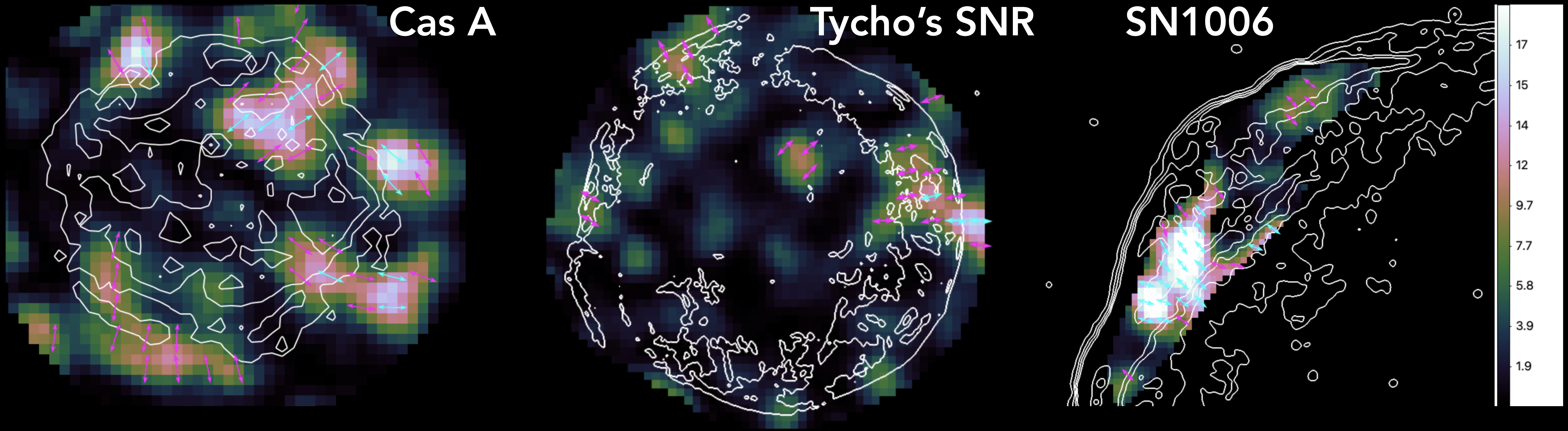
Measuring B-field orientations in X-rays with IXPE



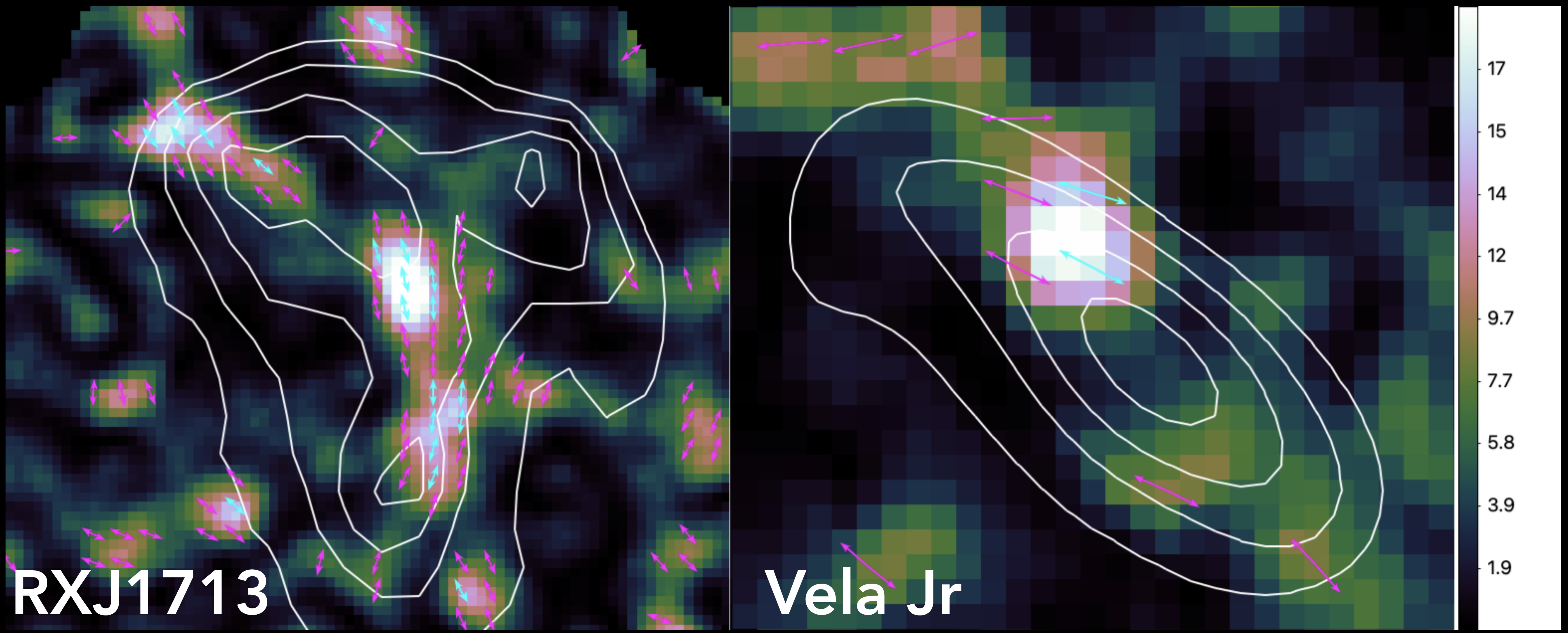


- Imaging X-ray Polarimetry Explorer (IXPE) launched Dec. 9 2021
- Carries 3 gas-pixel detectors
- Uses photo-electron direction to measure B-field EM wave
- Effective energy range: 2-7 keV

IXPE Statistical maps (χ^2_2)



- ~4-5σ detection of polarization
- correct for thermal contributions
- Cas A: only after some tricks:
  - entire SNR only
  - 5% pol. degree
    - high downstream turbulence

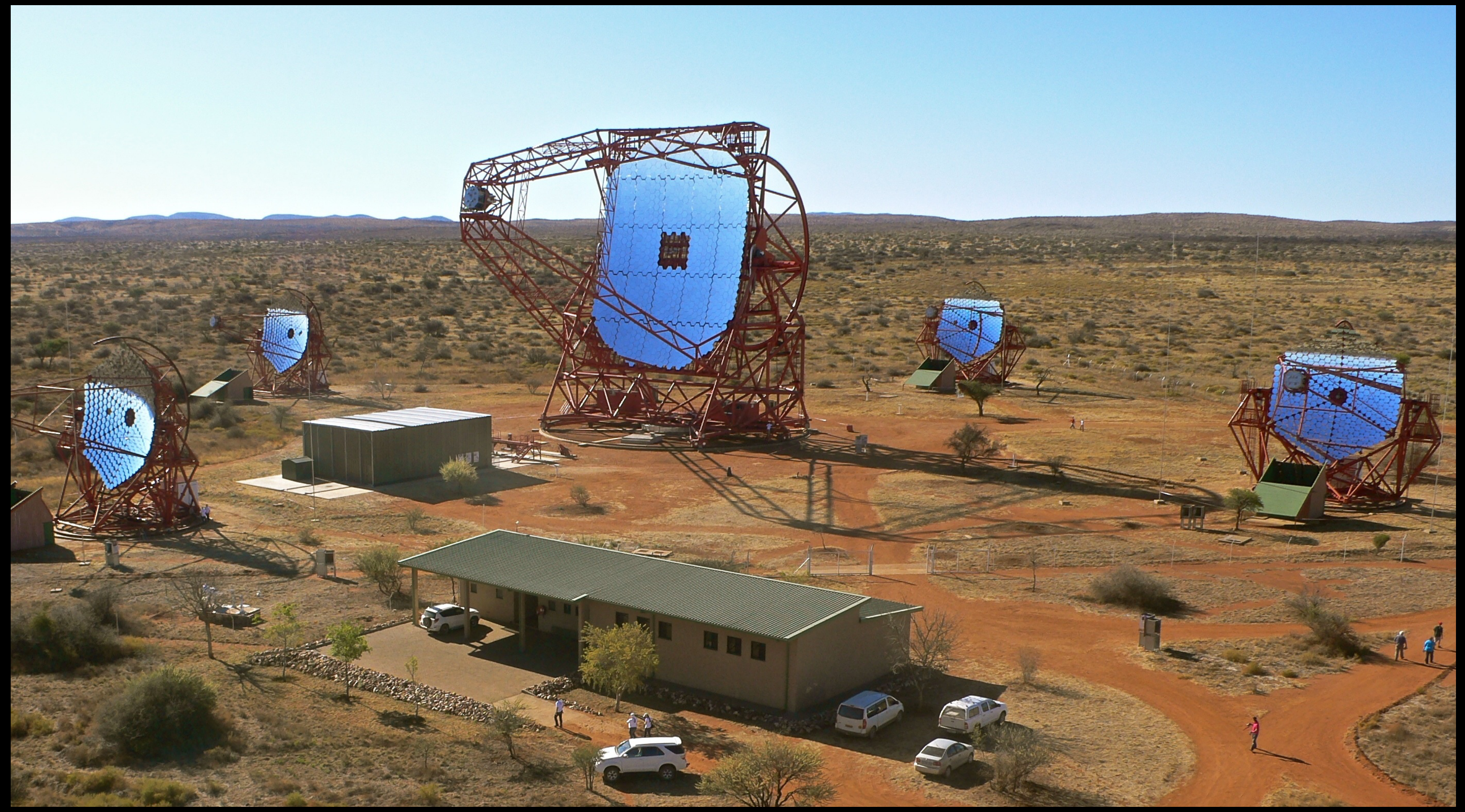


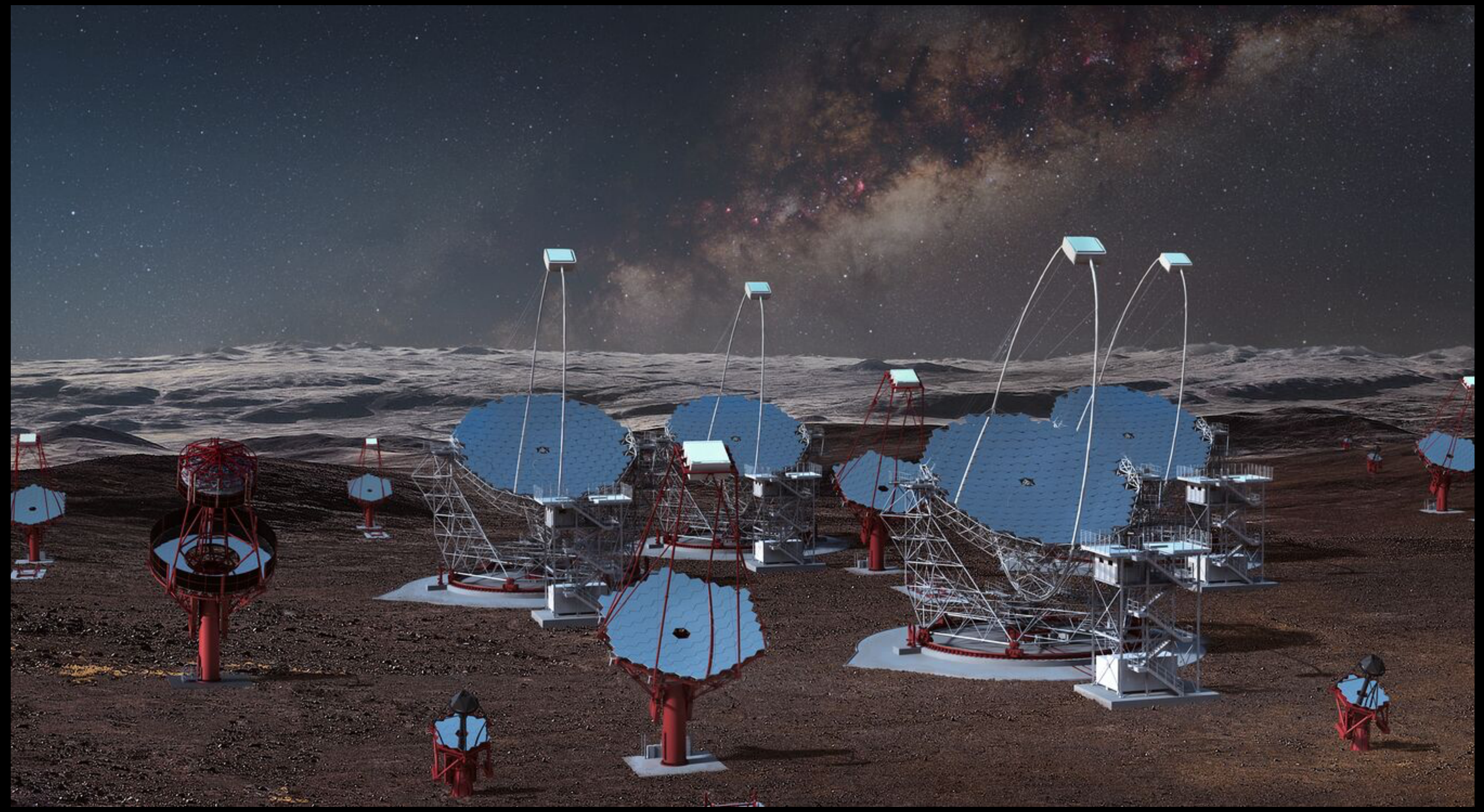
X-ray polarization overview

	Age (yr)	B field	P.F.	Orientation B-field	Ref.
Cas A	~350	~250 μG	~5%	radial	Vink+ '22
Tycho	452	~200 μG	~10%	radial	Ferrazzoli+ '23
SN1006	1018	~80 μG	~20%	radial	Zhou+ '23
RX J1713	~1500	~20 μG	26%—30%	tangential	Ferrazzoli+ '24
Vela Jr	~3000	~10 μG	10%—20%	tangential	Prokhorov+ '24

- Radial vs tangential: age (or B-field?) dependence in X-rays
  - hydrodynamic instabilities close to shock? (Inoue+ '13)
- pol. frac. low (5-10%)/high B turbulence
- Note: turbulence must be high enough to allow X-ray synchrotron (i.e. $\eta \approx 1$)
  - But: low B: long cooling time -> may affect volume of X-ray emission region
  - lack of theory regarding downstreem turbulence

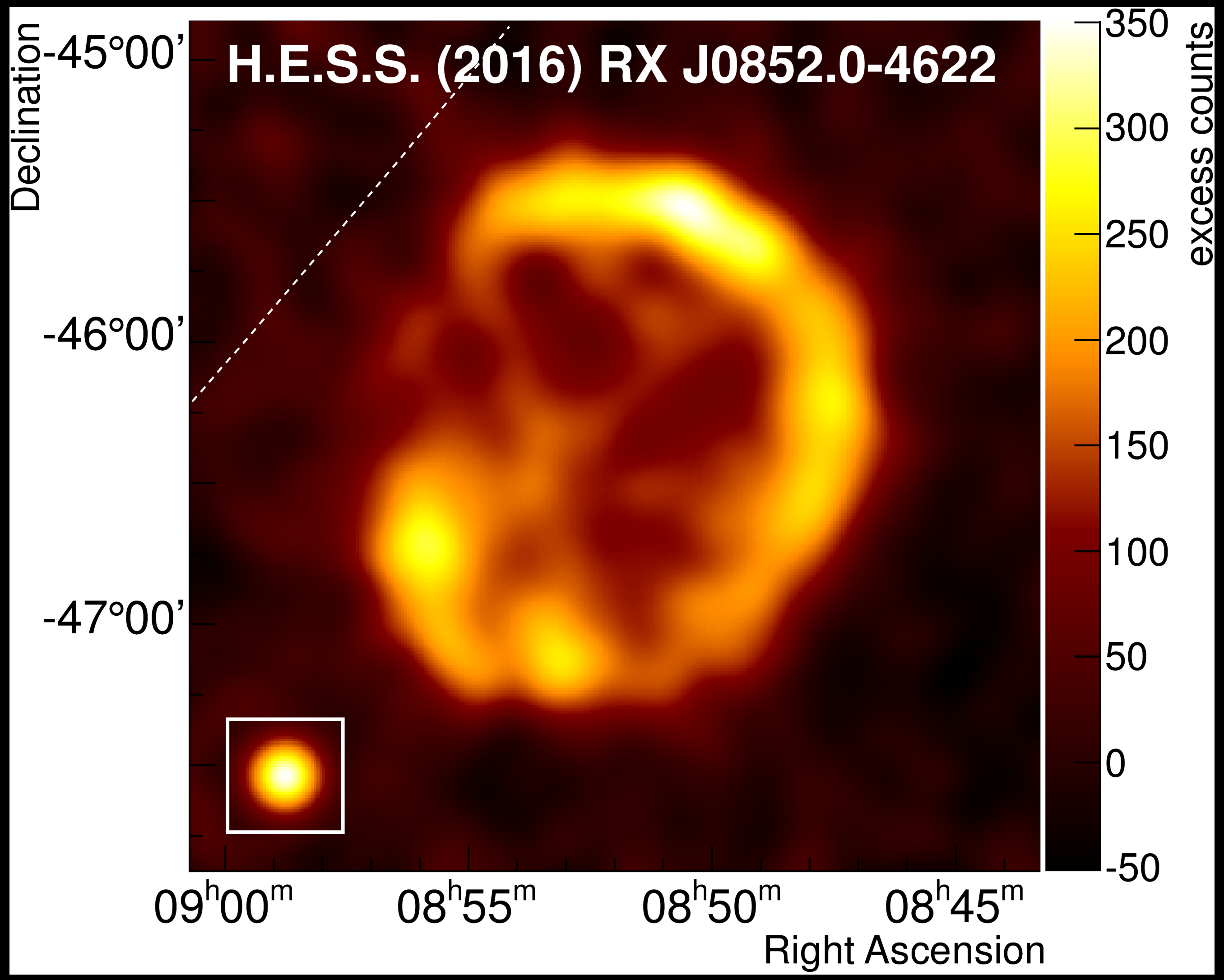
Gamma rays

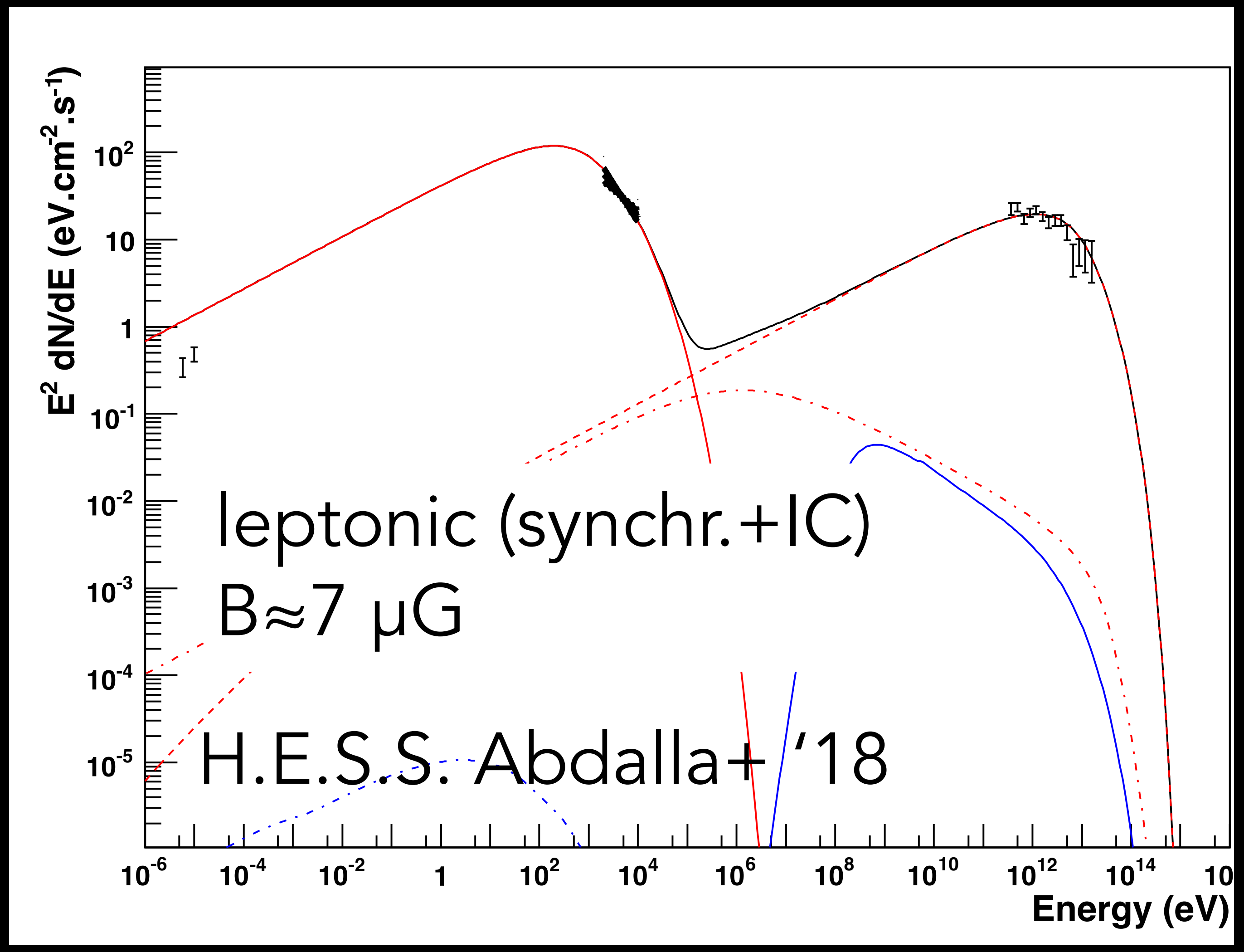


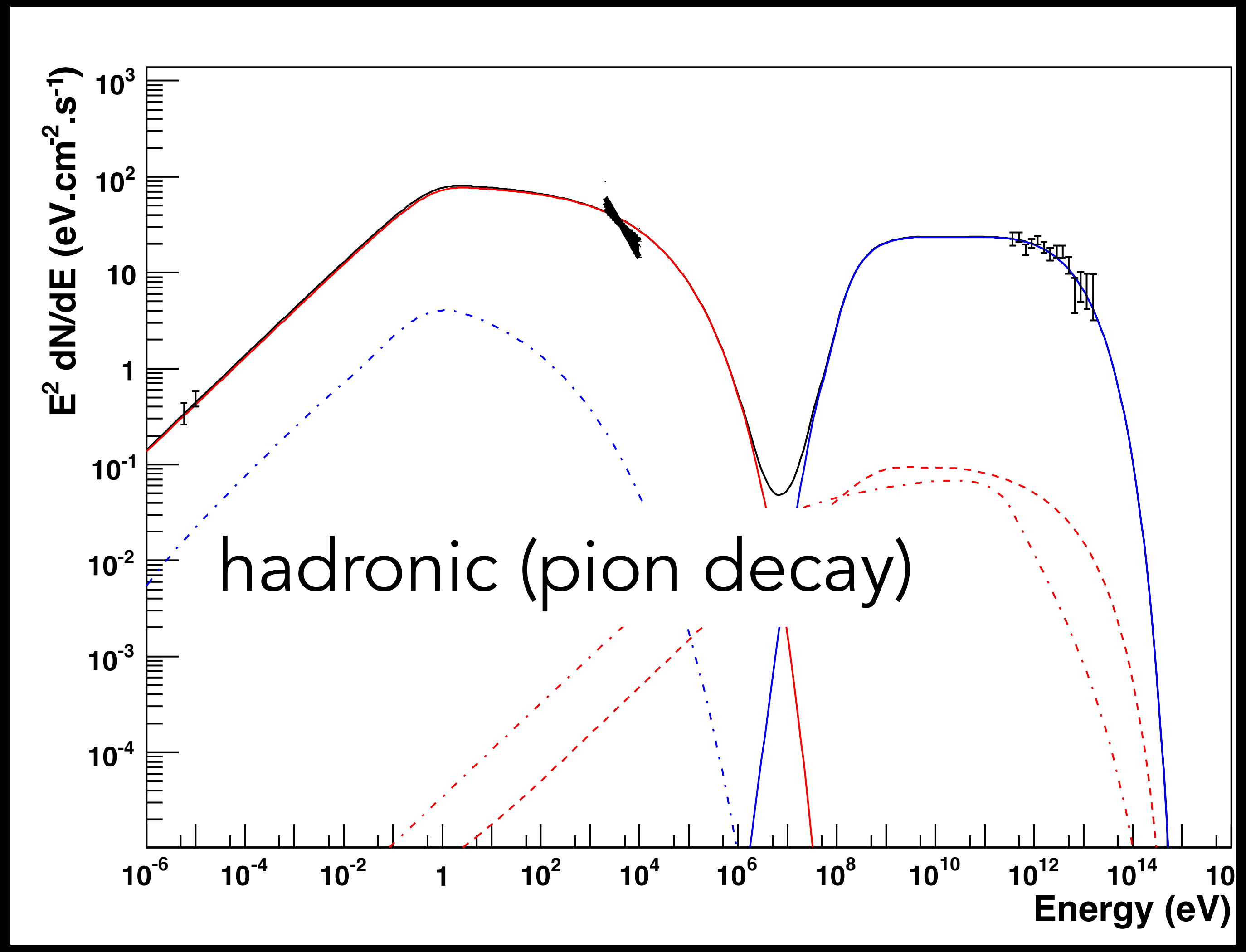


- In 2 decades big jump in knowledge:
  - GeV gamma rays: Fermi-LAT, Agile
  - TeV gamma rays: H.E.S.S., Veritas, MAGIC
  - TeV-PeV gamma rays: HAWC, LHAASO
- In the future: Cherenkov Telescope Array Observatory (CTAO), Southern Wide-field Gamma-ray Observatory (SWGO), upgrades LHAASO

SNRs in gamma rays



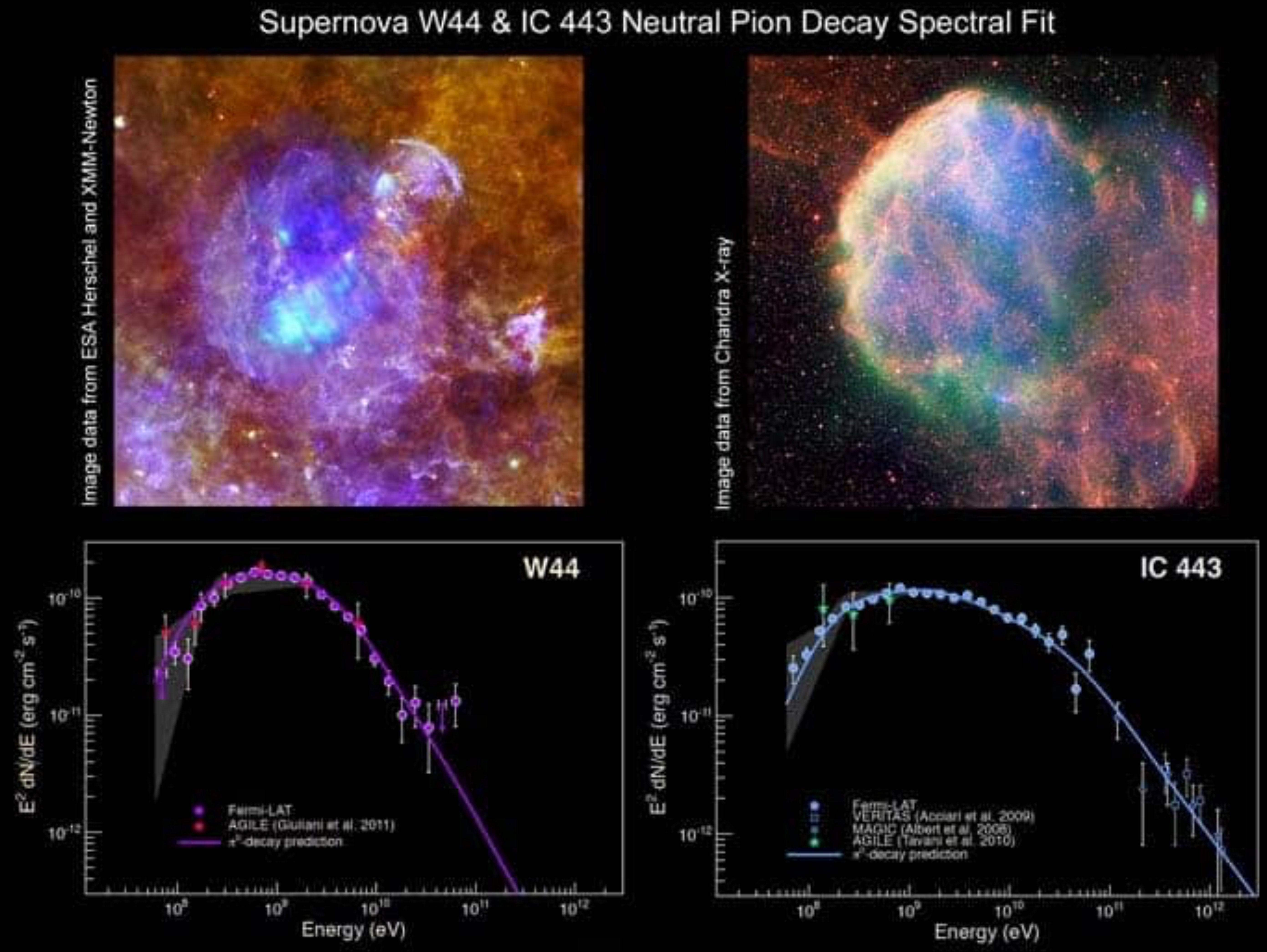




- Not always clear whether leptonic or hadronic (or combination)
  - Low B-field (≲30μG): likely leptonic
  - high CSM density: likely hadronic
- Some clear cases of hadronic emission
  - Older SNRs interacting with dense environment (pion bump)
  - Compact young SNRs (Cas A, Tycho's SNR, Kepler's SNR)

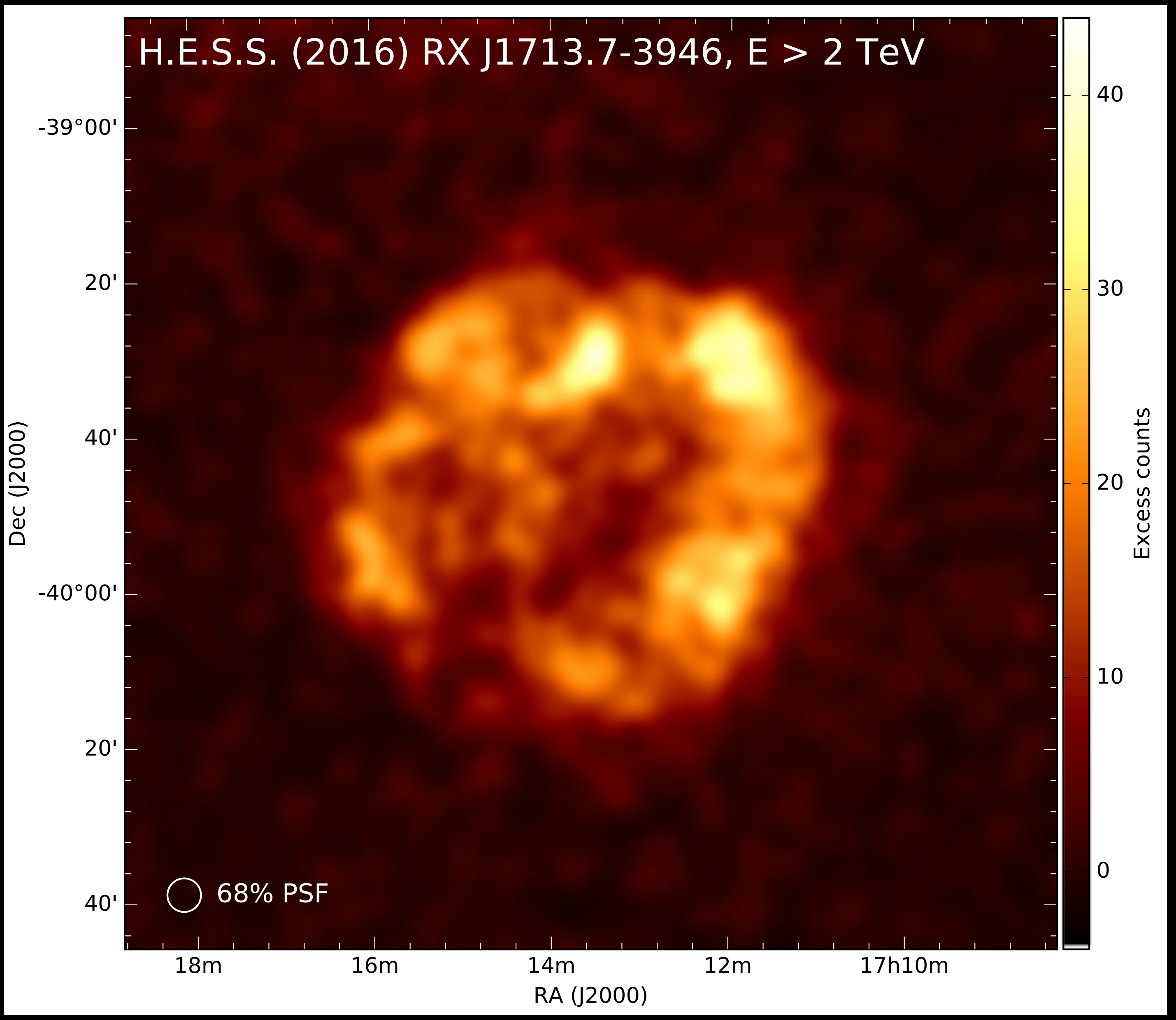
Some “mature” SNRs (≳104 yr)

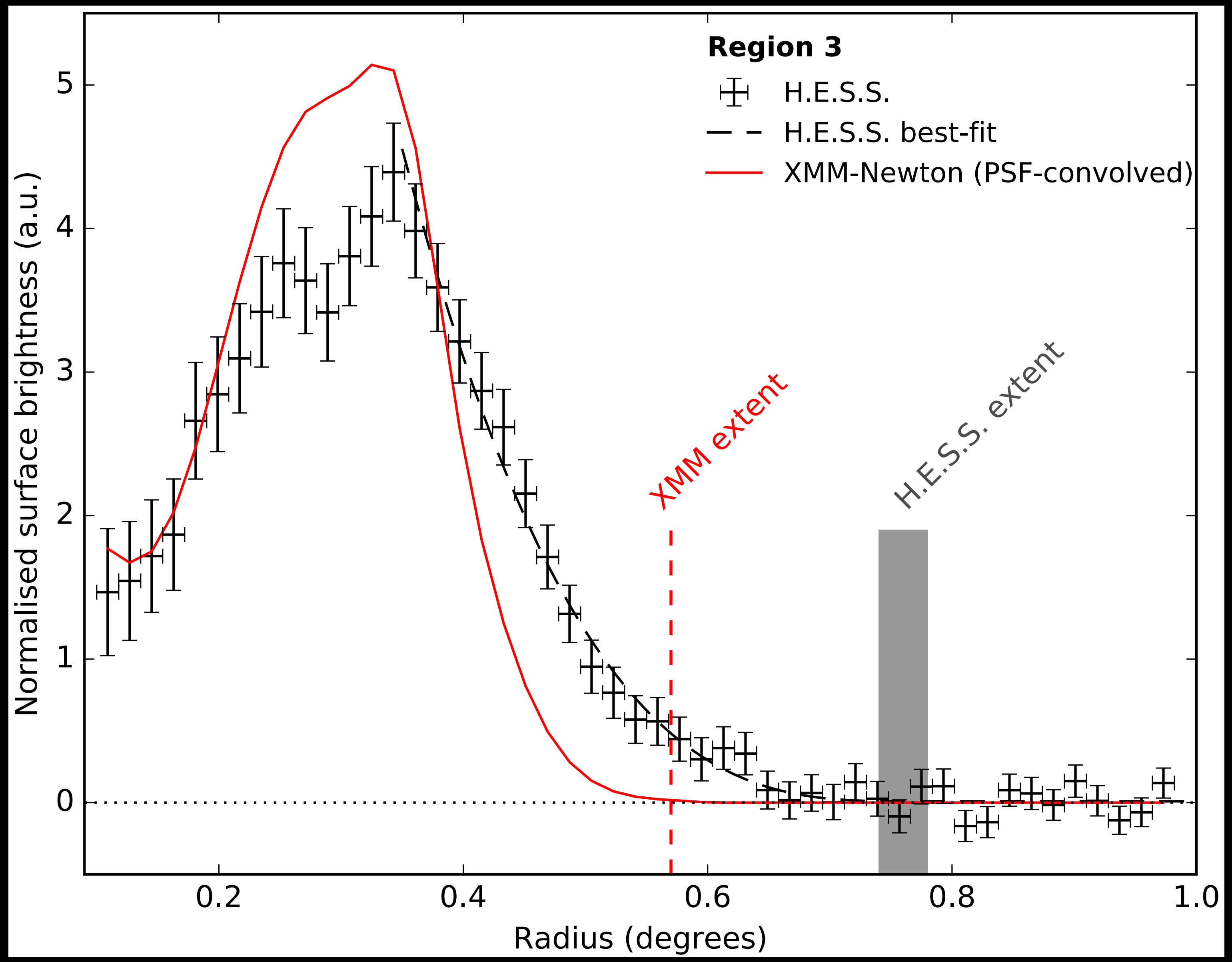
Ackermann+ ’13
(Fermi-LAT)



- Clear pion bumps
  - →Hadronic gamma rays
- Proton cutoffs 20—200 GeV
- Highest energy CRs must have escaped by t~10,000 yr
- Direct evidence for escape:
  - W28: nearby TeV source associated with MC
  - RX J1713: evidence for TeV gamma-rays outside X-ray boundary

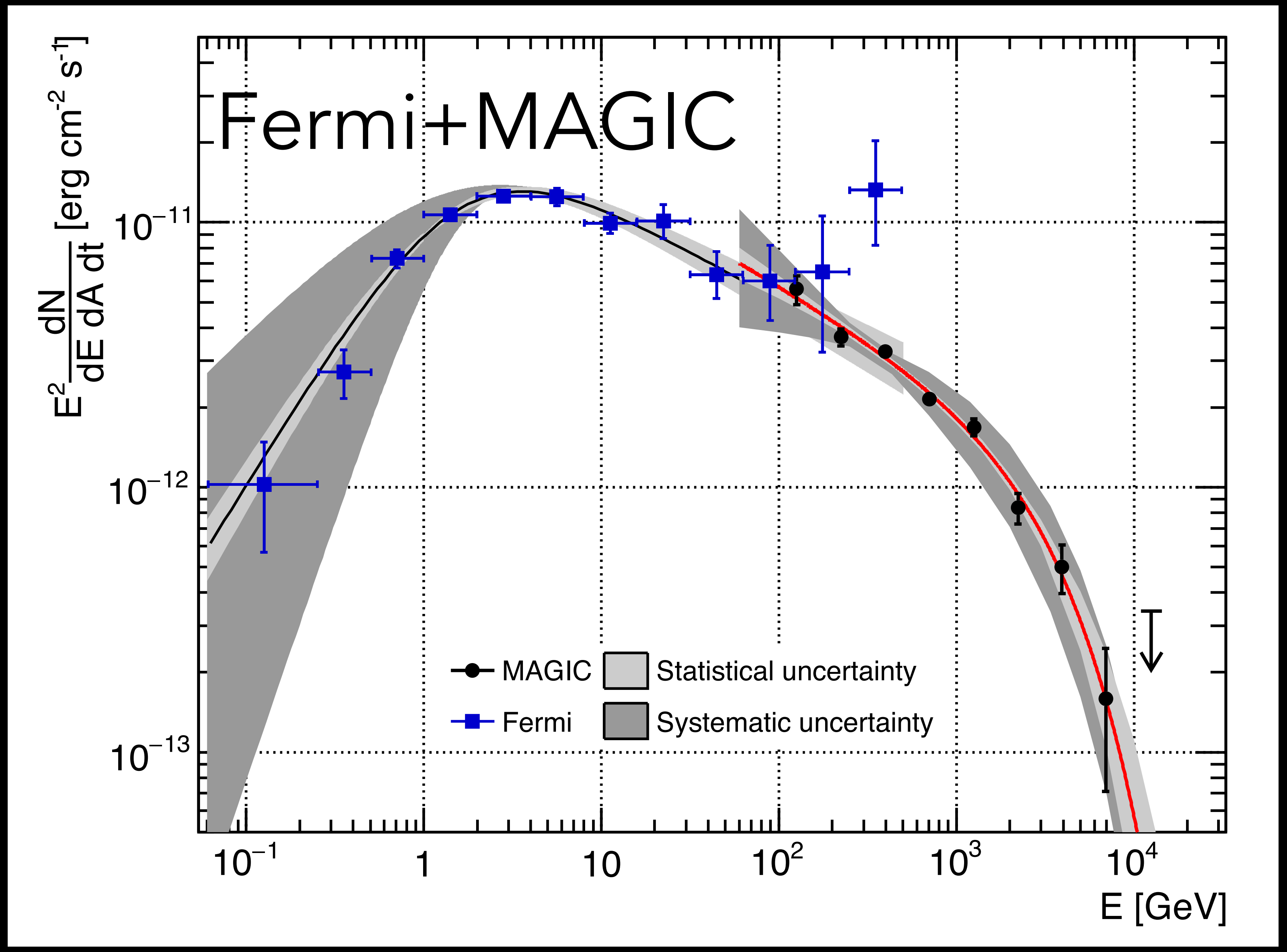
Escape of cosmic rays from RX J1713?





- Escape: CRs diffuse ahead with $\Delta r \gtrsim 0.1r$ (no longer in acc. process)
- RX J1713: measured 13% -> evidence for escape
- Diffusion inferrence: $\frac{B}{\eta} \approx 1.1 \left(\frac{E}{10\,\mathrm{TeV}}\right)\left(\frac{\Delta t}{500\,\mathrm{yr}}\right)\left(\frac{\Delta r}{\mathrm{pc}}\right)^{-2}\left[1+\frac{u_{\mathrm{shock}}\Delta t}{\Delta r}\right]^{-1} \mu\mathrm{G}$
  - suggest low B, or sudden dying down of turbulence ($\eta \gg 1$)

The puzzle of gamma rays from Cas A



- γ-rays: unresolved
- Inferred proton cutoff: $E_c \approx 3$ TeV (MAGIC '17;Veritas '20)

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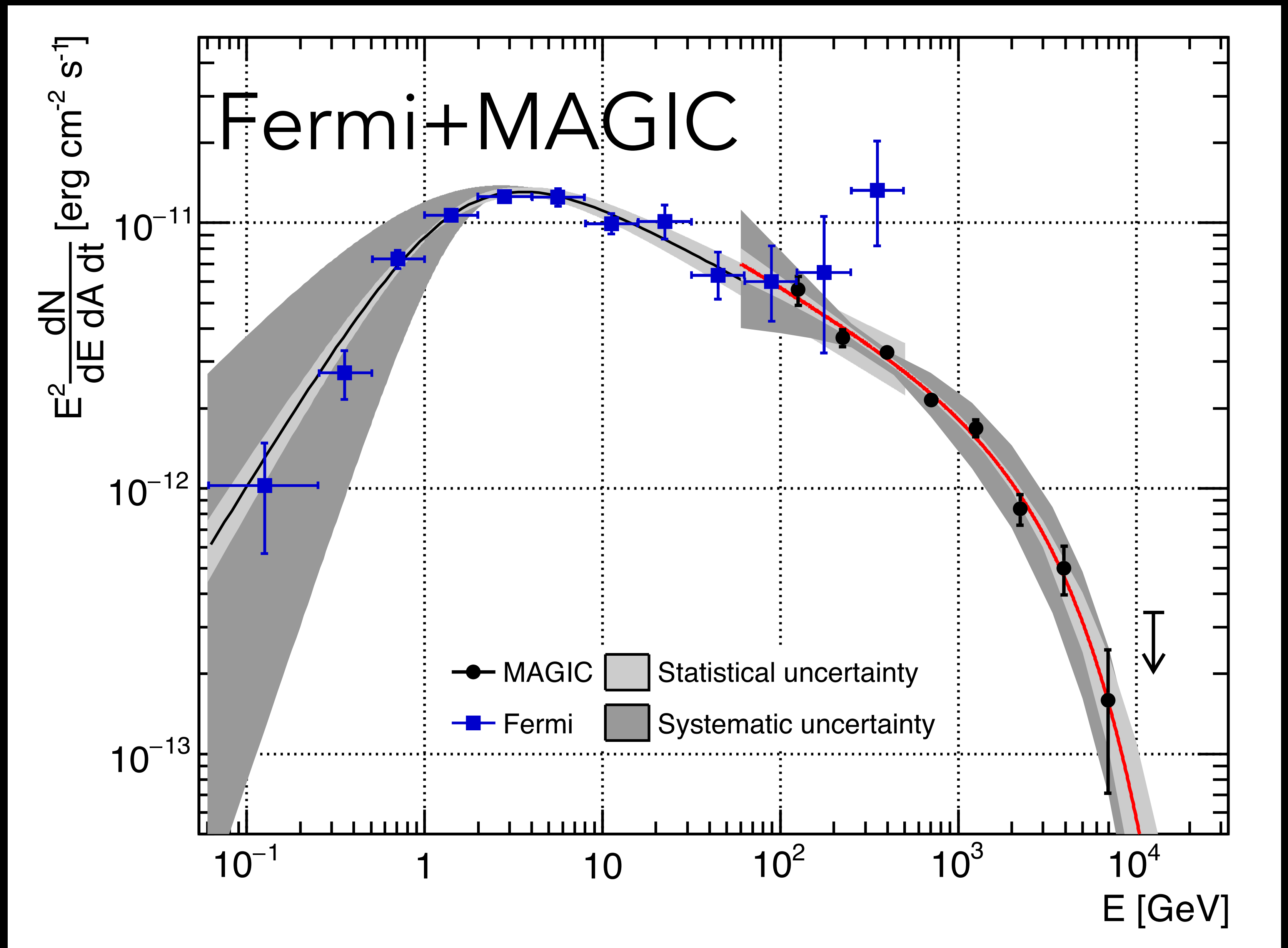

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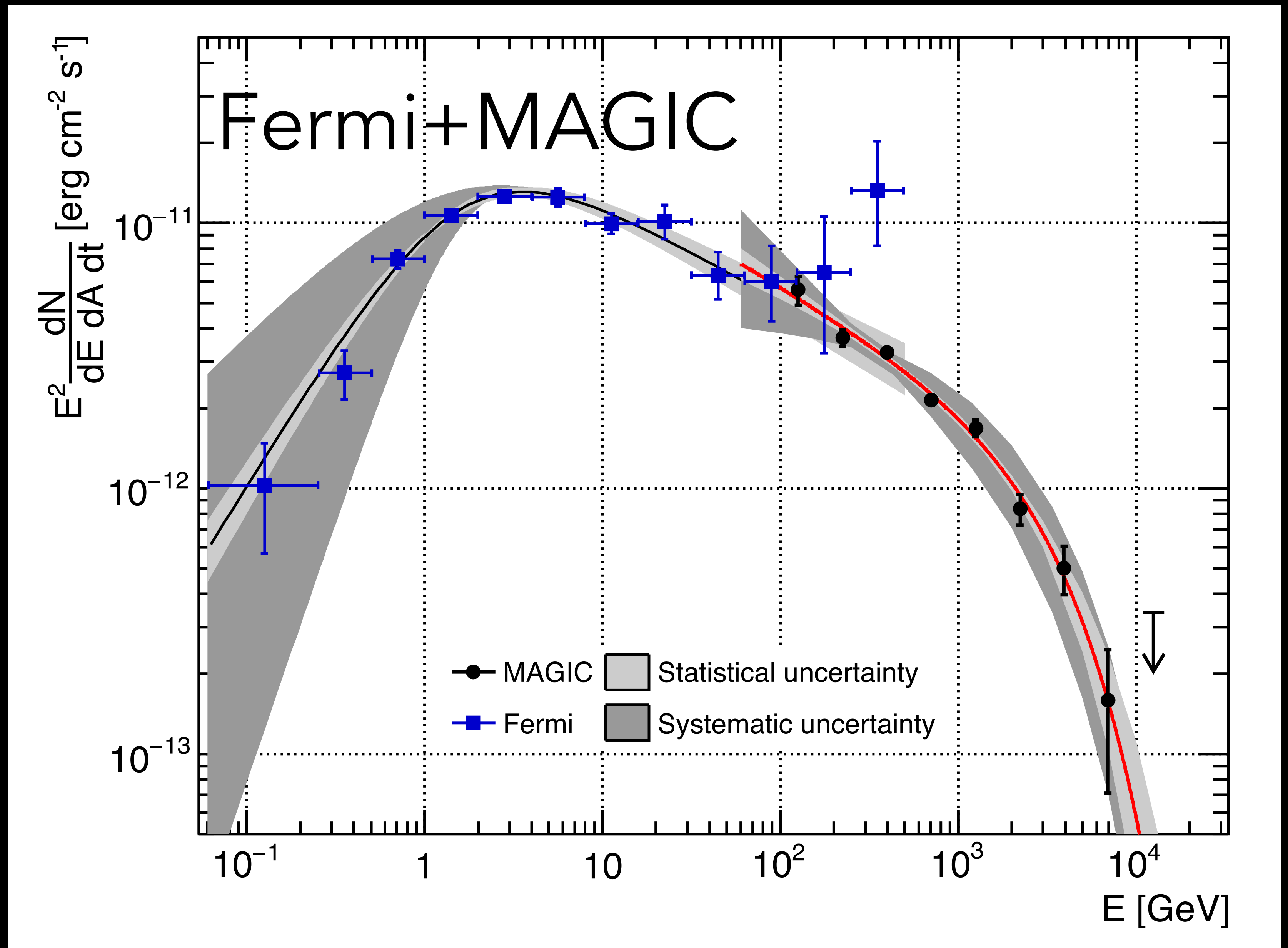

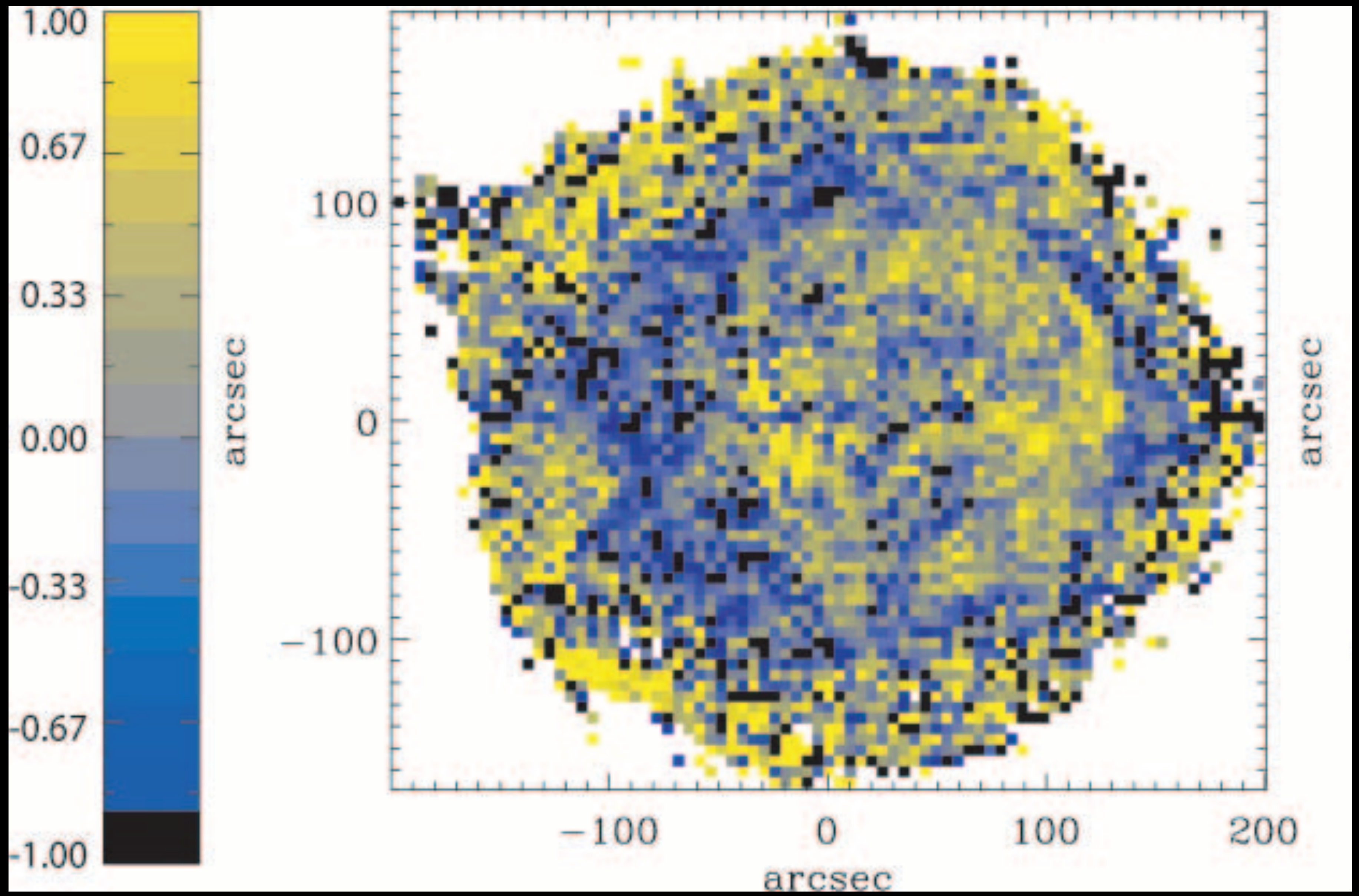

X-ray spectral index map (Helder&JV '08)

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- Problem: this is close to electron cutoff, and these are loss limited; expect: $E_p \gg E_e$!
- Possible solutions:
  - most hadronic γ rays from reverse shock region (dense!) with $V_s \sim 1500\text{-}8000$ km/s
  - in addition: most hadrons are not protons: Cas A oxygen dominated!; CSM: He/N!

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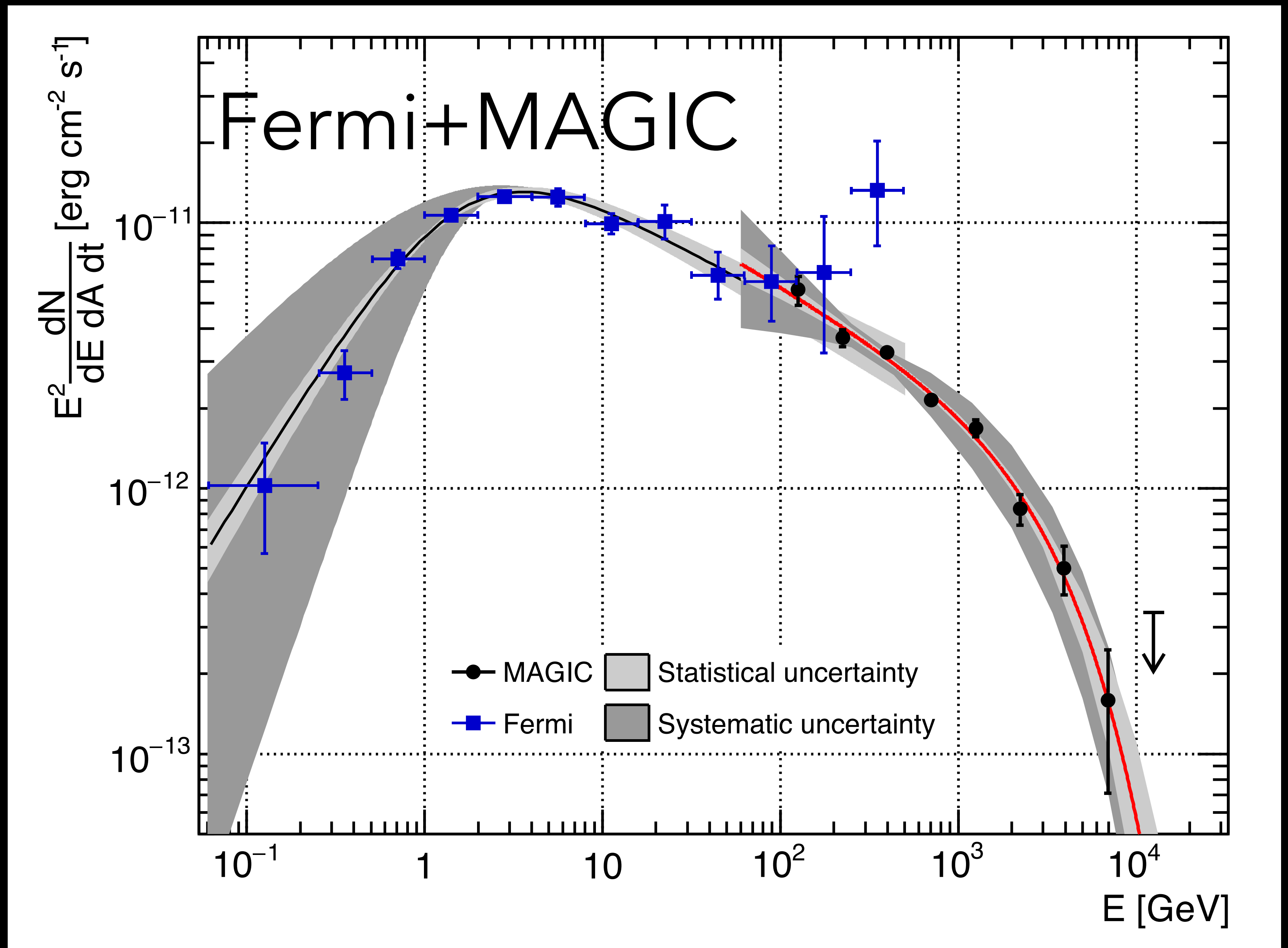

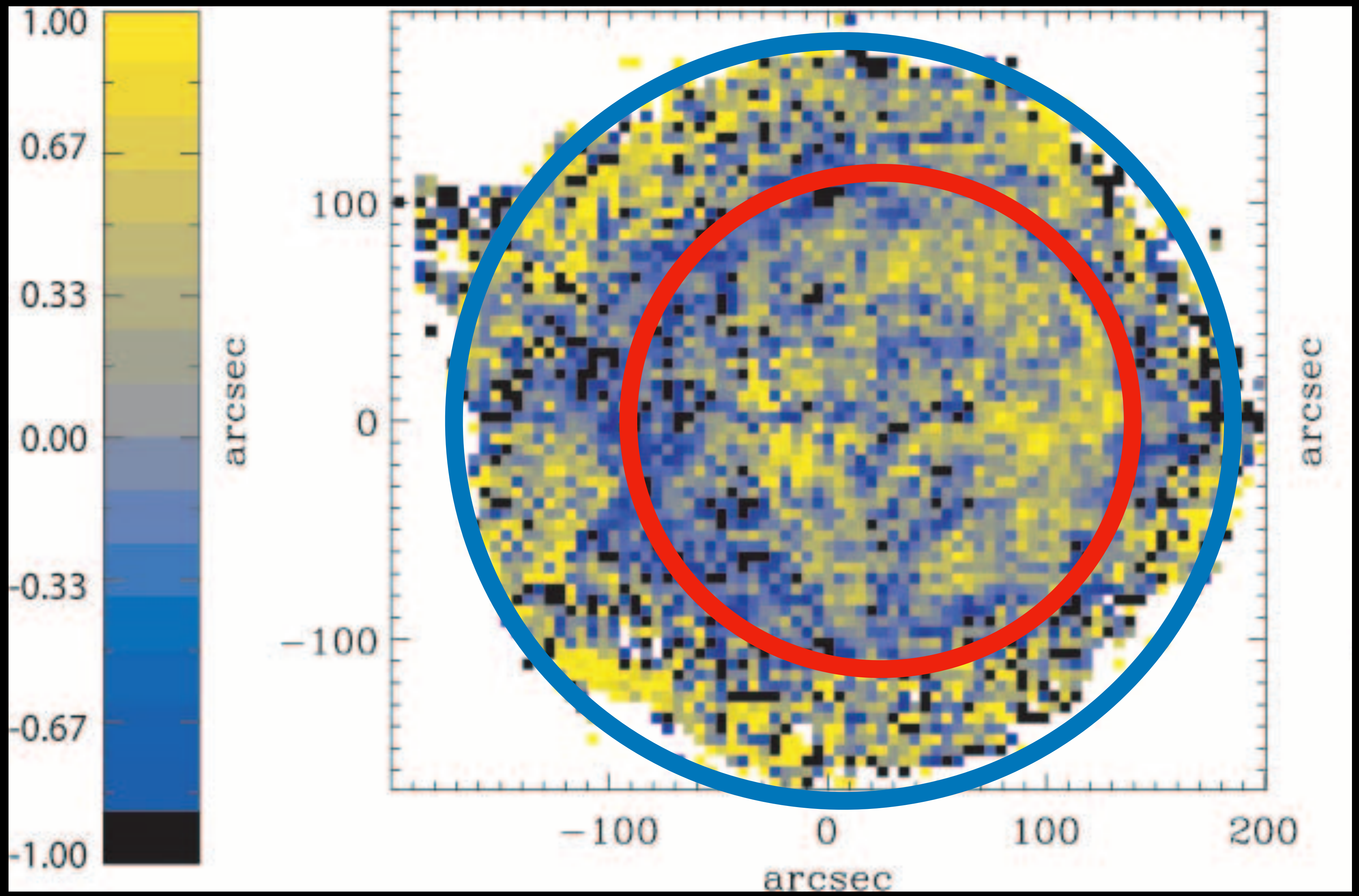

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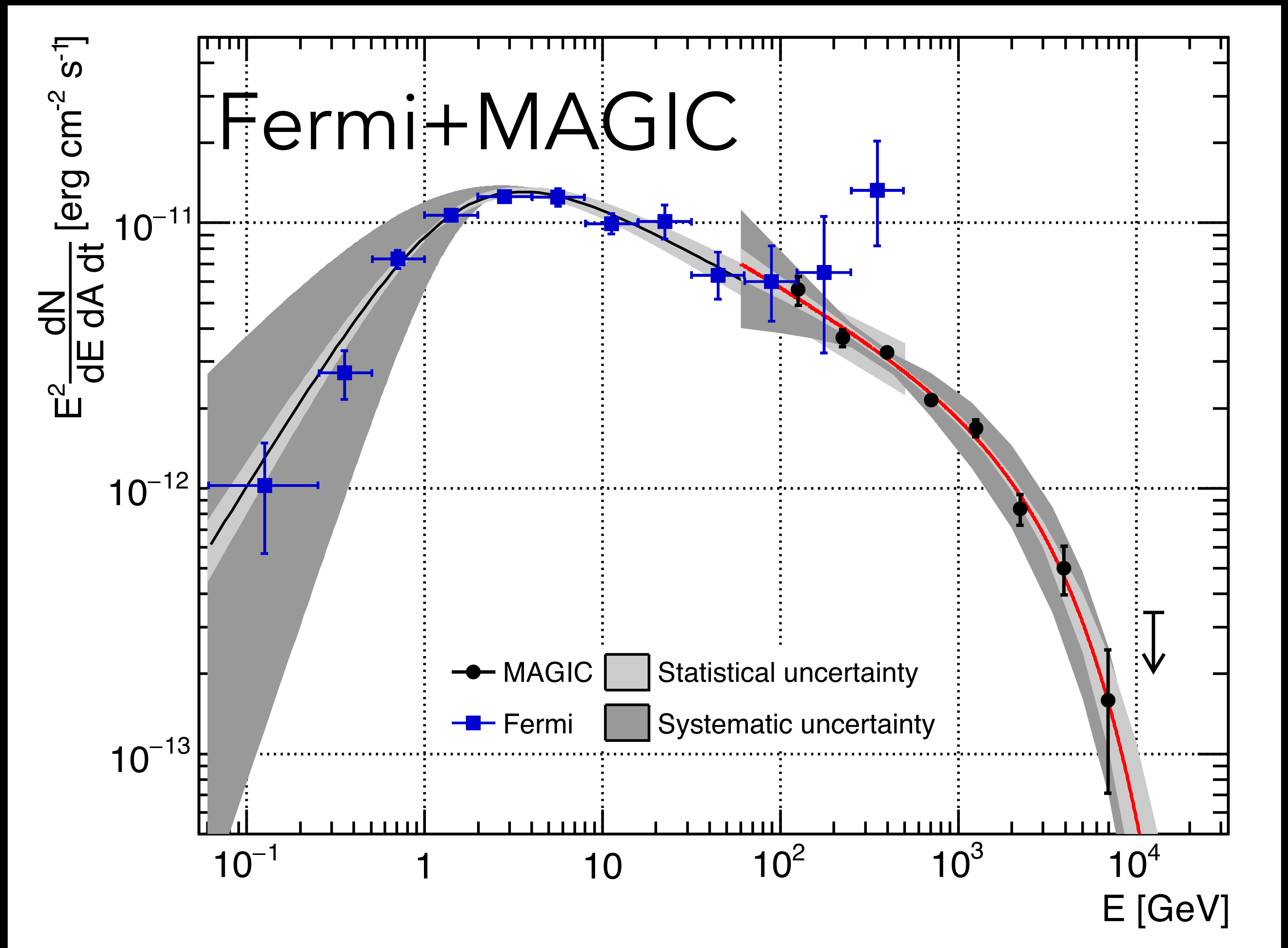

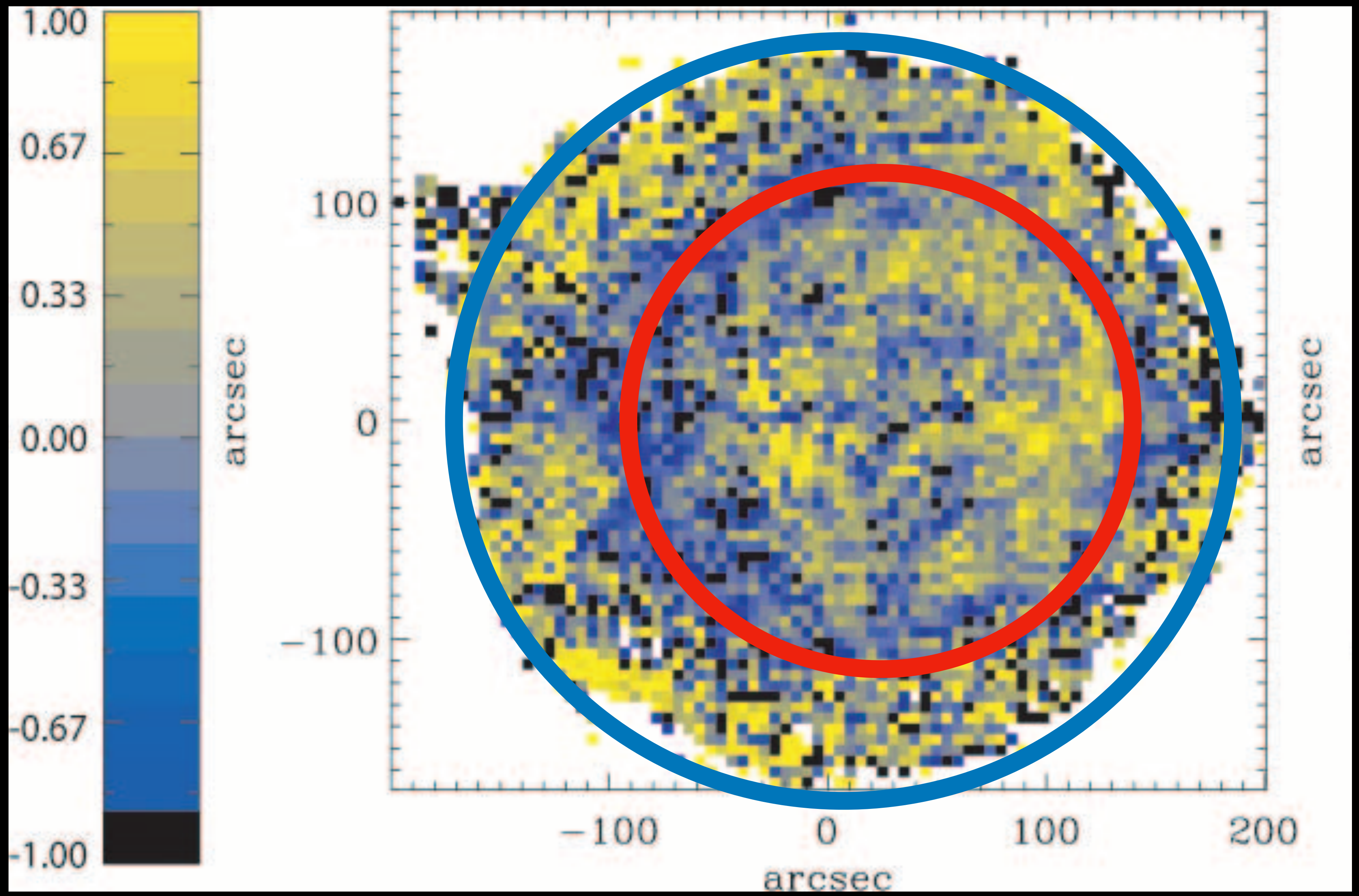

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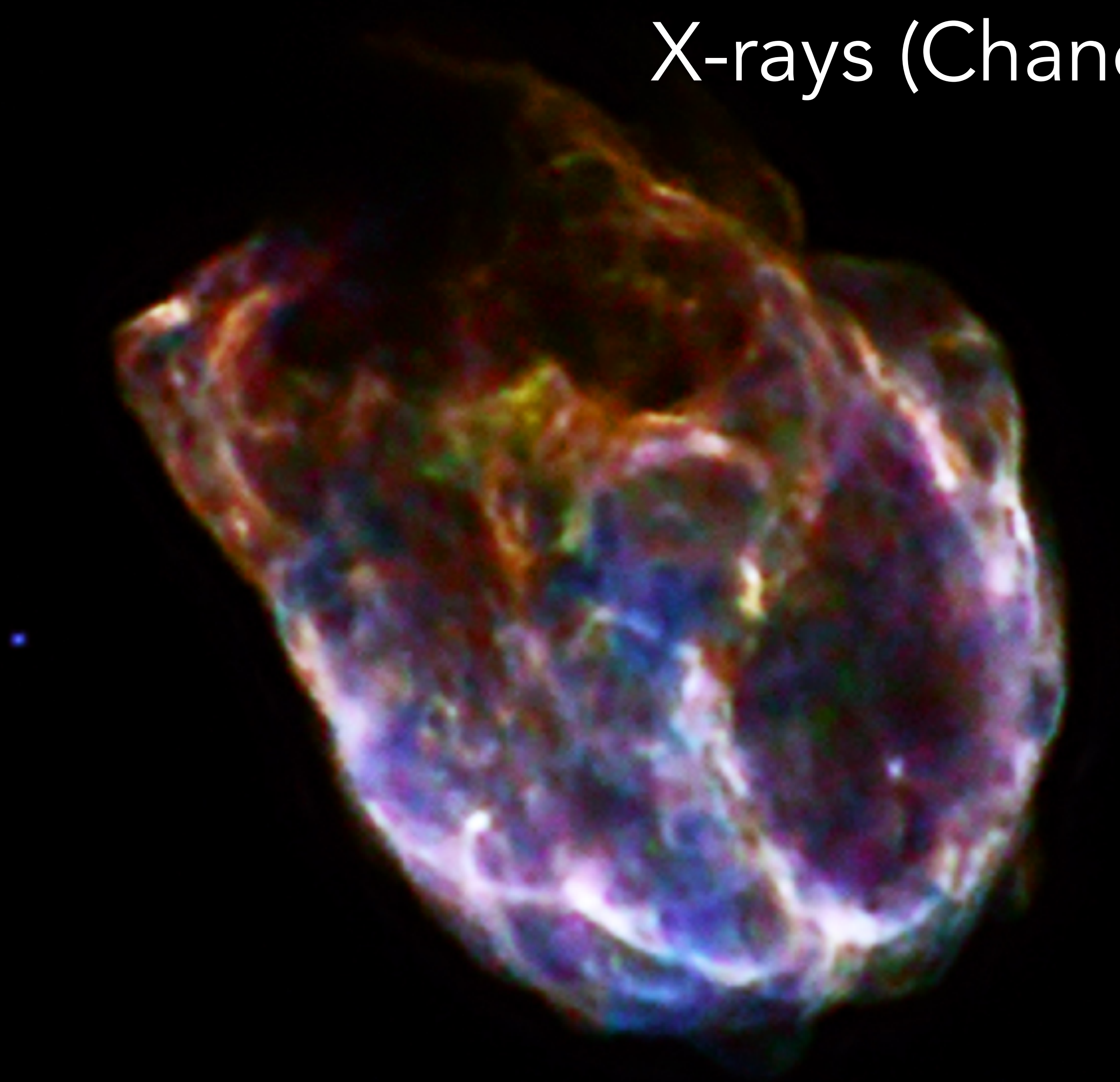
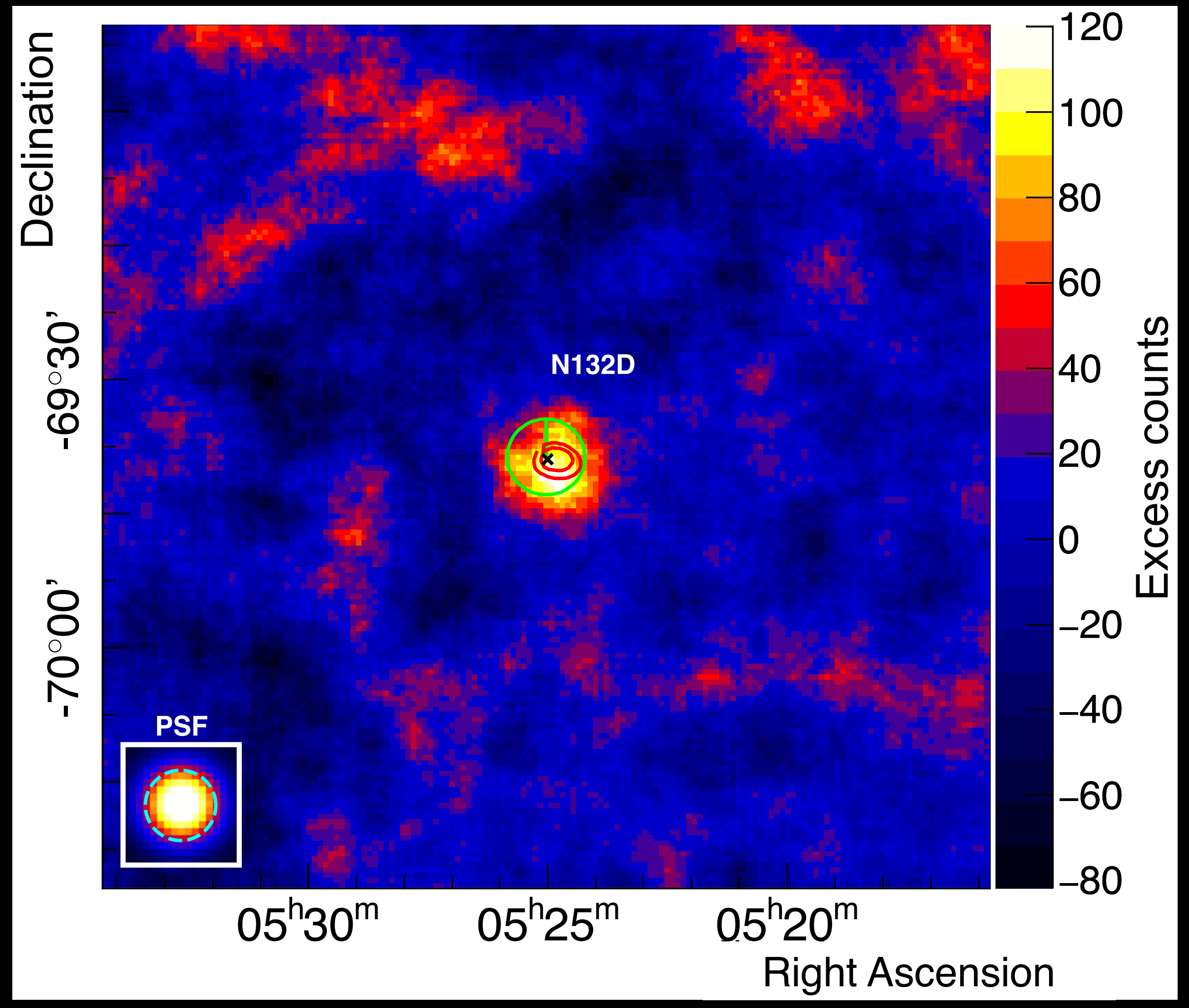
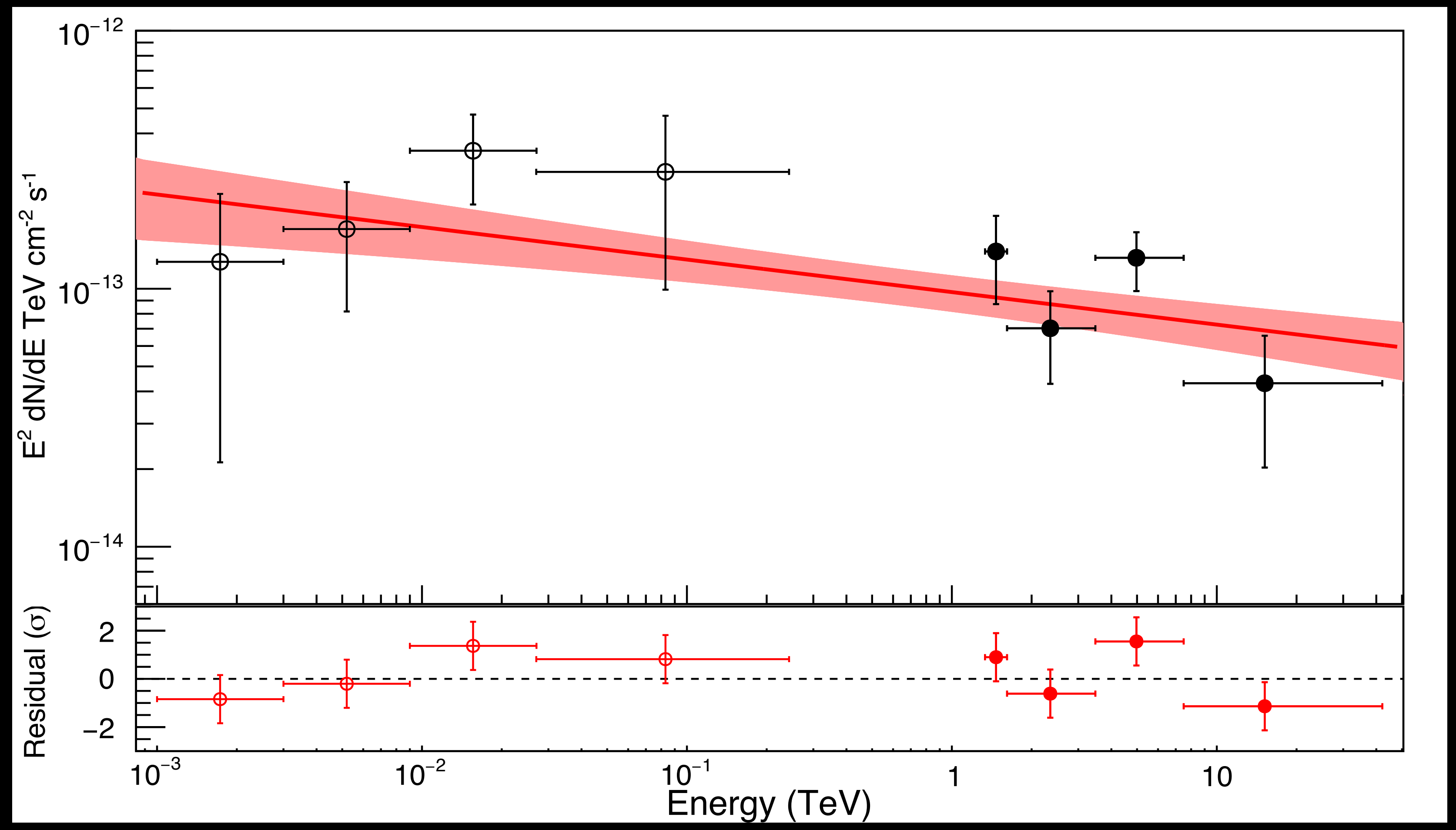
  - in addition: most hadrons are not protons: Cas A oxygen dominated!; CSM: He/N!
- CTAO/future: reveal a forward shock component to higher energies

A peculiar SNR N132D (LMC)

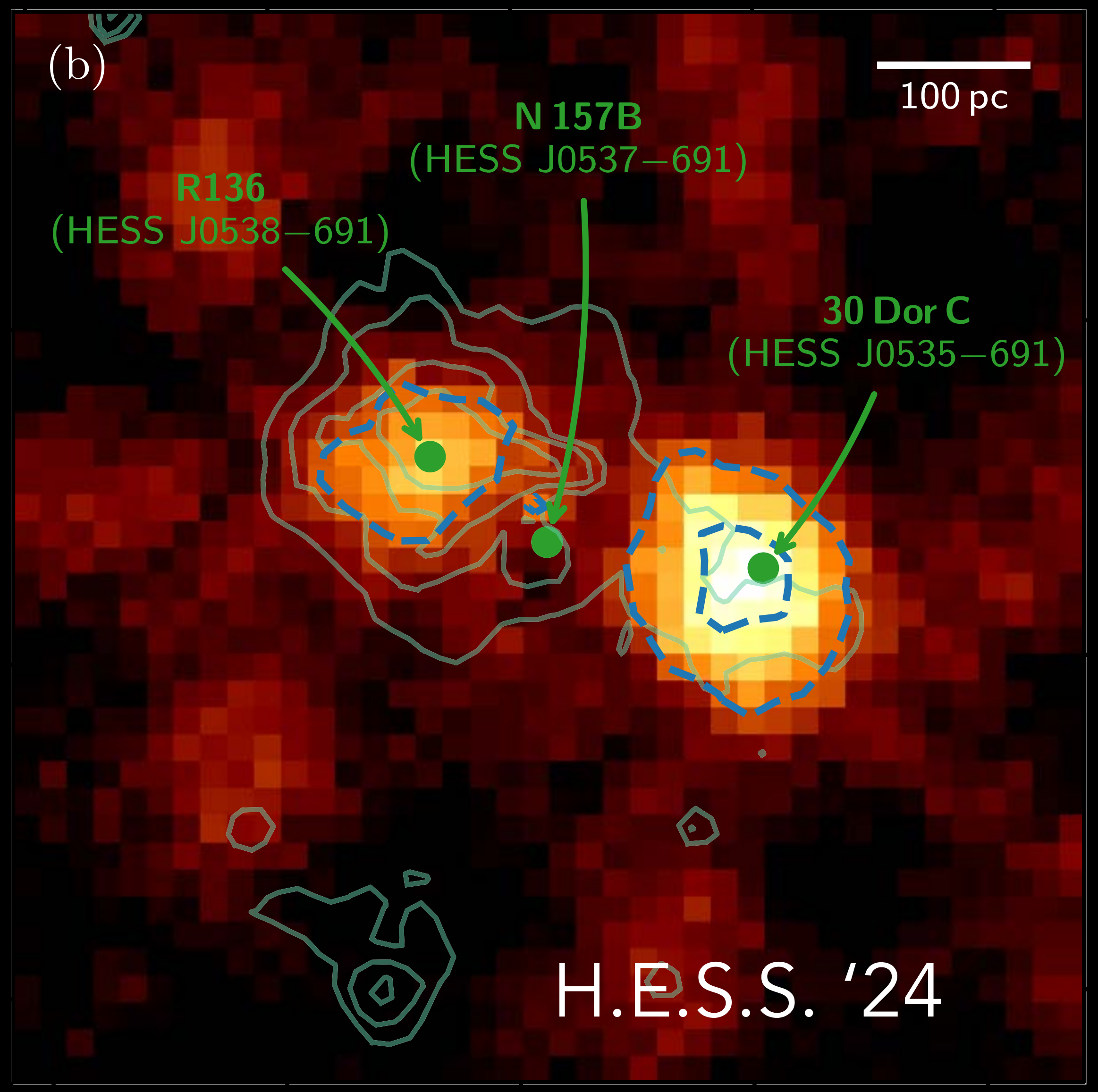


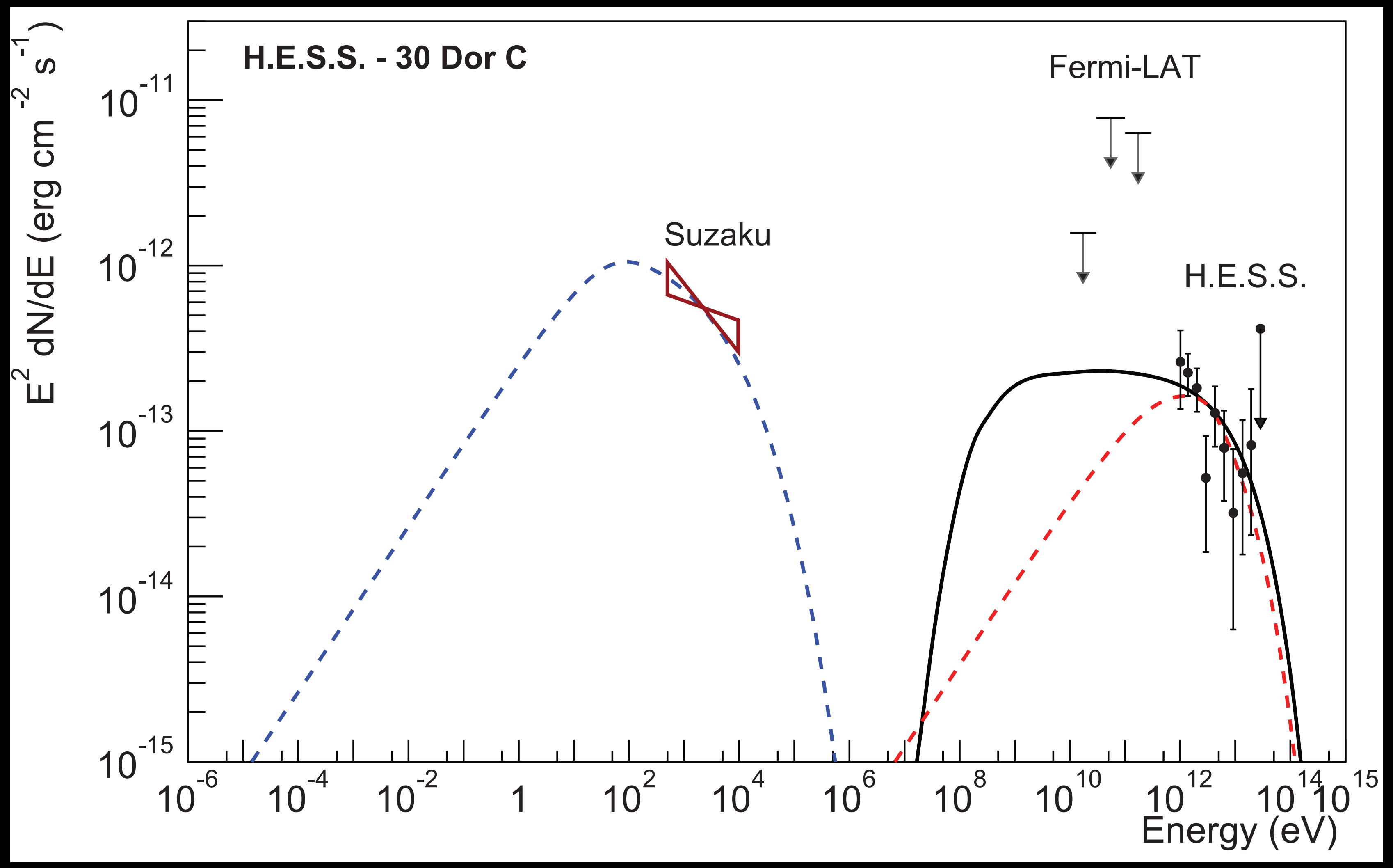


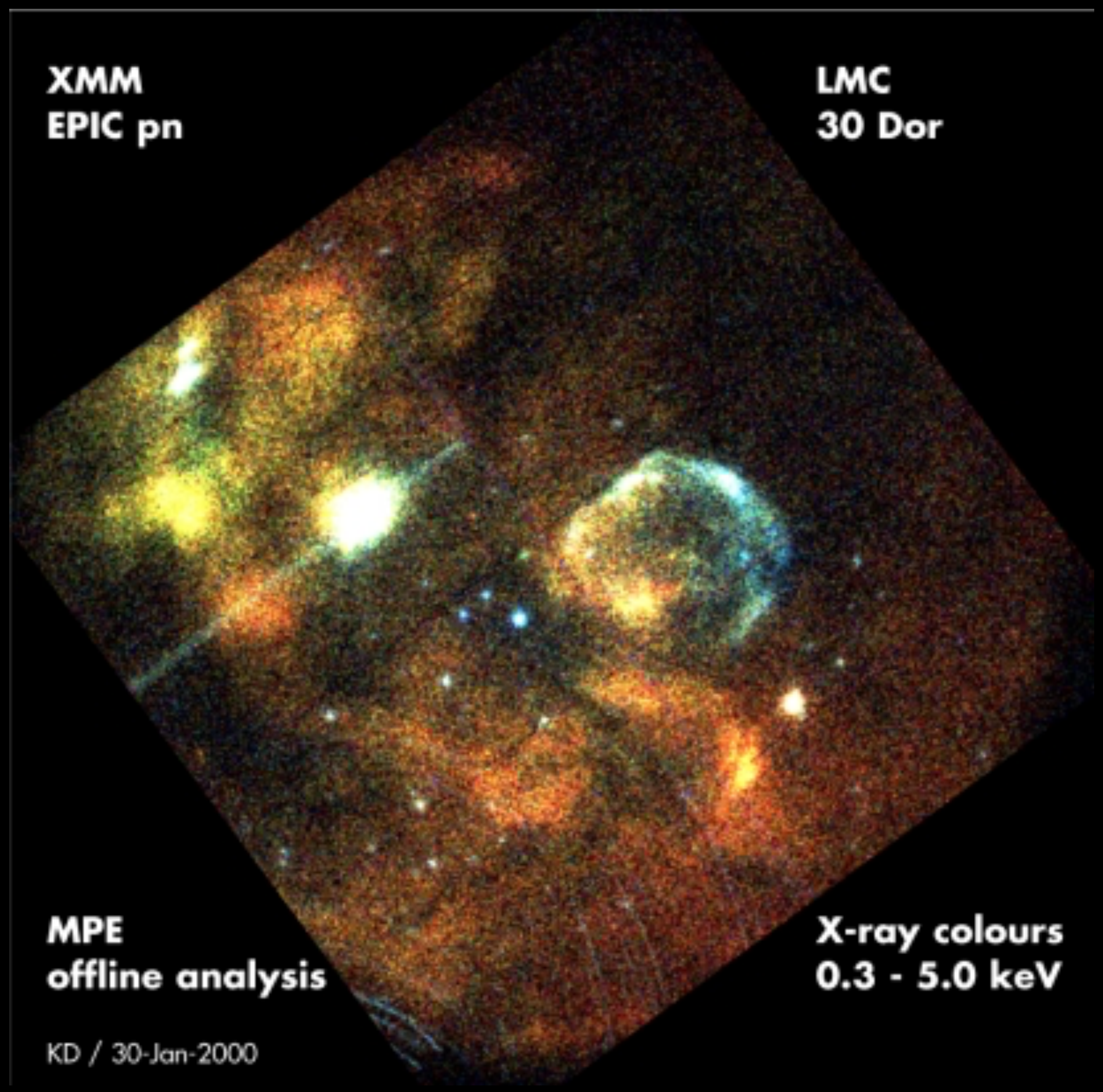


- Powerful SNR (E~5x10^{51} erg) evolving in windblown cavity
- Oxygen-rich: "older version" of Cas A, t~2500 yr
- Interacting with molecular cloud in SW
- H.E.S.S. (2021): no need for cutoff ($E_c = 19^{+60}_{-10}$ TeV, not significant)
- Proton cutoff ~120 TeV
- Older than Cas A, but cutoff (if any) at much higher energy!

30 Dor C in LMC: an SNR in a superbubble







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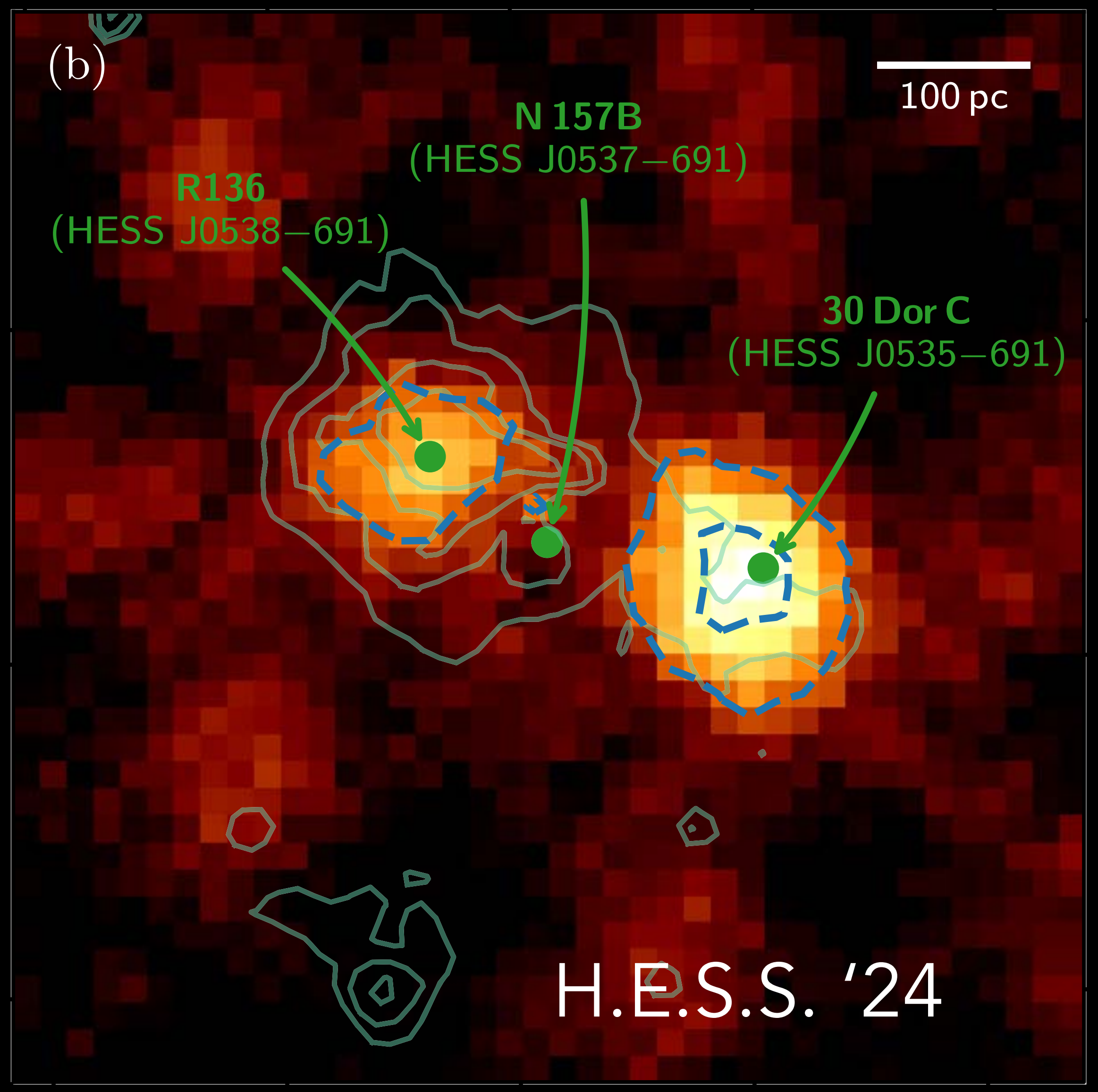

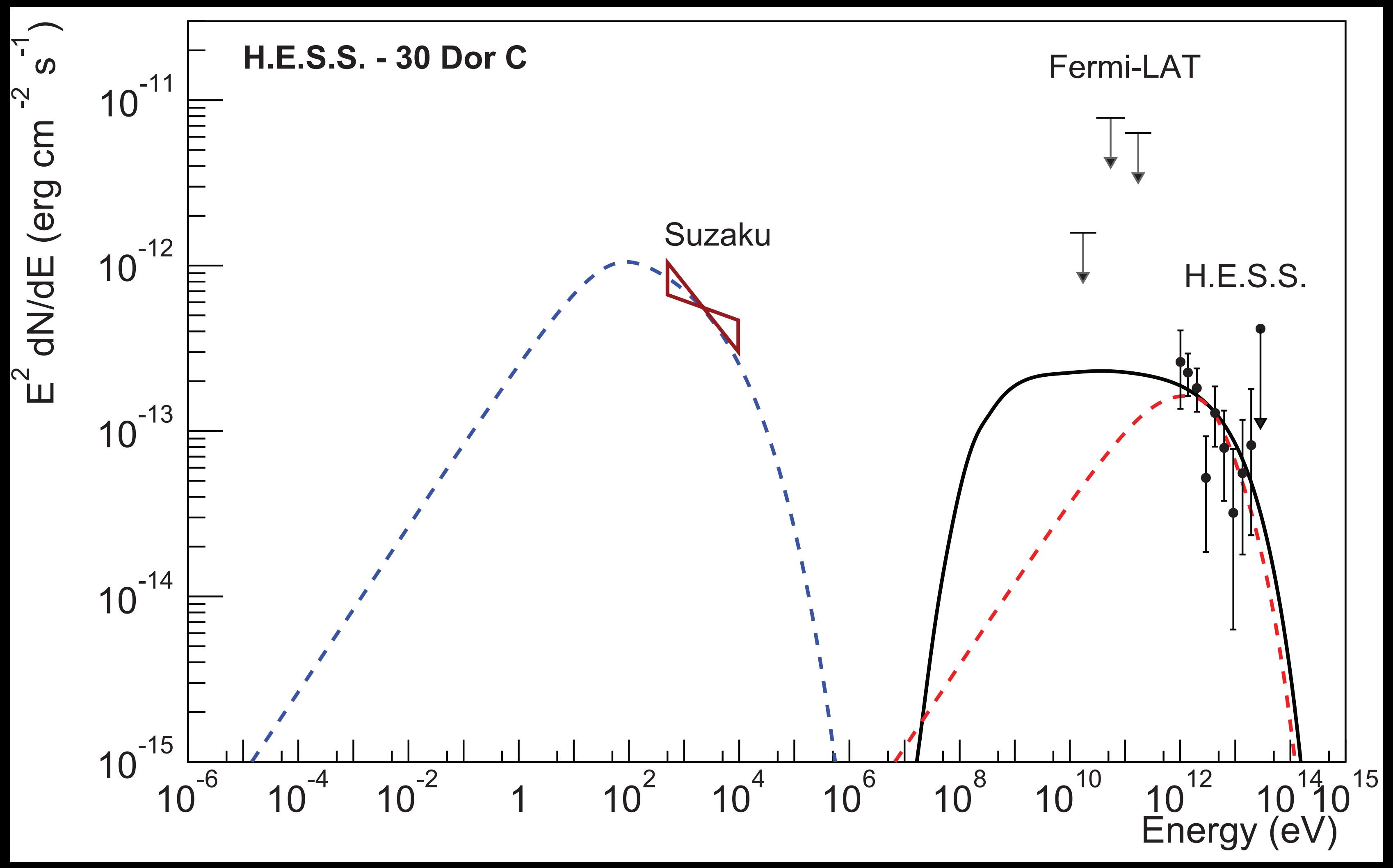

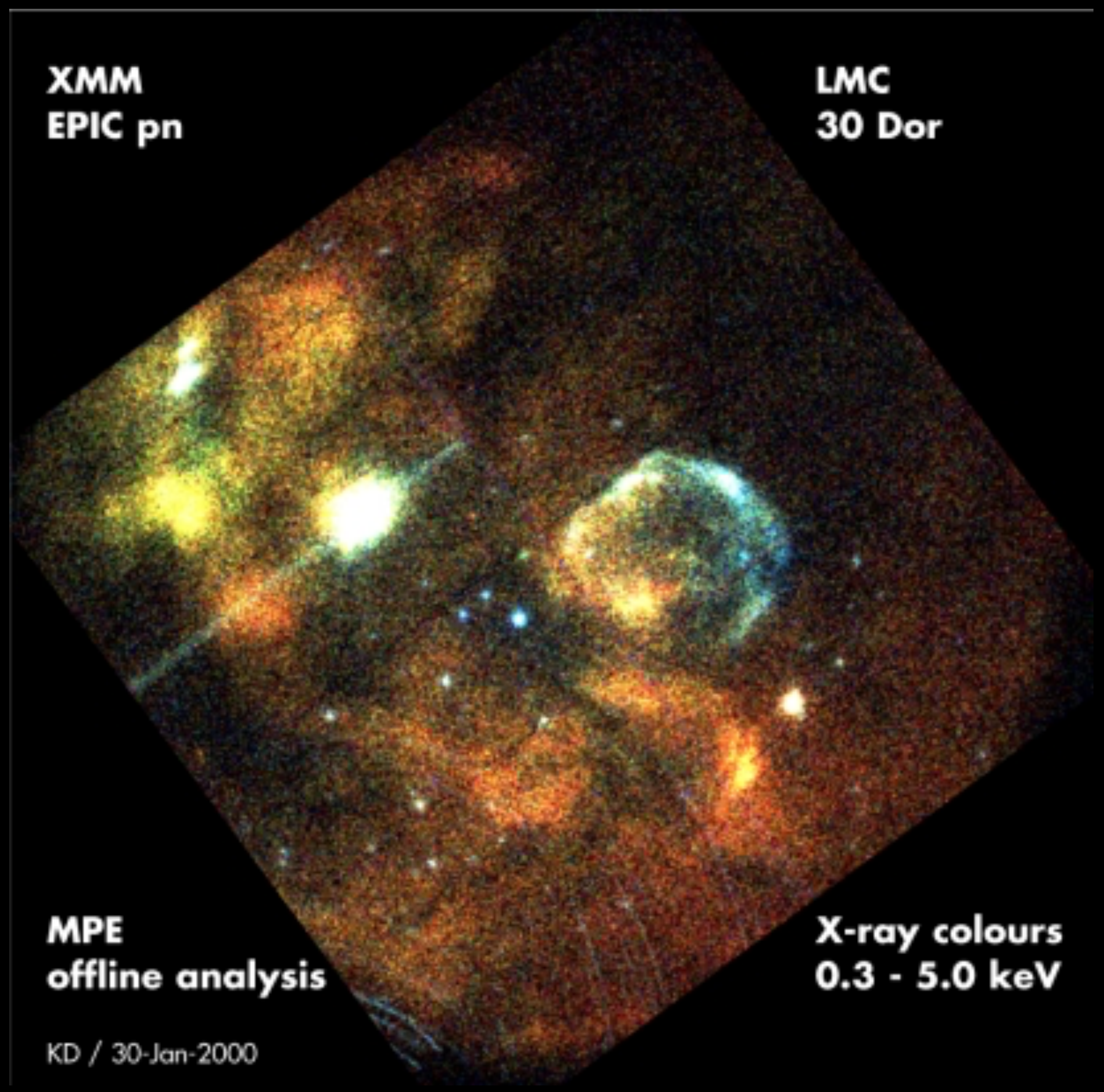

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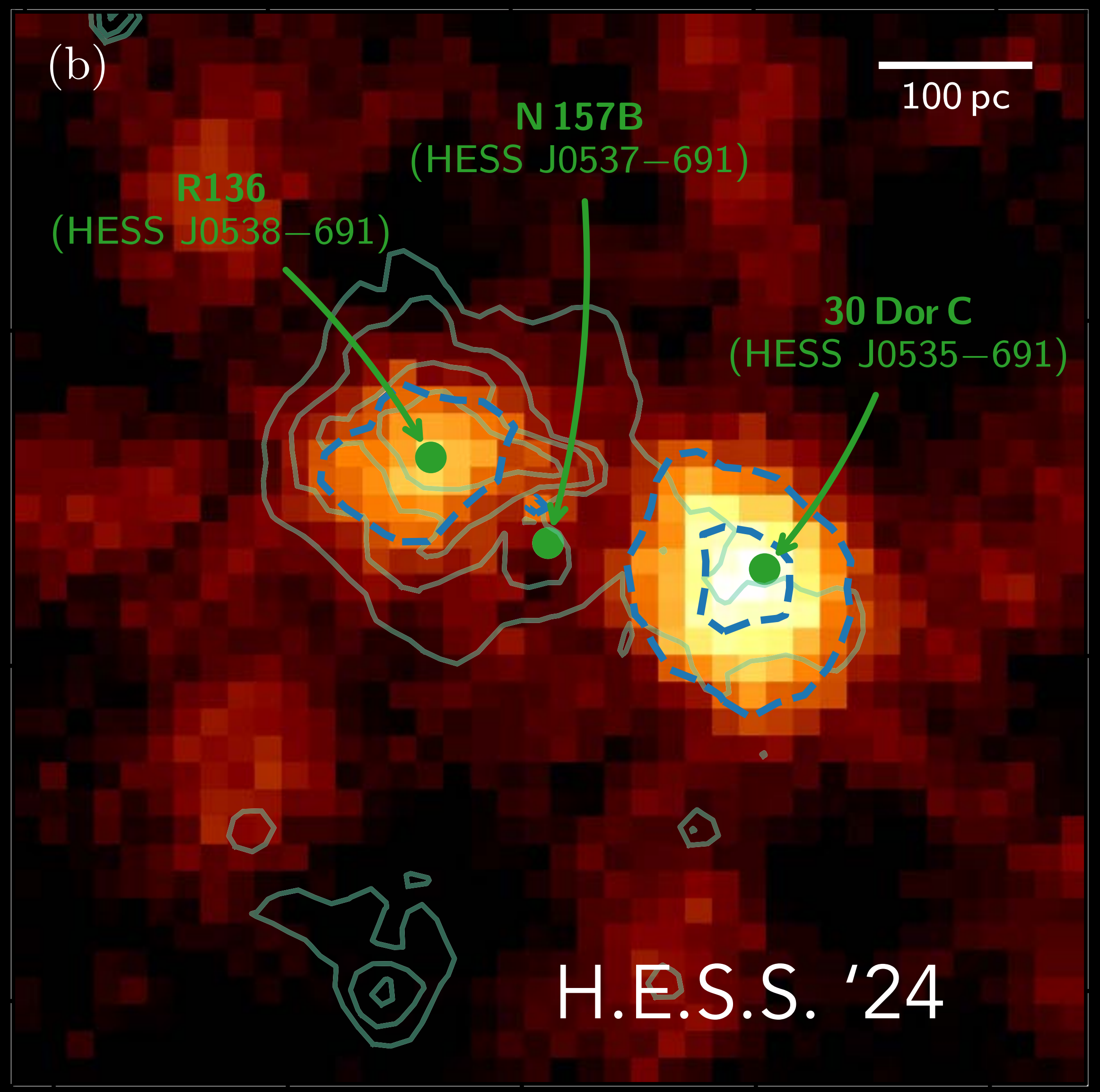

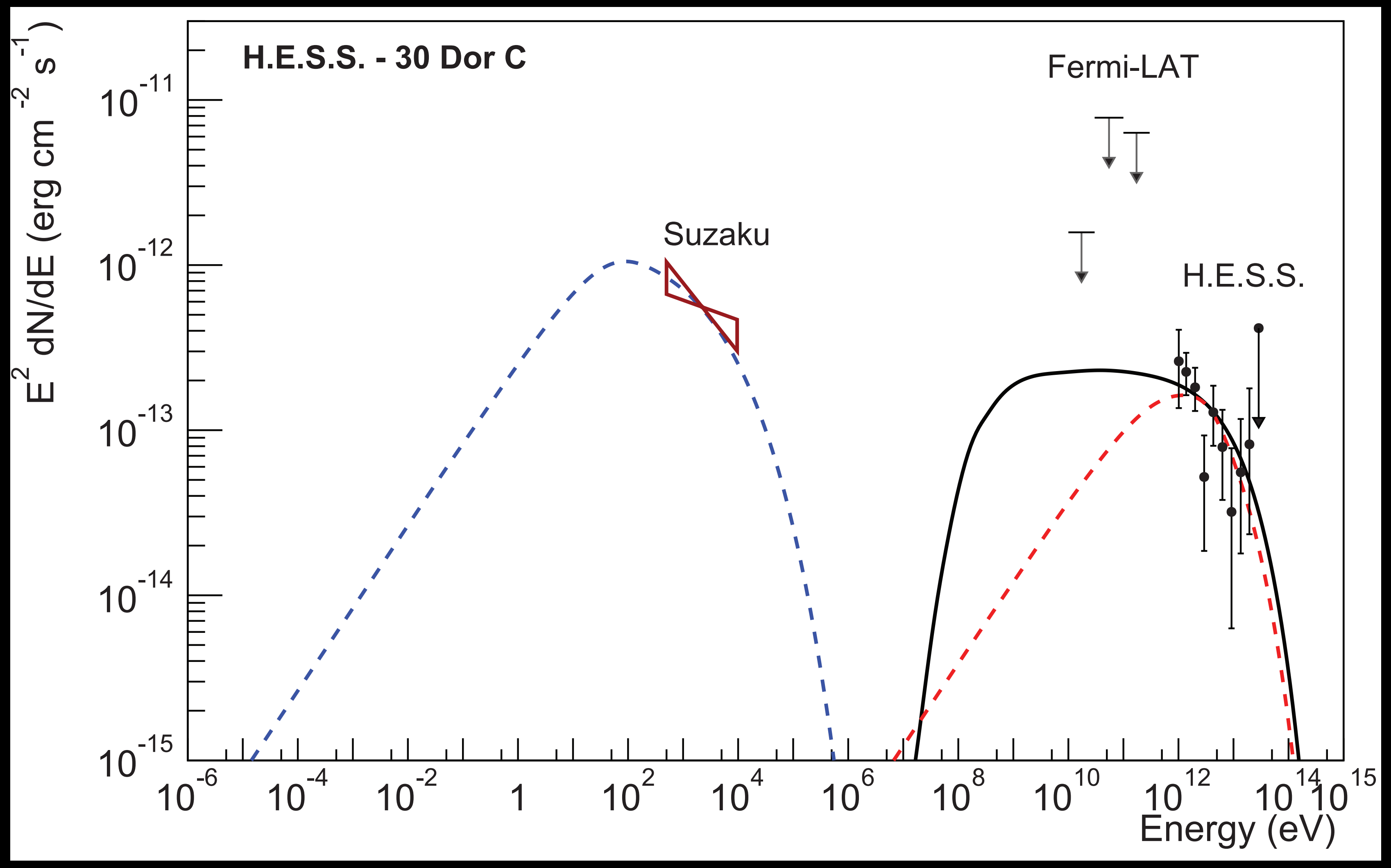

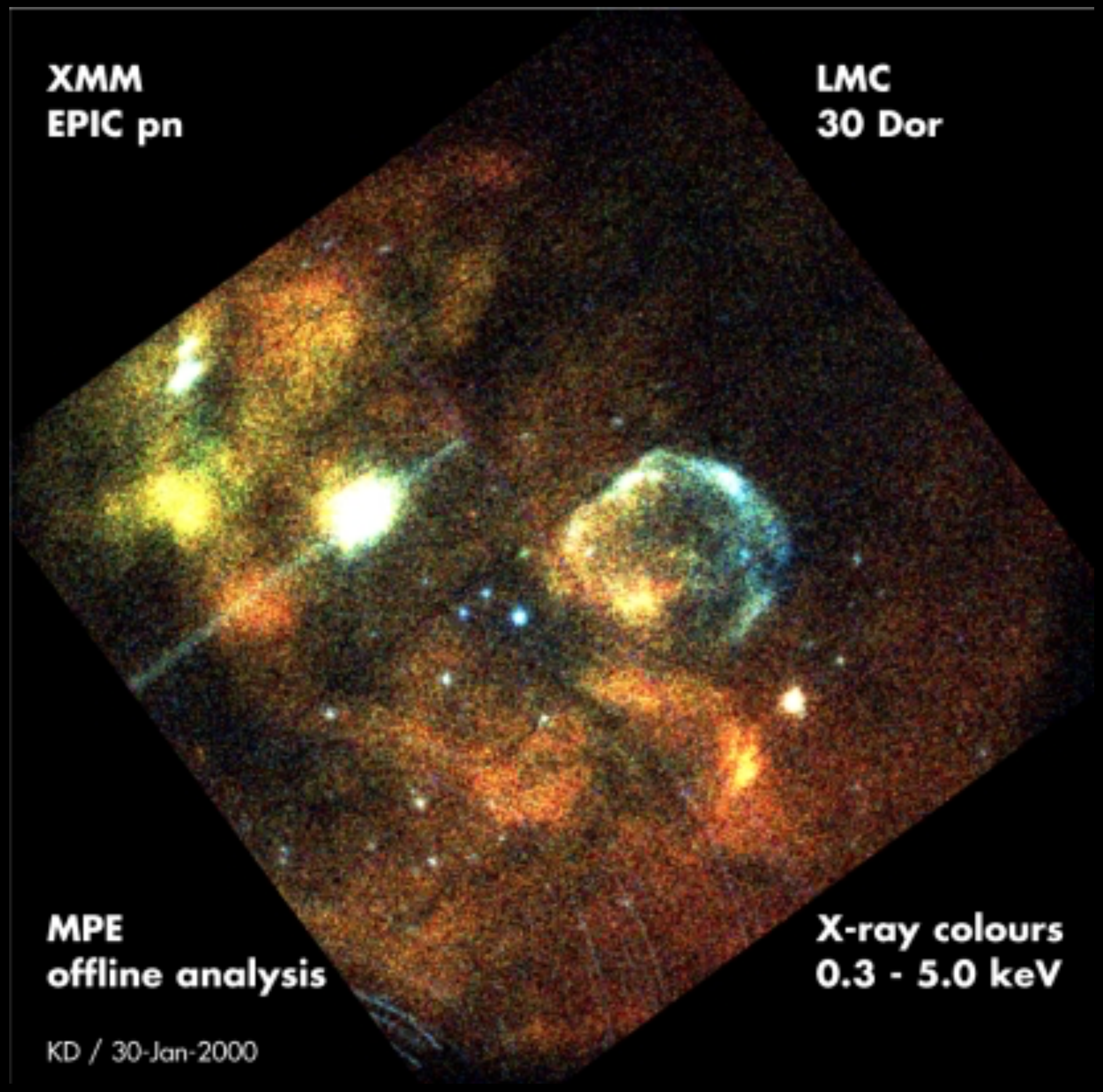

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  - requires V> 3000 km/s: much higher than superbubbles (~50 km/s)
  - requires SNR with t≈6000 yr expanding in low density $n_H \approx 5 \times 10^{-4} cm^{-3}$
  - long acceleration time → could potentially be a PeVatron!

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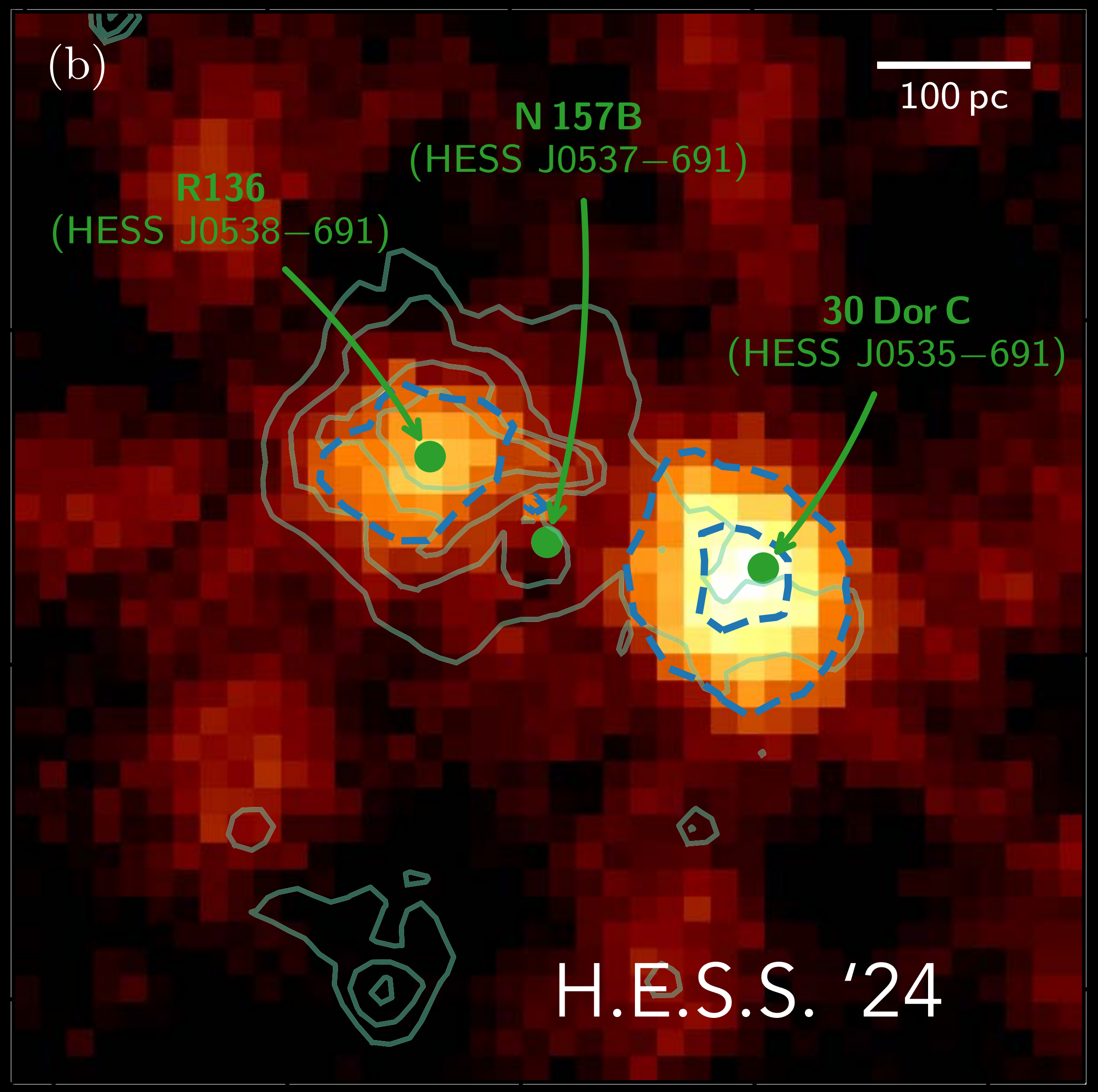

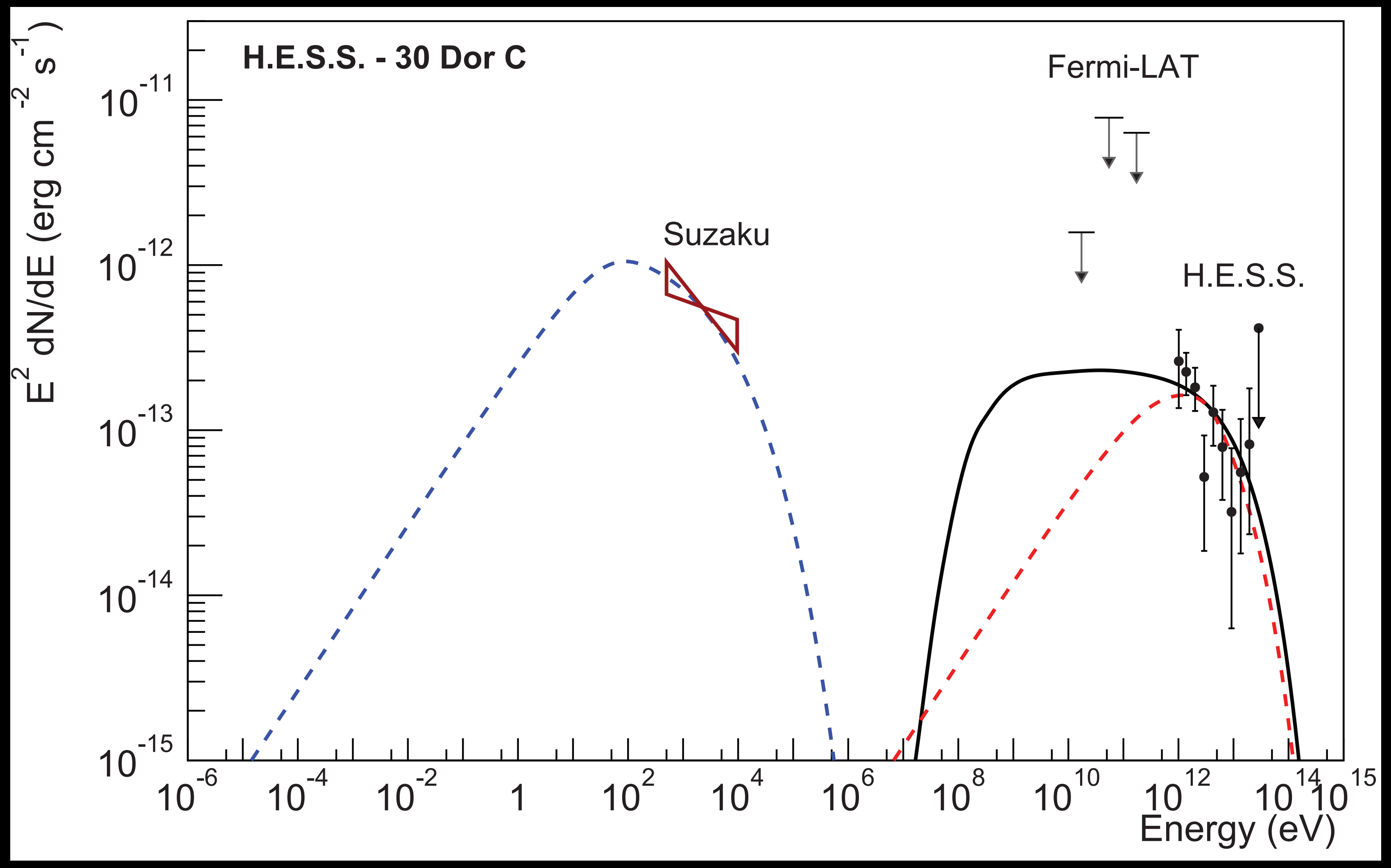

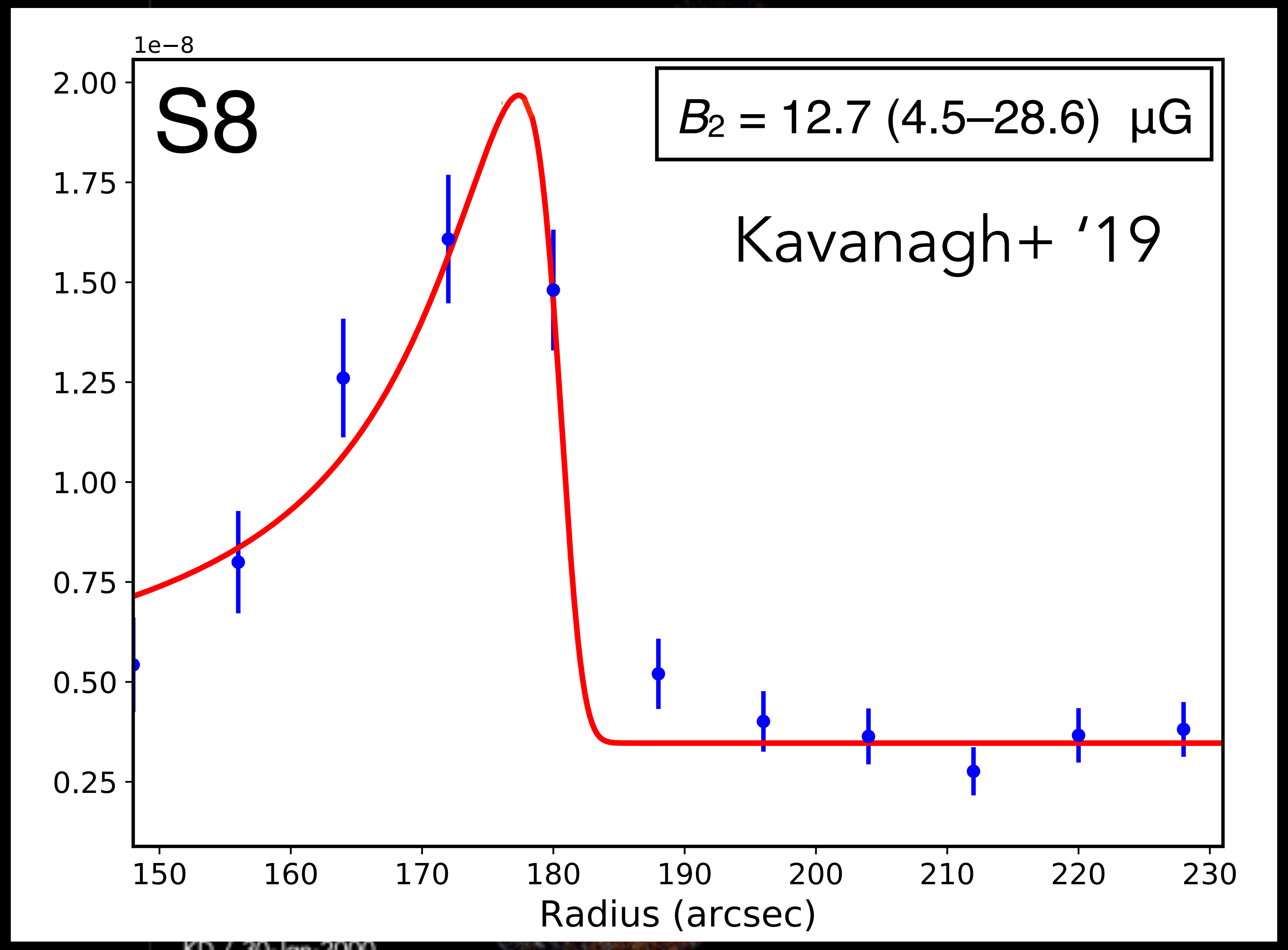

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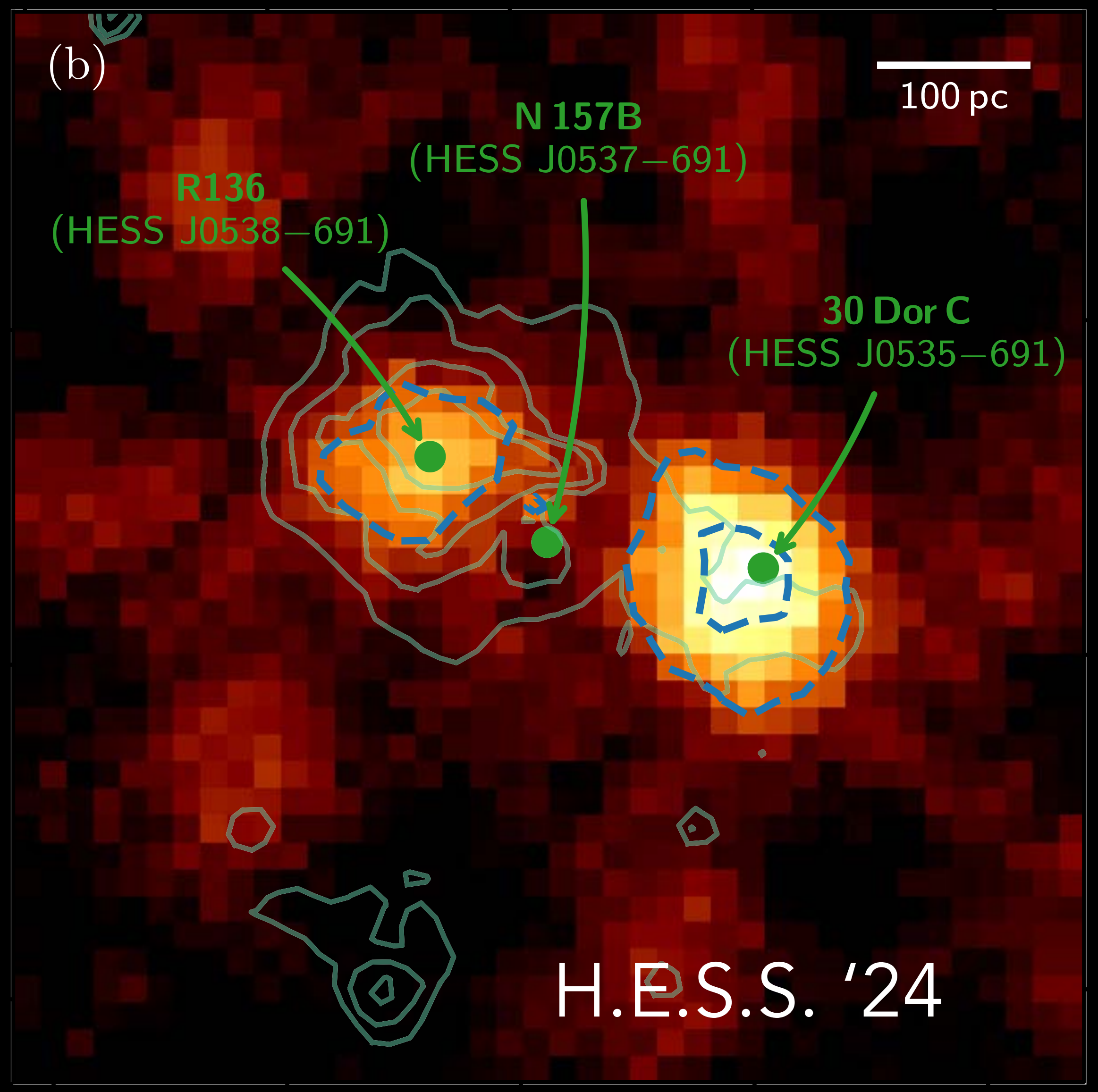

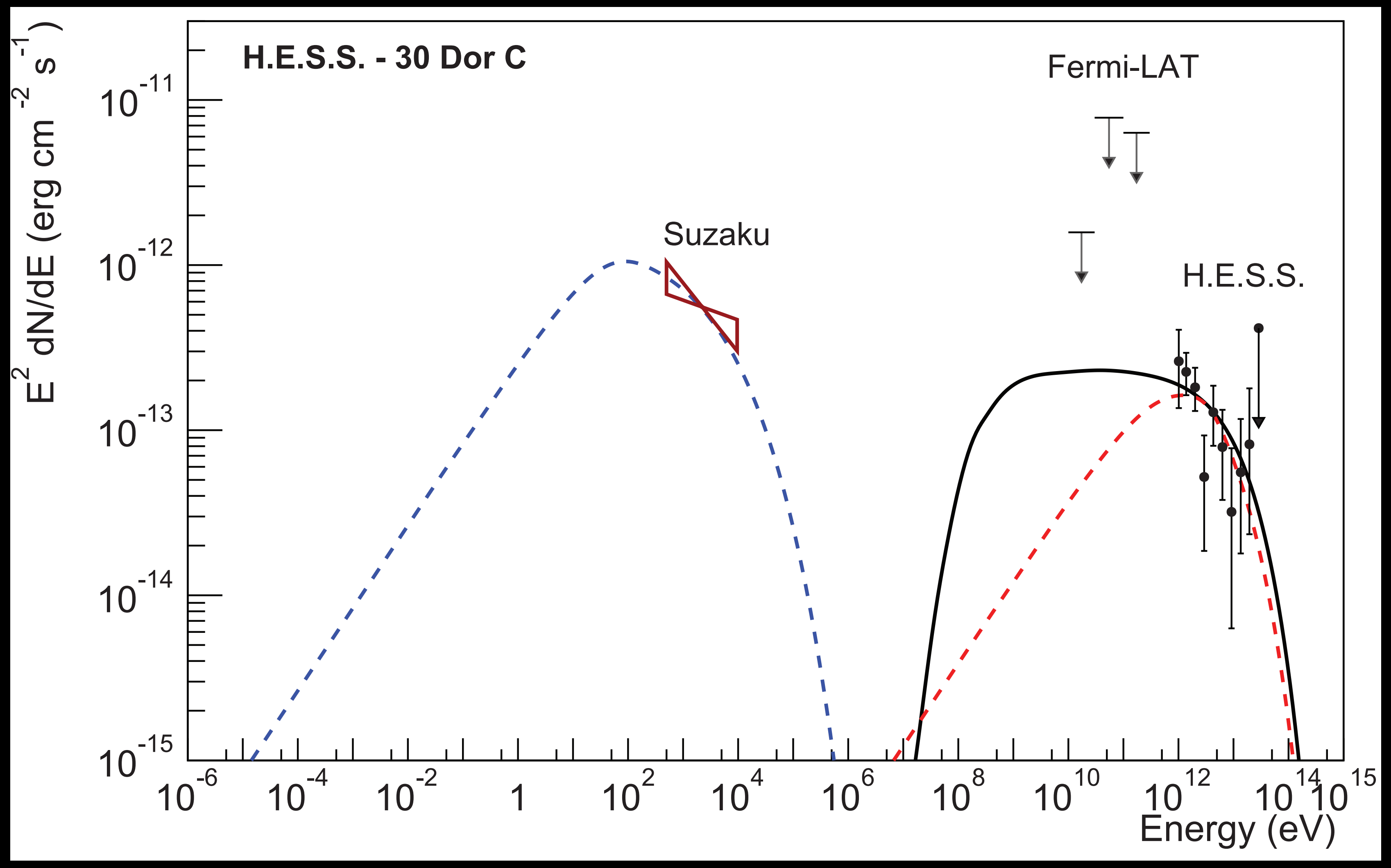

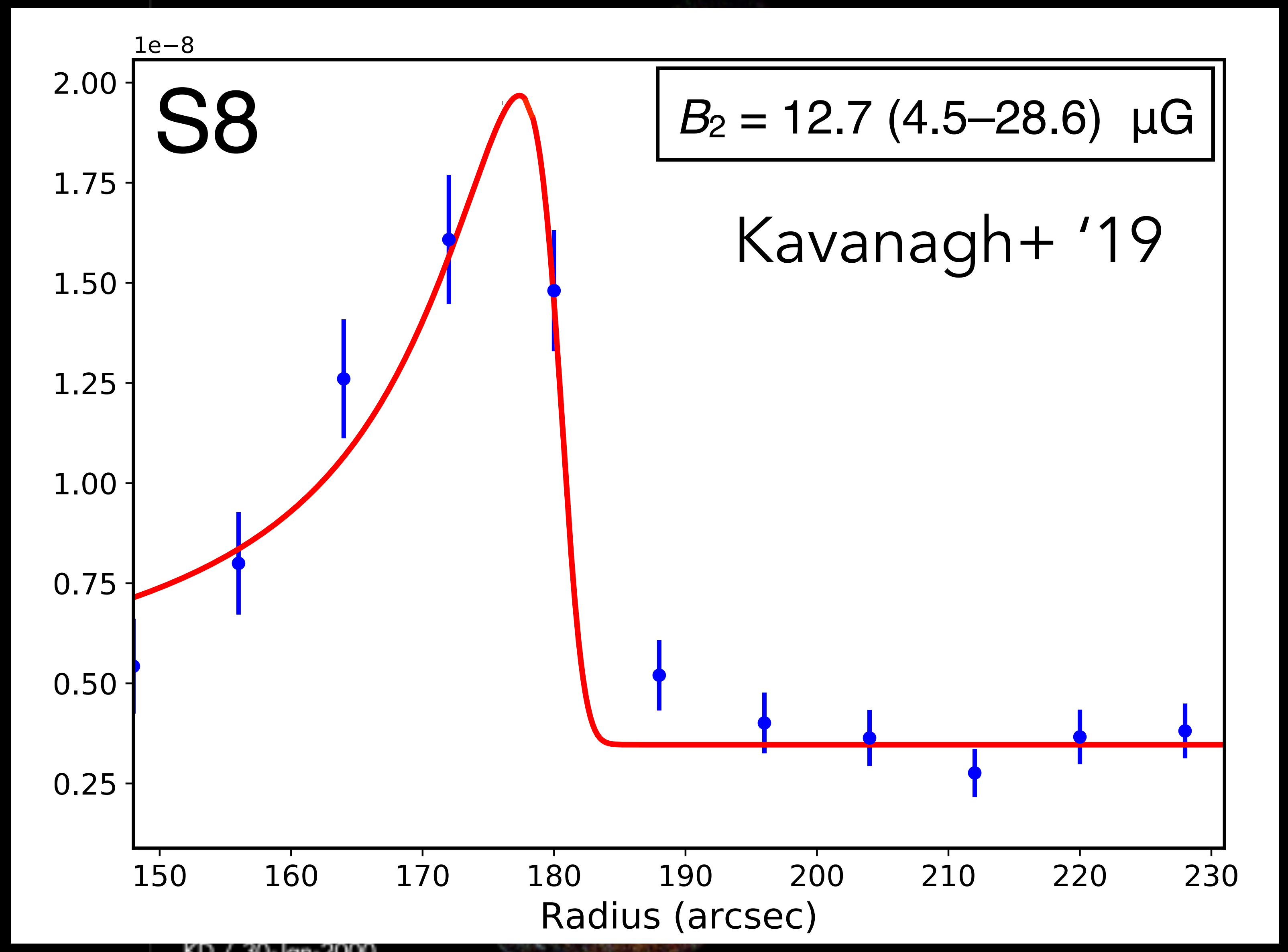

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- X-ray width: B~5-15 μG → gamma ray emission must be leptonic (Kavanagh+ '19)

Can SNRs be PeVatrons

- In general not PeVatrons:
  - Not observationally (at best E_{max}~100 TeV)
  - SNRs V<5000 km/s, B~10 μG, 1000 yr:

$$E_{\rm max} \approx 3 \times 10^{14} \eta^{-1} \left(\frac{B_0}{10\ \mu{\rm G}} \right) \left(\frac{V_{\rm s}}{5000\ {\rm km/s}} \right)^2 \left(\frac{t}{500\ {\rm yr}} \right)\ {\rm eV}$$

- But some hope: special cases (1% of SNe, see Giacinti talk)
  - long t → 30DorC in superbubble?
  - high B → Cas A (now >100 μG) at t=1-30 yr (B amplified, V_s~10000 km/s)
    - example: SN 1993J (B~50 Gauss, V~20000 km/s)
- Observationally: target young extragalactic SNe in dense CSM

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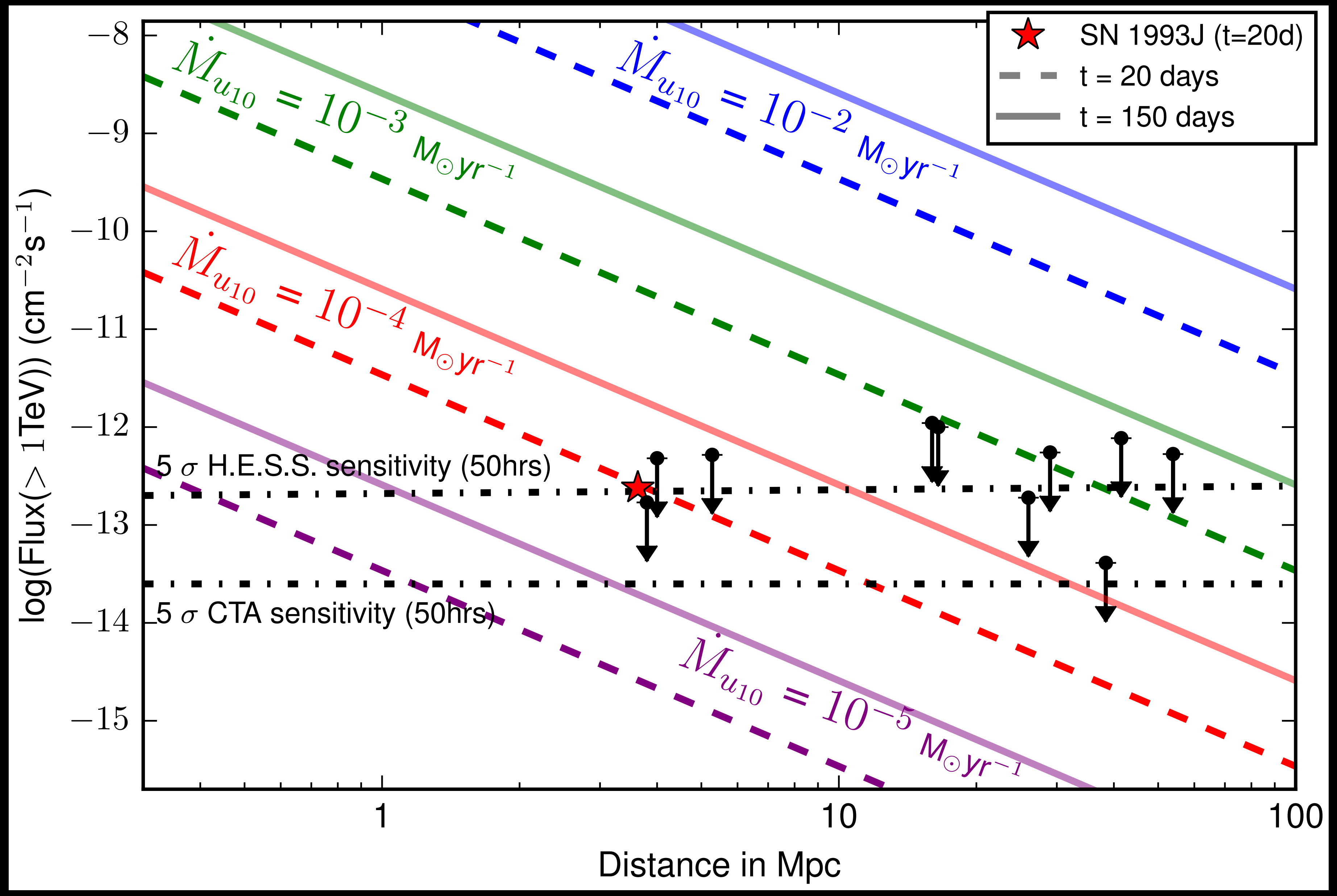

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Take away points

- SNRs are not generally PeVatrons
  - But some may be (when very young and/or in special environments)
- X-ray synchrotron to study DSA properties:
  - X-ray synchrotron constrains diffusion: close to Bohm for E~10-100 TeV
  - Clear evidence for B-field amplification (and $B^2 \propto \sim \rho V^3$)
  - IXPE: young SNRs radial & turbulent magnetic fields
- Gamma-rays
  - Evidence for particles up to 100 TeV in young SNRs
  - Mature SNRs: >1 TeV particles have escaped
  - Direct evidence for escaping cosmic rays
- Future:
  - Very young SNRs (SNe in dense CSM)
  - Look for SNR haloes of escaping CRs
  - Details in gamma-ray spectrum due to composition