X-Ray Synchrotron Emission & Magnetic Fields in Supernova Remnants

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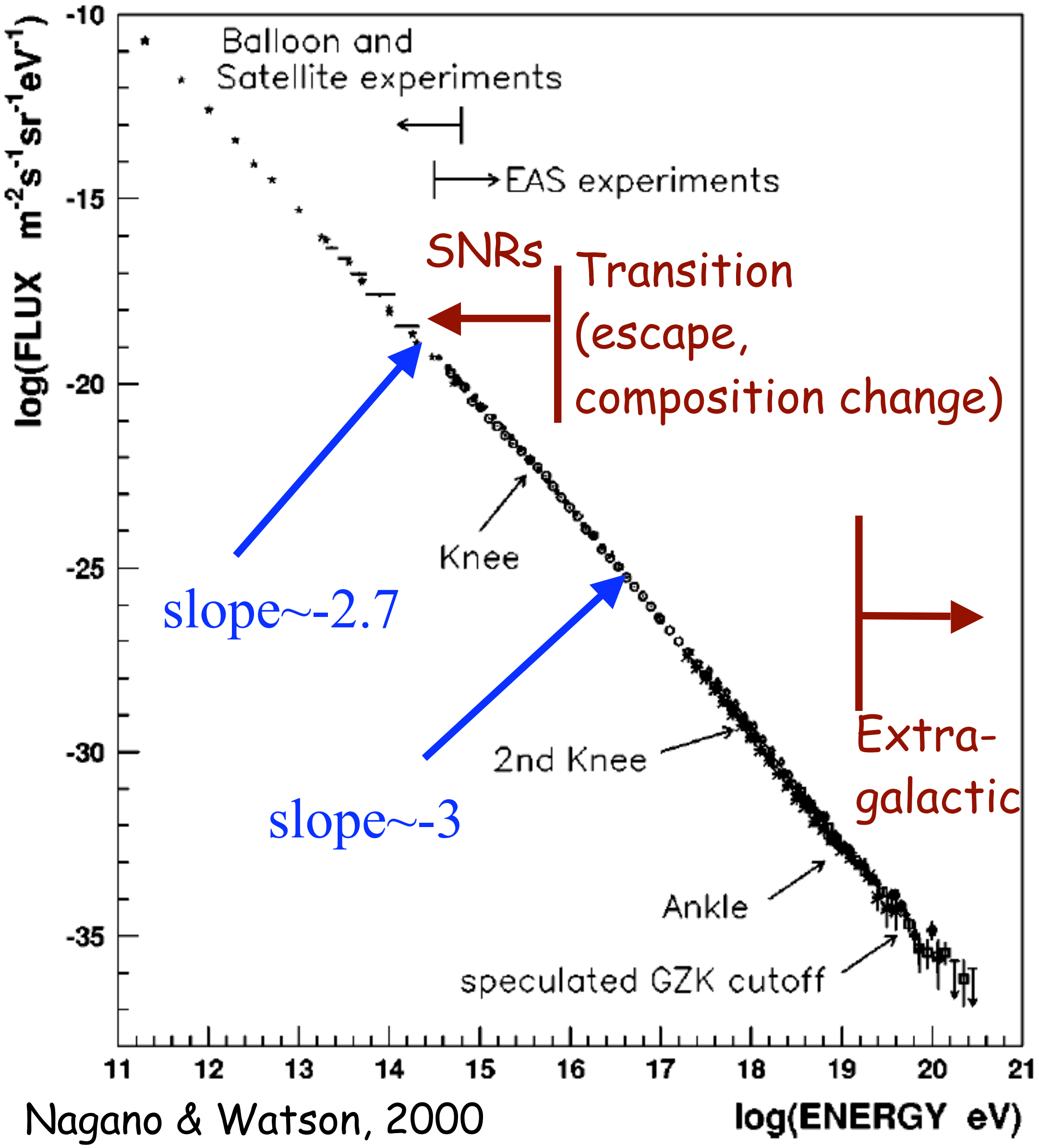
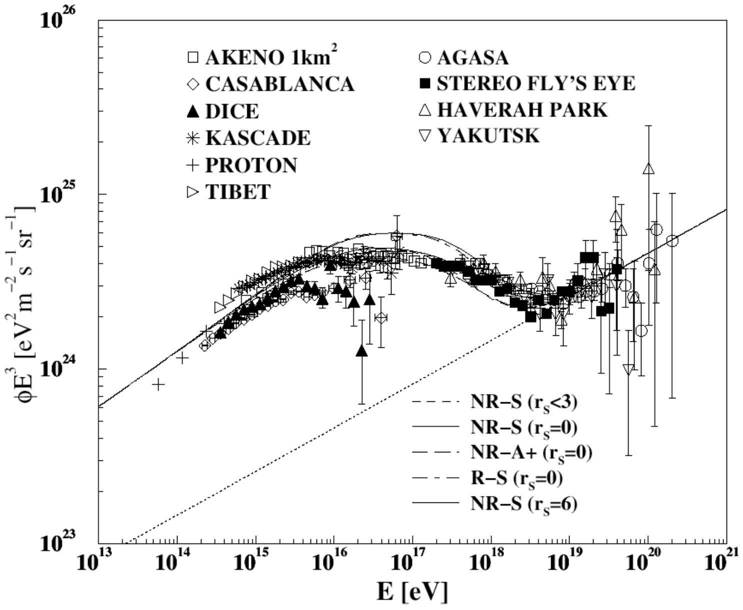
SN & GRB remnants
KITP, Santa Barbara, February 9, 2006

Observed Cosmic Ray Spectrum



Nagano & Watson, 2000



Candia et al 2002

Supernova remnants and Cosmic Rays

- SNe & SNRs most important source of energy in Galaxy
- But: Can they accelerate up to or beyond the "knee" ?
- According to standard shock acceleration/SNR scenario:

No

(assuming Galactic B-field, realistic parameters)

(Lagage & Cesarsky 1983)

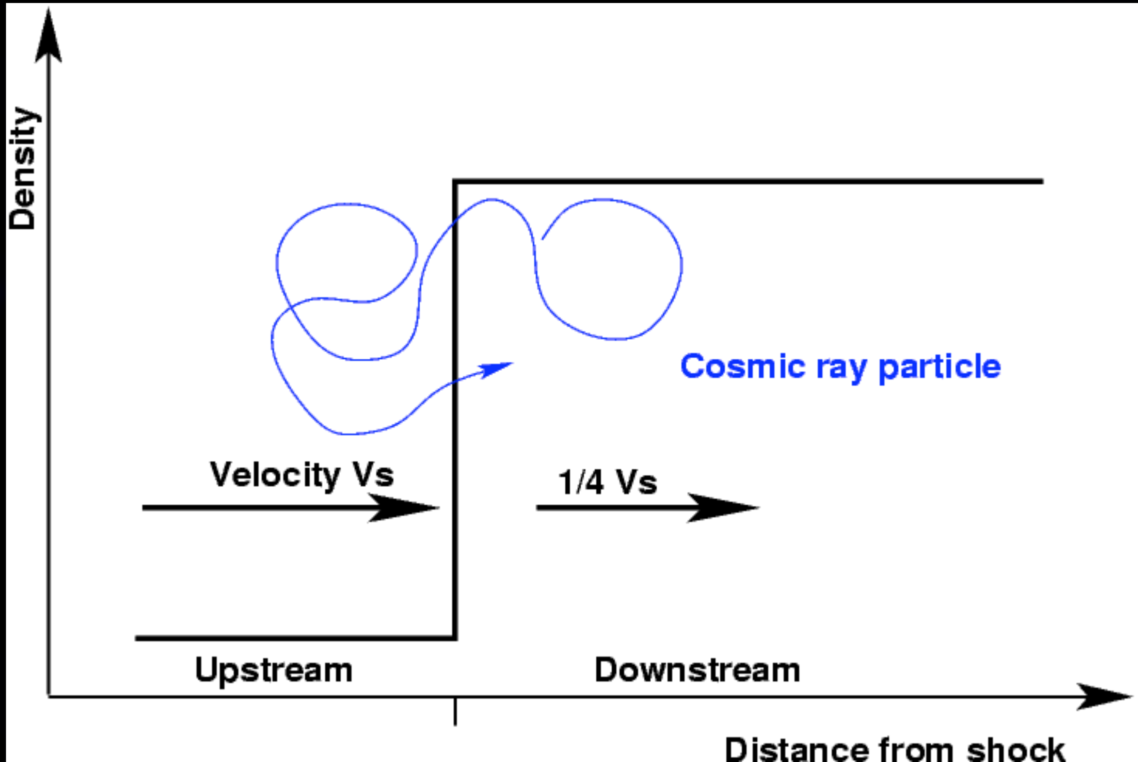
Needed for reaching high energies

- Fermi acceleration:

  particles bounce between shocked and unshocked medium
- High magnetic field:

  1) gyroradius << SNR size 2) fast acceleration
- Highly turbulent magnetic field:
  - particles scatter on magnetic field waves
  - the more scattering (higher diffusion) the earlier they recross the shock (on average)
  - most rapid acceleration: mean free path = gyroradius (Bohm diffusion)

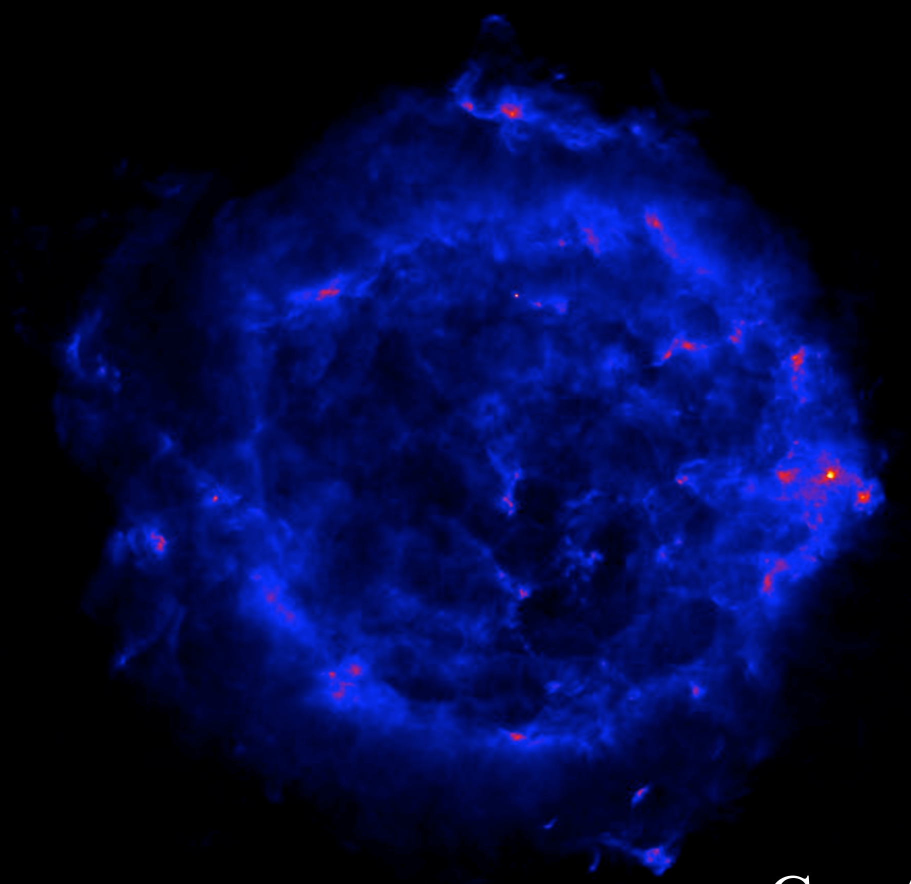
Some acceleration physics



- Particles scatter elastically from downstream to upstream
- Each shock crossing the particle increases its momentum with a fixed fraction ($\Delta p = \beta p$)
- Resulting spectrum (e.g. Bell 1978): $dN/dE = C\ E^{-(1+3/(X-1))}$

(X shock compression ratio, $X=4 \rightarrow dN/dE = C\ E^{-2}$)

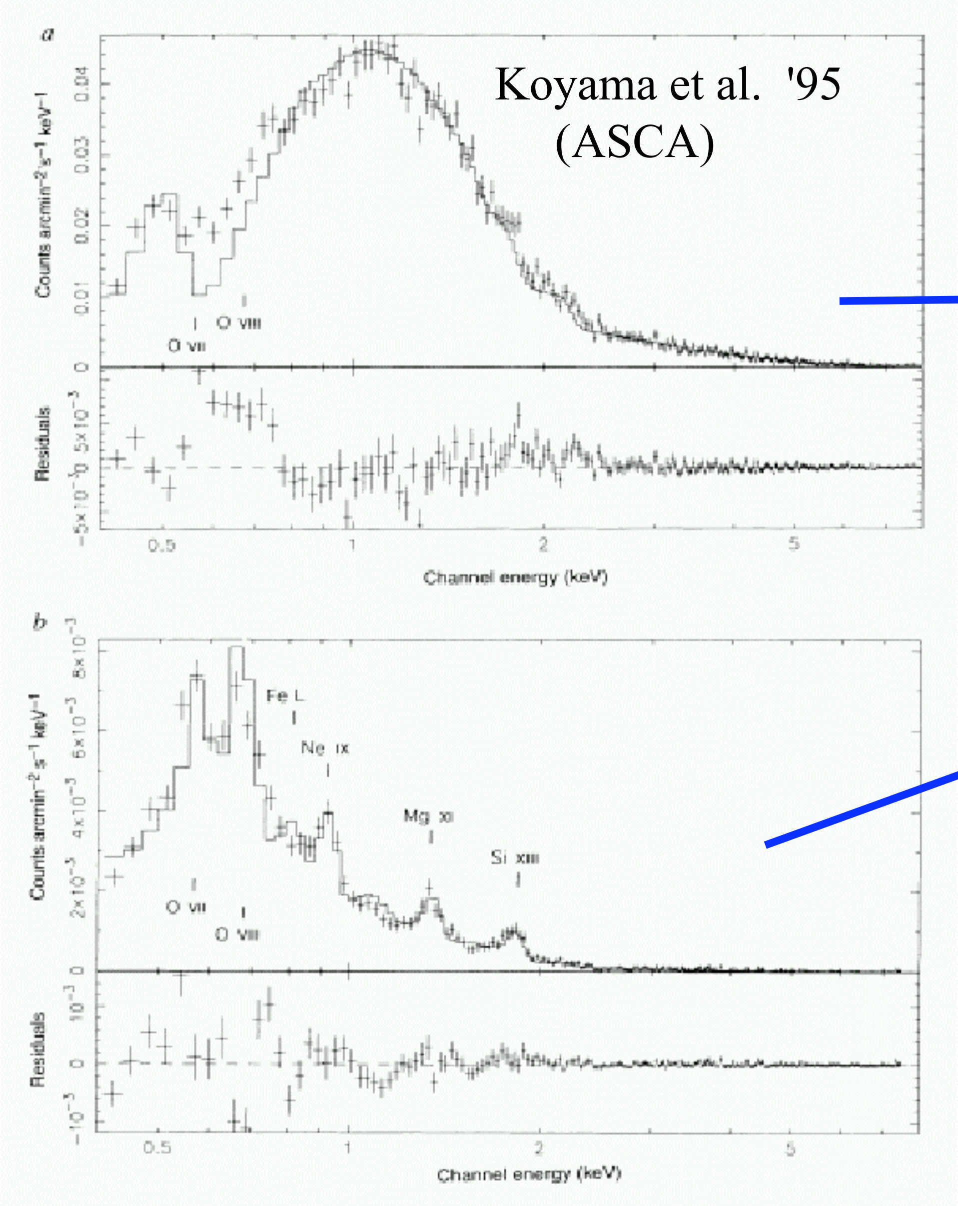
Earliest evidence for acceleration in Supernova Remnants



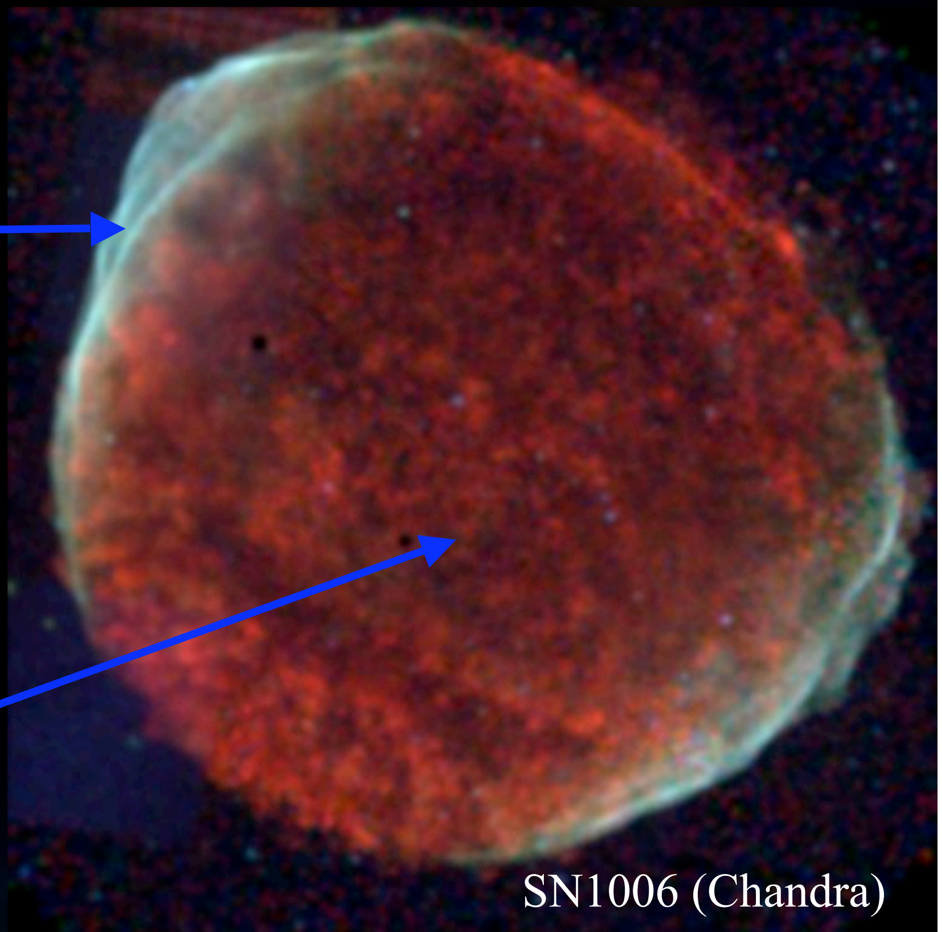
Radio emission:
only electrons &
low energies (GeV)

Cas A (VLA)

First Evidence for efficient CR acceleration



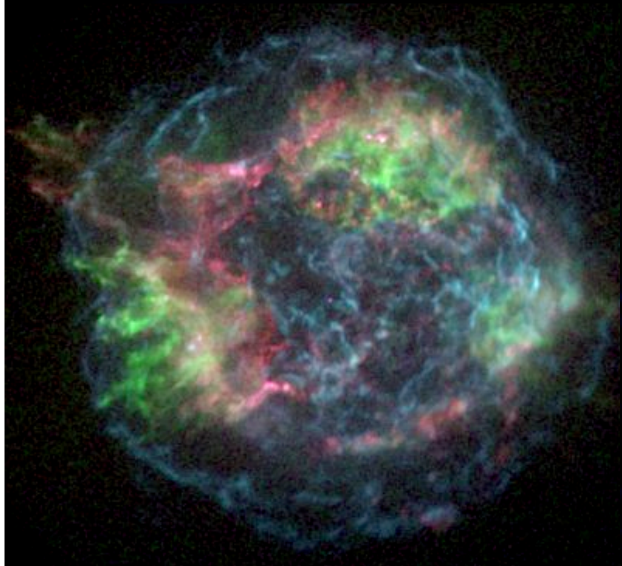
Koyama et al. '95 (ASCA)

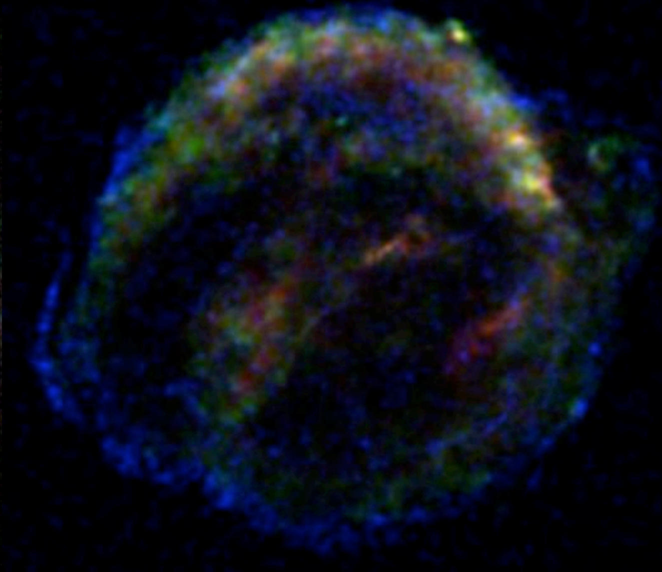


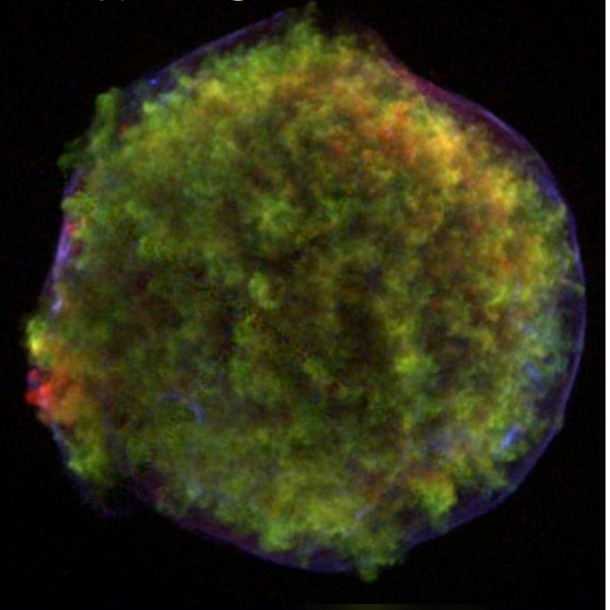
SN1006 (Chandra)

X-ray synchrotron radiation:
electrons up to ~5x10^{13} eV
(but depends on B-field)

Young Supernova Remnants







Cas A (SN1671?)

Kepler (SN1604)

Tycho (SN1572)

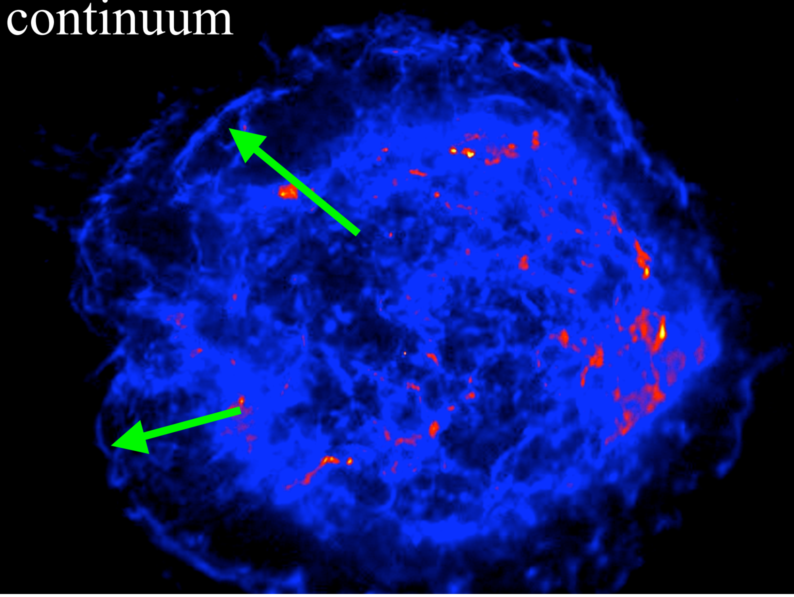
(continuum emission in blue)

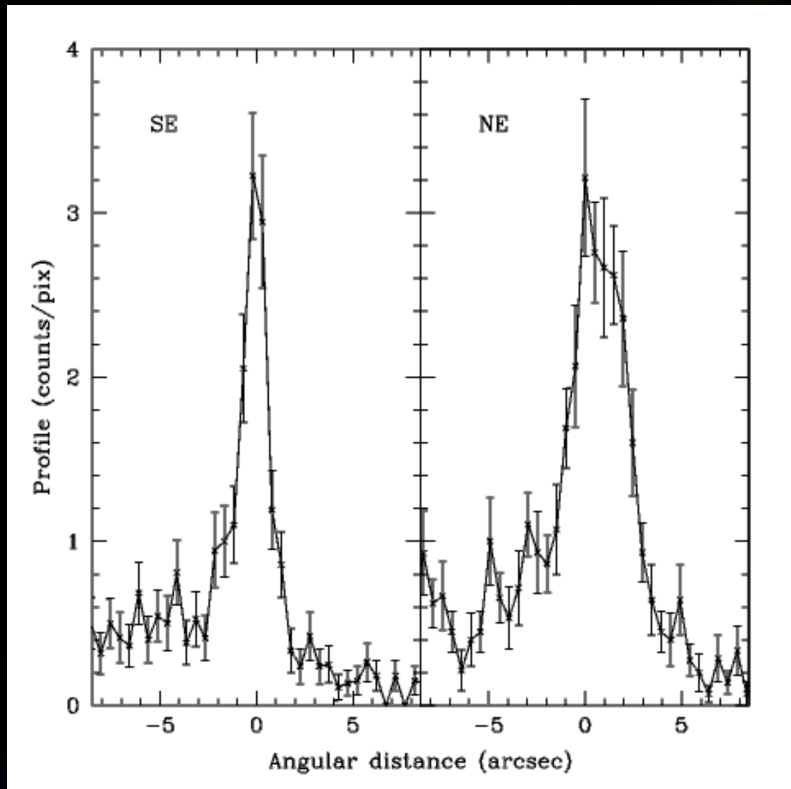
New developments:
1 TeV detections of SNRs (→Aharonian)
2 *All* young remnants emit X-ray synchrotron radiation from a narrow region near shock

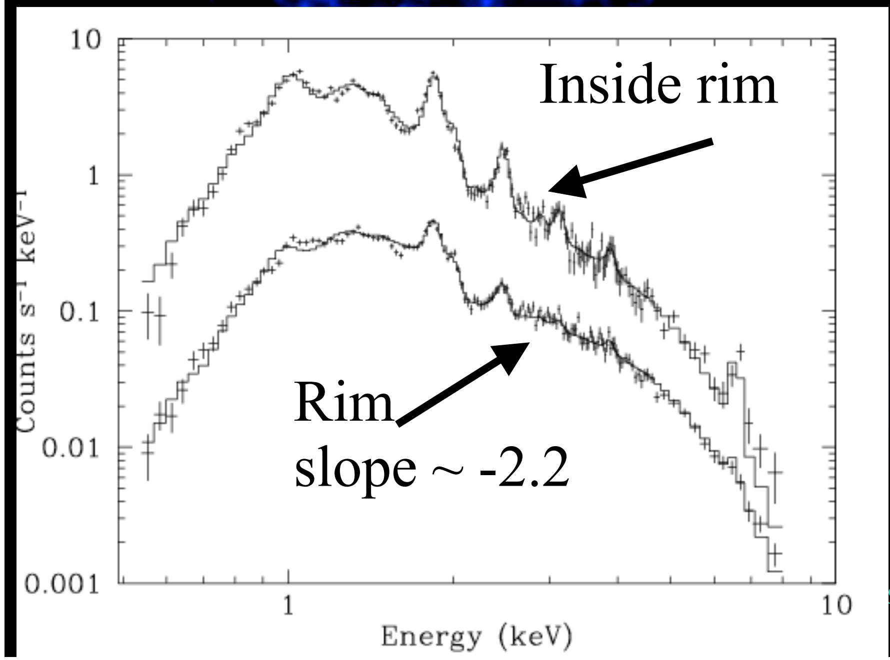
SN1006

Synchrotron rims of Cassiopeia A

Chandra
continuum







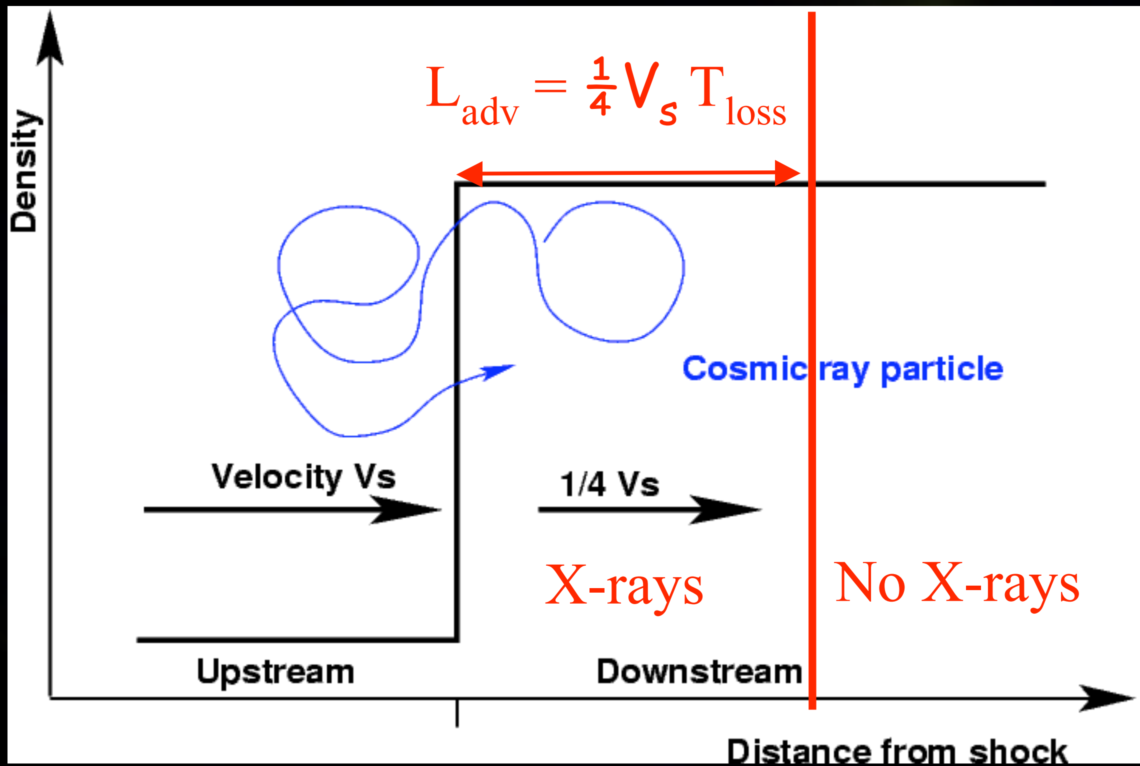
Rims are narrow and continuum dominated
1.5” to 4”
(0.025 – 0.07 pc)

(Vink & Laming 2003)

The Magnetic Field near the Shock

- Rim emission dominated by X-ray synchrotron radiation
- Rim width corresponds to synchrotron loss time, T, through $l_{adv} = \Delta V\ T$ (advection length)
- $V_s = 5200$ km/s (Vink et al. '98, Delaney et al. '03)
- $\Delta V = u = \frac{1}{4}V_s = 1300$ km/s (plasma velocity)
- Loss times 18 – 50 yr
- Loss time $T \sim 1/B^2E$
- $E_{photon} \sim E^2B$

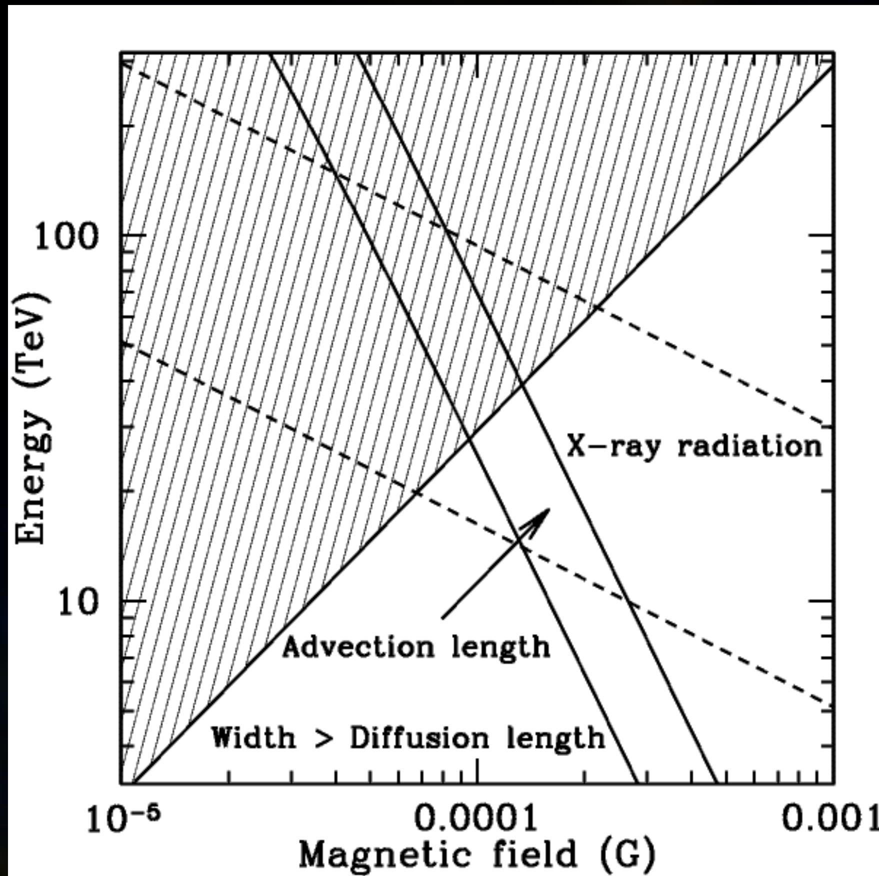
(Vink & Laming 2003)



Determining the Magnetic Field

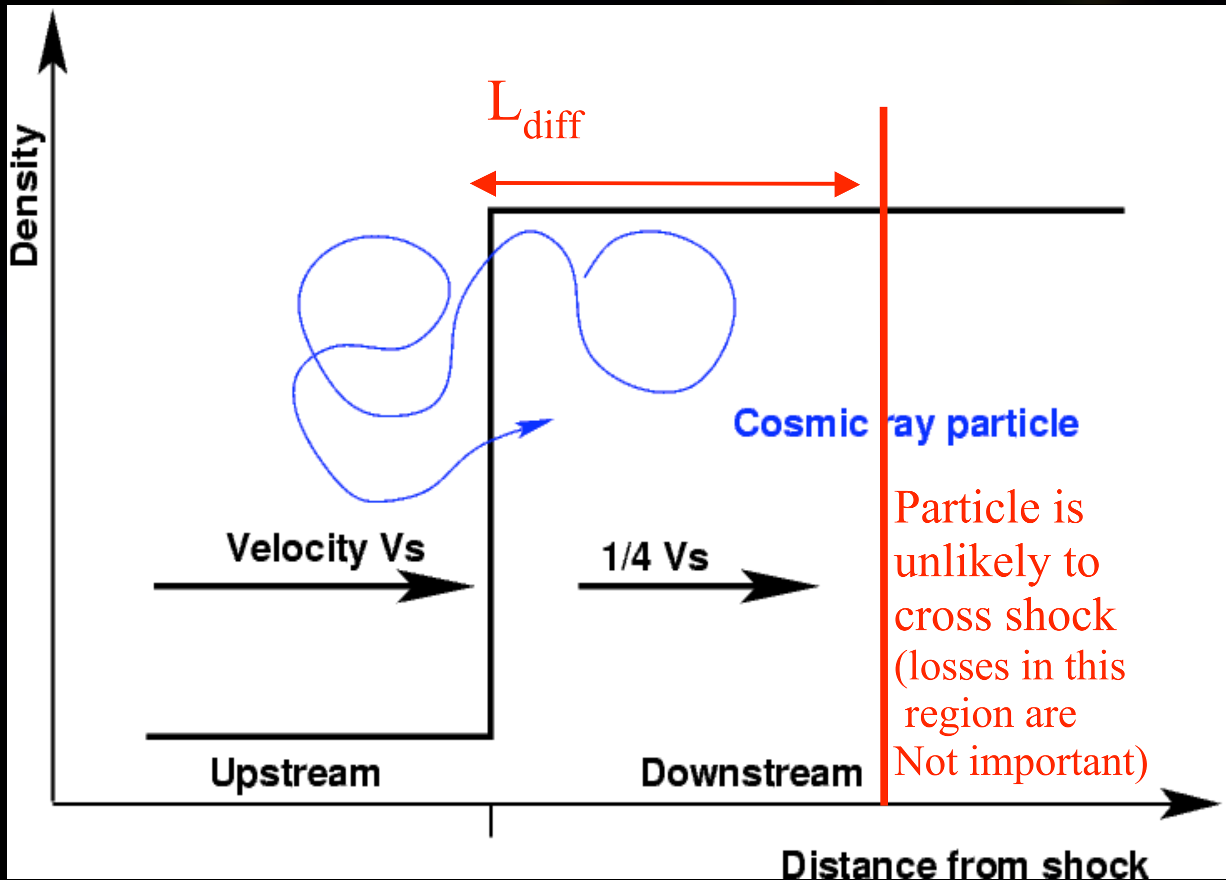
Combining gives:
B = 100 – 300 μG
downstream of shock!
(c.f. mean Galactic ~5 μG)

- Alternative:
  widths is set by diffusion length
  (Bamba et al. '04, for SN1006)
- $L_{diff} = D/u$
  - D diffusion parameter,
  - Bohm limit $D = cr_g/3 = Ec/3eB$
  - Bohm limit most efficient acc. $(\delta B/B \sim 1)$
- Clearly always width $l_{obs} \geq l_{diff}$



Why diffusion & advection give same B-field

- For efficient acceleration: $L_{adv} \geq L_{diff}$
- In X-rays: $L_{adv} \approx L_{diff}$, i.e. we see electrons with E_{max}
- Hence: power laws steeper than in radio, as observed
- $L_{adv} \approx L_{diff}$, for *Bohm-limit* → Observational evidence for Bohm-limit



A more formal approach

- Assume loss limited electron spectrum
- I.e. only a net acceleration when $T_{acc} < T_{loss}$
- Losses mostly downstream (higher B): $l_{adv} = uT_{loss}$
- Shock acceleration theory: $T_{acc} \approx D/u^2$
  (within a factor ~2)
- So accelaration only for : $D/u^2 < l_{adv}/u$
- But diffusion length $l_{diff} = D/u \Rightarrow l_{diff} < l_{adv}$

Consequence
For a loss limited spectrum
(i.e. steepened)

$$l_{diff} \approx l_{adv}$$
$$\Rightarrow$$
$$l_{obs} \approx (l^2_{diff} + l^2_{adv})^{1/2} = 0.7\, l_{adv}$$

Summary for all young remnants

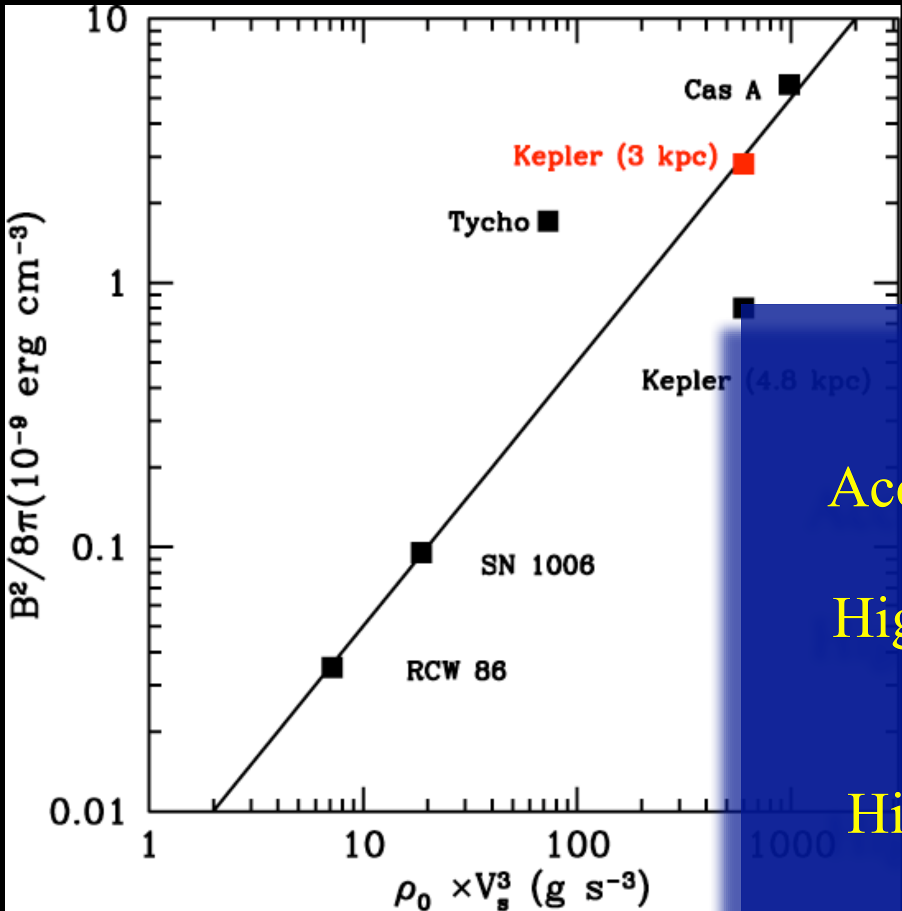
SNR	Age (yr)	Radius (')	V_s (km/s)	Width (")	B_{diff} (microG)	B_{loss} (microG)	$B_{combined}$ (microG)	P_B (dyne/cm^{-2})	P_{ram} (dyne/cm^{-2})	P_B/P_R X1000
Cas A	329	2.55	5189	0.5	298	249	376	2.5E-09	1.9E-06	1.3E+00
Kepler	396	1.64	5268	1.5	113	132	142	7.0E-10	2.3E-07	3.1E+00
Tycho	428	3.95	4482	2	165	156	208	9.6E-10	1.4E-07	6.8E+00
SN1006	994	14.37	4311	20	33	41	49	6.8E-11	4.3E-08	1.6E+00
RCW 86	1815	22.5	3533	45	20	19	30	1.5E-11	2.9E-08	5.0E-01

(see also Bamba et al. '05, Ballet '05, Voelk et al. 2005, Warren et al. ‘05)

1) All young SNRs have high B-fields
   Likely cause: B-field enhancements by cosmic ray streaming (Bell&Lucek 2001, Bell 2004)
2) B_{diff} ~ B_{loss}: Evidence for Bohm-diffusion!
3) Need ions to generate B-field and B-turbulence
4) B-field/V of Cas A high enough to reach
   $E = 1.5 \times 10^{15}\, Z$ eV

Magnetic Field Amplification

There is a clear correlation between ρ, V and B, in rough agreement with theoretical predictions (Bell 2004).
(See also Voelk et al. 2005)



NB large dynamic range in density not in V_s !

Young SNRs have high B-fields
→
Acceleration beyond the knee possible!
→
Highest B-field for dense environments & shock velocities
→
Highest CR energies early on in dense Red super giant winds (less shock deceleration and $\rho \propto r^{-2}$)

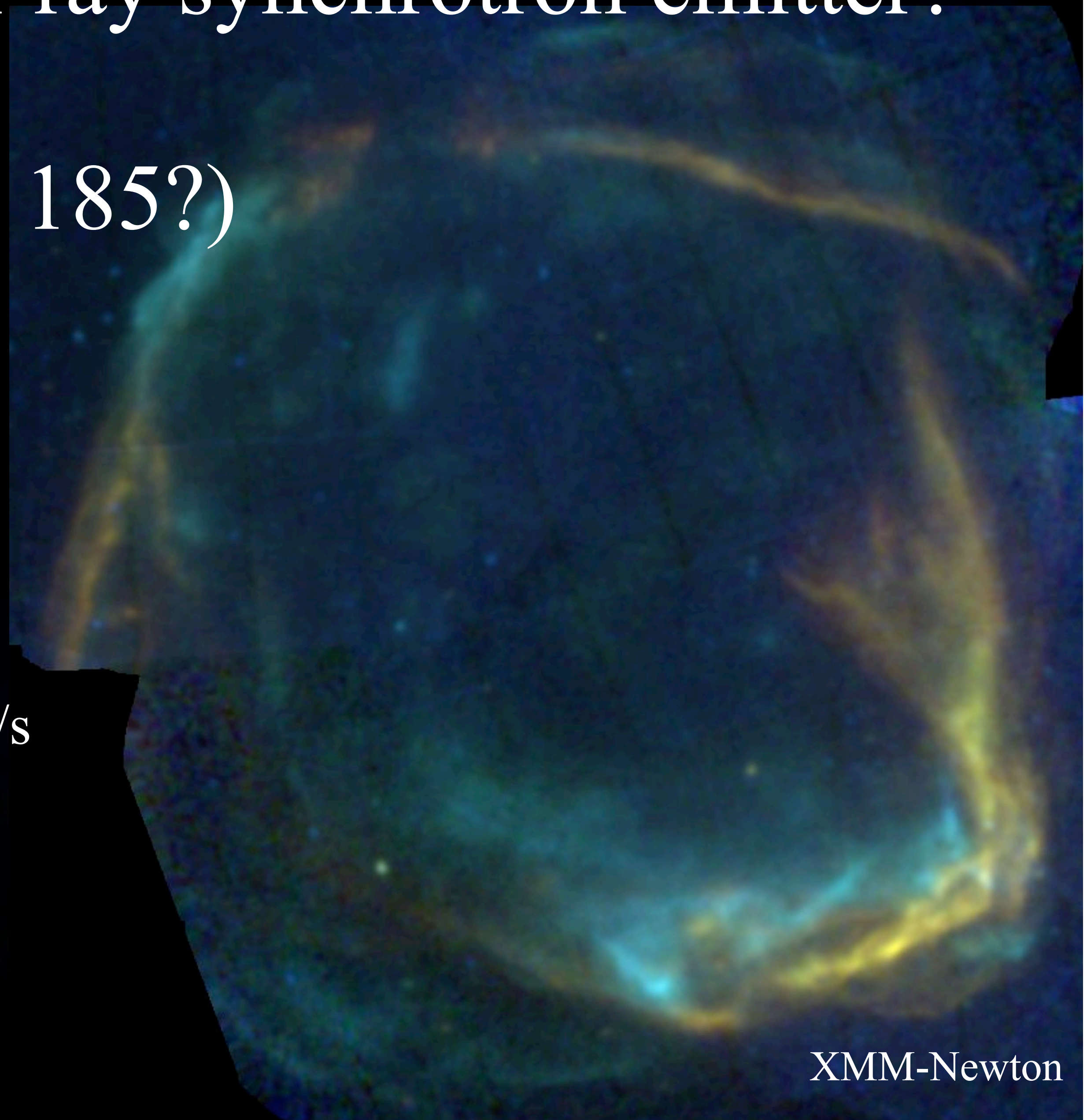
The oldest X-ray synchrotron emitter?

RCW 86 (SN 185?)

Problem:
Max synchrotron energy

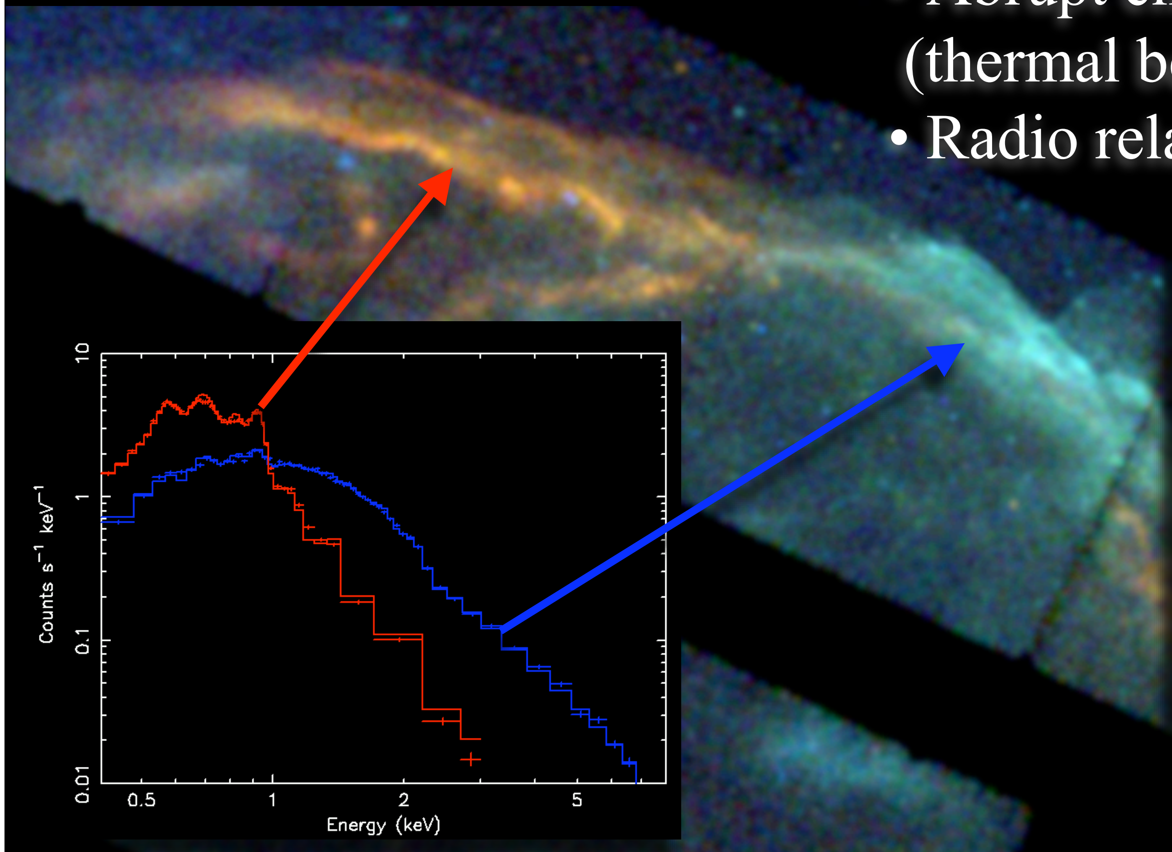
$$E_{max} \sim V_s^2$$

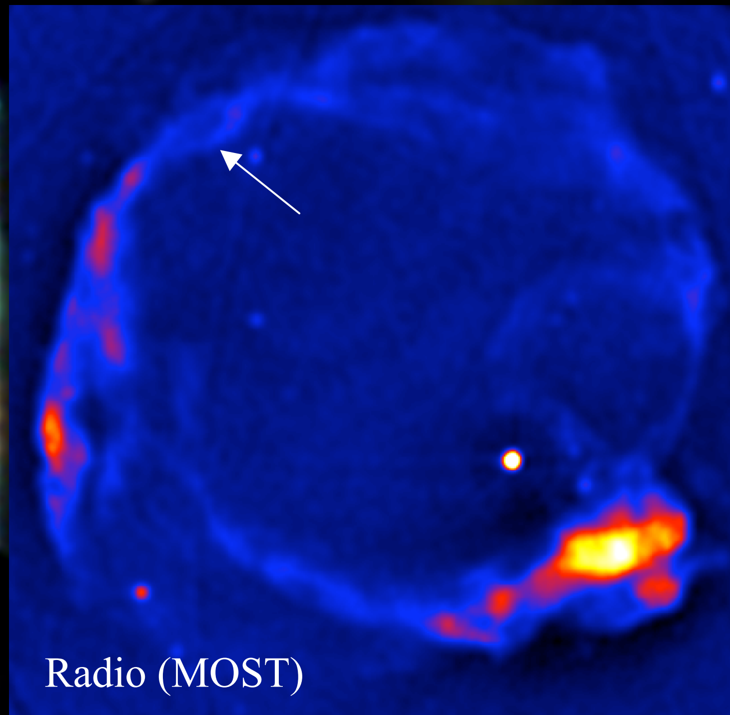
Independent of B!
(Aharonian & Atoyan 2001)
But measured V_s~700 km/s
(Ghavamian et al. '01)
much lower than Cas A,
Tycho, SN1006 etc.



Chandra/XMM-Newton observations of Northeastern shell

- In NE synchrotron from shock front (edge on: 3D geometry less uncertain)
- Abrupt change thermal to non-thermal (thermal becomes weaker)
- Radio relatively weak





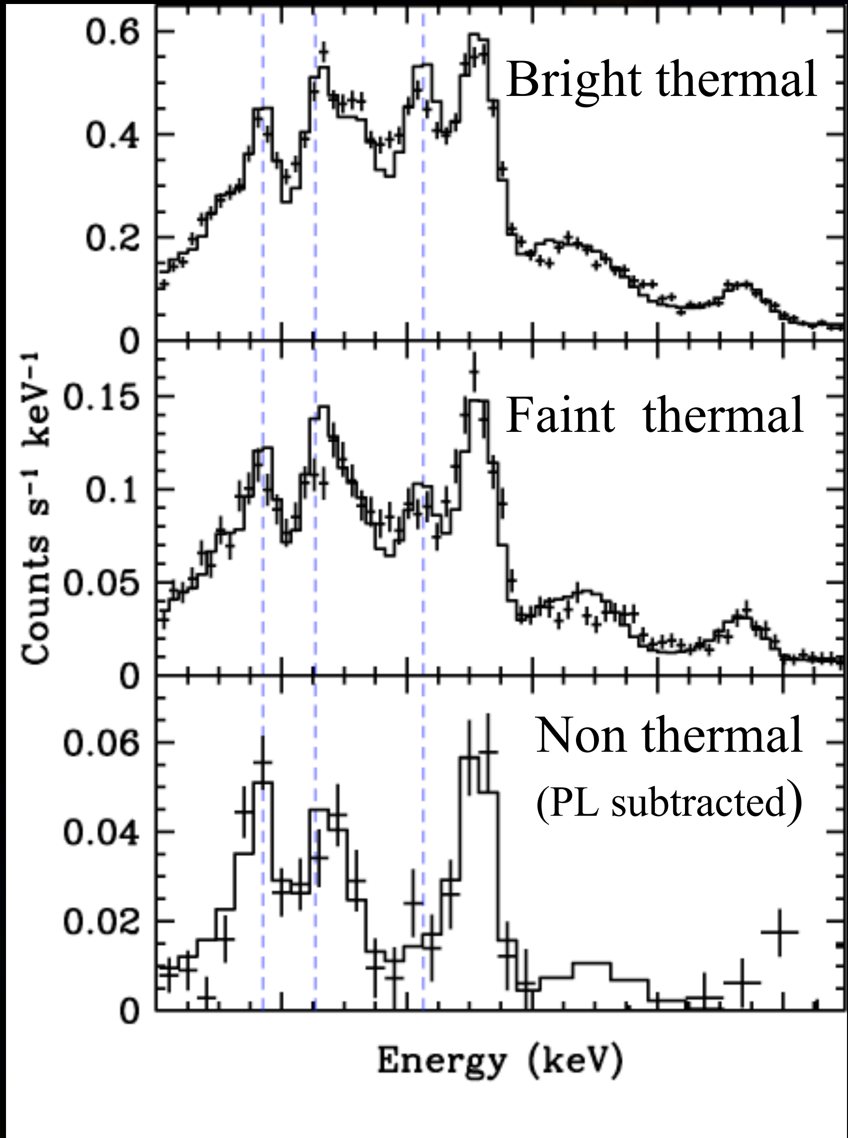
What are to make of this?

- From width (~45”) and demanding diffusion and advection give same B-field (~20μG) we obtain Vs ~ 3000 km/s
- Much higher than Hα measurements (~700 km/s Ghavamian et al.), but consistent with shock theory
- Requires large differences in V_s along shell
- Consistent with shock partially interacting with cavity wall
- High shock velocity is consistent with identification
  RCW86=SN185!!
- Suggests also why new X-ray synchrotron/TeV remnants are large and faint (Ueno PhD Thesis 2005):
  low density → V_s remains high for longer time

weakness of radio:
not more electrons are accelerated
they are accelerated to higher energies!

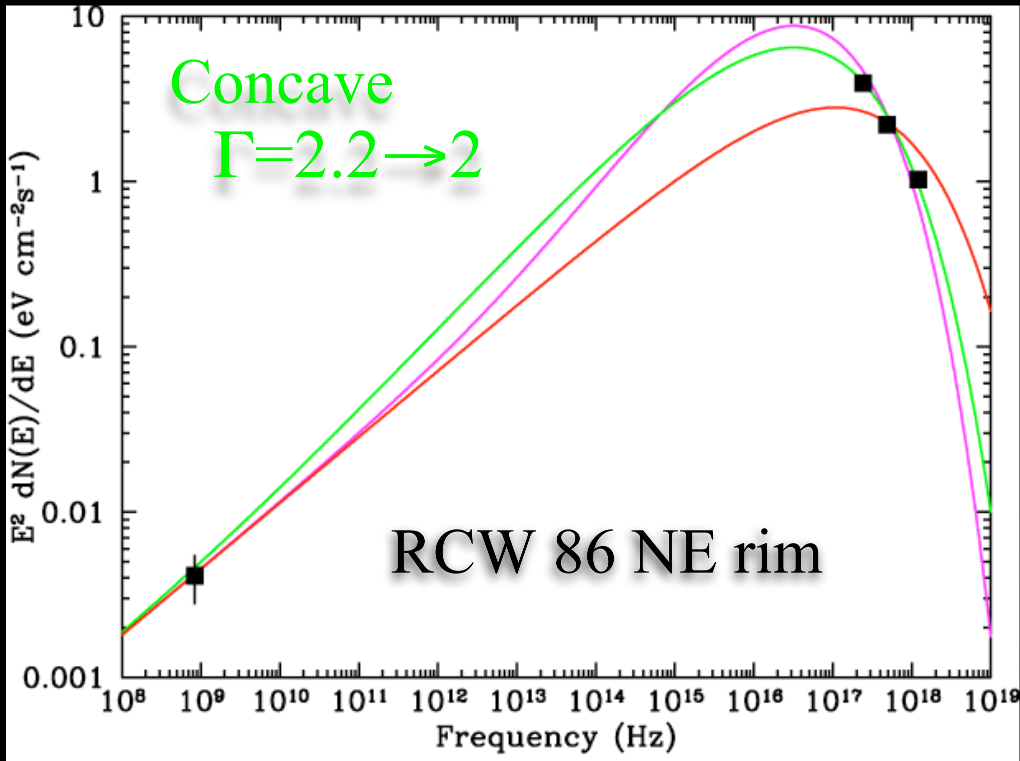
Thermal spectra

- Use thermal spectra to estimate time since interacting with cavity wall
- NE bright shell gives kT ~ 1 keV, $n_e t = 4\times10^9 cm^{-3} s$ (=ionization time)
- Emission measure: $n_e \sim 0.5\ cm^{-3}$
- Combining gives t ~ 250 yr
- So $\Delta R \sim \Delta V_s\, t = 0.8$ pc
  $\Delta R / R \sim 5\%$
  consistent with morphology!



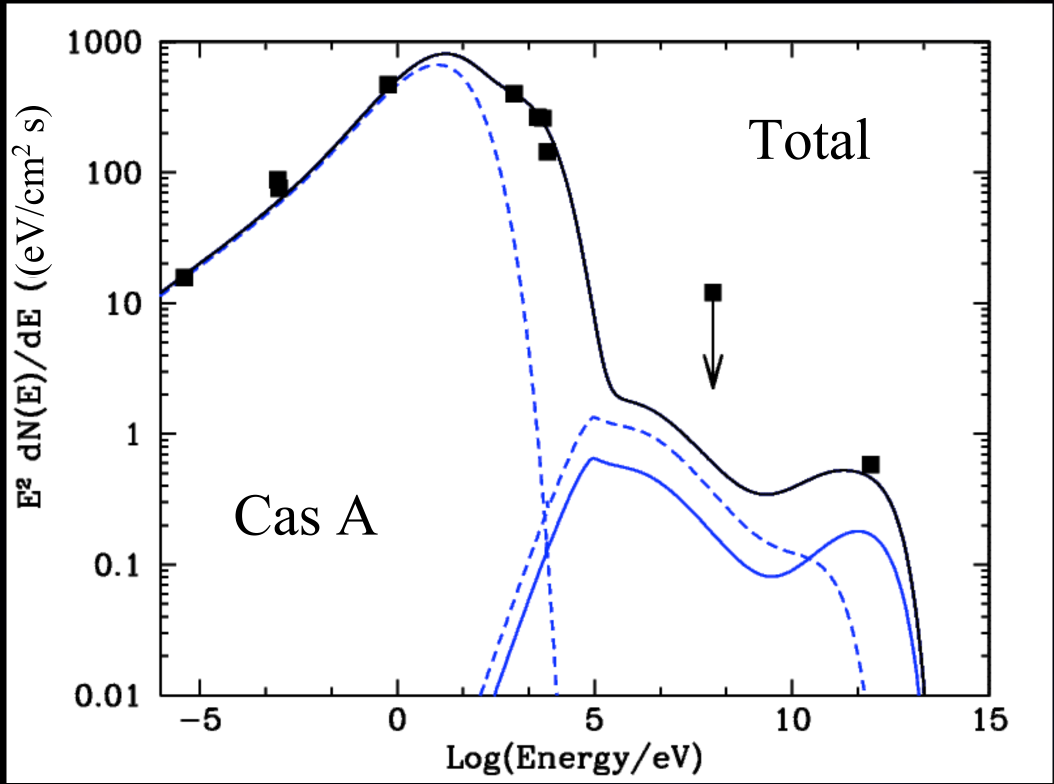
Radio vs X-ray synchrotron emission

How does weak radio emission fit in with X-ray synchrotron?



- Simple extrapolation of radio spectrum (srcut-like) does not fit
- X-ray index too steep!
- Requires flattening of spectrum to Γ=1.5 - 2
- Low maximum energy (e.g. ~8 TeV vs ~28 TeV)
- Flattening predicted for efficient cosmic ray acceleration (non-linear effects)

Concave spectra also fit Cas A better

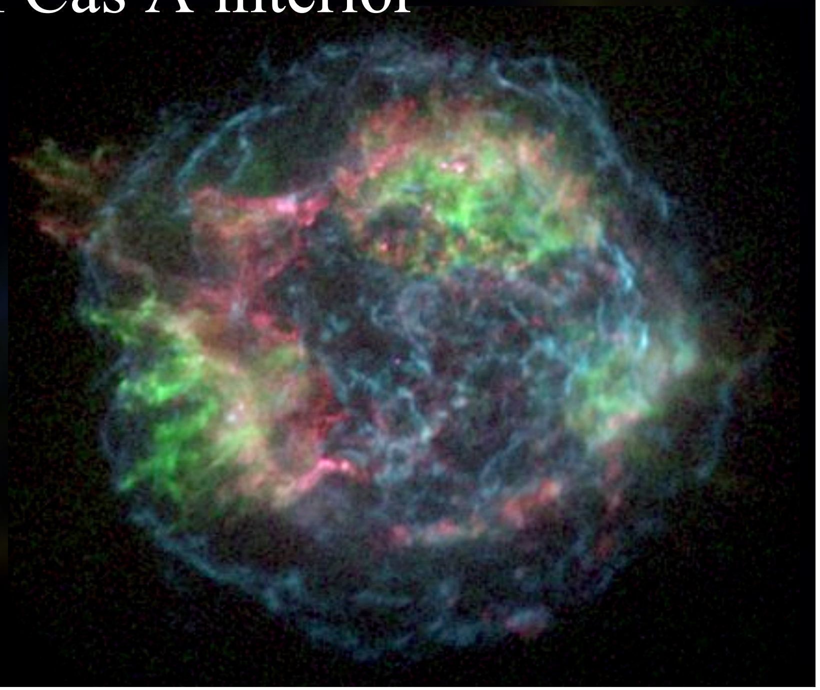


Drawback: less need for pion decay TeV emission!!

Uncertainties...

1 X-ray rim interpretation very consistent
diffusion vs advection, support for Bohm diffusion
But…
Assumption compression ratio = 4
Hydrodynamic models of Tycho give evidence for higher compression ratios

2 What is the correct interpretation of Cas A interior X-ray synchrotron filaments



Summary and Conclusions

- All young remnants show evidence for X-ray synchrotron emission
- Rim width can be interpreted as synchrotron cooling effect
- Rim width can be used to infer B-field
- Advection/Diffusion model requires Bohm diffusion
- B-field scales with density * Vα
- Highest CR energies reached early on in RSG winds
- RCW 86 X-ray synchrotron rim:
  - lowest B-field of historical remnants
  - need locally high shock velocity
  - concave electron spectrum needed
- Loose ends: - rim width model vs Tycho hydro model
  - interior X-ray synchrotron Cas A

36th COSPAR Assembly
16-23 July 2006, Beijing

Meeting E1.4:

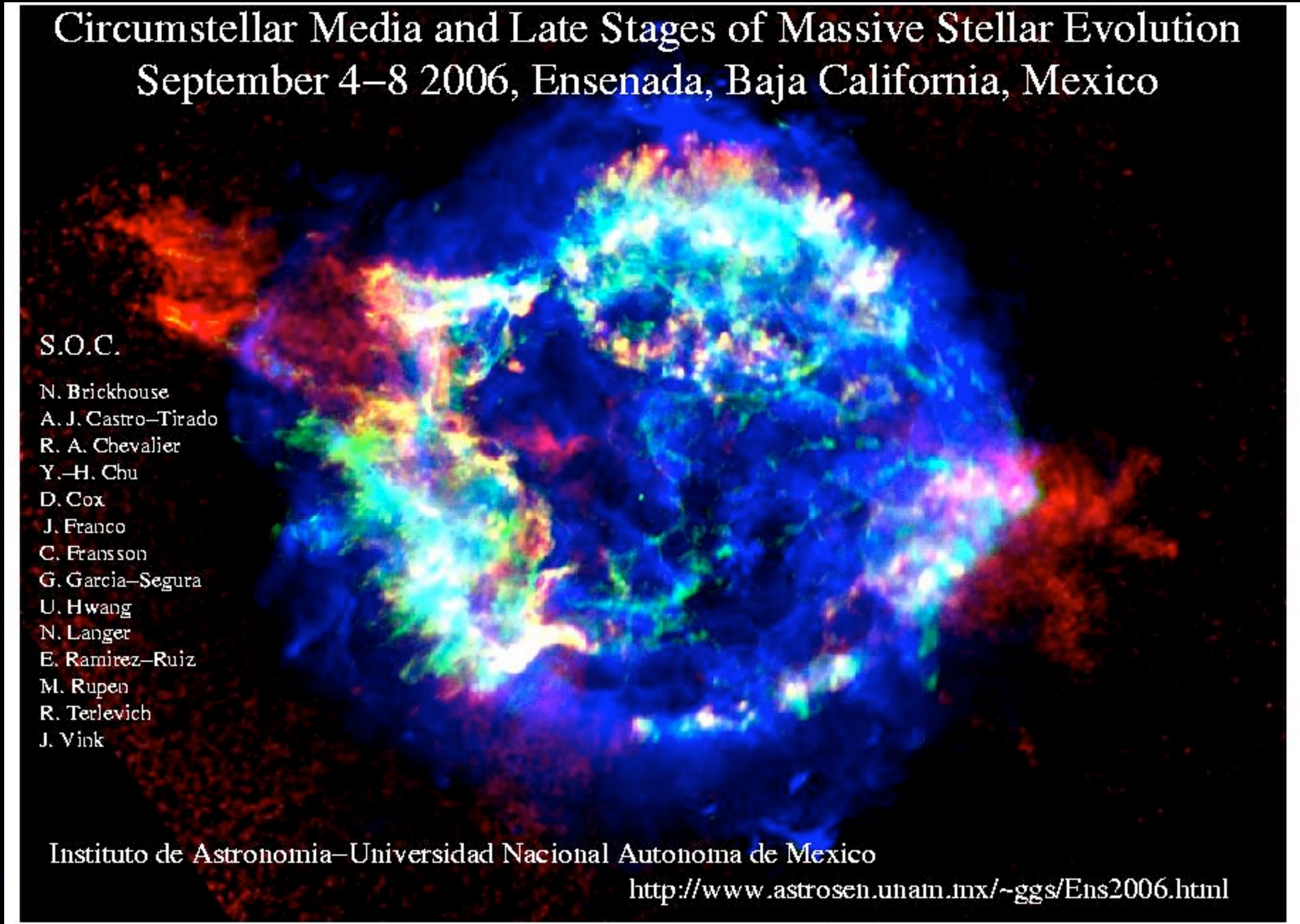
New High-Energy Results on Supernova Remnants and Pulsar Wind Nebulae

http://meetings.copernicus.org/cospar2006

Deadline for abstracts: 24th of February!

Invited speakers:
Z. R. Wang, K. Koyama, D. Helfand, P. Ghavamian, S. Park, M. Laming, M. Renaud, B. Gaensler, N. Bucciantini, D. Kaplan, G. Cassam-Genai, S. Funk, E. Berezhko, J. Hoerandel

Organizers: Jacco Vink, Patrick Slane, Aya Bamba, Fabrizio Bocchino, Yang Chen, Parviz Ghavamian, Anne Green, David Green, Una Hwang, Fang-Jun Lu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