Multi-wavelength Modeling of SNRs in the CTA Era

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with

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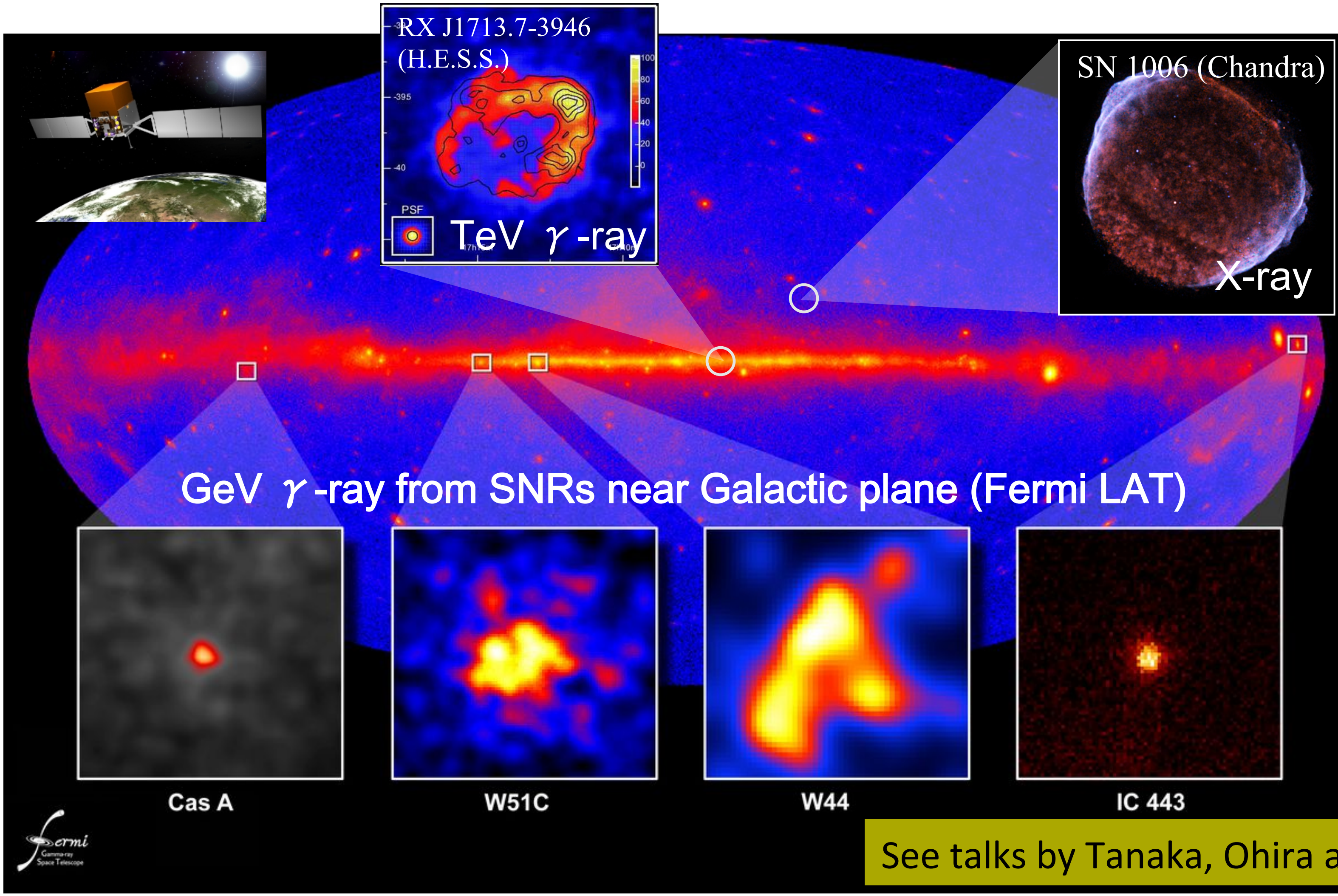
Ample Evidence for Energetic Particles at SNRs

- We are now sure that SNRs are accelerating relativistic particles efficiently
- Many questions remain･･･



See talks by Tanaka, Ohira and Sano

Outline

- Overview of diffusive shock acceleration (DSA)
- CR-hydro-NEI code
- Its many applications
- Prospects for SNR modeling with CTA and future multi-λ observations

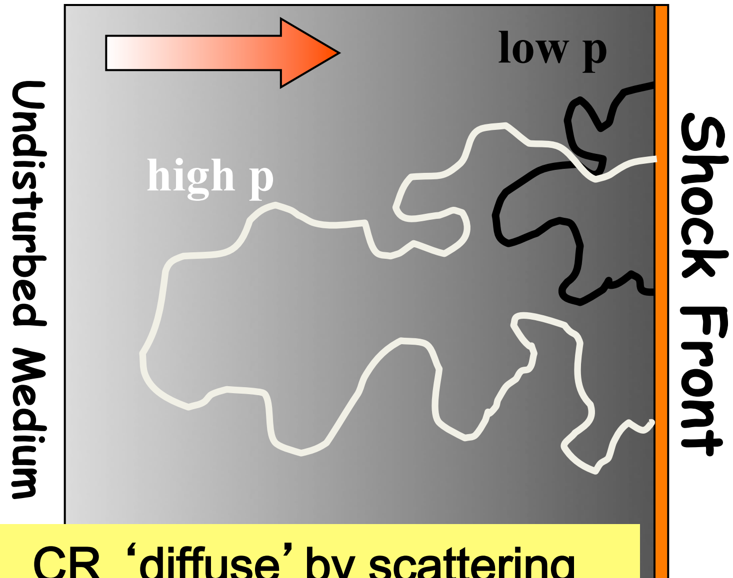
Diffusive Shock Acceleration

SNRs have **strong non-relativistic collisionless shocks**

→ **Diffusive Shock Acceleration (DSA) must occur (for the shocks to exist!)**

1. Superthermal particles **'diffuse'** through **elastic scattering w/ magnetic waves**
2. Particles *repeatedly* crossing the shock front
3. Each crossing, momentum gain = $\triangle p/p \sim \triangle u/c$

→ Acceleration efficiency for strong shocks easily >> 10% (e.g. Ellison+ 05)



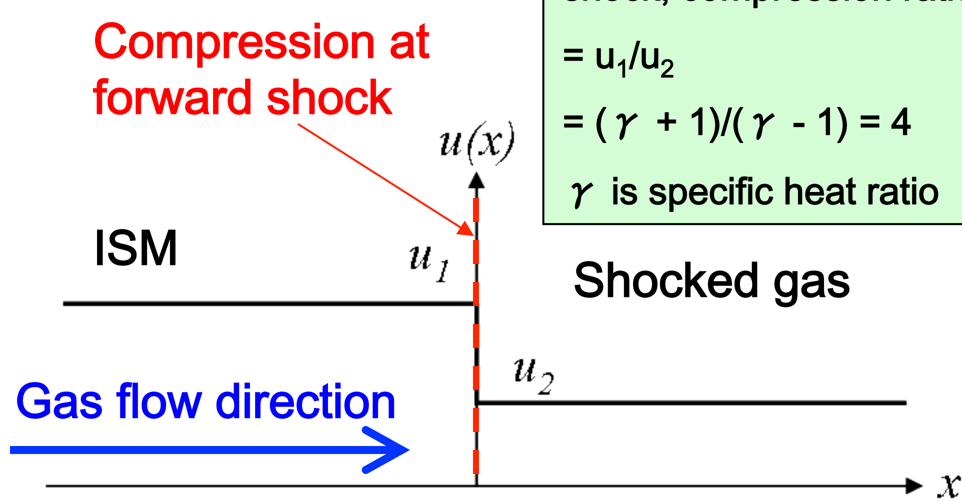
CR 'diffuse' by scattering with magnetic turbulence

For high Mach number shock, compression ratio R

$= u_1/u_2$

$= (\gamma + 1)/(\gamma - 1) = 4$

γ is specific heat ratio



u(x) is gas velocity

u_1 is shock speed

(In rest frame of shock)

The Universal Power-law

- ❑ CR can be treated as ***'test-particles'*** when $\mathbf{P_{CR} \ll P_{gas}}$

- ❑ For **strong shocks**, comp. ratio R → 4

  For particles with $v_p \gg u_{shock}$ (i.e. near isotropic distr.):

  $f(p) \sim p^{-q}$ $q = 3R/(R-1) = 4$ → famous $\mathbf{F(E) \sim E^{-2}}$ spectrum

'Universality' of q

- Shock acceleration **requires diffusion of CR**
- Diffusion coefficient D(x,p) contains all complex plasma physics
- Test particle limit

  → f(p) does NOT depend on plasma condition at all, only on R

But this simplicity almost never happens in nature!

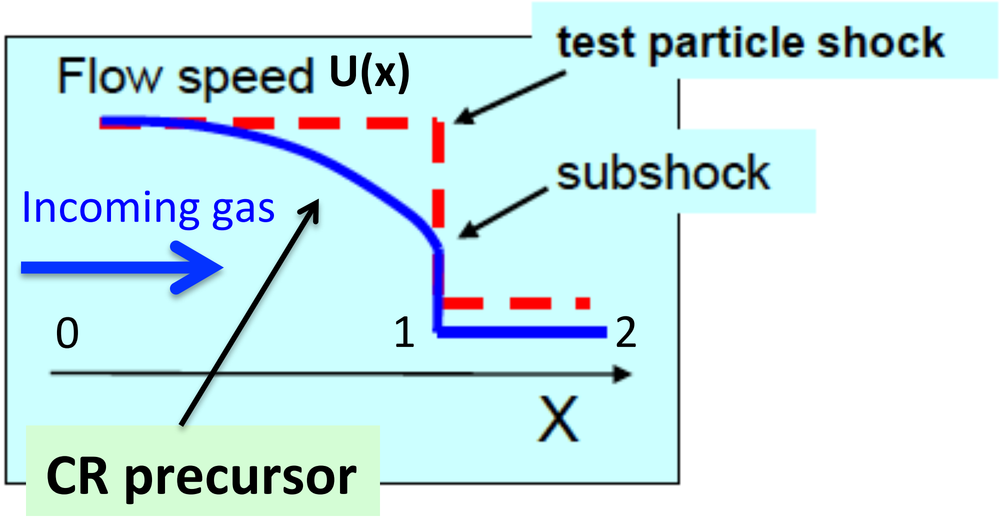
Modified Shock and NLDSA

Strong shocks found in SNRs (M_S > ~100) are intrinsically efficient CR accelerators

- X-ray, γ-ray observations
- Analytic models and simulations

❖ P_{CR} gets close to P_{gas} in a short time scale

❖ P_{CR} modifies simple jump shock into a **smoothed transition**
→ a **CR precursor** produced



CR acceleration becomes **non-linear**, since hydro and DSA are **inter-dependent** now!

Nonlinear diffusive shock acceleration

Some robust predictions of NLDSA

1. **Highly modified shock structure**

2. **'Concave' f(p), not simple PL**

   Now DSA depends on $D(x,p) \sim p^{\alpha}/B(x)$

   → CR with higher p diffuses farther

   → $\triangle p/p \sim \triangle u/c$ increases with p

   Harder gamma-ray spectrum

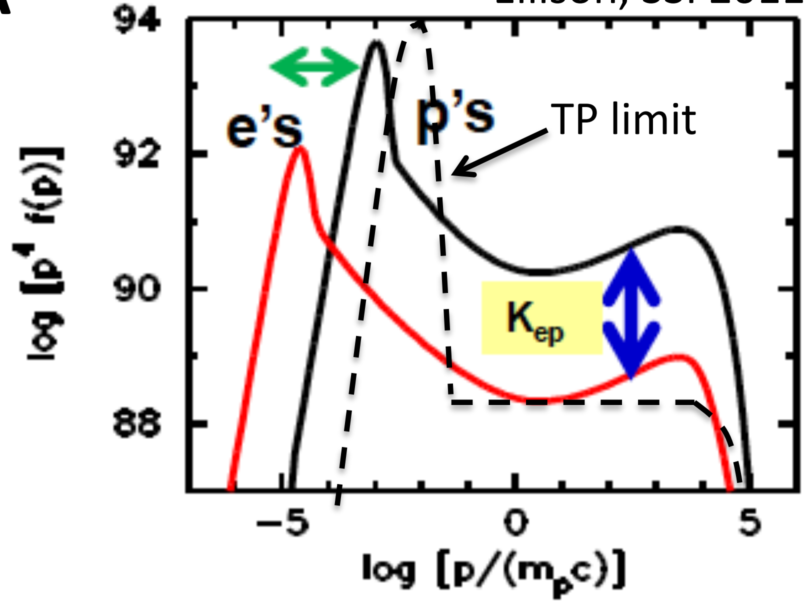
3. **Lowered shocked gas temp. and R_{FS}/R_{CD}**

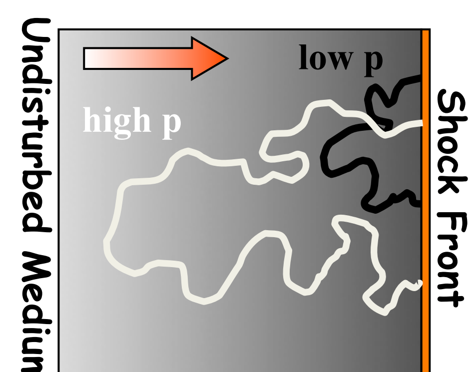
   Large fraction of bulk shock K.E. channeled into superthermal particles (i.e. CR),

   → Less available to gas heating (e.g. RCW86)

   → Shock velocity decays faster with age (e.g. Tycho)

Ellison, SSI 2011





Some Considerations on NLDSA

f(p) must cut-off at some max. momentum p_{max}

→ This implies *particle escape*

→ i.e. energy is drained from the system

→ EOS softens, $\gamma_{eff} << 4/3$ possible

→ Comp. ratio can be indefinitely high, $R >> 7$

→ f(p) becomes harder, EOS softens further, more escape etc…

i.e. Acceleration efficiency can become extremely high!

But, nature impose limitations by **self-regulatory mechanisms**:

1. Magnetic field amplification (MFA)
2. Damping of magnetic waves
3. Finite speed of magnetic waves, i.e. $v_{Alfven} \sim u_{shock}$

When all taken account of:
→ R usually keeps at 5 – 7 level, comparable to observations

Ways to model NLDSA

1. Analytic – Diffusion equation **Best for multi-λ models!**

$$[u(x) - v_A(x)]\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f}{\partial x}\right] + \frac{d[u(x) - v_A(x)]}{dx}\frac{p}{3}\frac{\partial f}{\partial p} + Q(x,p)$$

Pros: Fast and robust, covers most important physics

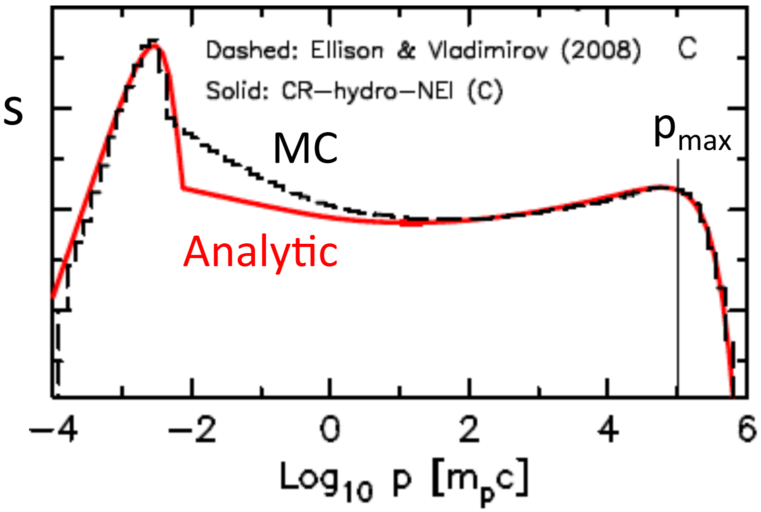
Cons: Assumes isotropic f(p), parametric recipe for injection

2. Monte Carlo simulation

Calculates pitch-angle scattering of particles

Pros: No isotropic assumption
Self-consistent injection

Cons: Slow, hard to couple with hydro



SHL+ (2012)

3. Particle-in-cell simulation

Pros: Can start from first principles

Cons: Heavy! Must be 3-D, needs many time-steps and momentum bins

Introduction to

CR-hydro-NEI code

and

its Applications

For details, see e.g. S.-H. Lee+ 2012, ApJ 750 pp. 16

The CR–hydro-NEI code

- CR-hydro-NEI
  - **1-D hydro** (*VH-1*, spherical symmetry) [Blondin+ (2001)]
  - **Non-linear diffusive shock acceleration** (NLDSA)
  - **Non-equilibrium ionization** (NEI) [e.g. Patnaude+ (2009)]
  - Effects like MFA, finite v_{Alfven}, wave heating, particle escape and propagation, etc…
- Hydro is non-linearly coupled to DSA and NEI
- Self-consistent multi-λ photon spectrum, including thermal X-rays
- **Fast and robust code**

Input Parameters

Hydro environment

- Upstream conditions
  - n_{gas}, B_0 (in a wind cavity or ISM)
- Initial conditions
  - E_{SN}, M_{ej}, $\rho_{ej}(r)$

DSA related

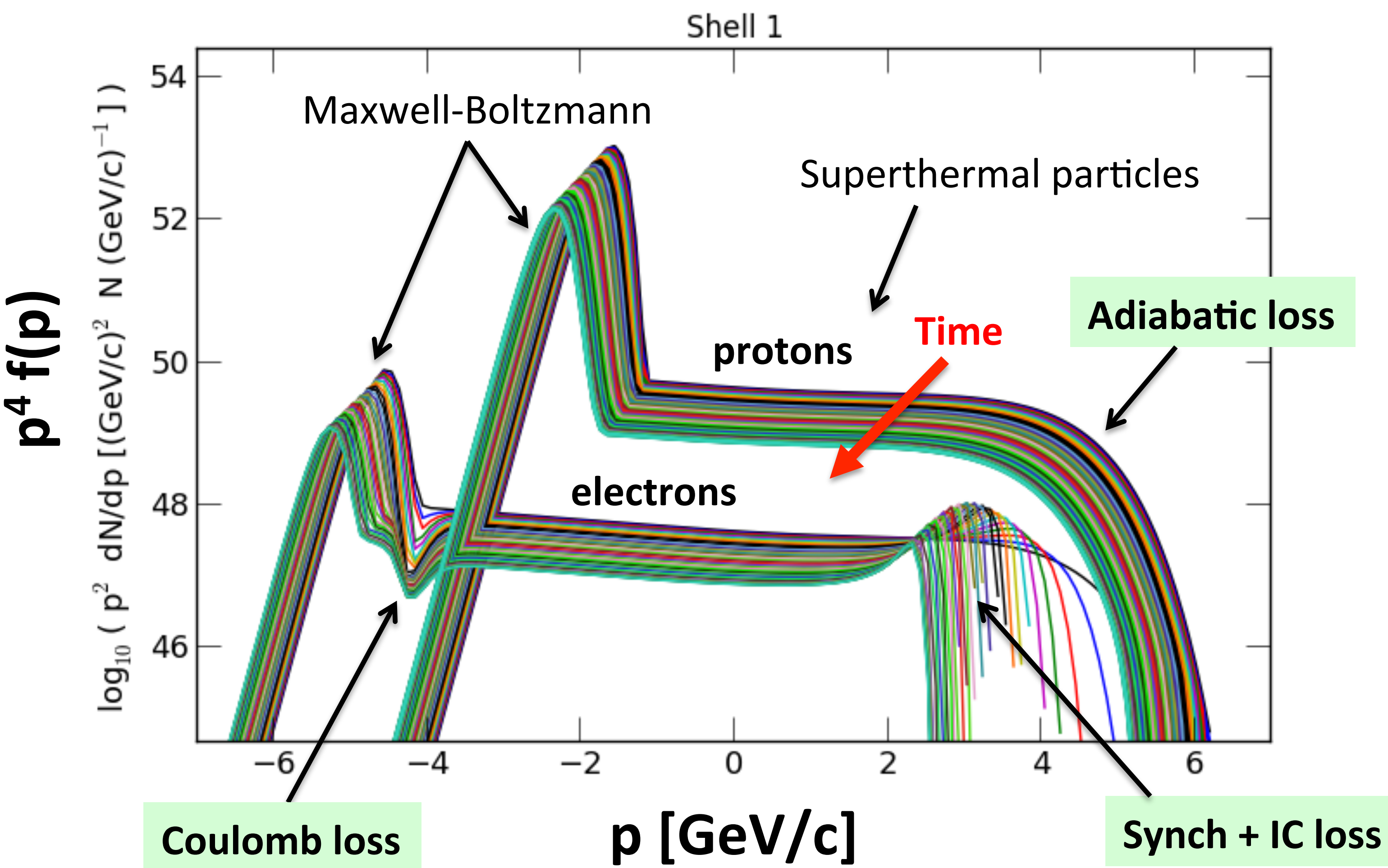
- Injection parameter χ_{inj} → accel. efficiency
- Number ratio of e^-/p → normalize e^- distr
- Free escape boundary f_{FEB} → p_{max} of protons

NEI related

- Equilibration model for T_e / T_p (e.g. Coulomb)

Time evolution of CR spectrum

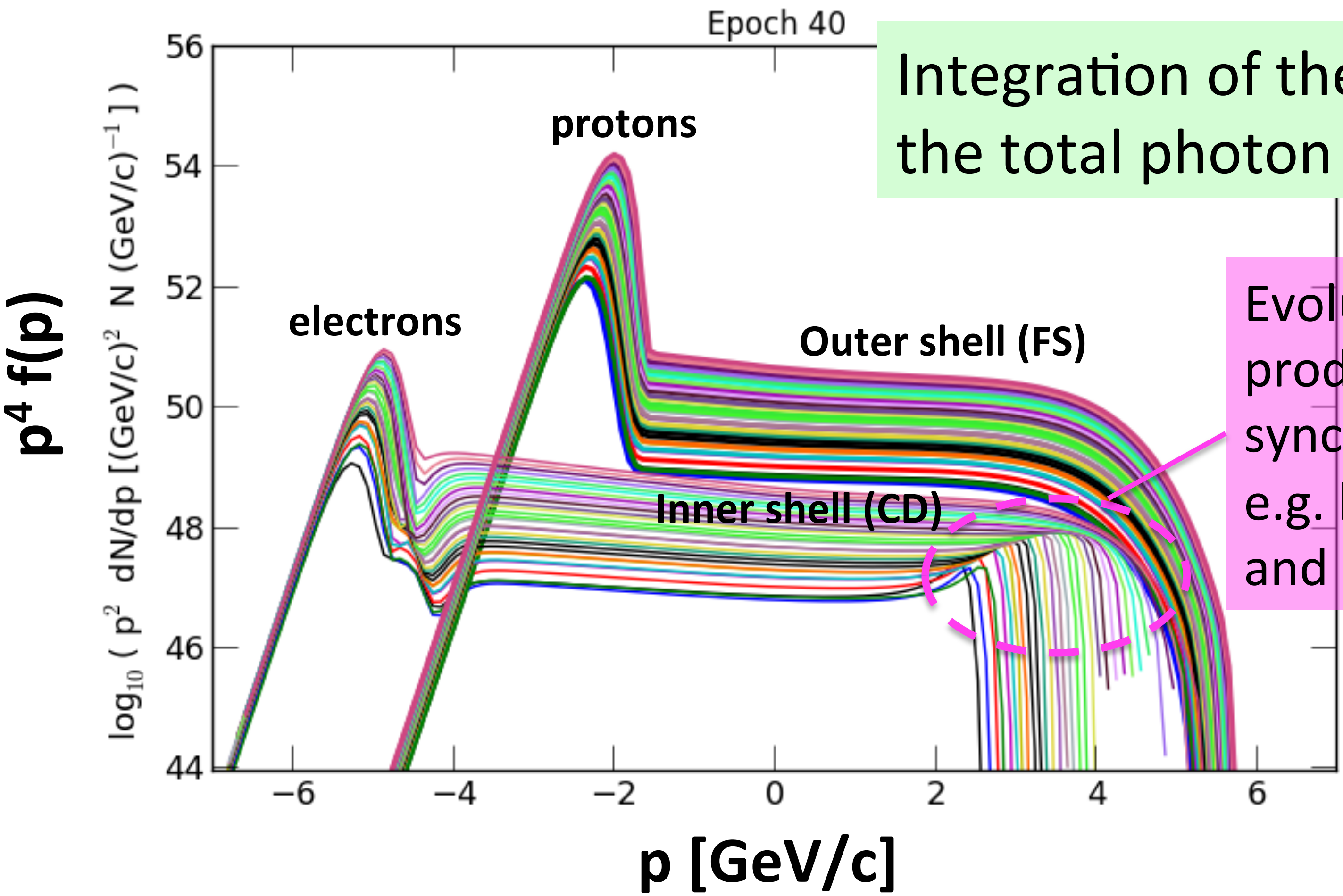
Evolution of f(p) in a Lagrangian grid cell during 100 – 2500 yr



Spatial variation of CR spectrum

Distribution of f(p) from FS to CD after 2500 yr of evolution

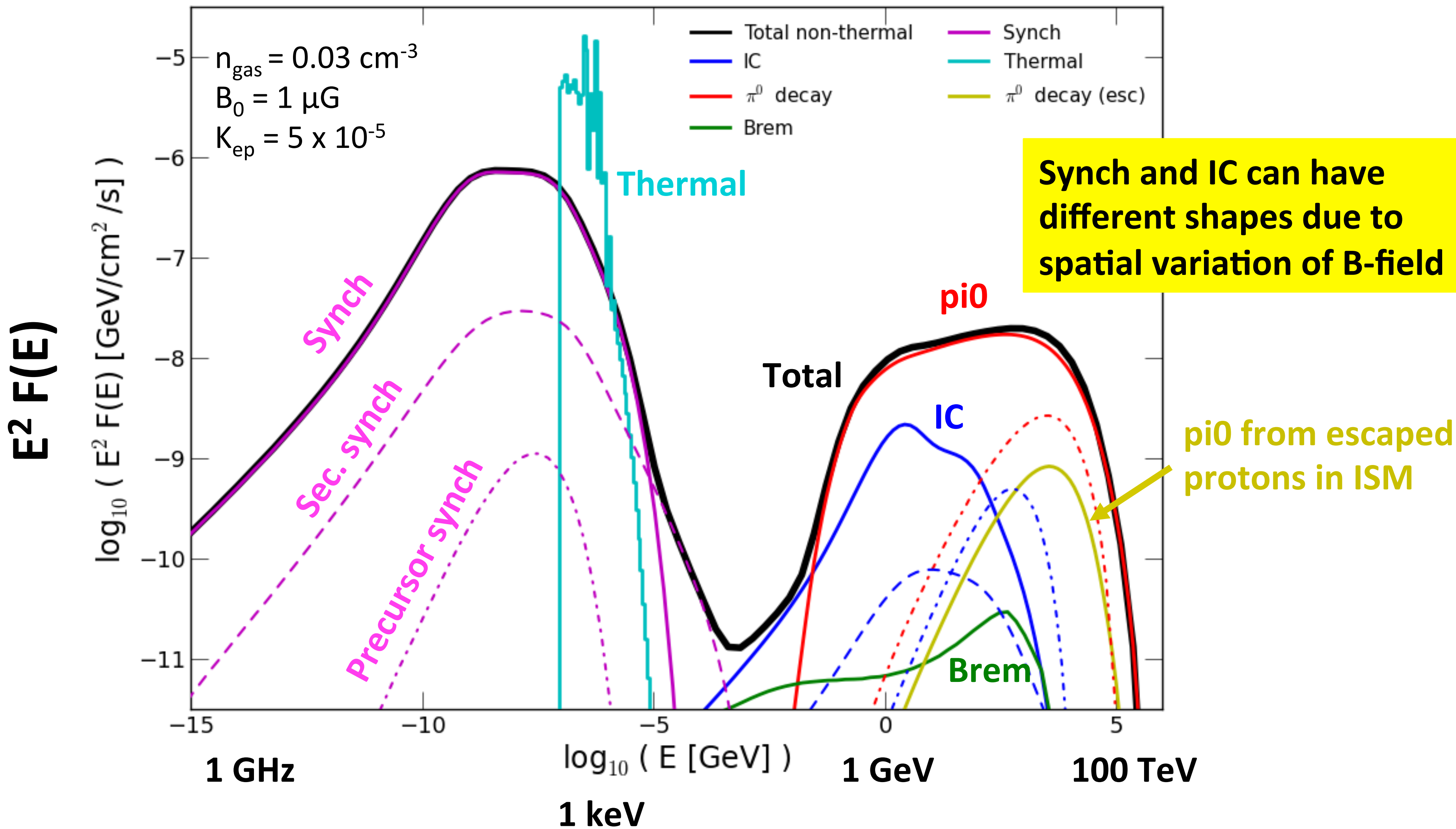
Integration of these produces the total photon spectrum



Evolution history can produce peculiar synch and IC spectra e.g. broad roll-overs and plateau

Volume-integrated Broadband Photon SED

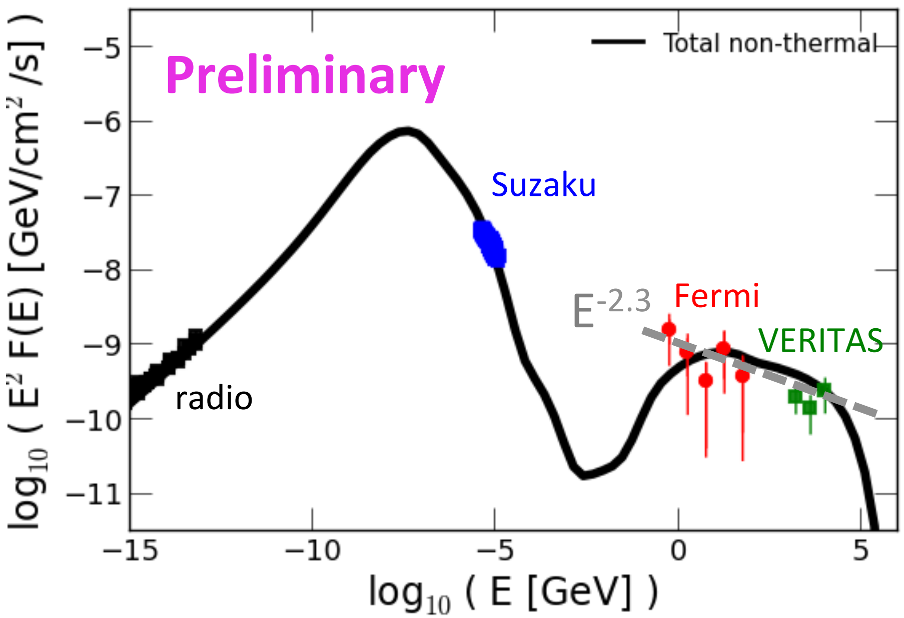
Example with uniform ISM, pi0-dominated γ-ray



The importance of finite Alfvén speed

Fermi LAT has discovered SNRs with spectrum **softer than E^{-2}** (i.e. q > 4), especially **young SNRs** with flat radio index

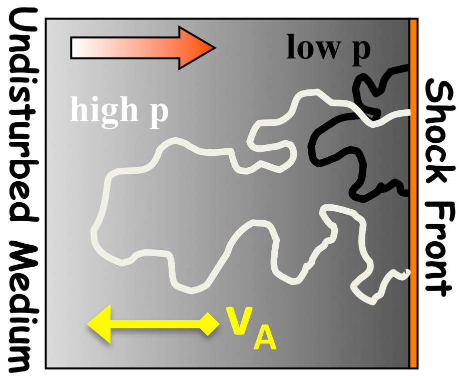
e.g. Tycho's SNR



Conventional NLDSA models cannot produce q > 4 unless the shock is very weak (M_S << 100)

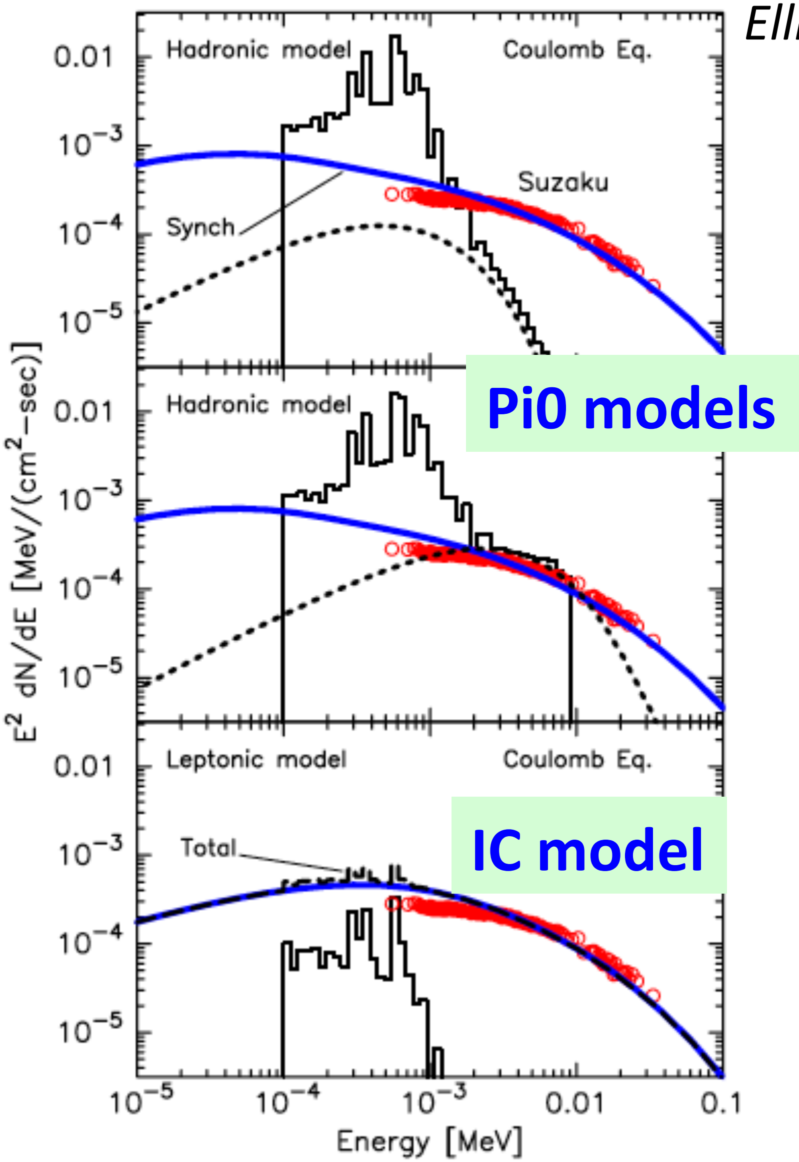
For strong shocks in young SNRs, one possibility is a **high v_A for the magnetic scattering center**

$$S_{\rm tot} = \frac{u_0 - v_{A,0}}{u_2 + v_{A,2}}$$



Effective comp. ratio S_{tot} < R → softer spectrum

Thermal X-ray as a strong constraint



*Ellison+ (2010) on RX J1713 using **CR-hydro-NEI***

Hadronic models require higher ambient gas density

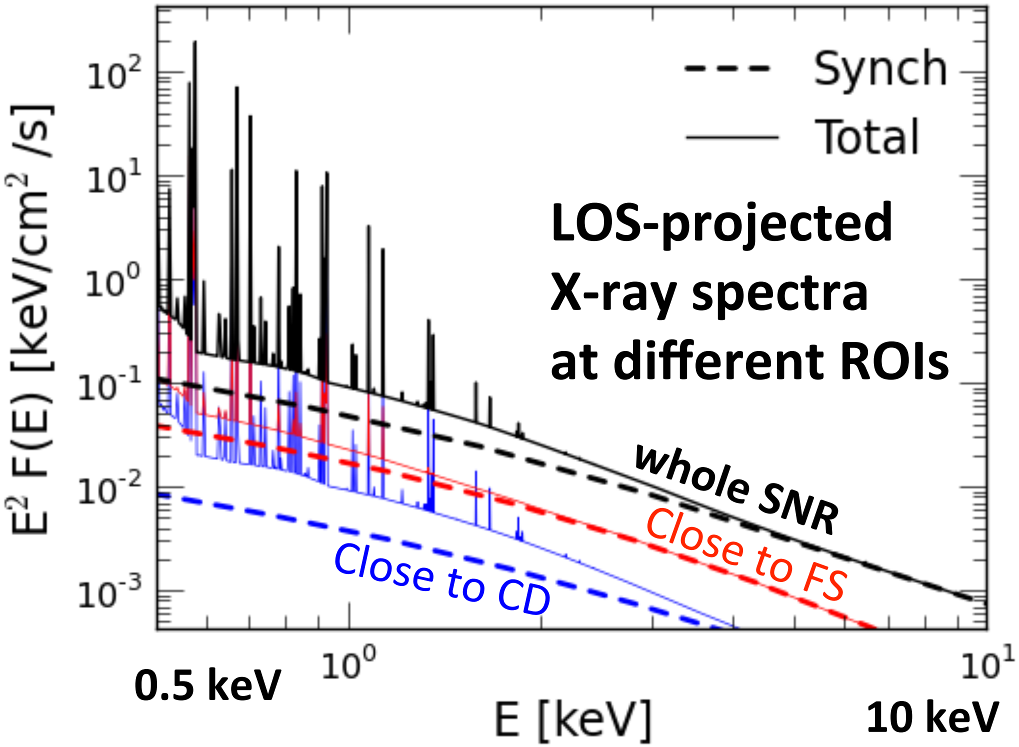
→ Must be accompanied by enhancement of thermal lines from the shocked gas

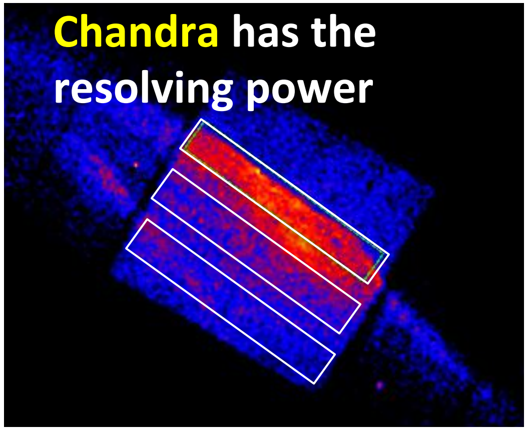
→ Usually a problem for TeV-bright, non-thermal dominated SNRs (e.g. RX J1713, Vela Jr, …)

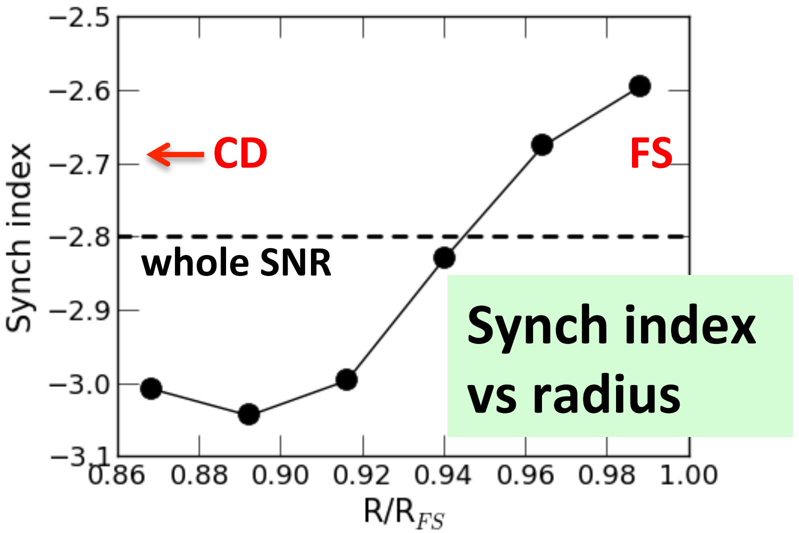
Astro-H will be most suitable for this kind of constraint

ROI-specific X-ray spectra

Spatial variation of X-ray spectral properties is another strong constraint of broadband models



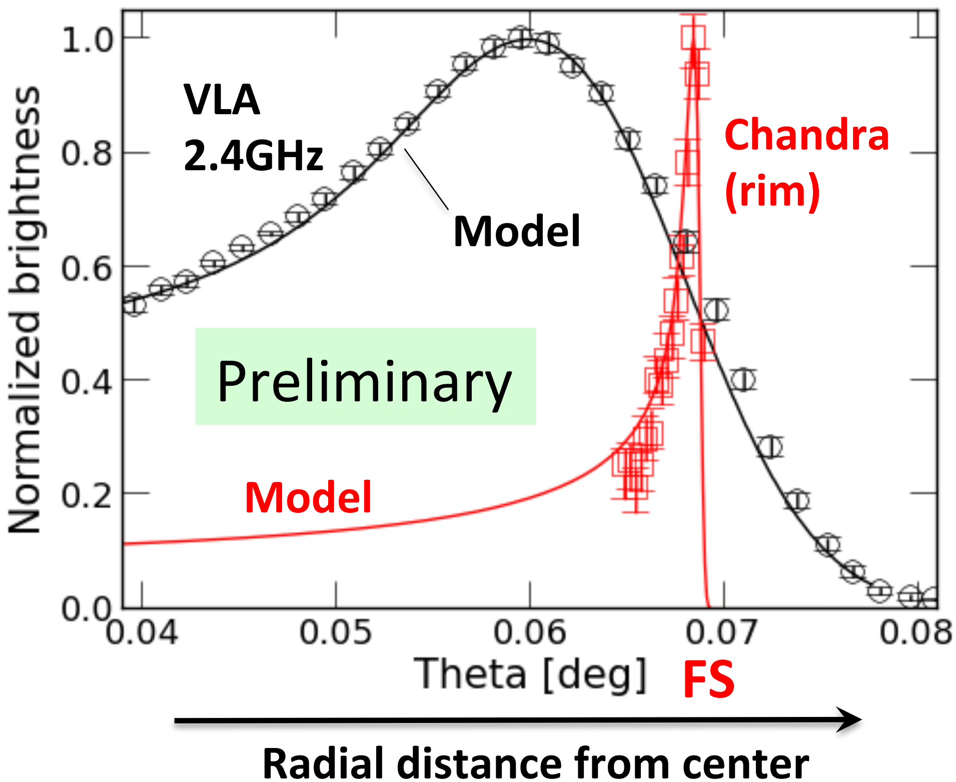


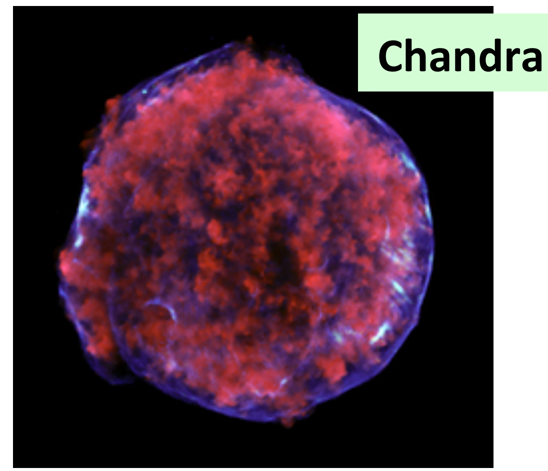


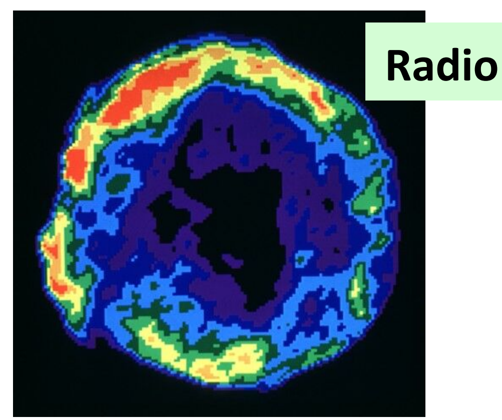
Radial Emission Profiles

Multi-λ surface brightness profiles are usually good discriminant and qualifier for models as well

e.g. Tycho's SNR







How CTA will help modelers

- ✧The best ever **angular resolution** in TeV
  - ✧Correlation study with X-ray in highest detail
    (e.g. Re-examine leptonic scenario for TeV-bright SNRs)
  - ✧TeV brightness profiles will confront models

- ✧High sensitivity up to **100 TeV** regime
  - ✧Extremely critical for locating **cut-off** (i.e. p_{max})
  - ✧If multi-λ models support hadronic scenario,
    100 TeV photon → Existence of ~**1 PeV proton**
  - ✧Many more detections

Prospects

- We have introduced the CR-hydro-NEI simulation code applied to SNR modeling

- To fully utilize multi-wavelength data from current and future observatories e.g. CTA and Astro-H, they must be confronted with state-of-the-art broadband emission models

- We advocate CR-hydro-NEI as a strong candidate

END