CR-hydro-NEI Simulation of Particle Acceleration and Broadband Emission at Supernova Remnants

Herman Lee YITP, Kyoto University
Don Ellison North Carolina State University
Shigehiro Nagataki YITP, Kyoto University

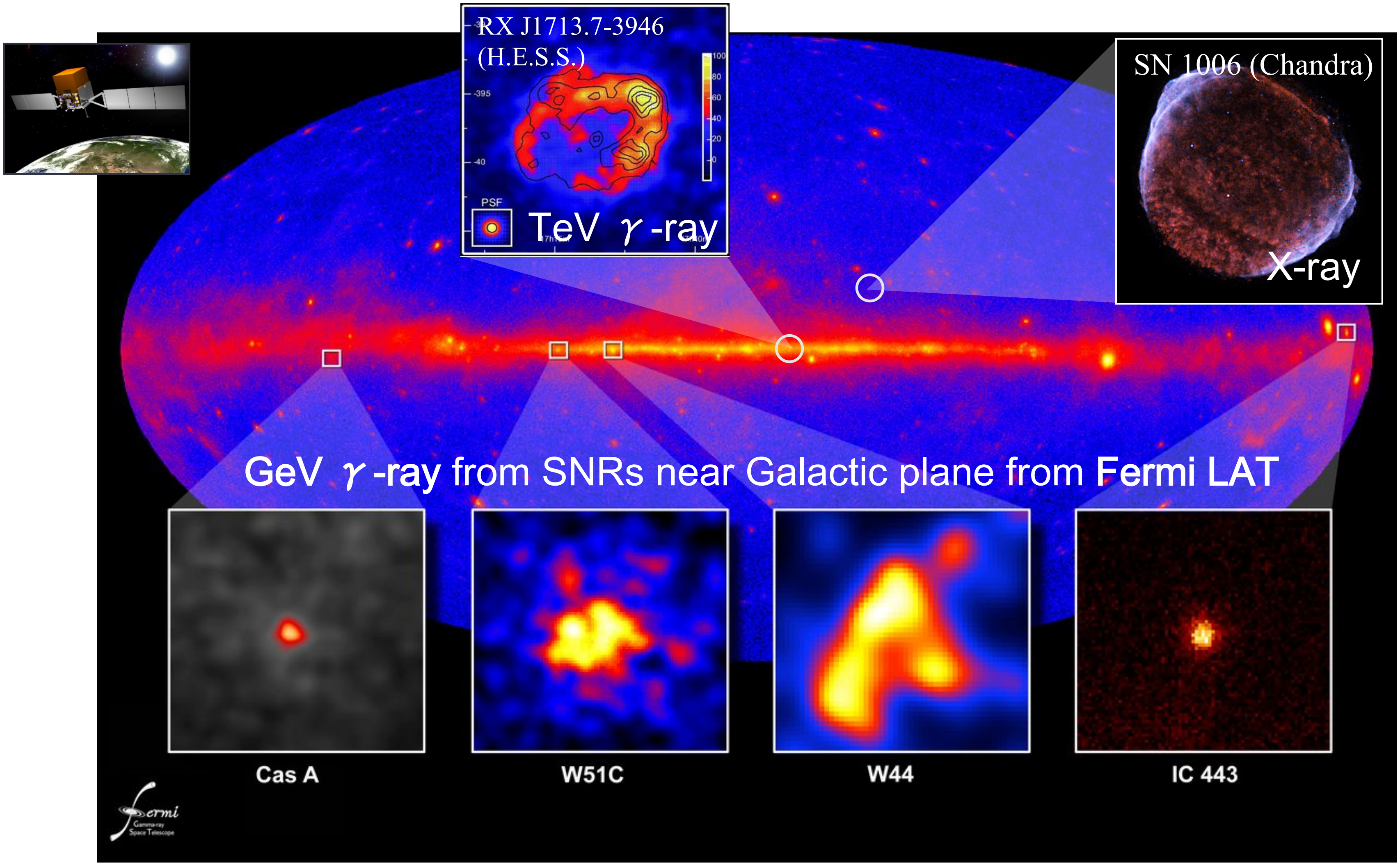
with the CR-hydro team:
Dan Patnaude, John Raymond, Pat Slane (Harvard, CfA), Andrei Bykov (Ioffe Institute)

Recent papers

Lee, Ellison & Nagataki (2012), submitted to ApJ
Ellison et al (2012), ApJ 744, 39E
Ellison & Bykov (2011), ApJ 731, 87E
Patnaude et al (2010), ApJ 725, 1476P

Evidence of Particle Acceleration at SNRs

- Strong **synchrotron X-ray** reveals electrons up to 200 TeV (e.g. SN1006, Koyama+ 95 ASCA)
- Detections of bright GeV & TeV γ-ray (e.g. RX J1713.7−3946, Aharonian+ 04 HESS)



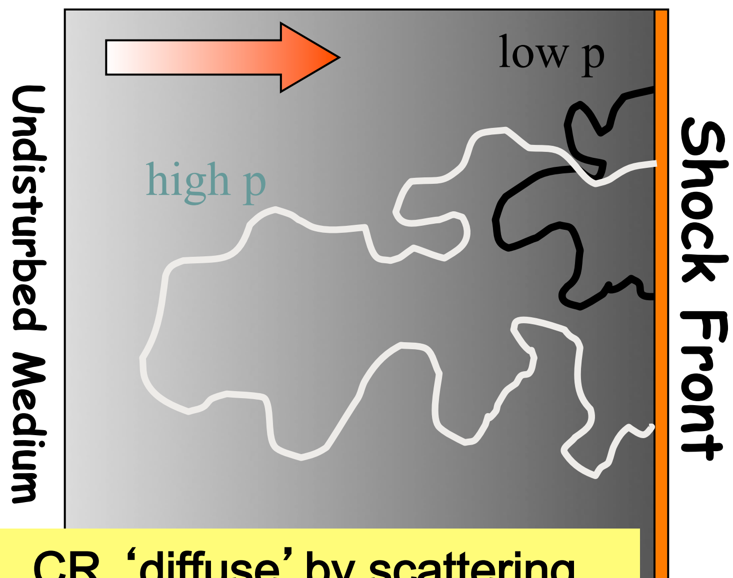
How particles get accelerated at SNRs

SNRs have strong non-relativistic collisionless shocks

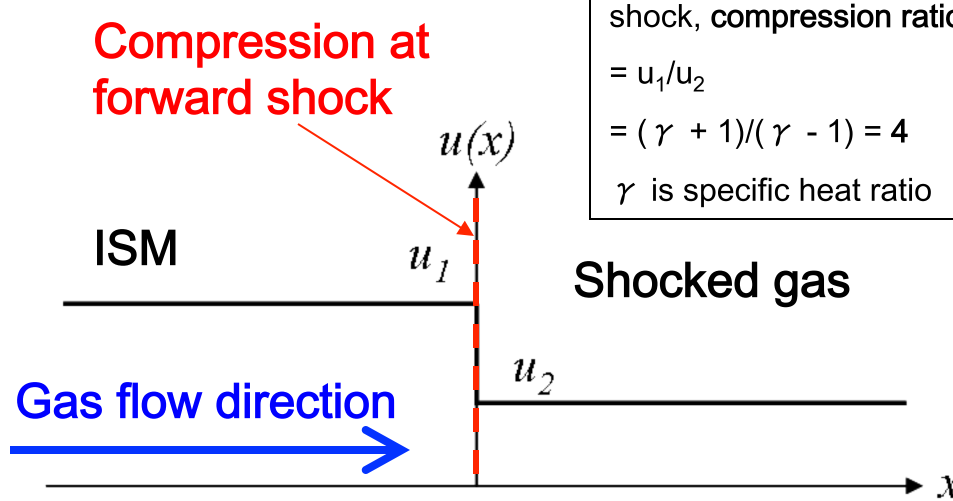
→ **Diffusive Shock Acceleration (DSA) [aka Fermi 1st order acceleration]**

- Particles gain momentum by repeatedly crossing a shock
- Momentum gain $\triangle p/p \sim (u_1 - u_2)/c$ every time they cross the shock
- 'Diffusion' by **elastic scattering** w/ magnetic waves on both sides of shock

→ 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)

Introduction to

CR-hydro-NEI code

The CR–hydro-NEI code

- Code with a pretty long development history
  - Nearly 20 papers published since ‘99
- CR-hydro = ??
  - **1D hydro** (VH-1, spherically symmetric) [Blondin (2001)]

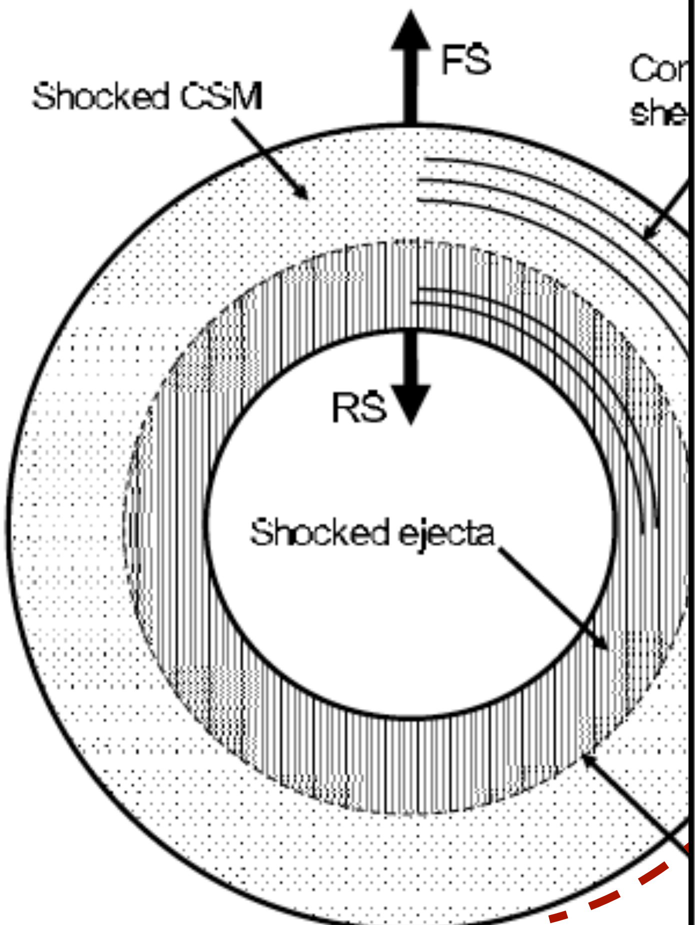
    PLUS
  - Semi-analytic **nonlinear diffusive shock acceleration** (NLDSA)

    [e.g. Amato & Blasi 2006, Caprioli et al 2010]
- Hydro is coupled to DSA, neither steady-state DSA nor pure hydro like many others
- **Fast code**, typical simulation time < 20 min for 1000 yr sim

Many cool features

- **Nonlinear DSA effects**
  - **CR precursor +** back-pressure to hydro
  - **Particle escape** at free escape boundary (FEB)
  - **Magnetic turbulence** generation + wave damping
  - → Magnetic field amplification (**MFA**), quasi-linear theory (QLT)
  - → **D(x,p)** can be calculated from self-generated B-field
- **Non-thermal radio-TeV SED**, space and time resolved
- Self-consistent calculation of **thermal X-ray line emission**
  - **NEI code**, with heavy element ionization/recombination (up to Fe)
  - **Coulomb equilibration** (e-p collision) and cooling determines $\mathbf{T_e(x,t)}$
- **Propagation of escaping CRs** and **interaction w/ clouds** using simple Monte Carlo

Basic Geometry



Time sequence of CR-hydro-NEI

1.) Hydro sweep step

2.) Find shock properties

3.) DSA & hydro feedbacks

4.) Propagate escaping CR (MC)
Energy loss of trapped CR
NEI
Electron heating/cooling, etc…

5.) Next hydro sweep step

A time step

Post processes

Broadband SED
X-ray line emissions from ion fractions

Input Parameters

Some important input model parameters

Hydro/environment

- Ambient environment (n_0, B_0, pre-SN wind, dense shell, …)
- Initial conditions (E_{SN}, ejecta properties, …)
- T_e equilibration model (instantaneous, Coulomb, …)
- $D_{ISM}(p)$ for escaping CR, or mean-free-path

DSA related

- Injection parameter χ_{inj}
- Magnetic wave damping rate f_{damp}
- Free escape boundary f_{FEB}
- $(e/p)_{rel}$ number ratio near p_{max}
- Seed CR populations, if any

Recent generalization of the CR-hydro-NEI code
Lee et al (2012), submitted to ApJ

Differences of generalized code with Ellison et al (2012) model

- ❑ The **old model** uses
  - ❑ Outdated DSA model from Blasi, Gabici & Vannori (2005)
  - ❑ Ad-hoc magnetic field amplification model
- ❑ **New DSA model** based on recent works by Blasi group
  - ☑ Acceleration of seed particles, e.g. Galactic CR [Blasi et al (2004)]
  - ☑ Explicit form for D(x,p) w/ space-dependence [Amato & Blasi (2005)]
  - ☑ Ability to calculate space-resolved f(x,p) in CR precursor
  - ☑ QL wave generation and self-generated D(x,p) [Caprioli et al (2009)]
  - ☑ CR precursor included in hydro for the first time
  - ☑ Effect of finite Alfven velocity on particle acceleration

Nonlinear diffusive shock acceleration

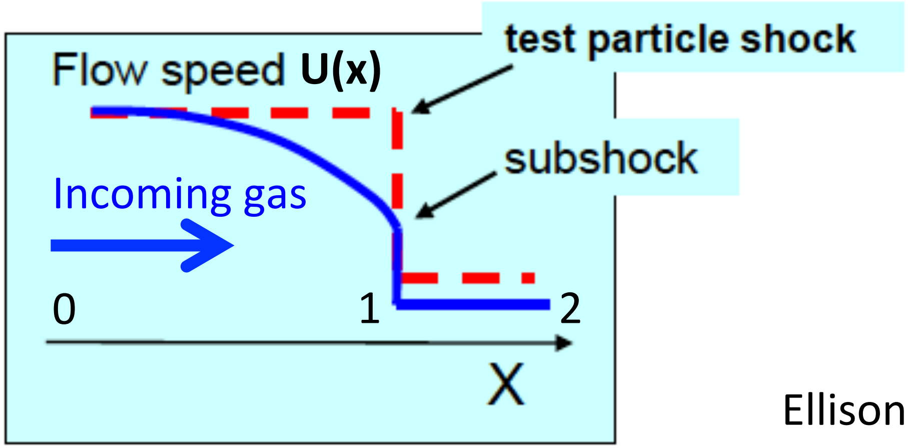
Solve transport eqn through recursive steps (intrinsically nonlinear)

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

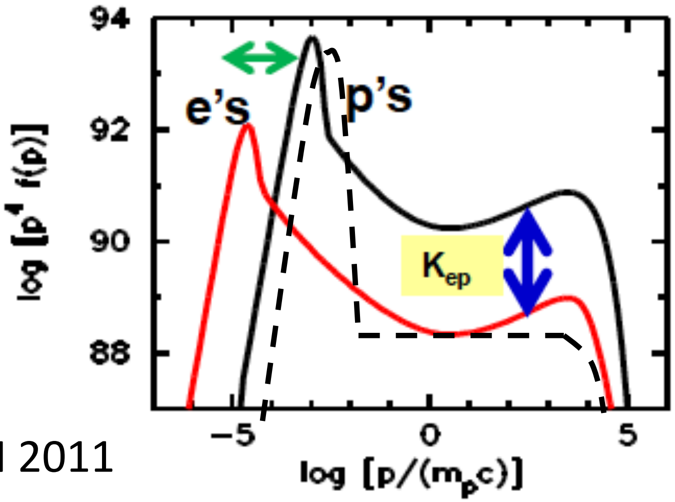
(All quantities in shock frame)

Typical solution w/ efficient DSA has…

highly modified shock structure, **'concave' f(p)**, **lower shocked temp.**



Ellison, SSI 2011



Diffusion coefficient in CR precursor

- D(x,p) contains **all info of (poorly known…) plasma physics**!
- In the code, two choices:
  - Simple parameterized form

$$D(x,p) = D_0 \left[\frac{3\mu\mathrm{G}}{B(x)}\right] \beta \left(\frac{p}{p_0}\right)^{\alpha}$$

  - From **self-generated** turbulent magnetic field δB(x)

$$D(x,p) = \begin{cases} \frac{2pc^2\beta}{3\pi e \delta B(x)} \ln\left(\frac{p_{\max}}{p_{\mathrm{inj}}}\right), & \text{if } \alpha = 1 \\ \frac{2p_{\max}c^2\beta}{3\pi(1-\alpha)e\delta B(x)} \left(\frac{p}{p_{\max}}\right)^{\alpha}, & \text{if } \alpha < 1 \end{cases}$$

Bohm-like

Kraichnan, Kolmogorov, ……

$W(x,k) \sim k^{2-\alpha}$

$$\frac{1}{2}\int W(x,k)dk = \frac{\delta B(x)^2}{8\pi}$$

(for Alfven waves)

Determining P_{max}'s

A. Age-limited case (early phase)

Condition: $t_{acc} = t_{age}$

$$t_{acc} \approx \frac{3}{u_0 - u_2} \int_{p_{inj}}^{p_{max}} \frac{dp}{p} \left(\frac{D_0(p)}{u_0} + \frac{D_2(p)}{u_2} \right)$$

For electrons:
If **fast cooling**, synch+IC loss time-scale determines p_{max}

B. Escape-limited case (later phase)

Condition: $L_{FEB} = \langle D/u \rangle_{precursor}$

Averaged diffusion length in precursor for p_{max} particles

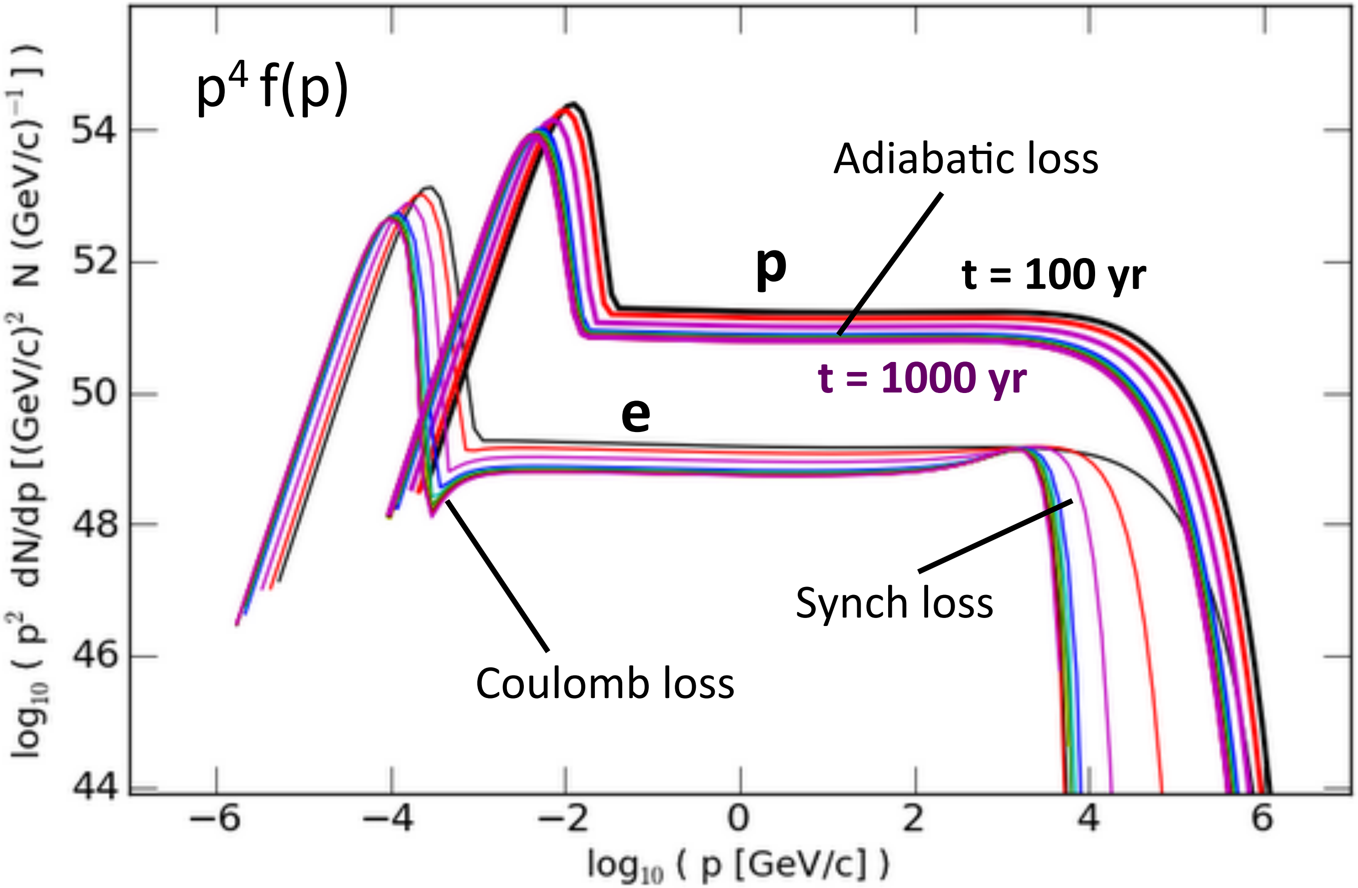
$$\langle D(x, p_{max})/u(x) \rangle = \int_{-L_{feb}}^{0} [D(x, p_{max})/u(x)] dx / L_{feb}$$

C. Cutoff from ion-neutral wave damping (e.g. Drury+ 1996)

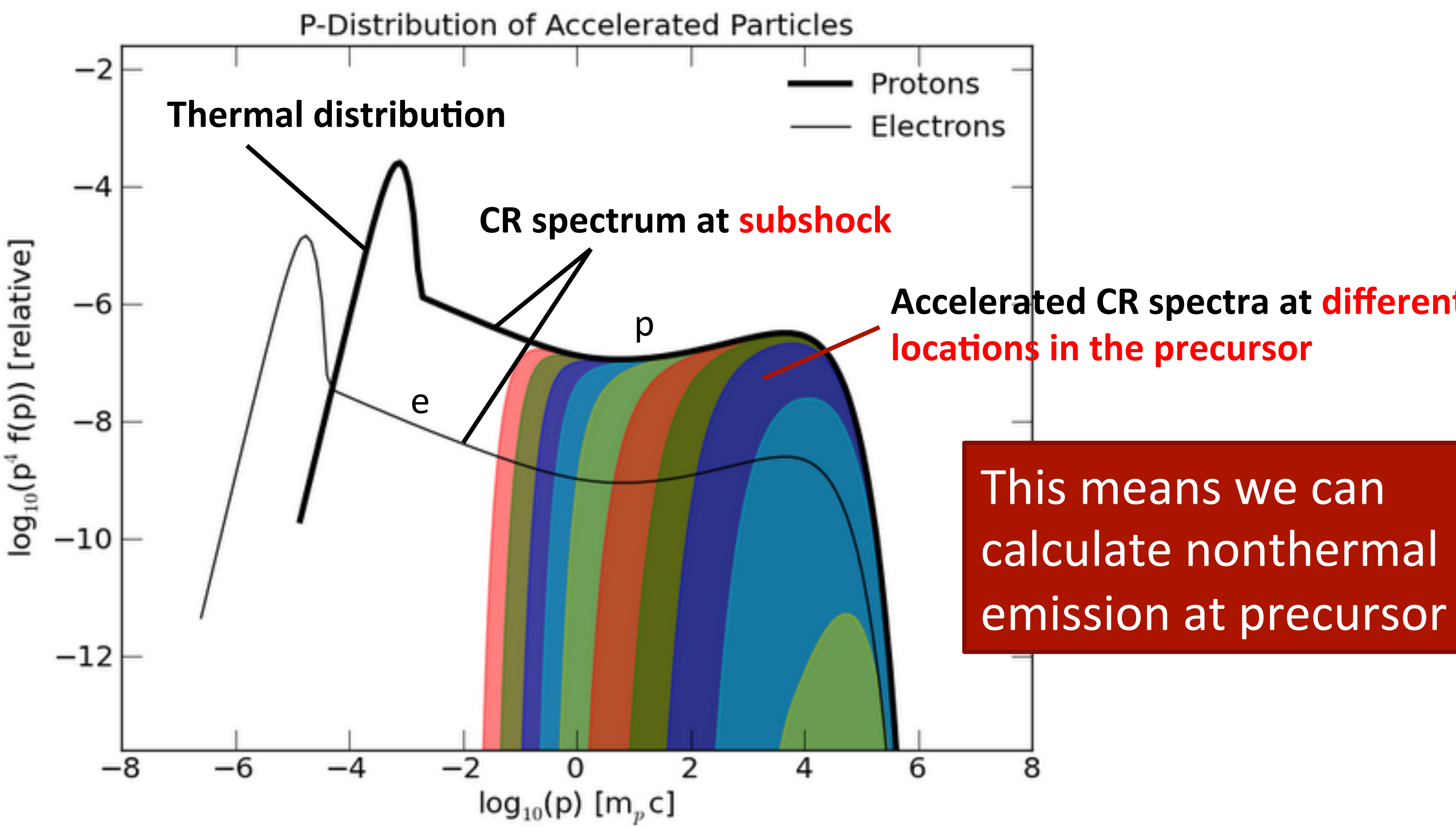
$$E_{max} \approx u_{0,7}^{3} T_{4}^{-0.4} n_{n}^{-1} n_{i}^{0.5} \xi_{CR,-1} \, \mathrm{GeV}$$

Origin: loss of CR trapping power
→ enhanced escape in partially ionized medium

Particle spectra evolution in a SNR shell

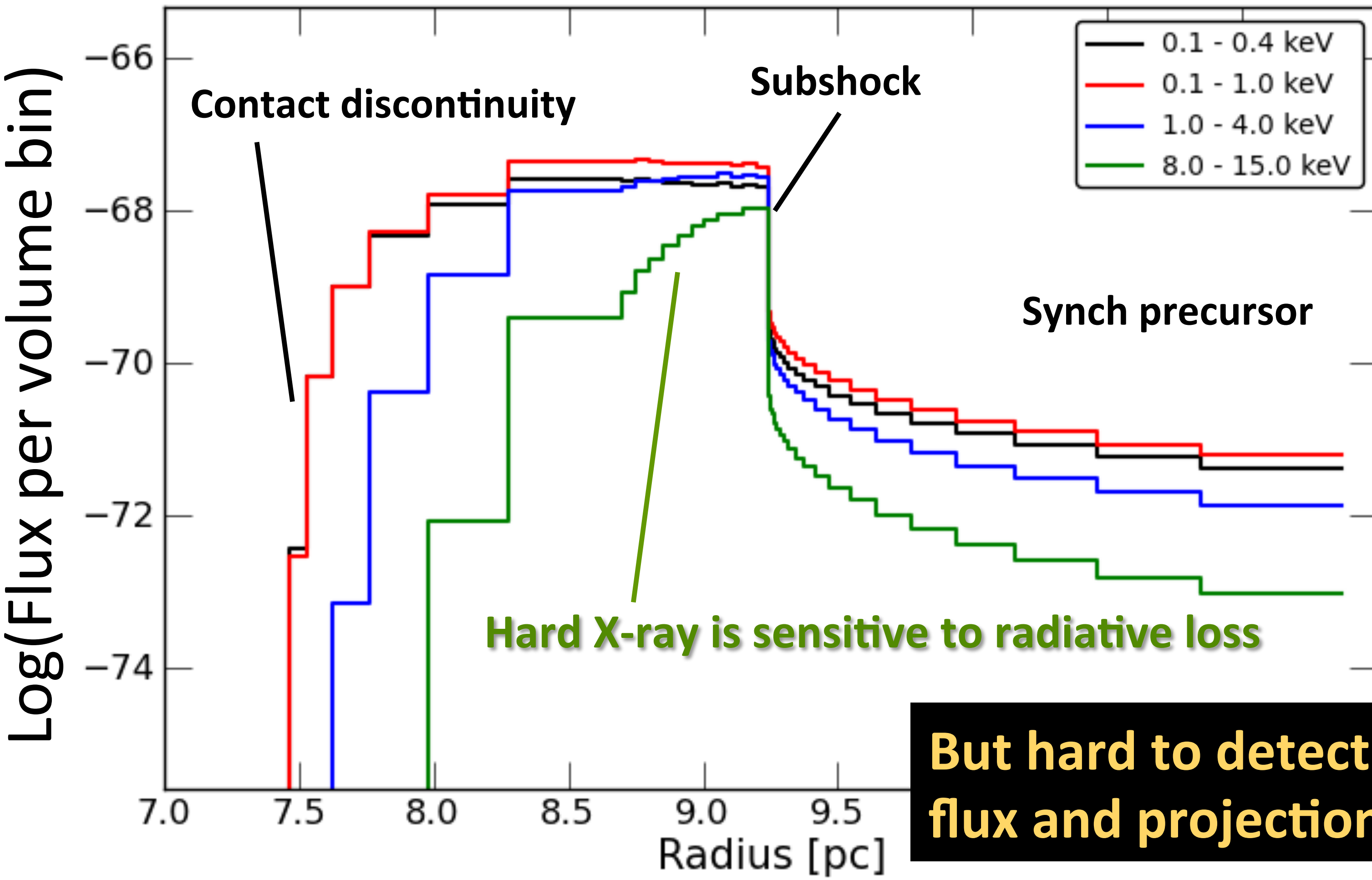


Space-resolved particle spectrum



This means we can calculate nonthermal emission at precursor

Example – synchrotron precursor



But hard to detect due to low flux and projection effect

Precursor magnetic field amplification

Alfven wave generation through streaming instability of protons

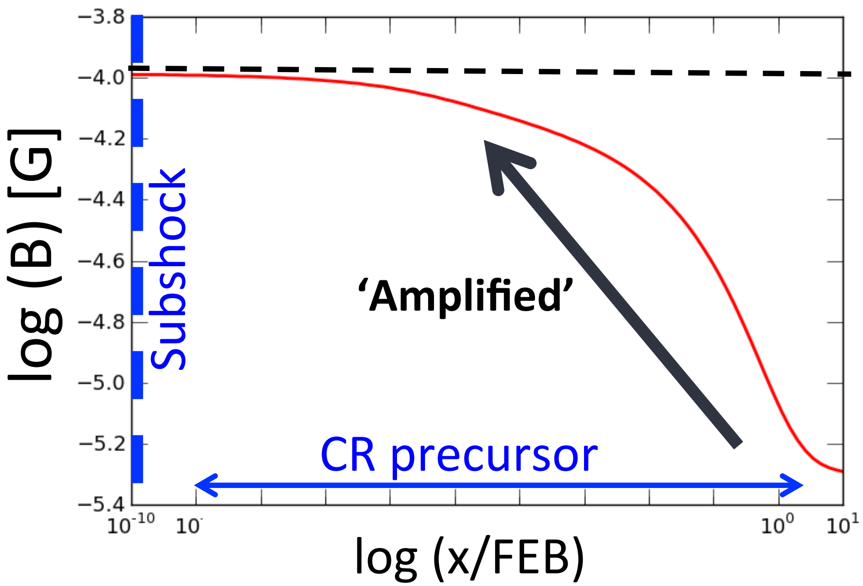
Quasi-linear solution for scalar **magnetic turbulence pressure P_w**

$$P_w(x) = \frac{\delta B(x)^2}{8\pi} = \frac{(1 - f_{\rm damp})\rho_0 u_0^2}{4M_{A,0}} \left(\frac{1 - U(x)^2}{U(x)^{3/2}}\right)$$

$U(x) = u(x)/u_0$ is flow speed in precursor

QL Alfven wave generation (roughly scales with gradient of CR pressure dP_{CR}/dx)

Adiabatic compression (assume frozen-in field)



$B_1 = 1 \times 10^{-4}$ G

$B_0 = 3 \times 10^{-6}$ G

Efficient DSA can easily amplify B_2 / B_0 ~ **100 fold**

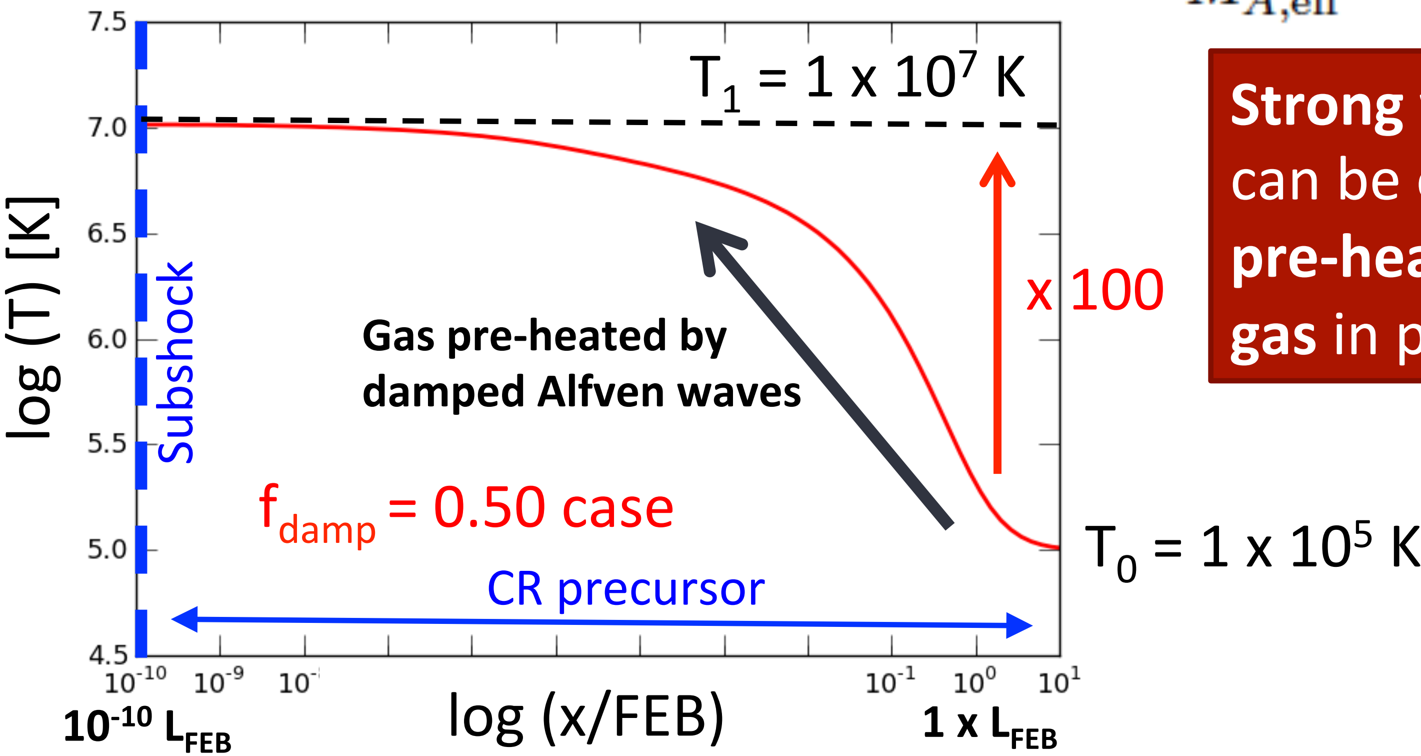
(note: we extend QLT to high amp. regime)

Precursor plasma heating

$$T(x) = T_0 \left[\frac{P_g(x)}{P_{g,0}}\right] U(x)$$

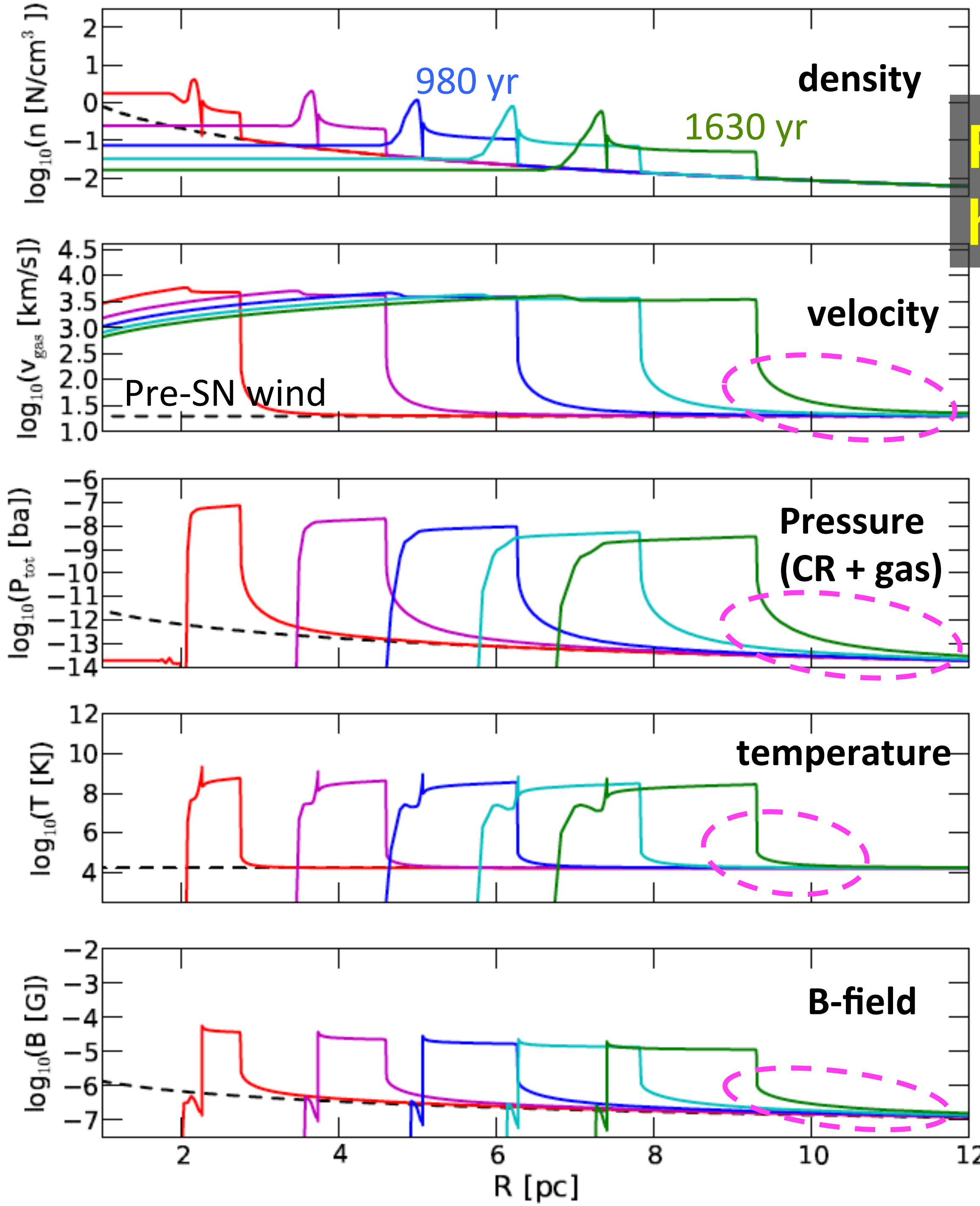
$$= T_0\, U(x)^{1-\gamma_g} \left[1 + f_{\rm damp}(\gamma_g - 1)\frac{M_0^2}{M_{A,\rm eff}}(1 - U(x)^{\gamma_g})\right]$$

Assumption:
wave damp rate = f_{damp} x (growth rate)



Strong wave-damping can be efficient for **pre-heating incoming gas** in precursor

Precursor included in hydro consistently



Upstream gas 'pre-accelerated' by CR precursor (smoothed shock)

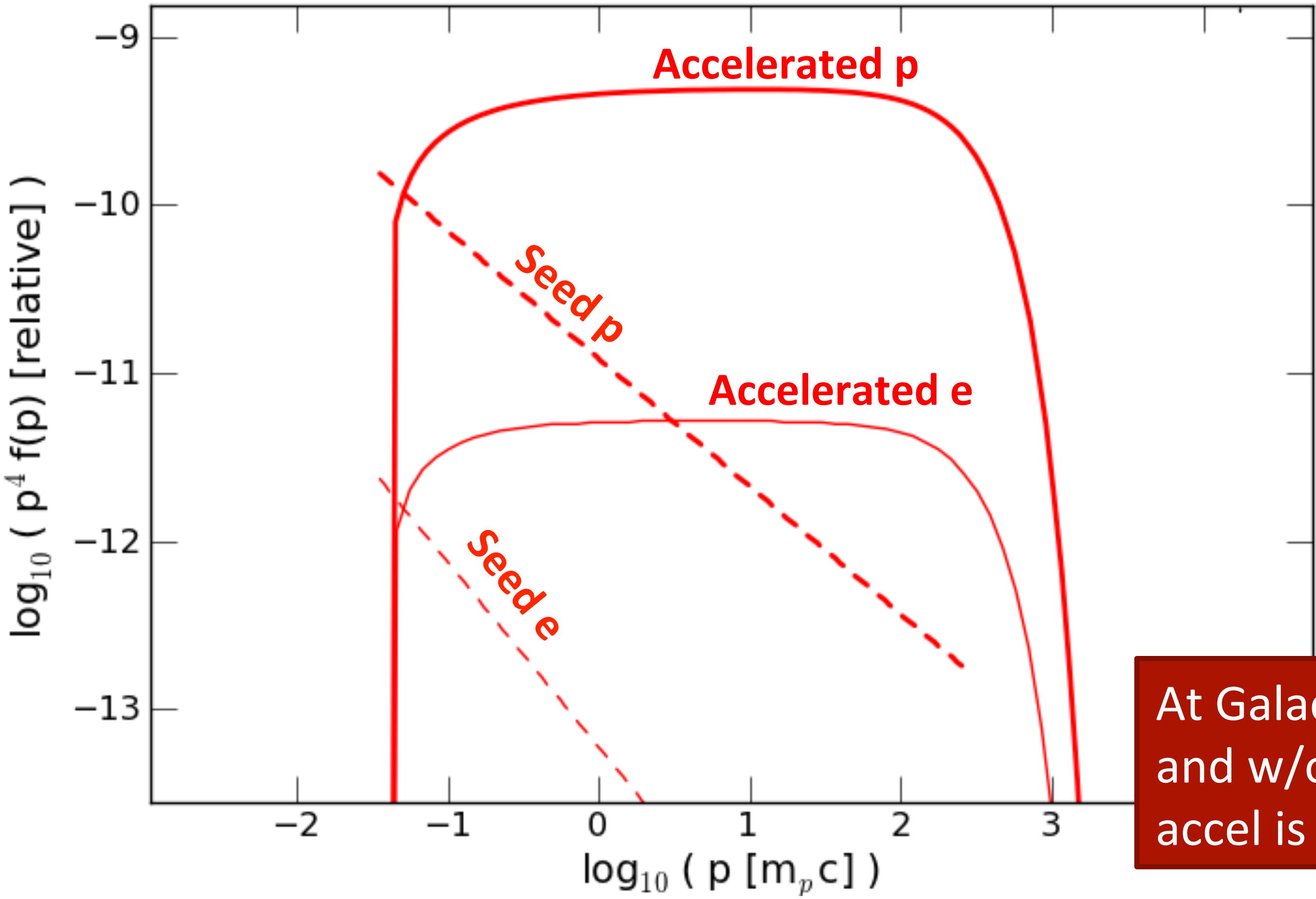
CR precursor exerts back-pressure in hydro

Precursor heating by damped waves + adiabatic compression

Magnetic field amplification

Acceleration of seed CR populations

(In addition to acceleration of thermal-injected particles)



Example

PL seed spectra

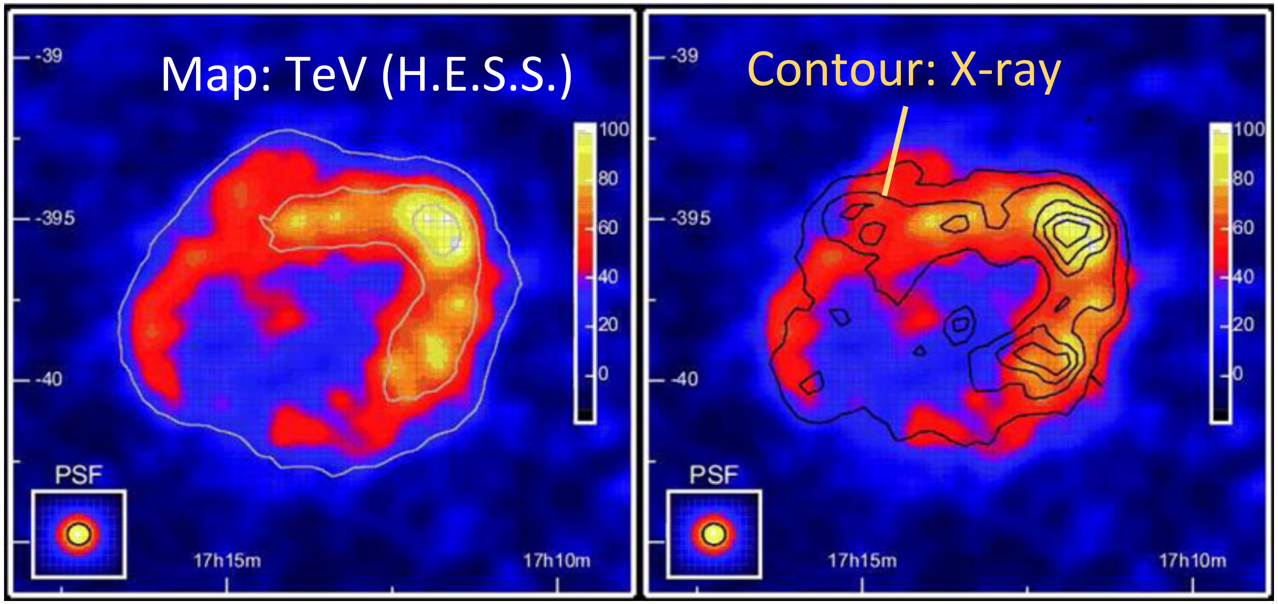
$f_p(p) \sim p^{2.76}$

$f_e(p) \sim p^{3.10}$

$P_{CR,0} / P_{gas,0}$
= 0.2 (p)
0.002 (e^-)

At Galactic CR level, and w/o thermal inj, accel is in **TP regime**

An application to young SNR
RX J1713.7-3946

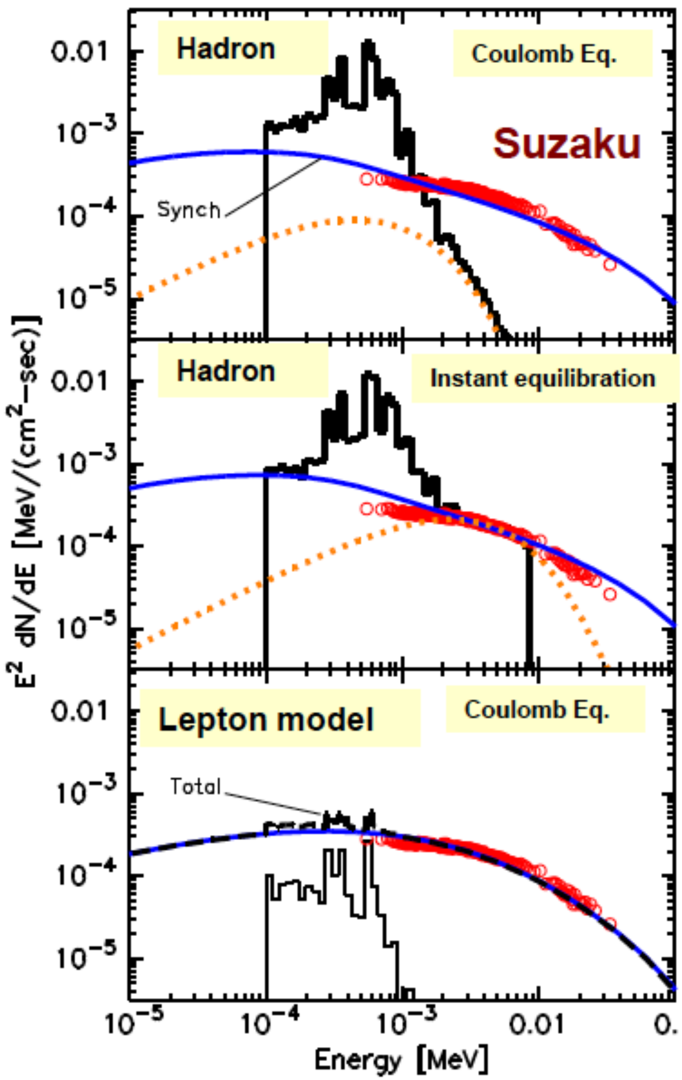


Gamma-ray - Hadronic or Leptonic?

Ellison et al (2010) model using an isolated remnant with uniform CSM

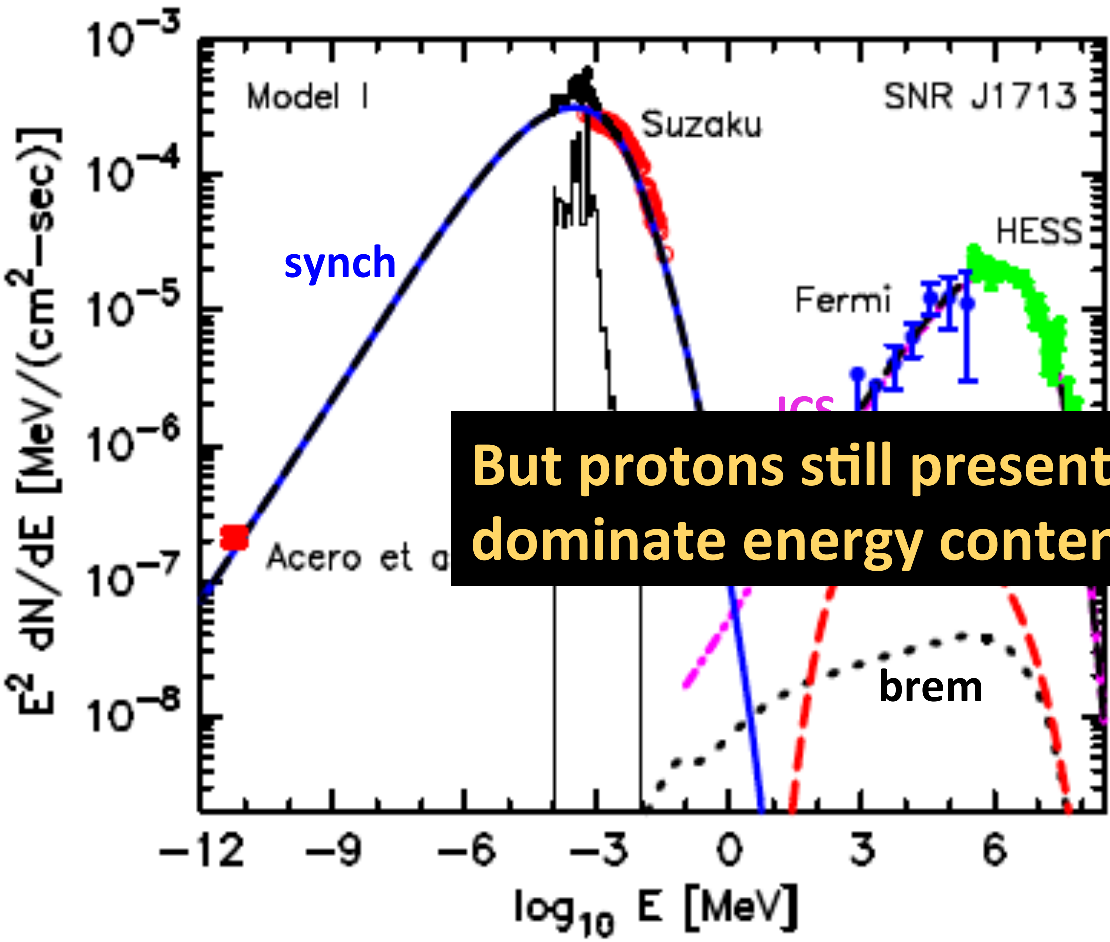
- **Gamma-ray origin**:
  - Answer lies in the **X-ray band**
- Hadronic model requires high ambient density for p-p to dominate over ICS in TeV
  - **Makes thermal X-ray too strong**
- **Leptonic model gives good fit throughout the spectrum**

Ellison et al (2010)



Broadband SED – a fit to RX J1713

Model with uniform CSM and pre-SN wind



But protons still present and dominate energy content!

Best-fit model is **not unique**

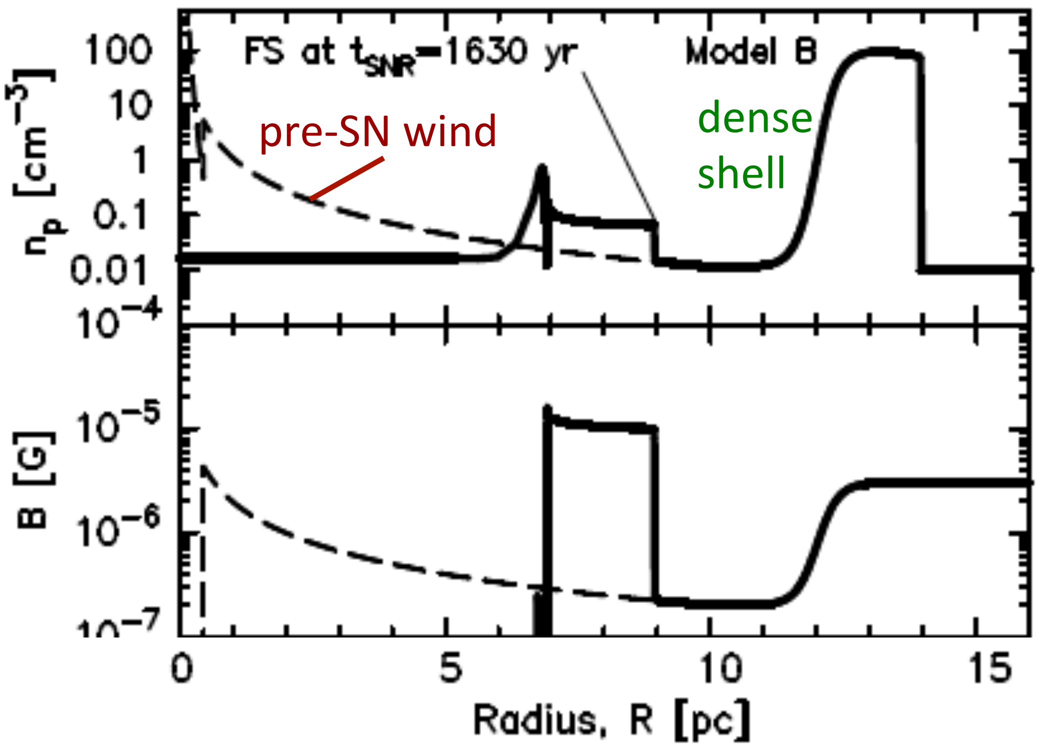
Allows a range (~20%) for some parameters to give reasonable fits

But conclusion is robust:
Leptonic model if SNR is isolated in uniform CSM

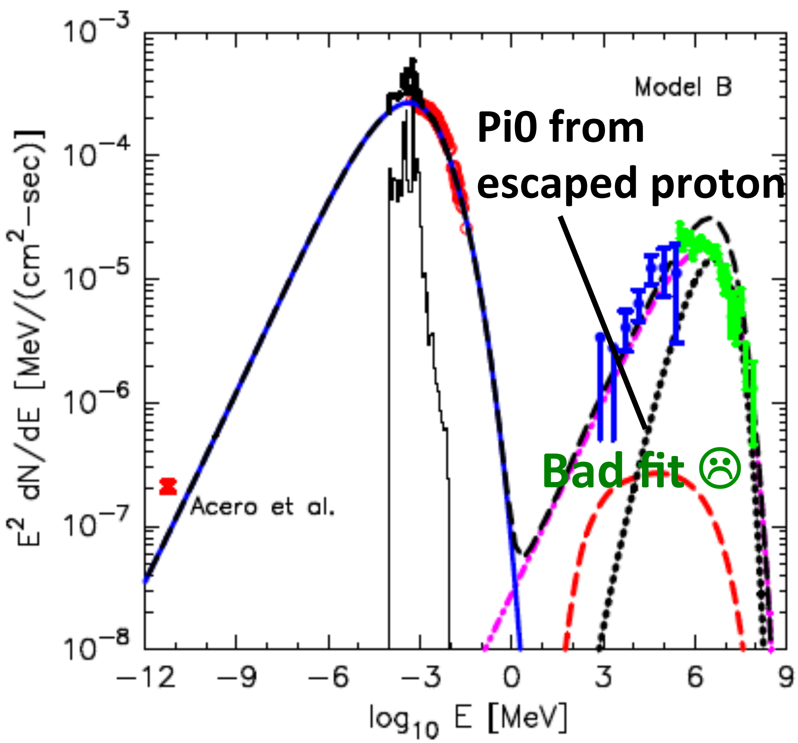
Possibility for interaction with clouds

Ellison et al (2012) – model B
w/ nearby isolated massive cloud

Escaped CR interacts with 10^4 solar mass cloud



Gamma-ray SED too 'peaky'?
But shape strongly depends on (poorly known) CR escape and diffusion properties



Possibility for interaction with clouds (2)

Ellison et al (2012) – model C

Shock runs into massive cloud

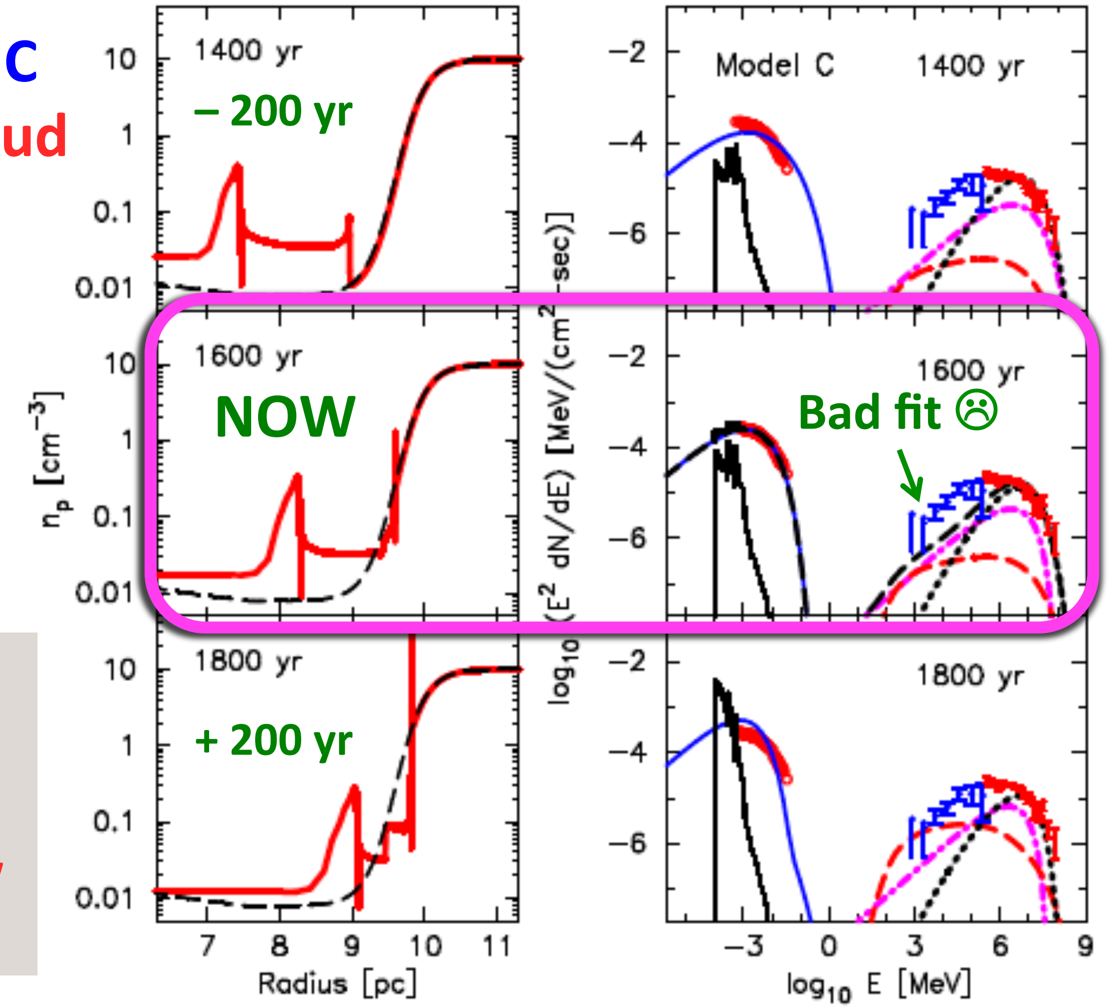
Escaped + trapped CR interacts with 10^4 solar mass cloud

Shock ascending 'density ramp'

- Need n_0 ~ 1 cm^{-3} to suppress thermal X-ray

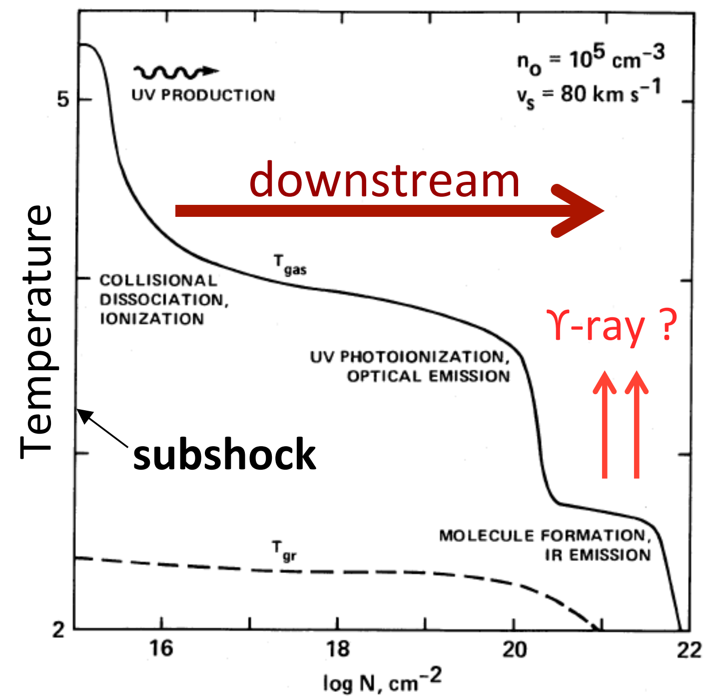
Thermal X-ray and pion gammas varies w/ 100 yr time-scale

Gamma-ray SED again too narrow at 1600 yr in the model



Current Effort

- Modeling DSA at **radiative shocks** found in 'middle-aged' SNRs
  - Current collaborators: Dan Patnaude, John Raymond (Harvard, CfA), S. Nagataki (YITP)
- Important for SNR **directly** interacting with molecular clouds w/ fast cloud shocks (v_{sk} ~ 100 km/s)
- **Enhanced gamma-rays in dense cold shell?**
  - **High density, compressed CR, high magnetic field**
  - (see e.g. Uchiyama et al 2011 for W44, IC443, …)
- Important things to implement:
  - Ion-neutral damping & spectral break/cutoff
  - Photoionization and heating by continua
  - Cooling by optical & NIR line emission
  - Molecule reformation
- **Approach: couple NLDSA to 1D radiative hydro**



Hollenbach & McKee (1989)

Summary

- We have introduced the **CR-hydro-NEI code**
  - **Non-linear particle acceleration coupled to dynamics** of SNR shocks
  - Important physics taken into account
  - Useful for realistic multi-λ spectral and morphological interpretations
- Code well tested against popular Monte Carlo and semi-analytic models
- Ongoing works:
  - extend code to handle fast radiative shocks in atomic/ molecular clouds
  - Interpret observations of young and mid-aged SNRs