Modeling the Thermal and Non-thermal Emission of Young Supernova Remnants

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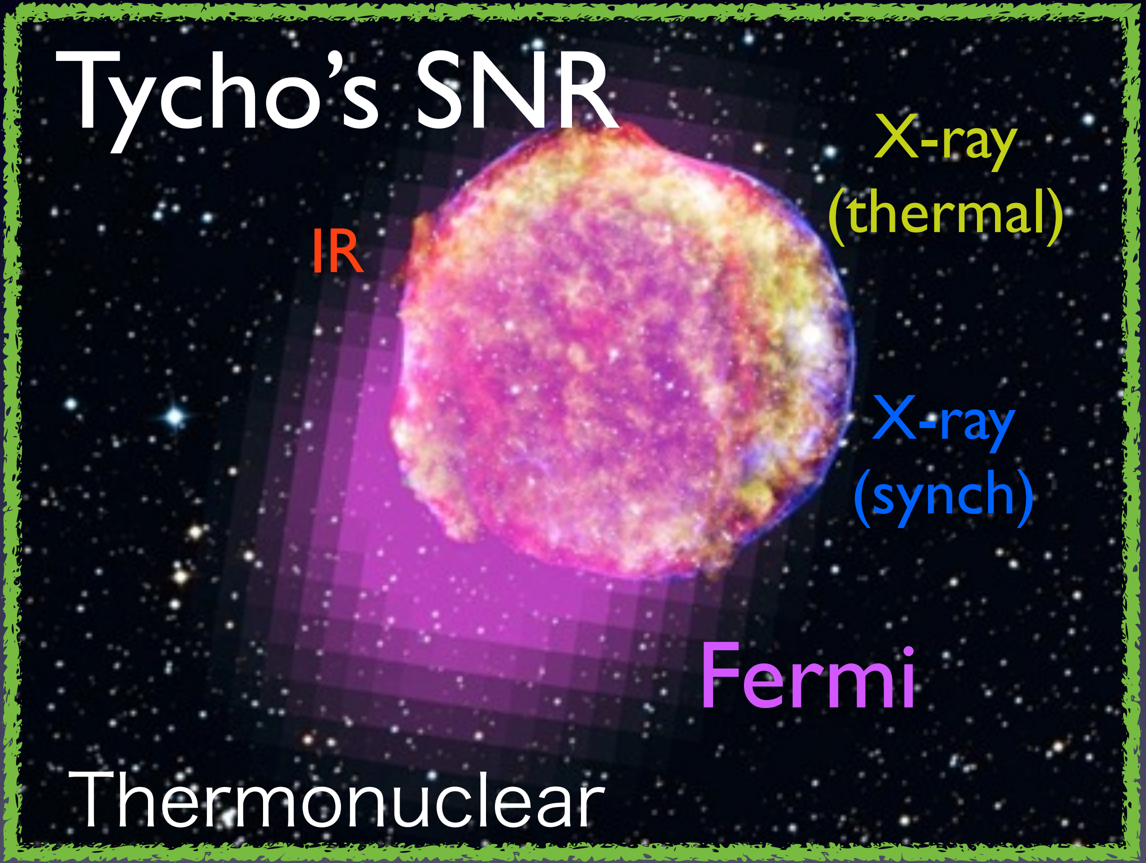
Outline

- The challenge of modeling the many facets of SNR broadband emission
  - What a physical emission model needs to account for
  - What "hurdles" from observation data it must overcome

- What we can learn from the models and their confrontations with current+future observations

Behold!

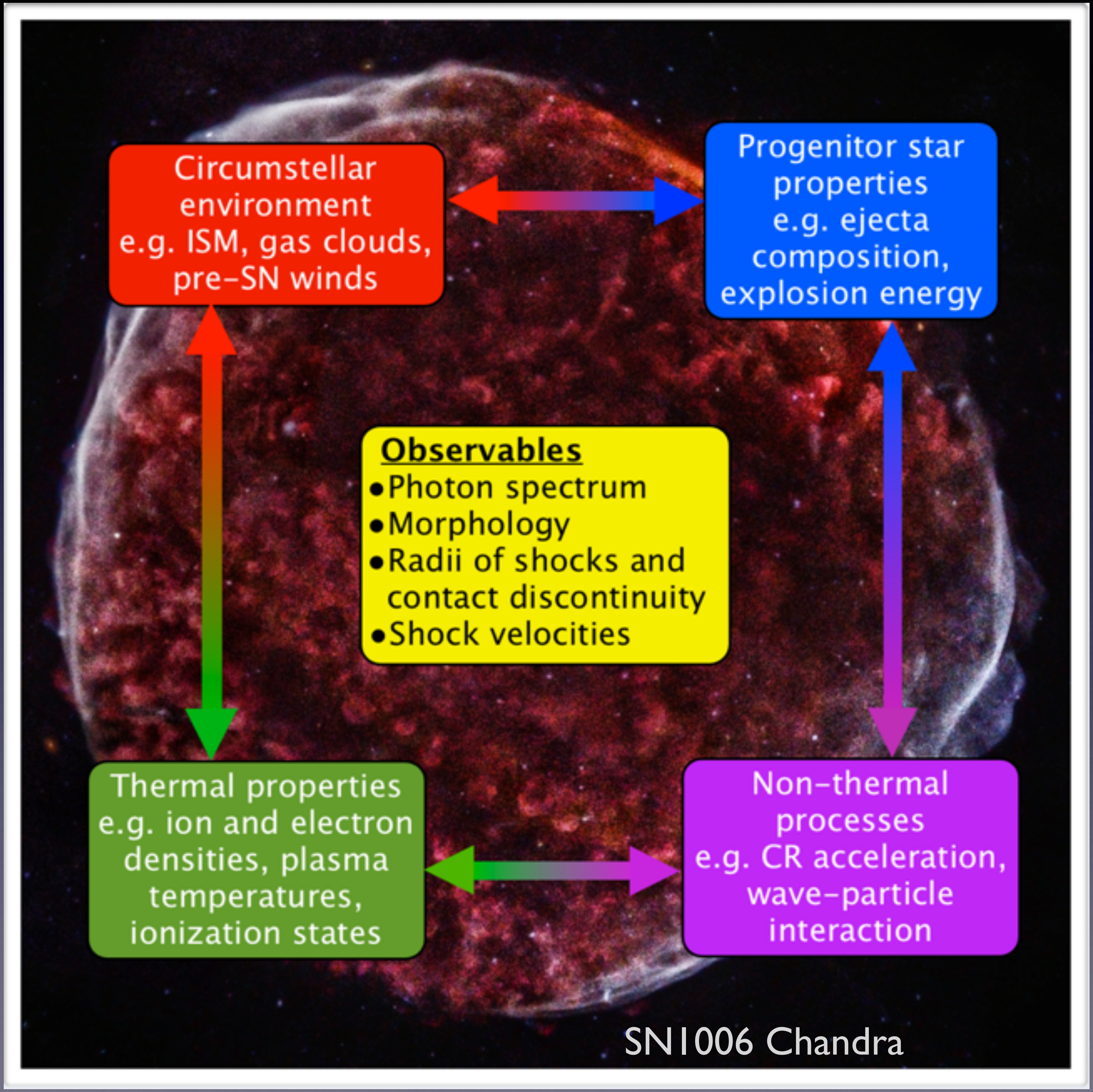
The **Multi-wavelength Era** has come



To build a truly successful model of SNR emission:

Synergy of all available broadband data AND modeling by a good physical model are the keys

SNRs are complex stuff



SNRs are complex stuff

For young SNRs,
all these are linked together
in non-linear fashion!
We need multi-λ info and
comprehensive models

Any serious broadband emission model of SNRs must overcome a number of **Hurdles from Observations**:

Matching FS, CD and RS radii

Matching shock speeds (expansion rates)

Non-thermal spectrum (radio - TeV)

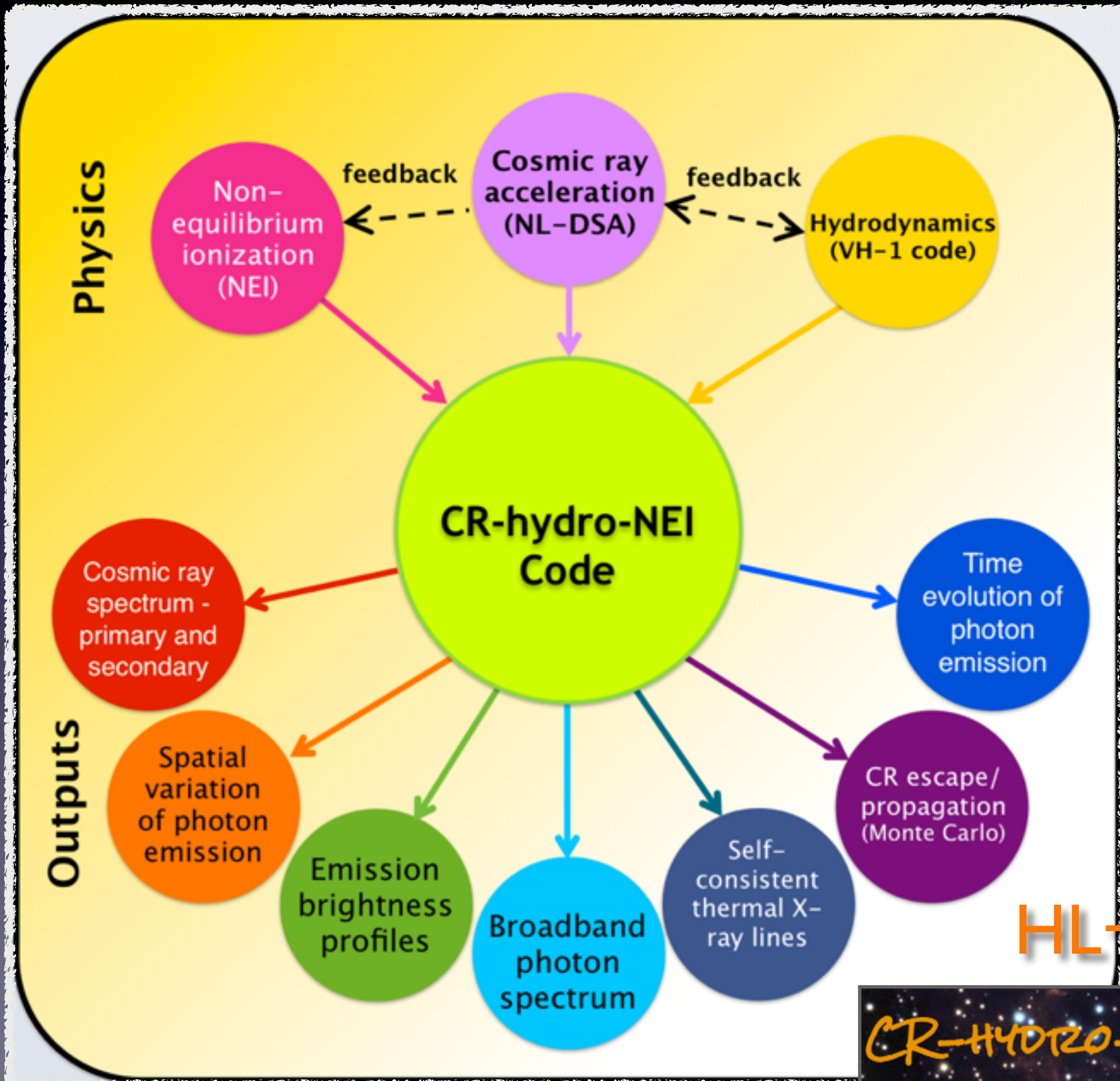
Thermal spectrum (ionization, composition)

Multi-λ morphology

Spectral variation in space-time

etc......

Our recipe to model SNR emission



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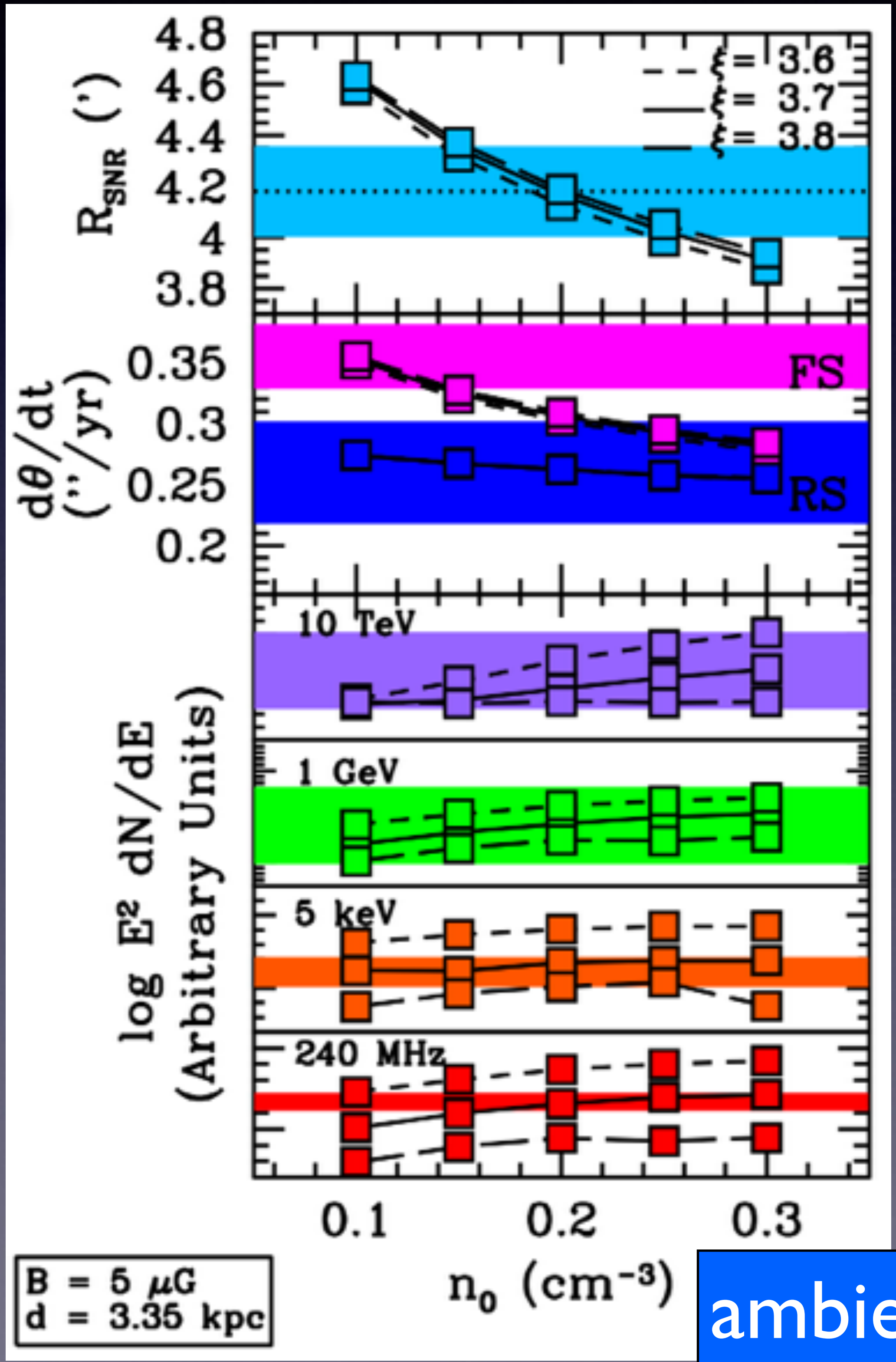
CR-HYDRO-NEI CODE

Code is inexpensive
Perfect for deep parameter search

Preliminary

Slane, HL+ submitted

First, we search for parameter space consistent with observational facts



fixed inputs

ambient density

SNR shell radius

Expansion rates

Photon flux

Gamma-ray

X-ray

Radio

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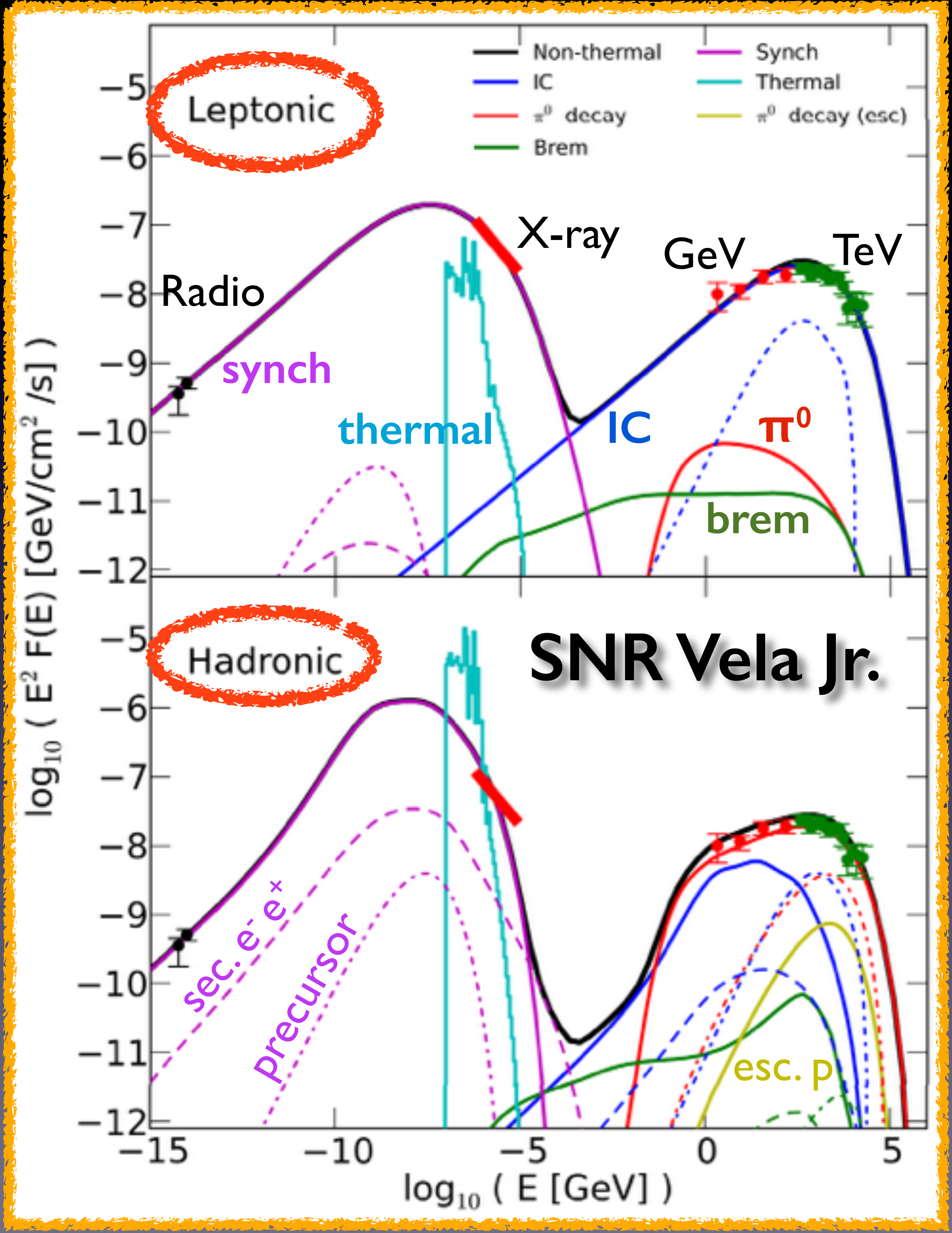
Broadband Spectrum

Check consistency of:

- Radio to TeV flux
- Spectral shapes
- Inferred CR energetics
- Required B-field, CSM, E_{SN}

But often, more than one acceptable models exist (e.g. hadronic vs leptonic)



Thermal X-ray can constrain Gamma-ray origin

In young SNRs, thermal X-ray emission is *coupled* to their broadband emission!

Very important:
Predicted thermal flux must not exceed observed X-ray flux
= another constraint

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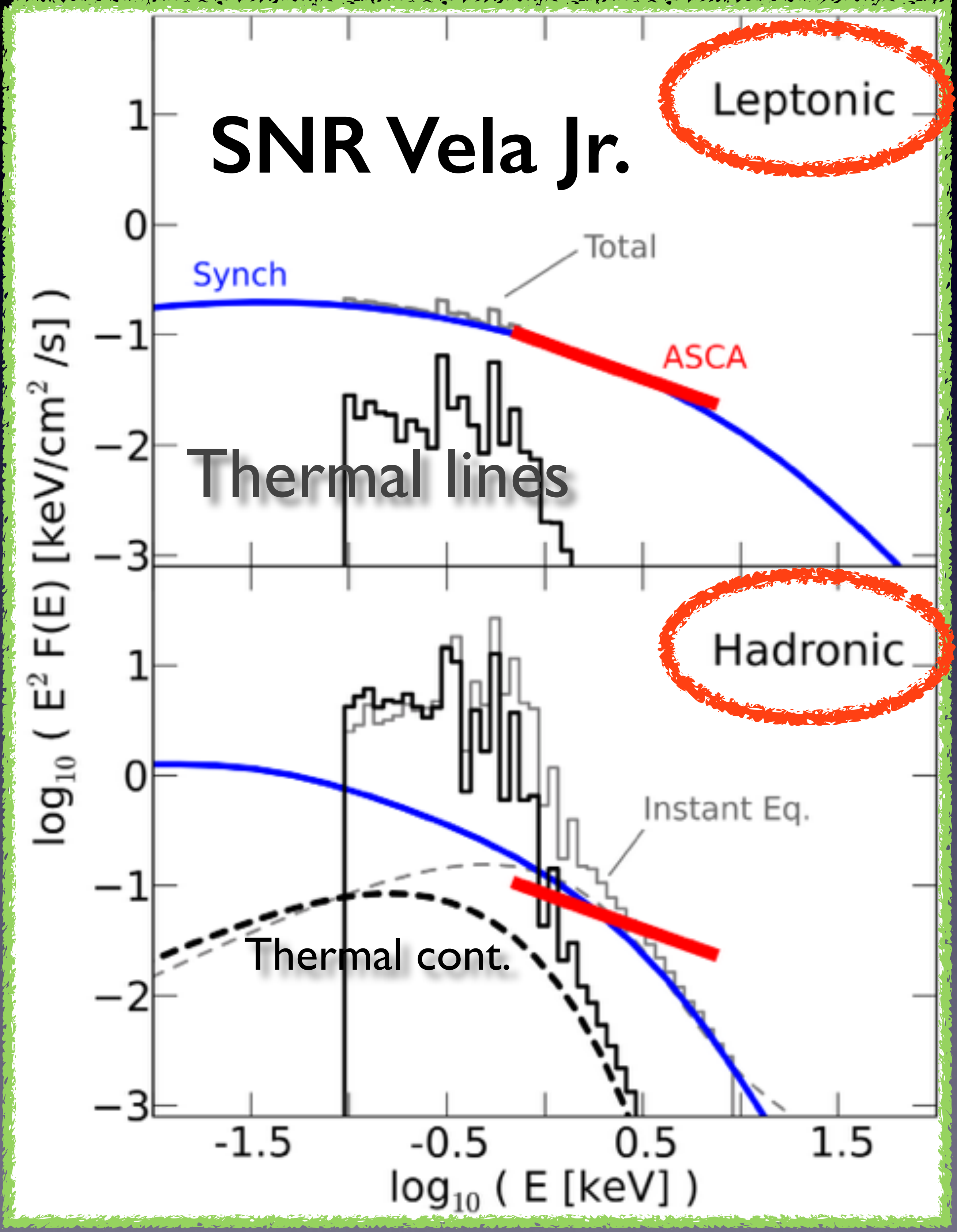
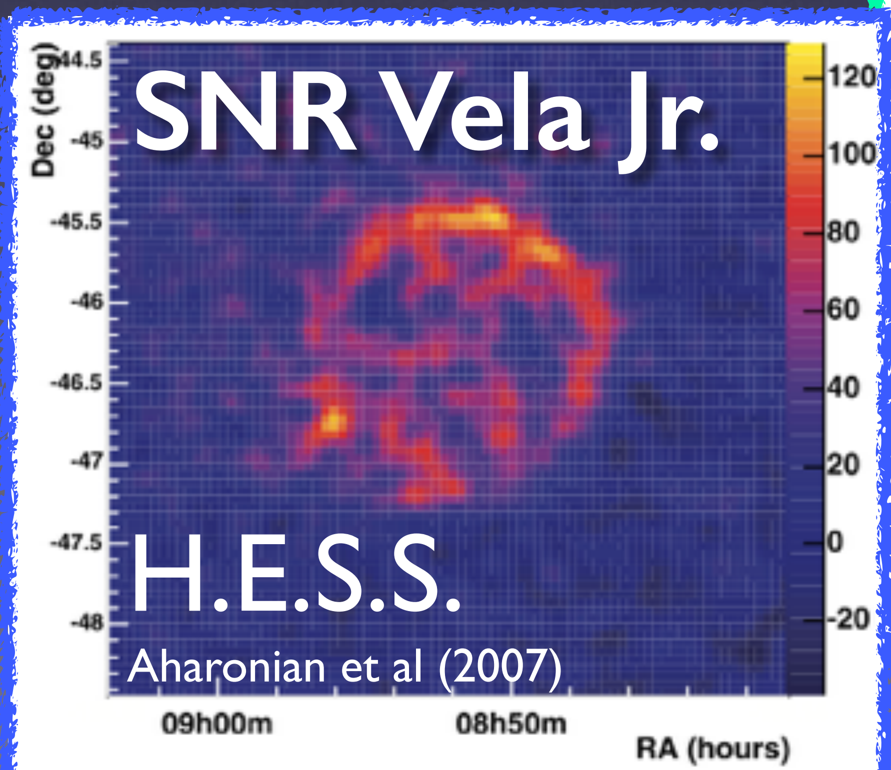
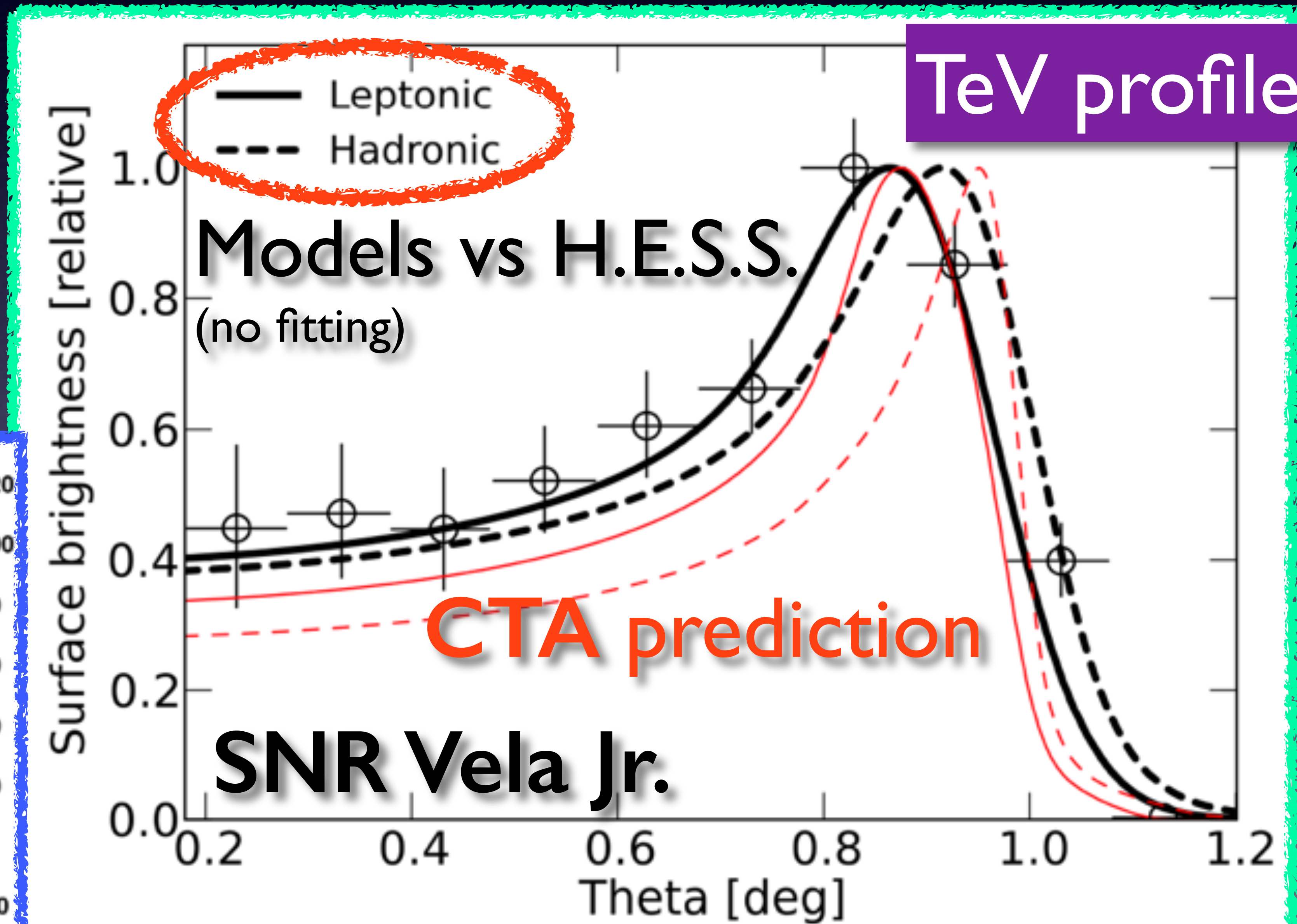


Radial emission profiles probe γ-ray origin & DSA efficiency

Radio, X-ray and TeV morphologies all constrain CR acceleration and energy loss history





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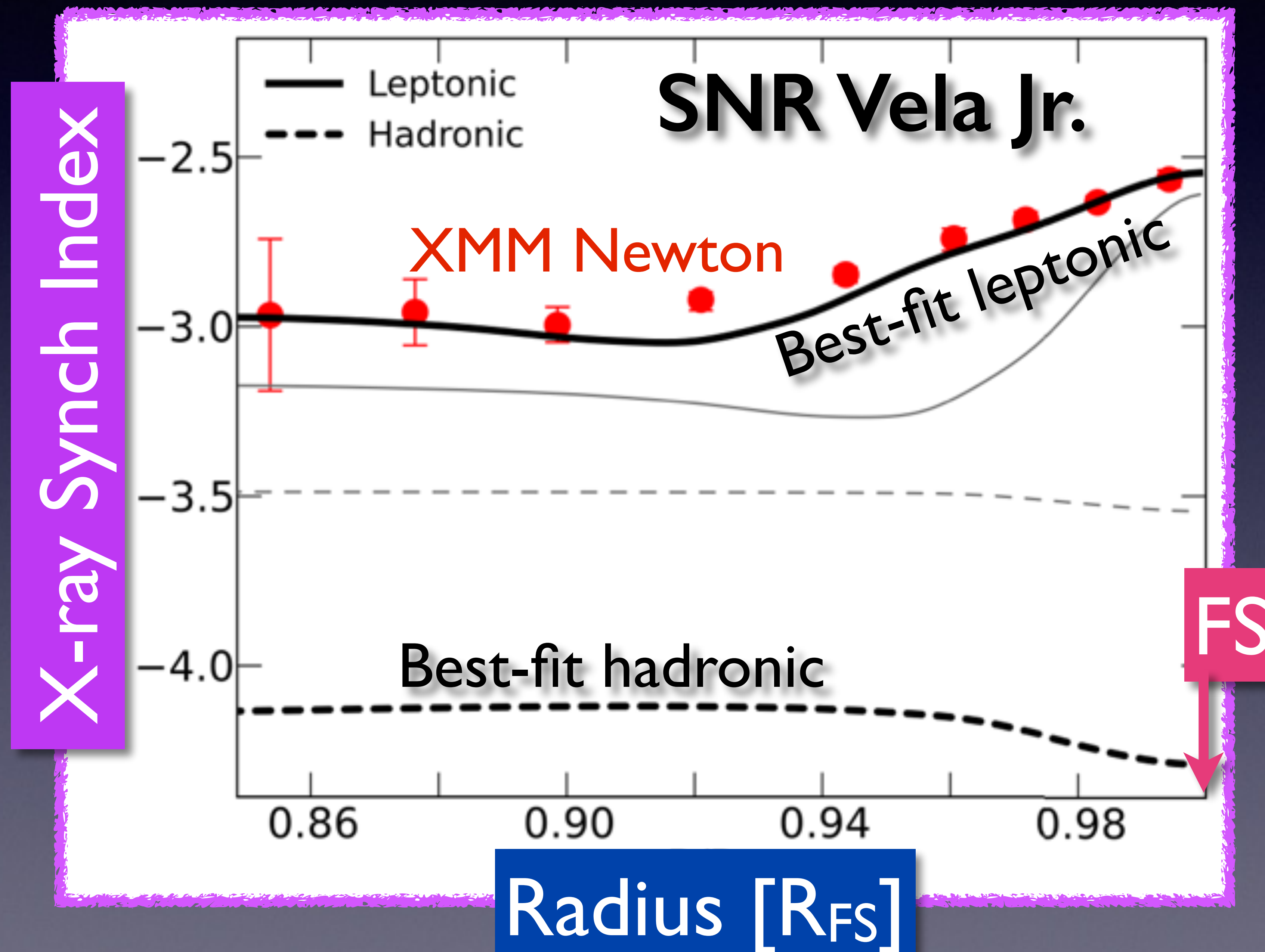
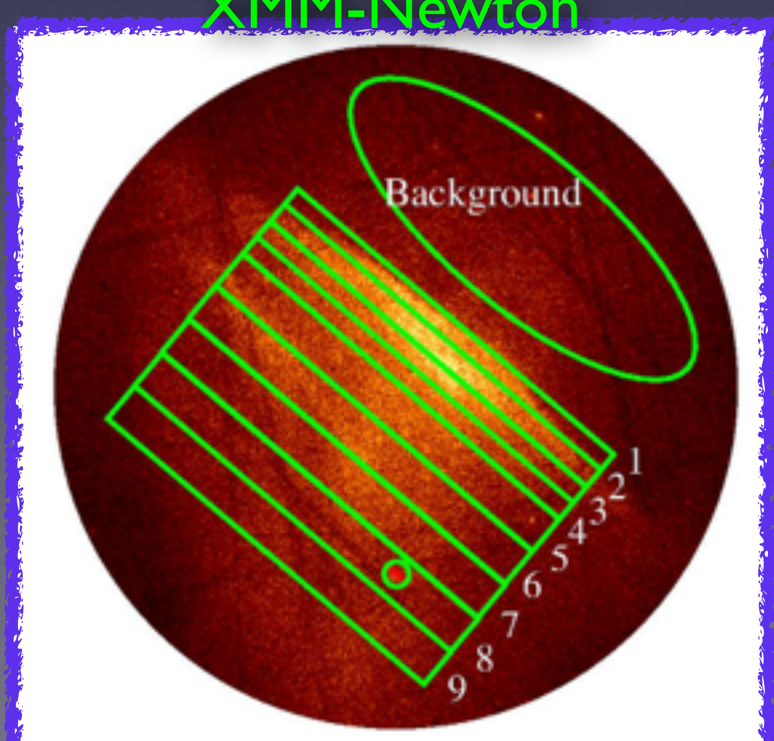
Spectral index distribution
as a model discriminator

Hadronic and leptonic models predict very different spectral index distributions (e.g. CSM, B-field)



Kishishita & Uchiyama 2013
XMM-Newton



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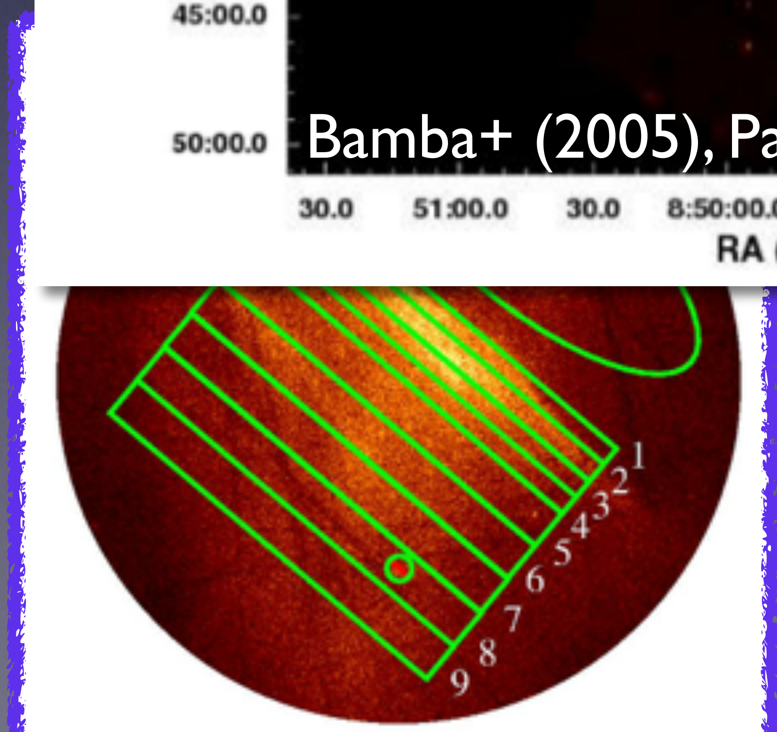
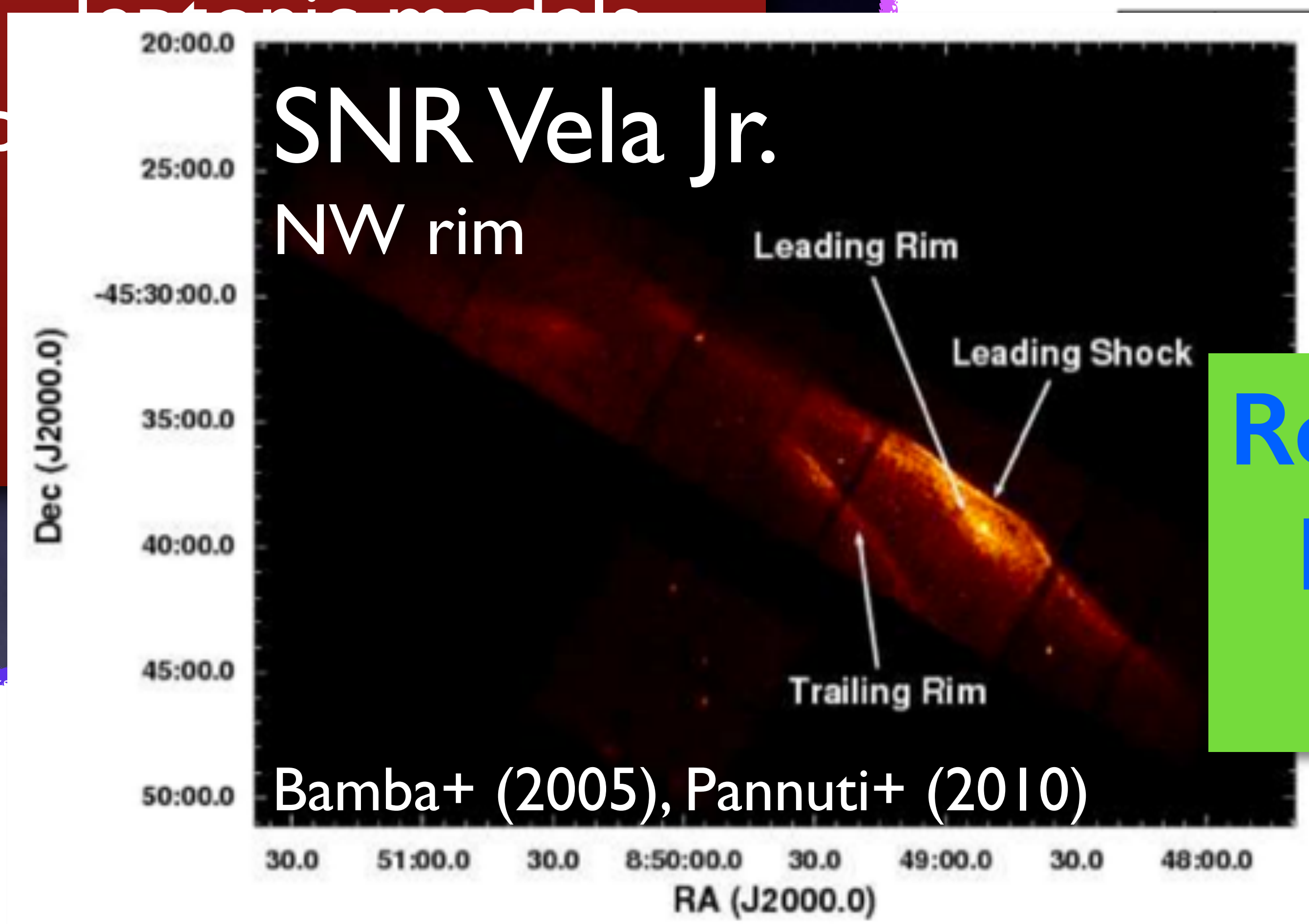
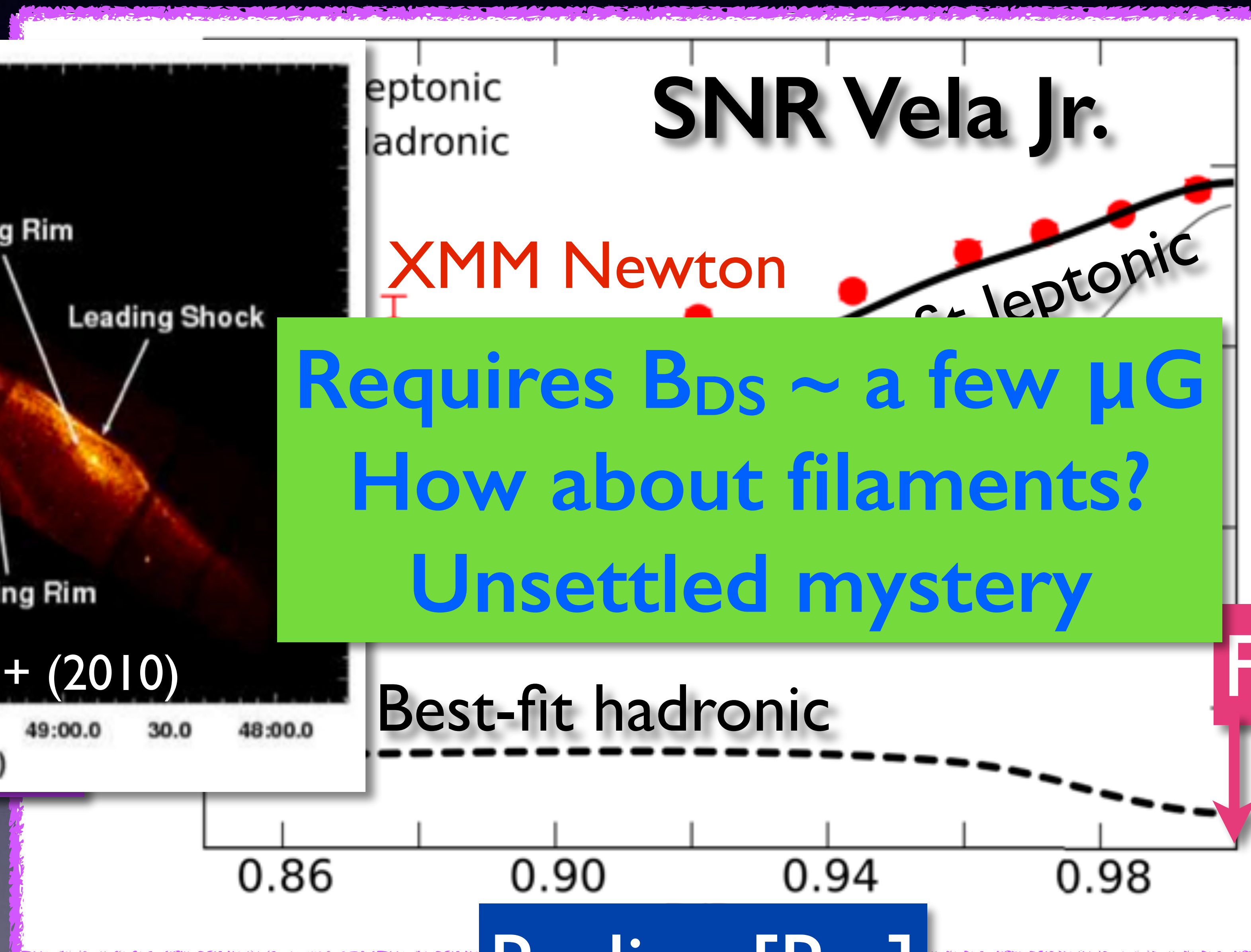
Spectral index distribution
as a model discriminator

Hadronic and







Requires B_{DS} ~ a few μG
How about filaments?
Unsettled mystery

Radius [R_{FS}]

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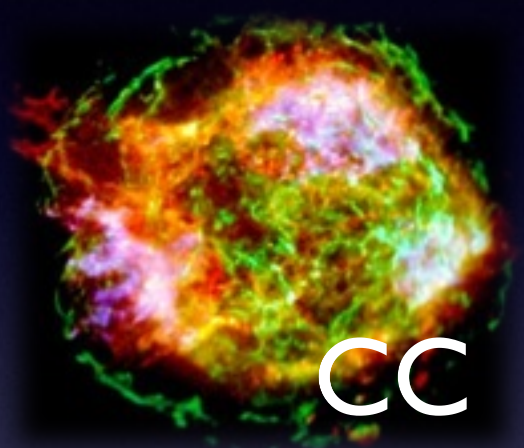
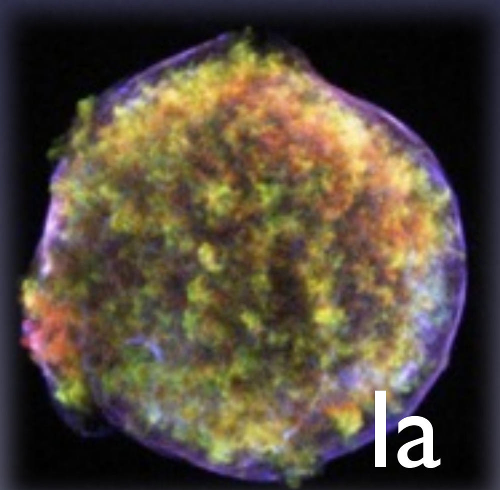
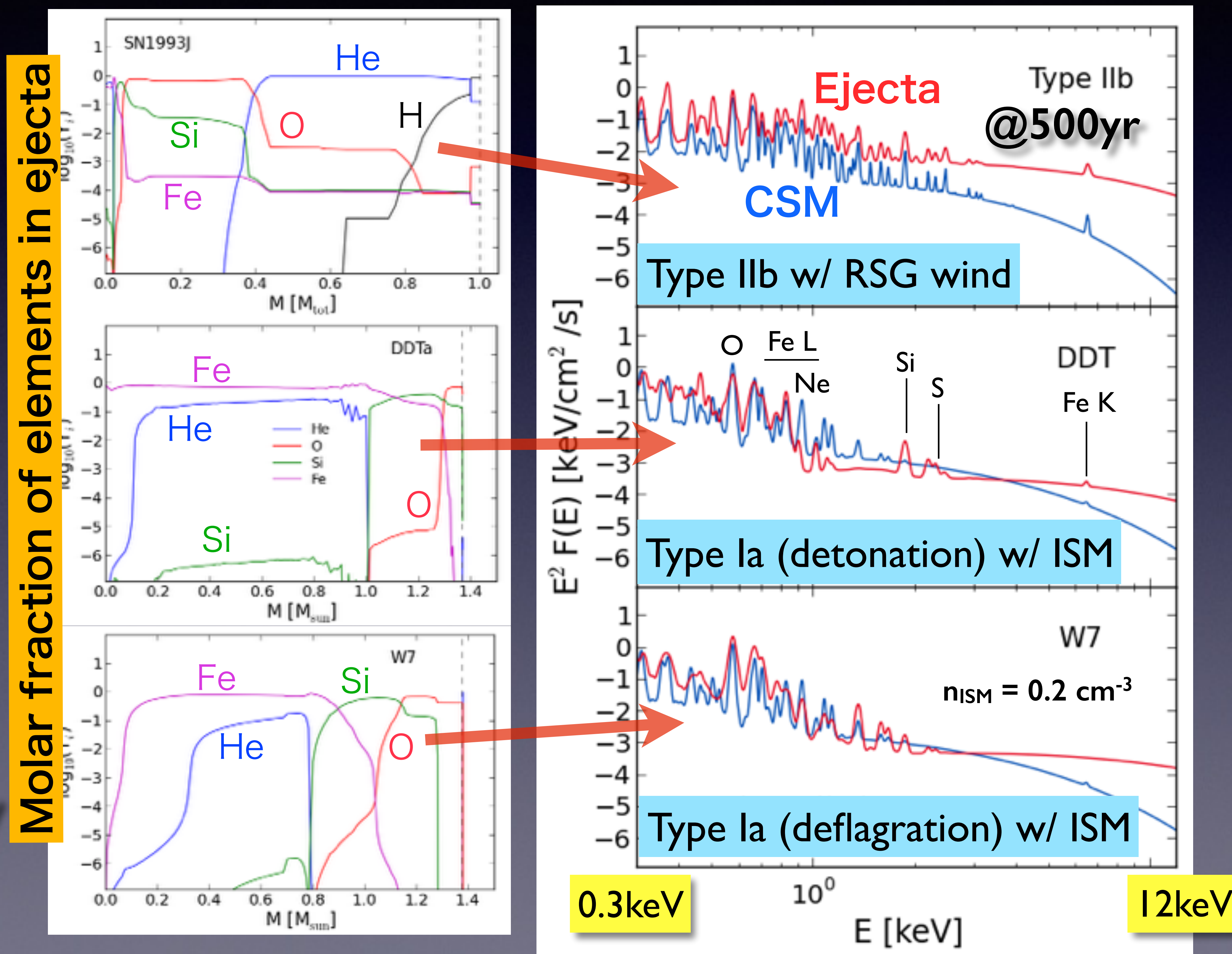
Ejecta/CSM models and synthetic X-ray spectrum





Preliminary
HL+ in prep



What do we learn?

- A good broadband emission model tightly constrained by MW observations can tell us a lot, e.g.:
  - Origin of γ-rays from a SNR (CR ion, or CR e^-, or a mixture)
  - Fraction of SN explosion energy converted to CR at given age (Note: CR ions always dominate total energy even for leptonic models)
  - Properties of ejecta, CSM, progenitor and its pre-SN winds
- We can quantify contributions of different types of SNR to Galactic CR in their lifetimes
  Note: hadronic and leptonic cases often predict very different E_{CR}
- Our models can consistently bridge state-of-the-art hydro and explosive nucleosynthesis simulations of SNe to the SNR phase by covering important (non-)thermal physics!

Synergy of future super telescopes for SNR studies

Hi-res X-ray spectroscopy

- Ejecta/CSM composition from faint lines
- Unveil progenitor properties of Ia and core-collapse SNRs
- SN explosion mechanisms, matter mixing and nucleosynthesis
- Broadened line profiles: gas dynamics, temperature equilibration

Hi-sensitivity, hi-res imaging

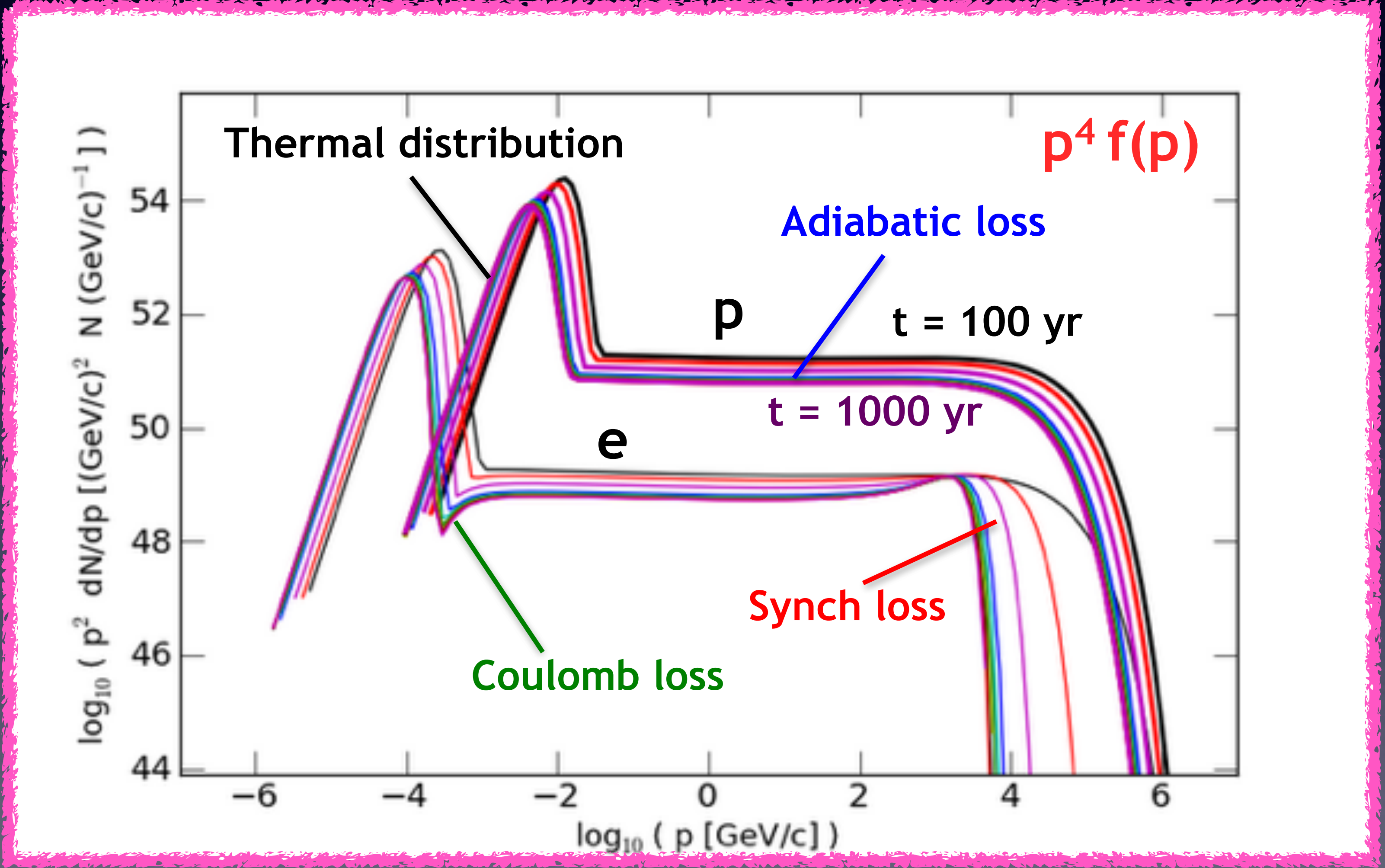
- Many new gamma-ray SNR discoveries
- Low-noise spectrum measurement from ~20GeV to >100 TeV
- Measure roll-over region of CR spectra!
- 3x better TeV morphology measurement to contrast with radio/IR/X-ray images

Last remarks

- CR-hydro-NEI code is a fast/versatile code for broadband emission calculations of SNRs
- Next target is full 3-D MHD/emission models (with essential physics inside!)
  Work now in progress (RIKEN/NCSU/Kyushu/…)
- Our self-consistent spherically symmetric calculations serve as important pilot study

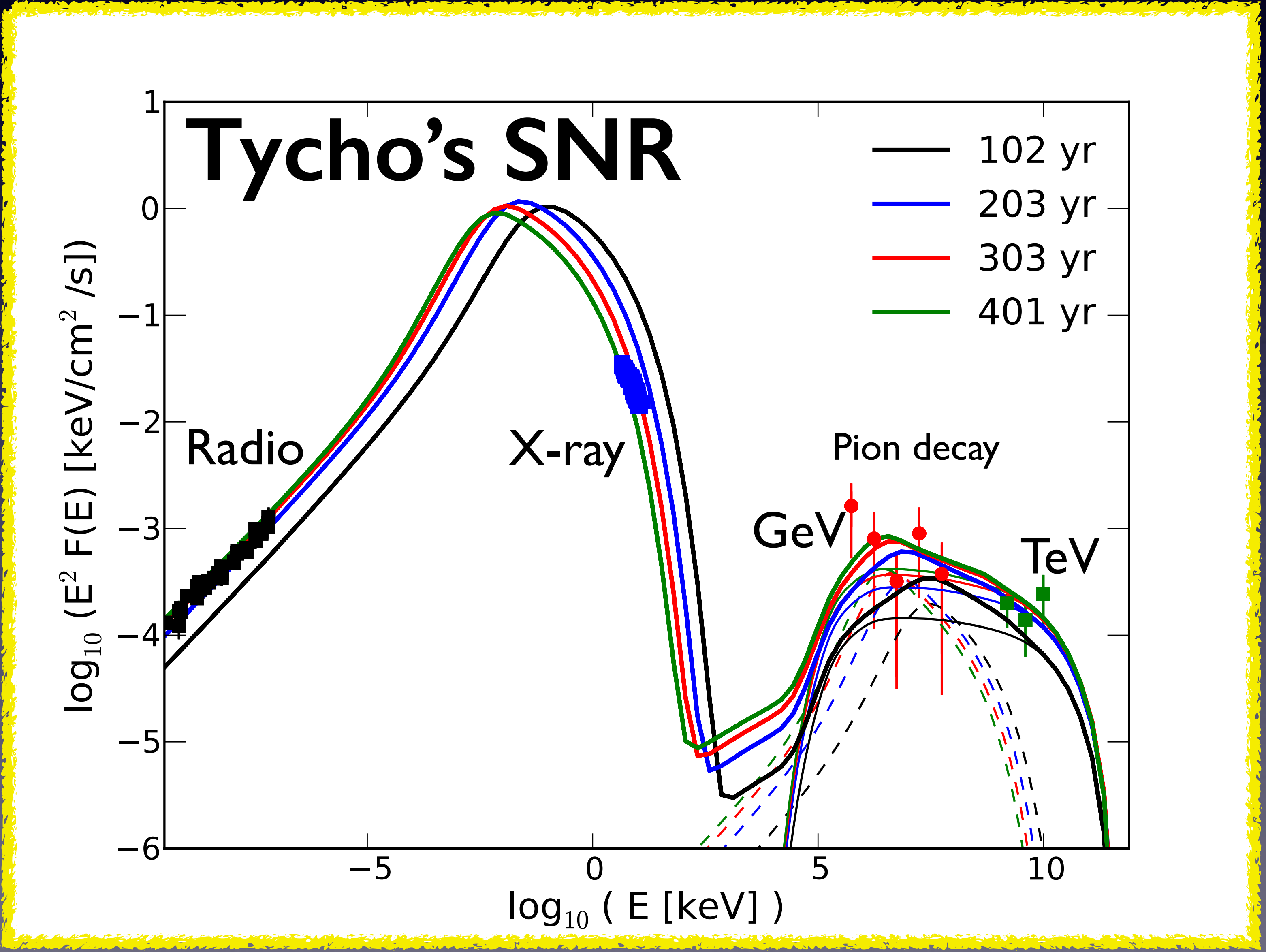
Additional info

CR Spectra



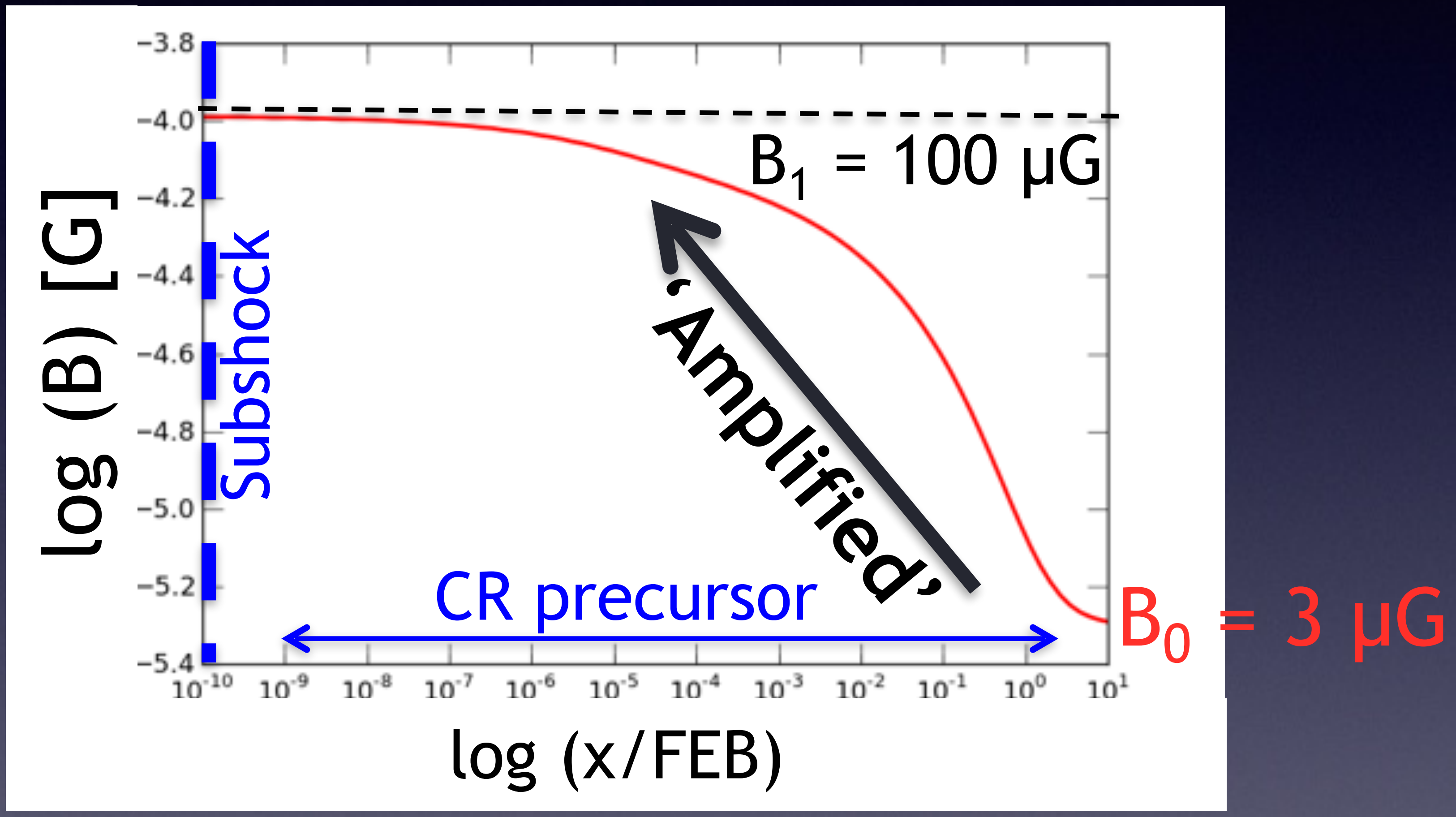
Thermal distribution
p⁴ f(p)
Adiabatic loss
p
t = 100 yr
t = 1000 yr
e
Synch loss
Coulomb loss
log₁₀ (p² dN/dp [(GeV/c)² N (GeV/c)⁻¹])
54
52
50
48
46
44
−6
−4
−2
0
2
4
6
log₁₀ (p [GeV/c])

Time evolution of broadband spectrum



Slane, HL+ submitted

Magnetic Field Amplification (MFA)



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

Alfven wave damping precursor gas heating

$$
\begin{aligned}
T(x) &= T_0 \left[\frac{P_g(x)}{P_{g,0}}\right] U(x) \\
&= T_0\, U(x)^{1-\gamma_g} \left[1 + f_{\rm damp}(\gamma_g - 1)\frac{M_0^2}{M_{A,\rm eff}}(1 - U(x)^{\gamma_g})\right]
\end{aligned}
$$

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