Efficient CR Acceleration and High-energy Emission at Supernova Remnants

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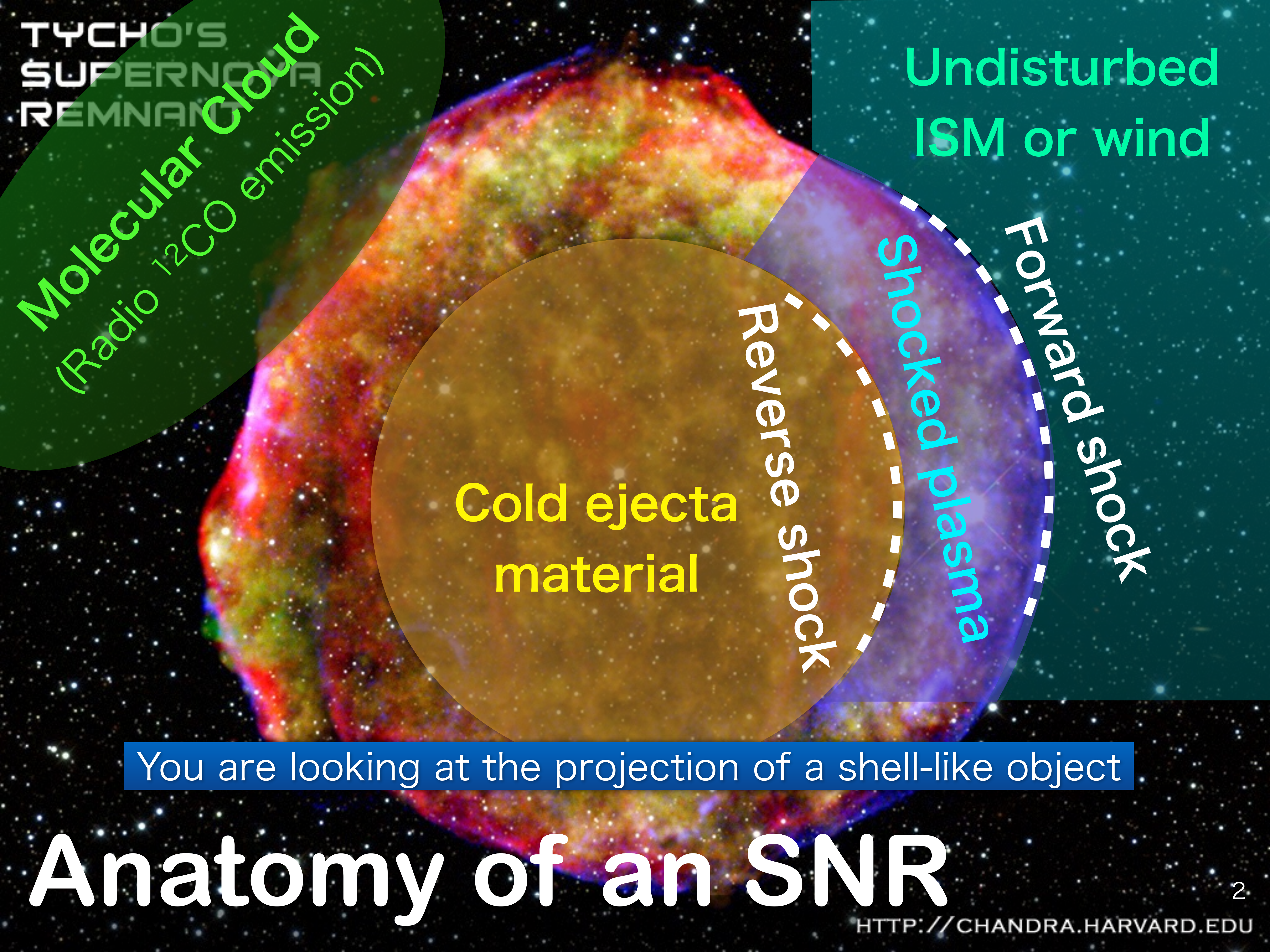
Explore to Realize

PACIFIC 2014, Moorea, French Polynesia, 15-20 Sep 2014


TYCHO'S SUPERNOVA REMNANT
Molecular Cloud
(Radio 12CO emission)
Undisturbed ISM or wind
Cold ejecta material
Reverse shock
Shocked plasma
Forward shock
You are looking at the projection of a shell-like object
Anatomy of an SNR
2
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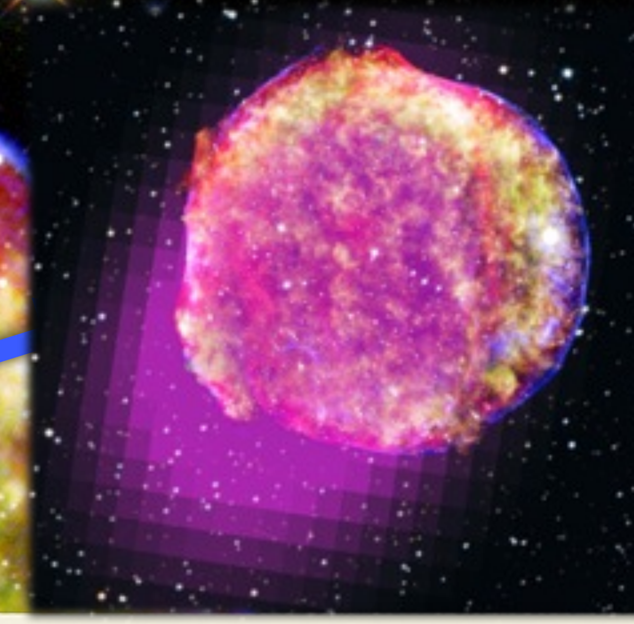
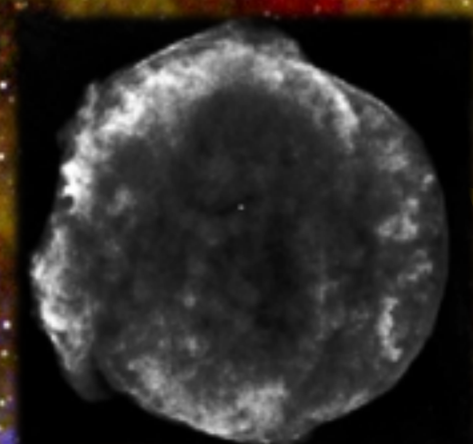
TYCHO'S SUPERNOVA REMNANT

IR/optical lines
Balmer shock Hα
Radiative shock

Non-thermal X-ray
Synchrotron radiation
Ultra-relativistic electrons



Radio emission
Synchrotron radiation
Mildly relativistic electrons



Gamma-rays
Sites of particle acceleration
Diffusive Shock Acceleration (DSA)
Cosmic rays factory!

Thermal infrared continuum
Hot dust (~10^2 K)
Shocked interstellar/ejecta dust

Thermal X-ray lines/continua
Very hot plasma (~10^8 K)
Shocked debris of exploded star

Emission from an SNR

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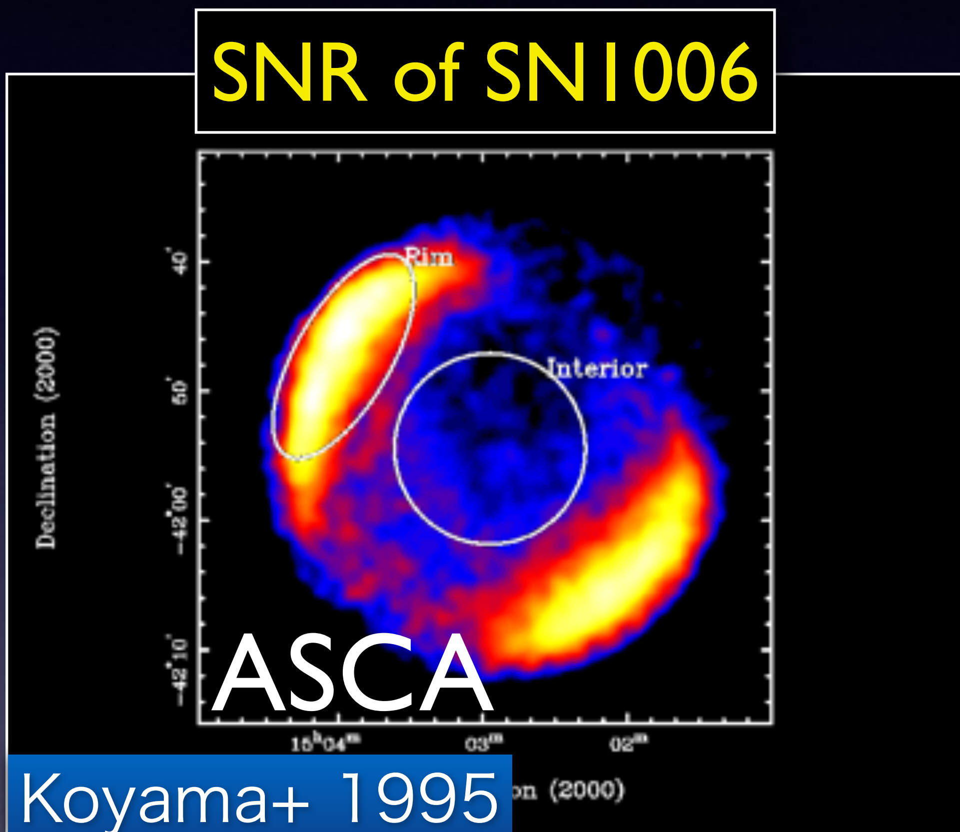
High-energy non-thermal emission = Fast-and-furious particles



Synchrotron X-rays at SNR collisionless shock
→ >100 TeV electrons

Sometimes accompanied by γ-rays
→ There are high-energy particles

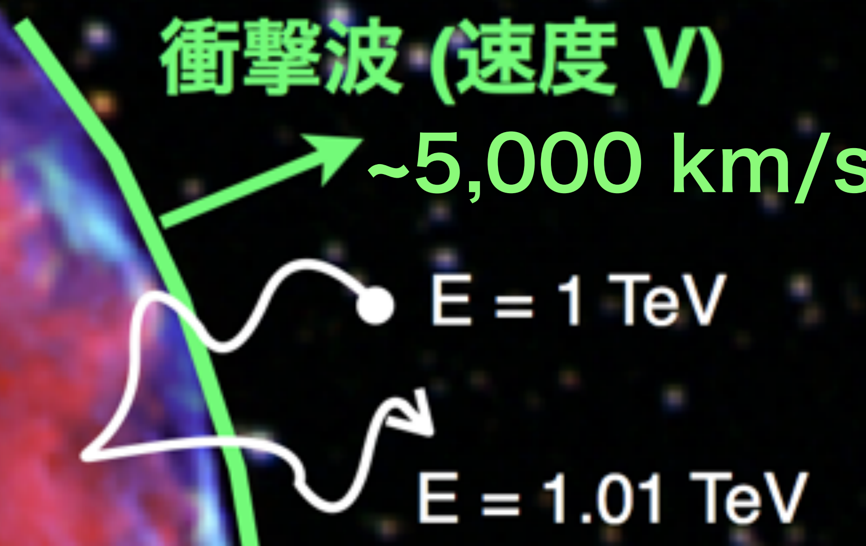
SNRs are cosmic particle accelerators

Q: What are these particles, how are they accelerated, and how much

Answers lead us to origin of Galactic CR

Particle acceleration at fast collision-less shock
"Diffusive Shock Acceleration (DSA)"


E. Fermi



Particles scattered by **magnetic turbulence** near shock **(elastic pitch-angle scattering)**

Particles cross shock repeatedly
Each crossing, gain energy from shock kinetic energy
$\Delta E/E \sim v_{sk}/c \sim 1\%$ (young SNR)

e.g. 1000 shock crossings
Energy gain ~ 20,000 times
1 GeV CR becomes 20 TeV

Real story = hard problem

- DSA is **nonlinear** ~~$N(E)\sim E^{-2}$~~
- **Coupled to hydrodynamics**
- **B-field geometry** (shock obliquity)
- **CR amplifies magnetic turbulence**
- **Amplified B-field supports DSA**
- **CR escapes into ISM**
- **Wave-particle** interactions → **D(x,p)**
- CR **e^- vs ion** injection/acceleration

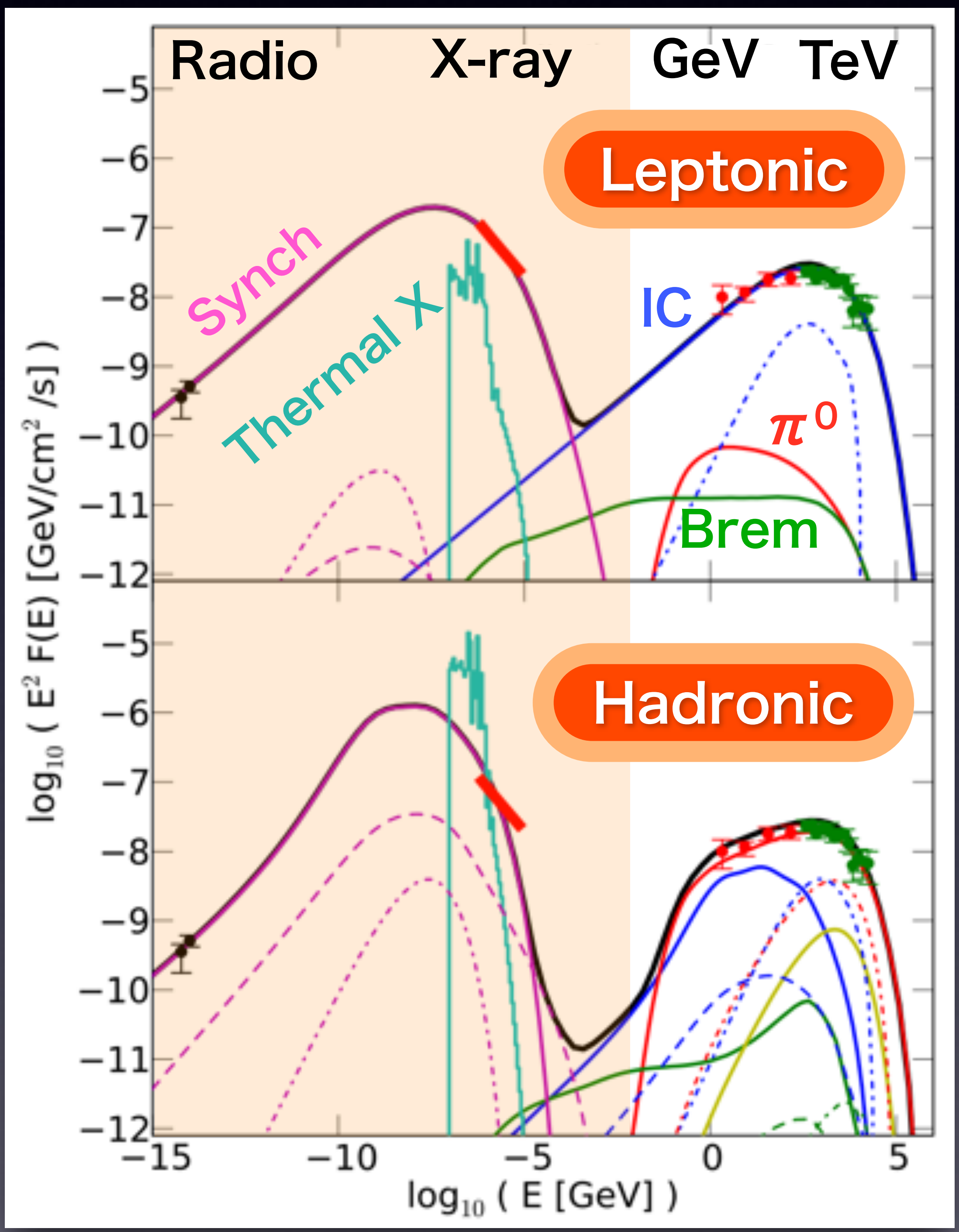
ISM: $n<1\,cm^{-3}$

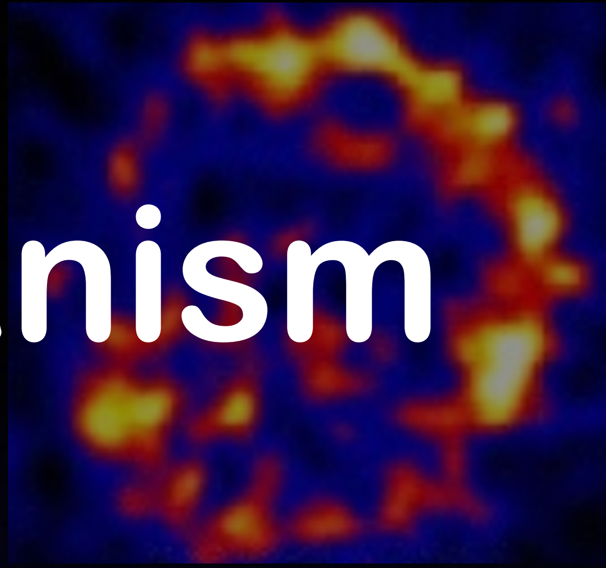
Strong shocks → universal power-law CR spectrum **$N(E) \sim E^{-2}$**

Courtesy: Y. Uchiyama

γ-ray emission mechanism

HL+ (2013) on **Vela Jr.**





π^0 decay

CR ion + gas → π^0
Flat'ish spectrum
Requires: high <n> (target)

"hadronic"

Inverse-Compton scatterings

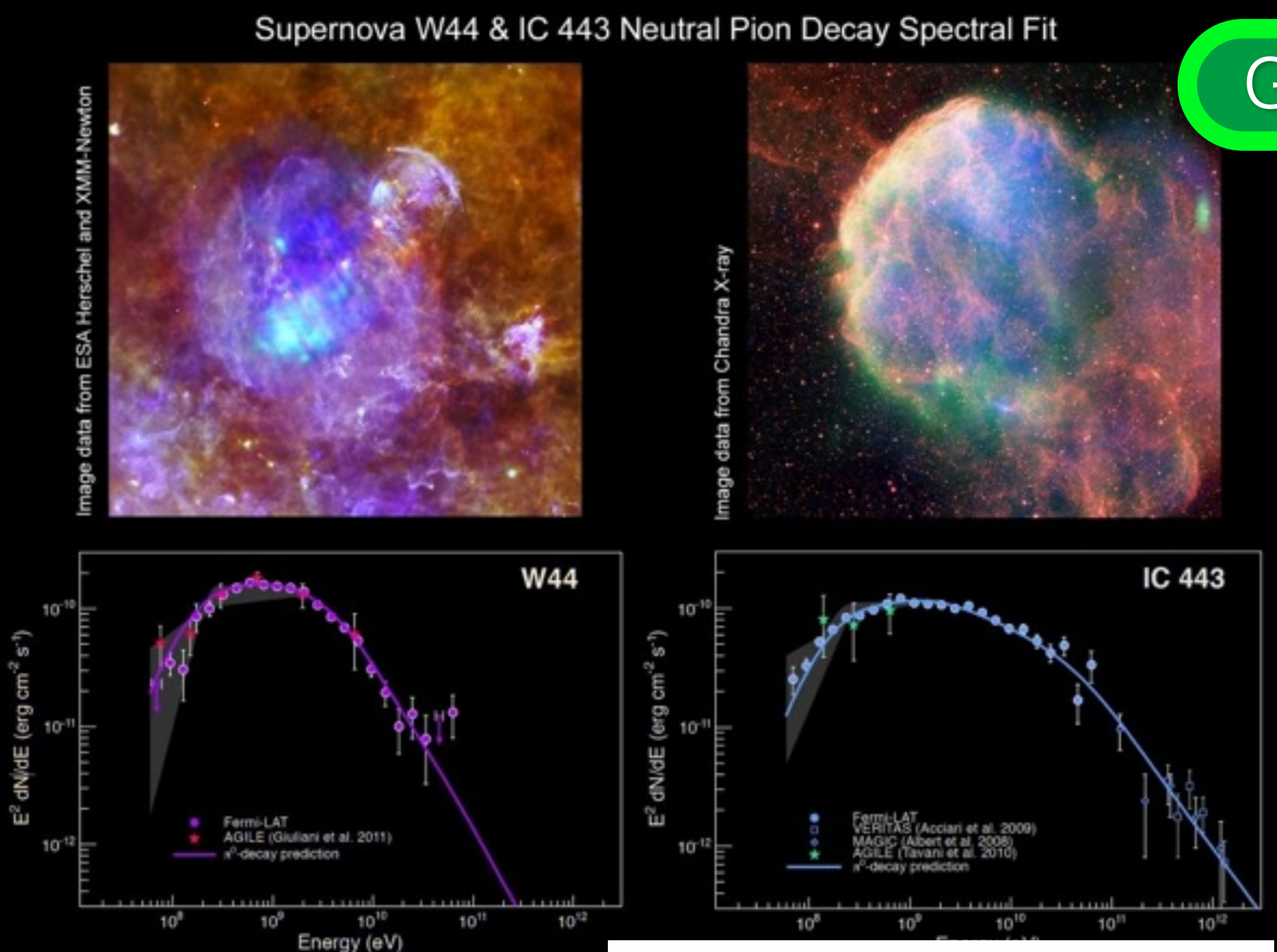
CR electron + photon fields → γ-ray
Hard spectrum
Requires: low <B> (synch loss)
low <n> (π^0 production)

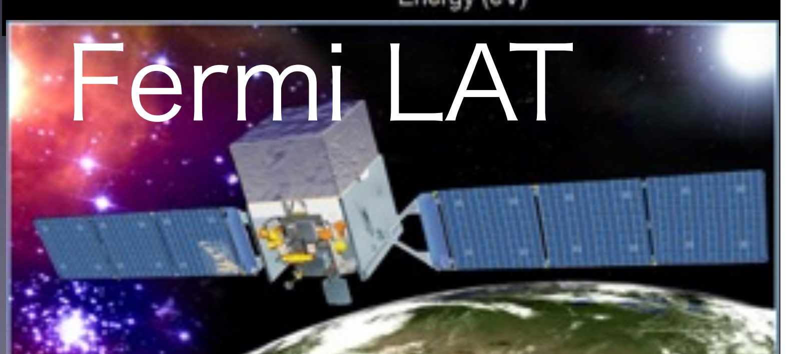
Non-thermal bremsstrahlung

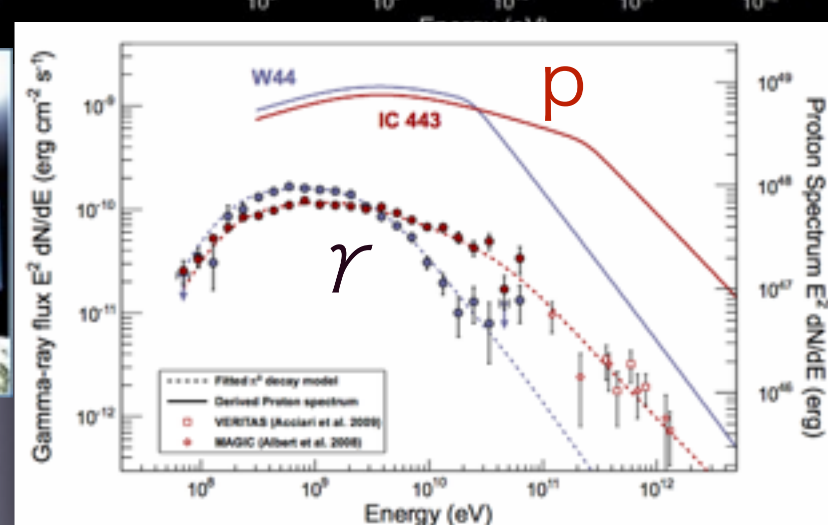
CR electron + gas → γ-ray
Same spectral index as CR
Requires: low <B> (synch loss)
high <n> (target)
low K_{ep} (π^0 production)

"leptonic"

Origin of γ-rays from observation







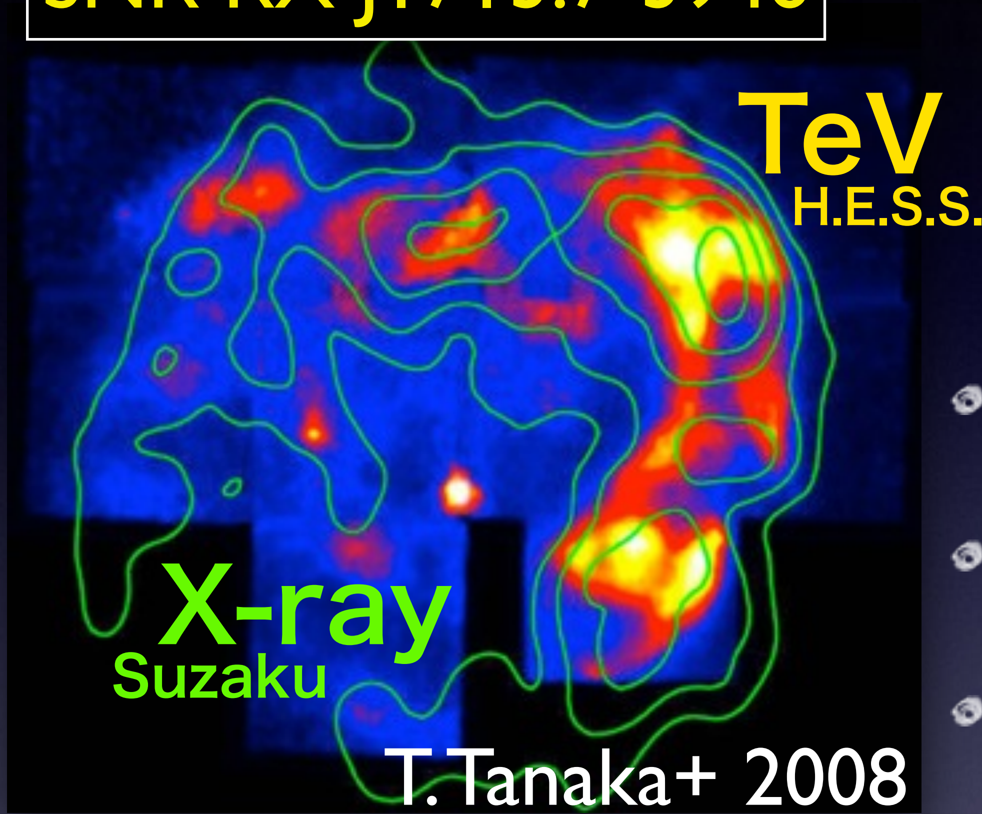
Funk, Tanaka, Uchiyama+ Science 2013

GeV-bright mid-age SNRs

- **Characteristic shape** of γ-ray spectrum
- GeV and radio bright
- No synchrotron X-ray
- 1720MHz OH masers and IR lines
- Shocks in molecular and atomic clouds
- **π^0-decay origin of γ-rays**
- **CR ion acceleration confirmed!**
- **Center-filled thermal X-ray** not related to non-thermal emission from shell
- Mechanism of CR ion acceleration unclear
  - Slow cloud shock
  - Fast Coulomb energy loss
  - Origin of energy break of CR spectra

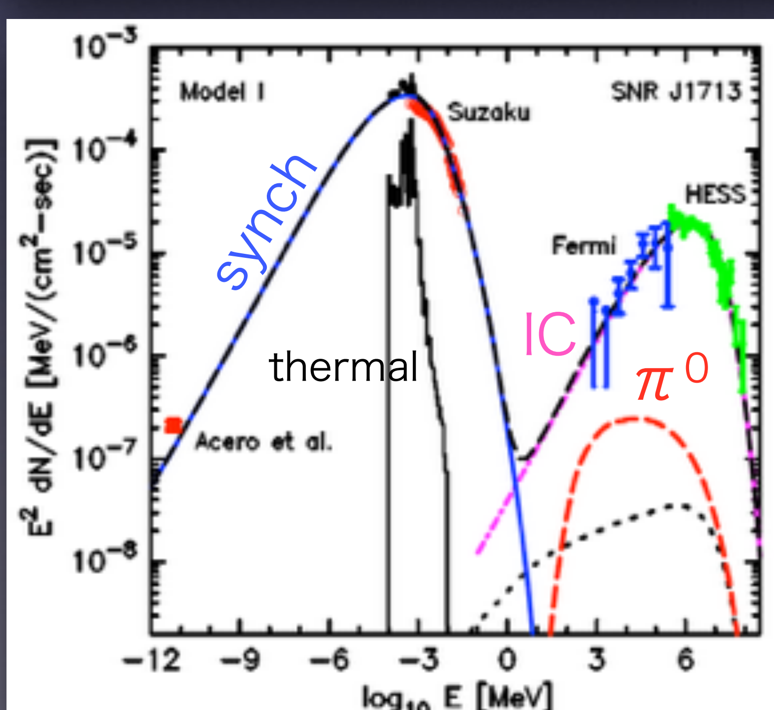
Origin of γ-rays from observation

SNR RX J1713.7-3946



TeV-bright young SNRs

- **Matching shape** of X-ray and TeV γ-ray
- Same origin of γ-ray and X-ray (from CR e^-)?
- Hard γ-ray spectrum → **inverse Compton?**
- **Non-detected thermal X-ray** → low density
- **'Leptonic' scenario** for γ-ray origin is natural



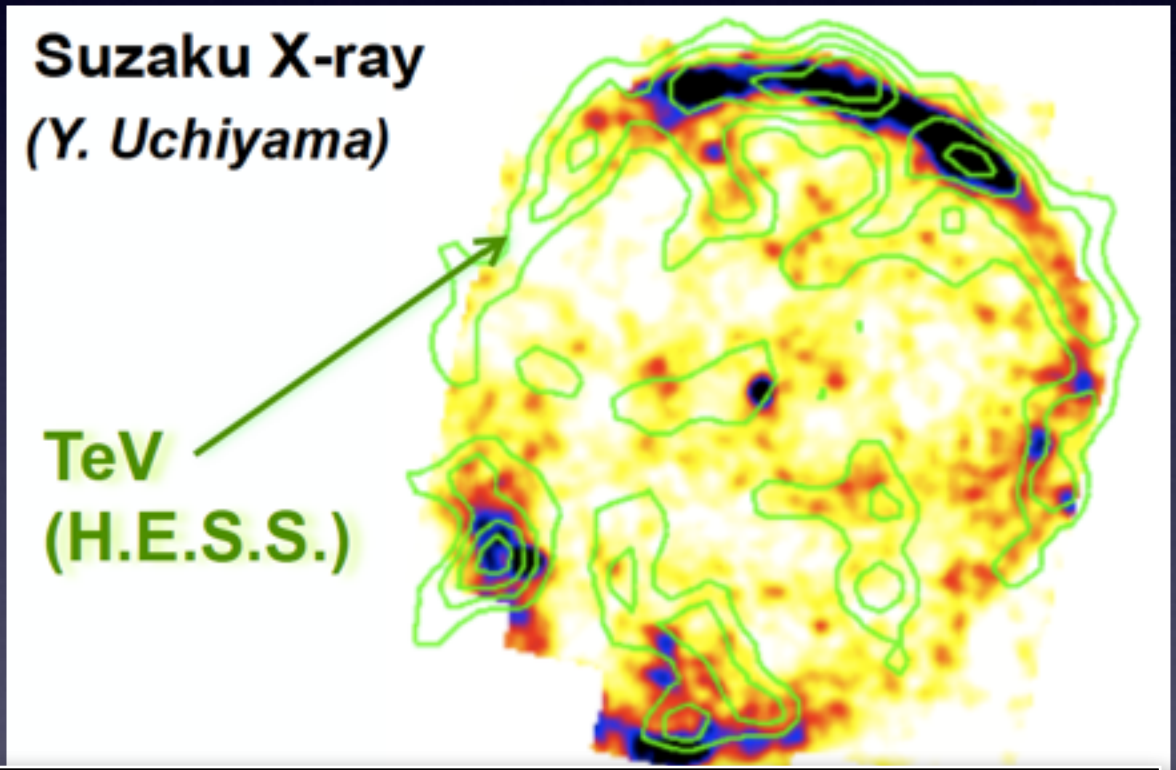
HL+ 2012

…but, not so fast

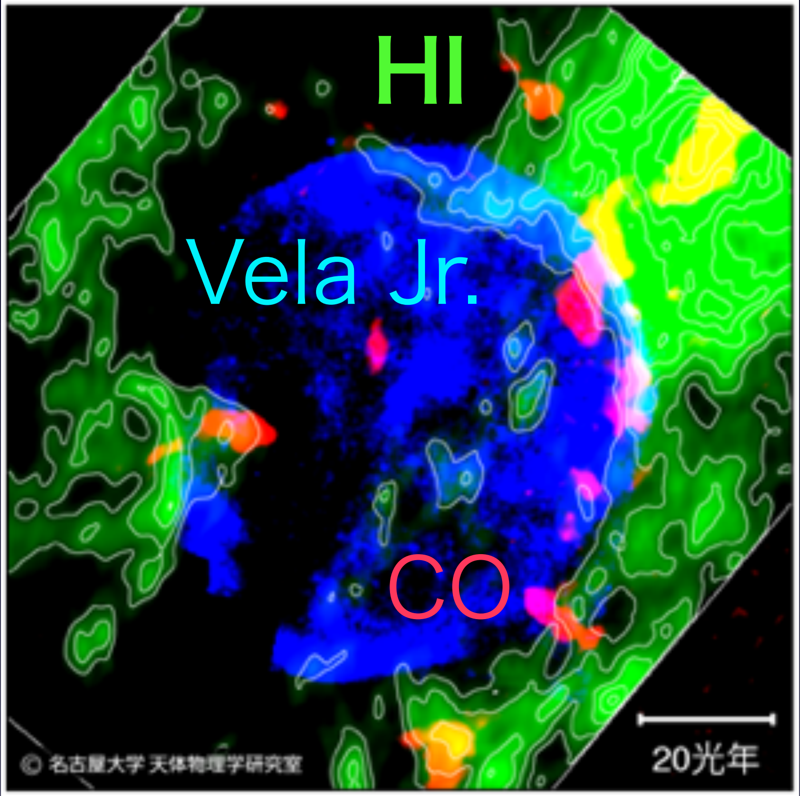
Reality: often not black or white

A similar SNR RX J0852.0-4622 (Vela Jr.)

Sign of shock-cloud interaction!



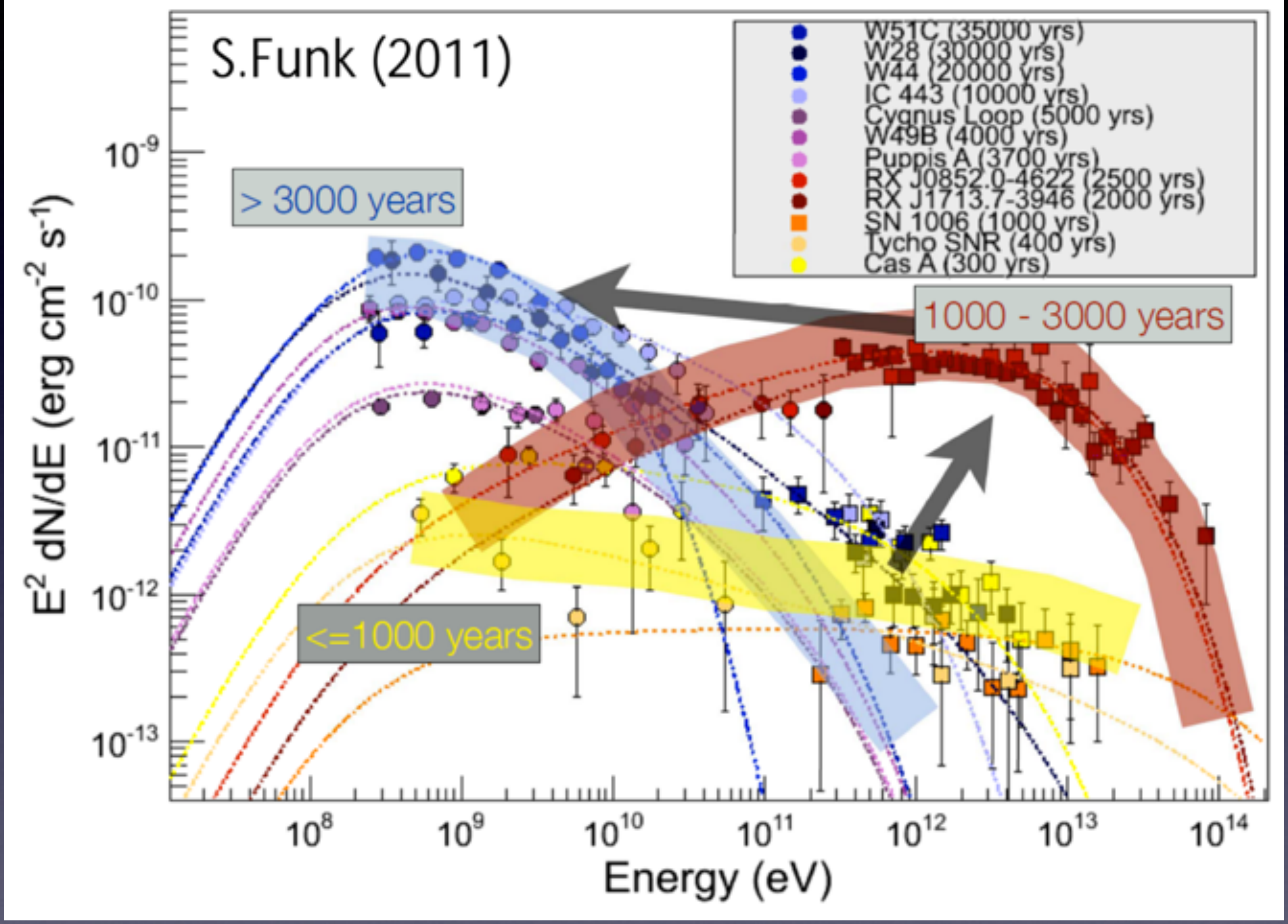
Regions of contrast seen between X and TeV



Nagoya Univ. radio astro group

Space-resolved spectral model needed to disentangle leptonic and hadronic components

Time evolution of γ-ray



- Different progenitors and CSM involved
- Unified evolution picture requires careful modeling of each type of SNR!

CR Acceleration at SNRs

Numerical Approaches

Particle-in-cell

Hybrid code

Fundamental shock/plasma physics

Computation cost
Limited dynamic ranges

Global MHD/HD

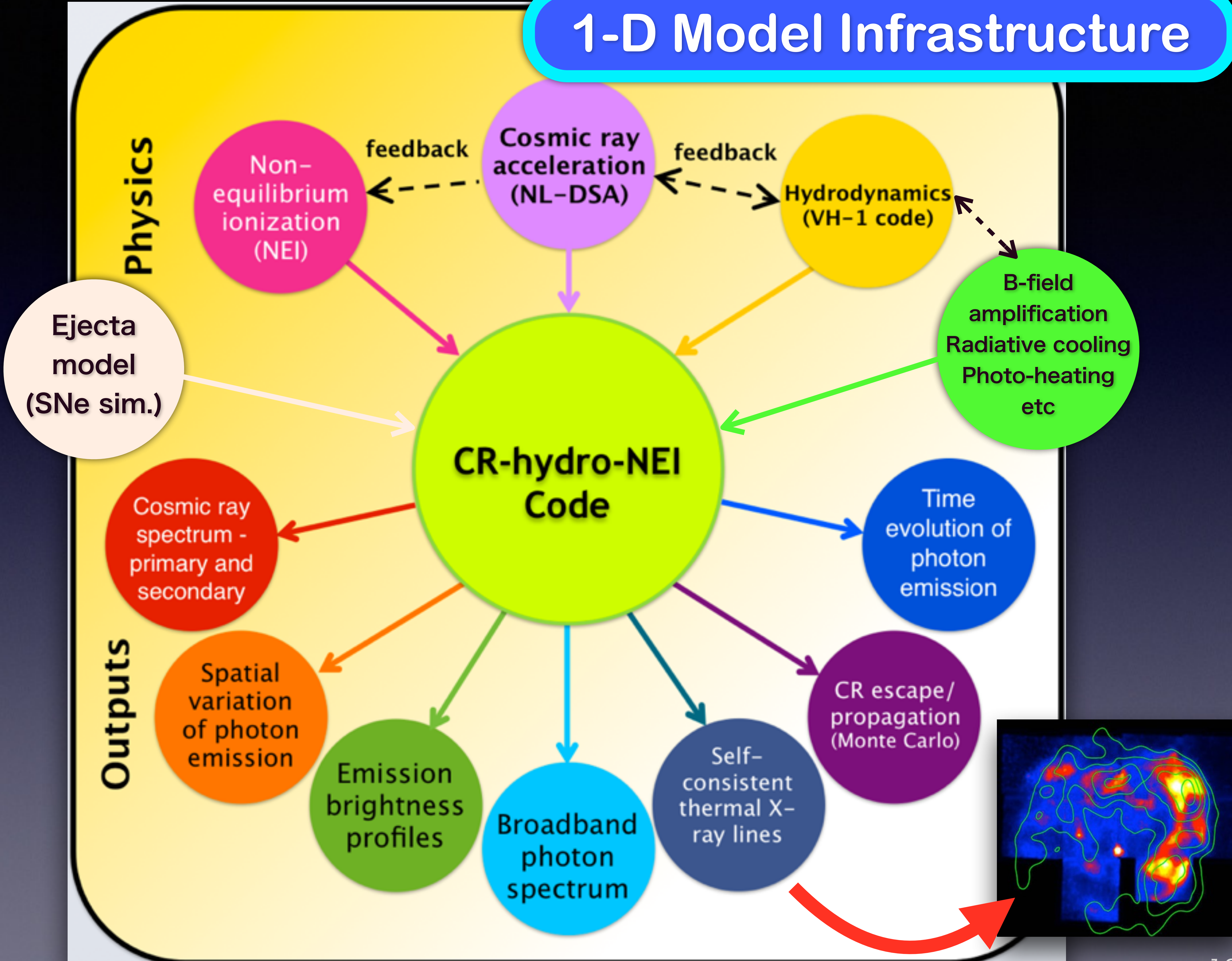
Semi-analytic DSA

Monte Carlo DSA

Phenomenological shock/plasma physics

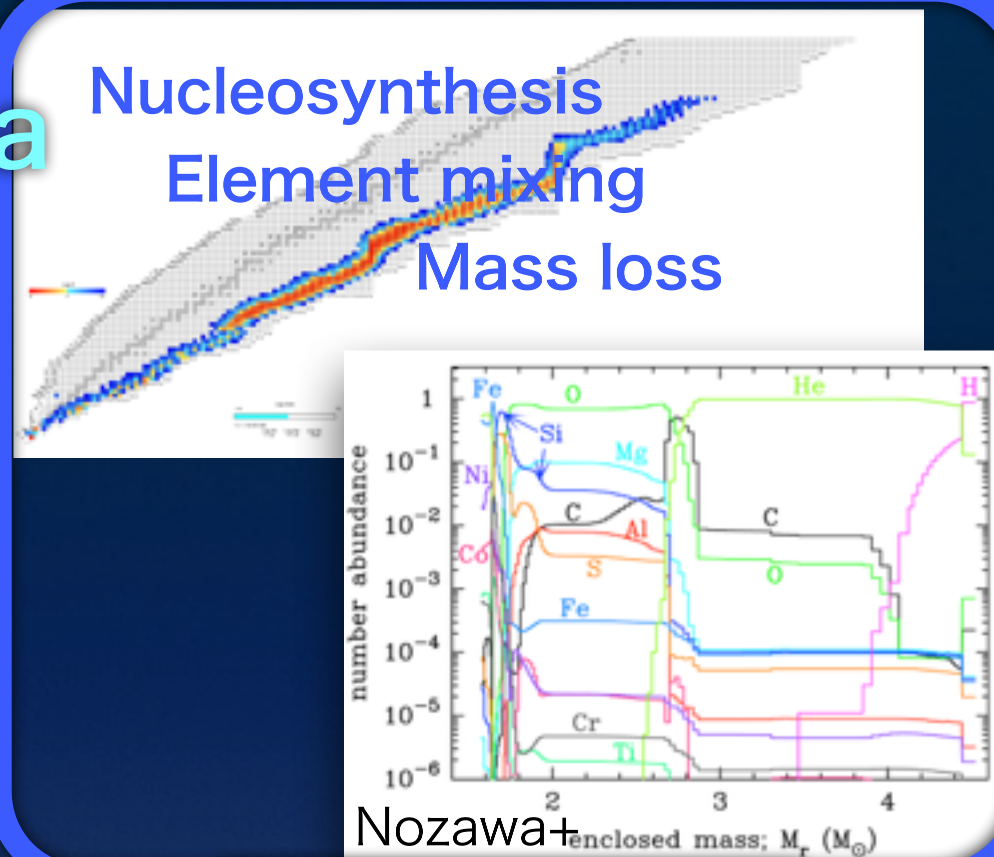
Constraints from multi-λ observations

1-D Model Infrastructure



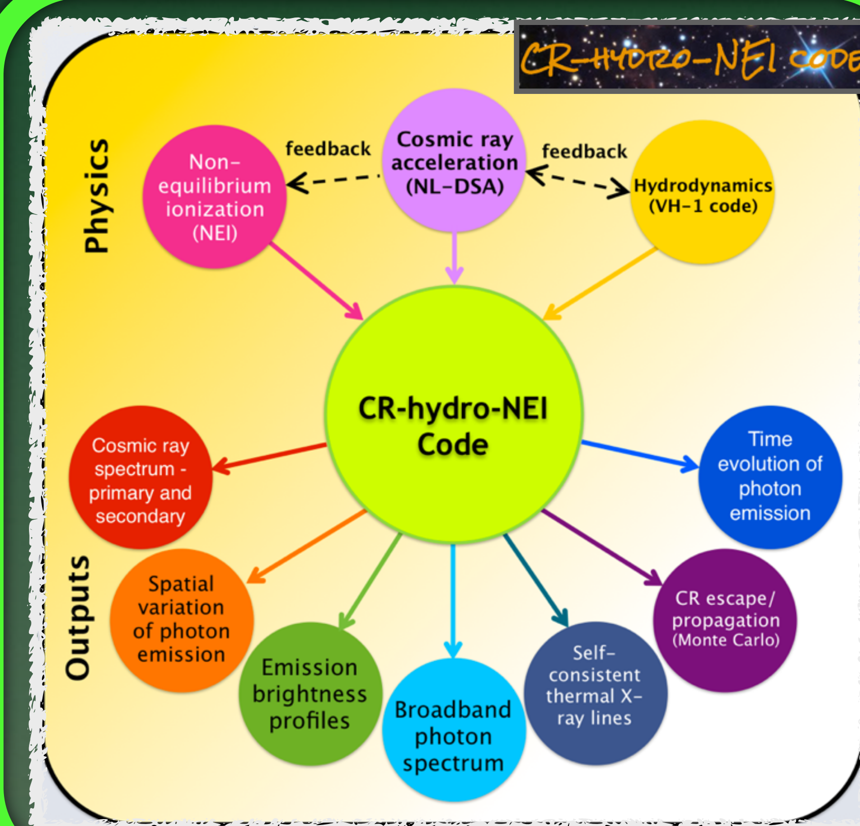
Iterative Work Flow

SN ejecta Model



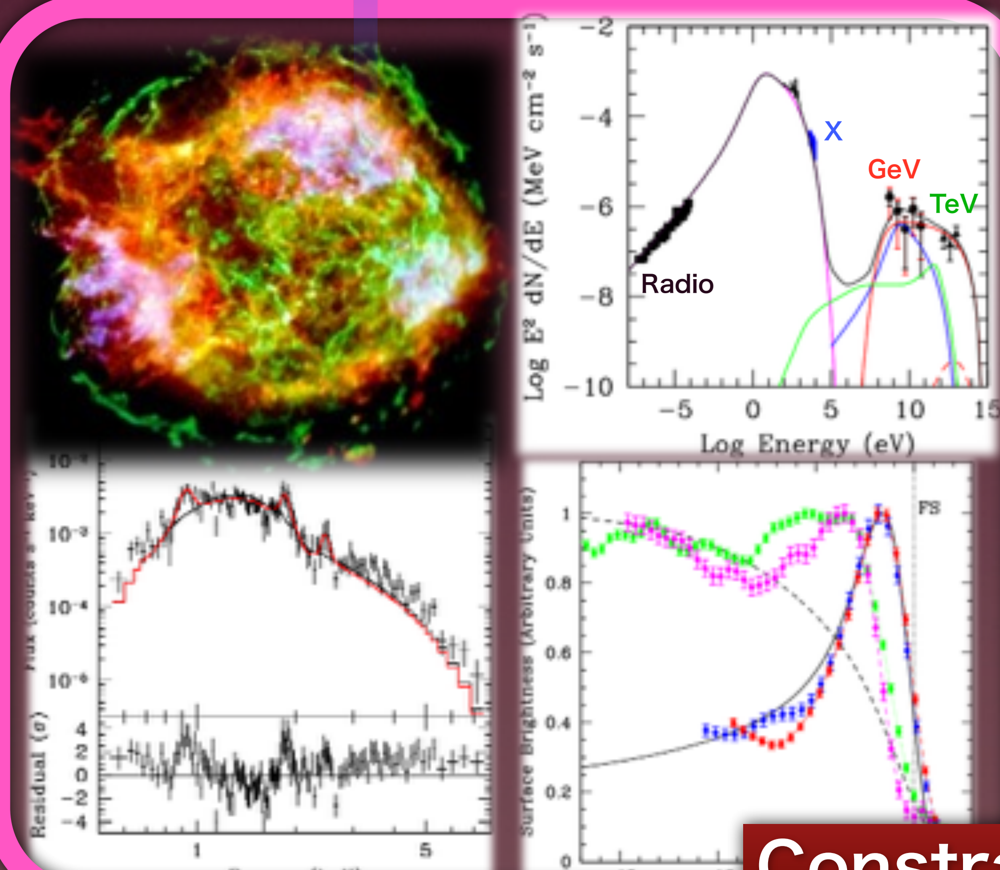
Initial conditions

CR-hydro Model



Dynamics, DSA,
B-field, ionization, radiation

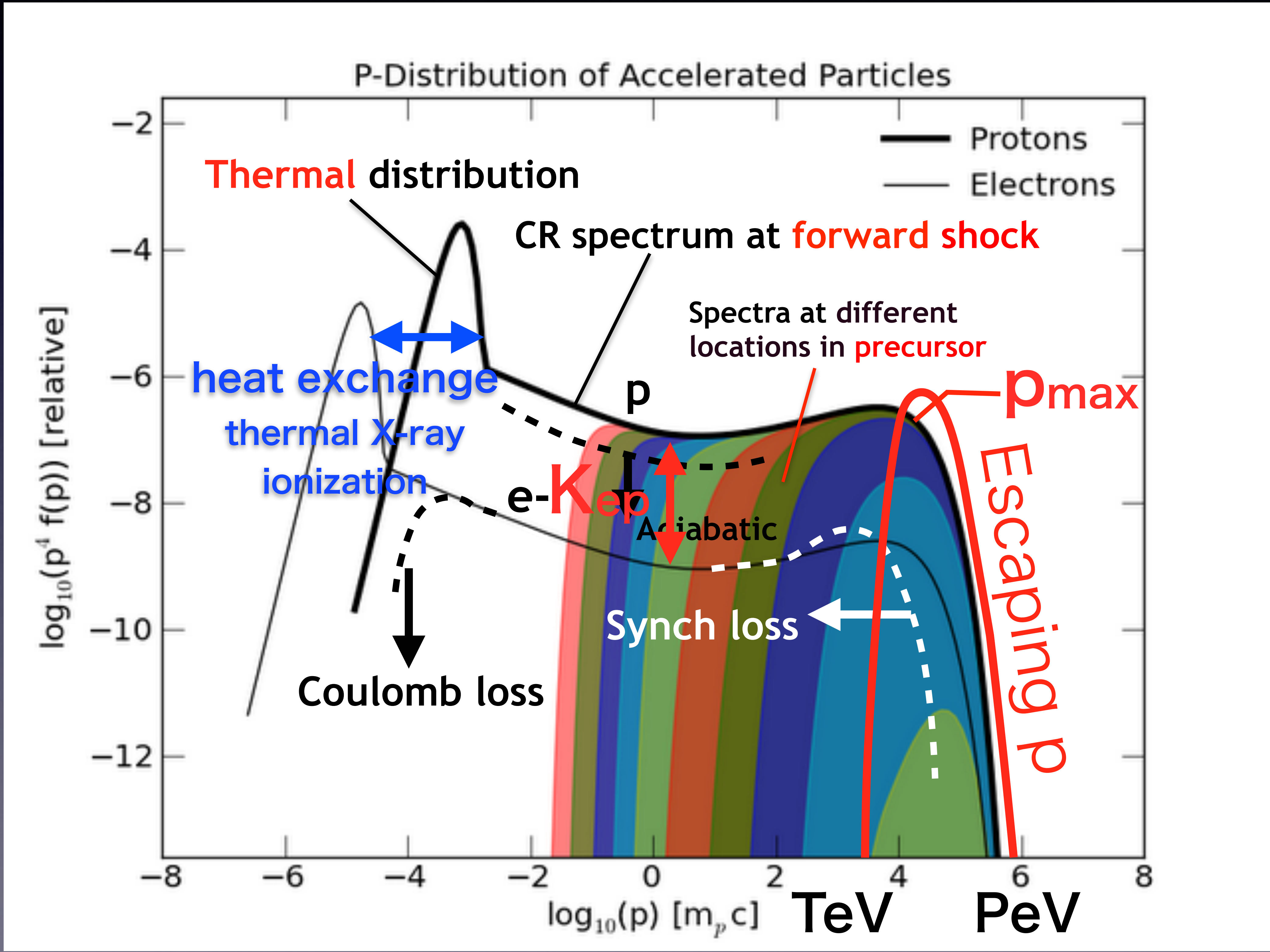
Multi-λ Data



Constraints!

Non-linear Diffusive Shock Acceleration

e.g. HL, Ellison & Nagataki (2012)

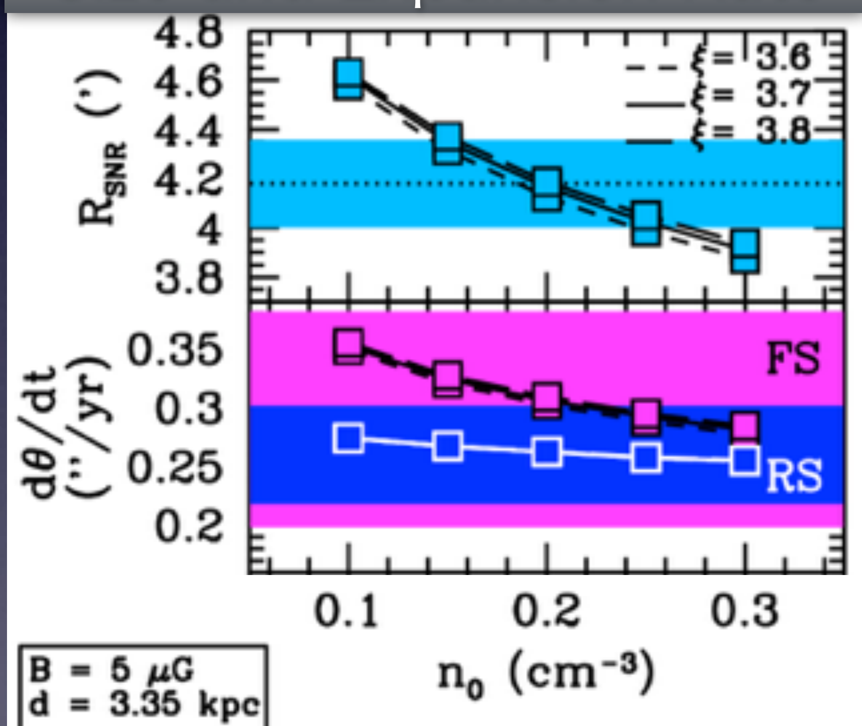


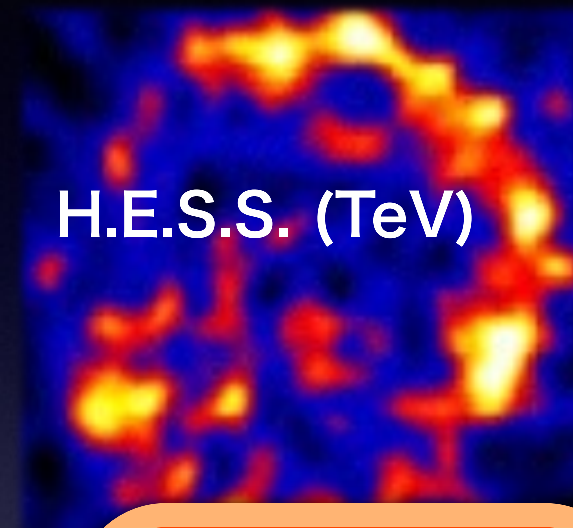
Application to young SNRs

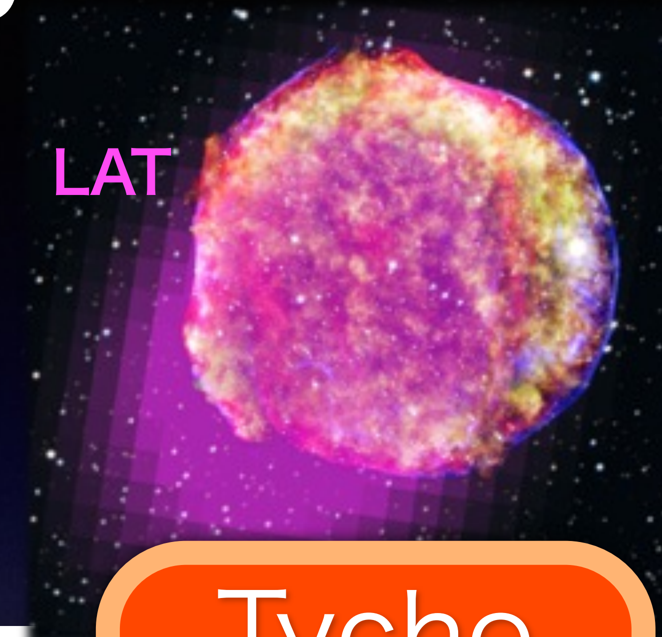
e.g. **HL+** (2013) **Vela Jr.**

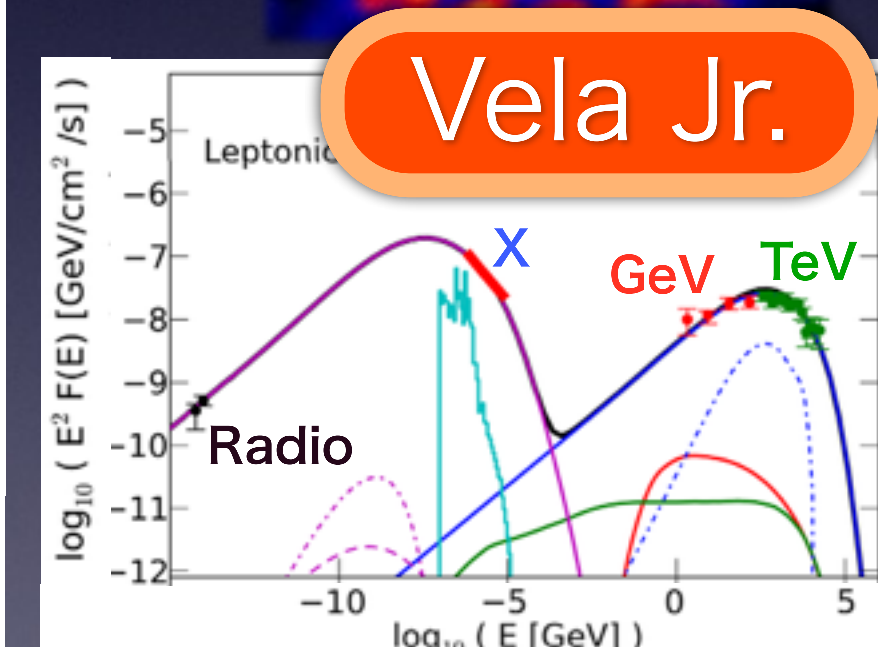
Slane, **HL+** (2014) **Tycho's SNR**

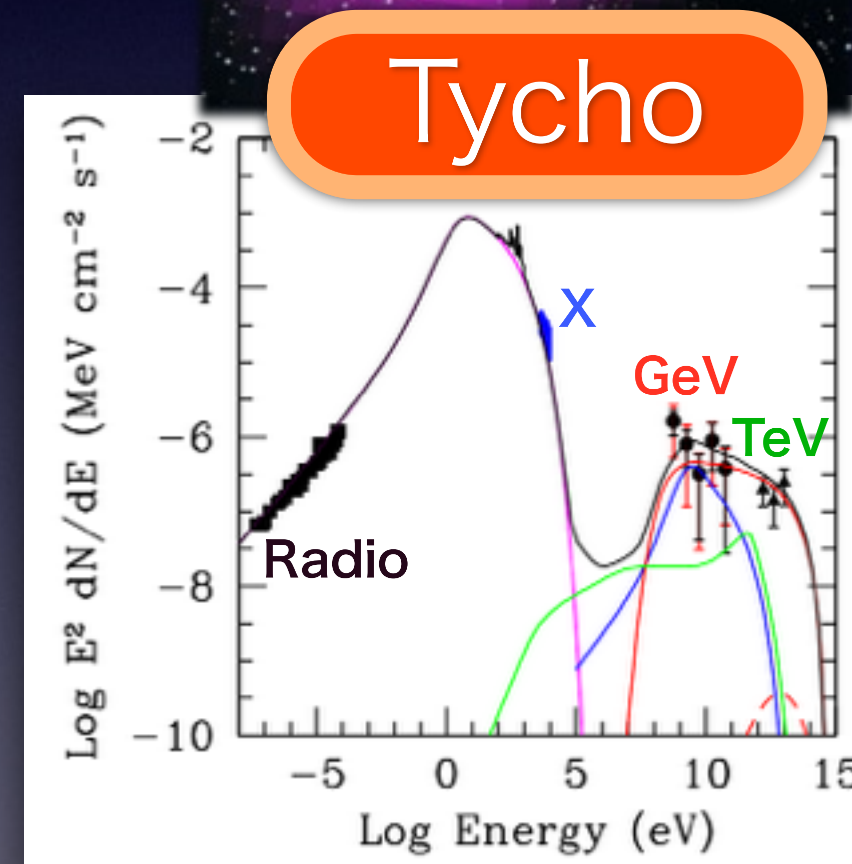
Size and Expansion Rate











Mostly leptonic

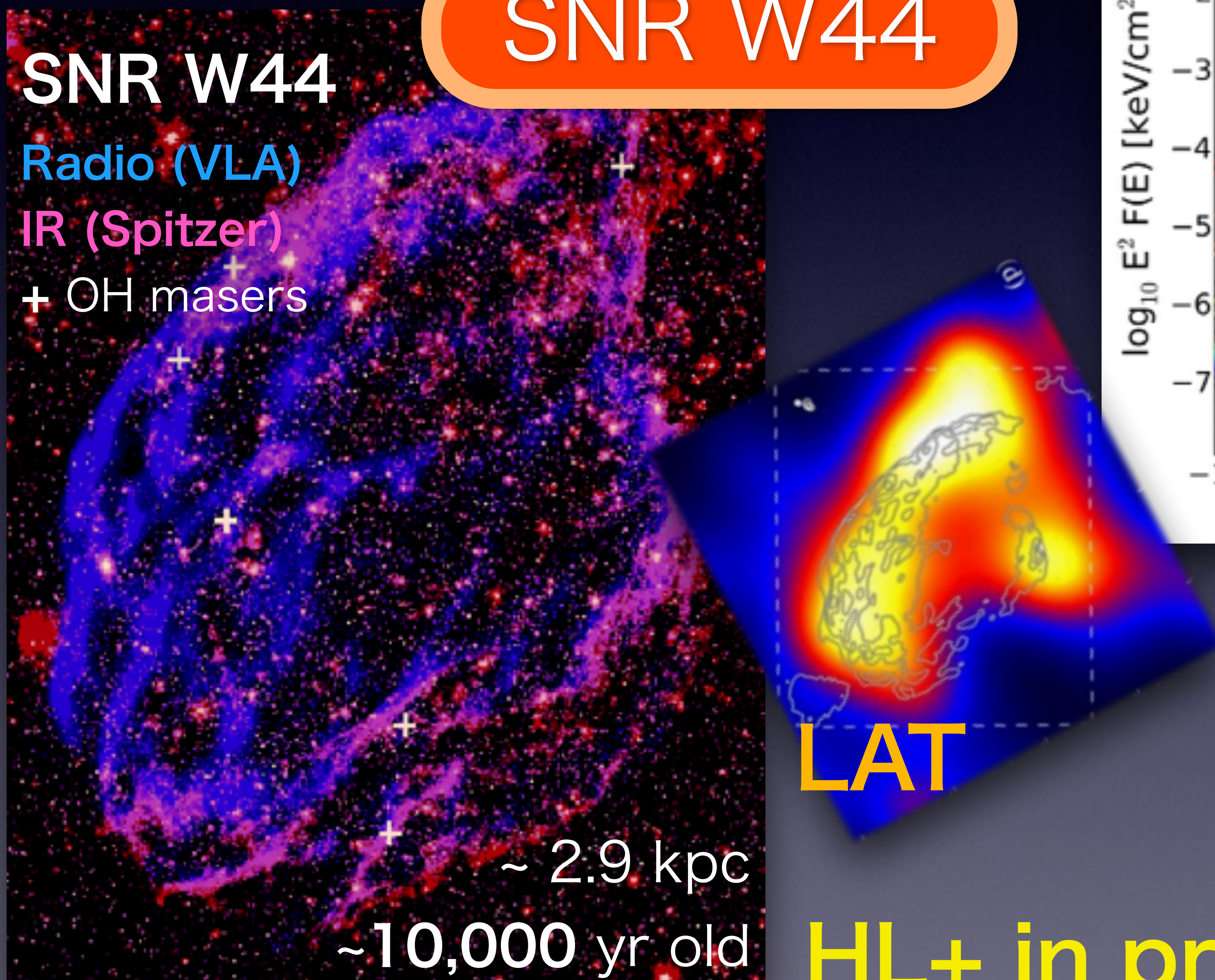
$E_{CR} = 0.15\ E_{SN}$

Hadronic + leptonic

$E_{CR} = 0.16\ E_{SN}$

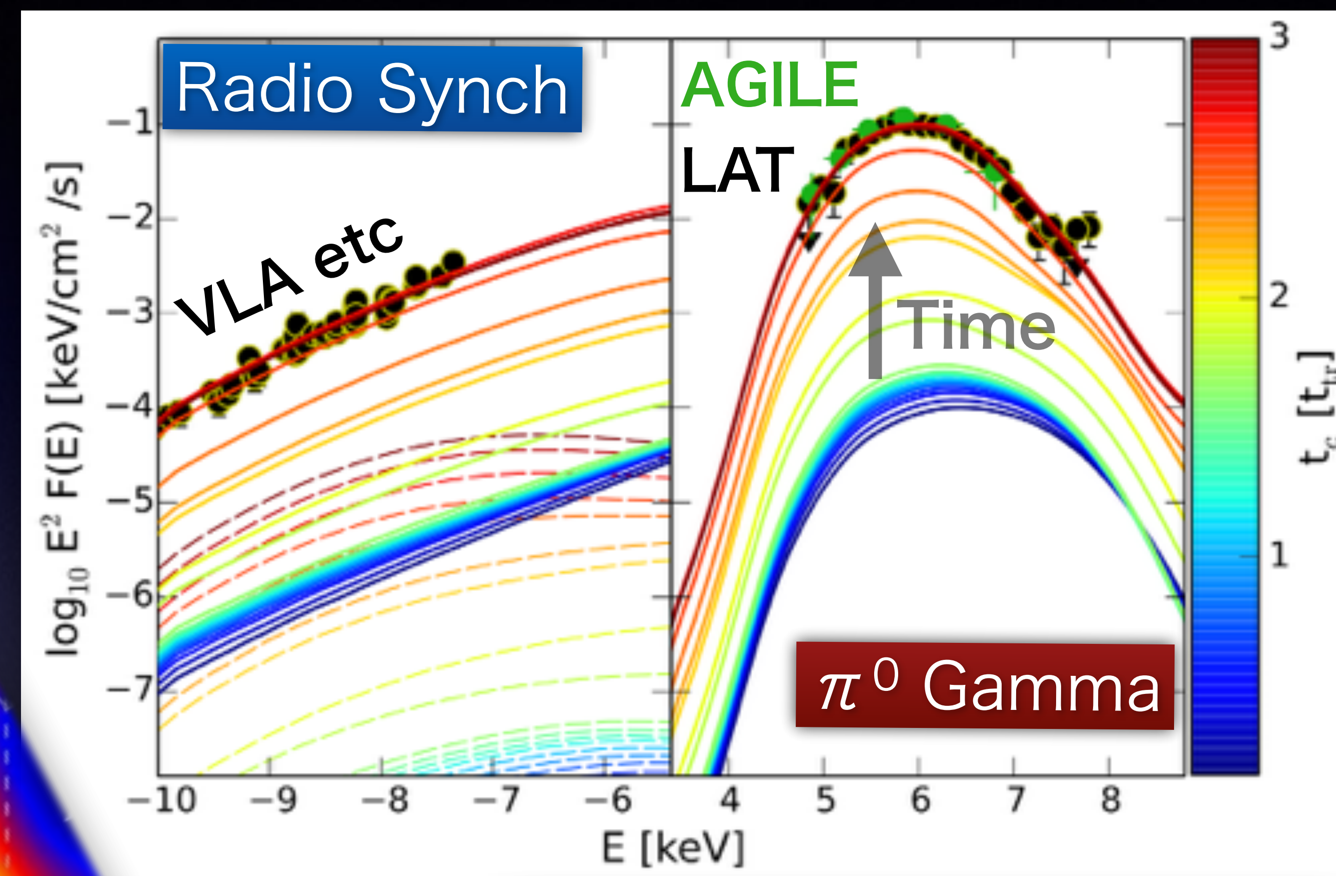
Application to Middle-aged SNRs with Radiative Shocks

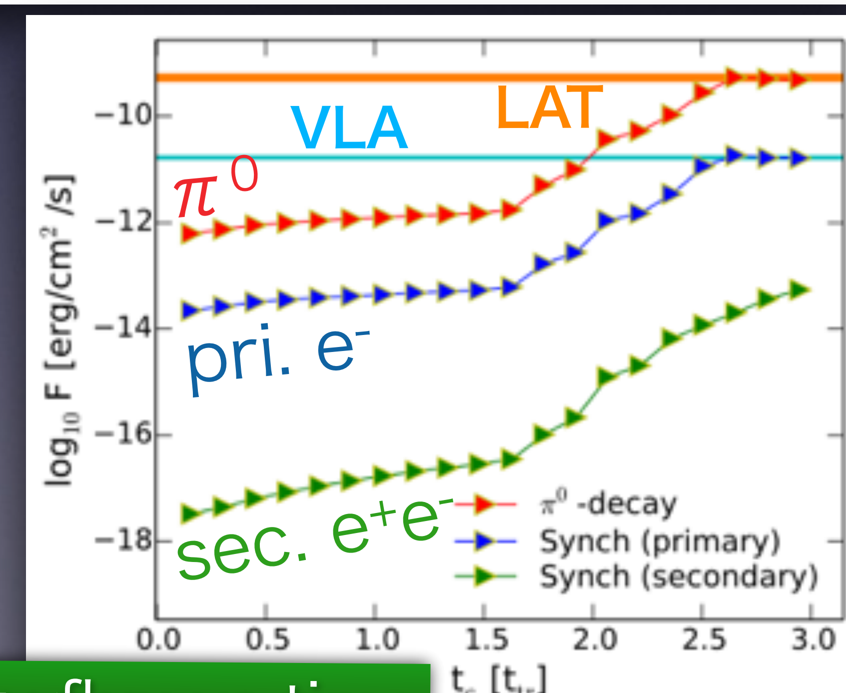
SNR W44



Castelletti+ 2007

HL+ in prep





Energy flux vs time

Nonlinear Diffusive Shock Acceleration with wave-particle interactions

Bykov, Ellison+ 2014

Monte-Carlo code

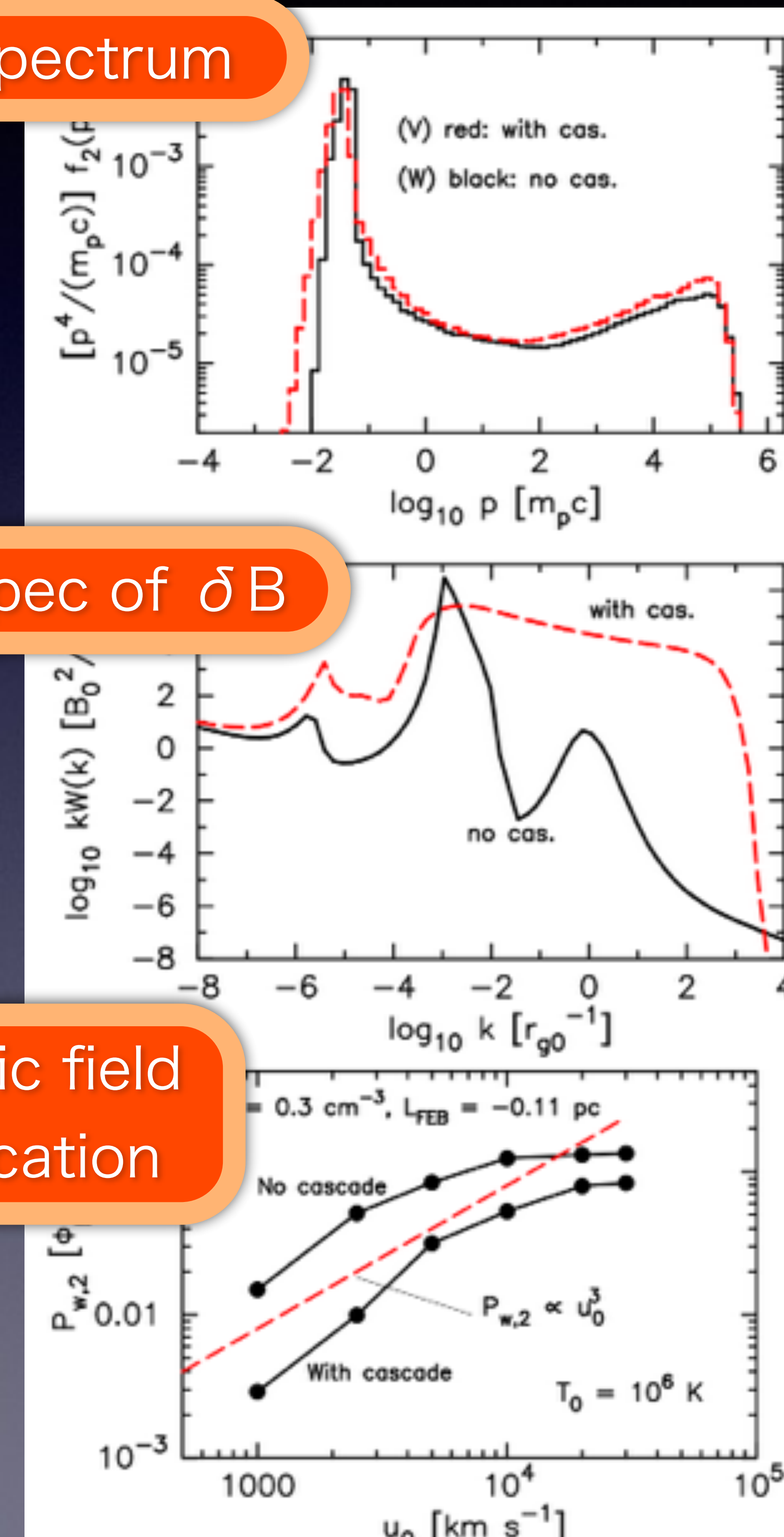
- Nonlinear CR acceleration
- Shock structure
- CR-driven magnetic turbulence
  - Resonant, Bell's, **Long-λ**
  - Cascading
- **Coming next:**
  - Couple with hydrodynamics
  - Heavy ion acceleration
  - Multi-λ emission
- Bridge the gap between PIC and semi-analytic models!

HL, Bykov, Ellison in prep

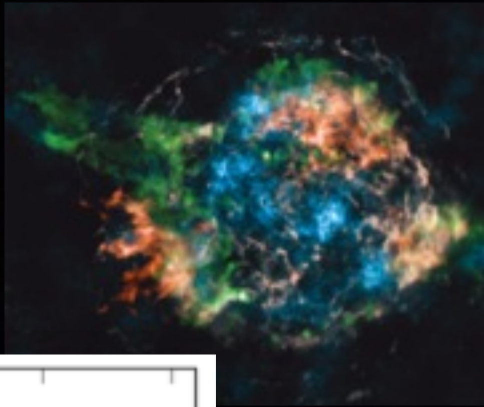
CR spectrum

Power spec of δB

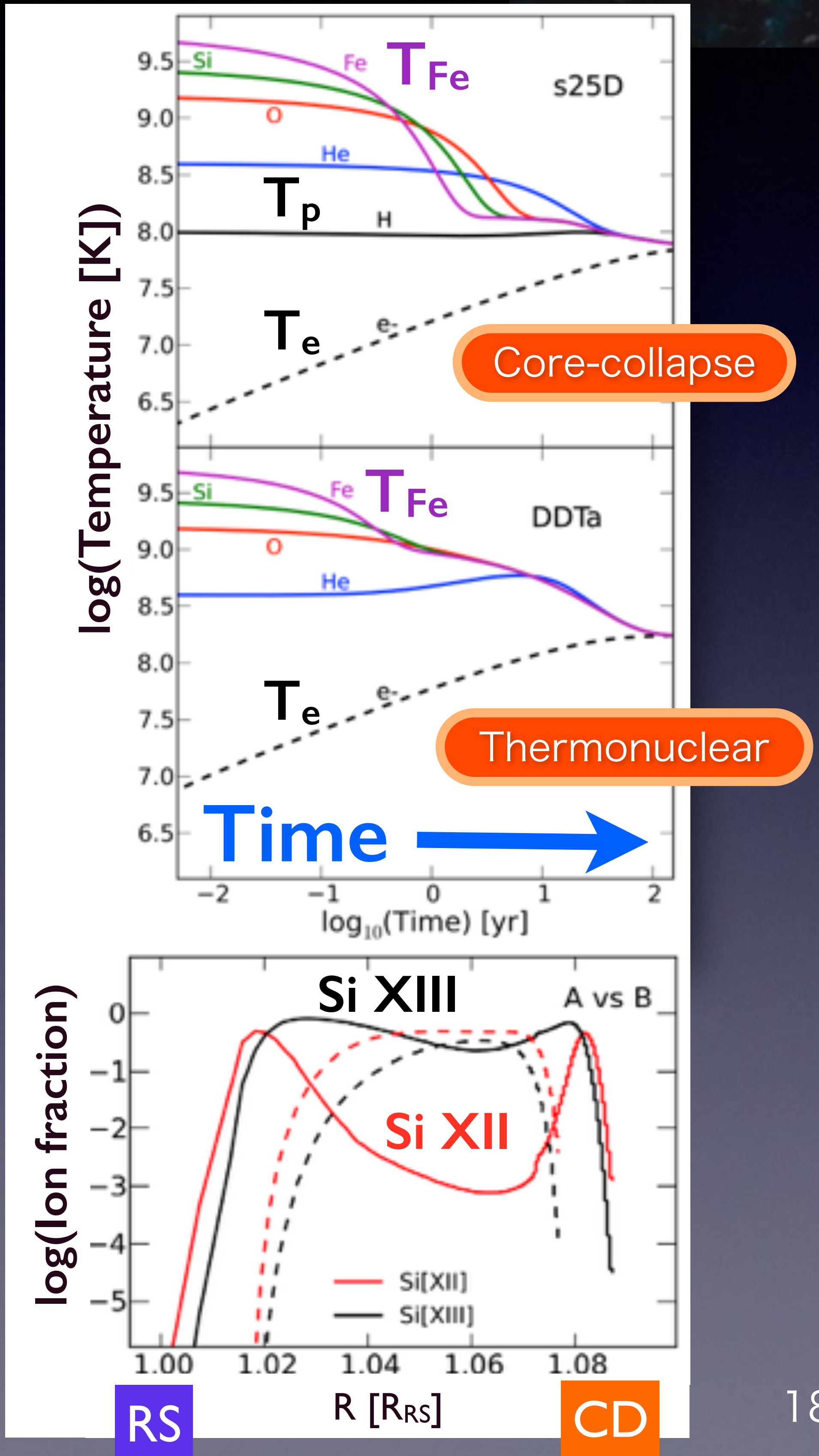
Magnetic field amplification



Thermal X-rays



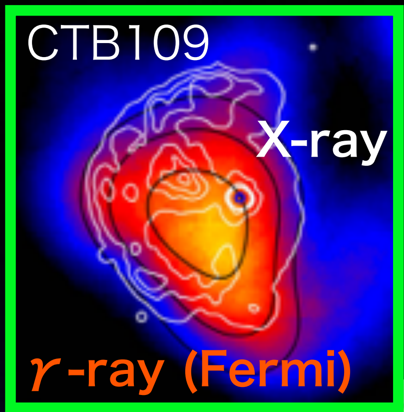
- **Thermal X-rays** of young SNRs tell us many things
  - Ejecta and CSM chemical composition
  - Temperatures and motions of ions, e-
  - Ionization history
  - Constrain non-thermal emission origin
- **Non-equilibrium ionization (NEI)** and **temperature evolution** of 152 ion species with hydrodynamics
- Predict **detailed thermal X-ray spectrum** (self-consistently with non-thermal)



HL, Patnaude+ (2014)

Powerful constraint of γ-ray origin

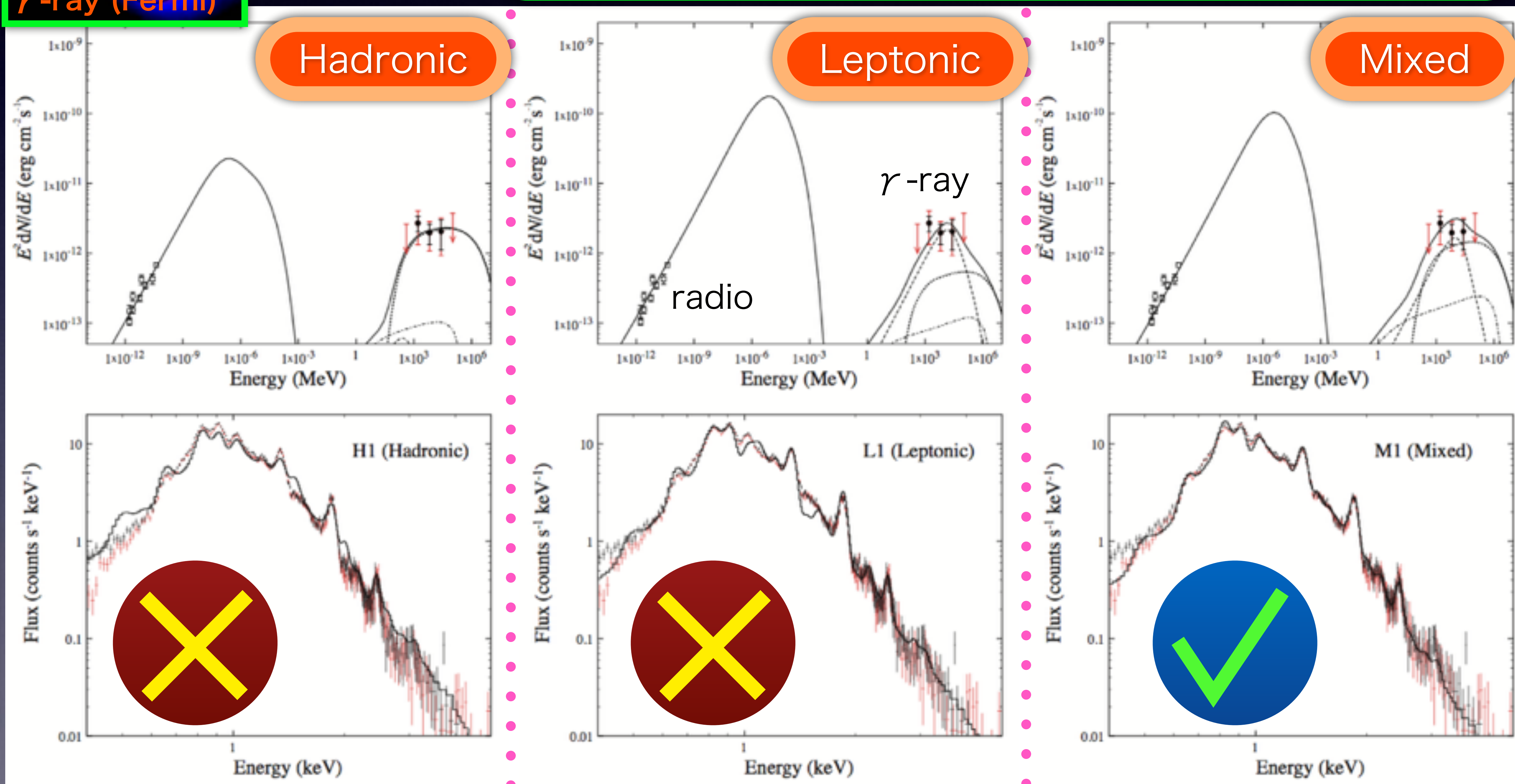
Thermal X-ray



e.g. CR-hydro-NEI model of SNR CTB109

Non-thermal

Thermal X

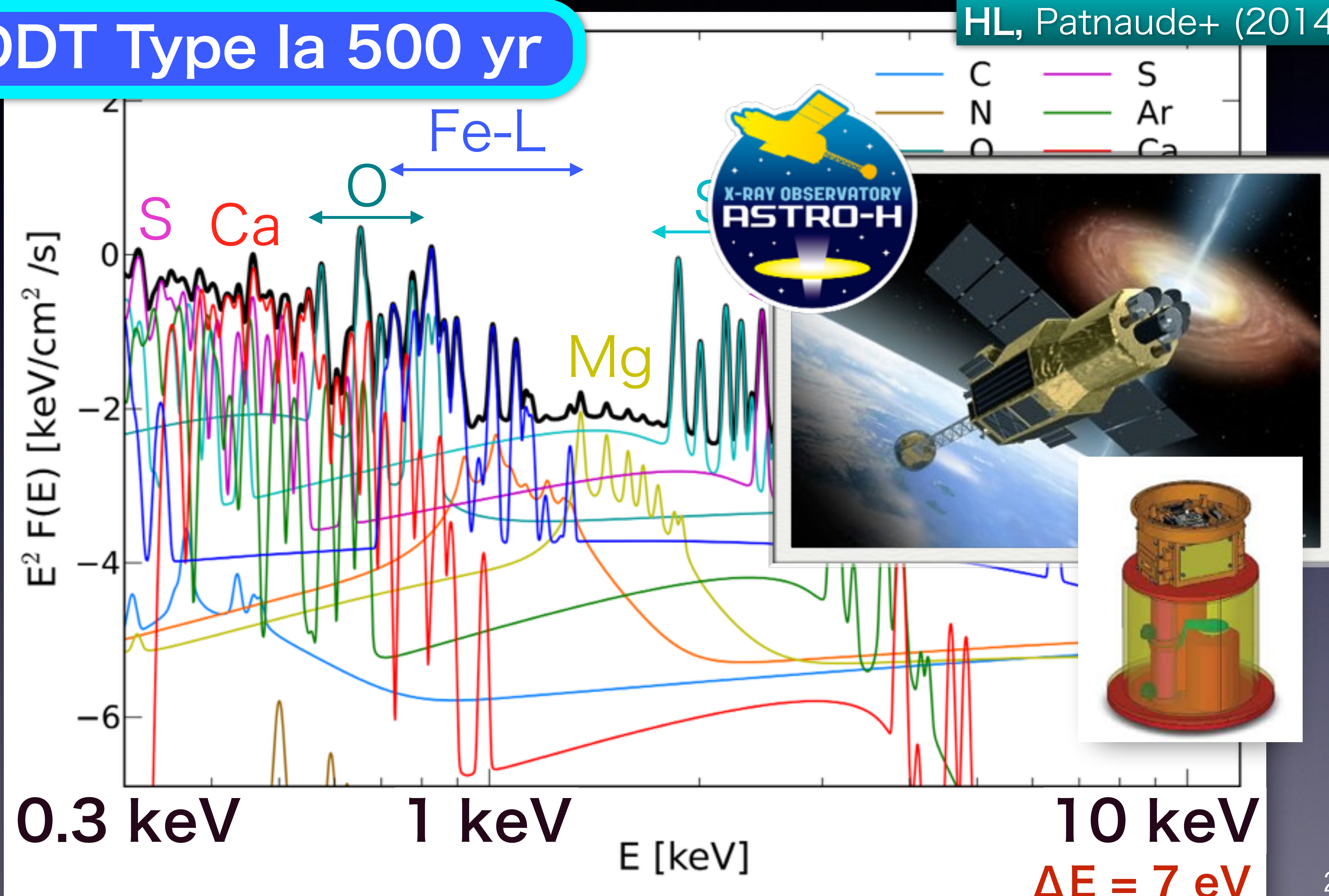


Castro+ 2012

Synthesis of detailed X-ray spectra

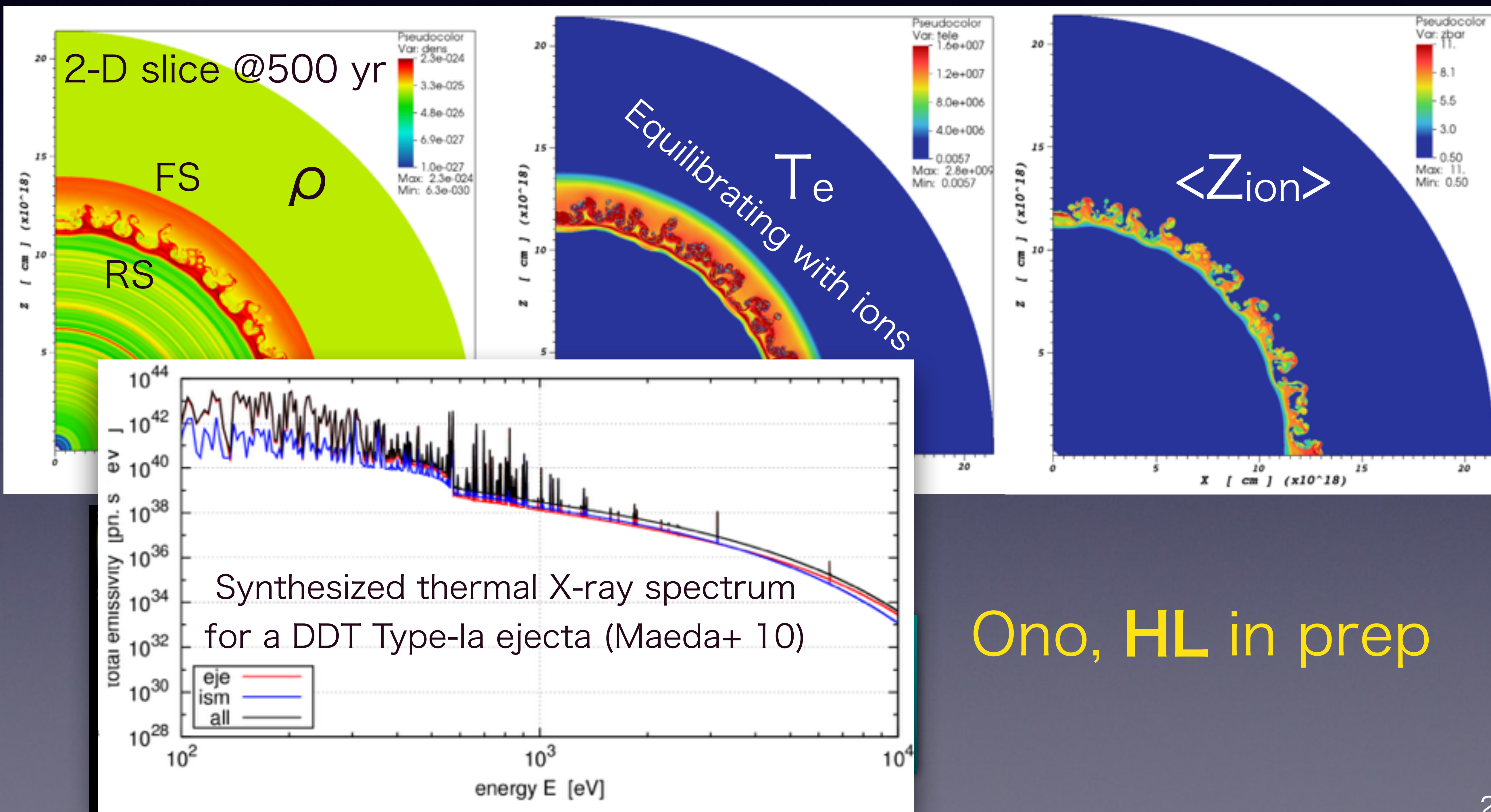
DDT Type Ia 500 yr

HL, Patnaude+ (2014)



Multi-D Hydro-NEI Simulation of SNRs

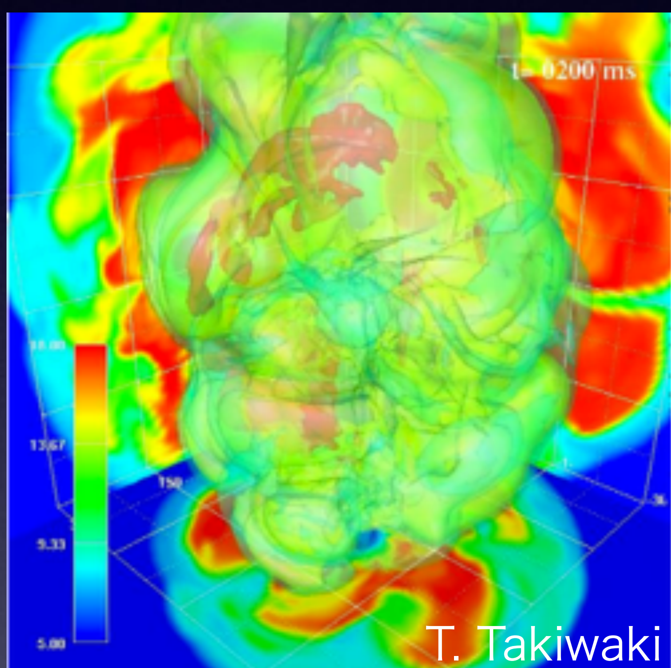
Path towards connecting SNe and SNRs!

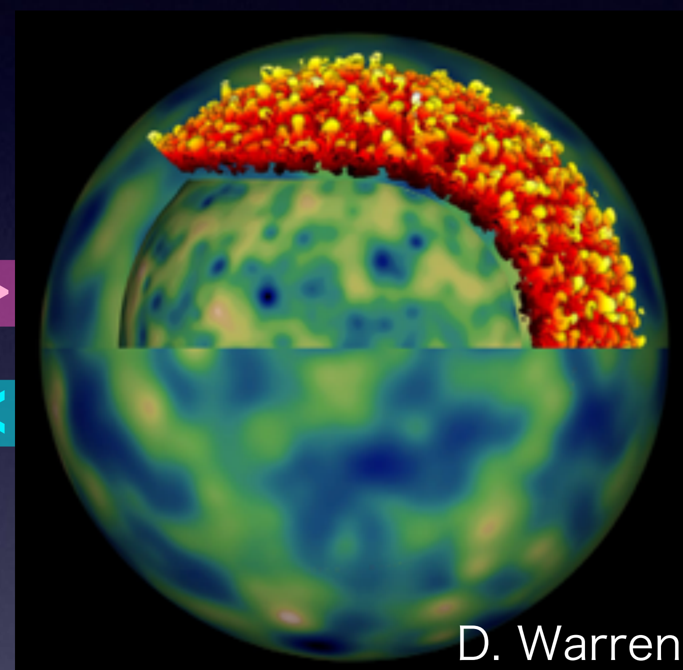


Ono, **HL** in prep

Ultimate Research Goal

"From engine to remnant, and back"



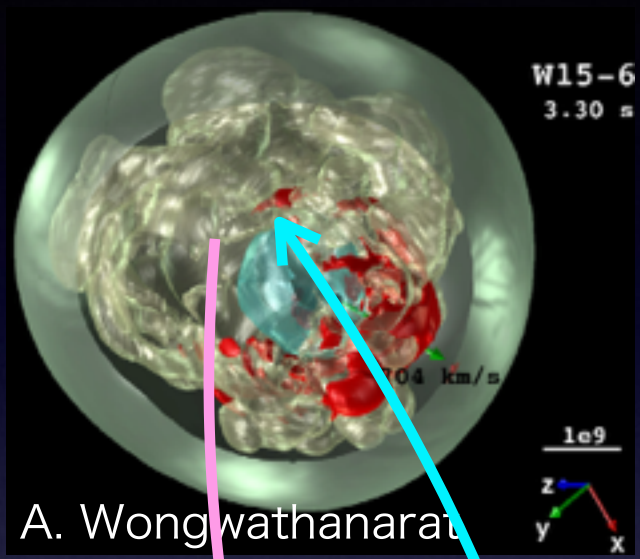


Engine | **Remnant** | **What's out there**

In computers

Iteration between improving models and observations
—> full understanding of last stage of stellar evolution

Roadmap



Towards true picture of CC and Ia SNe

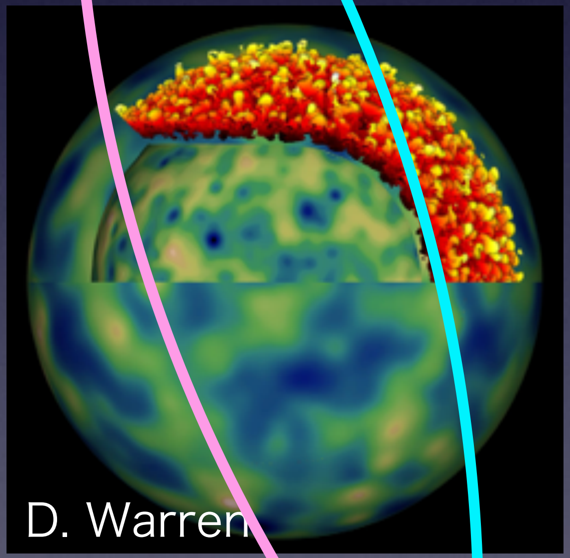
Progenitor star properties

Explosion mechanism

Nucleosynthesis, matter mixing

Shock breakout to early SNR phase

T. Takiwaki, A. Wongwathanarat, M. Ono, K. Maeda, A. Tolstov



Deeper understanding of SNRs and collisionless shocks

Diffusive shock acceleration (DSA) of CR e^- and ions

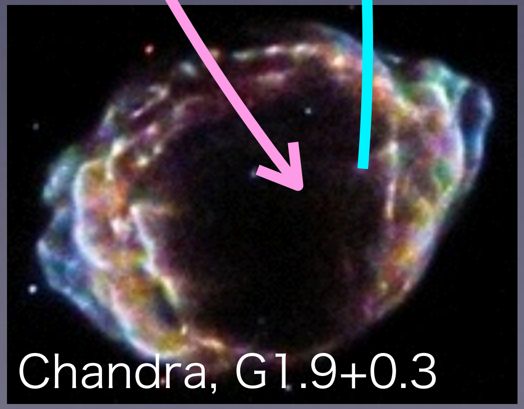
CR-driven magnetic turbulence

Hydro/MHD instabilities

Ejecta and CSM structure

H. Lee, D. Ellison, P. Slane, D. Patnaude, C. Badenes, D. Warren, A. Bykov

S. Nagataki, M. Ono, M. Barkov



Confront multi-λ data with state-of-the-art model

Future and current observations of SNe and SNRs young to old

NuStar, Suzaku, Chandra, LAT, IACTs, VLA, ALMA, Nanten-II, etc

In close future: **Astro-H**, **CTA**, SKA, and more

Summary

- SNRs never end to challenge us with puzzling phenomena
- Massive astrophysical significance
  - Origin of CRs, SN geometry, nucleosynthesis, etc…
- Treasure trove of fundamental physics
  - Collisionless shocks and plasma, NL-DSA, wave-particle interactions, etc…
- True understanding of SNRs **from engine to remnant** requires confrontation of new data with improving models
- We need close connection among SN, SNR and space plasma communities to fulfill our ambition