Current trends in SNR research

# Broadband SNR Models

## Current Status and Prospects

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ISAS/JAXA & RIKEN

RIKEN-RESCEU Joint Workshop 2016

# The Art of Broadband Modeling

- Nowadays, broadband models must satisfy zillion constraints from observations
  - Multi-wavelength spectra
  - Multi-wavelength morphology
  - Time evolution, dynamical information
  - Thermal as well as non-thermal properties
  - All different combinations of the above! (spectral image, spectral evolution etc)
- Also have to meet criteria from complex plasma physics and simulation results
  - A few parameters, from yet incomplete physical understandings
  - Approximations to work around complex processes, and/or computational cost

# Common Ingredients of a SNR Broadband Model

- (Magneto-) hydrodynamics
- Progenitor, supernova explosive nucleosynthesis models
- (Observation-motivated) picture for the surrounding environment
- Various implementations of Diffusive Shock Acceleration (DSA)
- Time and space-dependent micro-physical processes
  - Non-equilibrium ionization, charge exchange, …
  - Shock heating, temperature equilibration
  - Radiative cooling/heating
  - Magnetic turbulence generation and dissipation, feedbacks to DSA
- Thermal and non-thermal emission calculations to confront data in various forms

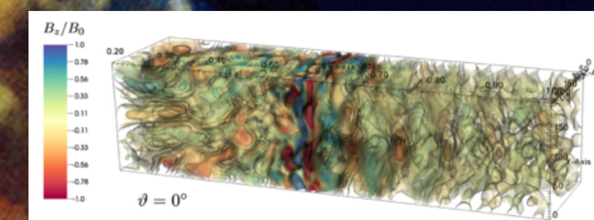
# Numerical Approaches for SNRs

Particle-in-cell

Hybrid

First principles
Few or no parameter/approx

Computational cost
Limited dynamical ranges
**Difficult for multi-$\lambda$ model**



Caprioli & Spitkovsky '14

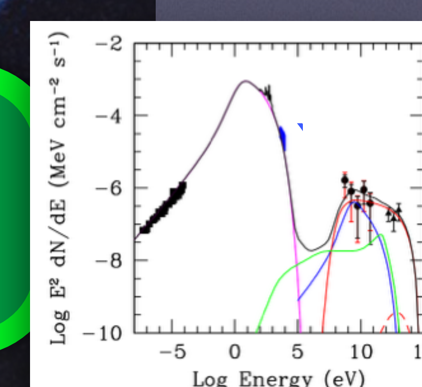
Monte Carlo

Semi-analytic

Global HD/MHD
with microphysics

More phenomenological
(parametric) plasma physics

Large dynamical ranges
**Constrained by**
**multi-$\lambda$ observations**




Slane, HL+ '14

P. Slane

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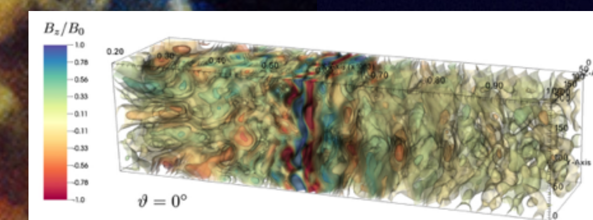

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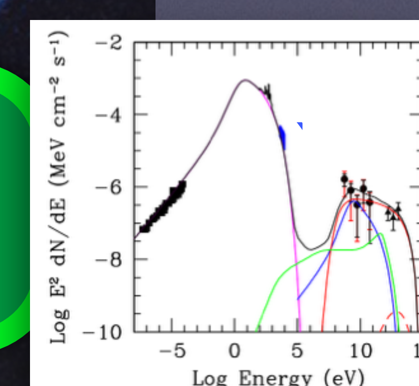


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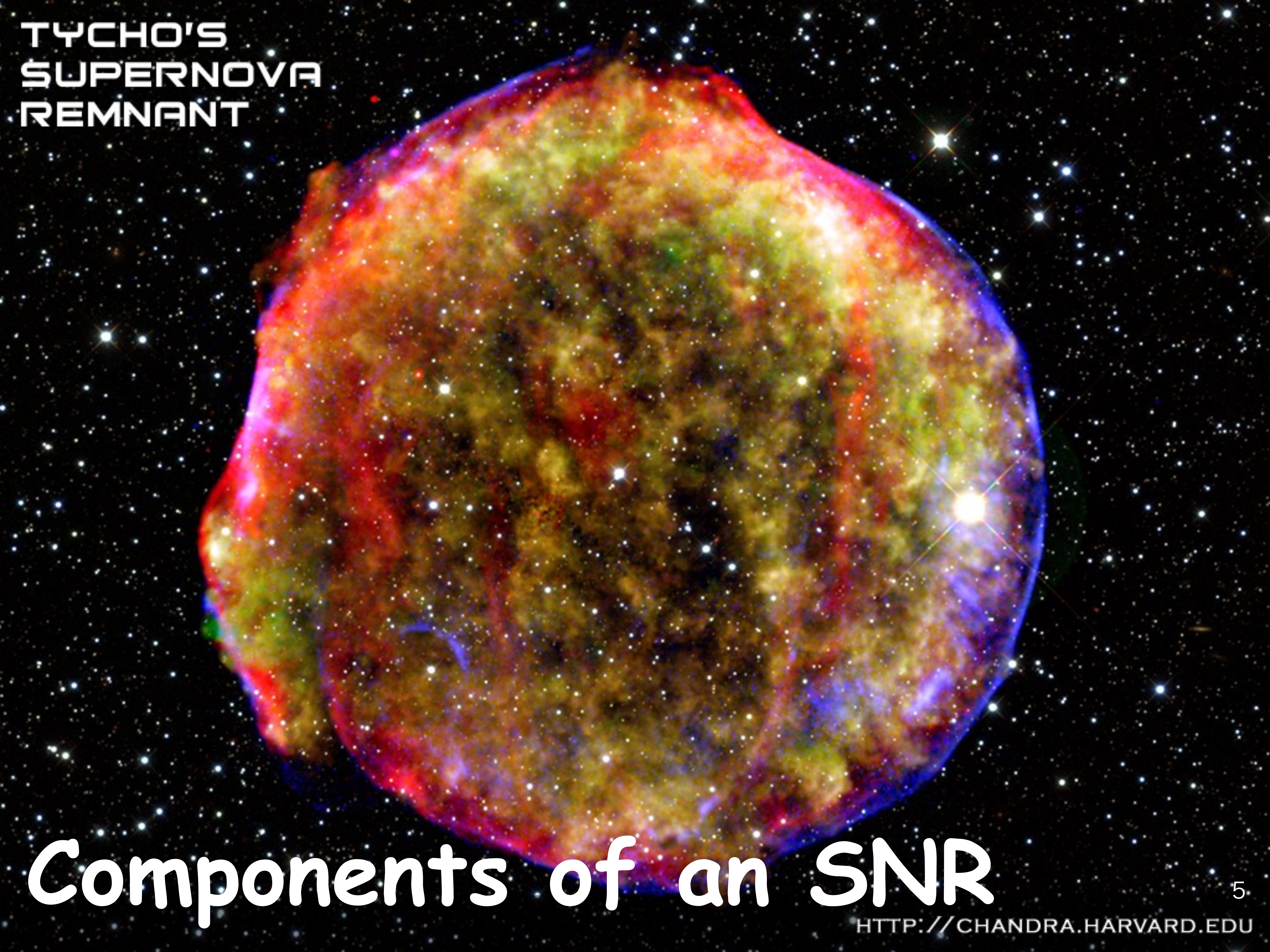
TYCHO'S
SUPERNOVA
REMNANT
Components of an SNR
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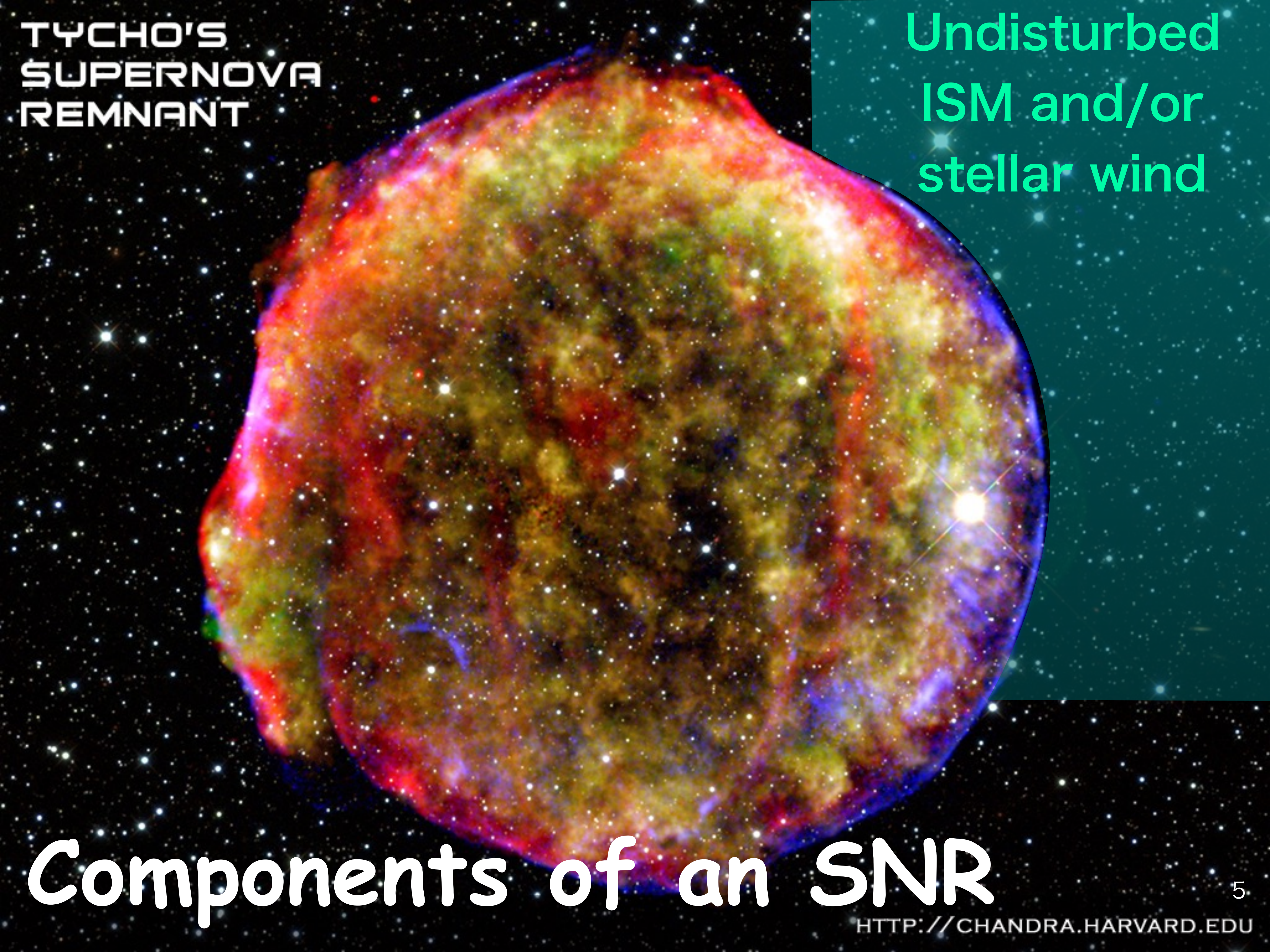
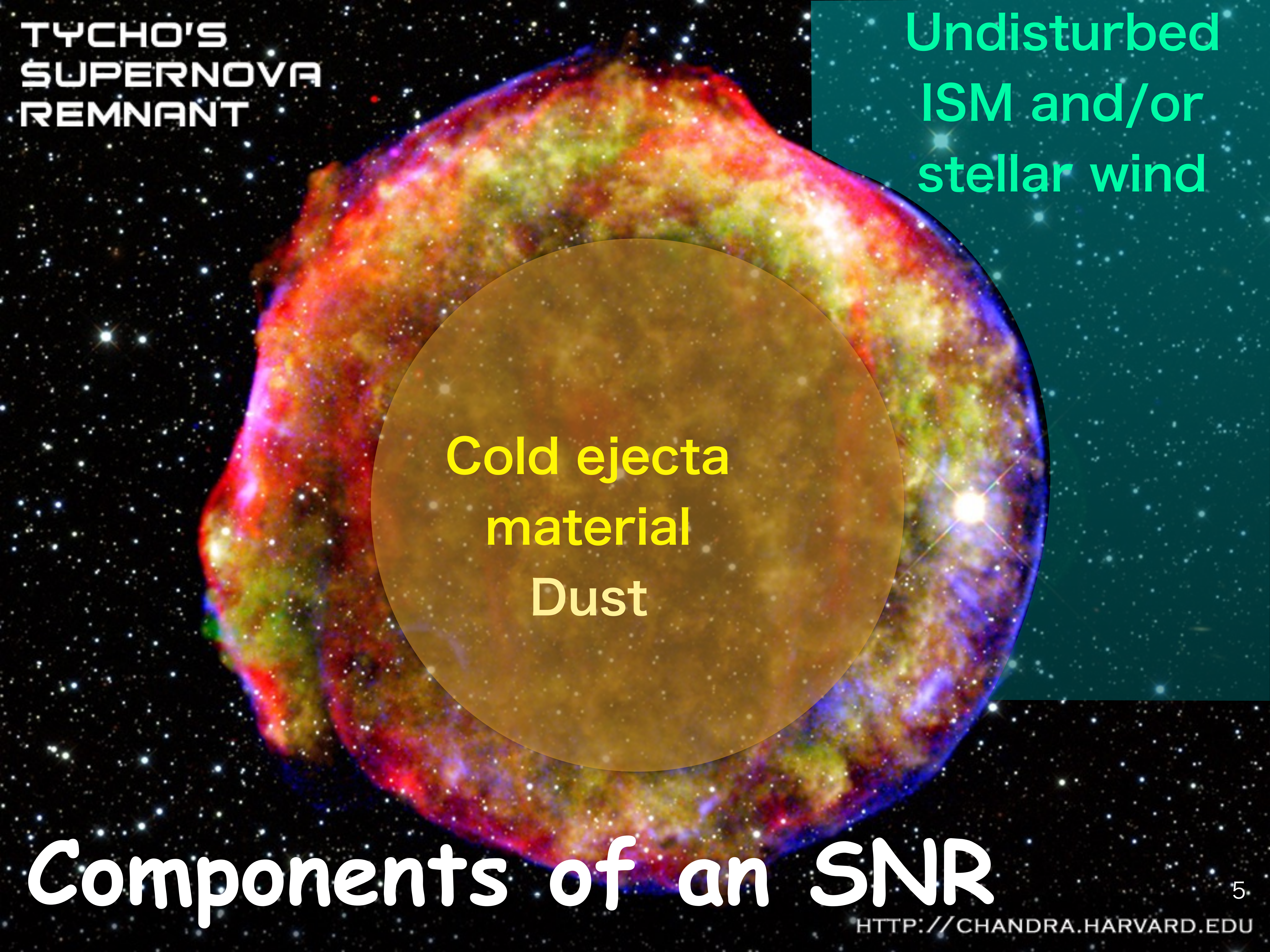
# Components of an SNR




TYCHO'S
SUPERNOVA
REMNANT
Undisturbed
ISM and/or
stellar wind
Cold ejecta
material
Dust
Components of an SNR
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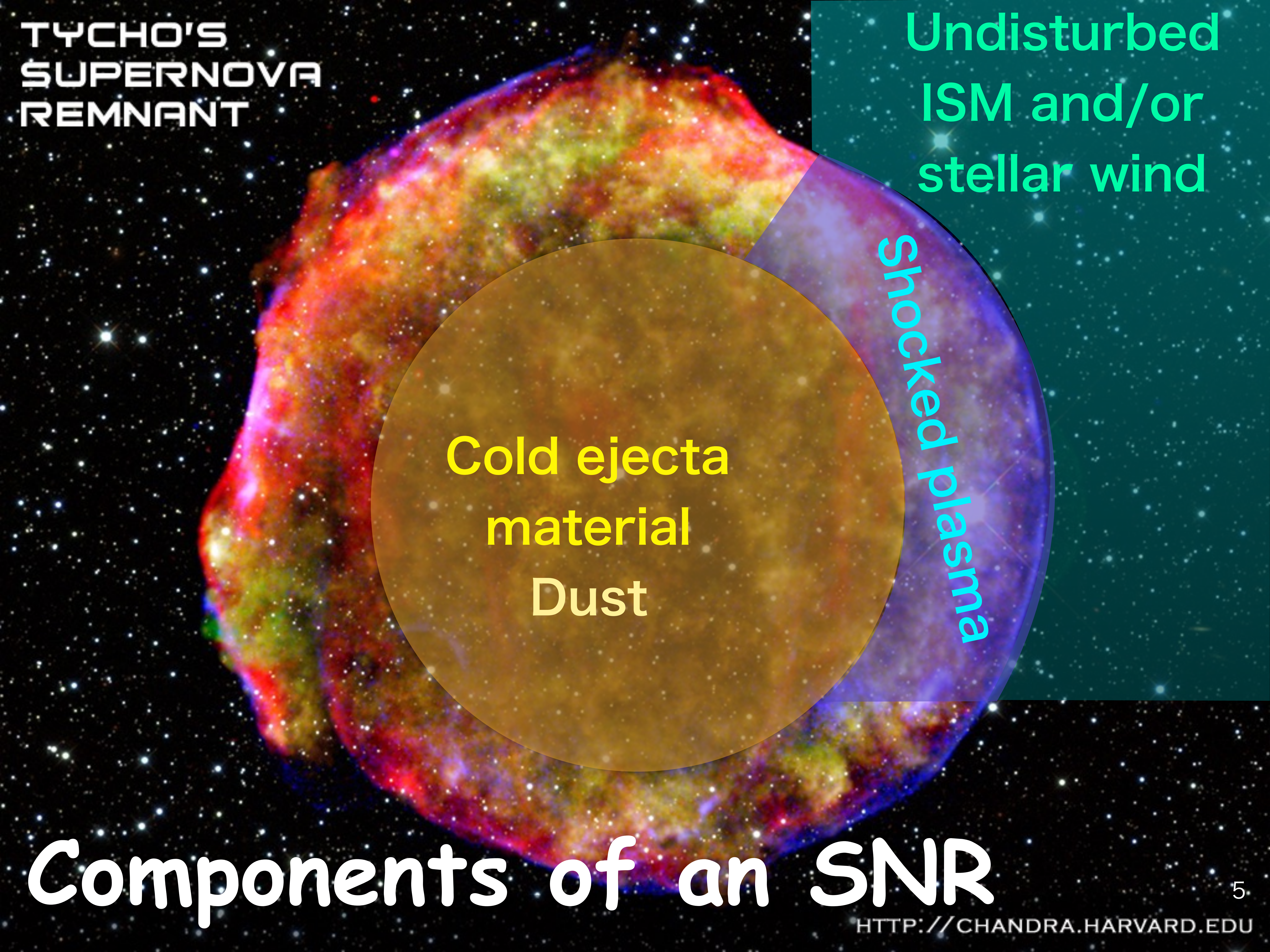

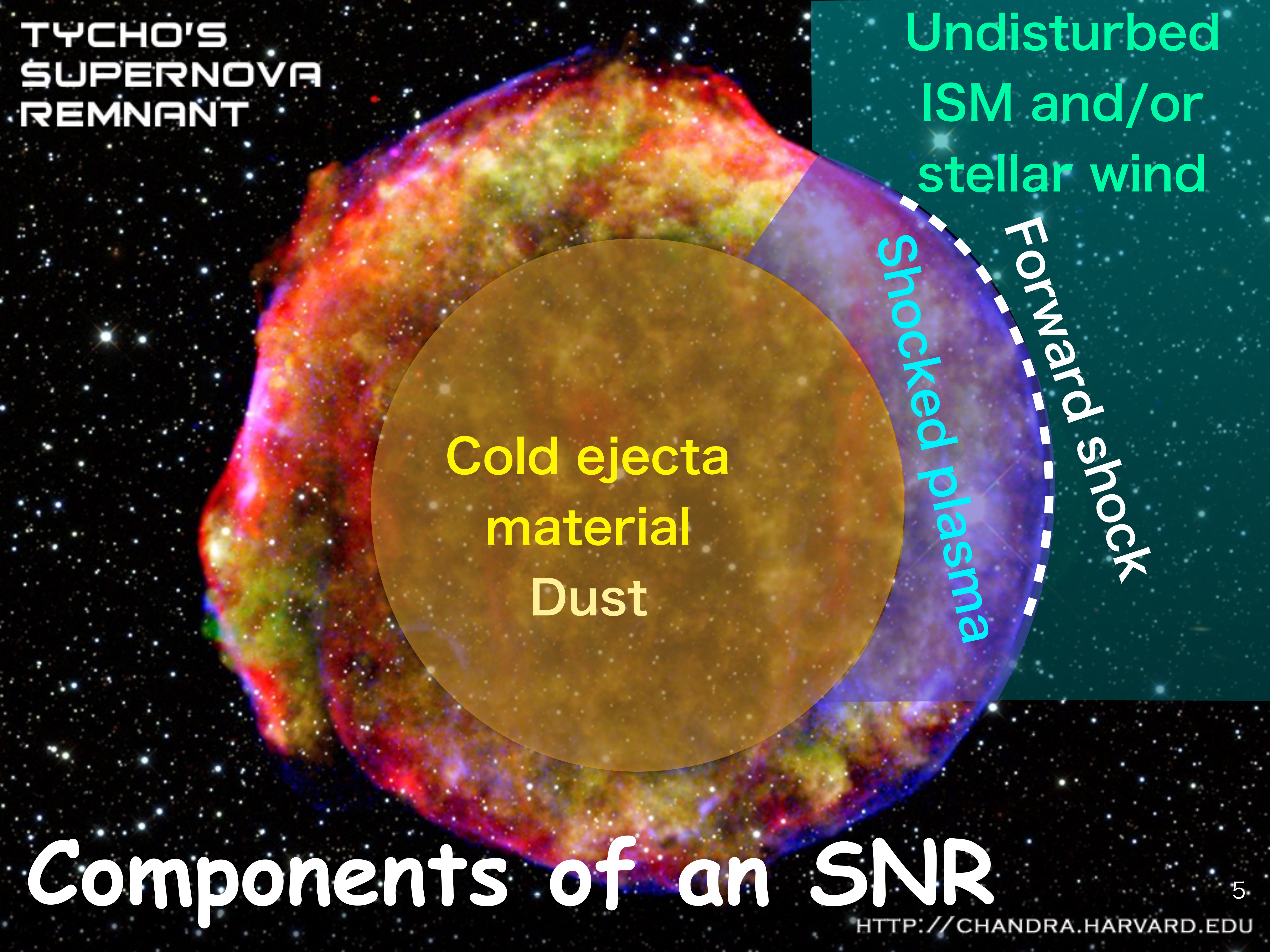
TYCHO'S
SUPERNOVA
REMNANT
Undisturbed
ISM and/or
stellar wind
Forward shock
Shocked plasma
Cold ejecta
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Dust
Components of an SNR
5
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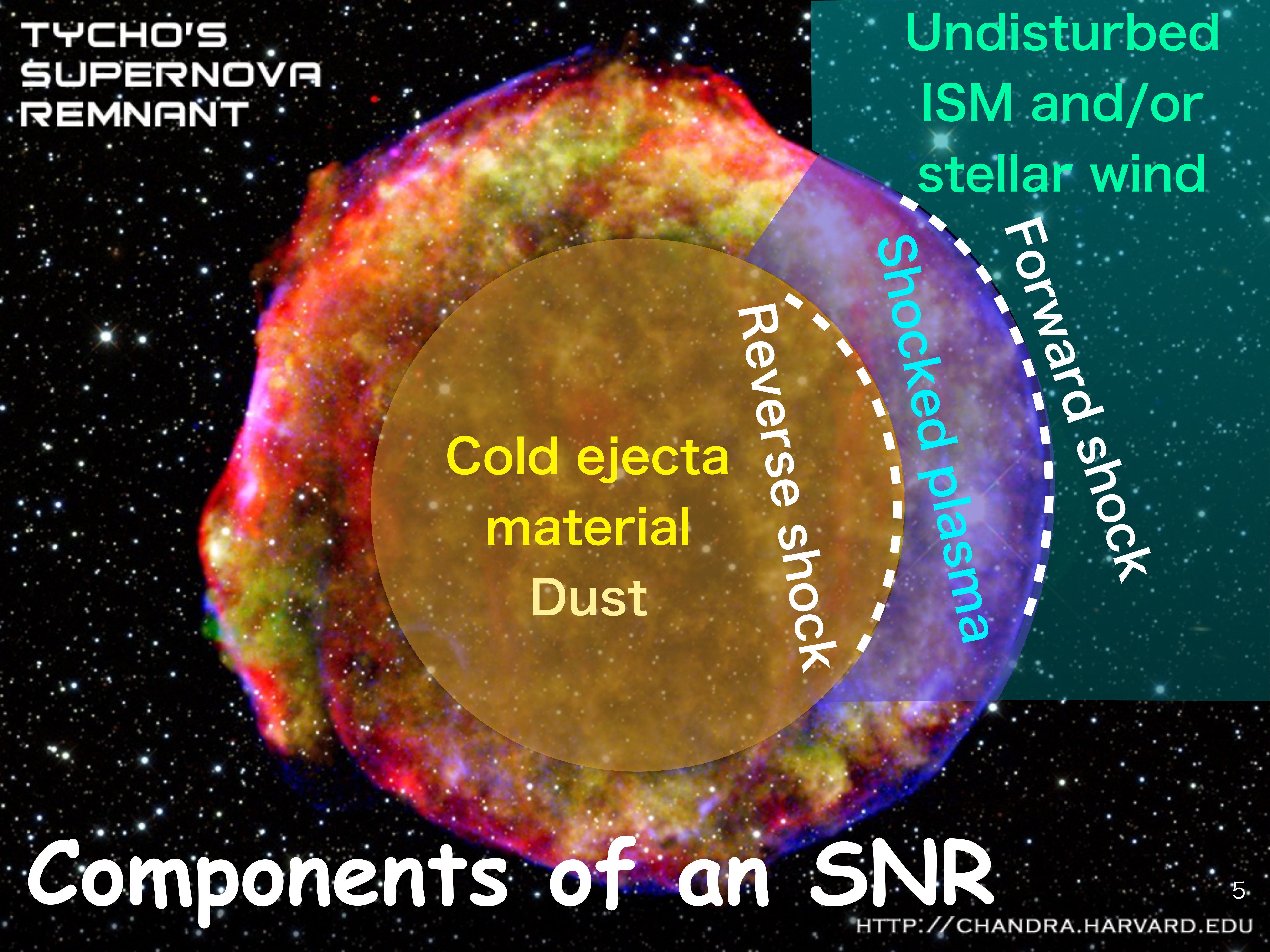
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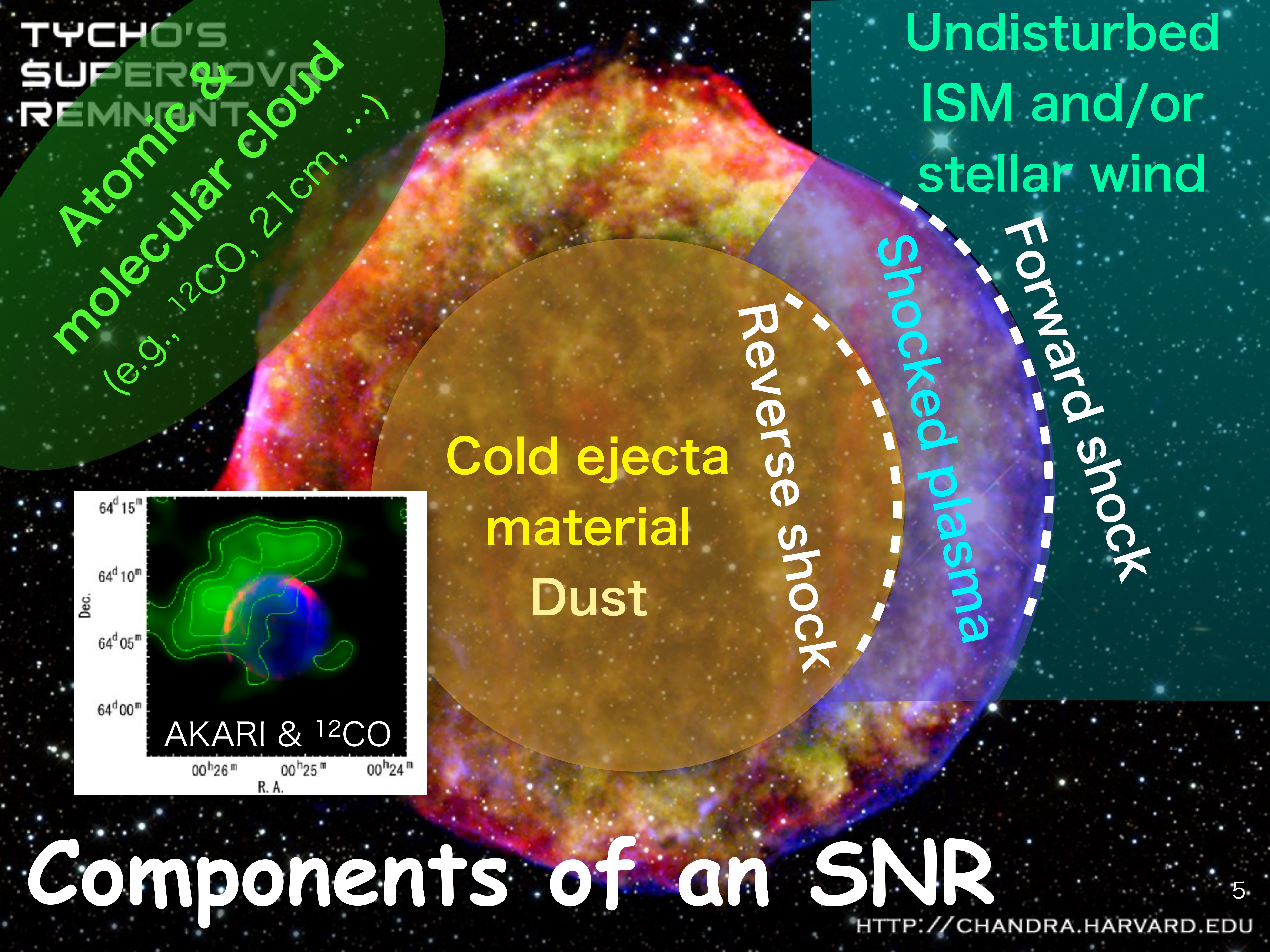
TYCHO'S SUPERNOVA REMNANT
Atomic & molecular cloud
(e.g., 12CO, 21cm, ...)
Undisturbed ISM and/or stellar wind
Forward shock
Shocked plasma
Reverse shock
Cold ejecta material
Dust
64d15m
64d10m
64d05m
64d00m
Dec.
00h26m
00h25m
00h24m
R. A.
AKARI & 12CO
Components of an SNR
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# 'Lights' from an SNR

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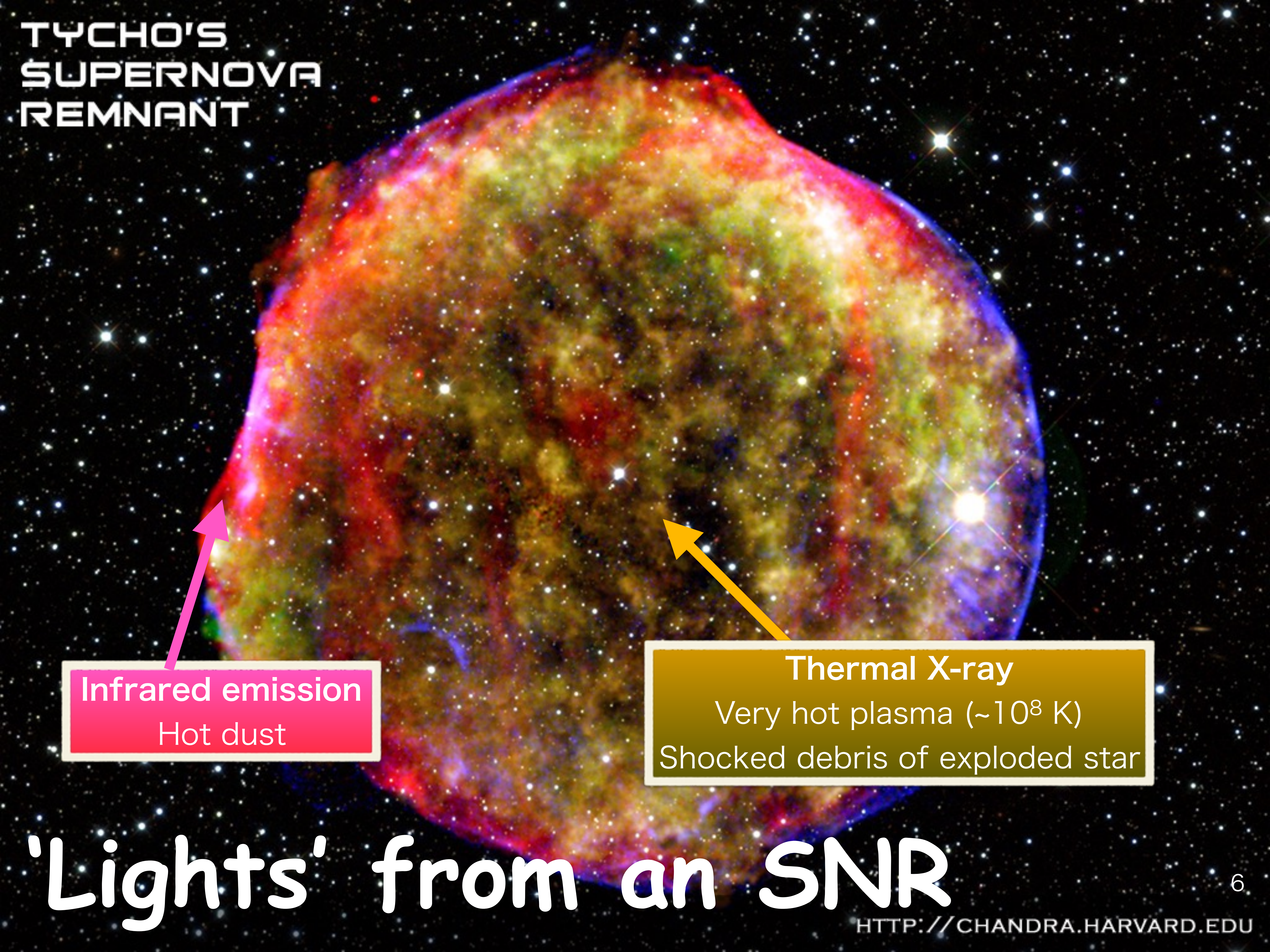

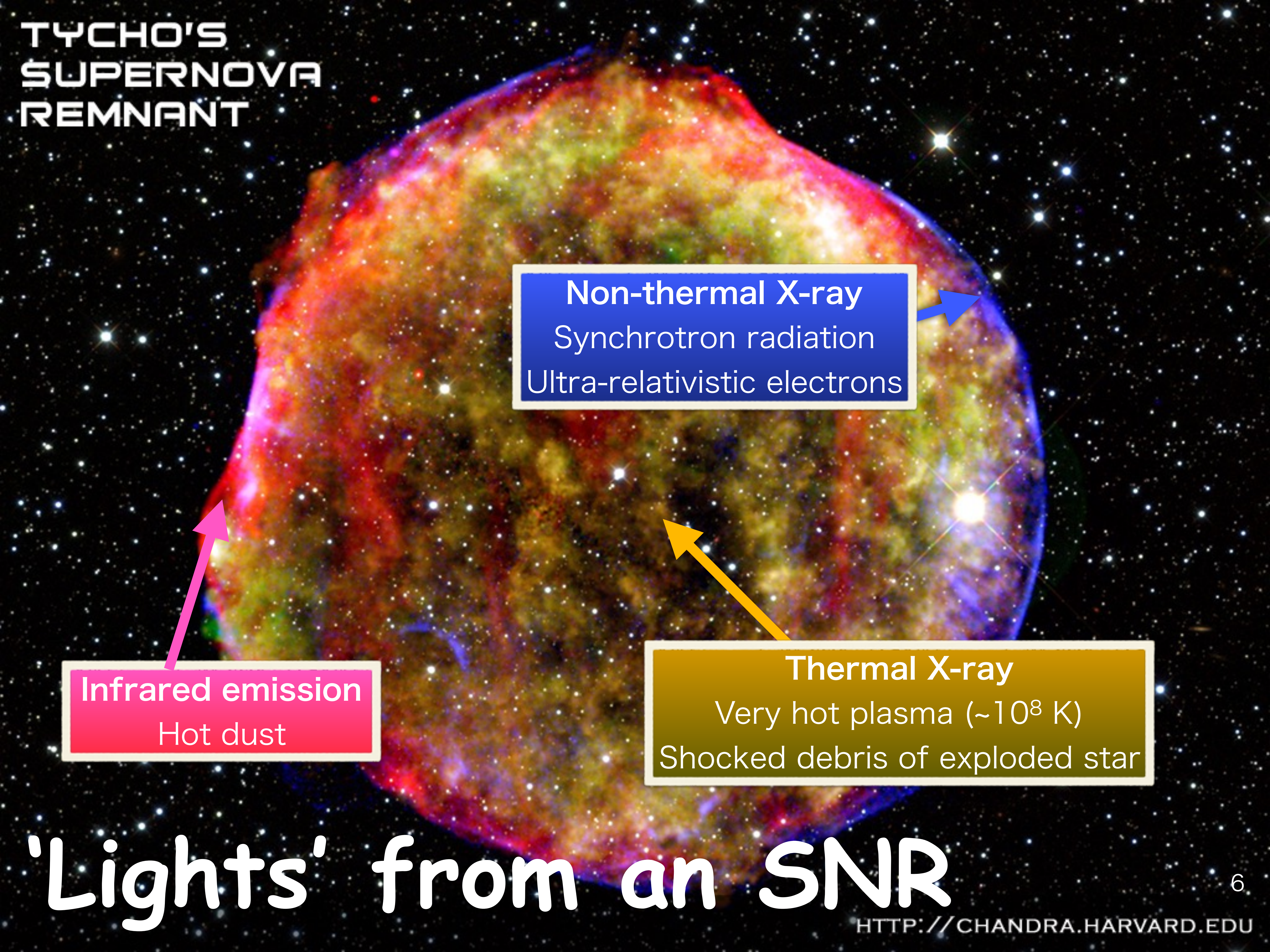


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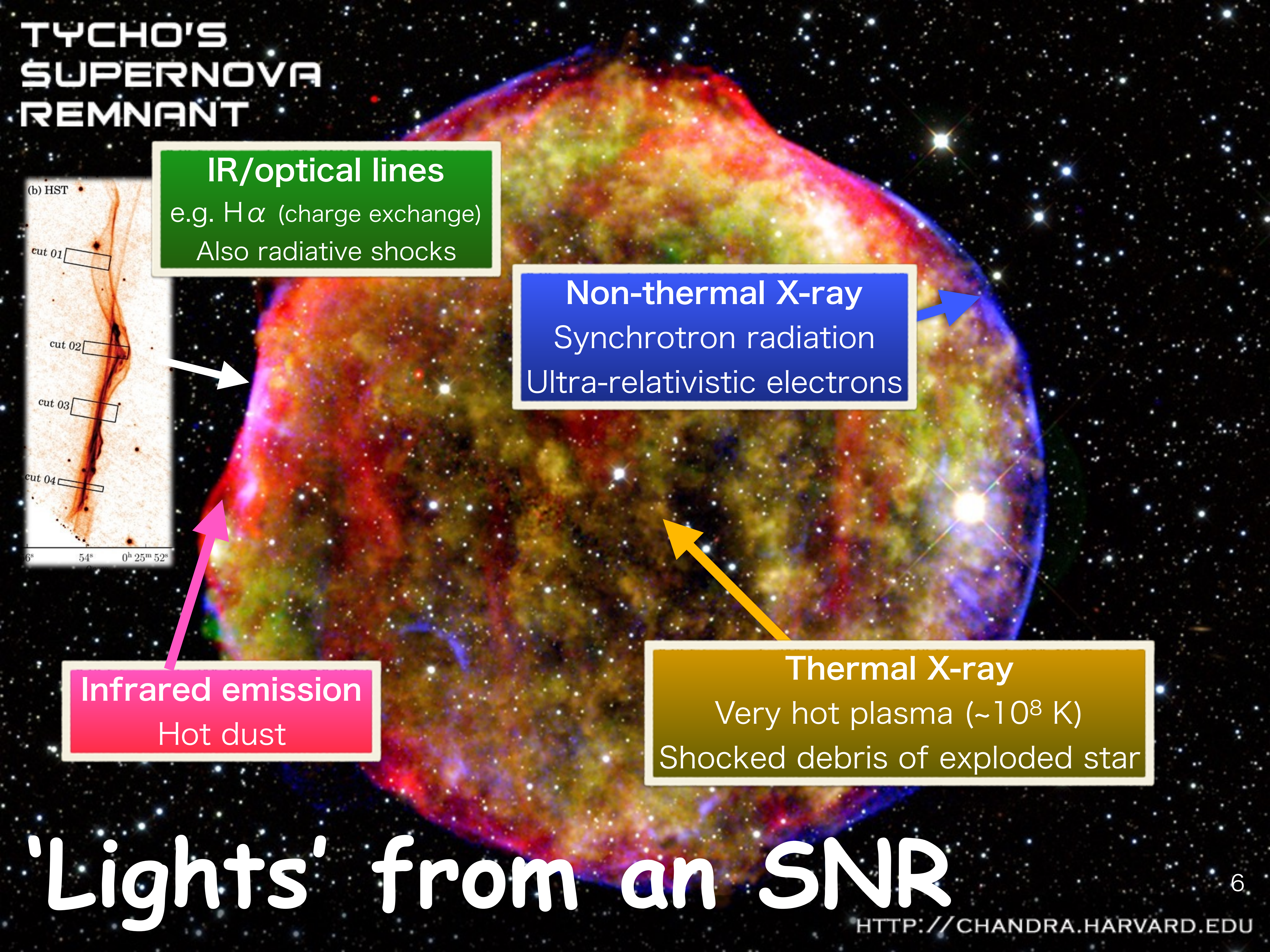
TYCHO'S SUPERNOVA REMNANT
(b) HST
cut 01
cut 02
cut 03
cut 04
6s
54s
0h 25m 52s
IR/optical lines
e.g. Hα (charge exchange)
Also radiative shocks
Non-thermal X-ray
Synchrotron radiation
Ultra-relativistic electrons
Infrared emission
Hot dust
Thermal X-ray
Very hot plasma (~10⁸ K)
Shocked debris of exploded star
'Lights' from an SNR
6
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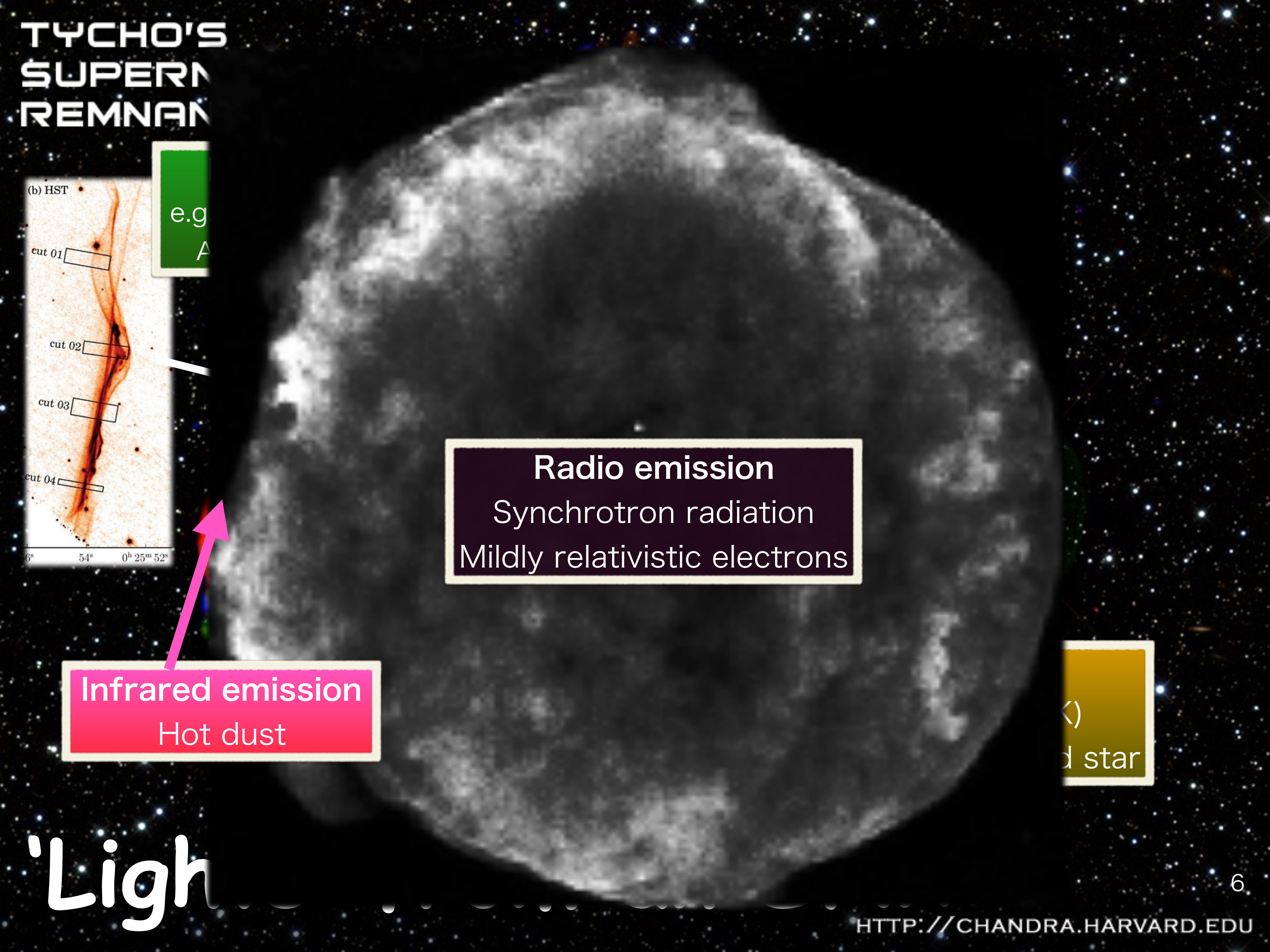
TYCHO'S
(b) HST
cut 01
cut 02
cut 03
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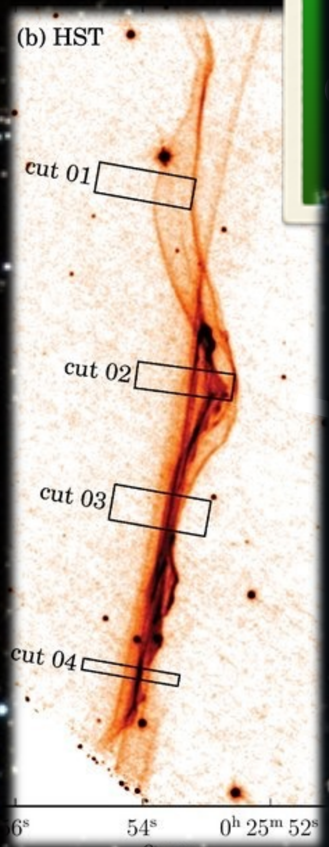
Radio emission
Synchrotron radiation
Mildly relativistic electrons
Infrared emission
Hot dust
HTTP://CHANDRA.HARVARD.EDU
6

TYCHO'S SUPERN
REMN




Infrar
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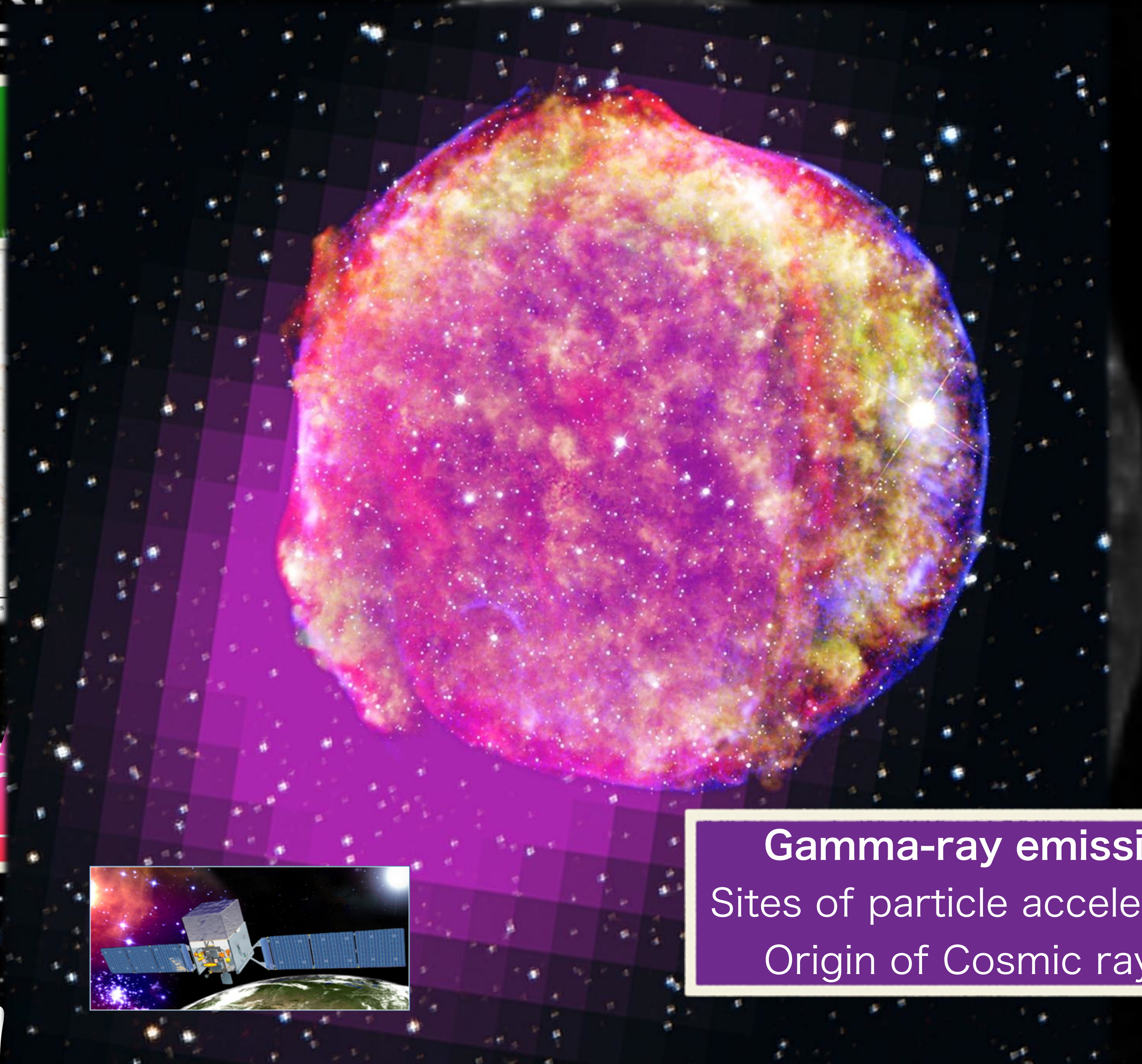

**Gamma-ray emission**
Sites of particle acceleration
Origin of Cosmic rays?

'Lig



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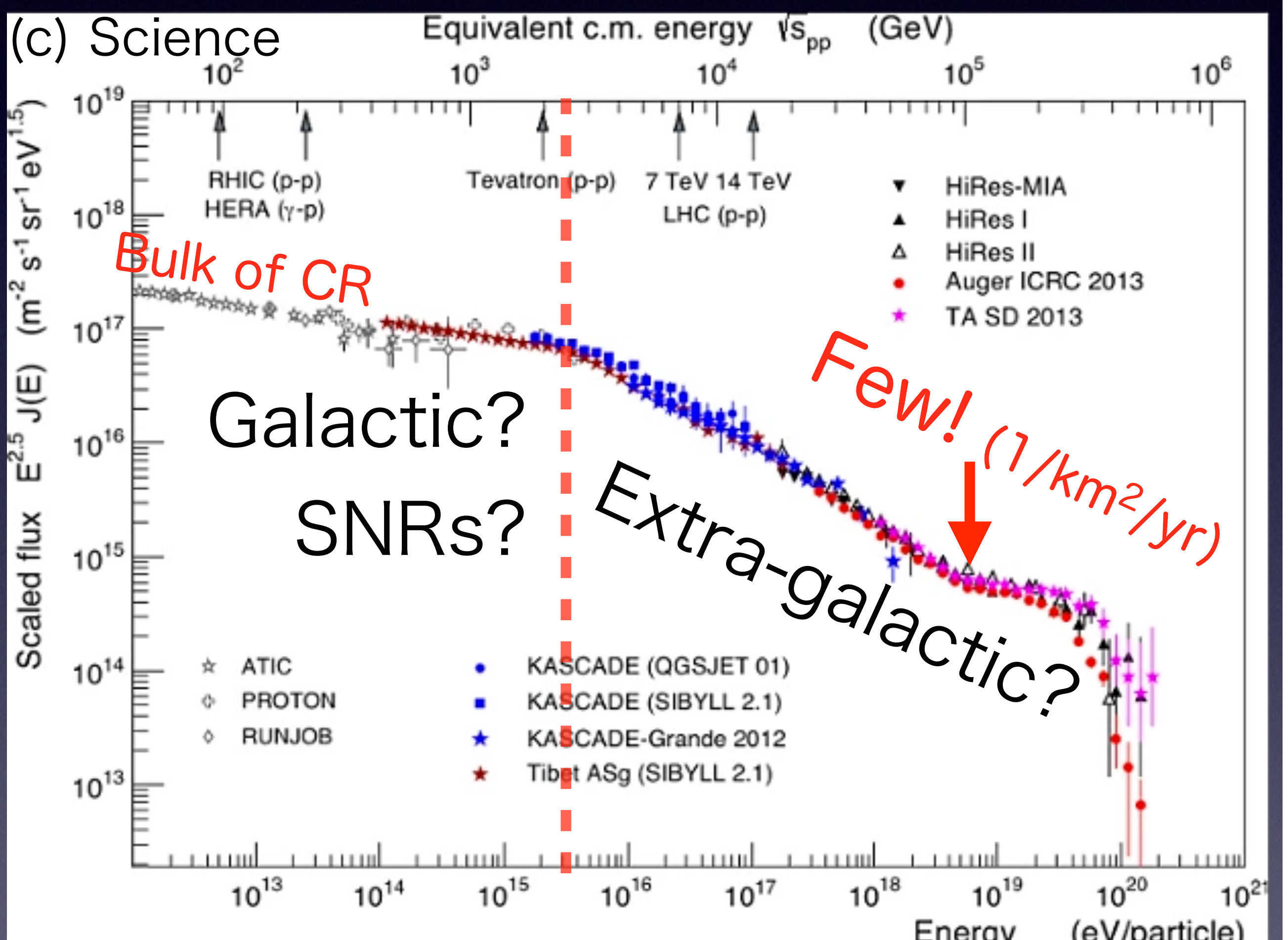
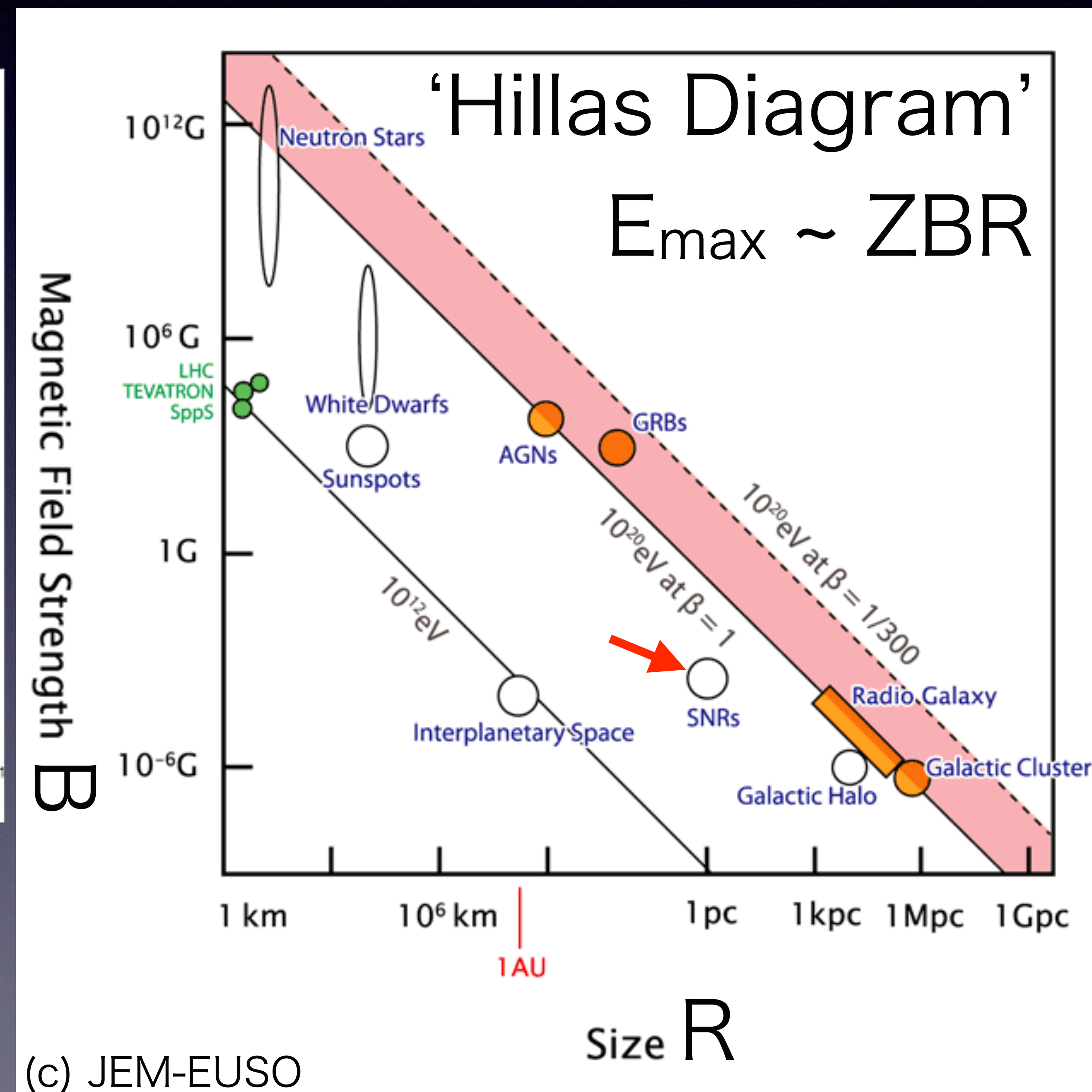
# SNRs as origin of cosmic rays in galaxies




TeV PeV EeV




**Galactic CR energy content**
**~10% of $E_{SN}$ —> $E_{CR}$** (~0.03 SN/yr)
**seems sufficient!**

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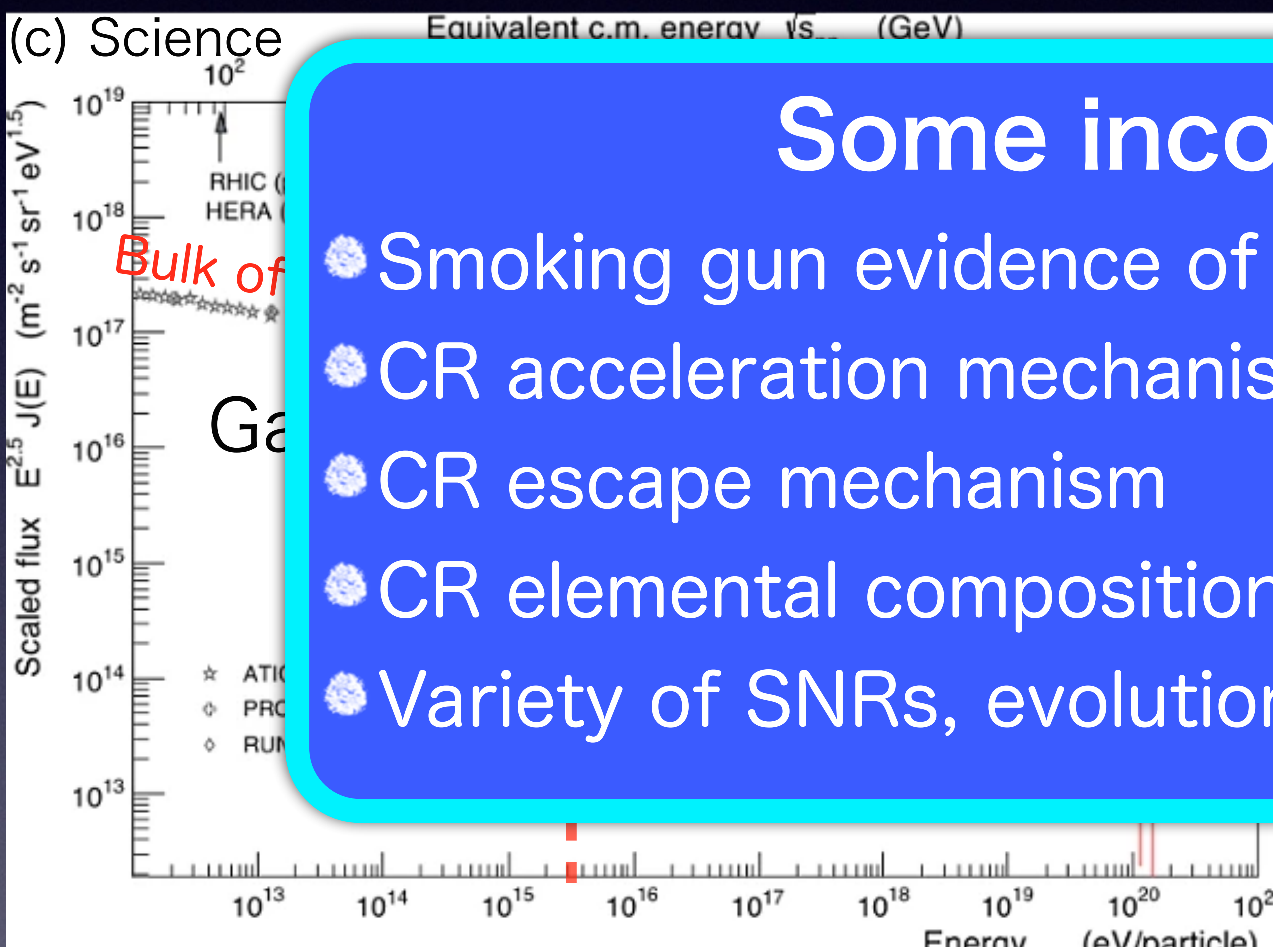


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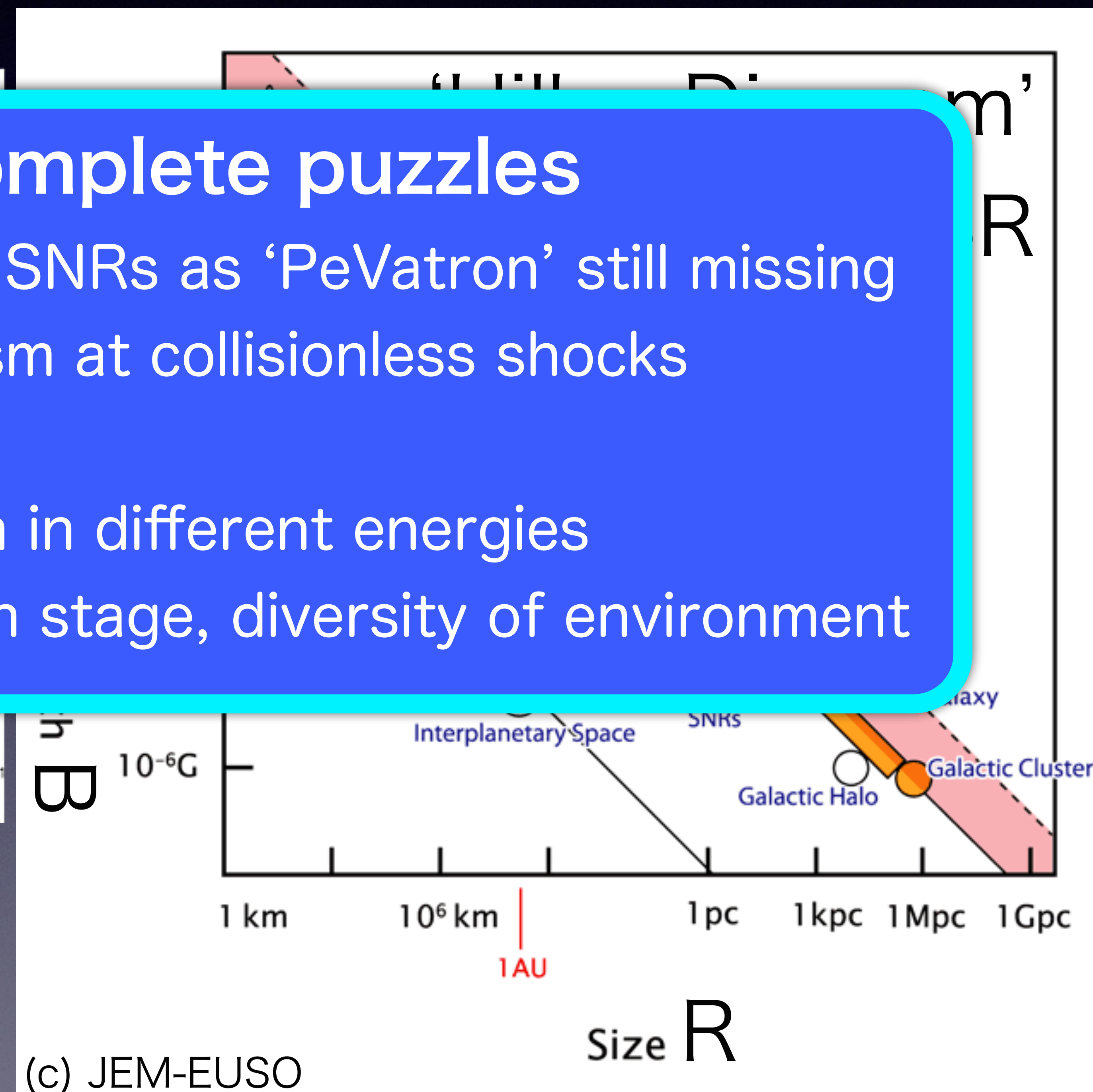


## Some incomplete puzzles

- Smoking gun evidence of SNRs as 'PeVatron' still missing
- CR acceleration mechanism at collisionless shocks
- CR escape mechanism
- CR elemental composition in different energies
- Variety of SNRs, evolution stage, diversity of environment

**Galactic CR energy content**

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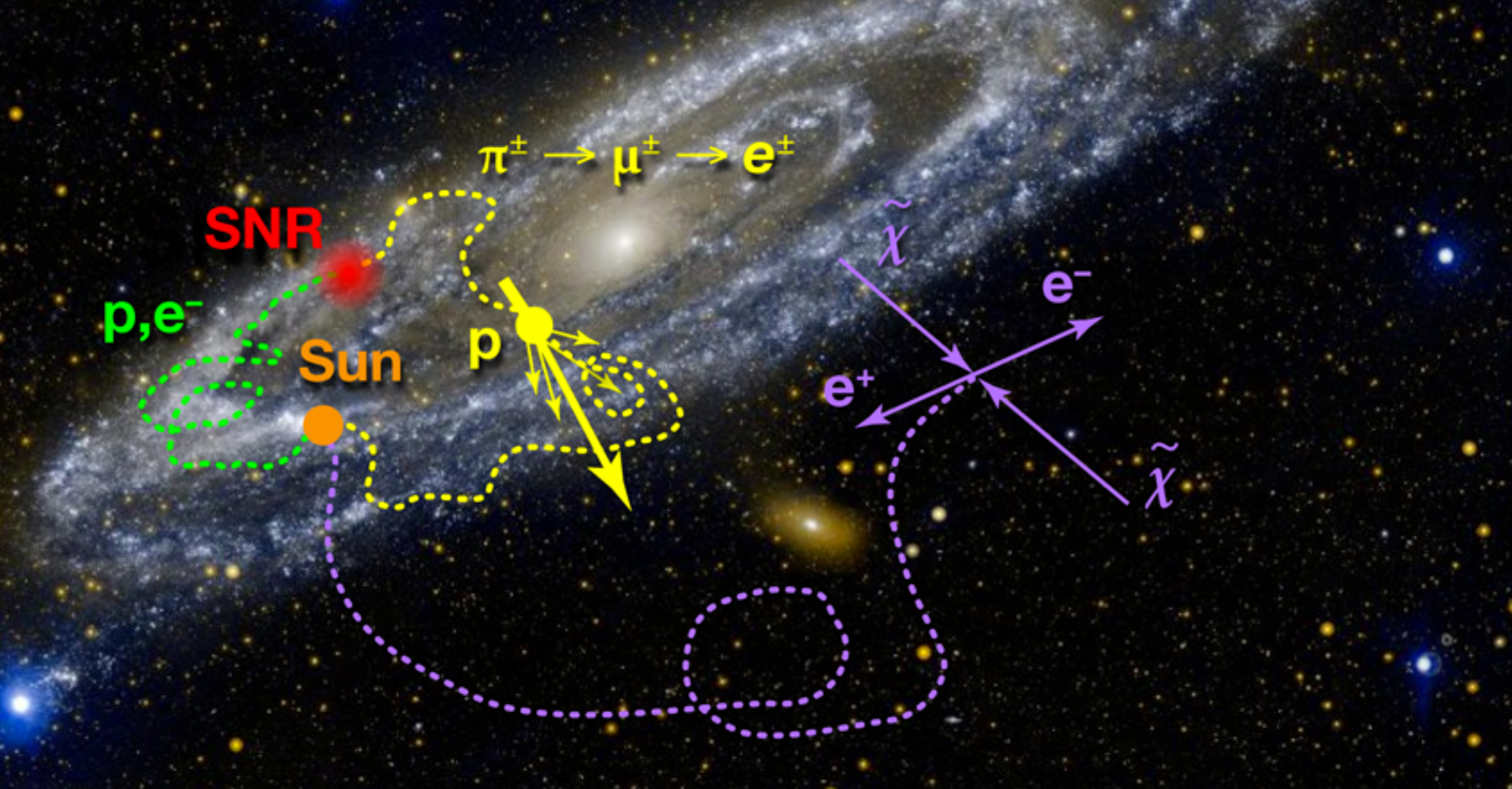
**seems sufficient!**

# Cosmic Ray Astronomy ain't gonna work bro




Credit: Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker

# Cosmic Ray Astronomy ain't gonna work bro

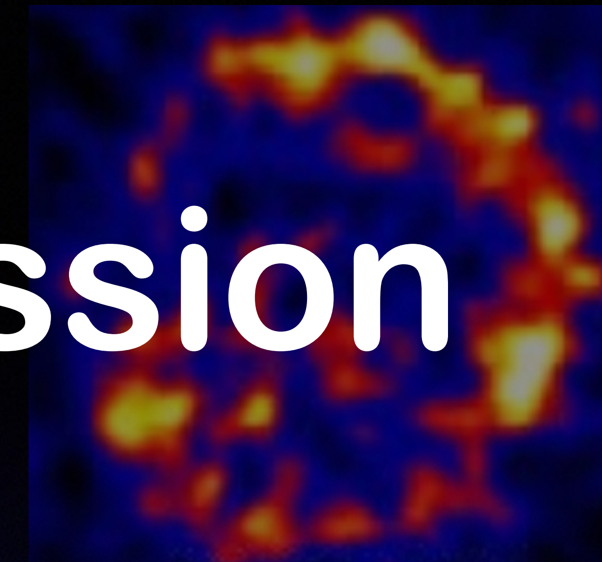

1st alternative: gamma-rays

They don't bend much

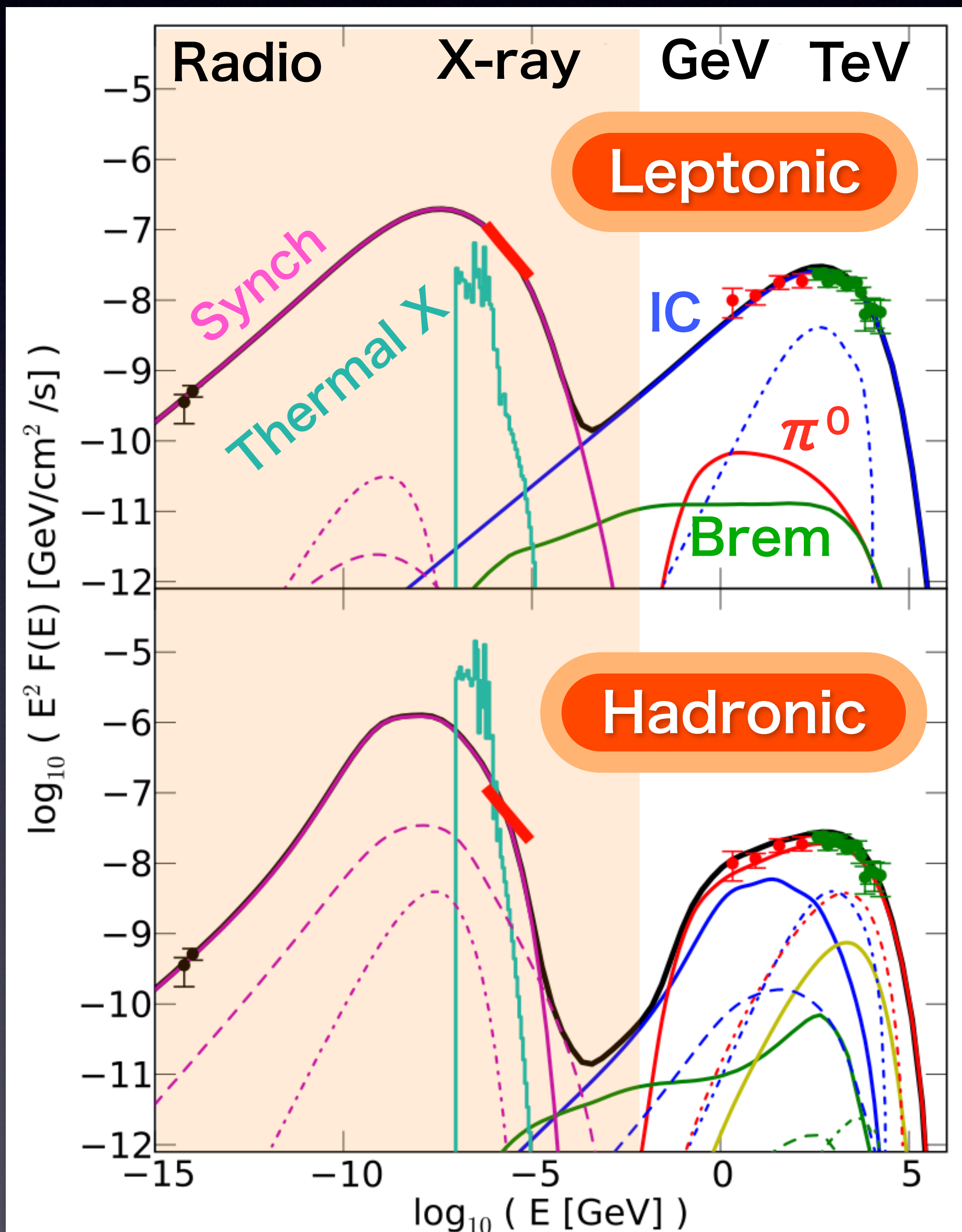
Not so much interaction in Galactic scale

Credit: Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker

# Origins of γ-ray emission



HL, Slane+ 2013 on SNR **Vela Jr.**




**$\pi^0$ decay**

CR **ion** + gas → $\pi^0$

Flat'ish spectrum

Requires **dense gas**

“hadronic”

**Inverse-Compton scatterings**

CR **electron** + seed photons → $\gamma$-ray

Hard spectrum

Requires: low B-field (avoid synch loss)

low density (suppress $\pi^0$)

**Non-thermal bremsstrahlung**

CR electron + gas → $\gamma$-ray

Same spectral index as CR

Requires: low B-field (synch loss)

dense gas (target)

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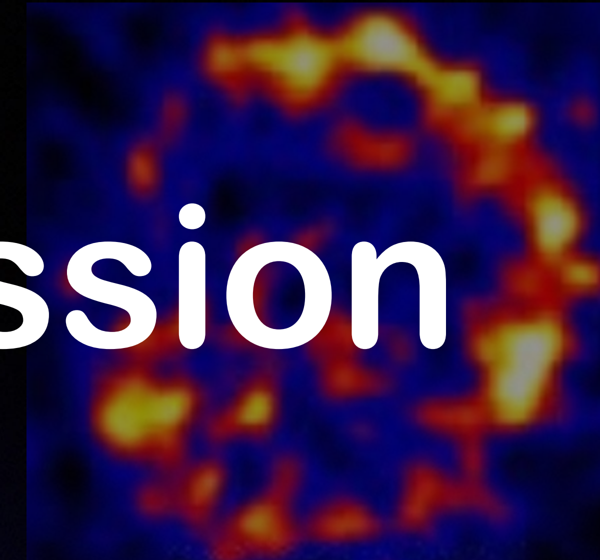

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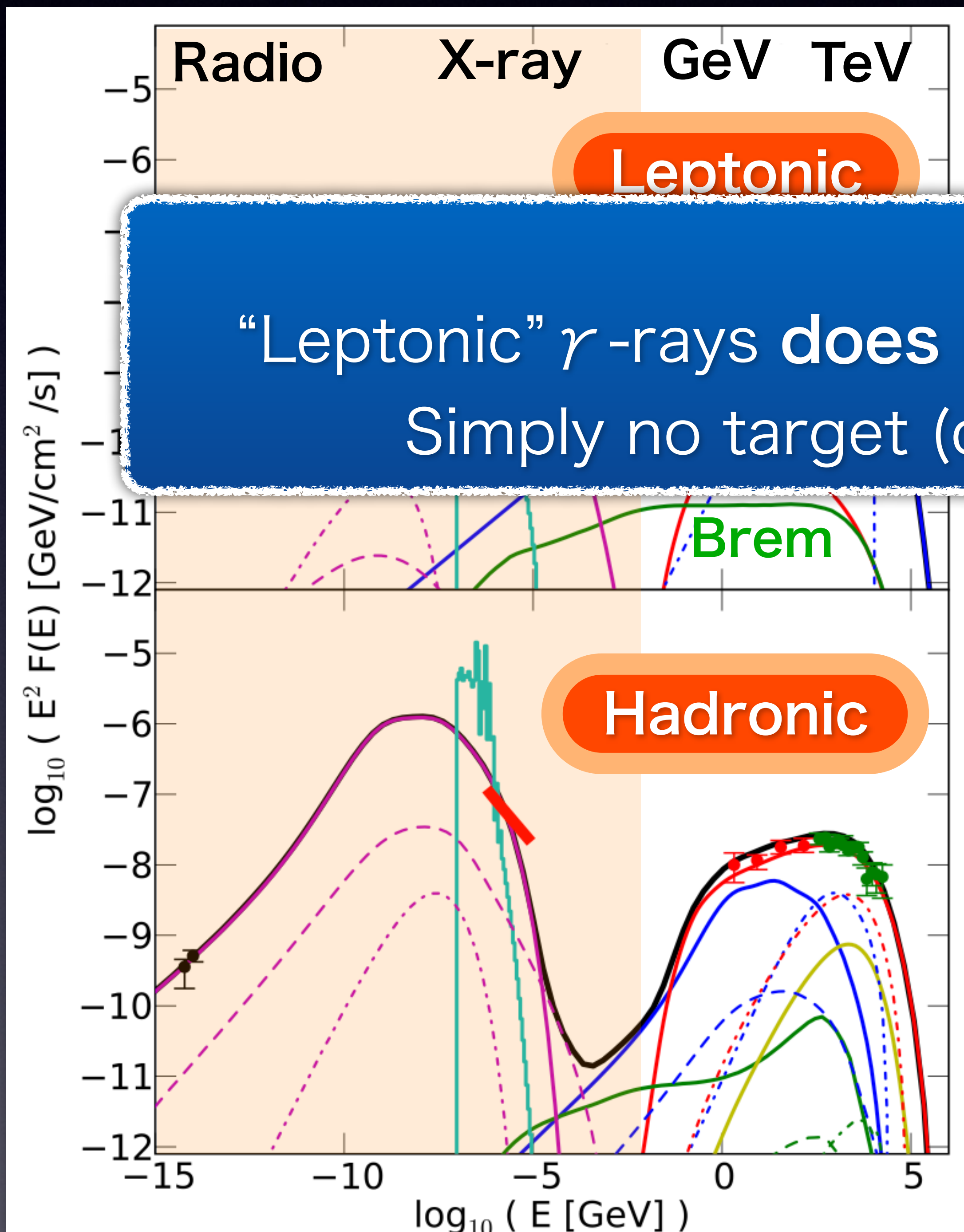


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**Caution**

"Leptonic" $\gamma$-rays **does NOT** mean no proton acceleration!

Simply no target (dense gas) for $\pi^0$ production

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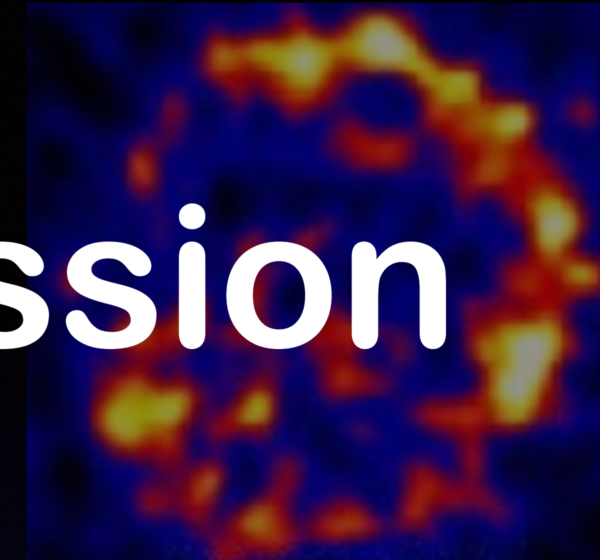

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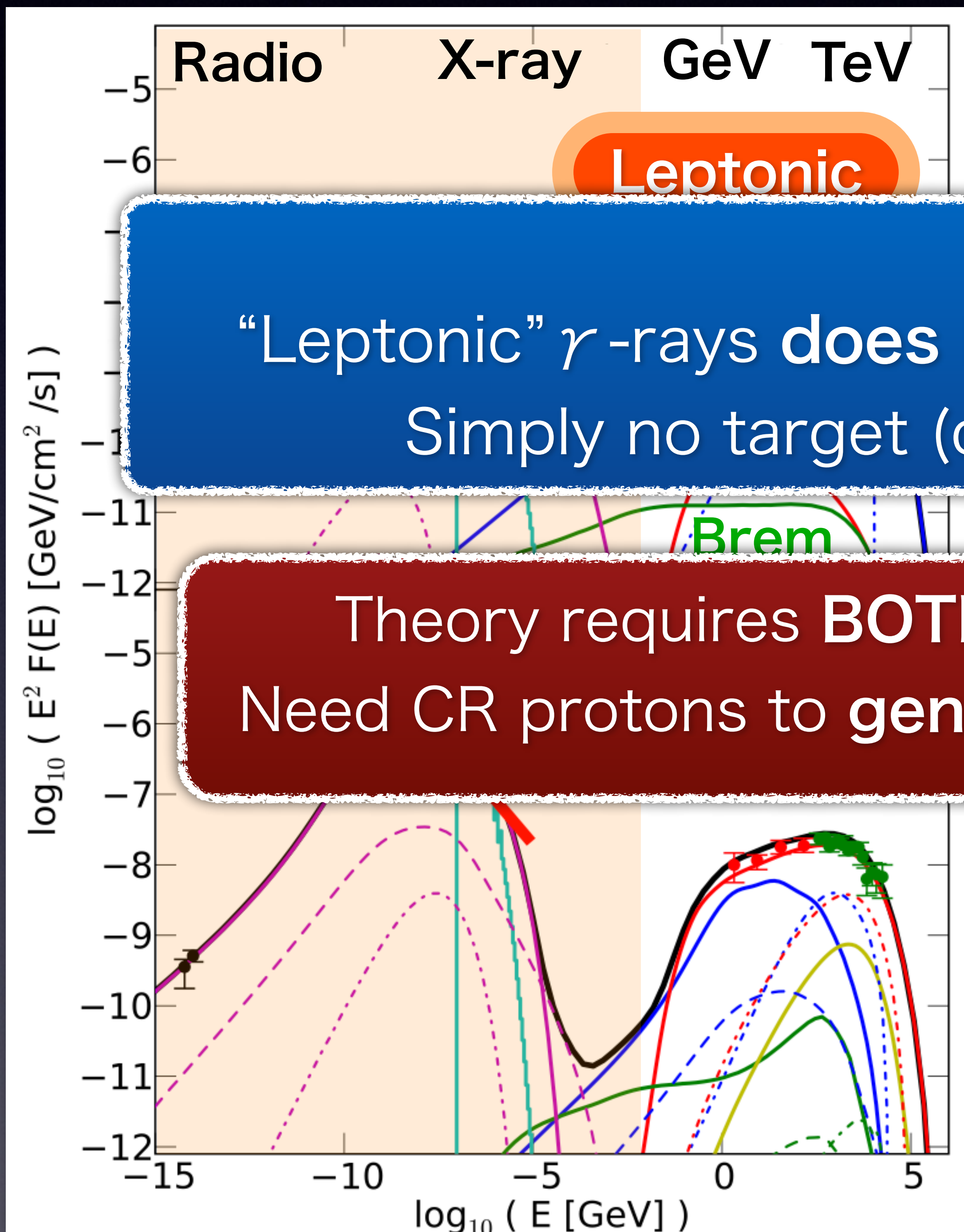


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CR **electron** + seed photons → $\gamma$-ray

Theory requires **BOTH** proton & electron acceleration

Need CR protons to **generate/amplify** magnetic turbulence

**Non-thermal bremsstrahlung**

CR electron + gas → $\gamma$-ray

Same spectral index as CR

Requires: low B-field (synch loss)

dense gas (target)

high e/p (suppress $\pi^0$ )

"leptonic"

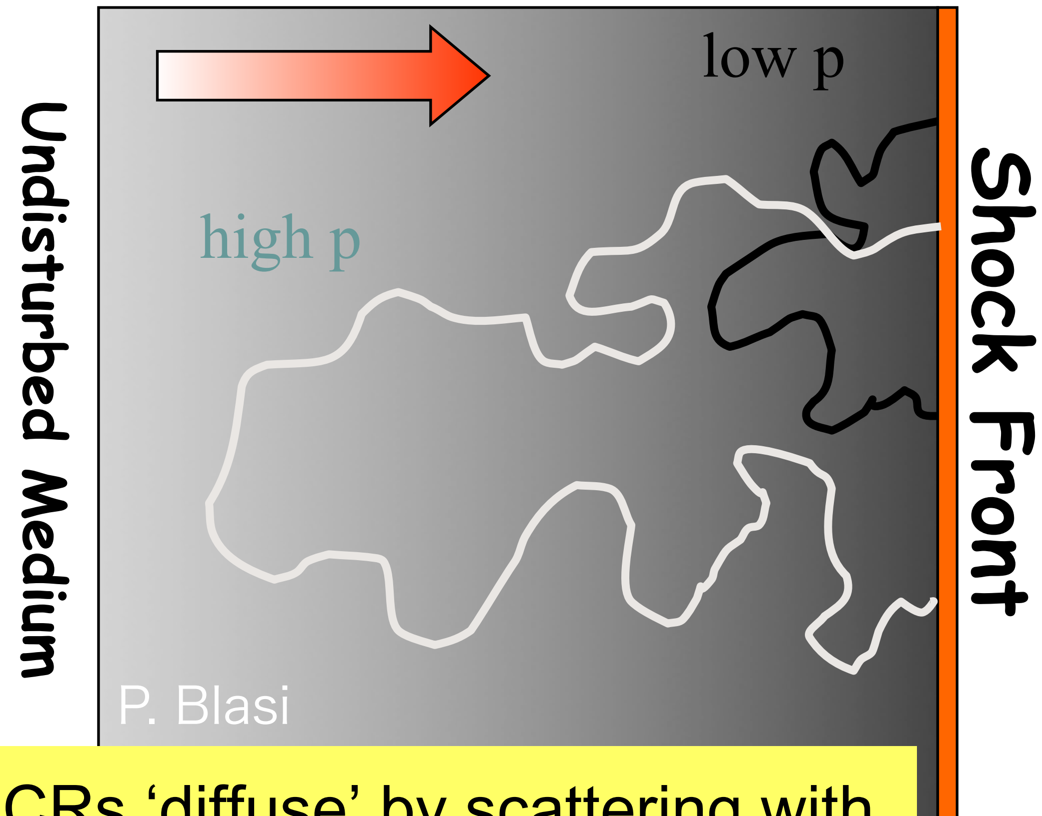
# How particles get accelerated

(Younger) SNRs have **strong non-relativistic collisionless shocks**

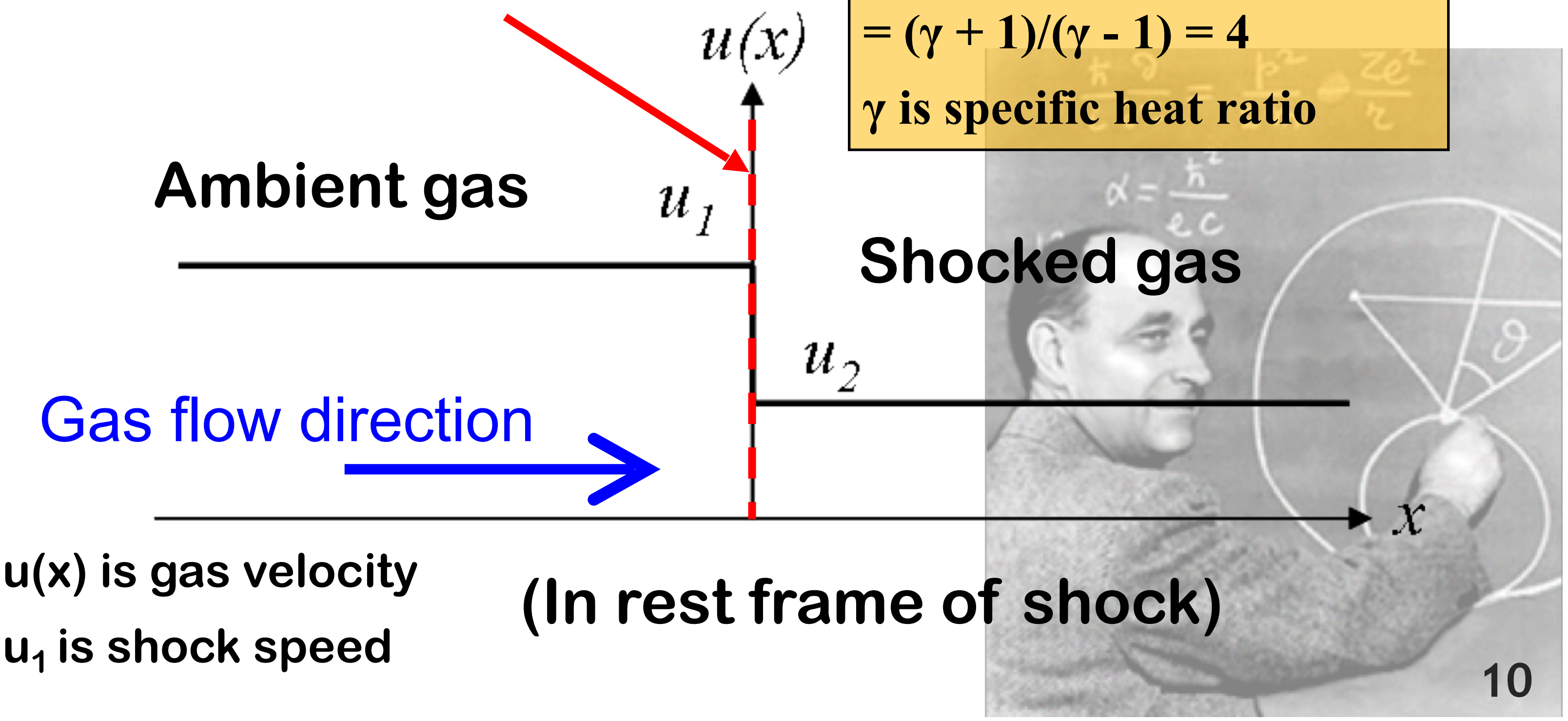
→ **Diffusive Shock Acceleration (DSA)** **[aka Fermi 1st order acceleration]**

- 'Diffuse' by **elastic scattering w/ magnetic turbulence** on both sides of shock
- Particles **repeatedly crossing the shock front**
- Each time, **fractional momentum gain** △p/p ~ (velocity difference)/(speed of light)

→ Young SNRs: cosmic ray energy easily > 10% of $E_{SN}$ (e.g. Ellison+ 05)




CRs '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

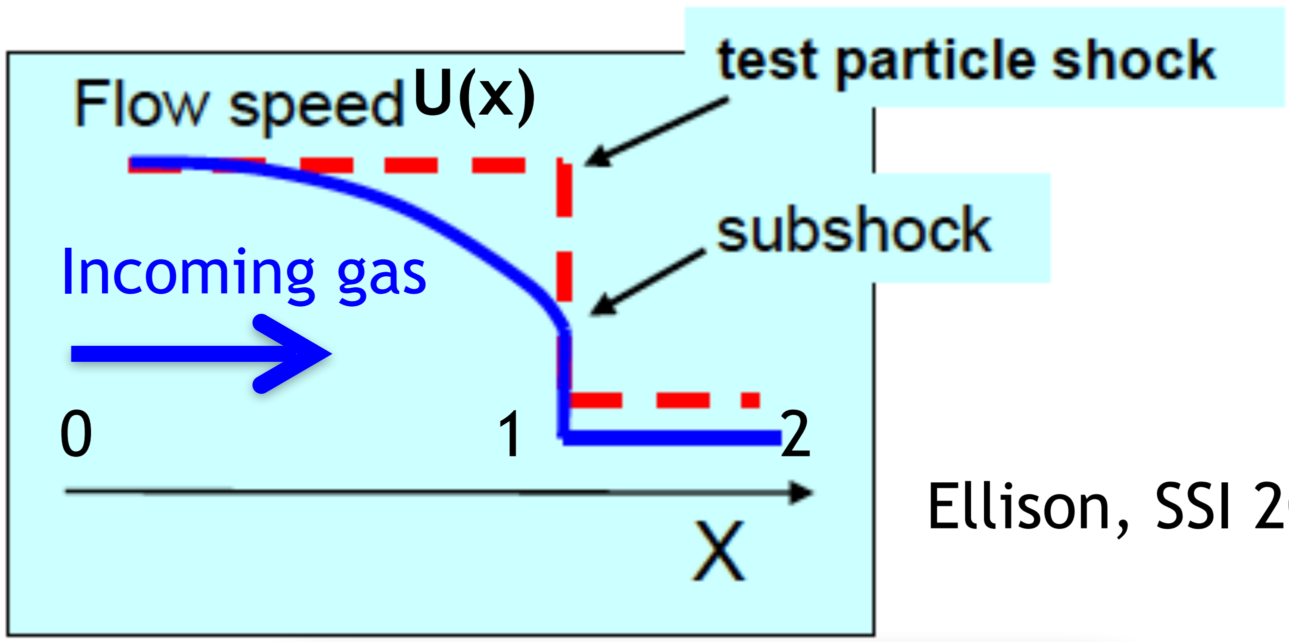
u(x) is gas velocity

$u_1$ is shock speed

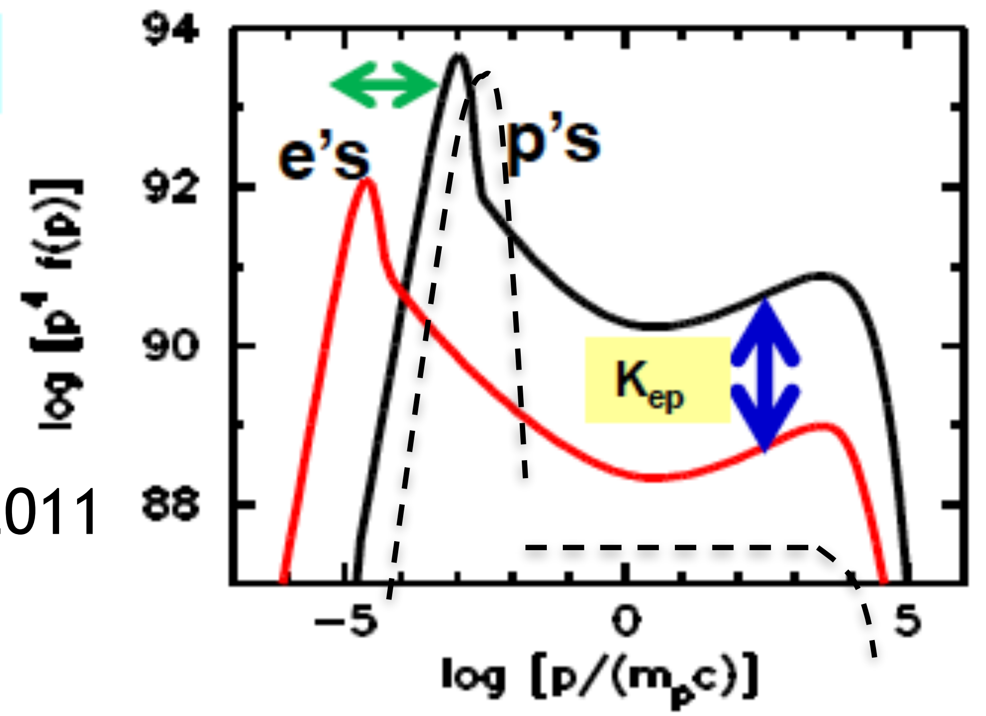
(In rest frame of shock)

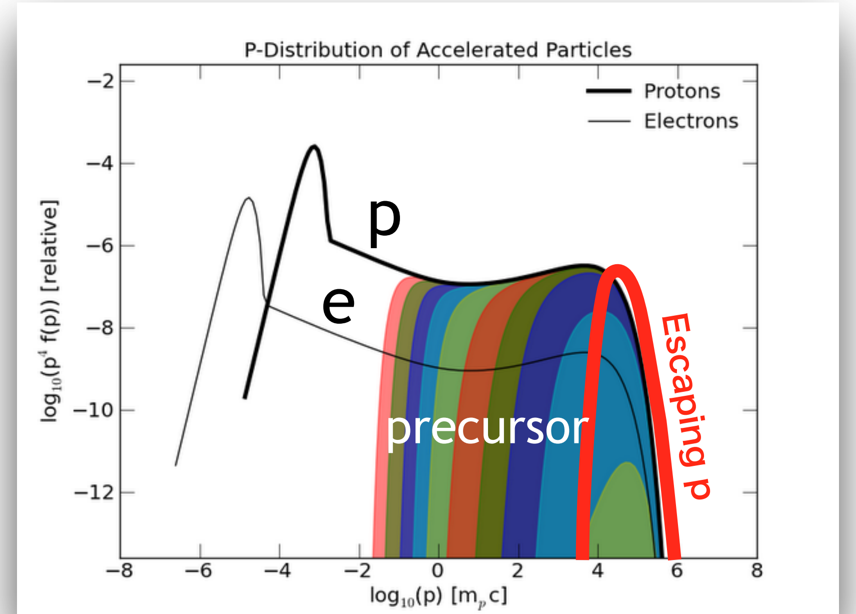
# Nonlinear diffusive shock acceleration

Efficient particle acceleration leads to funny consequences, e.g.,
highly modified shock flow, 'concave' spectrum, lower shocked temp




Ellison, SSI 2011




e.g., HL+ 2012

# The CR-hydro-NEI (ChN) Code

- **Nonlinear DSA physics** (HL, Ellison & Nagataki 2012)
  - CR back-pressure → feedback to shock structure, vice versa
  - Particle escape
  - Magnetic turbulence generation + wave damping
    → Magnetic field amplification (MFA)
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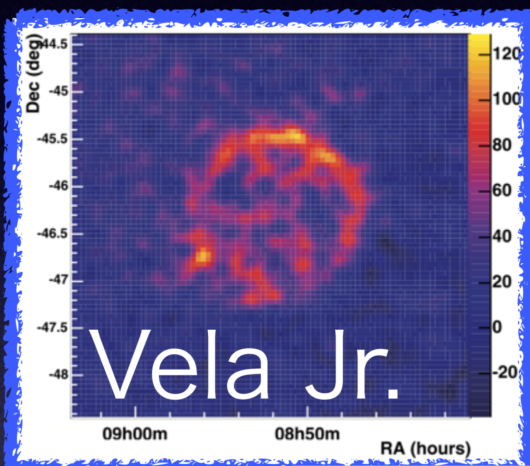
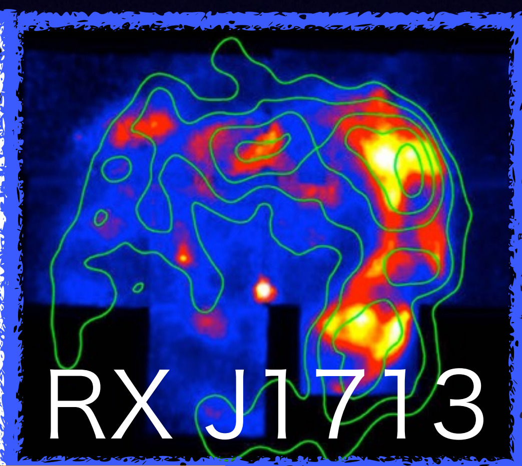
- **Ejecta from SN nucleosynthesis models** (HL, Patnaude+ 2014)

# CR-hydro-NEIコードと多波長データで迫る

## 多様な超新星残骸のガンマ線起源

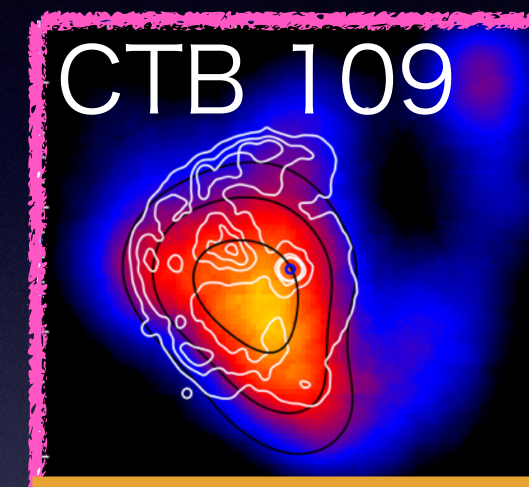
e.g., Lee+ 2008, 2012-2015, Castro+ 2012, Slane, Lee+ 2014



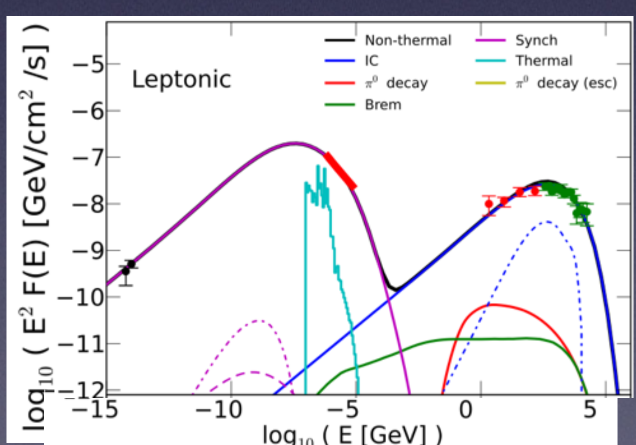



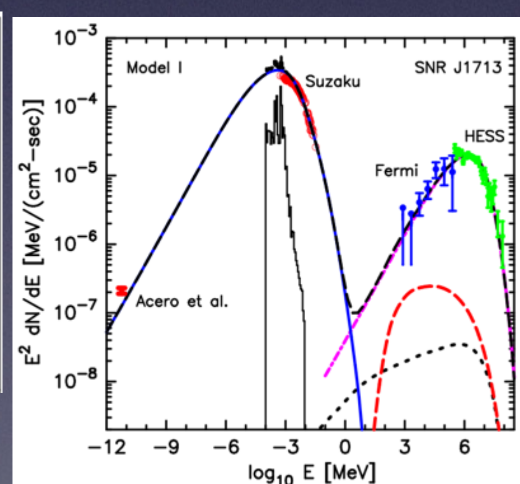

~2,000 yr

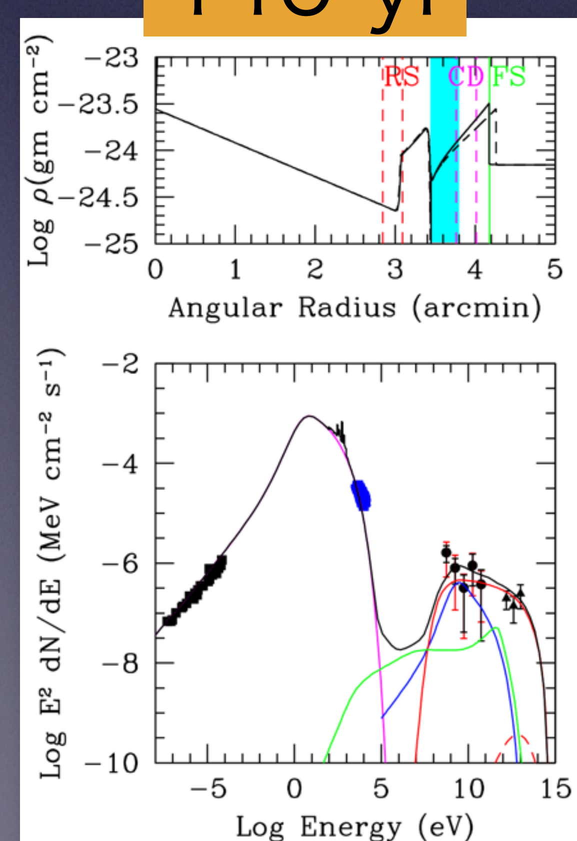

440 yr

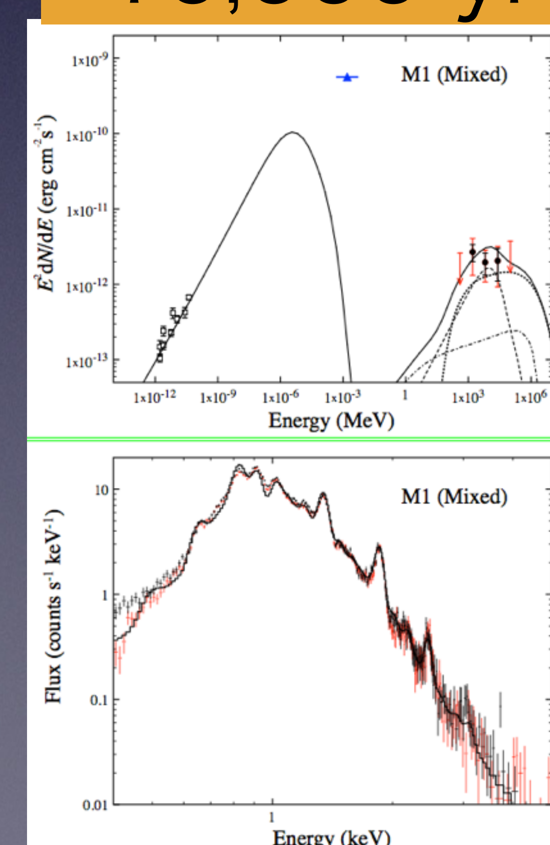



~10,000 yr



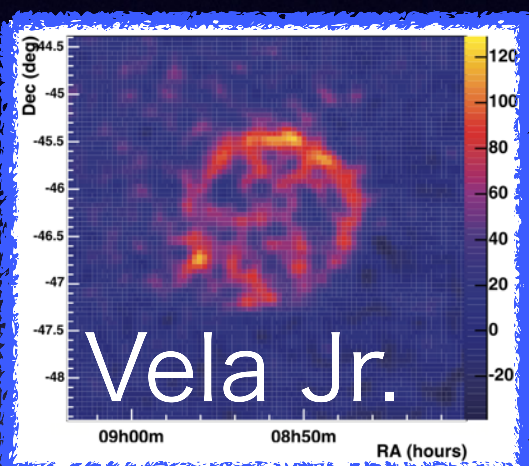



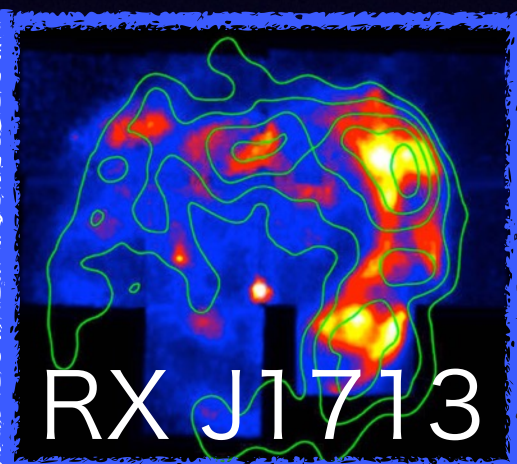



# CR-hydro-NEIコードと多波長データで迫る

## 多様な超新星残骸のガンマ線起源

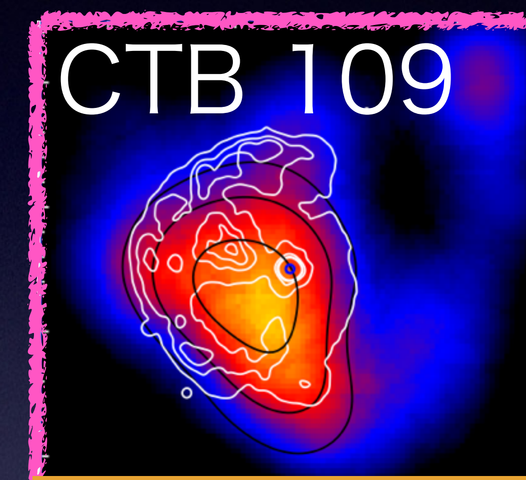
e.g., Lee+ 2008, 2012-2015, Castro+ 2012, Slane, Lee+ 2014



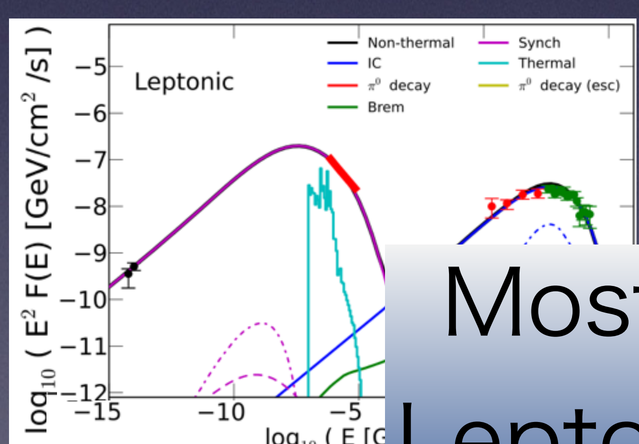



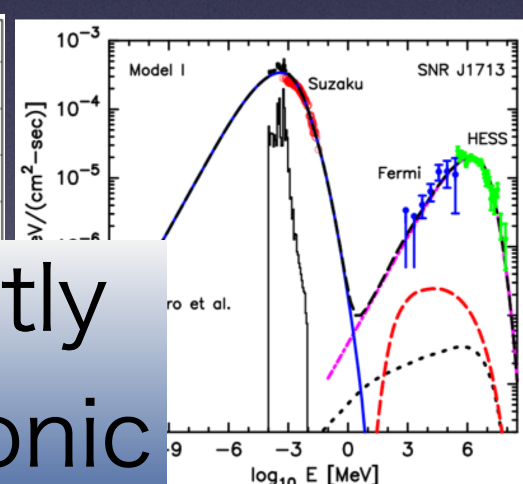

~2,000 yr


440 yr

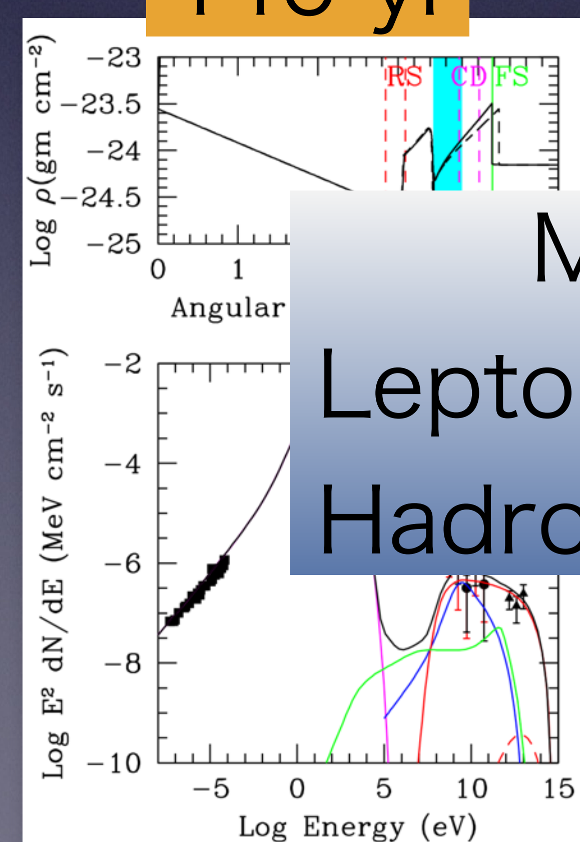


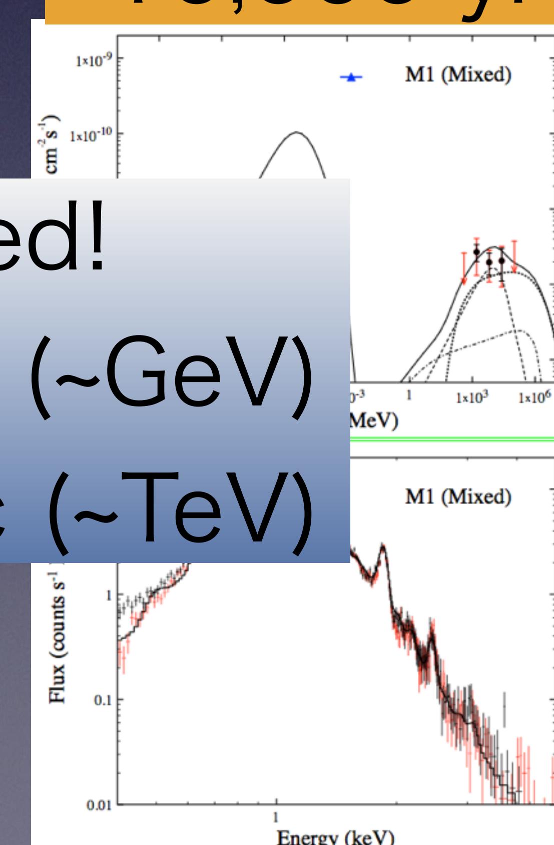

~10,000 yr




Mostly
Leptonic



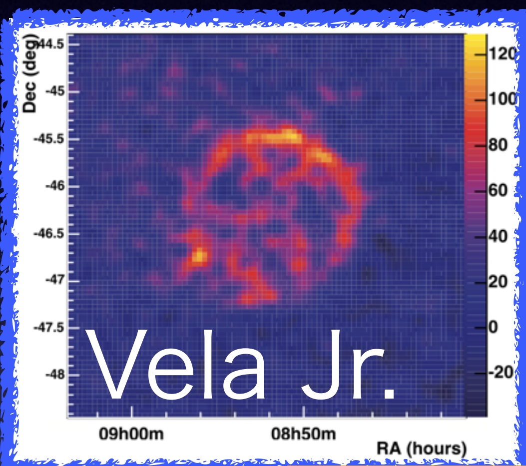



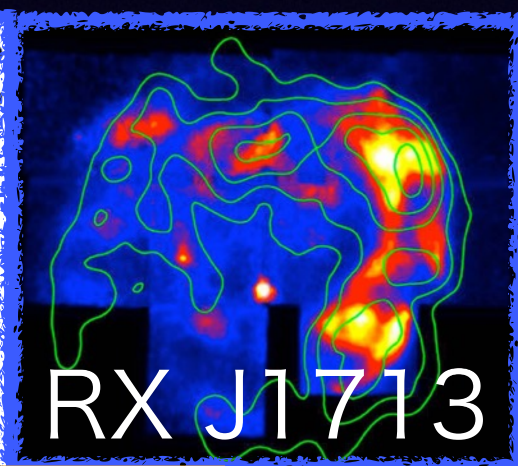

Mixed!
Leptonic (~GeV)
Hadronic (~TeV)

# CR-hydro-NEIコードと多波長データで迫る

## 多様な超新星残骸のガンマ線起源

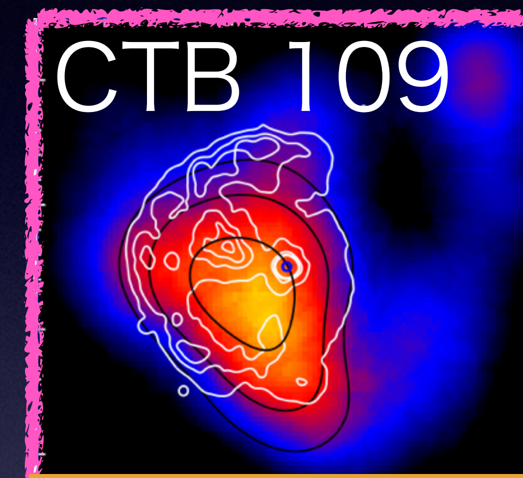
e.g., Lee+ 2008, 2012-2015, Castro+ 2012, Slane, Lee+ 2014



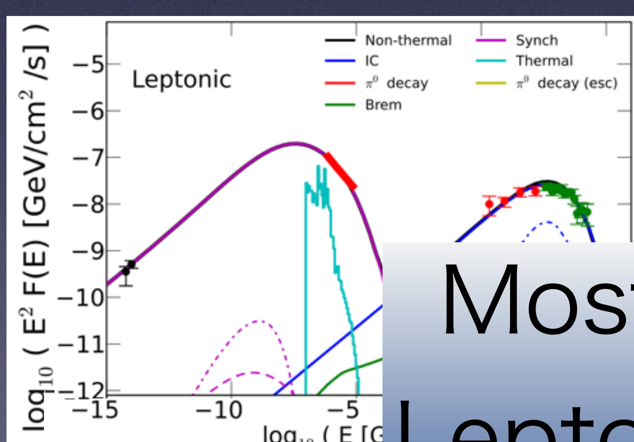



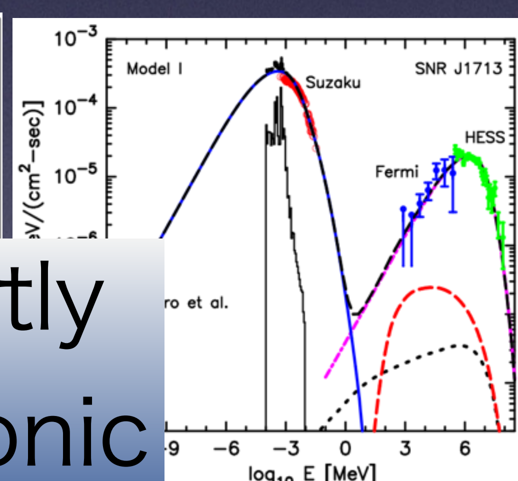

~2,000 yr


440 yr

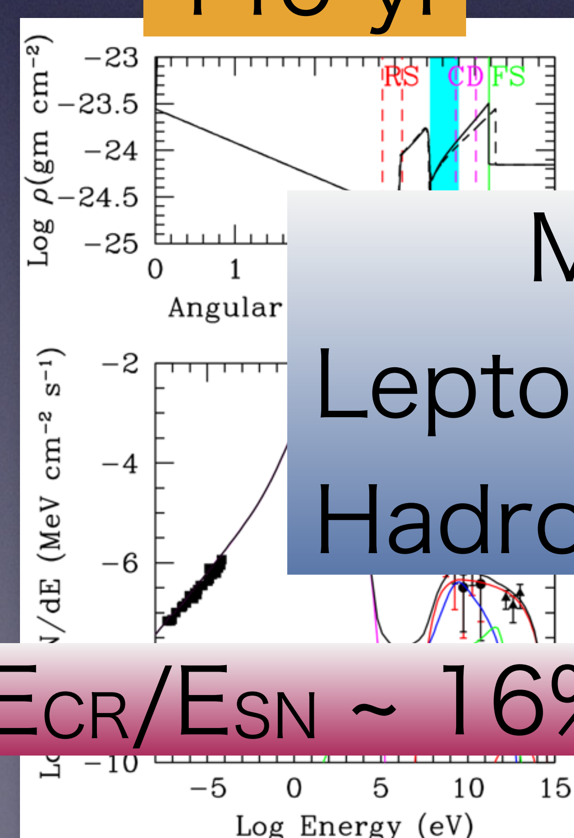


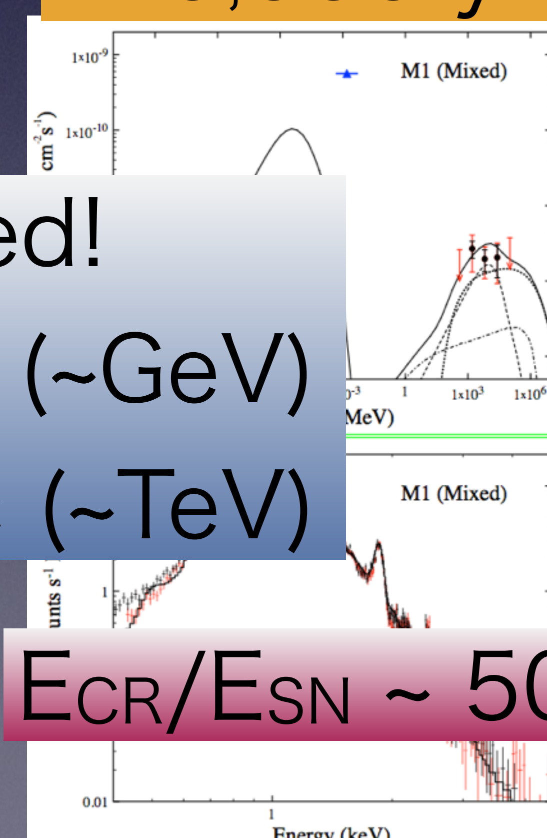

~10,000 yr




Mostly Leptonic




Mixed!
Leptonic (~GeV)
Hadronic (~TeV)

$E_{CR}/E_{SN}$ ~ 15%

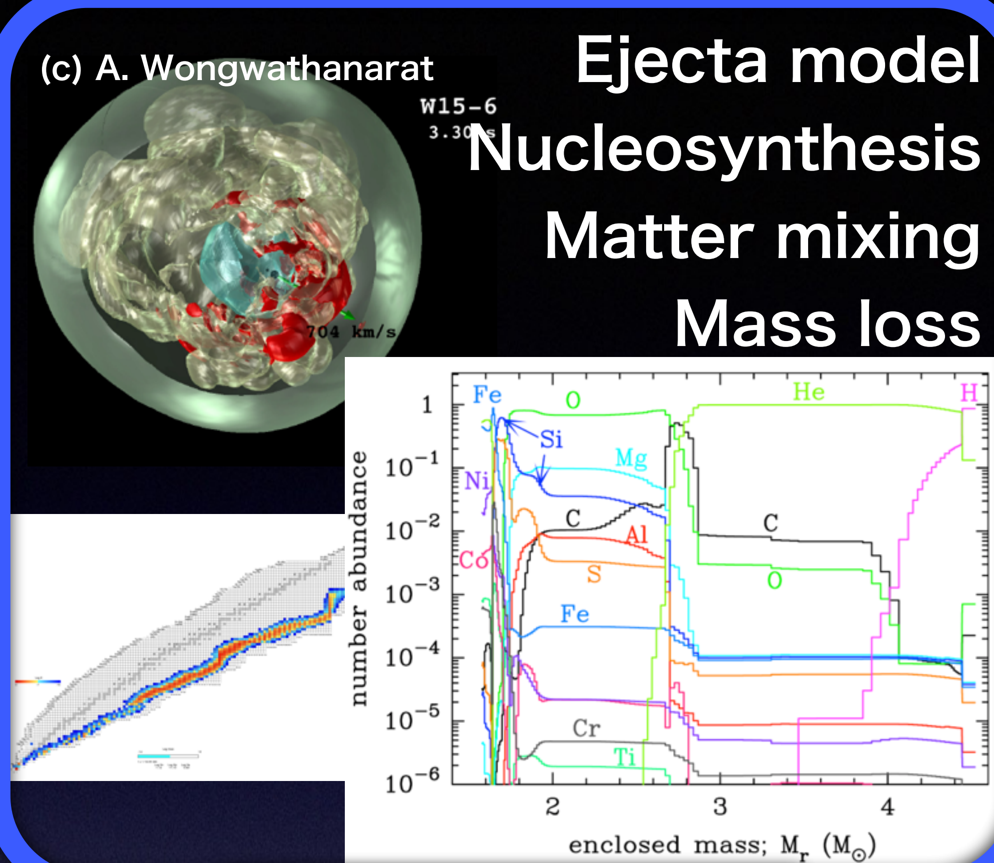
$E_{CR}/E_{SN}$ ~ 16%

$E_{CR}/E_{SN}$ ~ 50%

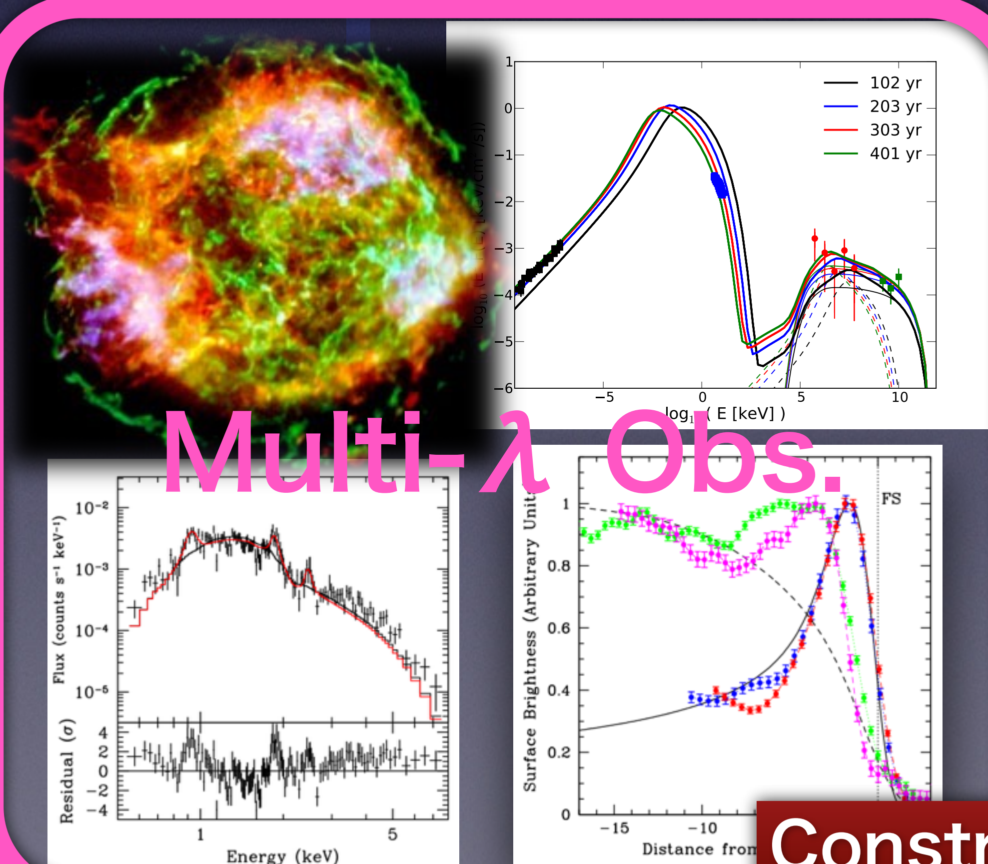
# Iterative Work Flow

## CR-hydro-NEI SNR Model

Ejecta model
Nucleosynthesis
Matter mixing
Mass loss

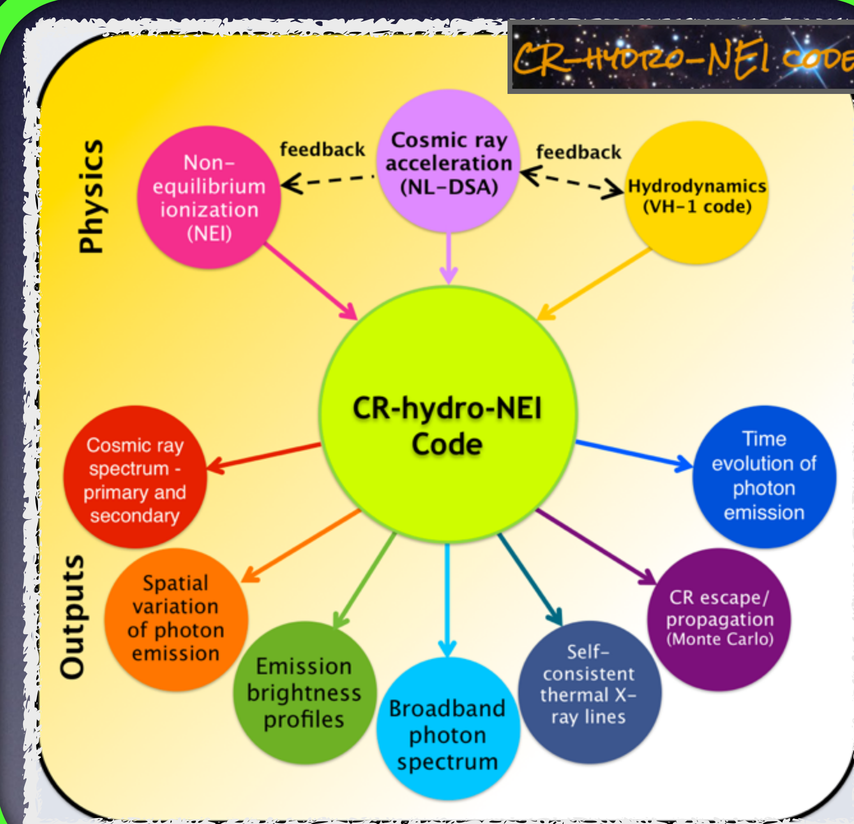



**Initial conditions**




**Multi-λ Obs.**

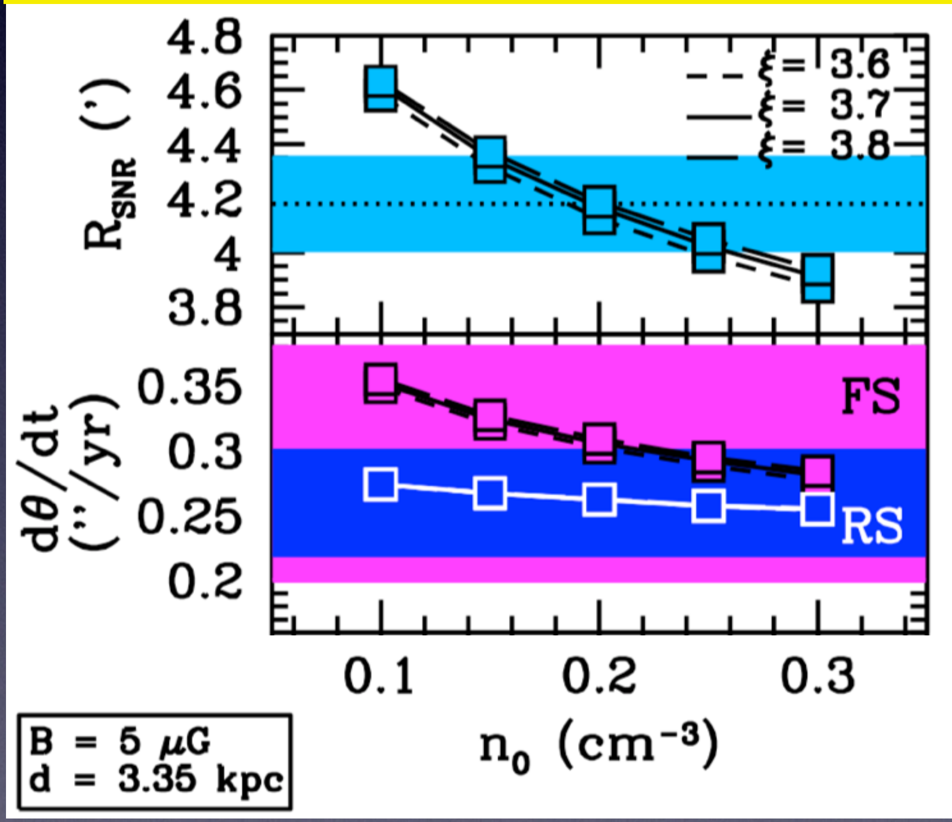
**Constraints!**



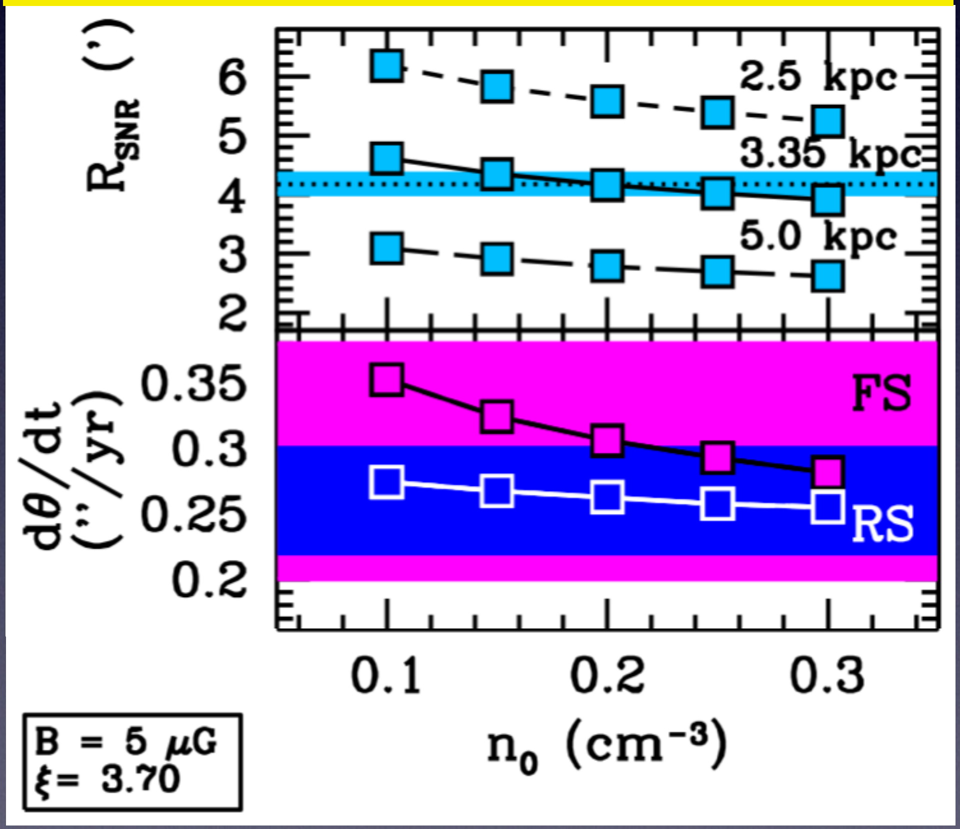

**Dynamics, NLDSA, B-field, ionization, radiation**

# First step
# Get the size right (dynamics)

Vary DSA efficiency vs $n_0$




Vary distance vs $n_0$

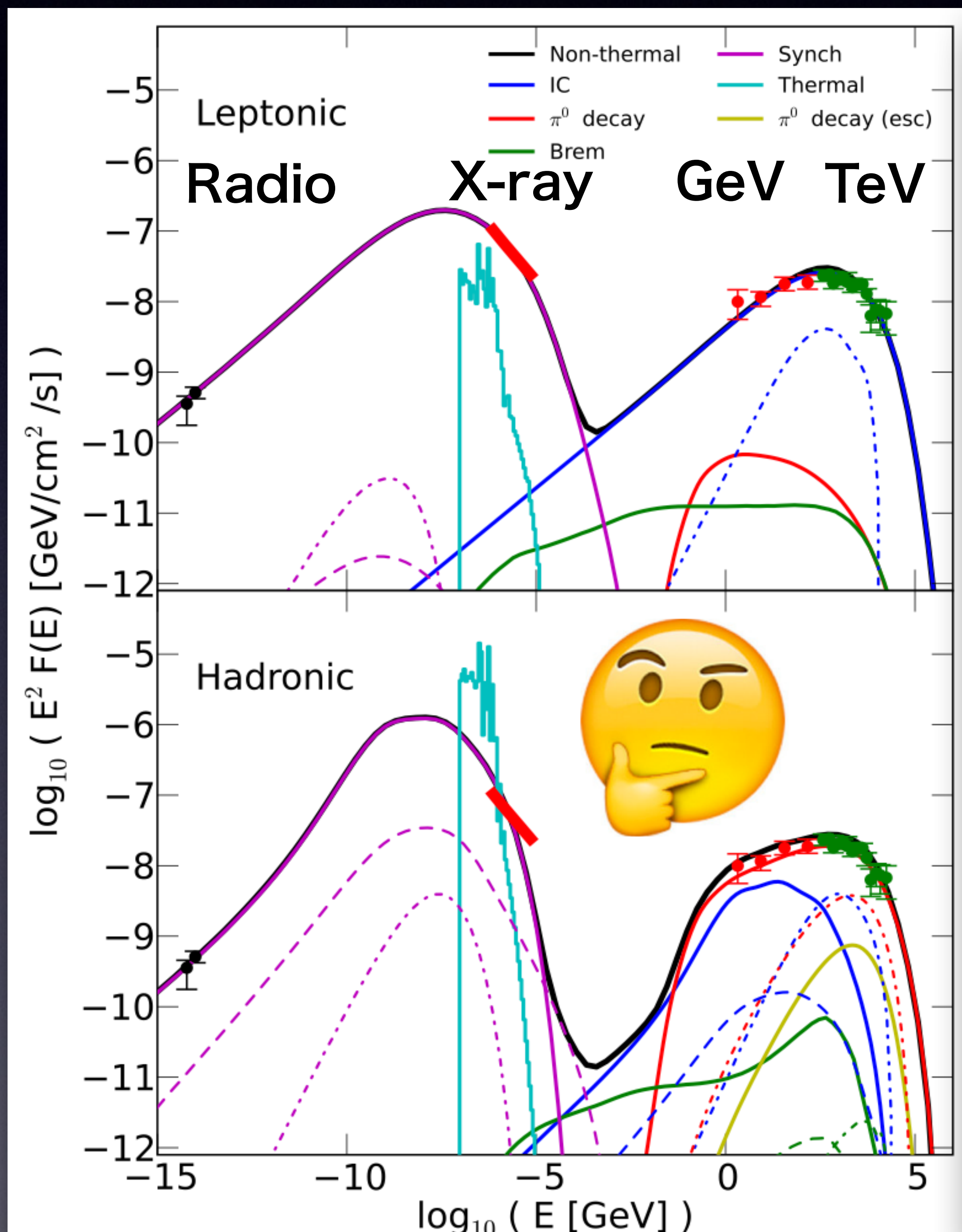



**Slane, HL et al. (2014)**
**on Tycho's SNR**

# Then, the all important non-thermal spectrum

**In some cases, things are not so conclusive…**

**HL, Slane+ 2013** on SNR **Vela Jr.**

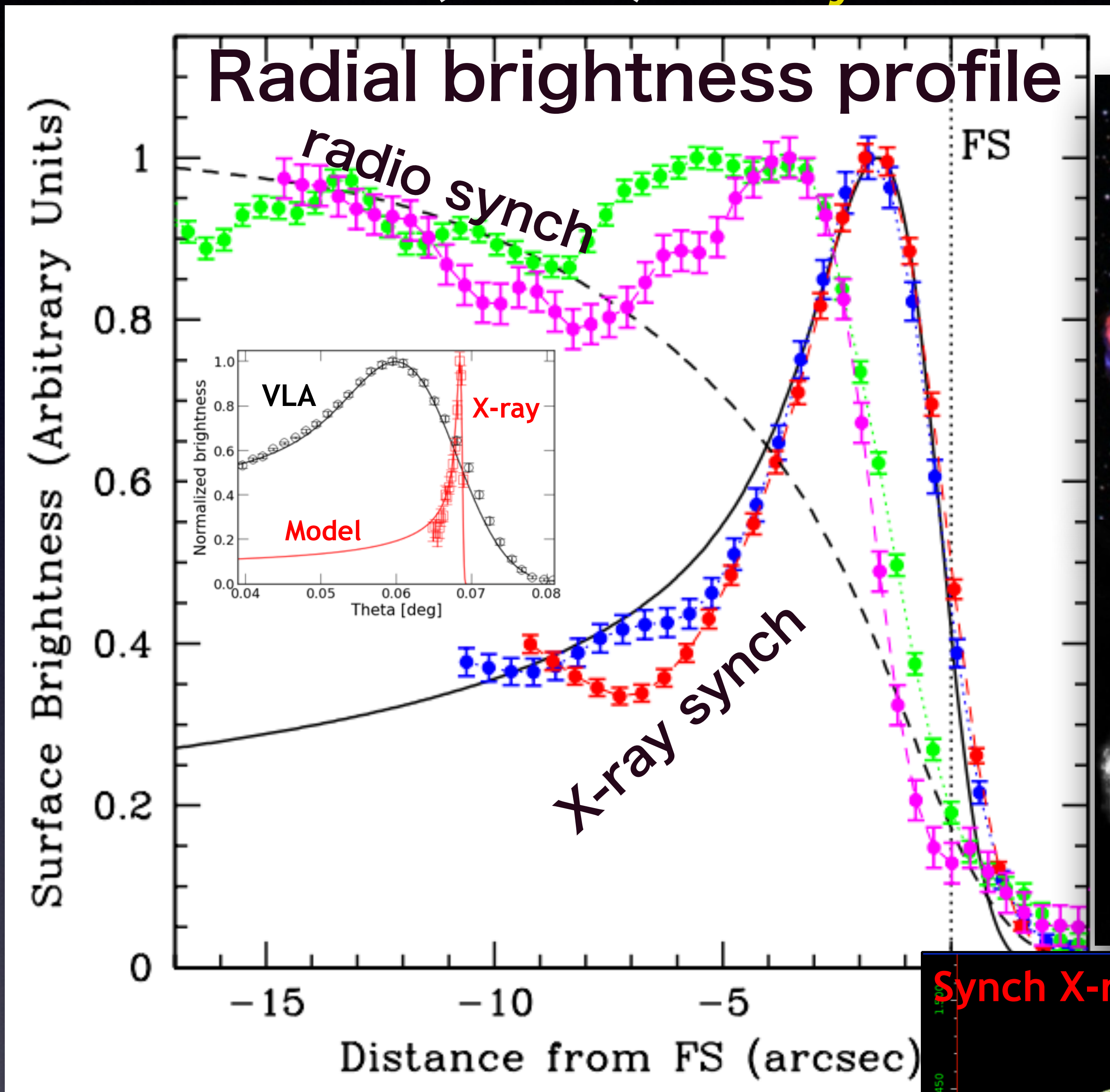


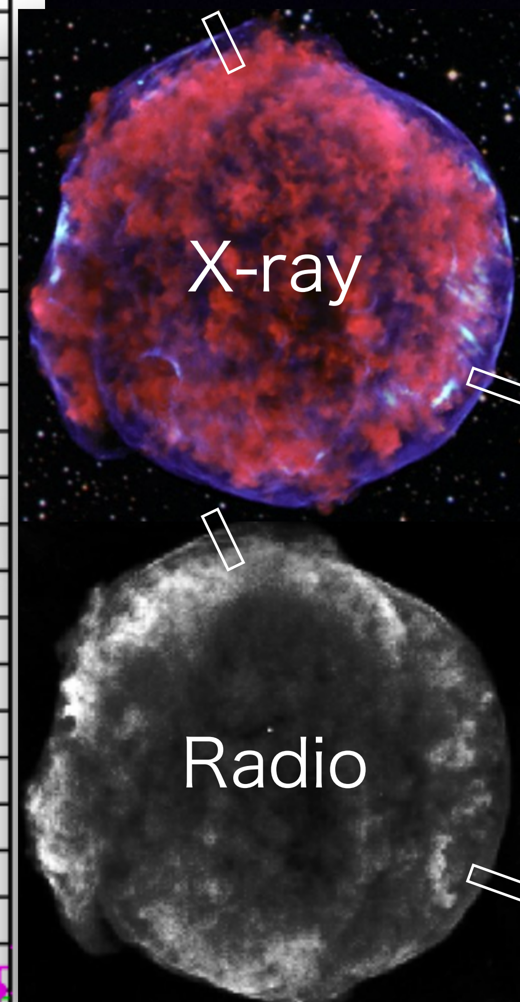

| | Hadronic[b] | Leptonic[c] |
|---|---|---|
| **Input parameters** | | |
| $d_{SNR}$ (kpc) | 0.74 | 0.88 |
| $n_0$ (cm$^{-3}$) | 0.033 | 0.002$^\dagger$ |
| $B_0$ ($\mu$G) | 0.5 | 0.14$^\dagger$ |
| $dM/dt$ ($10^{-6}$ $M_\odot$ yr$^{-1}$) | … | 7.5 |
| $V_{wind}$ (km s$^{-1}$) | … | 50 |
| $\sigma_{wind}$ | … | 0.02 |
| $K_{ep}$ | $1.5 \times 10^{-4}$ | 0.015 |
| $\alpha_{cut}$ | 0.75 | 0.50 |
| $f_{FEB}$ | 0.15 | 0.12 |
| $f_{alf}$ | 0.10 | 1.00 |
| **Output quantities** | | |
| $R_{FS}$ (pc) | 12.7 | 15.2 |
| $R_{CD}$ (pc) | 10.3 | 12.5 |
| $V_{FS}$ (km s$^{-1}$) | 2130 | 4700 |
| $p_{max}$ ($p$) (TeV/$c$) | 26.7 | 5.2 |
| $p_{max}$ ($e^-$) (TeV/$c$) | 13.3 | 5.2 |
| $R_{tot}$ | 9.30 | 4.69 |
| $R_{sub}$ | 3.69 | 3.99 |
| $B_2$ ($\mu$G) | 34.1 | 4.8 |
| $T_2$ ($10^8$ K) | 0.16 | 3.62 |
| $\epsilon_{acc}$ | 0.84 | 0.36 |
| $\epsilon_{esc}$ | 0.34 | 0.12 |
| $E_{CR}/E_{SN}$ ($f_{SN}$) | 0.48 | 0.14 |

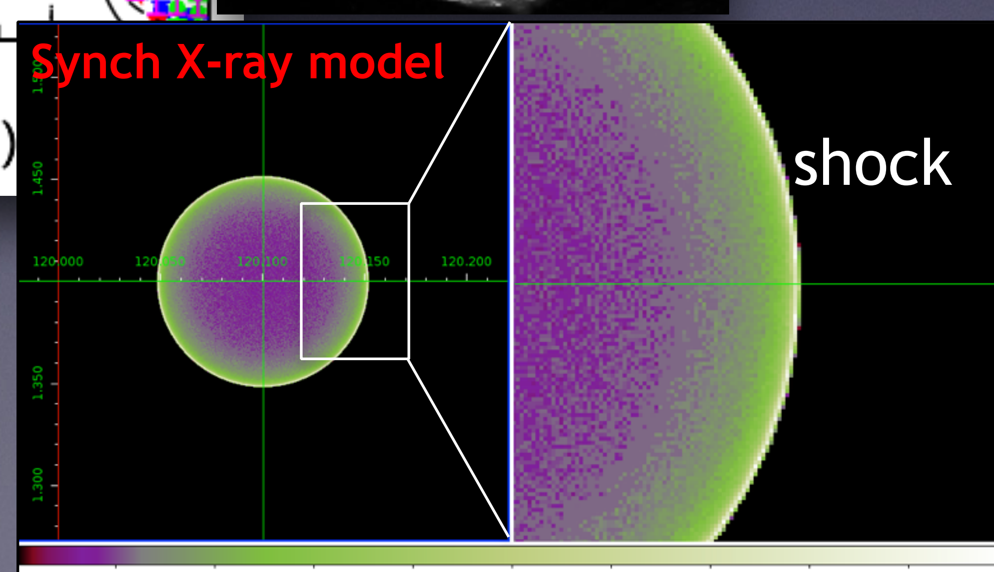
Hadronic vs leptonic has impact: big difference in $E_{CR}$ and temperature

# Brightness profiles are helpful too

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



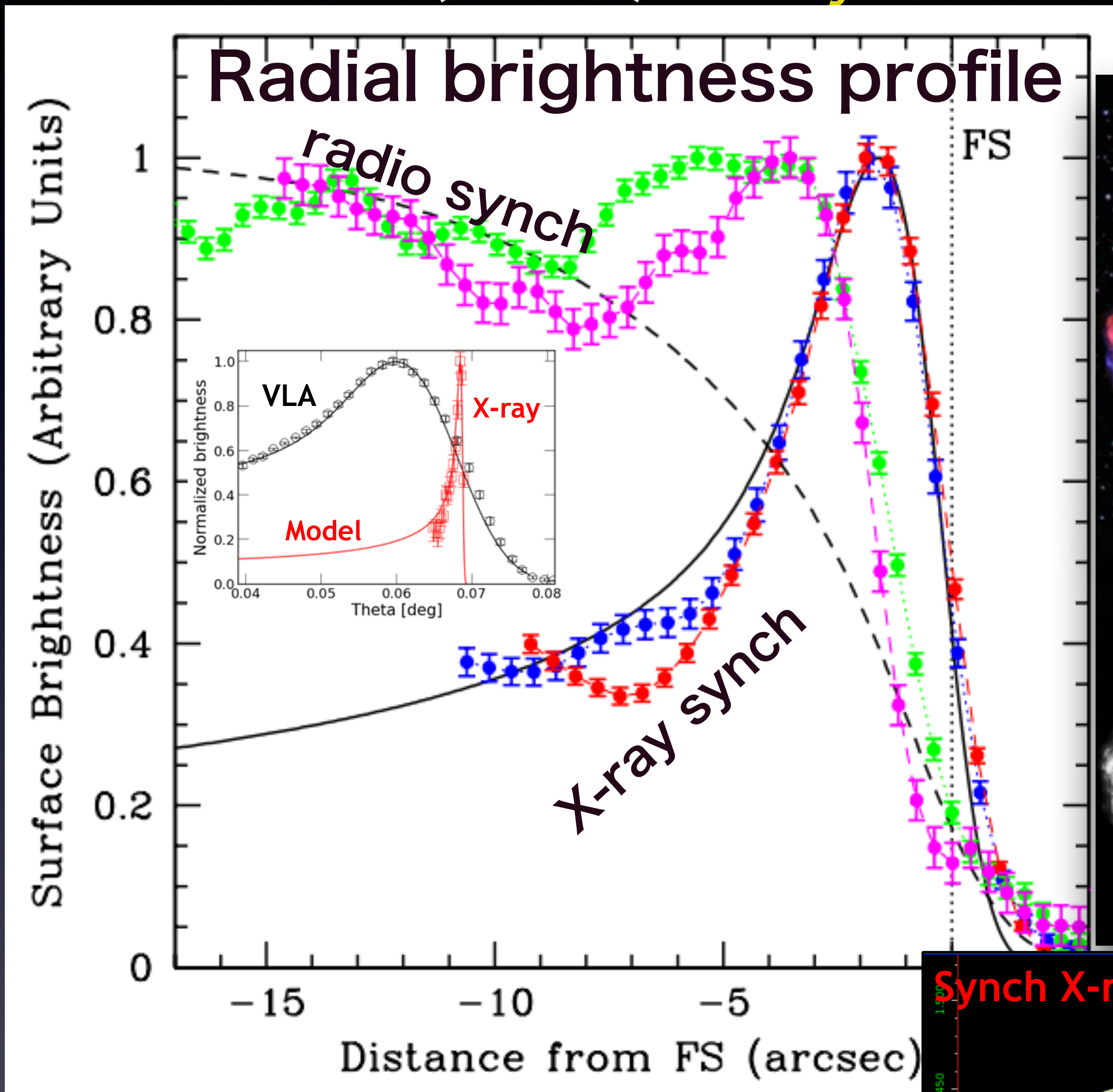



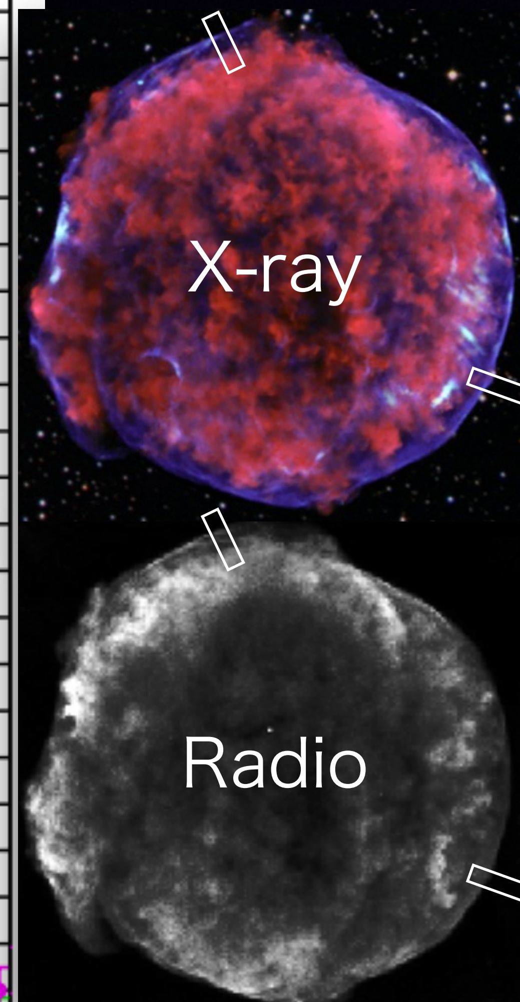




Must be done in multi-wavelength!

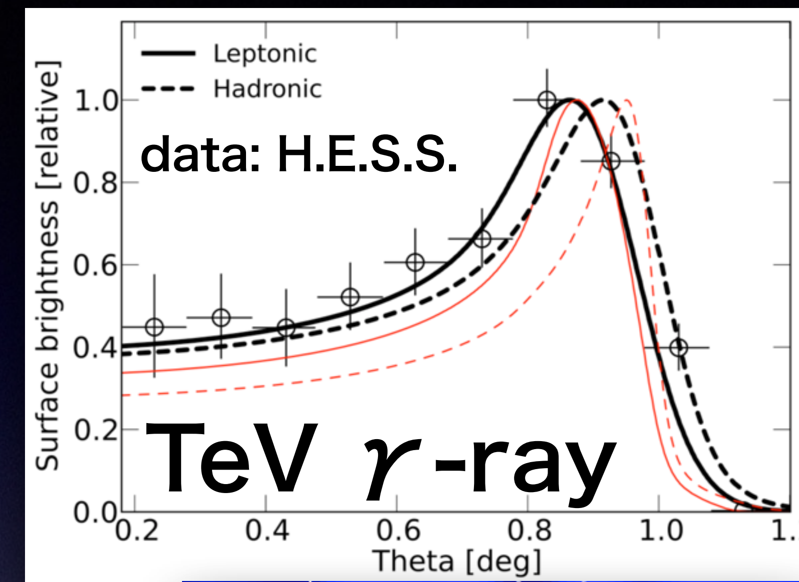
# Brightness profiles are helpful too

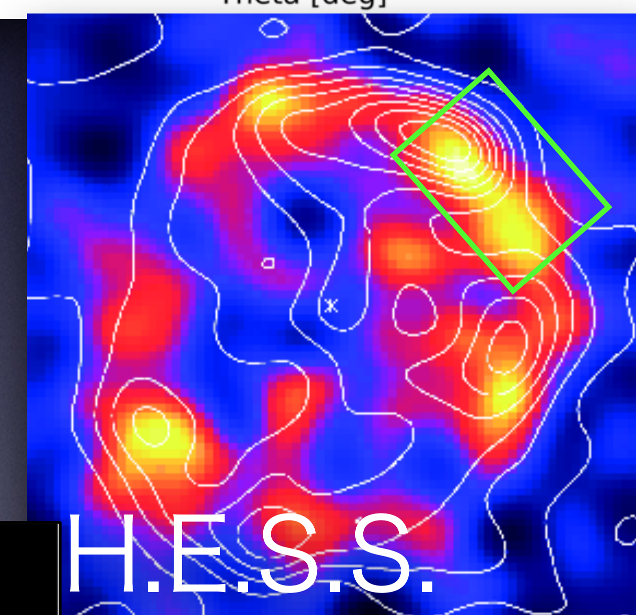
Slane, HL+ (2014) on Tycho's SNR

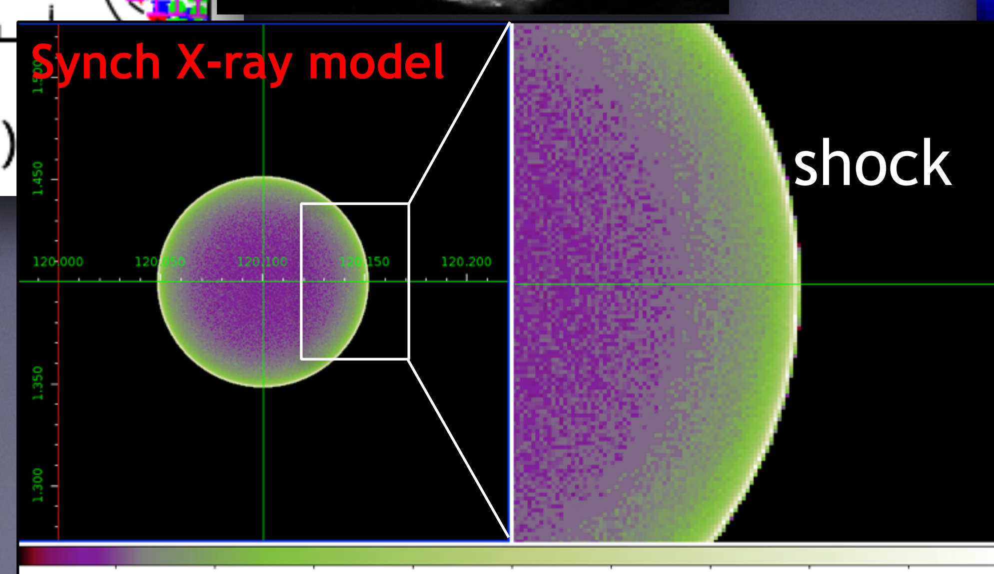



HL, Slane+ (2013) on Vela Jr.



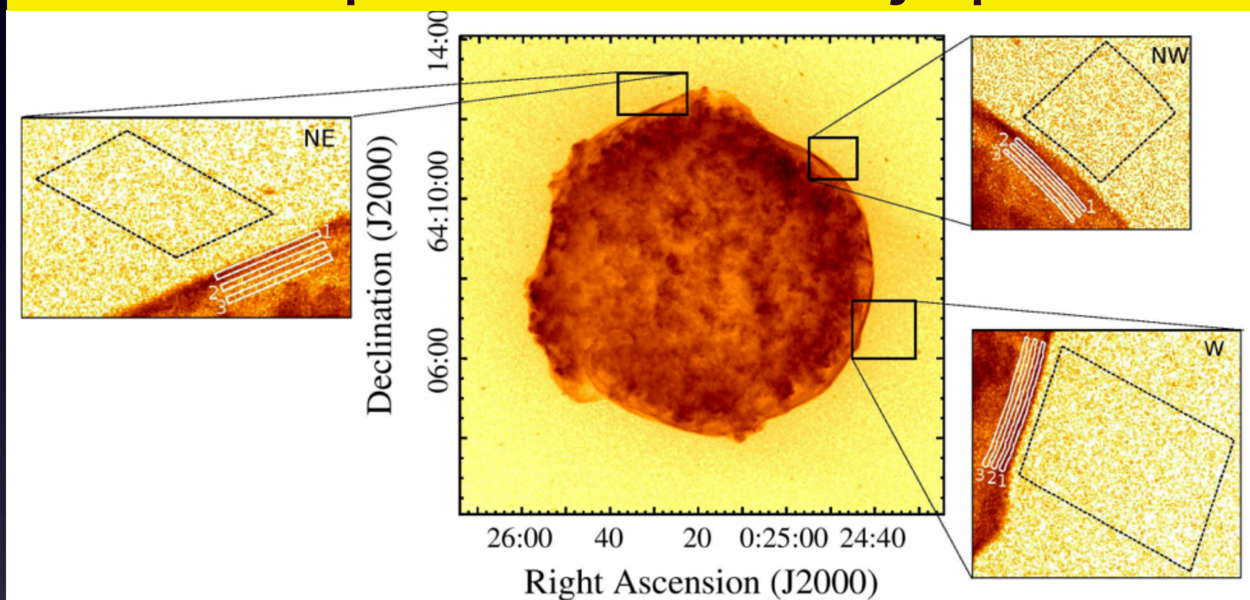



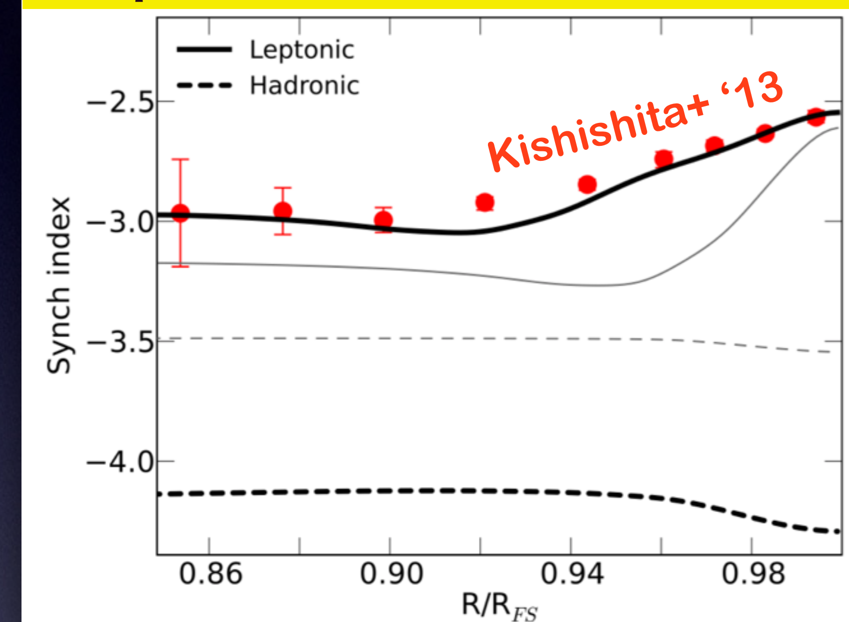

Must be done in multi-wavelength!

# One step further
# Using "spectral images"

**Chandra space resolved X-ray spectrum**

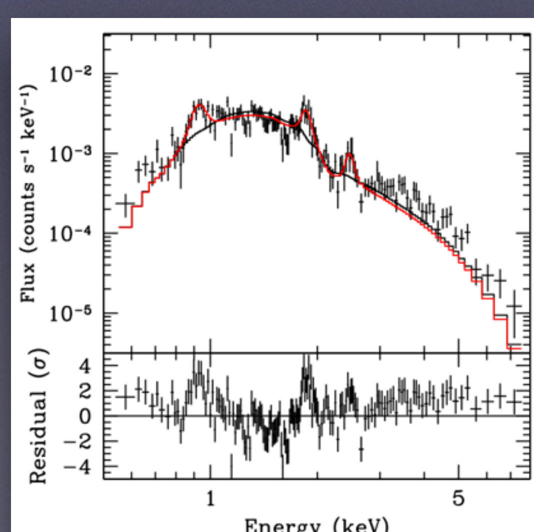


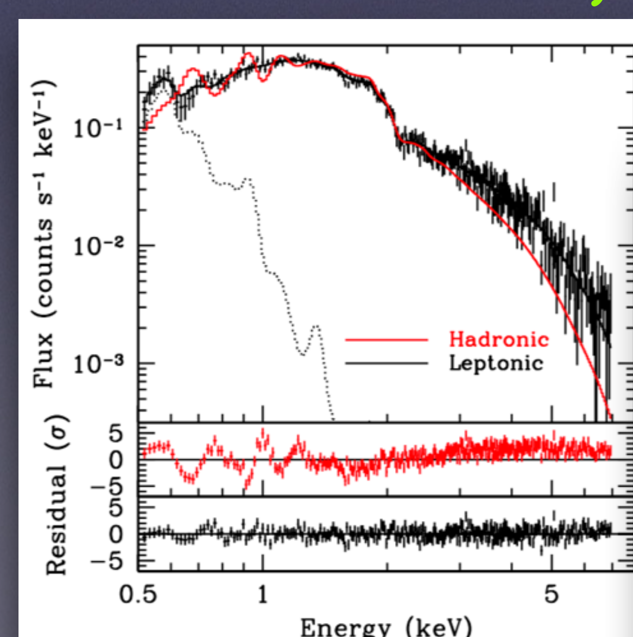

**Spectral index vs radius**

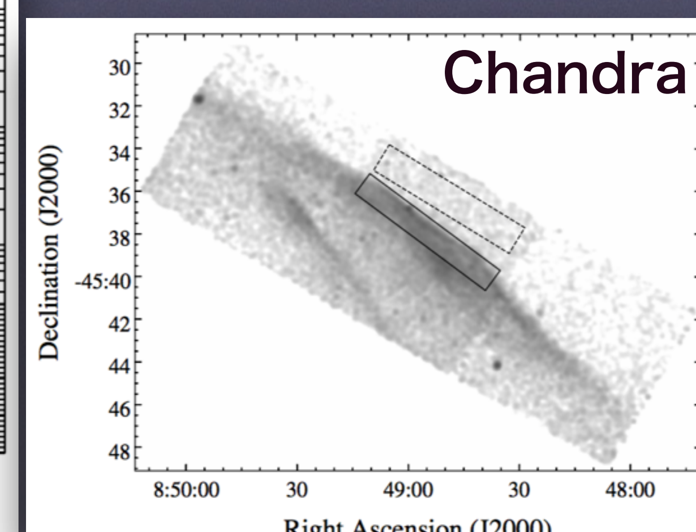



**Slane, HL et al. (2014)**
**Tycho's SNR**

**HL, Slane et al. (2013)**
**Vela Jr. SNR**



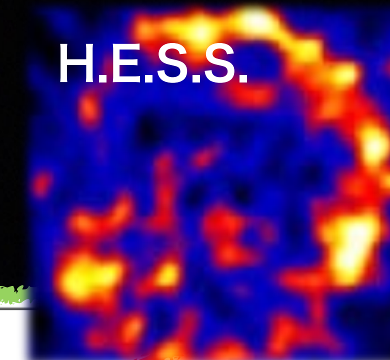



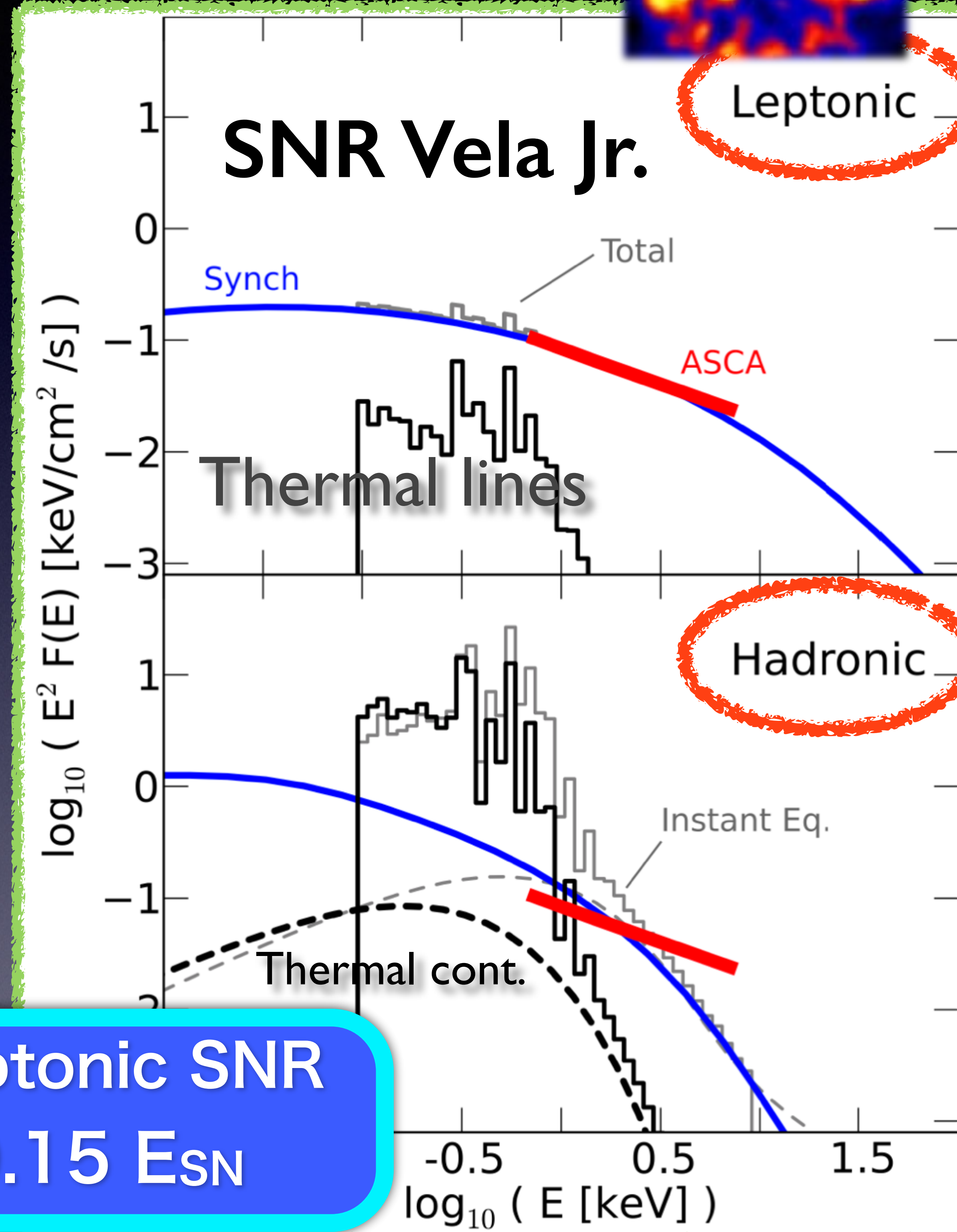
# Thermal X-ray can constrain Gamma-ray origin

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

Predicted thermal flux must NOT exceed observed X-ray flux

HL, Slane+ 2013



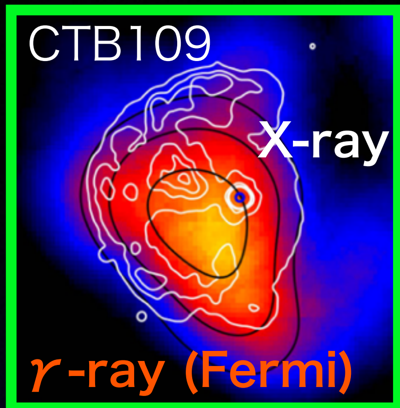




Mostly leptonic SNR

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

# Powerful constraint of non-thermal origin

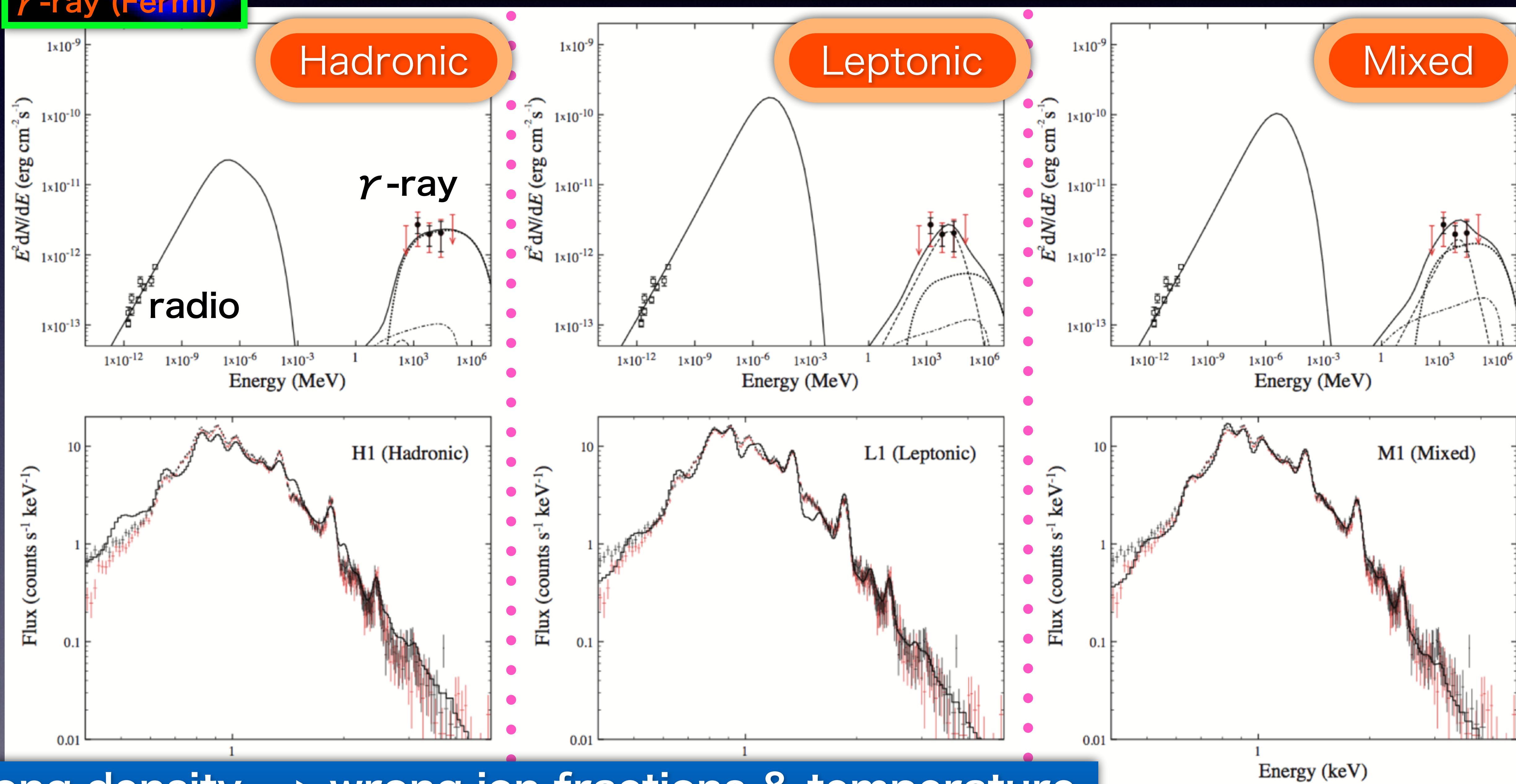
## Thermal X-ray Spectrum




CR-hydro model by Castro+ (2012) on mid-aged CTB109

Non-thermal

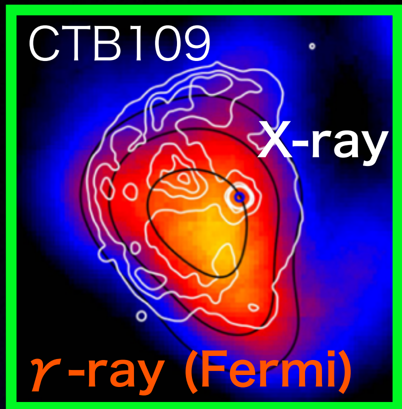
Thermal X




Wrong density —> wrong ion fractions & temperature
—> wrong thermal X-ray spectrum

# Powerful constraint of non-thermal origin

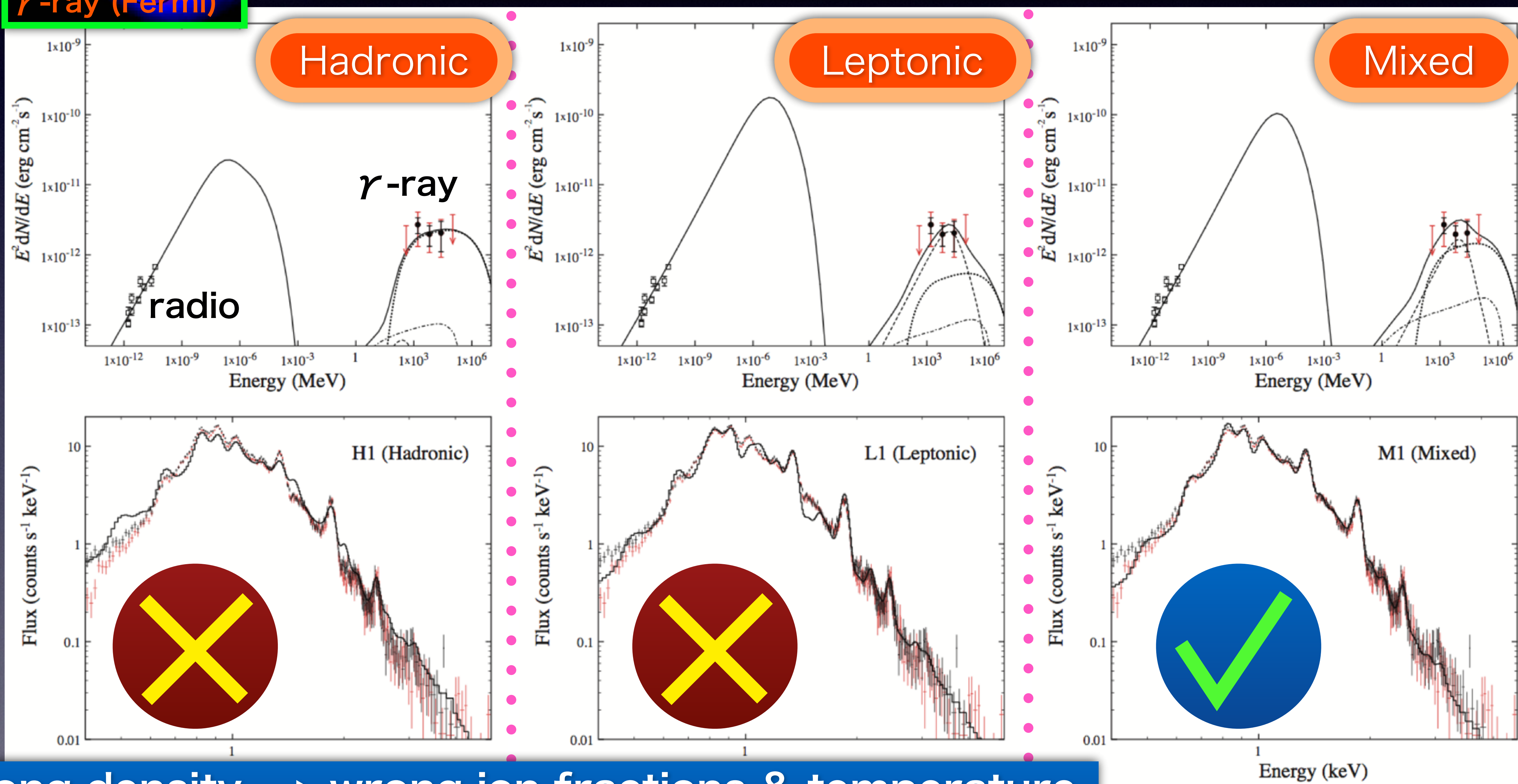
## Thermal X-ray Spectrum




CR-hydro model by Castro+ (2012) on mid-aged CTB109

Non-thermal

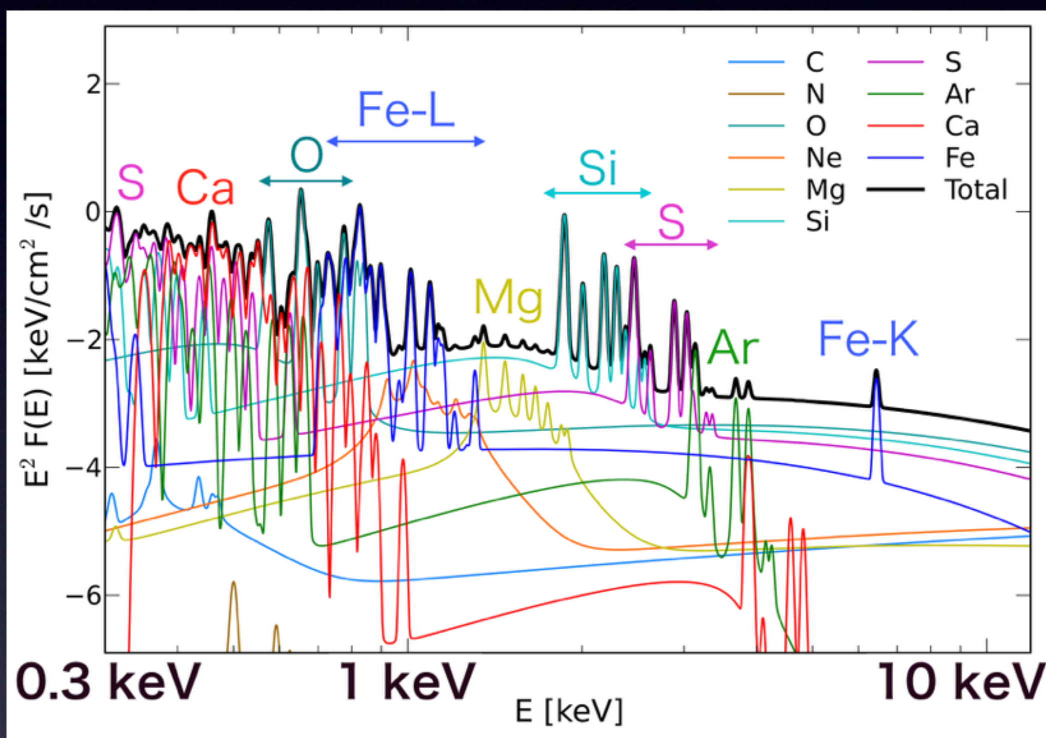
Thermal X



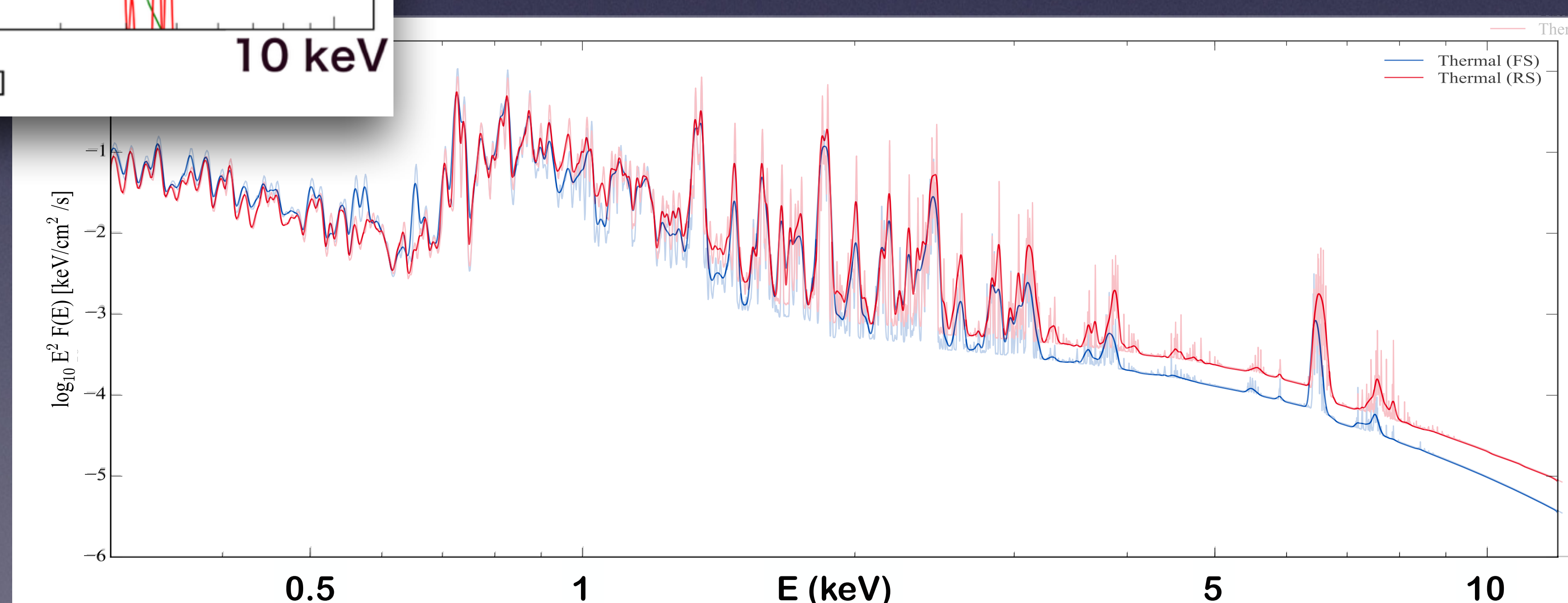

Wrong density —> wrong ion fractions & temperature
—> wrong thermal X-ray spectrum

# Detailed thermal models for future X-ray spectroscopy

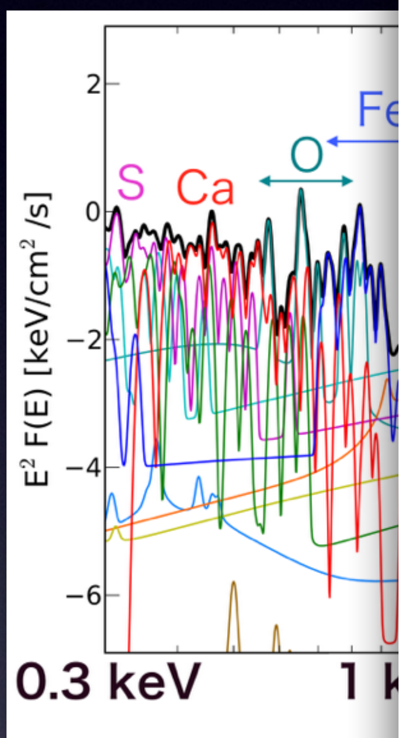
Mass fractions

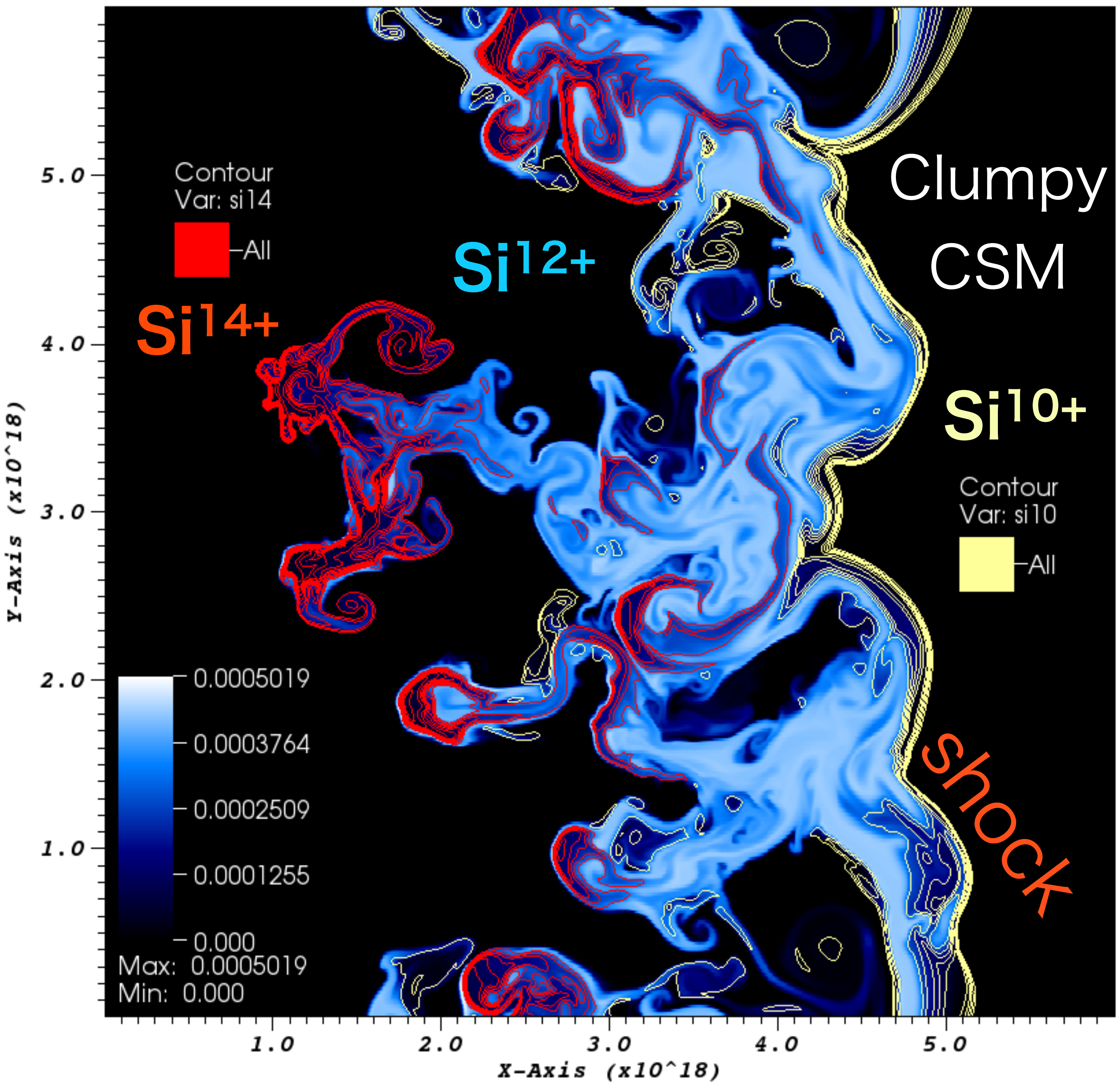



**CR-hydro-NEI code**
**+ SN Ejecta model**
**+ APEC v3.0.2 (NEI)**



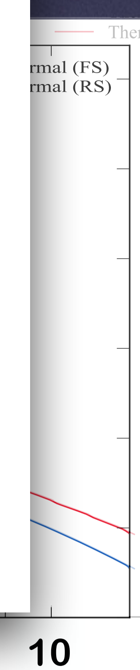

Lee 2016




**Spatial distribution of ions important too!**

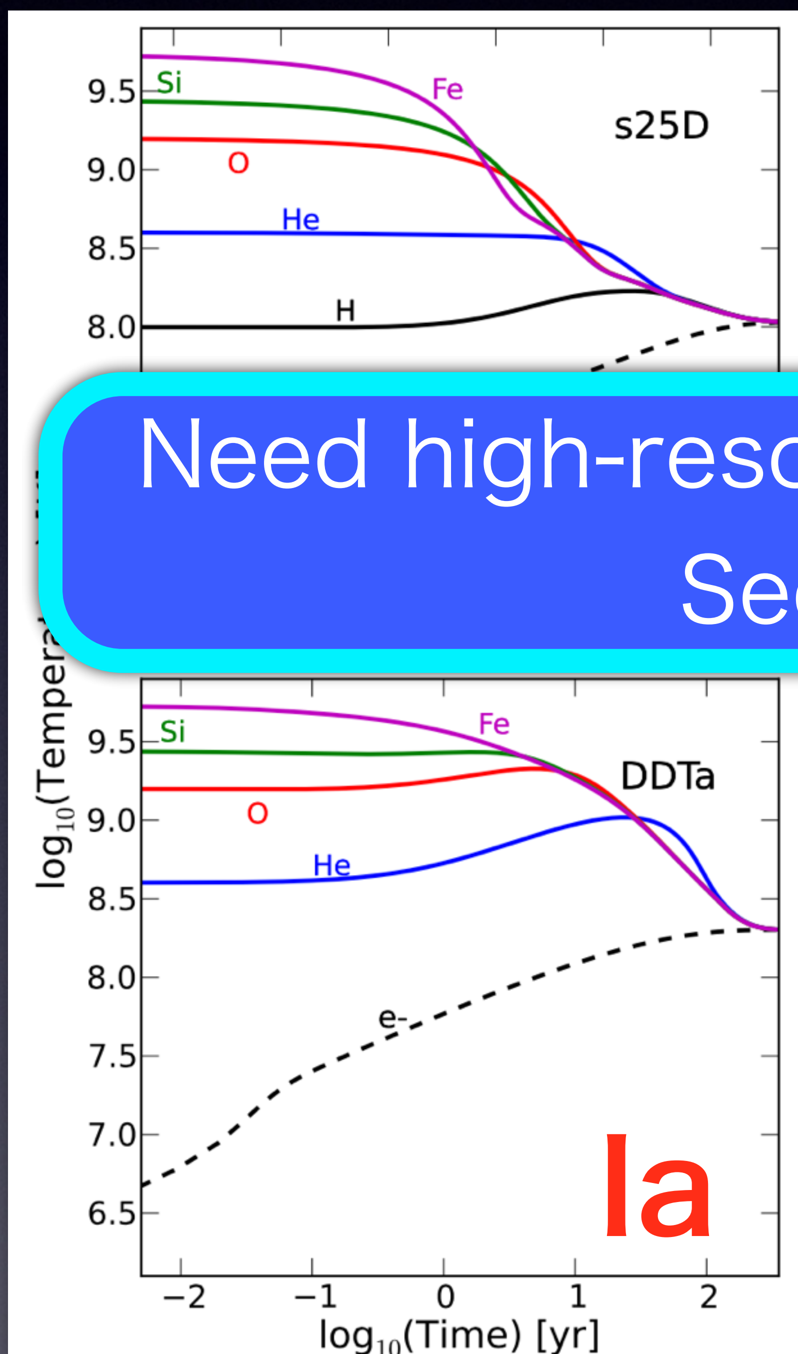
de
del
EI)

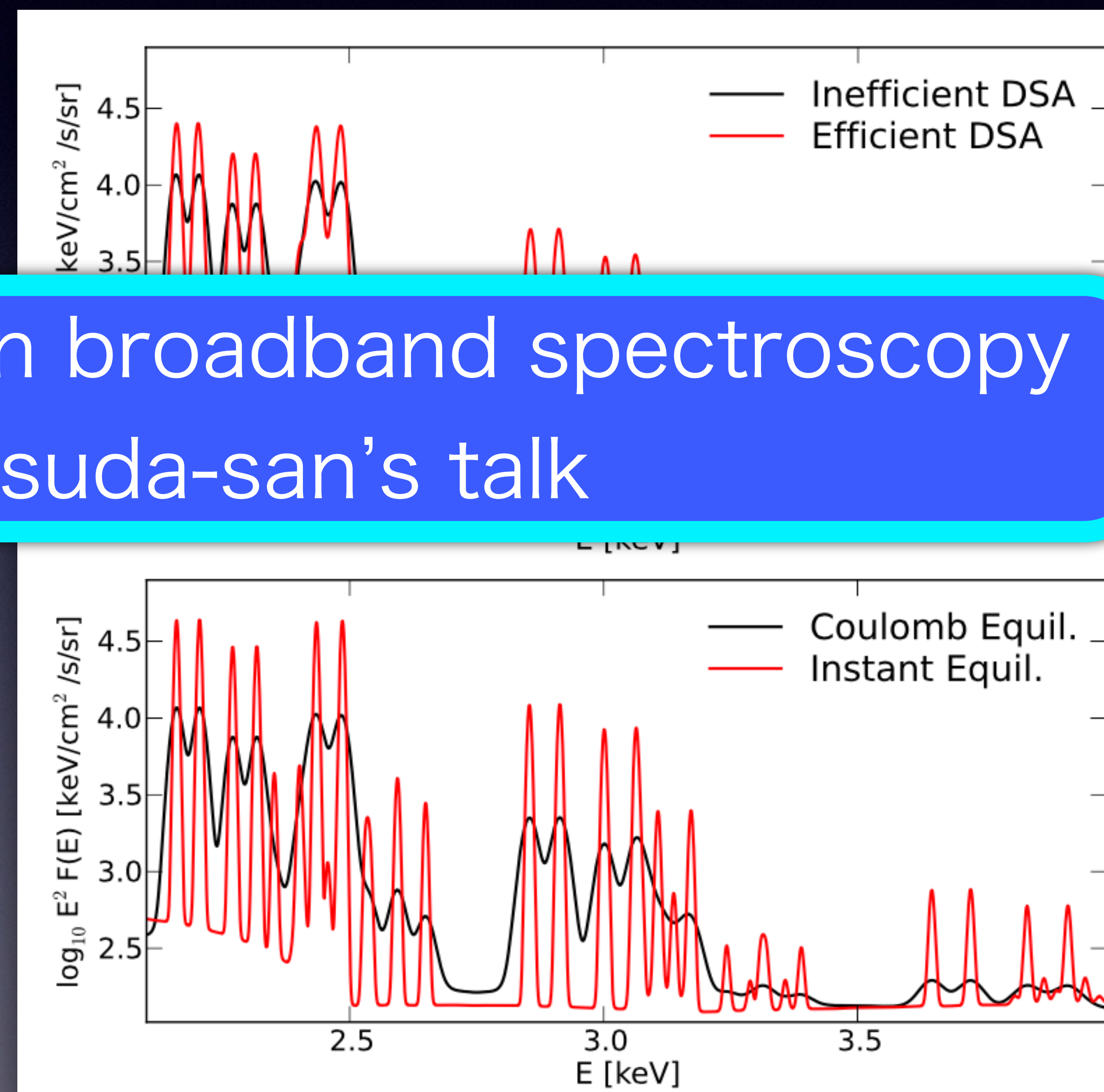



Lee 2016

# Thermal line broadening

## Progenitor, equilibration and particle acceleration




Need high-resolution broadband spectroscopy

See Katsuda-san's talk

HL, Patnaude+ (2014)

# Radiative shock hydrodynamics

## with full non-equilibrium ionization (NEI) and cosmic-ray re-acceleration

$$3/2\, k_B\, dT/dt = -(n_e n_p/n)\, \Lambda + \Gamma + (\kappa/n) \nabla^2 T$$

### Cooling function

- ★ Follow NEI of 12 elements: H, He, CNO, Ne, Mg, Si, S, Ar, Ca, Fe
- ★ UV/optical continua and lines
- ★ Cooling is fast, close to isochoric

### Heating function

- ★ Radiative transfer of strong UV lines and continua
- ★ Absorption, photoionization
- ★ Heating by photoelectrons

(e.g. Gnat & Steinberg 2009)

### Thermal conduction

- ★ Conductivity $\kappa = f\, \kappa_{\rm Spitzer}$
- ★ f = 0.3 for collisionless plasma, hindrance by B-field

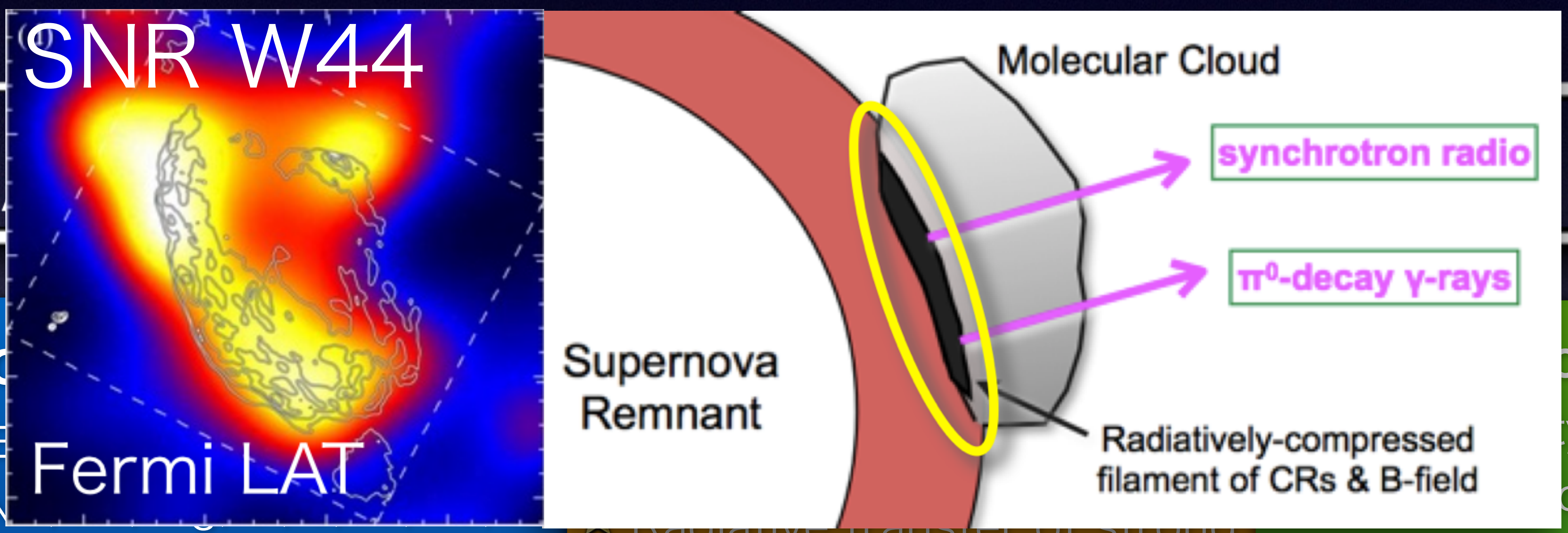
(e.g. Zakamska & Narayan '03, Bale+ '13)

HL, Patnaude, Raymond+ 2015

# Radiative shock hydrodynamics

## with full non-equilibrium ionization (NEI) and cosmic-ray re-acceleration

3 ... $\nabla^2 T$




**Coo**

- ★ Follow NE H, He, CN
- ★ UV/optical continua and lines
- ★ Cooling is fast, close to isochoric

- ★ Radiative transfer of strong UV lines and continua
- ★ Absorption, photoionization
- ★ Heating by photoelectrons

(e.g. Gnat & Steinberg 2009)

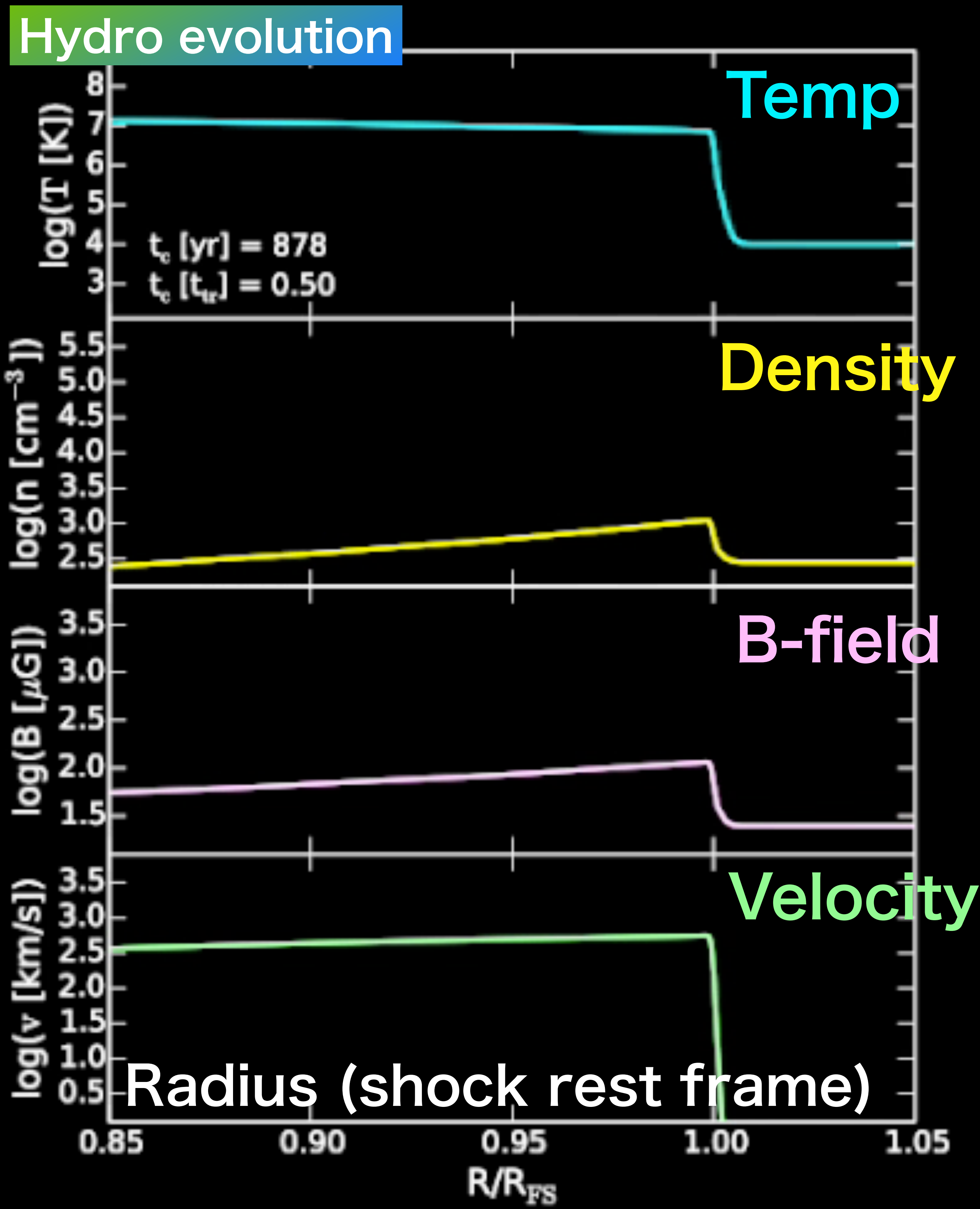
**conduction**

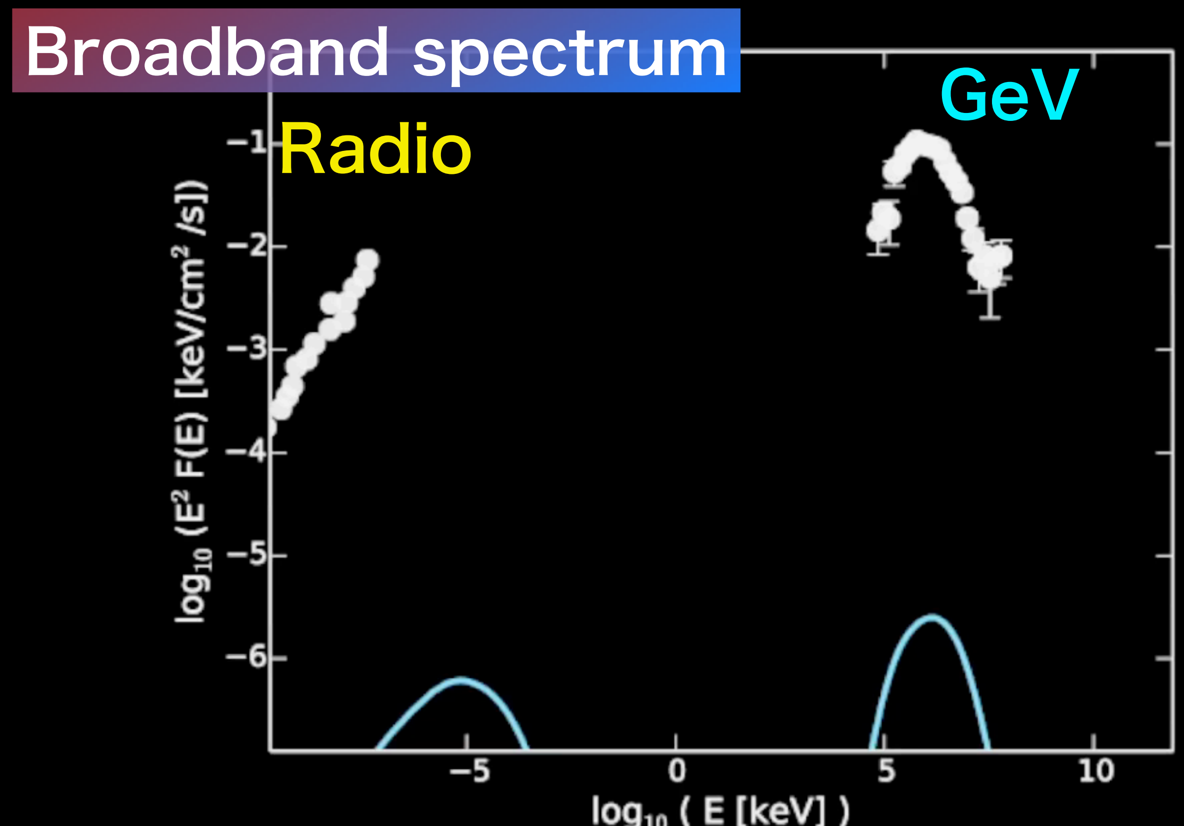
- ty $\kappa = f \kappa_{\rm Spitzer}$ collisionless plasma, hindrance by B-field

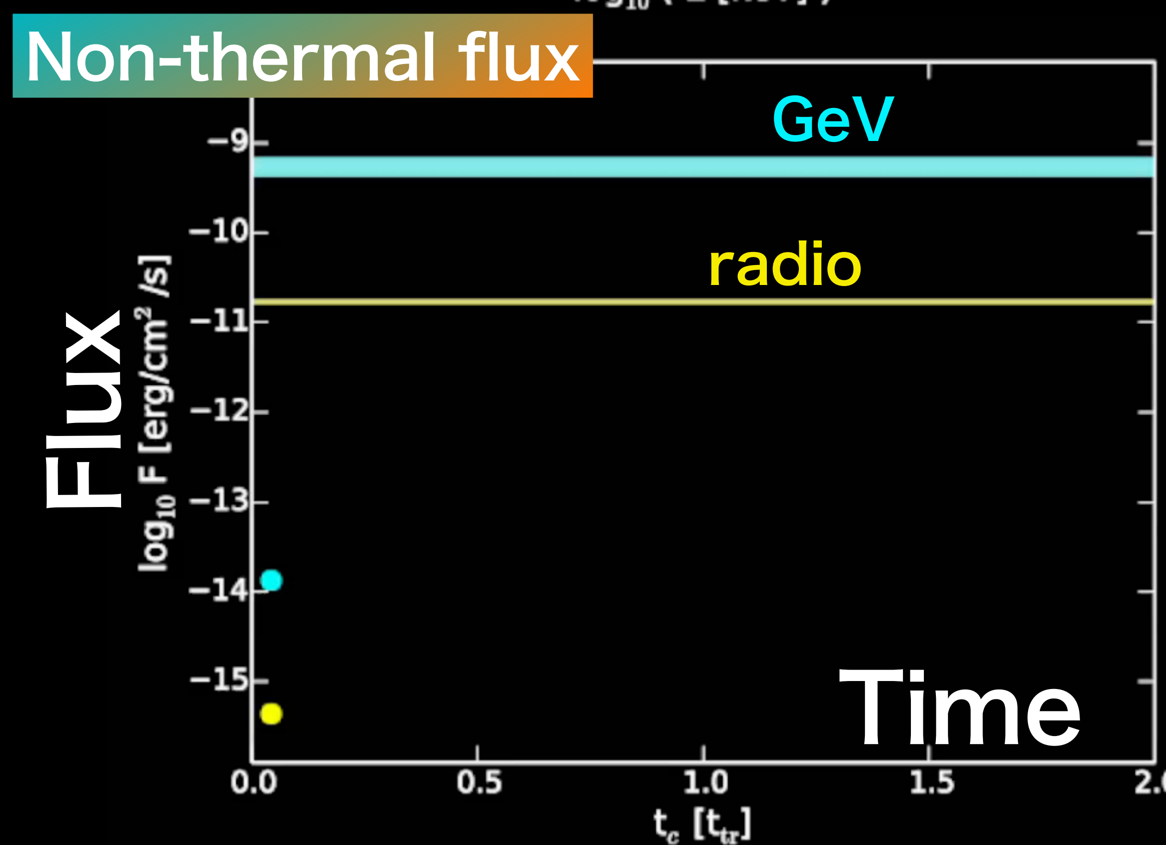
(e.g. Zakamska & Narayan '03, Bale+ '13)

HL, Patnaude, Raymond+ 2015

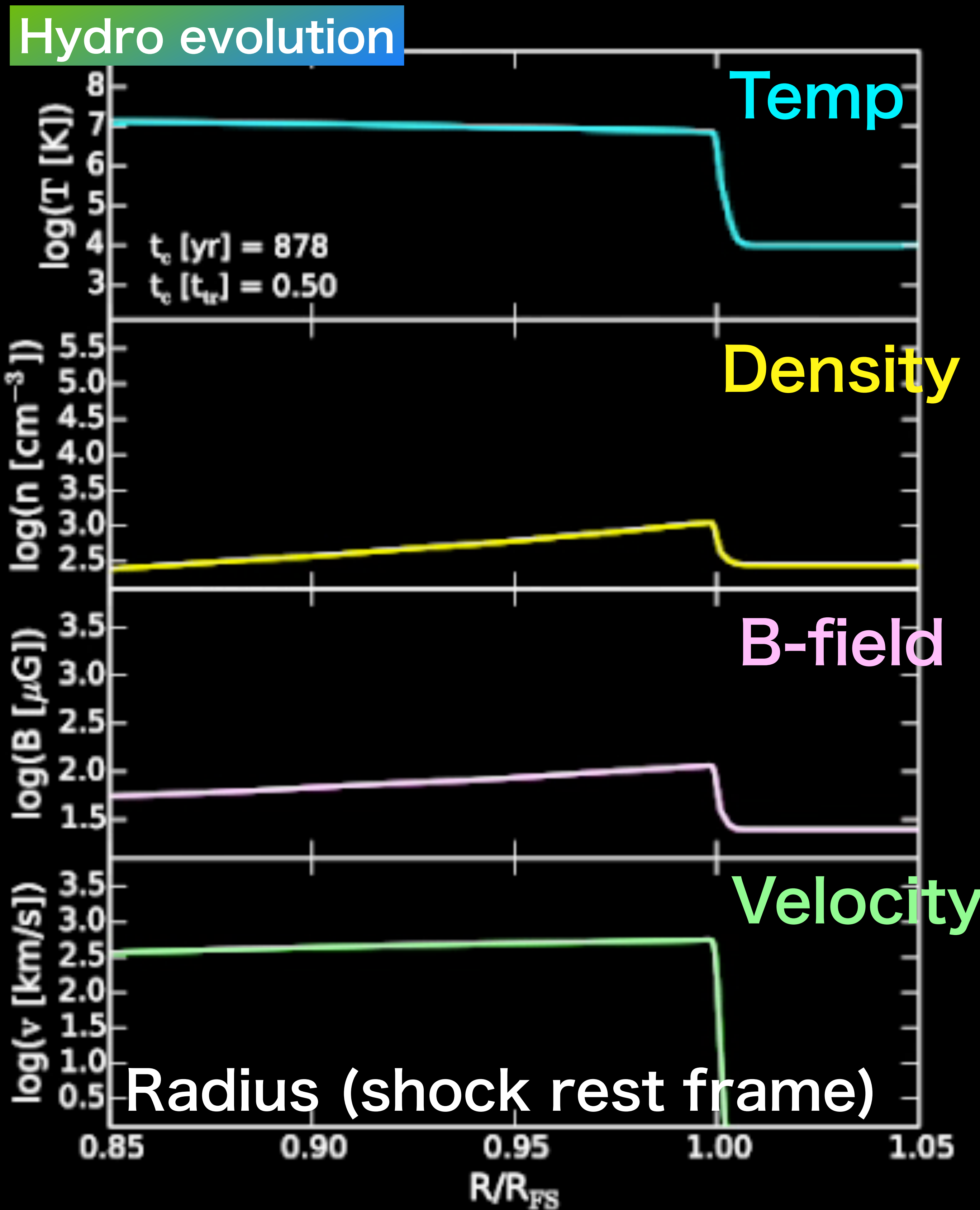
# Model for mid-aged SNRs

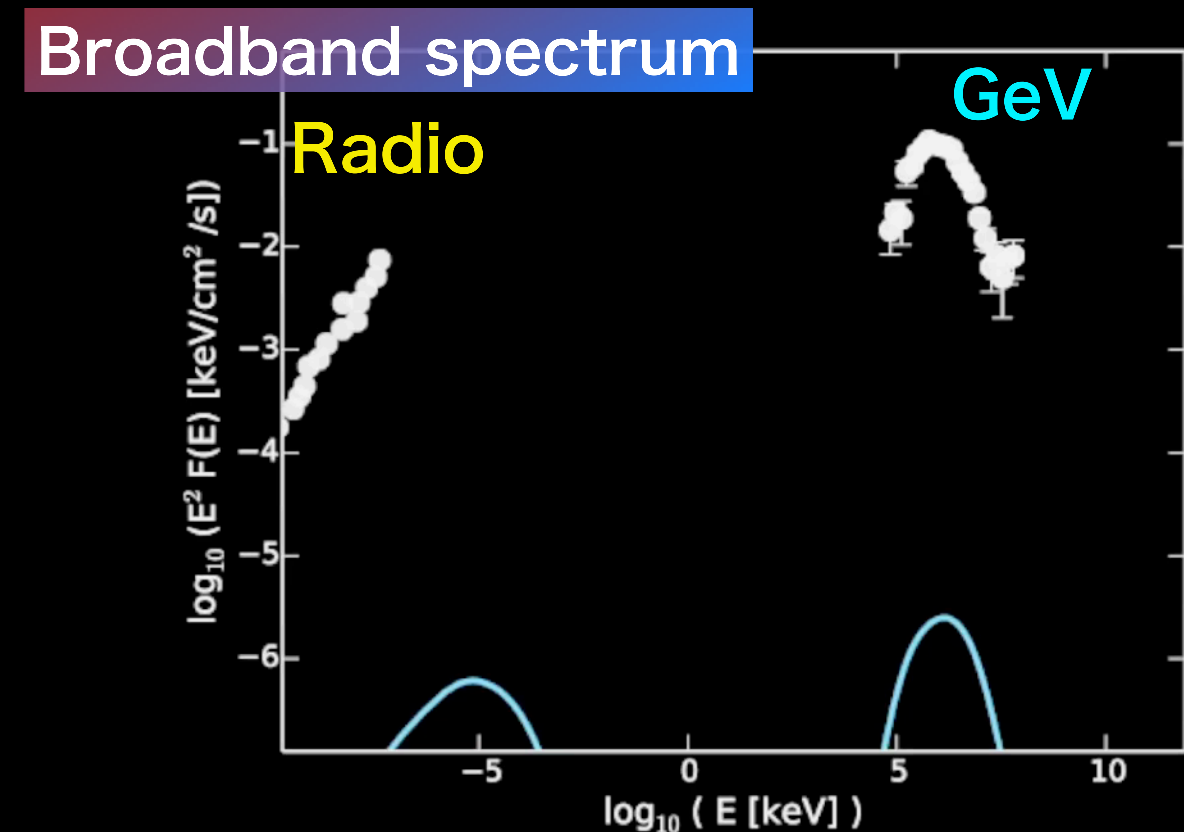


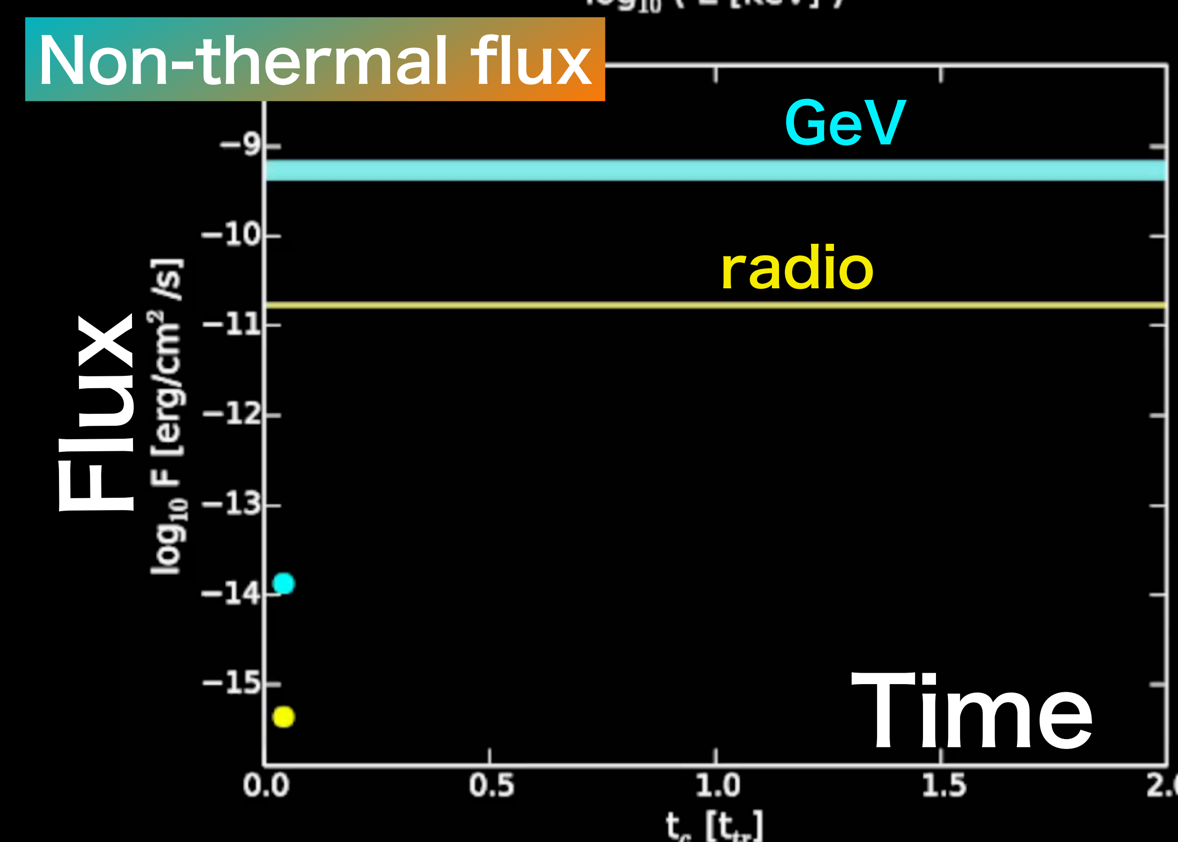



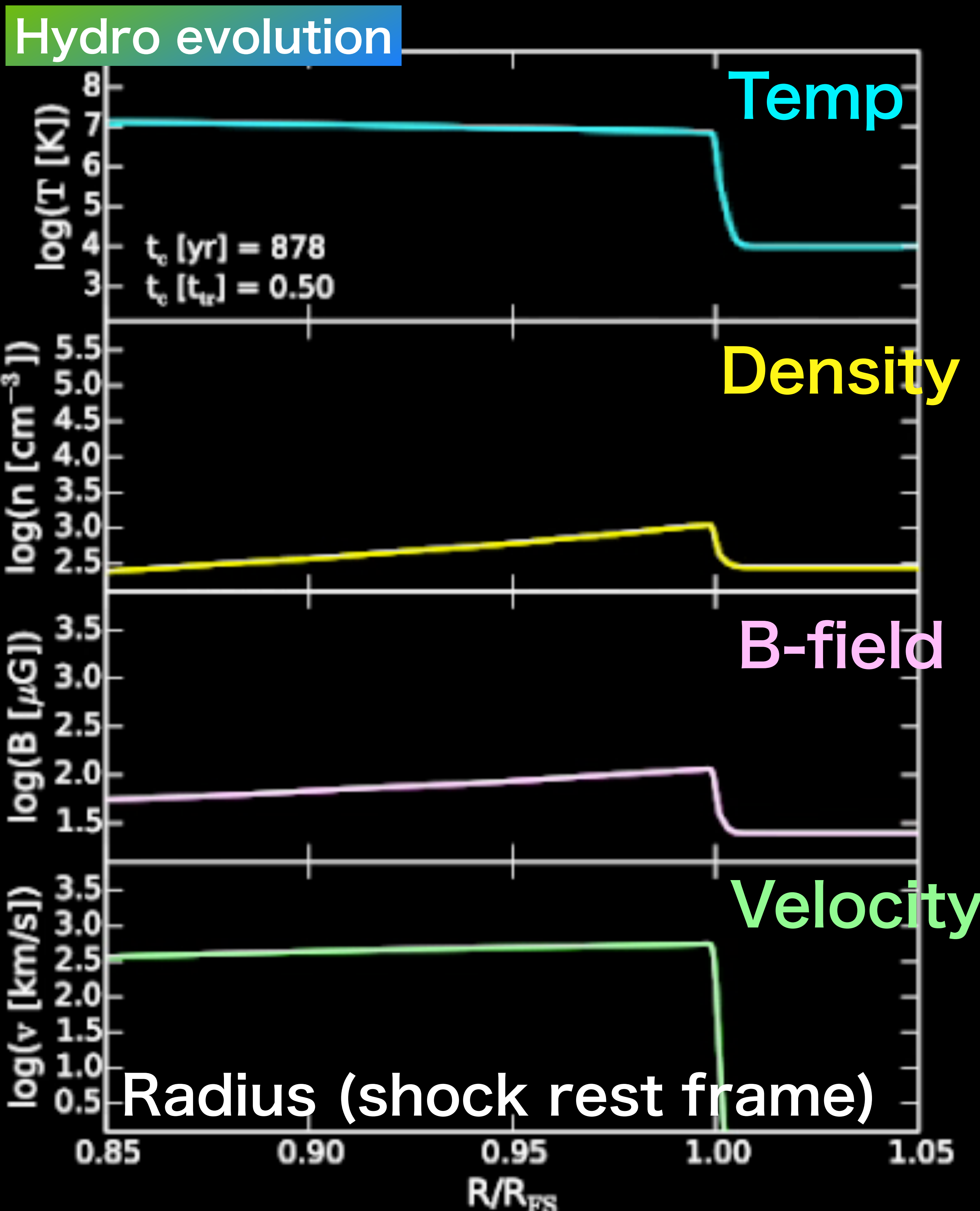
# Model for mid-aged SNRs

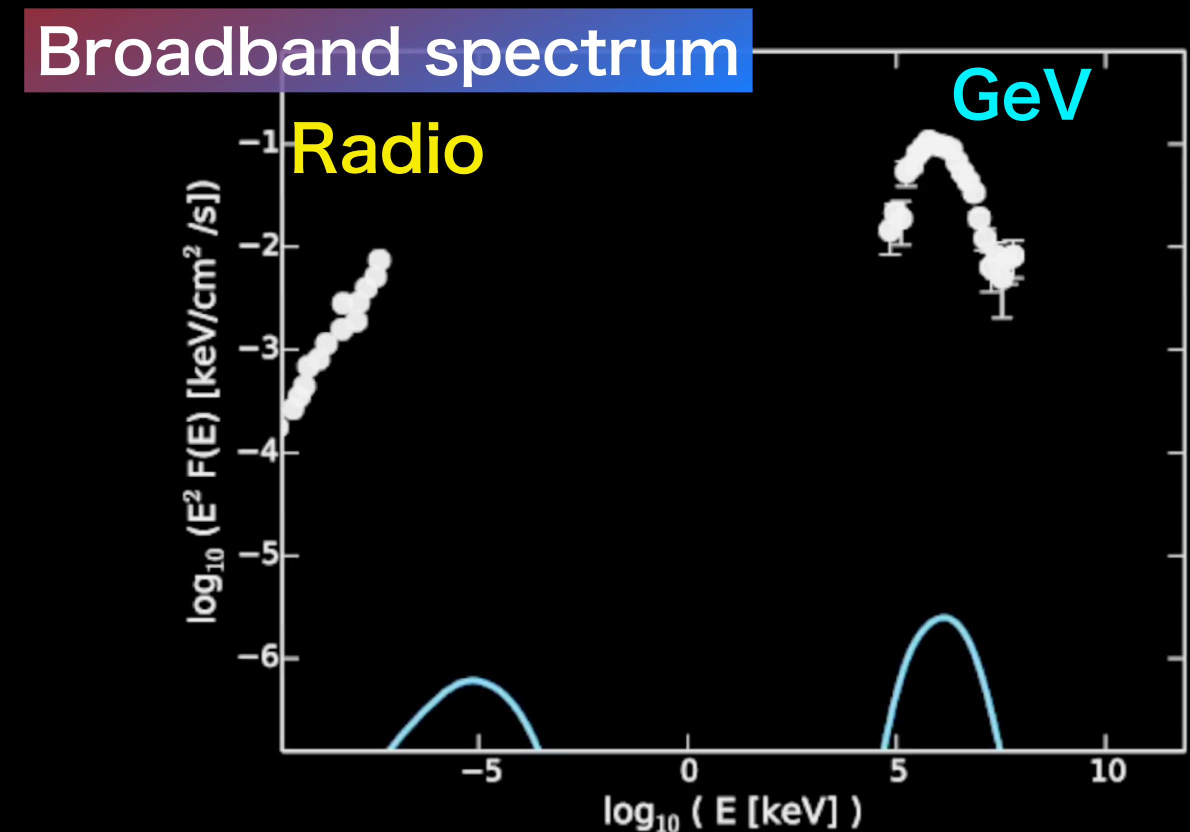


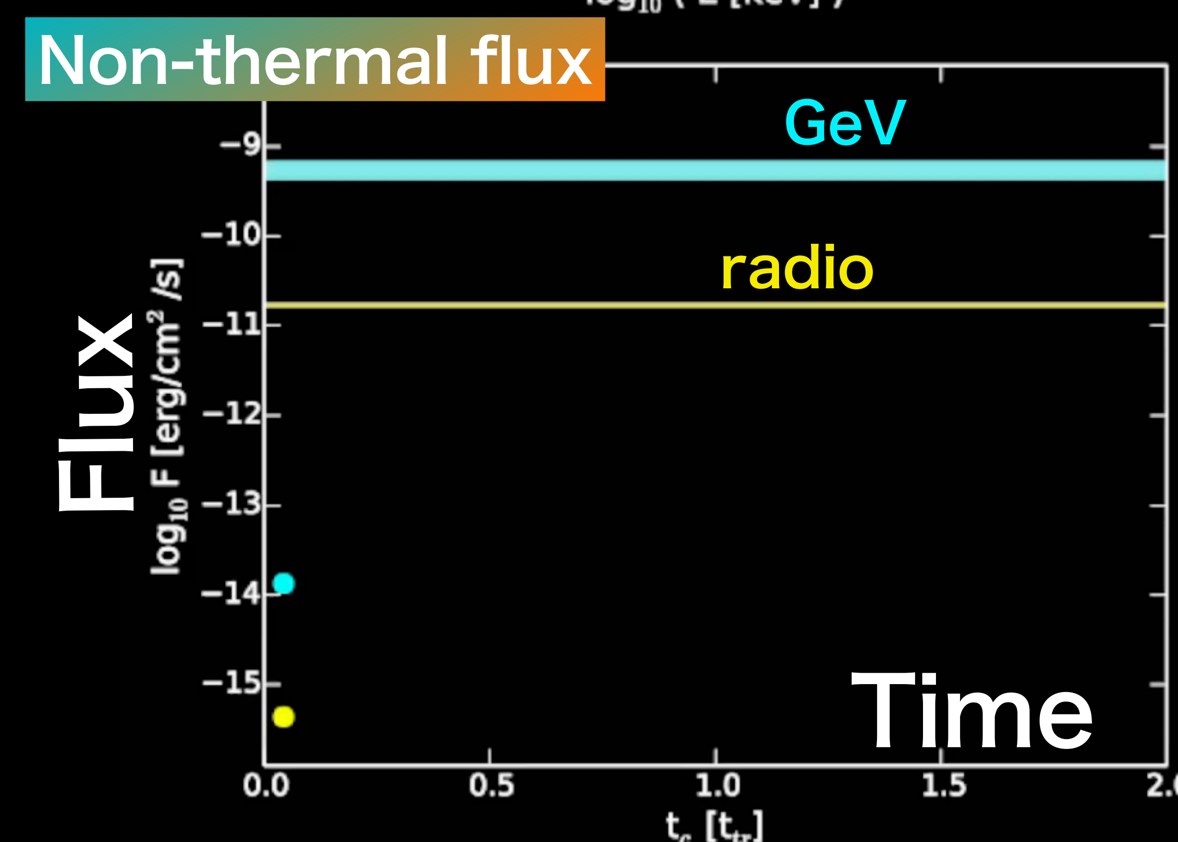



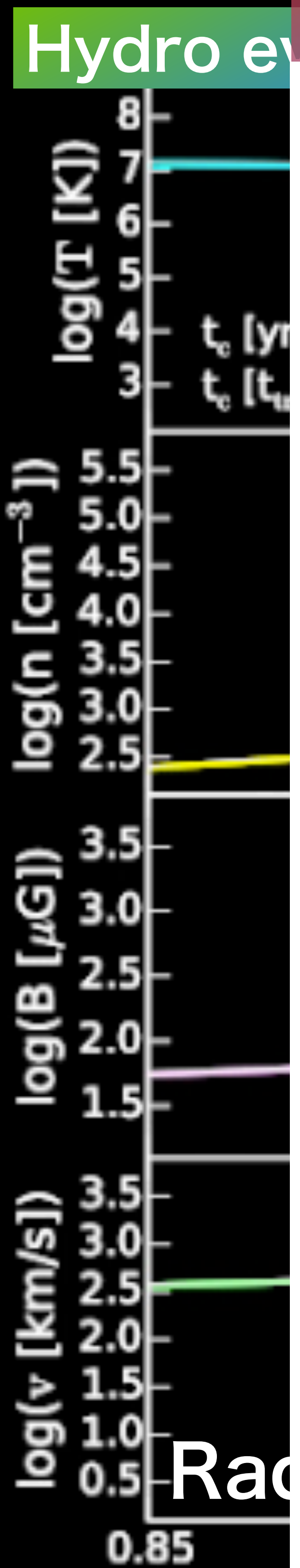
# Model for mid-aged SNRs

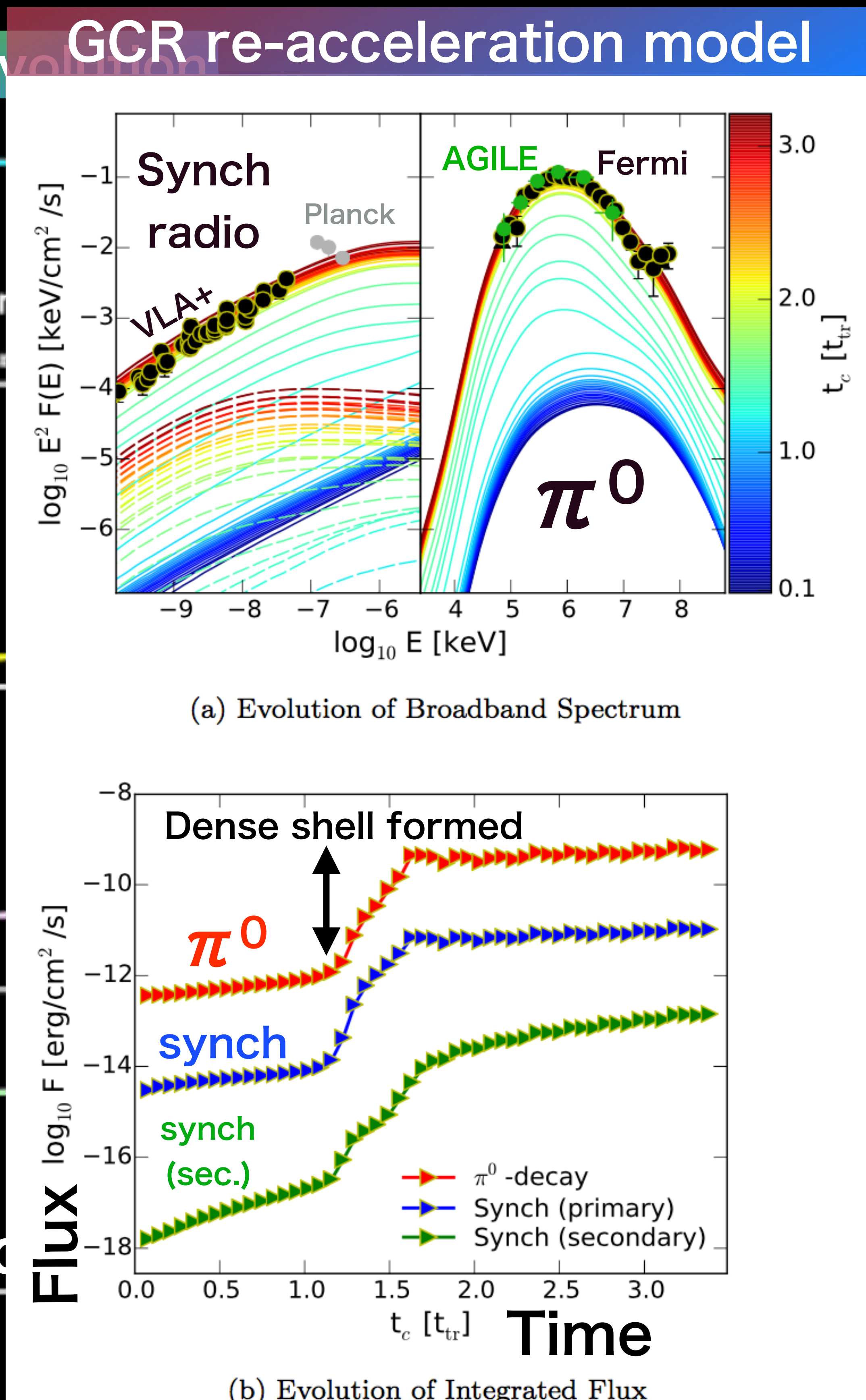


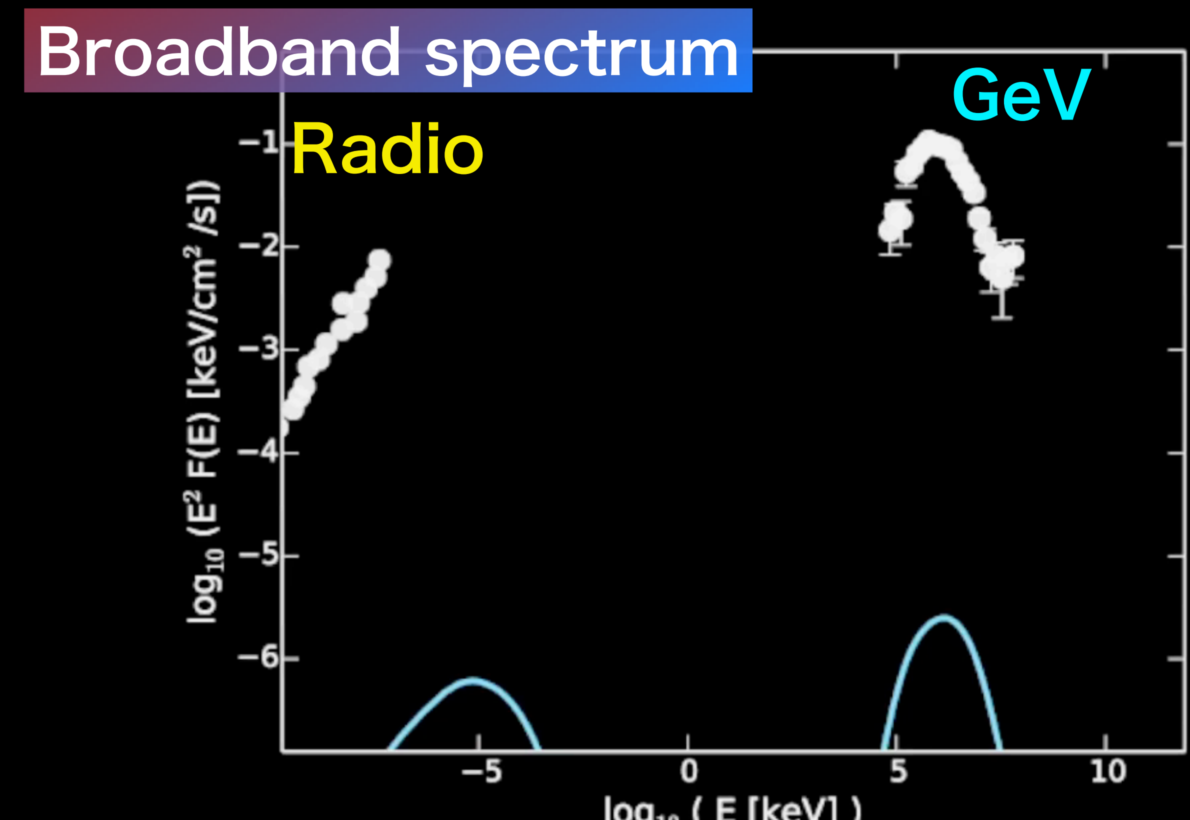
# Model for mid-aged SNRs

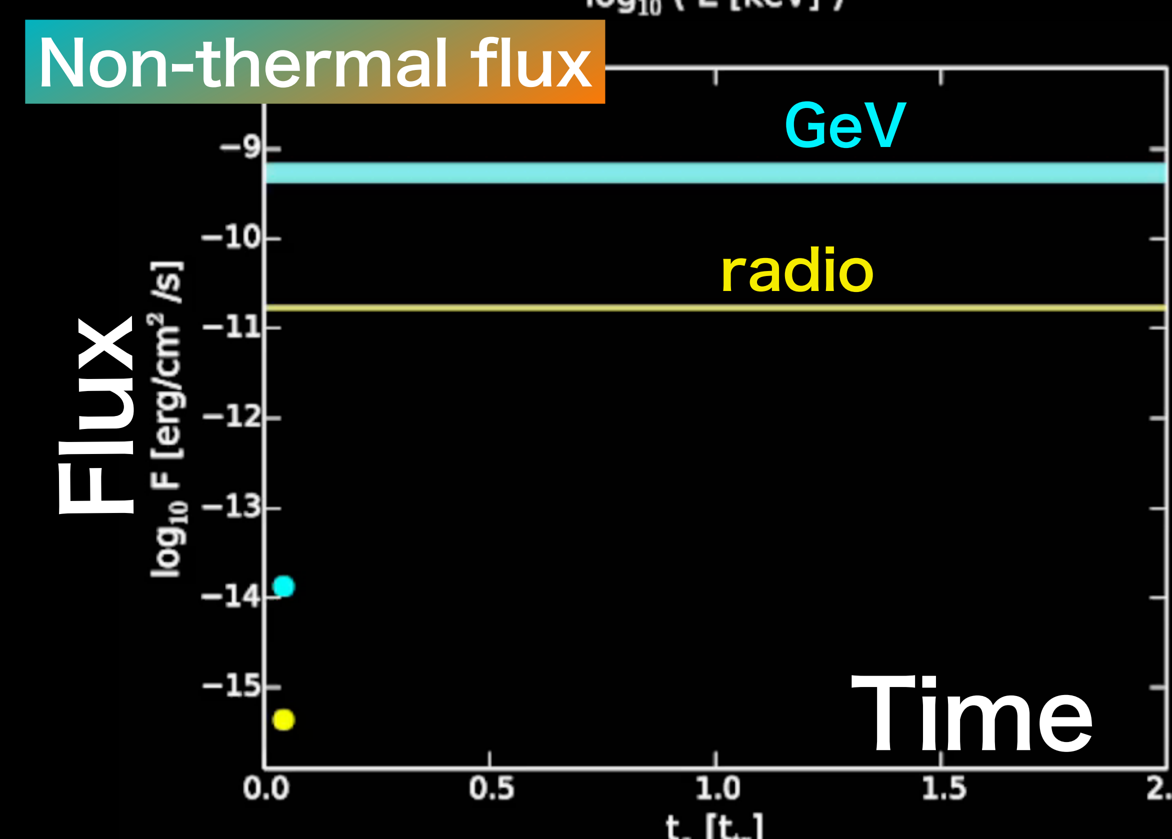


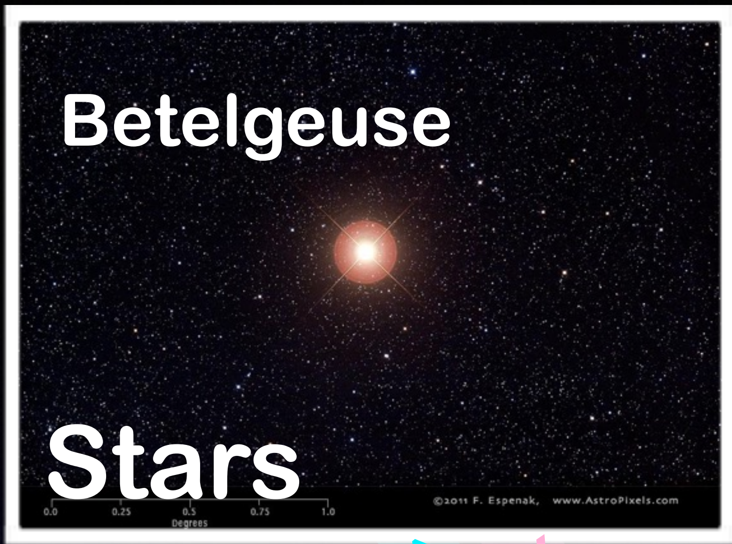



(a) Evolution of Broadband Spectrum

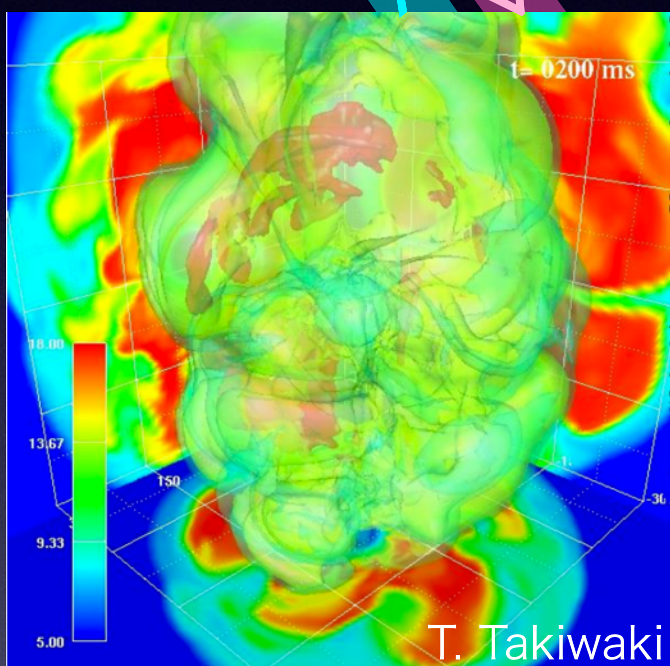
(b) Evolution of Integrated Flux



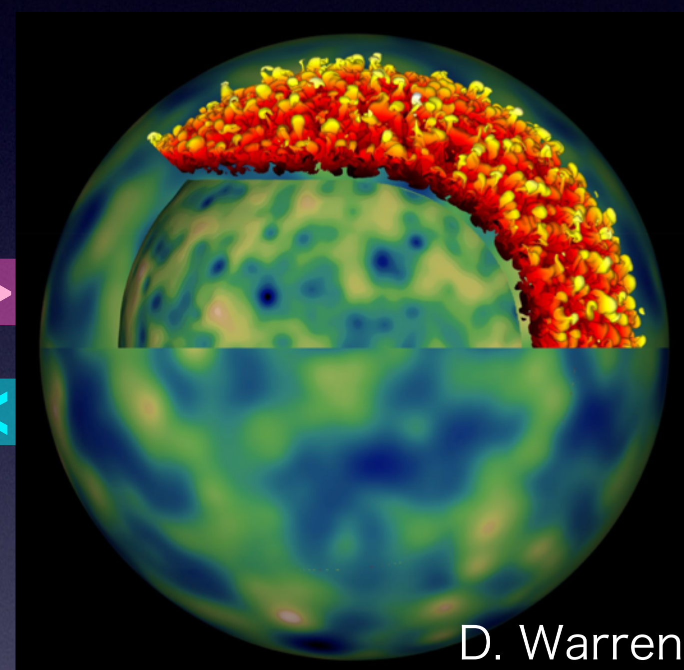






# "From engine to remnant"




SNe

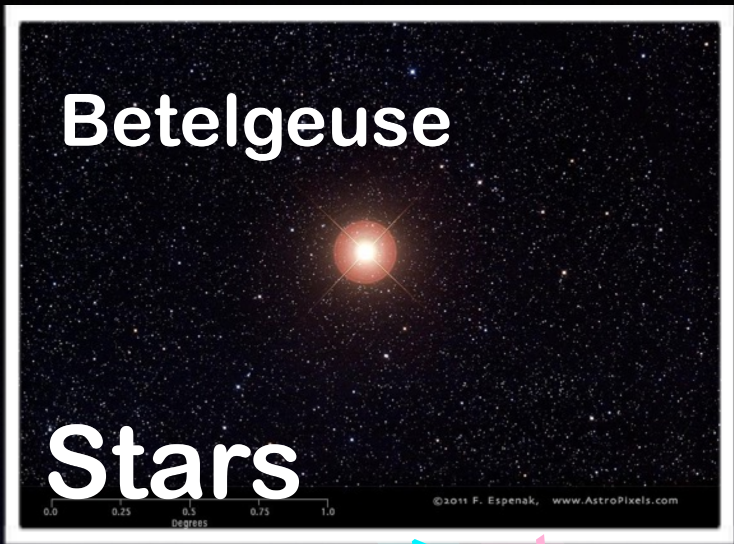


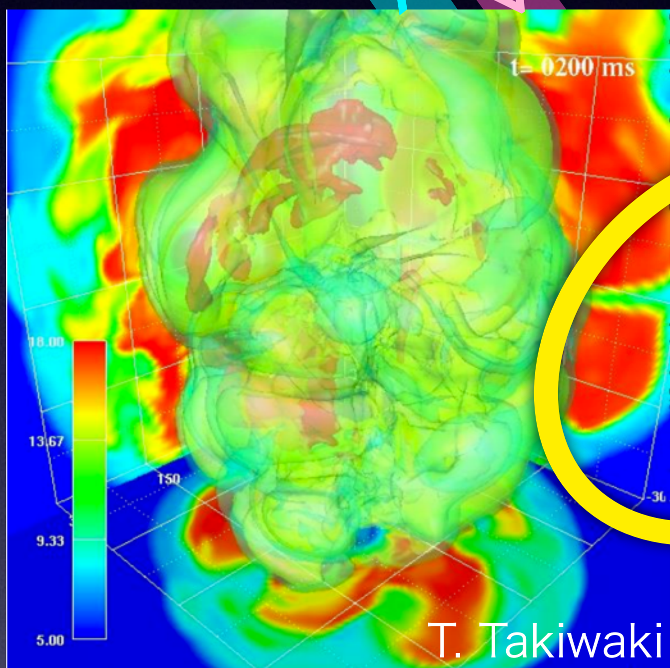

SN Remnants


Data

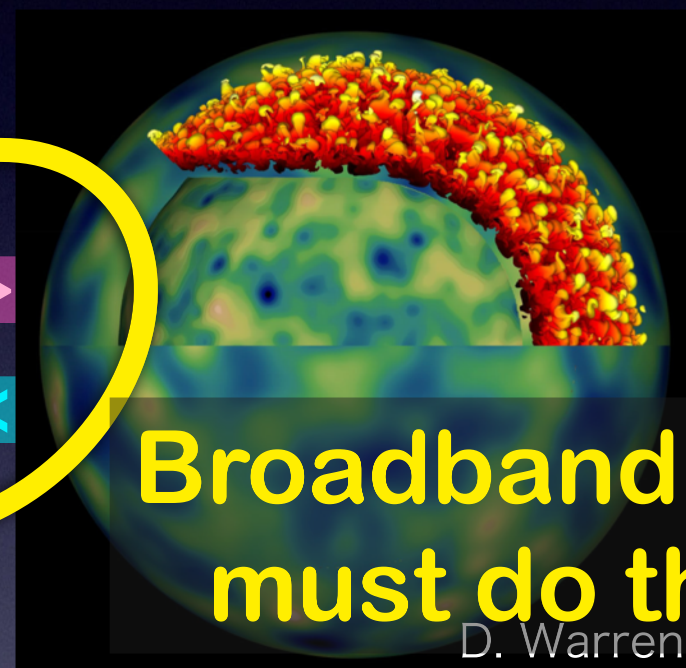
Improve communication between SNe and SNR communities
—> fuller understanding of late-stage stellar evolution

# “From engine to remnant”

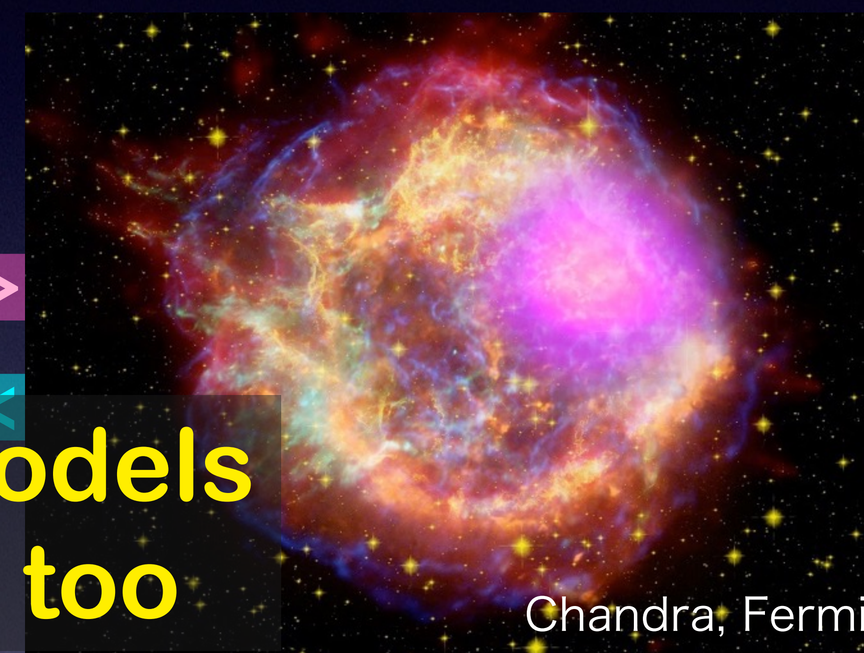



SNe




SN Remnants




Data

>>> <<<

**Broadband models must do this too**

**Improve communication between SNe and SNR communities**
**—> fuller understanding of late-stage stellar evolution**

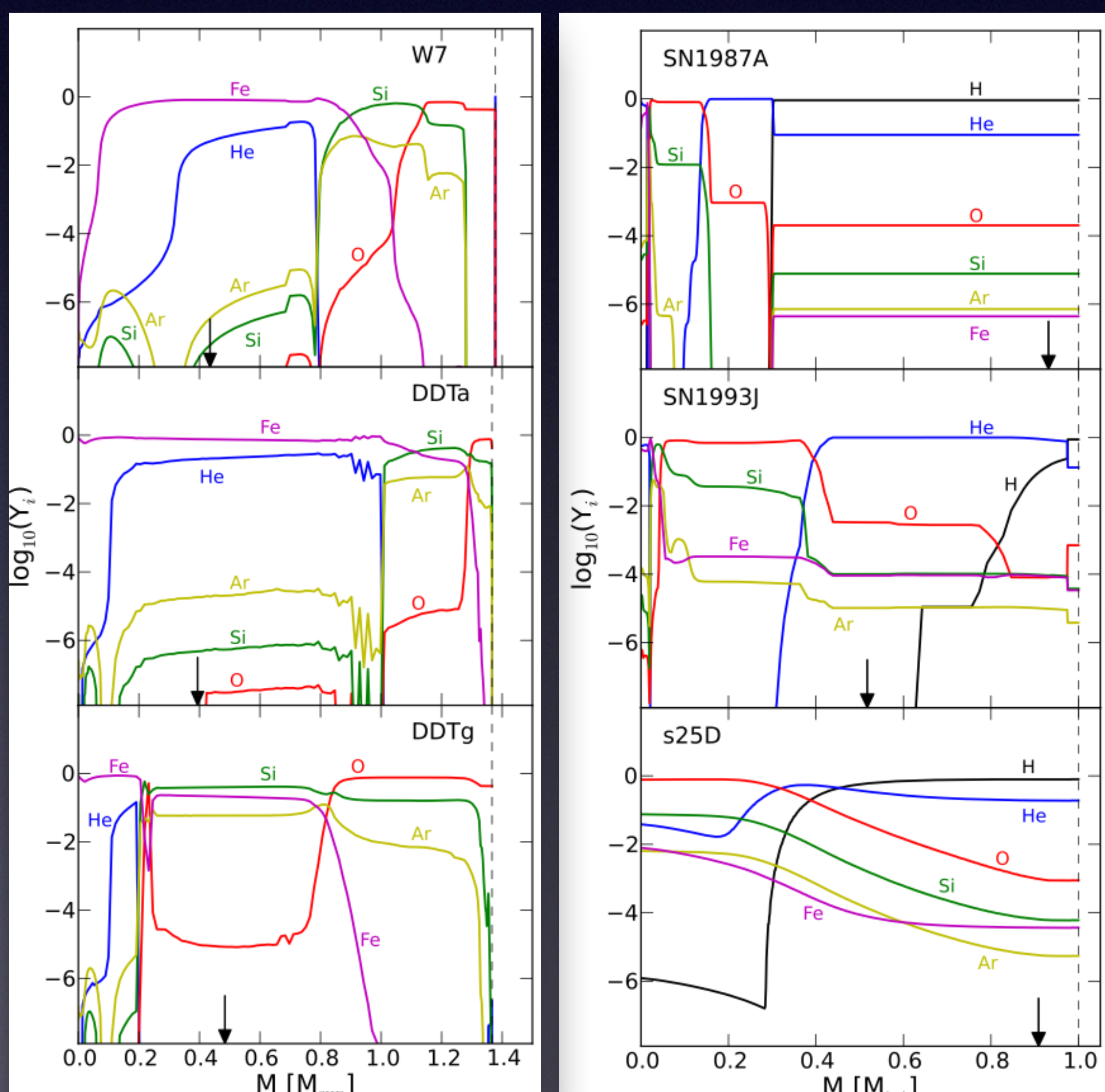
# An Important Application

## Q: Are current SN models consistent with SNR observations?

Basic method:

- ☑ Evolve an SN ejecta to its SNR phase
- ☑ Calculate the emission properties self-consistently with evolution!

Chemical Abundance



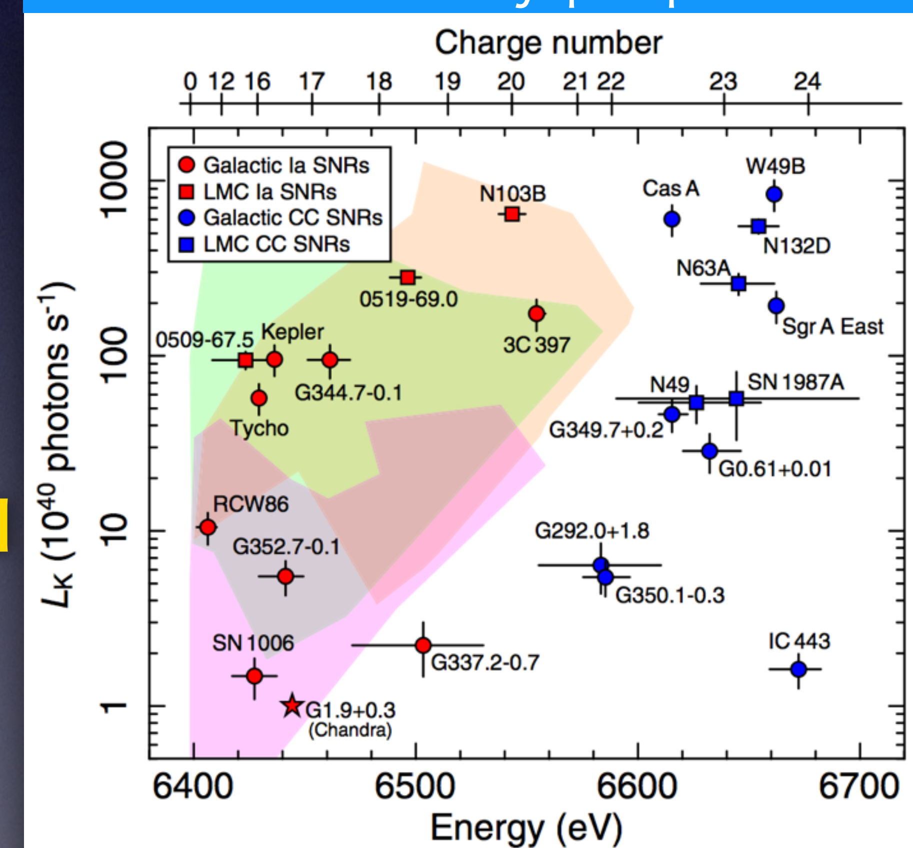

Mass coordinate

HL, Patnaude+ 2014

**Check**

Broadband model

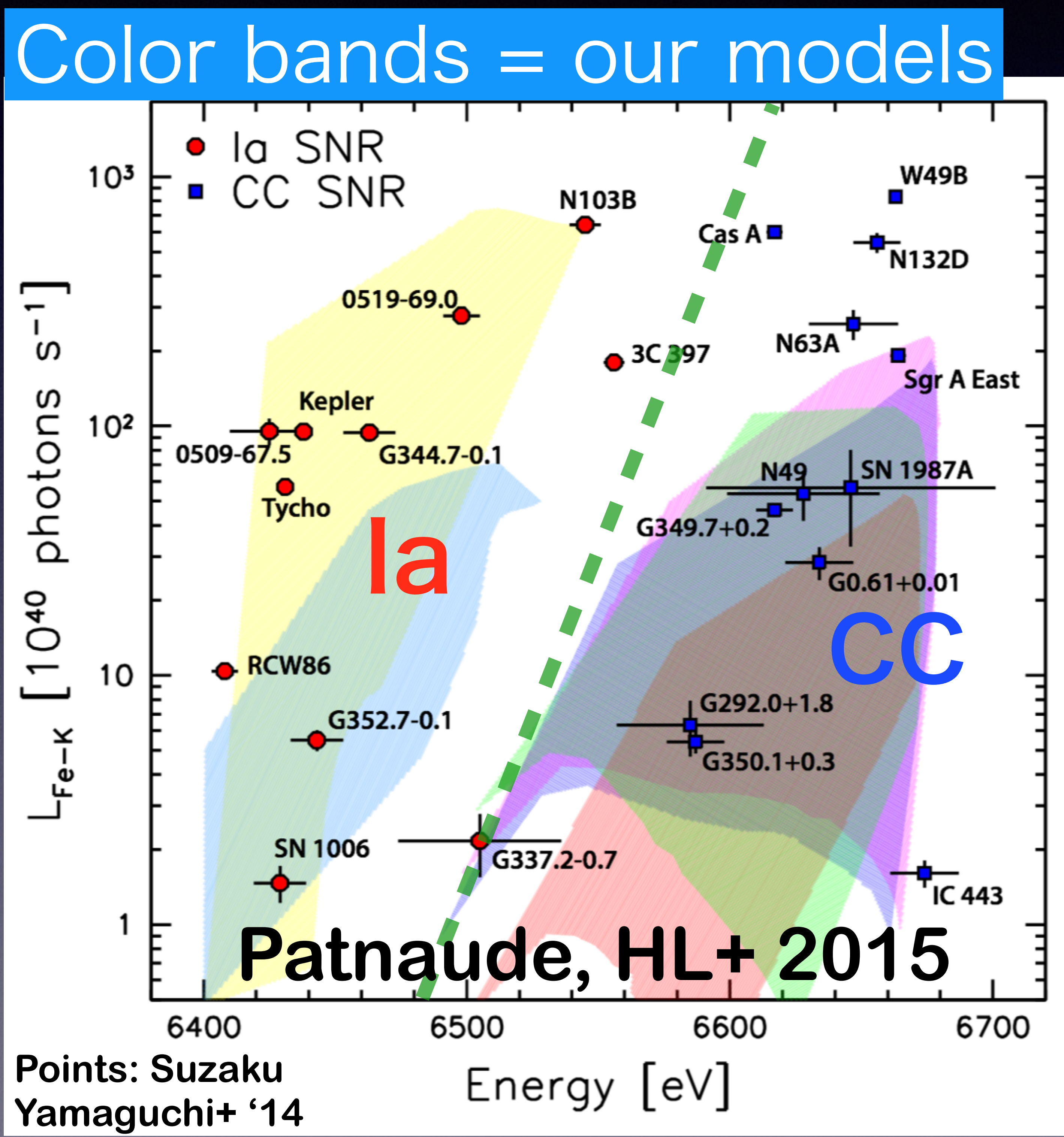
Observed X-ray properties




Suzaku/Chandra, Yamaguchi+ 2014

# Separation of Fe-K line centroid between Ia & CC

## Broad consistency between SN model and SNR data




- Key is ***general difference in circumstellar environment!***
- **CC encounters dense wind**
  i.e., ejecta hit dense wind
  —> stronger reverse shock
  —> higher ionization state
  —> higher line centroid energy
- **Ia usually has more uniform low-$\rho$ ISM**
- Origin of scattering in plot
  = dispersion in age, progenitor and wind properties
- Several 'special' outliers:
  Often dense cloud interaction

# Conclusions

- We have reviewed on the general methodology and capabilities of modern broadband models for SNRs

- Current limitations from yet incompletely understood physics

  - Rely on rich MW observational data and breakthroughs from first principle simulations to remove ‘free’ parameters

- Future is in cross-field collaborations
Importance of progenitor-SN-SNR connection
More realistic, less ambiguity, more fun