Now and the Future of Broadband Models for Supernova Remnants

Herman S.-H. Lee
Department of Astronomy
Kyoto University

D. Patnaude, P. Slane, J. Raymond, D. Castro (CfA/Harvard)
C. Badenes, H. Martinez-Rodriguez (Pitt)
S. Nagataki (RIKEN)
D. Ellison (NCSU)

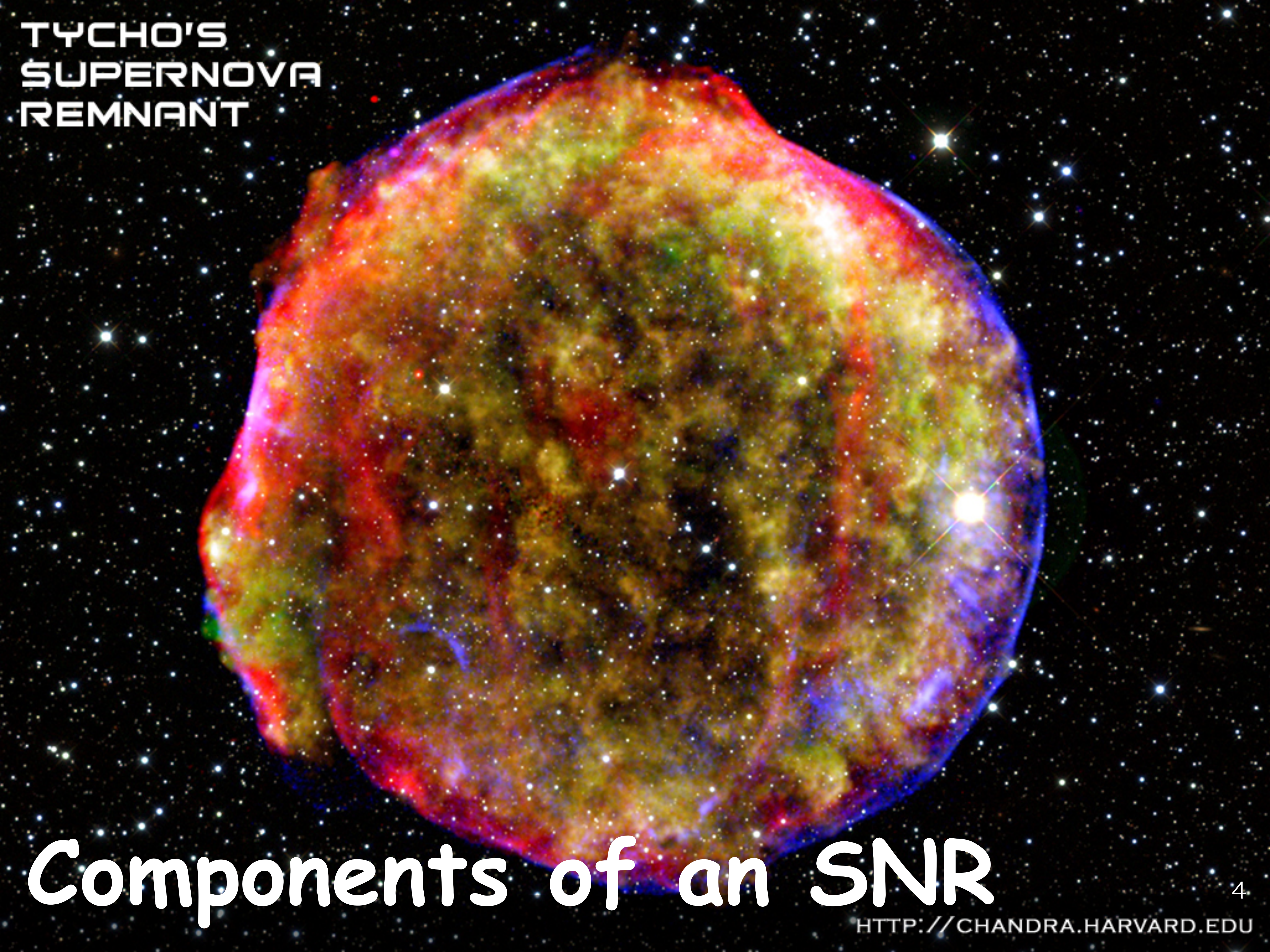
VHEPU @ ICISE, Quy Nhon, 15 Aug 2018

The Art of
Broadband SNR Modeling

- Nowadays, broadband models must satisfy many constraints from observations
  - Multi-wavelength spectra
  - Multi-wavelength morphology
  - Dynamical properties
  - Thermal + non-thermal emission
  - All different combinations of the above! (spectral map, spectral evolution etc)
- Also have to meet criteria from complex plasma physics and simulations
  - A few parameters, from yet incomplete physical understandings

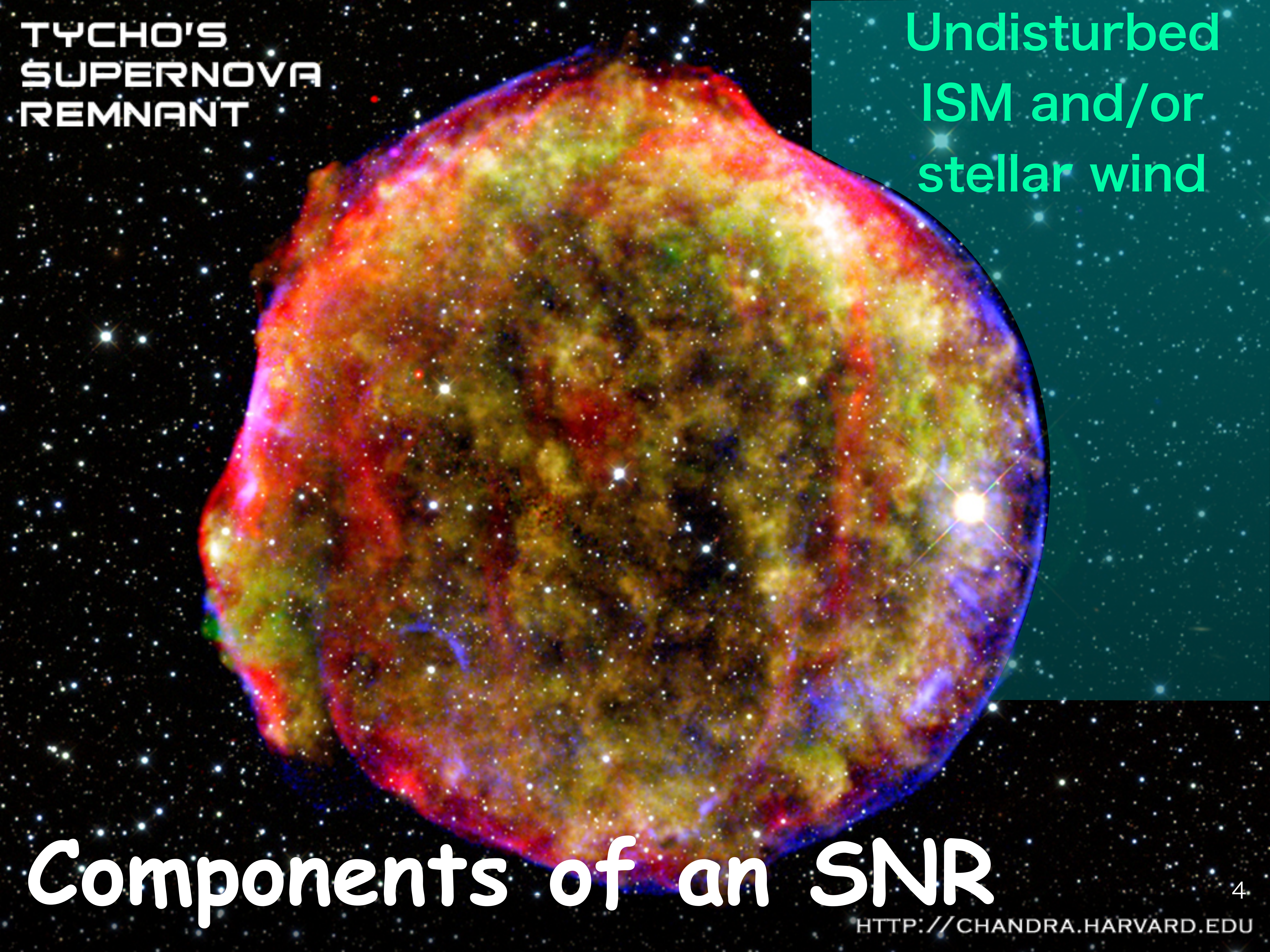
Common Ingredients of a SNR Broadband Model

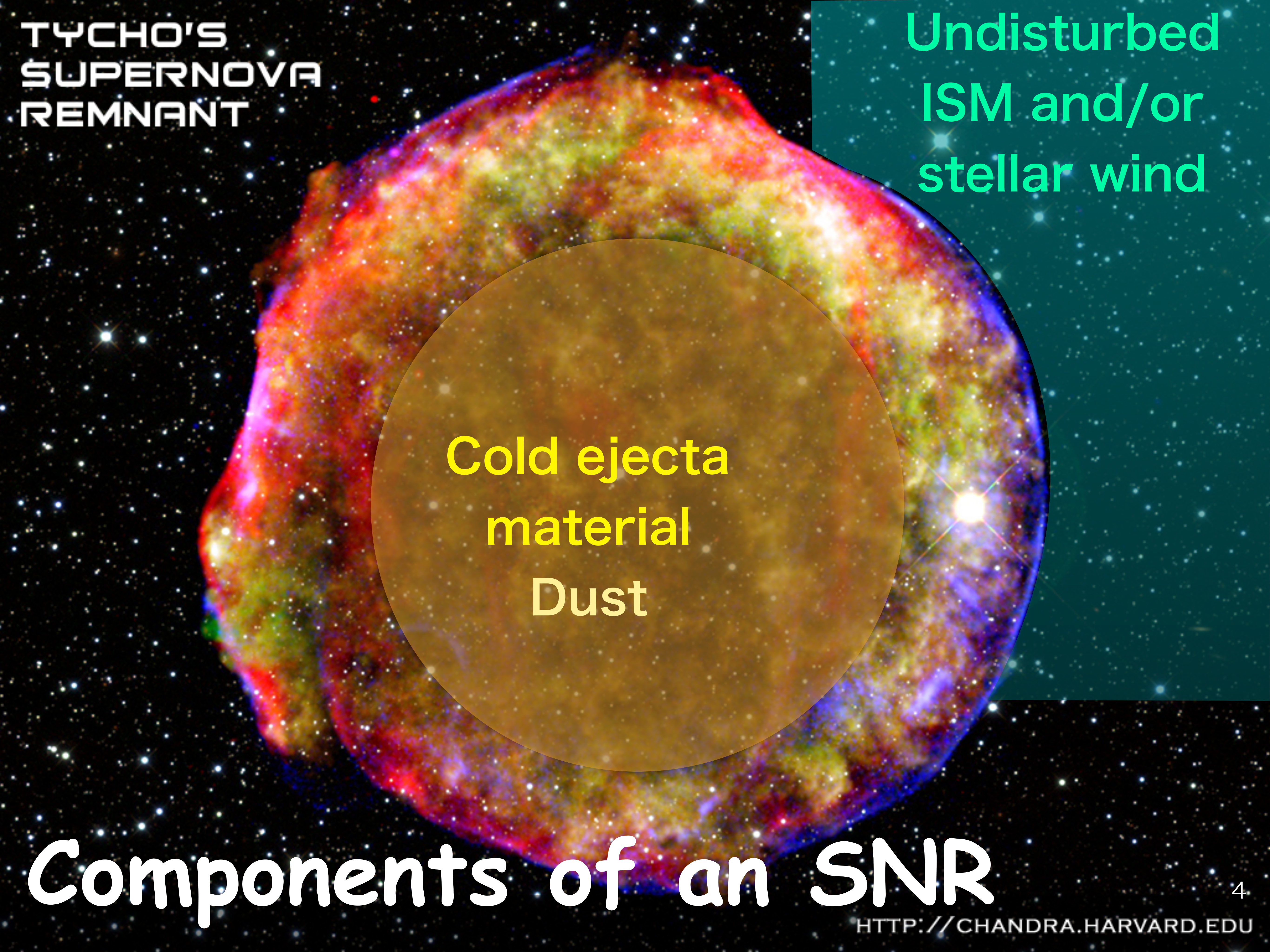
- (Magneto-) hydrodynamics
- Models of progenitor, supernova and explosive nucleosynthesis (Ia & CC)
- Picture of surrounding environment
- Various implementations of Diffusive Shock Acceleration (DSA)
- Time and space-dependent microphysical processes
  - Non-equilibrium ionization (NEI), charge exchange, …
  - Shock heating, temperature equilibration
  - Radiative cooling/heating
  - Magnetic turbulence generation and dissipation, feedbacks to DSA etc
- Thermal and non-thermal emission calculations to confront data in various forms

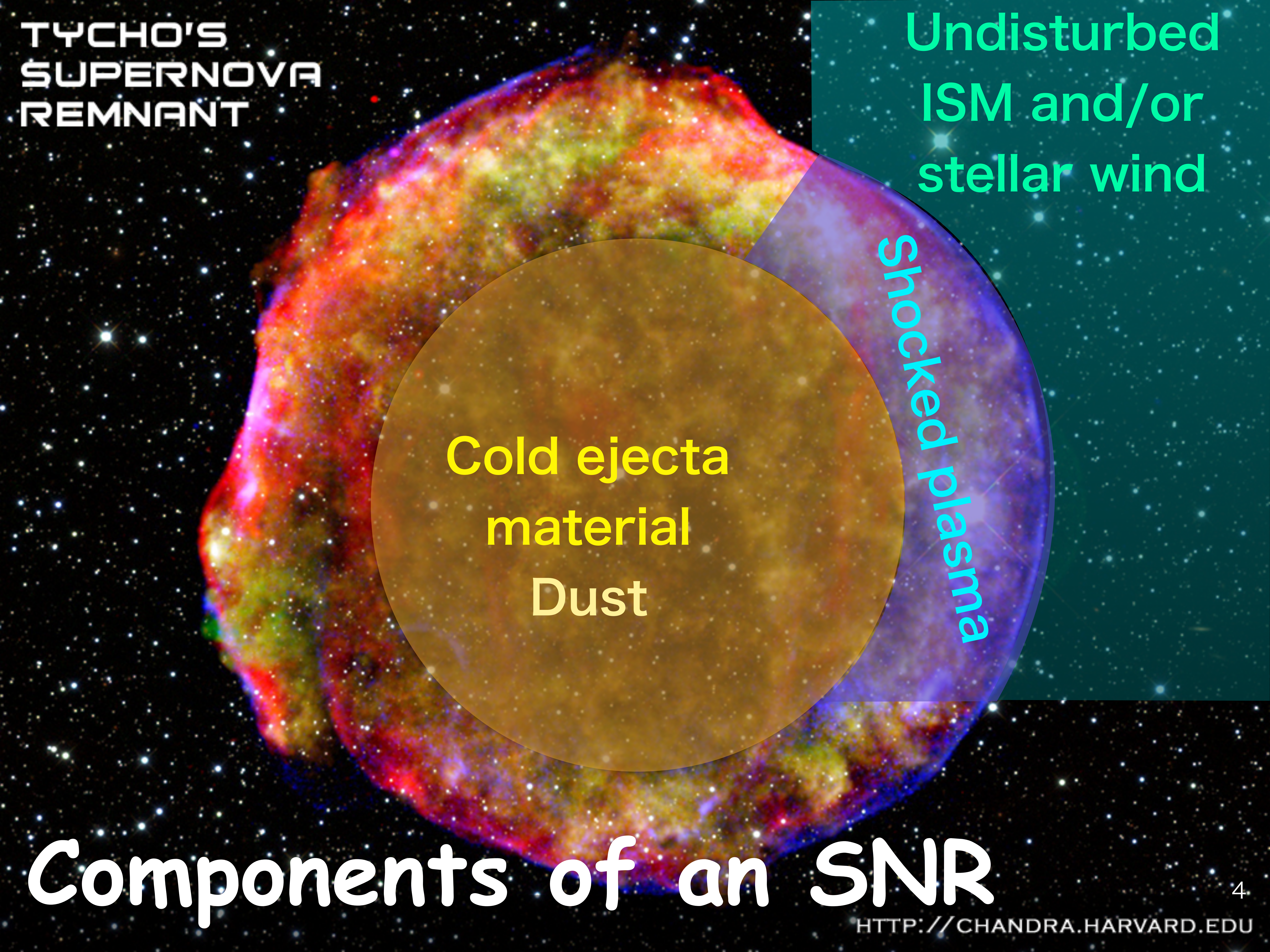


Components of an SNR

Components of an SNR




TYCHO'S SUPERNOVA REMNANT
Undisturbed ISM and/or stellar wind
Cold ejecta material
Dust
Components of an SNR
HTTP://CHANDRA.HARVARD.EDU


TYCHO'S
SUPERNOVA
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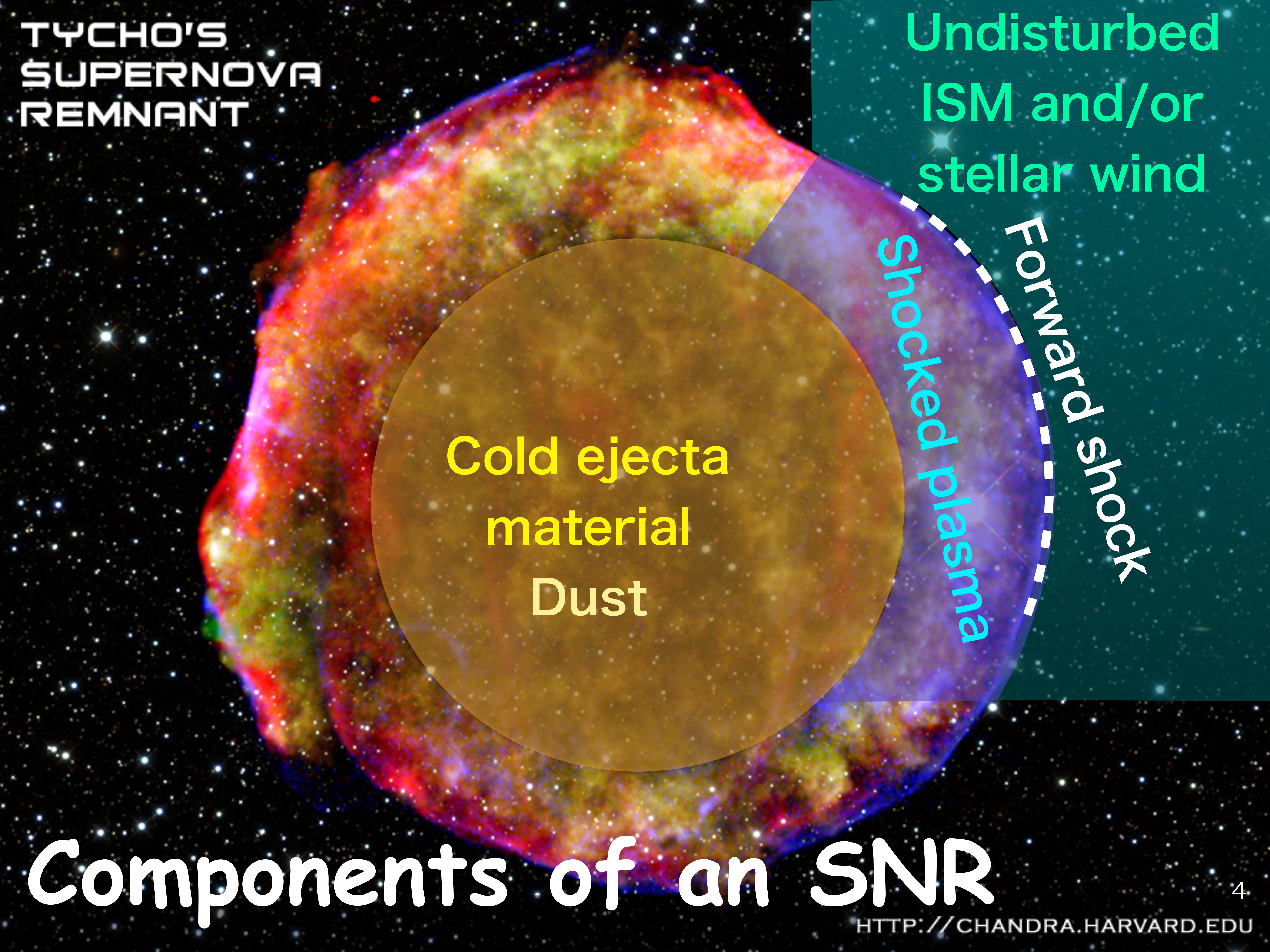
TYCHO'S SUPERNOVA REMNANT
Undisturbed ISM and/or stellar wind
Forward shock
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Dust
Components of an SNR
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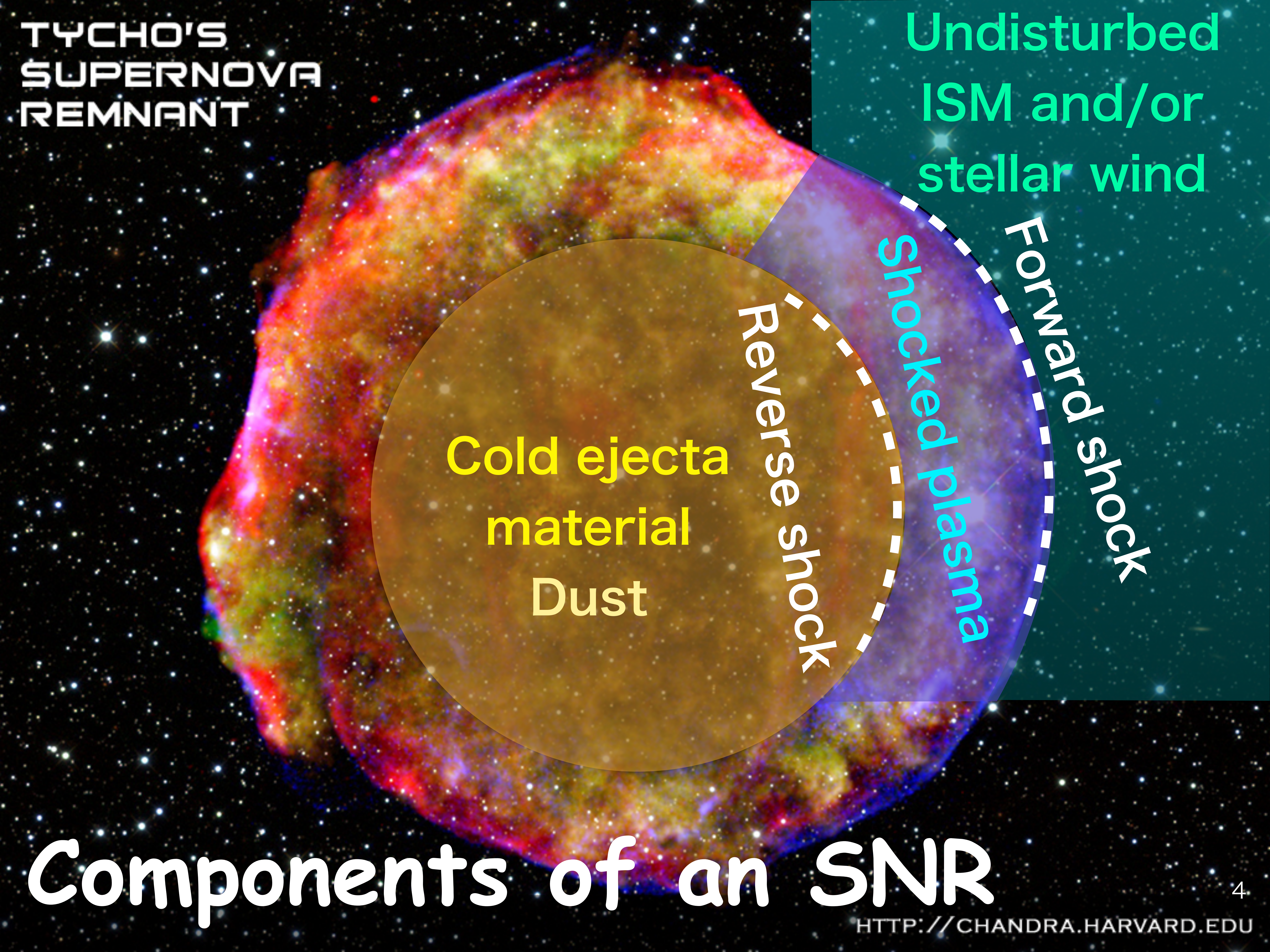
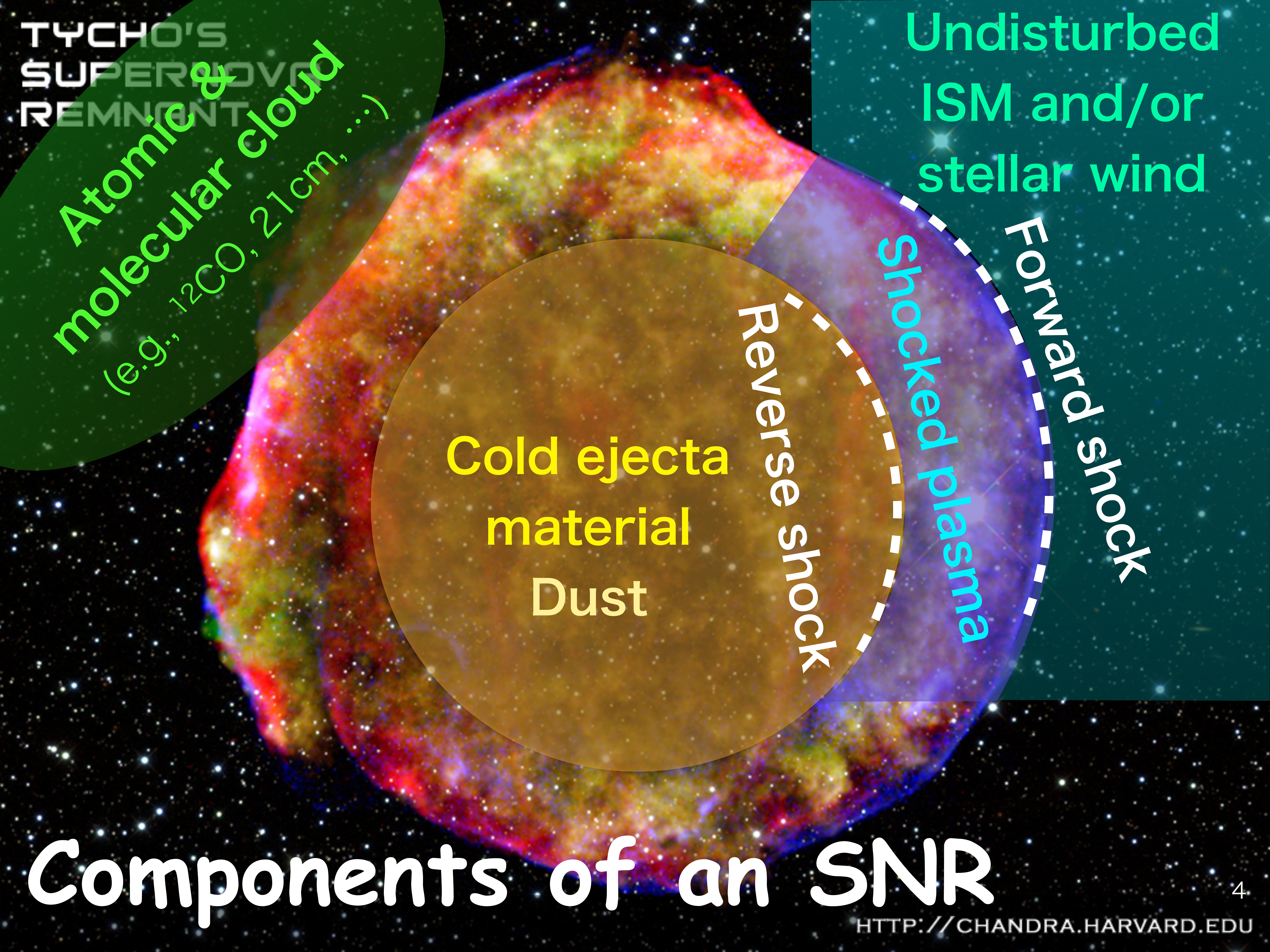
Components of an SNR

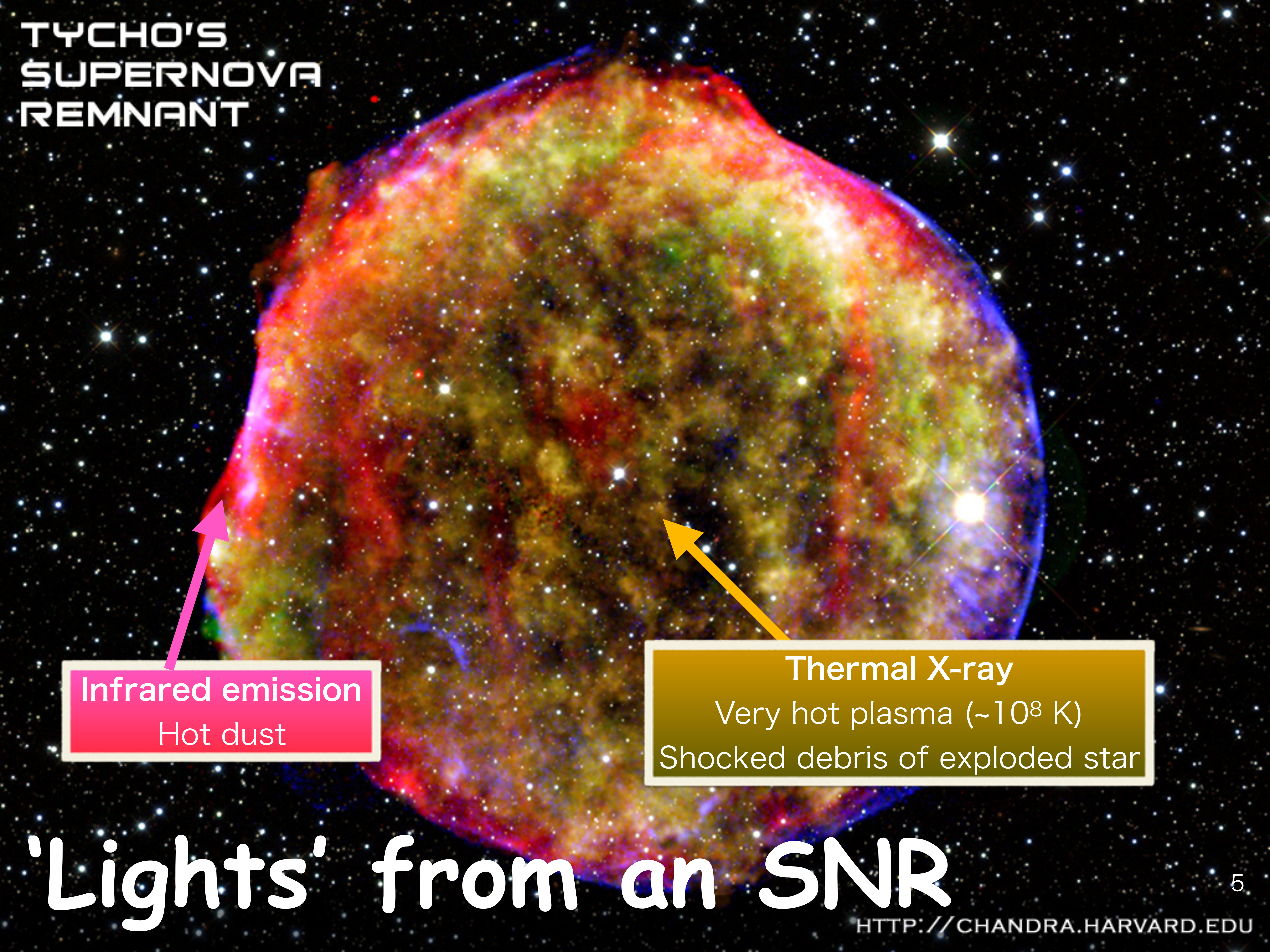




Components of an SNR

'Lights' from an SNR

'Lights' from an SNR


TYCHO'S SUPERNOVA REMNANT
Infrared emission
Hot dust
Thermal X-ray
Very hot plasma (~10⁸ K)
Shocked debris of exploded star
'Lights' from an SNR
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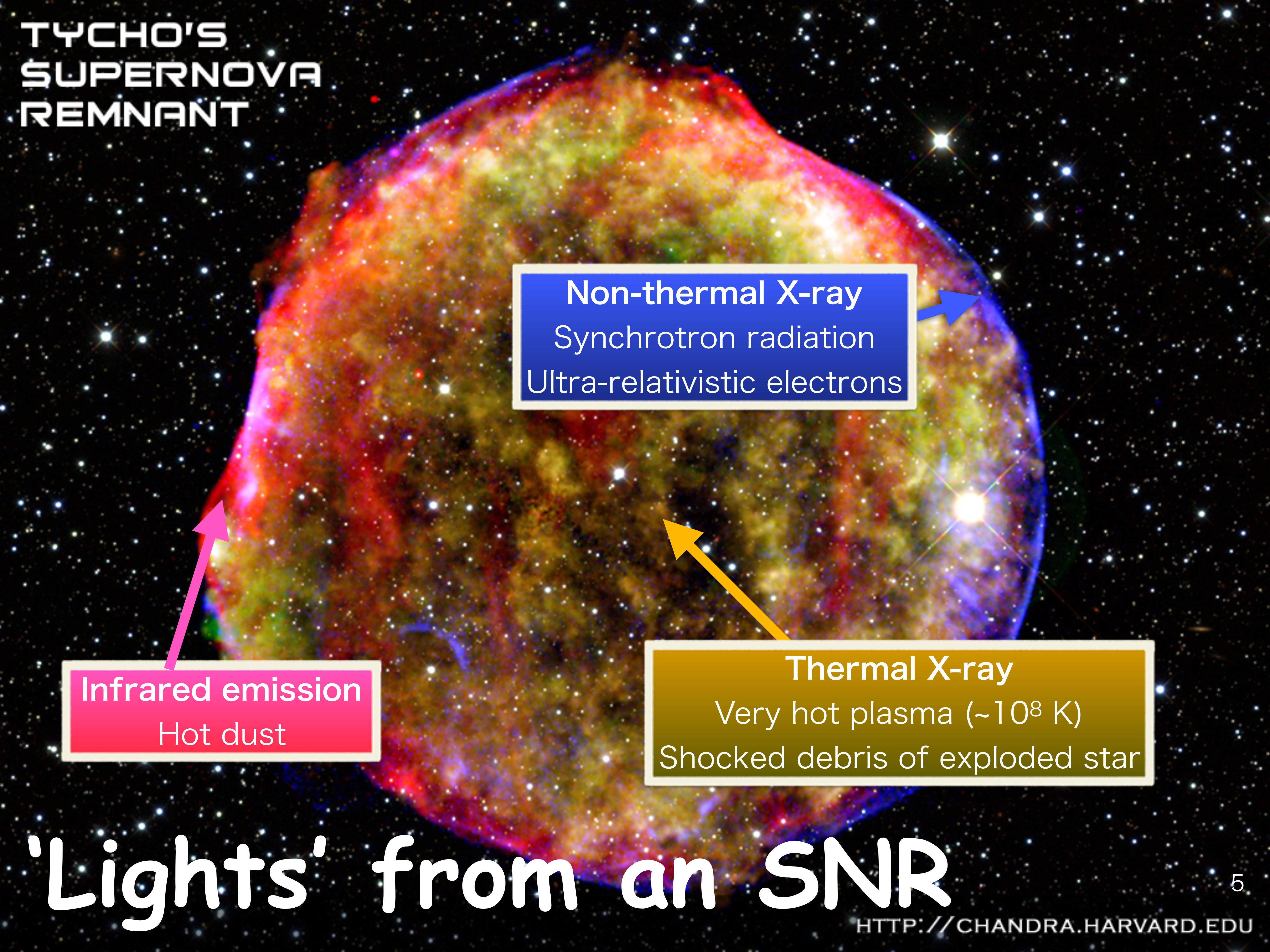
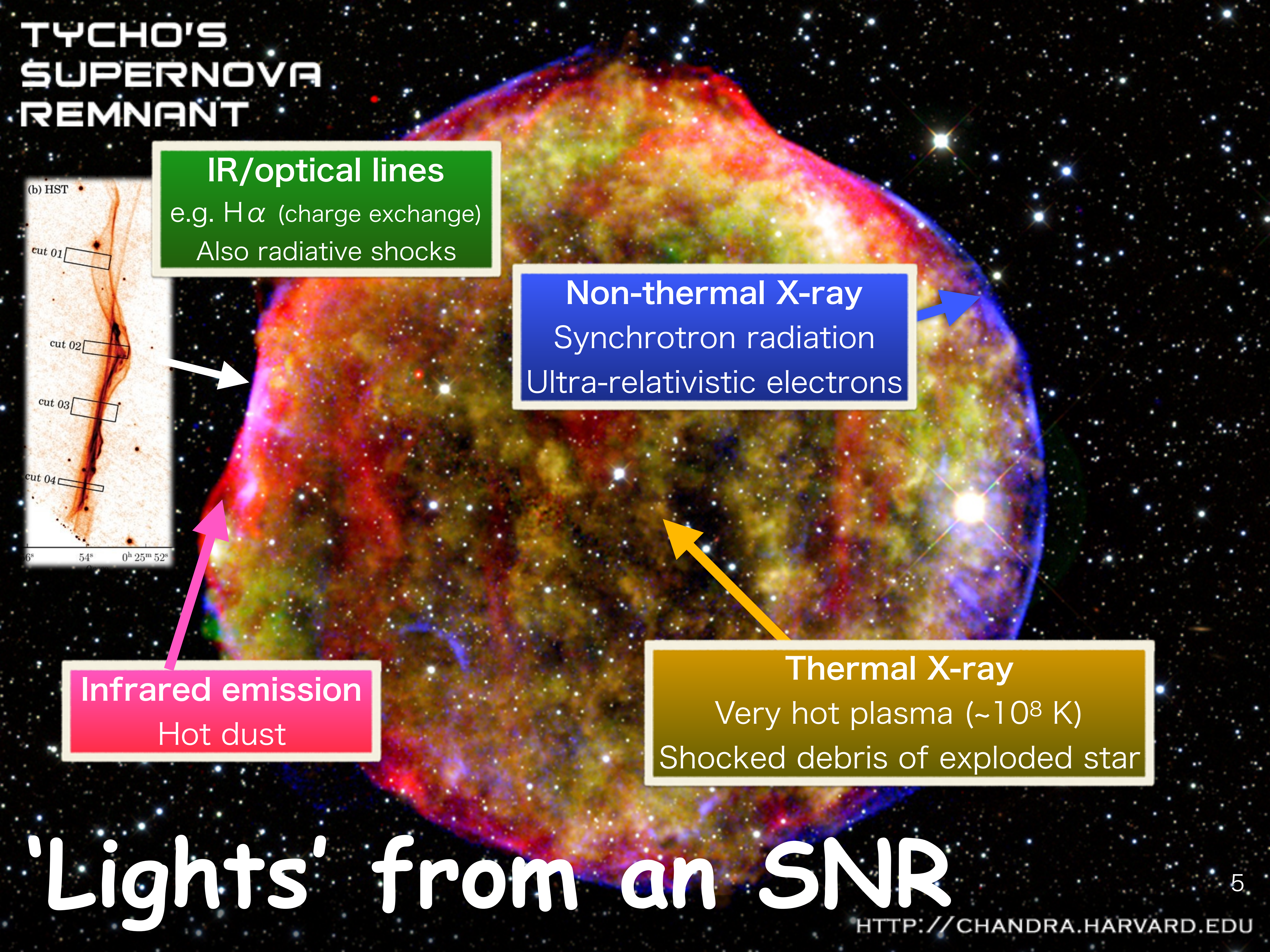
‘Lights’ from an SNR




TYCHO'S SUPERNOVA REMNANT
(b) HST
cut 01
cut 02
cut 03
cut 04
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 (~10^8 K)
Shocked debris of exploded star
'Lights' from an SNR
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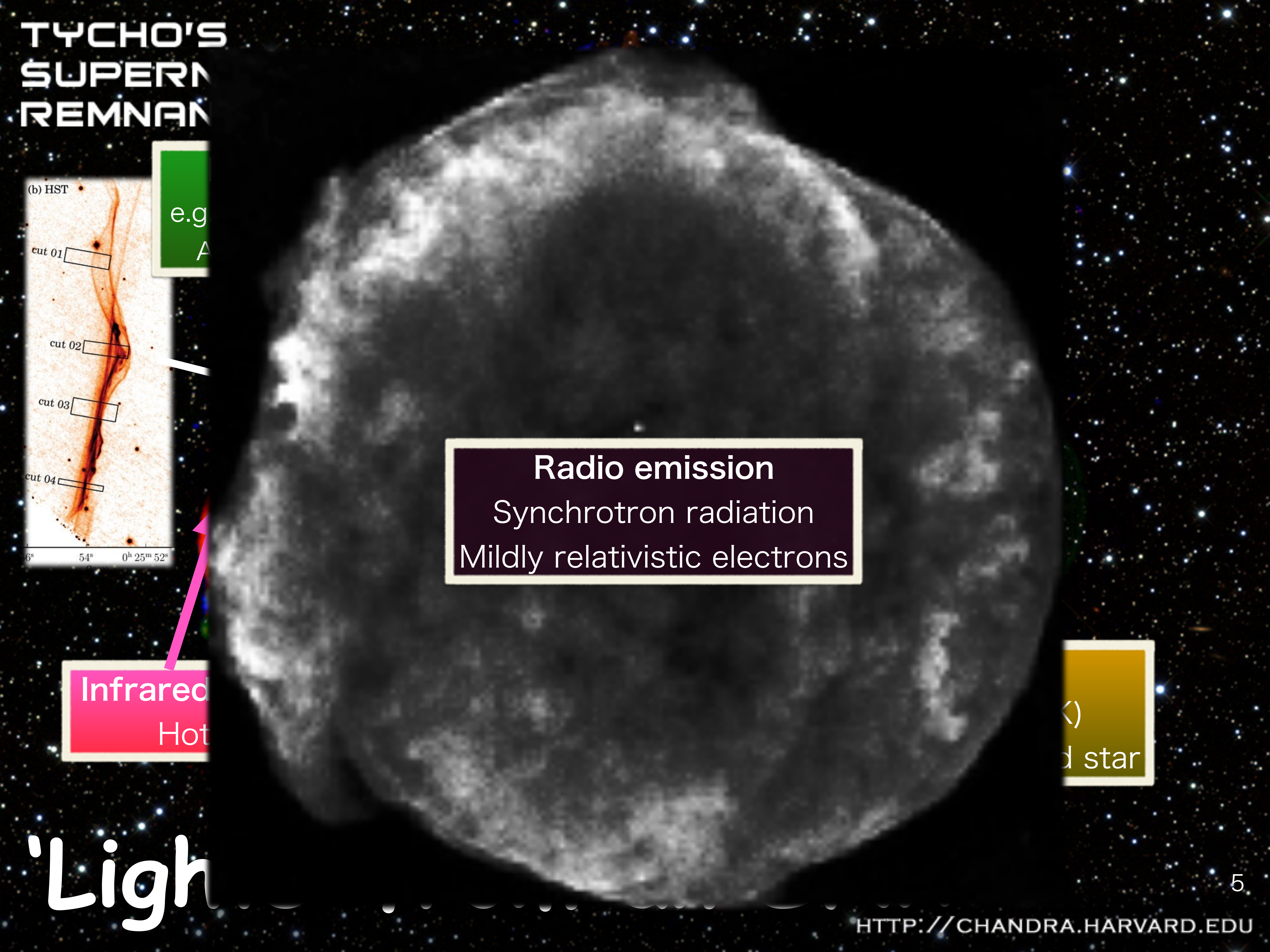
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X)
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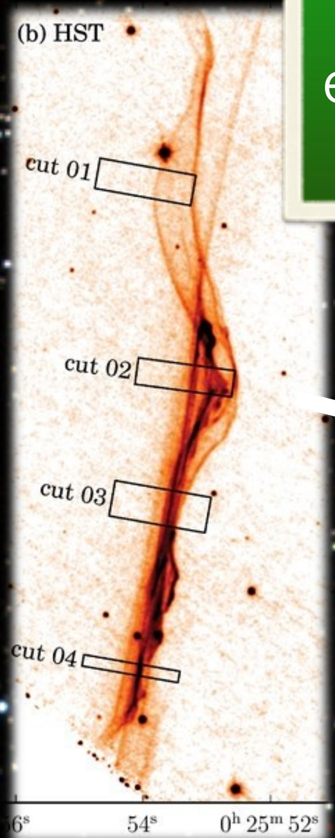

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Infrare
Ho

Gamma-ray emission
Sites of particle acceleration
Bulk origin of galactic CRs?
(See talk by David Williams & Francesco de Palma)

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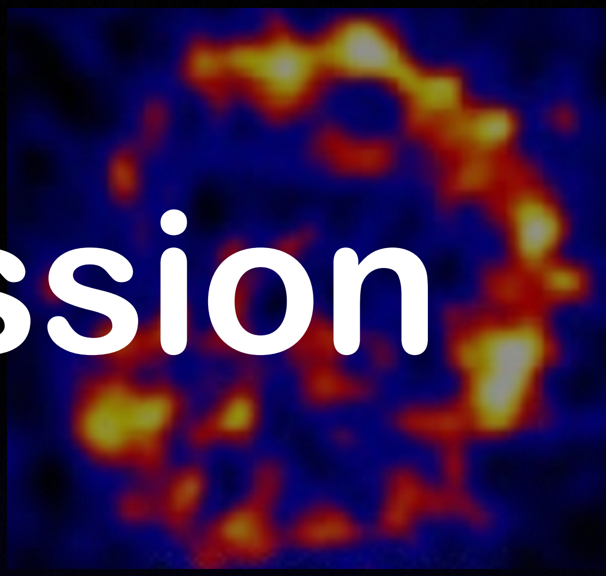
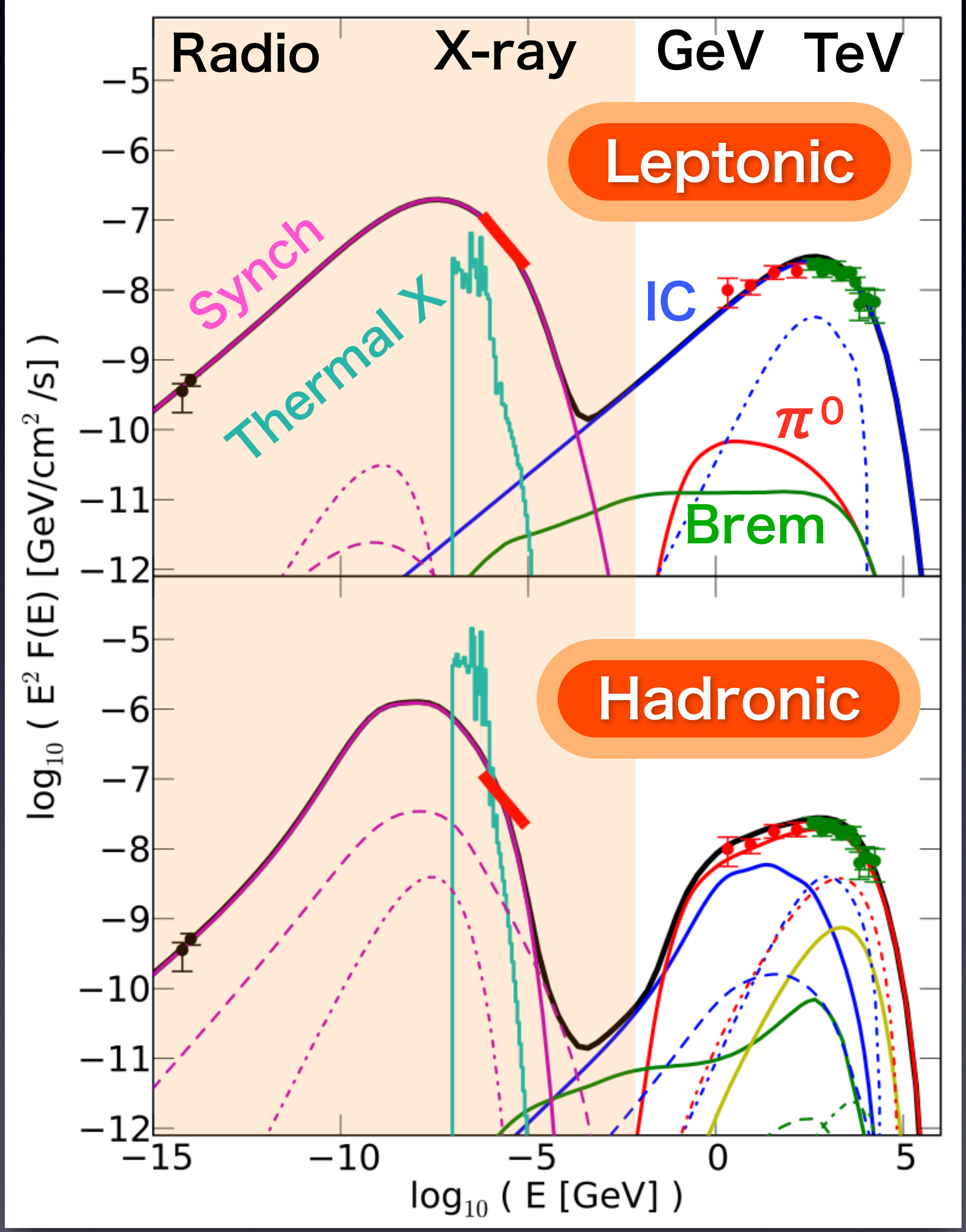
Origins of γ-ray emission

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





π^0 decay

CR **ion** + gas → π^0

Flat'ish spectrum

Requires **dense gas**

"hadronic"

Inverse-Compton scatterings

CR **electron** + seed photons → γ-ray

Hard spectrum

Requires: low B-field (avoid synch loss)

low density (suppress π^0)

Non-thermal bremsstrahlung

CR electron + gas → γ-ray

Same spectral index as CR

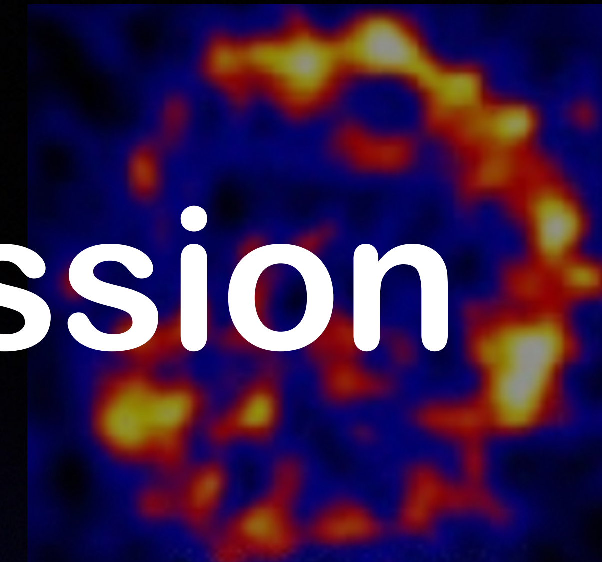
Requires: low B-field (synch loss)

dense gas (target)

high e/p (suppress π^0)

"leptonic"

Origins of γ-ray emission



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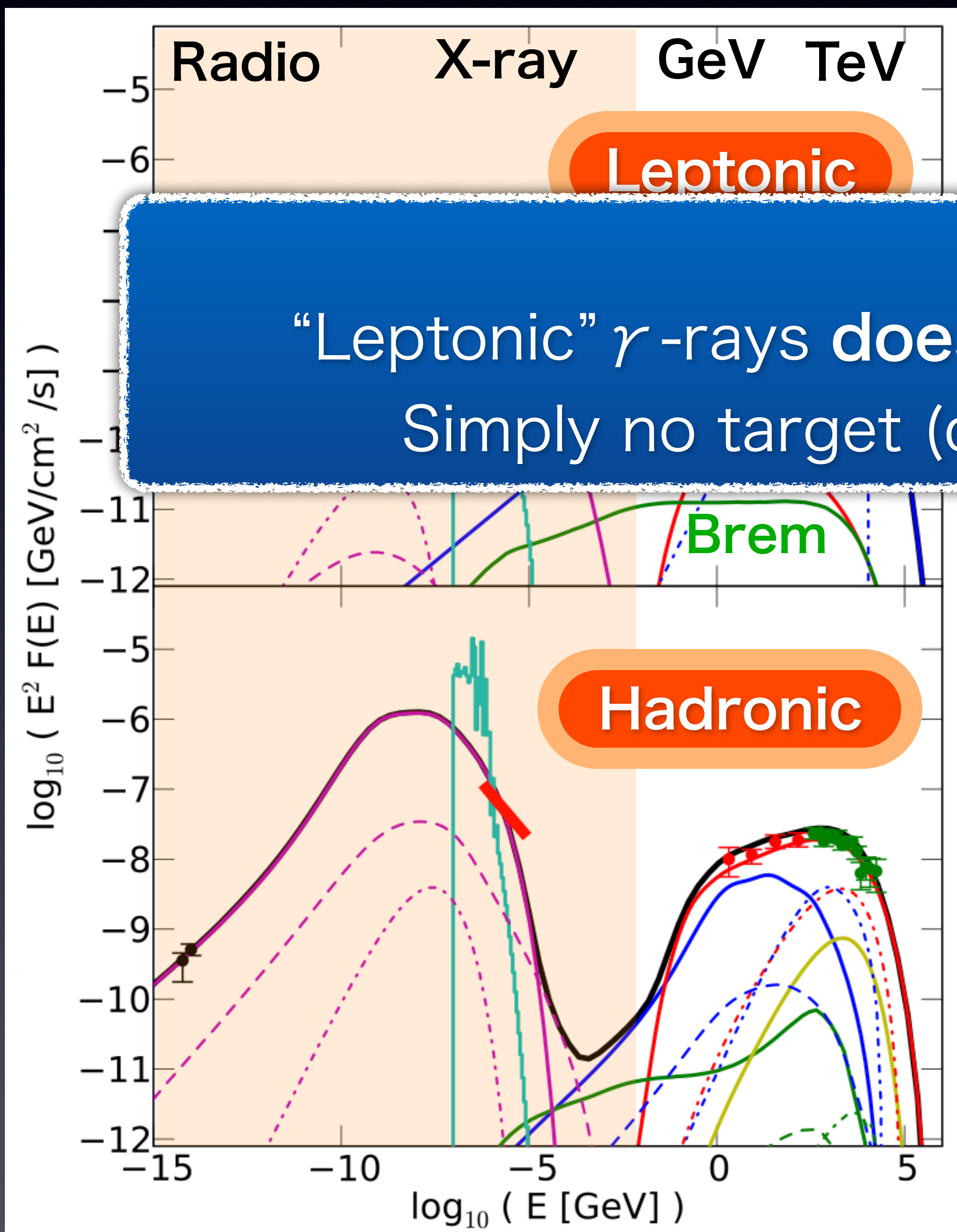

π^0 decay

CR **ion** + gas → π^0

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Caution

"Leptonic" γ-rays **does NOT** mean no ion acceleration!

Simply no target (dense gas) for π^0 production

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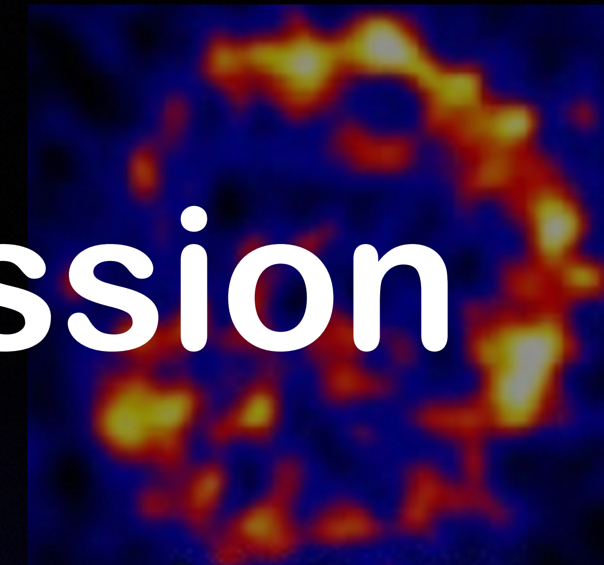

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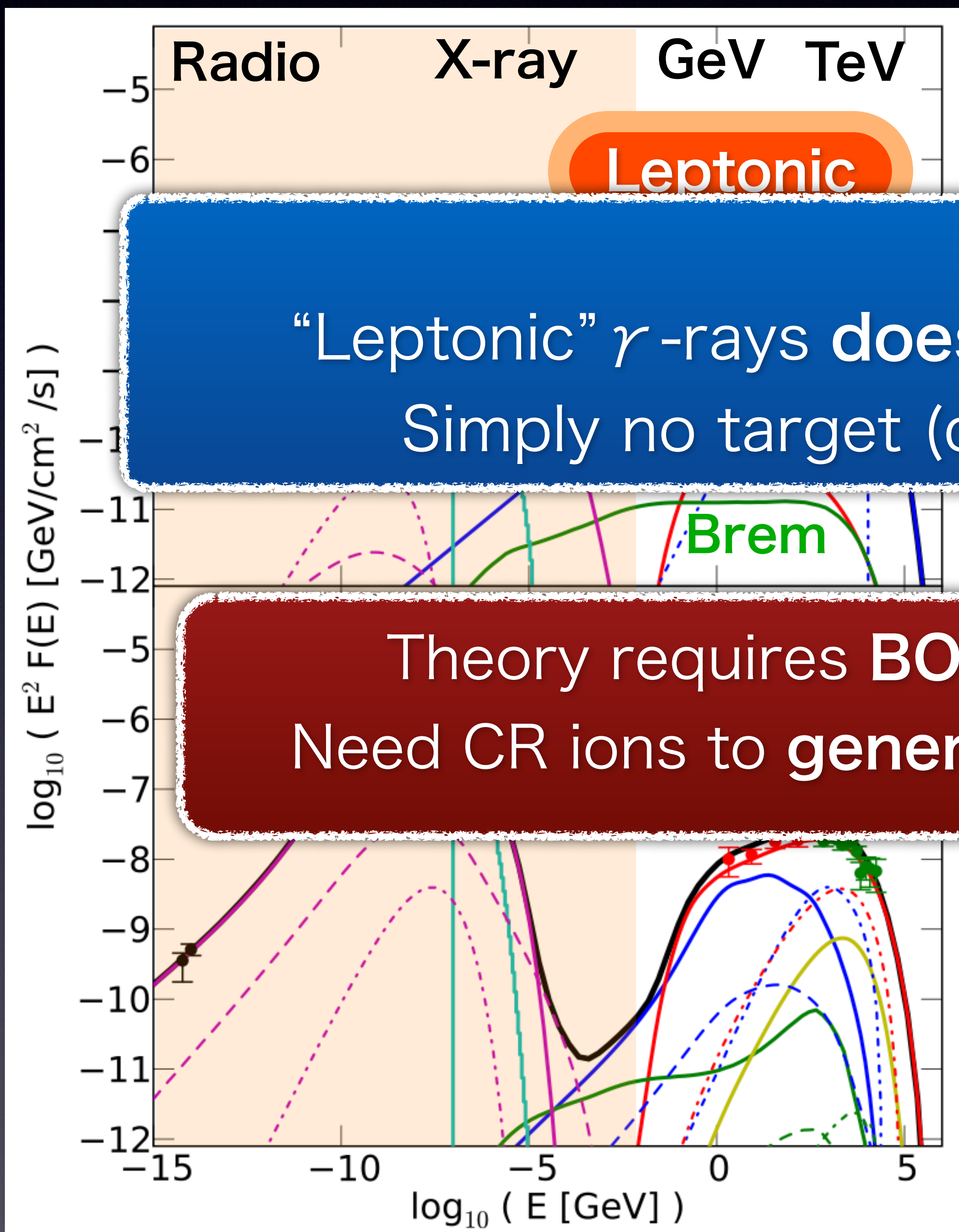


π^0 decay

CR **ion** + gas → π^0

"hadronic"

Caution

"Leptonic" γ-rays **does NOT** mean no ion acceleration!

Simply no target (dense gas) for π^0 production

CR **electron** + seed photons → γ-ray

Hard spectrum

Theory requires **BOTH** ion & electron acceleration

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

Non-thermal bremsstrahlung

CR electron + gas → γ-ray

Same spectral index as CR

Requires: low B-field (synch loss)

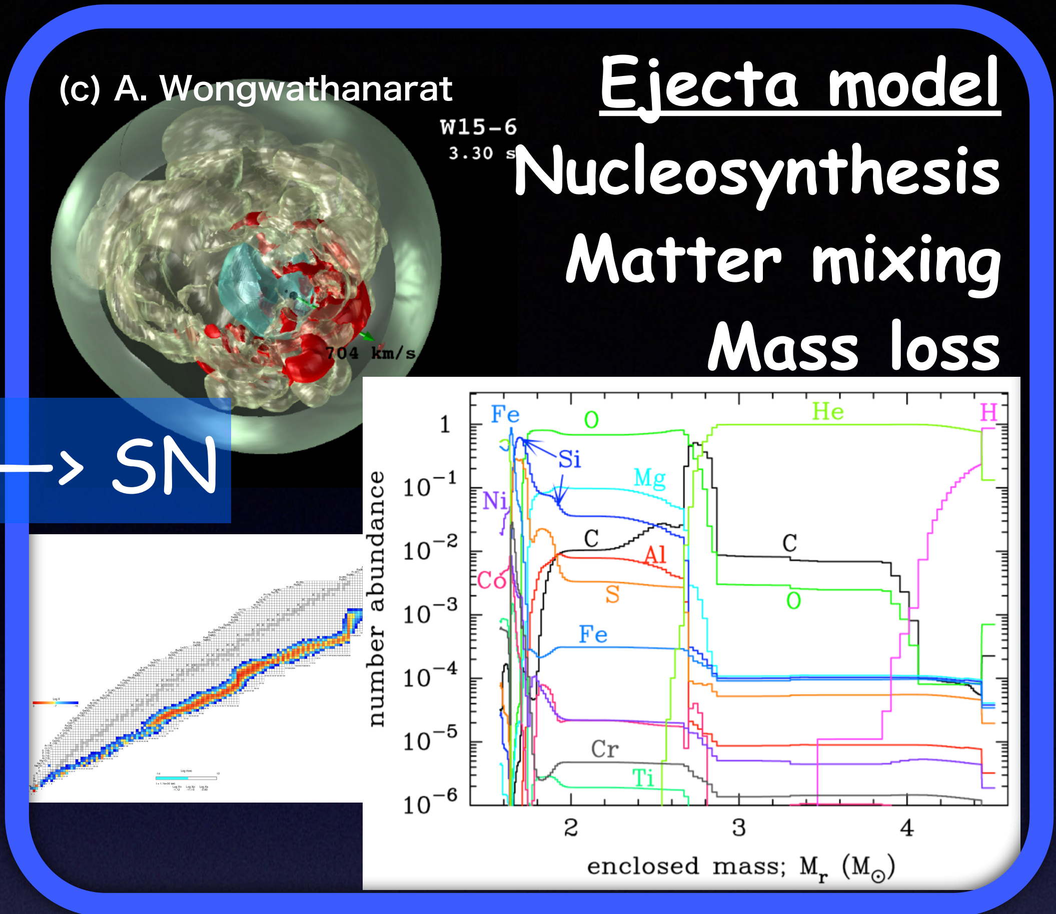
dense gas (target)

high e/p (suppress π^0)

"leptonic"

Work Flow
of a SNR model

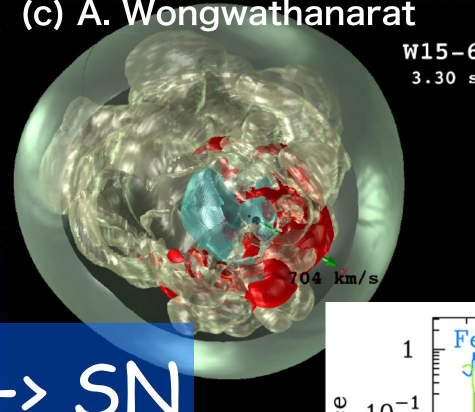
Work Flow of a SNR model



Progenitor —> SN

Work Flow of a SNR model

(c) A. Wongwathanarat



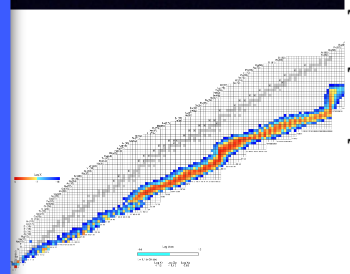
Ejecta model

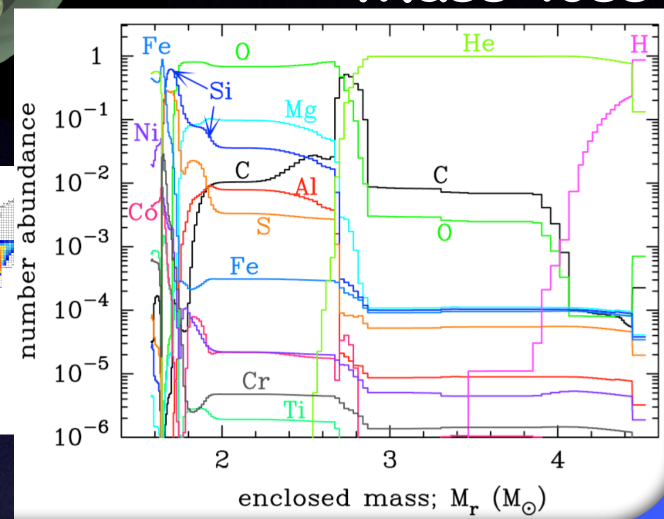
Nucleosynthesis

Matter mixing

Mass loss

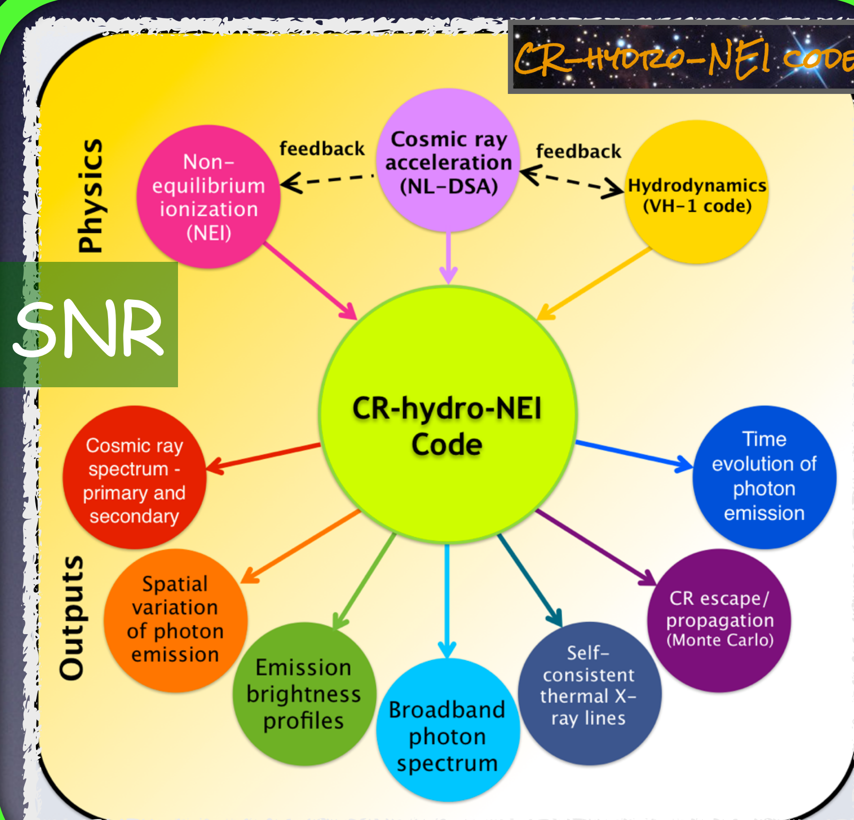
Progenitor —> SN





CR-hydro-NEI simulation

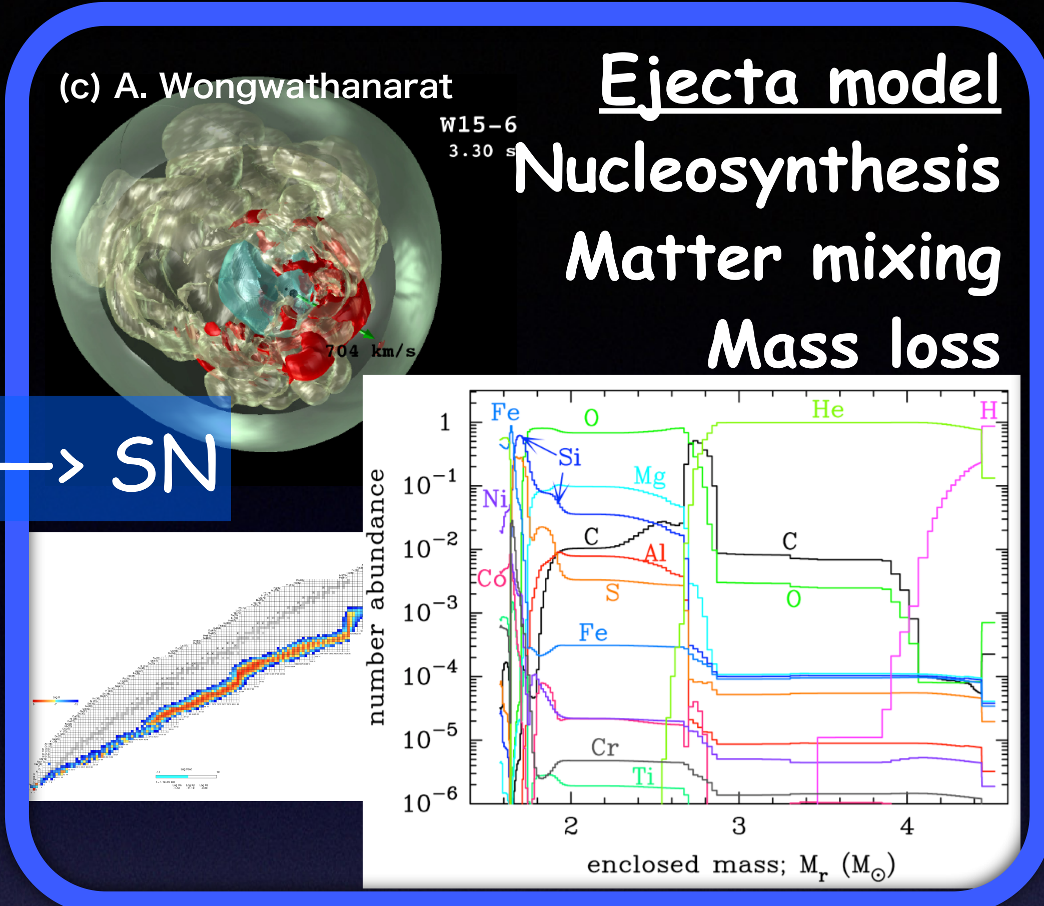
SN —> SNR



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

Work Flow of a SNR model

Progenitor —> SN



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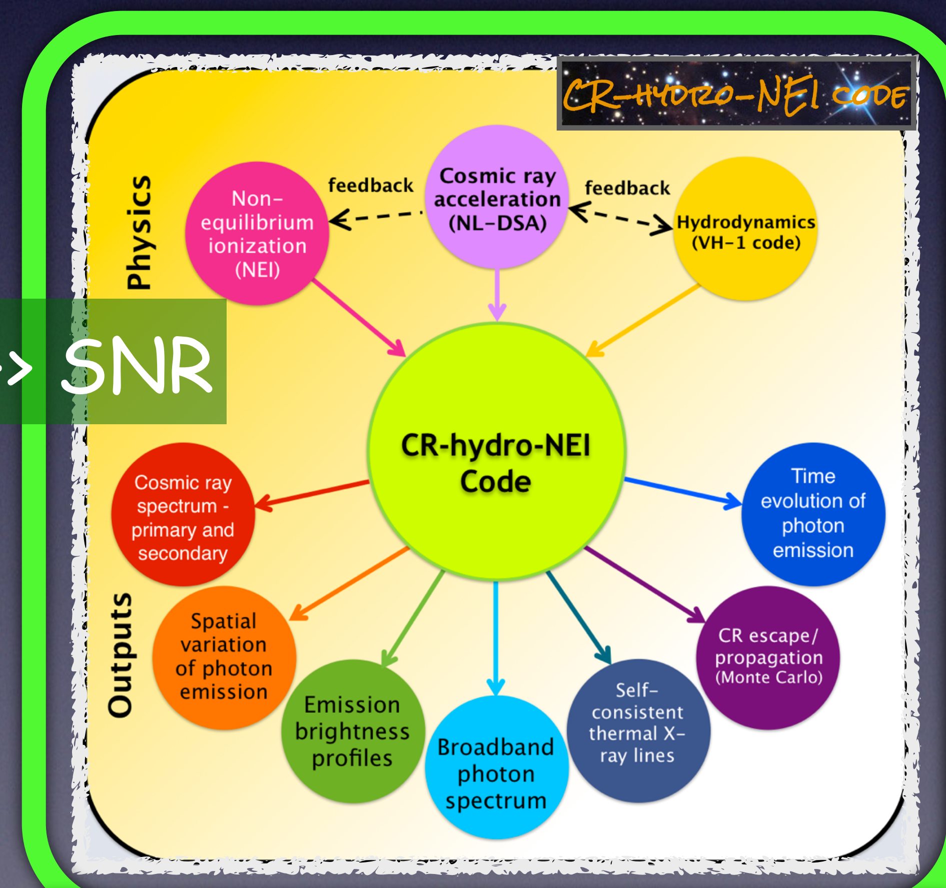

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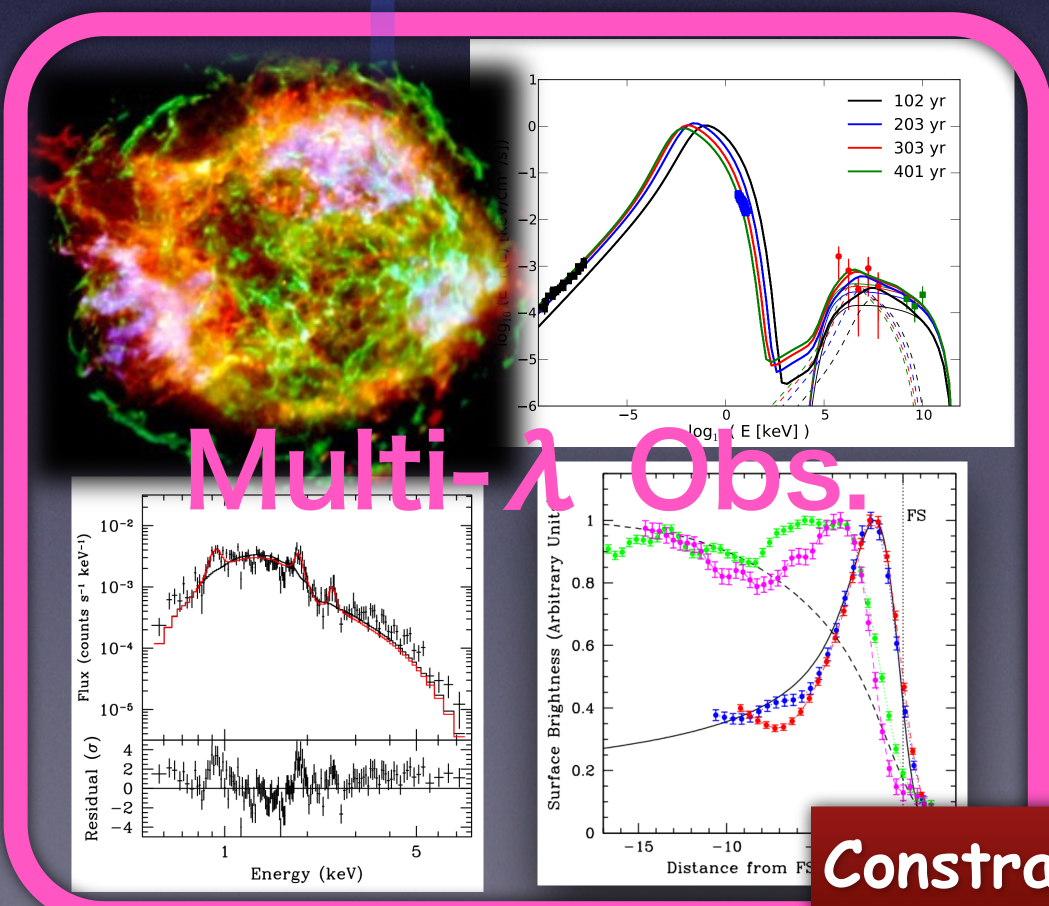
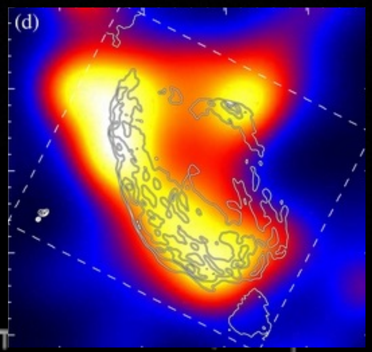
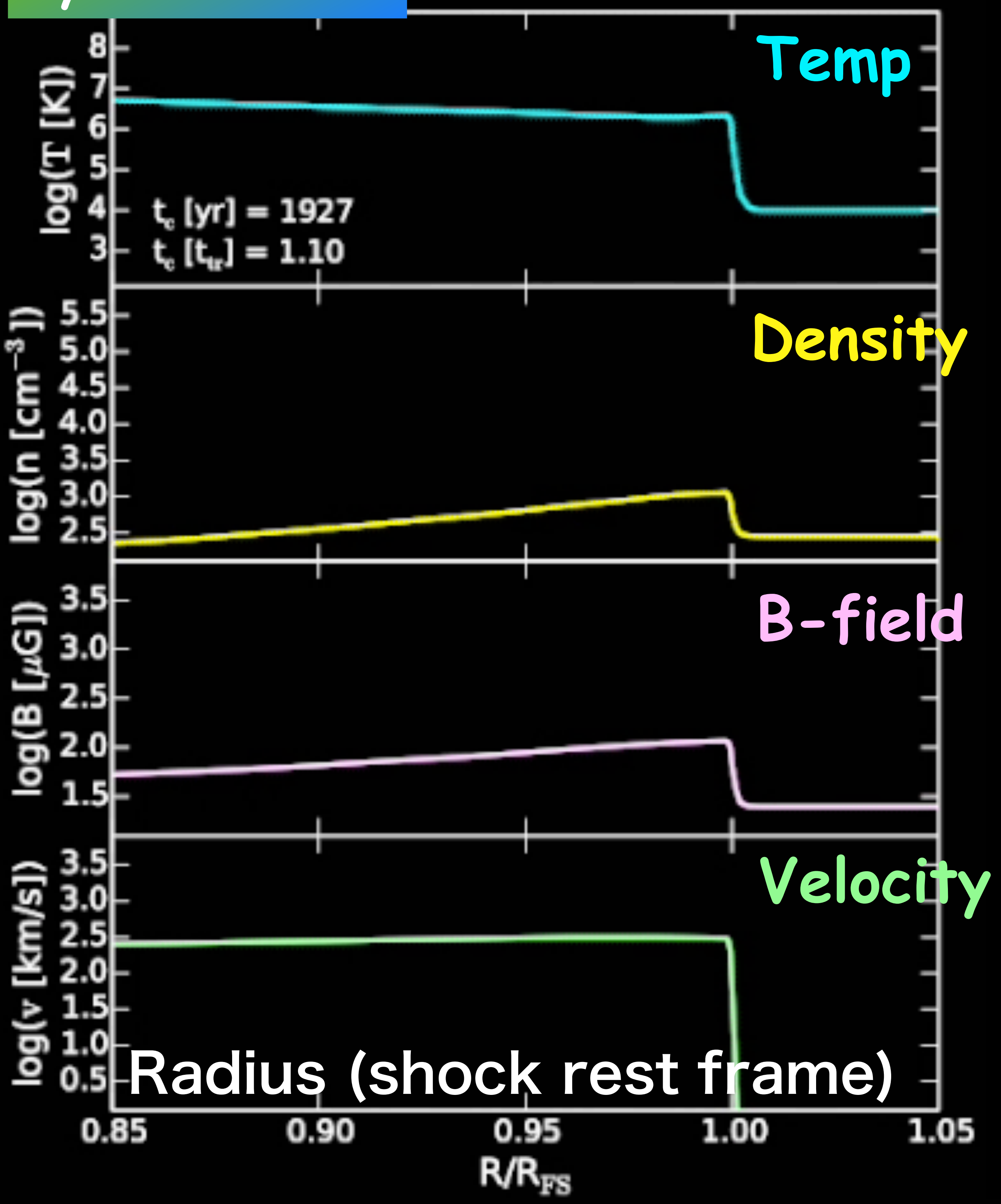


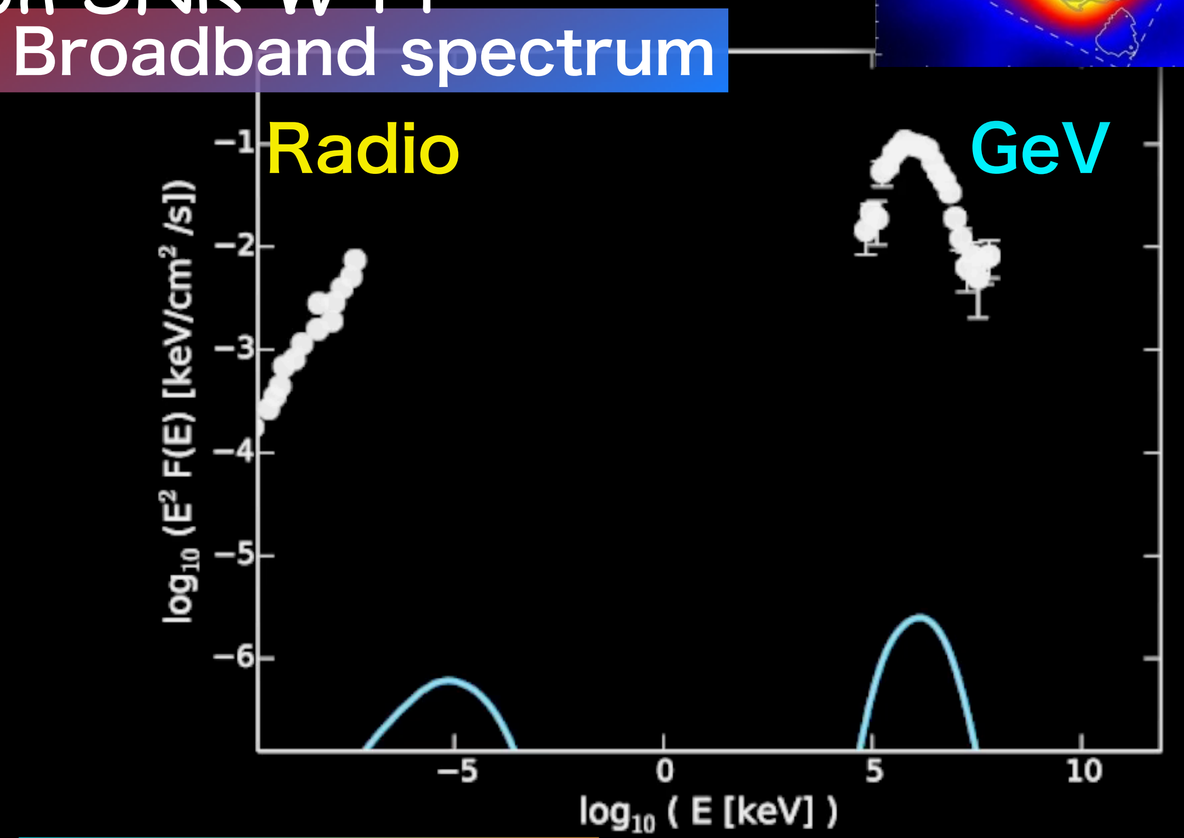
Constraints!

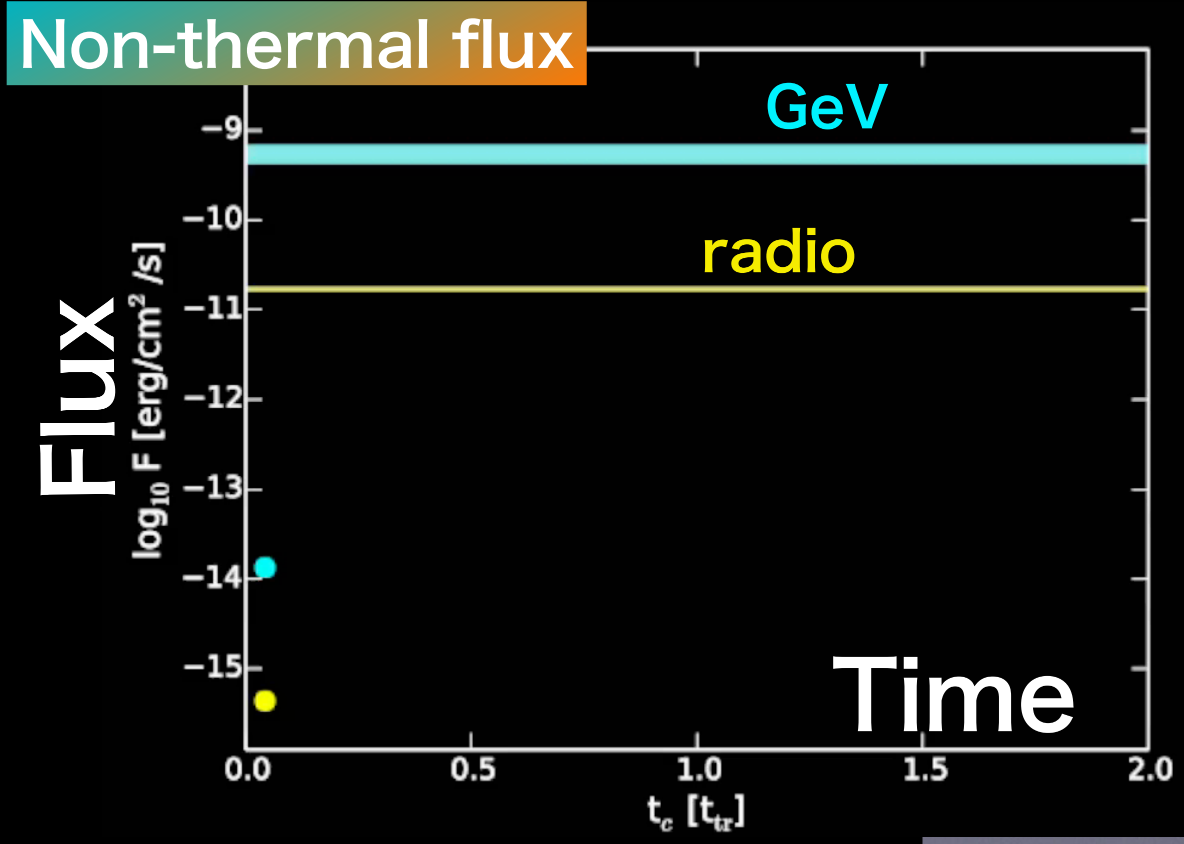
Hydro & Spectral Evolution

HL, Patnaude+ (2015) on SNR W44

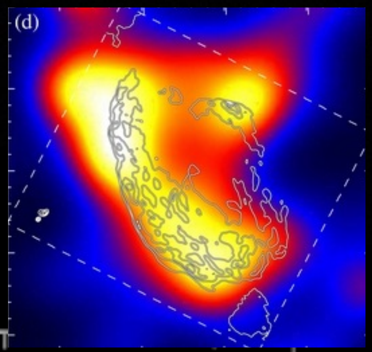








Hydro & Spectral Evolution



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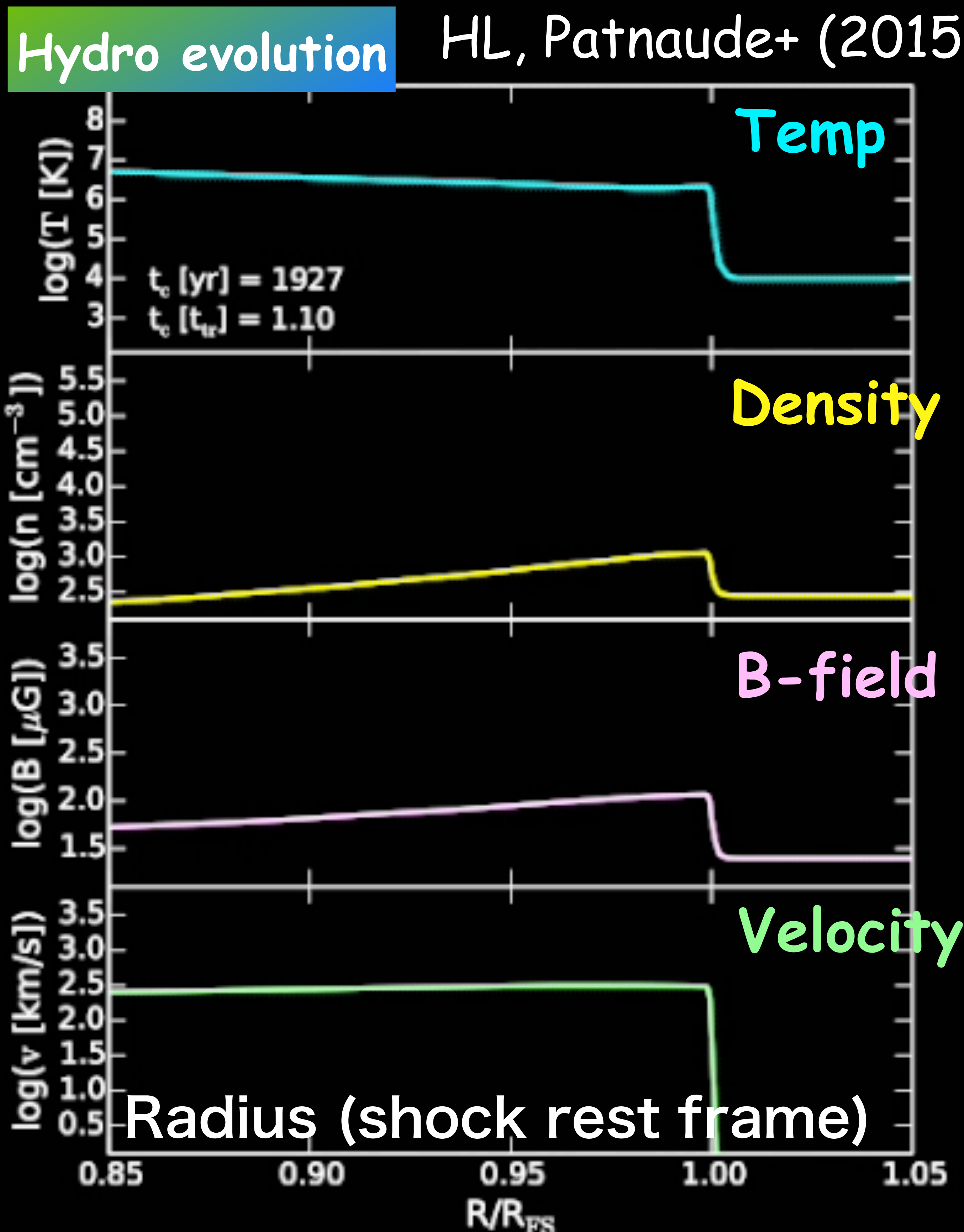

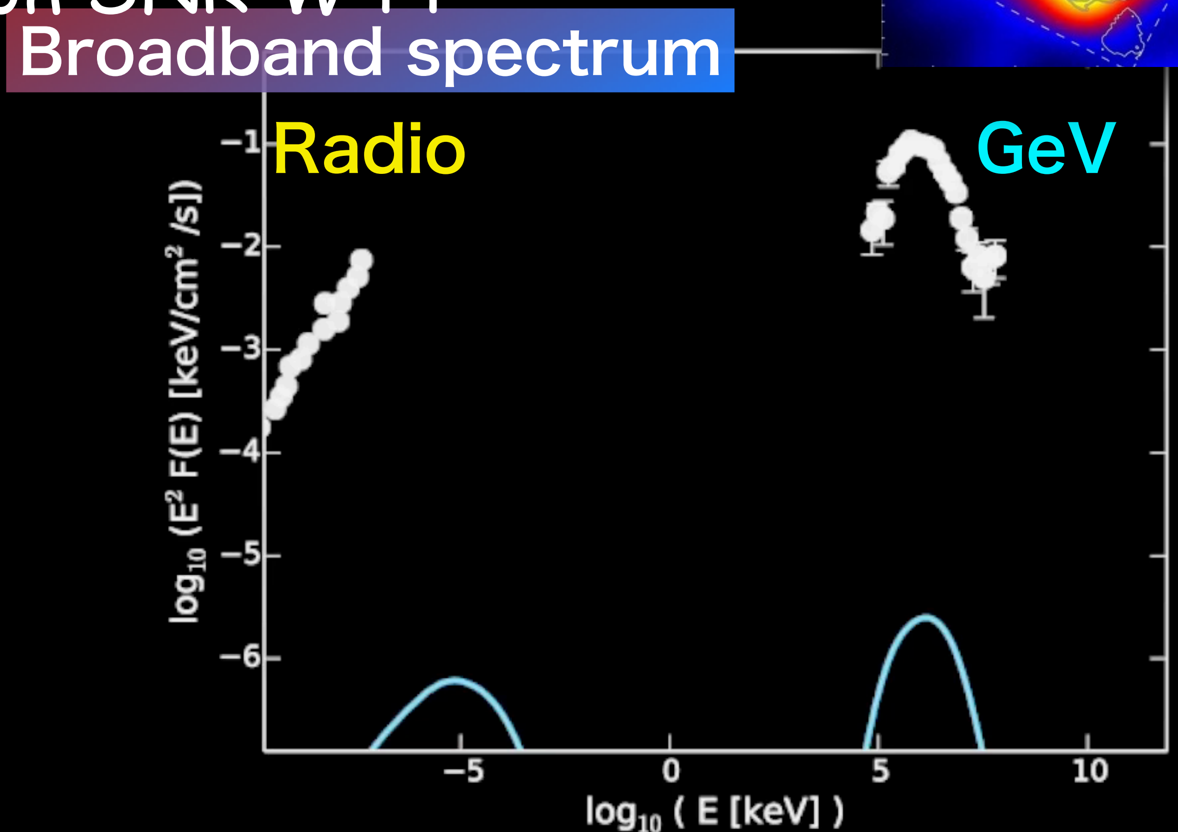

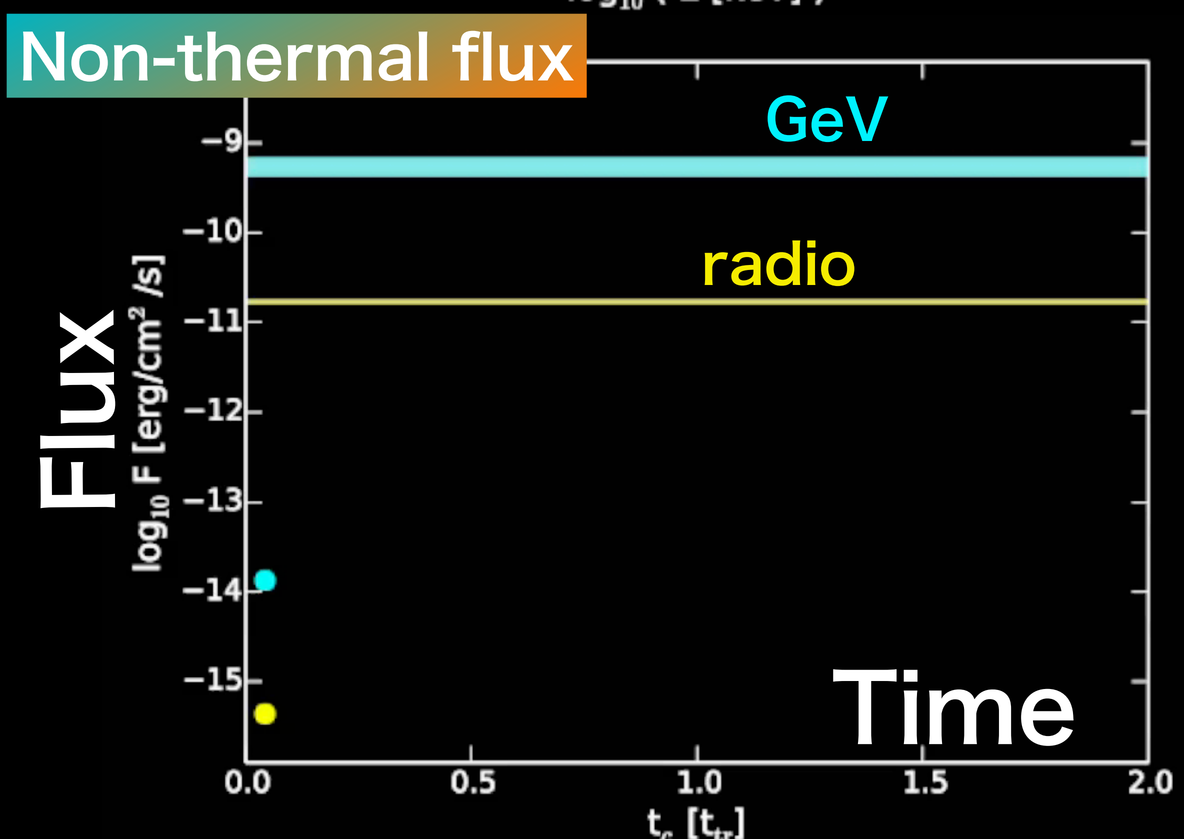

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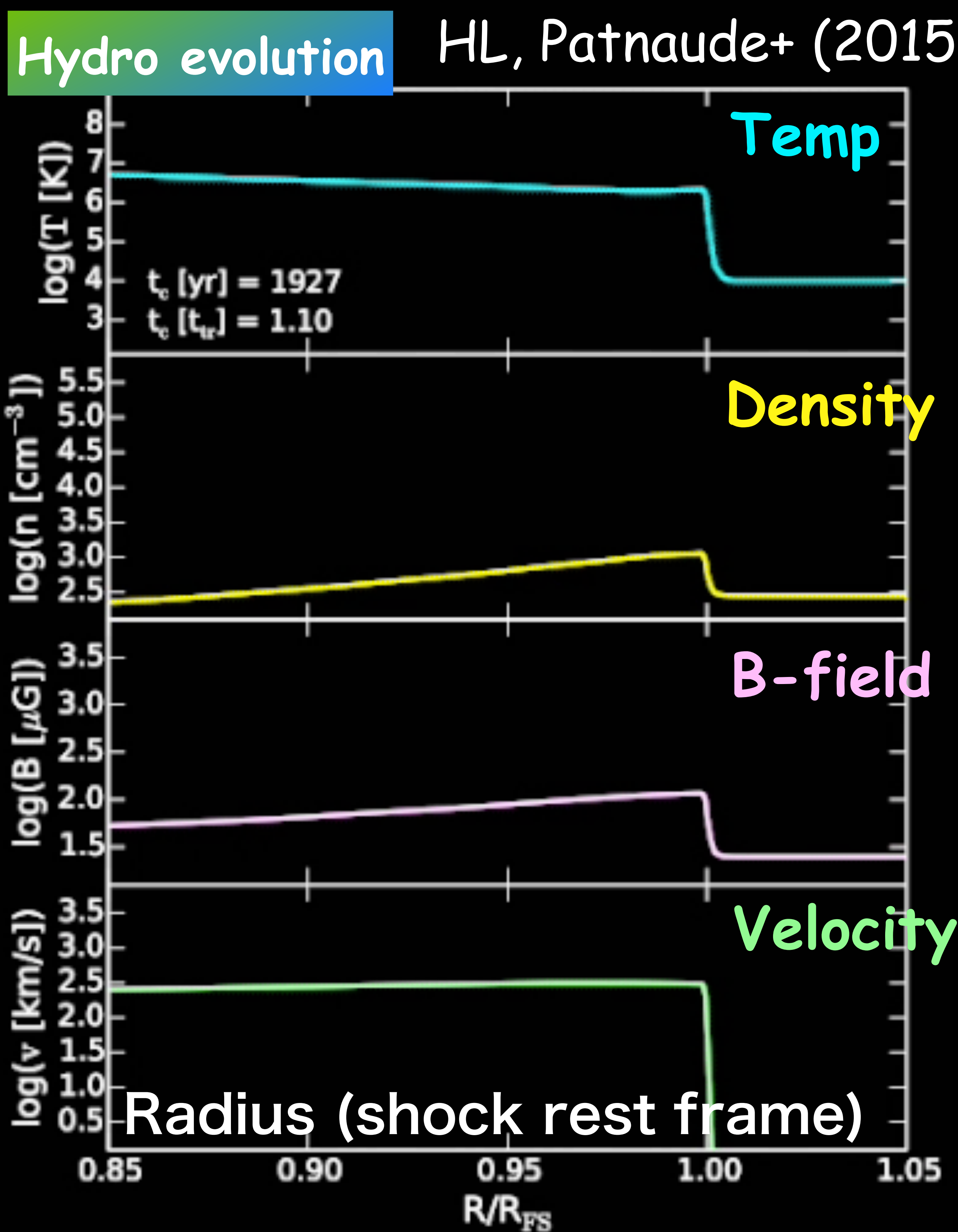
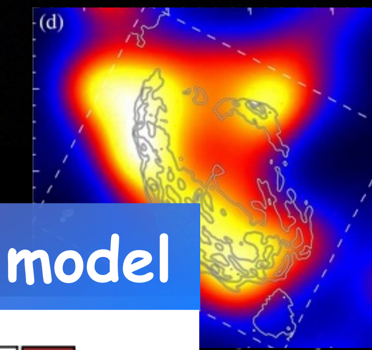
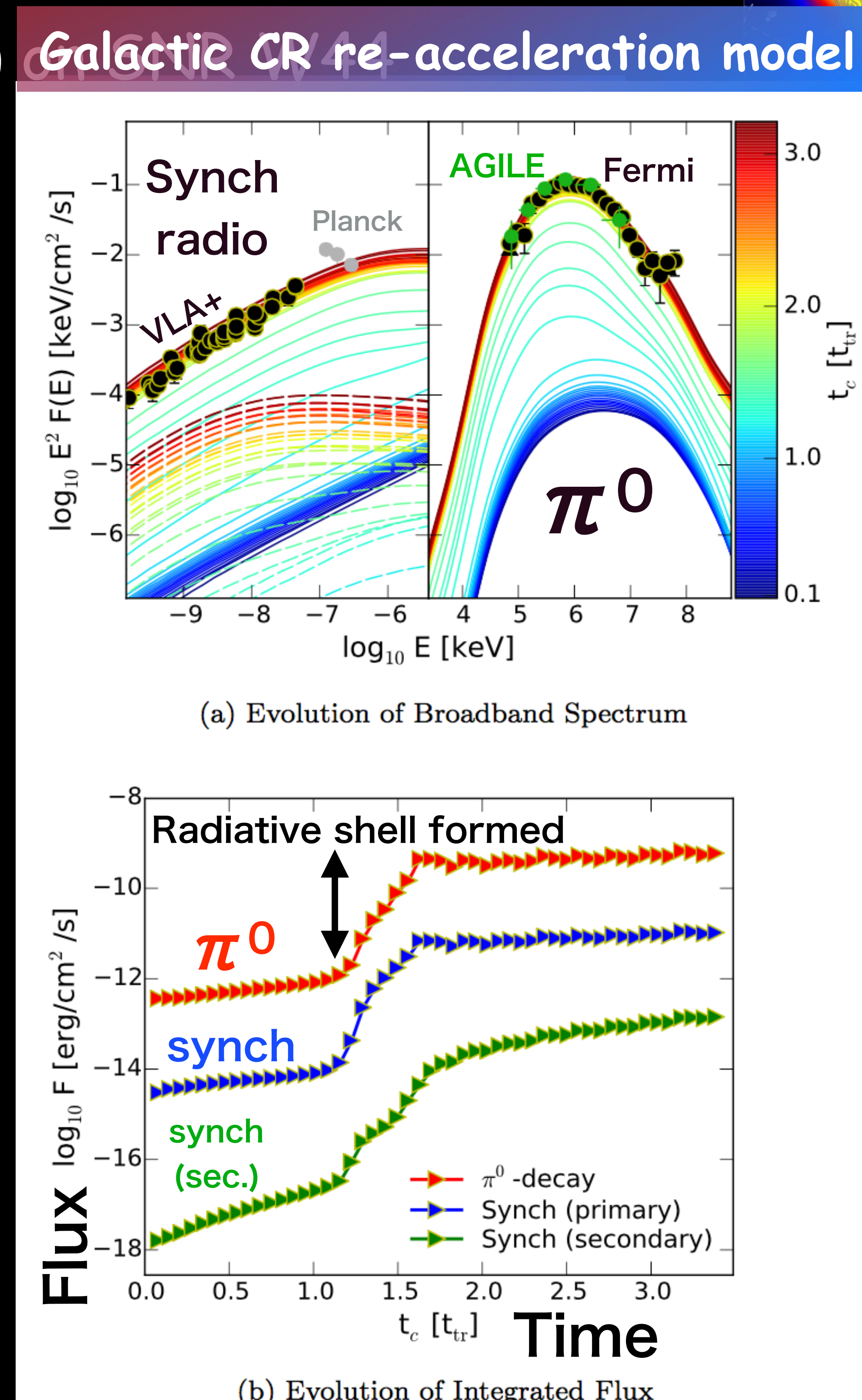




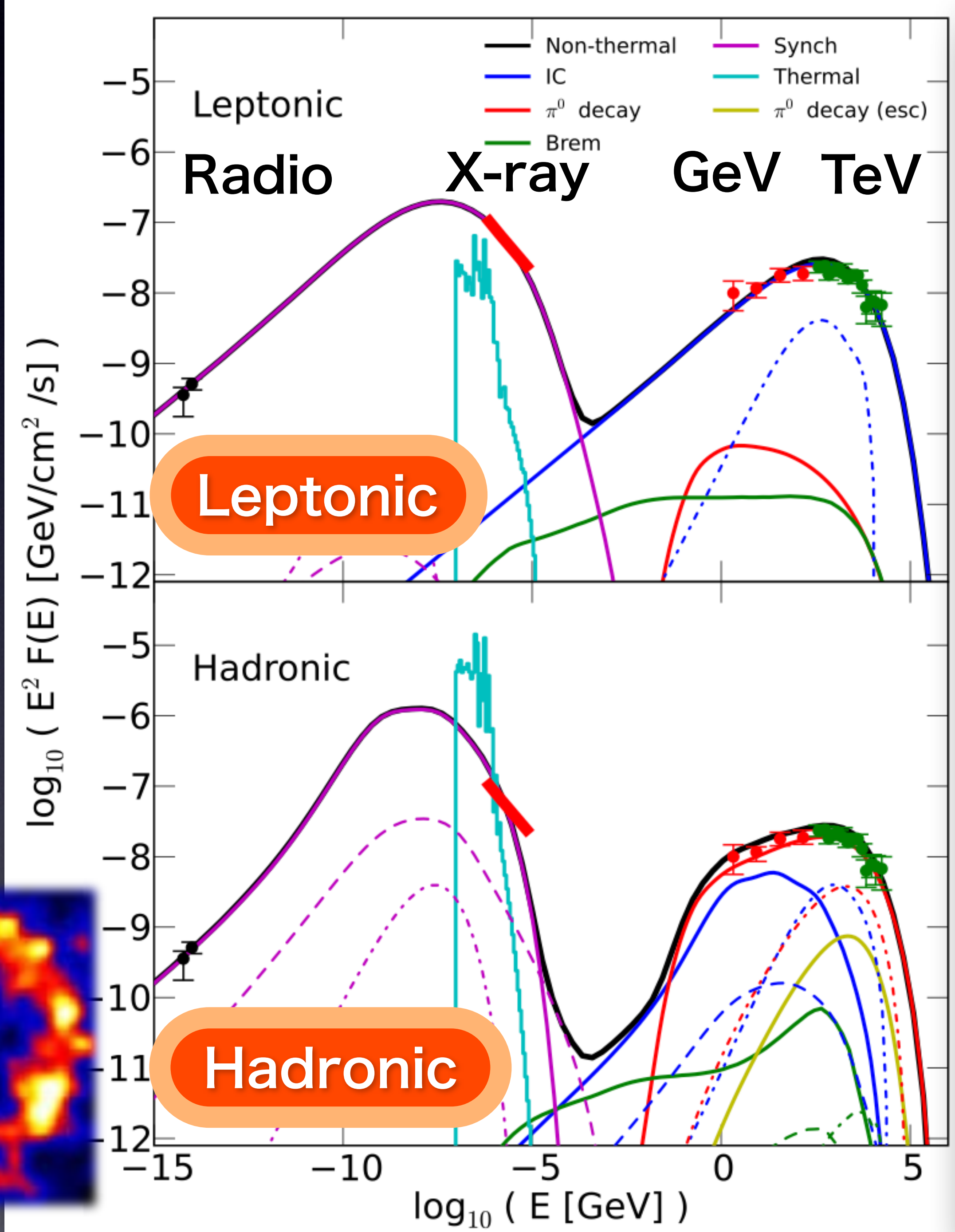


(a) Evolution of Broadband Spectrum

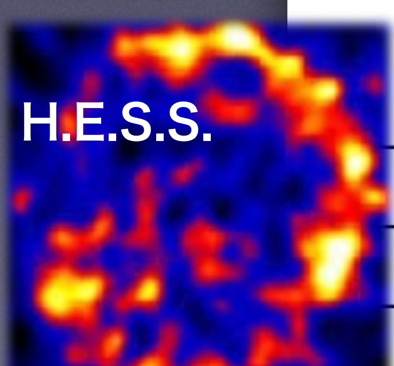
(b) Evolution of Integrated Flux

The all-important broadband spectrum

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†
B_0 (μG)	0.5	0.14†
dM/dt (10^{-6} $M_\odot$ yr^{-1})	...	7.5
V_{wind} (km s^{-1})	...	50
σ_{wind}	...	0.02
K_{ep}	1.5×10^{-4}	0.015
α_{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 (μG)	34.1	4.8
T_2 (10^8 K)	0.16	3.62
ϵ_{acc}	0.84	0.36
ϵ_{esc}	0.34	0.12
E_{CR}/E_{SN} (f_{SN})	0.48	0.14

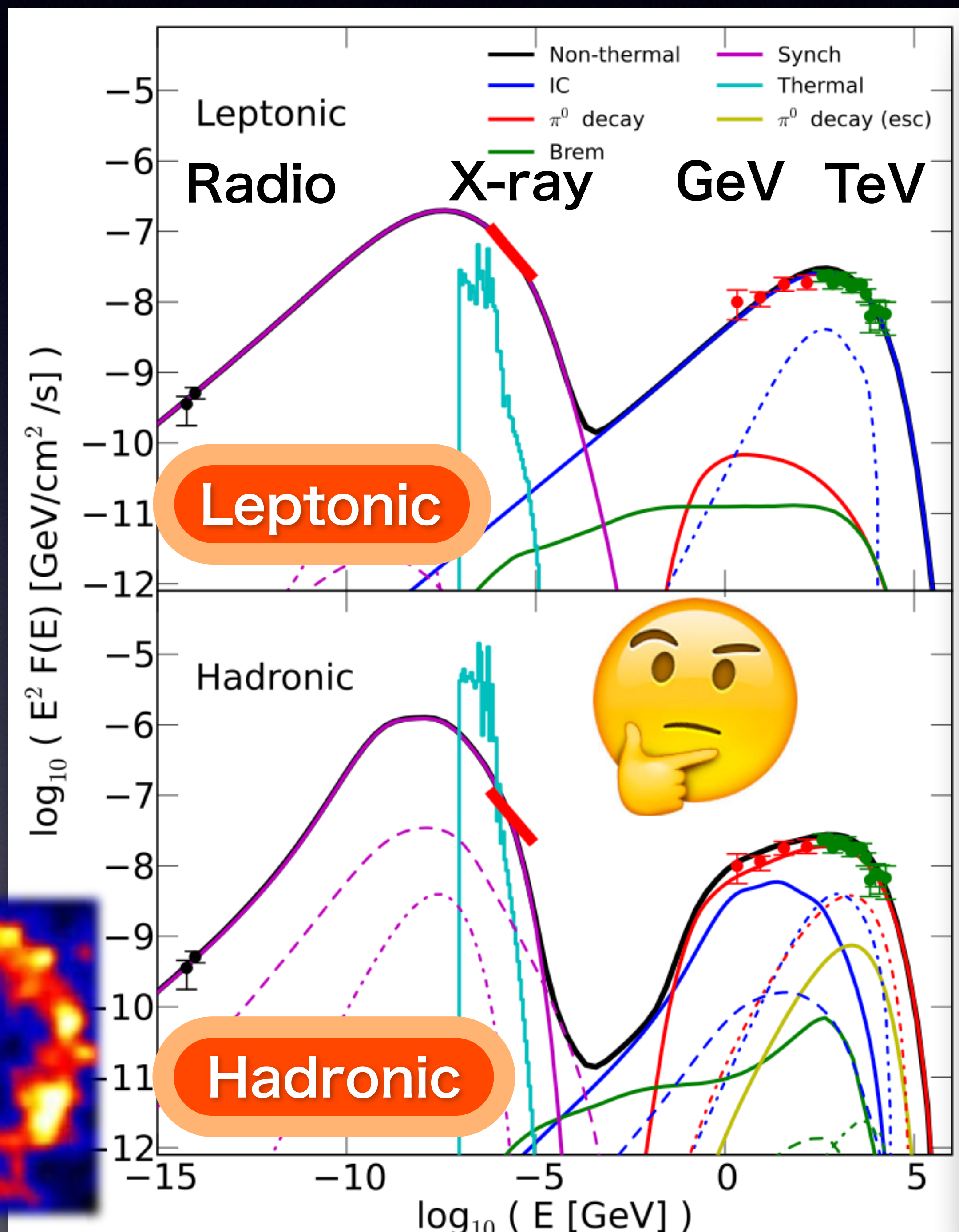


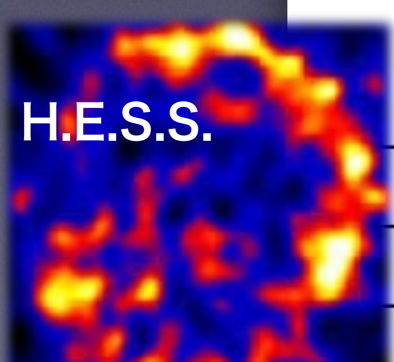
Hadronic vs leptonic has profound implication: big difference in $E_{CR}(t)$

The all-important broadband spectrum

In <u>some</u> cases, things ain't so conclusive…

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





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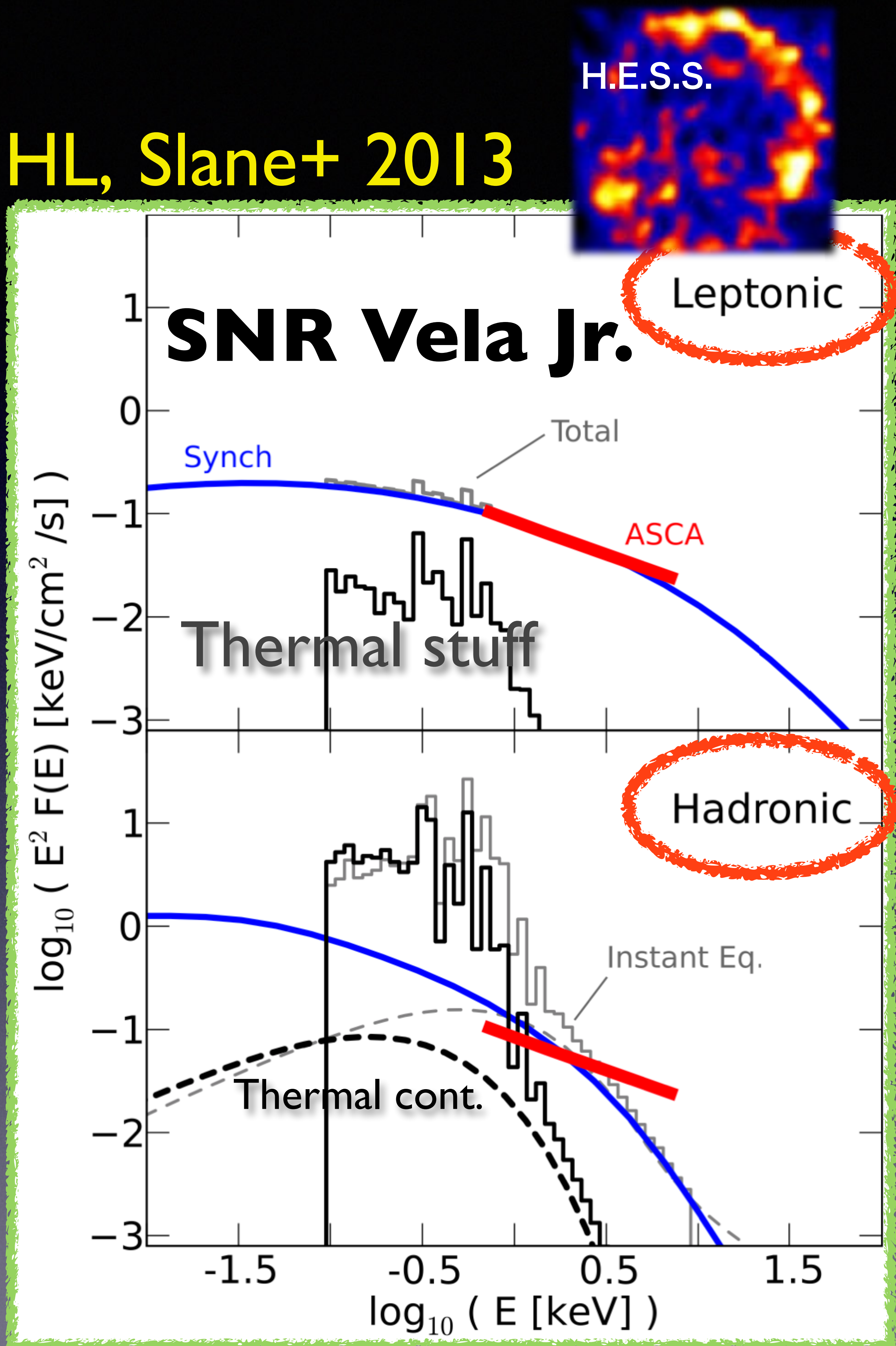
Hadronic vs leptonic has profound implication: big difference in $E_{CR}(t)$

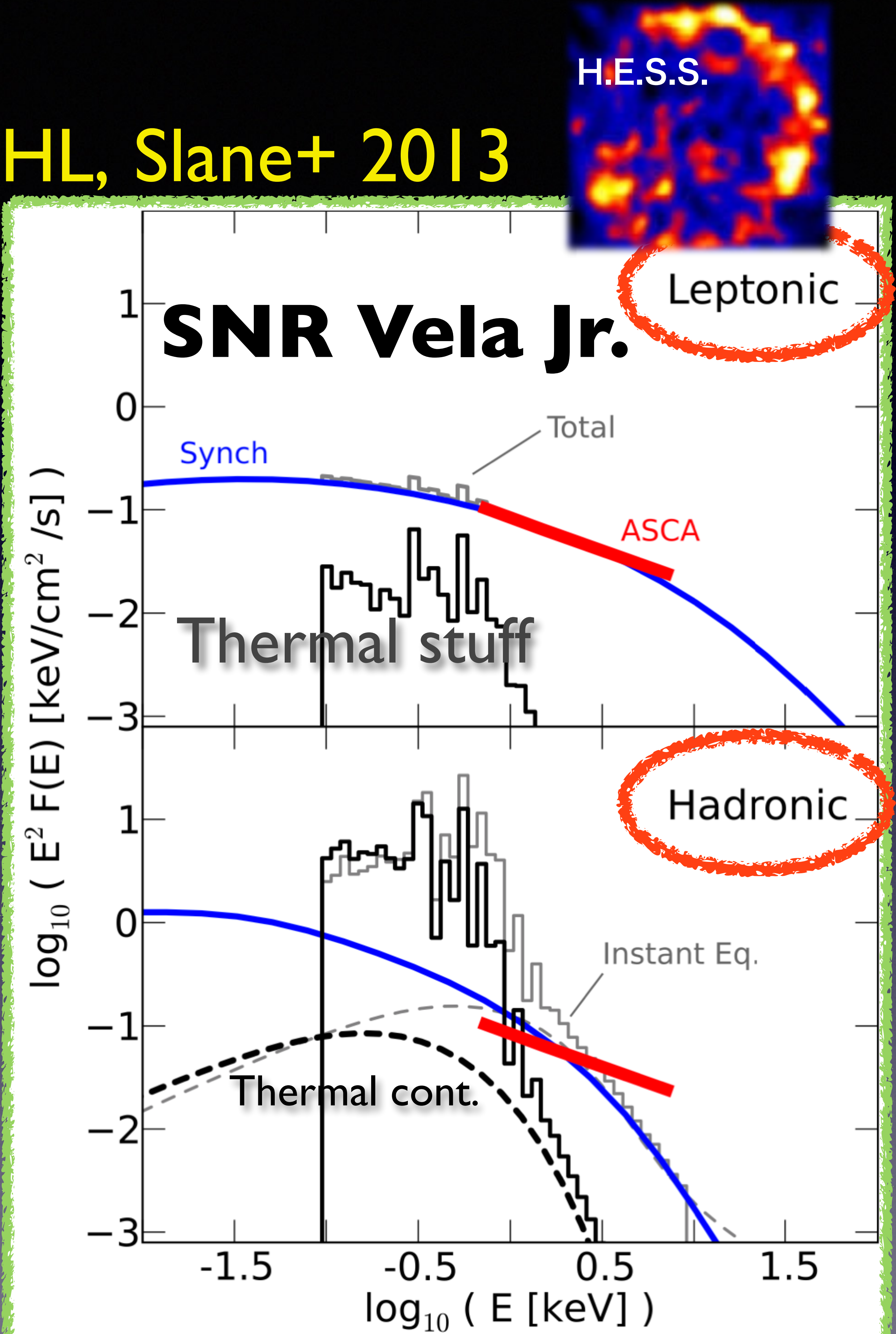
HL, Slane+ 2013



Thermal X-ray can constrain Gamma-ray origin

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

HL, Slane+ 2013



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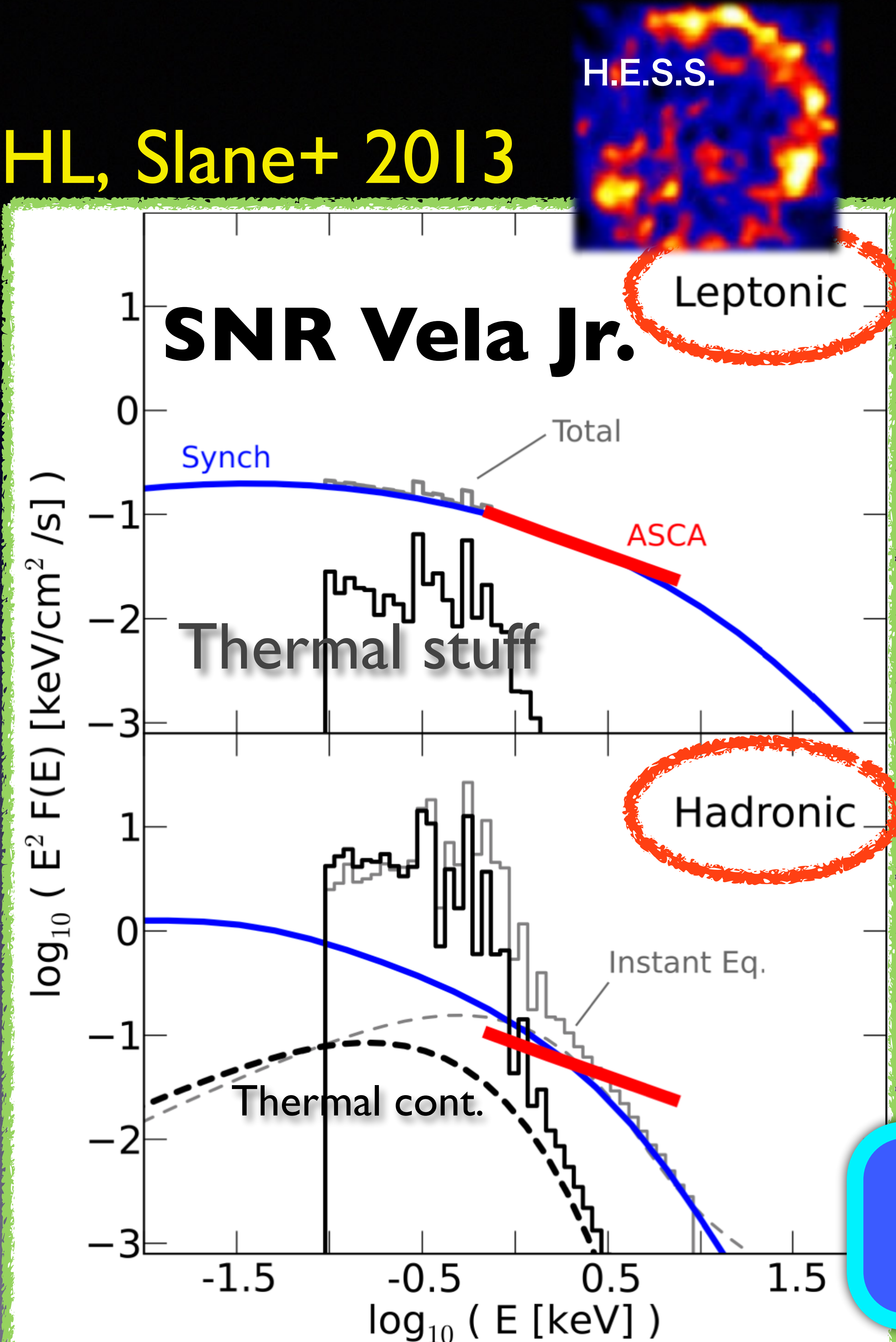
Predicted thermal flux must NOT exceed observed X-ray flux

HL, Slane+ 2013



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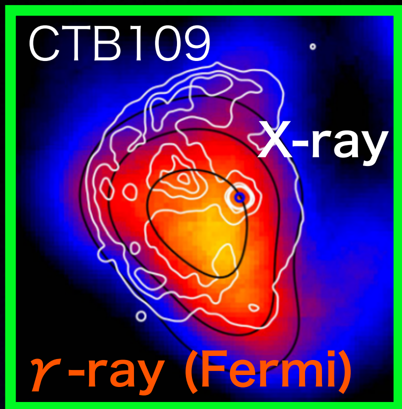
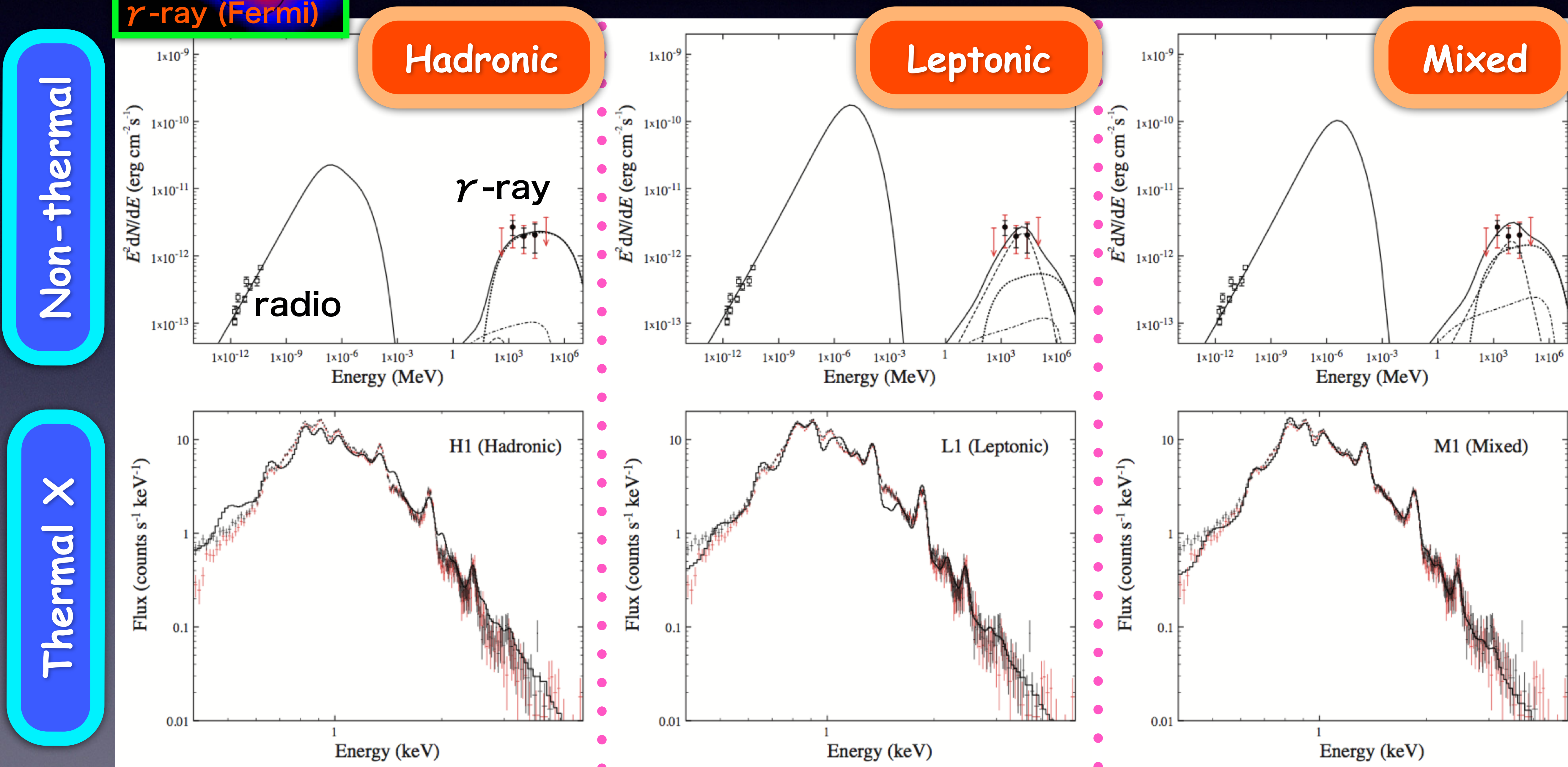
A mostly leptonic SNR?
$E_{CR} = 0.15\ E_{SN}$

Powerful constraint of non-thermal origin

Thermal X-ray Spectrum



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



Powerful constraint of non-thermal origin

Thermal X-ray Spectrum

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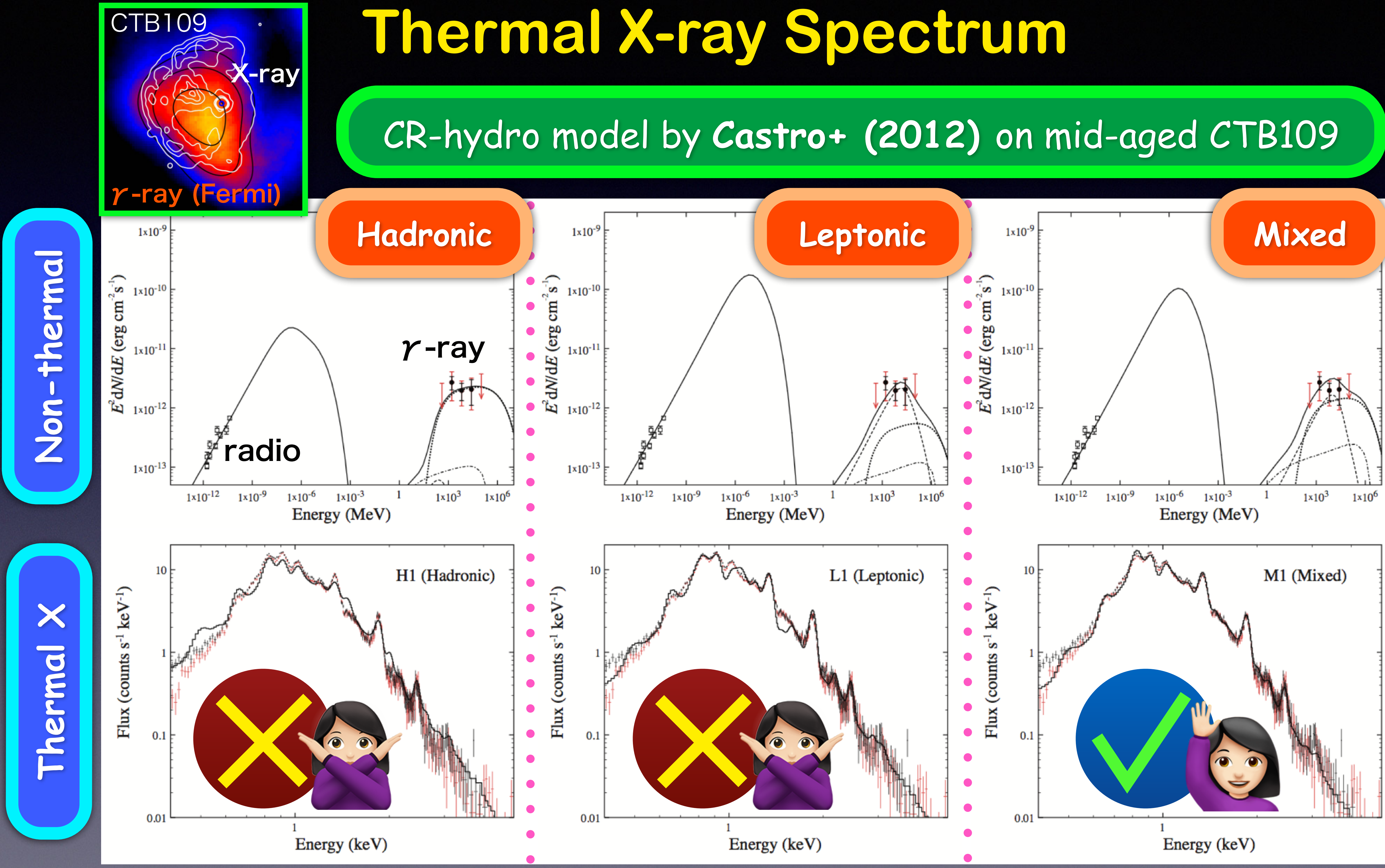
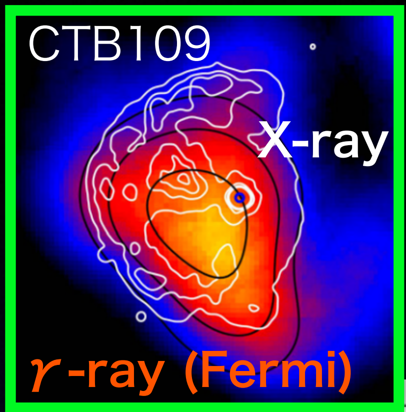


Powerful constraint of non-thermal origin

Thermal X-ray Spectrum



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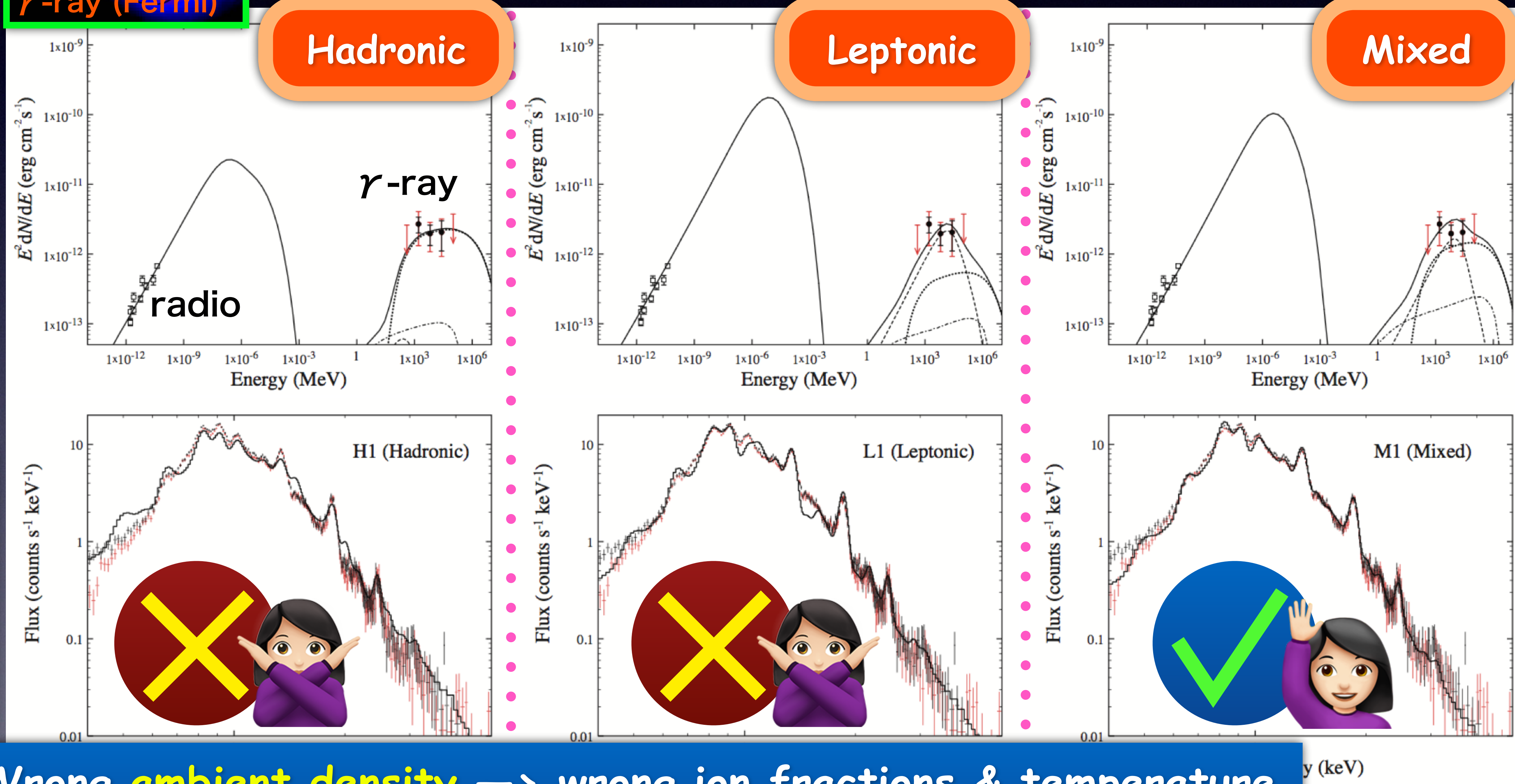
Non-thermal

Thermal X

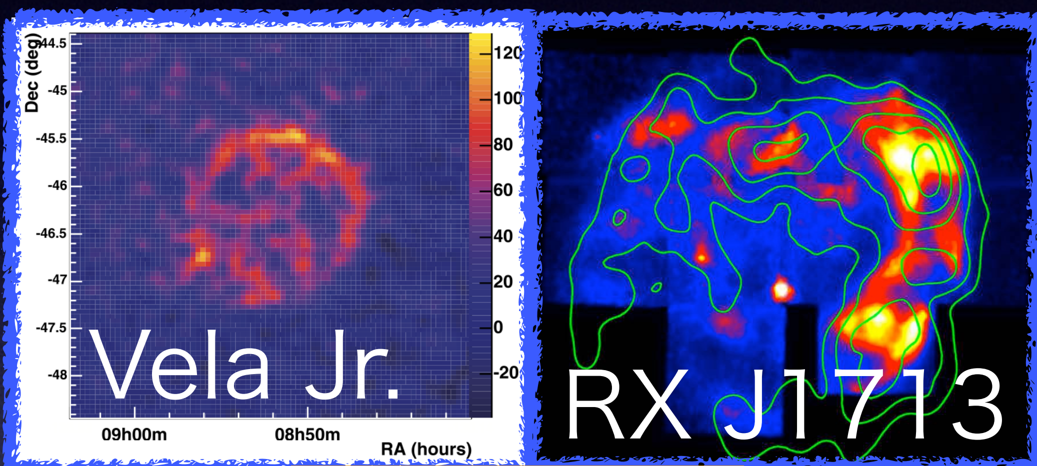


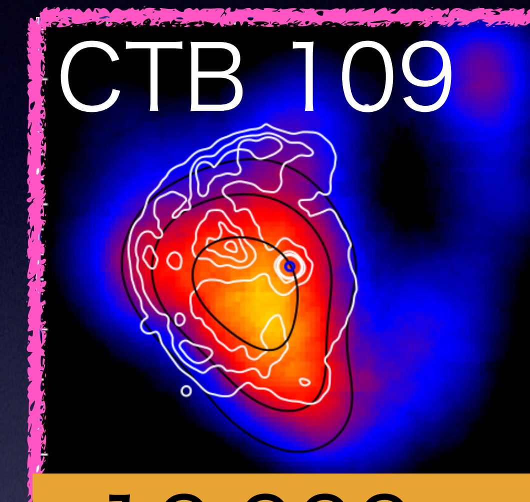
Wrong ambient density —> wrong ion fractions & temperature
—> wrong thermal X-ray spectrum

Decipher MW emission by CR-hydro-NEI simulations

Diversity of SNR γ-ray Origin

e.g., HL+ 2008 to 2015; Slane, HL+ 2014; Castro+ 2012

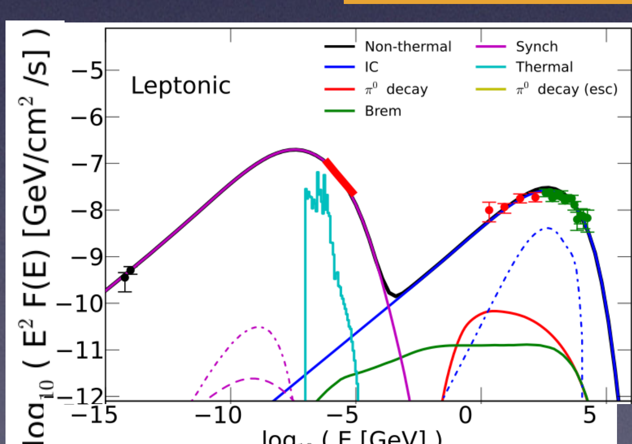


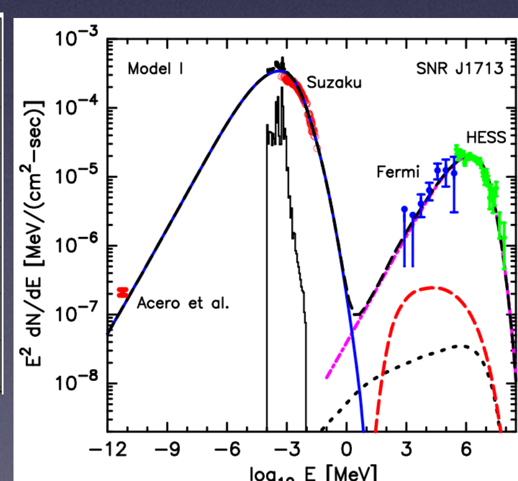


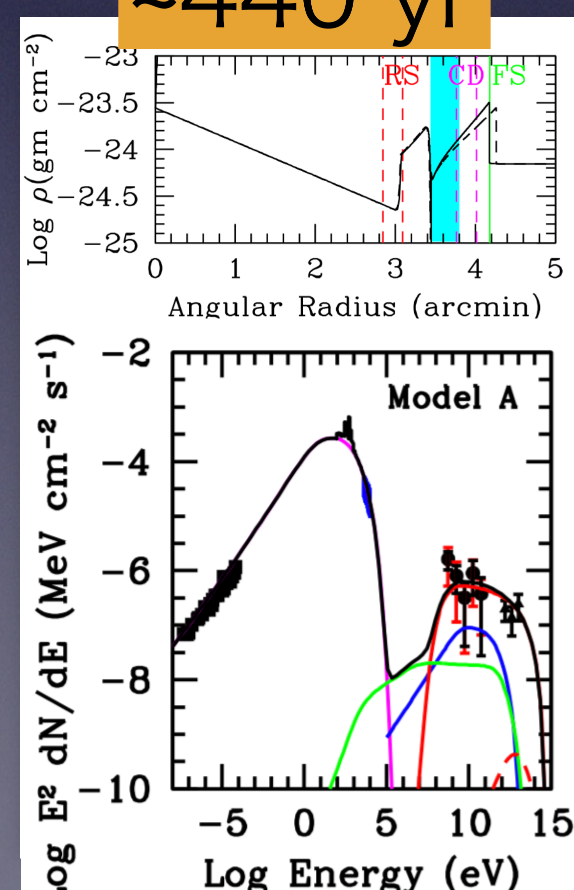
~2,000 yr

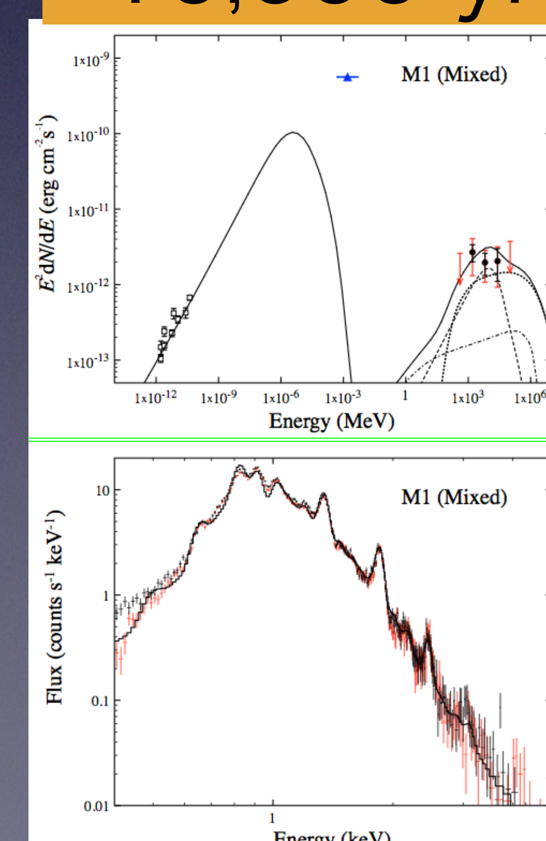
~440 yr

~10,000 yr









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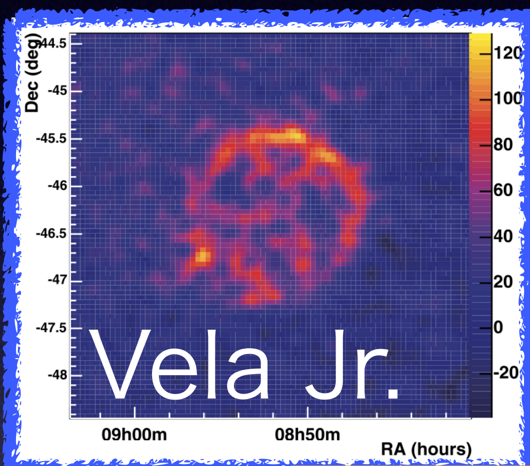

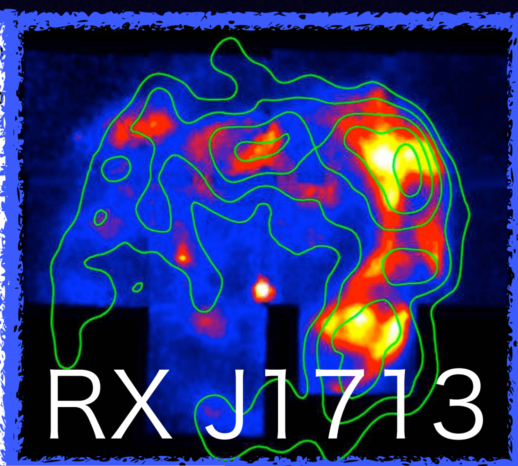

~2,000 yr

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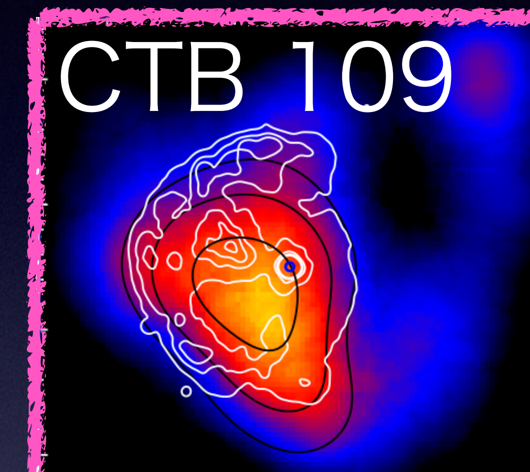
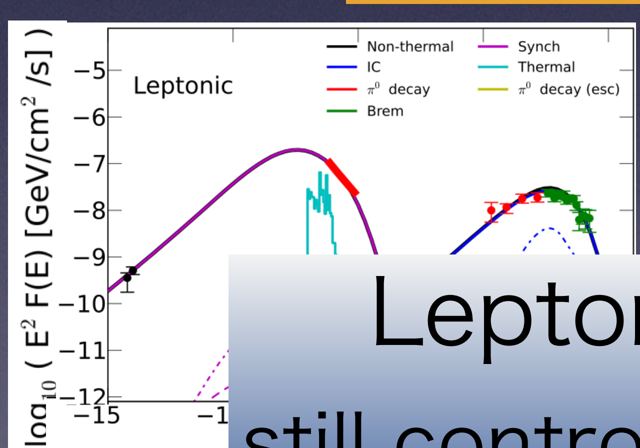
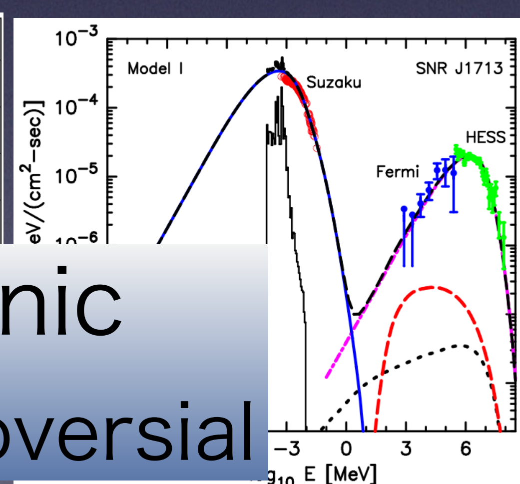


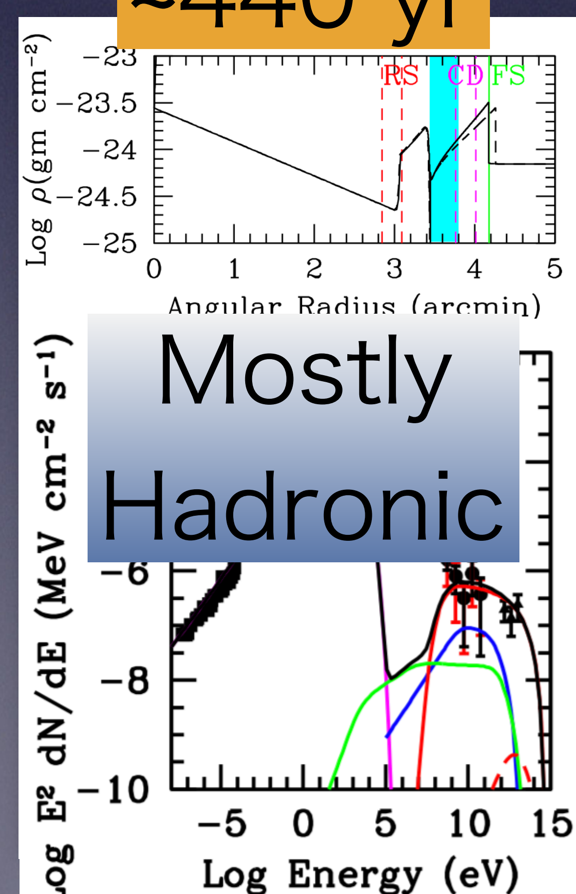
~10,000 yr





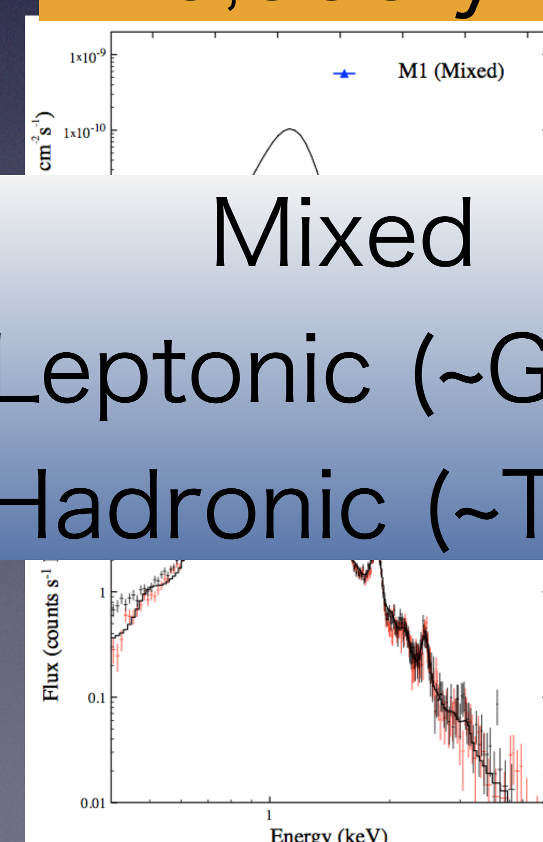
Leptonic

still controversial



Mostly

Hadronic



Mixed

Leptonic (~GeV)

Hadronic (~TeV)

Decipher MW emission by CR-hydro-NEI simulations

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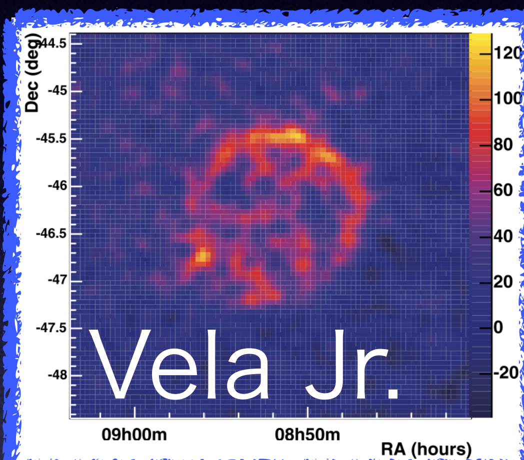
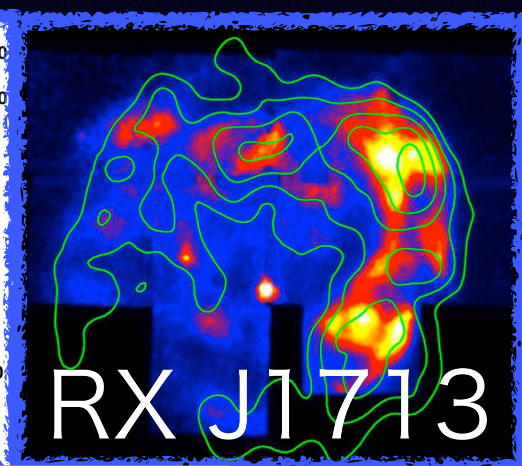
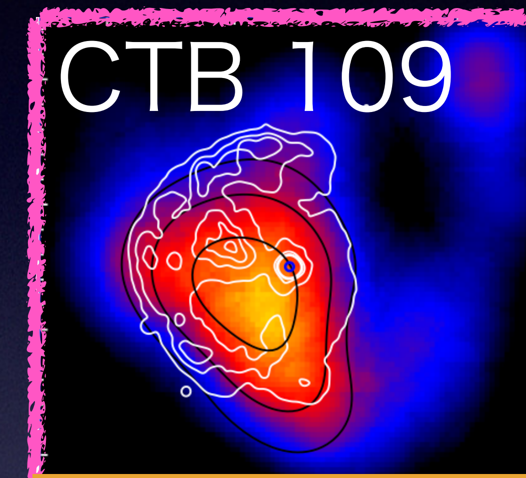
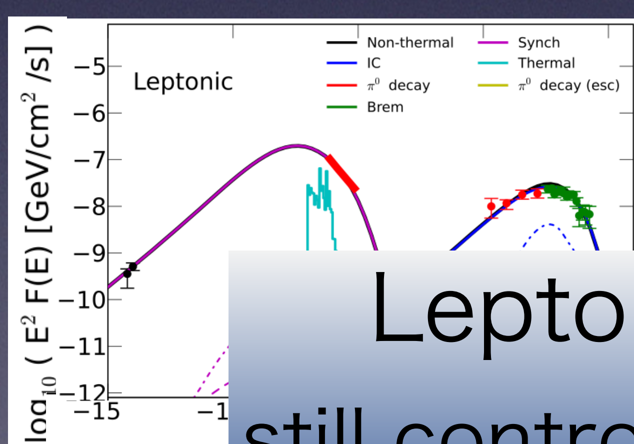
e.g., HL+ 2008 to 2015; Slane, HL+ 2014; Castro+ 2012

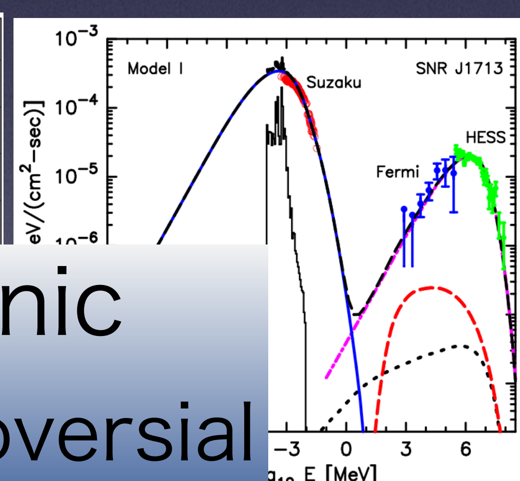






~2,000 yr



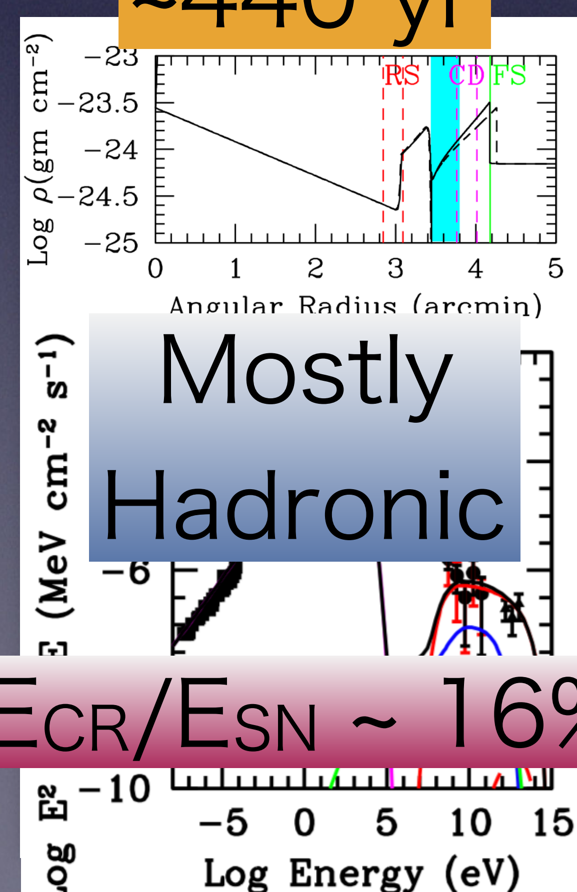


Leptonic

still controversial

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

~440 yr



Mostly

Hadronic

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

~10,000 yr

Mixed

Leptonic (~GeV)

Hadronic (~TeV)

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

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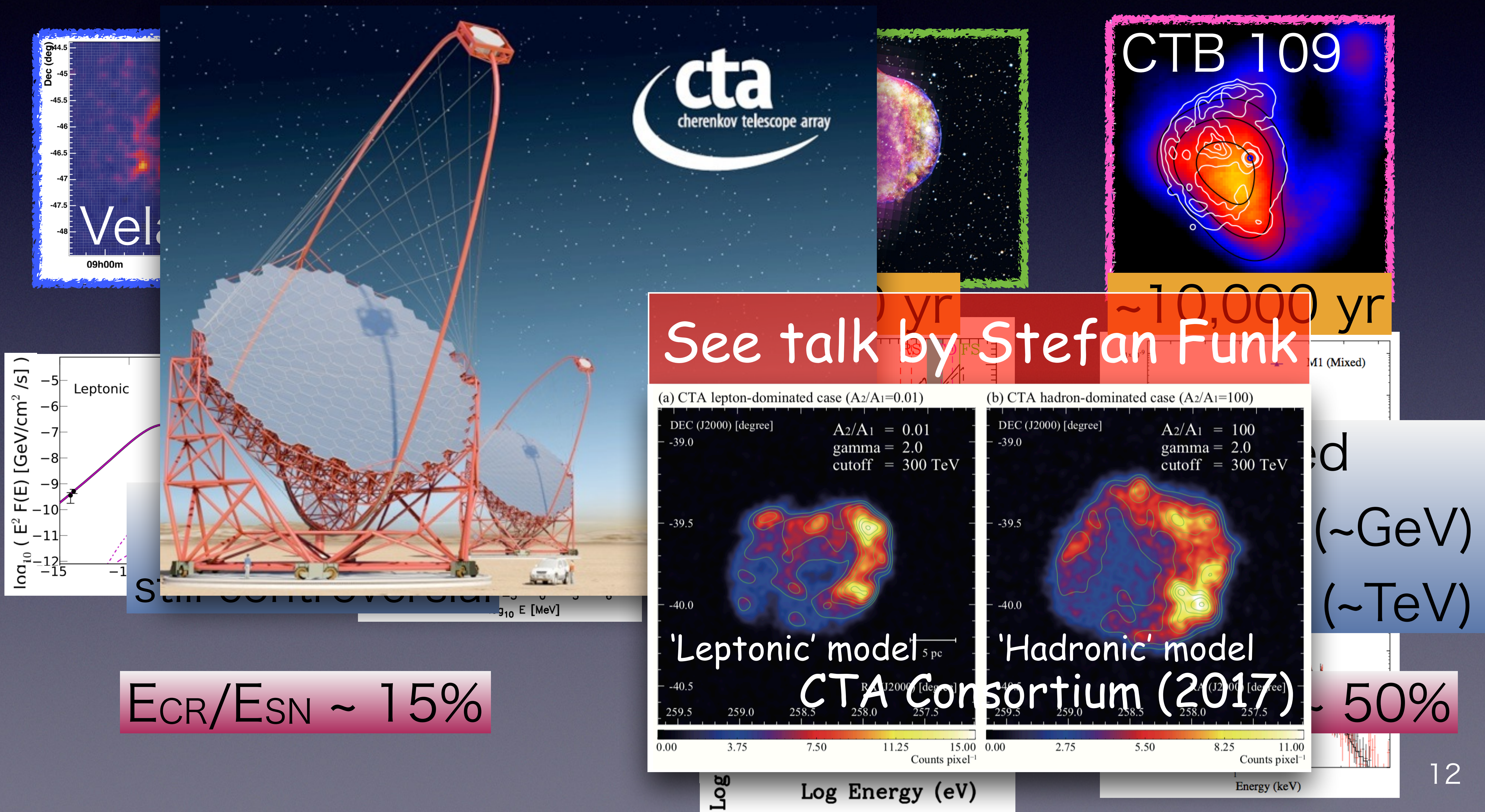

Other Big Questions

- ★ How do supernovae happen?
- ★ What are their progenitors?
- ★ How do they synthesize chemical elements essential to life?
- ★ How massive stars lose their mass before explosion?

(P. Slane)

Other Big Questions

(P. Slane)

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- ★ What are their progenitors?
- ★ How do they synthesize chemical elements essential to life?
- ★ How massive stars lose their mass before explosion?

In the end, all these questions are linked to each other

The 1st attack

We joined the first two pieces together:
ejecta models from SN simulations + "CR-hydro-NEI" SNR model

- ☑ Evolve SN ejecta of different progenitors to SNR phase
- ☑ Calculate the emission properties self-consistently with hydro

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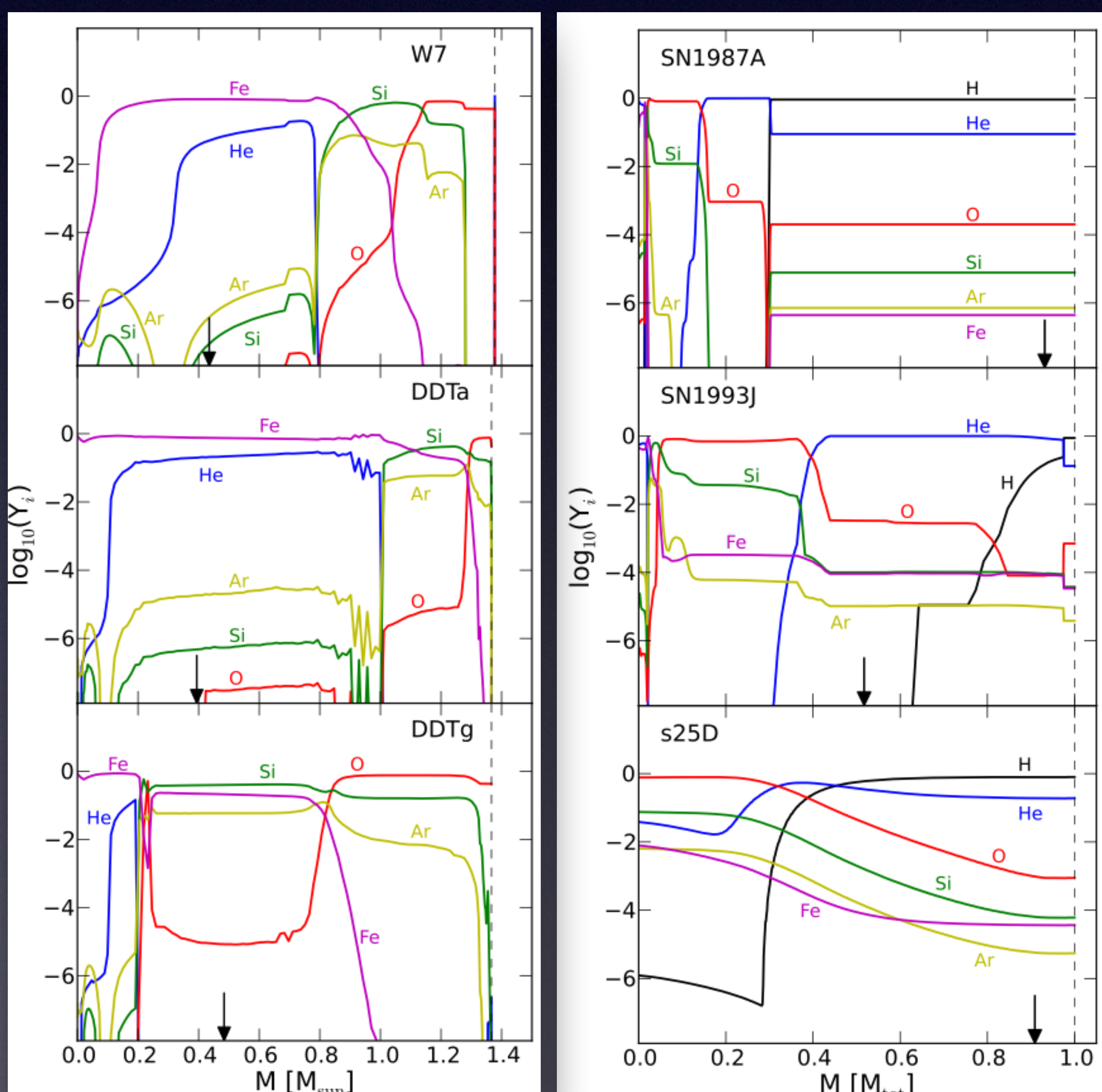
Chemical Abundance



Mass coordinate HL, Patnaude+ 2014

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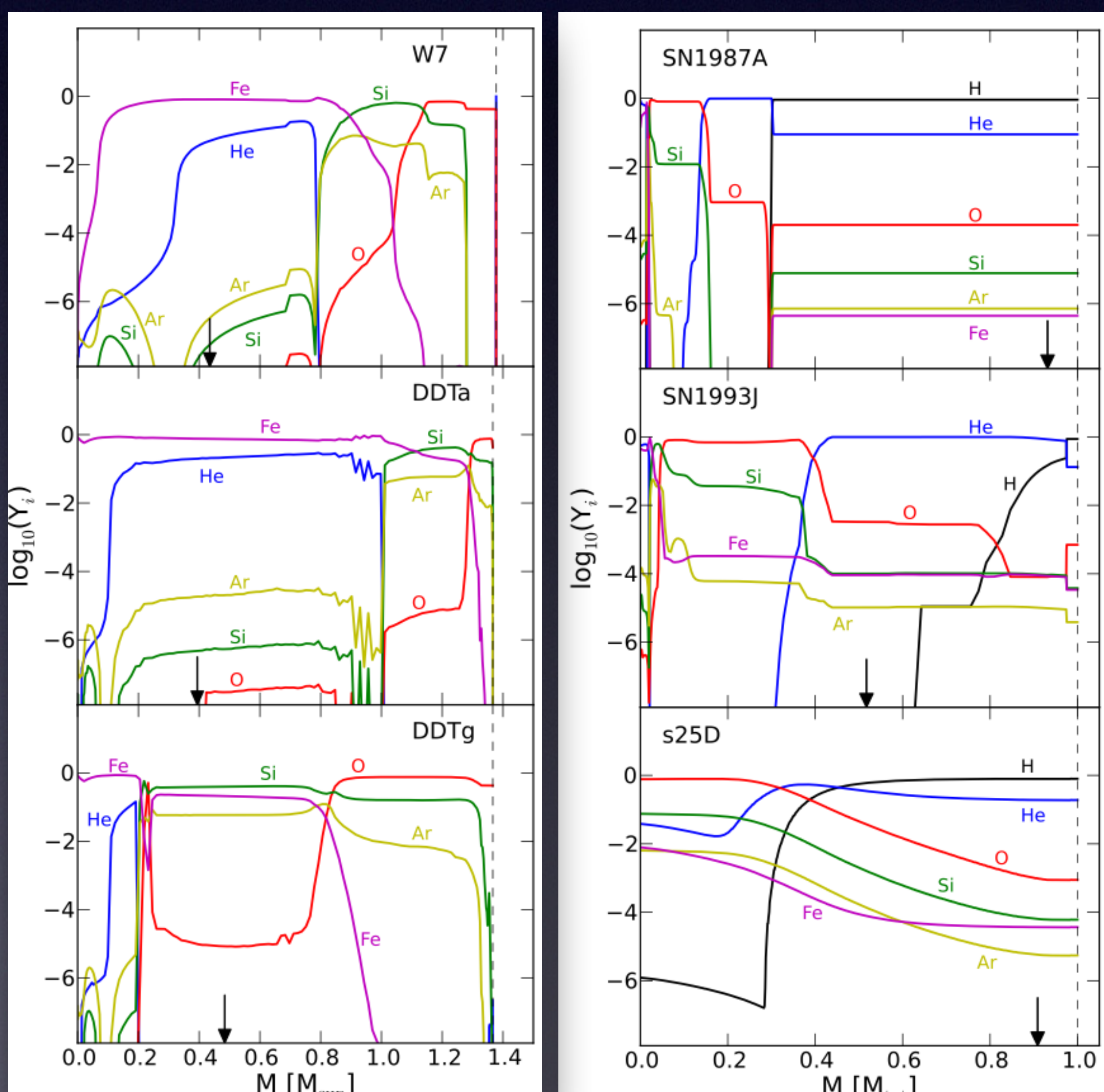
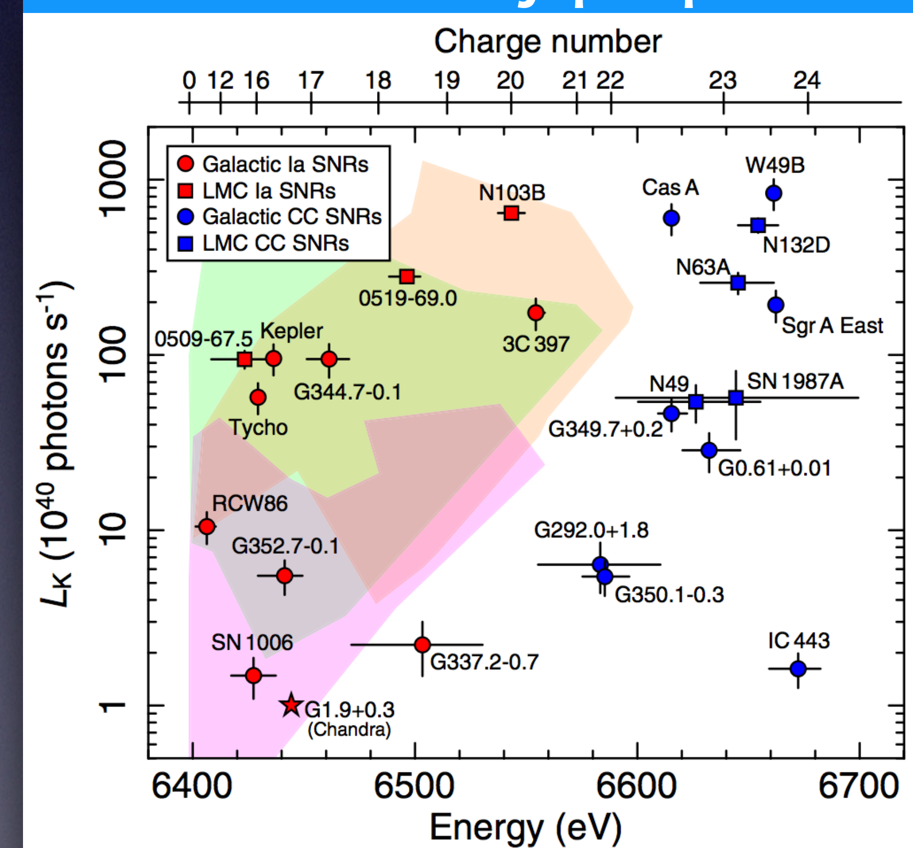


Mass coordinate

HL, Patnaude+ 2014

Observed X-ray properties



Suzaku/Chandra, Yamaguchi+ 2014

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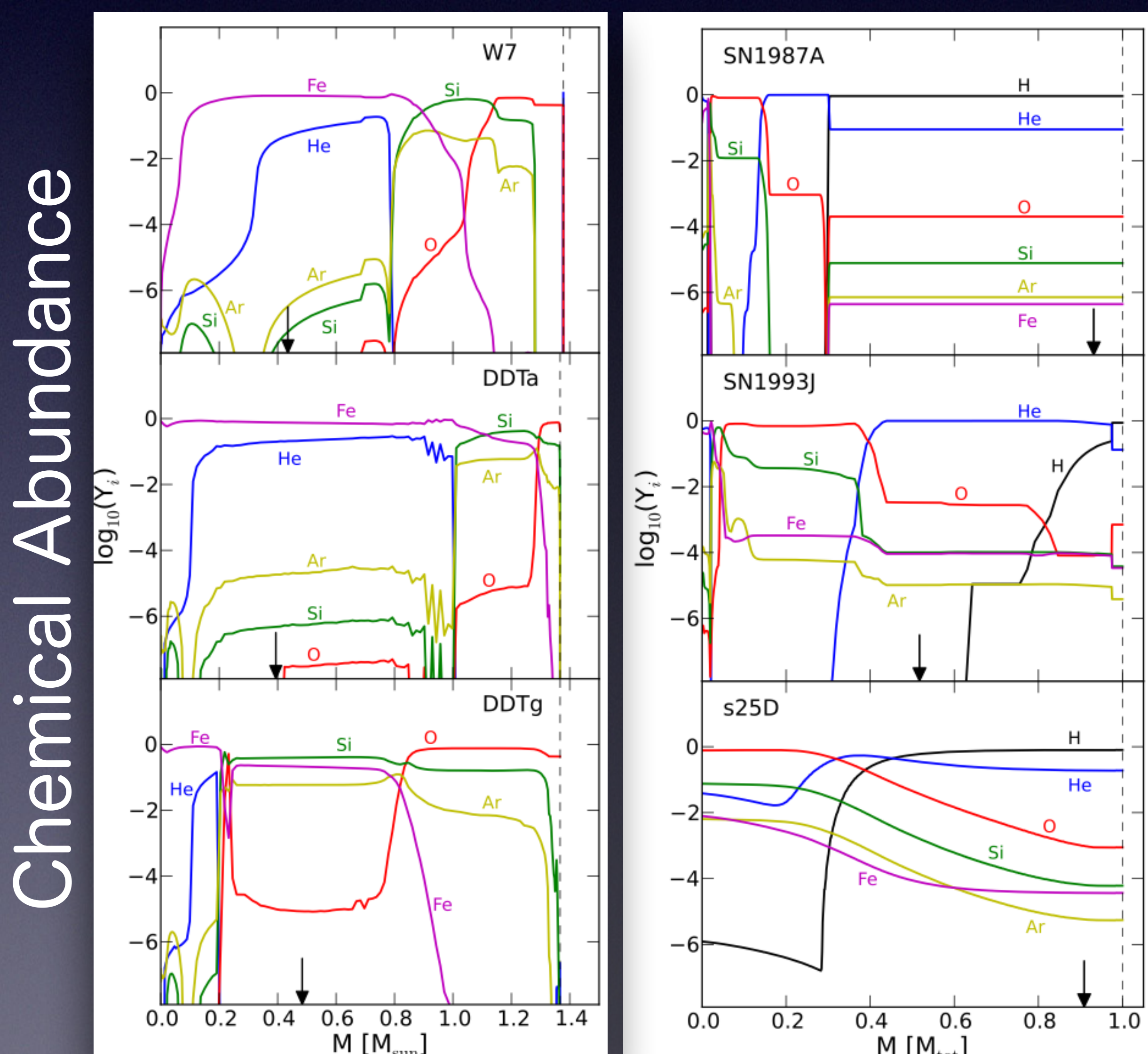
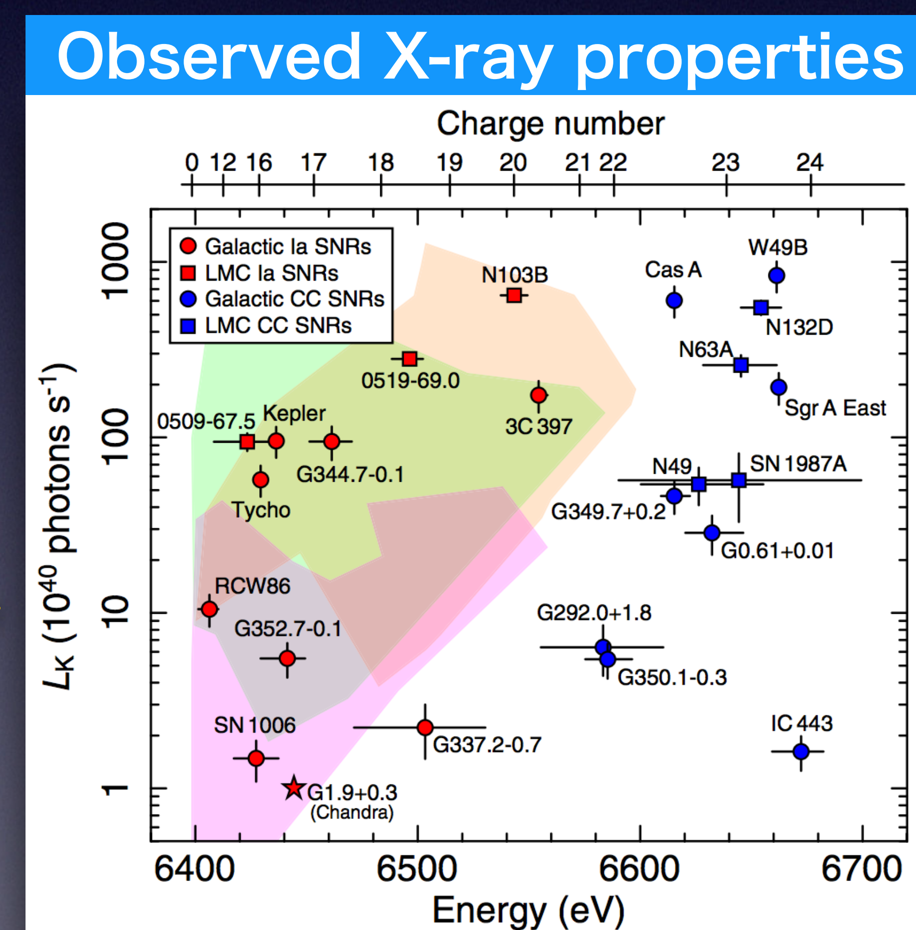


Evolve to SNR

Check consistency with bulk obs. properties



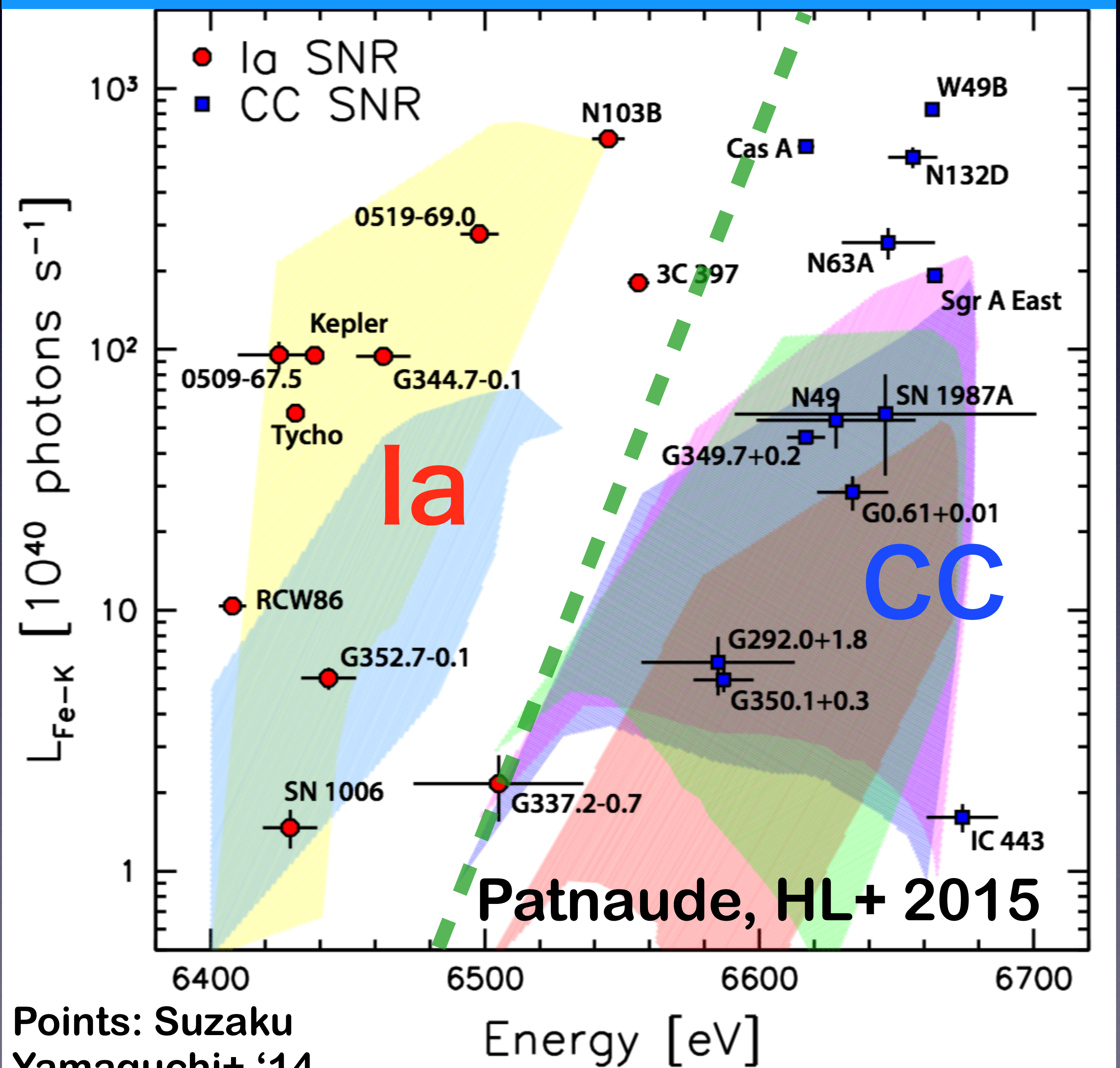
Suzaku/Chandra, Yamaguchi+ 2014

HL, Patnaude+ 2014

Separation of Fe-K line centroid between Ia & CC

Broad consistency of SN models & SNR data!

Color bands = our models



Points: Suzaku
Yamaguchi+ '14

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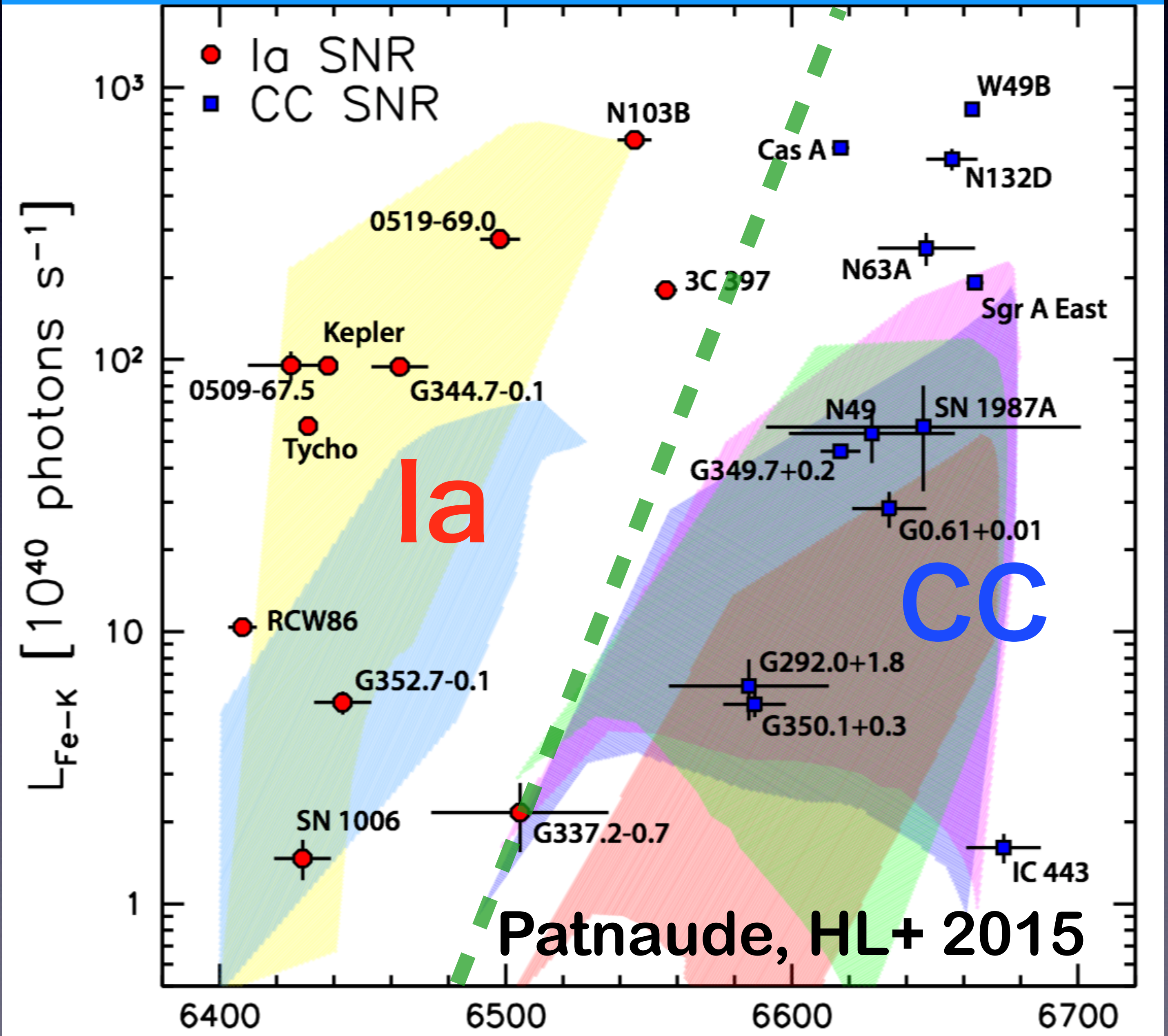

Points: Suzaku Yamaguchi+ '14

- Key: difference in CSM environment!
- CC ejecta hit dense wind
  —> faster collisional ionization
  —> higher line centroid energy
- Ia ejecta hit low-ρ uniform ISM (usually...)

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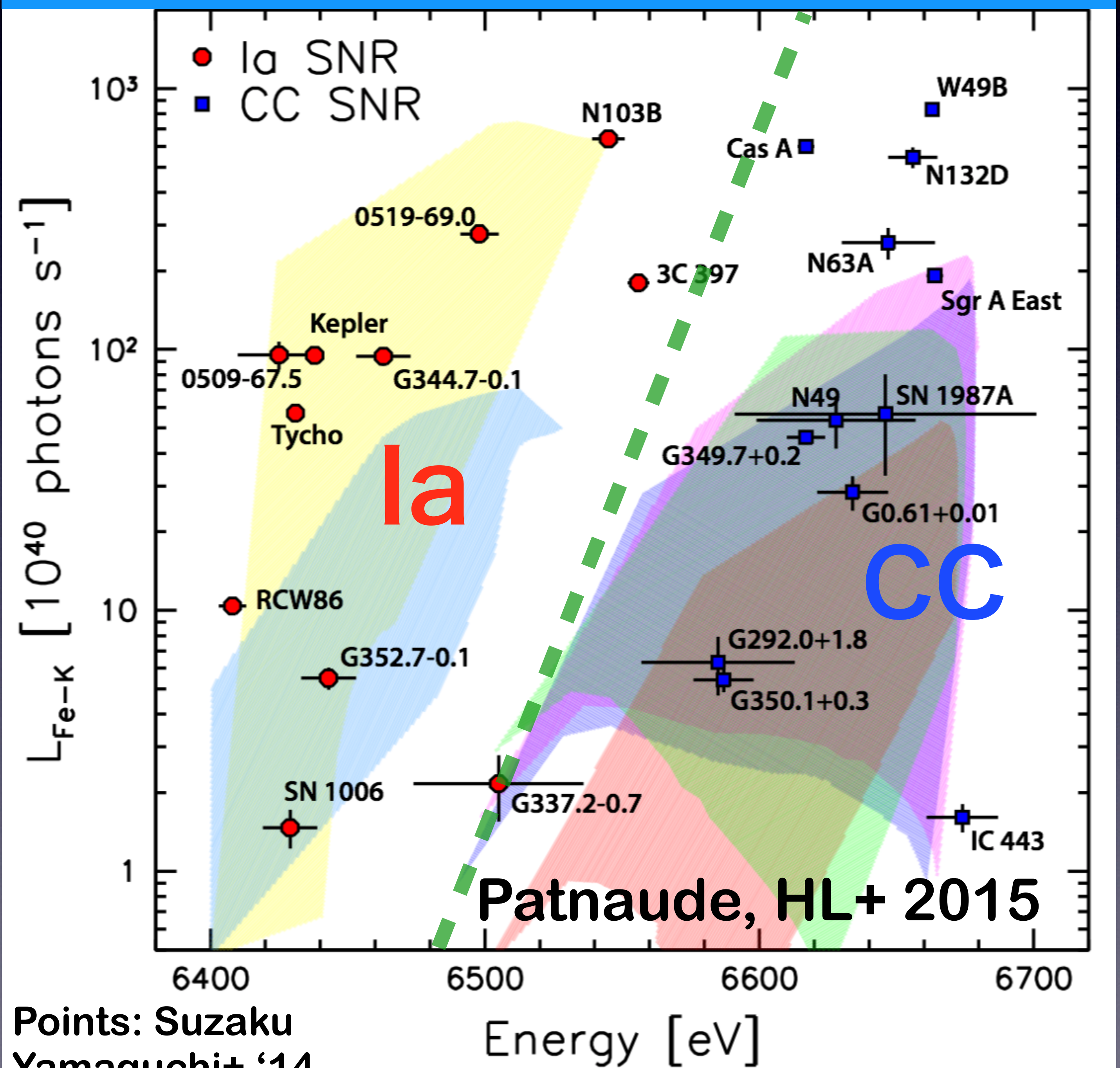
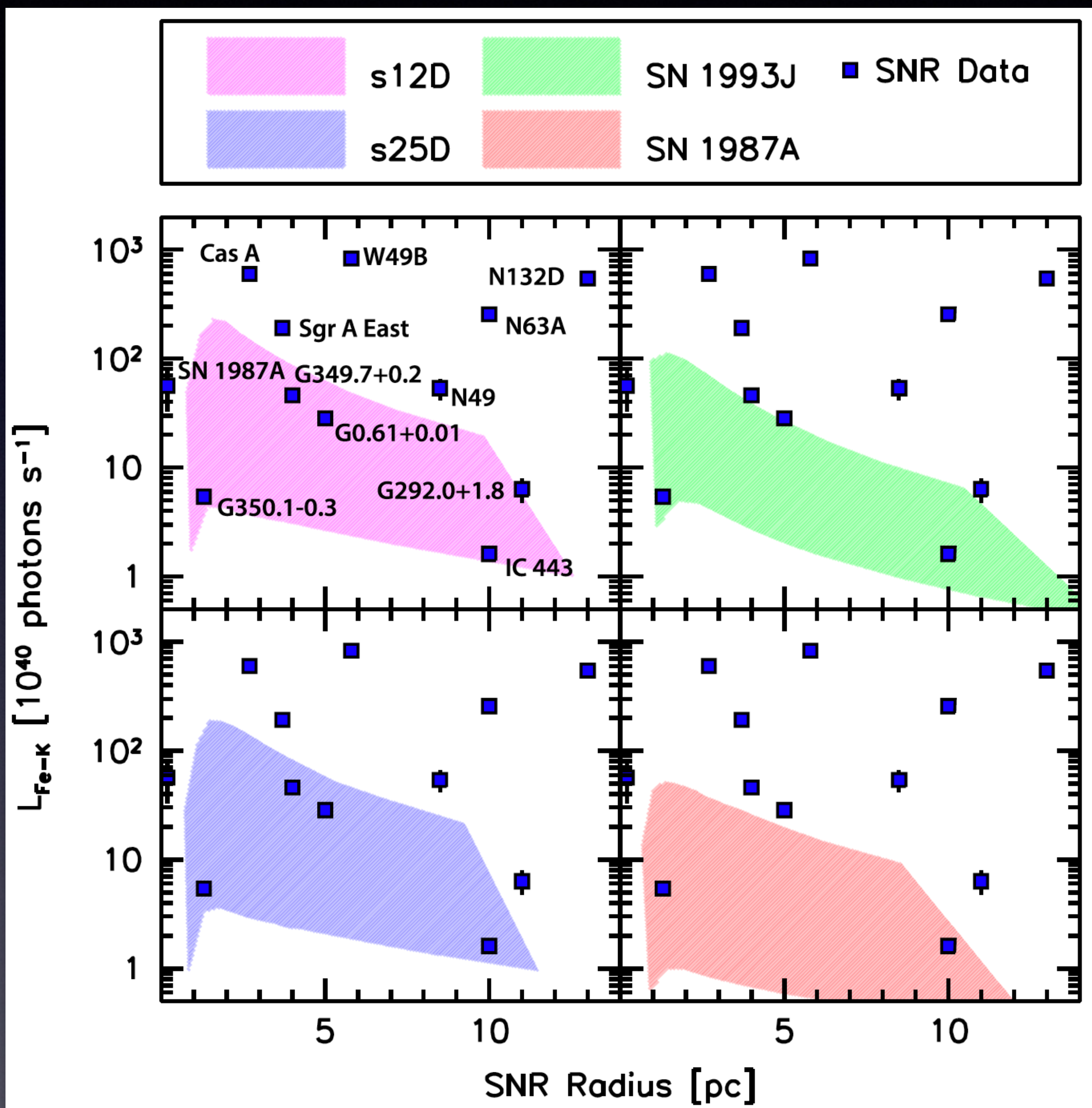


Points: Suzaku Yamaguchi+ '14

- Key: difference in CSM environment!
- CC ejecta hit dense wind —> faster collisional ionization —> higher line centroid energy
- Ia ejecta hit low-ρ uniform ISM (usually...)

- Scattering of data: dispersion in age, progenitor and CSM properties
- Luminous "outliers": dense shell or cloud interaction

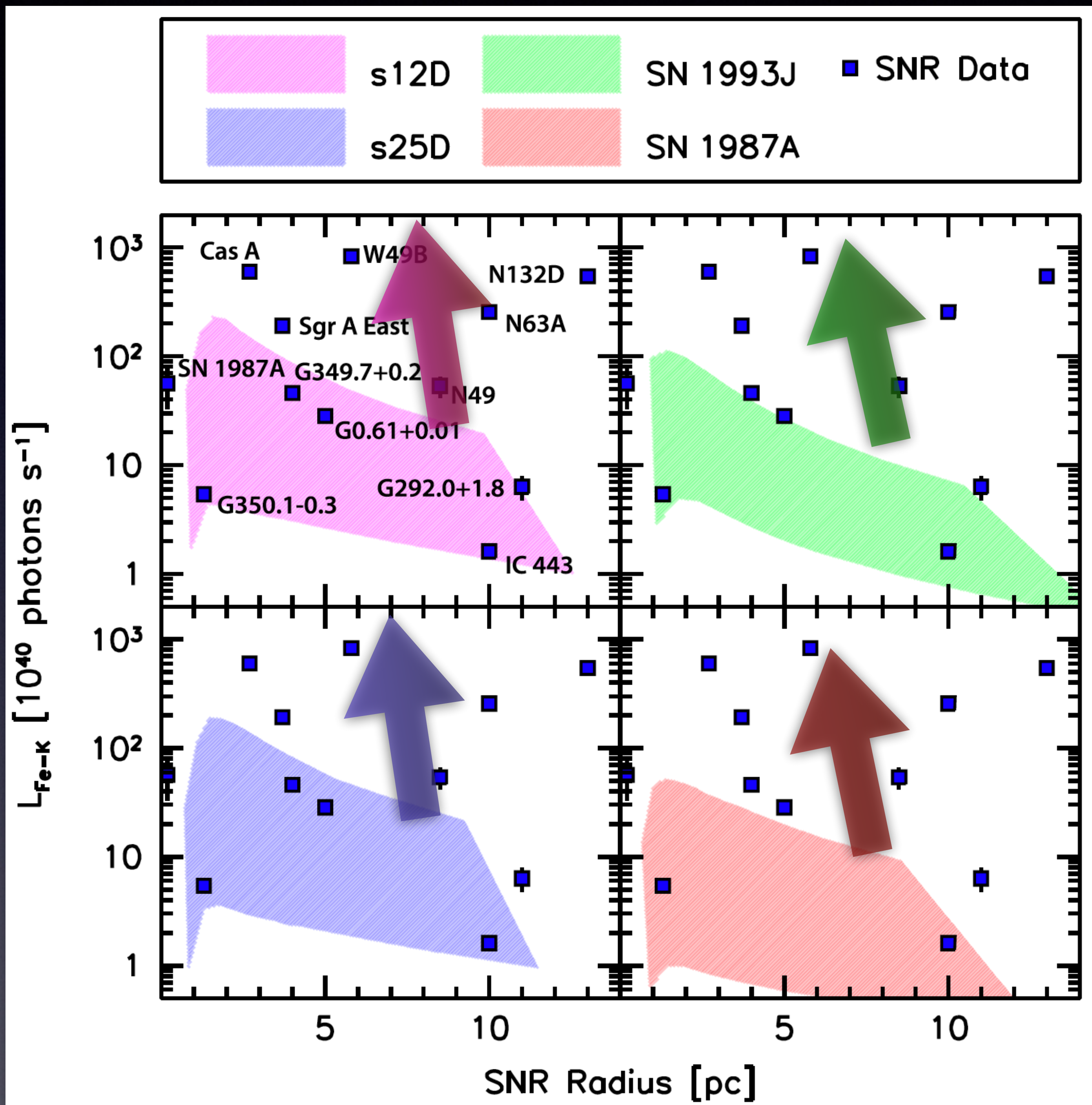
Not without any problem



Patnaude, HL+ 2015

- Dynamics seems not reproduced well among CC SNRs, why?

Not without any problem



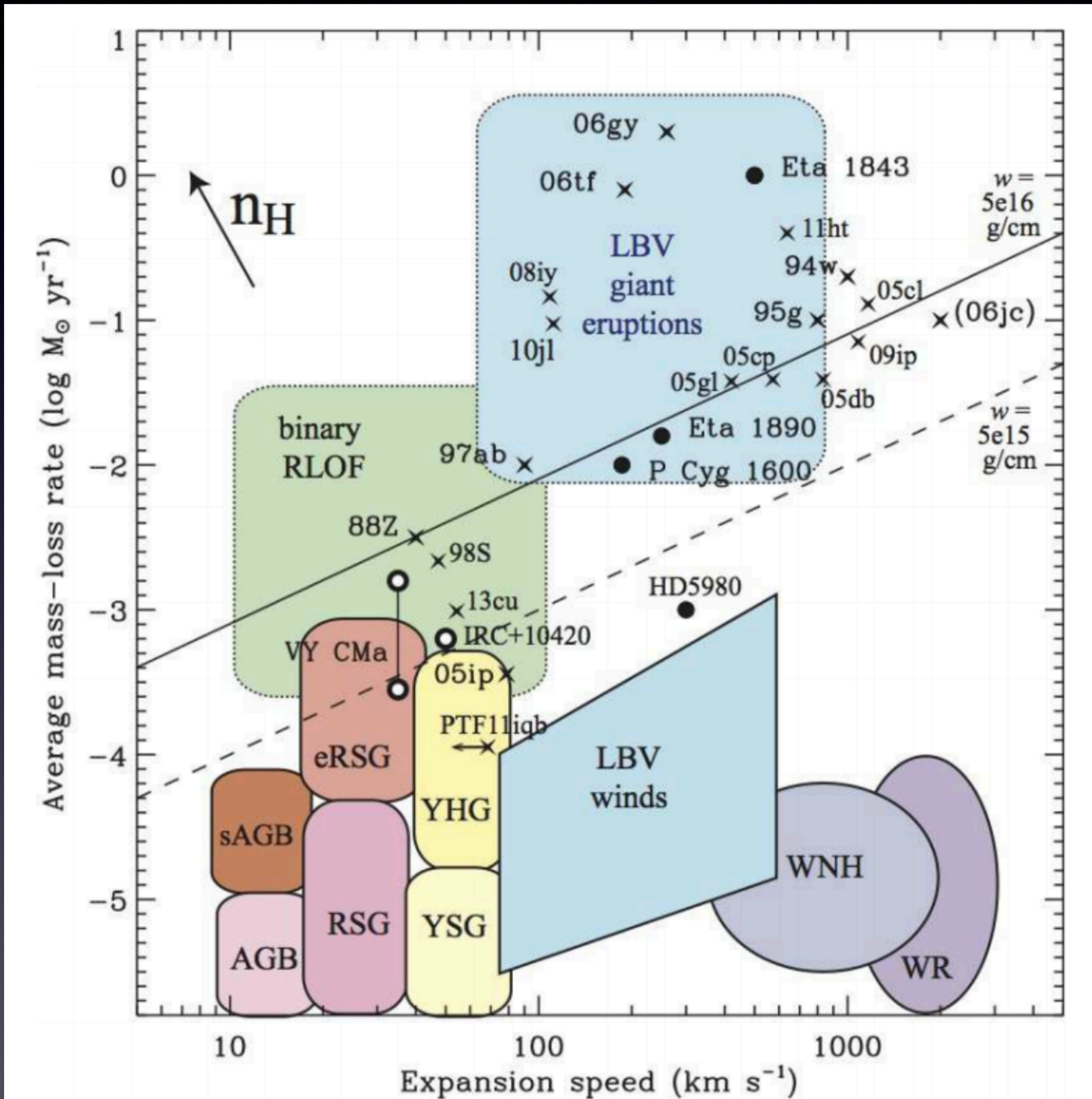
Patnaude, HL+ 2015

- Dynamics seems not reproduced well among CC SNRs, why?
- We assumed steady mass-loss history (i.e., r^{-2} wind); is not always true…
- Late-time enhanced mass loss boosts L_X, but NOT affect dynamical evolution (i.e., R_{SNR}) as much

$$R_b \propto \left[\frac{Ag^n}{q}\right]^{1/(n-s)} t^{\frac{n-3}{n-s}}$$

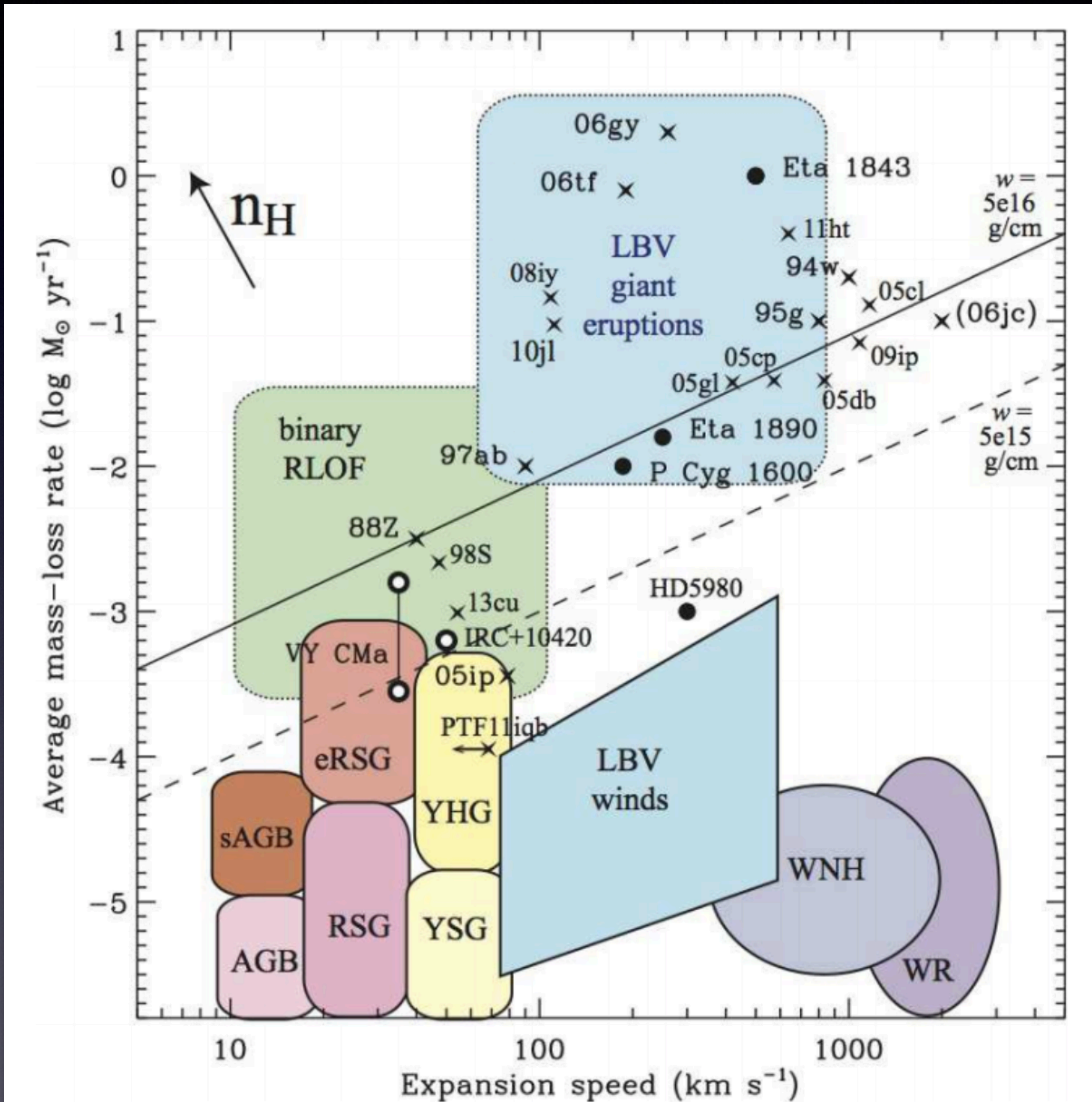
$$L_X \propto q^2 \qquad q = \dot{M}/(4\pi v_w)$$

Probing Mass Loss History



Smith 2016

Probing Mass Loss History



Q: Can we use **SNR observations** to probe late-time mass loss episodes to constrain SN progenitors?

Smith 2016

2nd Attack

We now couple 3 codes together for true "end-to-end" models

- Construct progenitor models with `MESA`
- Let stars evolve until CC onset
- Prescribed episodes of pre-SN mass loss history
- CC explosion and nucleosynthesis using `SNEC`
- SNR evolution using `CR-hydro-NEI`
- Explore any SNR emission properties "inherited" from pre-SN mass loss history

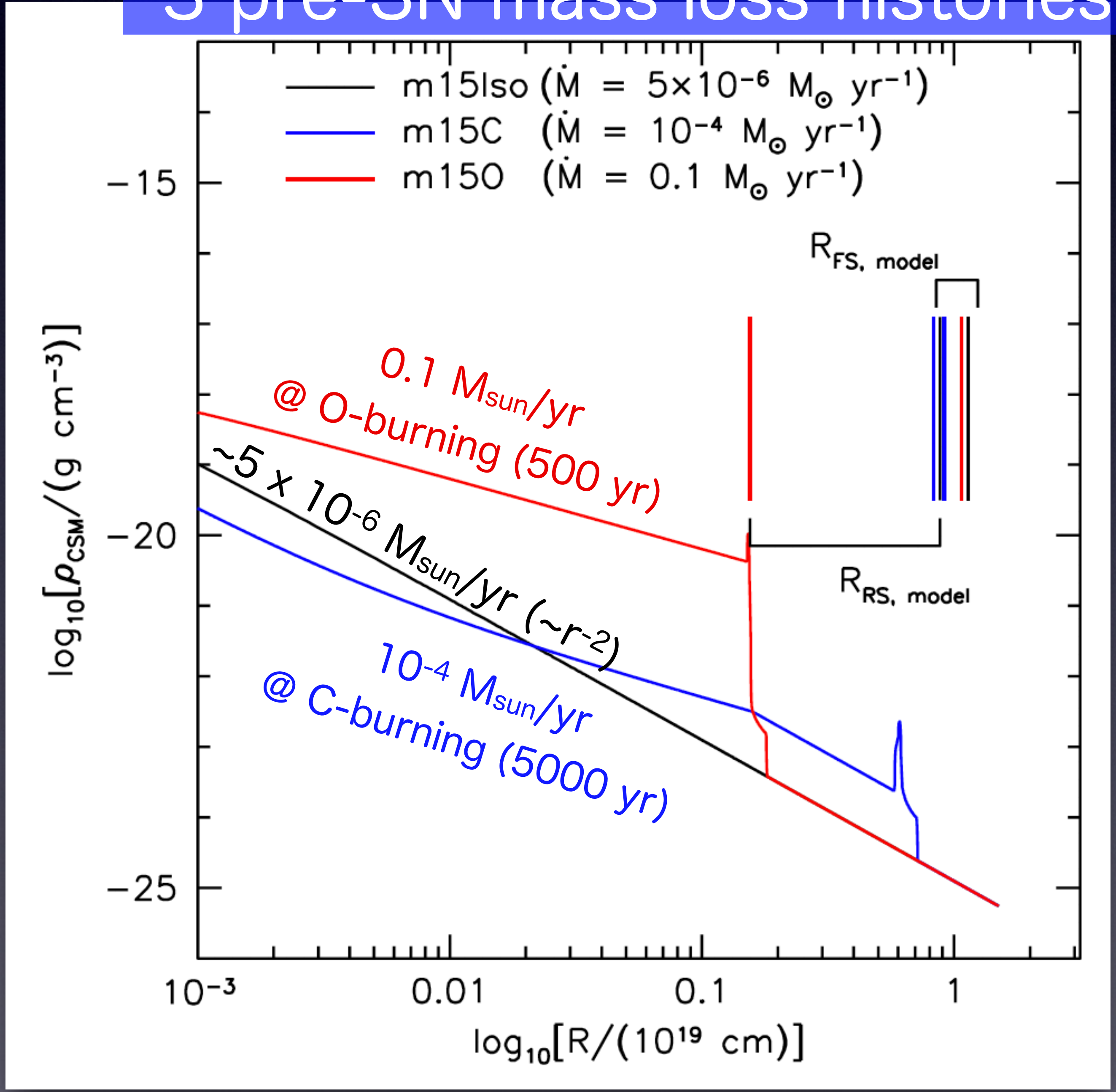
Patnaude, HL+ 2017

Showcase examples

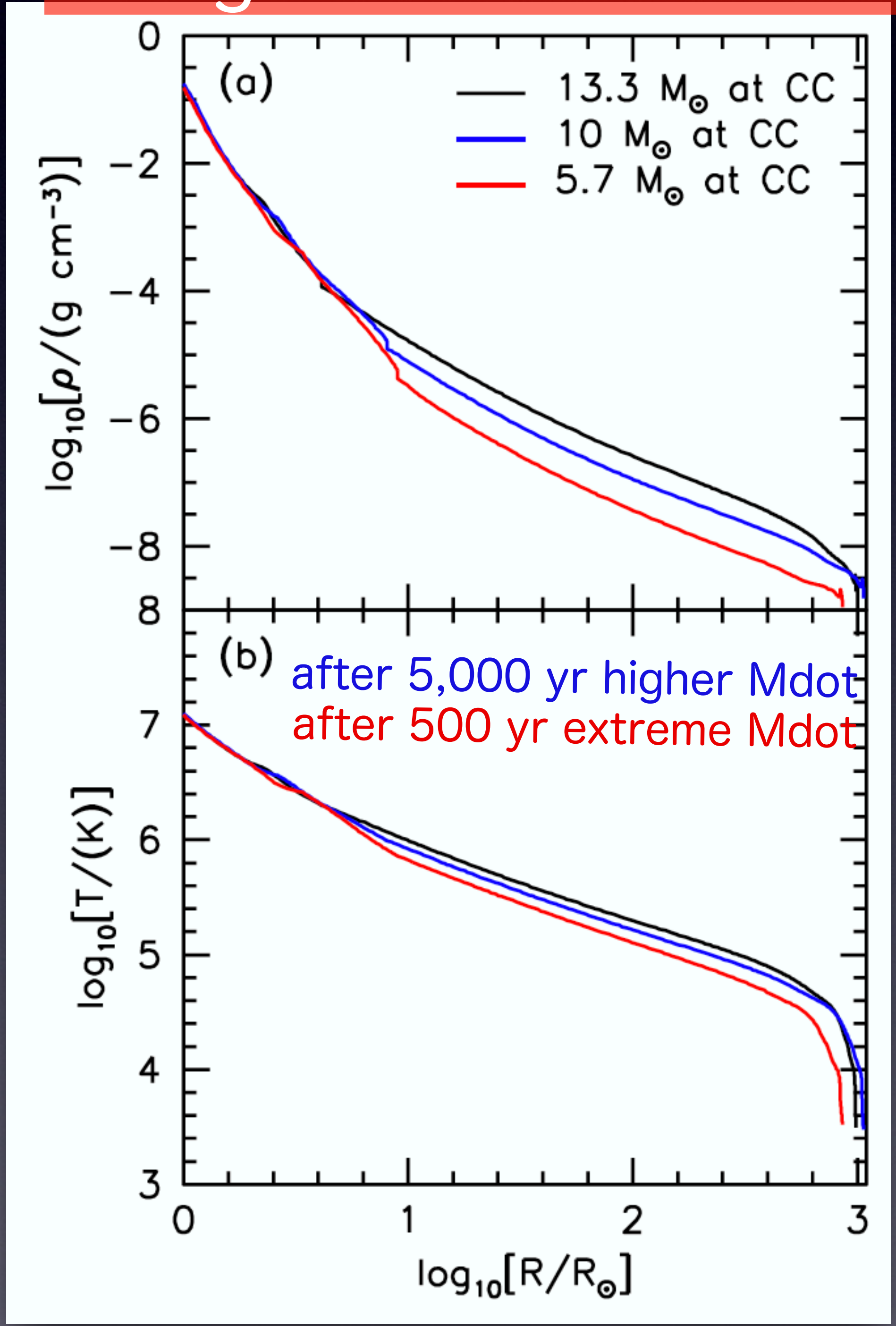
15 Msun ZAMS

with 3 different mass loss histories

CSM profiles from 3 pre-SN mass loss histories

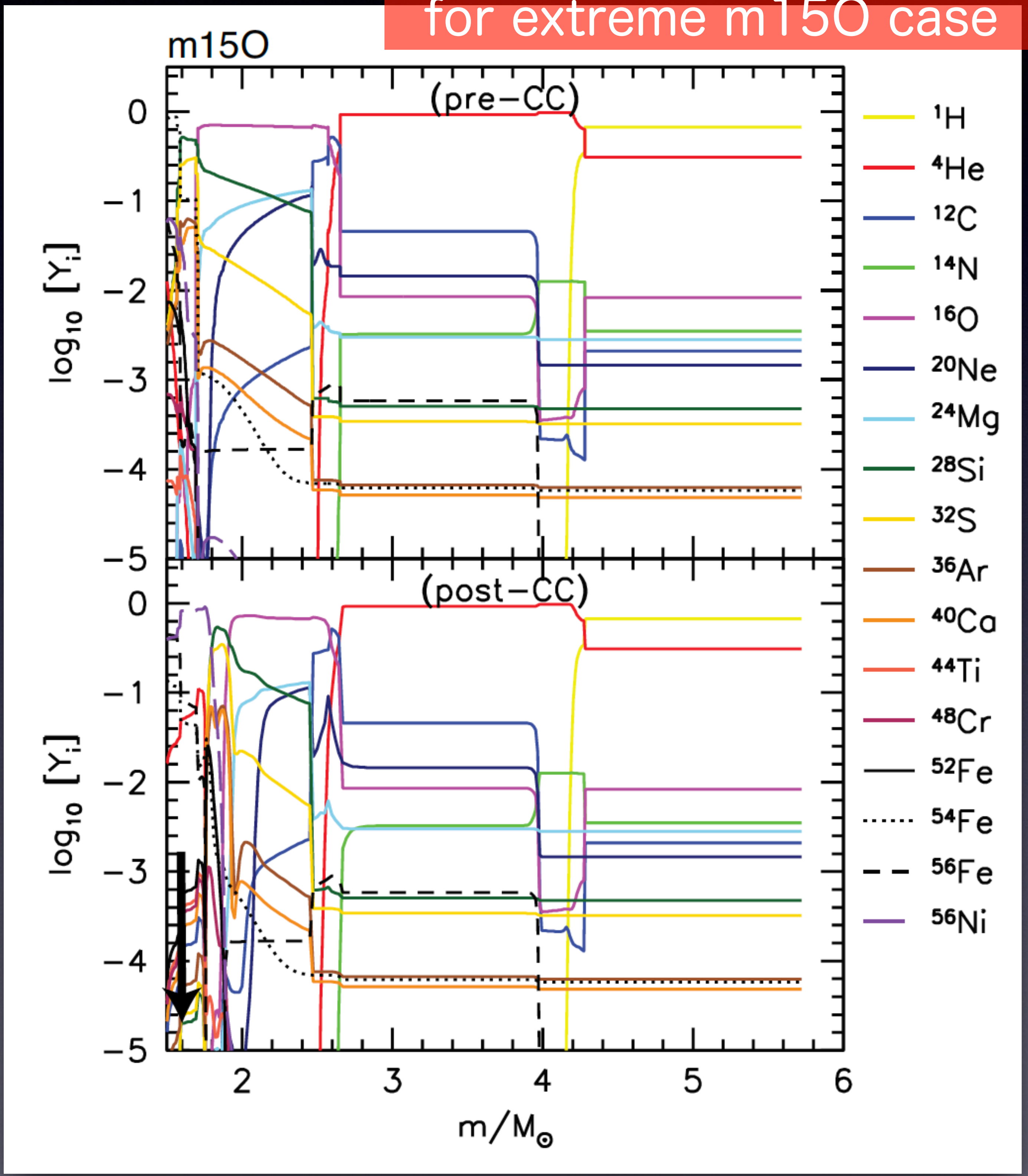


Progenitor @ CC onset



Getting the SN ejecta

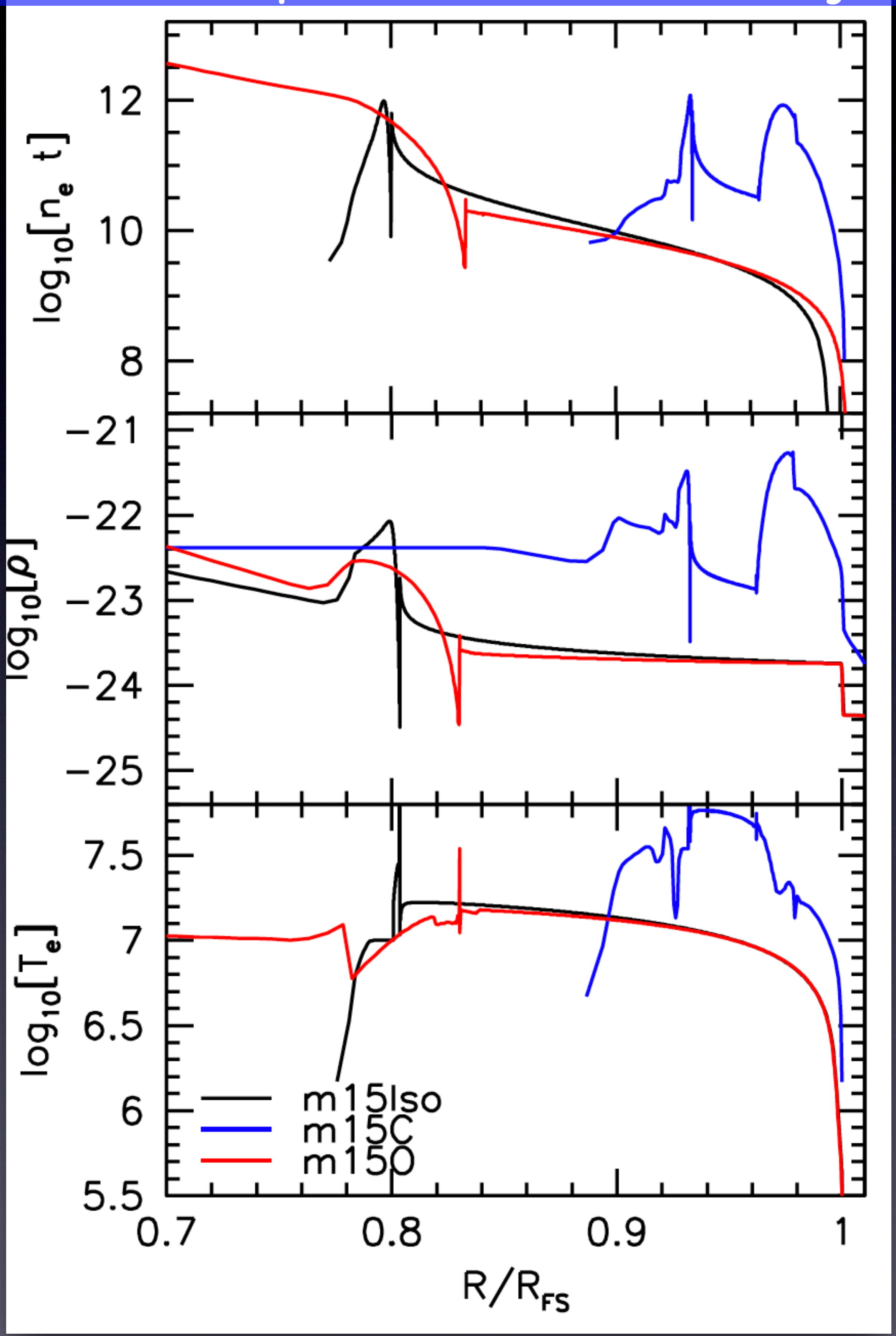
Pre-CC & post-CC ejecta
for extreme m15O case



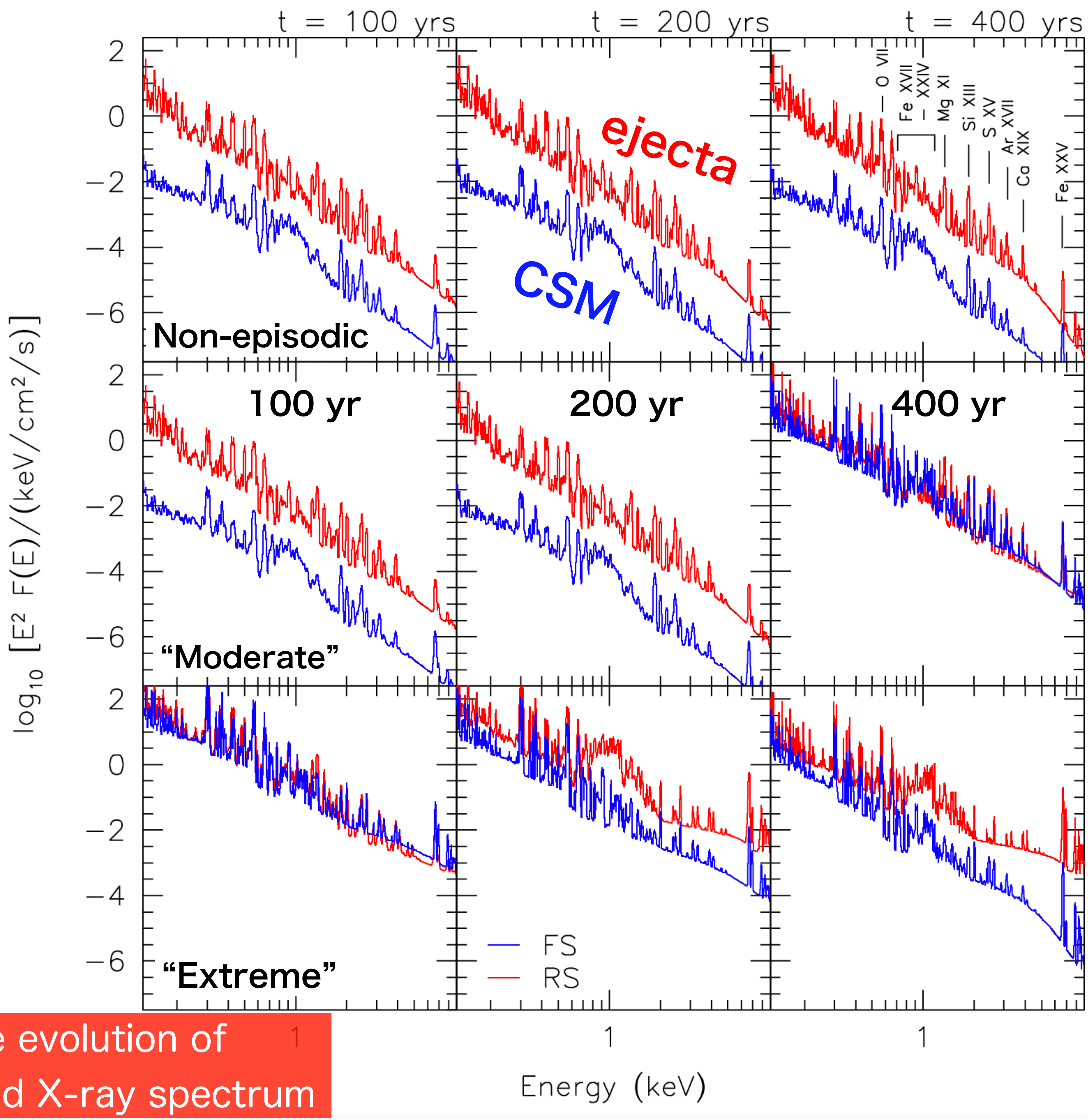
- 3 evolved progenitors from MESA go through CC explosion (10^{51} erg) using SNEC
- (No matter-mixing assumed)
- 3 resulted ejecta model differ much in H-envelope mass
- i.e., large effect on X-ray emission from their SNRs! (e.g., think of location of RS at given age)

Becoming SNRs

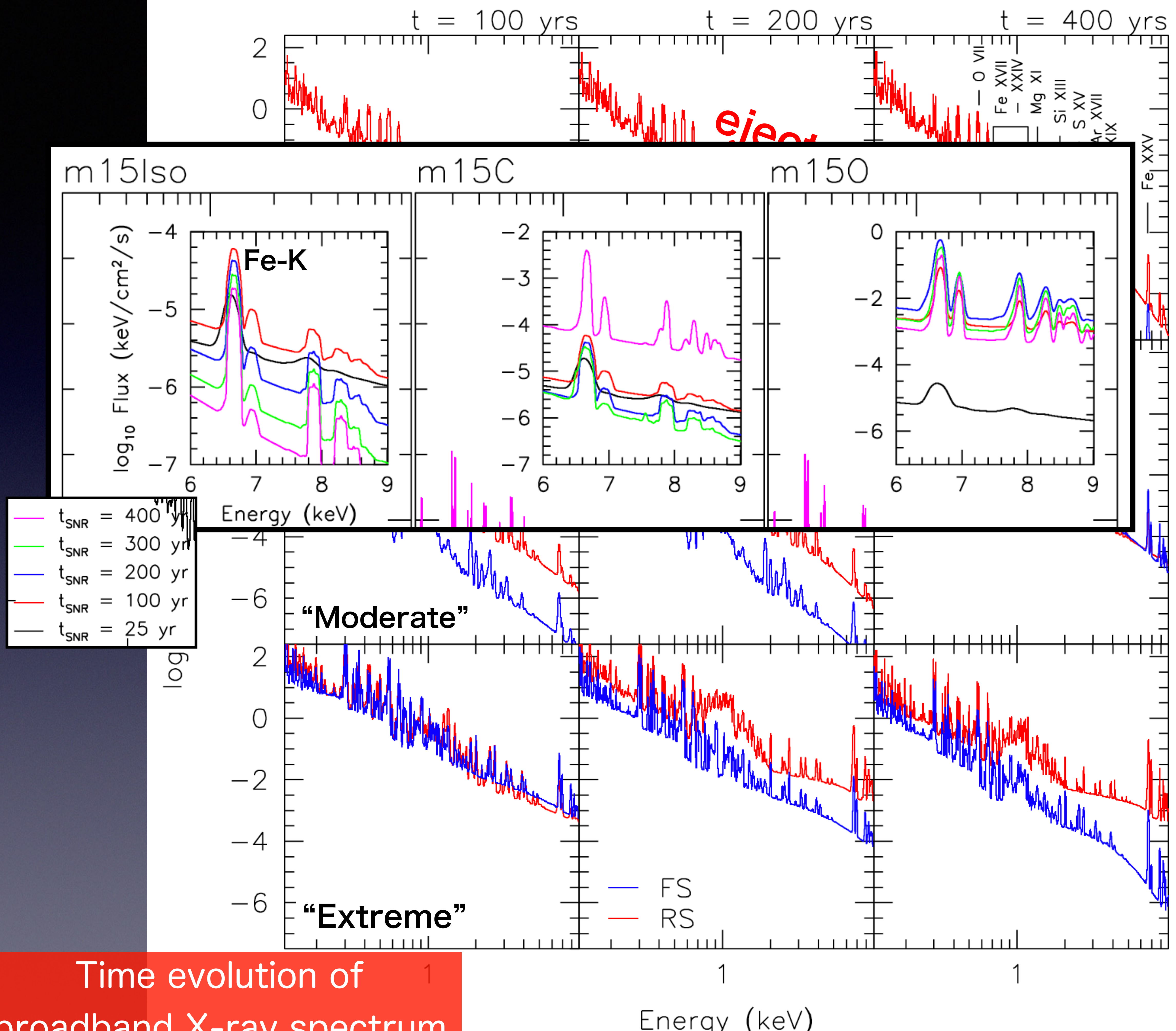
Thermal profiles after 400 yr



- 3 ejecta then evolved to a few 100 yr old SNRs using a CR-hydro-NEI code
- NEI state and $T_{e,i}$ evolution (~200 ion species) fully followed everywhere
- Highly contrasting hydro profiles of 3 models witnessed
- Immediately expect striking differences in X-ray emission properties



Time evolution of broadband X-ray spectrum



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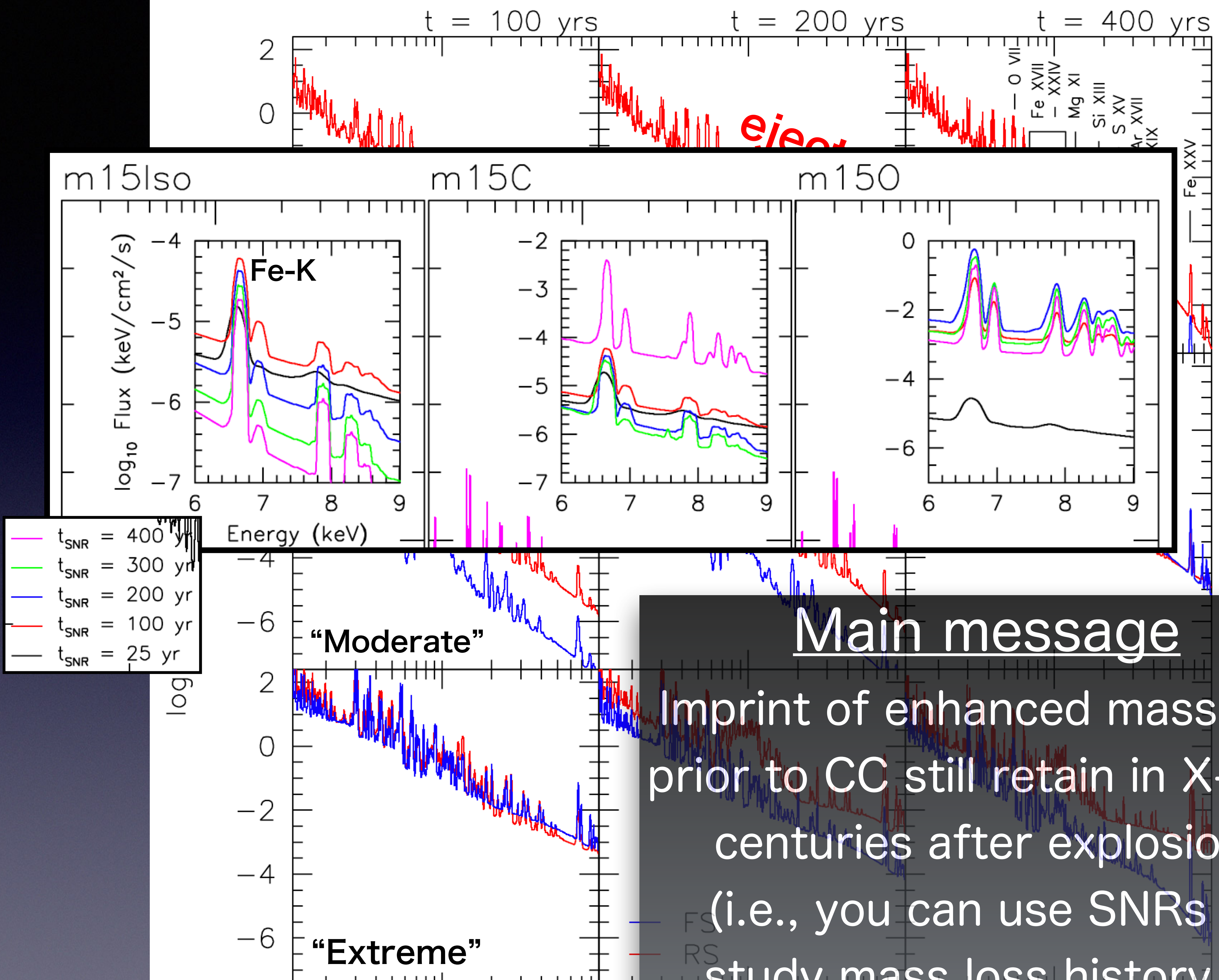
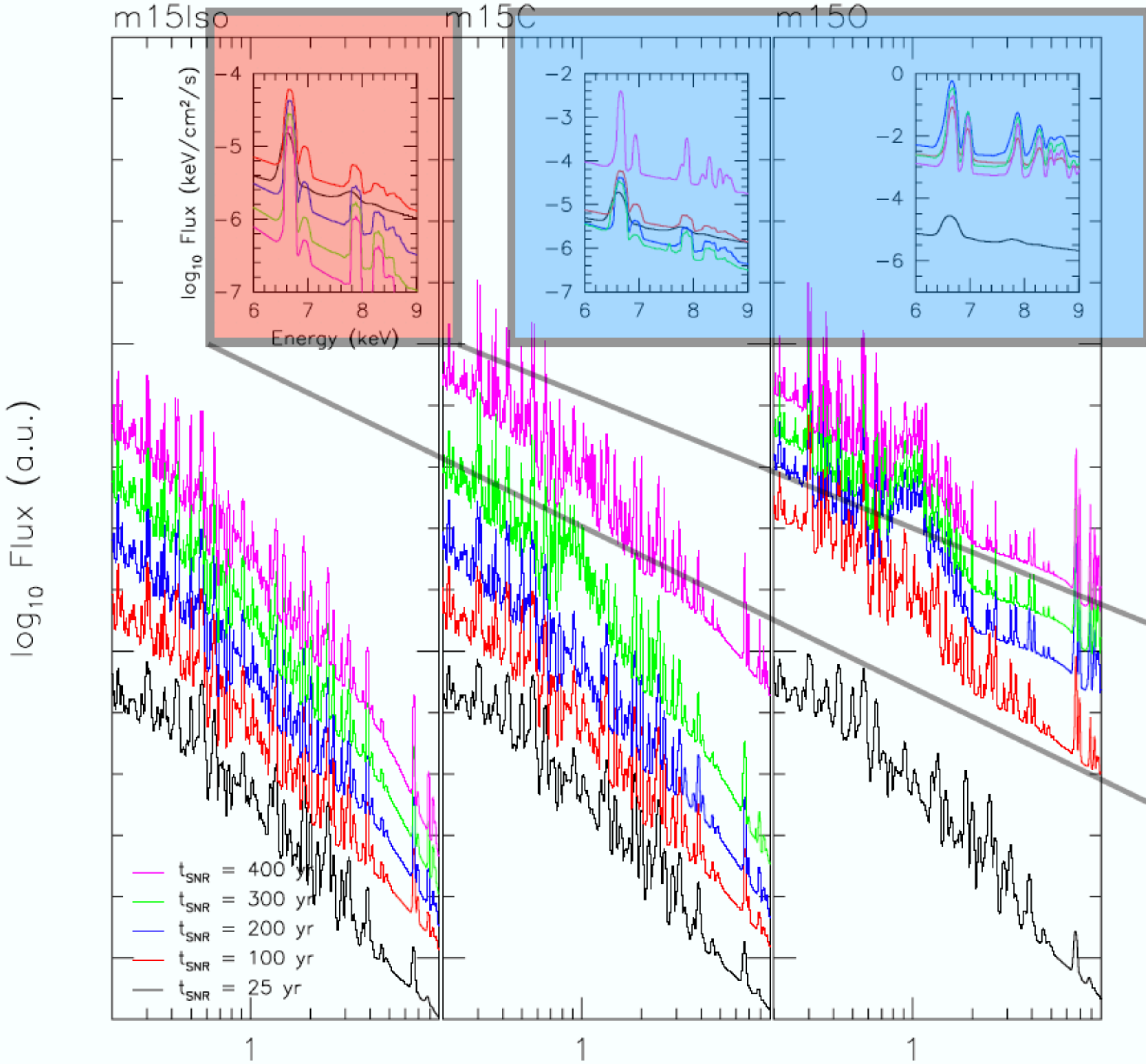


Time evolution of broadband X-ray spectrum

Main message

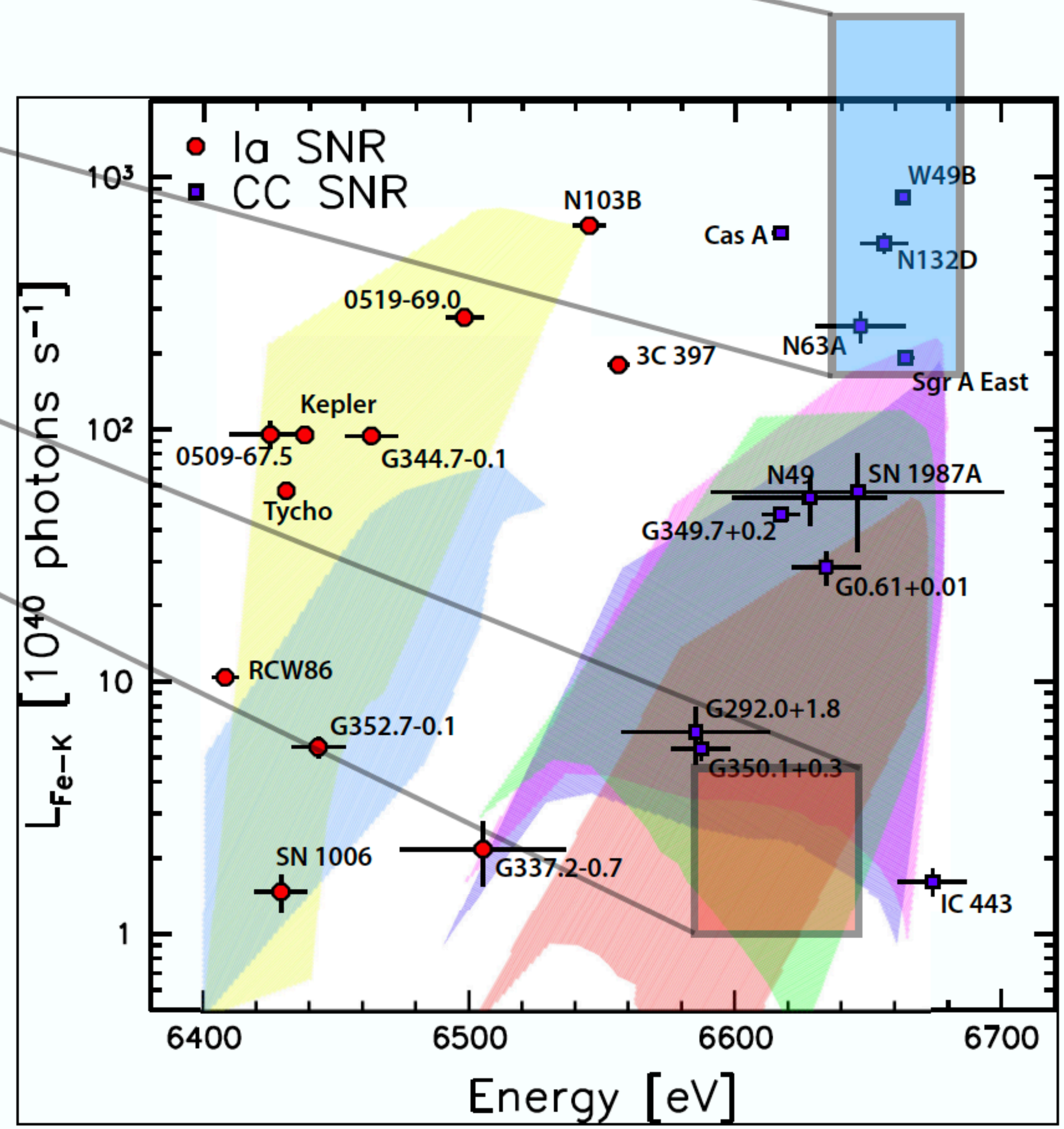
Imprint of enhanced mass loss prior to CC still retain in X-rays centuries after explosion!

(i.e., you can use SNRs to study mass loss history of massive stars)



Isotropic RSG wind

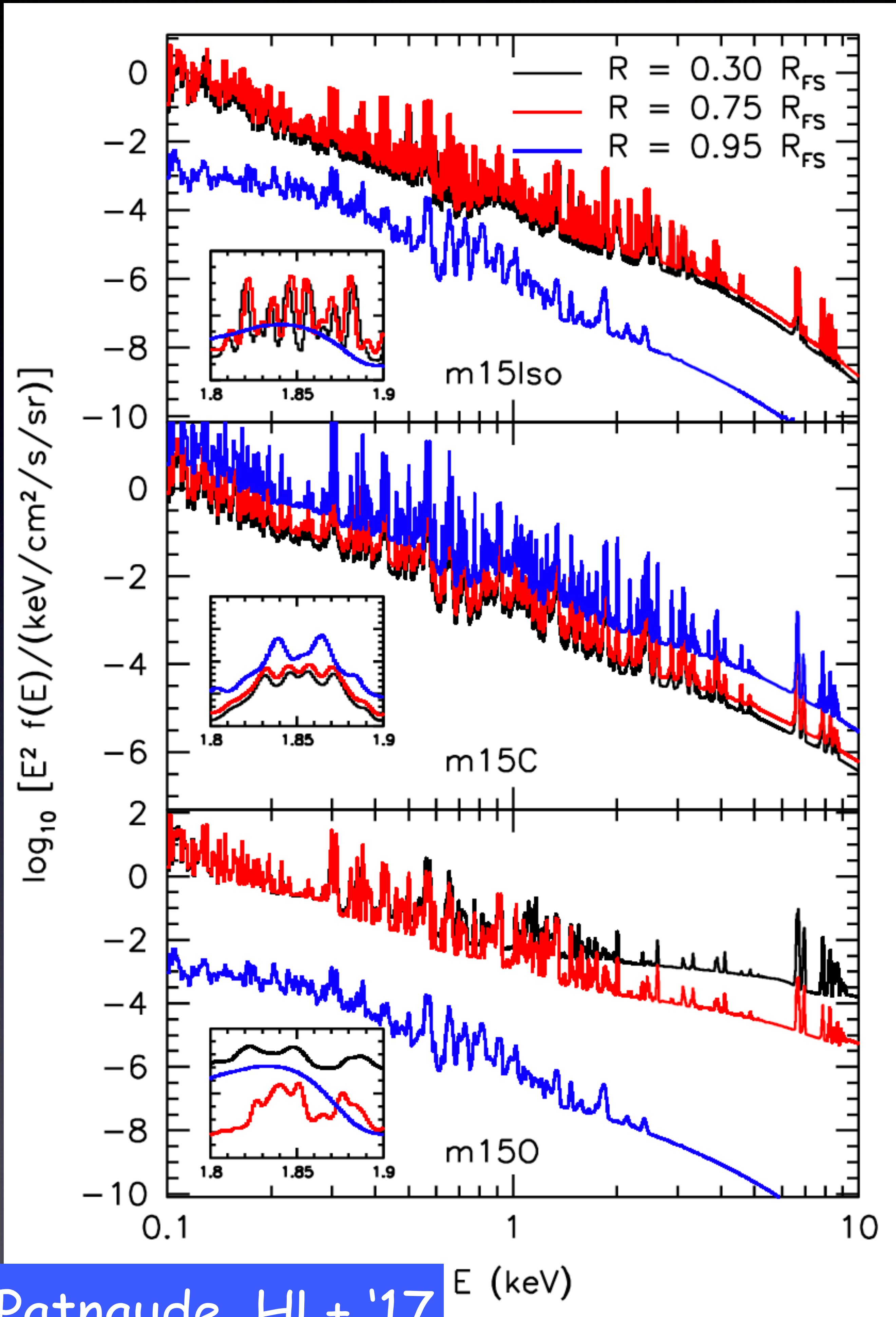
Enhanced Mdot cases



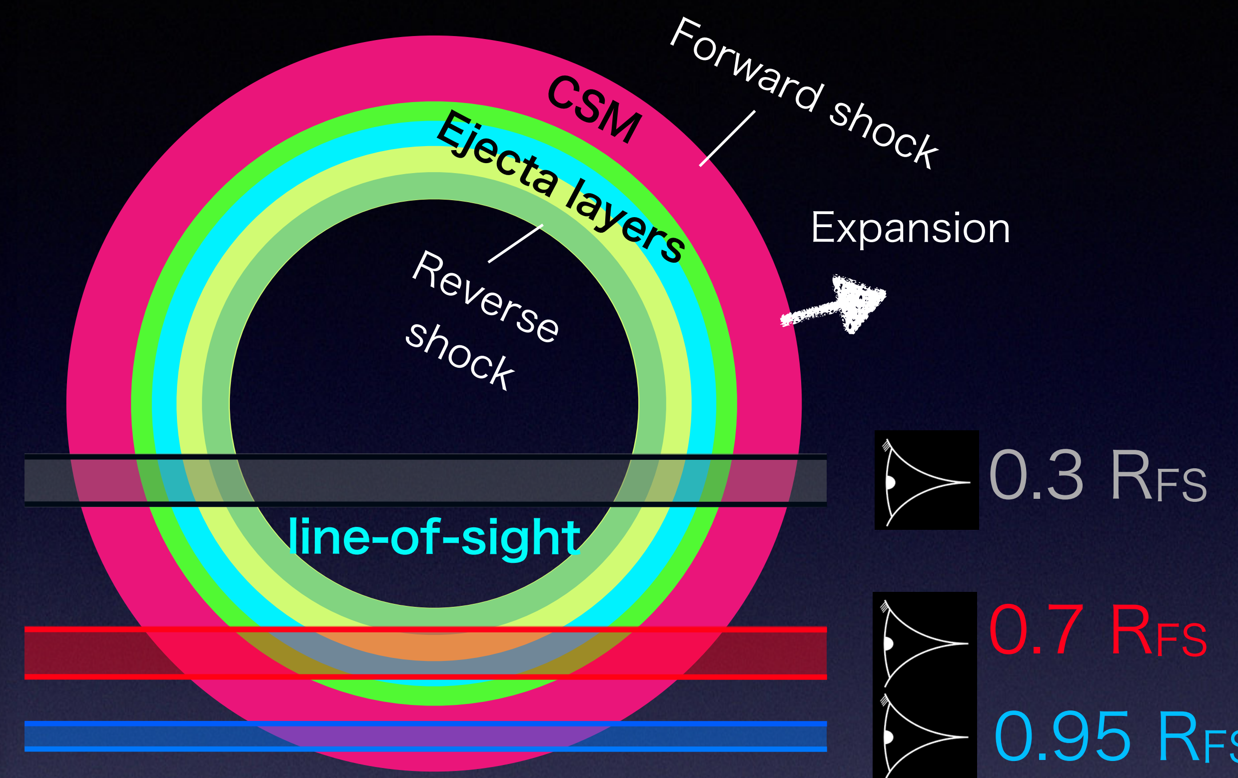
Compare newly synthesized spectra and dynamics to previous models

Patnaude, HL+ '17

Line profile!



Patnaude, HL+ '17

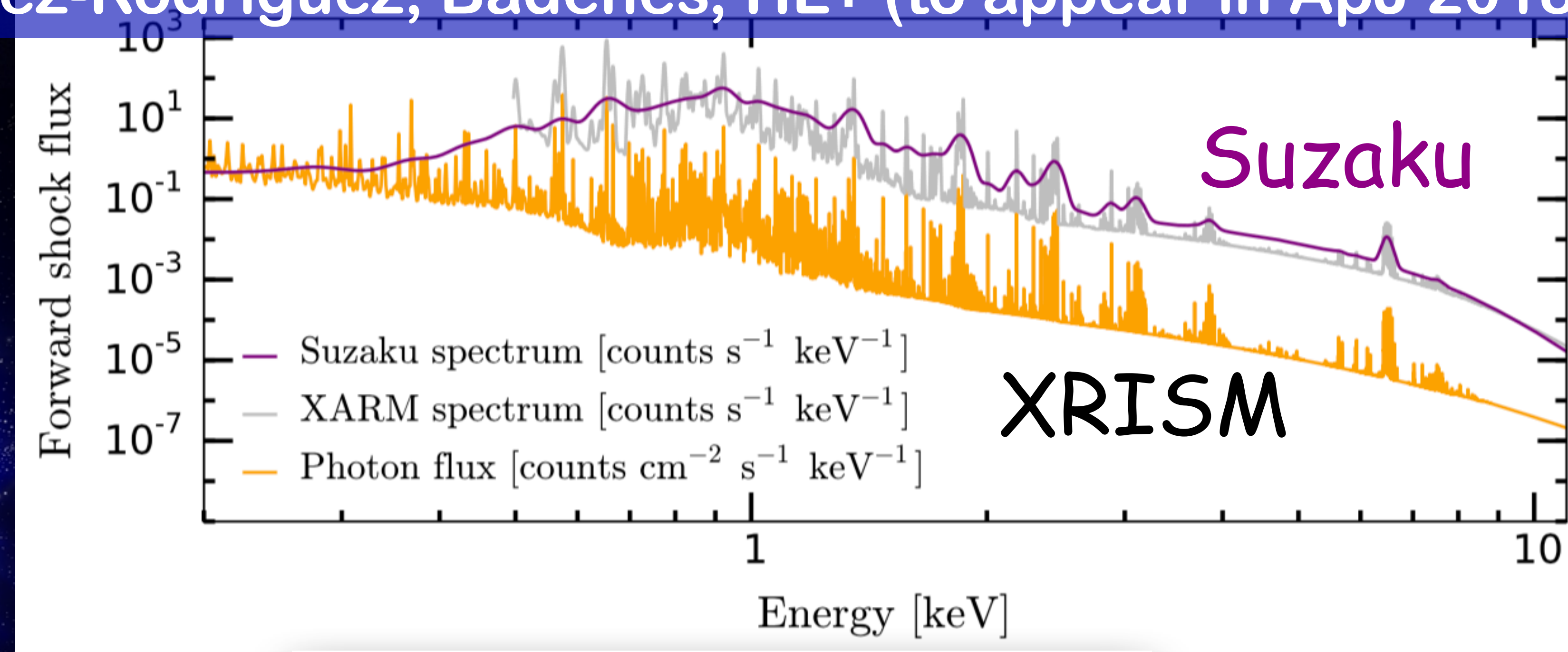


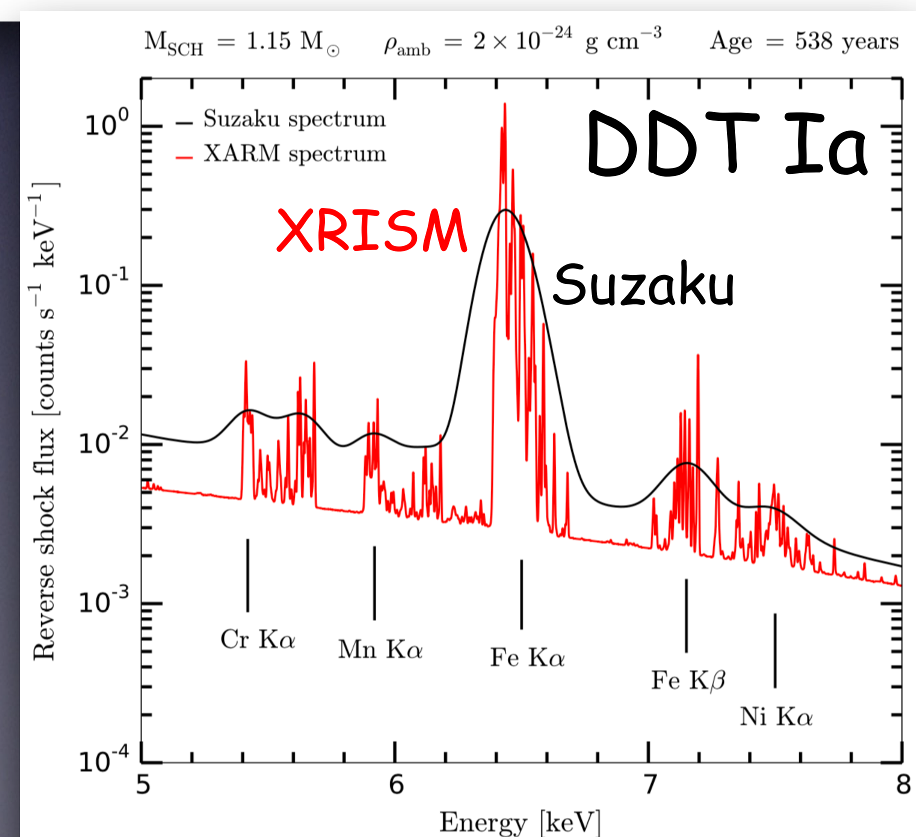
- Difference in mass loss history also inherited in line-of-sight projected X-ray line profiles
- A battle of CSM vs ejecta
  - density, dynamics, temperatures

Extensive grid of end-to-end simulations to interpret future μ-cal X-ray spectra

Martinez-Rodriguez, Badenes, HL, Patnaude, & Yamaguchi+

Martinez-Rodriguez, Badenes, HL+ (to appear in ApJ 2018)





Summary

- We have reviewed the general methodology and capabilities of modern broadband models for SNRs
- Current limitations are mainly from yet incompletely understood microphysics
  - Rely on rich MW observational data AND breakthroughs from first principle simulations to remove "free" parameters
- The future will be on progenitor-SN-SNR connection
  - Bigger picture, less ambiguous, "multi-disciplinary", more fun