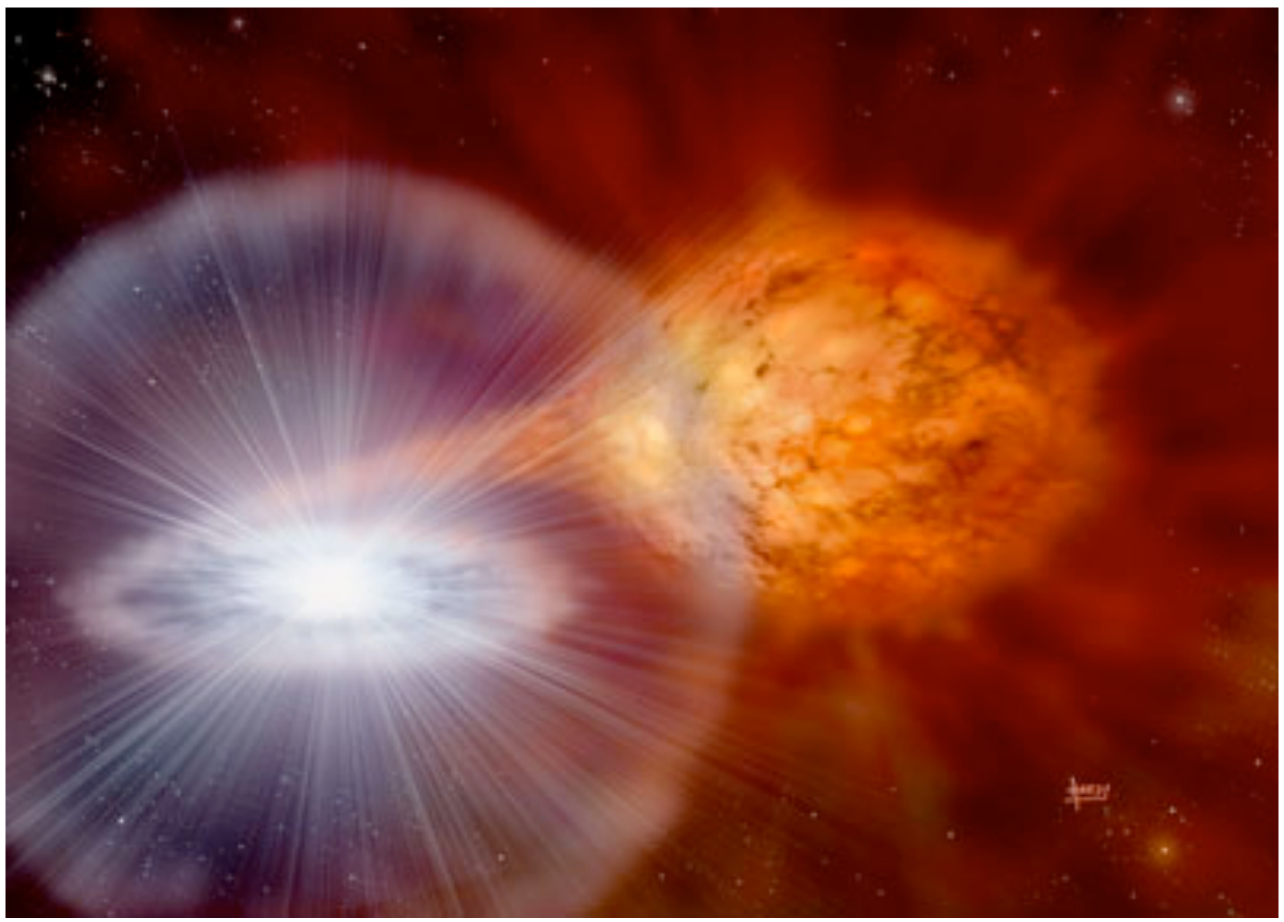
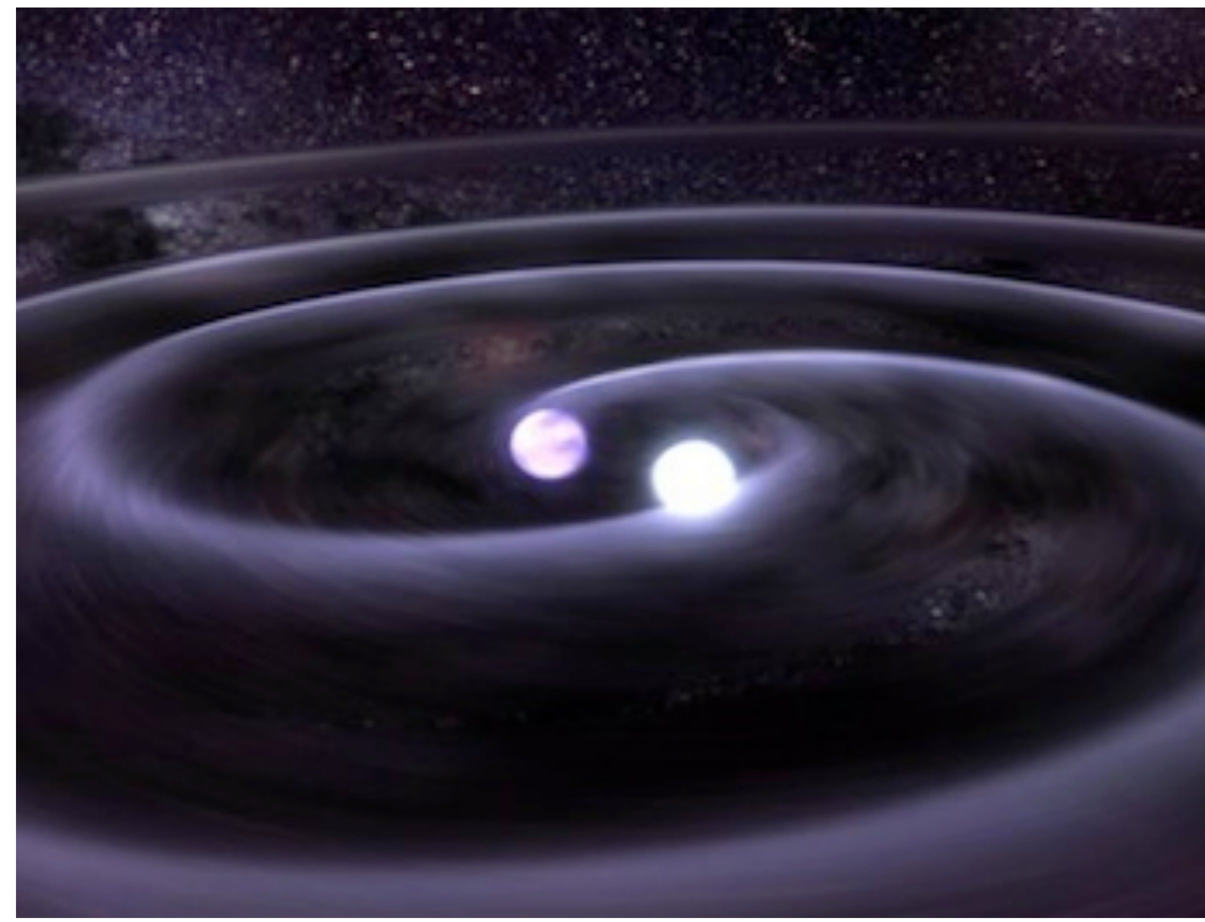
Type Ia supernova progenitor issue
~ recent progress and future prospect ~





Hiroya Yamaguchi (JAXA/ISAS)

Outline

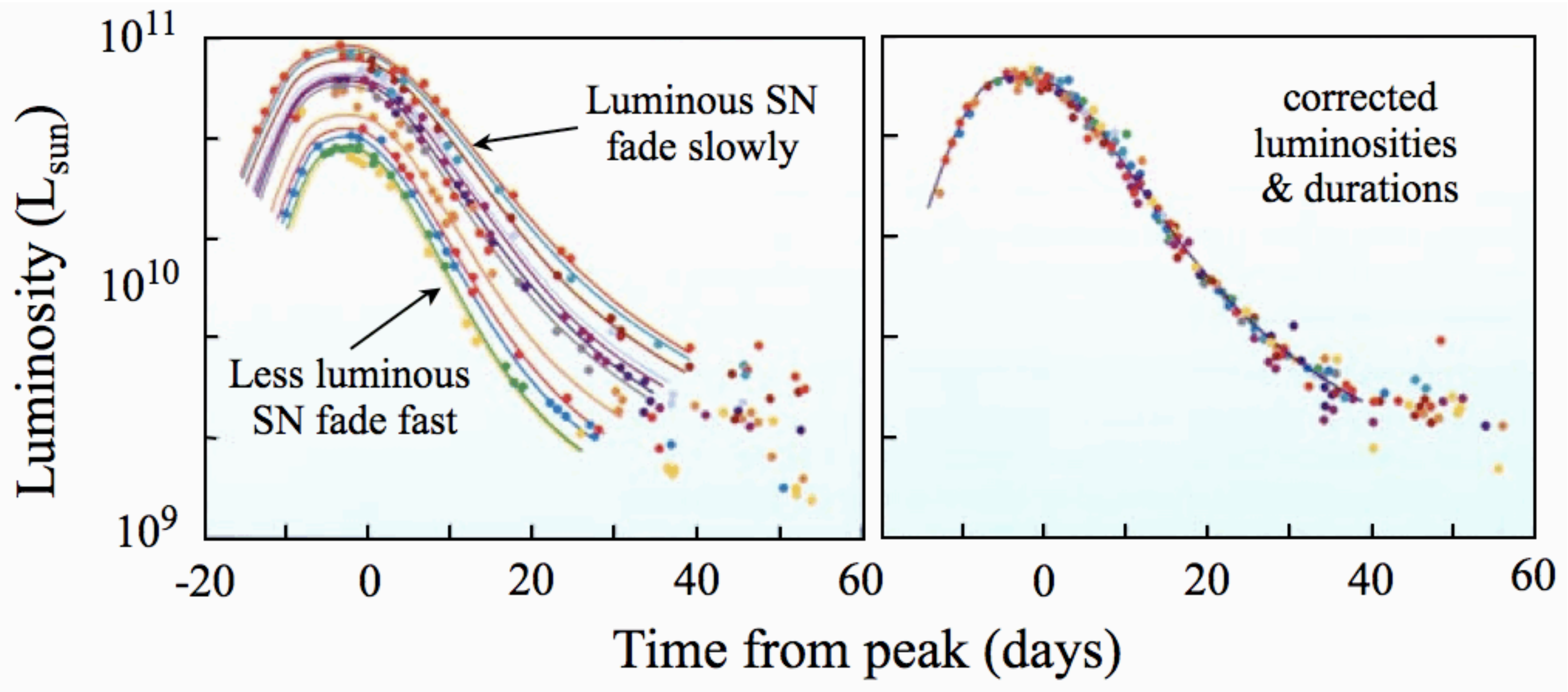
- Type Ia supernova progenitor issue
  - Single Degenerate vs Double Degenerate
  - Review recent studies against SD scenario
  - Variety of DD models
  - Supernova remnant with an SD origin
- Future prospects
  - <u>XMM/NuSTAR joint observations of 3C 397</u>
  - Gravitational wave with space interferometers

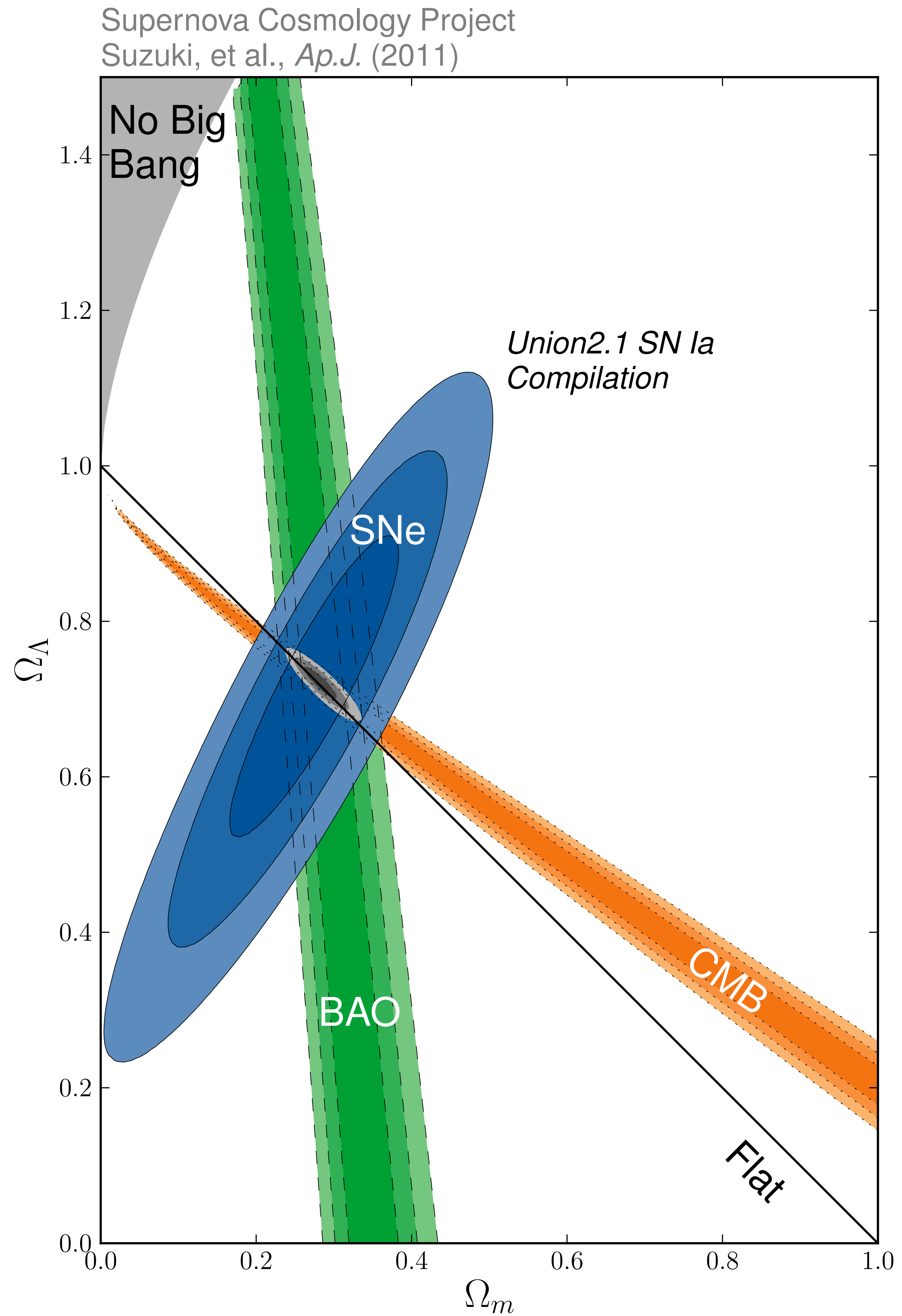
Type Ia supernovae (SNe Ia)

"Standard candle" in cosmology

As bright as one galaxy at L_{max}

Almost uniform brightness

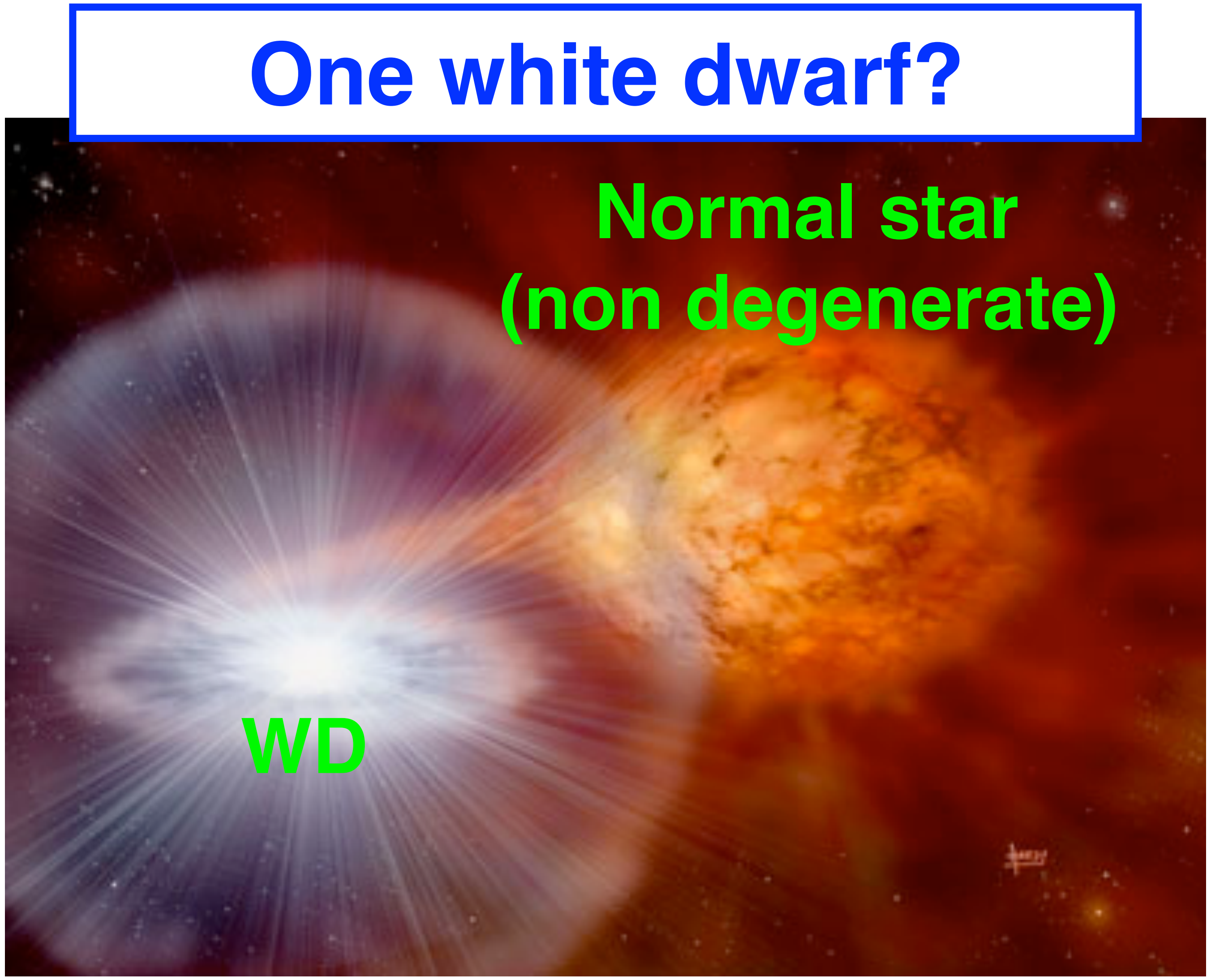




Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)
No Big Bang
Union2.1 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

SN Ia progenitor issue

Origin binary system still unknown

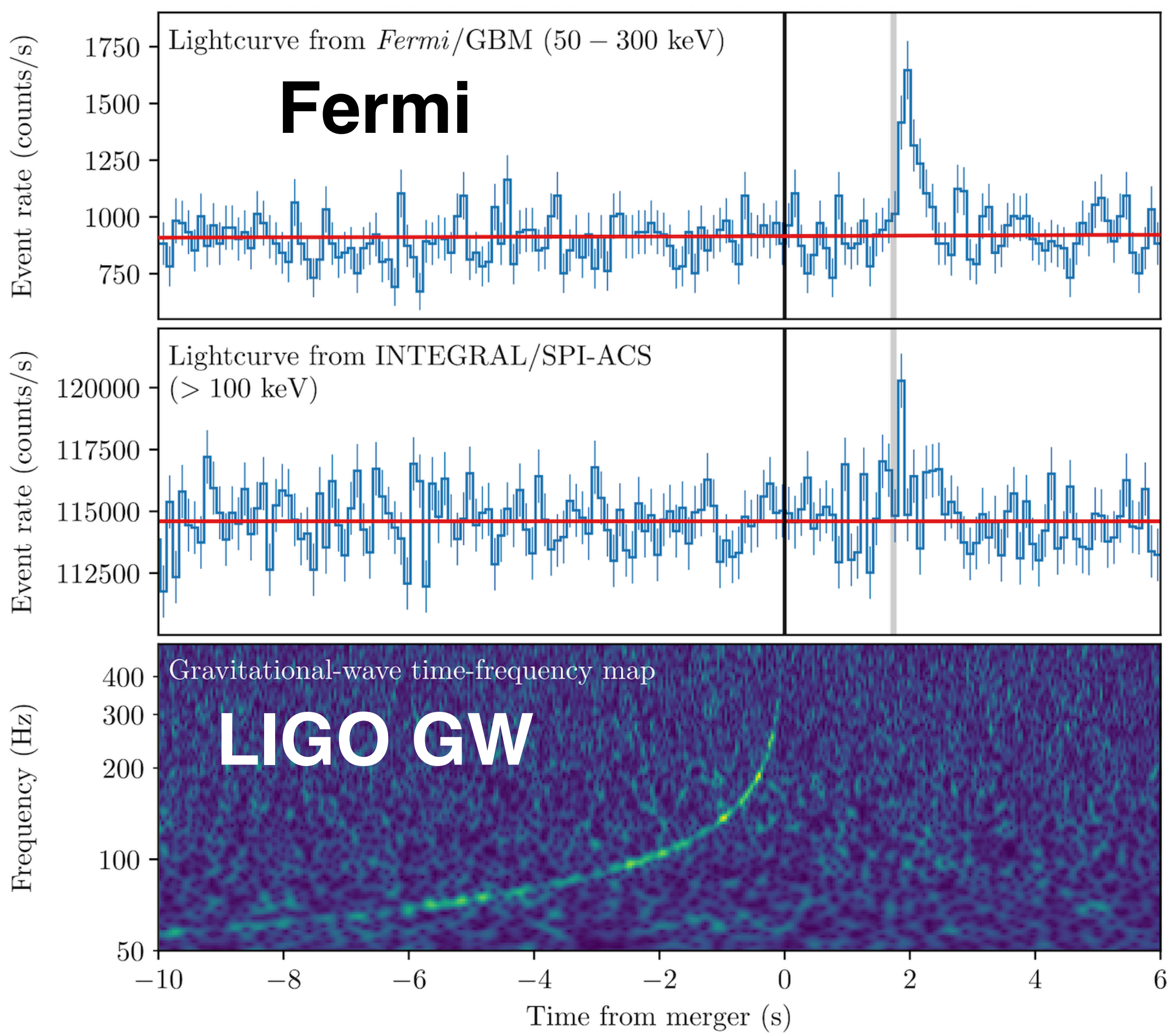


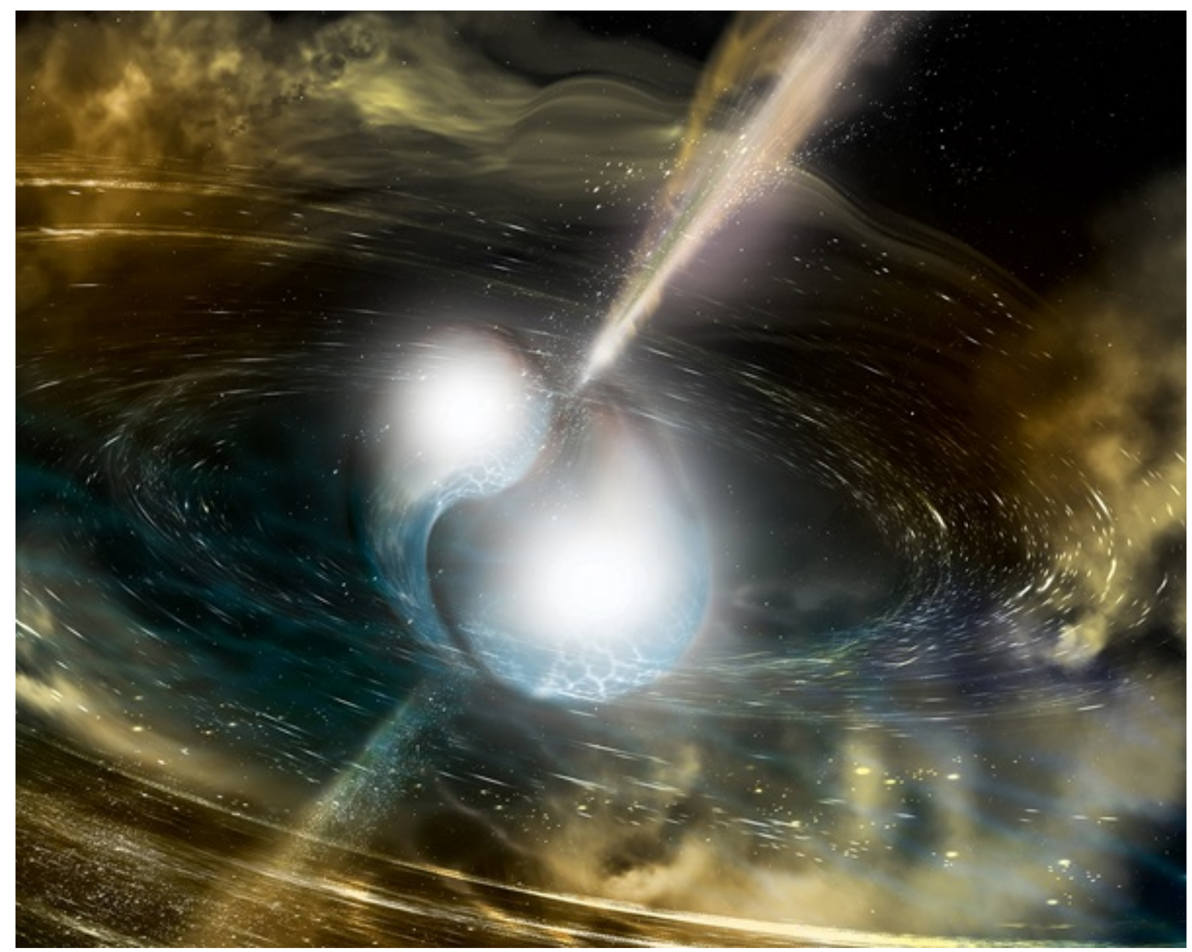
SNe Ia observed since 1940s

cf. Kilonova (GW source)

The term "kilonova" first used in 2010

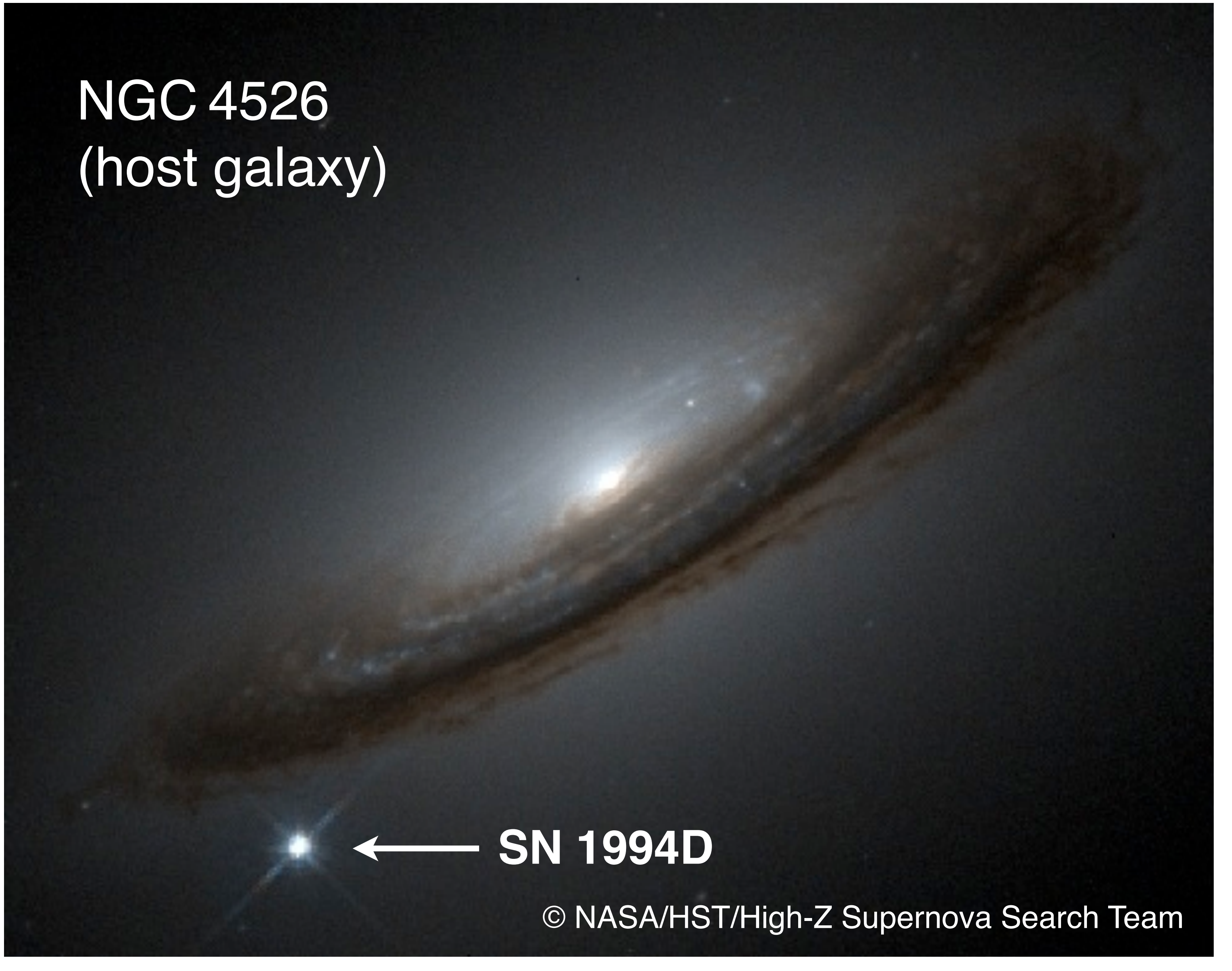
GW170817





NS-NS merger = Short GRB = Kilonova = *r*-process source

SN Ia's environment

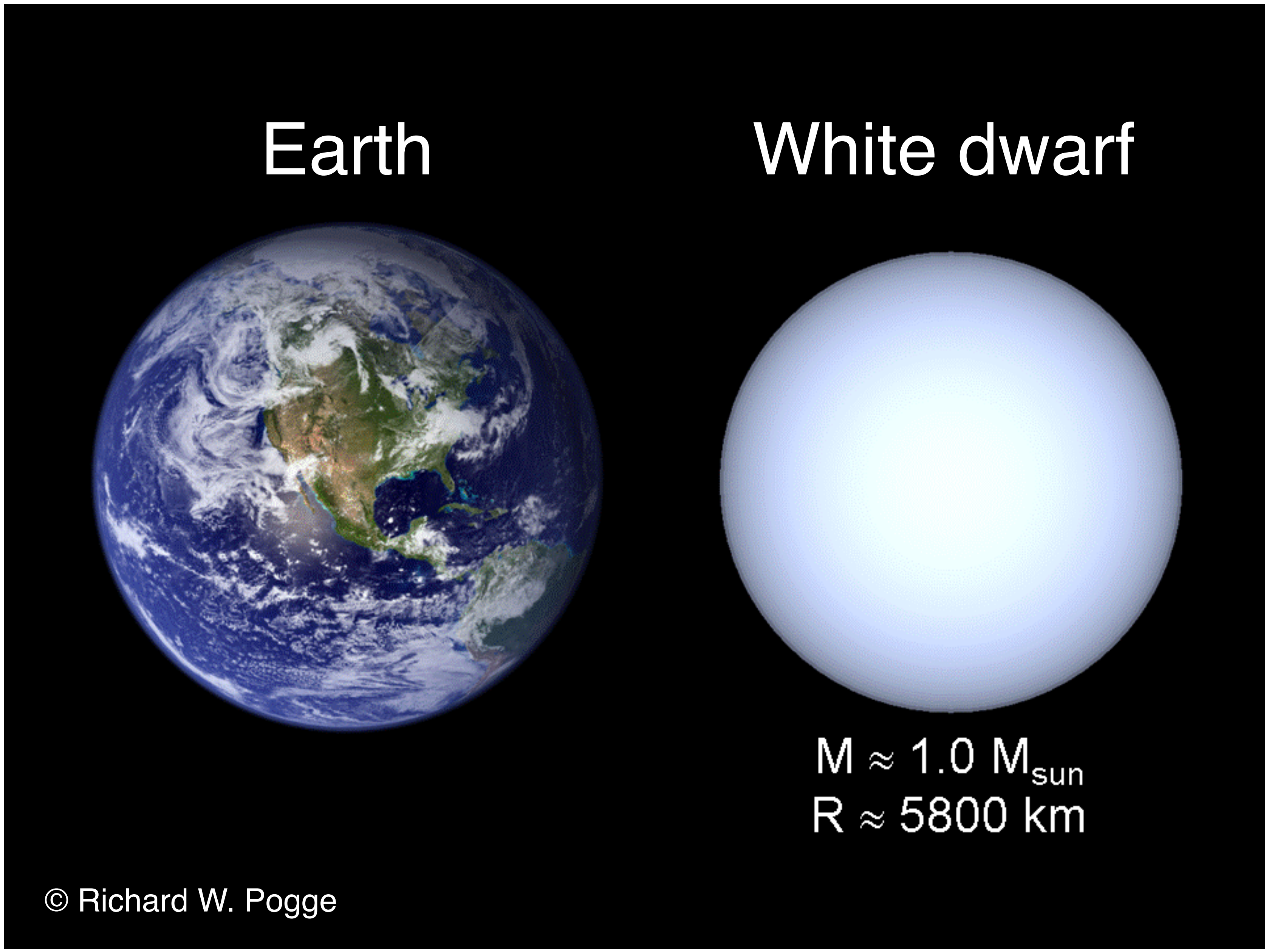


Not associated with star-forming regions

→ **Old progenitors (i.e., not massive stars)**

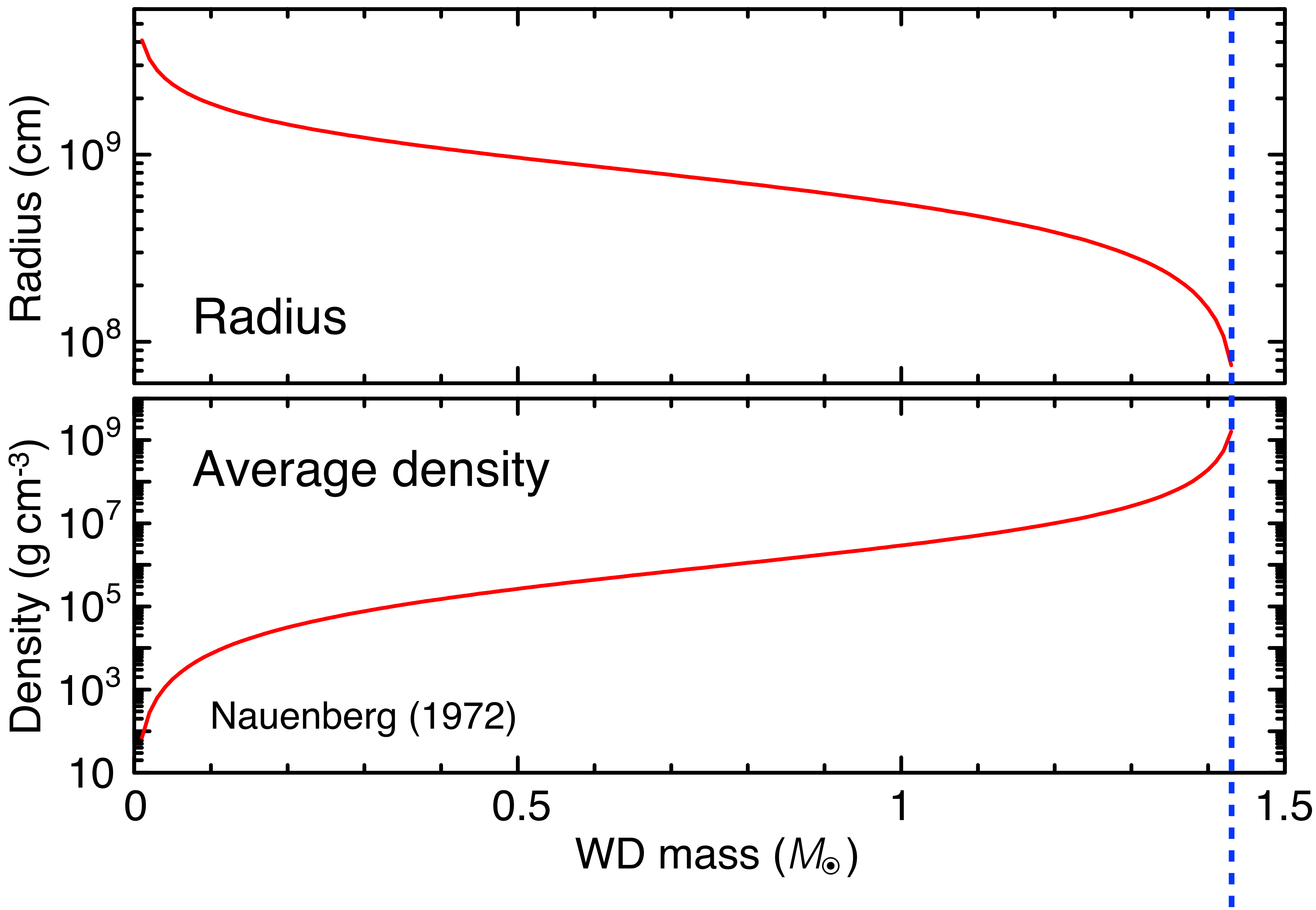
SN Ia's progenitor/nature

Thermonuclear explosion of white dwarfs



Compact star supported by degeneracy pressure

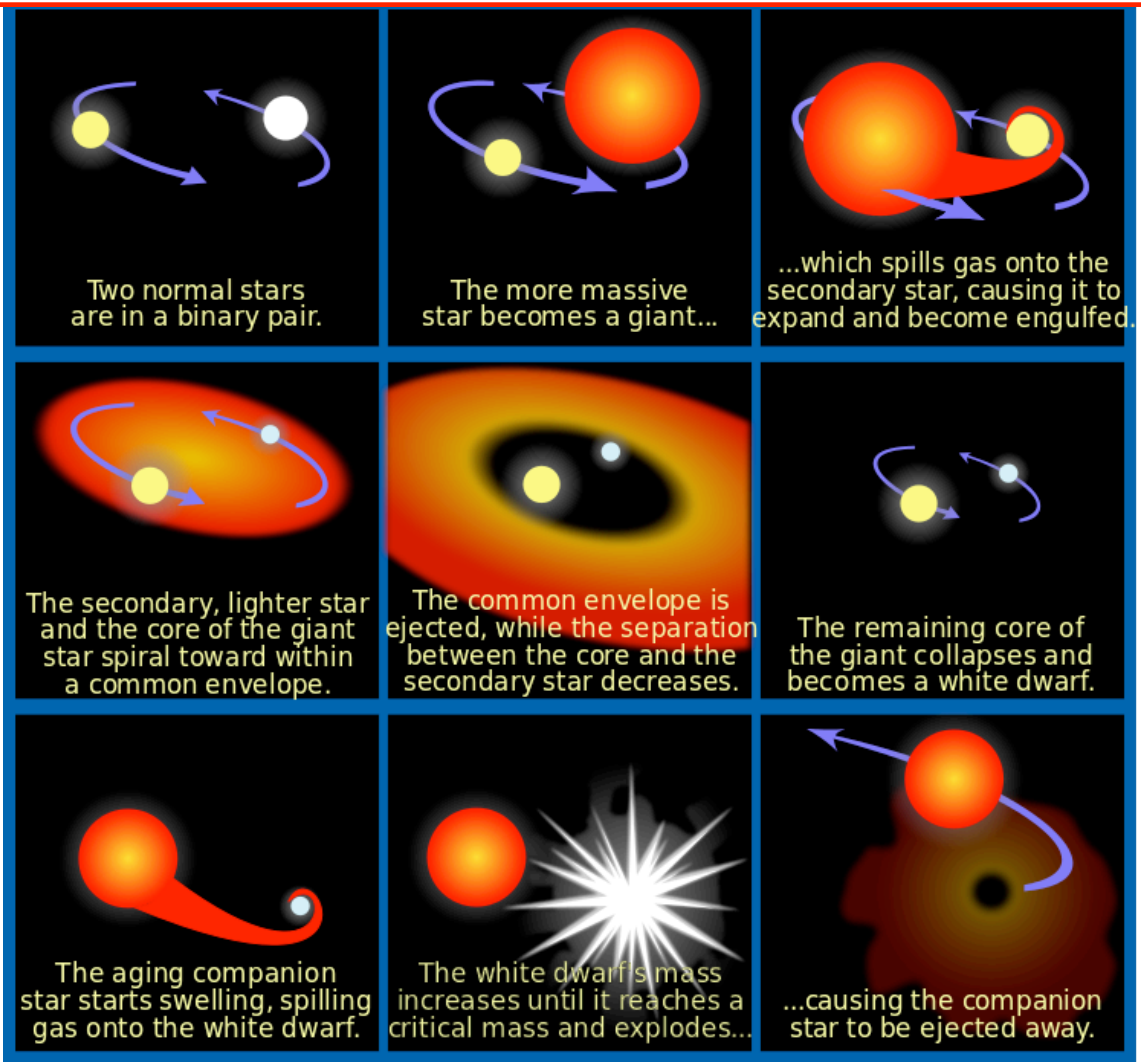
There is a mass limit!



Chandrasekhar limit (M_{Ch})

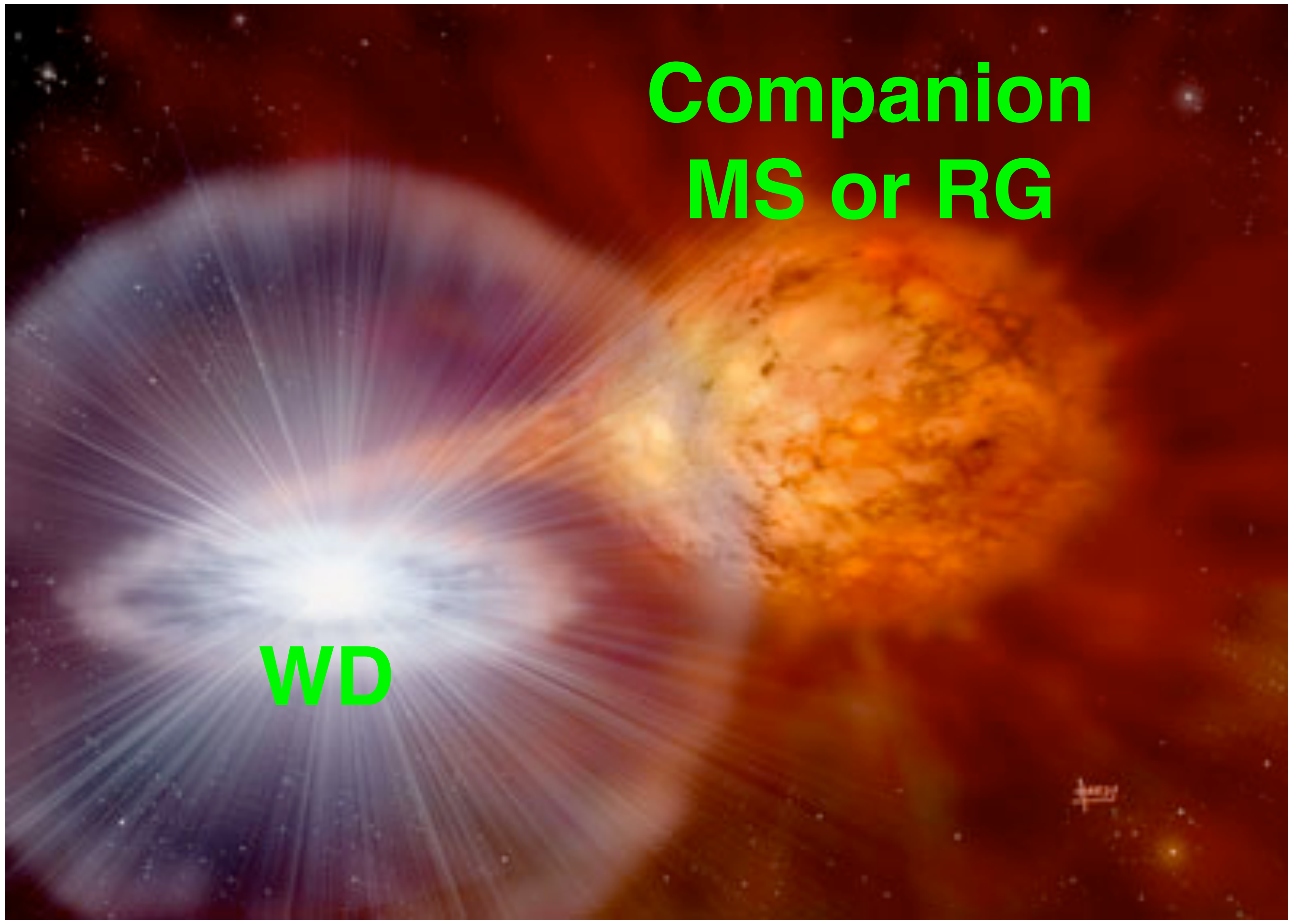
Degeneracy pressure can no longer support self-gravity

Progenitor evolution in *'standard'* scenario



Standard scenario now doubted

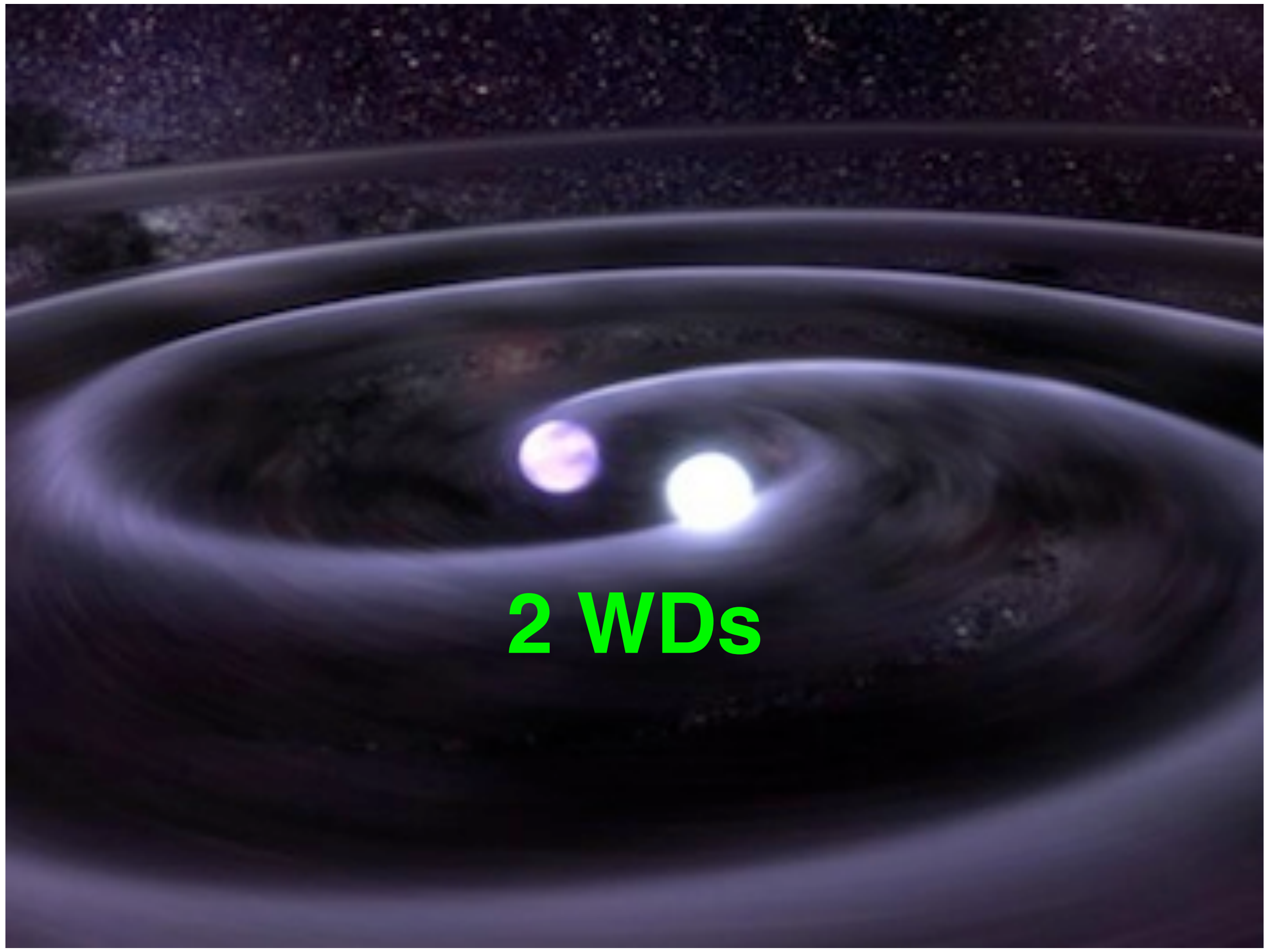
Single Degenerate (SD)



WD + MS or RG

Mass accretion to get ~ M_{Ch}

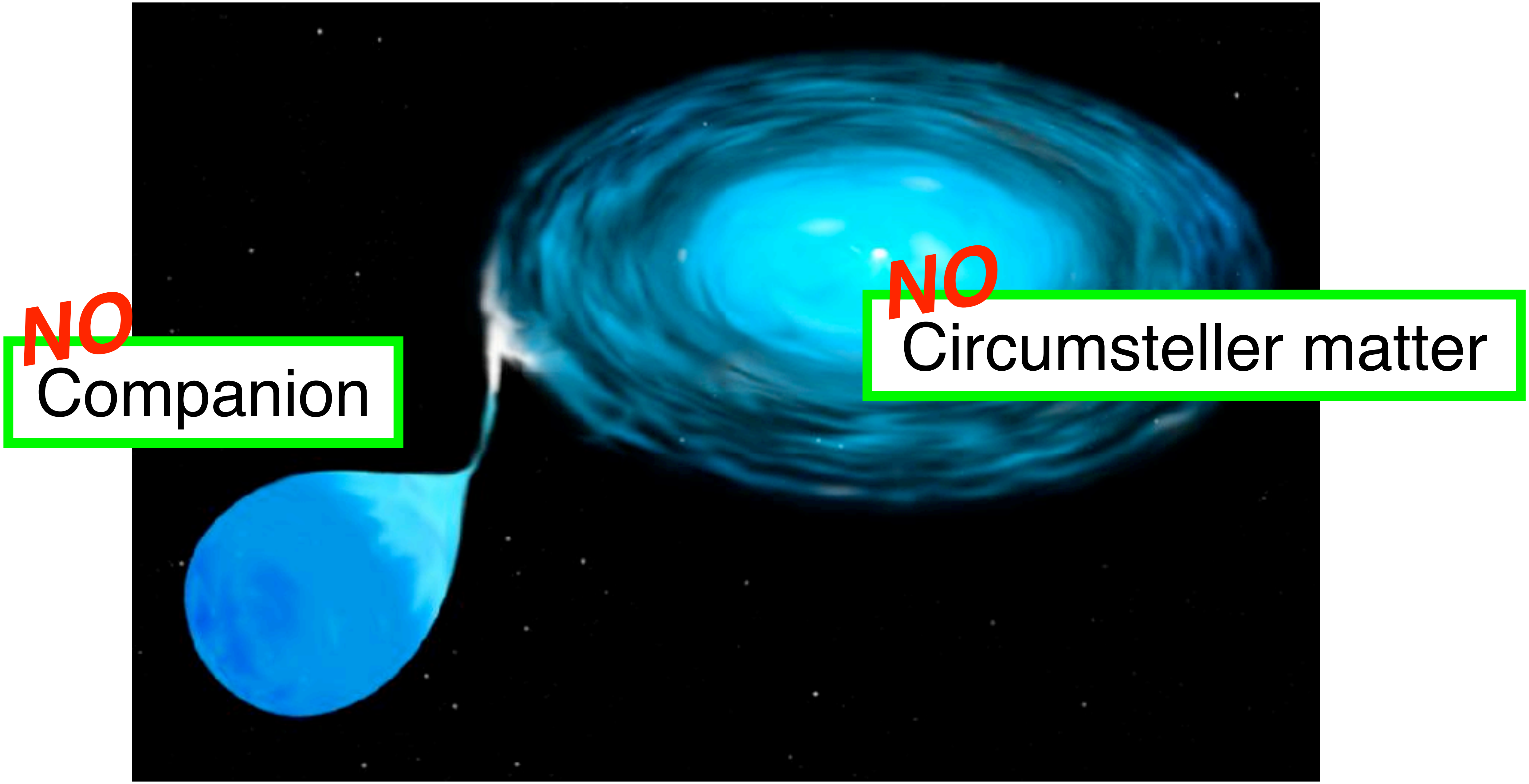
Double Degenerate (DD)



WD + WD binary

Merger or one WD explosion

Evidence against SD scenario



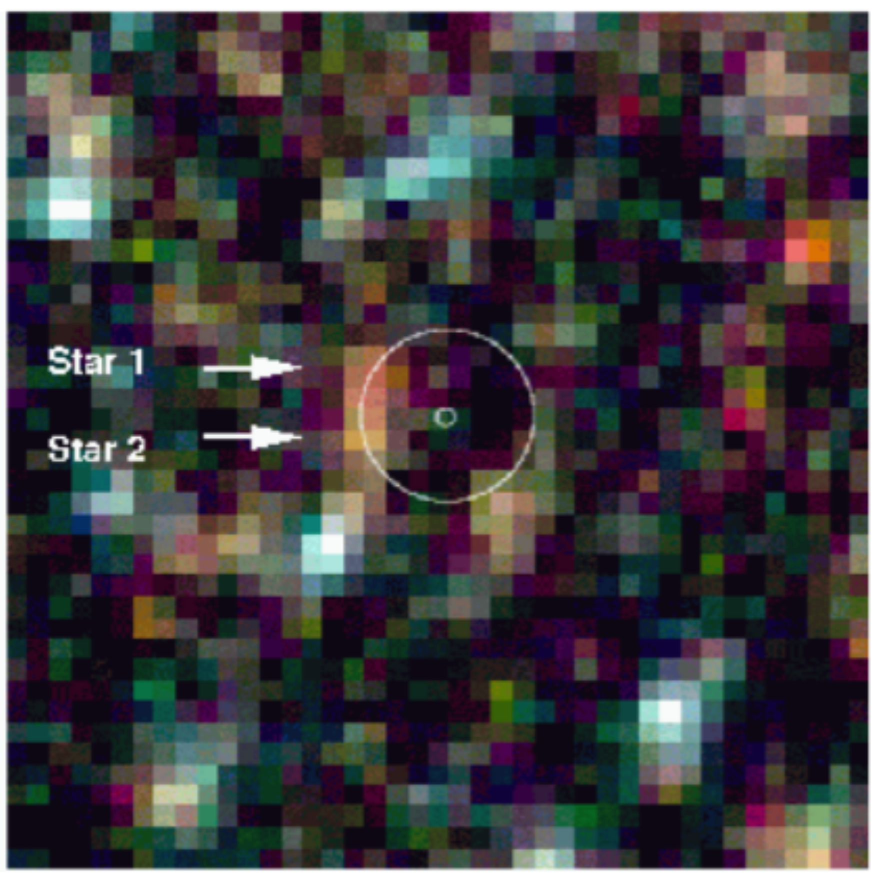
Search for pre-explosion companion

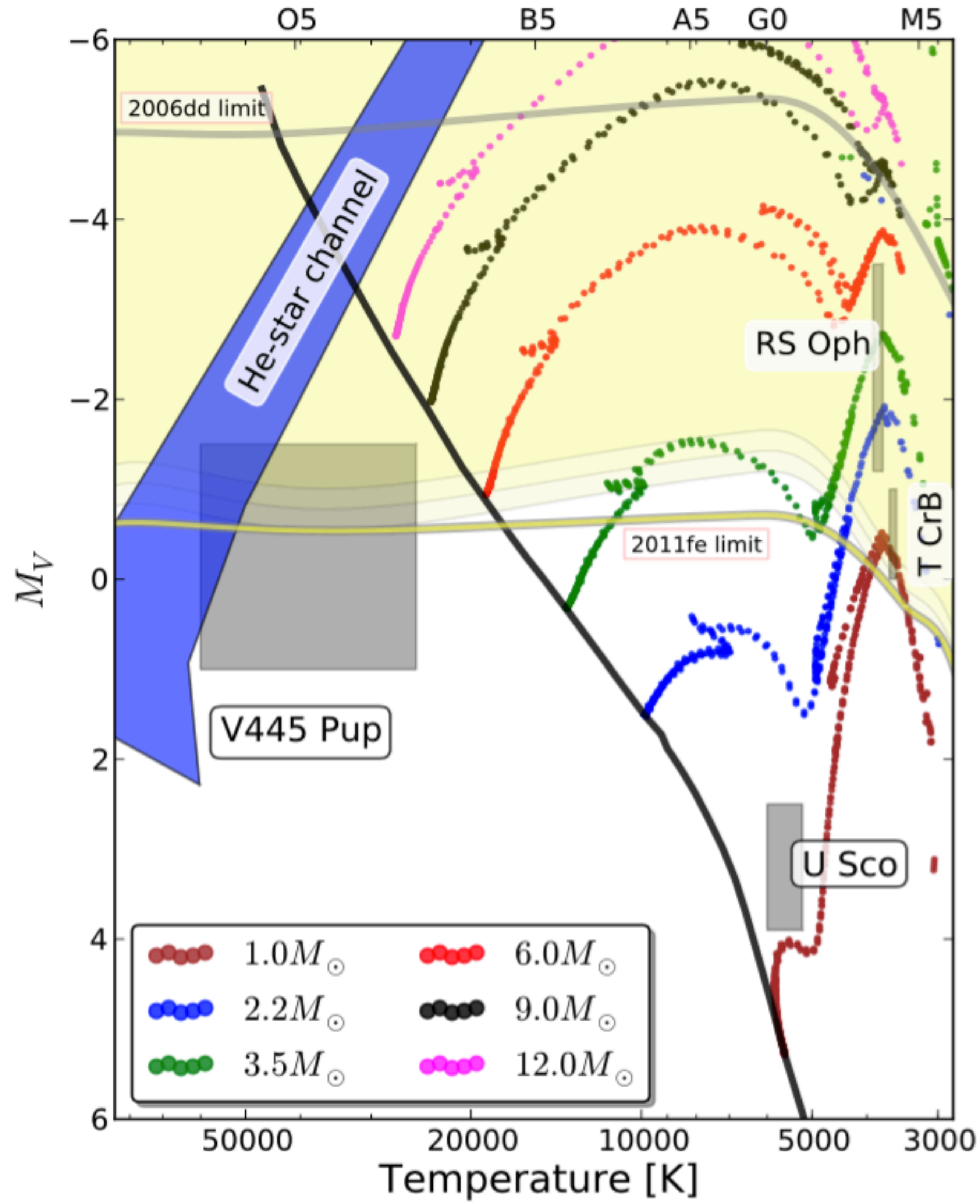
SN 2011fe (M101/Pinwheel Galaxy: 6.4 Mpc)

Search for pre-explosion companion

SN 2011fe:

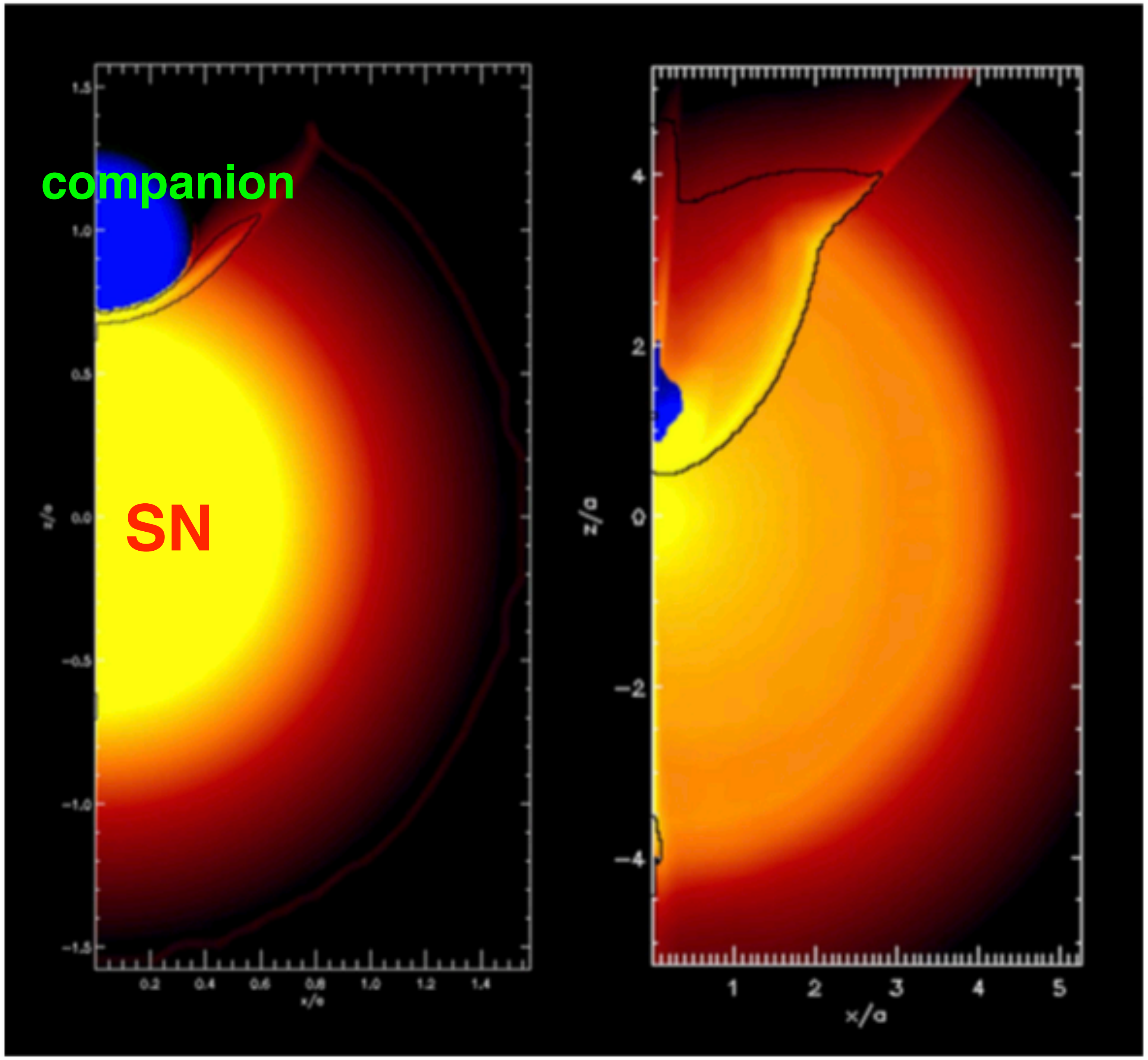
Hubble Space Telescope rules out > 3.5$M_\odot$ MS and RG companion (Li+2011)





Companions can survive explosion

Kasen 2010



Search for surviving companion

SNR 0509-67.5

in Large Magellanic Cloud

HST provided stringent U.L.

$M_V < +8.4,\ L_V < 0.04 L_{\odot V}$

➔ **All SD cases ruled out**

(Schaefer+2012, Litke+2017)

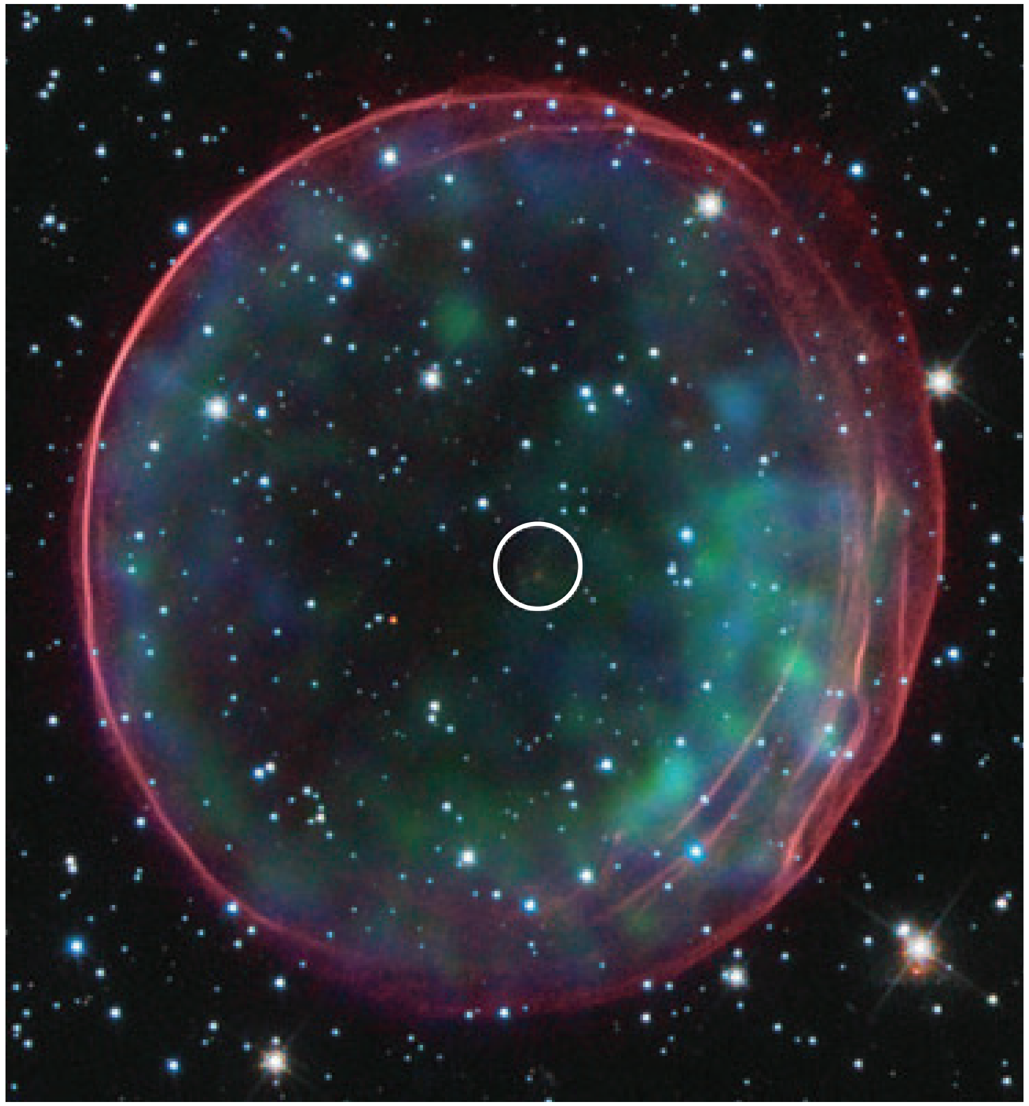
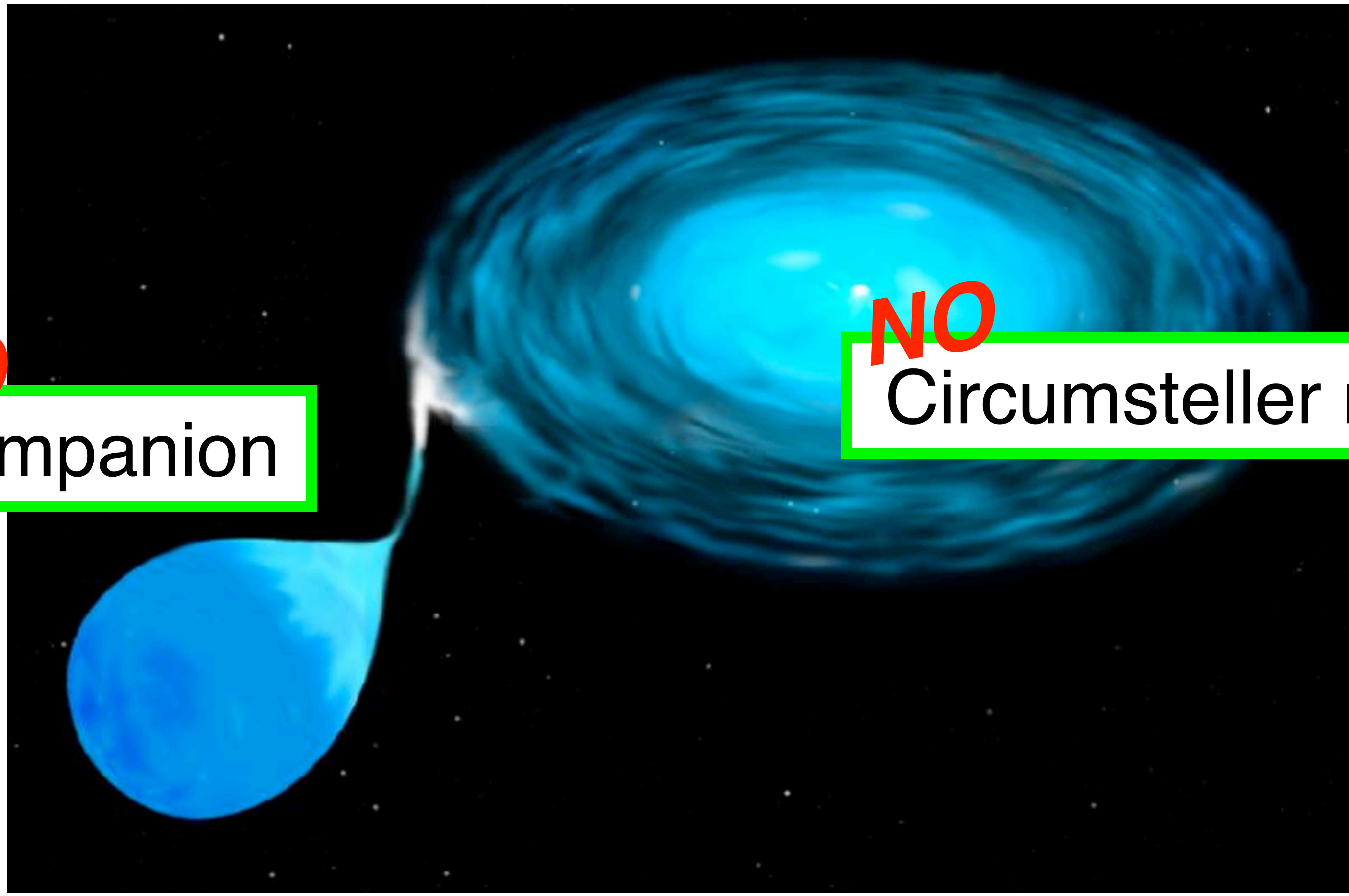


Table 1 | Candidate progenitor classes

Candidate class	P_{orb} (d)	$v_{ex\text{-}comp}$ (km s^{-1})	Surviving companion	M_V (mag)	V range in LMC (mag)
Double-degenerate	NA	NA	None	NA	NA
Recurrent nova	0.6–520	50–350	Red giant or subgiant	−2.5 to +3.5	16–22
Symbiotic star	245–5,700	50–250	Red giant	−2.5 to +0.5	16–19
Supersoft source	0.14–4.0	170–390	Subgiant or >1.16 $M_{\odot}$ MS	+0.5 to +4.2	19–22.7
Helium star donor	0.04–160	50–350	Red giant or subgiant core	−0.5 to +2.0	18–20.5
Spin-up/spin-down	245–5,700	50–250	Red giant or subgiant core	−0.5 to +2.0	18–20.5

Evidence against SD scenario

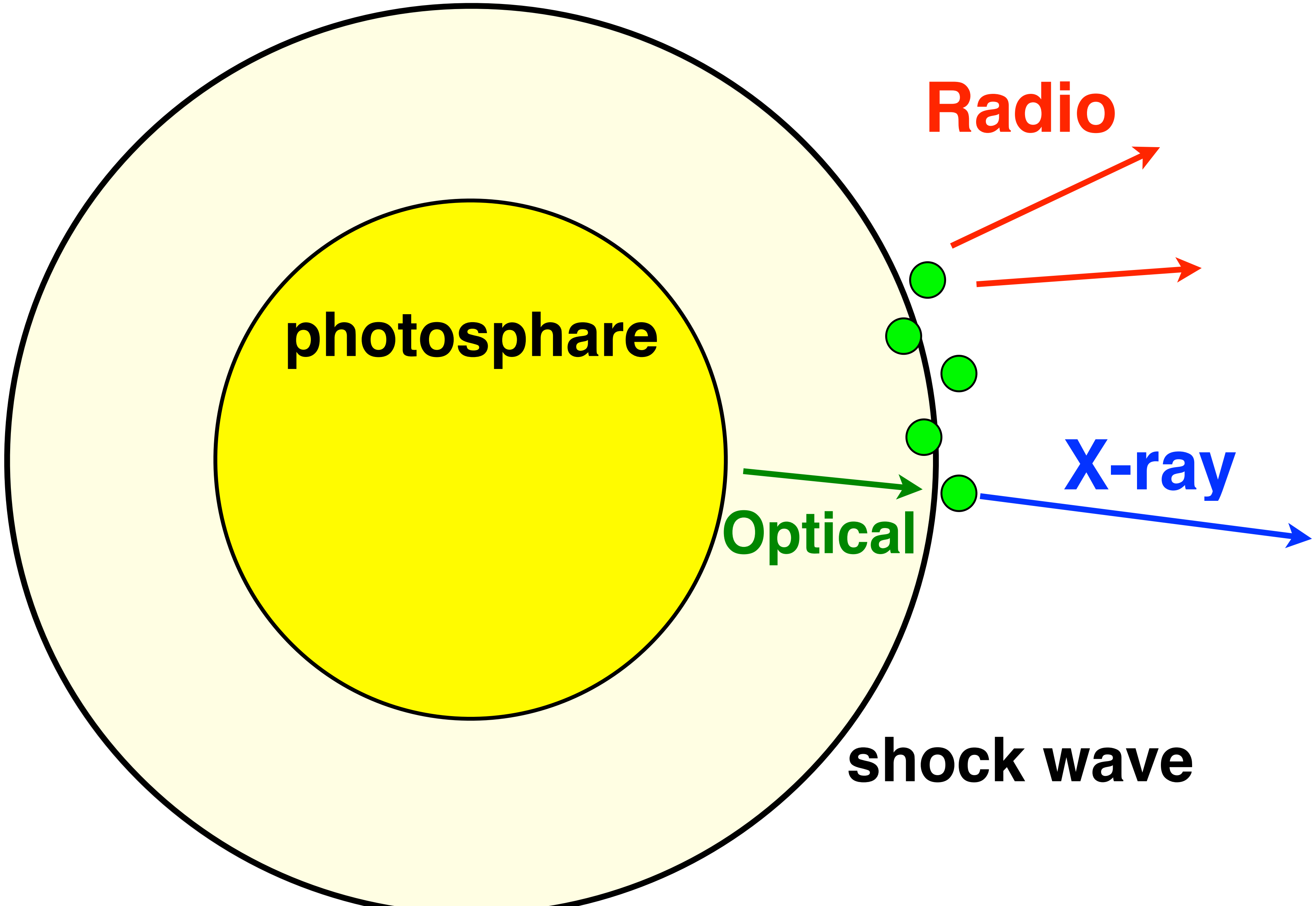


Over-accreting materials form CSM (Hachisu+1996)

Search for CSM in SNe

Collision b/w ejecta and CSM ➔ shock wave

➔ radio (nonthermal e-) + X-rays (IC with optical)



Search for CSM in SNe

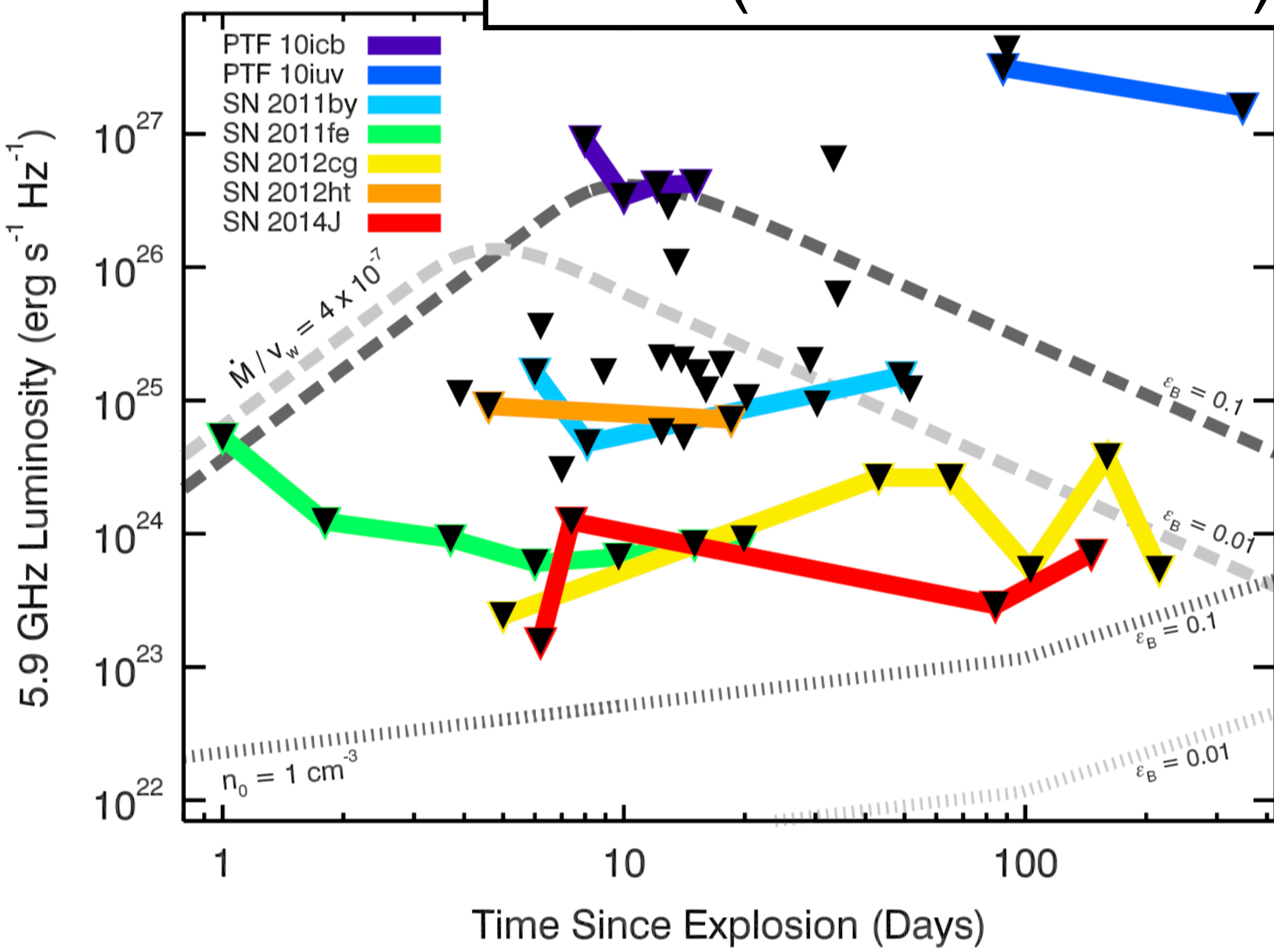
Collision b/w ejecta and CSM ➔ shock wave

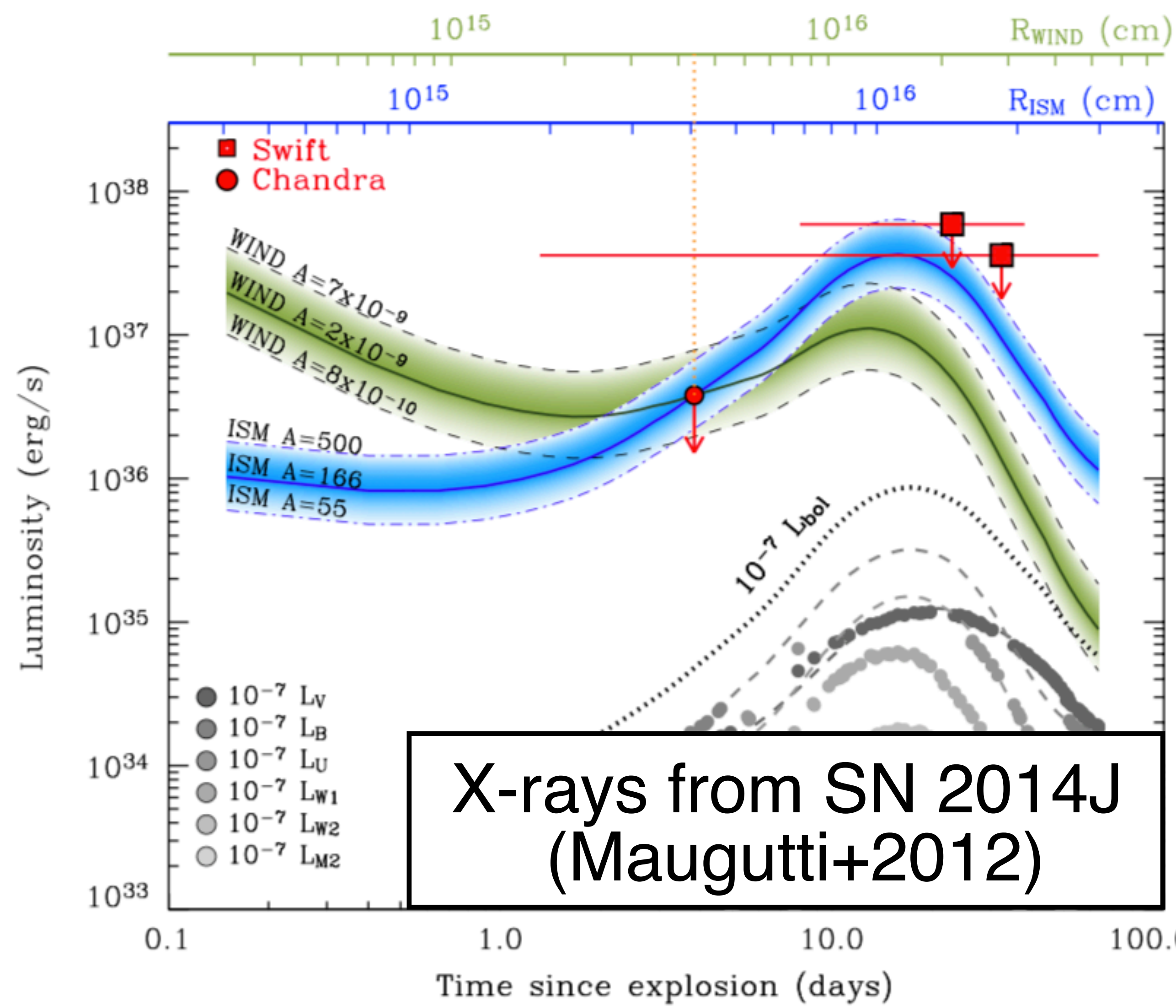
➔ radio (nonthermal e-) + X-rays (IC with optical)

No significant detection from SNe Ia

(e.g., SN 2014J: dM/d$t \lesssim 10^{-9}\,M_\odot\,\mathrm{yr}^{-1}$)

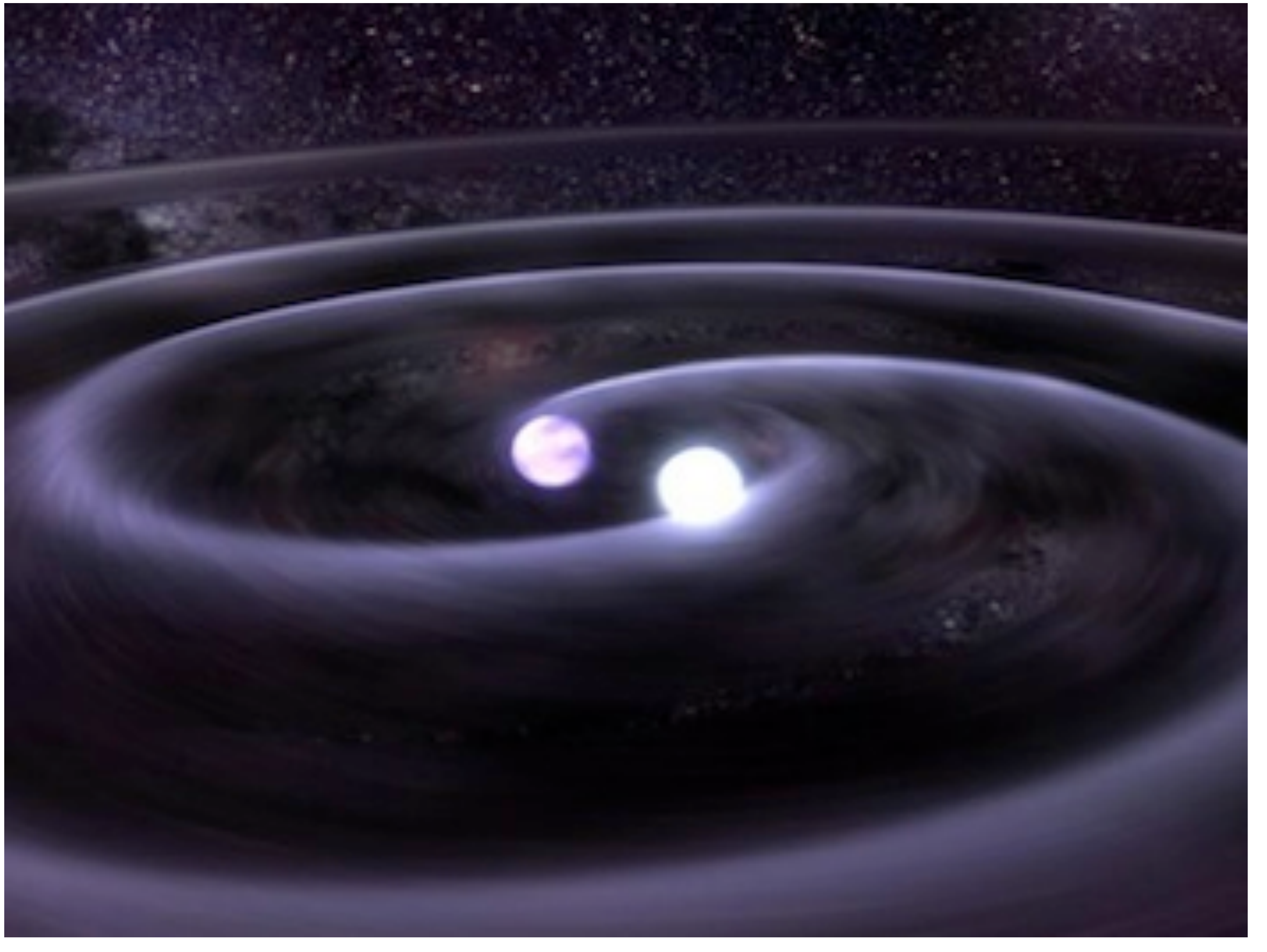
Radio (Chomiuk+2016)





X-rays from SN 2014J (Maugutti+2012)

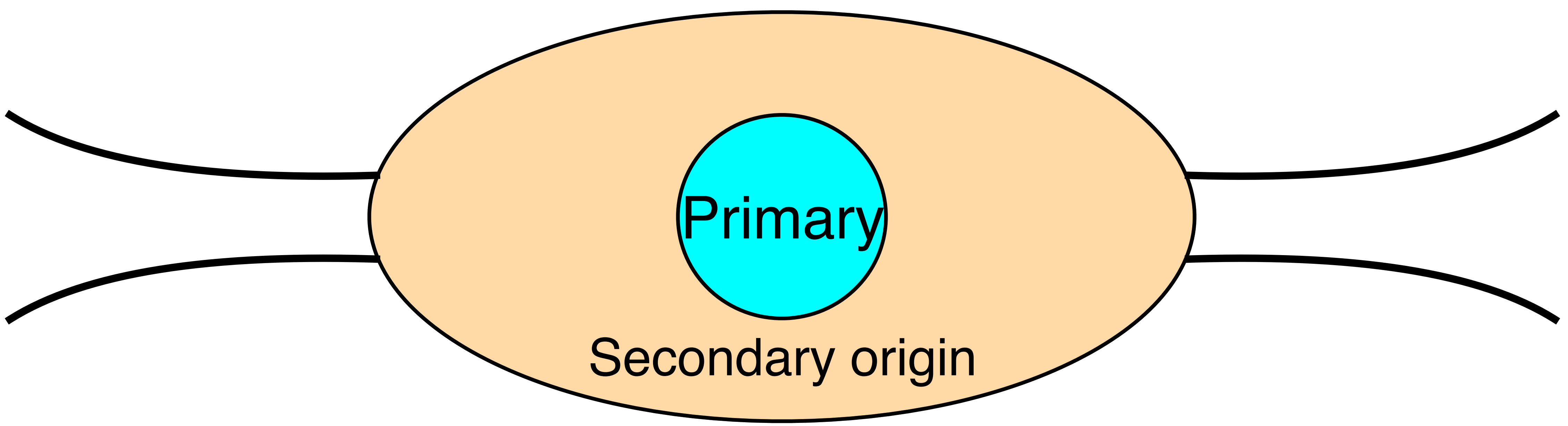
Double Degenerate (DD) scenario



No companion or CSM needed

Classical DD model (80s~90s)

The secondary WD accretes onto the primary so the total mass exceeds M_{Ch} (Webbink 1984)

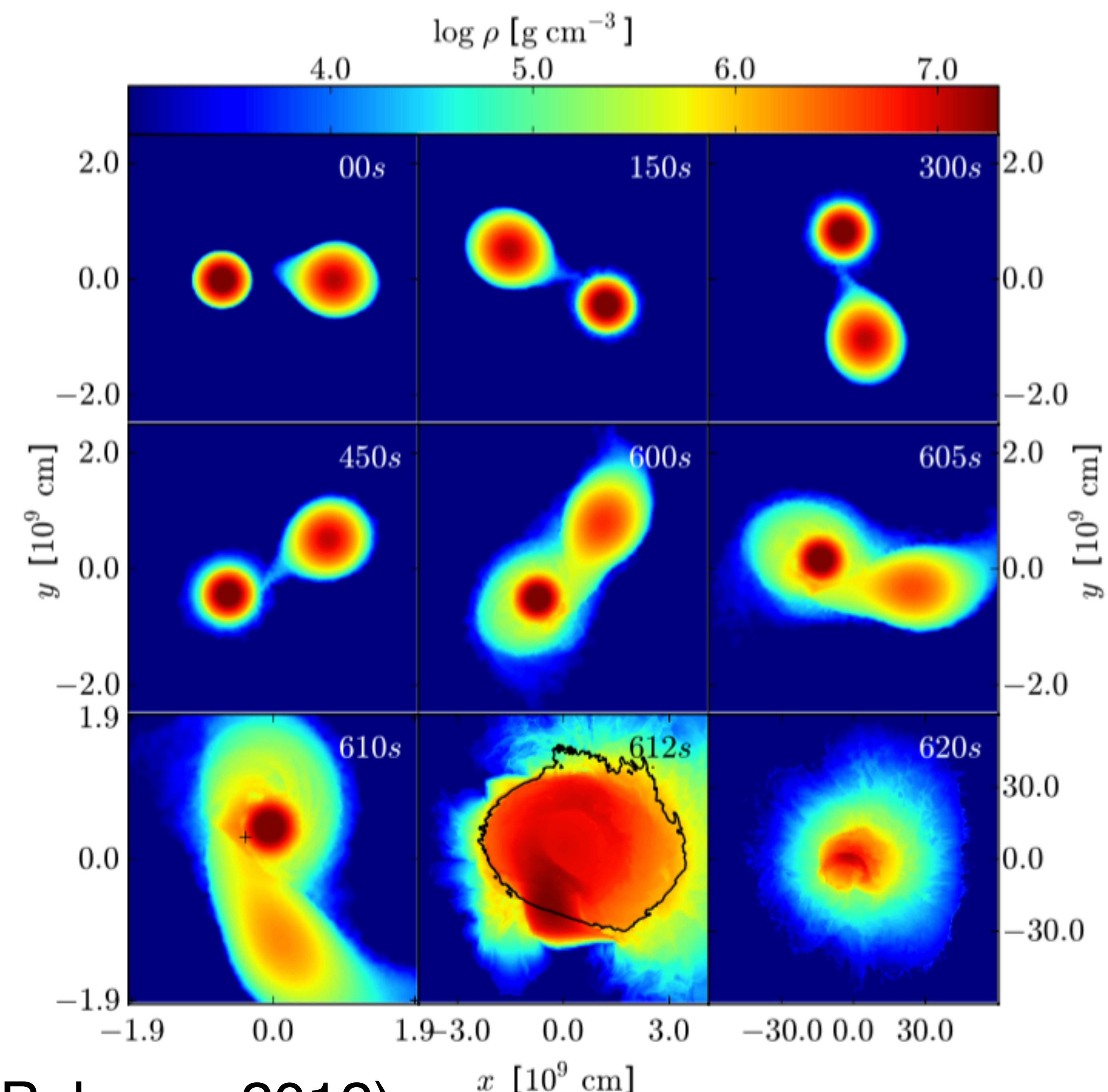


Explosion unsuccessful

Collapse into NS via O-Ne-Mg WD (Saio+1985)

Updated DD model

Violent merger (e.g., Pakmor+2010, 2012)



(Pakmor+2012)

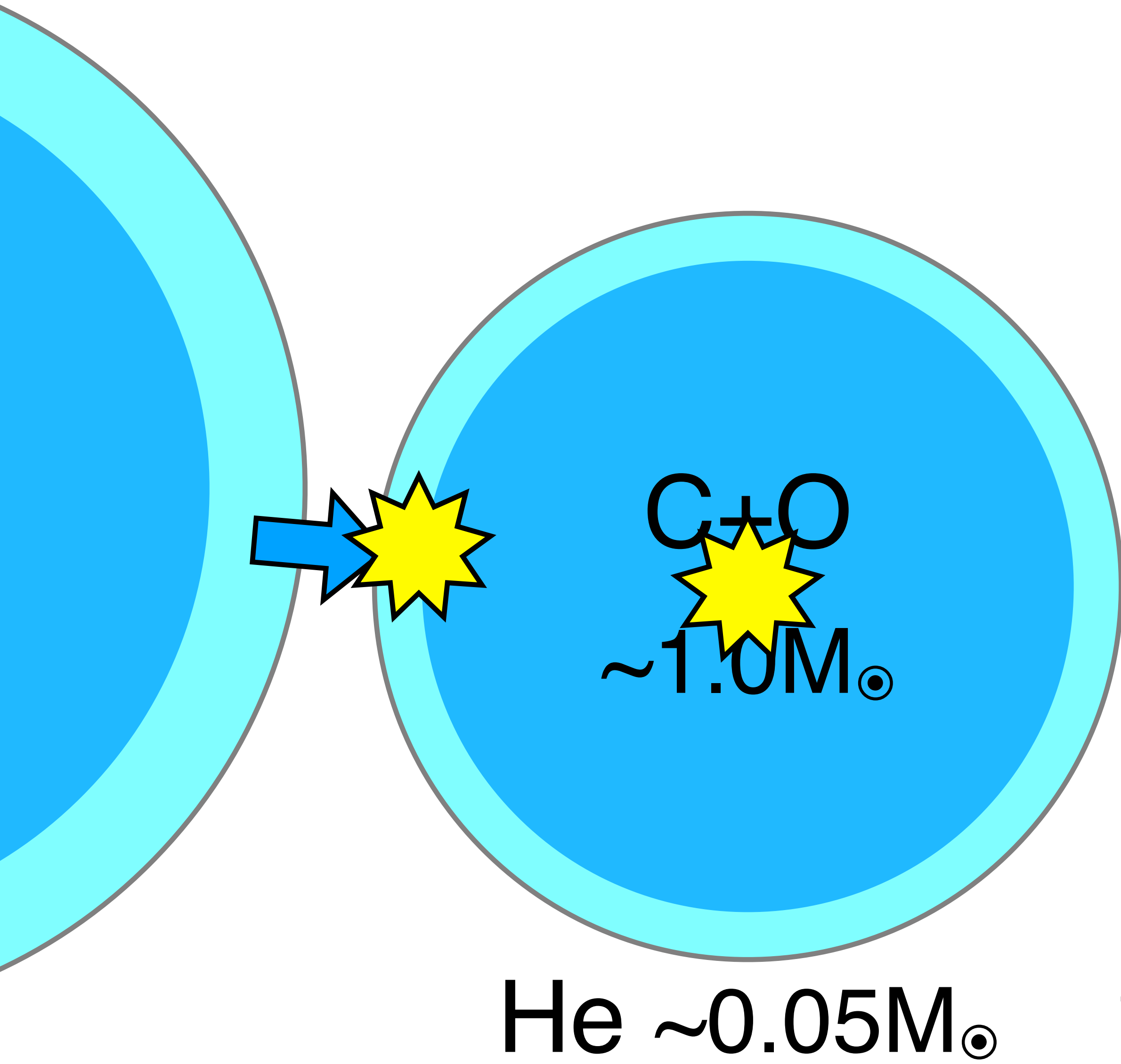
Explodes within ~ 100 s

M_1 ~1.1M$_\odot$, M_2 ~0.9M$_\odot$ required for typical SN Ia

Hard to explain observed SN rate.

Latest DD model

Dynamically-driven double degenerate double detonation (D^6: e.g., Shen+2018)



Accretion of tidally stripped materials from secondary ignites He detonation on primary surface

➔ Triggers C detonation

Secondary WD remains intact

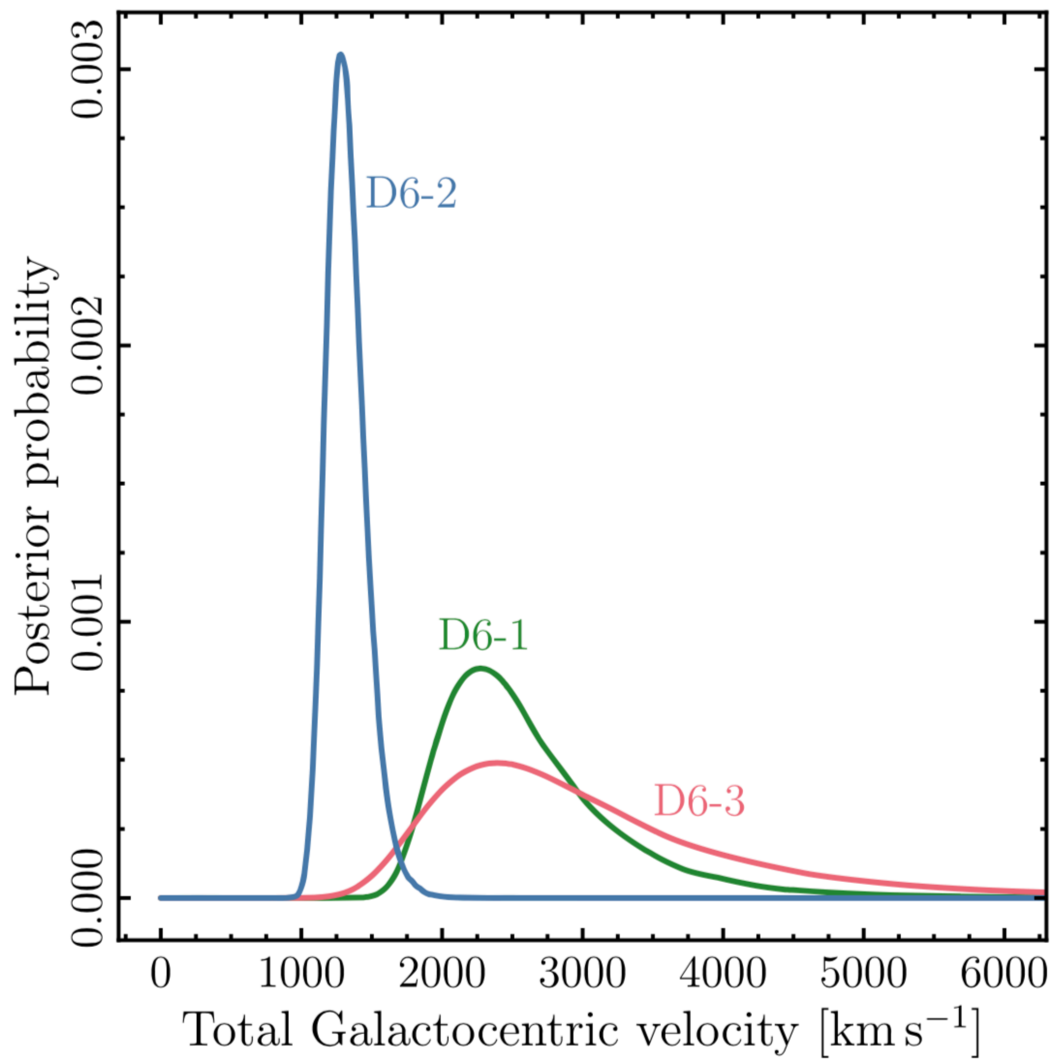
➔ sub-M_{Ch} ejecta + high-v WD

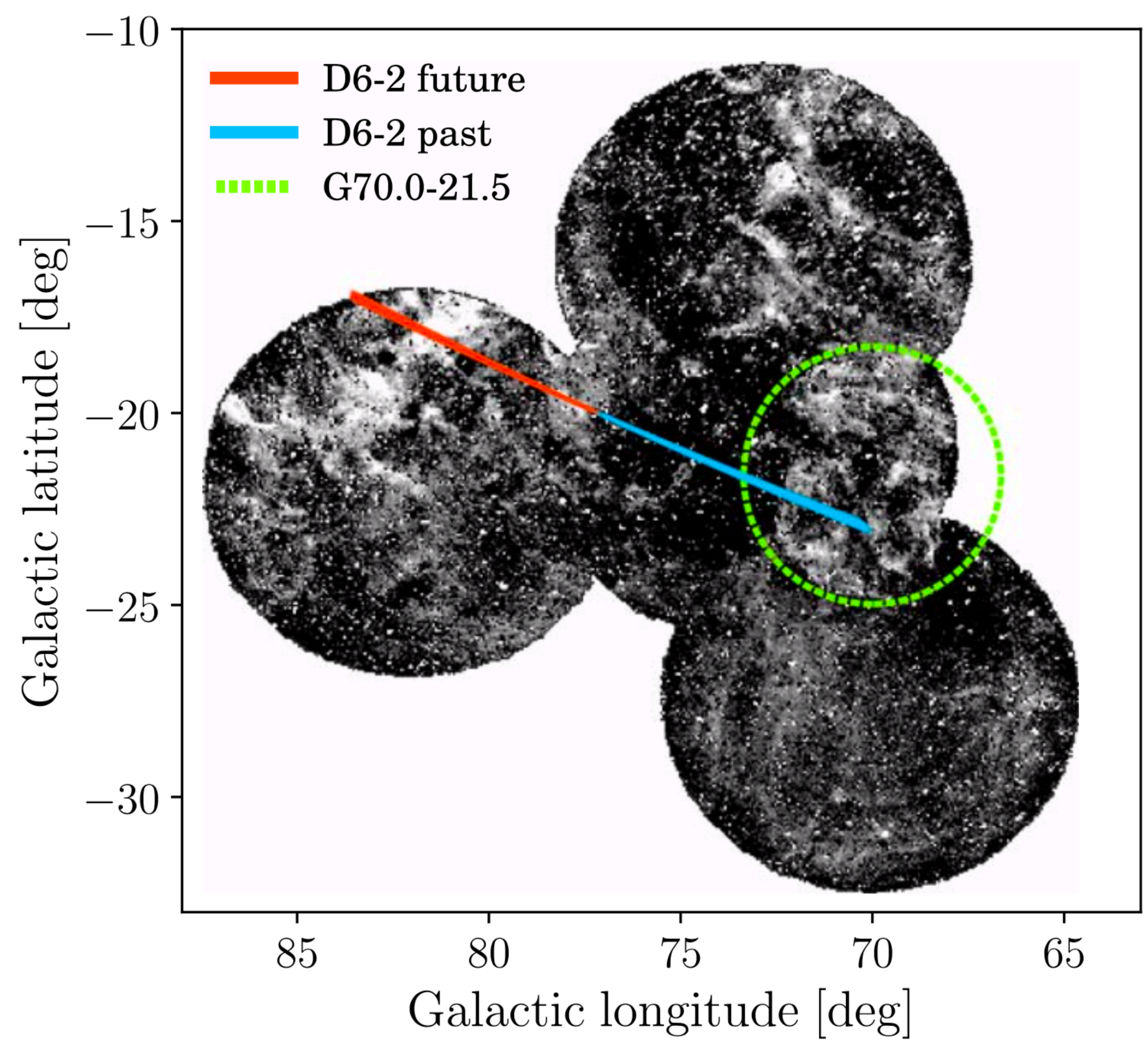
Evidence for D^6?

Three Hypervelocity White Dwarfs in *Gaia* DR2: Evidence for Dynamically Driven Double-degenerate Double-detonation Type Ia Supernovae

3 runaway ($v > 1000$ km/s) WDs discovered.
One of them likely associated with an SNR.

(Shen+2018)





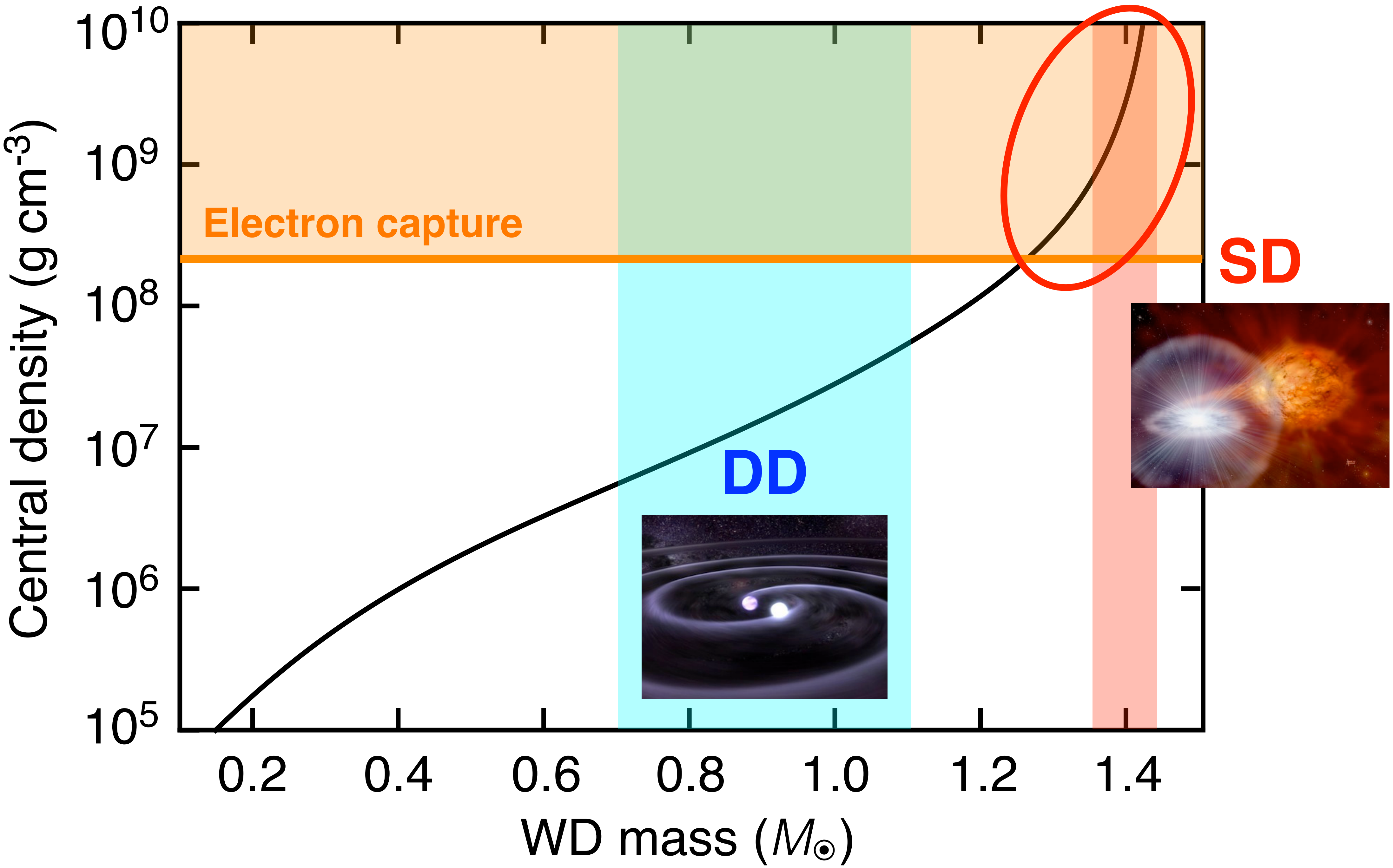
Suggested association

	SD	Classical DD	Violent merger	D[6]
Primary mass	M_{Ch}	M_{Ch}	sub-M_{Ch}	sub-M_{Ch}
Ejecta mass	M_{Ch}	$\sim M_{Ch}$	super-M_{Ch}	sub-M_{Ch}
Secondary	MS or RG (surviving)	WD (exploding)		WD (surviving)
CSM	Yes	No		

Suggested association

	SD	DD (D^6)
Primary/ejecta mass	M_{Ch}	sub-M_{Ch}
Secondary	MS or RG (surviving)	WD (surviving)
CSM	Yes	No

WD mass-density relation

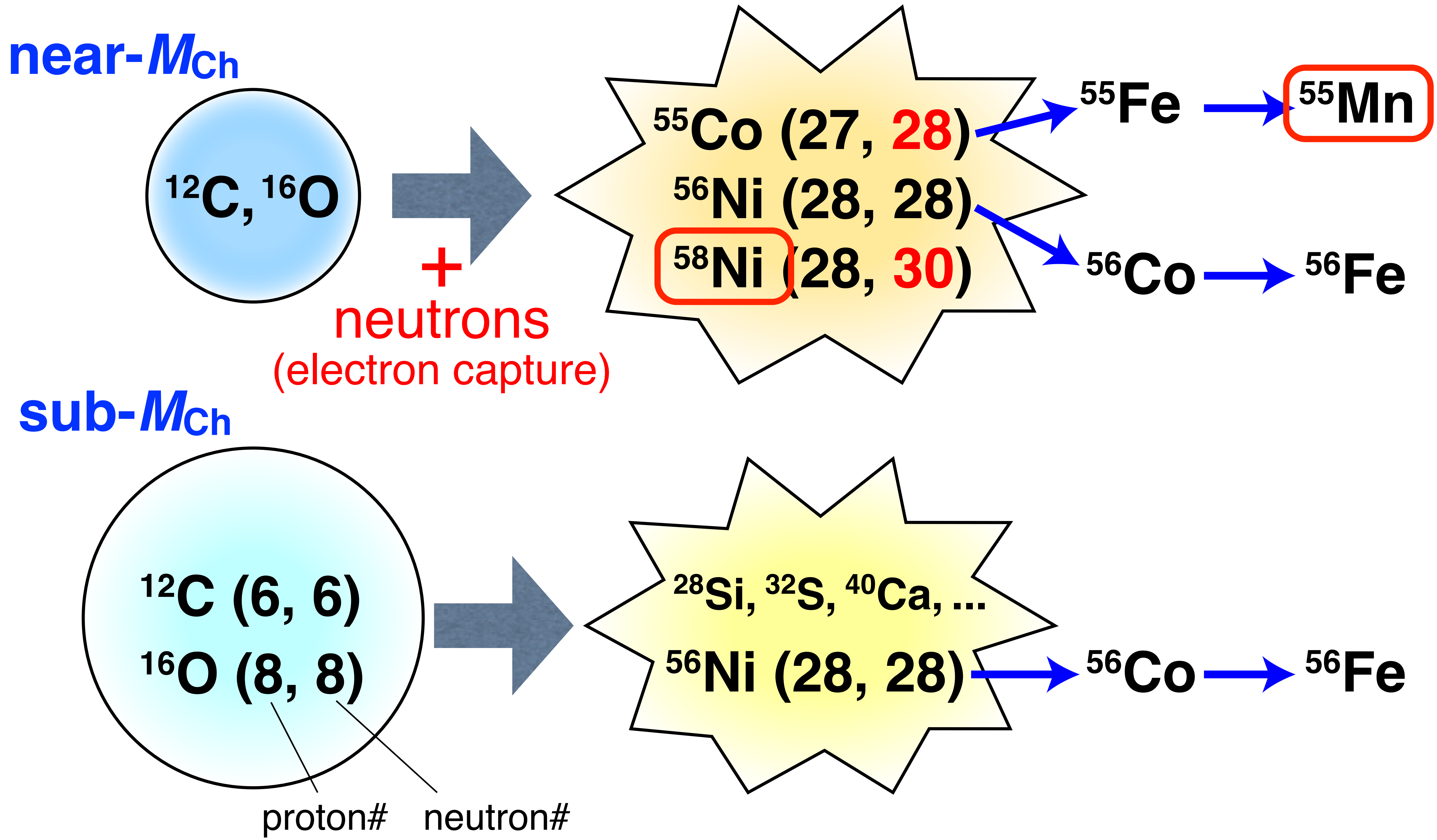


Electron capture: $\boldsymbol{p} + \mathbf{e}^- \rightarrow \boldsymbol{n} + \boldsymbol{\nu}_\mathbf{e}$ (only in $\sim M_{\mathrm{Ch}}$ WD)

Suggested association

	SD	DD
Primary/ejecta mass	M_{Ch}	sub-M_{Ch}
Electron capture	Yes	No
Secondary	MS or RG	WD
CSM	Yes	No

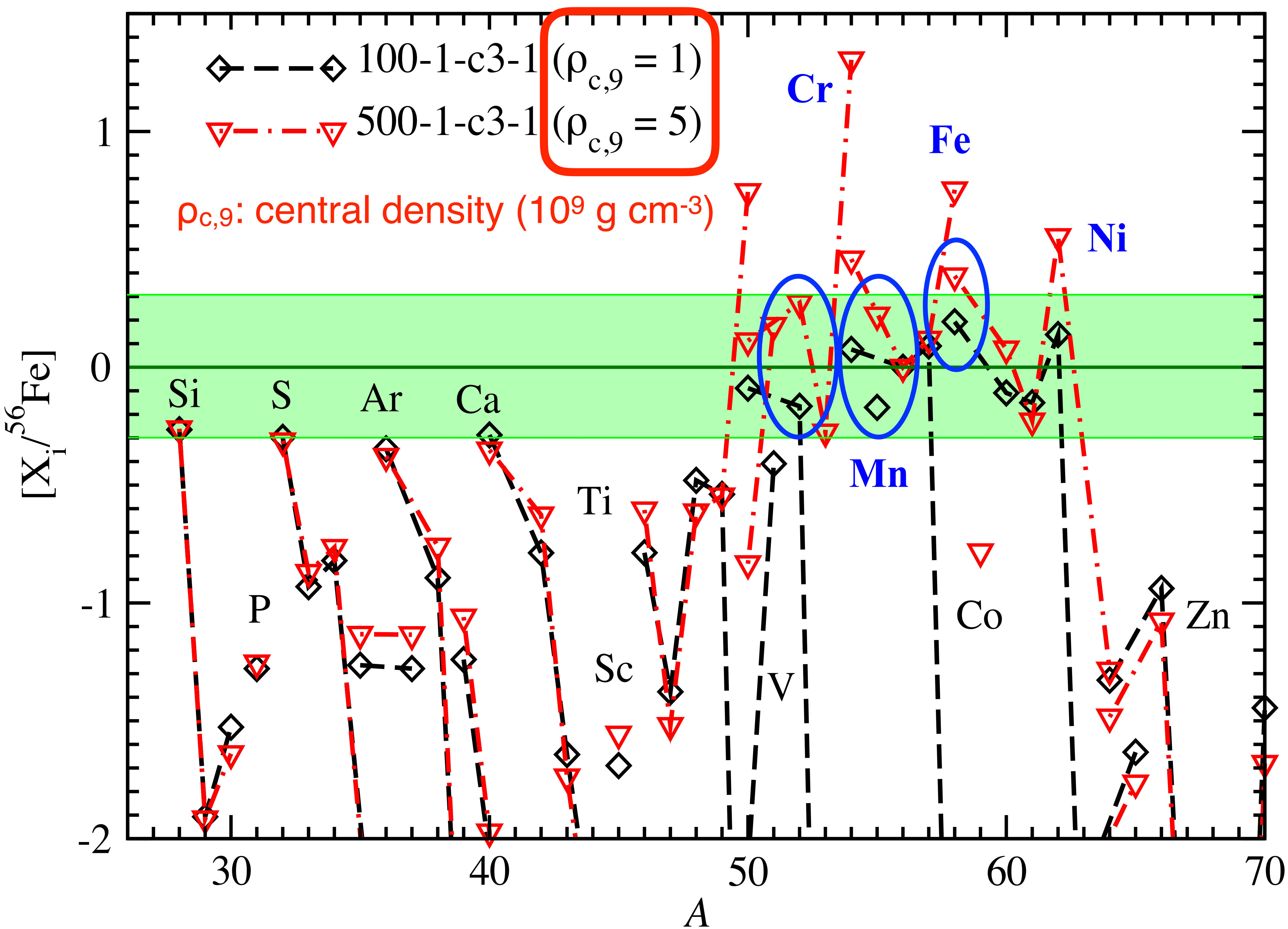
Density-dependent nucleosynthesis



More Ni and Mn produced in ~M_{Ch} SN Ia

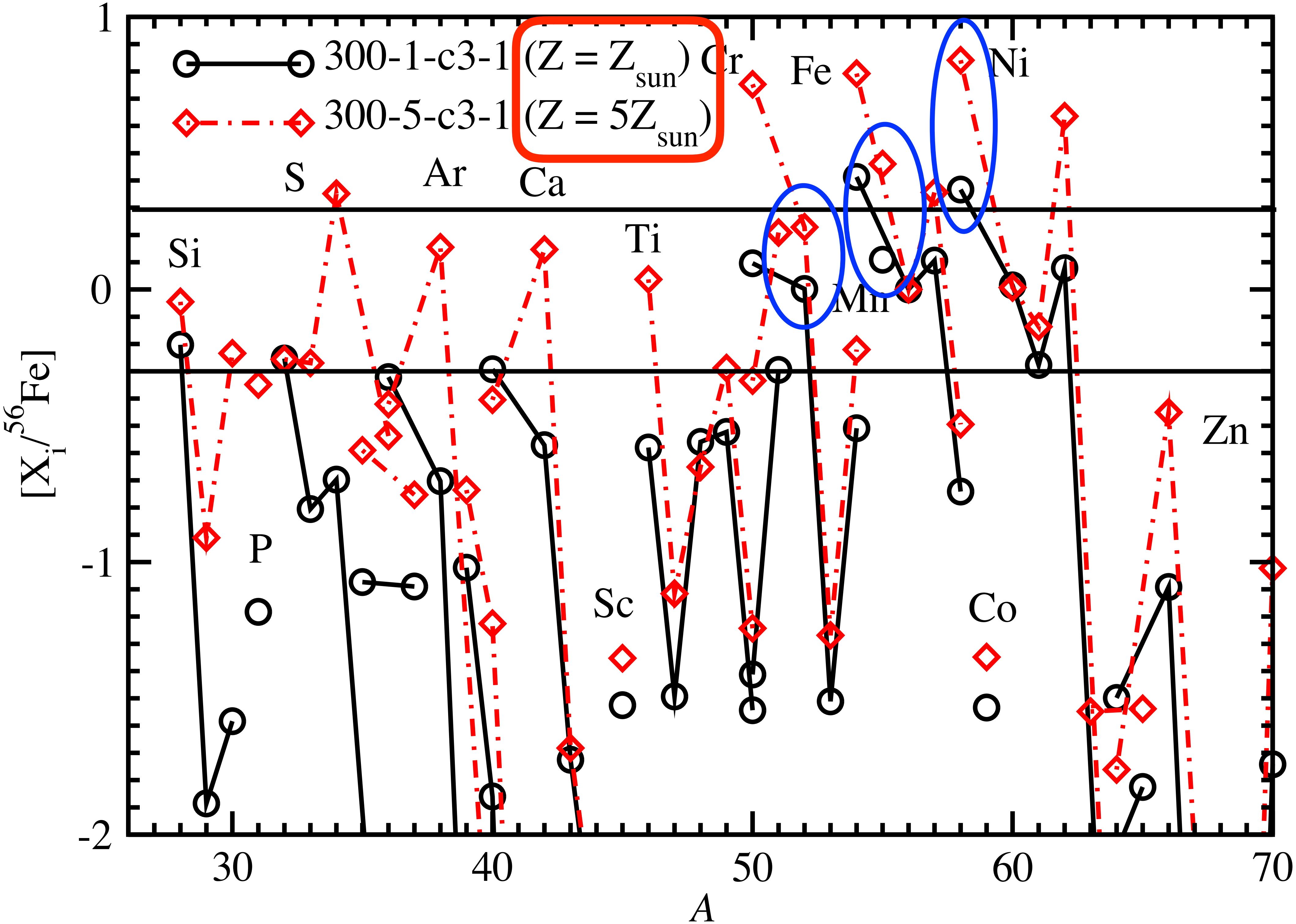
Central density effect

Leung & Nomoto 2017



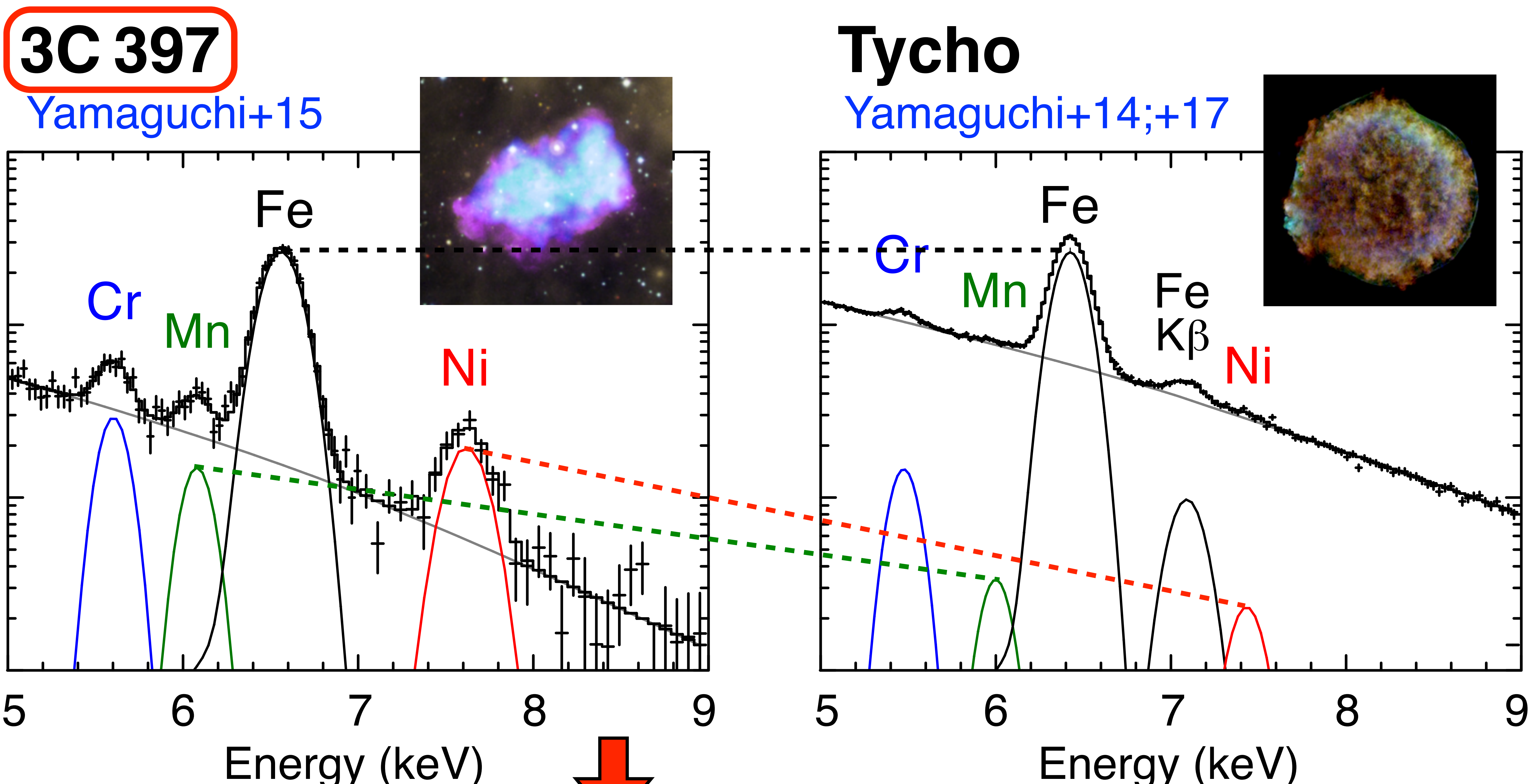
Metallicity effect

Leung & Nomoto 2017



Discovery Mn & Ni-rich SNR Ia

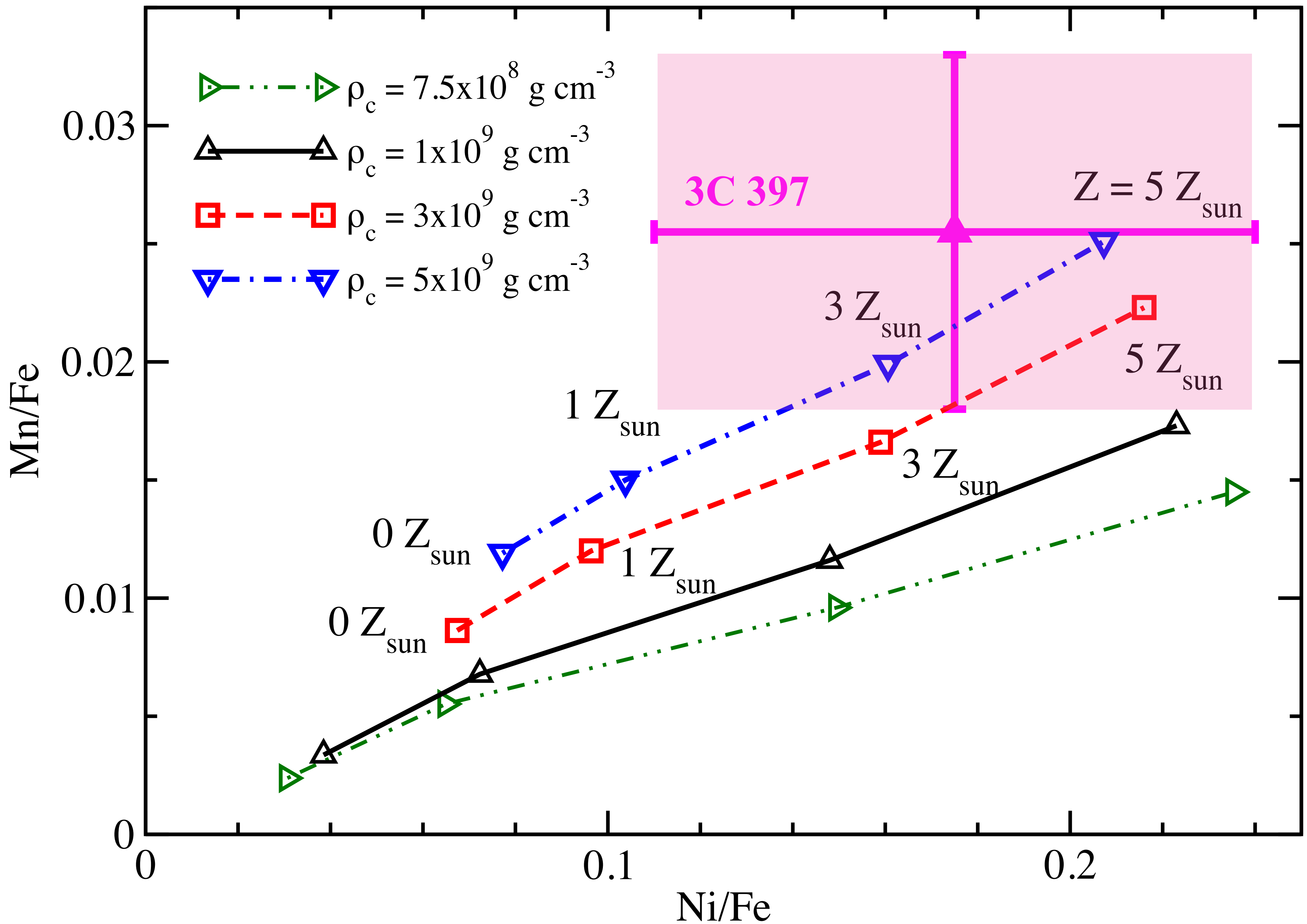
Enabled by high sensitivity of *Suzaku* satellite



Ni/Fe ≈ 0.17 Mn/Fe ≈ 0.025 (sub-M_{Ch} ruled out)

Comparison with SN Ia yields

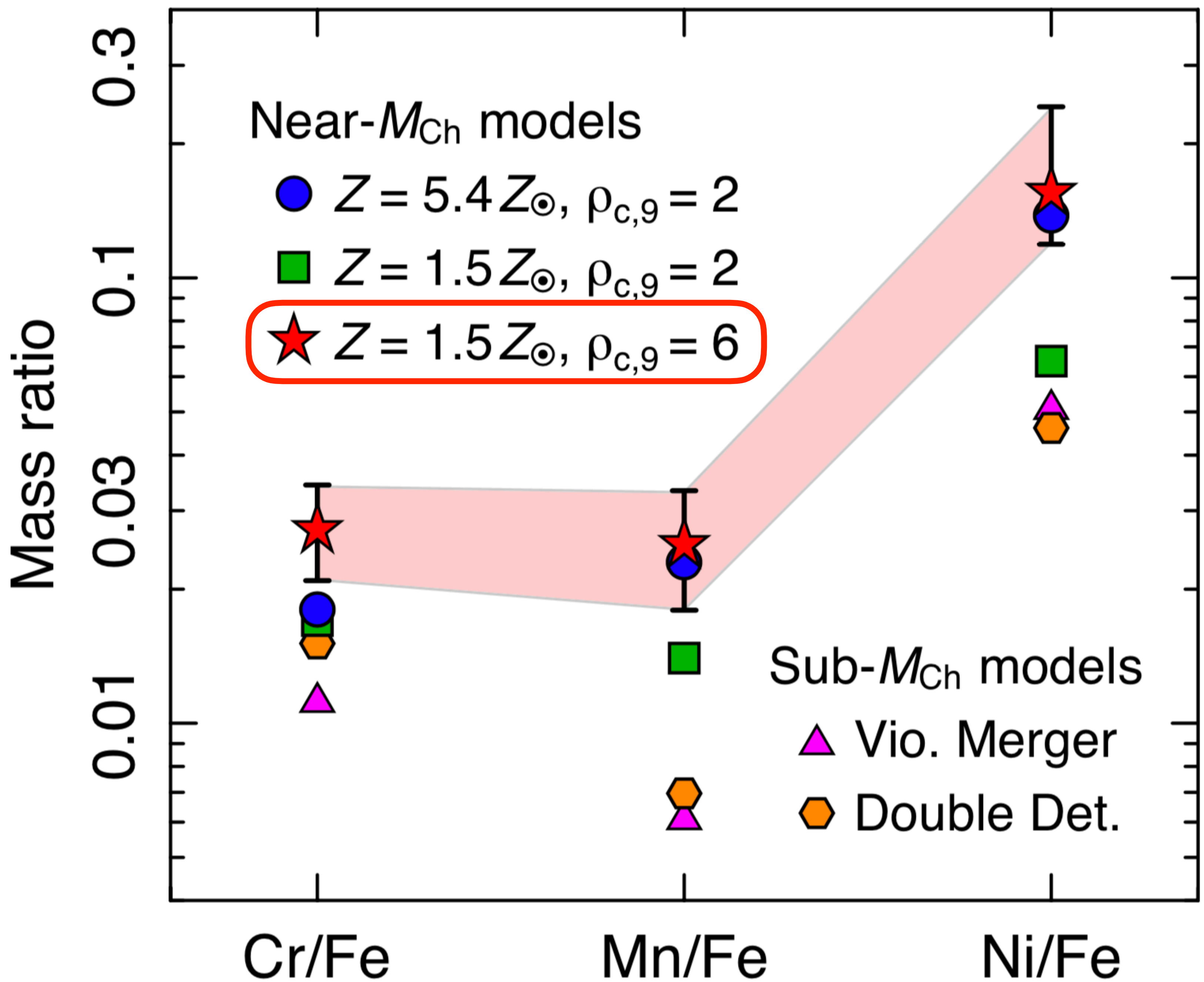
Leung & Nomoto 2017



High central density and/or high metallicity

Comparison with SN Ia yields

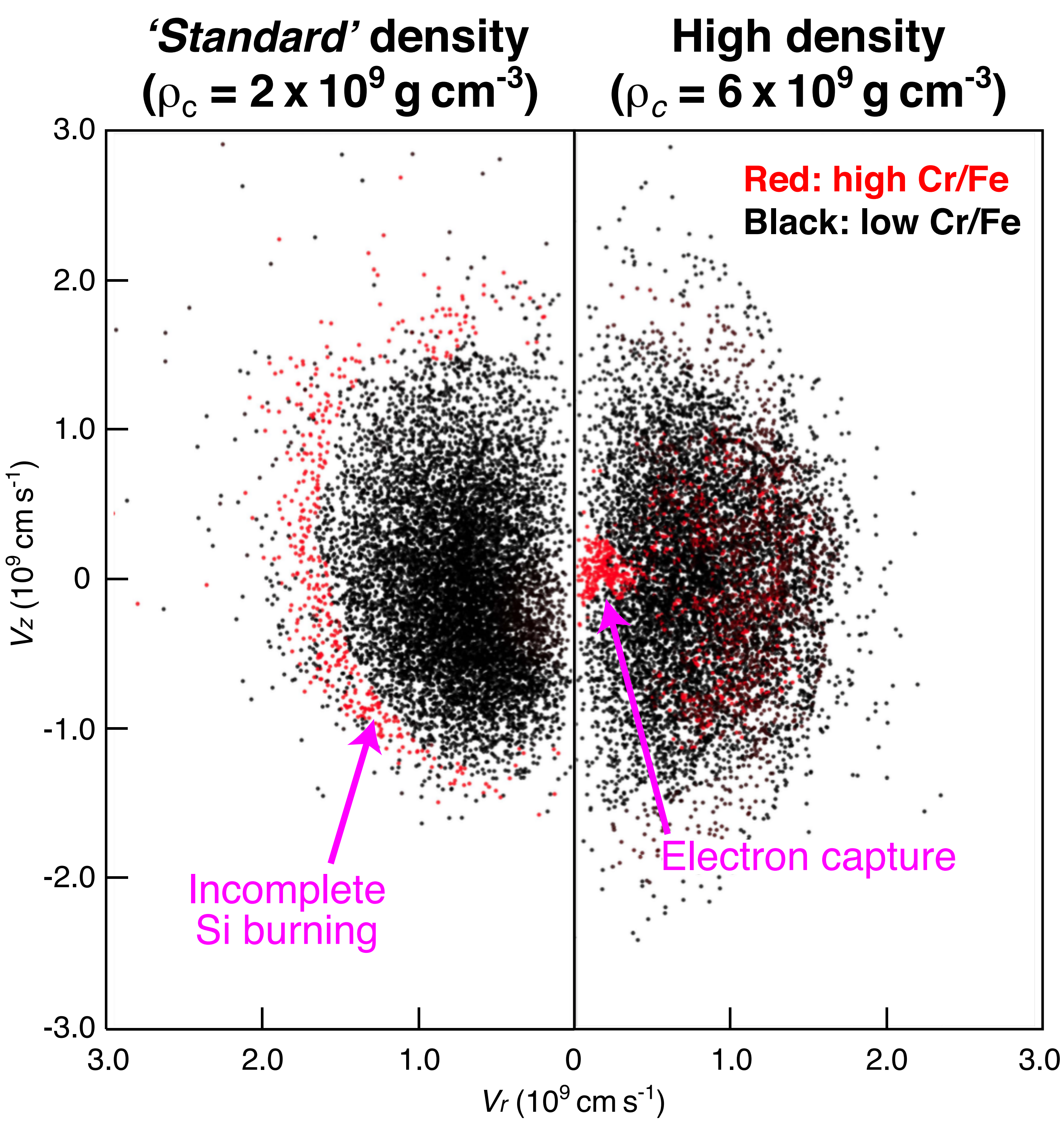
Dave et al. 2016 (U Mass group)



High central density and/or high metallicity

To disentangle the degeneracy…

Cr's (and Mn's) origin/distribution are the key



High metallicity case:

Cr, Mn (Ar, Ca)

➔ Si burning

Ni ➔ *n*-rich NSE

High density case:

Cr, Mn, Ni

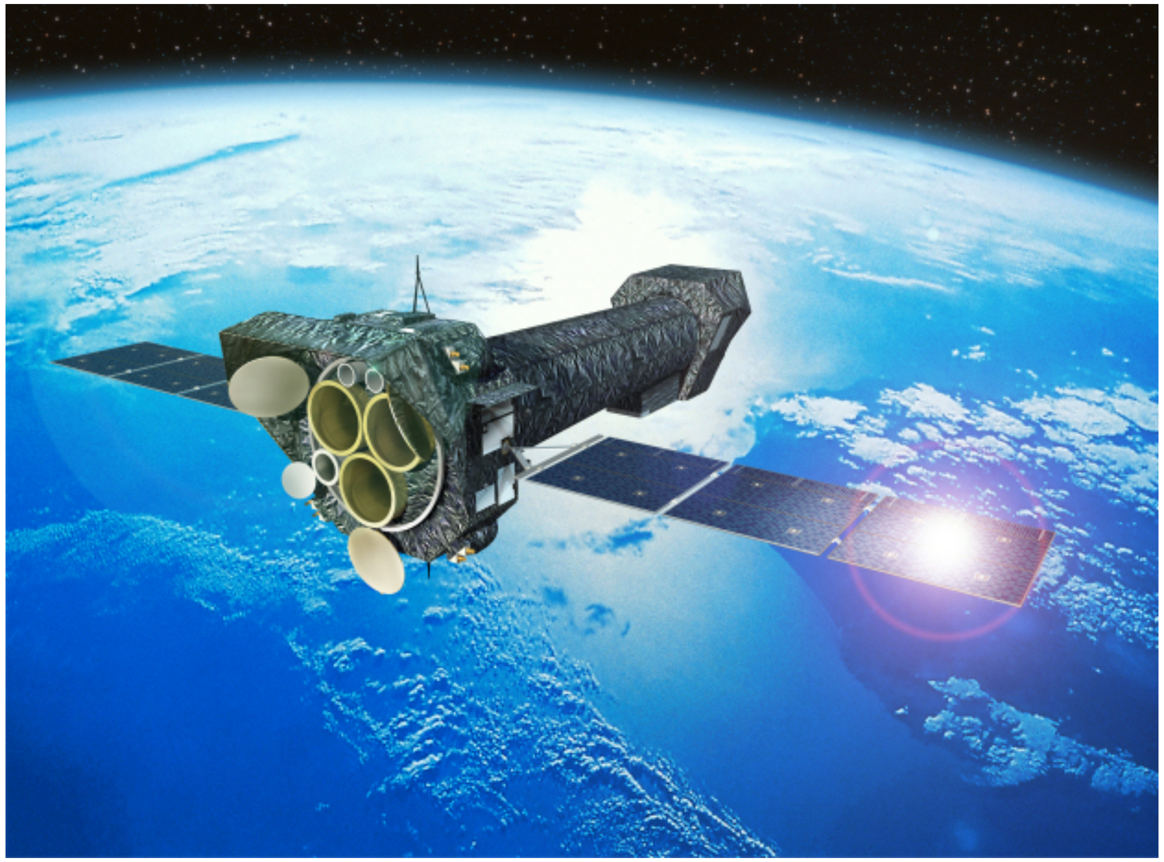
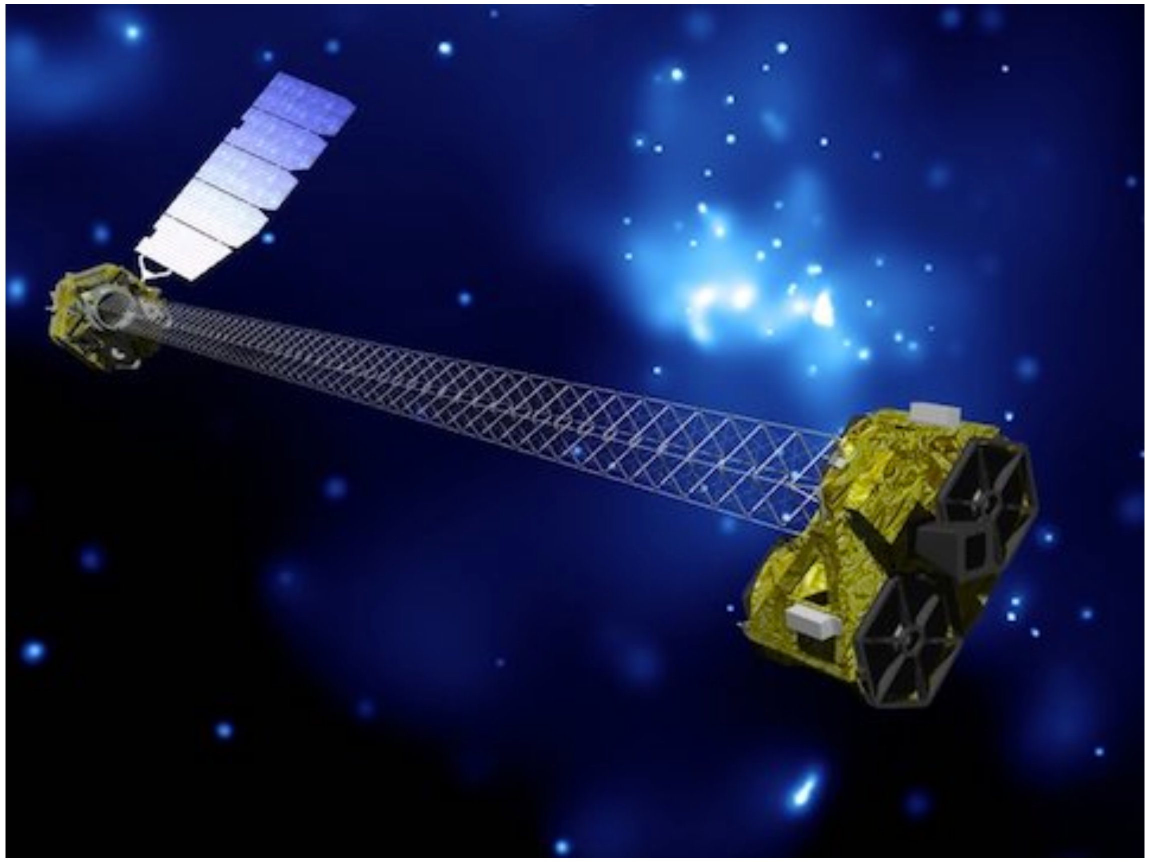
➔ *n*-rich NSE

(3 elements coincident)

Near-future prospects

Project we've proposed

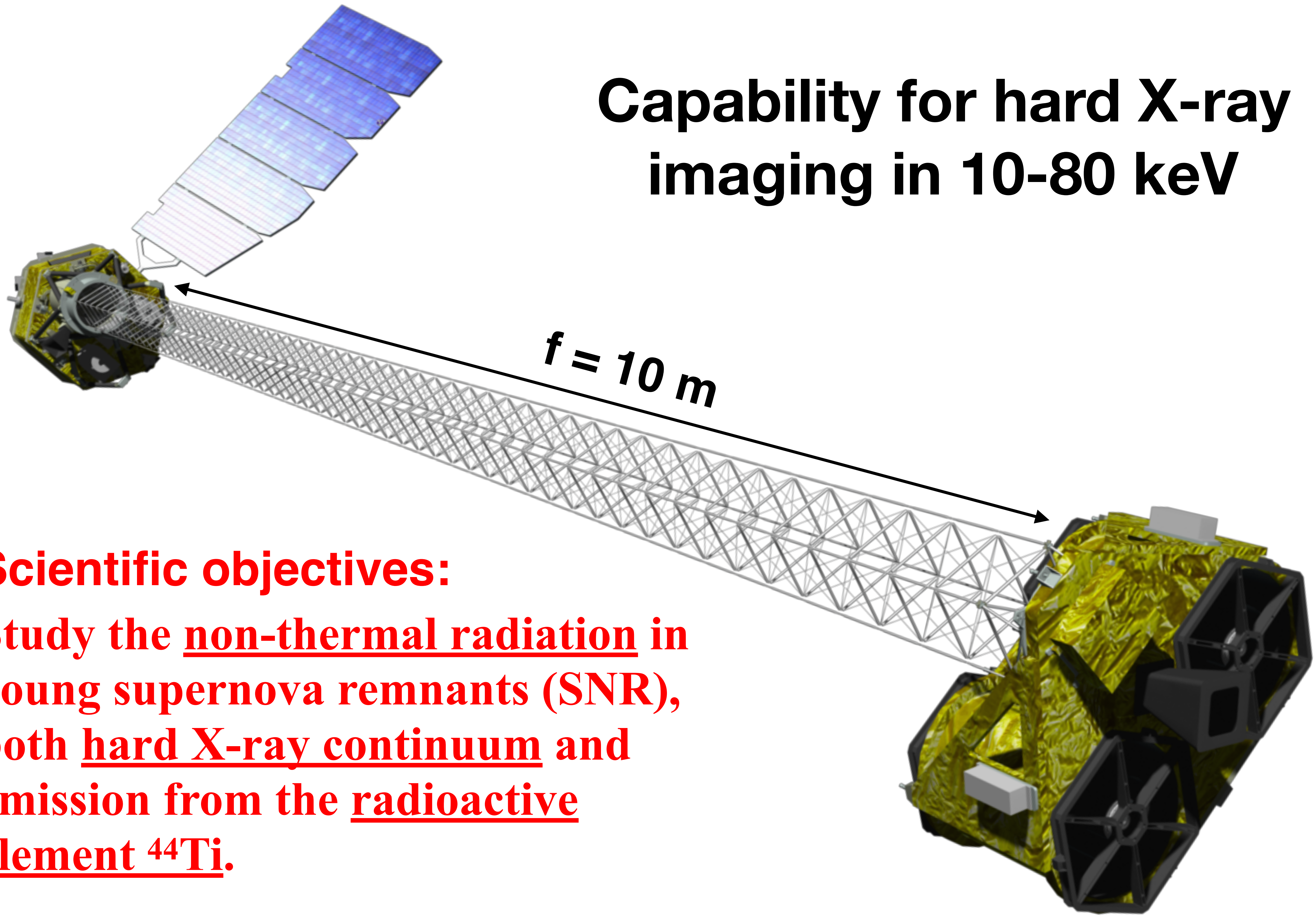
XMM/NuSTAR joint observations of 3C397

XMM-Newton	***NuSTAR***
	
~110 ks	~140 ks

Approved in NuSTAR Cycle 4

NuSTAR!?

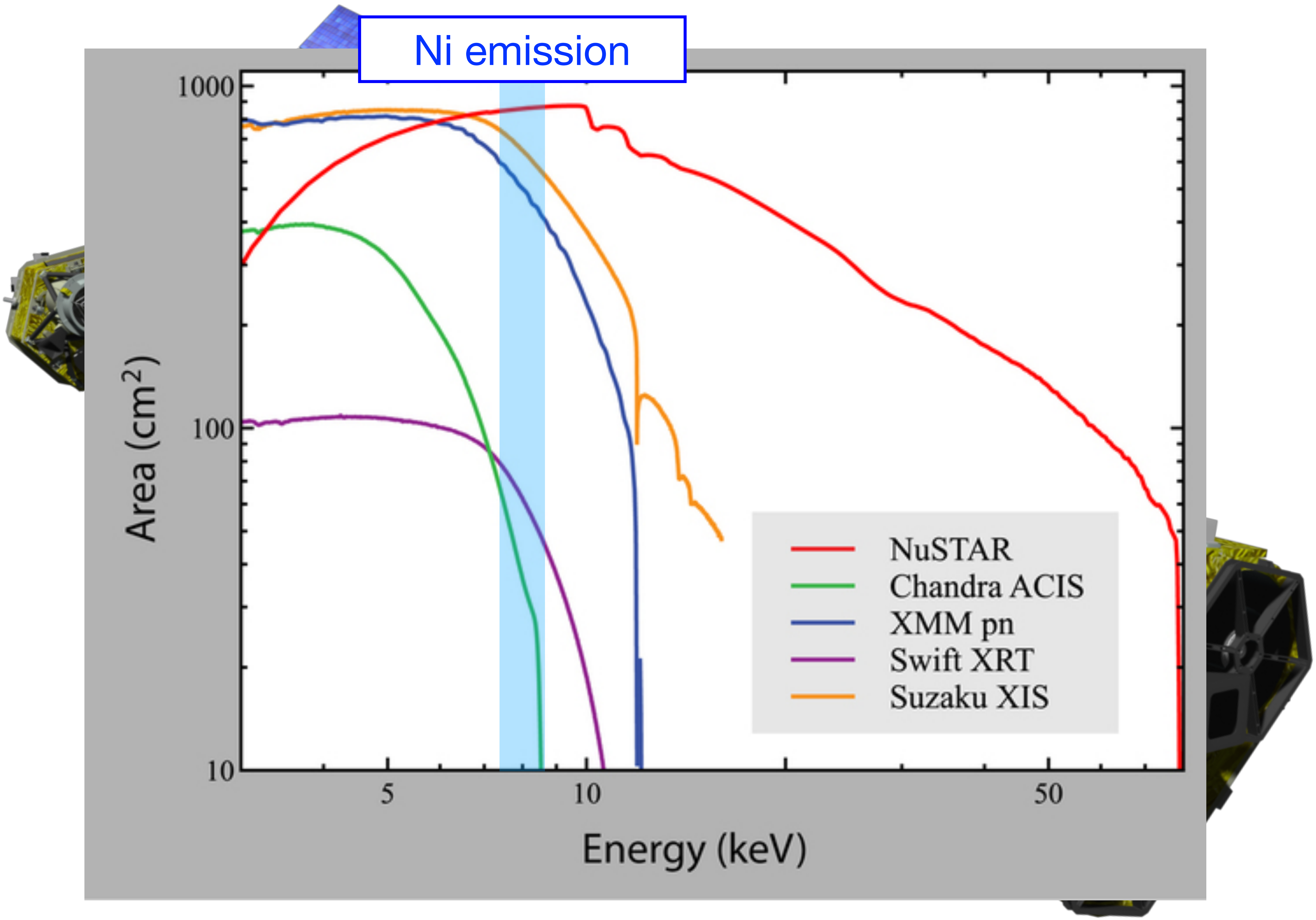
Capability for hard X-ray imaging in 10-80 keV



Scientific objectives:

Study the <u>non-thermal radiation</u> in young supernova remnants (SNR), both <u>hard X-ray continuum</u> and emission from the <u>radioactive element ^{44}Ti</u>.

NuSTAR!?

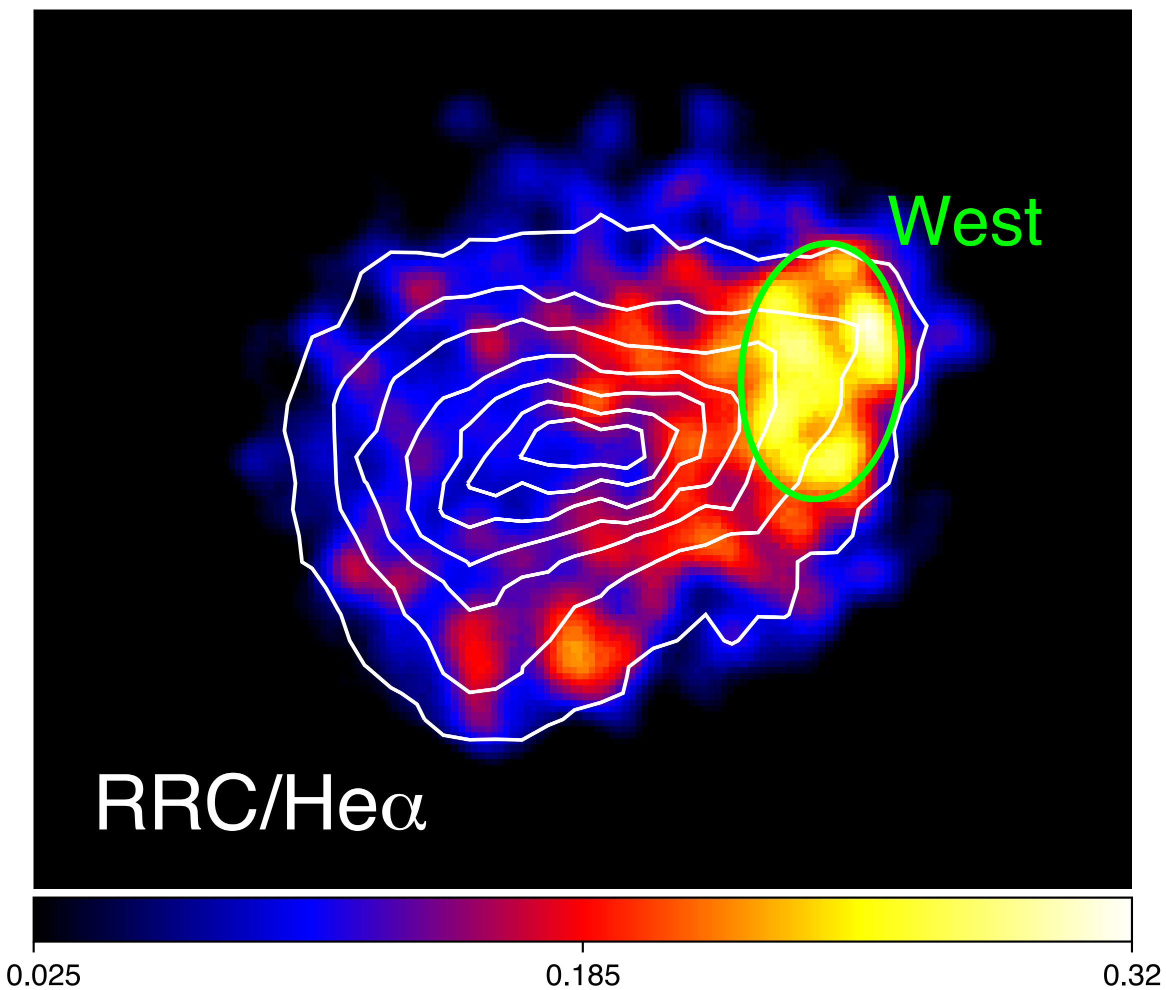


Ni emission
1000
100
10
5
10
50
Area (cm^2)
Energy (keV)
NuSTAR
Chandra ACIS
XMM pn
Swift XRT
Suzaku XIS

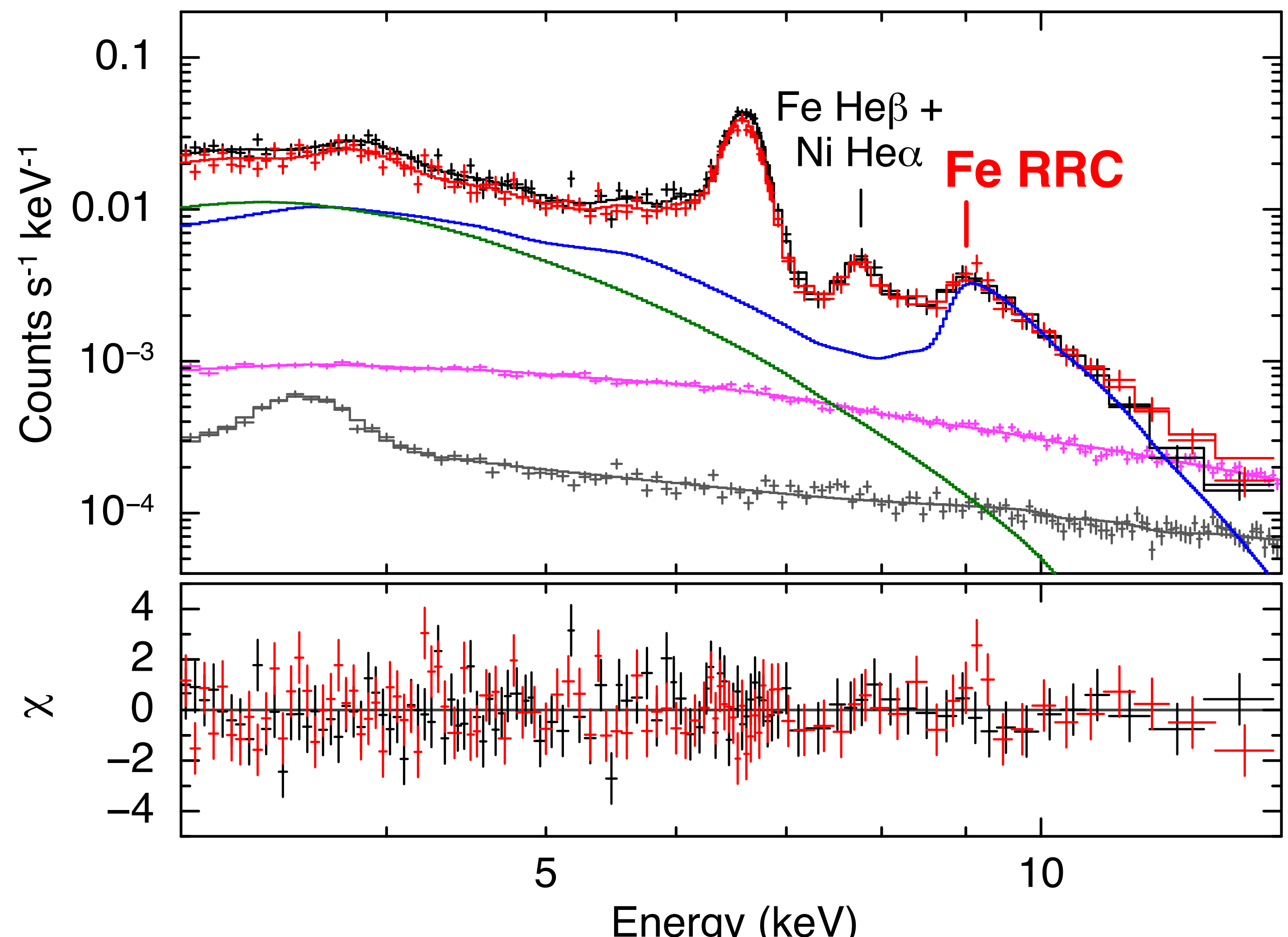
Thermal X-rays with *NuSTAR*

Localization of strong RRC in SNR W49B

(Yamaguchi+2018, ApJL in press, arXiv:1811.04426)



RRC [8.8-10 keV] / Line [6.4-6.8 keV] ratio map



See also Tanaka+2018

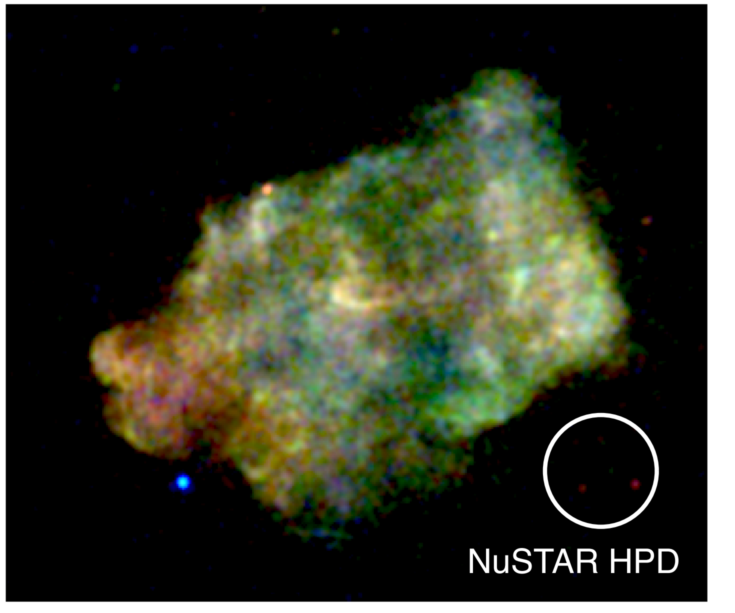
2 ApJ Letters from 1 Pri.C observation

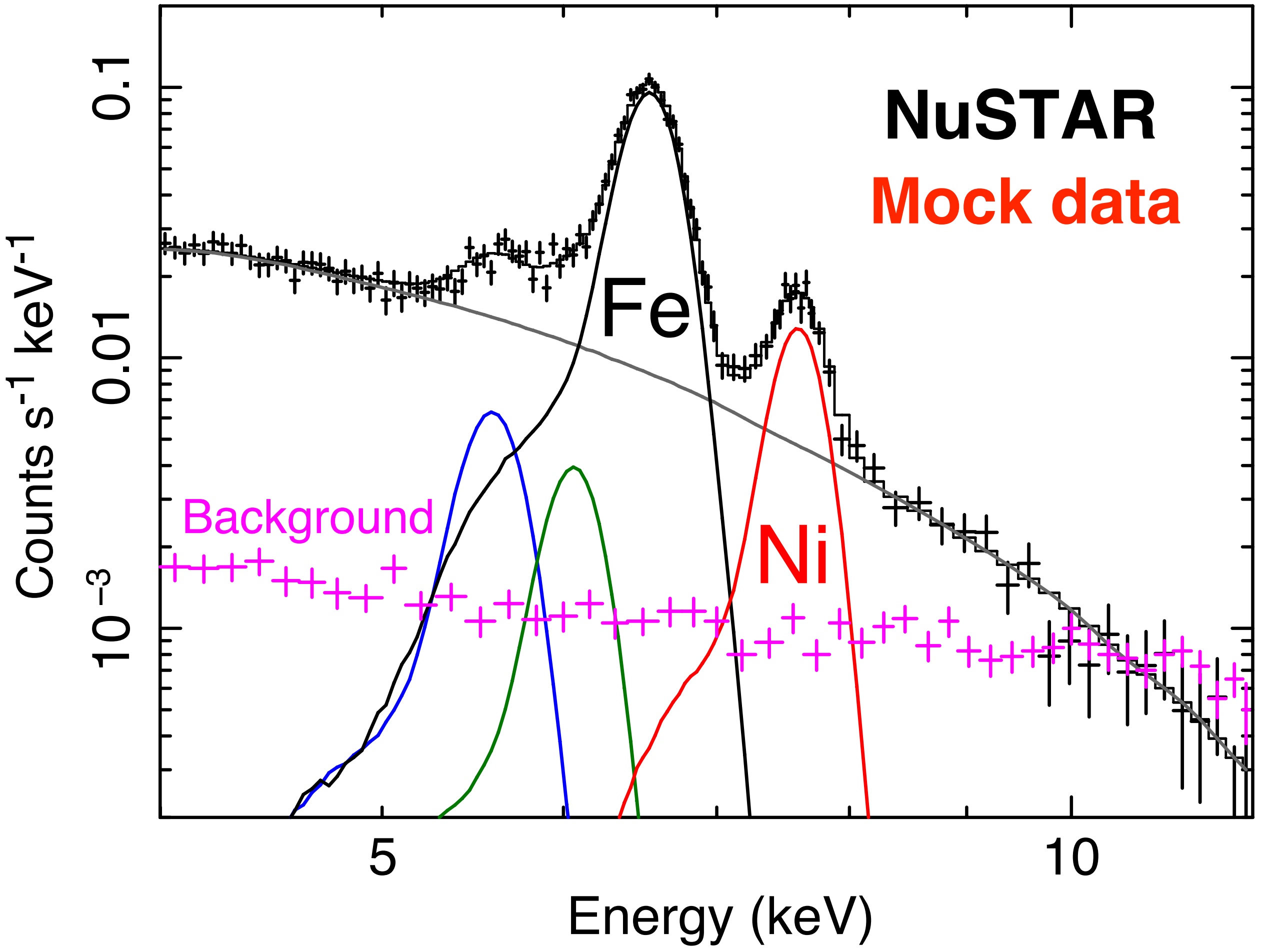
Objective of 3C 397 observations

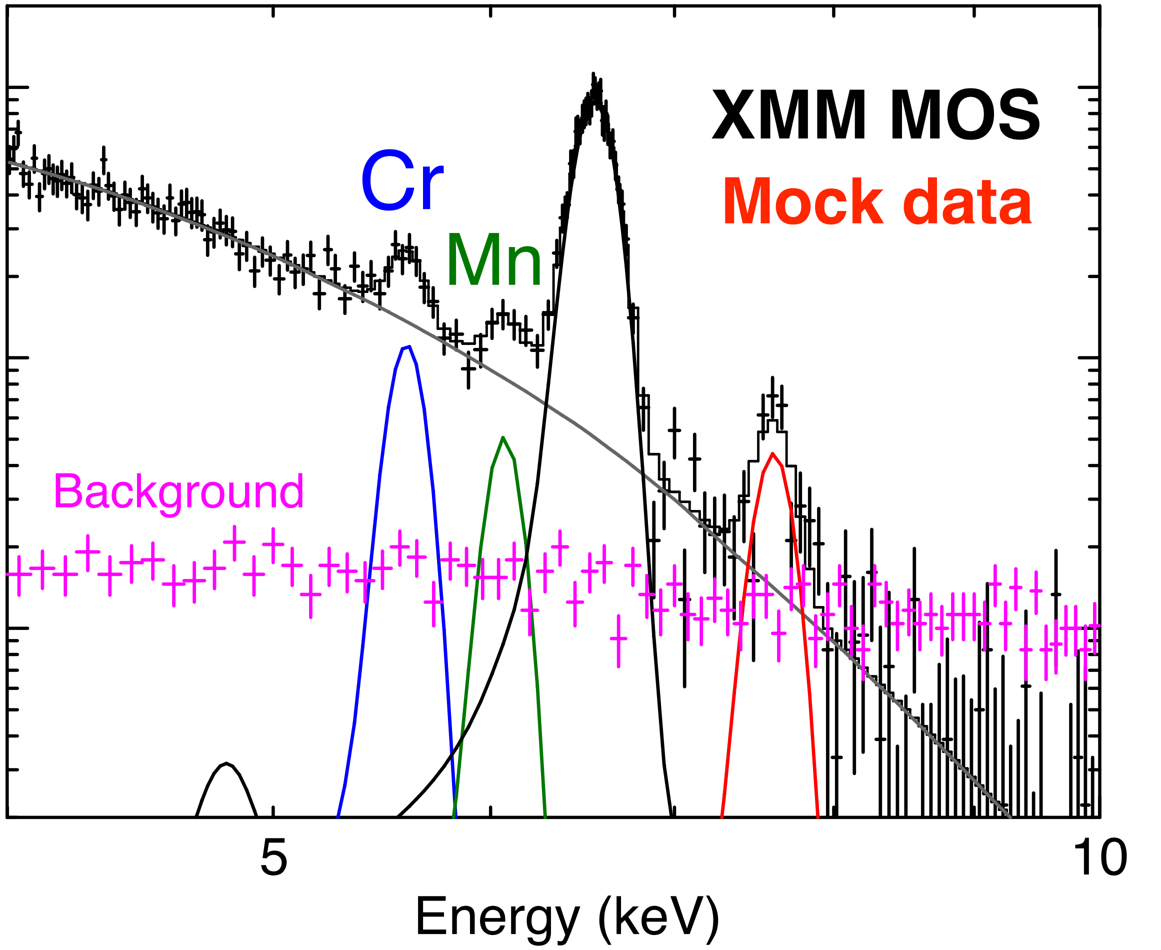
Comparison of morphologies of Ni (NuSTAR) and Cr (XMM)

If identical

→ <u>high density progenitor</u>!

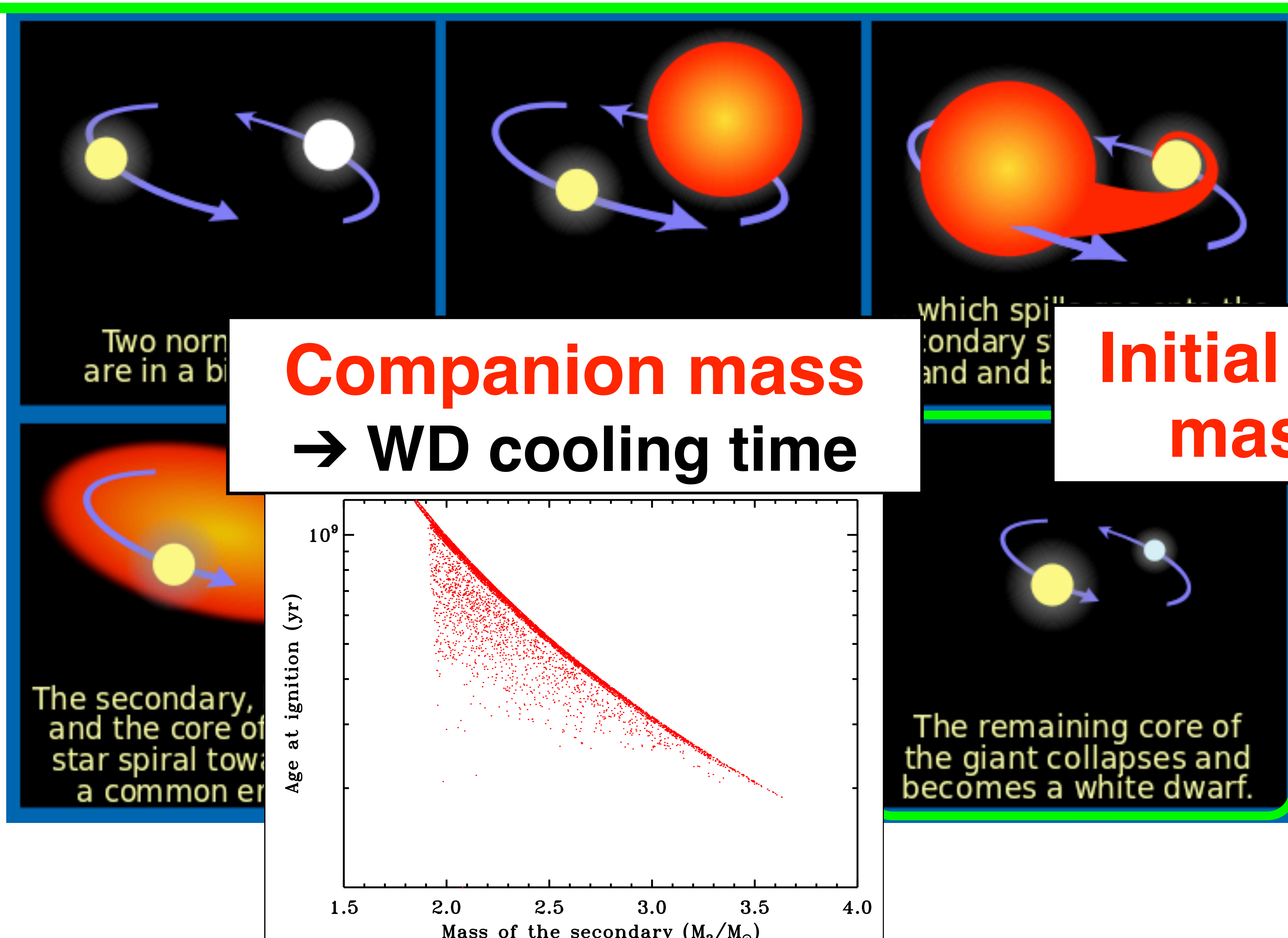






How’s high WD density achieved?

Binary evolution in SD scenario



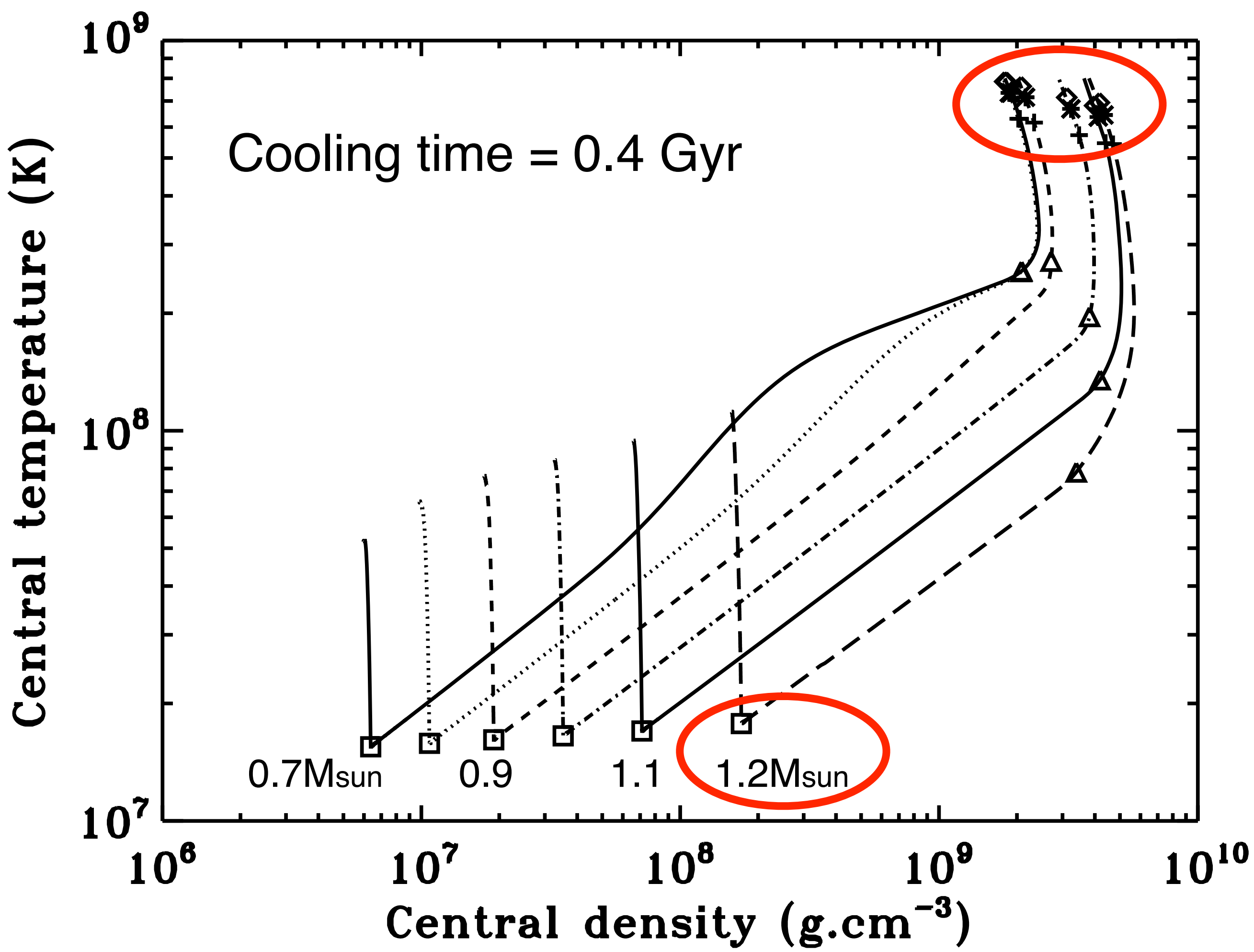
Companion mass
→ WD cooling time

Initial WD mass

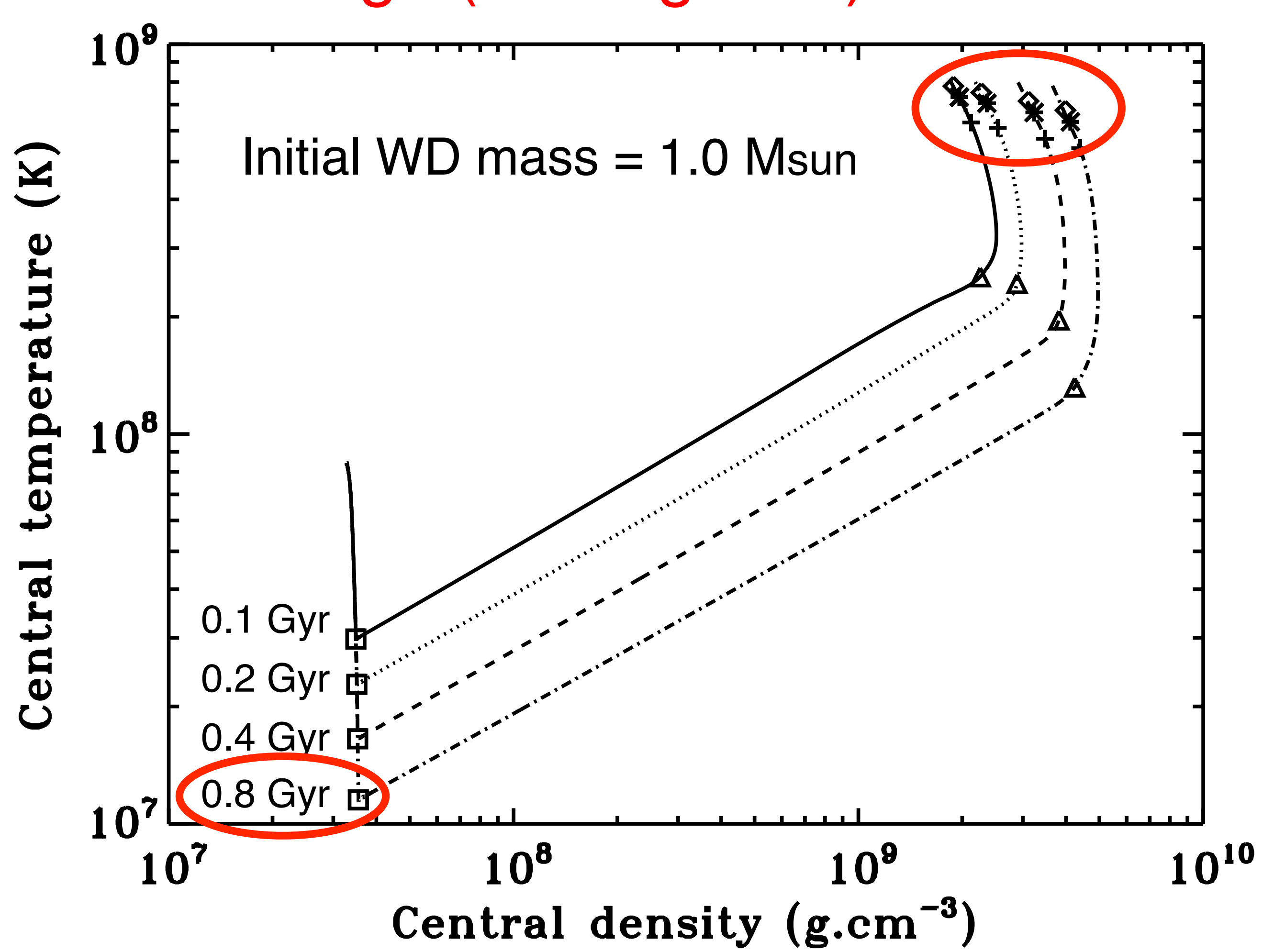
How's high WD density achieved?

Central density at the time of explosion depends on the initial WD condition.

Initial WD mass effect

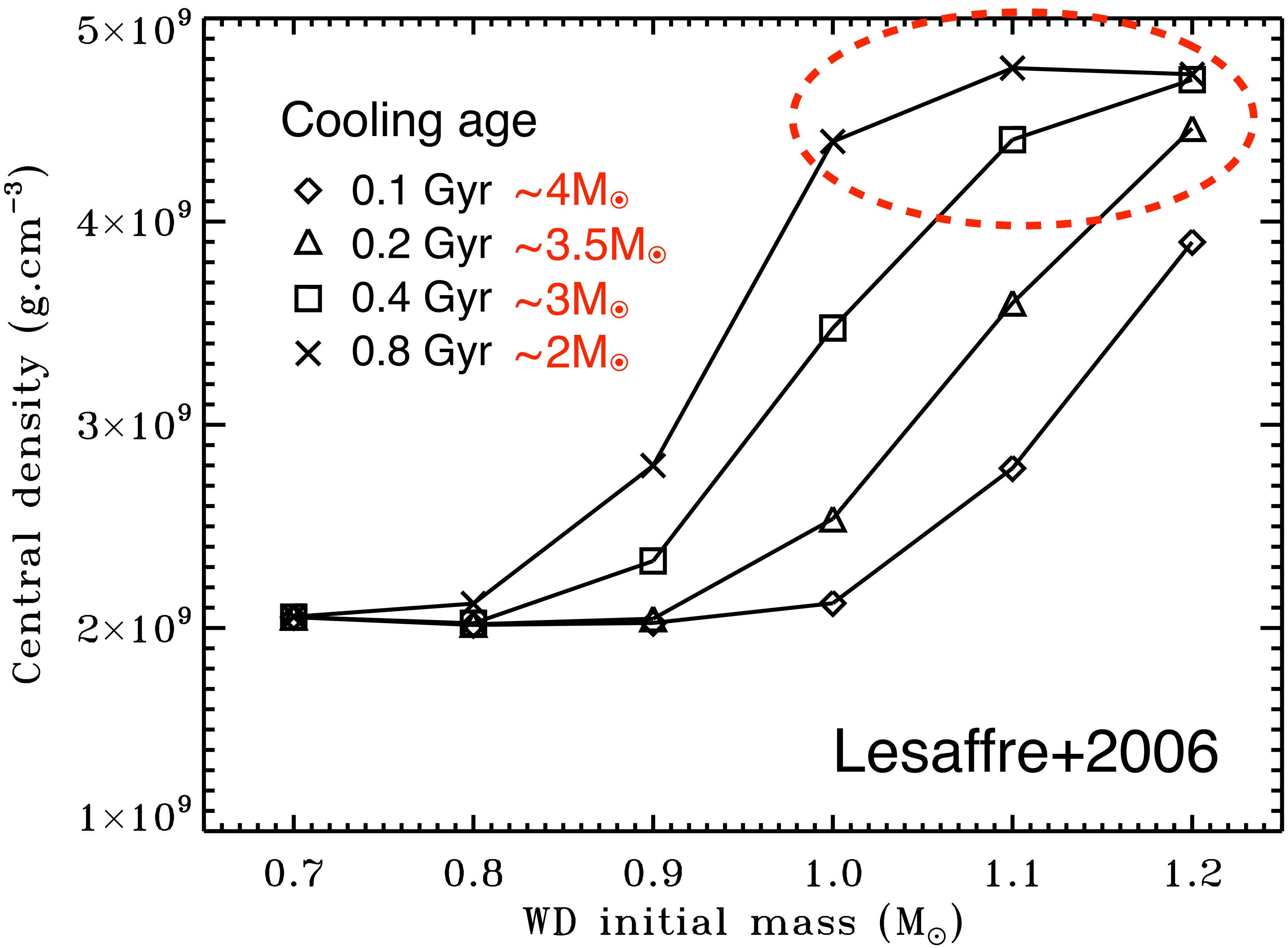


Age (cooling time) effect



Lesaffre+2006

How's high WD density achieved?



3C 397's progenitor = (i) high-mass (≳1M☉) primary + (ii) low-mass (≲2M☉) companion *if high-ρ_c confirmed*

Scientific impact

Why $\rho_c = 2 \times 10^9$ g cm^{-3} has often been adopted:

To explain the solar abundance of *n*-rich isotopes
solely with near-M_{Ch} SNe Ia (Nomoto+1997, Woosley+1997)

Now we know sub-M_{Ch} progenitors may significantly contribute to SNe Ia.

Aggressive(?) hypothesis:

SN Ia = "higher-ρ_c M_{Ch}" + "sub-M_{Ch}"

so that averaged SN Ia yields match the solar abundance of *n*-rich isotopes

Questions

(1) What's the highest ρ_c that a single WD can get?
- Depends significantly on accretion rate?

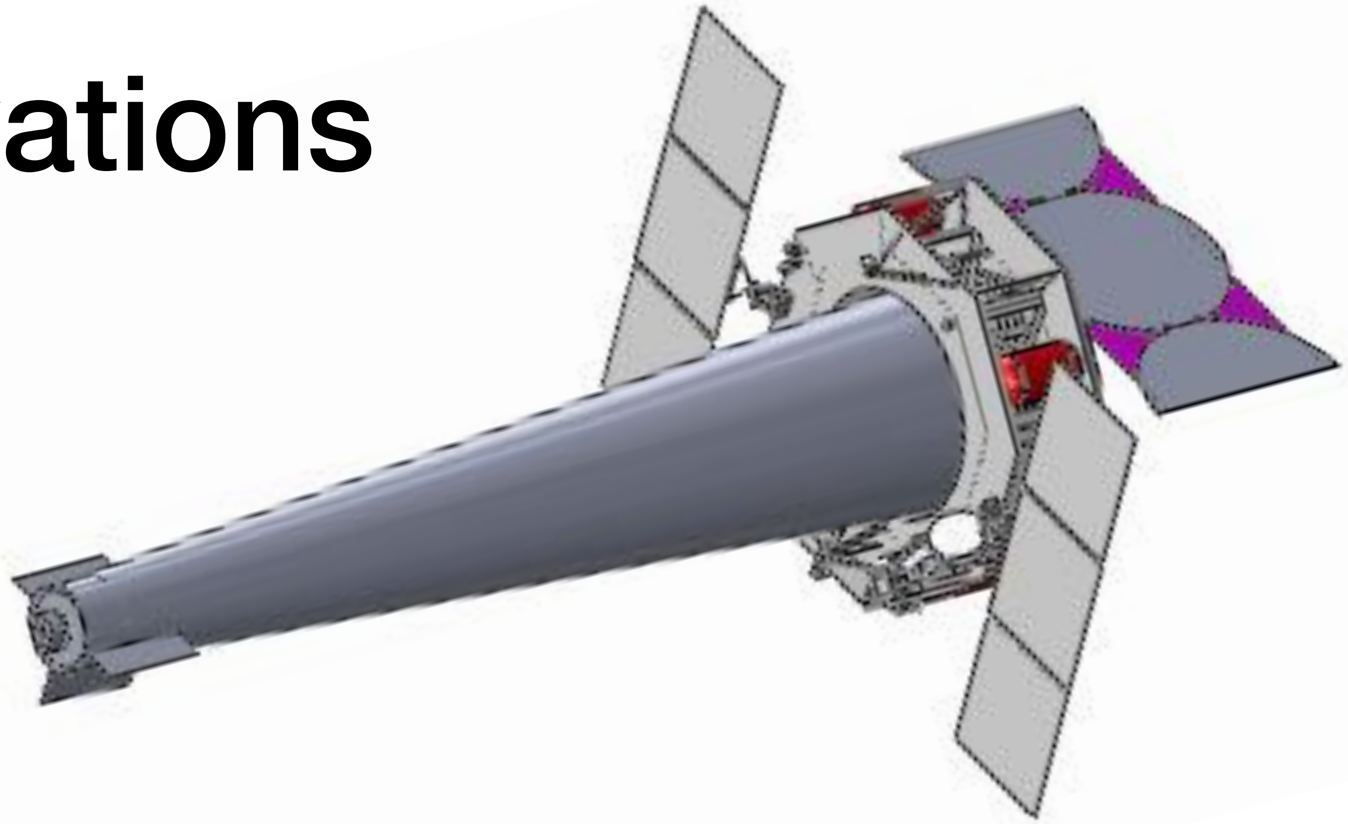
(2-a) Can high ρ_c be achieved in 'classical' DD?
- Higher accretion rate
- More matter (total mass), longer cooling time

(2-b) Other paths to get high ρ_c?

(3) Nucleosynthesis models starting from stellar evolution?

Far-future prospects

Deep X-ray observations with AXIS



One of NASA probes (< $1B) under concept study.

Aimed to be launched in late 2020s.

PI: Richard Mushotzky (Univ. of Maryland)

Major partners: NASA/GSFC (mirror) and MIT (detector)

Super Chandra: High angular resolution < 0.5 arcsec

Super XMM: Large effective area > 4000 cm^2 @ 1 keV

Super Suzaku: Low background (< 20% of Chandra)

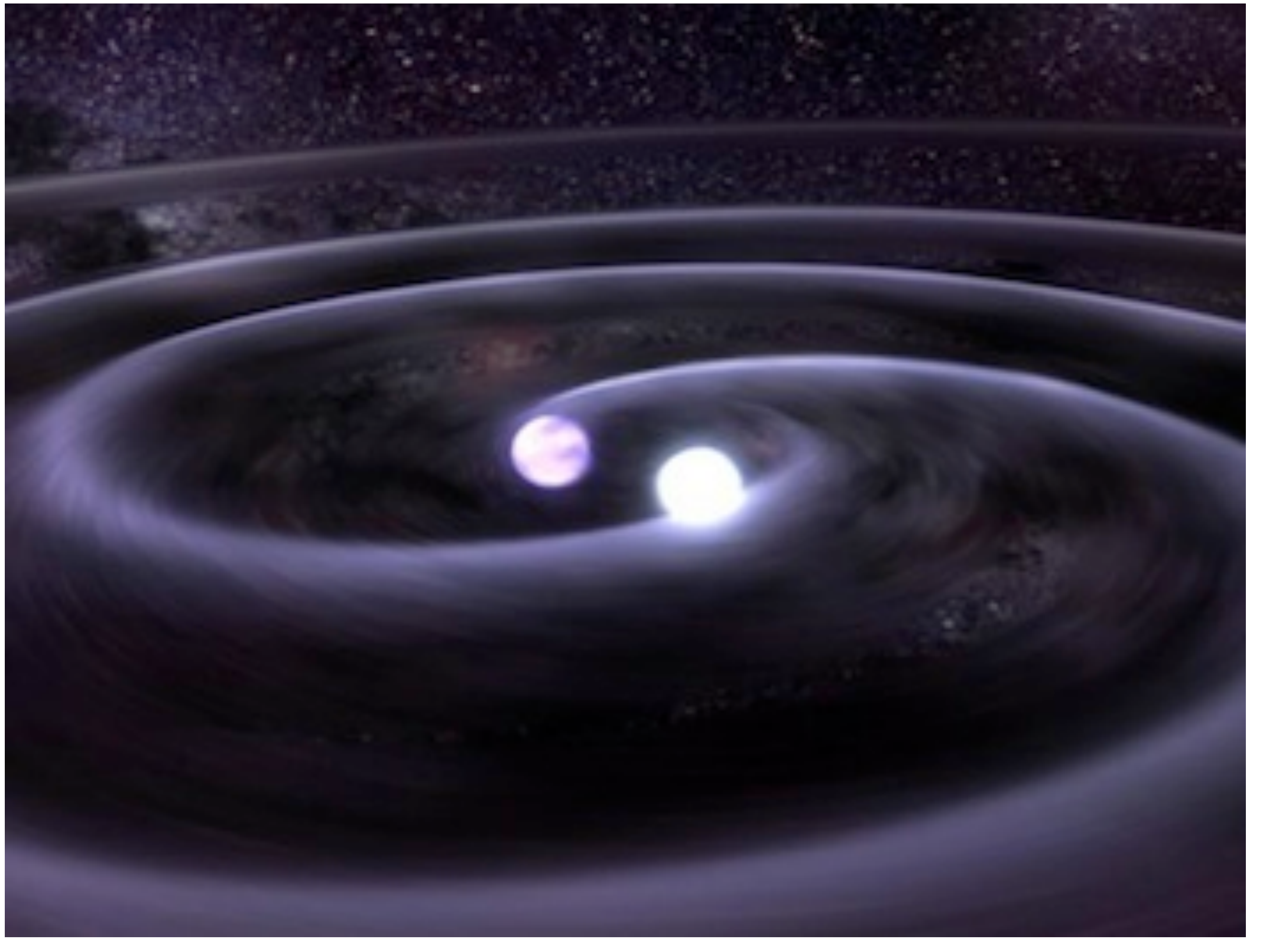
Visit us at http://axis.astro.umd.edu

AXIS

Area	Value	Requirement
Angular Resolution	~0.3 arcsec	Point source detection, separation, excision
Bandpass	~0.1-16 keV	Soft and hard X-ray sensitivity
Effective Area	7000 cm^2 @ 1 keV 1500 cm^2 @ 6 keV	Faint/low surface brightness source analysis
Energy Resolution	~150 eV @ 6 keV (CCD resolution)	Emission line separation
Timing Resolution	<50 ms	Variable source analysis
Field of View	>15 arcmin (diameter)	Extended source analysis, surveys
Detector Background	4-5x less then Chandra	Sensitivity to low surface brightness
Slew rate	120 deg / 5 min	Observing efficiency / TOOs

Gravitational wave

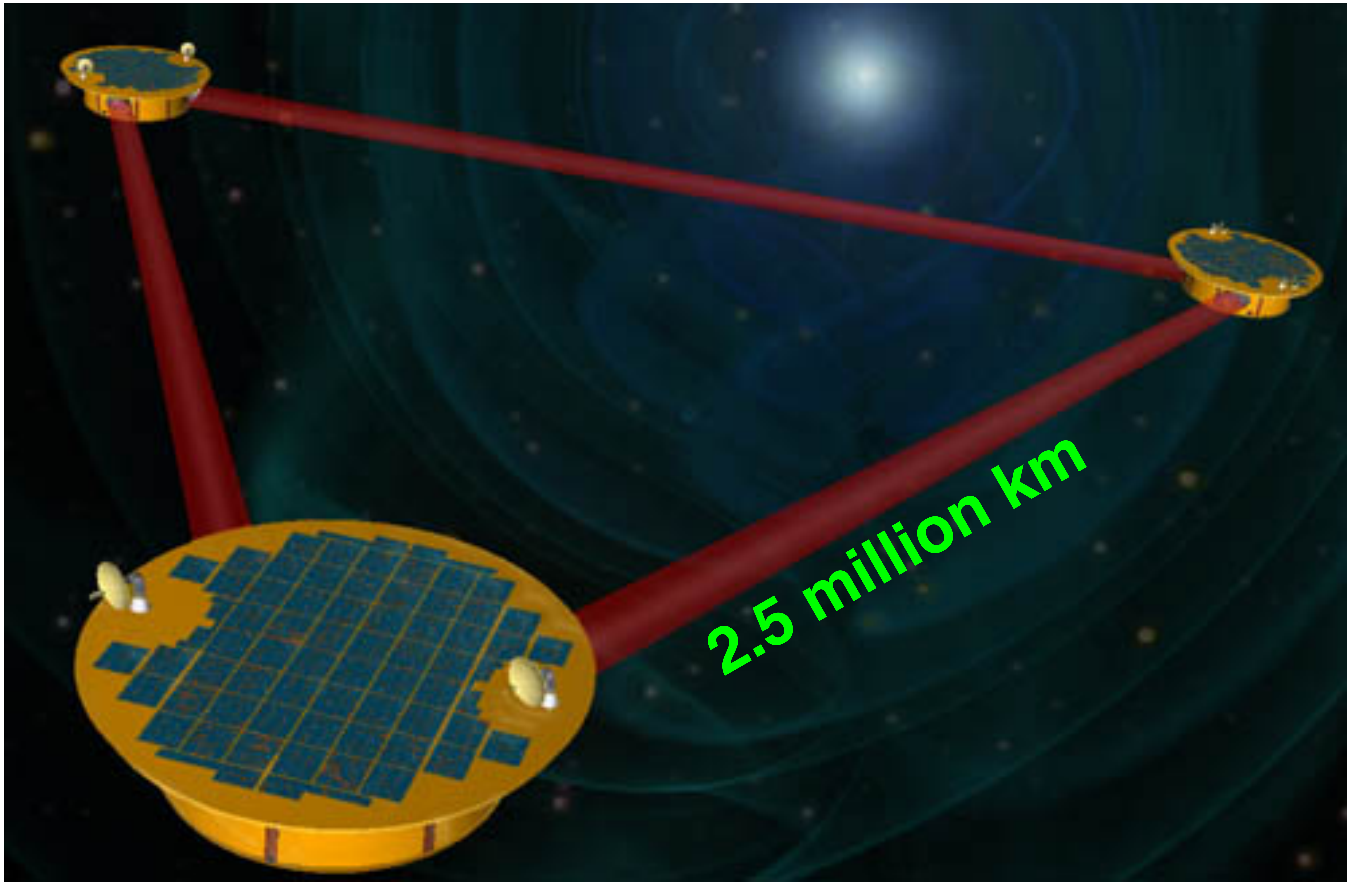
GW radiation predicted by DD scenario



$\underline{f \approx 0.1\ \mathrm{Hz}}$ when tidally disrupted

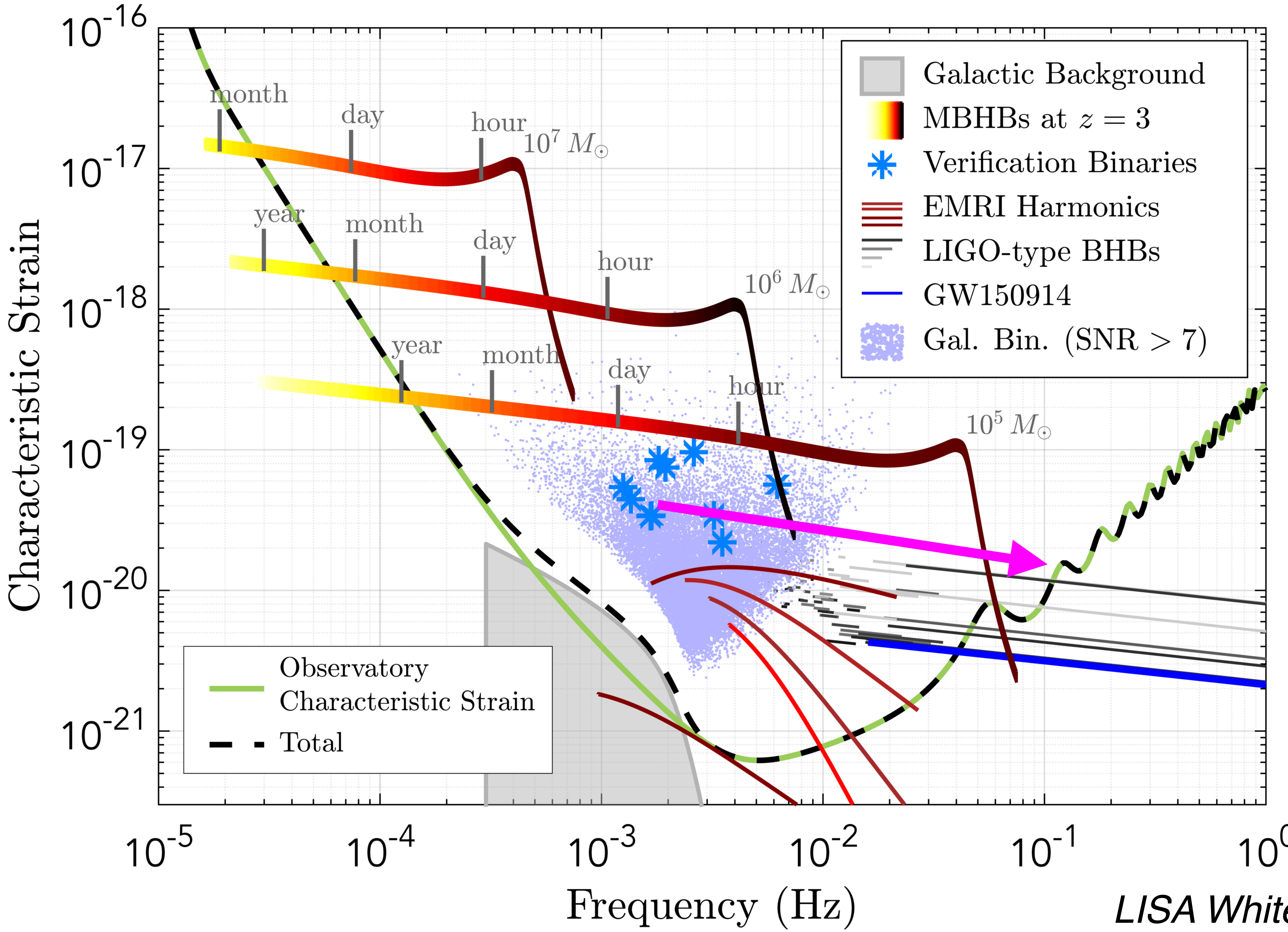
LIGO: sensitive to $\gtrsim$ 10 Hz

Laser Interferometer Space Antenna (LISA)

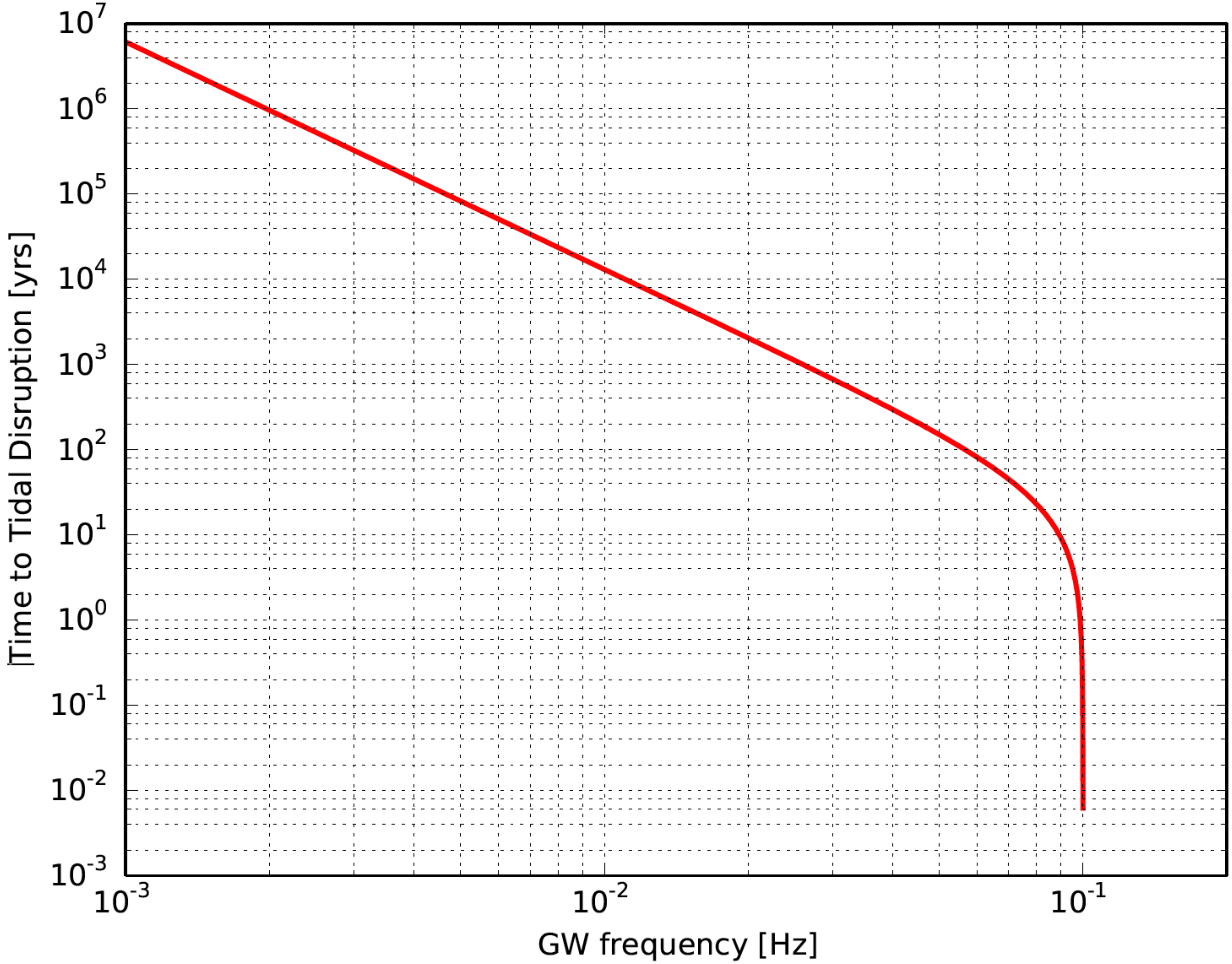


ESA's mission to be launched in ~2034

Laser Interferometer Space Antenna (LISA)

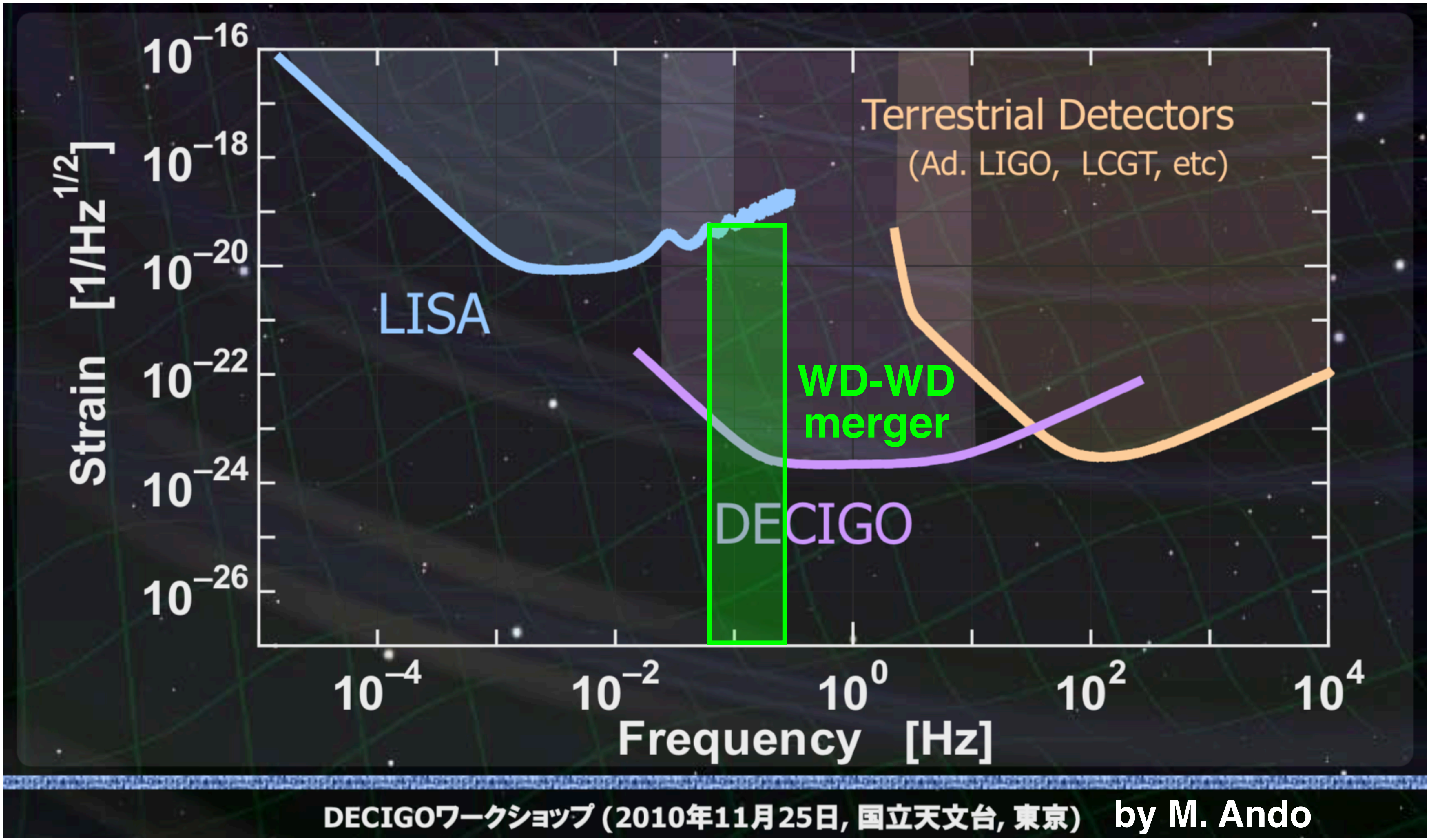


LISA White Paper



Calculated by Kiwamu Izumi (ISAS)

DECIGO



Can directly detect WD-WD mergers!

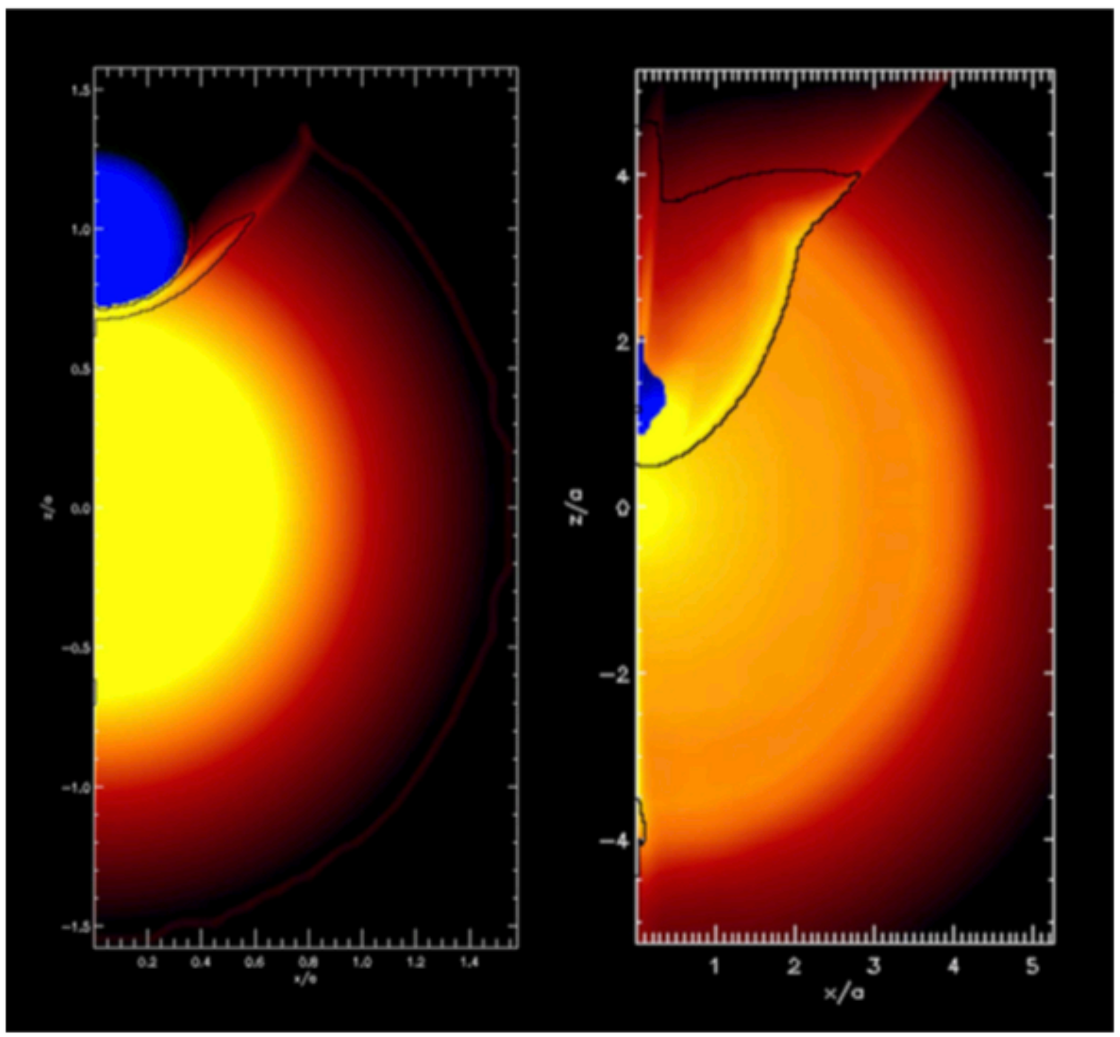
Summary

- SN Ia progenitor issue is a hot topic.
- A number of observations show evidence against SD scenario. (supporting DD?)
- SD-like SNe/SNRs do exist, suggesting both contribution of SD and DD channels.
- Future electromagnetic/gravitational wave observations are crucial.

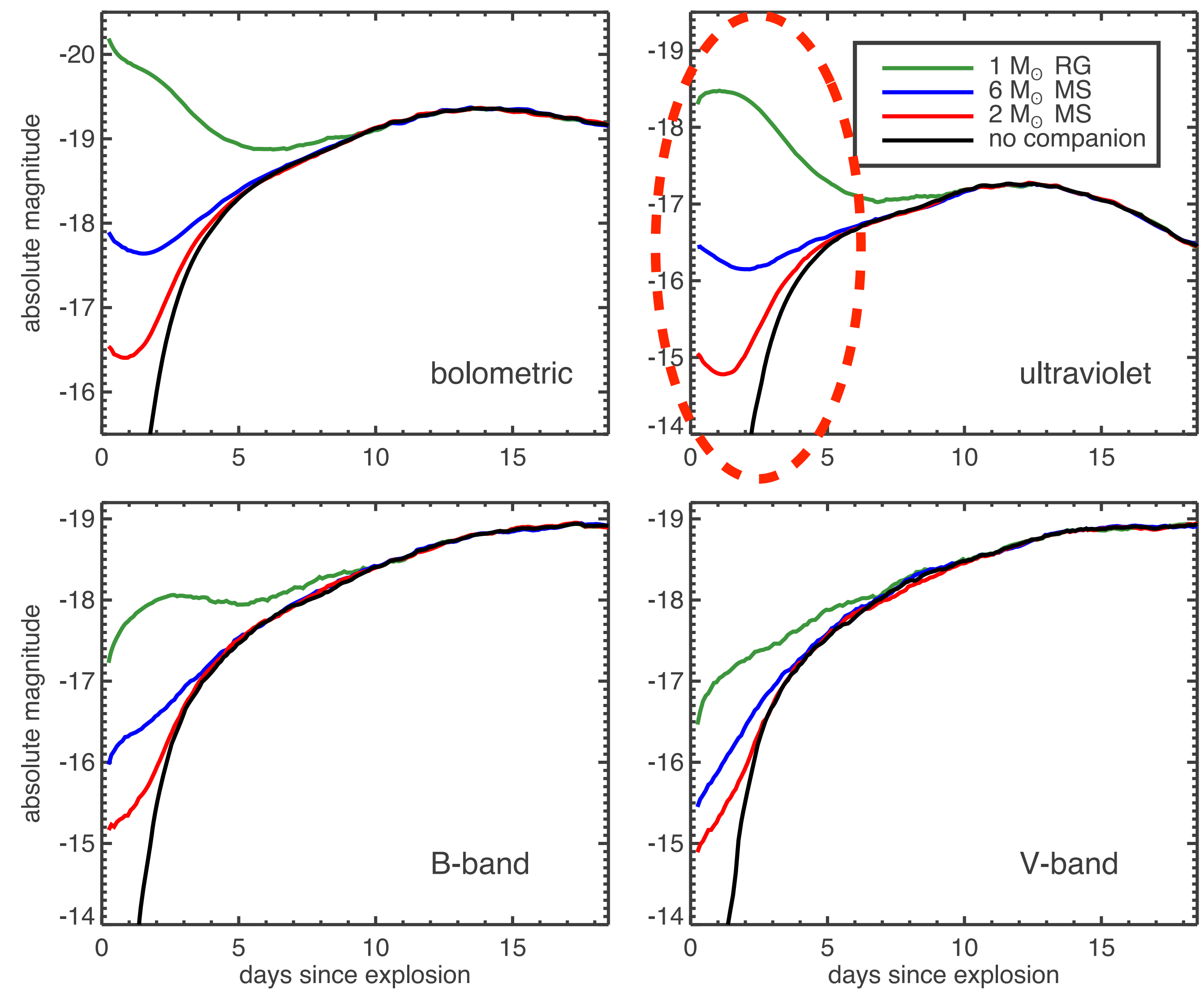
Back-up slides

Collision-induced thermal emission

Excess in X-rays ~ UV/optical at a few days after the explosion is predicted (Kasen 2010)

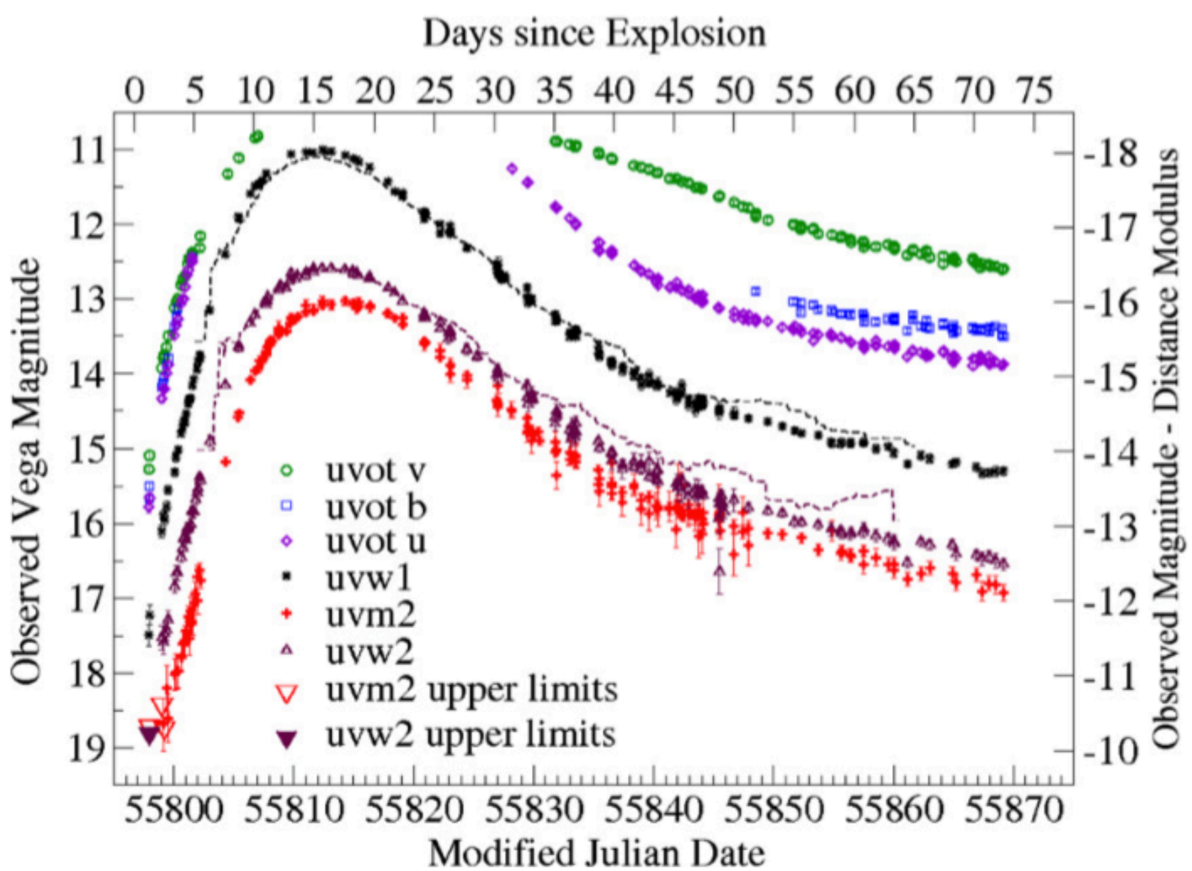


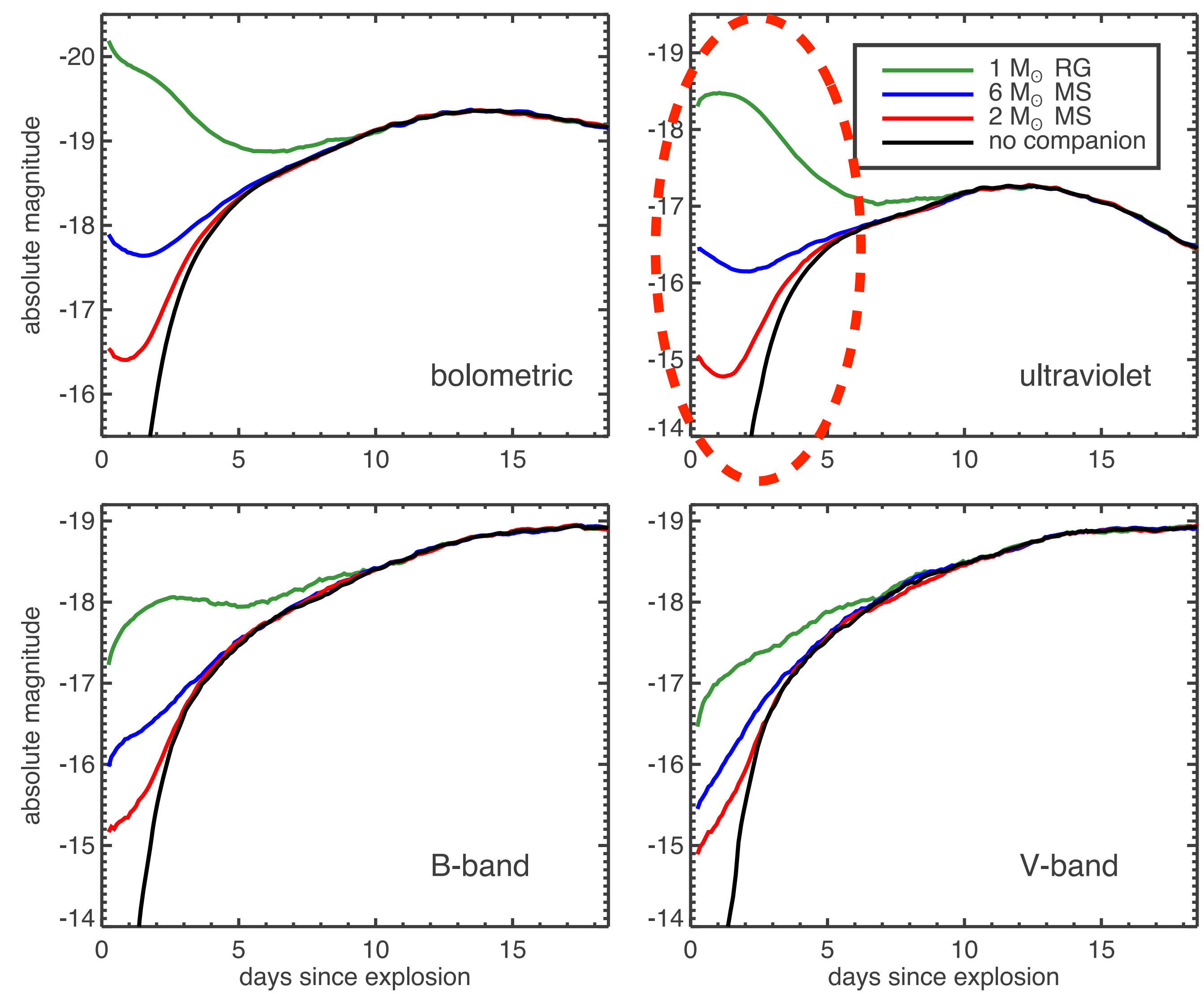
Kasen 2010



Collision-induced thermal emission

Excess in X-rays ~ UV/optical at a few days after the explosion is predicted (Kasen 2010)





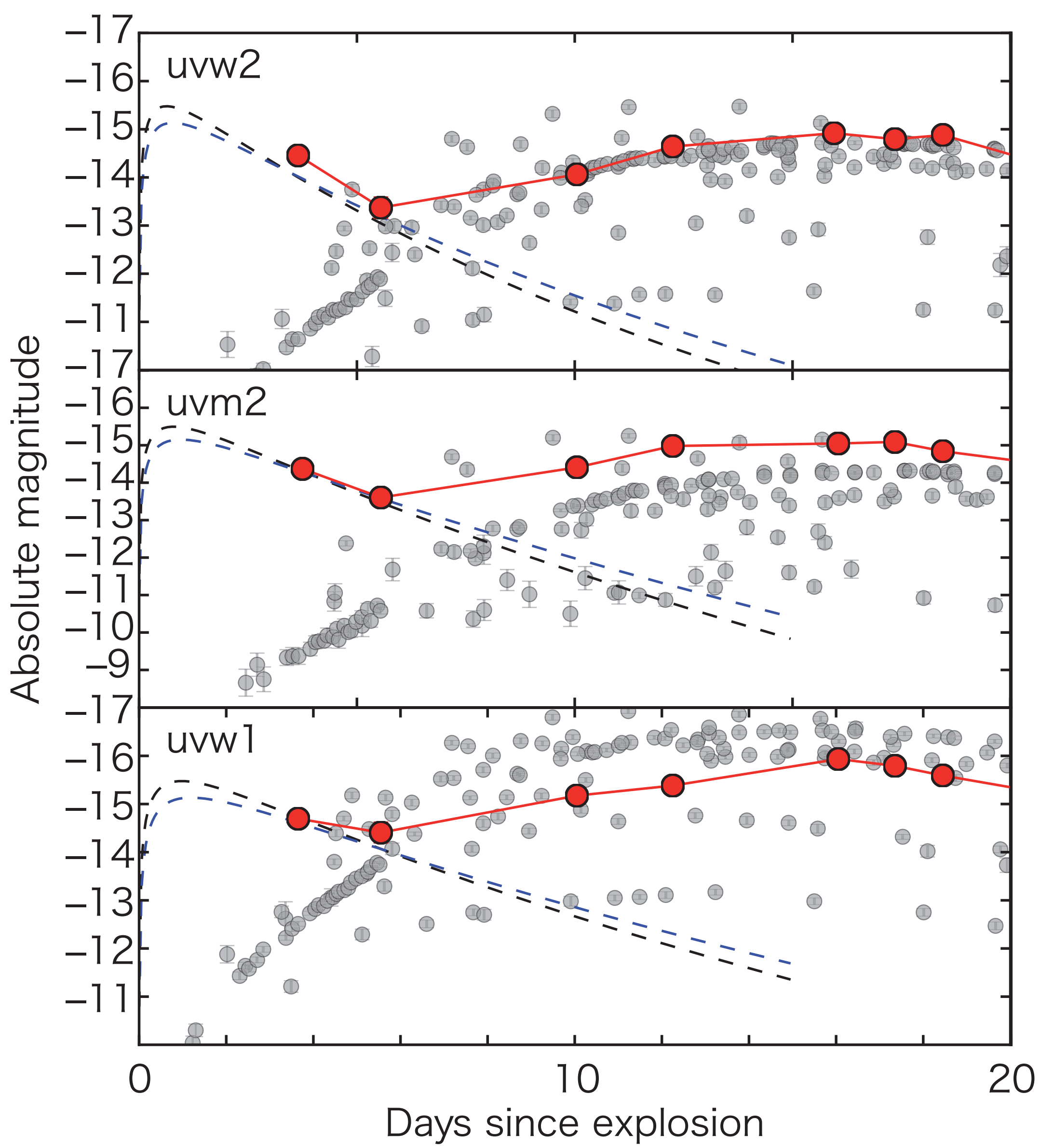
SN 2011fe:

***Swift* rules out >1M☉ MS with > 95% confidence**

(Blown 2012)

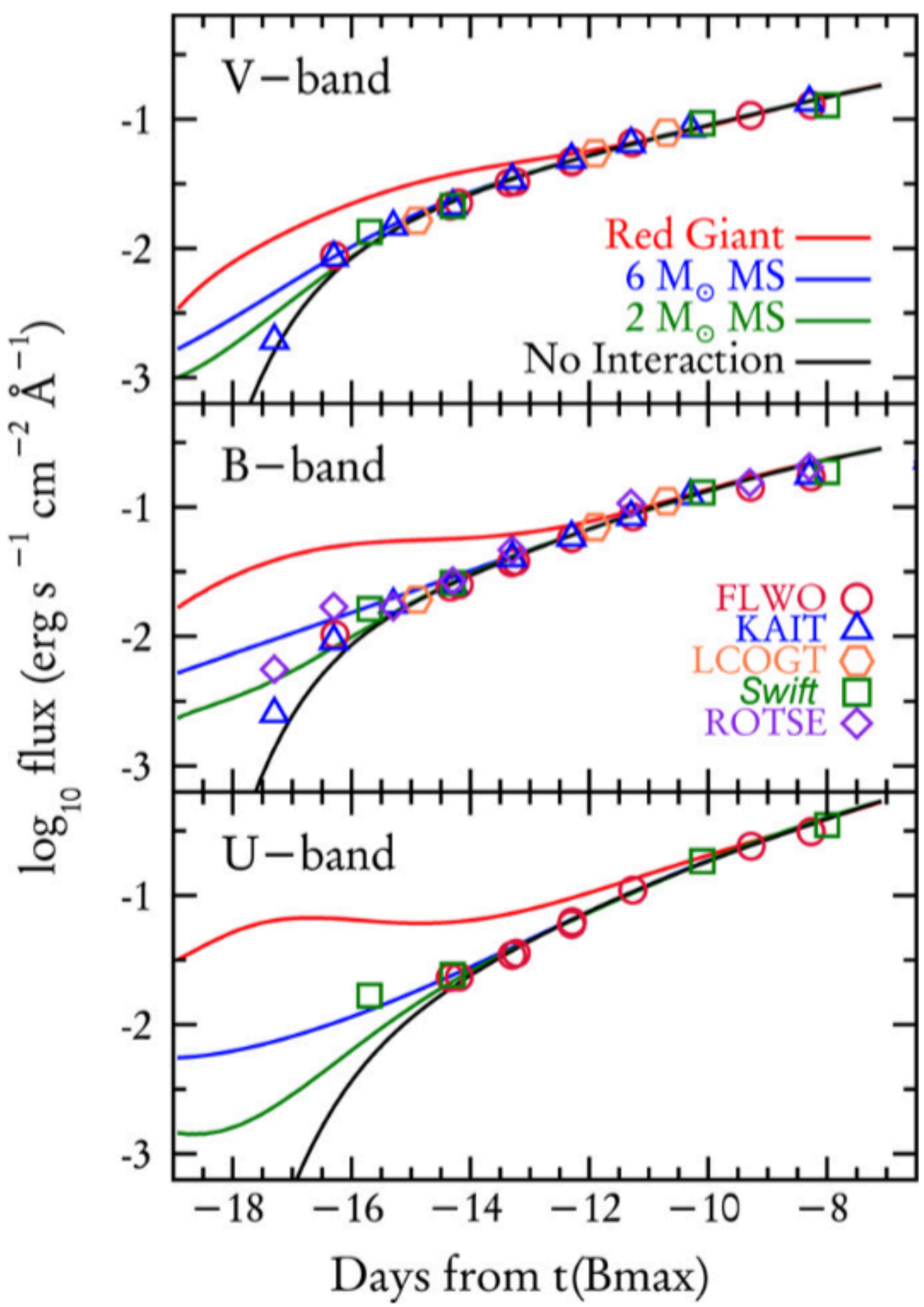
Collision-induced thermal emission

iiPTF14atg
(Cao+2015)



Excess detected from some outliers

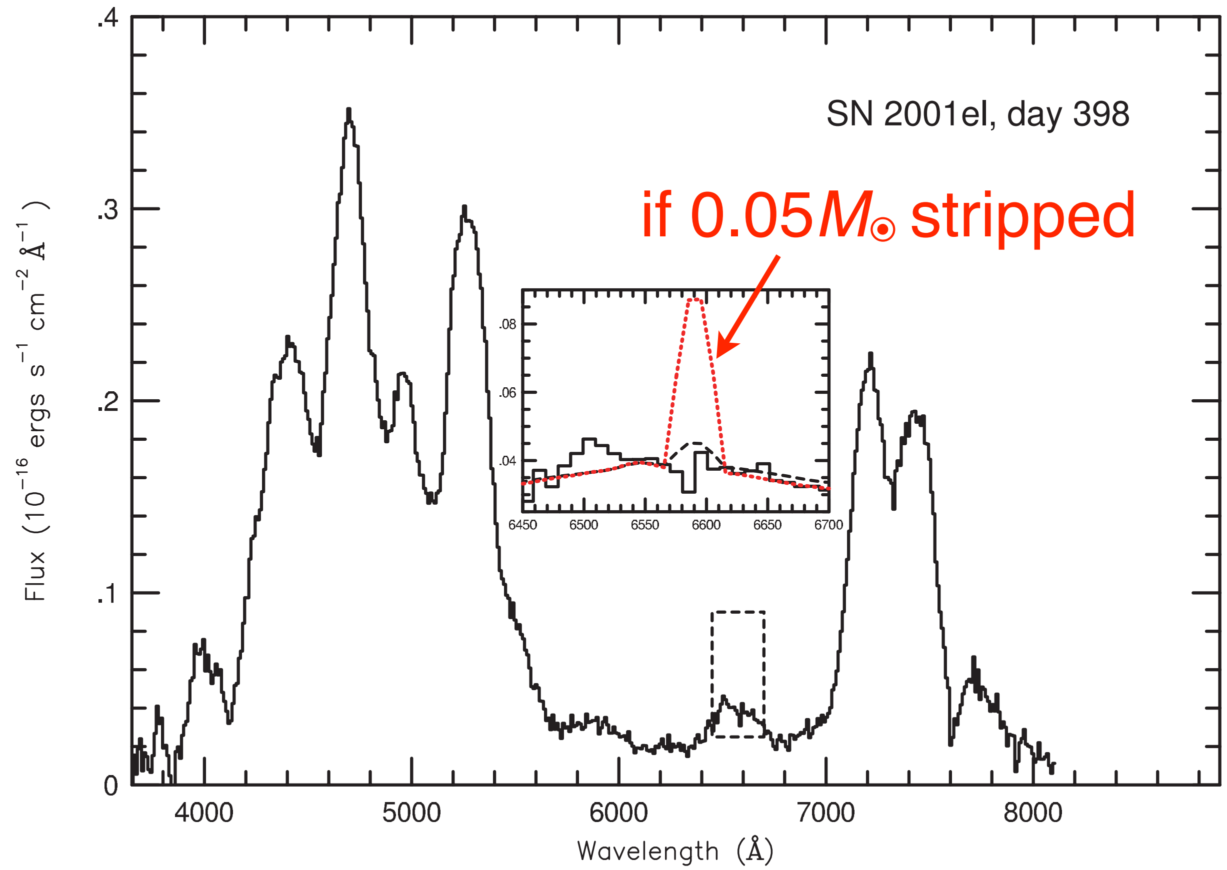
SN 2012cg
(Marion+2016)



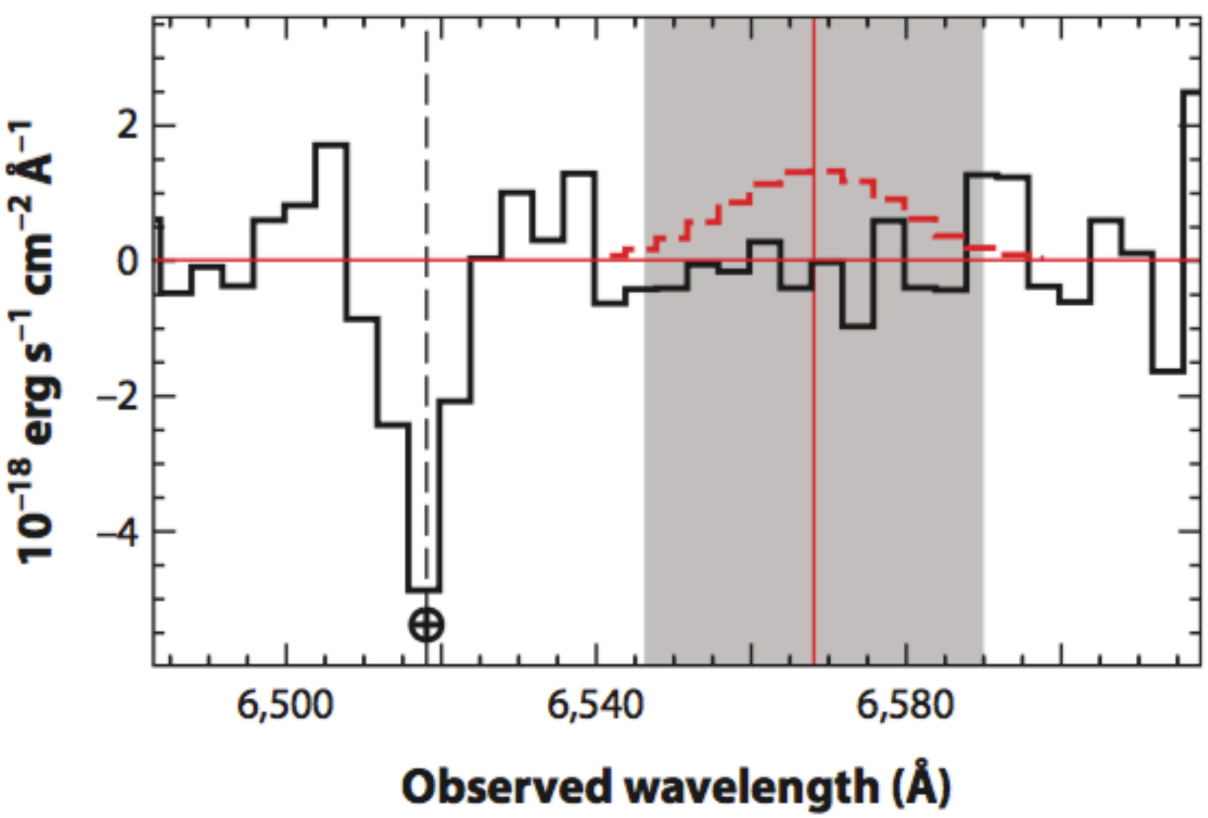
Stripped envelope

Blast wave strips <u>~ $0.1 M_\odot$ of hydrogen</u> from companion

- ➔ Excited by γ from ^{56}Co
- ➔ Hα emission in nebular phase (e.g, Mattila+2005)



SN 2011fe (Shappee+13)



SN 2011fe:

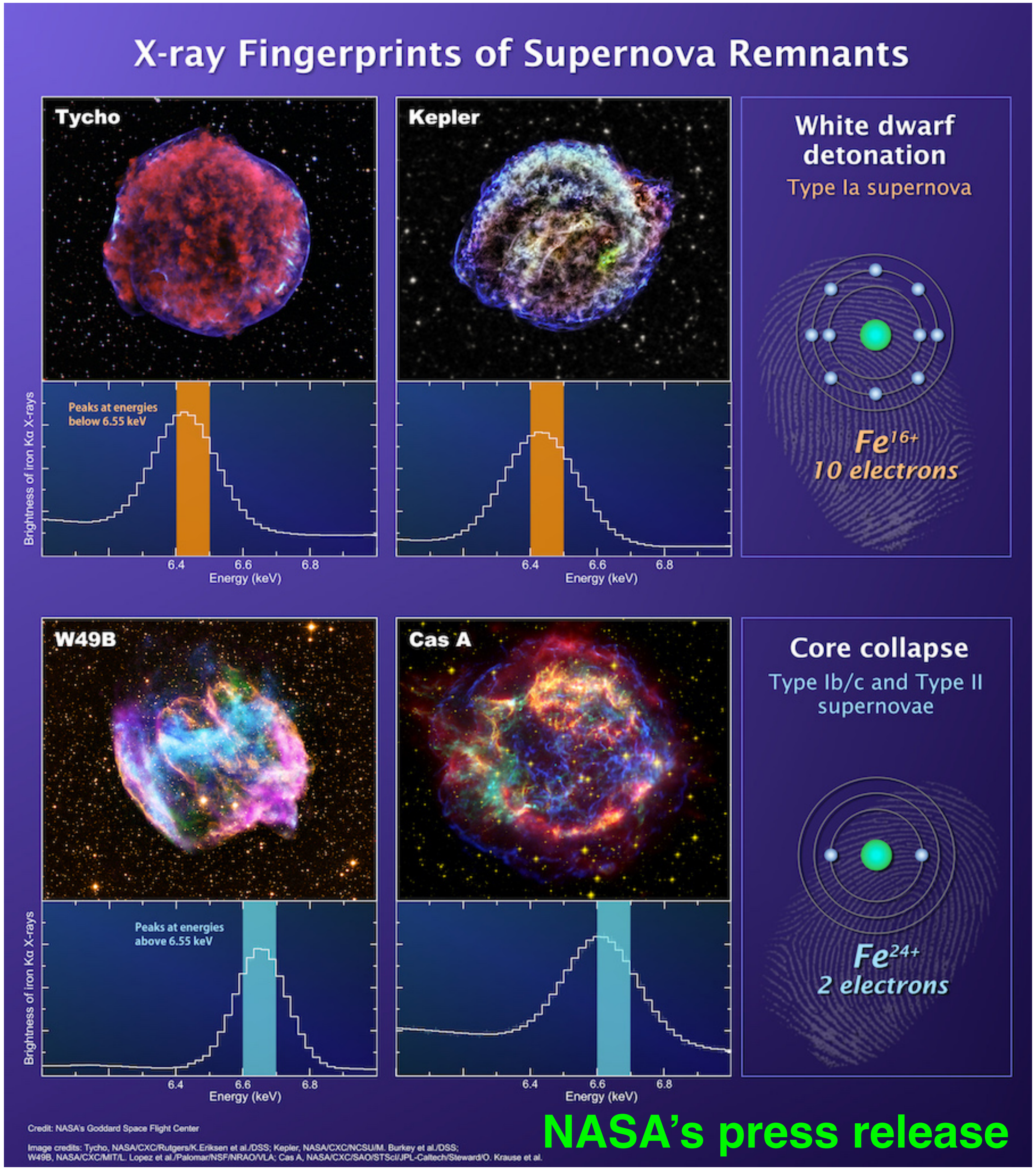
$< 0.001 M_\odot$ (Shappee+2013)

$< 10^{-4} M_\odot$ (Botyanszki+2017)

SN 2014J:

$< 0.005 M_\odot$ (Lundqvist+2015)

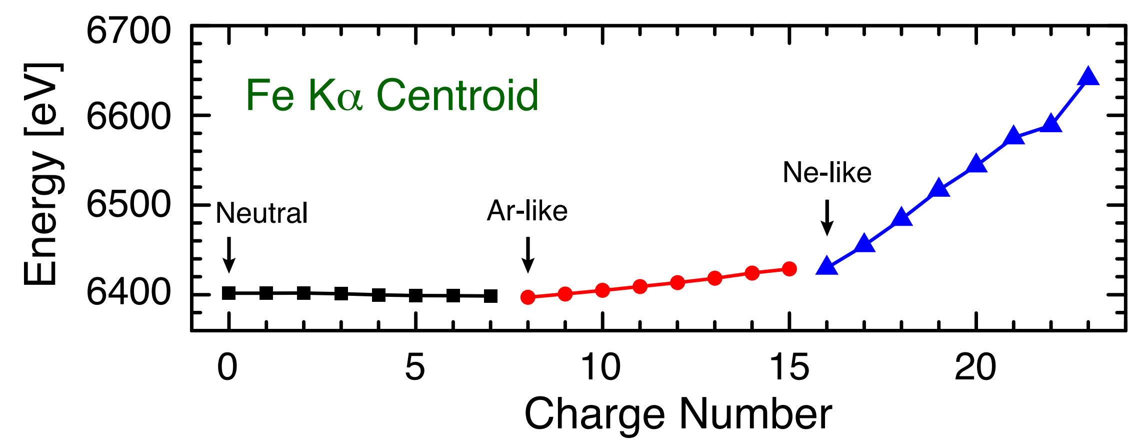
Search for CSM in SNRs



Collision with CSM

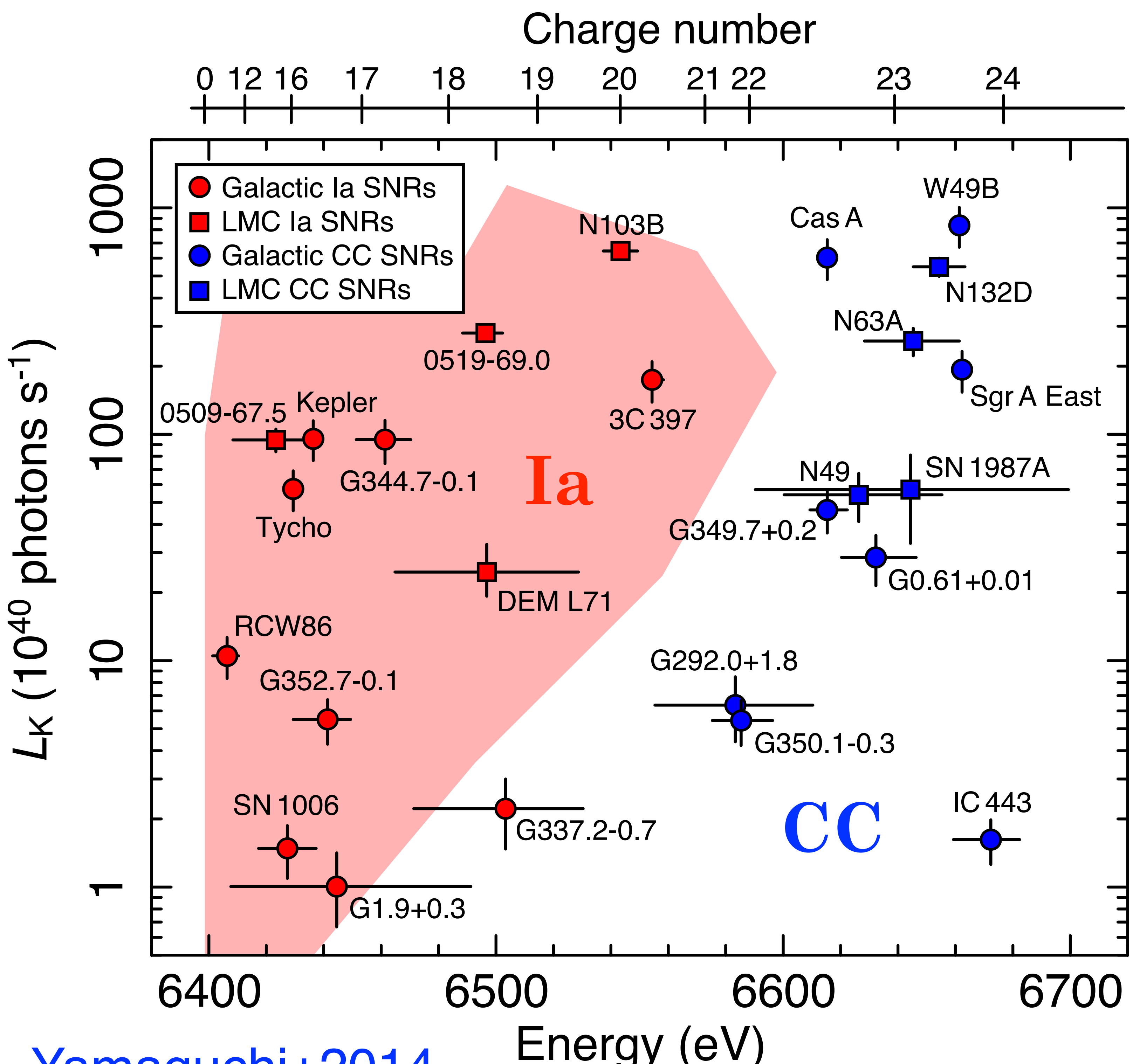
➔ Ejecta highly ionized

➔ Fe line centroid shifts toward higher energy



Fe centroid generally high in core-collapse SNRs (Yamaguchi+2014)

Search for CSM in SNRs



Yamaguchi+2014

Clean environment:

No evidence for large-scale CSM, like those observed in CC SNRs.

Consistent with hydro simulations assuming uniform ISM.

- Ambient medium: $1–5 \times 10^{-24}$ g cm^{-3}
- Age: < 5000 yr

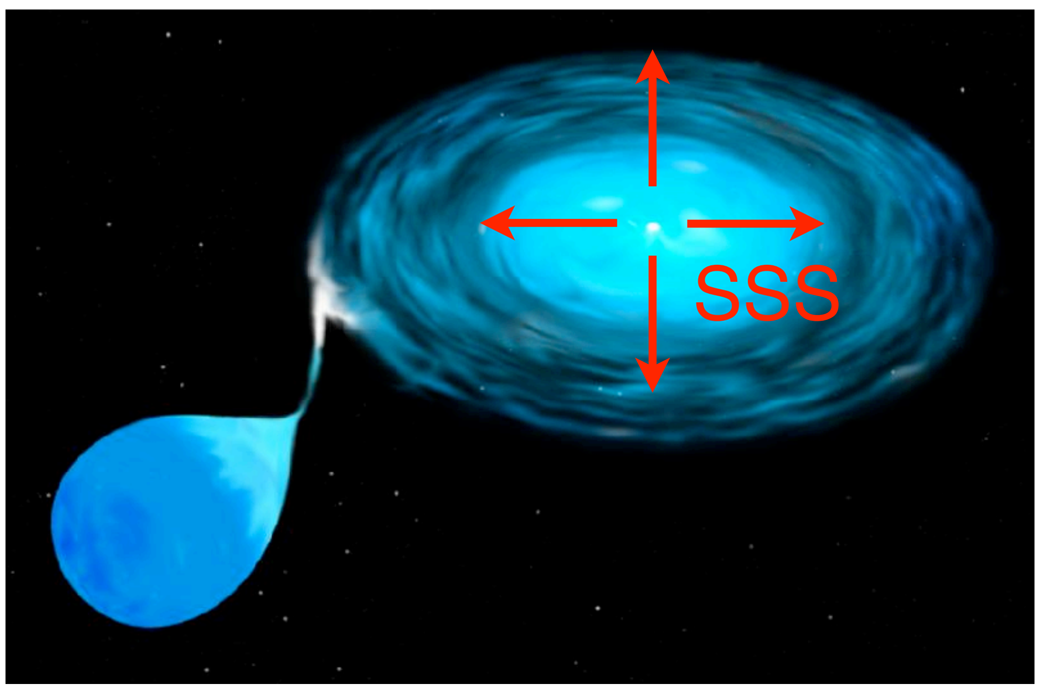
Super-soft source (SSS)

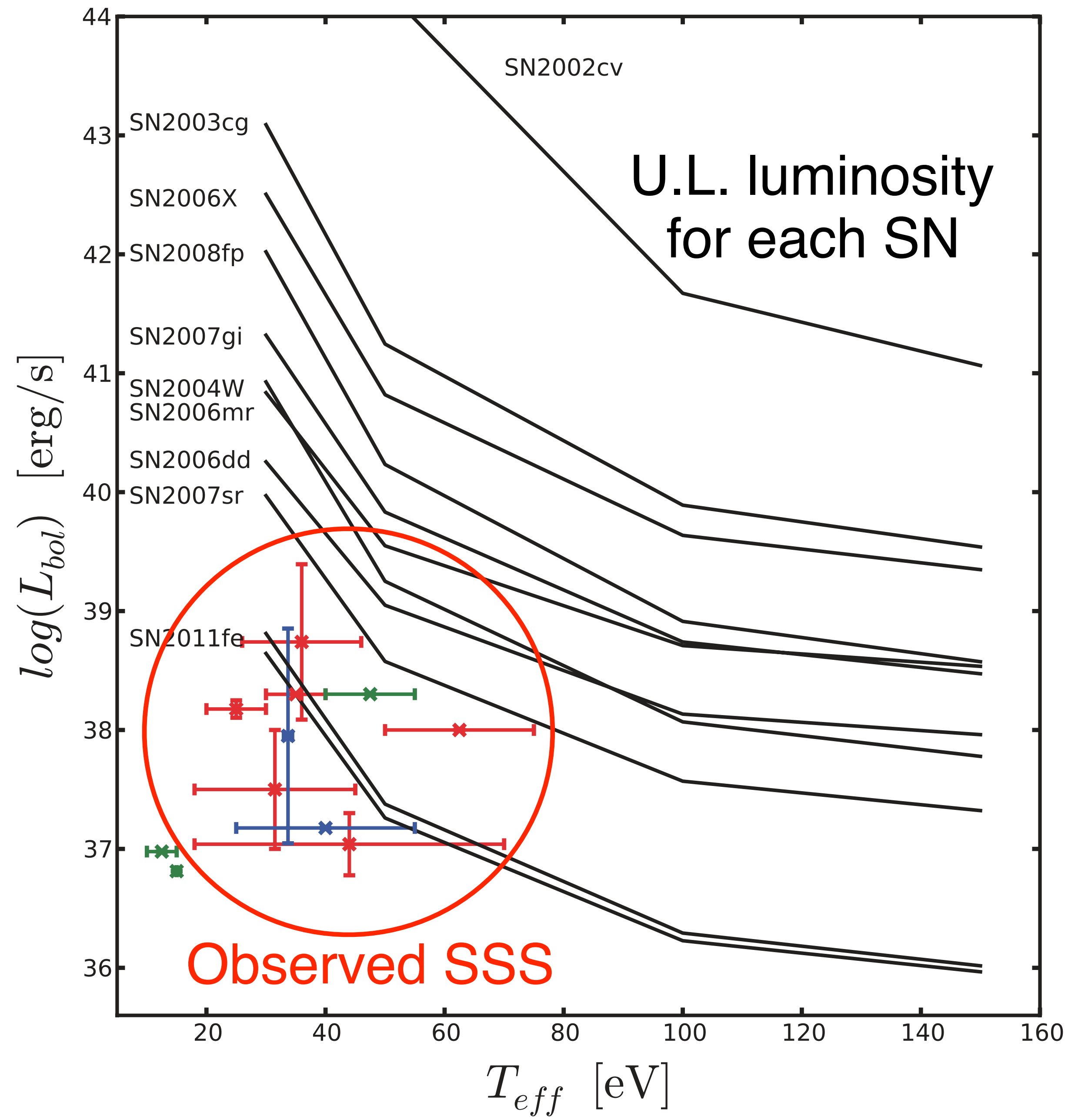
Steady burning of accreting materials (H ➔ He ➔ C/O)

$T_{BB} \sim 10^{5\text{–}6}$ K

➔ soft X-ray radiation

$L_{bol} \sim 10^{37\text{–}38}$ erg s^{-1}





Pre-explosion SSSs searched by Chandra

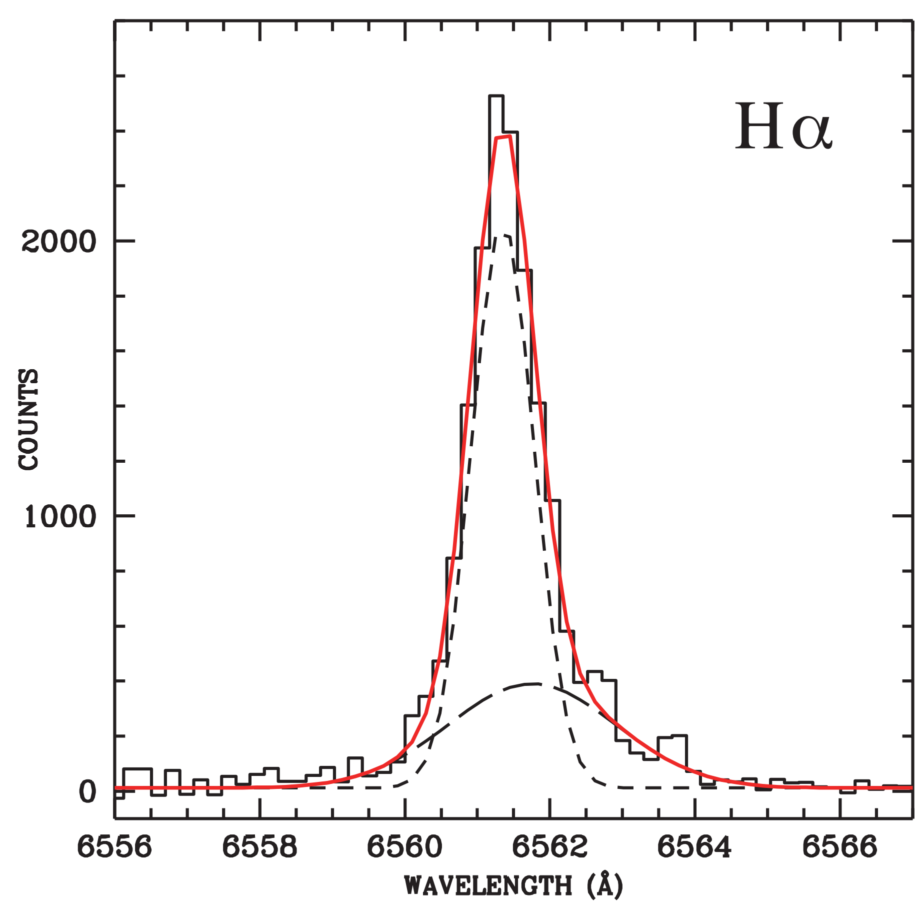
Nielsen+2012, 2013, 2014

SSS as an ionizing source

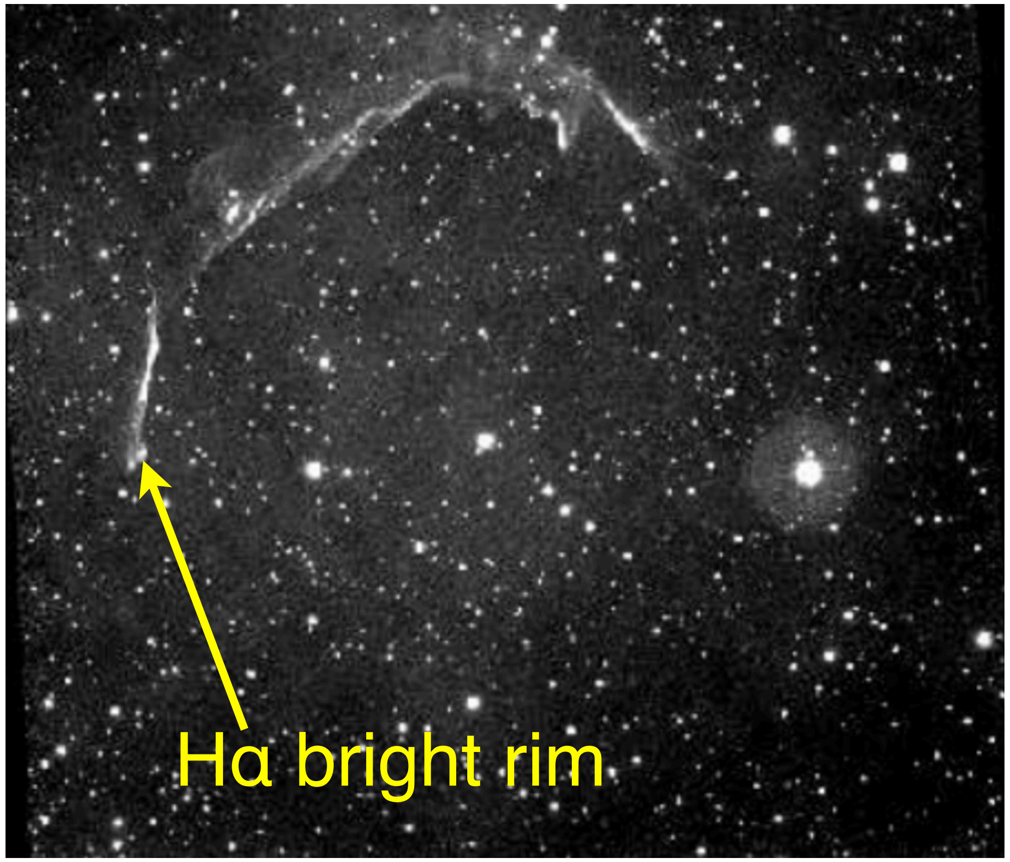
UV/X-rays from SSS may ionize surrounding ISM.

$t_{rec} \sim 10^5/n$ yr ➔ not yet recombined in remnant stage.

Neutral hydrogen commonly exist in SNR Ia blast wave.
(e.g., Ghavamian+2003)



Tycho SNR (Williams+2013)

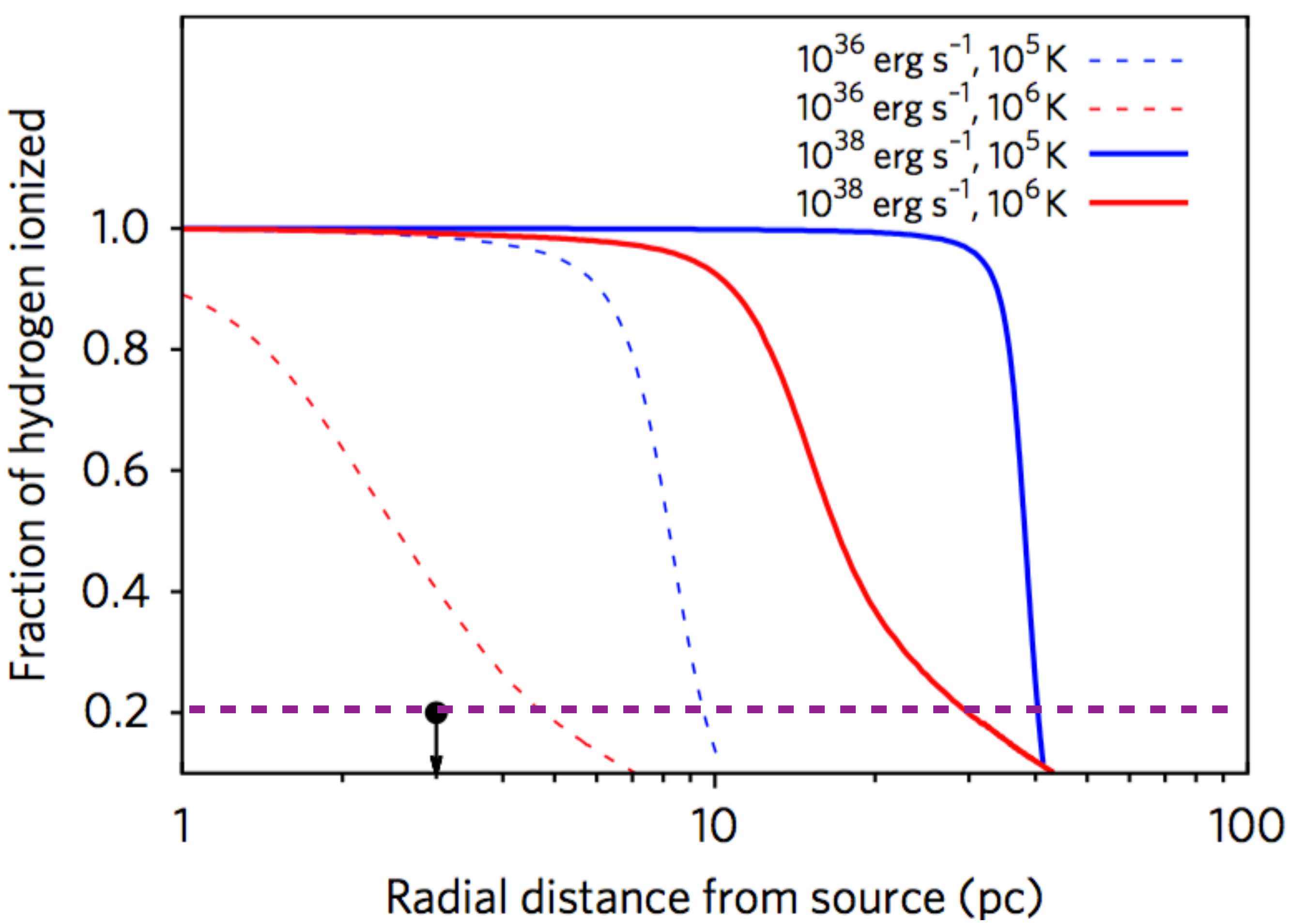


SSS as an ionizing source

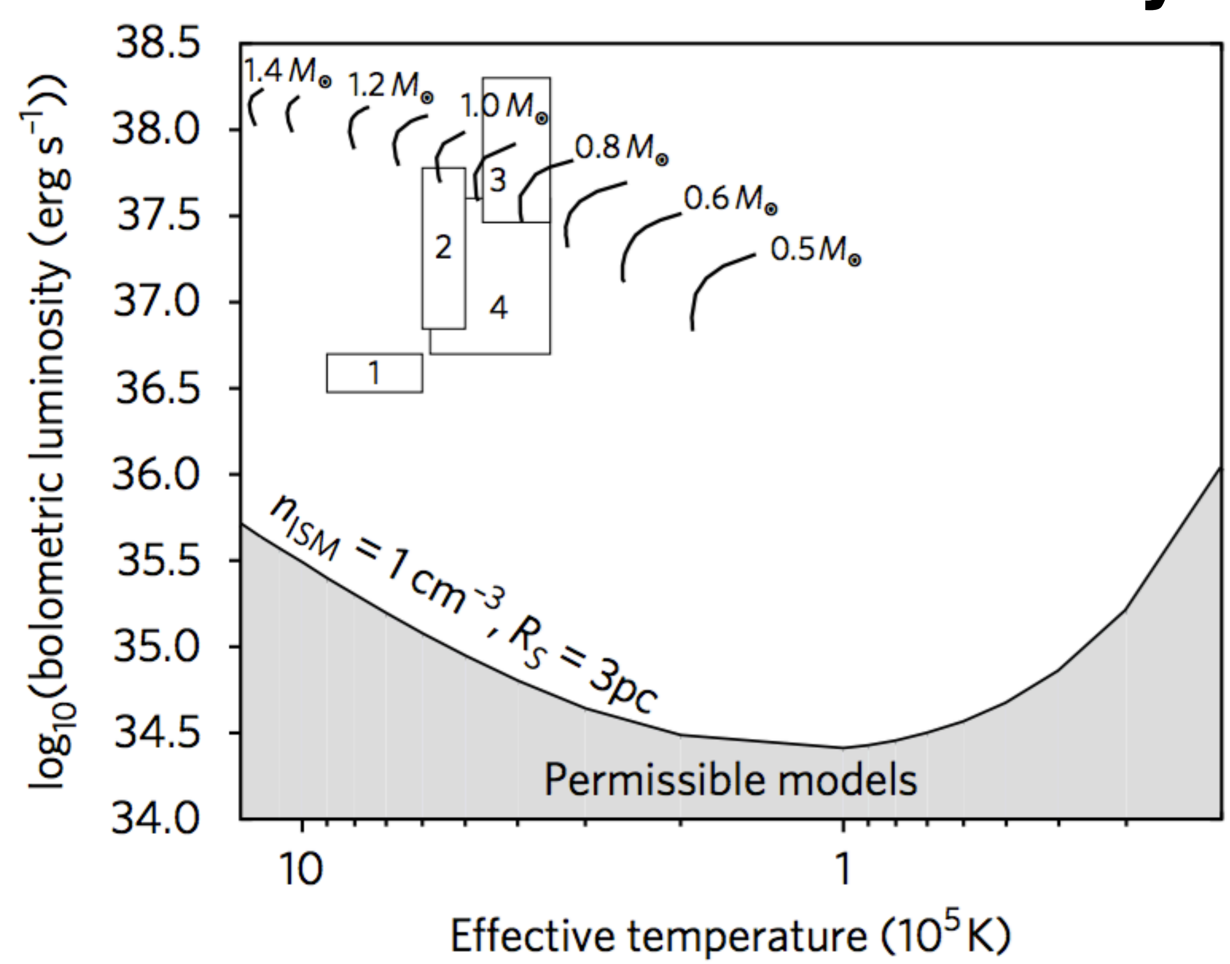
UV/X-rays from SSS may ionize surrounding ISM.
$t_{rec} \sim 10^5/n$ yr ➔ not yet recombined in remnant stage.

Ionization degree of < 20% around Tycho SNR.
➔ No SSS at pre-explosion stage (Woods+2017)

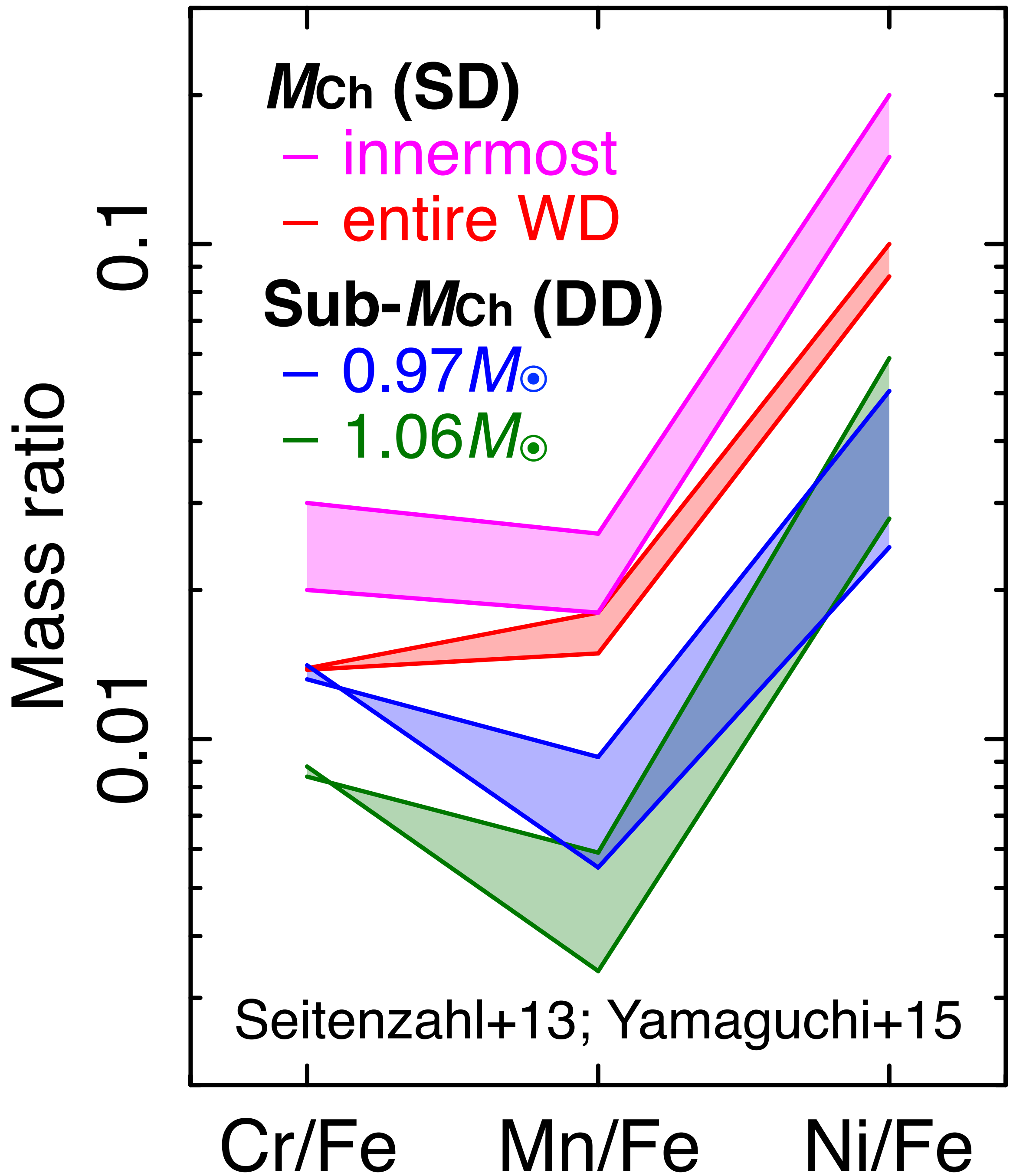
U.L. of ionization degree

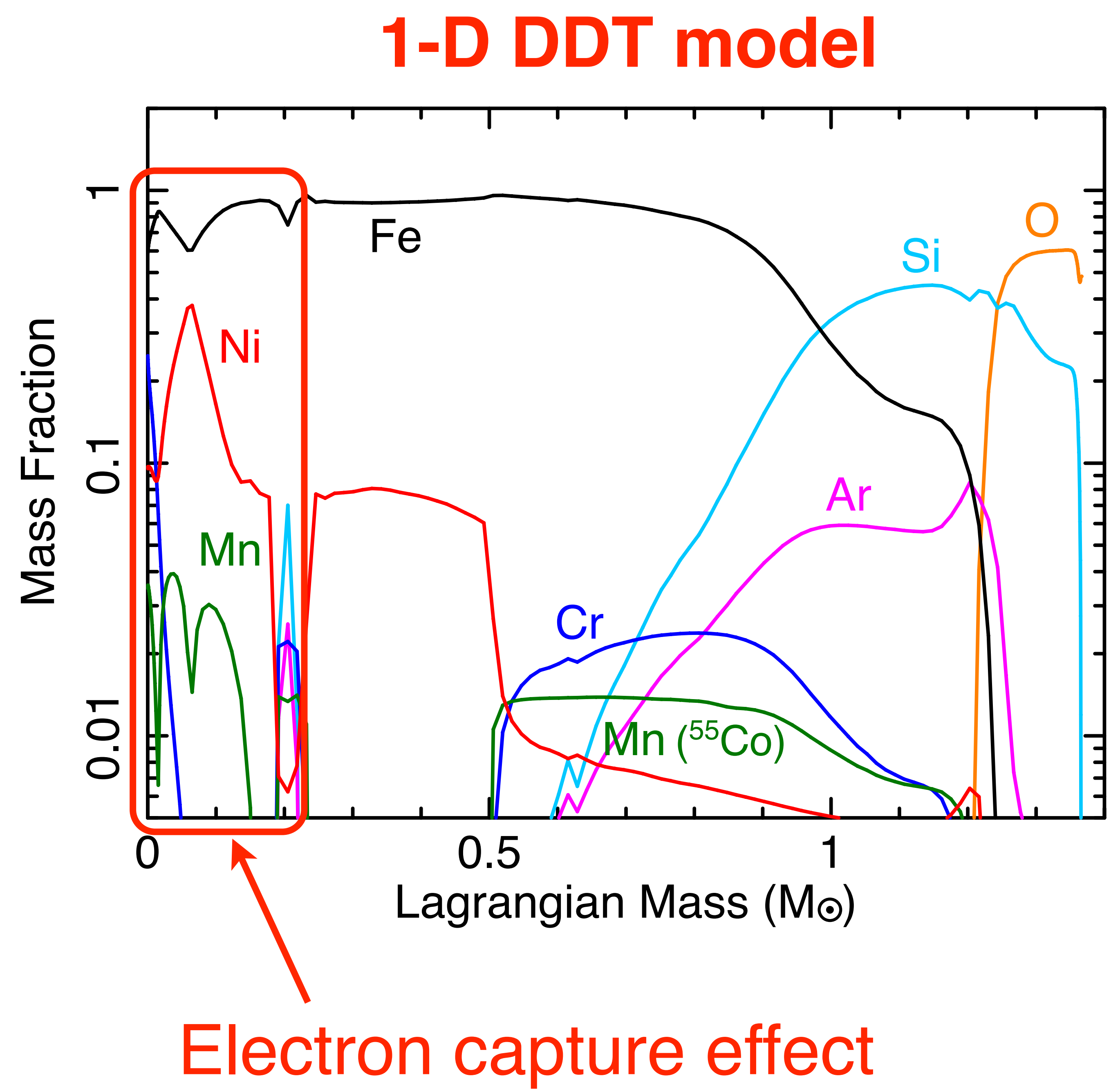


U.L. of SSS luminosity



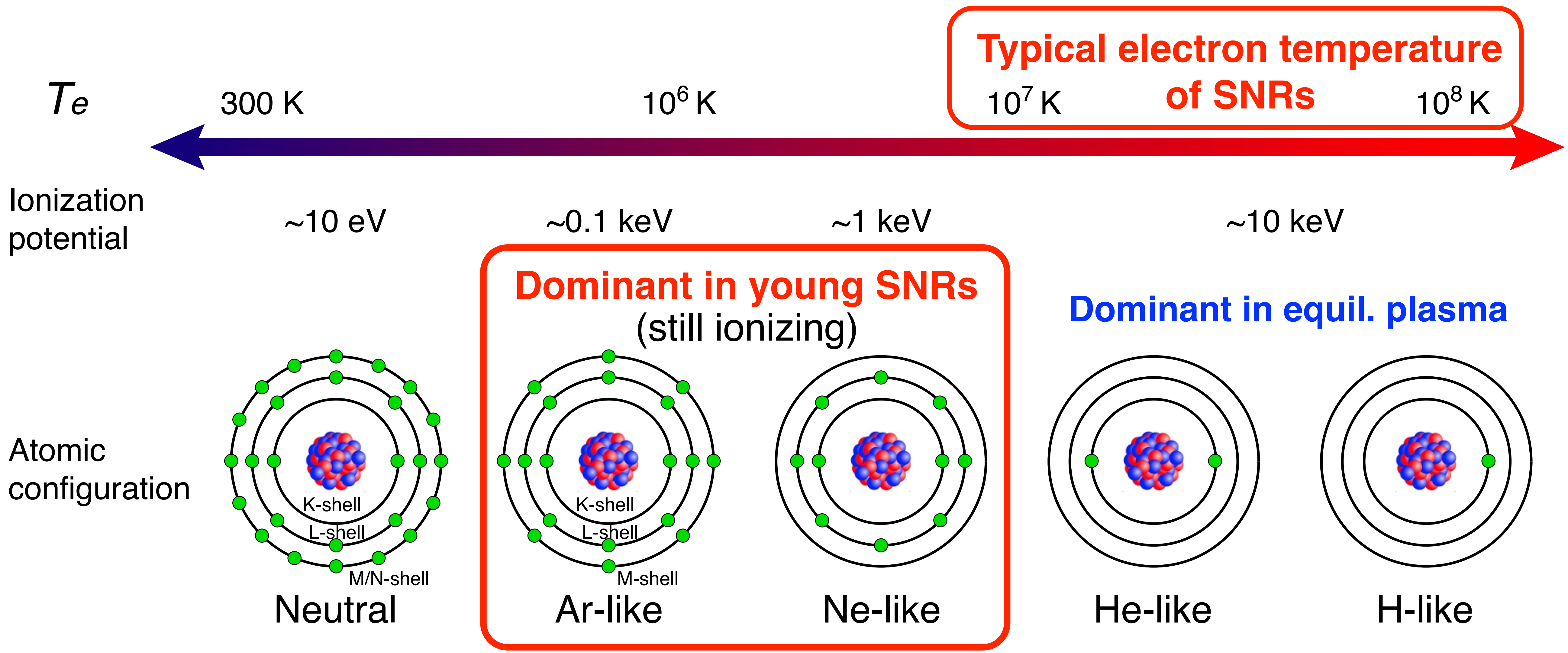
Theoretical predictions





Let's find SNe Ia with high Ni/Fe and Mn/Fe ratios

Non-Equilibrium Ionization (NEI)



Innershell processes are the key