Modelling thermonuclear supernovae

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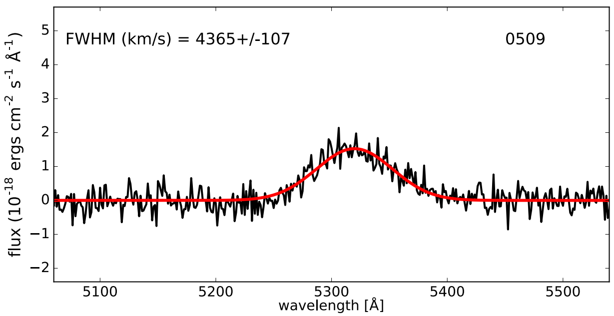


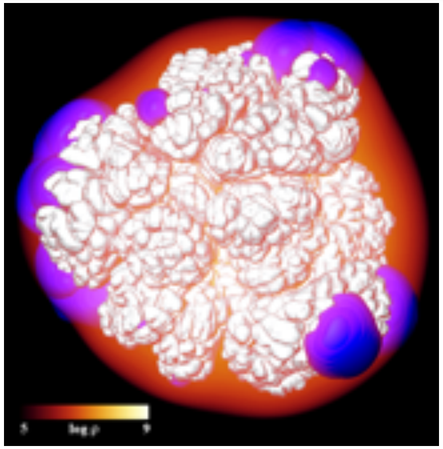
explosion simulations

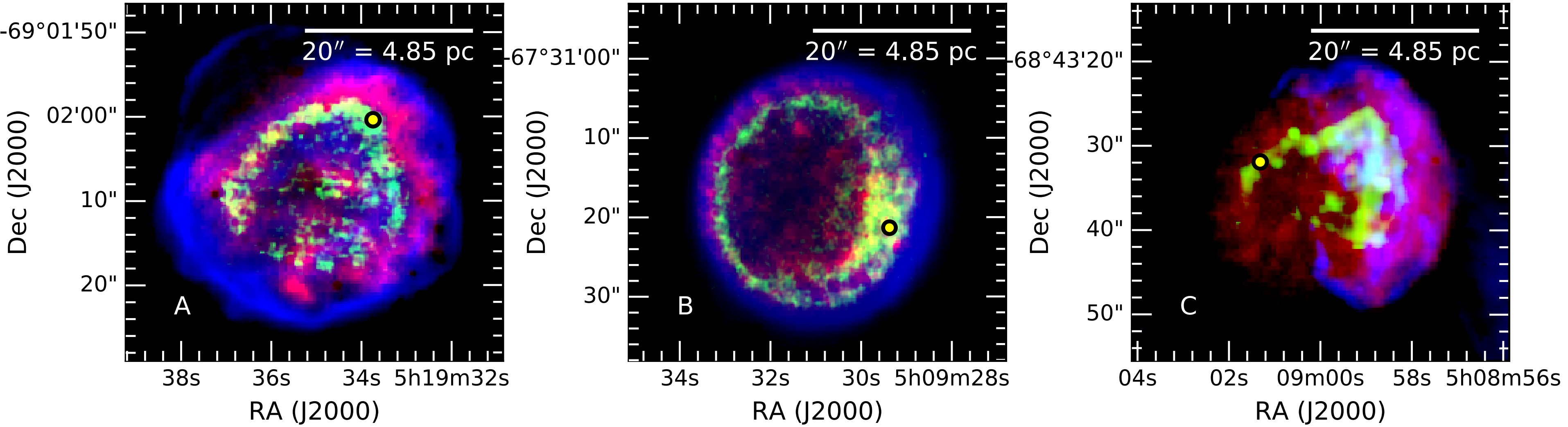
nucleosynthesis

observables

Ivo Seitenzahl

UNSW Canberra @ ADFA





IPMU, Japan

9 May 2019

University of New South Wales Canberra at the Australian Defence Force Academy

overview

&

simulations

SNe Ia gave use the accelerating Universe
What else besides Cosmology?

- Nobel Prize for the discovery of the accelerated expansion of the Universe
- SNe Ia used by SN Cosmology Project (Perlmu (Schmic
- High-rec **Univers expans**

Adam Riess Saul Perlmutter Brian Schmidt

In spite of the Nobel Prize, progenitor system(s) and explosion mechanism(s) of SNe Ia are unknown.

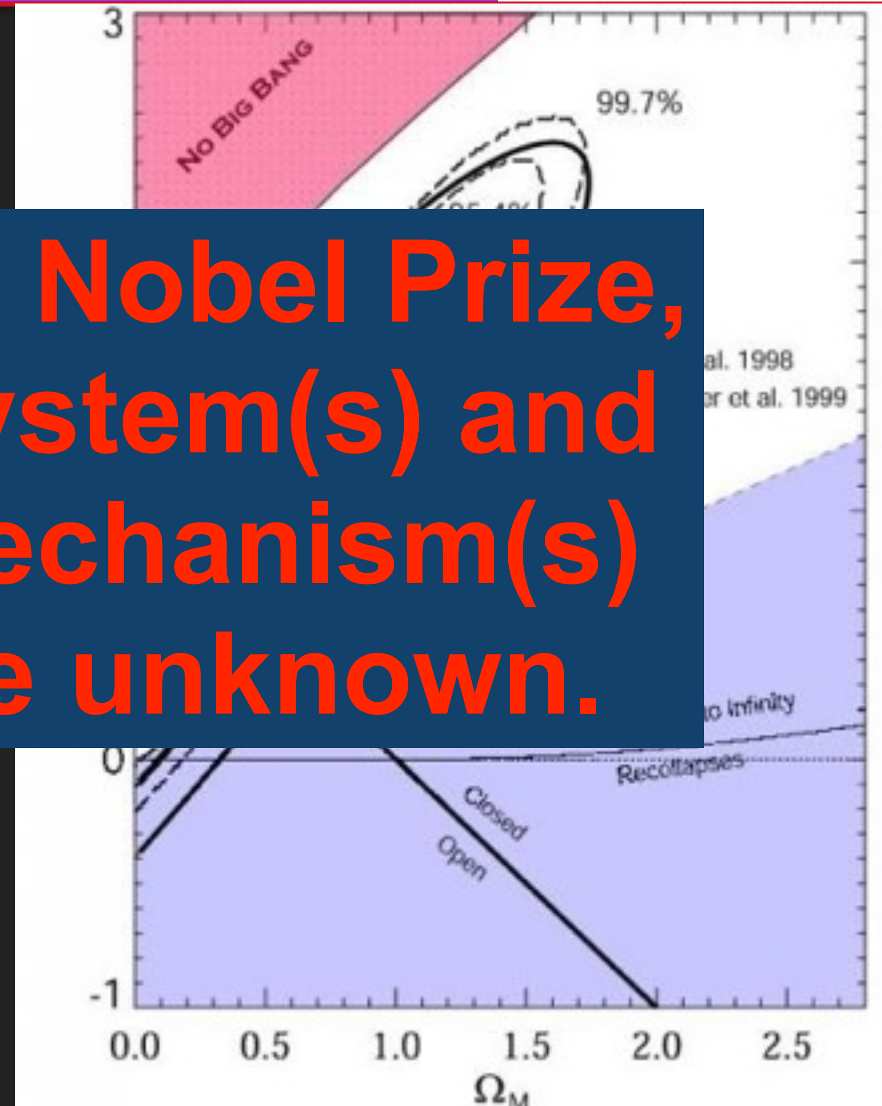


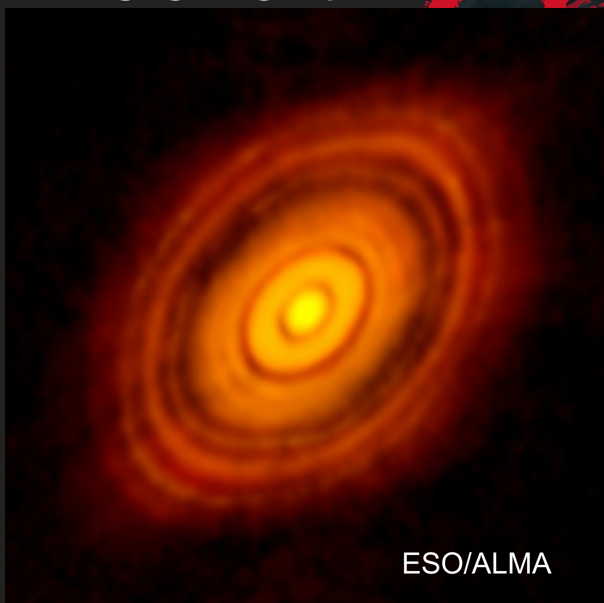
Image: cfa.harvard.edu/supernova/newdata/data.html

SNe Ia gave use the accelerating Universe
What else besides Cosmology?

Interstellar medium

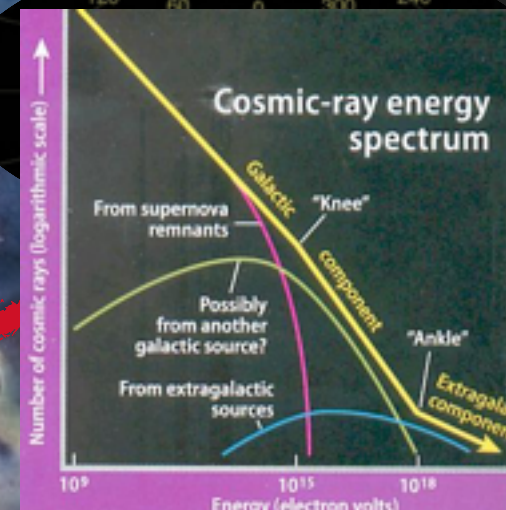
Type Ia supernova

Heavy element



ESO/ALMA

Positron production



Supernova remnant

Dissipation of kinetic energy / galaxy feedback / star formation

Cosmic rays / high energy photons

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progenitor WD structure

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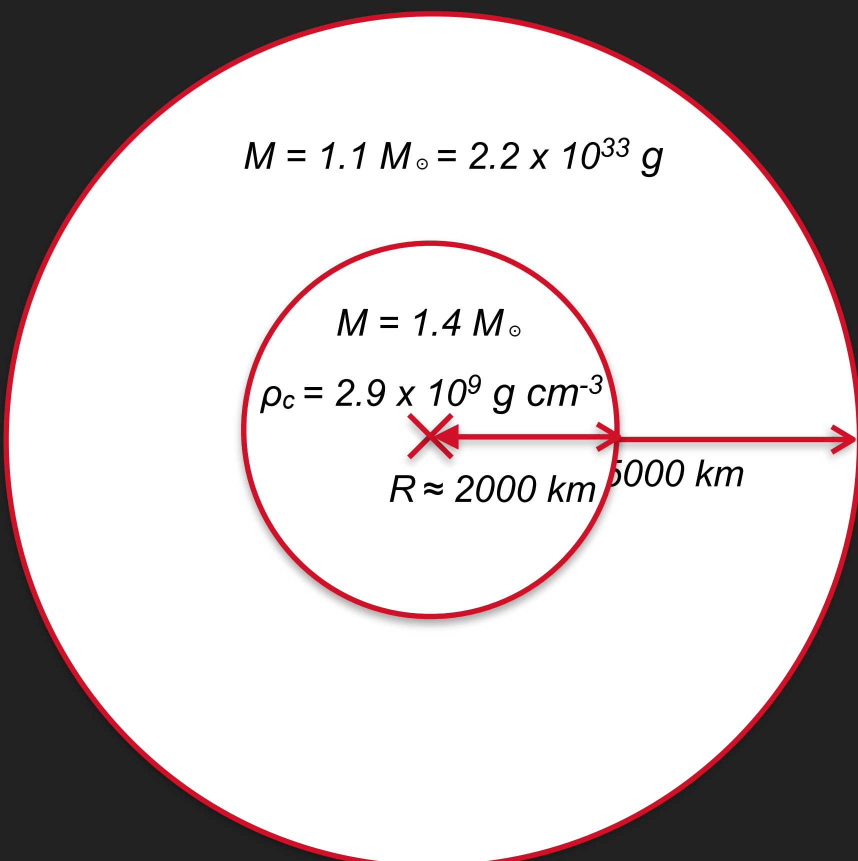
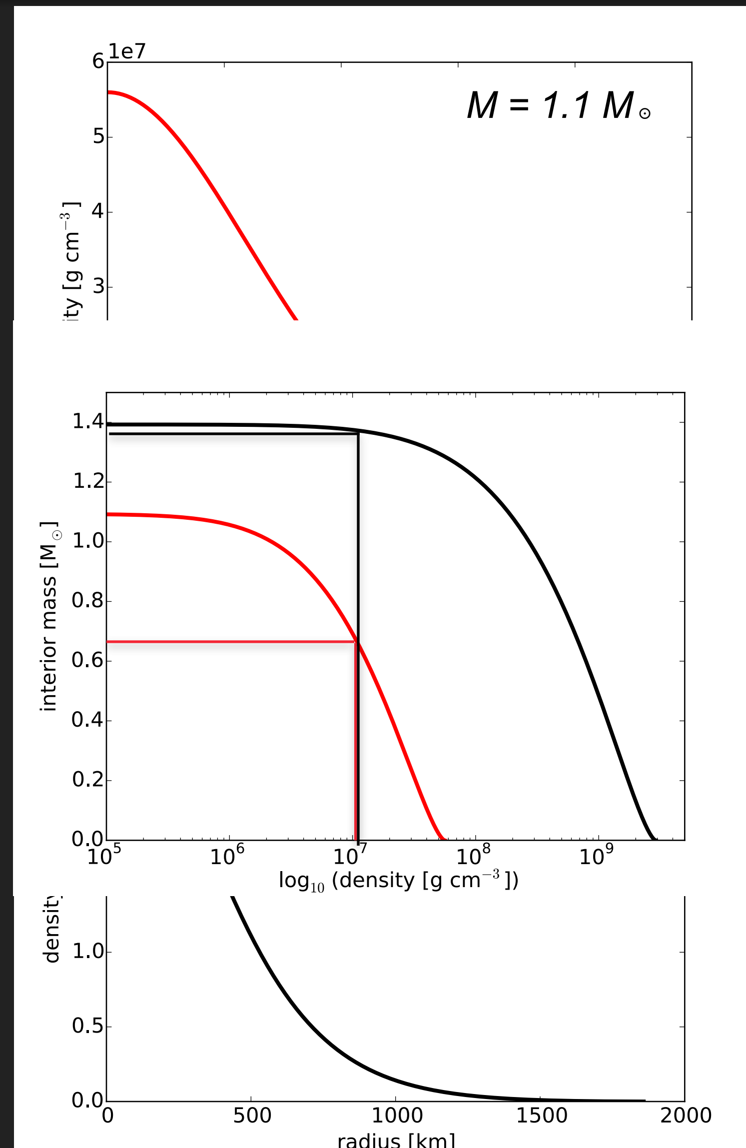
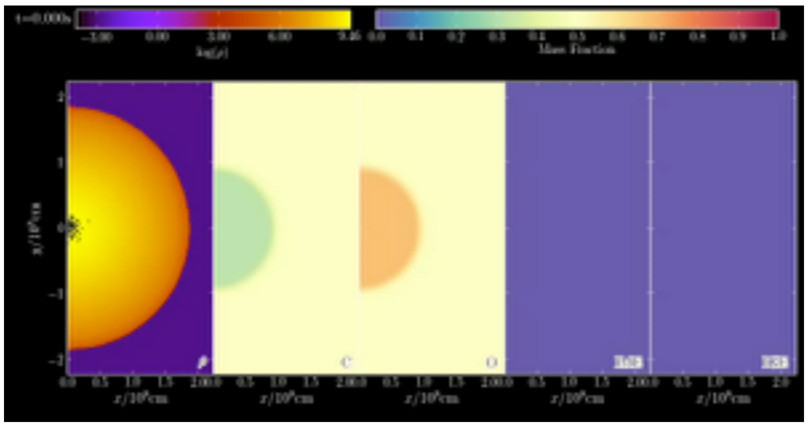
white dwarf star





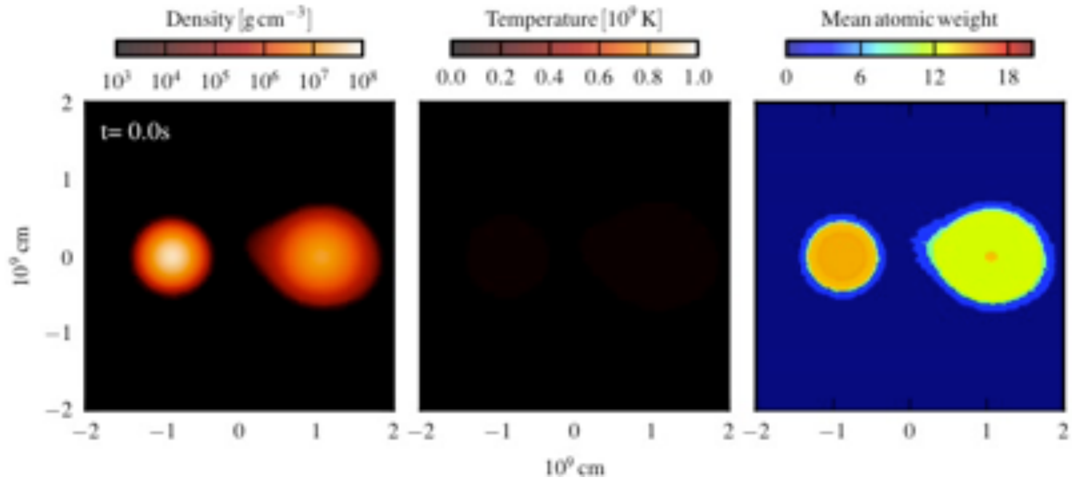
2 major categories near-M_{Ch} vs sub-M_{Ch}

e.g., delayed detonations
pure turbulent deflagrations



- ➡ $M_{primary} \approx 1.4$ solar masses
- ➡ ignition of deflagration by pycno-nuclear fusion of ^{12}C at high dens.
- ➡ explode expanded/-ing profile
- ➡ burning includes high density
  - ★ low entropy freeze-out
  - ★ electron captures

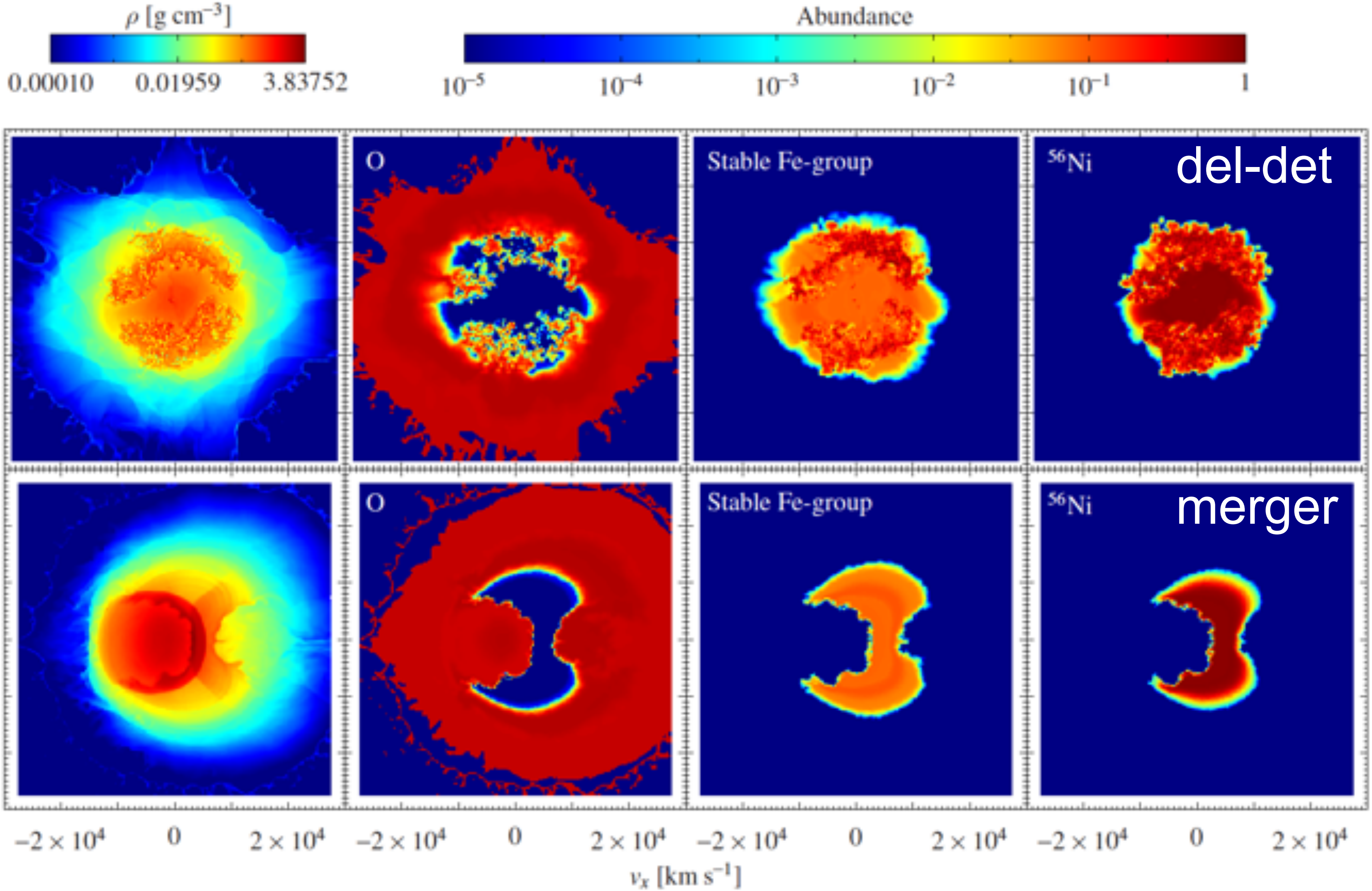
e.g., violent mergers
He double-detonations



- ➡ $M_{primary} \approx 0.8$ —1.1 solar masses
- ➡ ignition occurs as
  - ★ violent accretion stream triggers detonation
  - ★ He-layer detonates
- ➡ detonate hydrostatic profile
- ➡ burning at relatively low density

N100 delayed-detonation (Seitenzahl+2013) 1.1+0.9 Msun violent merger (Pakmor+2012)

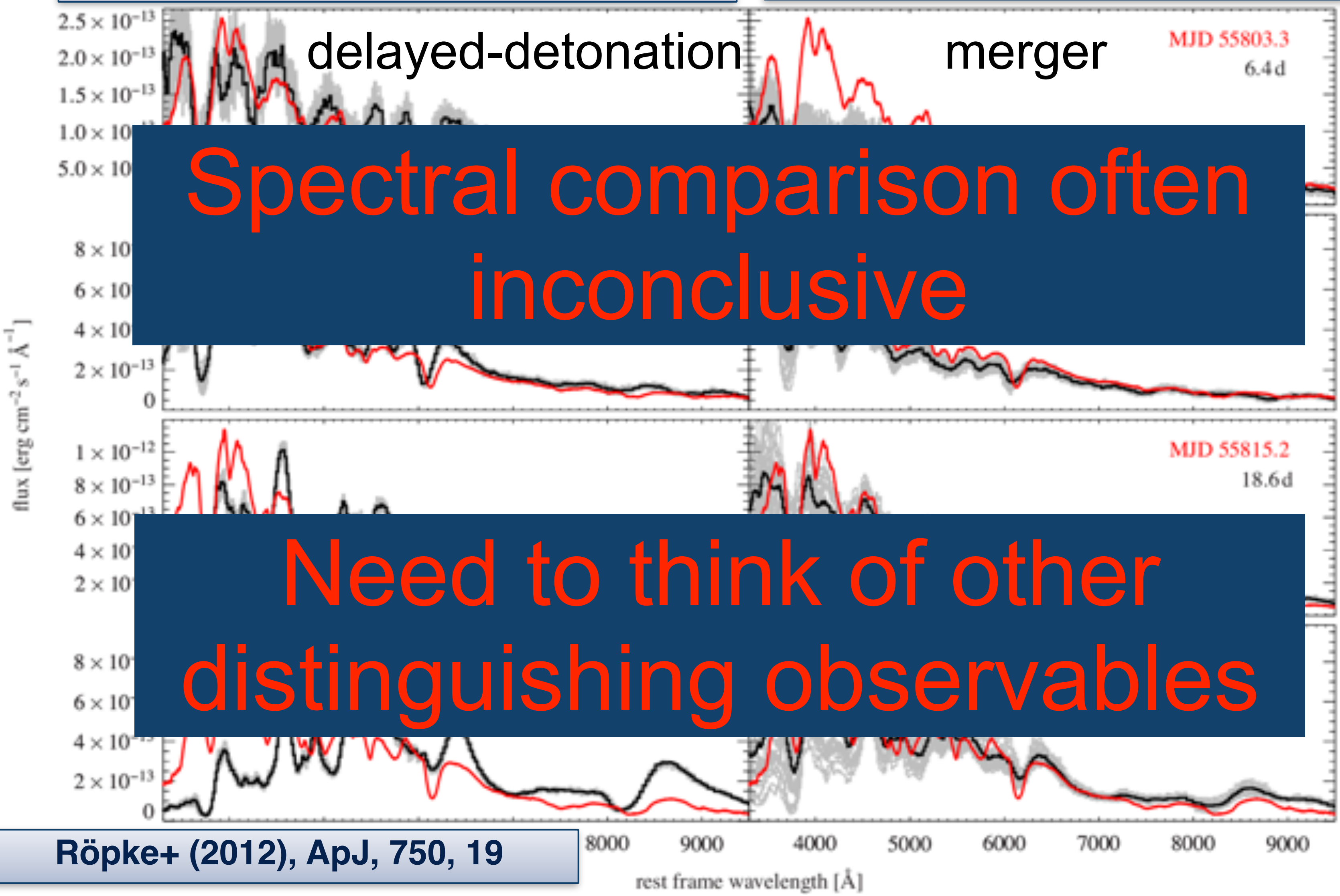
Same ^{56}Ni mass, morphology different



Spectral comparison inconclusive

Seitenzahl+ (2013), MNRAS, 429, 1156

Pakmor+ (2013), ApJ, 747, 10



Spectral comparison often inconclusive

Need to think of other distinguishing observables

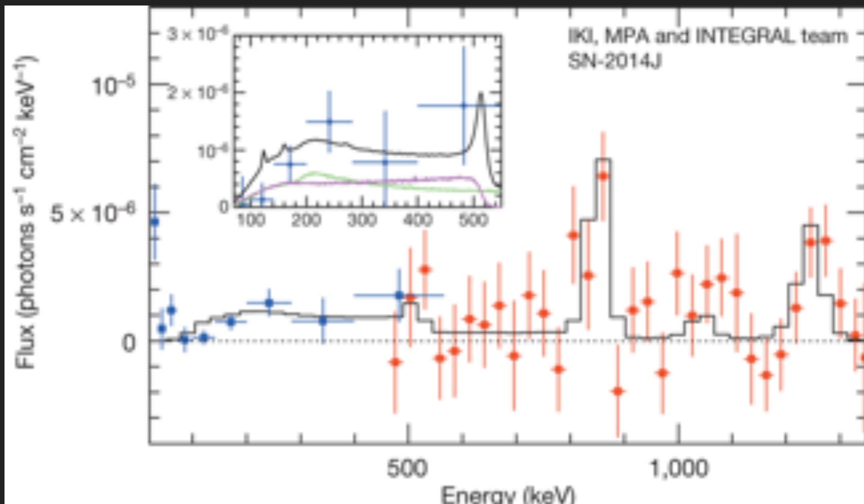
Röpke+ (2012), ApJ, 750, 19

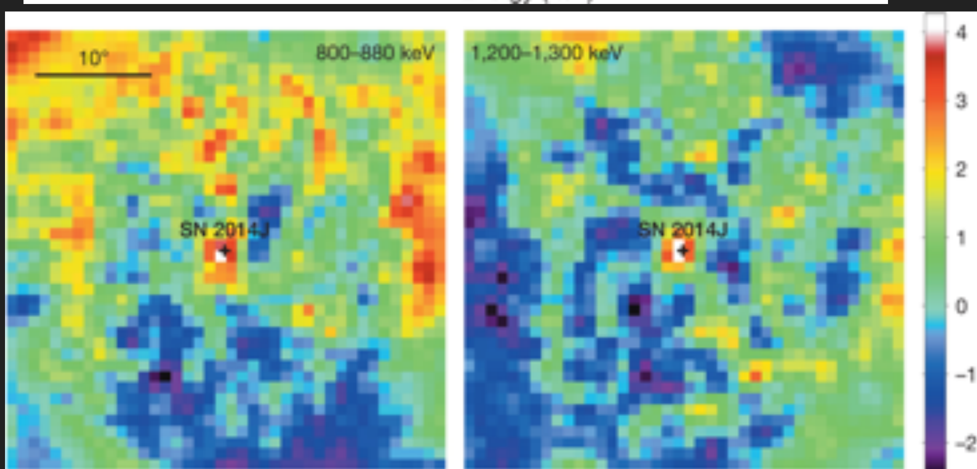
Other

distinguishing

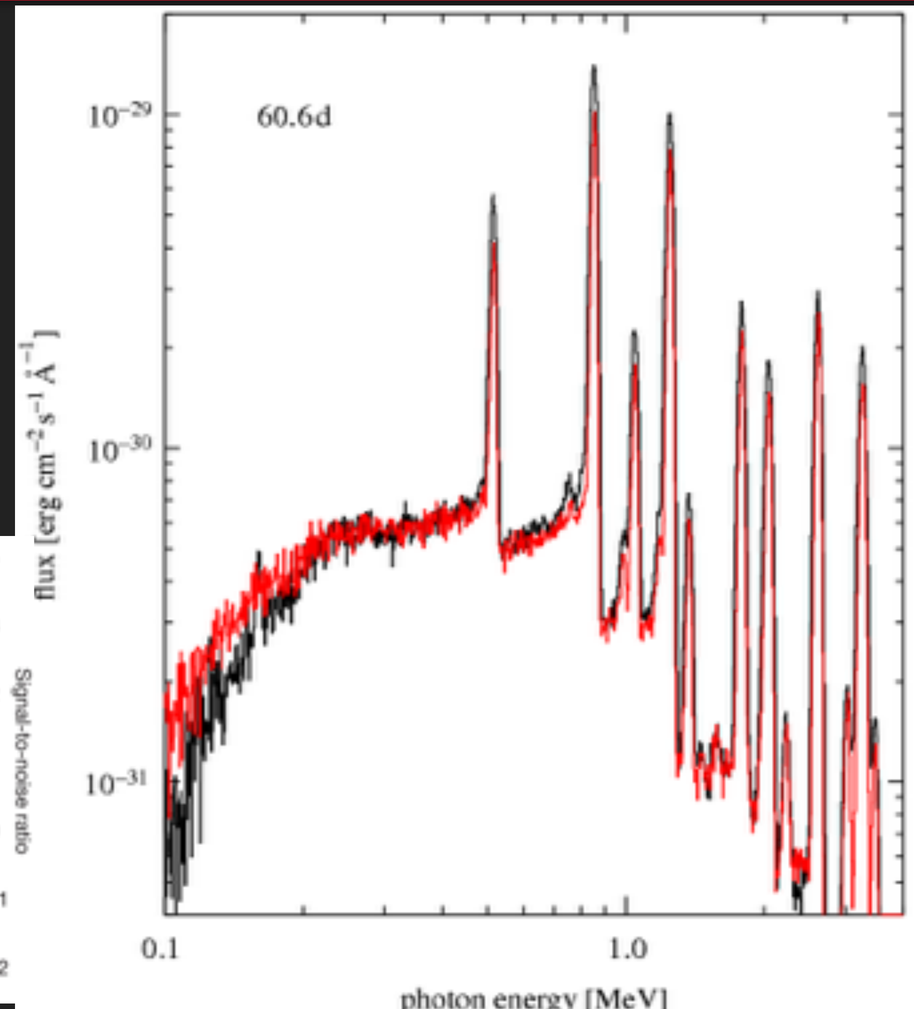
observables?

^{56}Ni and ^{56}Co γ-rays detected for SN 2014J by INTEGRAL





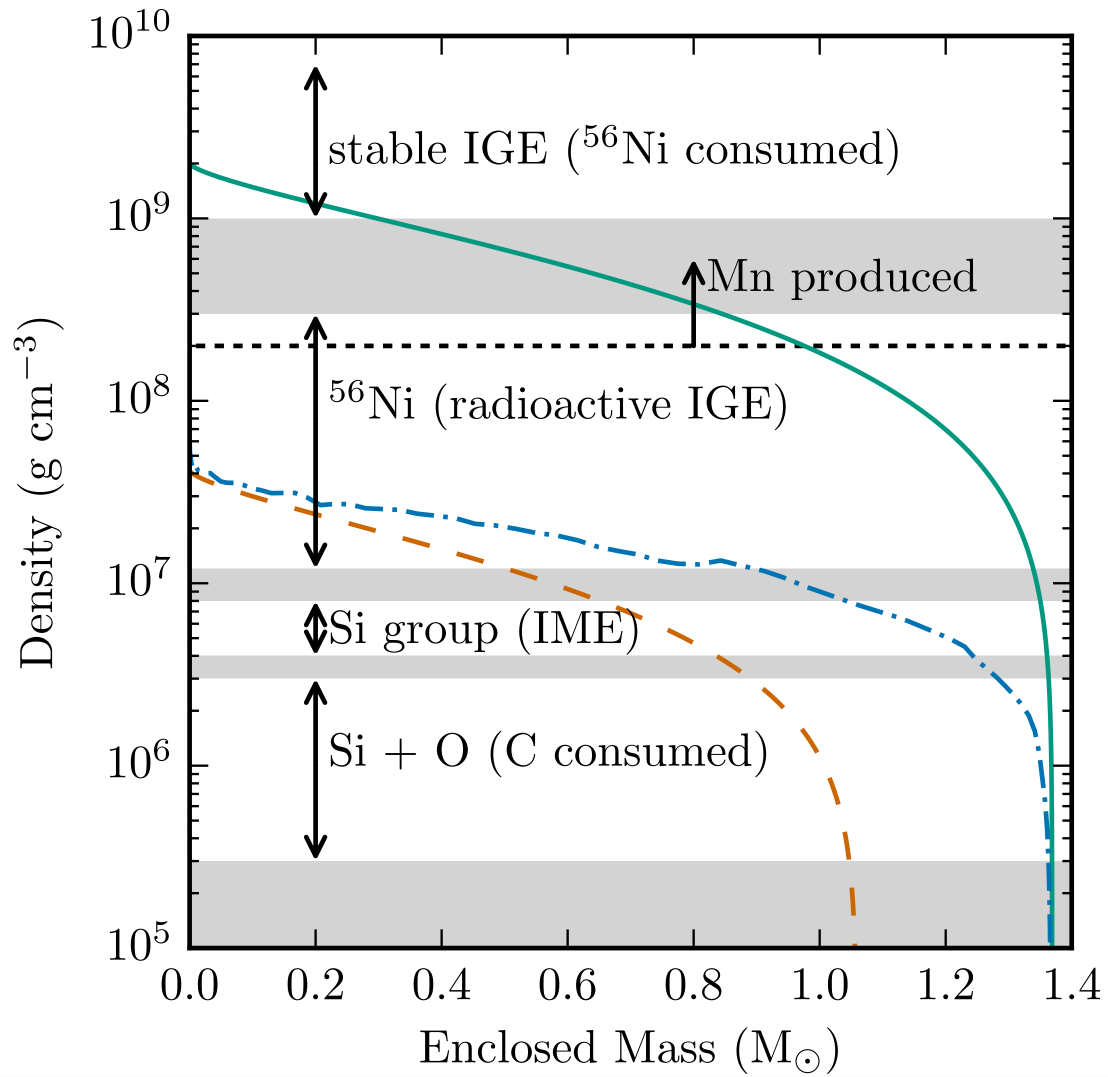
Churazov+ (2014), Nature, 512, 406
Diehl+ (2014), Science, 345, 1162



Summa+ (2013), A&A, 554, 678

nucleosynthesis considerations

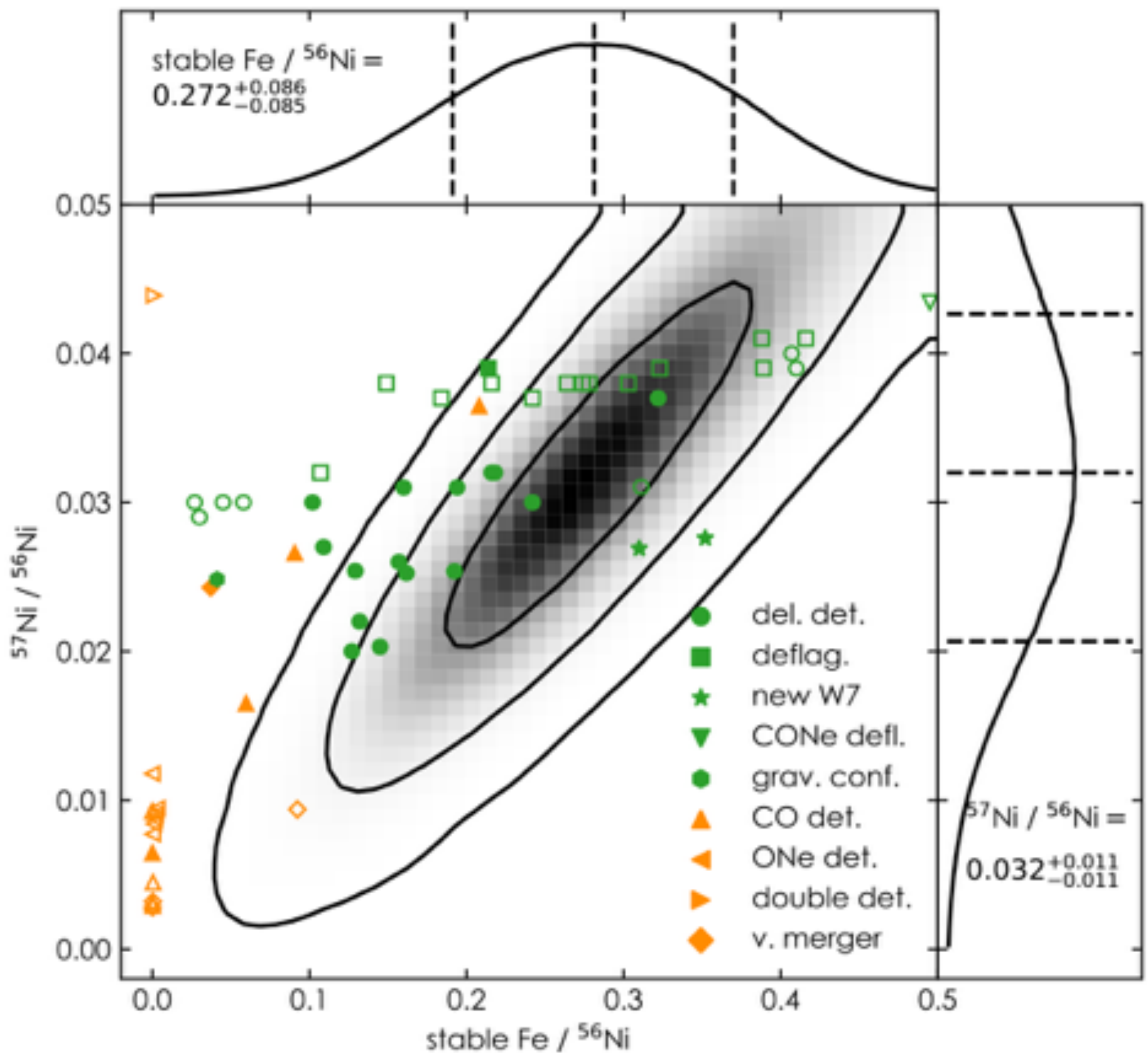
Regimes of explosive carbon/oxygen burning



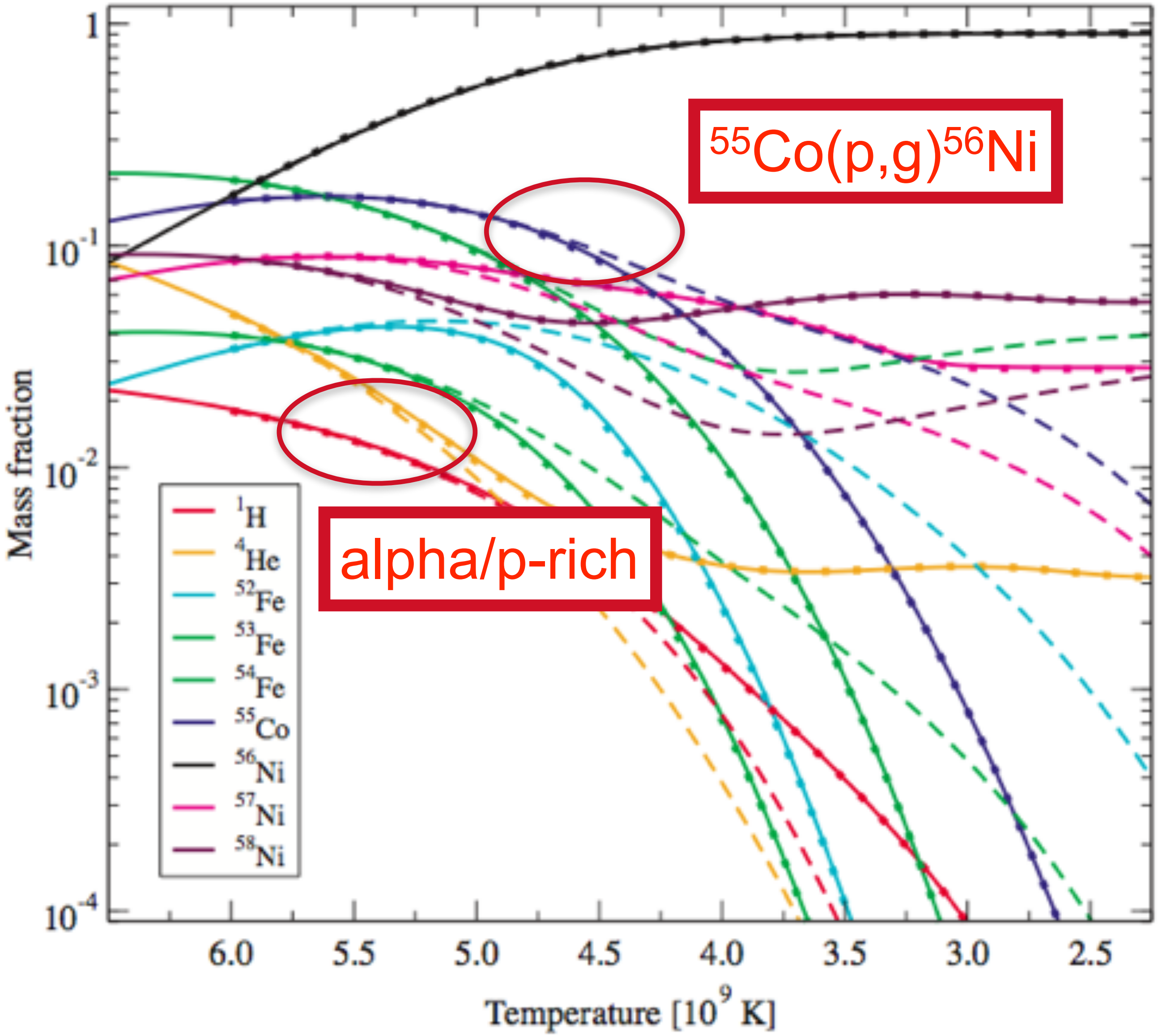
Seitenzahl & Townsley (2017) *Handbook of Supernovae*

Stable Fe and ^{57}Ni

Flörs et al., 2018, A&A 620, 200



NSE freeze-out



—— network

- - - - NSE

$F = (U - Q) - TS$

$S \sim T^3 / \rho$

Manganese - Mn

- 1: low entropy NSE
  most ^{55}Co is produced here
- 2: high entropy NSE
  $^{55}Co(p,g)^{56}Ni$ destroys ^{55}Co
- 3: incomplete Si-burning
  some ^{55}Co is produced here

- Densities in merger model too low to enter [1]
- Merger model produces less ^{55}Co for same ^{56}Ni
- $^{55}Co \rightarrow {}^{55}Fe \rightarrow {}^{55}Mn$
- $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

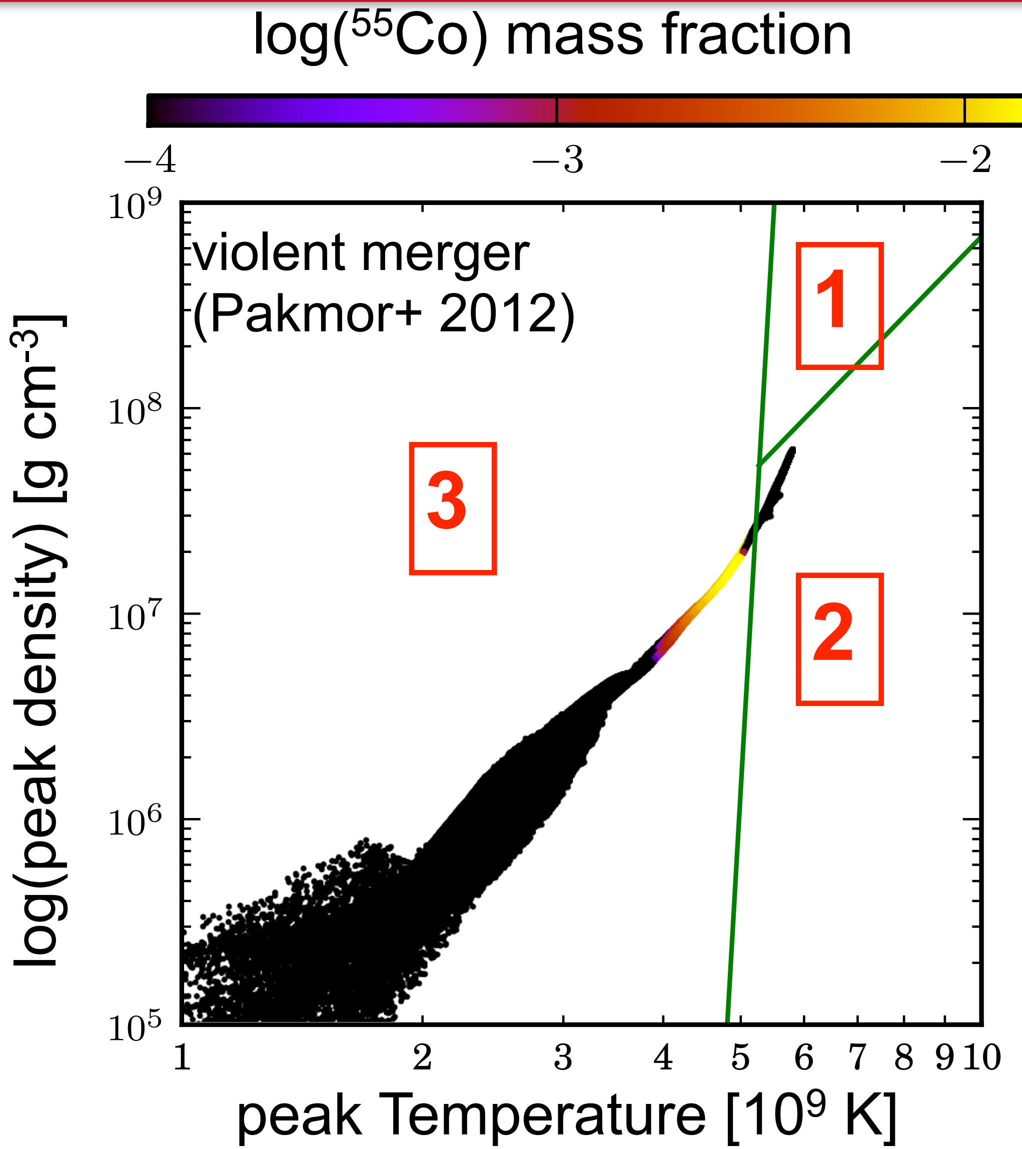


Figure by Florian Lach (Universität Würzburg)

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Manganese - Mn

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$[\mathrm{Mn/Fe}] \coloneqq \log(N(\mathrm{Mn}) / N(\mathrm{Fe}))_{\star} - \log(N(\mathrm{Mn}) / N(\mathrm{Fe}))_{\odot}$

To explain the Mn to Fe ratio in the Sun, SNe Ia from near-M_{ch} primaries must exist!

model name	SN type	masses	[Mn/Fe]
N150def	Ia	near-M_{Ch}	0.42
W7	Ia	near-M_{Ch}	0.15
W7	Ia	near-M_{Ch}	0.02
WW95B[b]	II	$11 < M/M_{\odot} < 40$	-0.15[c]
LC03D[d]	II	$13 < M/M_{\odot} < 35$	-0.27[c]
N06	II+HN	$13 < M/M_{\odot} < 40$	-0.31[c]

GCE simulations give best match to solar neighbourhood for mix of near-M_{ch} and sub-M_{ch}

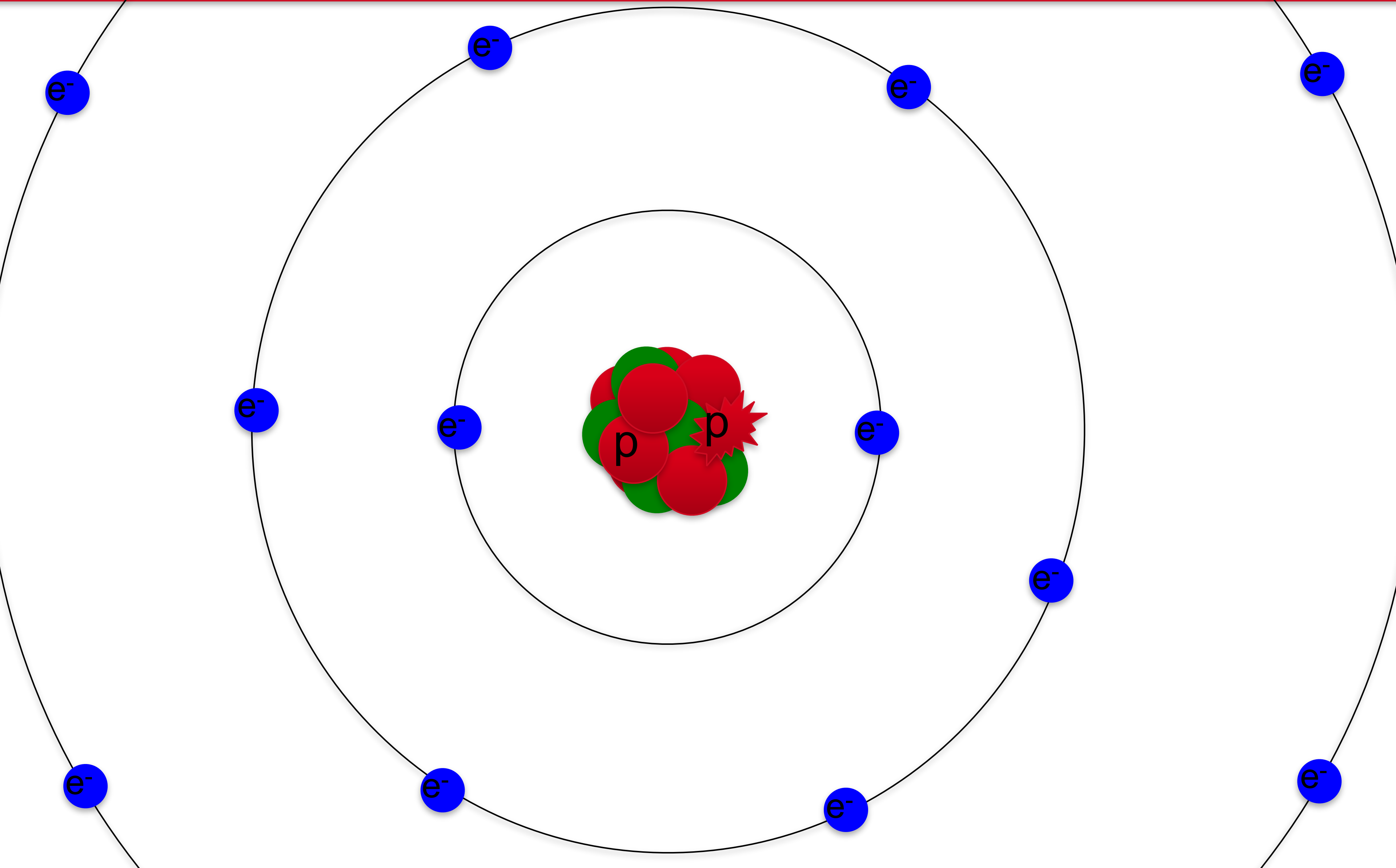
Seitenzahl et al. (2013), A&A, 559, L5

late phases

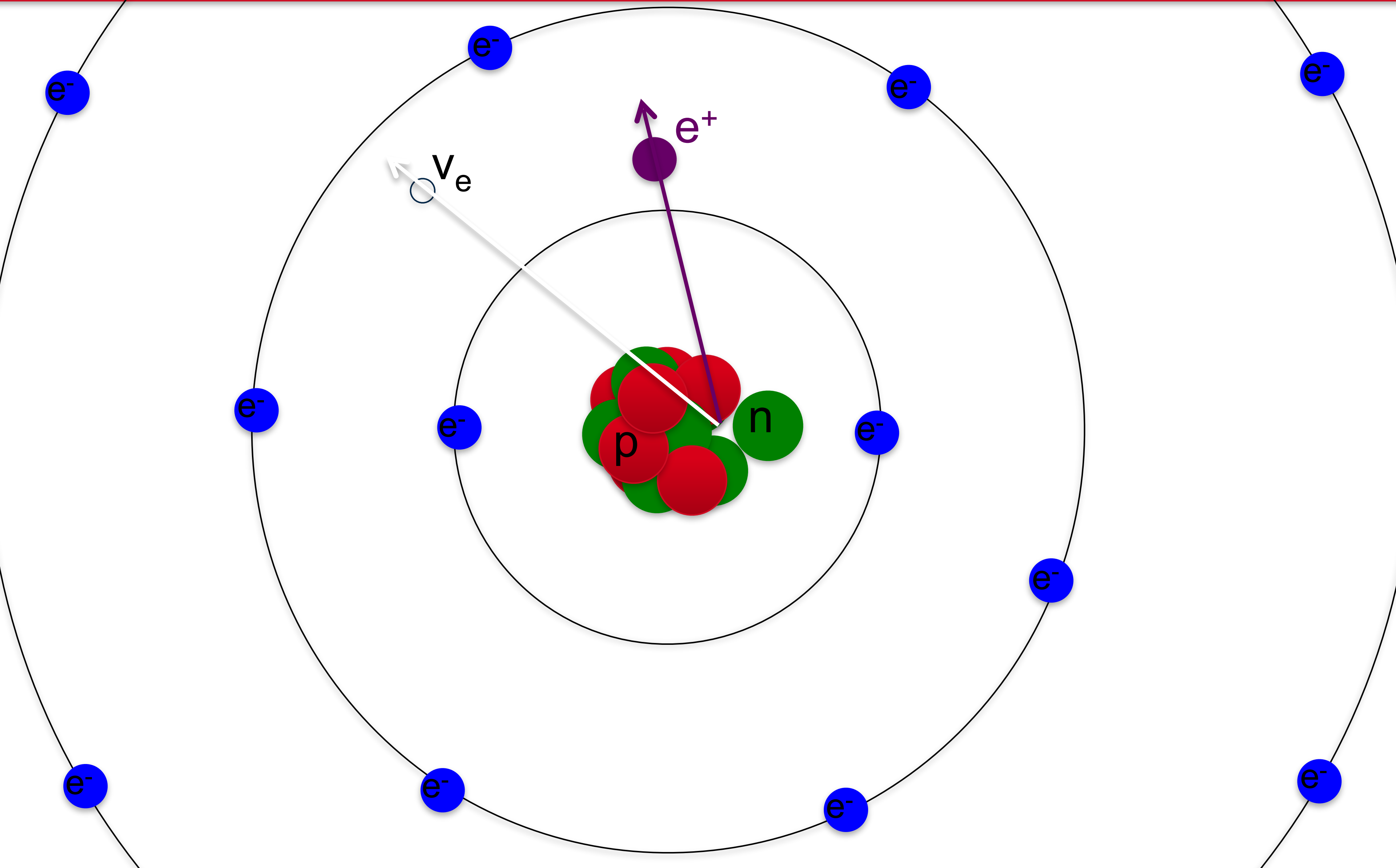
&

radioactivity

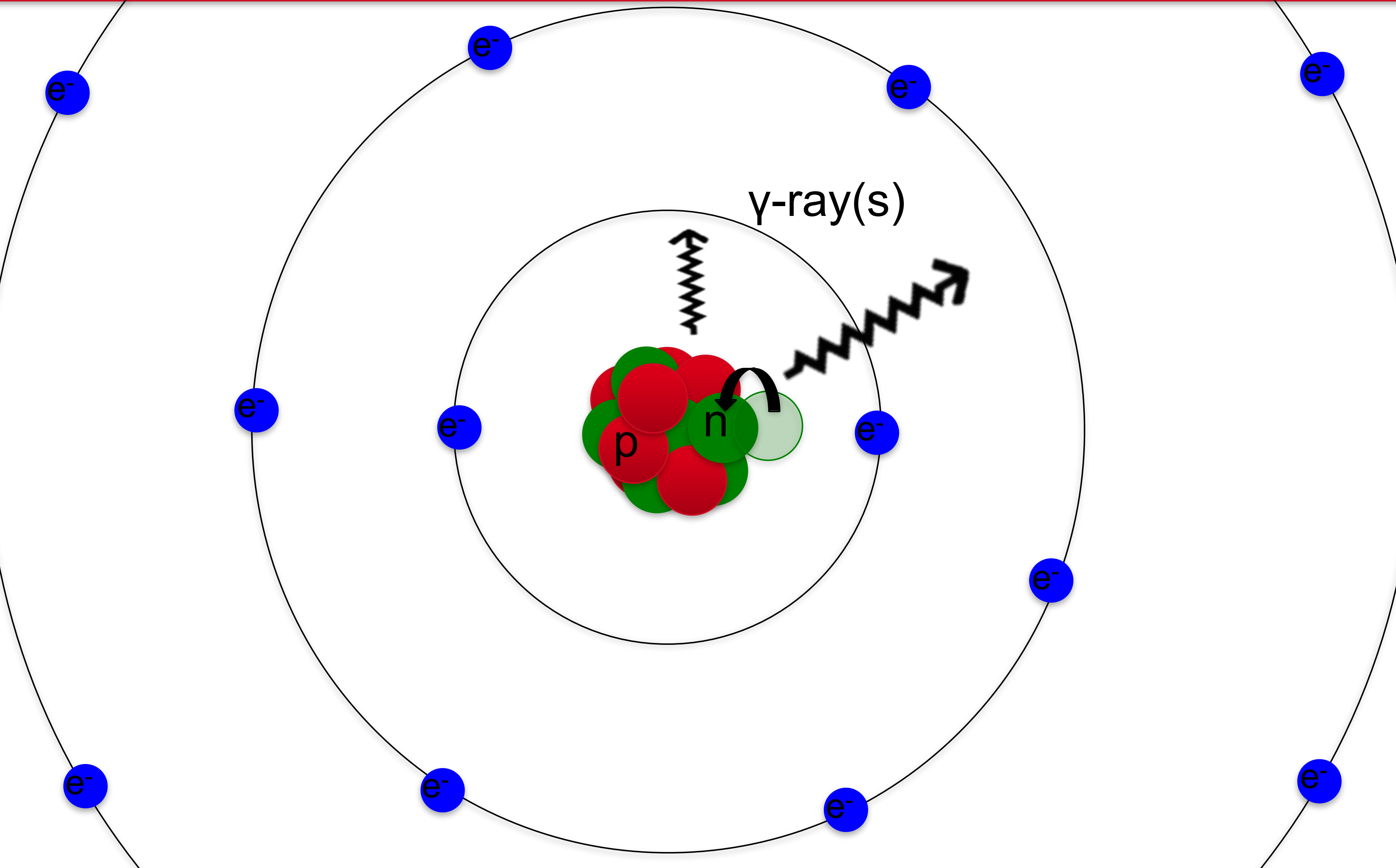
β^+ decay



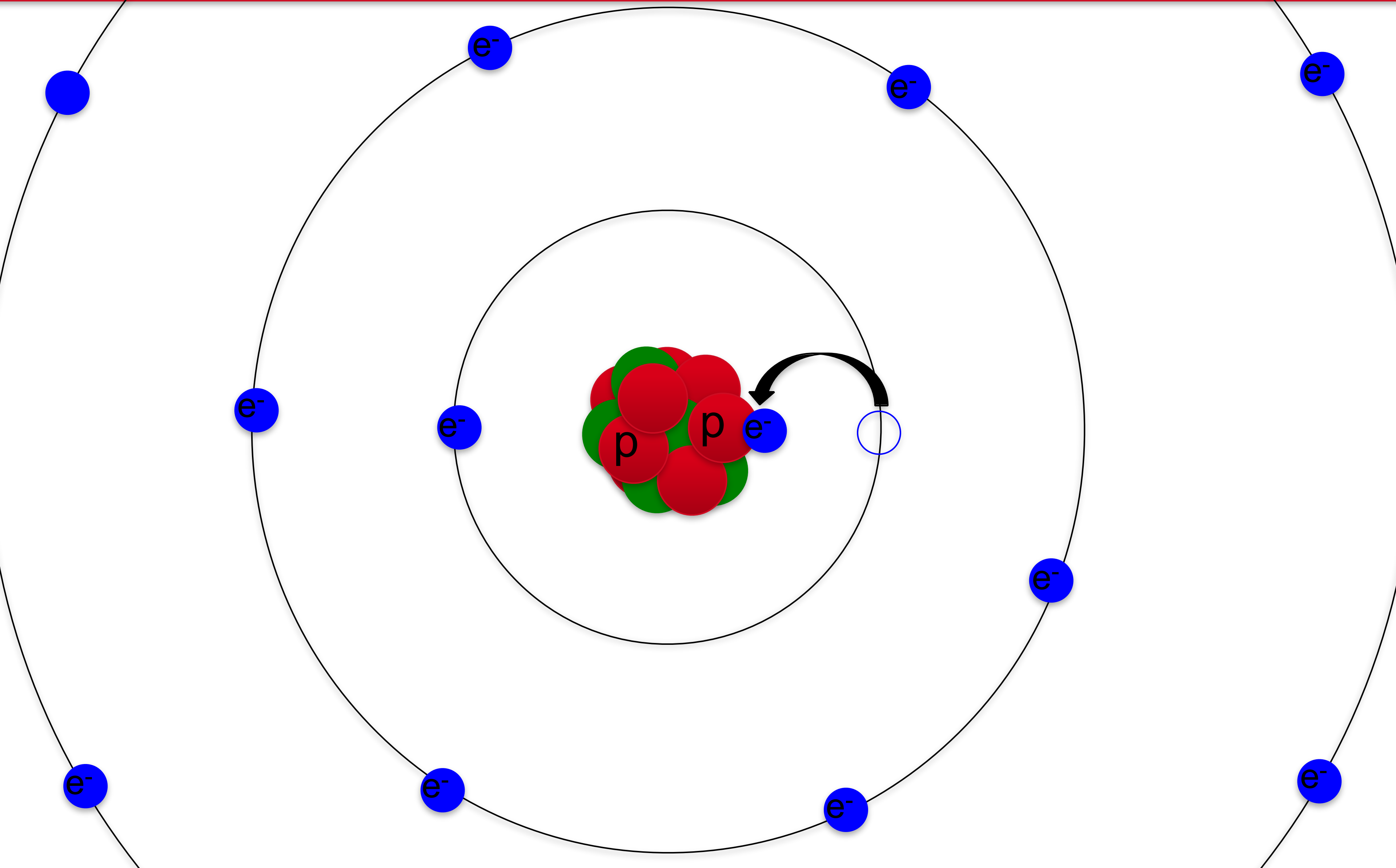
positron emission



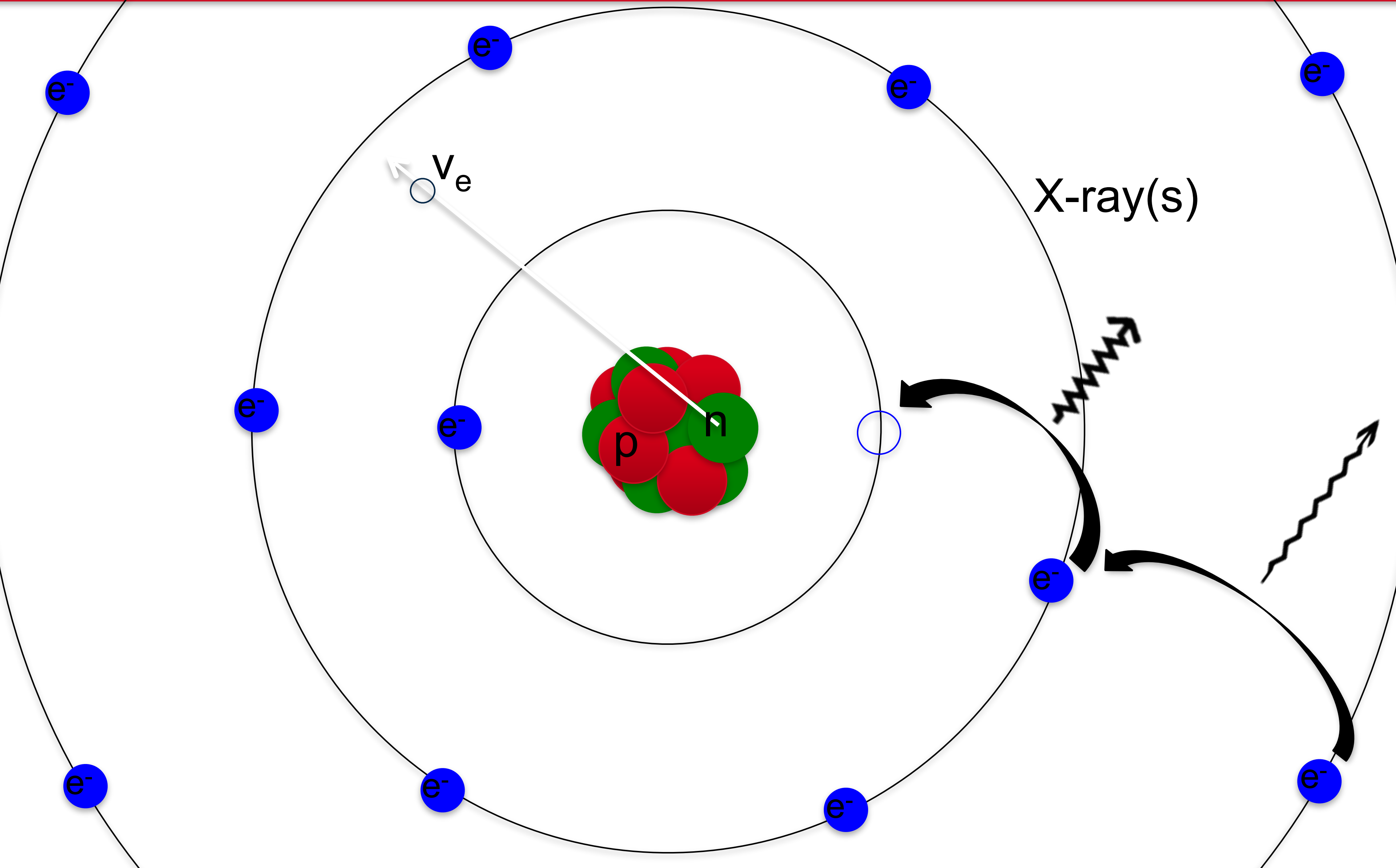
gamma-rays



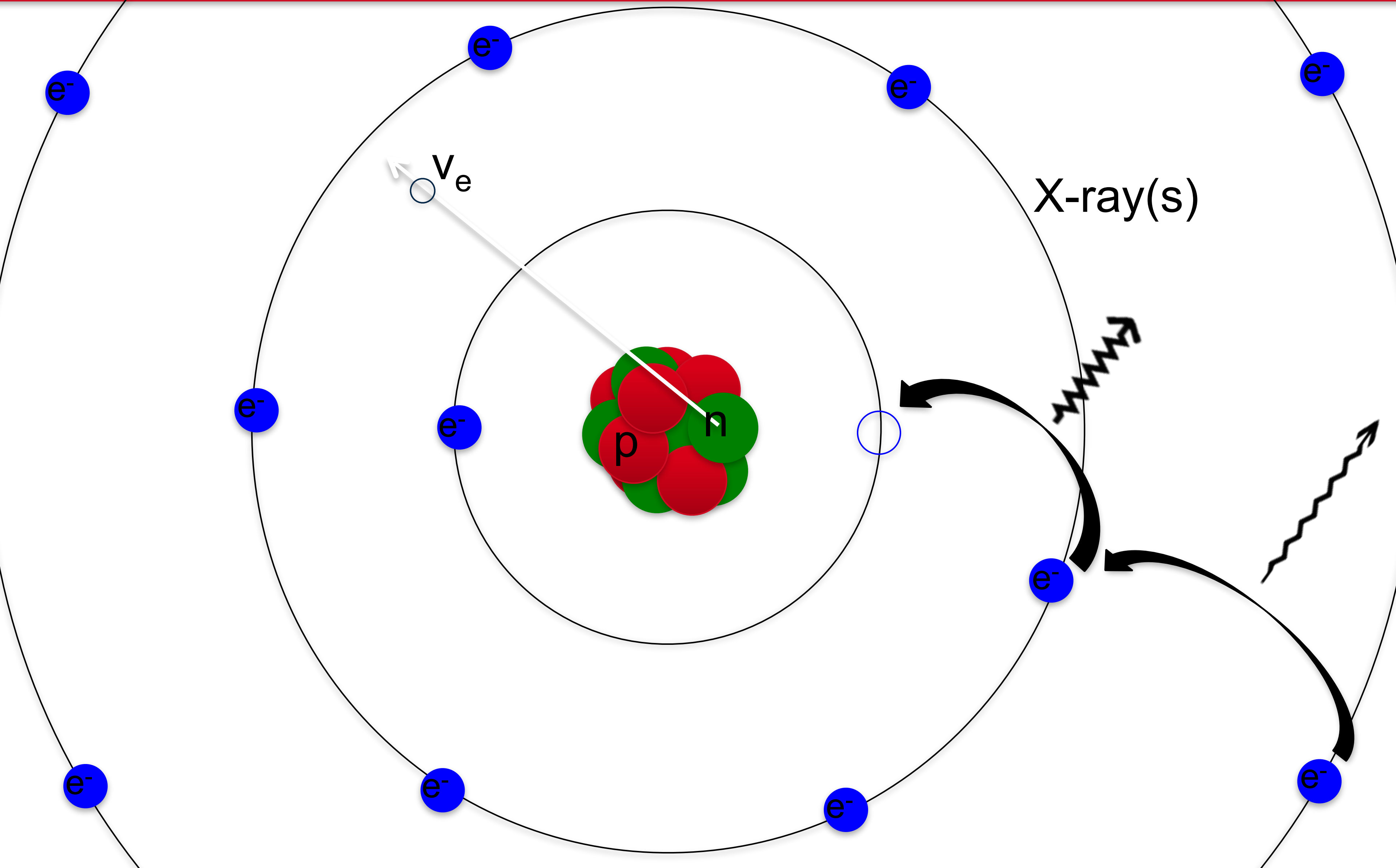
electron capture



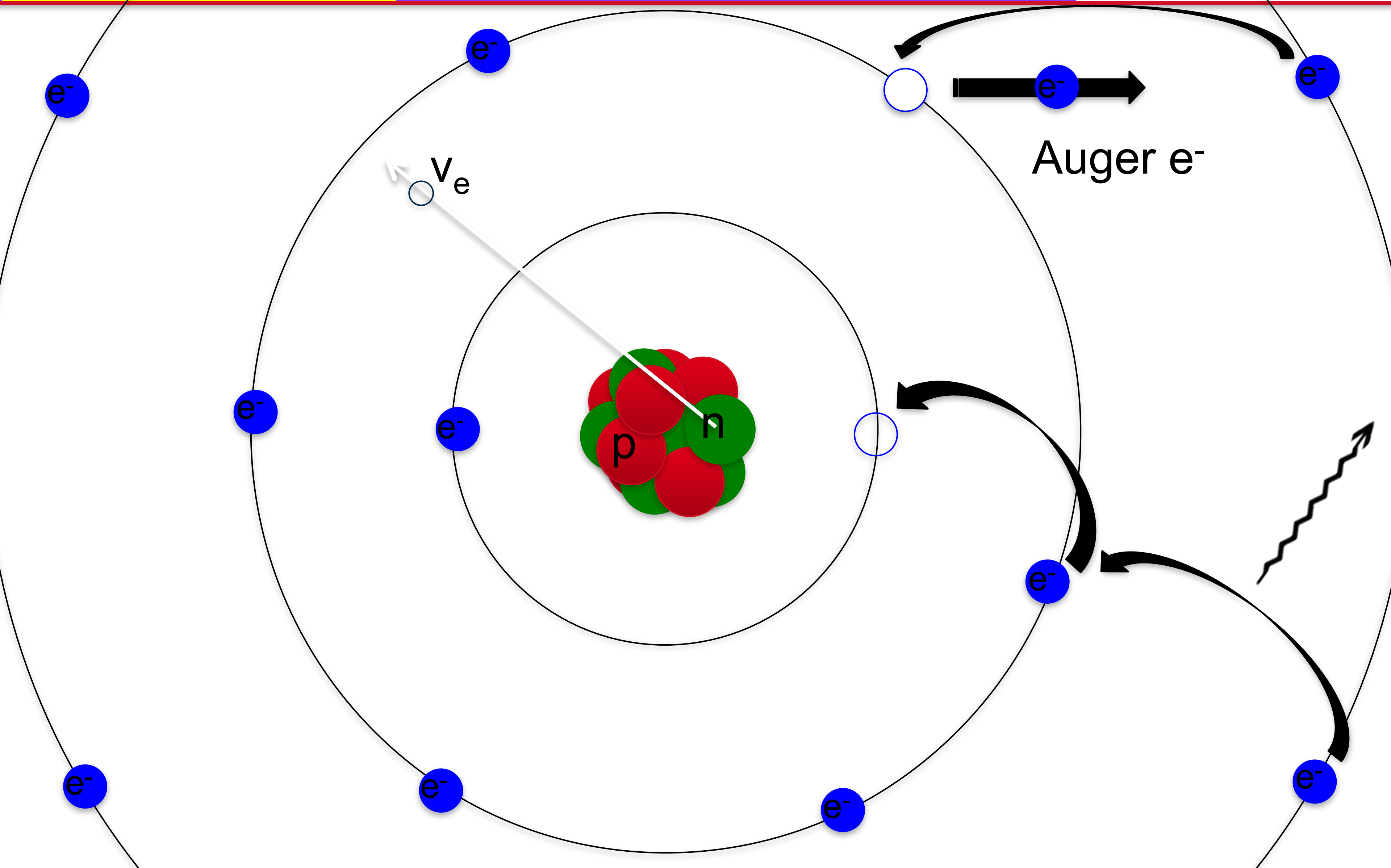
X-rays



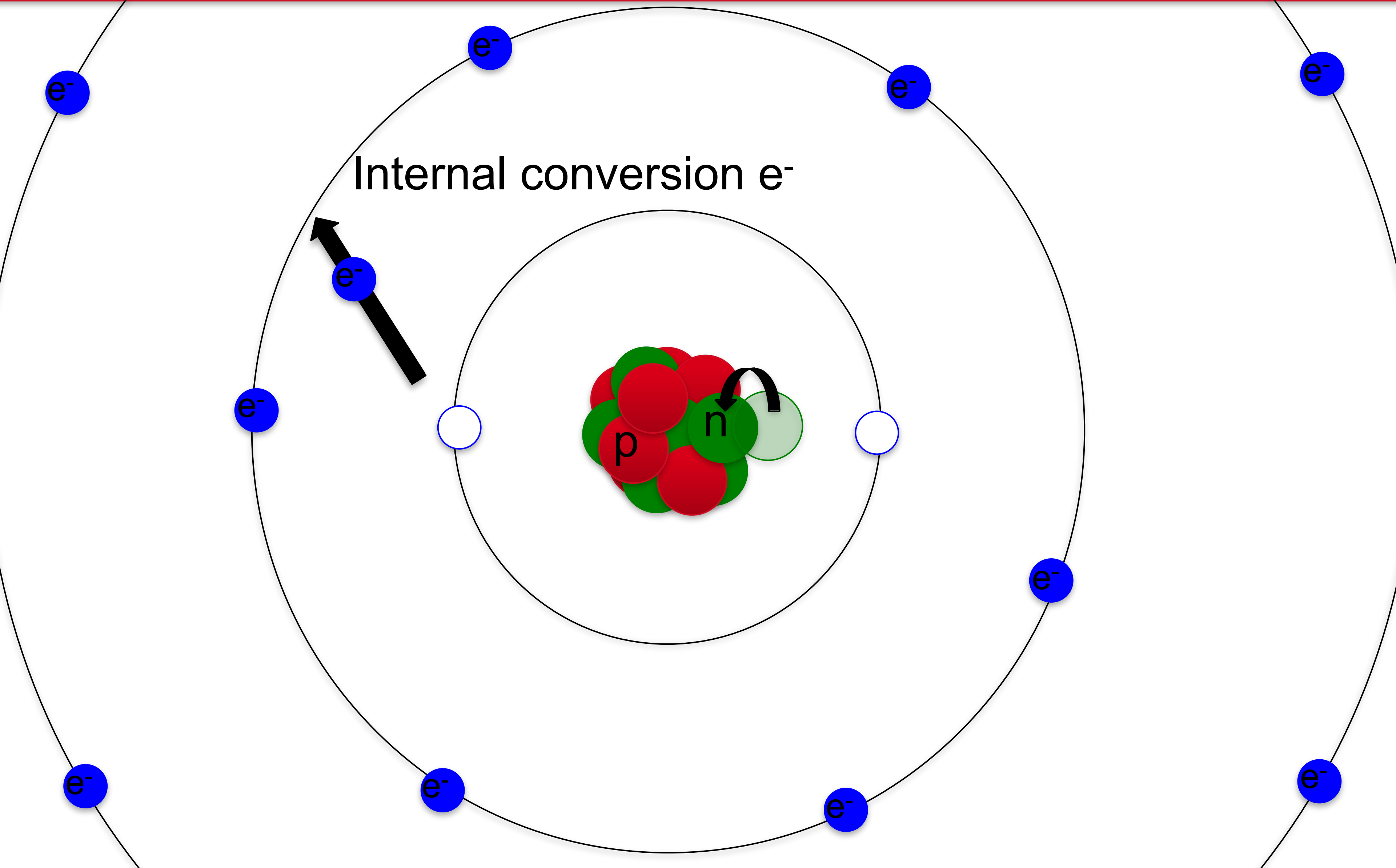
X-rays



Auger e⁻



Internal conversion e^-



decay chains

$$^{56}\mathrm{Ni} \xrightarrow{t_{1/2}=\,6.08d} {}^{56}\mathrm{Co} \xrightarrow{t_{1/2}=\,77.2d} {}^{56}\mathrm{Fe}$$

$$^{57}\mathrm{Ni} \xrightarrow{t_{1/2}=\,35.60h} {}^{57}\mathrm{Co} \xrightarrow{t_{1/2}=\,271.79d} {}^{57}\mathrm{Fe}$$

$$^{55}\mathrm{Co} \xrightarrow{t_{1/2}=\,17.53h} {}^{55}\mathrm{Fe} \xrightarrow{t_{1/2}=\,999.67d} {}^{55}\mathrm{Mn}$$

Table 1. Radioactive decay energies (keV decay^{-1})

Nucleus	Auger e^-	IC e^-	e^+	X-ray
^{57}Co	7.594	10.22	0.000	3.598
^{56}Co	3.355	0.374	115.7	1.588
^{55}Fe	3.973	0.000	0.000	1.635

Seitenzahl, Taubenberger & Sim (2009), MNRAS, 400, 531

At late times, internal conversion electrons, Auger electrons, and X-rays matter/become dominant sources for energy injection.

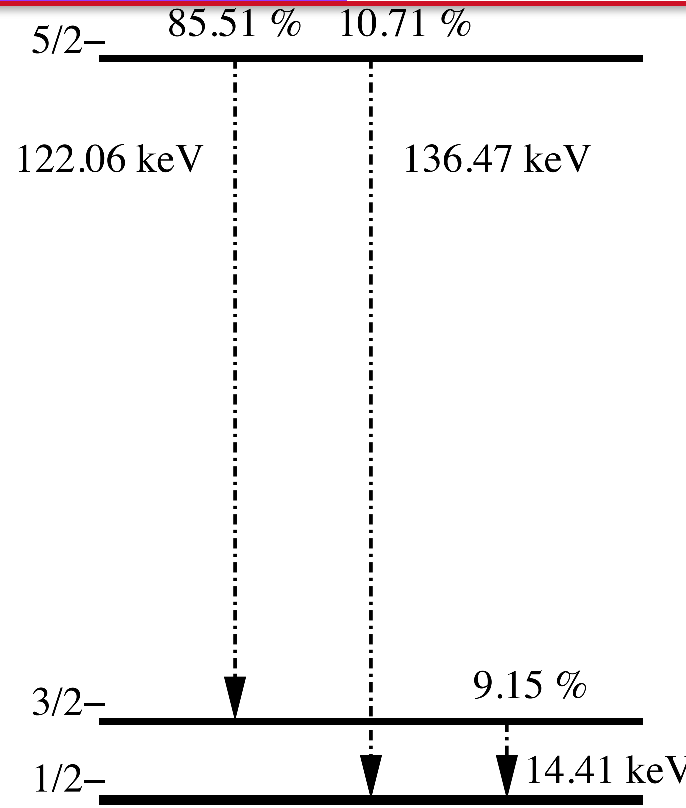
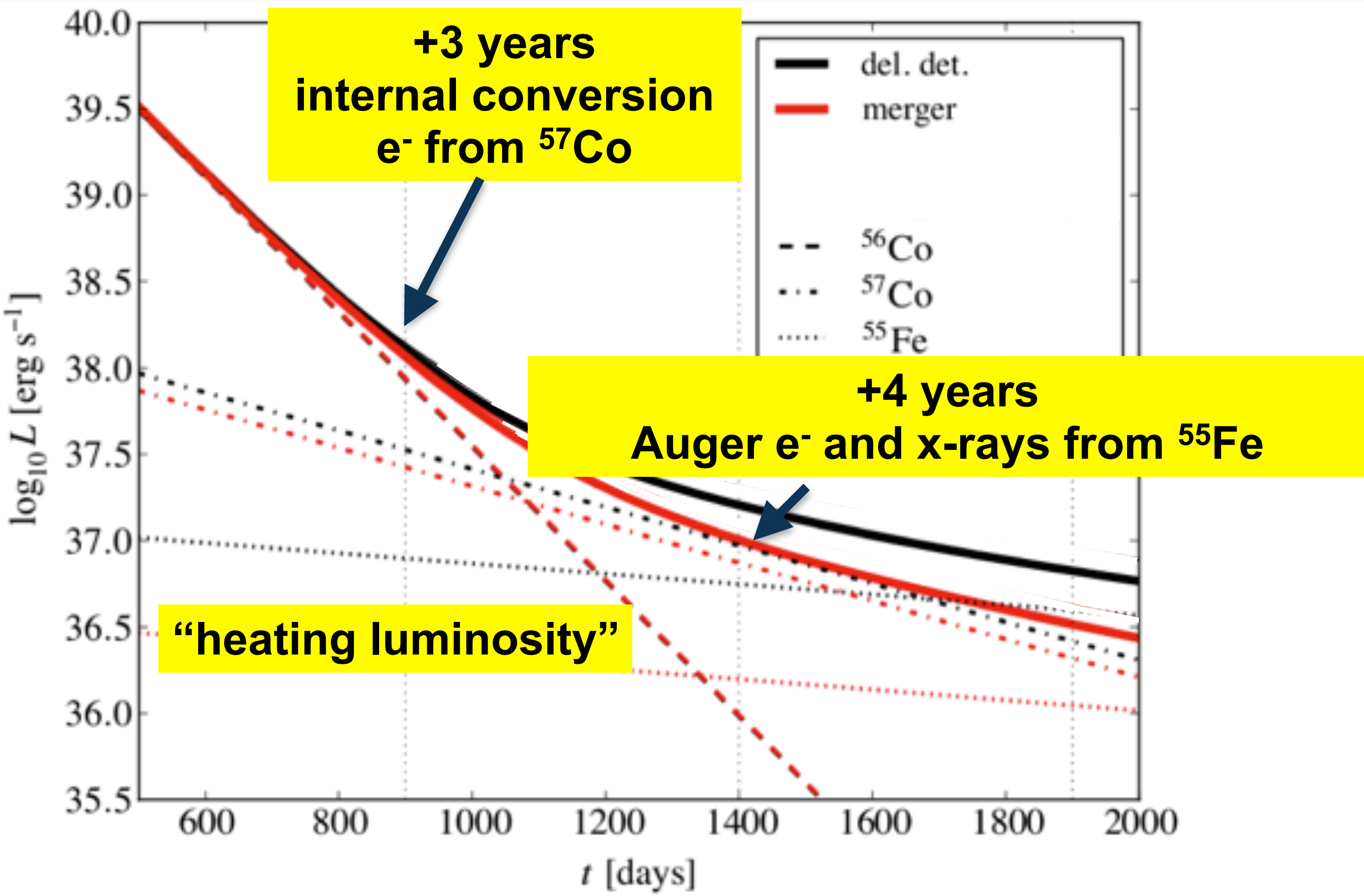


Figure 1: Ground state and first two exited levels of ^{57}Fe showing γ-ray energies and intensities for the decay of ^{57}Co.

Seitenzahl (2011), PrPNP, 66, 329

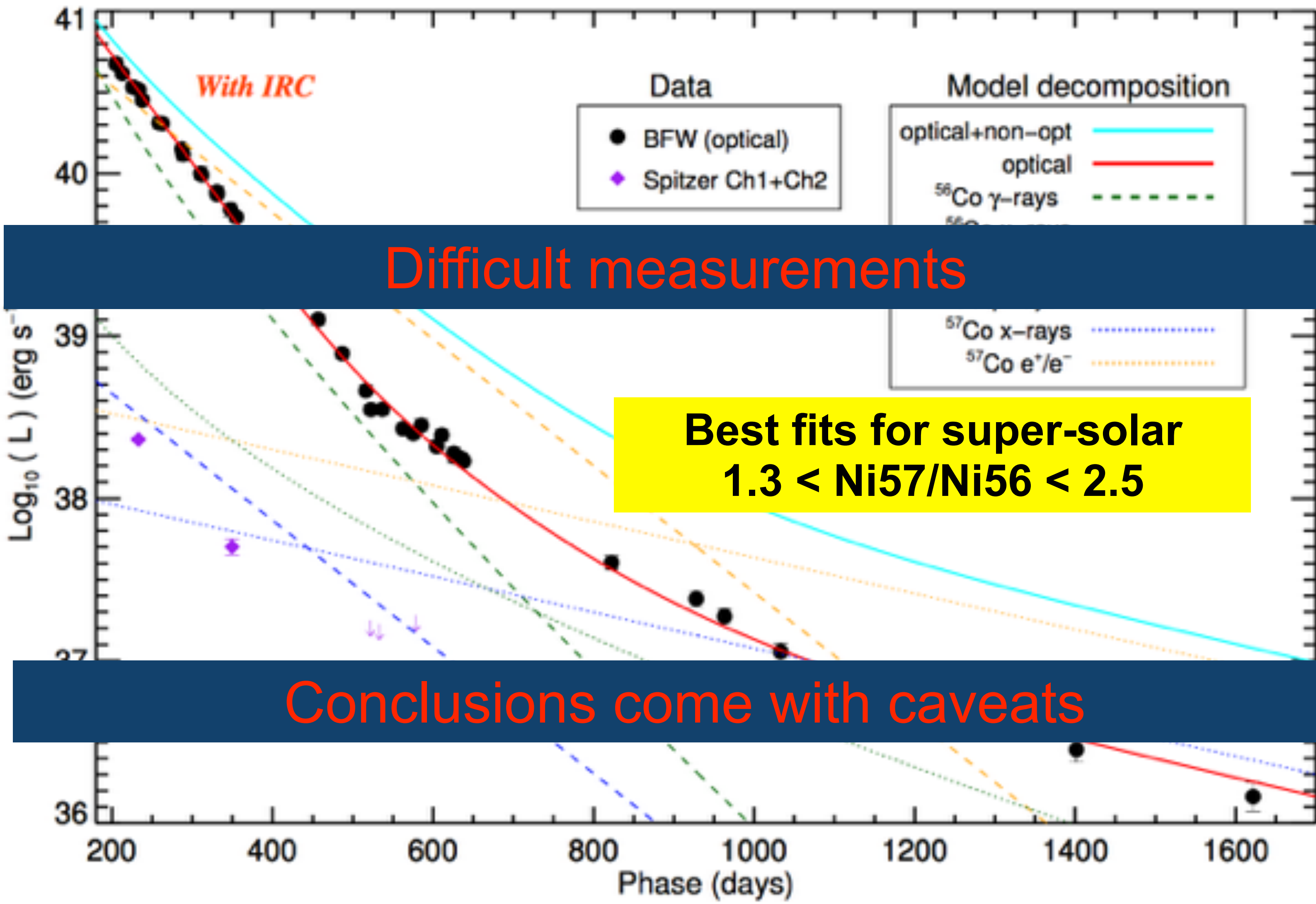
distinguishing models at late-time



Seitenzahl+ (2009), MNRAS, 400, 531 ; Röpke+ (2012), ApJL, 750, L19

distinguishing models at late-time

Dimitriadis+ 2017, MNRAS, 468, 3798



Difficult measurements

Best fits for super-solar $1.3 < Ni57/Ni56 < 2.5$

Conclusions come with caveats

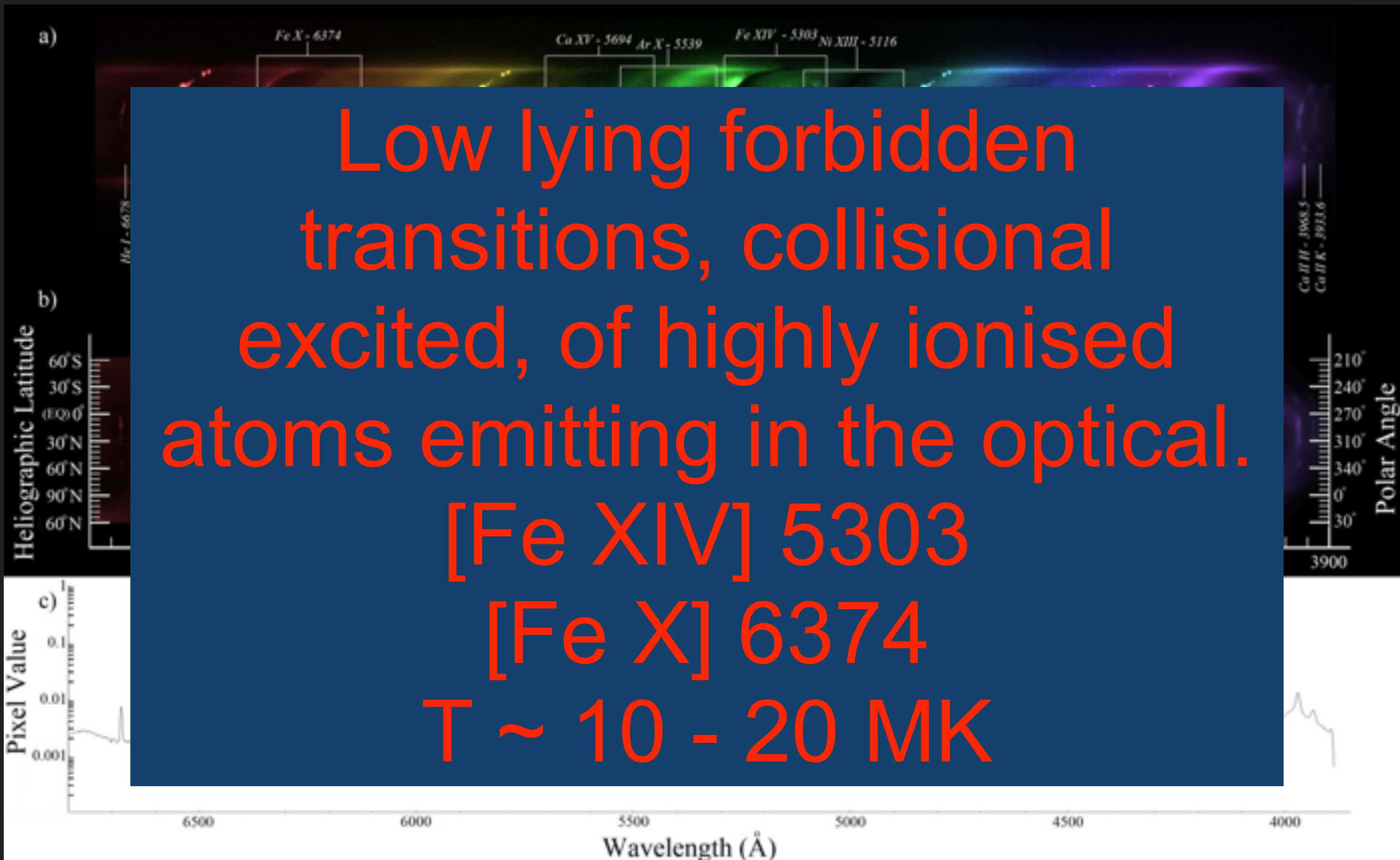
supernova remnant tomography

with

coronal lines in the shocked ejecta

Coronal lines

Voulgaris et al. 2012, Solar Physics, 278, 187



Low lying forbidden transitions, collisional excited, of highly ionised atoms emitting in the optical.

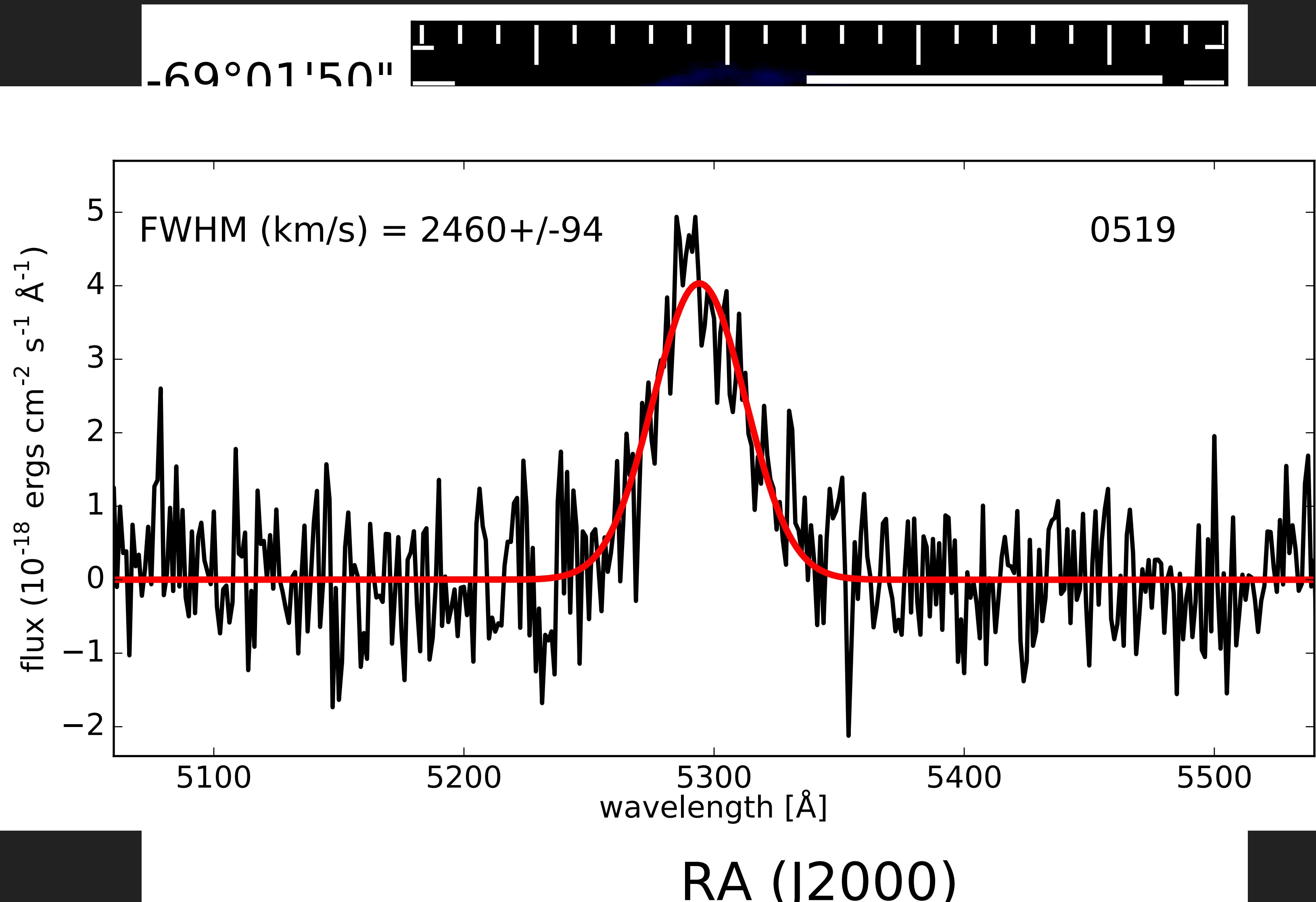
[Fe XIV] 5303

[Fe X] 6374

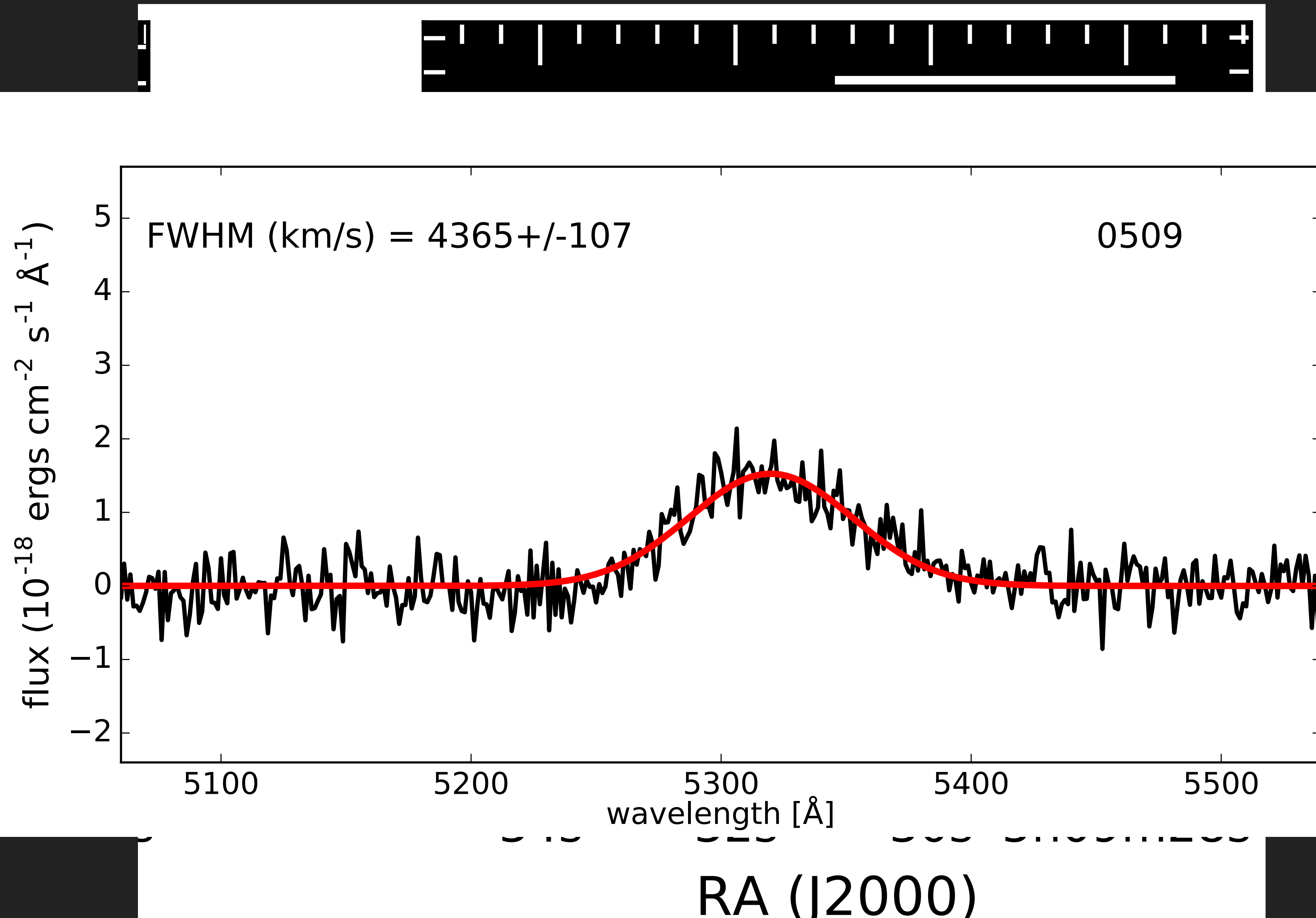
T ~ 10 - 20 MK

MUSE on UT4 “Yepun”

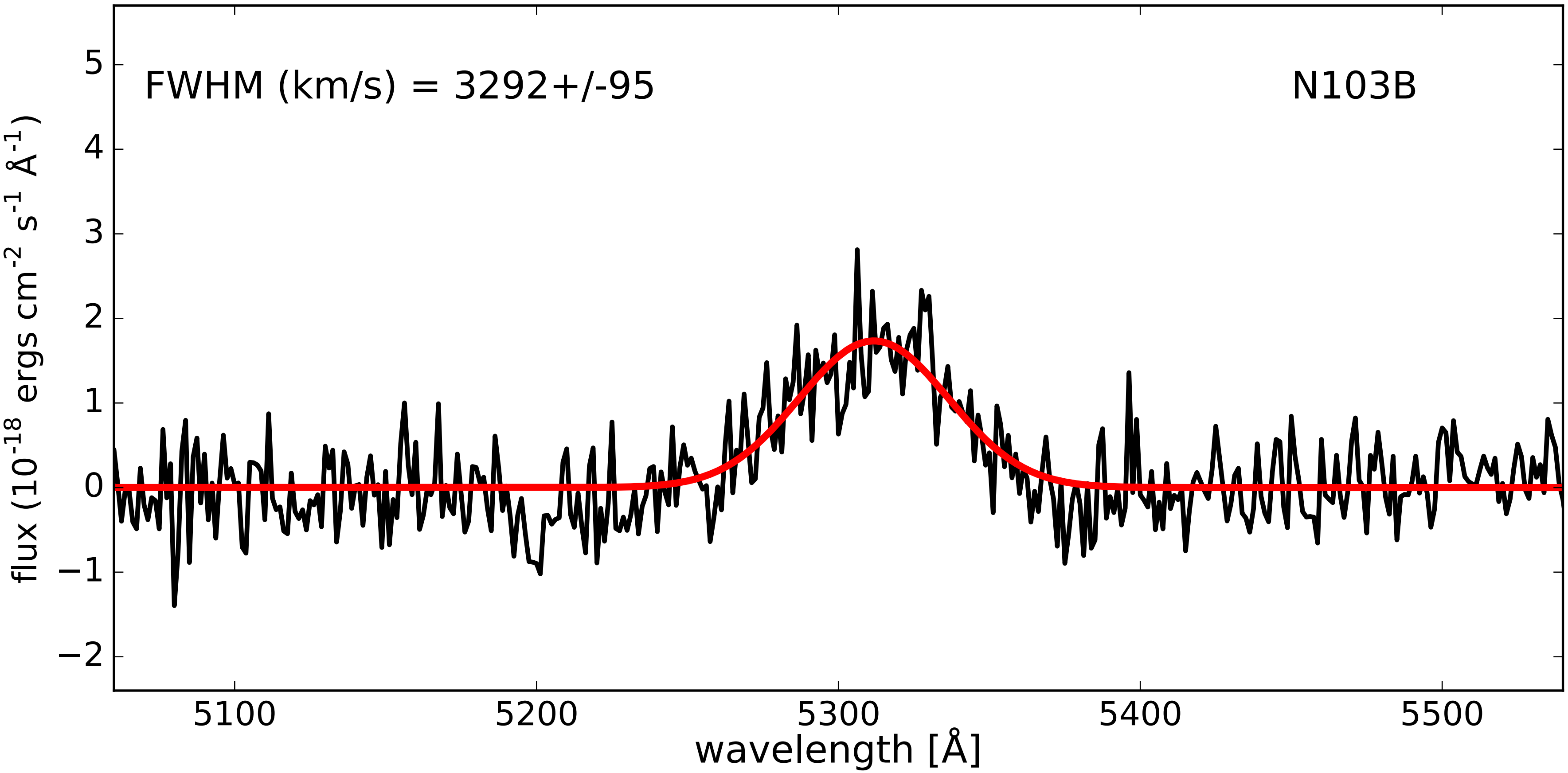
SNR 0519-69.0
R: X-ray, G: Fe XIV, B:Ha



SNR 0509-67.5
R: X-ray, G: Fe XIV, B:Ha



N103B
R: X-ray, G: Fe XIV, B:Ha

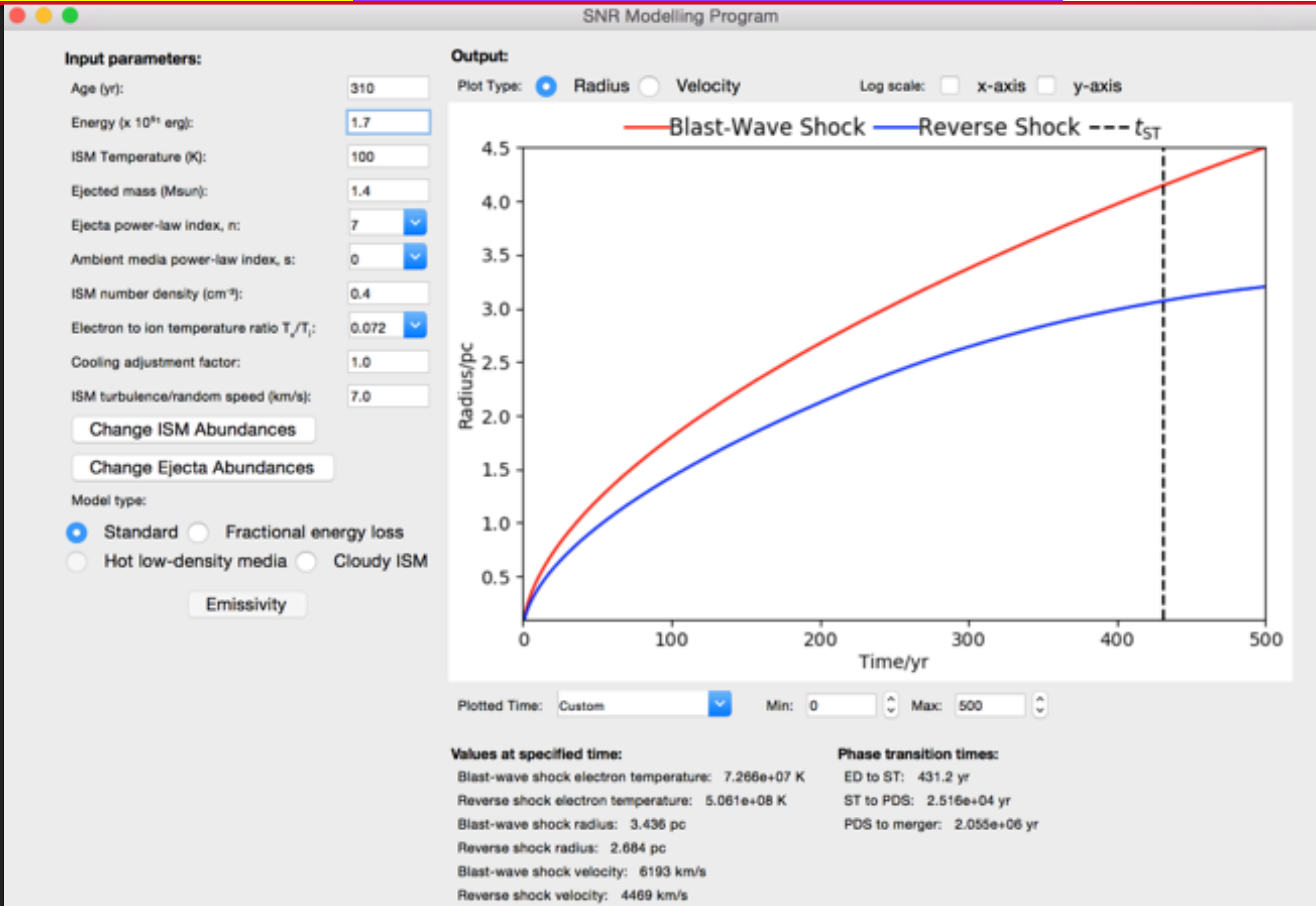


04s 02s 09m00s 58s 5h08m56s

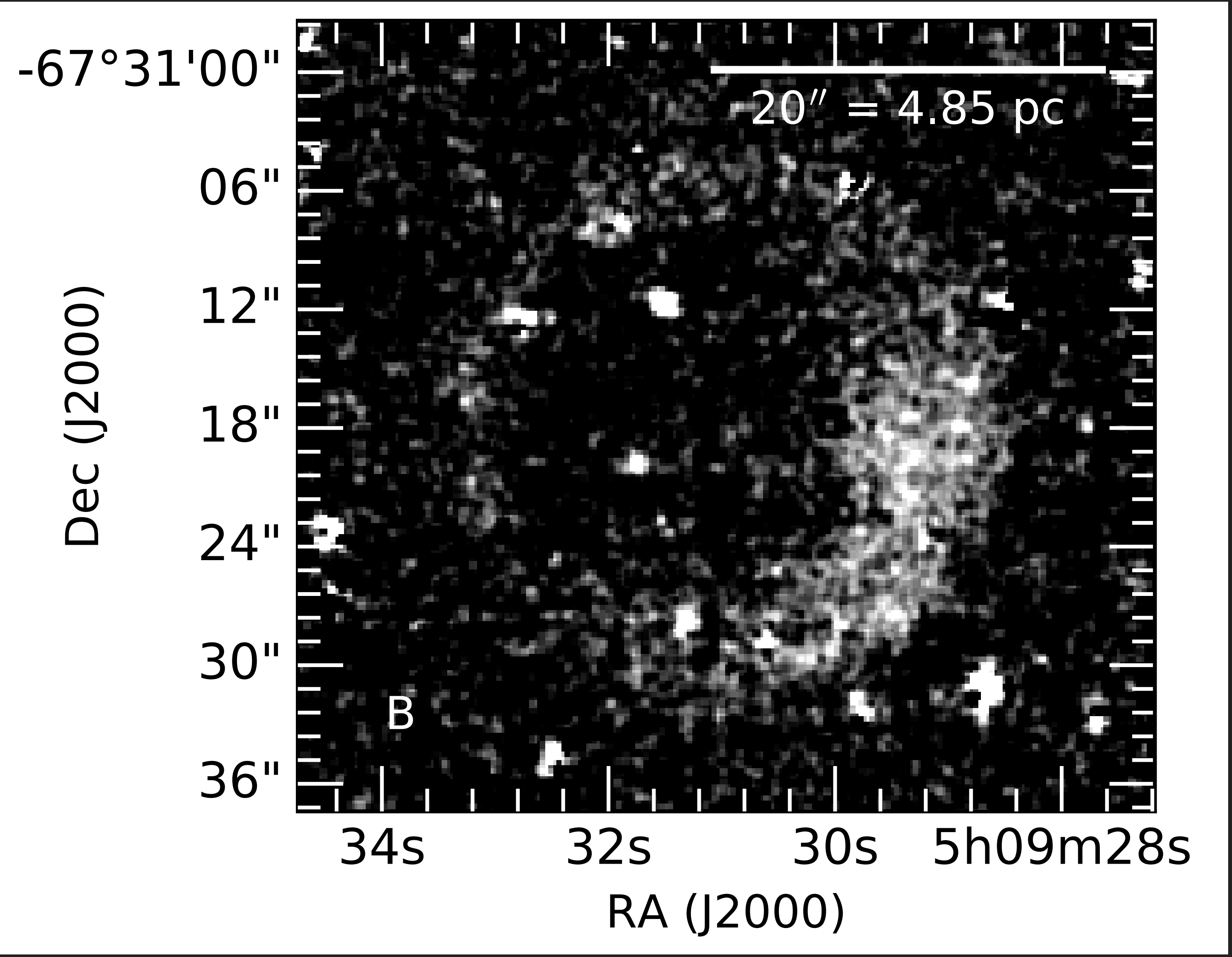
RA (J2000)

Constraining the models with SNR evolution

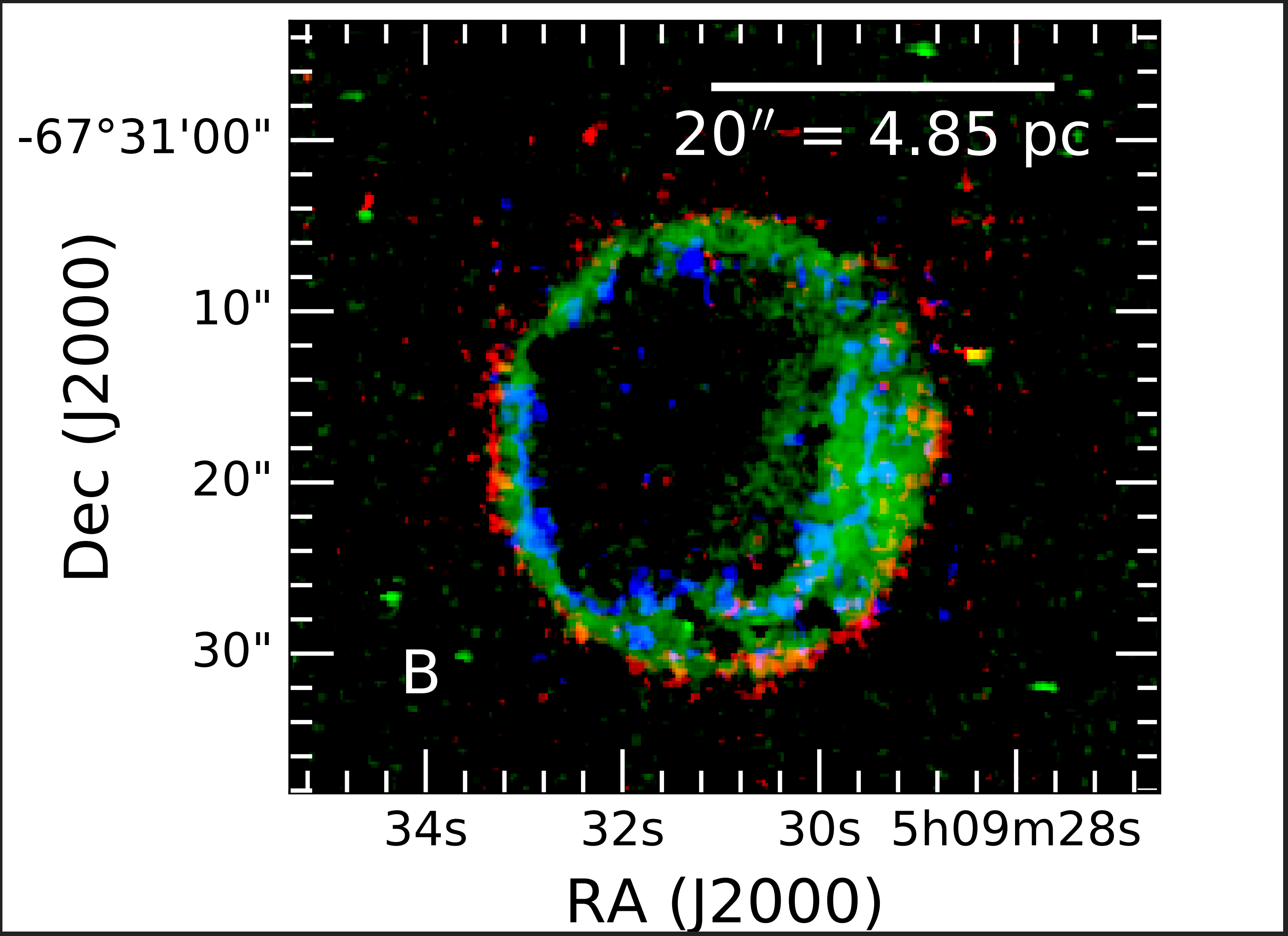
Leahy & Williams, ascl:1703.006



Also [Fe XV] 7062.1



[S XII] 7613.1 (red)
[Fe IX] 8236.8 (blue)



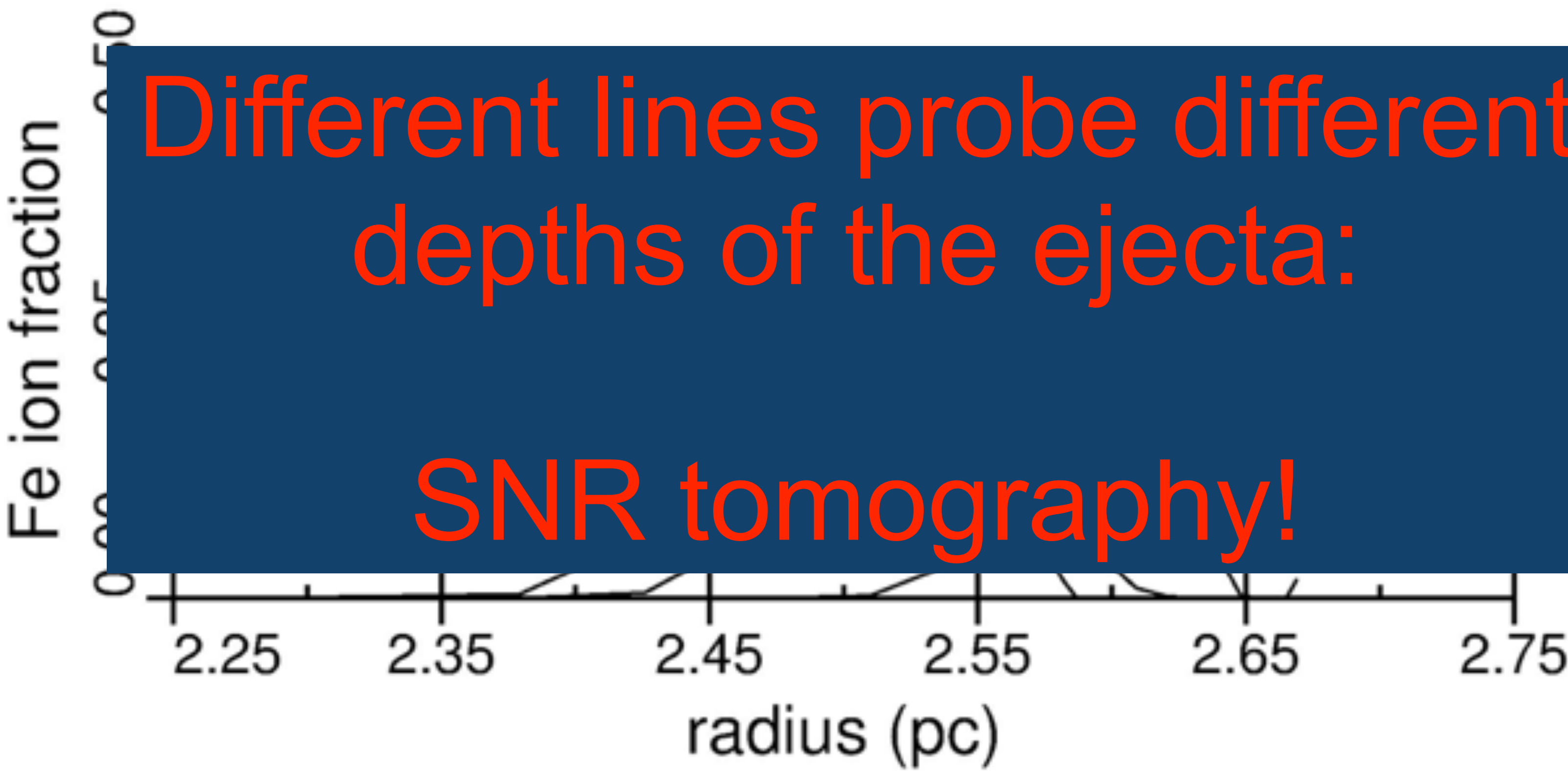
BLASPHEMER models

BLASt Propagation in Highly EMitting EnviRonment

by Martin Laming

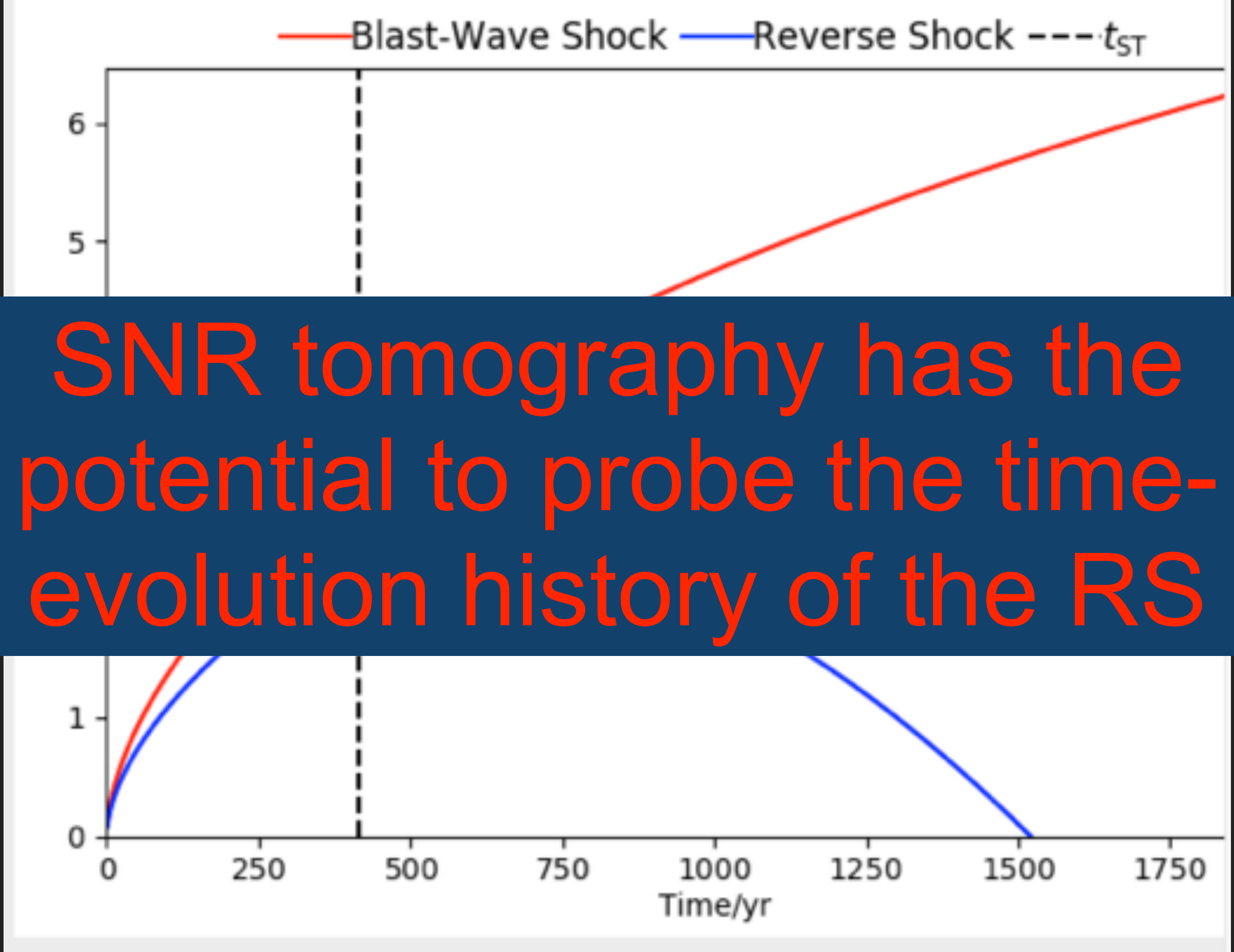
Different lines probe different depths of the ejecta:

SNR tomography!



Shock velocities time-dependent

Leahy & Williams, ascl:1703.006

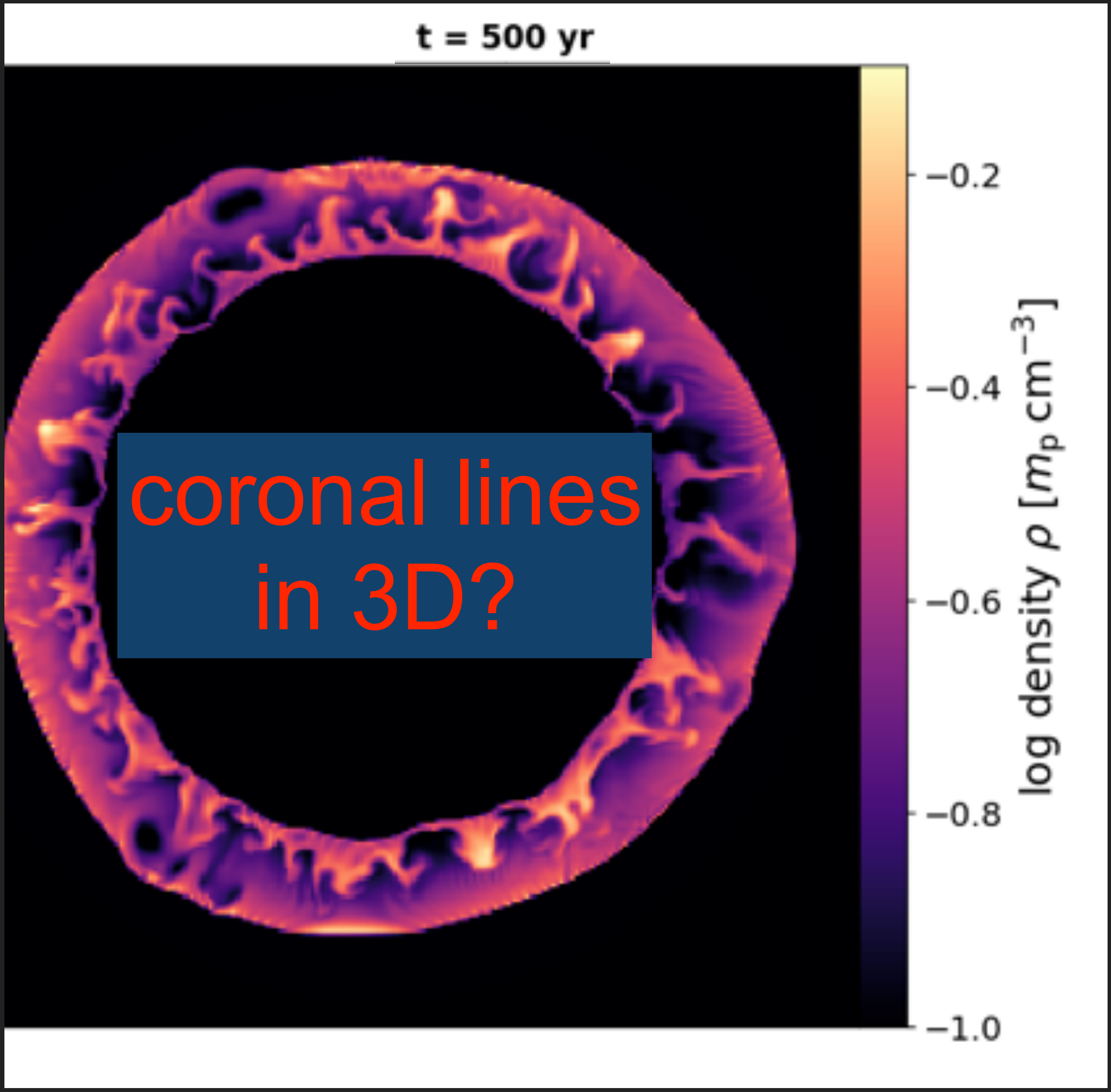


SNR tomography has the potential to probe the time-evolution history of the RS

Final thoughts

- Broad coronal lines in ejecta behind RS in three young Type Ia SNRs in the LMC: **NEW DIAGNOSTIC**
- Gives first direct measurement of reverse shock speed
- If ages are known, then we can constrain allowed explosion parameters via SNR evolution models
  - (mass, ambient density, explosion energy)
- Further coronal lines allow for supernova tomography of the nucleosynthesis products in the ejecta

Ferrand, Warren, Ono, Nagataki, Röpke, Seitenzahl, 2019, ApJ (accepted)



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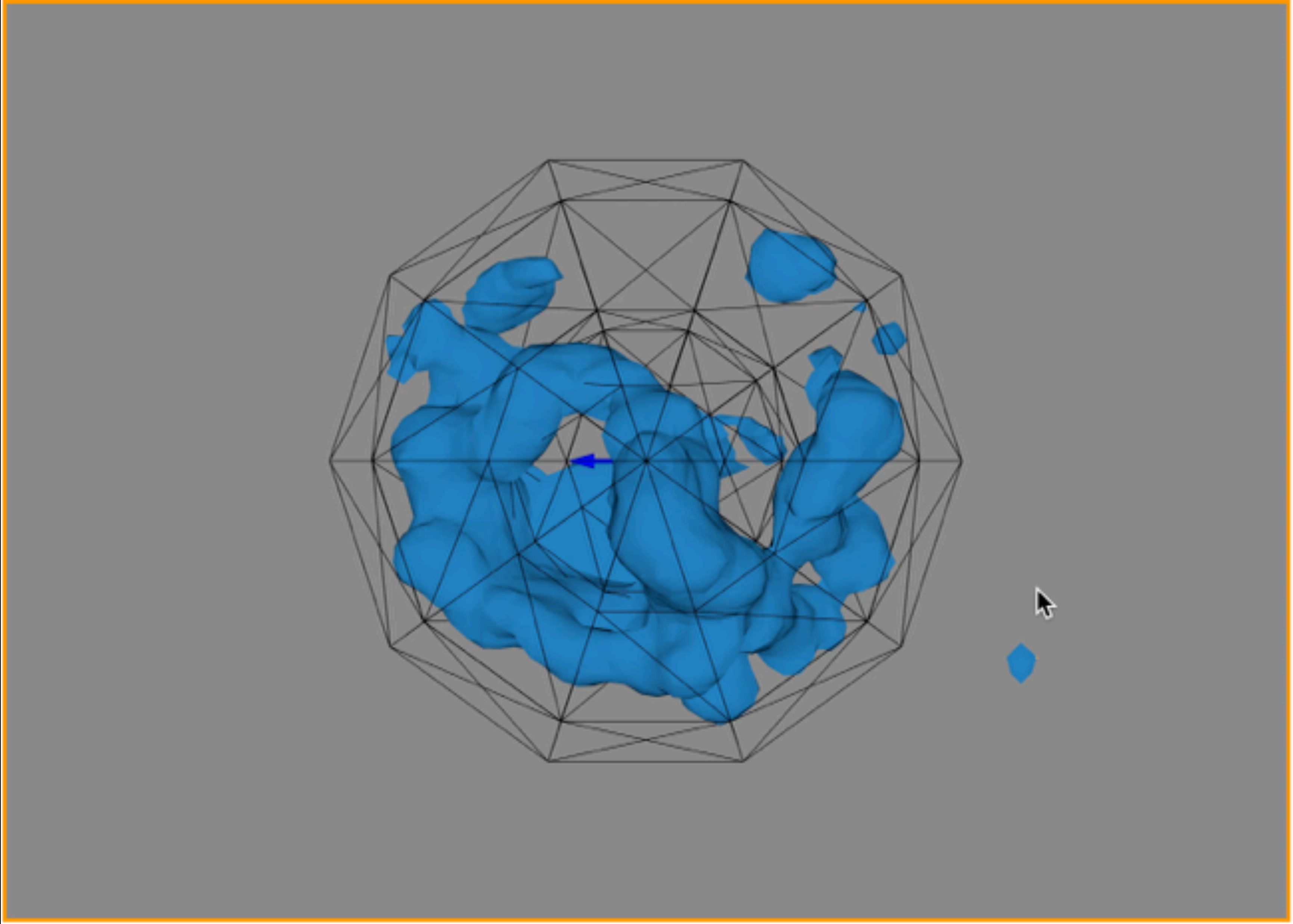
END



Screenshot: New → Vogt, IRS, Dopita & Ruiter 2017, PASP, 129

Outer flux density level: 7.0×10^{-17} erg s^{-1} cm^{-2} Å^{-1} +layer -layer

CAASTRO ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

ESO PR image
[O III] green, Ne I red, X-ray blue

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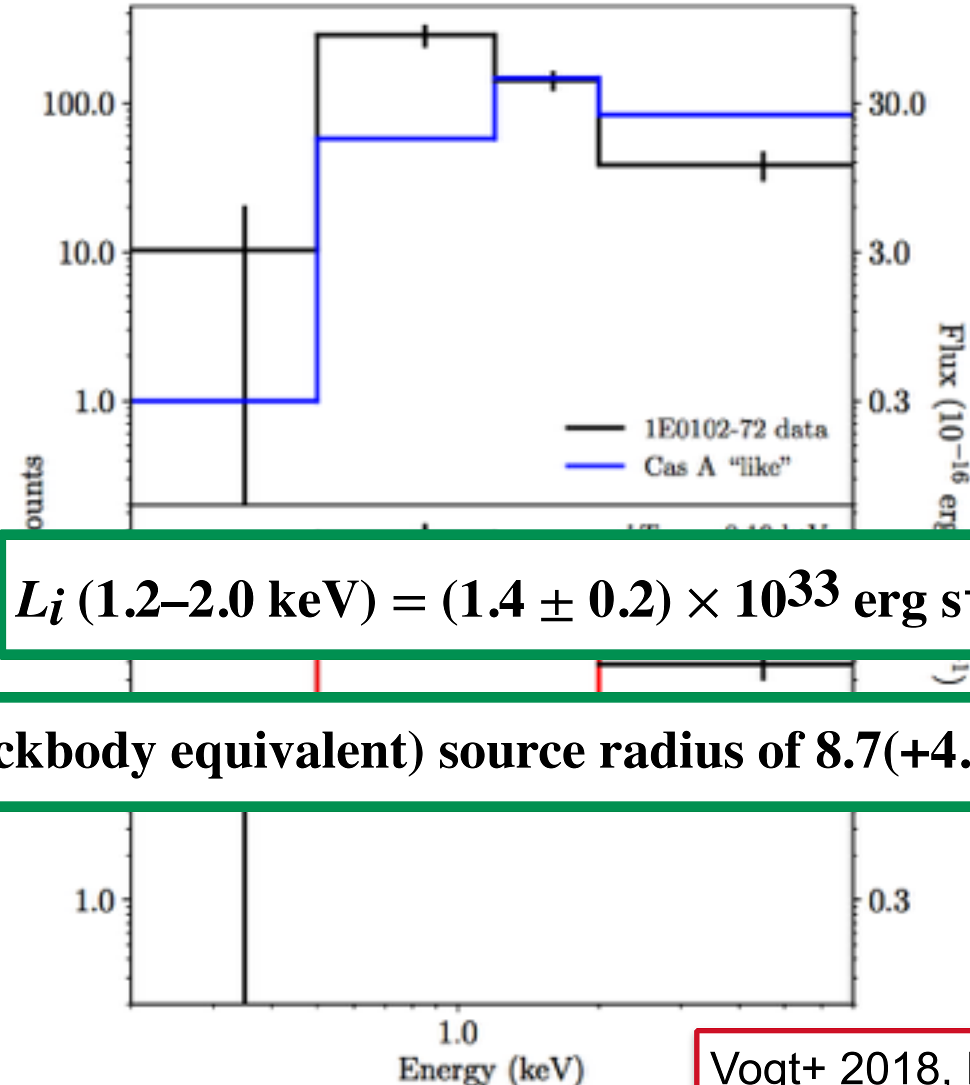


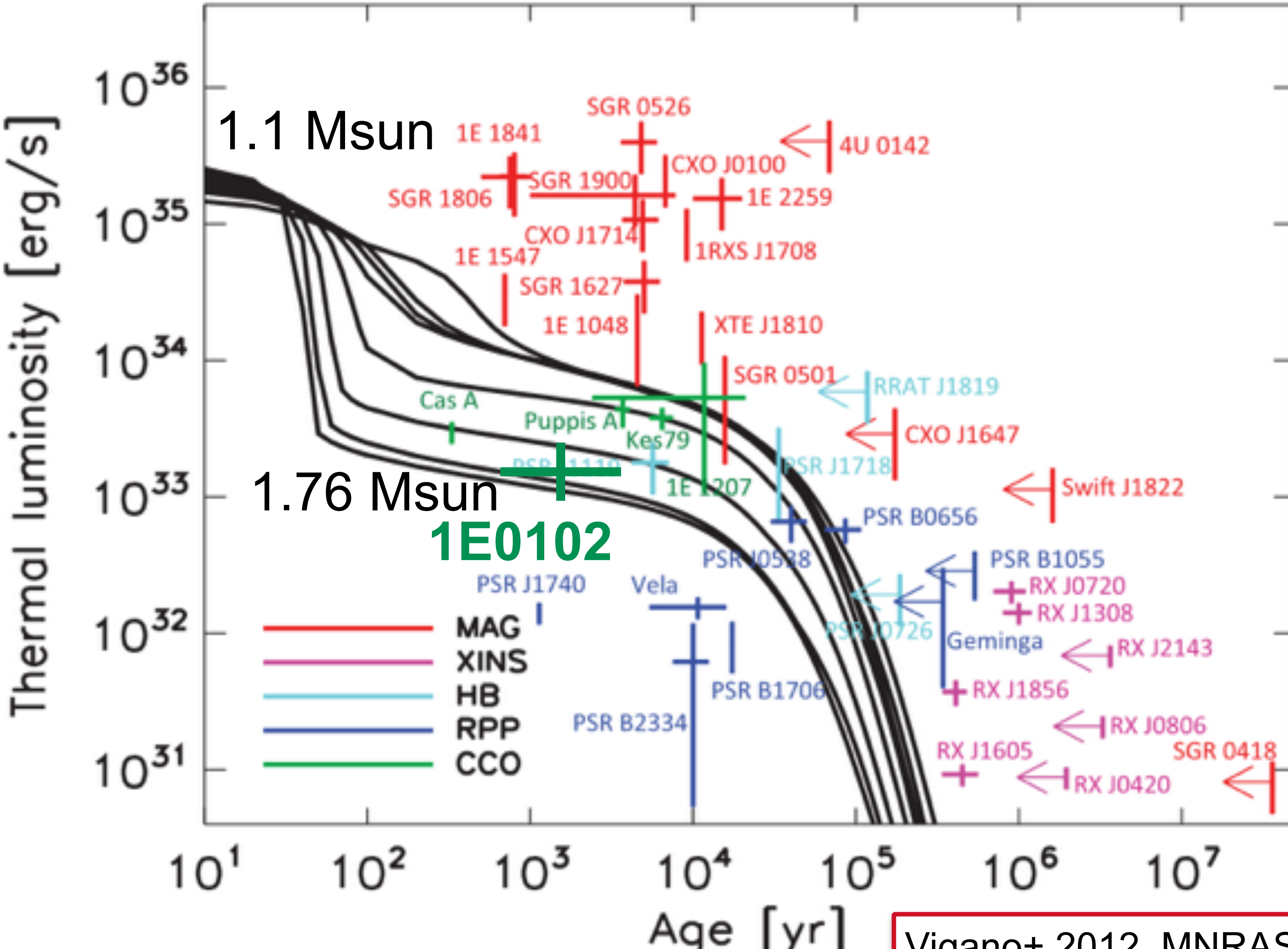
L_i **(1.2–2.0 keV) =** $\mathbf{(1.4 \pm 0.2) \times 10^{33}}$ **erg** $\mathbf{s^{-1}}$**.**

(blackbody equivalent) source radius of 8.7(+4.9 -2.7) km

Vogt+ 2018, Nat. Astron., 2, 465

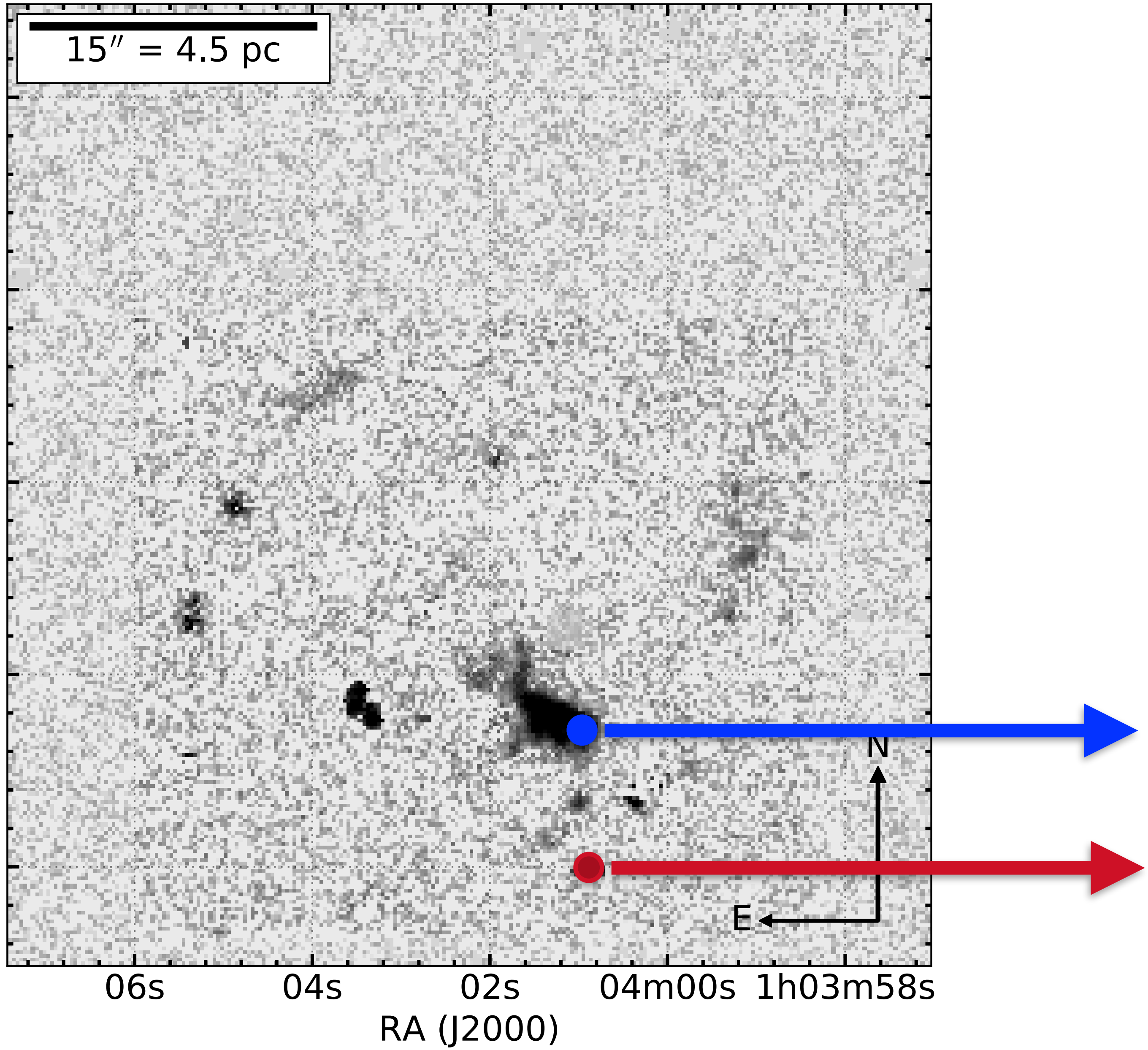
Fig. 1. Energy distribution of the X-ray point source *p1* in E 0102 (black curve), compared with that of a Cas A-like CCO observed at the same distance (blue curve, top), and our best-fit, absorbed, single blackbody component model with $kT_{\rm BB}$ = 0.19 keV (red curve, bottom). Given its brightness and spectral signature, *p1* is consistent with being a CCO ~0.2 keV cooler than that of Cas A (Pavlov & Luna 2009).

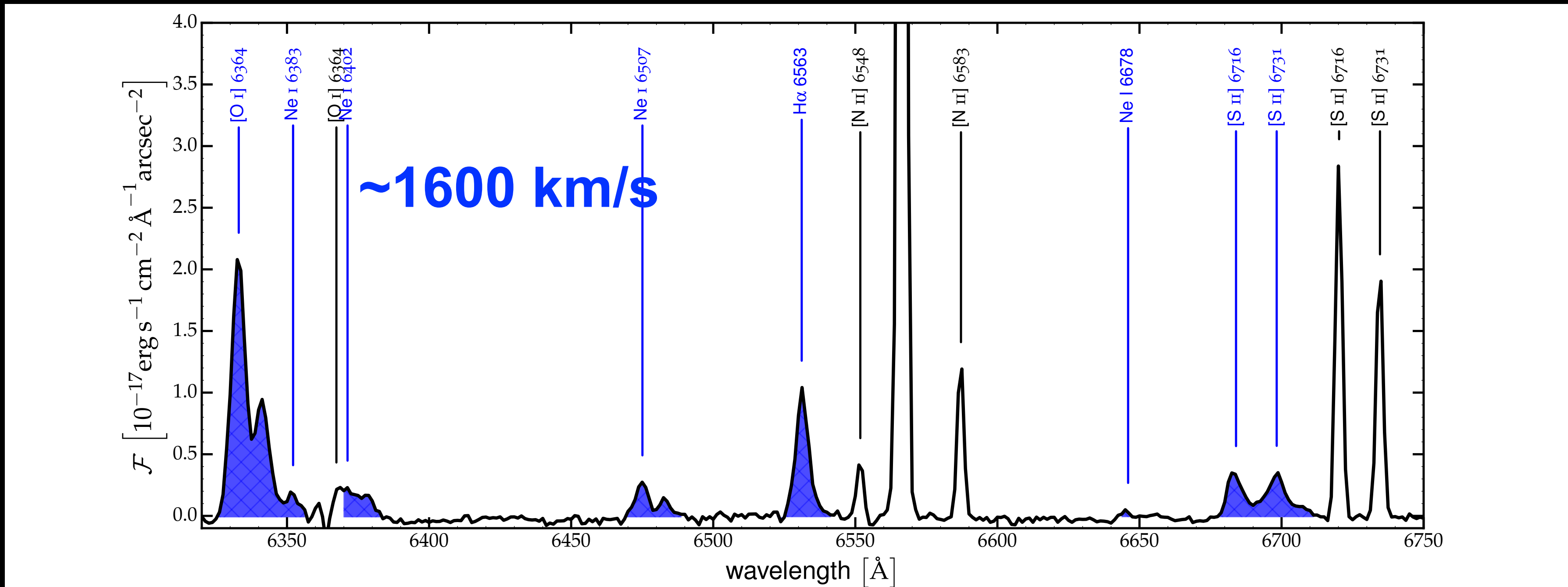
NS cooling curves for light elem. env.



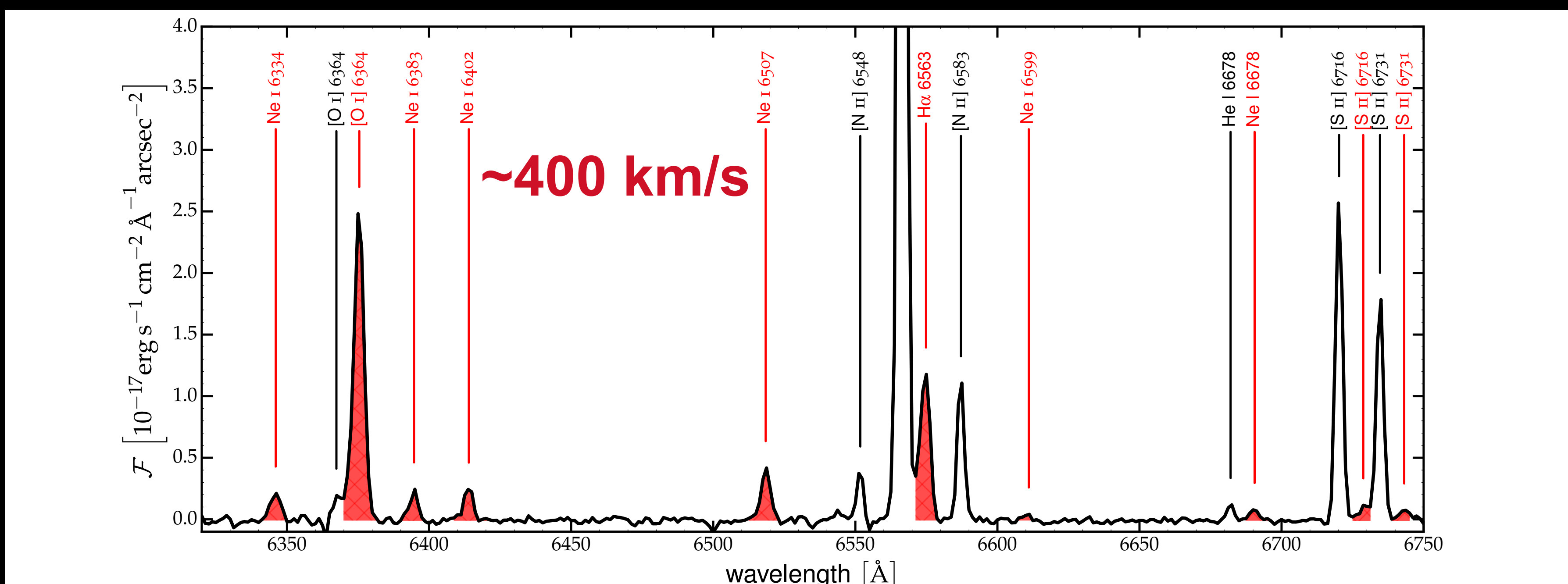
Vigano+ 2012, MNRAS, 434, 123

Fitted red- and blue-shifted H-alpha





~1600 km/s
[O I] 6364
Ne I 6383
[O I] 6364
Ne I 6402
Ne I 6507
Hα 6563
[N II] 6548
[N II] 6583
Ne I 6678
[S II] 6716
[S II] 6731
[S II] 6716
[S II] 6731
$\mathcal{F}$ [10^{-17} erg s^{-1} cm^{-2} Å^{-1} arcsec^{-2}]
wavelength [Å]

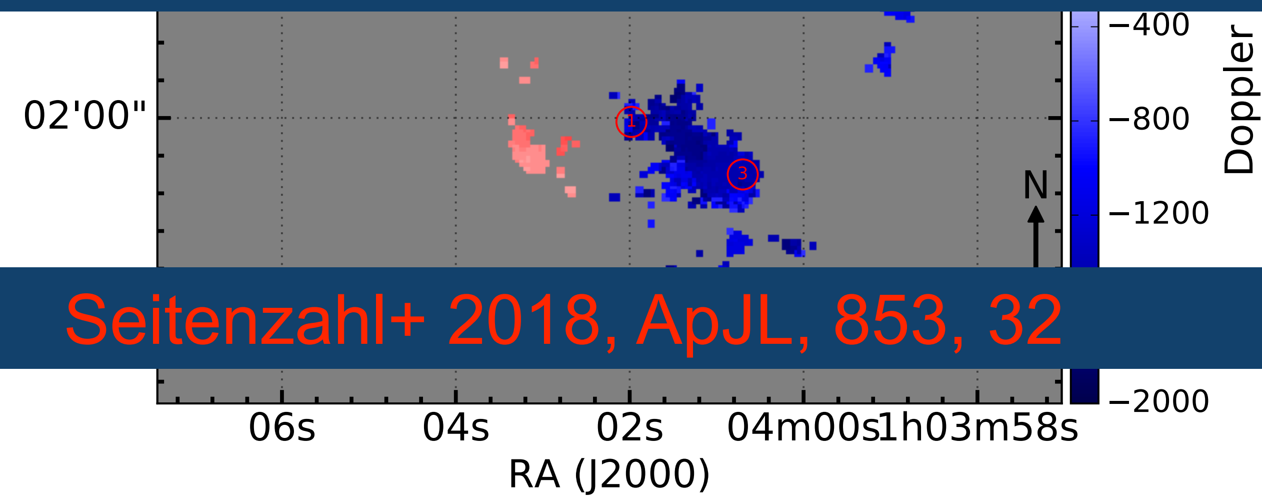


~400 km/s
Ne I 6334
[O I] 6364
[O I] 6364
Ne I 6383
Ne I 6402
Ne I 6507
[N II] 6548
Hα 6563
[N II] 6583
Ne I 6599
He I 6678
Ne I 6678
[S II] 6716
[S II] 6716
[S II] 6731
[S II] 6731
$\mathcal{F}$ [10^{-17} erg s^{-1} cm^{-2} Å^{-1} arcsec^{-2}]
wavelength [Å]

1E0102.2-7219 with MUSE

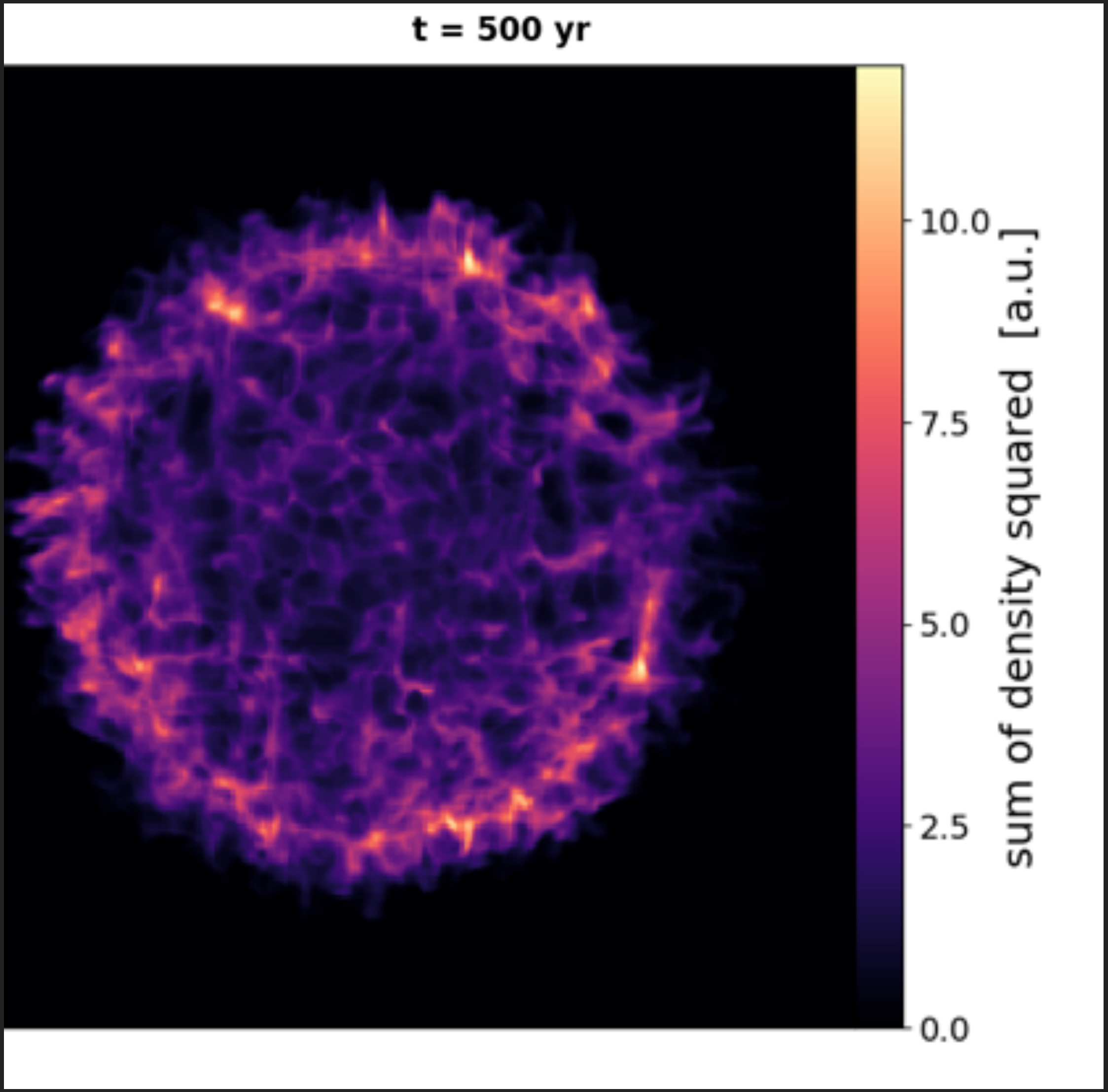
Our *Mappings* shock model calculations indicate enhancements relative to hydrogen in region 1:

235,000 times SMC for O
100,000 times SMC for S
160,000 times SMC for Cl
195,000 times SMC for Ar

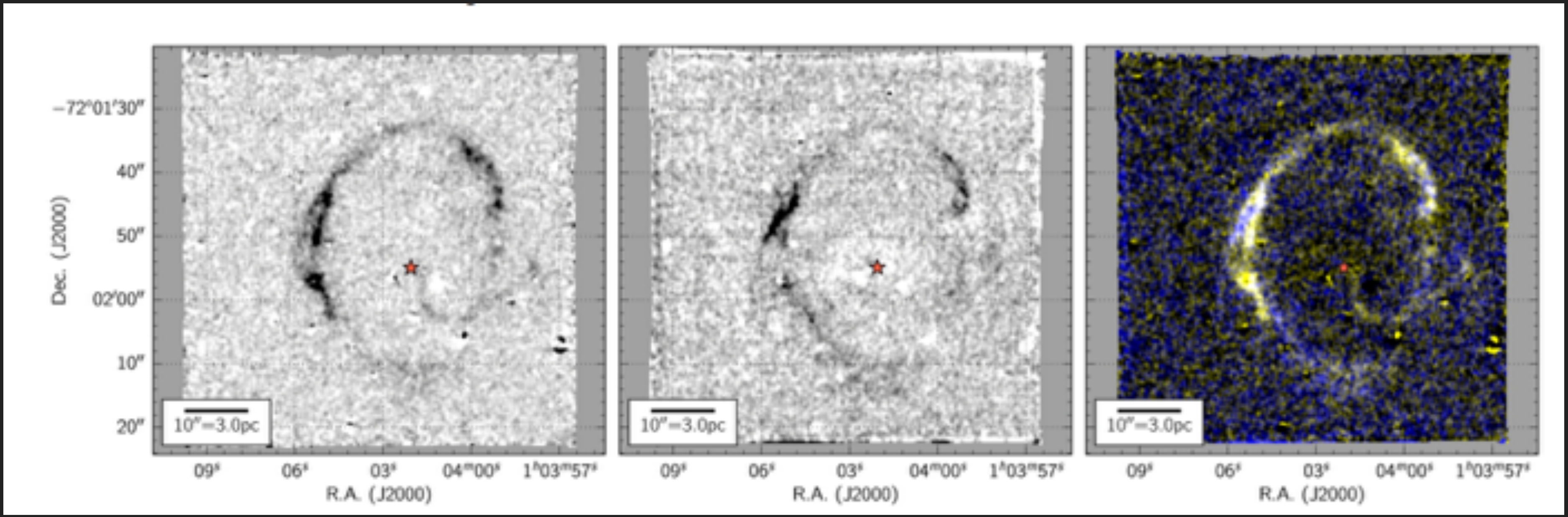


Seitenzahl+ 2018, ApJL, 853, 32

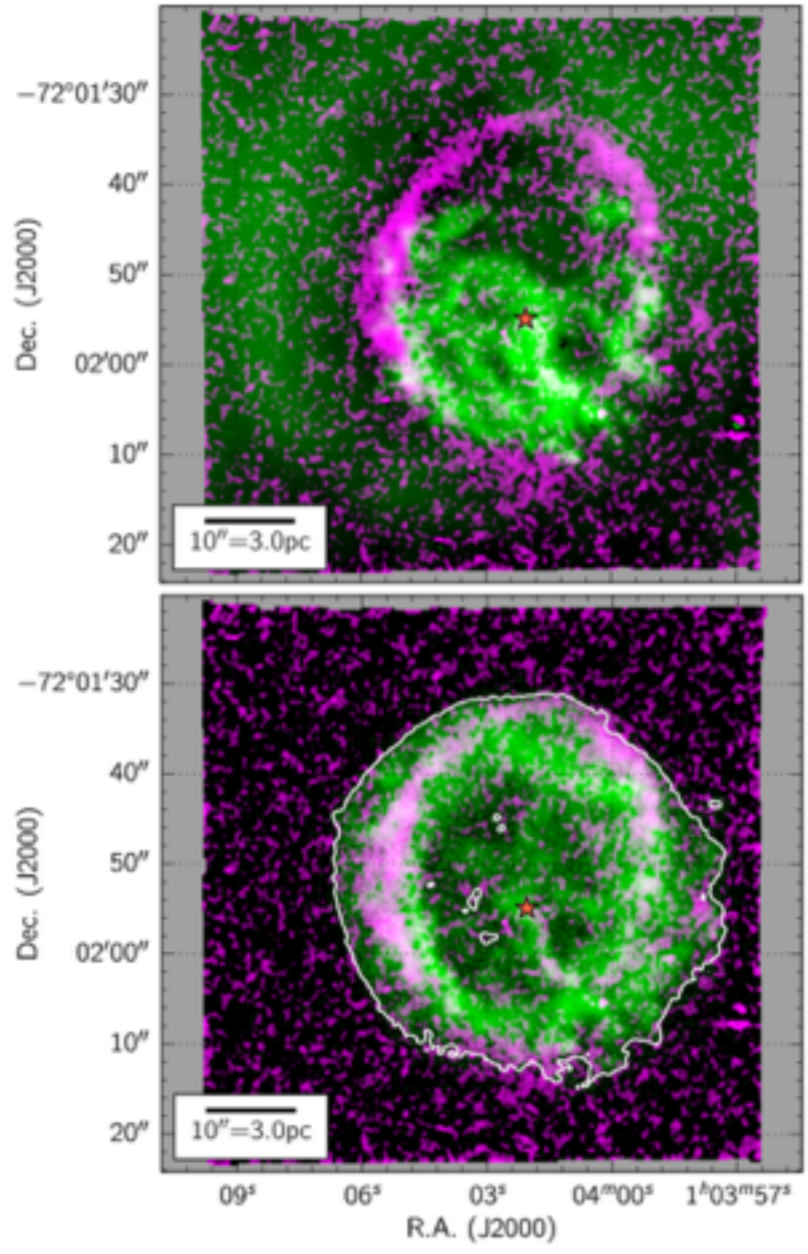
Ferrand, Warren, Ono, Nagataki, Röpke, Seitenzahl, 2019, ApJ (accepted)



Vogt, Seitenzahl et al, A&A, 602, L4



Vogt, Seitenzahl et al, A&A, 602, L4

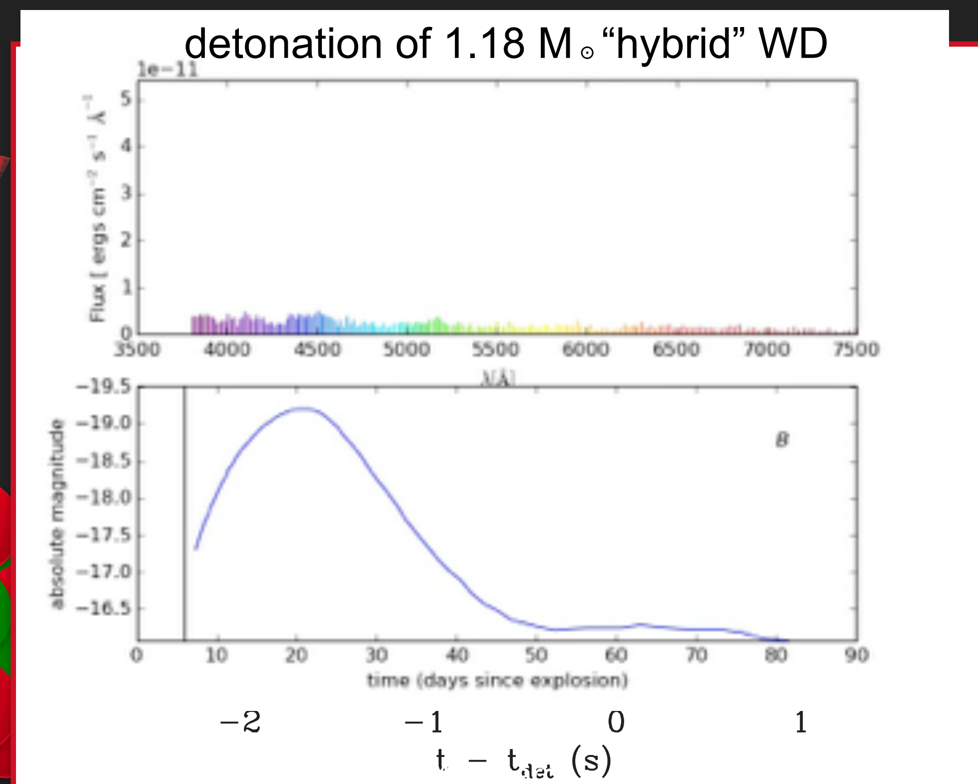


SN Ia energetics

initial composition

~10^{51} erg released during ~1 sec of explosive burning transformed into E_{kin} and work against gravity.

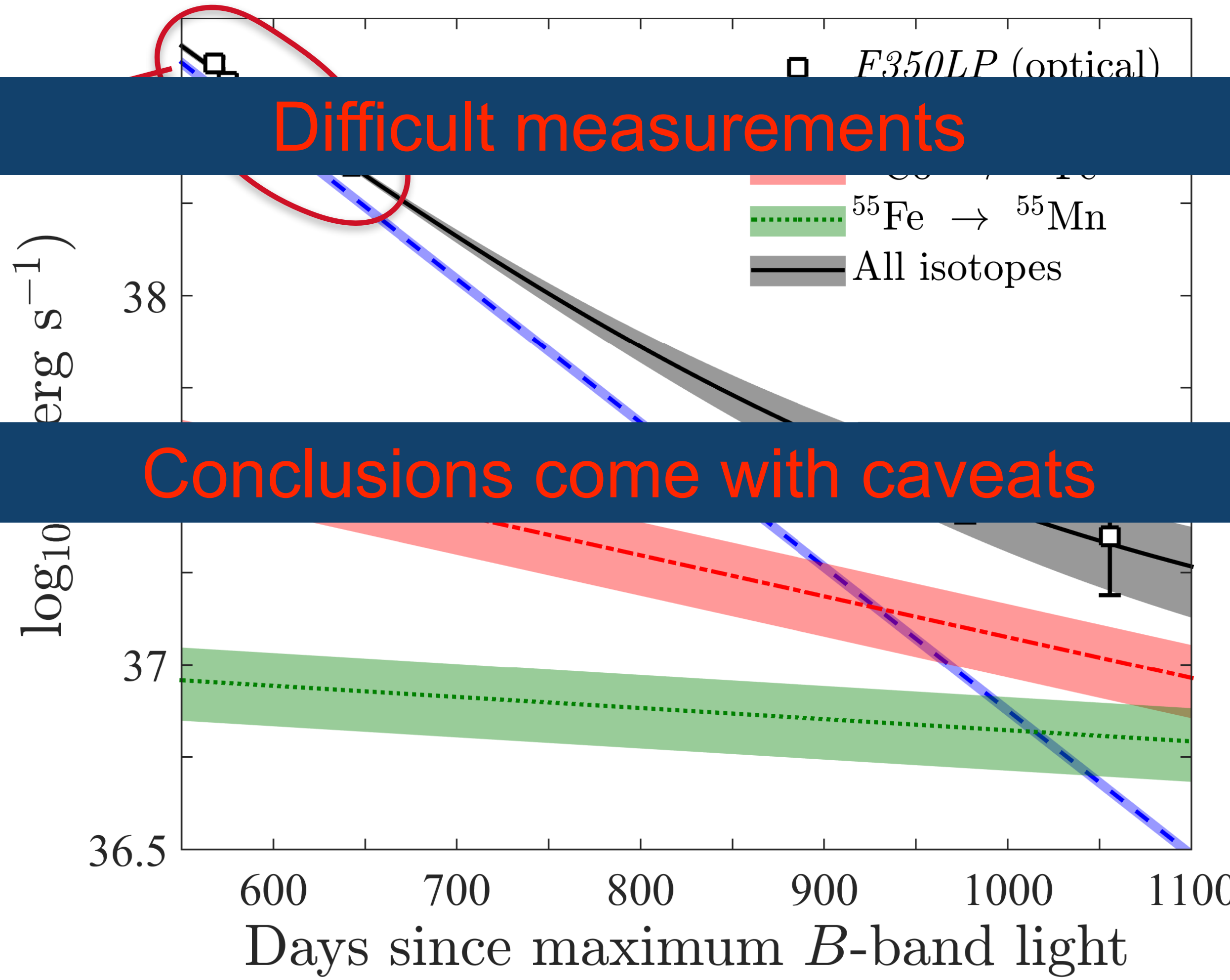
0.8 MeV/nuc * 6×10^{23} nuc/g * 2×10^{33} g * 1.6×10^{-6} erg/MeV = 1.5×10^{51} erg



distinguishing models at late-time

We find evidence for ^{57}Co dominated phase

Best fit to model: **2 x solar ^{57}Ni/^{56}Ni**



Difficult measurements

Conclusions come with caveats

Graur+ (20 ApJ, 819, 31