Radioactivity in supernovae and kilonovae

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Swedish Research Council

European Research Council

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EXPLOSIVE TRANSIENT ARE MOSTLY POWERED BY RADIOACTIVITY

Luminosity from shock power:

$$L \approx 6 \times 10^{42} E_{51} M_{M_\odot}^{-1} R_{0,500} \kappa_{0.2}^{-1} \text{ erg s}^{-1}$$

(Type I SNe, Type II similar expression)

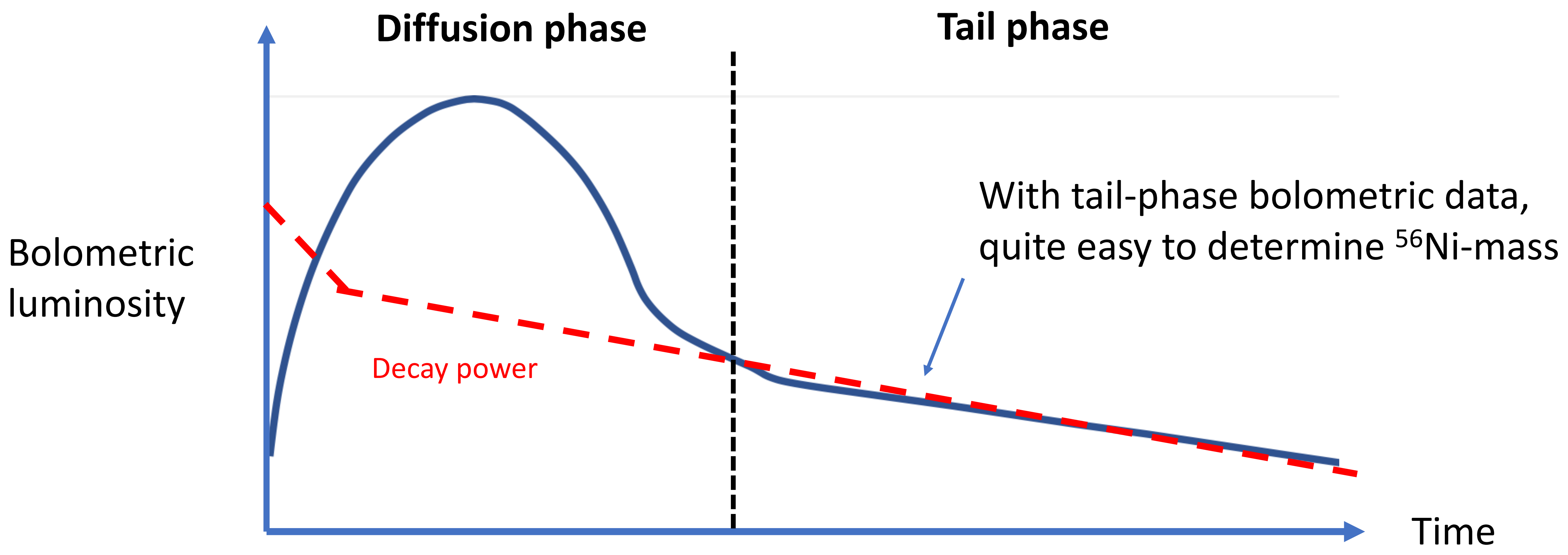
Star	SN type	R_0 ($R_\odot$)	L_{peak} (Explosive, Eq 24) (erg/s)	L_{peak} (Observed) (erg/s)
RSG	IIP	500	6×10^{41} ($M_{M_\odot} = 10$)	$3 \times 10^{40} - 3 \times 10^{42}$
BSG	II-pec	50	6×10^{40} ($M_{M_\odot} = 10$)	$\sim 1 \times 10^{42}$
WR star	Ibc	5	6×10^{39} ($M_{M_\odot} = 10$)	$\sim 1 \times 10^{42}$
WD	Ia	0.01	1×10^{38} ($M_{M_\odot} = 1$)	$\sim 1 \times 10^{43}$

To the rescue: $^{56}Ni \xrightarrow{8.8d} {}^{56}Co \xrightarrow{111d} {}^{56}Fe$

$$E_{decay} = 2 * 10^{49} \left(\frac{M(^{56}(\mathrm{Ni}))}{0.1\, M_\odot}\right) \text{erg}$$

$$P(t) = 1.4 * 10^{42} \left(\frac{M(^{56}(\mathrm{Ni}))}{0.1\, M_\odot}\right) e^{-t/111d} \text{ erg/s}$$

$^{56}Ni/^{56}Co$-POWER IN SUPERNOVAE

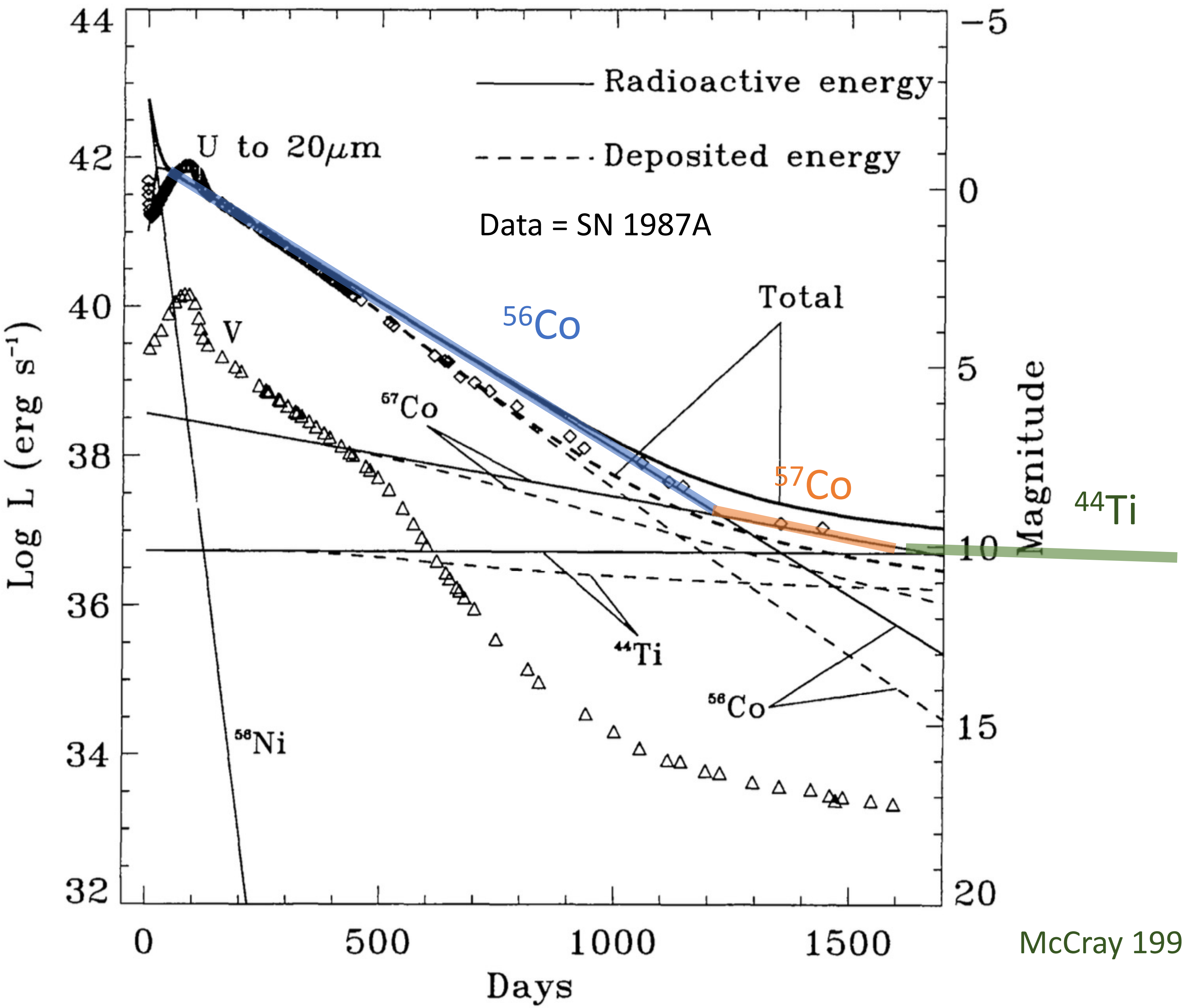


^{56}Ni mean production:

Type II SNe: 0.04 $M_\odot$ — Rodriguez+2021

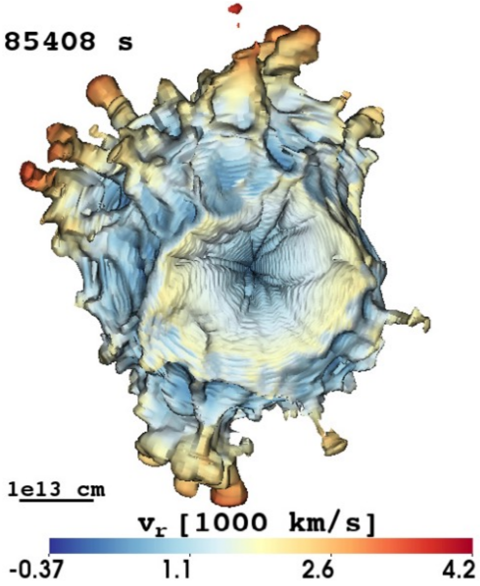
Type I SNe: 0.08 $M_\odot$ — Afsariardchi+2021

^{56}Co, ^{57}Co, ^{44}Ti take turns powering the SN

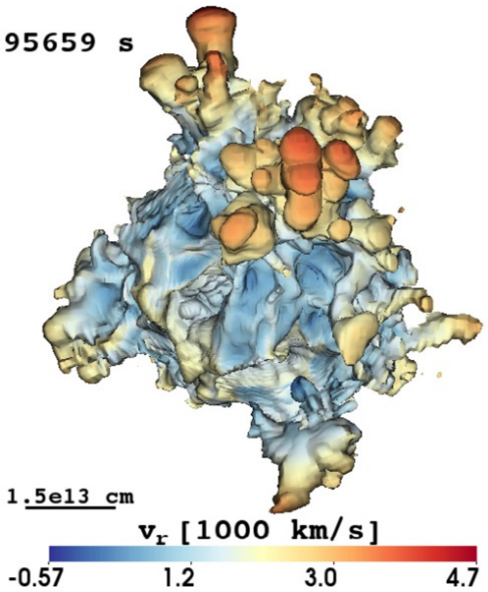


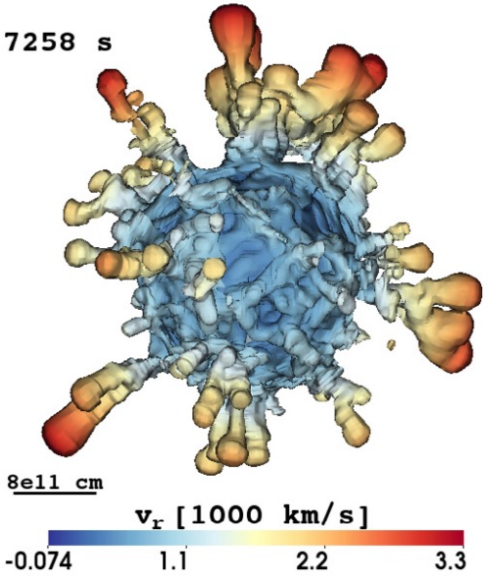
McCray 1993

TESTING 3D EXPLOSION MODELS WITH ^{56}CO DECAY LINES

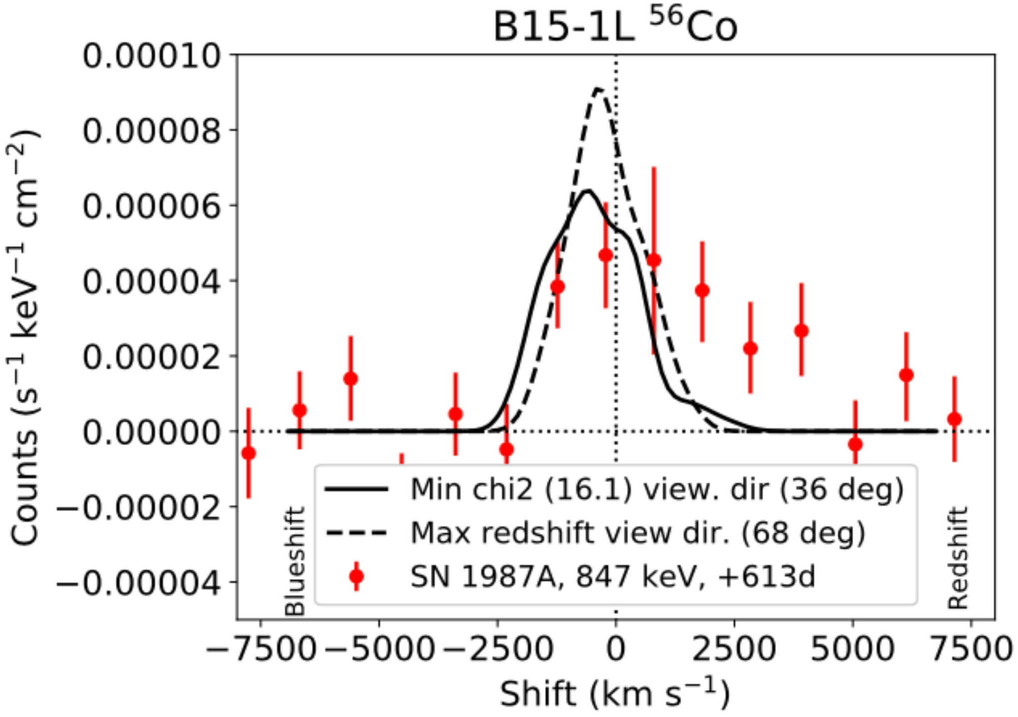


Long-term 3D simulations from Garching group





3D Compton scattering code



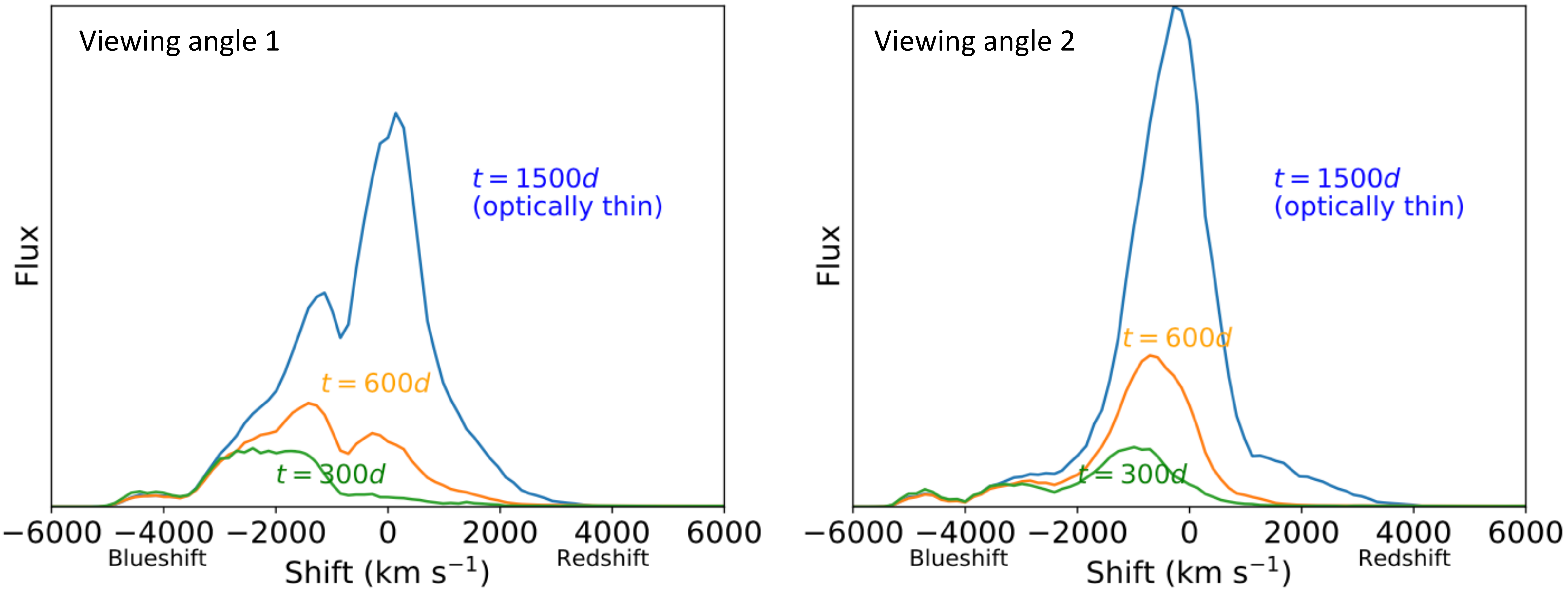
Gamma line profiles, compare to observed ones

AJ+2020, MNRAS

TESTING 3D EXPLOSION MODELS WITH ^{56}CO DECAY LINES

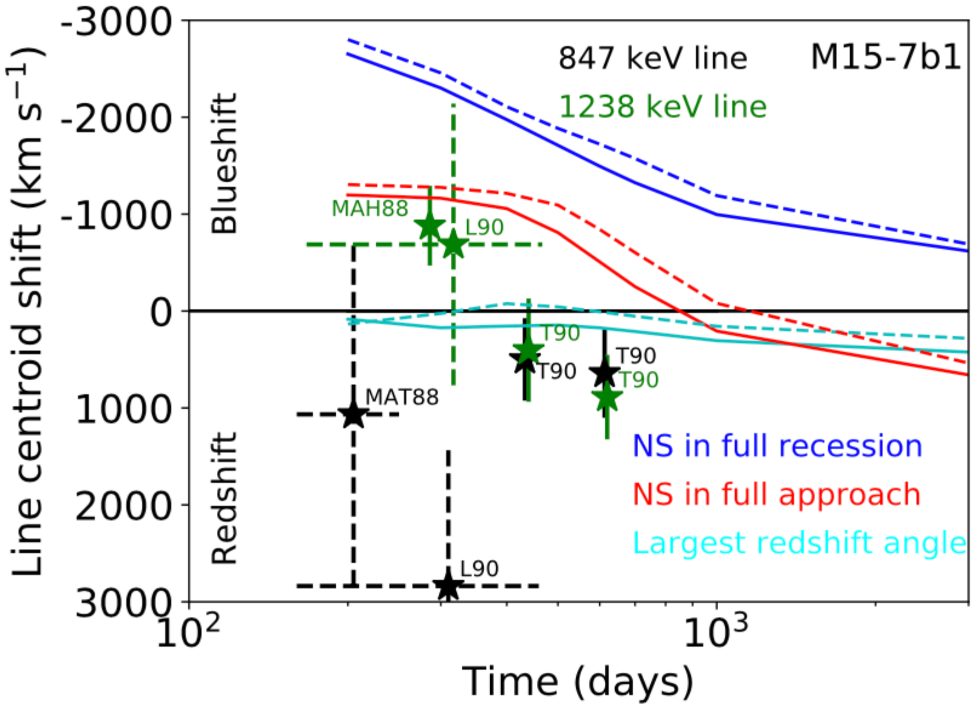
Line profile (for given viewing angle) depends on
1) ^{56}Ni morphology and ***2) total ejecta mass (+ morphology)***

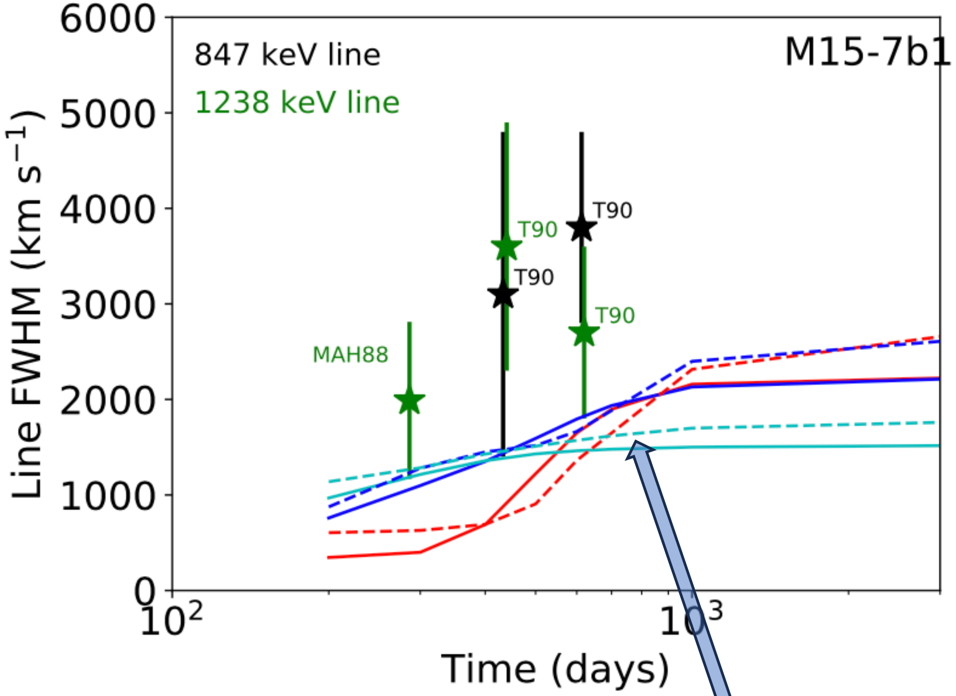
AJ+2020, MNRAS
See also Hungerford+2003,2005, Maeda+2006, Wollaeger+2017, Alp+2019

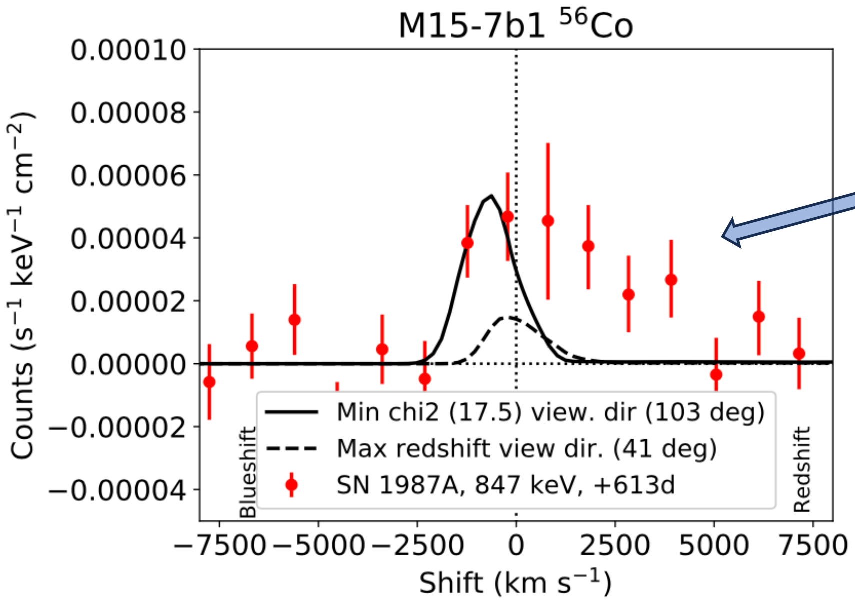


MODEL COMPARISONS TO SN 1987A

AJ+2020, MNRAS



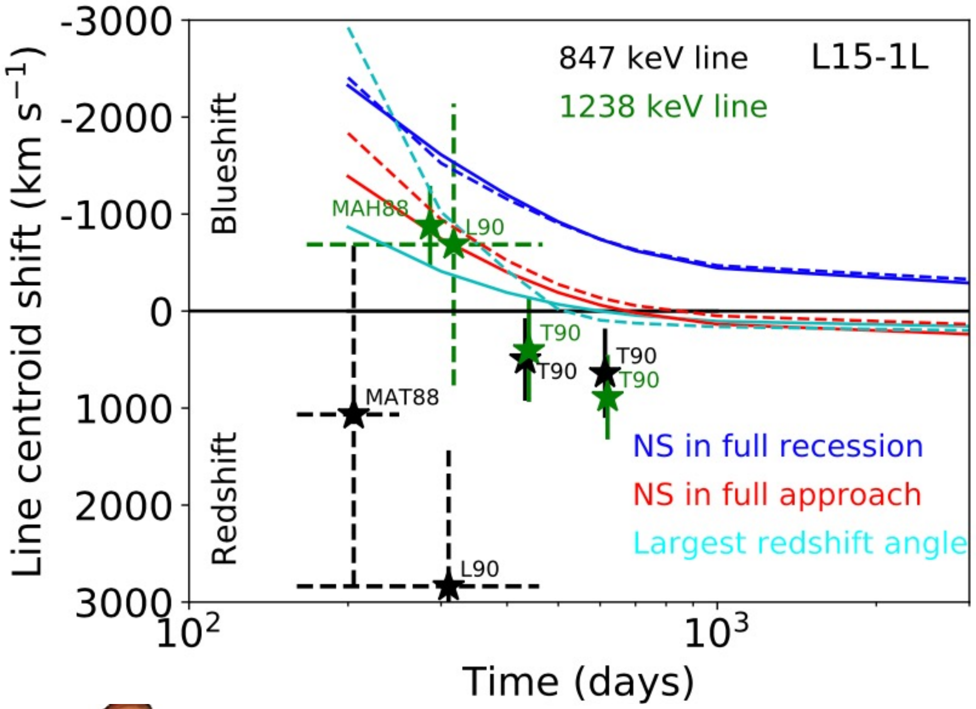


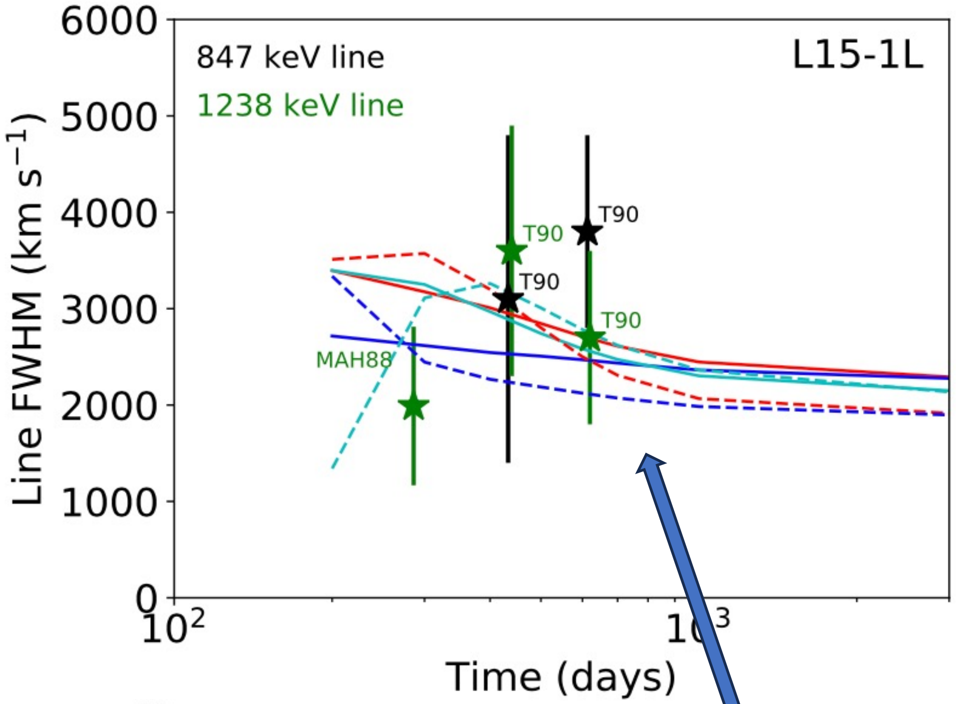


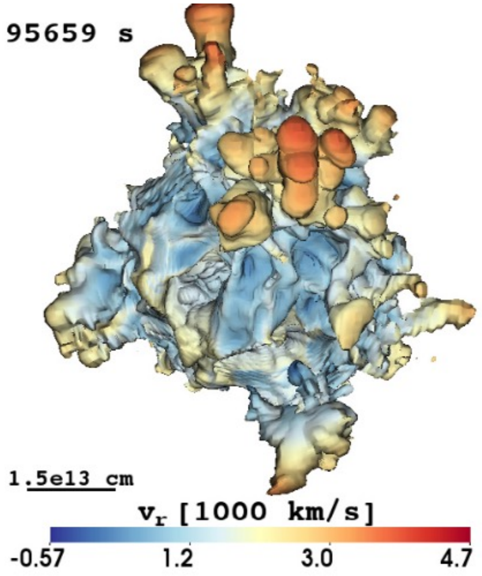
Lines too narrow
in this (merger) model,
and too blueshifted.

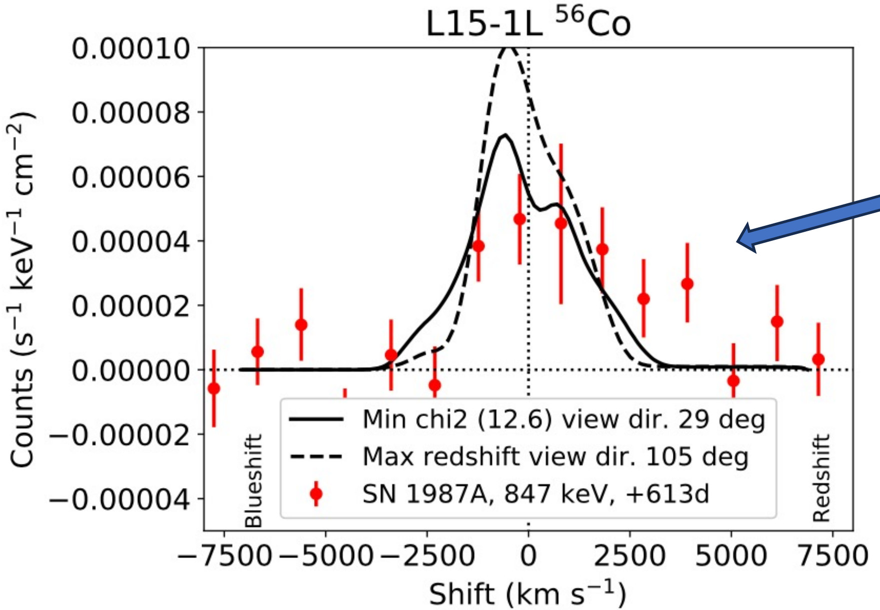
MODEL COMPARISONS TO SN 1987A

AJ+2020, MNRAS





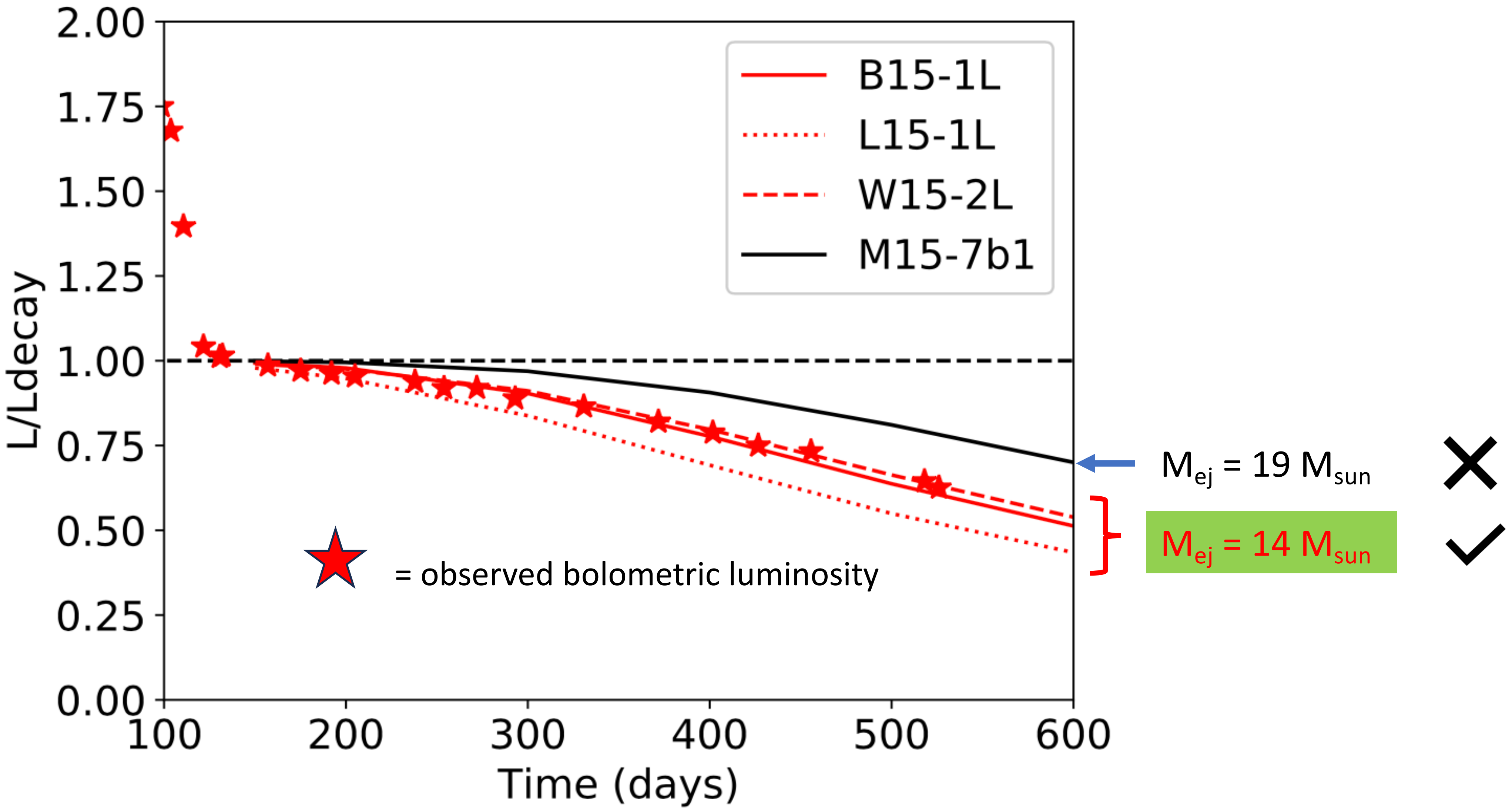




This model both properties better

$V_{shift}(^{56}Ni)$ = 400 km/s
M_{ej} = 14 Msun

SN 1987A UVOIR LIGHT CURVE → INDEPENDENT TEST FOR EJECTA MASS



AJ+2020, MNRAS

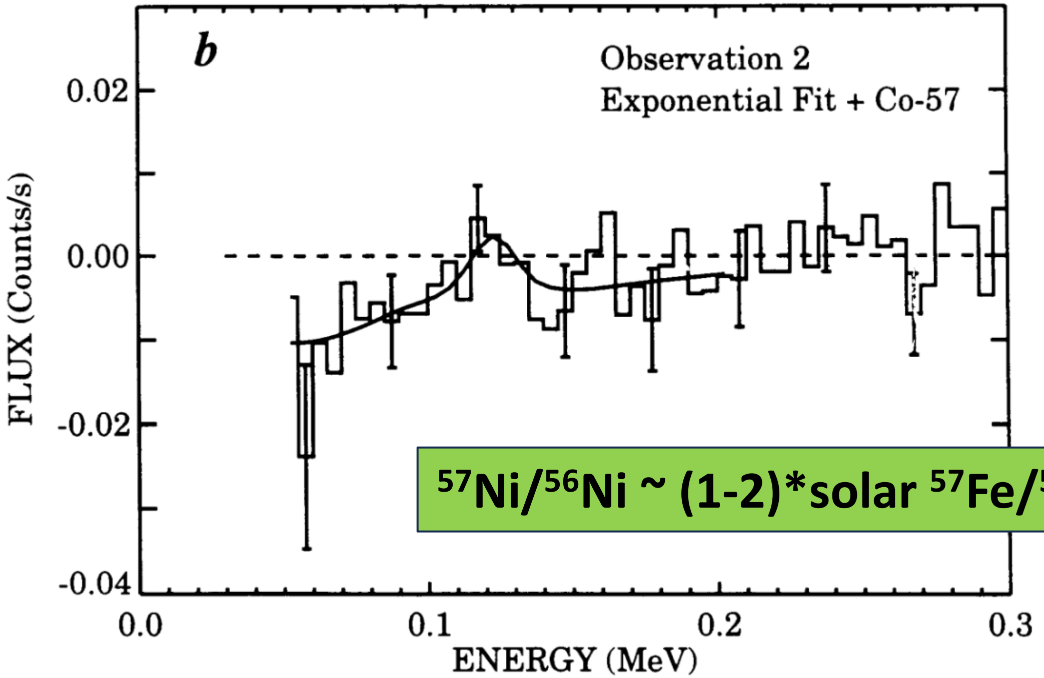
Ready player 2 : ^{57}Ni

2.1d 384d

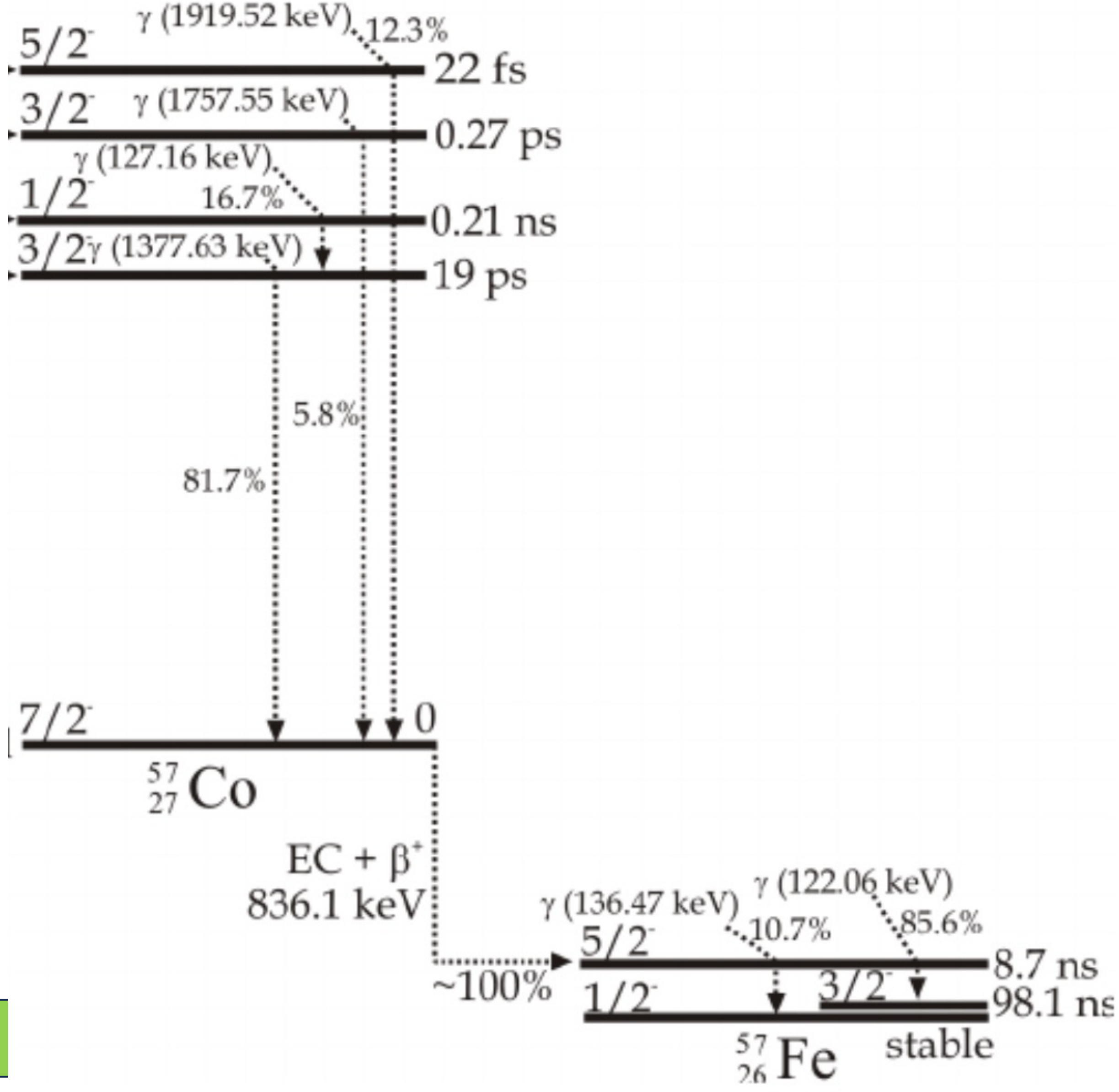
$^{57}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

Main power source
between ~ 1200 - 1600 days.

Gamma-rays "detected"
from SN 1987A (Kurfess+1992)

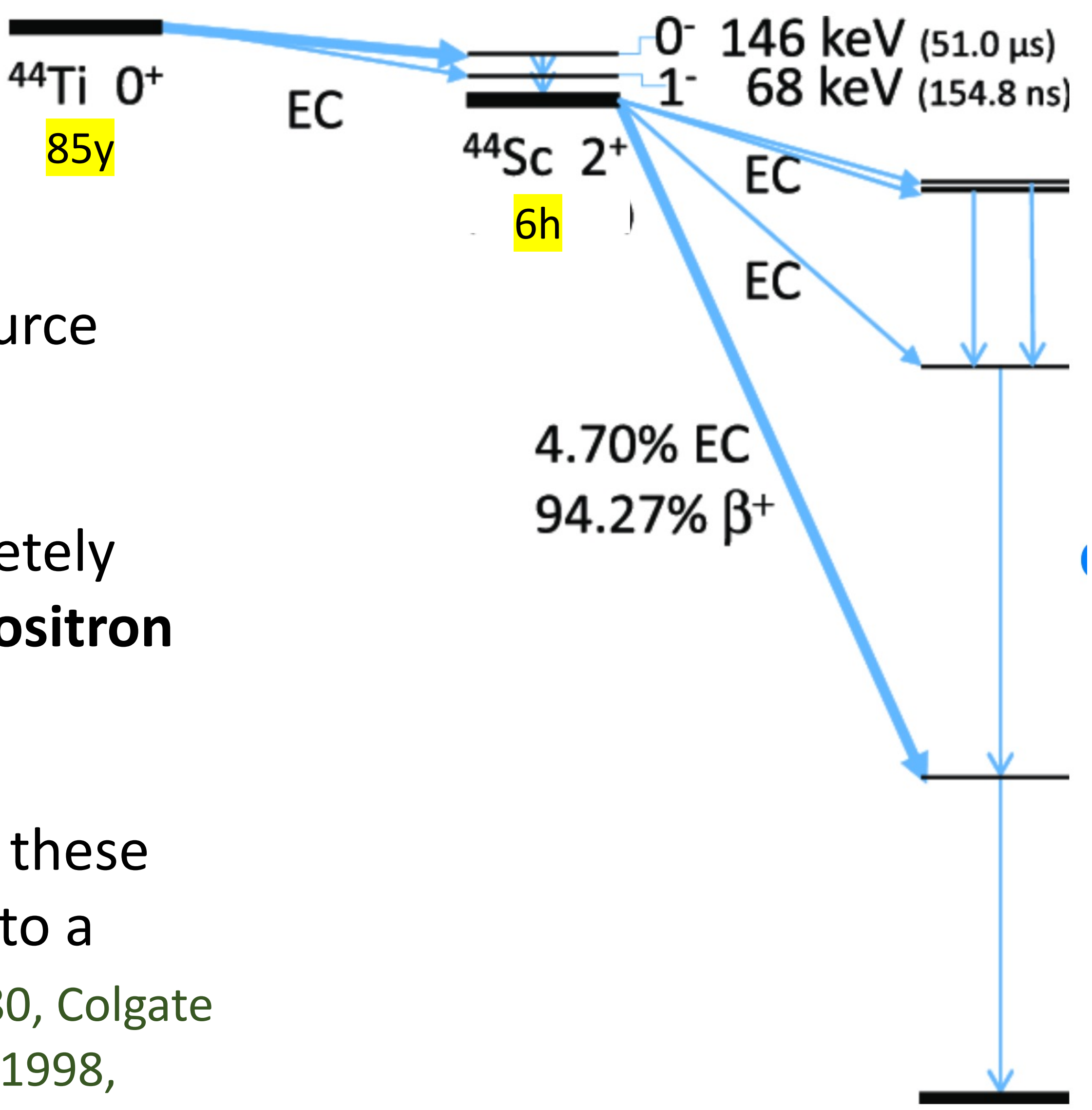


^{57}Ni/^{56}Ni ~ (1-2)*solar ^{57}Fe/^{56}Fe



Probes neutron excess of burn layer

Player 3: ^{44}Ti

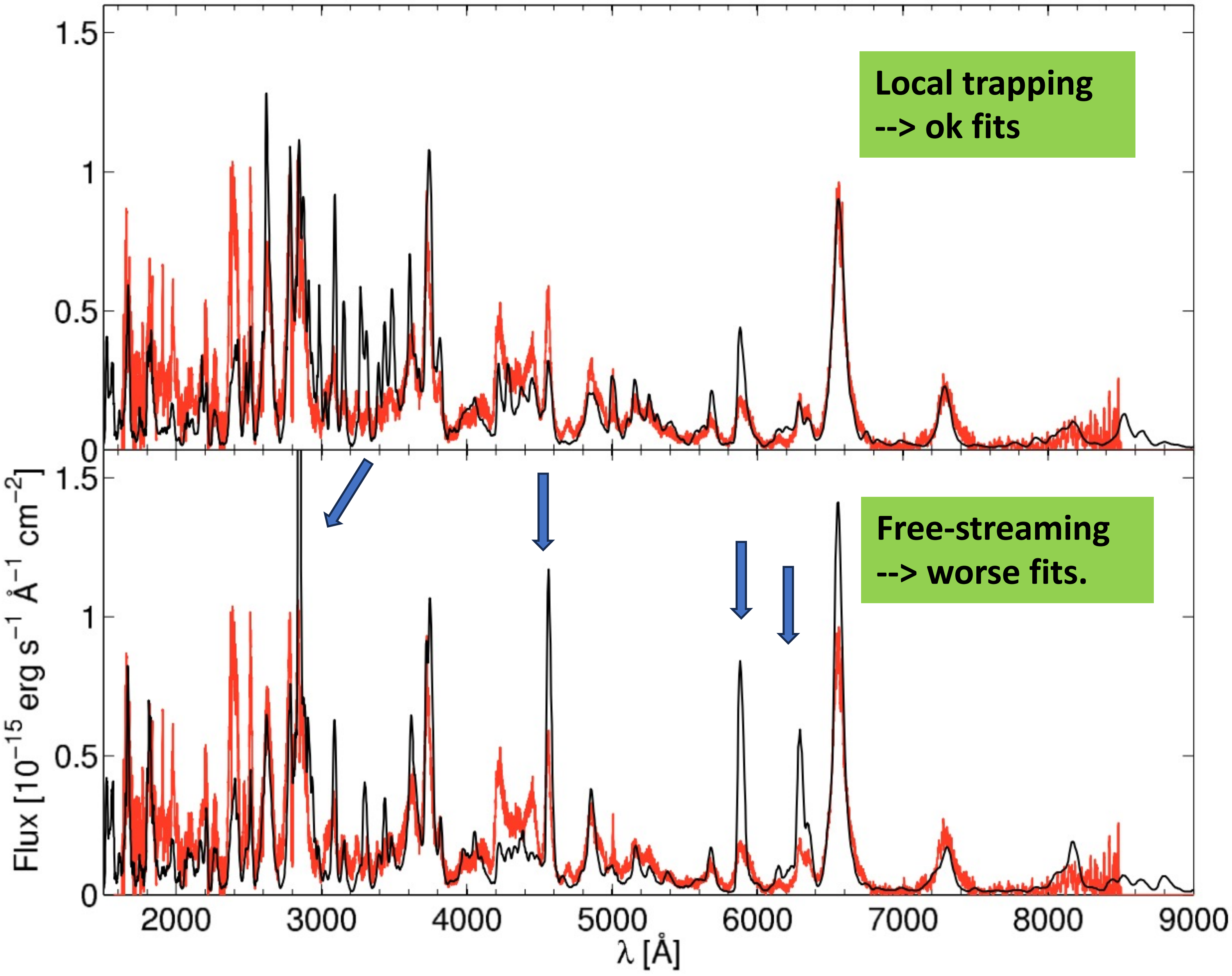


Becomes main power source after **about 4 years**.

Gamma-rays then completely escape; powering is by **positron channel**.

Important topic whether these **stream** or **stay local** due to a tangled B-field Axelrod 1980, Colgate 1980, Ruiz-Lapuente & Spruit 1998, AJ+2011.

^{44}Ti positron trapping in SN 1987A

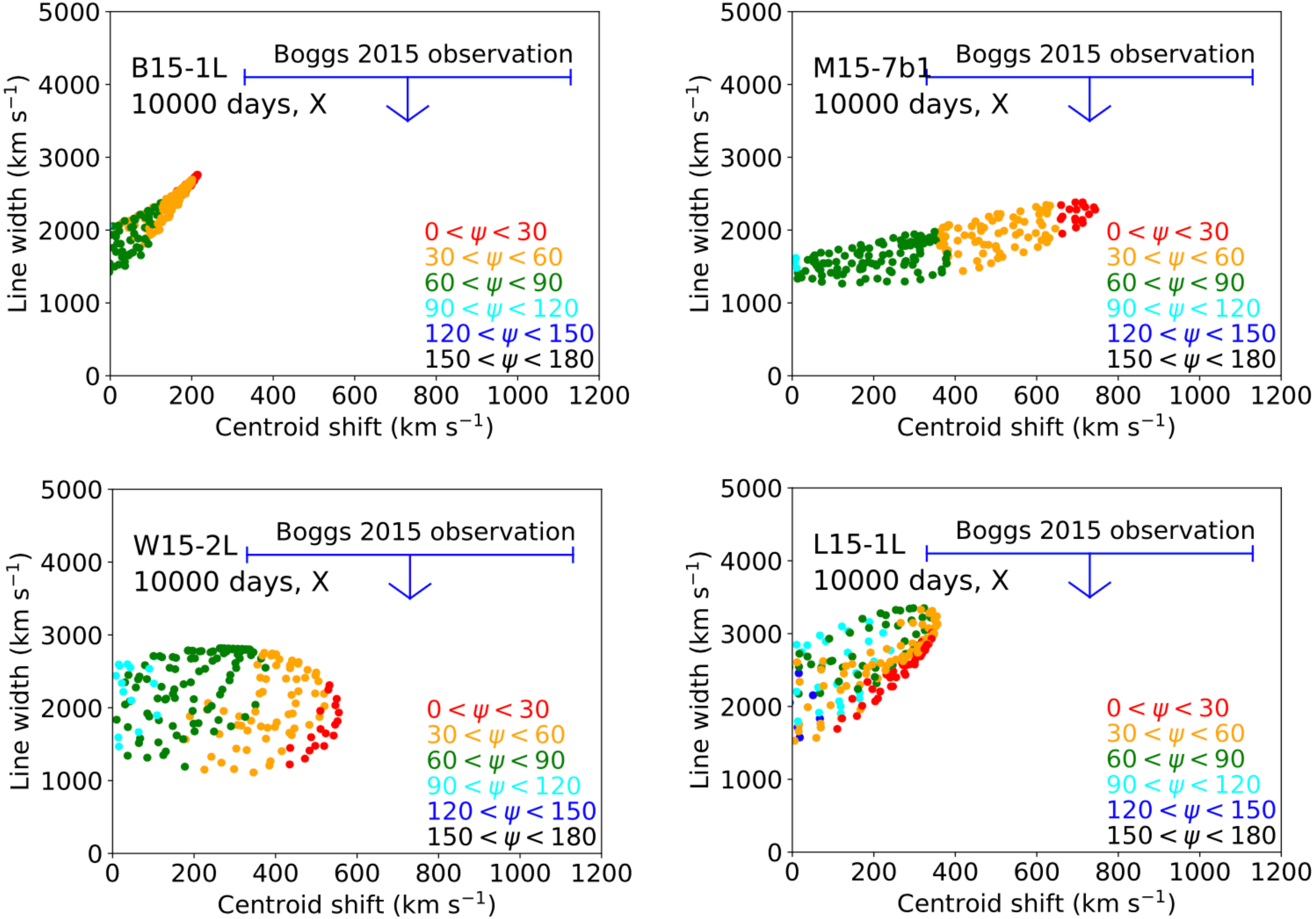


An aside: we typically need ejecta **not mixed** on microscopic scales
to fit optical spectra (AJ 2017); relevance for grain formation theory.

Note a shell merger would give a situation similar to this case

AJ+2011

Constraints from ^{44}Ti line profiles in SN 1987



Many current 3D explosion models give too small ^{44}Ti asymmetry: some ok

Cas A similar picture

AJ+2020, MNRAS

Other radionuclides of potential importance

Table 2 Decay data for the most common radioactive isotopes. Fractions of decay energy going to γ-rays, positrons, electrons, and X-rays are listed. Annihilation radiation from positrons is included in the gamma fraction (contribution in parenthesis). Fractions smaller than 10^{-3} have been put to zero (Data from Nuclear Data Sheets 2011)

Decay	τ	$\hat{Q}$ (keV decay^{-1})	f_{γ}	f_{e+}	f_{e-}	f_{X-ray}	Source
^{56}Ni → ^{56}Co	8.77d	1724	0.996	0	0.0025	0.0013	Si burning
^{56}Co → ^{56}Fe	111d	3732	0.966 (0.053)	0.032	0.001	0	
^{57}Ni → ^{57}Co	35h	2096	0.924 (0.21)	0.074	0.001	0	Si burning
^{57}Co → ^{57}Fe	391d	143	0.850	0	0.125	0.025	
^{44}Ti → ^{44}Sc	88y	150	0	0	0.070	0.929	α-rich freeze-out
^{44}Sc → ^{44}Ca	6h	2732	0.78(0.35)	0.22	0	0	
^{55}Co → ^{55}Fe	17h	2429	0.822(0.32)	0.18	0.001	0	Si burning
^{55}Fe → ^{55}Mn	3.87y	5.6	0	0	0.71	0.29	
^{22}Na → ^{22}Ne	2.60y	2392	0.918(0.38)	0.082	0	0	C burning
^{60}Co → ^{60}Ni	5.27y	2600	0.963	0	0.037	0	C burning

AJ 2017 (Handbook of SNe)

NI/FE RATIOS

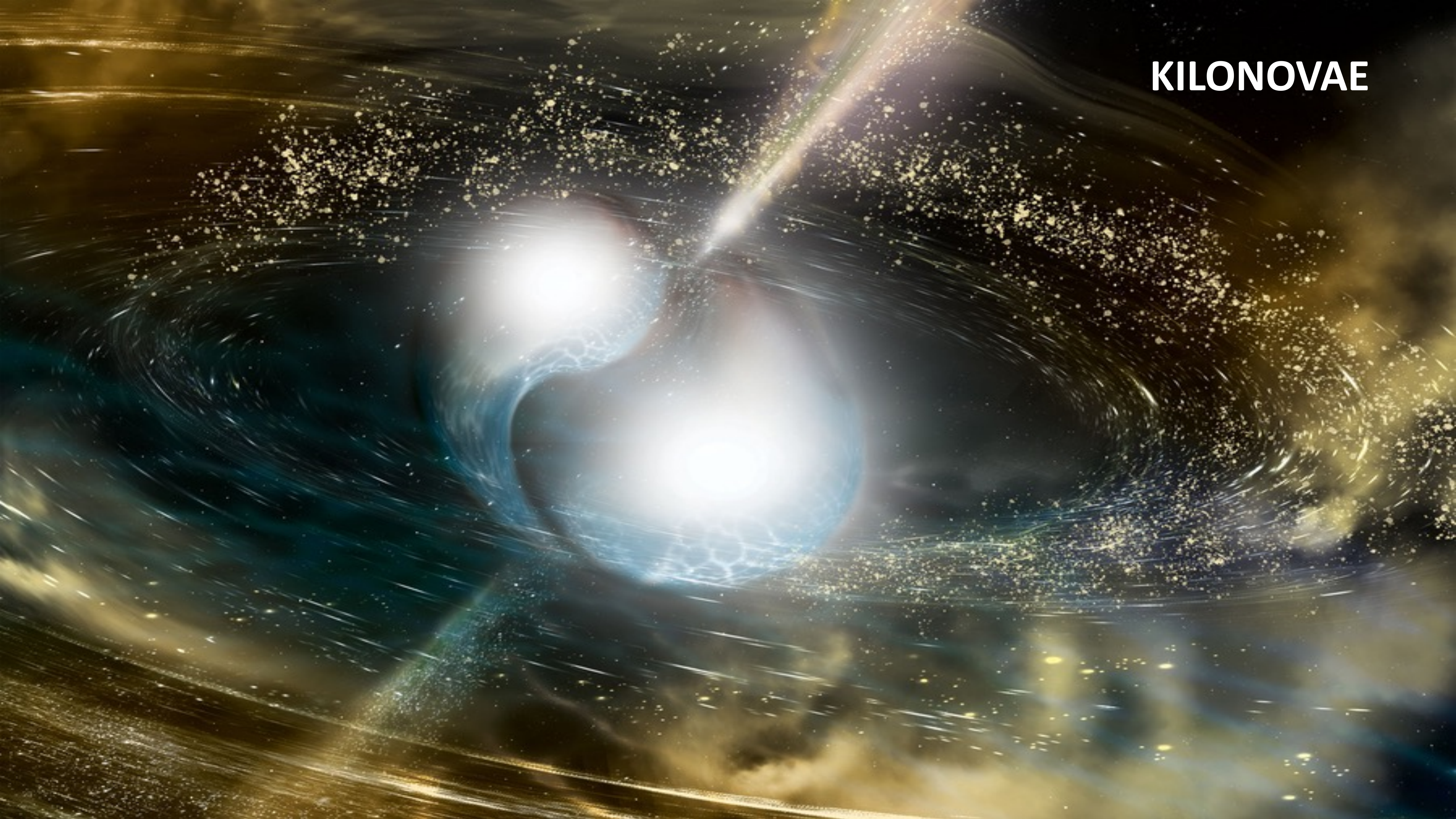
Ni/Fe ratios in 8 CCSNe
(set by ^{58}Ni / ^{56}Ni production ratios)

SN	Ni/Fe (times solar)	Reference
Crab	60 – 75	Macalpine1989, Macalpine2007
SN 1987A	0.5 – 1.5	Rank1988, Wooden1993, AJ+2015
SN 2004et	∼1	AJ+2012
SN 2006aj	2 – 5	Maeda+2007, Mazzali+2007
SN 2012A	∼ 0.5	AJ+2015b
SN 2012aw	∼ 1.5	AJ+2015b
SN 2012ec	2.2 – 4.6	AJ+2015b
SN 2024aexc	~1	Barmentloo & AJ, in prep.

Two main groups: ~solar and ~2-5 times solar

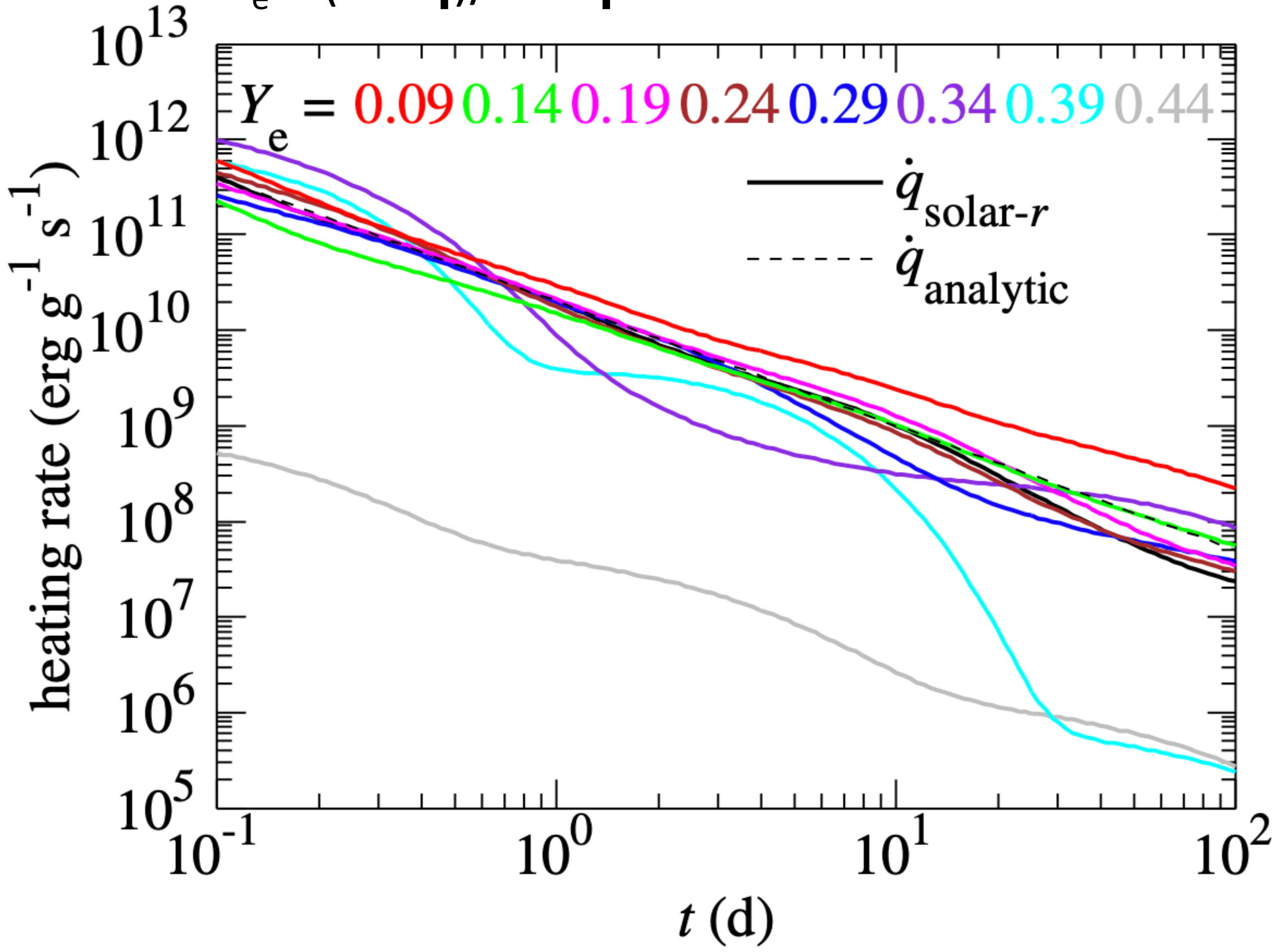
Interpretation: AJ, Timmes, Magkotsios+2015, ApJ

KILONOVAE



R-PROCESS RADIOACTIVE POWER

$Y_e = (1 - \boldsymbol{\eta})/2$ $\boldsymbol{\eta}$ = neutron excess



Wanajo 2014

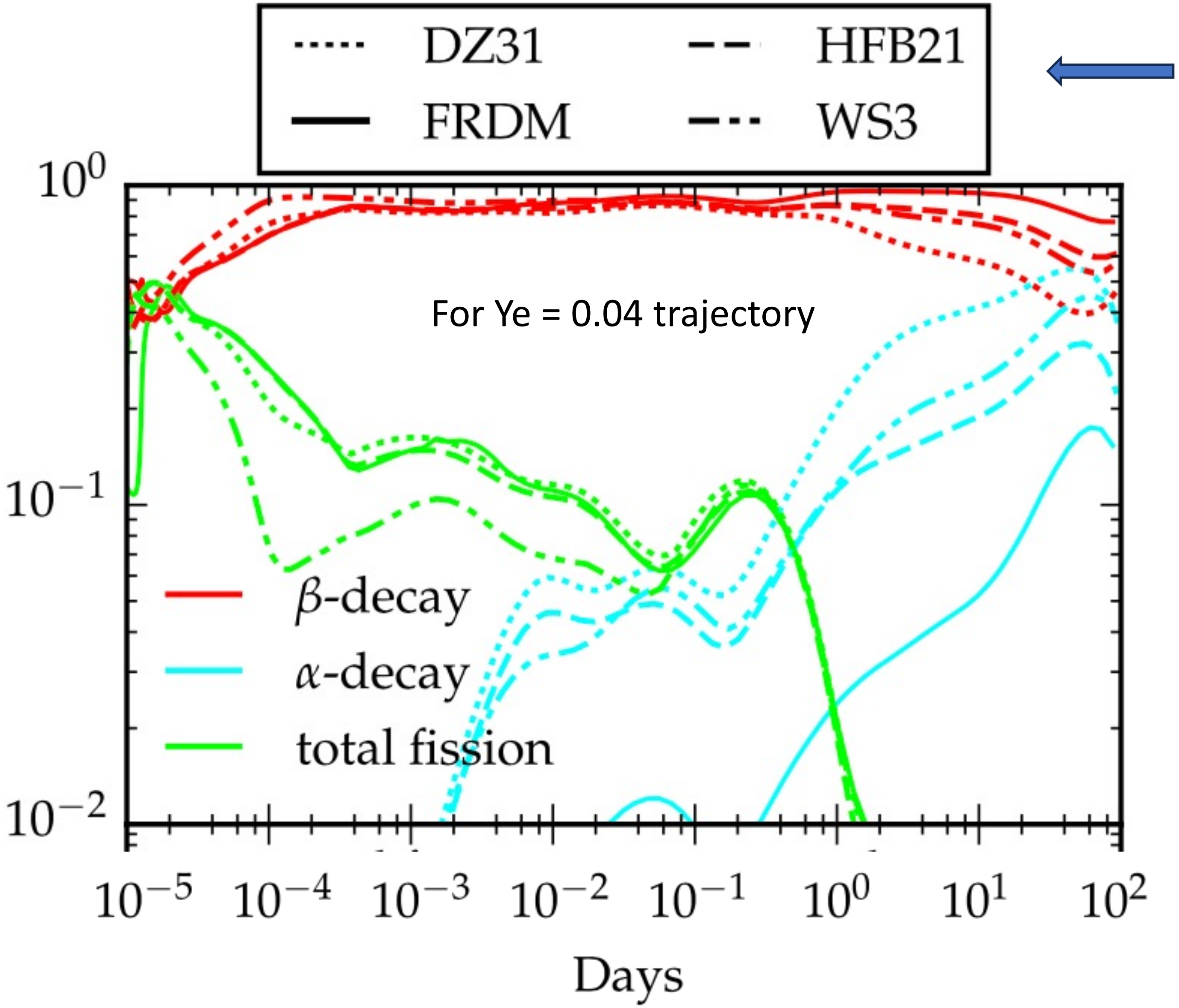
Canonical picture, radioactive piles:

$dn/dt \sim t^{-1}$
$\langle e_{decay} \rangle \sim t^{-0.3}$ ⇒ $P(t) \sim t^{-1.3}$

Reasonably matched for Y_e <~ 0.25 compositions.

Higher Y_e : dominance of individual isotopes → diverse time functions

R-PROCESS RADIOACTIVE DECAY CHANNELS



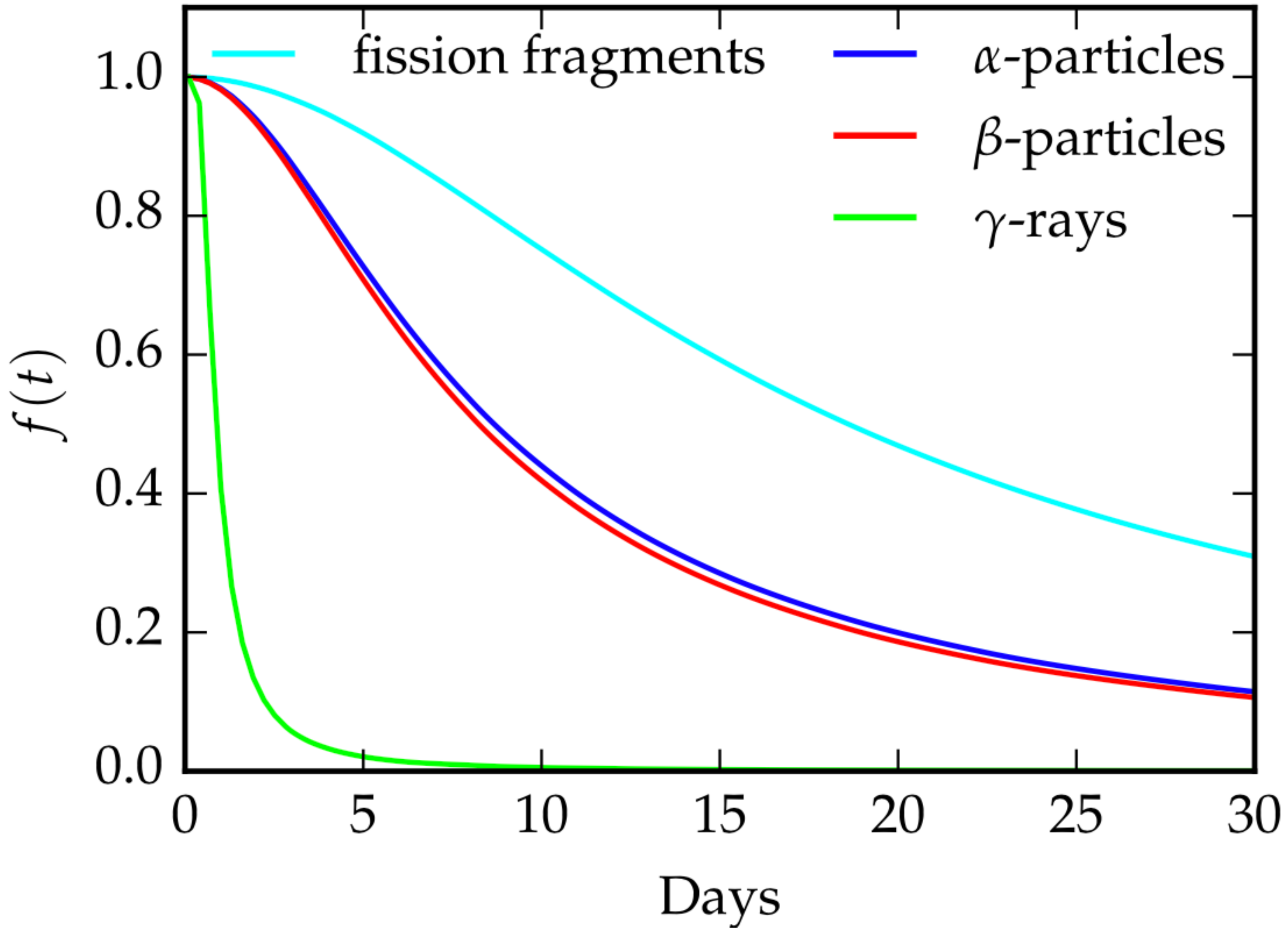
Different nuclear mass models

Beta decay (→ β particles and γ rays) dominant, followed by α decay.

α decay may be relevant for >~ 10d

Barnes+2016

THERMALIZATION



Degradation of decay particles gets slow and spread over long time → "**thermalization efficiency**" < 1, declines with time

α's trap better than β's
→ become increasingly important

Barnes+2016

LTE vs NLTE

LTE

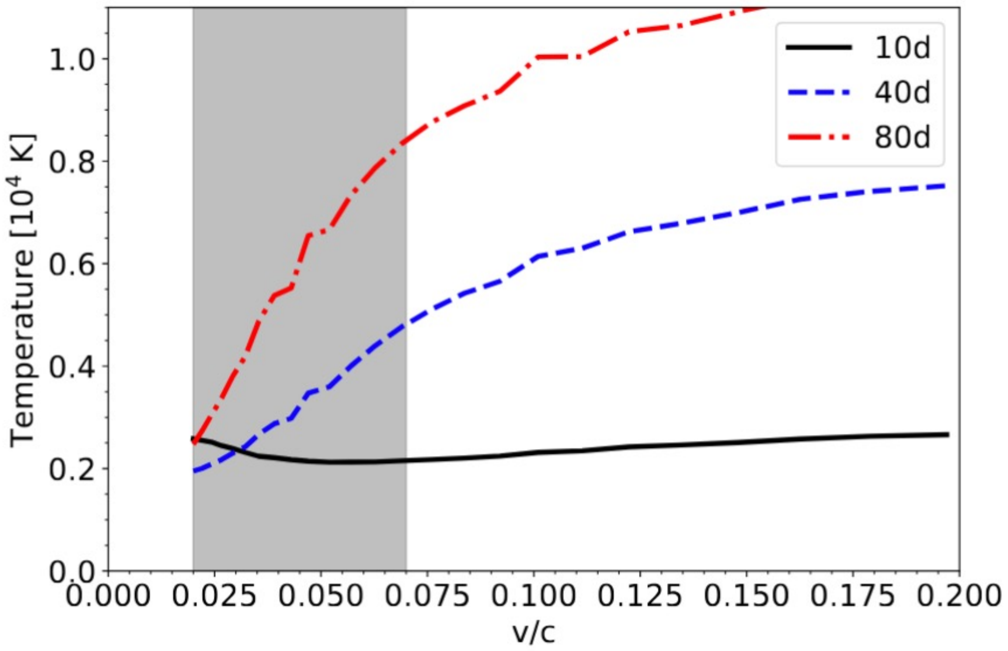
- Sufficient to know total deposition, so need radioactive decays + thermalization description.

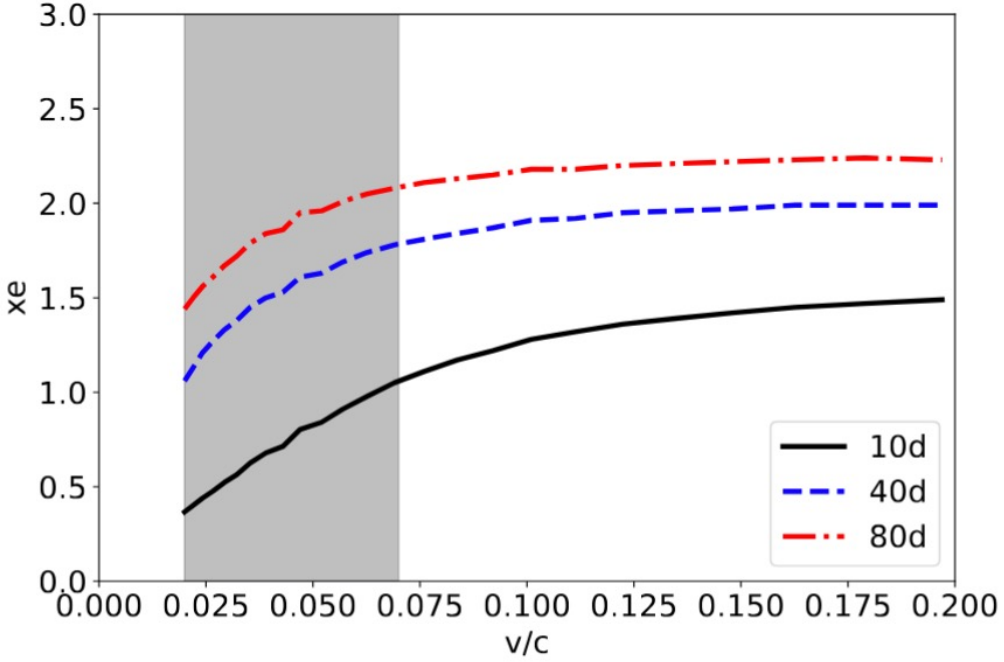
NLTE

- Need to solve for energy cascade and compute division into heating, ionization, excitation.

Our group papers (Pognan,AJ+2022a,b, 2023, AJ+2026), use

- Wanajo decay tables +
- Analytic expressions for thermalization +
- Solve cascade (Spencer-Fano equation).





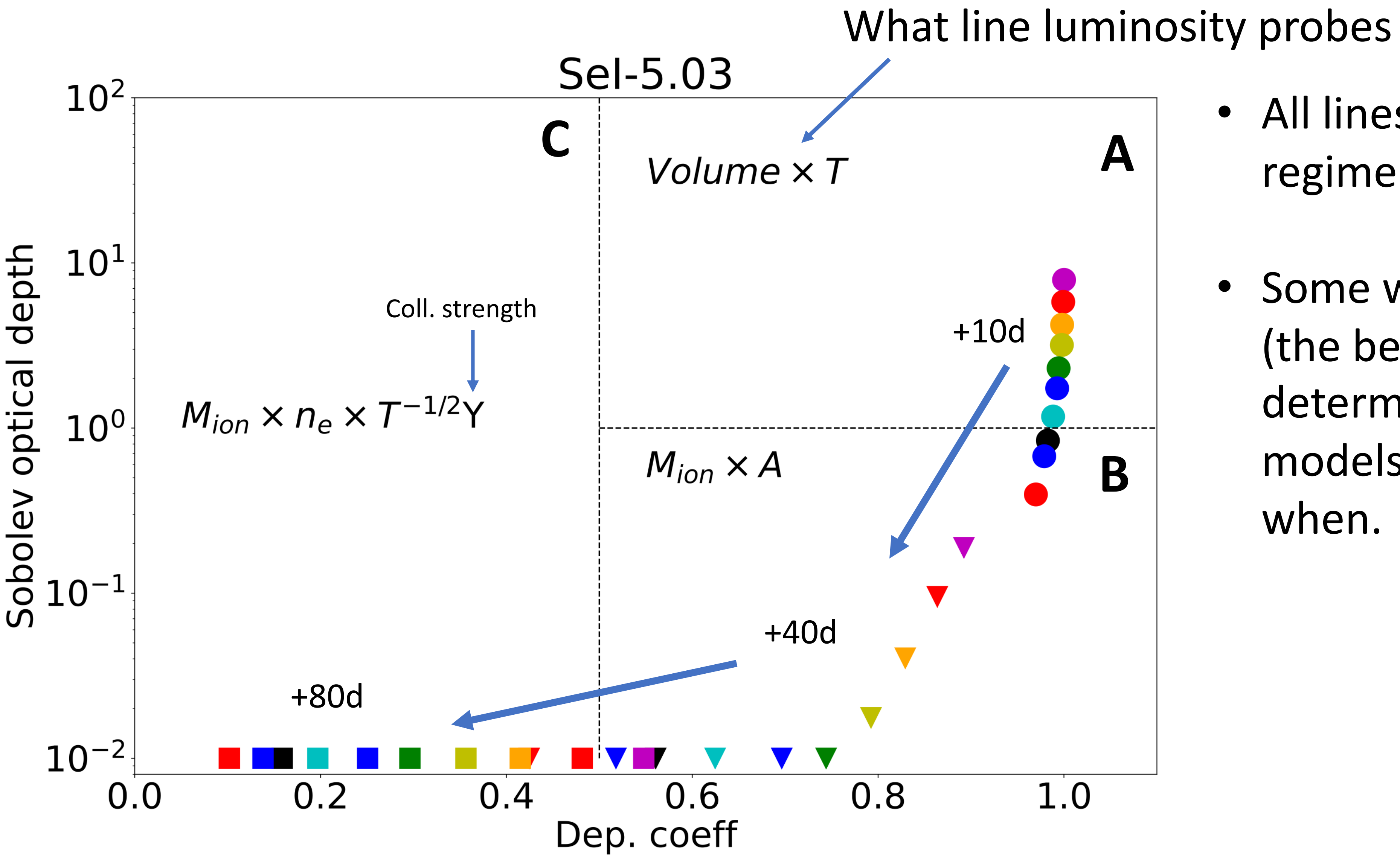
COMPUTE PHYSICAL CONDITIONS IN NLTE

Impact on opacities: Pognan, AJ+2020b

Spectra: Pognan,AJ+2022a,2023,2026, AJ+2026

Impact of improved atomic data: Banerjee, AJ+2025

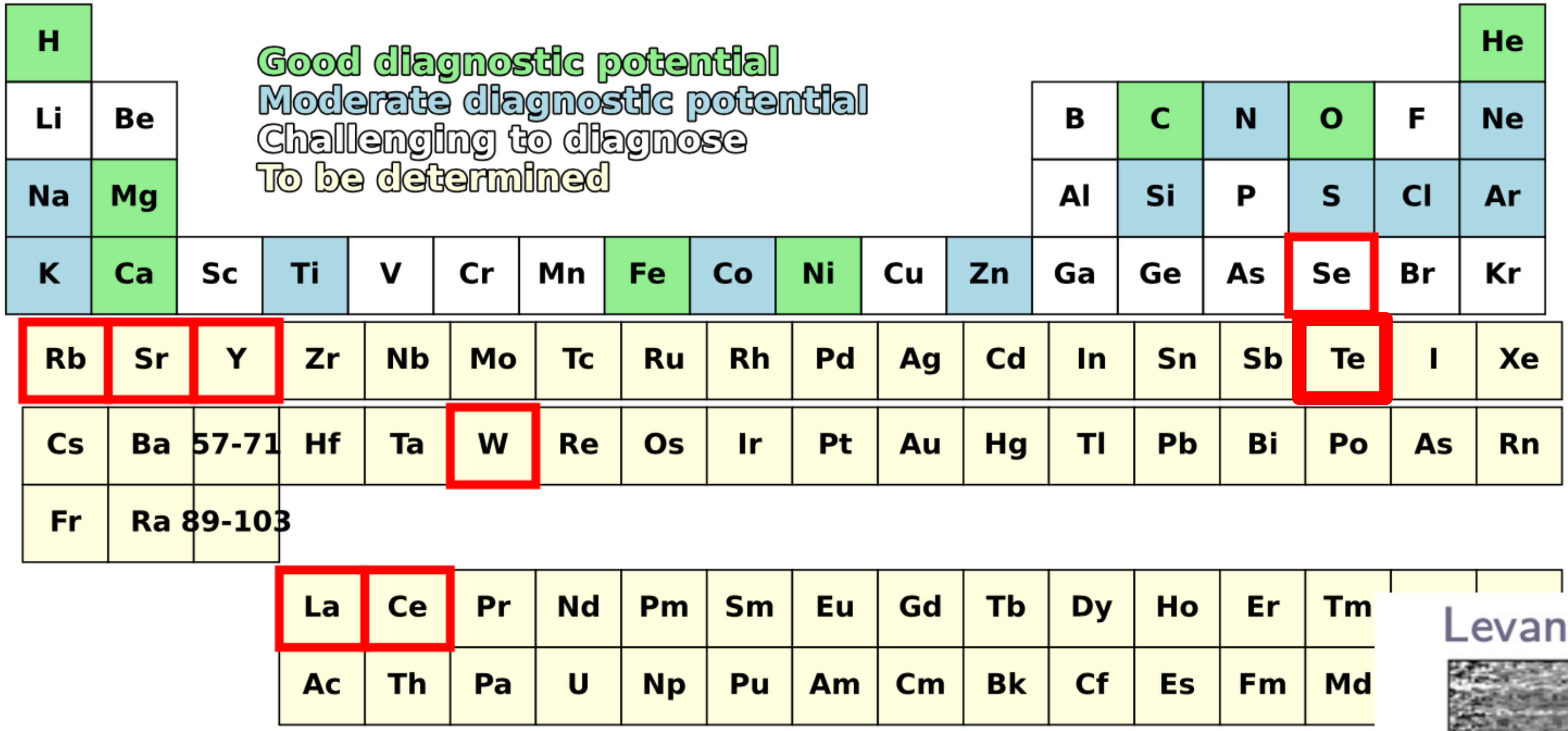
IR EMISSION LINE DOMAINS



- All lines will move from regime **A** to **C** over time.
- Some will pass through **B** (the best regime to determine ionic mass) : models guide which and when.

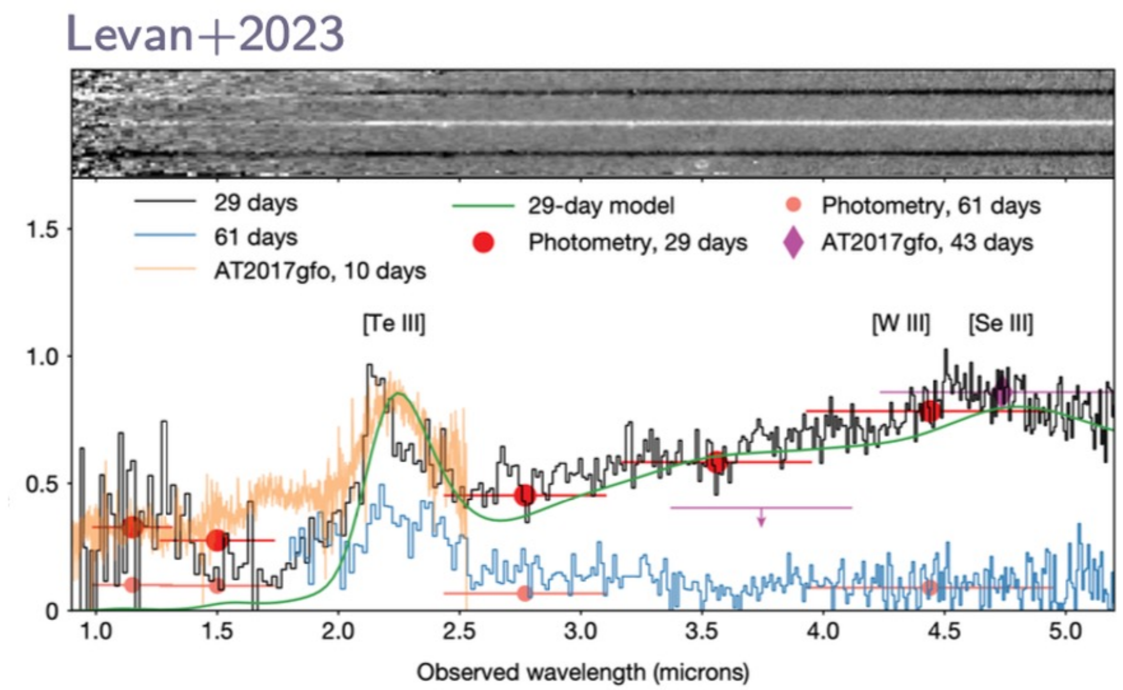
AJ+2026

KILONOVA NUCLEOSYNTHESIS



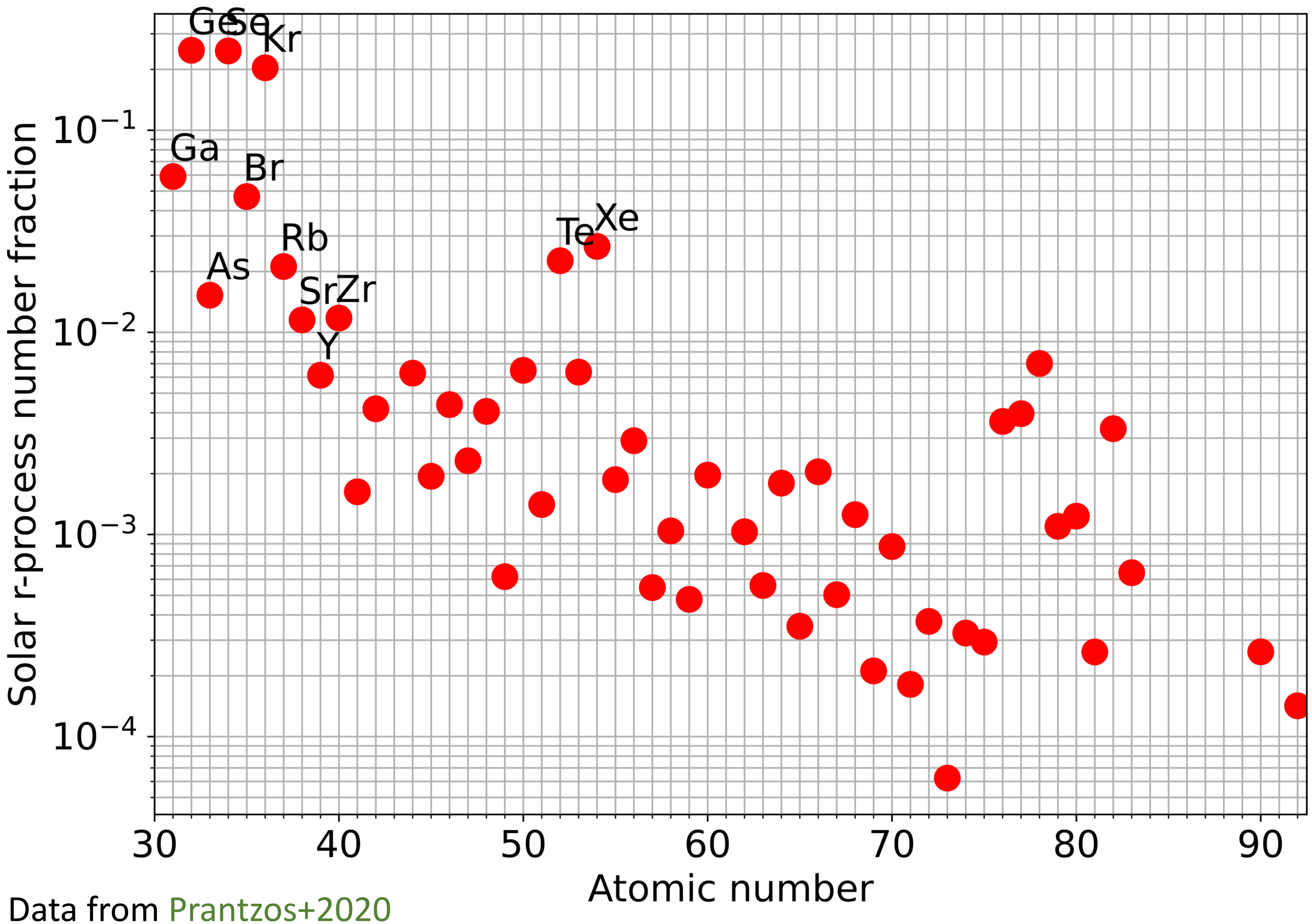
= Possible detection in AT2017gfo

Watson+2019, Sneppen+2023, Gillanders+2024, Vieira+2023, Hotokezaka+2024
Pognan,AJ+ 2023, AJ+2026



Cool continuum in AT2017gfo may be indication of dust formation

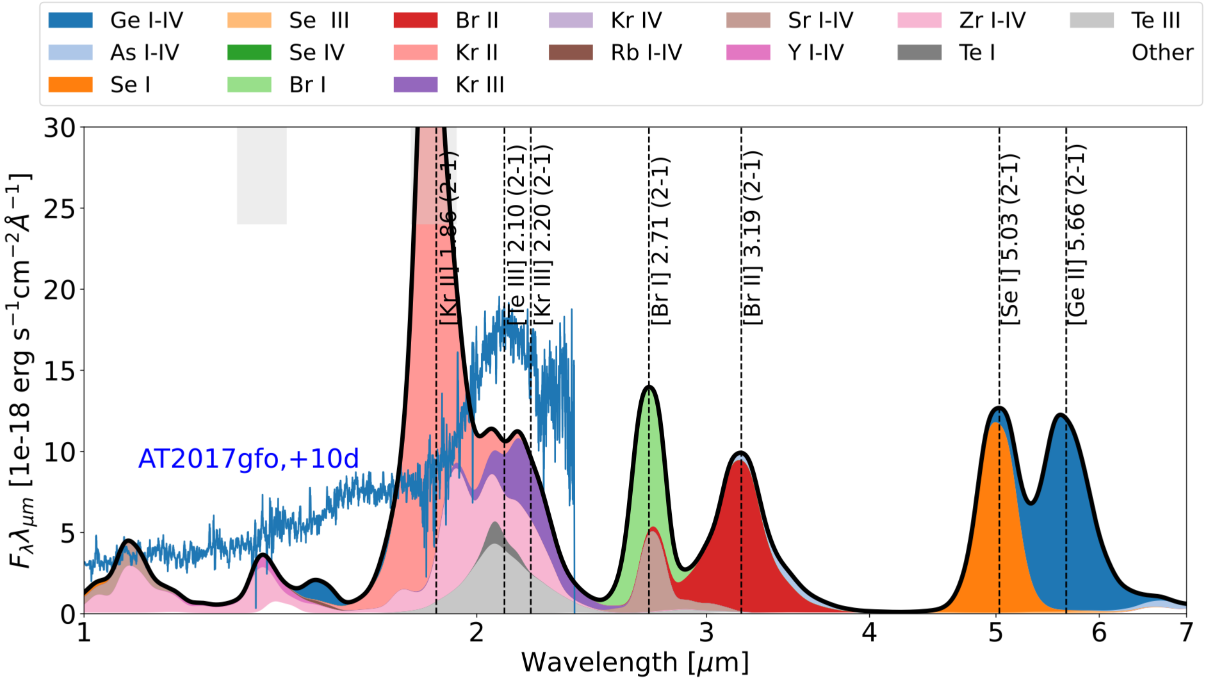
THE SOLAR R-PROCESS ABUNDANCES: 80% IN Z < 40



Data from Prantzos+2020

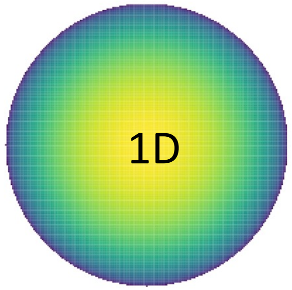
- *Do NSM make all the r-p elements?*
- In nebular phase **<u>emission prop. to abundance</u>** → 1st peak elements are good targets.
- Focus atomic data and modelling efforts on these (**rec. rates**: Banerjee,AJ+2025), **collision strengths**: AJ+2026)

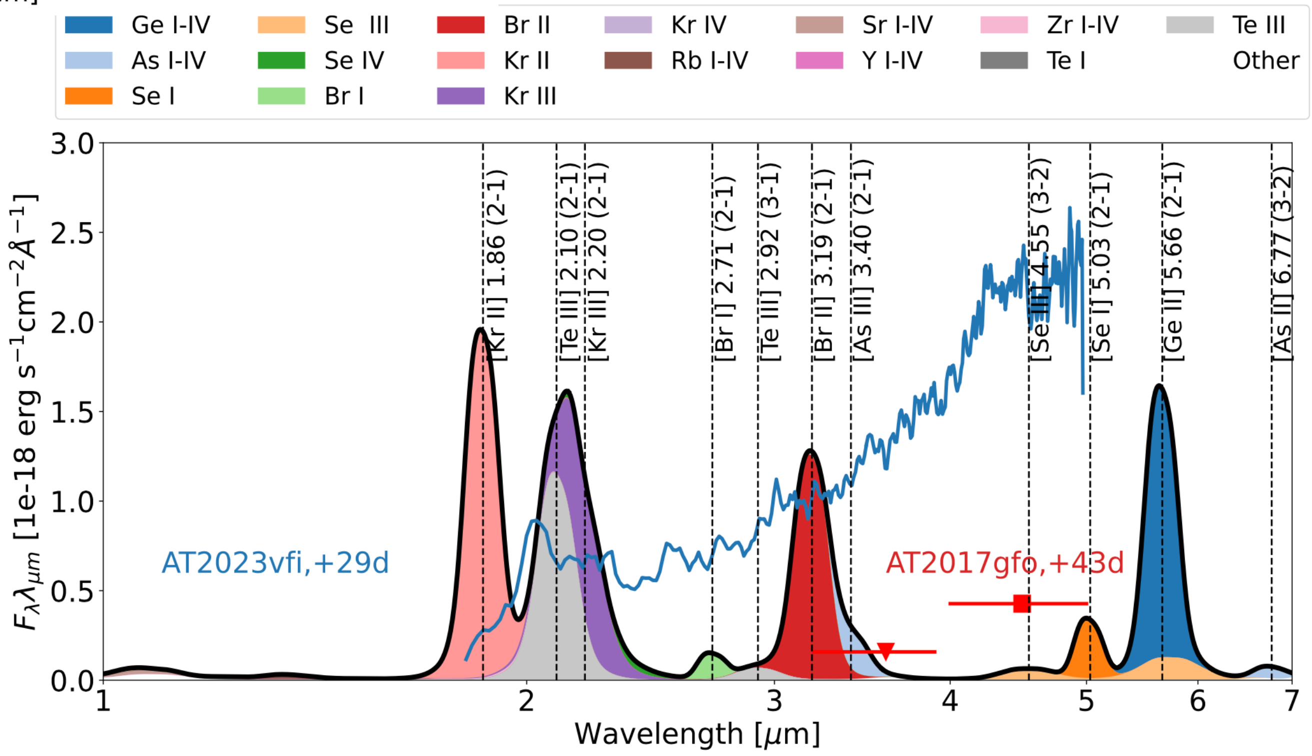
1st PEAK CONSTRAINTS AJ+2026



Indication KNe make subsolar 1st/2nd peak : **missing Kr and BrI lines in observations**

Model:





$M_{ejecta} = 0.05\ M_\odot$

$\rho(v) \propto v^{-3}$

Z=30-40, 52, 54

solar composition

KEY TAKEAWAYS

- Supernovae and kilonovae reveal synthesis of **^{56}Ni**, **^{57}Ni**, **^{44}Ti** directly by decay lines and indirectly by light curves/spectra; probe explosion morphology. Current (Garching) explosion models; some quite good agreement, others insufficient asymmetries for explosive yields when compared to SN 1987A and Cas A.

- Optical spectra give important independent probe of **^{58}Ni/^{56}Ni** production and **^{44}Ti positron trapping**.

- Kilonovae probe r-process radioactivity, high-Y_e events could probe individual isotopes.

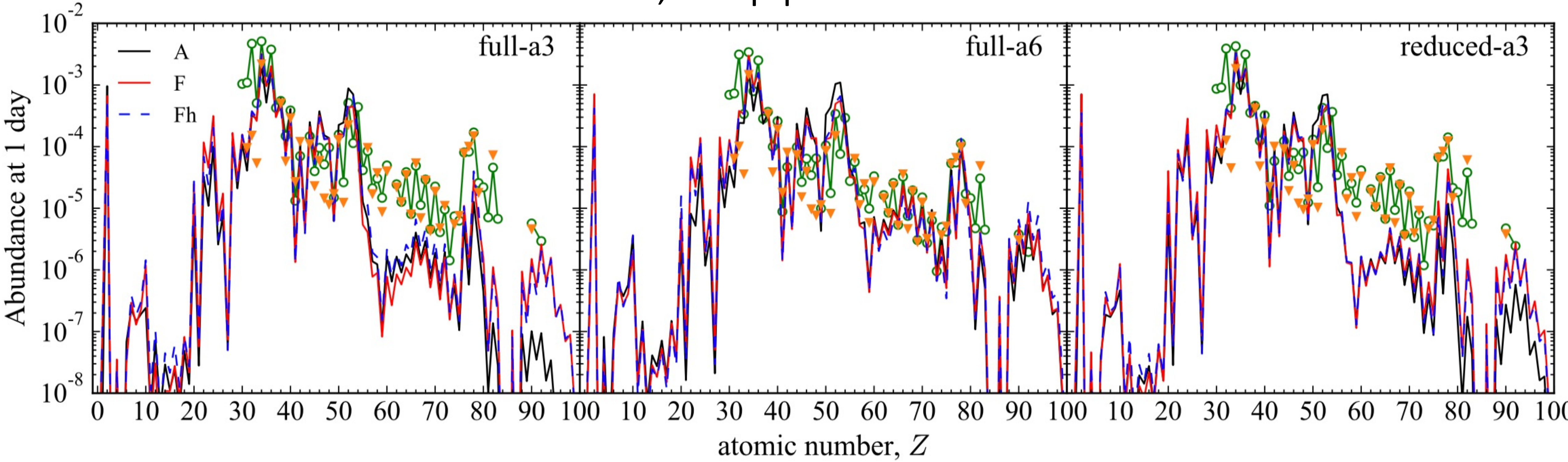
- New NLTE kilonova models show **diagnostic potential of NIR/MIR lines at late times**.
  - Should be able to derive abundances or strong constrains on Ge, Se, Br, Kr.
  - AT2017gfo and AT2023vfi data indicate **significantly subsolar 1st peak production** : an important piece of puzzle for understanding the origin of 1st peak r-process elements.

Thank you for listening!

RESERVES

INTERPRETATION

Fernandez+2024, full rp-pattern in a KN from Z = 33



- Also SNe can make the solar pattern up to Z ~ 38 (e.g. Sukhbold+2016, Wanajo+2018).

- Hints from low-metallicity stars : a transition somewhere between Z=32 and Z=38 for main source (Cowan 2005, Roederer+2012,2022).

^{44}Ti measurements

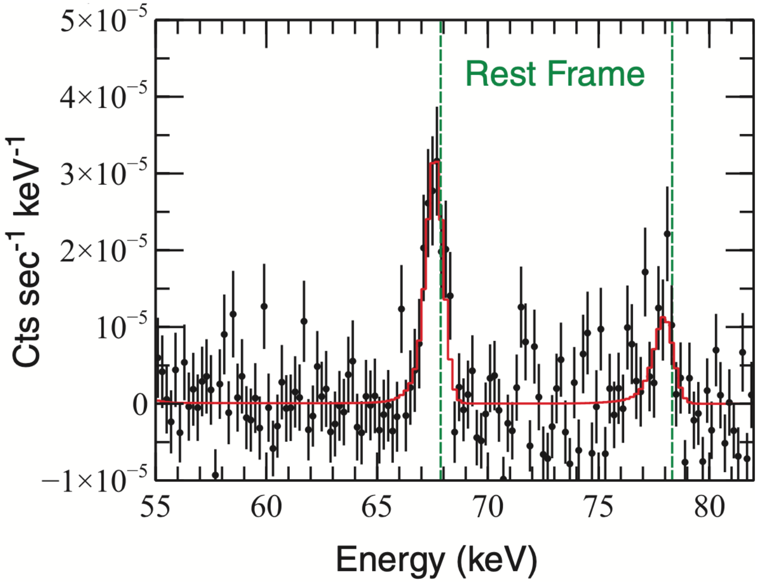
68,78, and 1157 keV decay lines detected in two (core-collapse) supernovae:

SN 1987A

$$1.5^{+0.3}_{-0.3} \times 10^{-4} M_\odot$$

Boggs+2015, Science

See also Giuffrida+2025

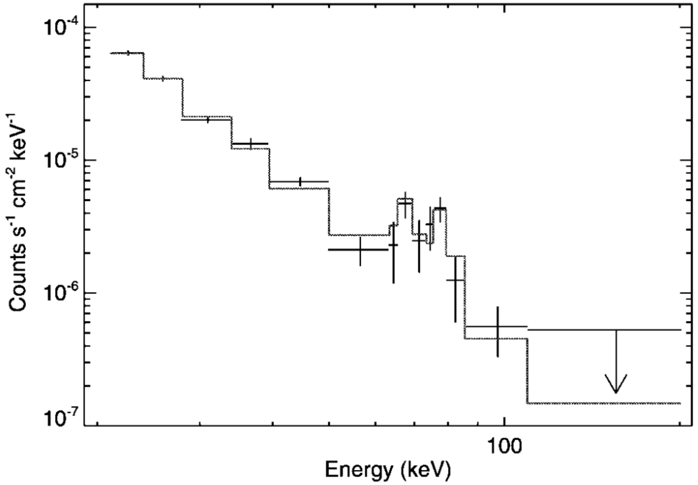


Cas A

$$1.6^{+0.6}_{-0.3} \times 10^{-4} M_\odot$$

Renaud 2006

See also Siegert+2015, Weinberger+2024,

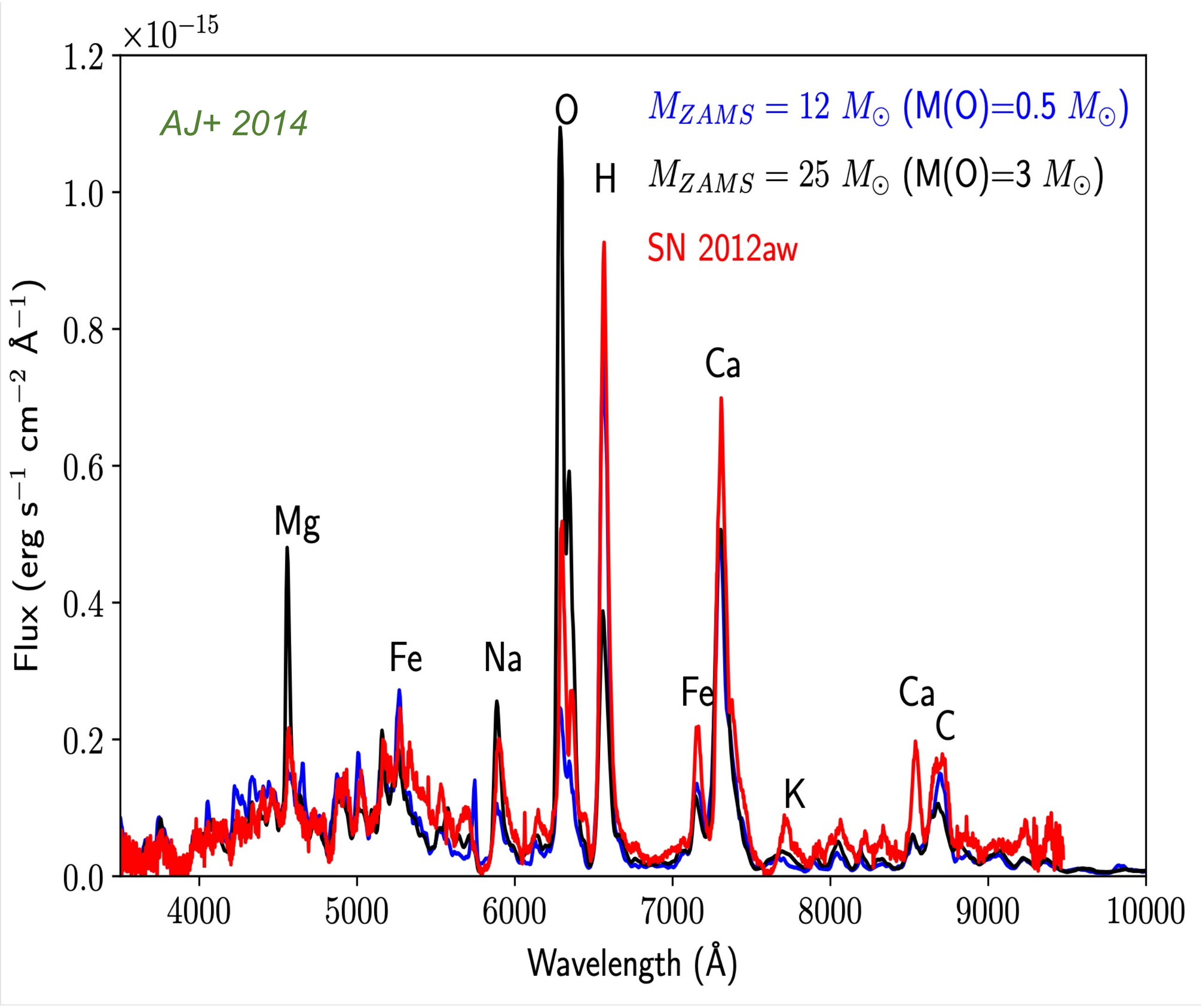


Gives **(^{44}Ca/^{56}Fe) ratios** of ~ 1.5E-4 / 0.07 = 0.002 **= 1.5 * solar**

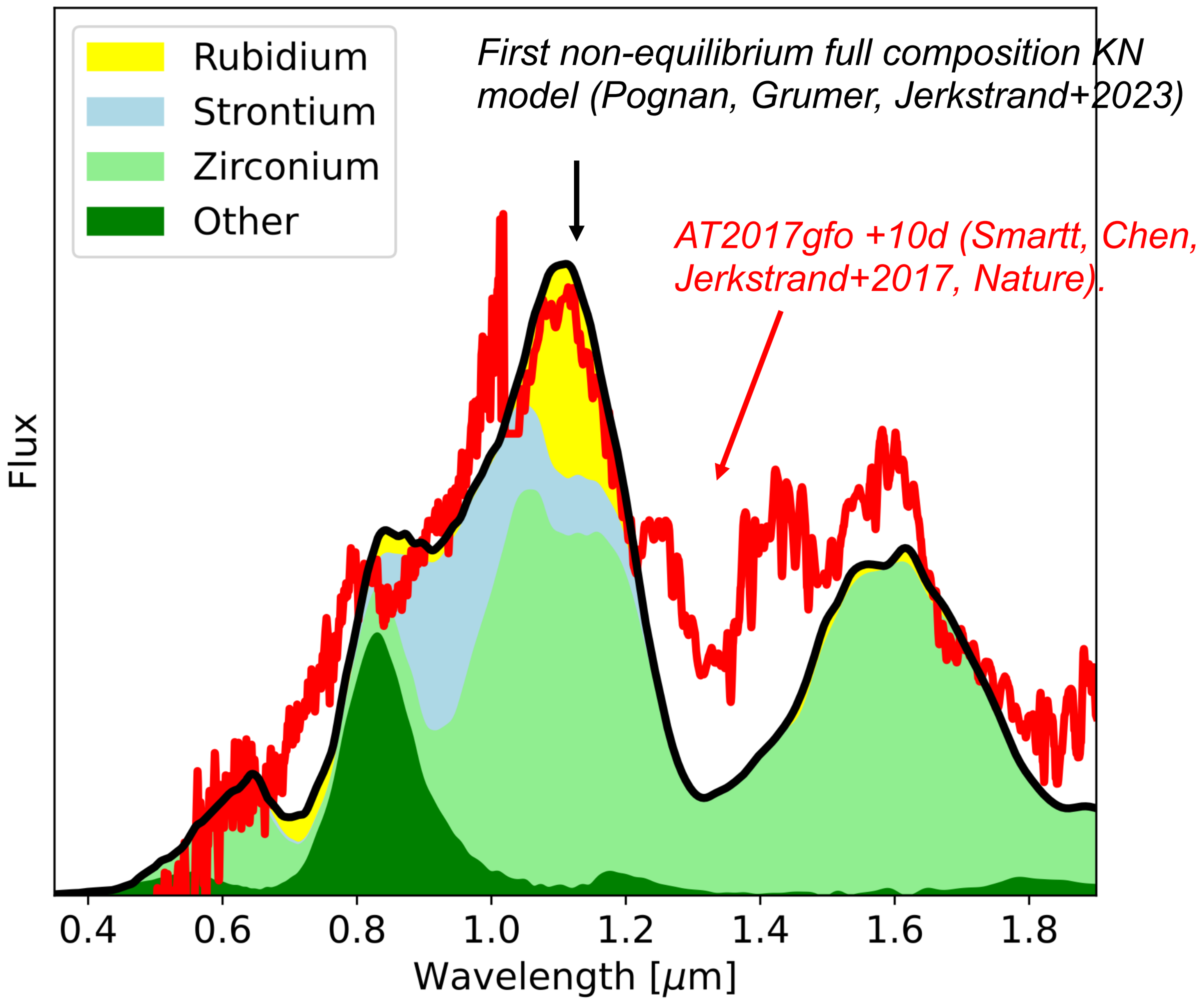
What is means: See Wongwathanarat+2017, Sieverding+2023, Wang & Burrows 2024, Boccioli+2026

SUMO MODEL EXAMPLES

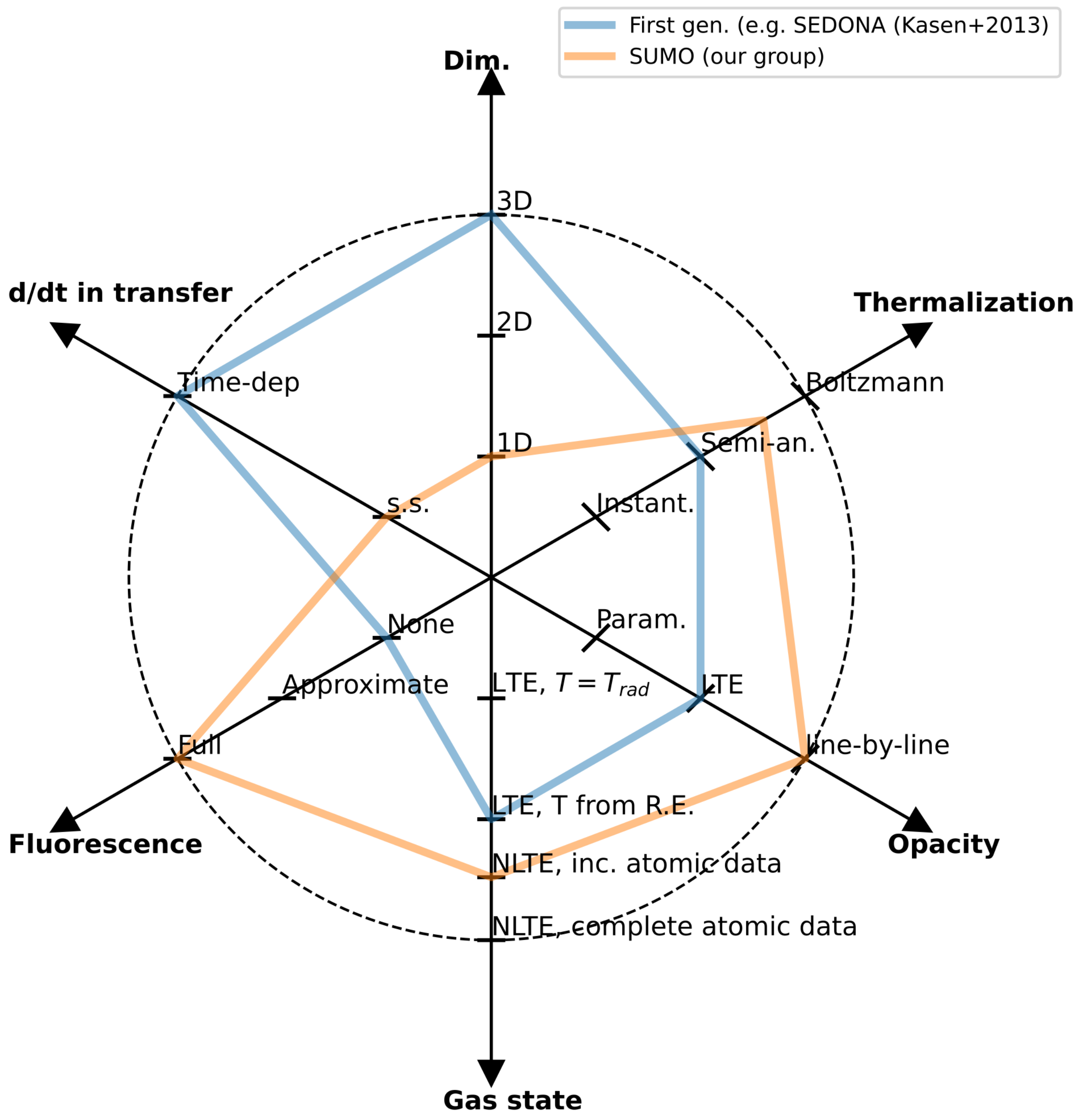
Supernova case



Kilonova case



TRANSIENT SPECTRAL MODELLING



- No code does "all" → match code physics to desired thing to predict, to what accuracy.

- In our group we operate the NLTE codes **SUMO** (1D) and **EXTRASS** (3D)
  AJ+2011,2012,2015,2020
  Liljegren, AJ+ 2020, 2022
  Pognan, AJ+ 2023
  Van Baal & AJ 2026