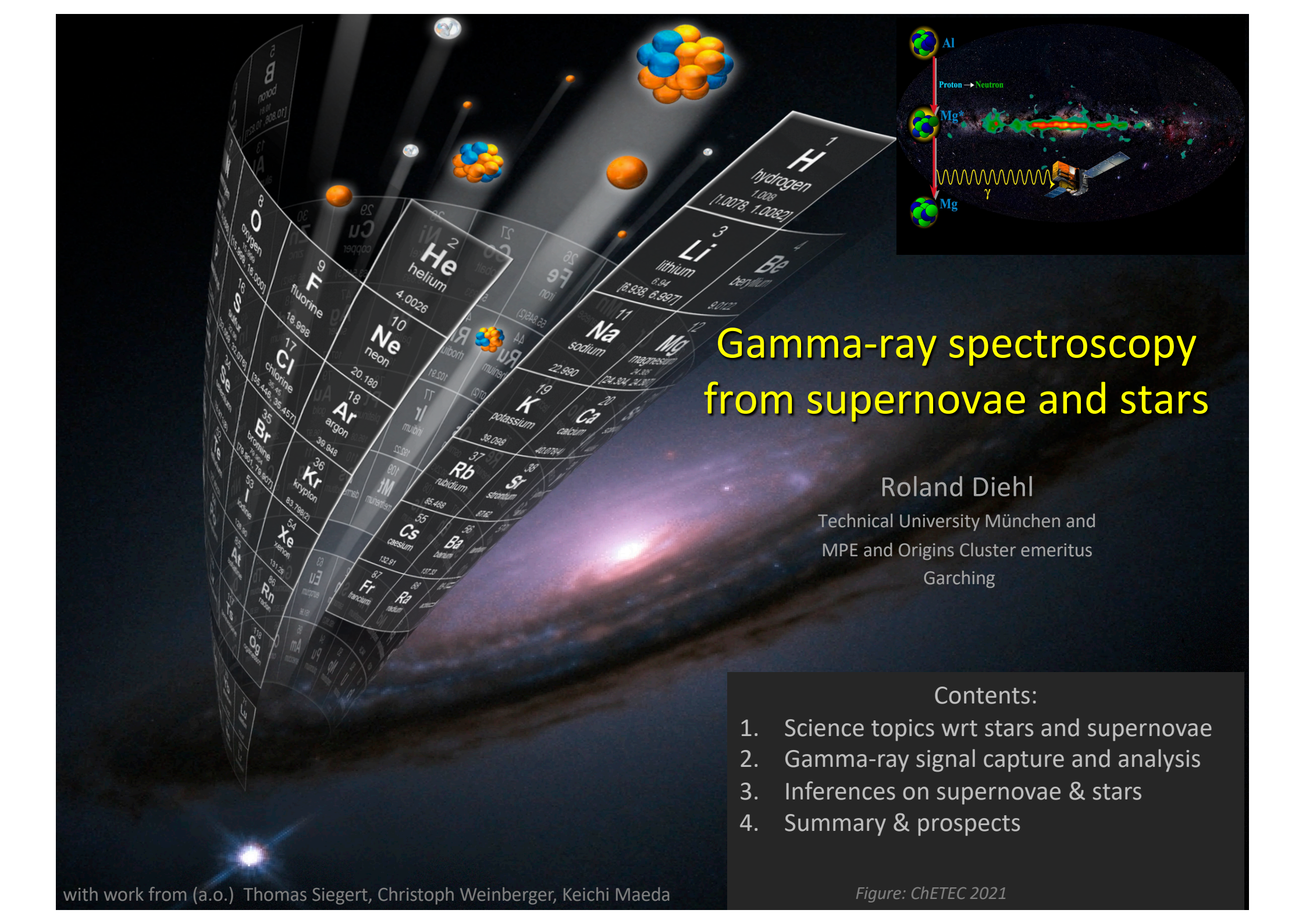




Gamma-ray spectroscopy from supernovae and stars

Roland Diehl

Technical University München and
MPE and Origins Cluster emeritus
Garching

Contents:

1. Science topics wrt stars and supernovae
2. Gamma-ray signal capture and analysis
3. Inferences on supernovae & stars
4. Summary & prospects

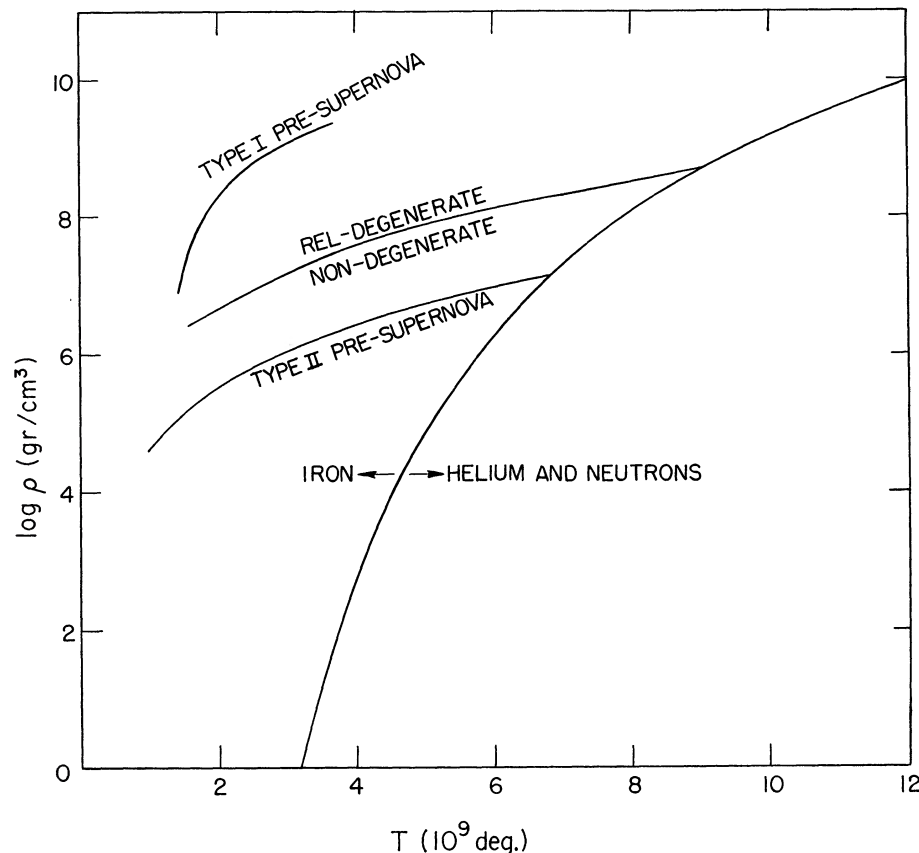
What is a Supernova?

★ *Nuclear-physics aspect:* Rapid release of nuclear binding energy

- Making the tightest-bound nuclei: ^{56}Fe : 8.8 MeV/nuc versus $(13\alpha+4n)$: 6.6 MeV/nuc
→ 2.2 MeV/nuc, $= 1 \cdot 10^{18}$ erg/g $> 10^{51}$ erg/ $M_{\odot}$
- H burning too slow; He, C, O, ... fuels are "explosive"

★ *Astrophysics aspect:* Explosions from stellar matter

- Implosion – explosion:
heat from collapse, $\text{Fe} \rightarrow \text{He}$ prevents thermal stabilization of star, explosive light nuclei → SNI
- Explosive light nuclei under degenerate conditions → SN I → C,O White Dwarf!



NUCLEOSYNTHESIS IN SUPERNOVAE

F. HOYLE

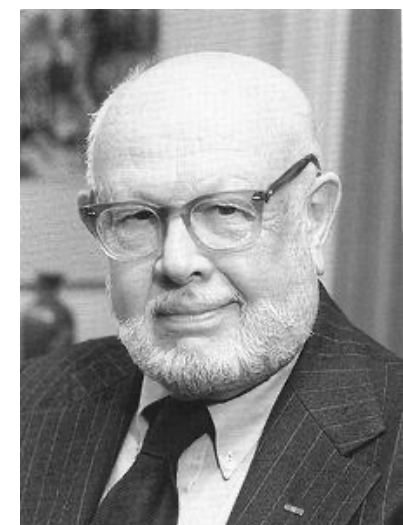
St. John's College, Cambridge, and California Institute of Technology

AND

WILLIAM A. FOWLER

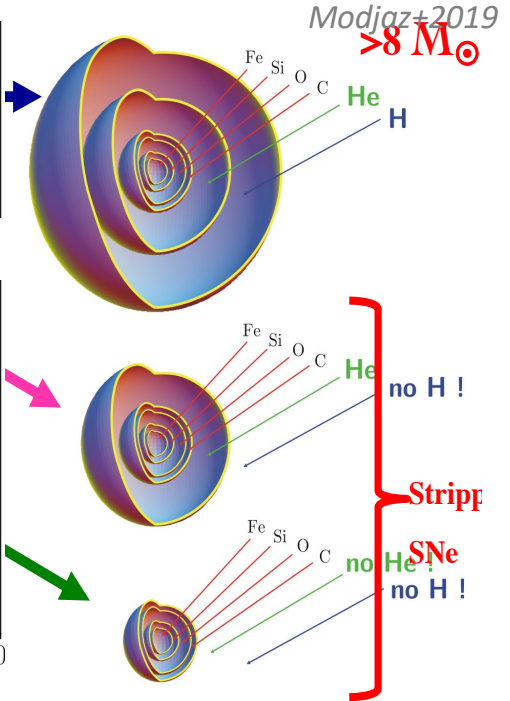
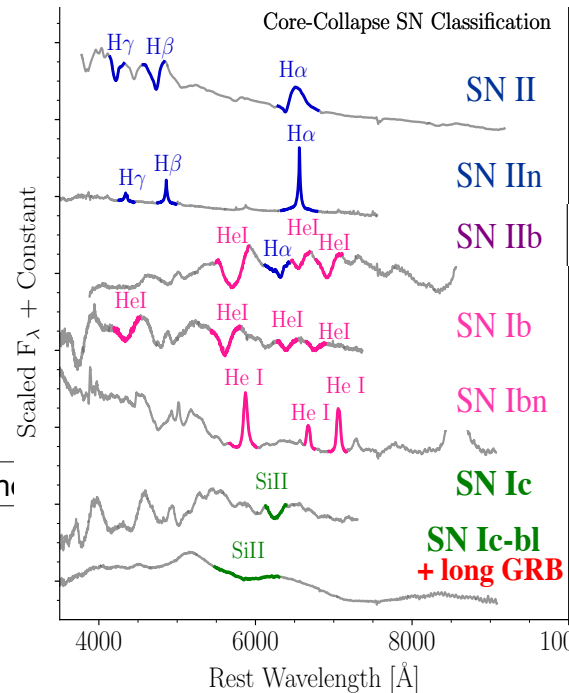
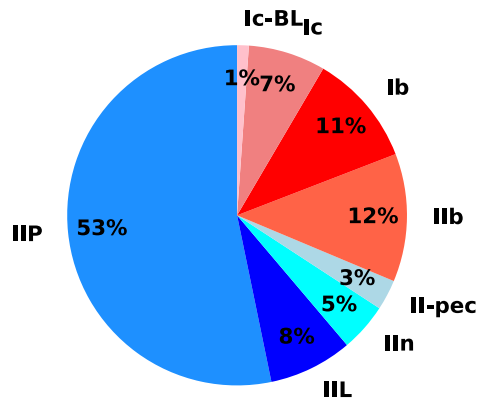
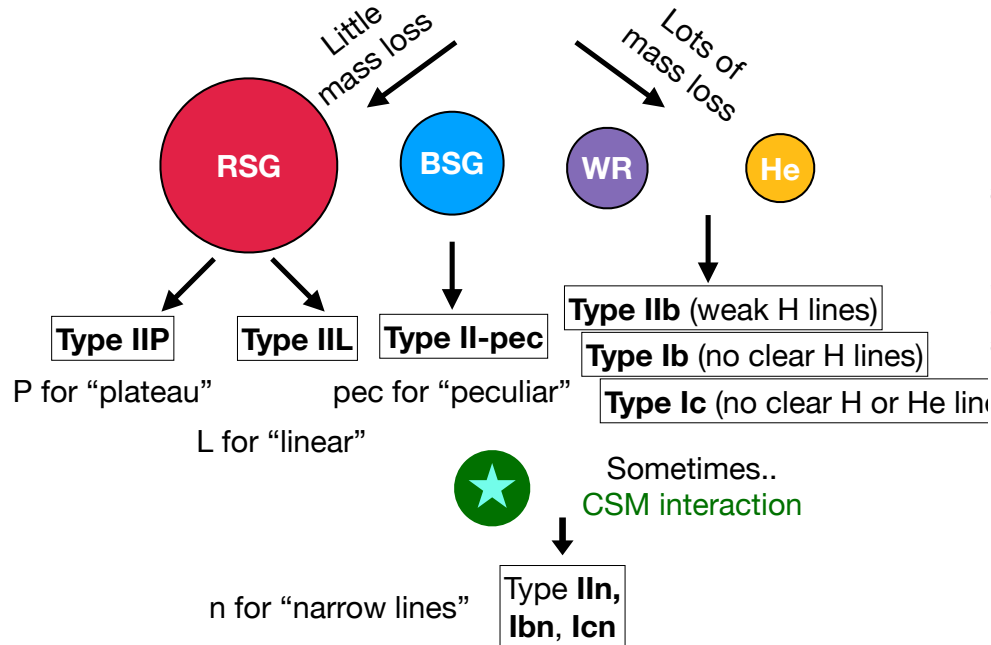
California Institute of Technology

Received May 21, 1960



ccSN progenitors, classifications, and frequencies

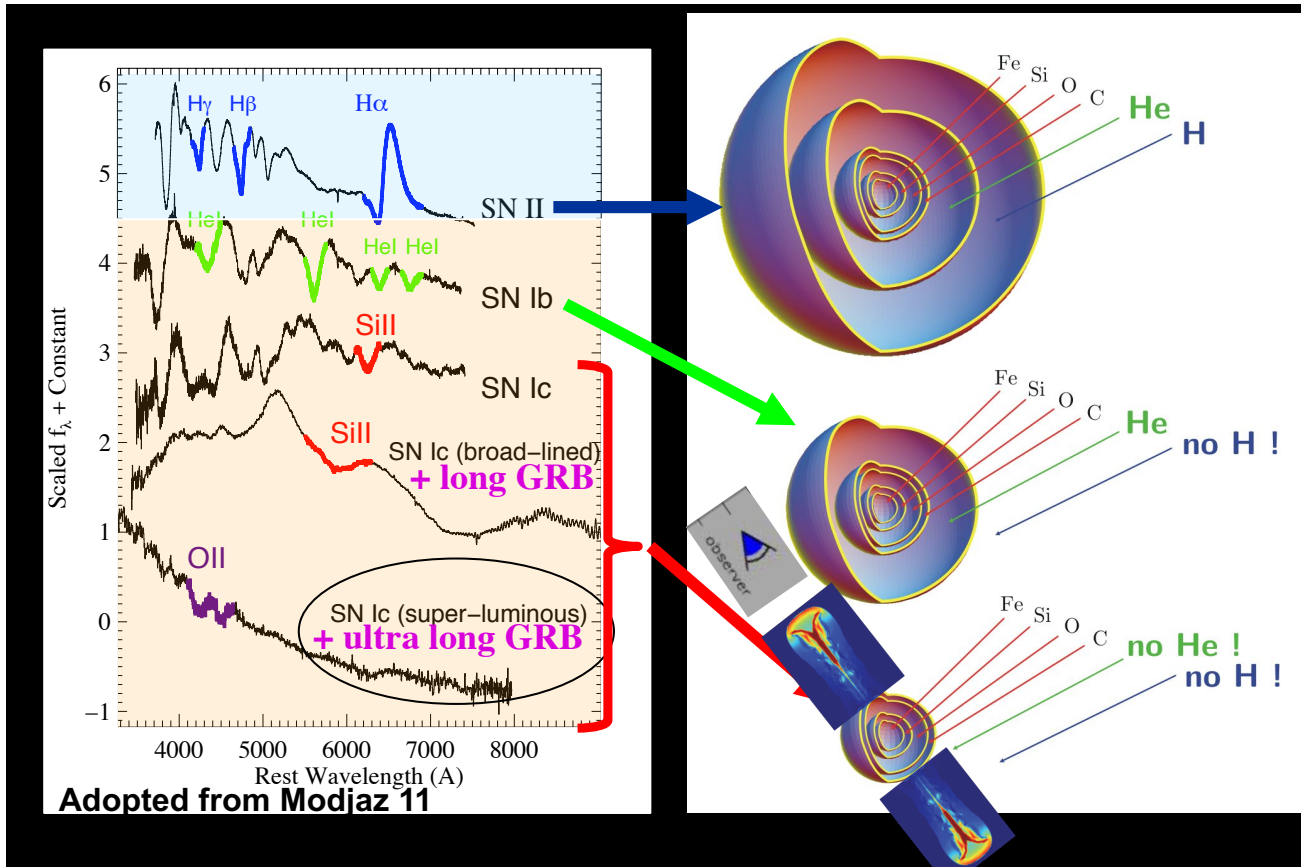
Jerkstrand+2025



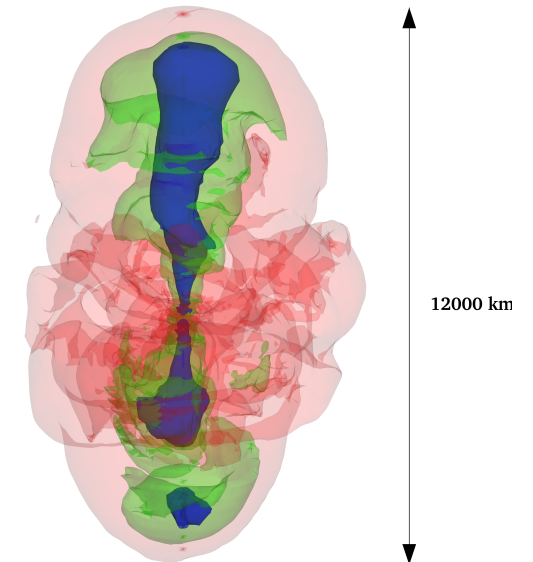
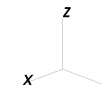
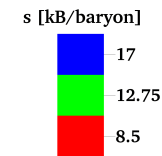
- surface composition $\leftrightarrow$ mass loss history
- light curve shape $\leftrightarrow$ envelope role
- narrow lines $\leftrightarrow$ CSM role

ccSNe and their (exotic) variants

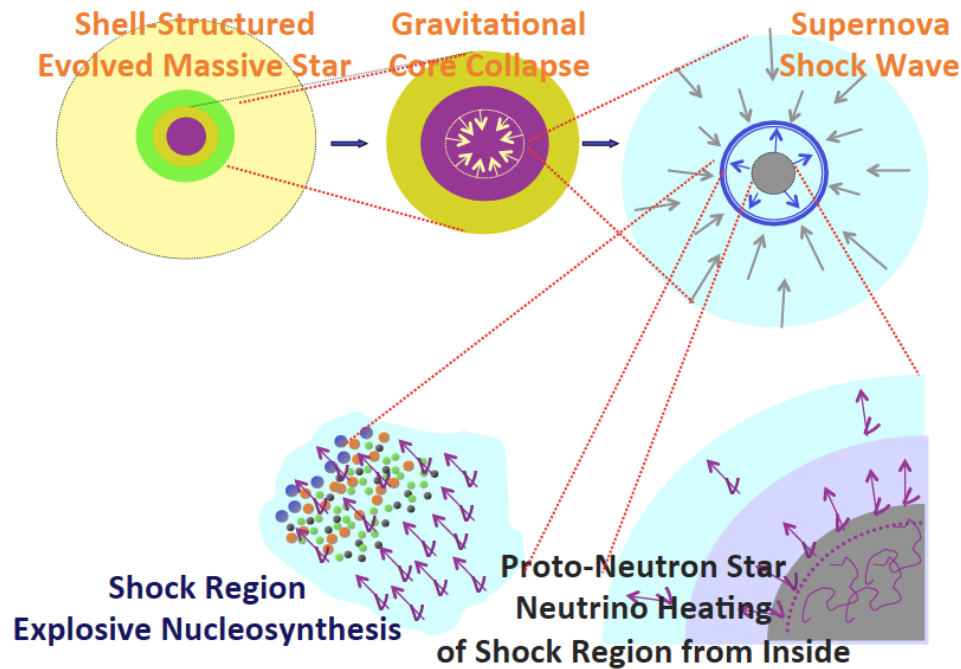
Modjaz+2019



Bugli+2021

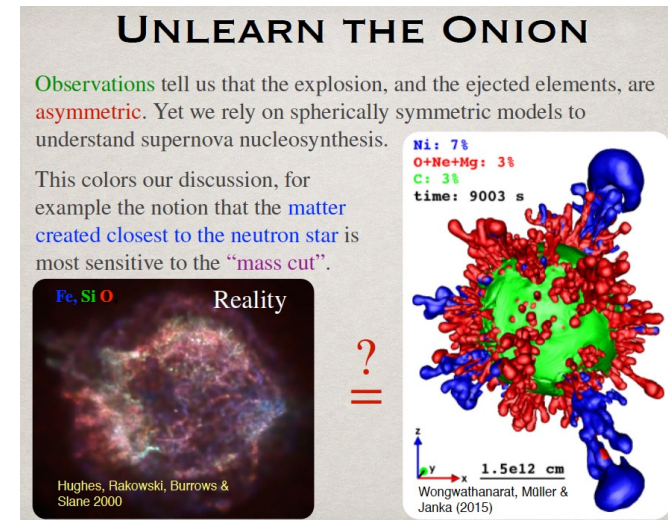


Complexities of Gravitational Collapse and SN

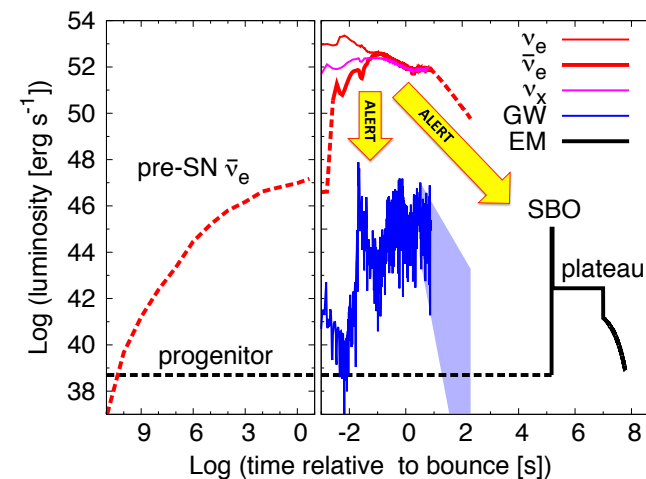


★ Basic processes are more complex than the 'standard model' says:

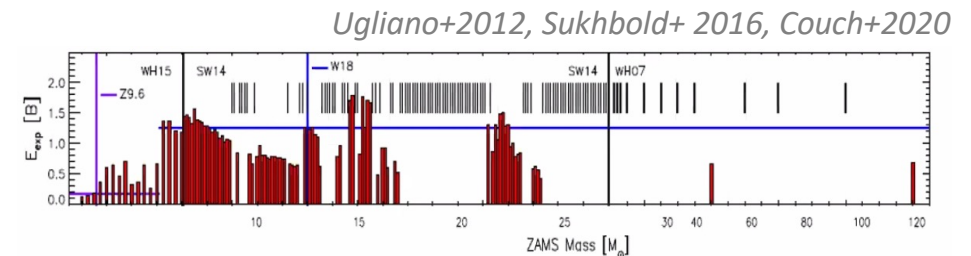
- ☞ pre-SN structure is complex → the trigger of collapse can be EC, fuel exhaust, e^+e^- creation
- ☞ collapse, ignition, and outflows all occur simultaneously
- ☞ collapse and accretion continue long after ignition of nuclear burning
- ☞ late accretion and fallback make explosion fail for more massive stars



Raph Hix 2016

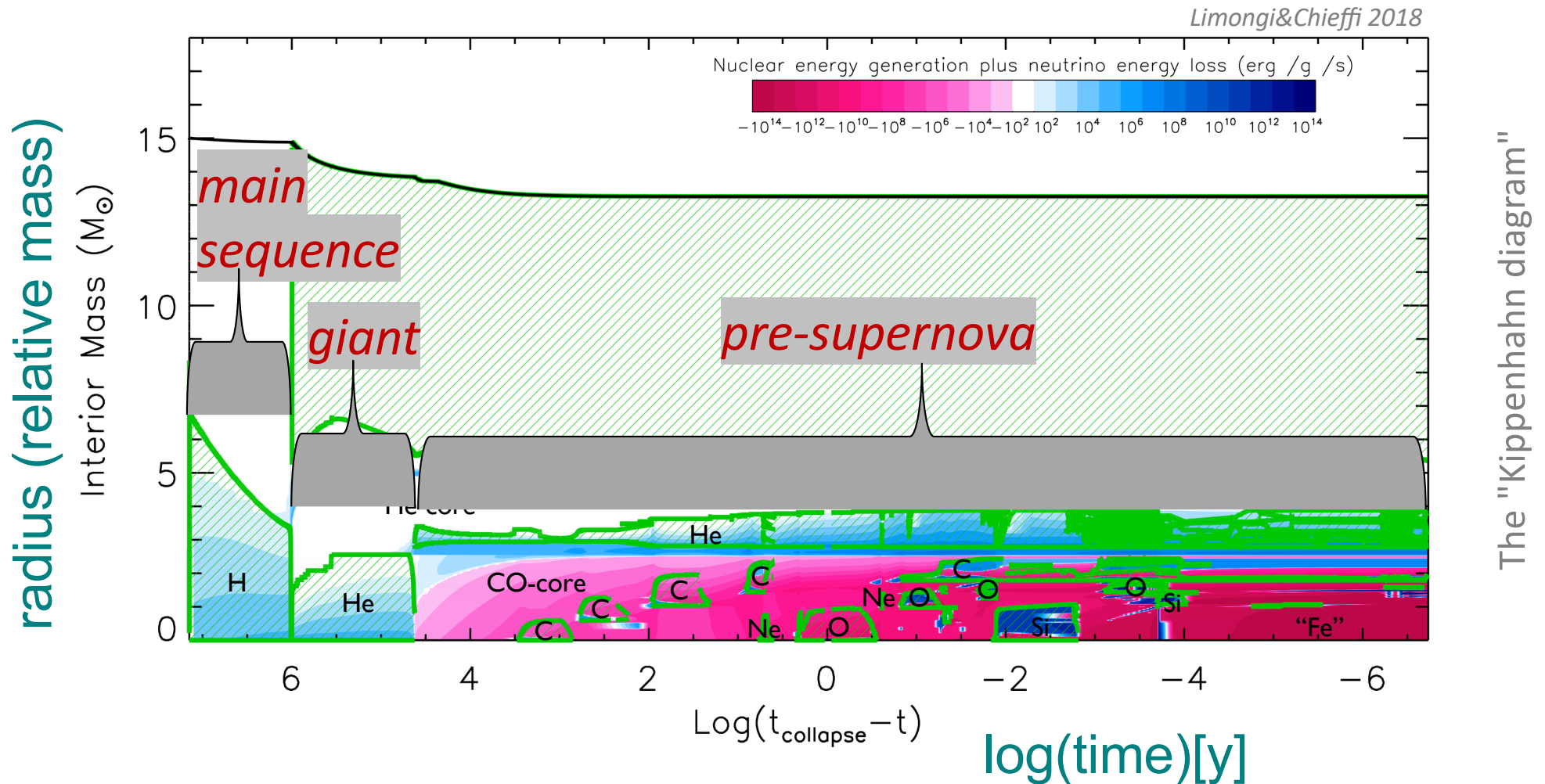


Kharoussi+ 2020



How stars evolve

- ★ Nuclear energy release in core and shell regions
- ★ Energy transport and constraints from gradients in gravity & composition

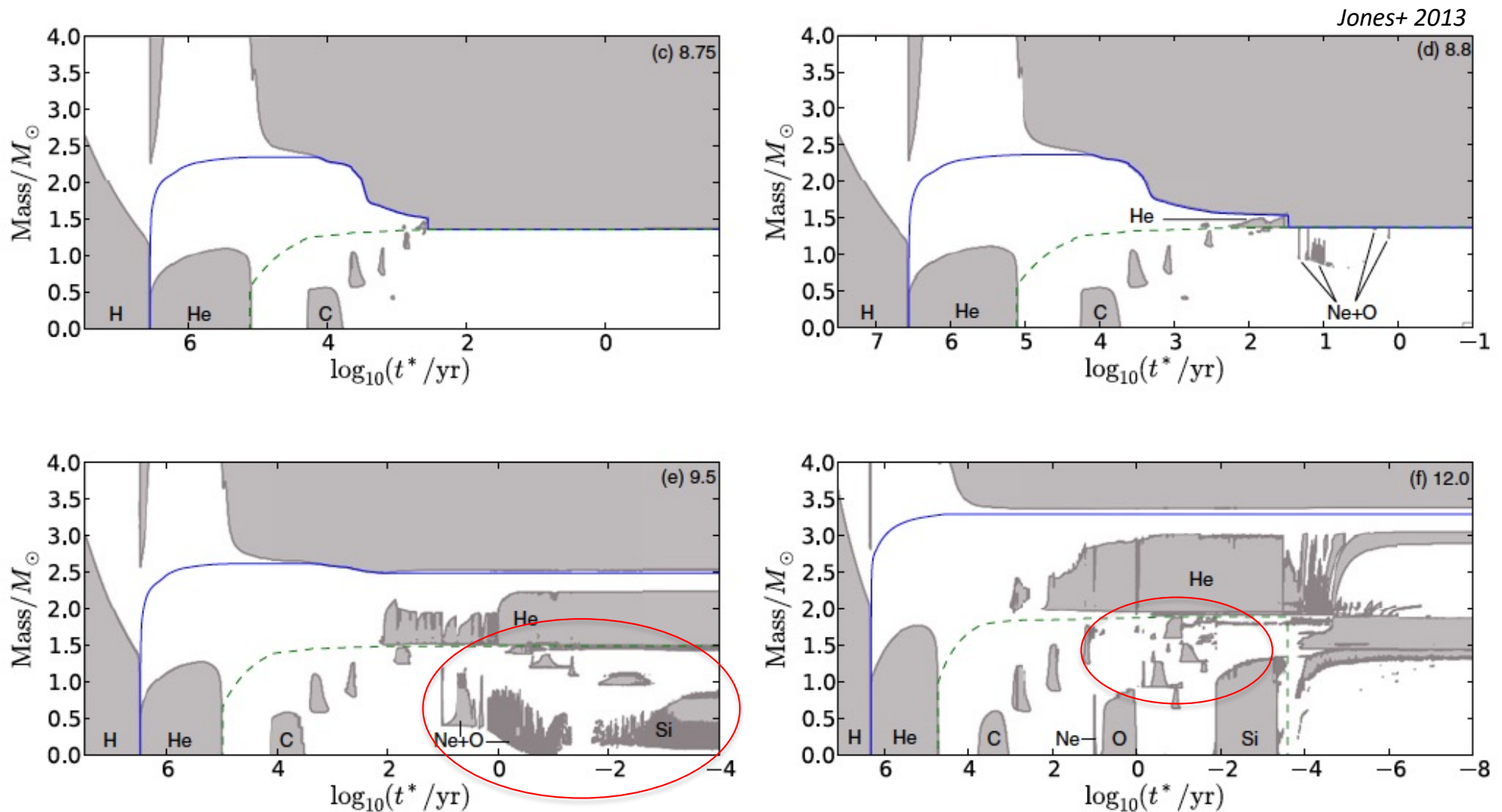


The Evolution of Massive Stars 7...15 M_☉

Limongi+2024



Late burning stages

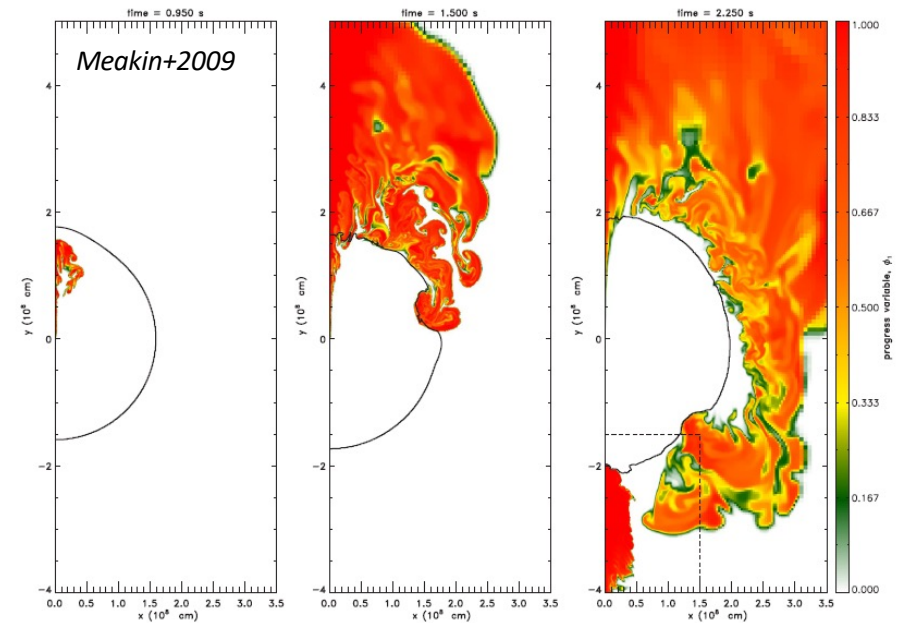
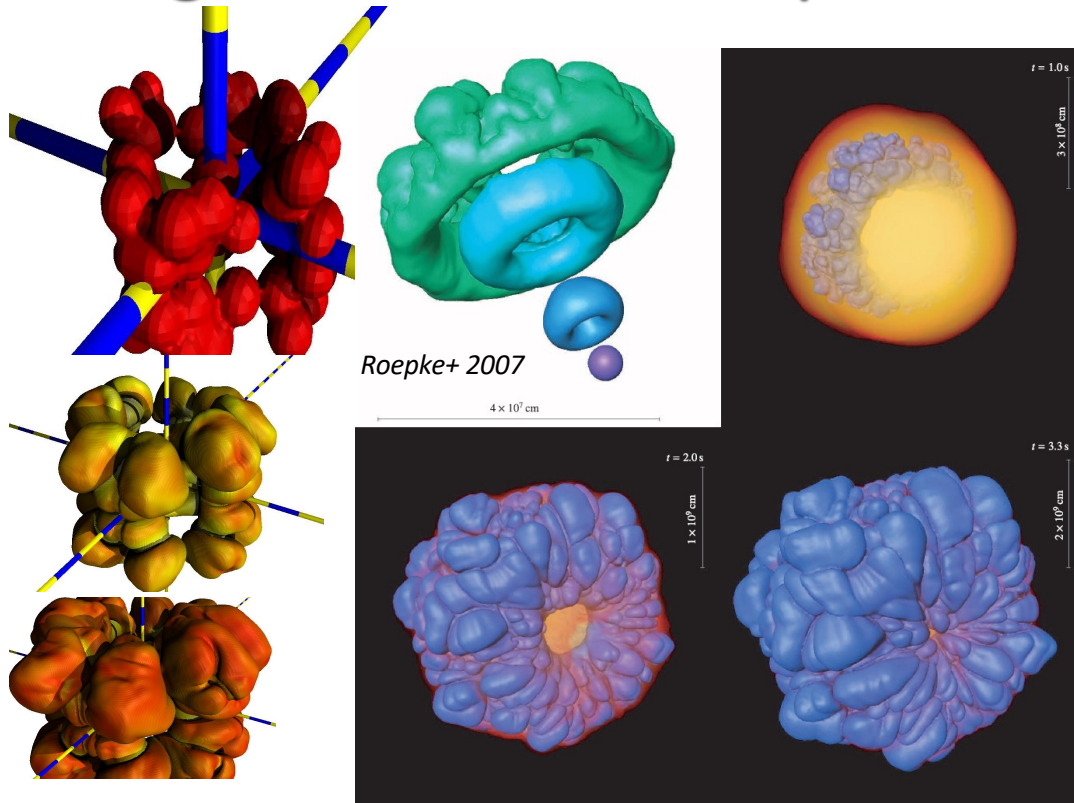


Shell burning stages are intermittent

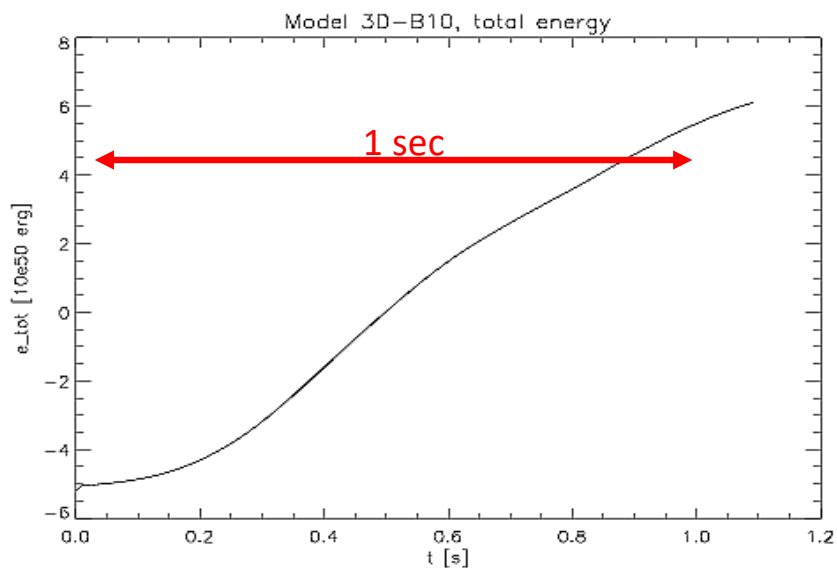
Shells may ignite off-core, merge, ... proceed inwards

→ pre-SN structure is ~uncertain!

degenerate-matter explosion dynamics could be a variety

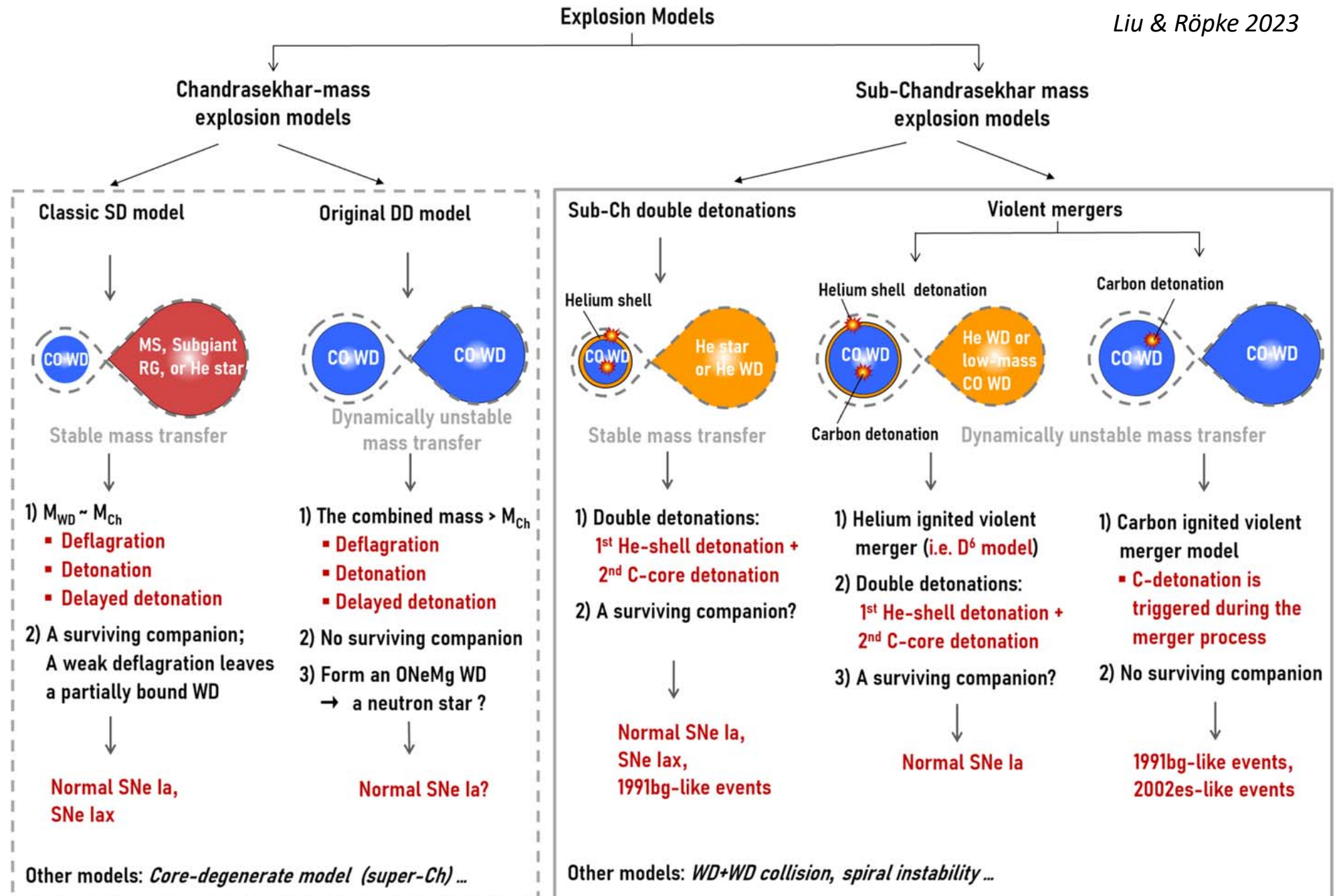


- C Ignition: at M_{Ch} limit / triggered (possibly not in WD center)
- Turbulent thin-flame propagation
- WD expansion → flame extinction
- Issues:
 - Rapid time scale,
 - Large spatial dynamic cange
 - » Nuclear burning $\text{C}+\text{O} \rightarrow {}^{56}\text{Ni}$...
 - » Expansion, unburnt C,O
 - » Mixing, non-sphericities



a SN Ia could arise from variants of progenitors

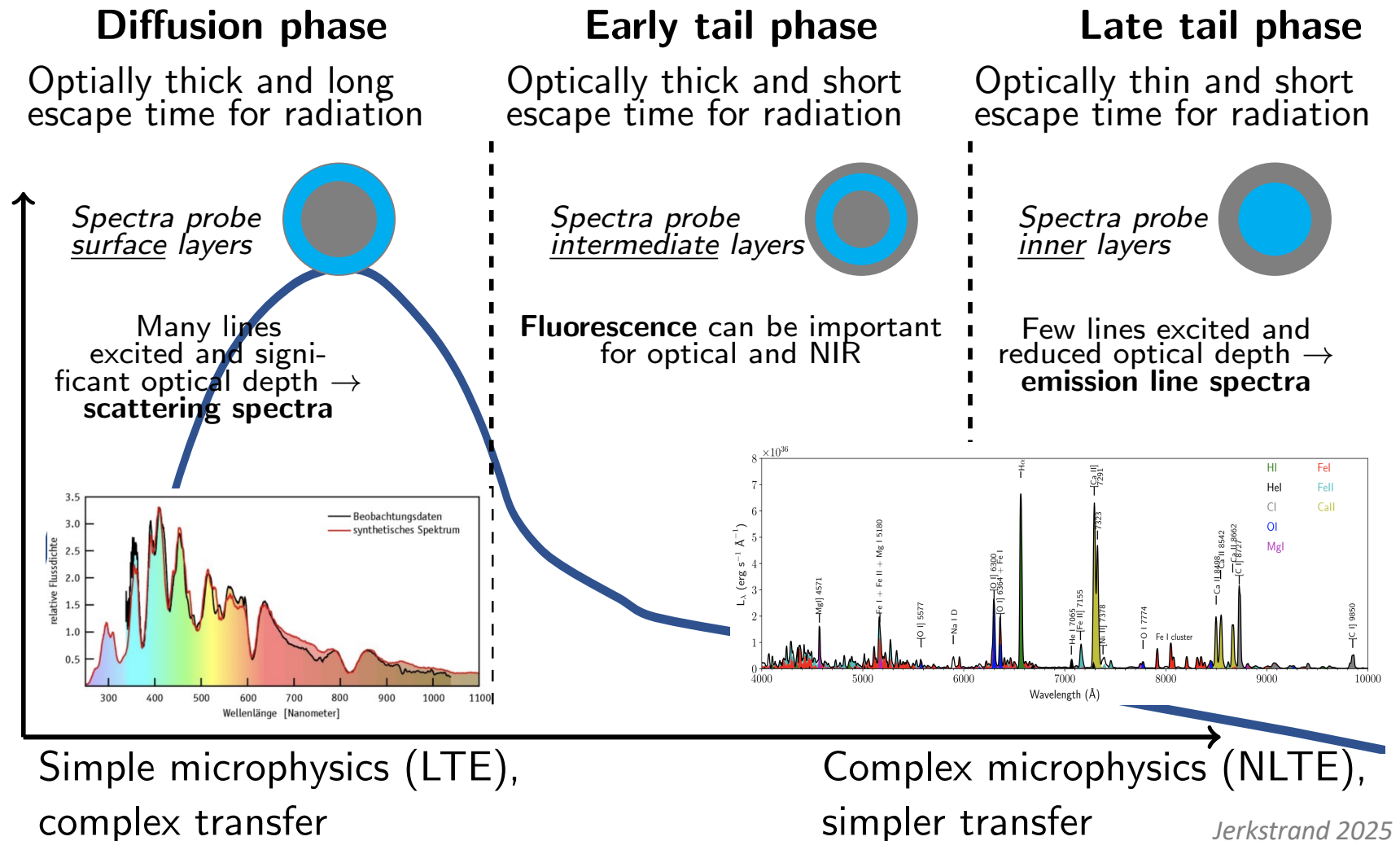
Liu & Röpke 2023



Energy and radiation in and after an explosion

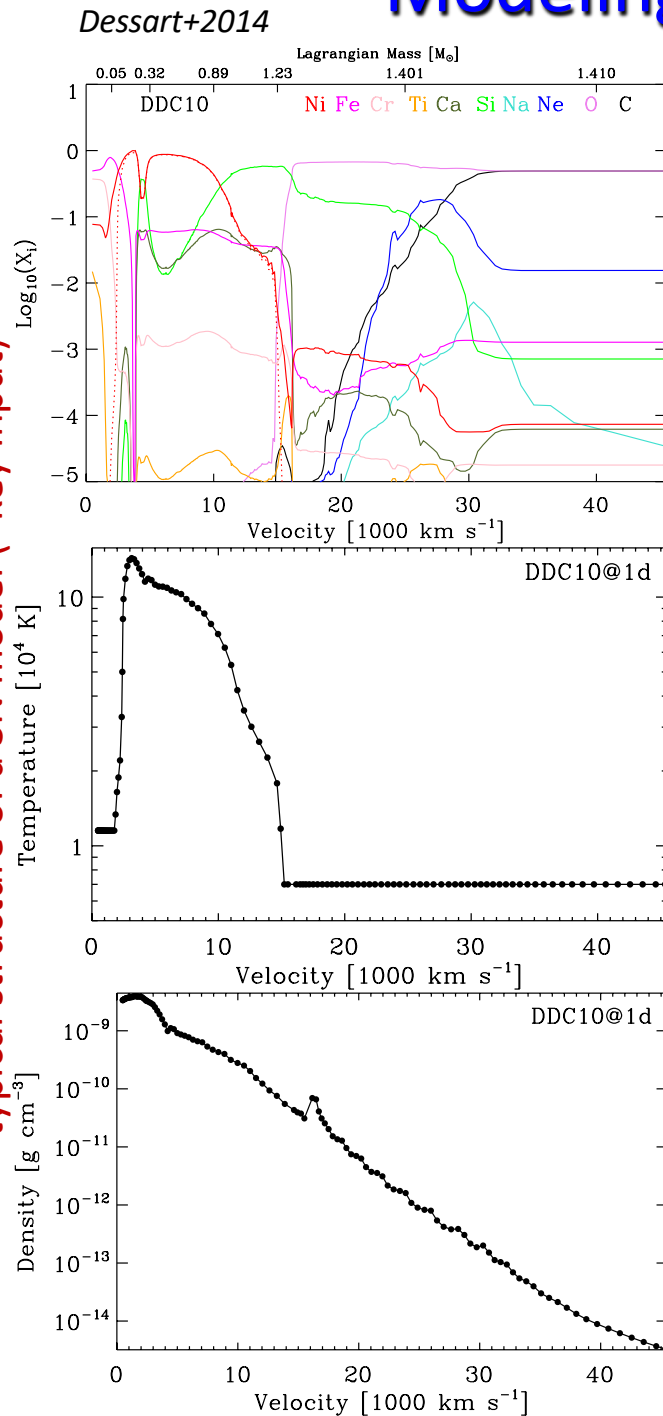
- Optical spectra are a result of complex radiation transport

Explosive transient evolution



Modeling radiation transfer in SN Ia

typical structure of a SN model (=key input)



Assuming spherical symmetry and local ⁵⁶Ni energy deposits, LTE is adopted to determine & trace atomic transitions in the expanding SN

→ light curve in different bands
→ spectra as they evolve

Challenges (wrt ccSNe):

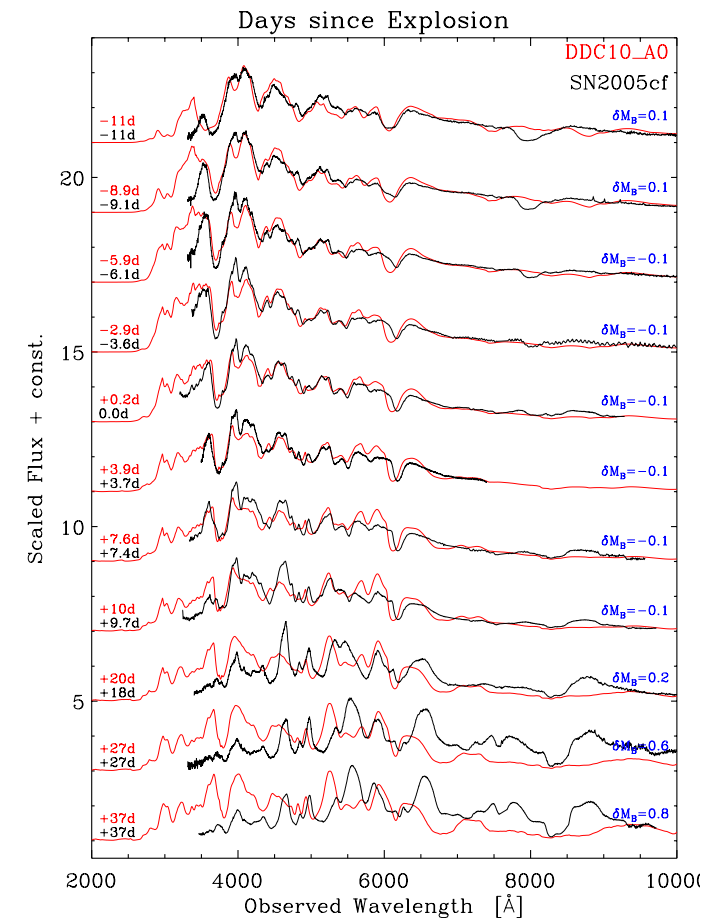
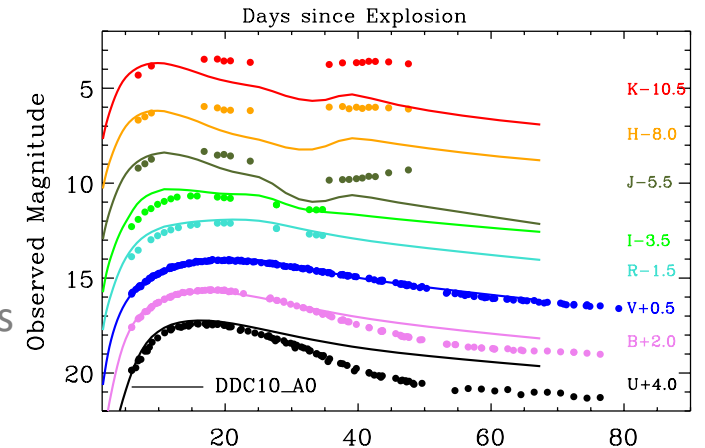
- small ϵ opacity by mass
 - multitude of metal lines
- ~reasonable agreement up to ~40+ days

Critical components:

- SN model (density, velocities, composition)
- ⁵⁶Ni escape (γ , e^+)
- atomic data (NLTE!)
- non-thermal processes

Less critical

- non-sphericities



Determining ^{56}Ni mass from light curve fitting

("Arnett's law")

one-zone modeling of the SN envelope reradiating ^{56}Ni energy

- ★ ^{56}Ni decay energy is deposited beneath the photosphere
- ★ deposited energy diffuses through the SN; some γ rays escape
- ★ deposited energy appears at the photosphere, as the SN evolves

👉 energy balance: $\dot{E} + P \dot{V} = \epsilon_{\text{inp}} - \frac{\partial L}{\partial m}$ diffusive transport $L = -\frac{4\pi r^2 \lambda c a}{3} \frac{\partial T^4(x, t)}{\partial r}$

with diffusion timescale $t_0 = 3\kappa R_0^2 / V_0 \alpha c = \kappa M / \beta c R_0$

👉 ^{56}Ni -powered luminosity

$$L(t) = \frac{2M_{\text{Ni}}}{t_d} e^{-\left[\frac{t^2}{t_d^2} + \frac{2R_0 t}{vt_d^2}\right]} \left[(\epsilon_{\text{Ni}} - \epsilon_{\text{Co}}) \int_0^t \times \left[\frac{R_0}{vt_d} + \frac{t'}{t_d} \right] e^{\left[\frac{t'^2}{t_d^2} + \frac{2R_0 t'}{vt_d^2}\right]} e^{-t'/t_{\text{Ni}}} dt' + \epsilon_{\text{Co}} \int_0^t \left[\frac{R_0}{vt_d} + \frac{t'}{t_d} \right] e^{\left[\frac{t'^2}{t_d^2} + \frac{2R_0 t'}{vt_d^2}\right]} e^{-t'/t_{\text{Co}}} dt' \right] (1 - e^{-At^{-2}})$$

with γ -ray optical depth $\tau_\gamma = \kappa_\gamma \rho R = At^{-2}$

Chatzopoulos+2011,2012

this does not account for time-dependent ionization and opacity

Gamma-ray line spectroscopy: the science potential

Radioactive trace isotopes from nucleosynthesis reactions and released in source's ejecta:

Isotope	Decay Time	Decay Chain	γ -Ray Energy [keV]	Detected Source	Source Type
^{208}Tl	4 min	$^{208}\text{Tl} \rightarrow ^{208}\text{Pb}$	511, 722, 861, 2615	(none)	NSMs
^{128}Sb	13 h	$^{128}\text{Sb} \rightarrow ^{128}\text{Te}$	75, 404, 482	(none)	White Dwarf AIC, NSMs
^{132}I	4.6 d	$^{132}\text{Te} \rightarrow ^{132}\text{I} \rightarrow ^{132}\text{Xe}$	506, 523, 630, 668, 773, 1318	(none)	White Dwarf AIC, NSMs
^{89}Sr	50 d	$^{89}\text{Sr} \rightarrow ^{89}\text{Y}$	909	(none)	accr White Dwarf, AIC
^7Be	77 d	$^7\text{Be} \rightarrow ^7\text{Li}^*$	478	(none)	Novae
^{56}Ni	8.8 d; 111 d	$^{56}\text{Ni} \rightarrow ^{56}\text{Co}^* \rightarrow ^{56}\text{Fe}^* + e^+$	158, 812; 847, 1238	SN2014J; SN1987A, SN1991Y	Supernovae
^{57}Ni	390 d	$^{57}\text{Co} \rightarrow ^{57}\text{Fe}^*$	122	SN1987A	Supernovae
^{22}Na	3.8 y	$^{22}\text{Na} \rightarrow ^{22}\text{Ne}^* + e^+$	1275	(none)	Novae
^{44}Ti	85 y	$^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca}^* + e^+$	68, 68; 1157	SNR Cas A	Supernovae
$^{229/230}\text{Th}$	$\sim 1.0 \cdot 10^5$ y	$^{229/230}\text{Th} \rightarrow \dots \rightarrow ^{208}\text{Pb}$	352... 609...2615	(none)	NSMs, SNe
^{126}Sn	$3.3 \cdot 10^5$ y	$^{126}\text{Sn} \rightarrow ^{126}\text{Sb}^* \rightarrow ^{126}\text{Te}$	666; 695; 87; 64	(none)	NSMs, SNe
^{26}Al	$1.04 \cdot 10^6$ y	$^{26}\text{Al} \rightarrow ^{26}\text{Mg}^* + e^+$	1809	Massive-Star Groups Cyg, Ori...	Stars, Novae Supernovae
^{60}Fe	$3.5 \cdot 10^6$ y	$^{60}\text{Fe} \rightarrow ^{60}\text{Co}^* \rightarrow ^{60}\text{Ni}^*$	59, 1173, 1332	Galaxy (?)	Supernovae, Stars
e^+	$10^5 \dots 10^7$ y	$e^+ + e^- \rightarrow \text{Ps} \rightarrow \gamma\gamma..$	511, <511	Galactic Bulge, Disk	Supernovae, Novae, Pulsars, Microquasars...

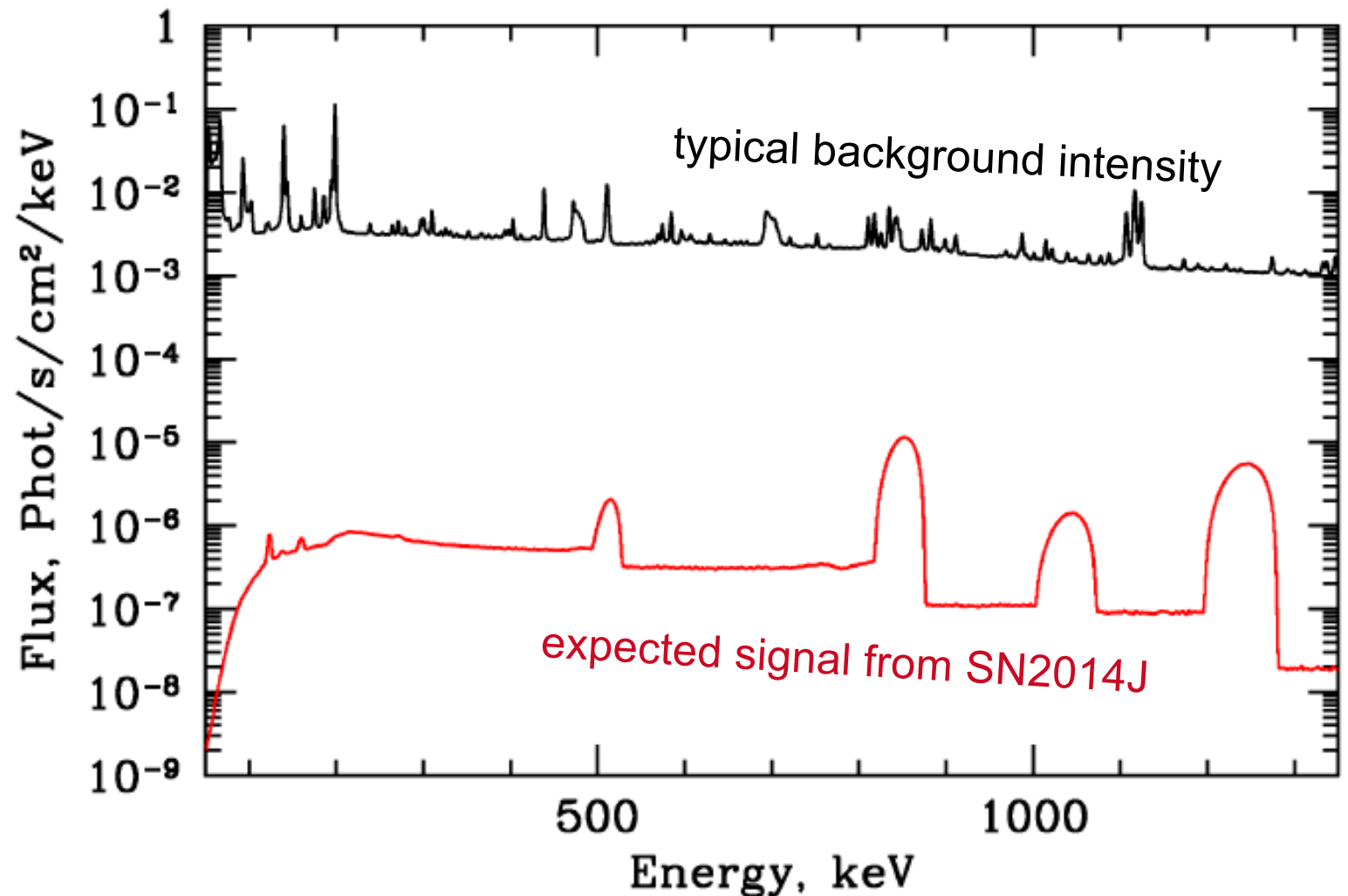
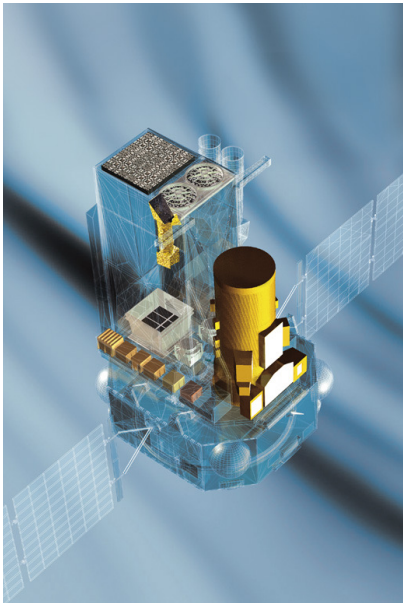
- Only the most-plausible candidates per source type are listed

(abundance; decay time (weeks $\ll \tau < 10^8$ y) long enough to survive ejection/not too long to be bright)

The Challenge of Finding SN2014J Gamma-Rays

★ Current Gamma-Ray Telescopes Have Large Intrinsic Background

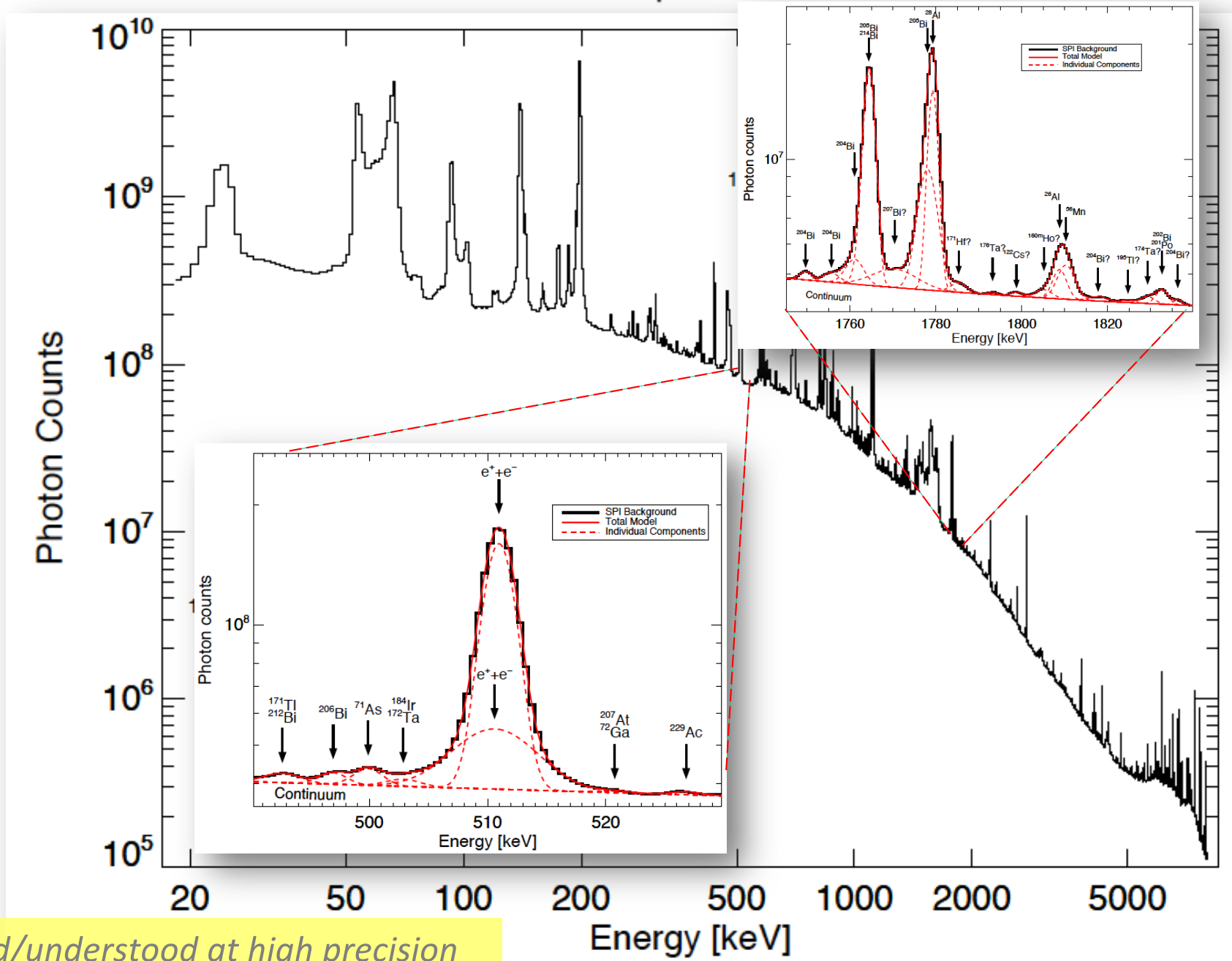
👉 Cosmic Ray Activation of Spacecraft and Instrument



from Churazov et al., 2014

INTEGRAL: Dominance of instrumental background

SPI Ge detector spectra



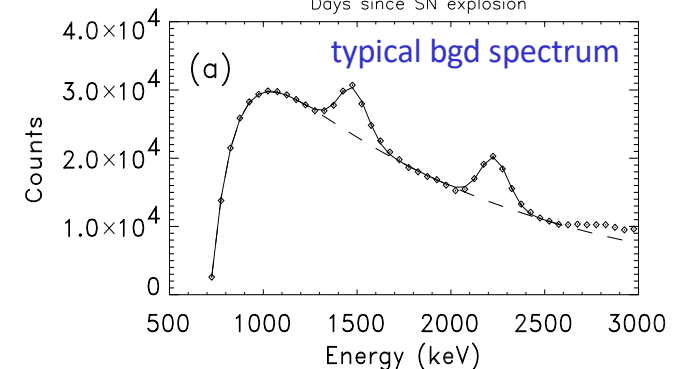
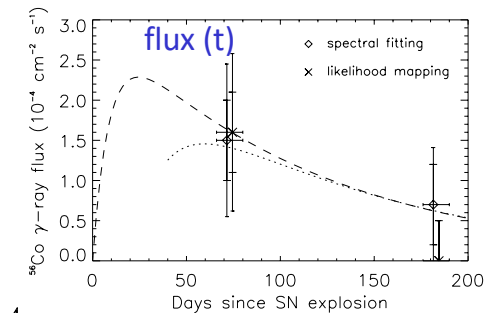
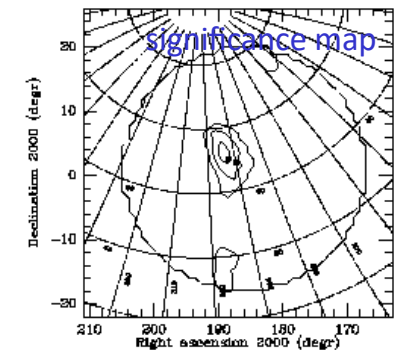
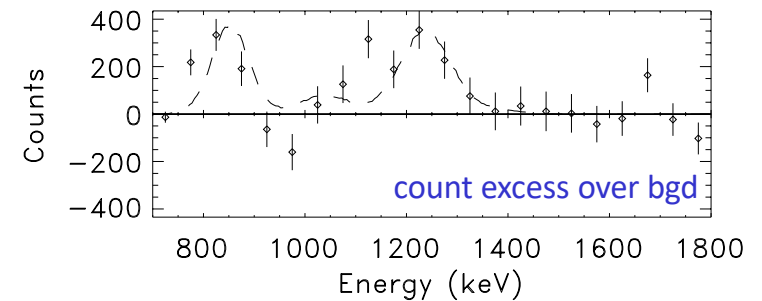
Modelled/understood at high precision

SN1991T: ^{56}Ni decay gamma rays

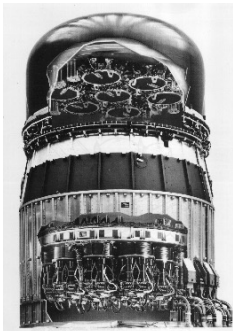
Morris+ 1995; 1997; 2002

SN 1991T:

- ★ ~10 Apr 1991 in NGC4527 ($d \sim 13 \pm 2$ Mpc)
- ★ unusually bright
 - ☞ $\max_V \sim 11.5$ ~20 Apr 1991; high reddening, slow decline
- ★ spectroscopy → clear Fe enrichments



COMPTEL observation results:



- ☞ ~28 days of observation ($t=66-79$, $t=176-190$)
- ☞ modeling instrumental background; likelihood analysis
- ☞ spectroscopy: ^{56}Co line detection (3.6σ)
- ☞ imaging: 3.1σ point source excess @ SN91T position
- ☞ ^{56}Co line fluxes (847/1238 keV) $(7 \pm 2) (4 \pm 1) / 10^{-5} \text{ ph cm}^{-2} \text{ s}^{-1}$

★ $M_{56\text{Ni}} \sim 1.5 M_{\odot}$ (>0.6)

★ other estimates of $M_{56\text{Ni}}$:

- ☞ optical spectra model: $0.9-1 M_{\odot}$
- ☞ NIR Fe lines: $0.4-1.2 M_{\odot}$

SN2014J

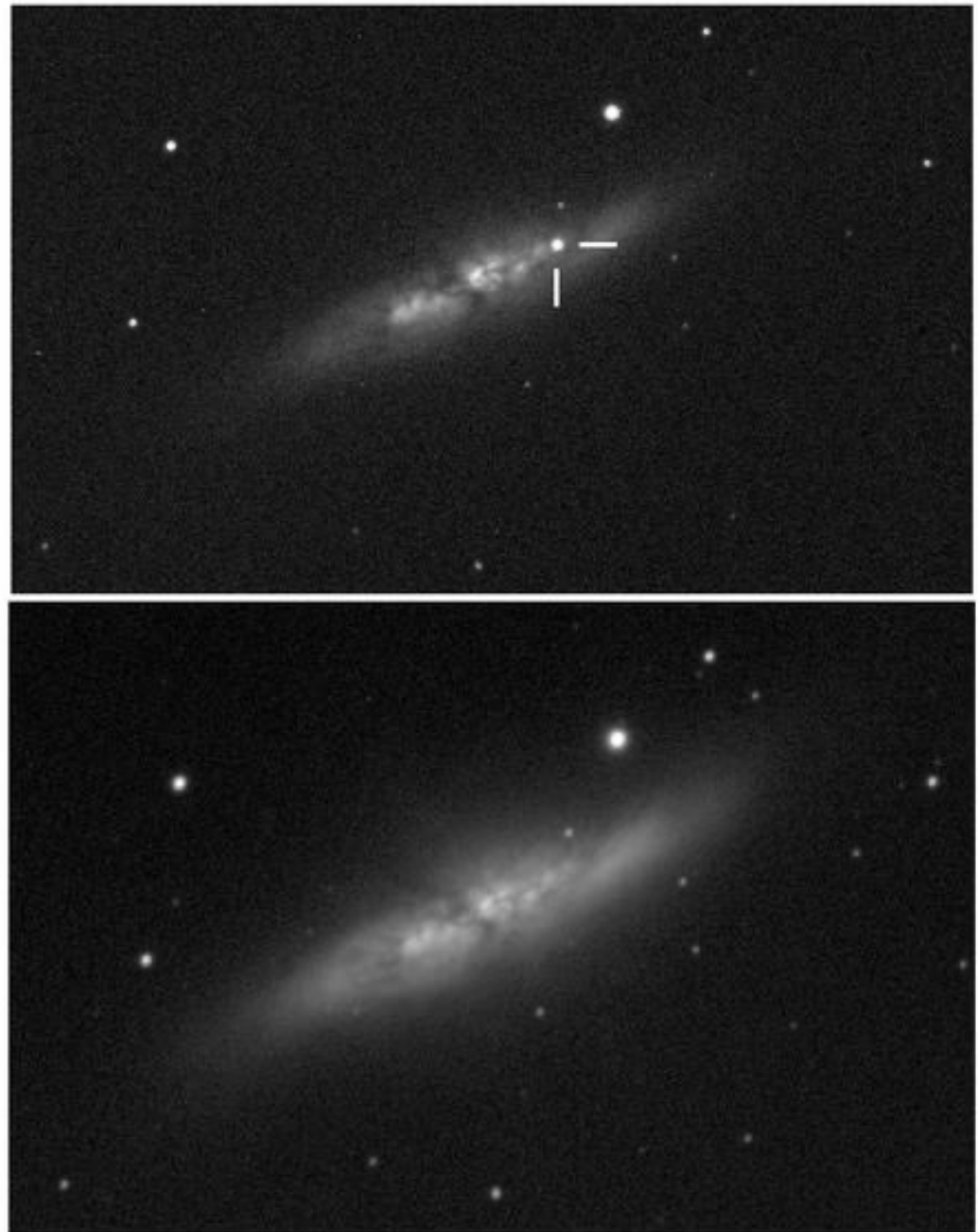
- SN2014J in M82
(Starburst Galaxy)

- 👉 Discovered 22 Jan 2014

- 👉 Likely Explosion Date:
14 Jan 2014 (14.75 $\pm$ 0.3d)

- 👉 Distance 3.3...3.53 Mpc,
 $l=141.41^\circ$, $b=40.56^\circ$

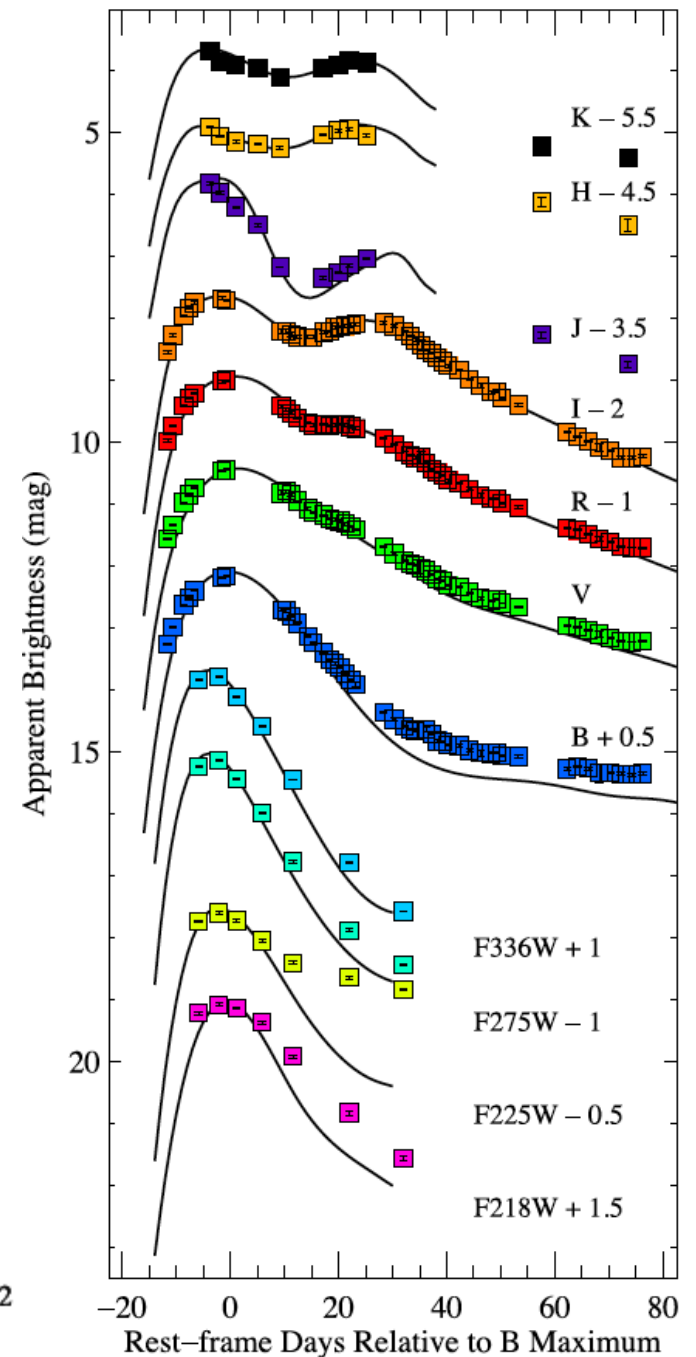
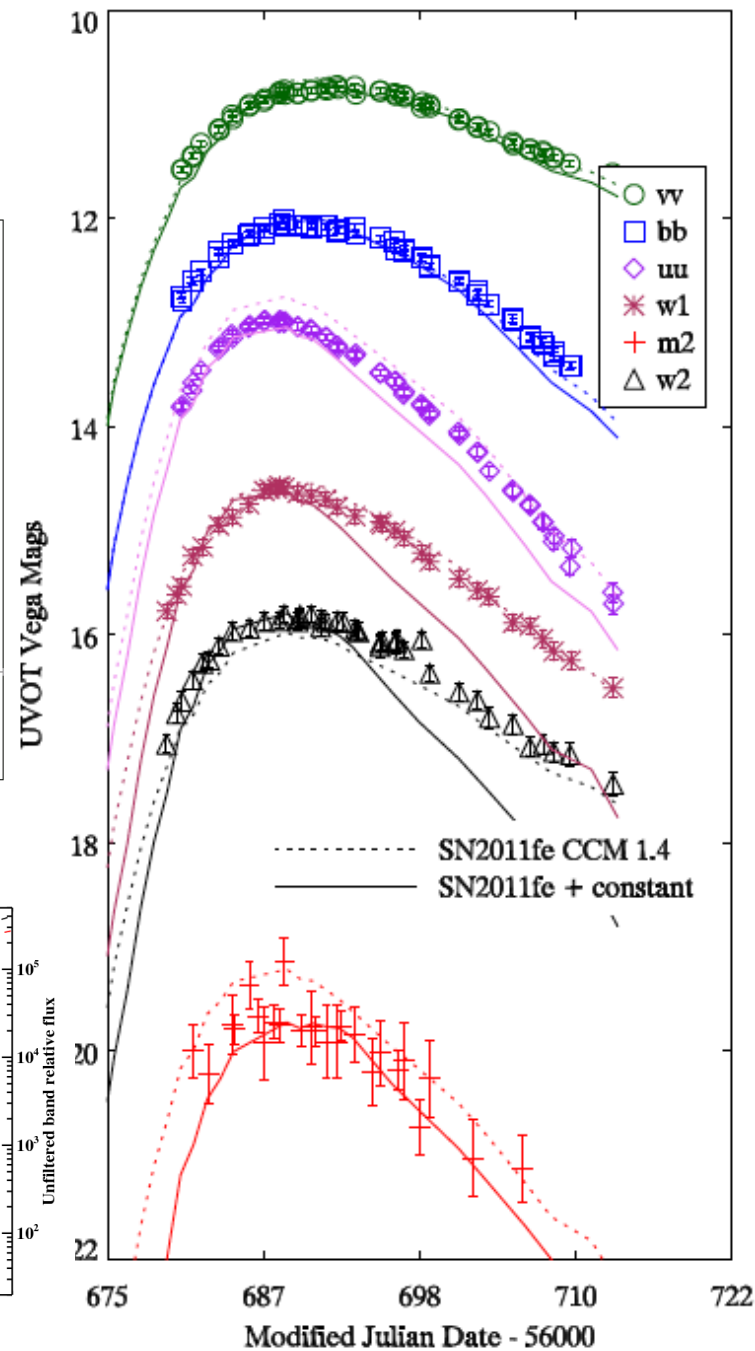
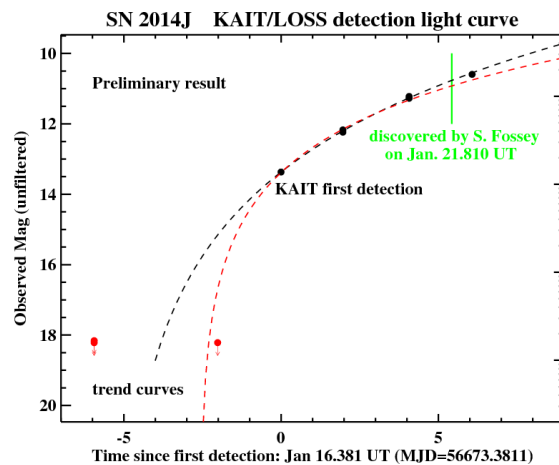
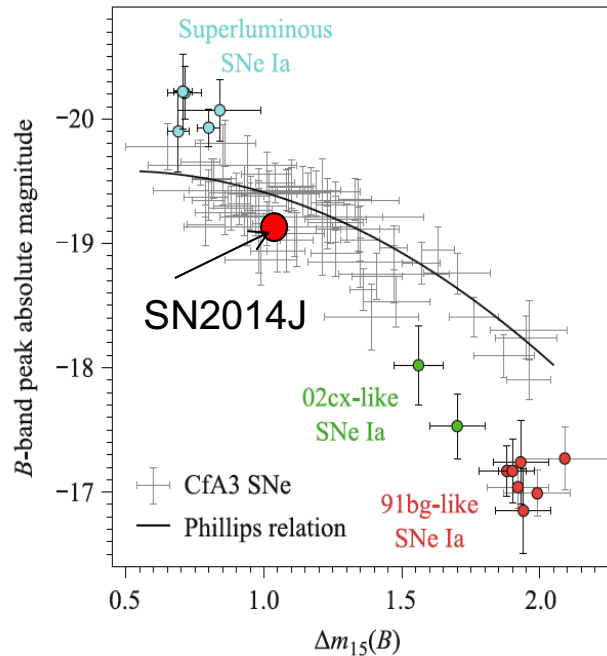
- 👉 Closest SN Ia in 40 y!



SN2014J evolution in std spectral bands

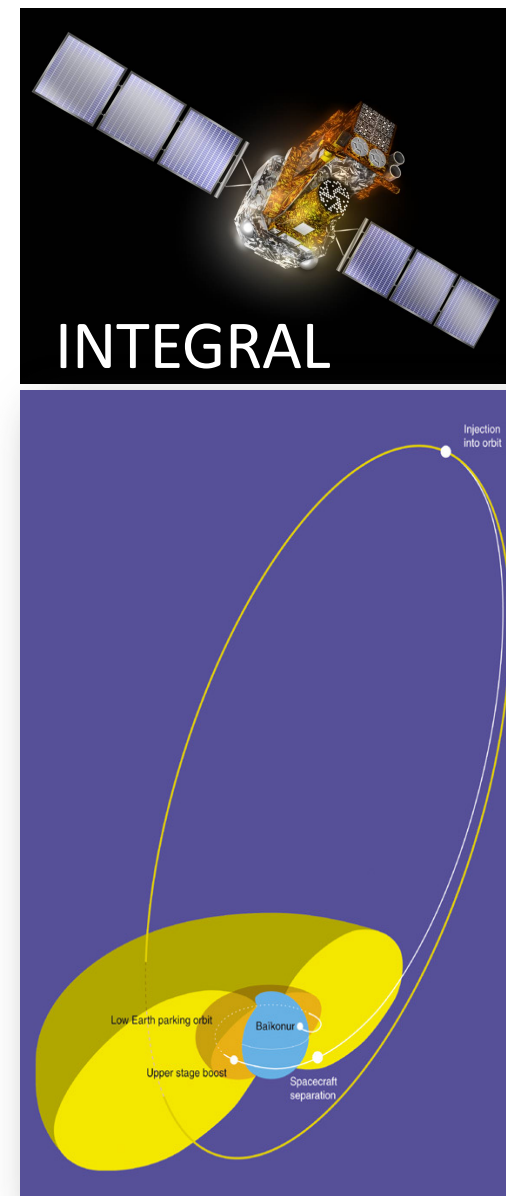
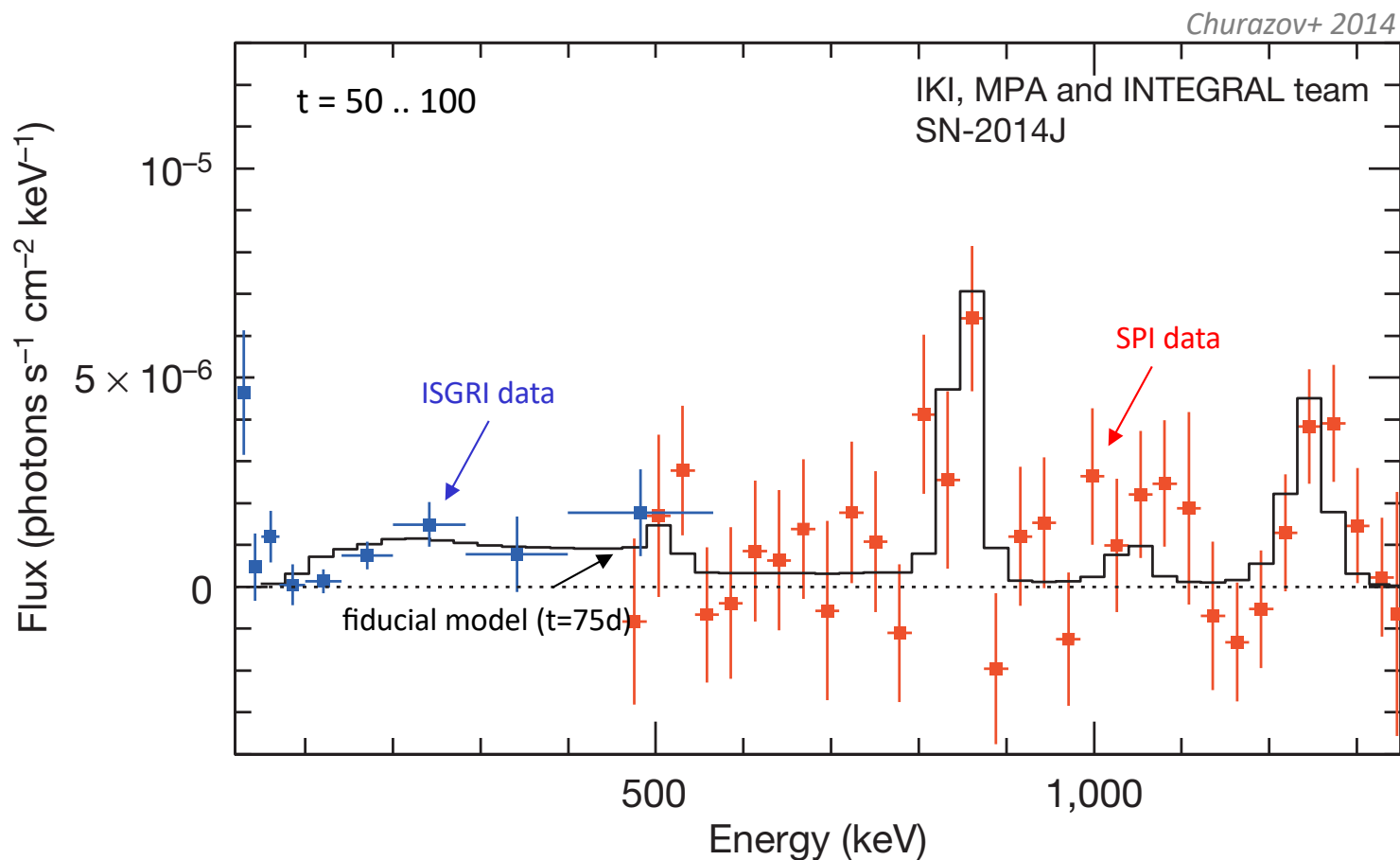
Brown+ 2014, Foley+ 2014, ... →

Consistent with a
“normal SN Ia”



SN2014J: SNIa model verification through ^{56}Ni decay lines

★ ^{56}Ni decay chain line spectroscopy: 847 and 1238 keV lines clearly detected



>40 years after its proposal

SN2014J: SNIa model verification through ^{56}Ni decay lines

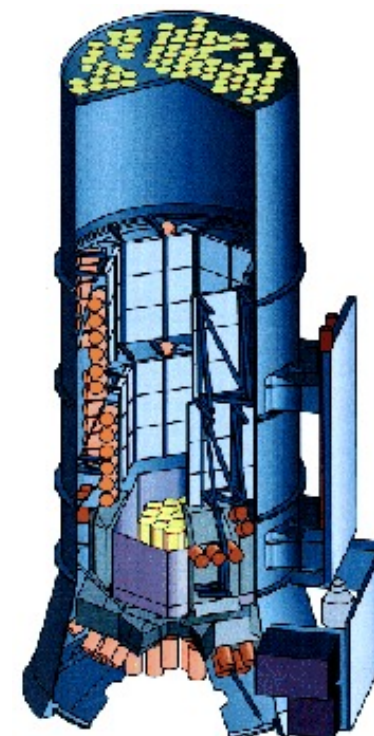
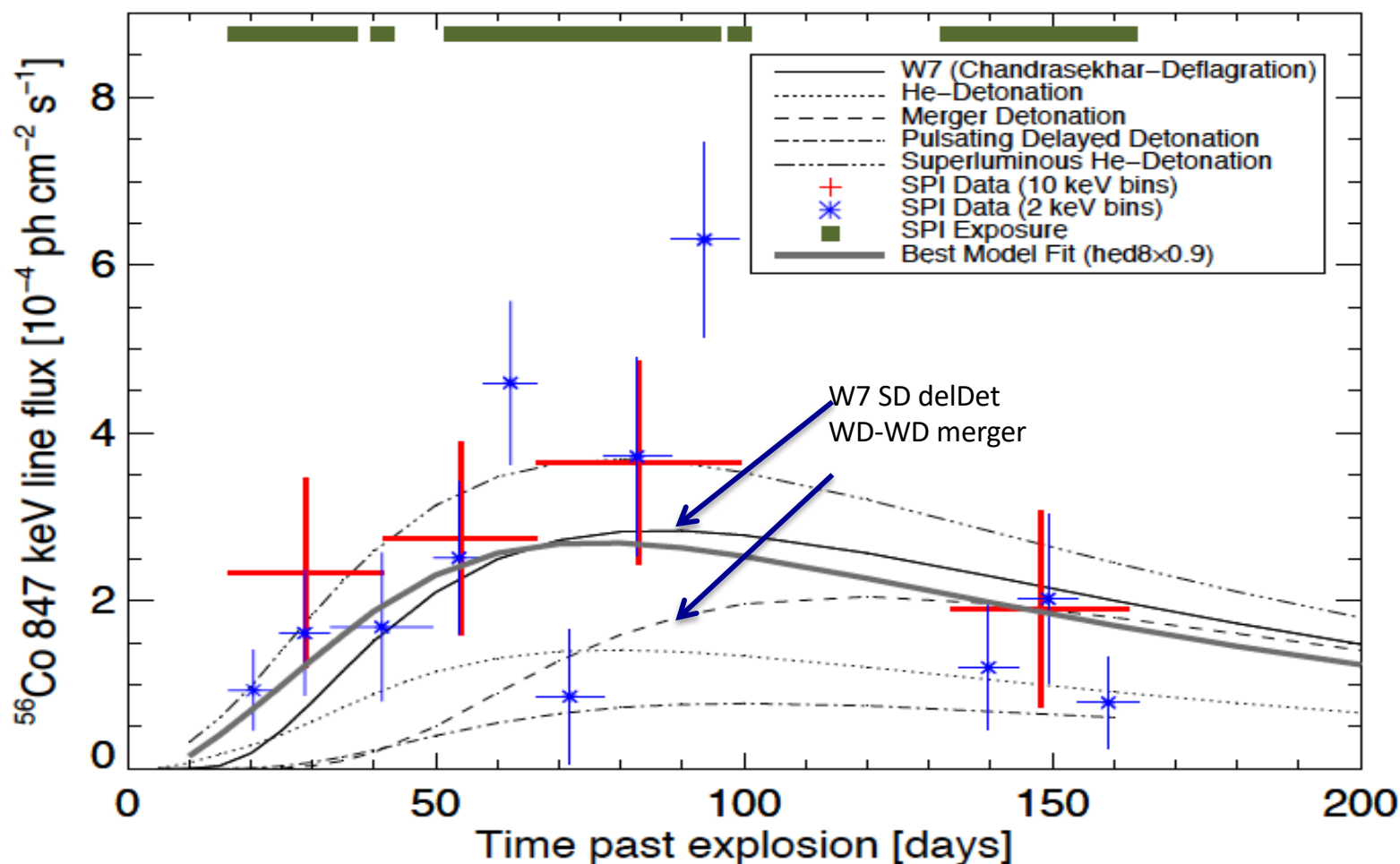
Tracing the light curve of gamma-ray lines →

★ ^{56}Ni mass: $0.49 \pm 0.09 M_{\odot}$

(cmp from bol. Light → $0.42 \pm 0.05 M_{\odot}$)

from models → $0.5 \pm 0.3 M_{\odot}$

Diehl+ 2015



SN Ia model verification through ^{56}Ni decay lines

Investigating the potential of gamma-ray lines for SN Ia parameter estimates →

- 👉 simulate SN Ia model gamma-ray spectra vs. time after explosion
- 👉 use an adopted instrument for a gamma-ray measurement
- 👉 use derived line fluxes & spectra to constrain SN Ia parameters
- 👉 vary gamma-ray source and propagation assumptions:
 - single scattering shell
→ determine ^{56}Ni mass and gamma-ray leakage time
 - adding spectral shape constraints through multiple shells of homologous expansion
→ determine also the ejecta mass

Leising 2022

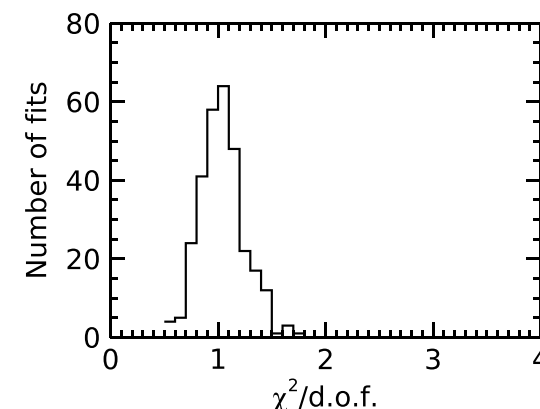
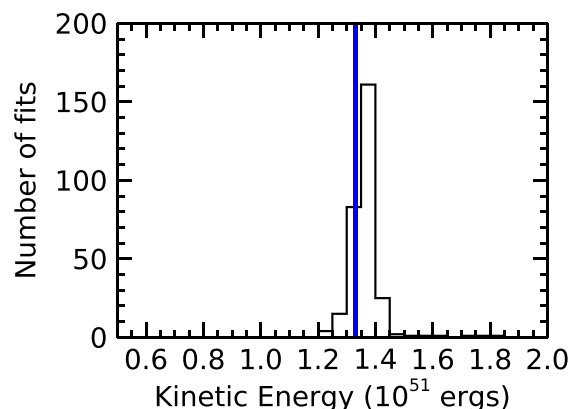
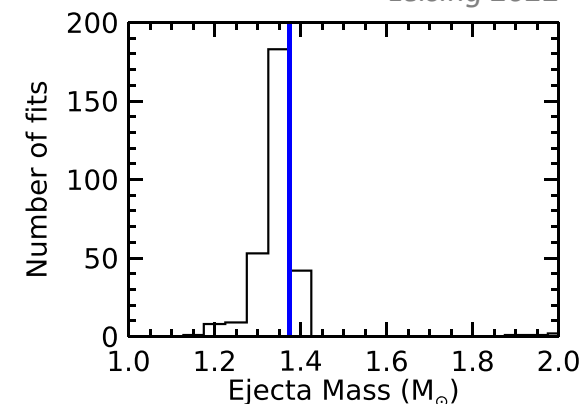
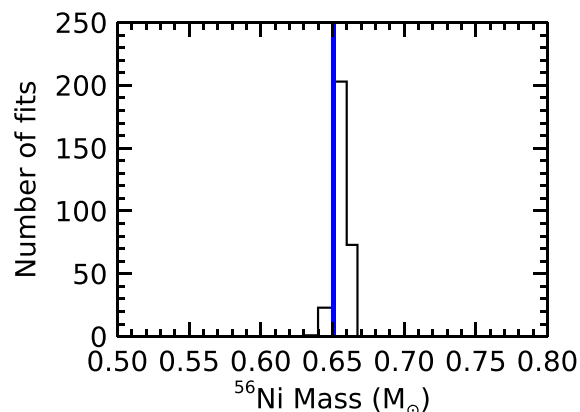
★ ^{56}Ni mass can be determined to $\pm 0.02 M_{\odot}$ (4%)

- next-generation instrument; several SNe/y

★ Application to SN2014J:
(with current data)

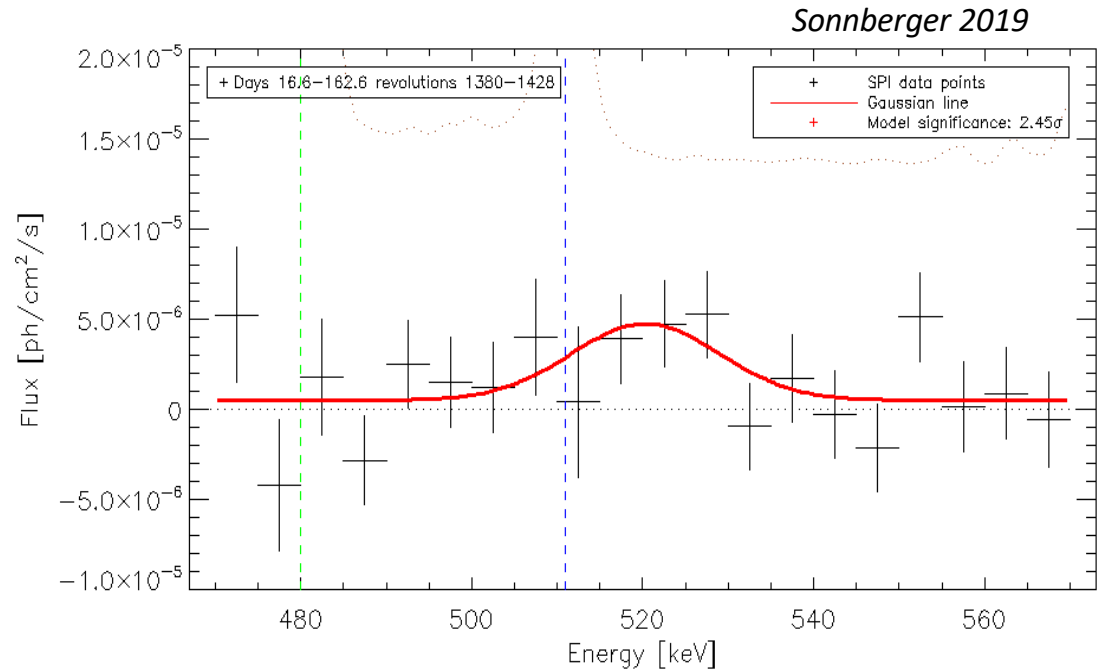
^{56}Ni mass: $0.4 \pm 0.1 M_{\odot}$

(cmp $0.49 \pm 0.09 M_{\odot}$ by Diehl+2015)



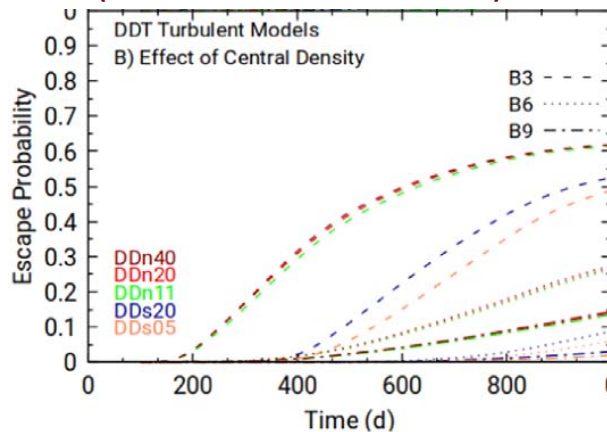
Positron annihilation in SN2014J

- 511 keV line emission suggested (1.7σ)
 - ★ Flux consistent with $\sim^{56}\text{Co}$ line fluxes
 - $\sim$ all e^+ annihilating
 - ★ Blue-shifted by 10-15 keV (??)

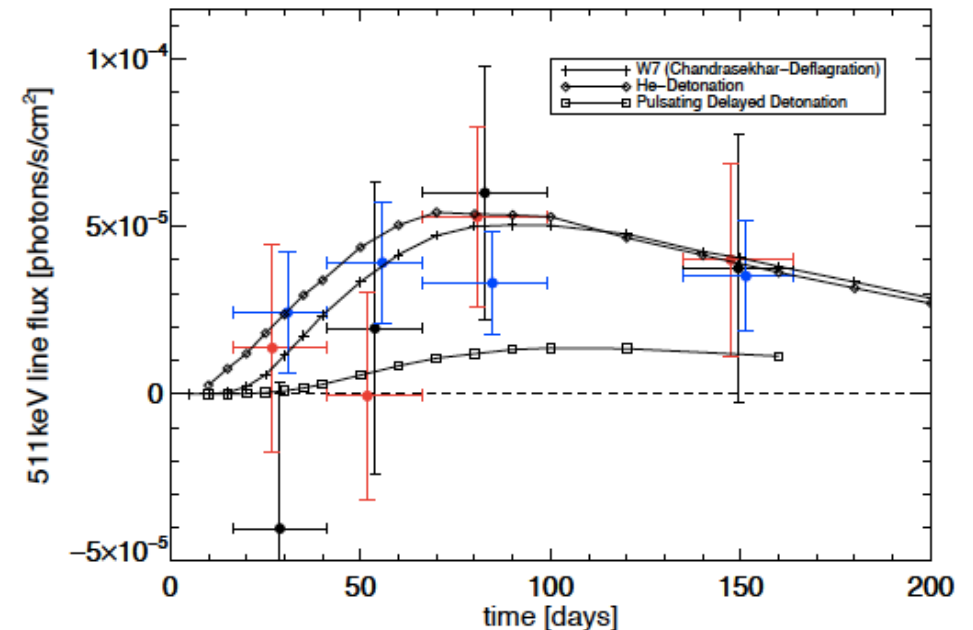


Model study

👉 positron escape is $\sim 10^{52}/\text{SNIa}$ ($< 2\%$ of all Galactic e^+)



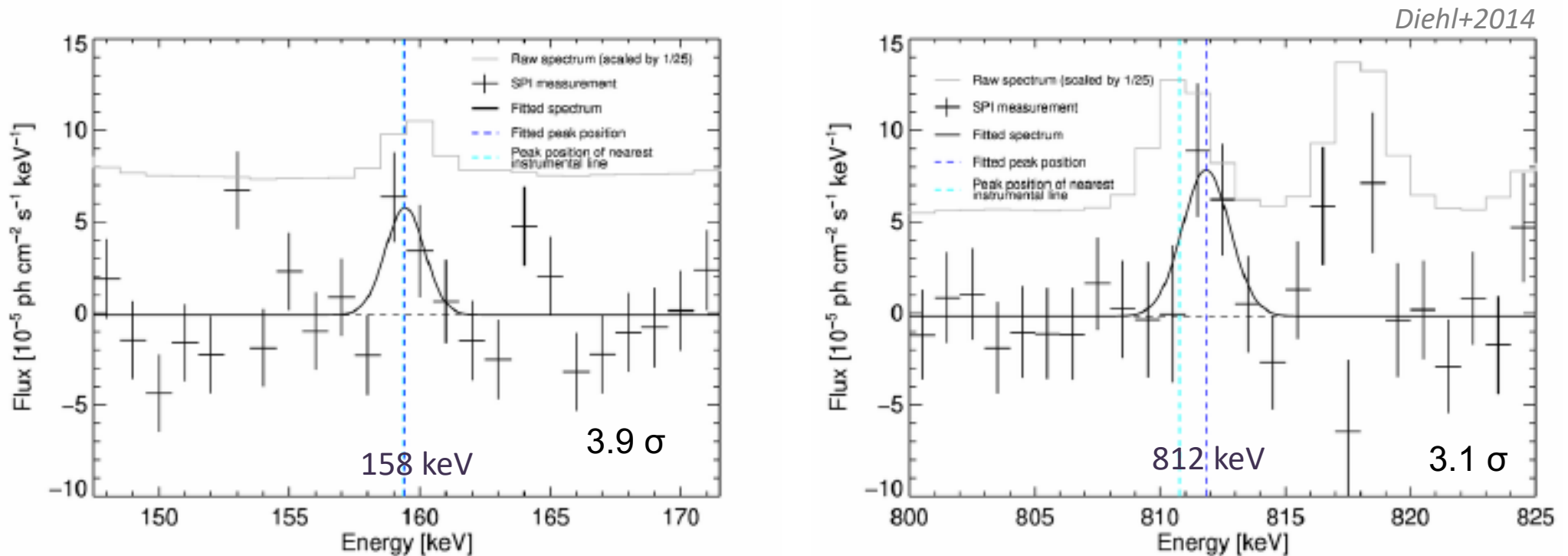
Mera Evans+ 2022



SN2014J: Early ^{56}Ni ($\tau \sim 8.8\text{d}$)

Spectra from the SN at ~ 20 days after explosion

★ Clear detections of the two strongest lines expected from ^{56}Ni



★ Intensities:

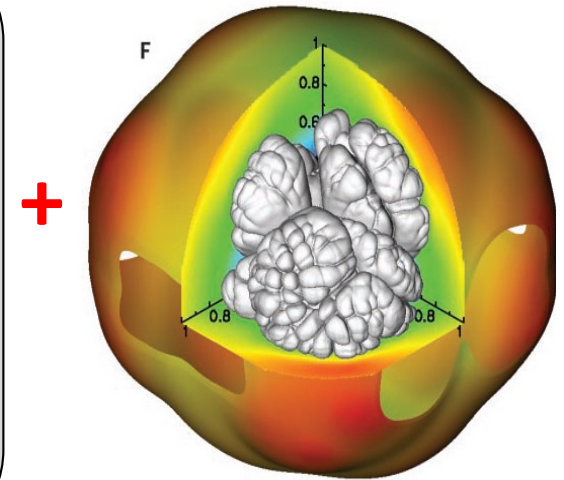
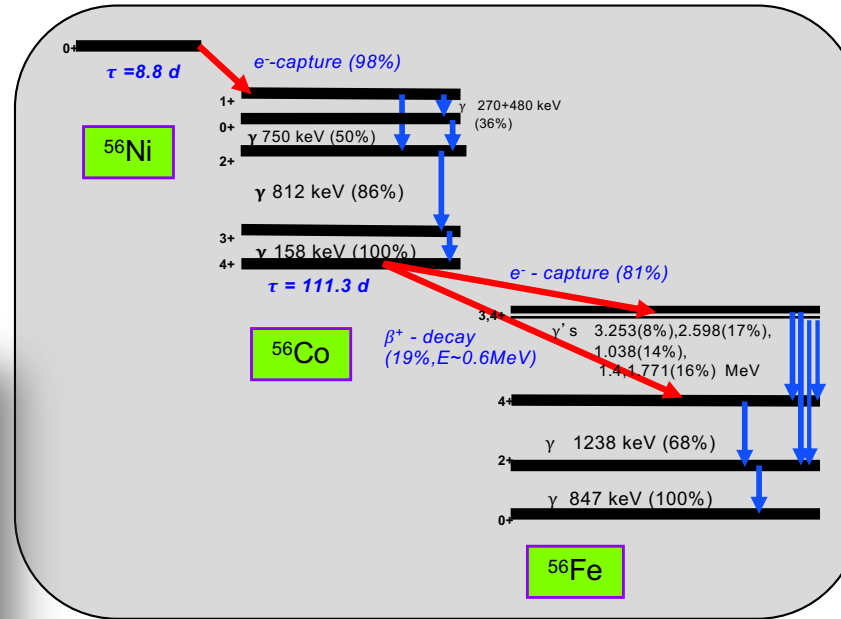
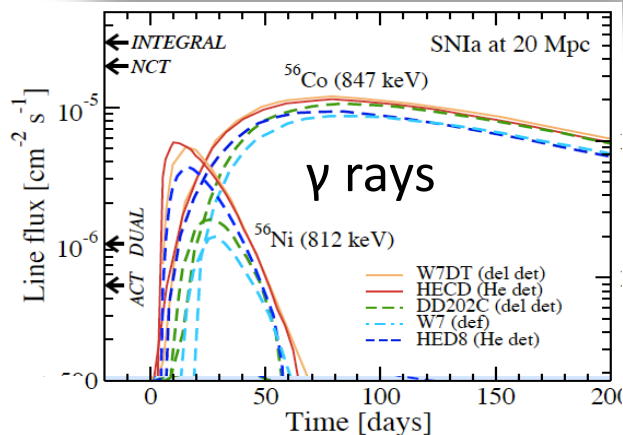
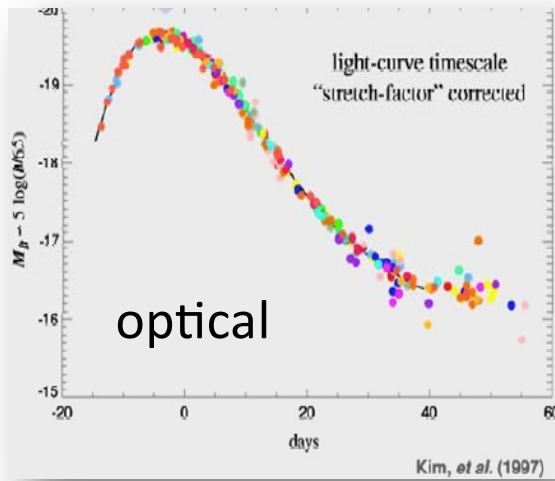
$(1.14 \pm 0.43) 10^{-4}$ ph cm^{-2} s^{-1} (158 keV line)

and $(1.91 \pm 0.67) 10^{-4}$ ph cm^{-2} s^{-1} (812 keV line)

→ ^{56}Ni mass estimate (backscaled to explosion): $\sim 0.06 M_{\odot}$ ($\sim 10\%$)

^{56}Ni radioactivity $\rightarrow \gamma$ -Rays, e^+ $\rightarrow$ leakage/deposit evolution

SN Ia



Nuclear BE release from $0.6M_{\odot}$ [$\text{C}, \text{O} \rightarrow ^{56}\text{Ni}$]

^{56}Ni decay γ rays and e^+ in expanding/diluting envelope $\rightarrow$

Heating of envelope material by absorbed γ, e^+

$\rightarrow$ Re-radiation of deposited energy in opt...IR radiation

Leakage as envelope expands

$\rightarrow$ Escaping γ, e^+ lead to γ ray signals

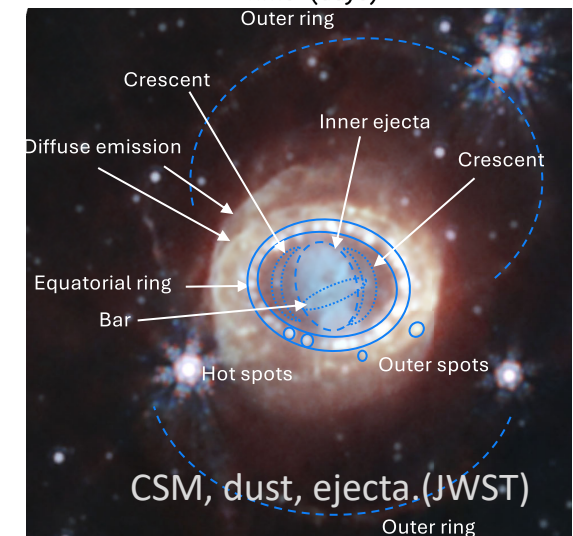
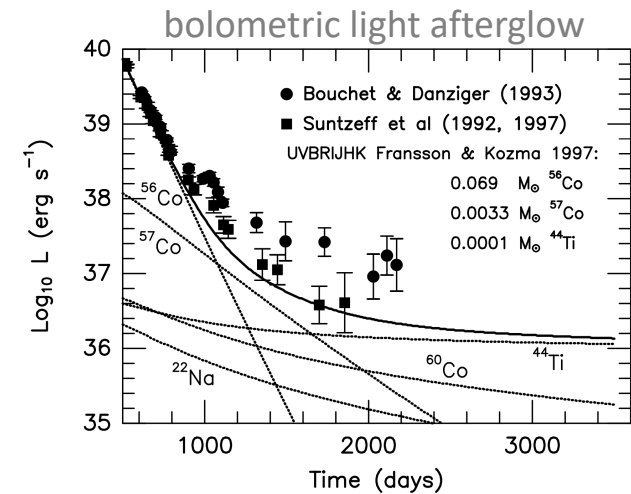
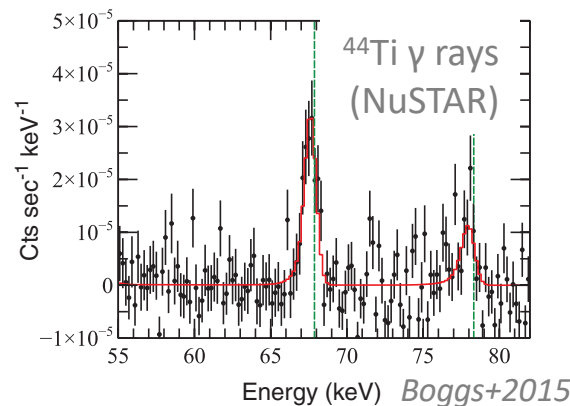
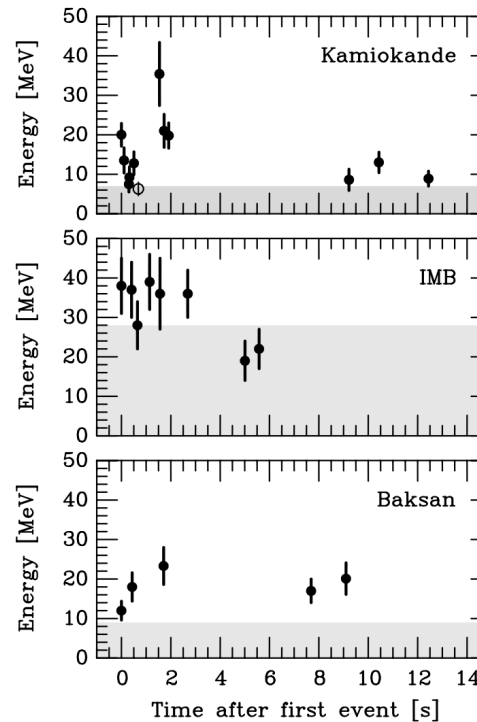
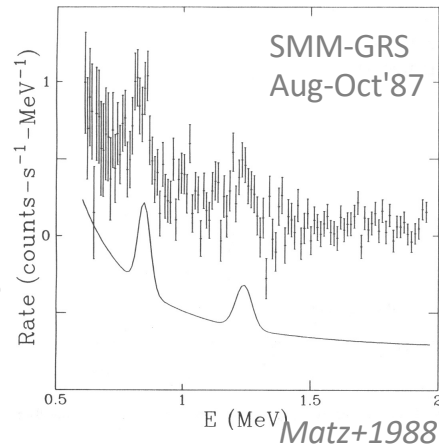
Light curves in optical & γ rays complement each other

SN1987A

- Witnessing the final core collapse of a massive star of mass $22 M_{\odot}$ in Feb 1987

- Witness neutrino burst from core collapse

- Witness radioactively-powered SN afterglow and γ rays as its source

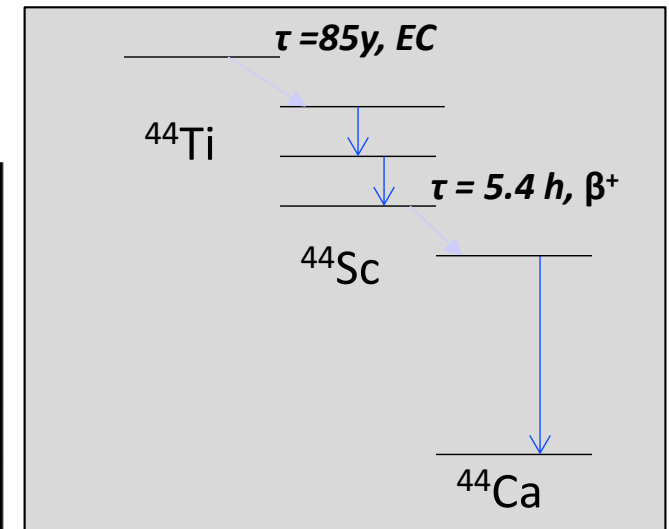
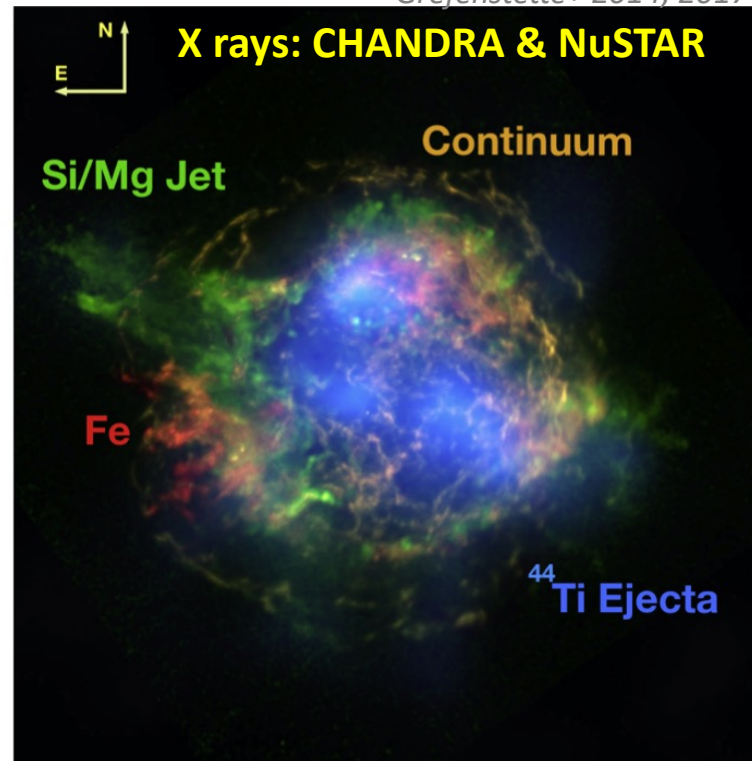


X rays and beyond: Locating the inner Ejecta in Cas A

NuSTAR Imaging in hard X-rays (3-79 keV; ^{44}Ti lines at 68,78 keV) →

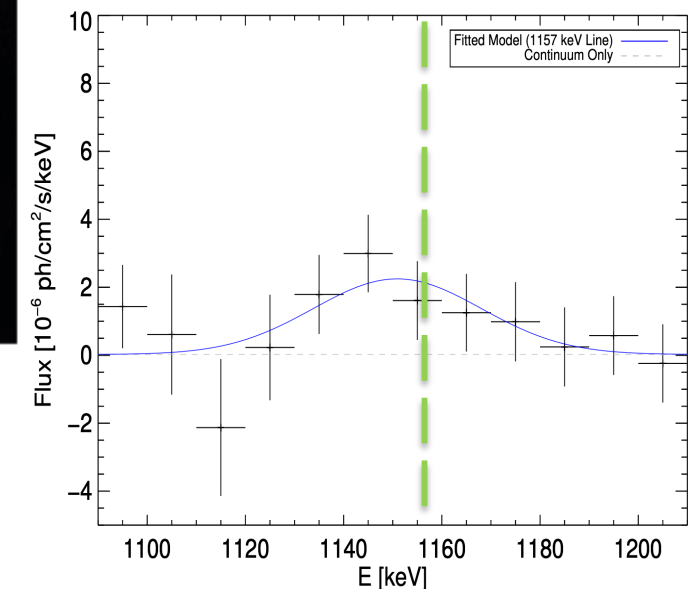
👉 first mapping of radioactivity in a SNR

- Both ^{44}Ti lines detected clearly
- redshift ~ 0.5 keV
→ 2000 km/s asymmetry
- ^{44}Ti flux consistent with earlier measurements
- Doppler broadening:
(5350 ± 1610) km s^{-1}
- Image differs from Fe!!



👉 ^{44}Ti → TRUE locations of inner-SN ejecta

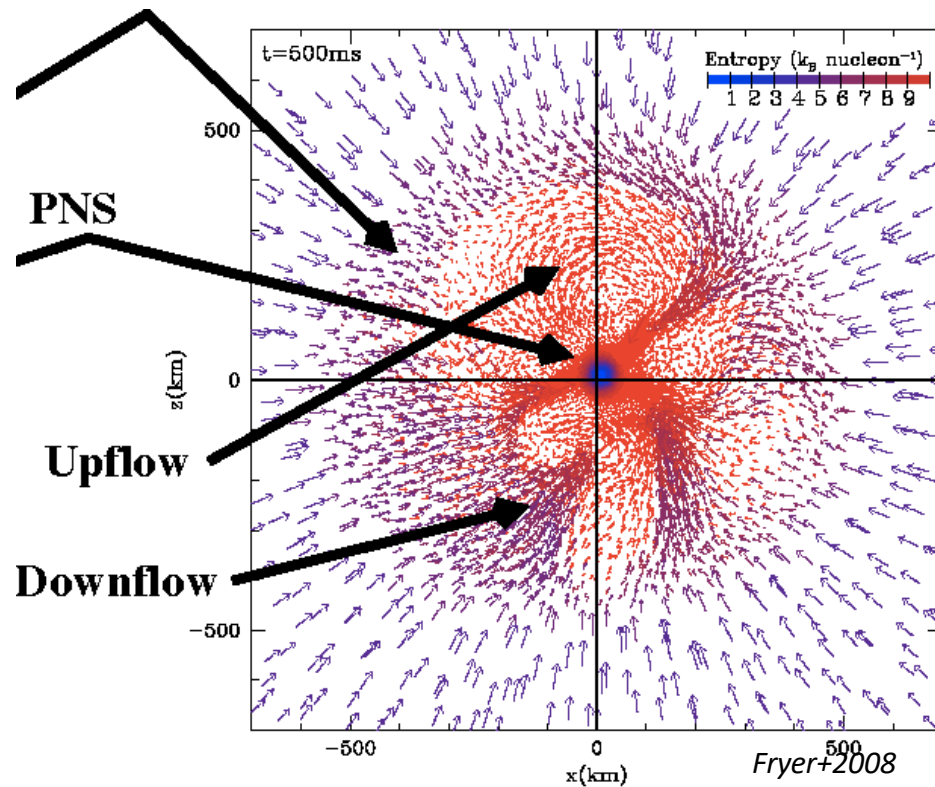
👉 Fe-line X-rays are biased from ionization of plasma by reverse shock



INTEGRAL/SPI → clear Doppler shift of ^{44}Ti
(1800 ± 800 km s^{-1} away from observer)

Nucleosynthesis in (3D!) cc-SN :

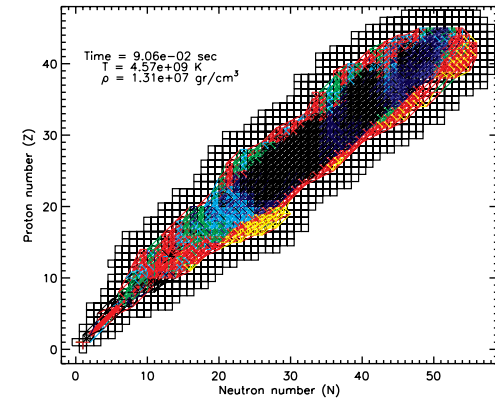
Density/Temperature Regimes in INNER Regions



“For each specific region,
only certain reactions
affect the yields of ^{44}Ti ”

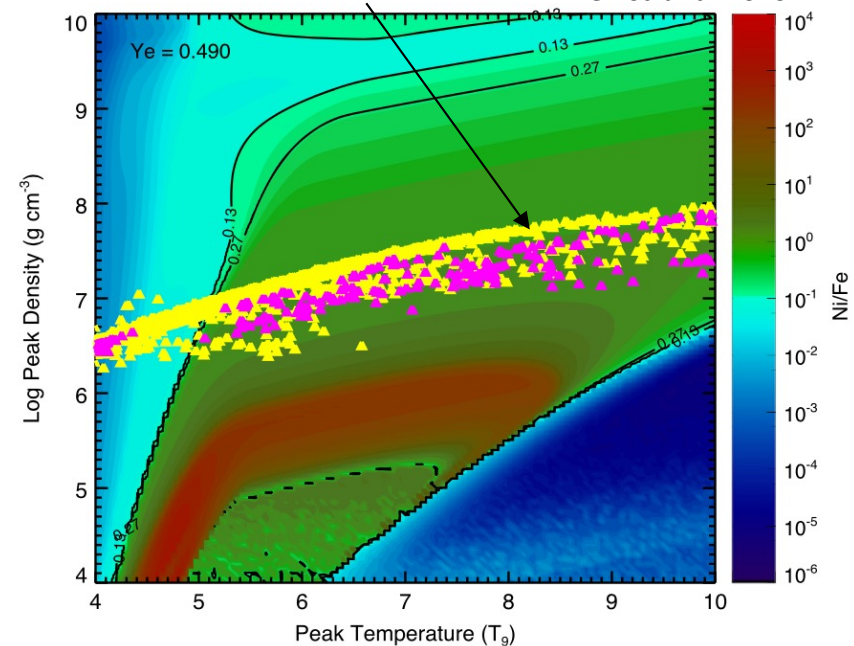
Final
Mass
fraction

NuGrid collaboration (Magkotsios et al., ApJ 2011)
nuclear reaction network



typical ccSNparameter regions

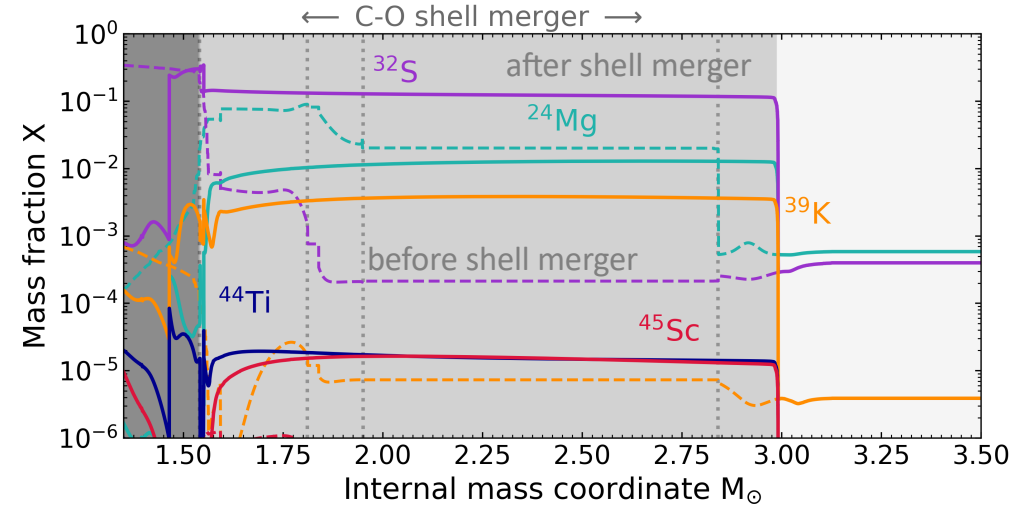
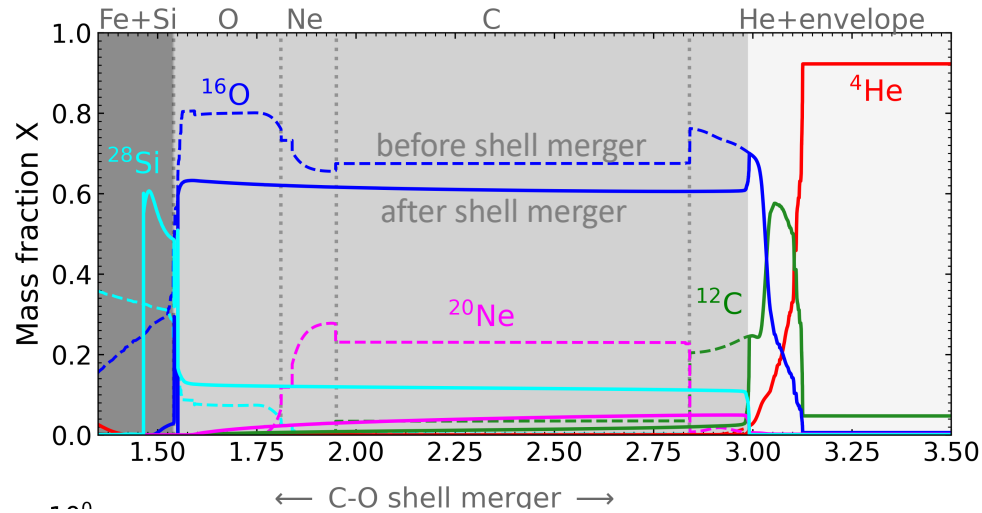
Jerkstrand+2015



Late stellar evolution: shell merging

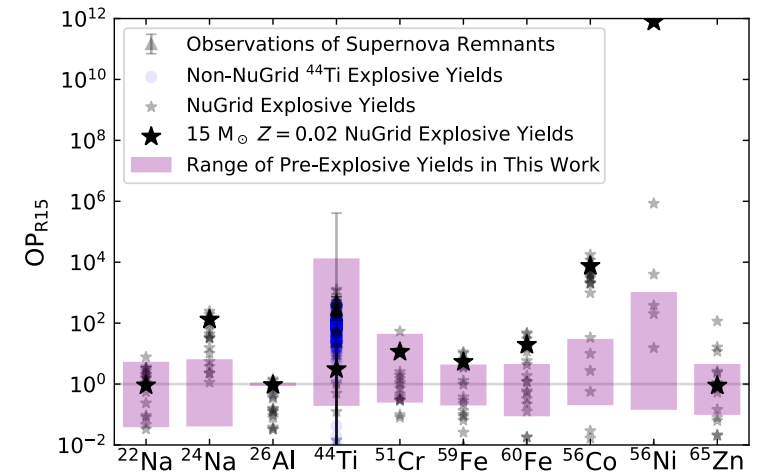
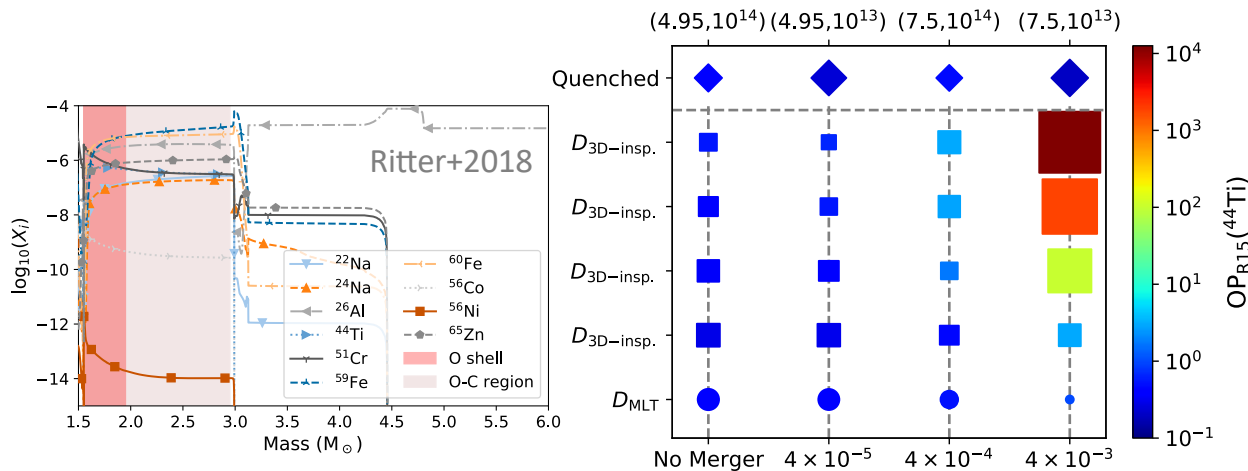
★ merging shells affect pre-SN structure and late nucleosynthesis

Roberti+2025

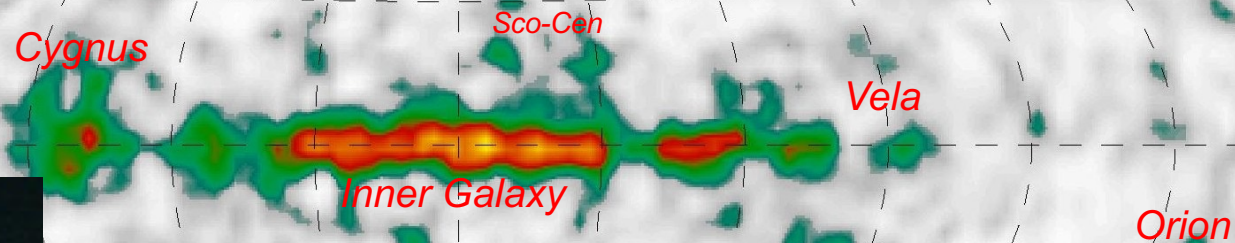
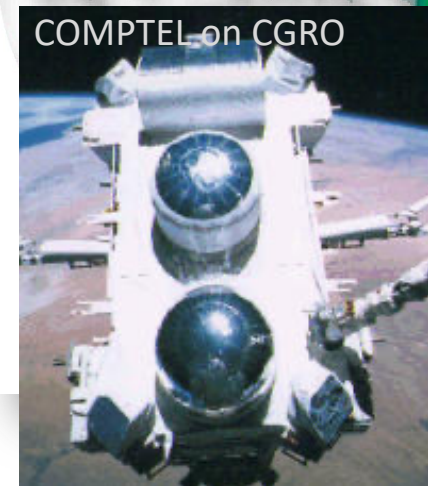
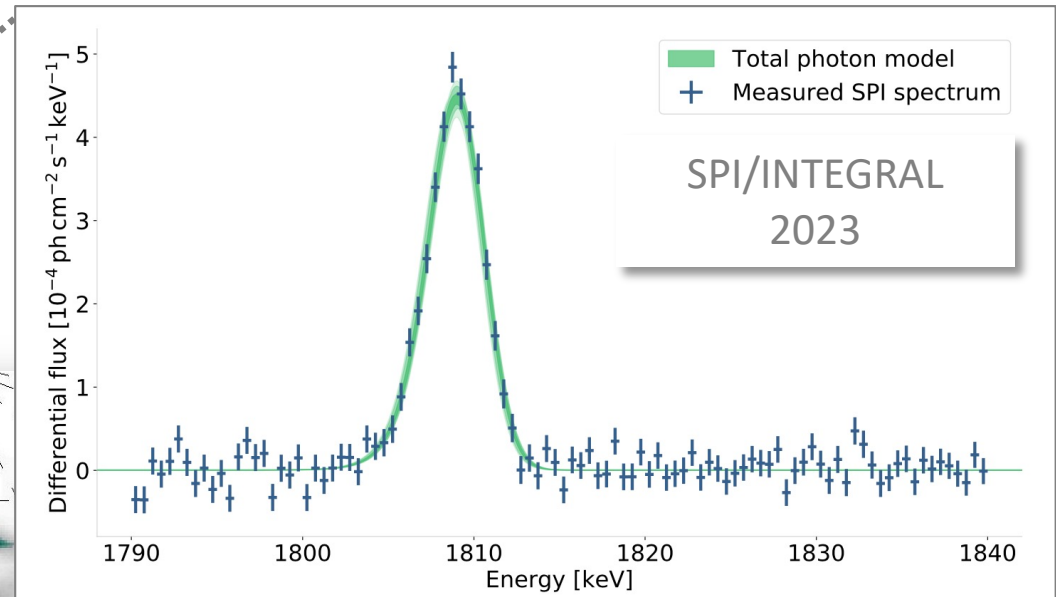


★ pre-explosive ^{44}Ti production is possible

Issa&Herwig 2025



^{26}Al γ -rays and the galaxy-wide massive star census



Cumulative from Massive-Stars & ccSNe

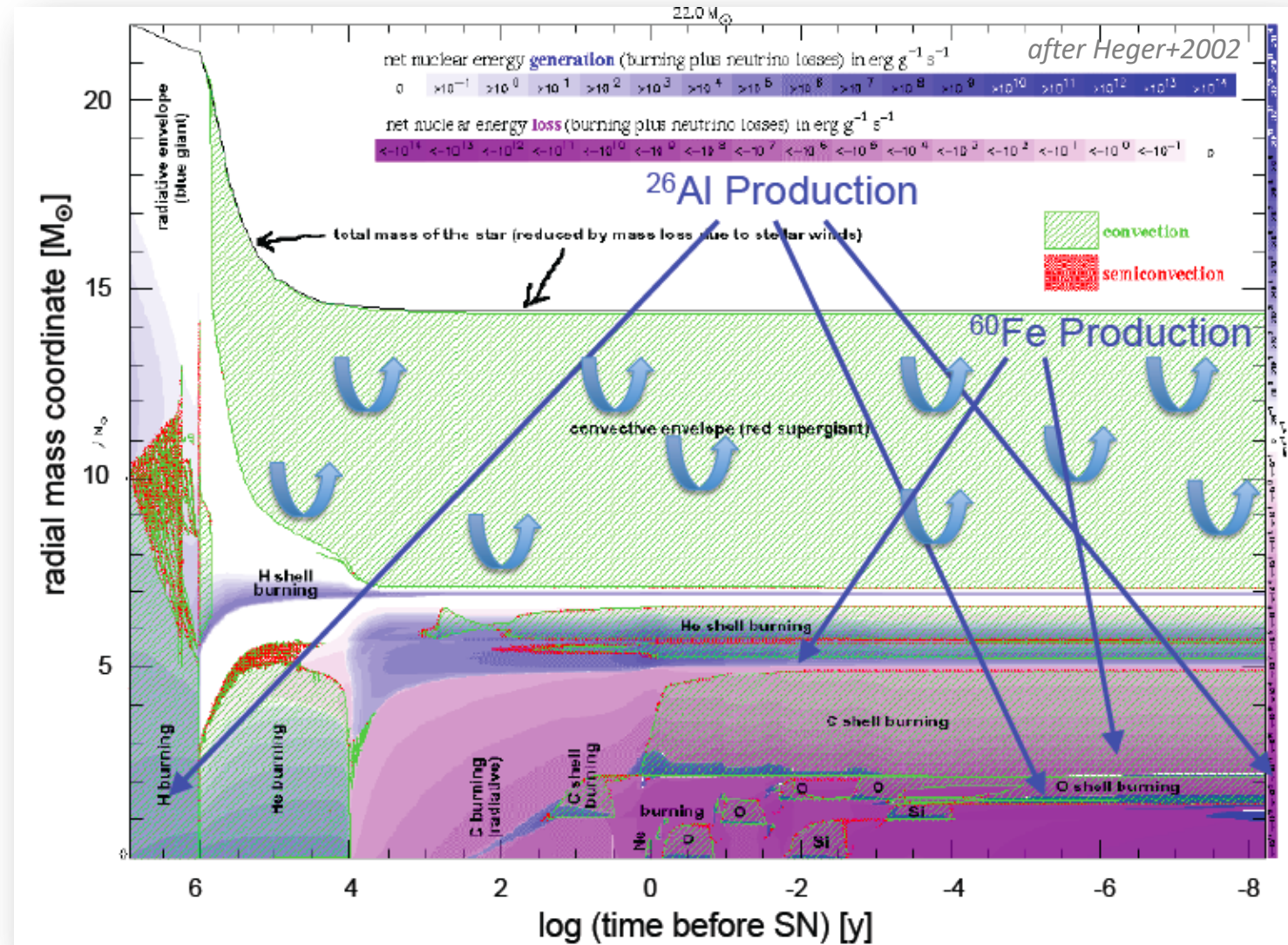
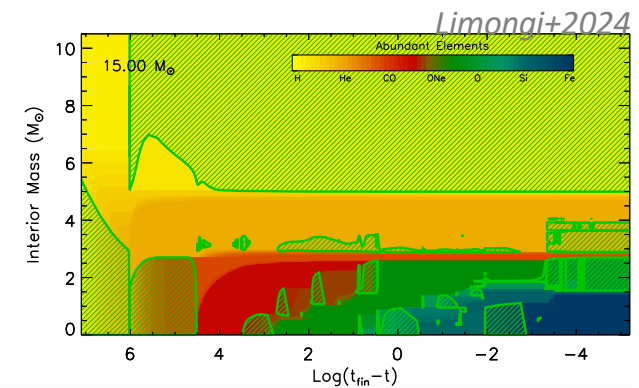
γ -ray flux $\rightarrow$ cc-SN Rate = $1.3 (\pm 0.6)$ per Century

Radioactivities from massive stars:

^{60}Fe , ^{26}Al

→ Messengers from Massive-Star Interiors!

...complementing neutrinos and asteroseismology!



Processes:

- ★ Hydrostatic fusion
- ★ WR wind release
- ★ Late Shell burning
- ★ Explosive fusion
- ★ Explosive release

Modelling a Massive-Star Group

Extract massive-star properties (as a function of their mass)

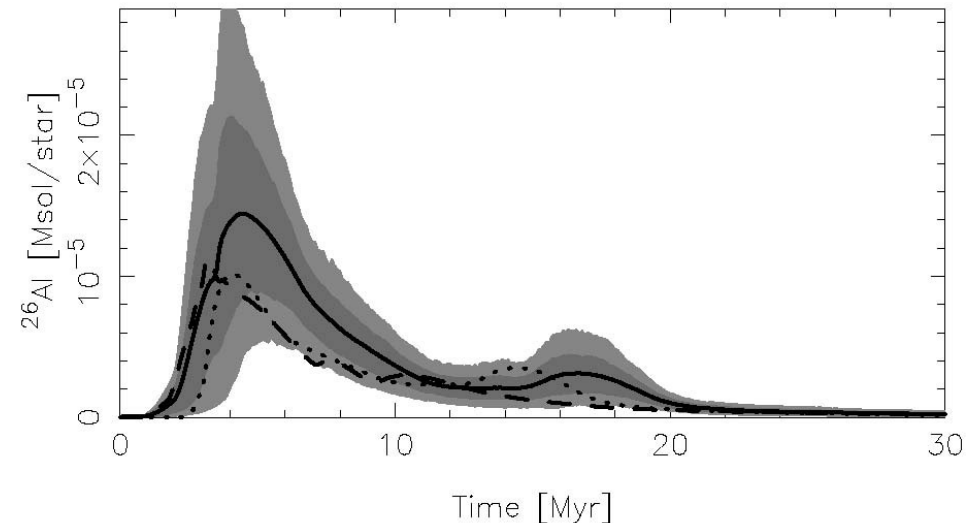
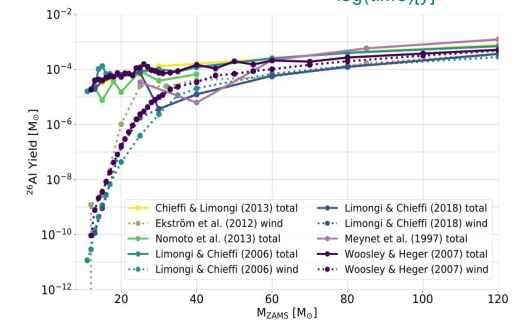
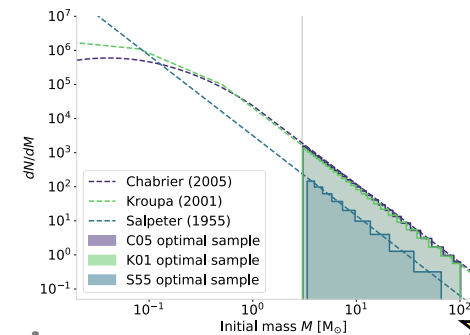
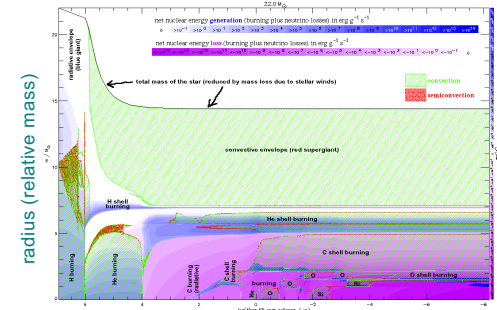
- ★ Stellar-evolution phases and their durations
- ★ Characteristic emissions in radiation, winds, and ccSN energy
- ★ Characteristic yield in nucleosynthesis

Create a sample for a group of stars

- ★ Exploit the mass distribution (IMF)

Accumulate the group outputs versus time

- 👉 loop over the star sample in small time steps and summing up outputs
- 👉 Time profiles of characteristic emissions
- 👉 Statistical variations



Population synthesis: impact of different inputs

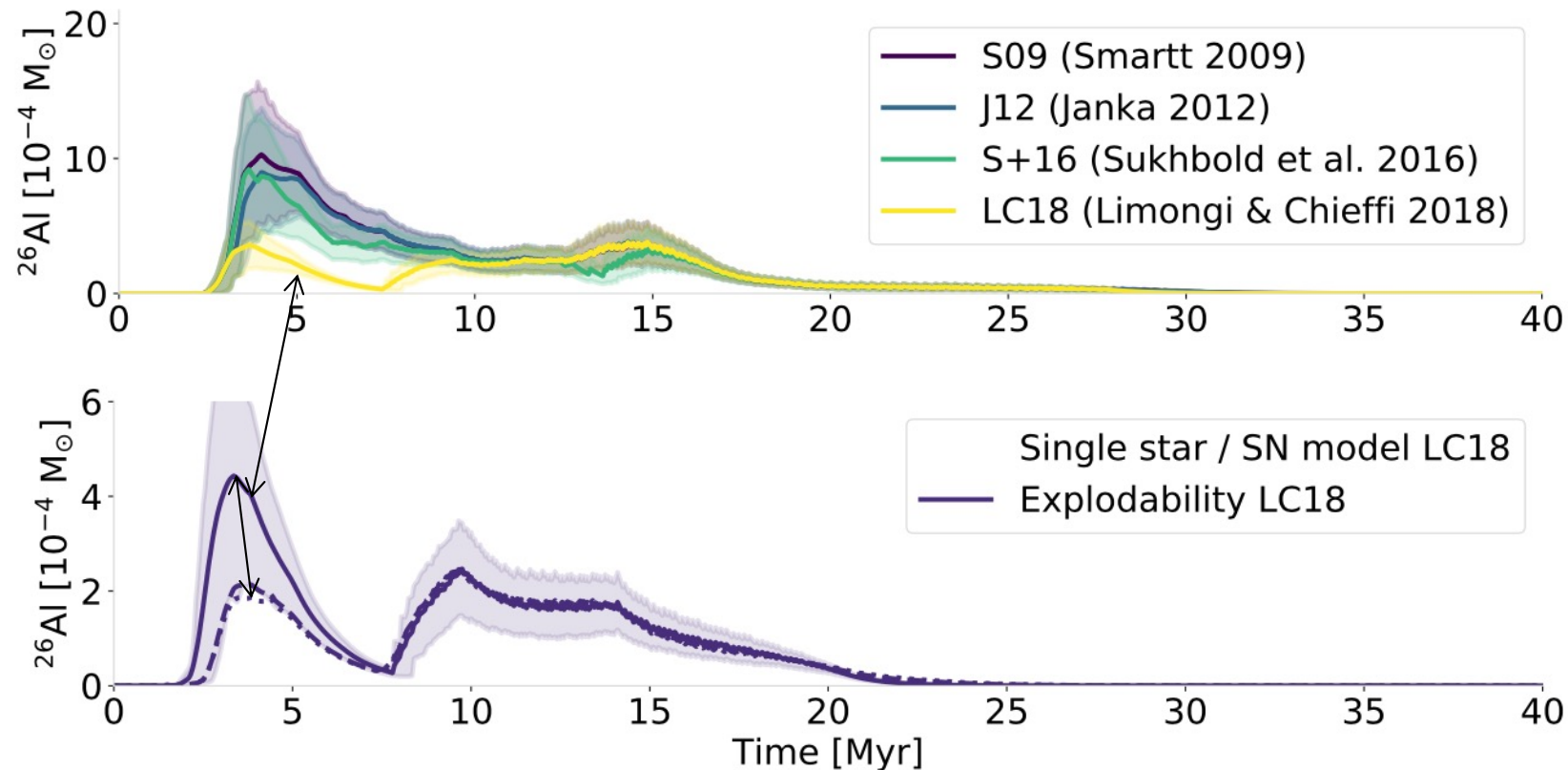
Acronym	Exploding stellar models
S09	$M_* \geq 8$
J12	$8 \leq M_* \leq 100$ and $140 \leq M_* \leq 260$
S+16	Irregular islands and valleys of explodability
LC18	$8 \leq M_* \leq 25$

variation of explodability

Pleintinger 2020

stic yields

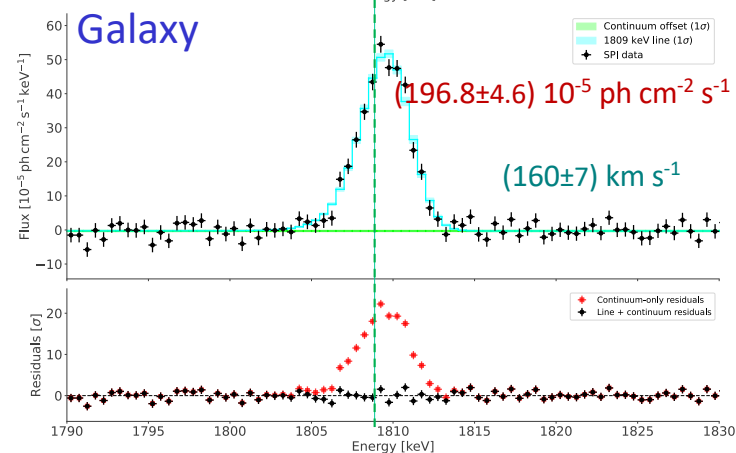
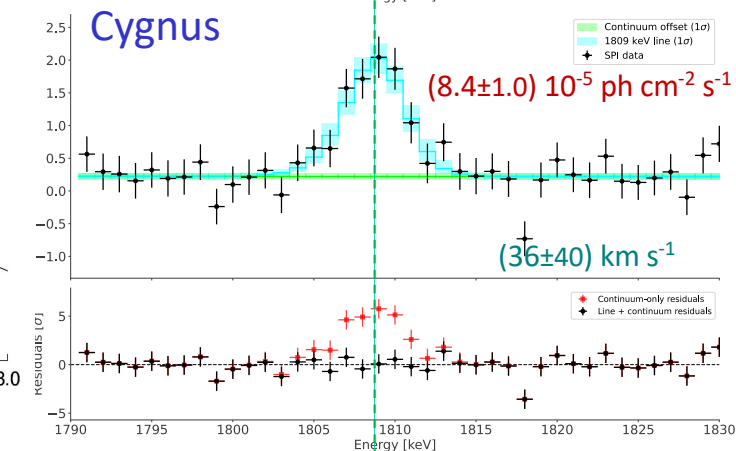
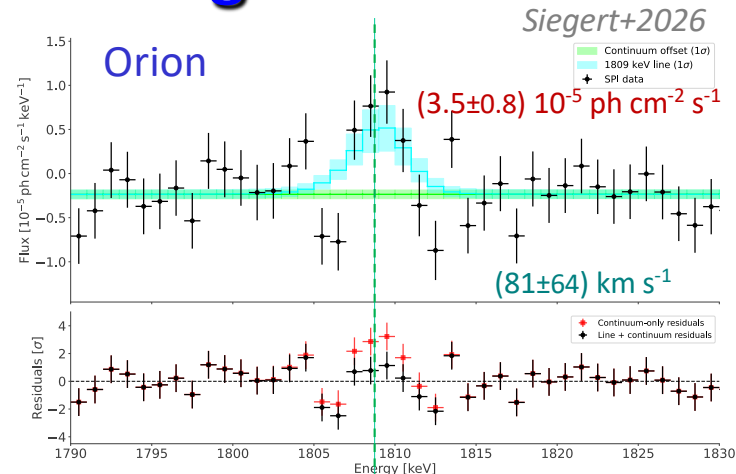
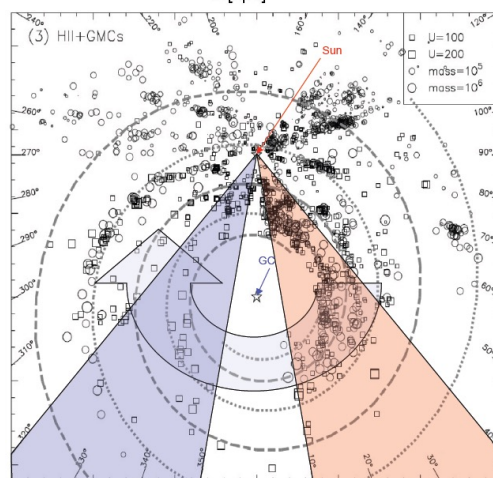
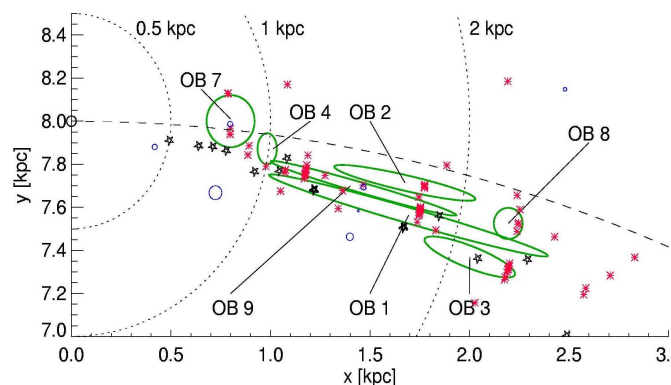
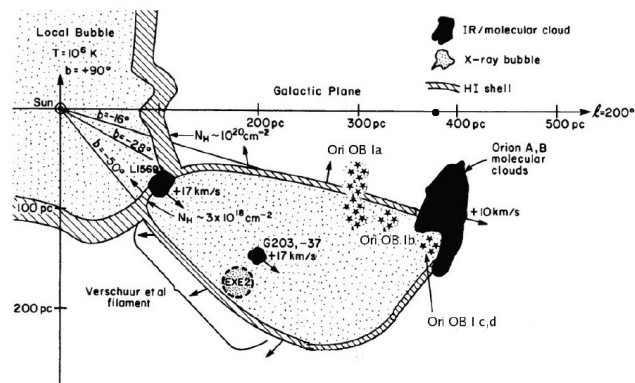
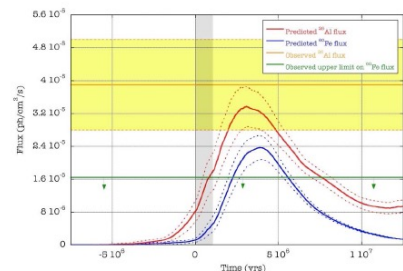
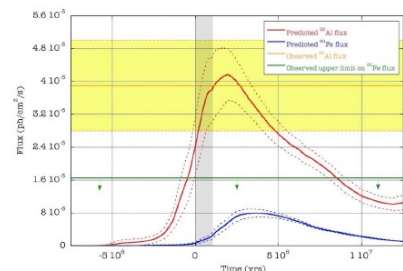
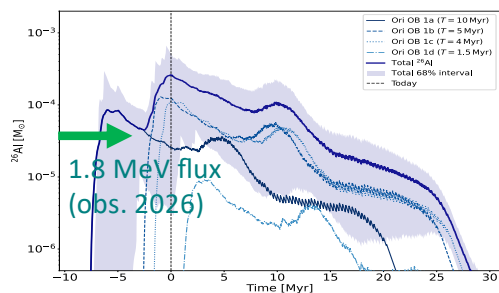
& Chieffi 2006



Binary wind yields from Brinkman + 2019

- Binary fraction = 0.0
- - - Binary fraction = 0.7
- Binary fraction = 0.9

Measuring ^{26}Al from massive-star regions

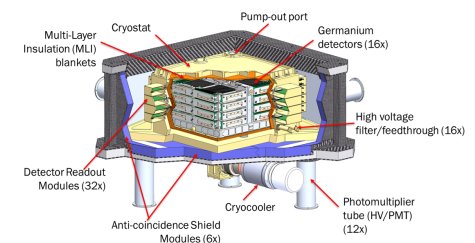
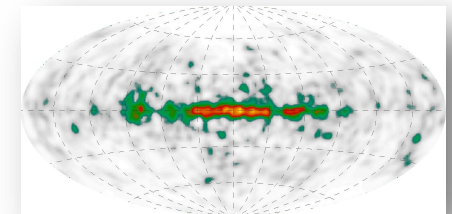
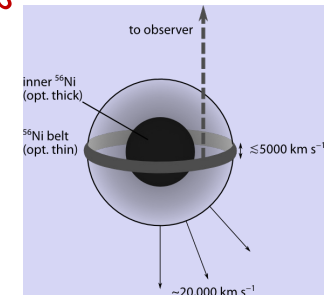


Gamma-Ray Spectroscopy - Summary

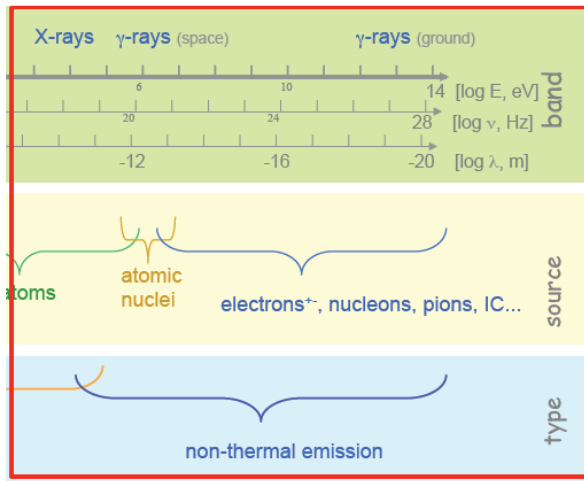
- ☆ ^{56}Ni mass has been determined to 20% precision (SN2014J),
~4% precision as a near-future perspective
- ☆ (even) SN Ia explosions appear not spherically symmetric:
 ^{56}Ni 'clumps' (SN2014J) → ignition off-center ?
- ☆ cc SNe reveal their inner asymmetries through ^{44}Ti ejecta:
Doppler shift reflects global asymmetry (Cas A)
- ☆ ^{26}Al (and ^{60}Fe) ejecta reflect shell-burning histories:
different massive-star groups provide probes at different ages;
ejecta can be traced flowing into circum-group (super-)bubbles
- ☆ Messengers complement each other with essential diagnostics:
Let us exploit nuclear physics expertise!

☞ Radioactivity provides a different view independent of T, ρ
on supernovae (explosion trigger; asphericity; pre-SN evolution)

☞ A next gamma-ray telescope (Laue lens / Compton telescope)
in 2040+??; INTEGRAL ended 2025; COSI (2027) is a great first step ...



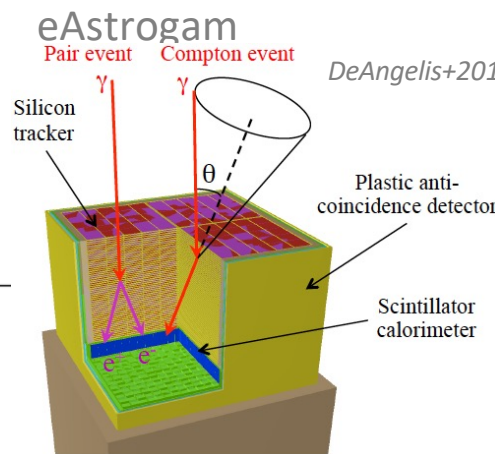
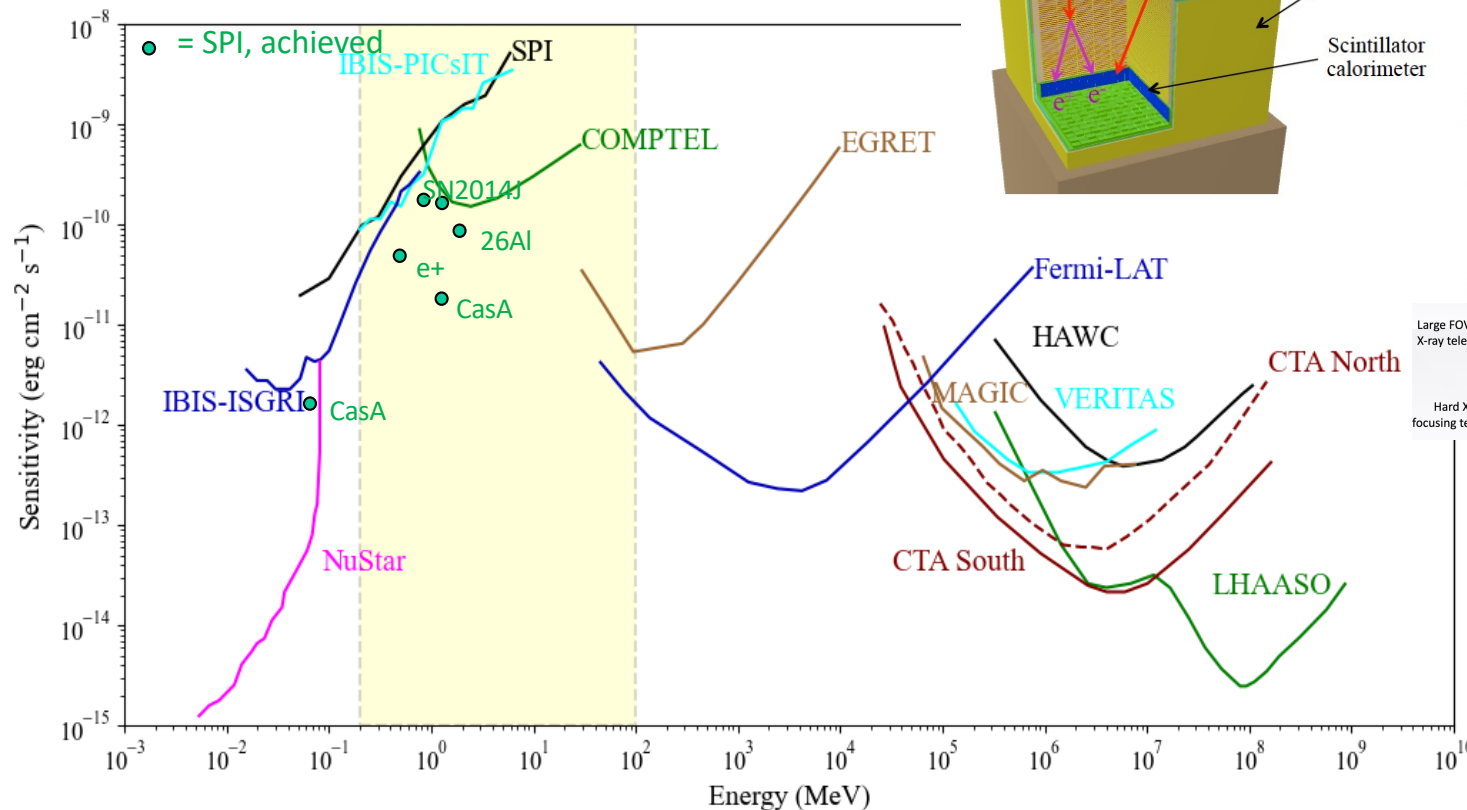
the 'MeV gap' challenge: significant astrophysics with new instruments



We can build on achievements for brightest sources
(and prospects from theoretical considerations: 'new'!)

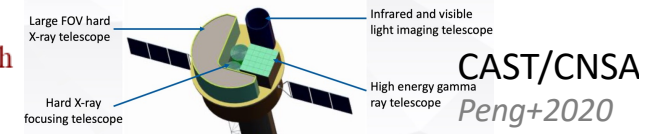
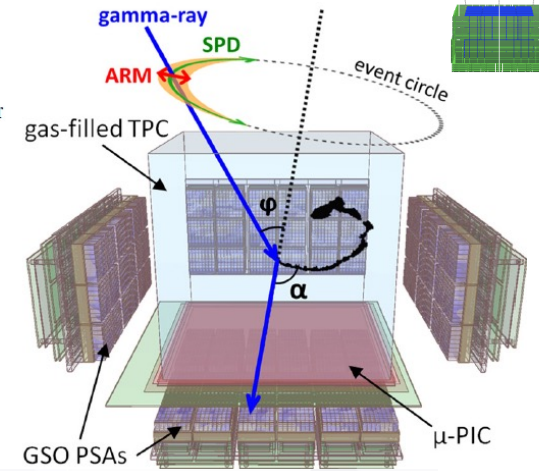
We can do now >one o.o.m. better now

Compton Telescopes+.. are being developed in labs

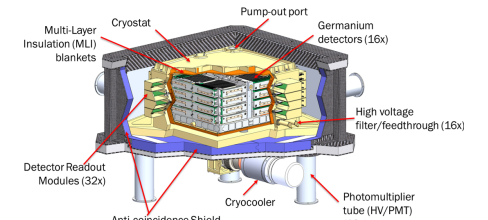


DeAngelis+2017, 2018

ETCC
Tanimori+2015



COSI/NASA
Tomsick+2021



Low-energy gamma rays: Complementary Messengers

- ^{56}Ni , ^{44}Ti , ... provide diagnostics of stellar explosions
- ^{26}Al radioactivity
gamma rays trace nucleosynthesis ejecta over $\sim$ few Myrs
- Radioactive emission is independent of density, ionisation states, ... , and provides a clock
- Positrons, when annihilating, produce a bright 511 keV line

