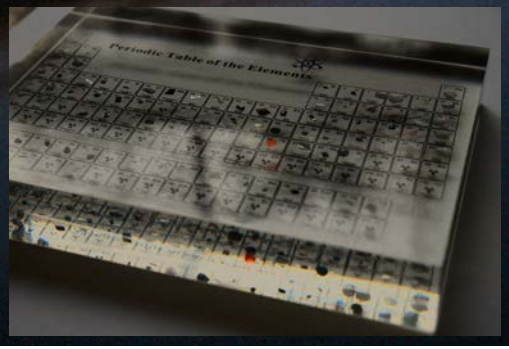


vanGogh: Starry Night

Nuclear Astrophysics with γ-ray Lines

Roland Diehl

MPE and TUM, Garching, Germany



Contents:

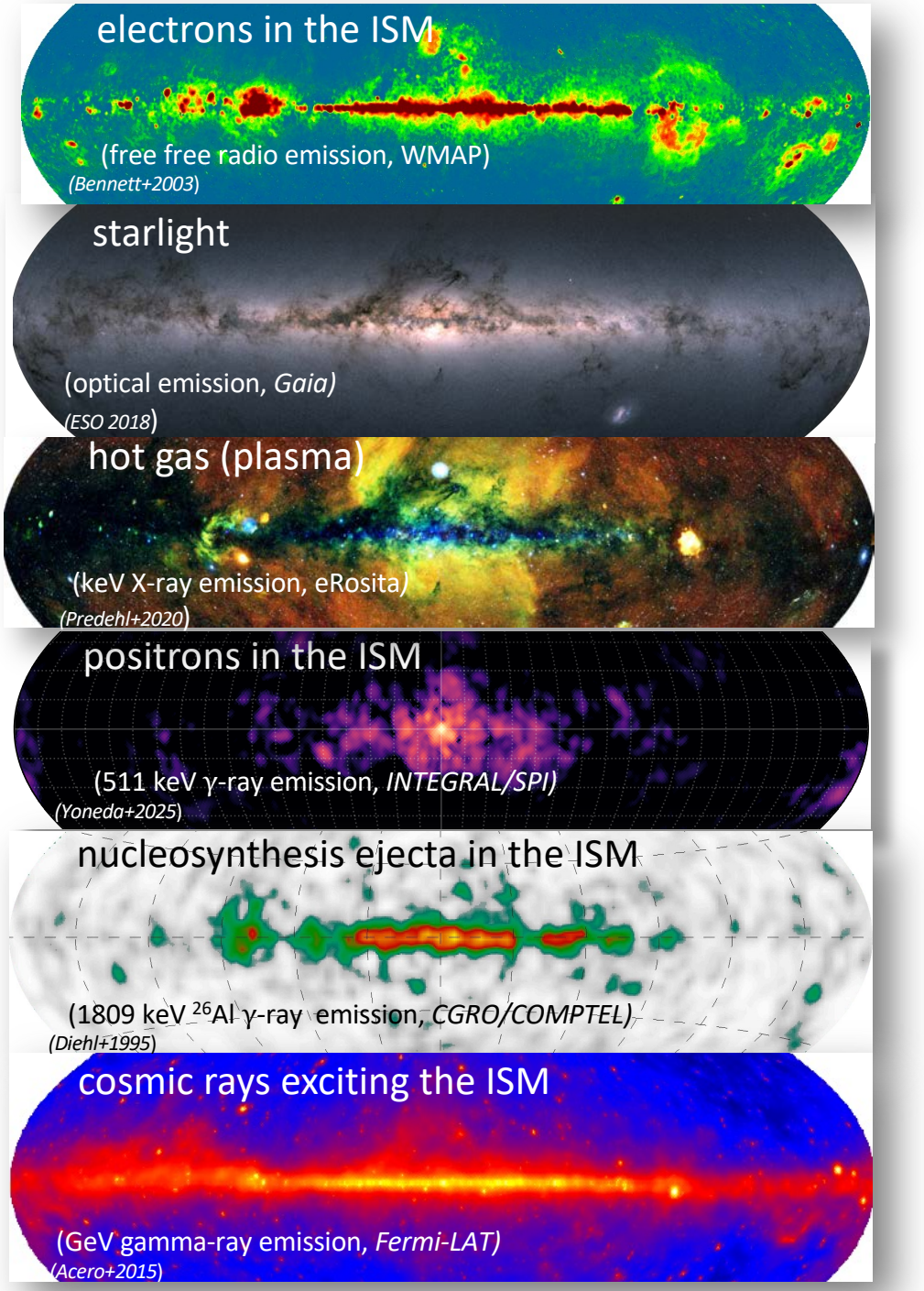
1. The MeV window in astronomy
2. Nuclear reactions and astrophysics
3. MeV lines from stars and explosions

Figure: ChETEC 2021

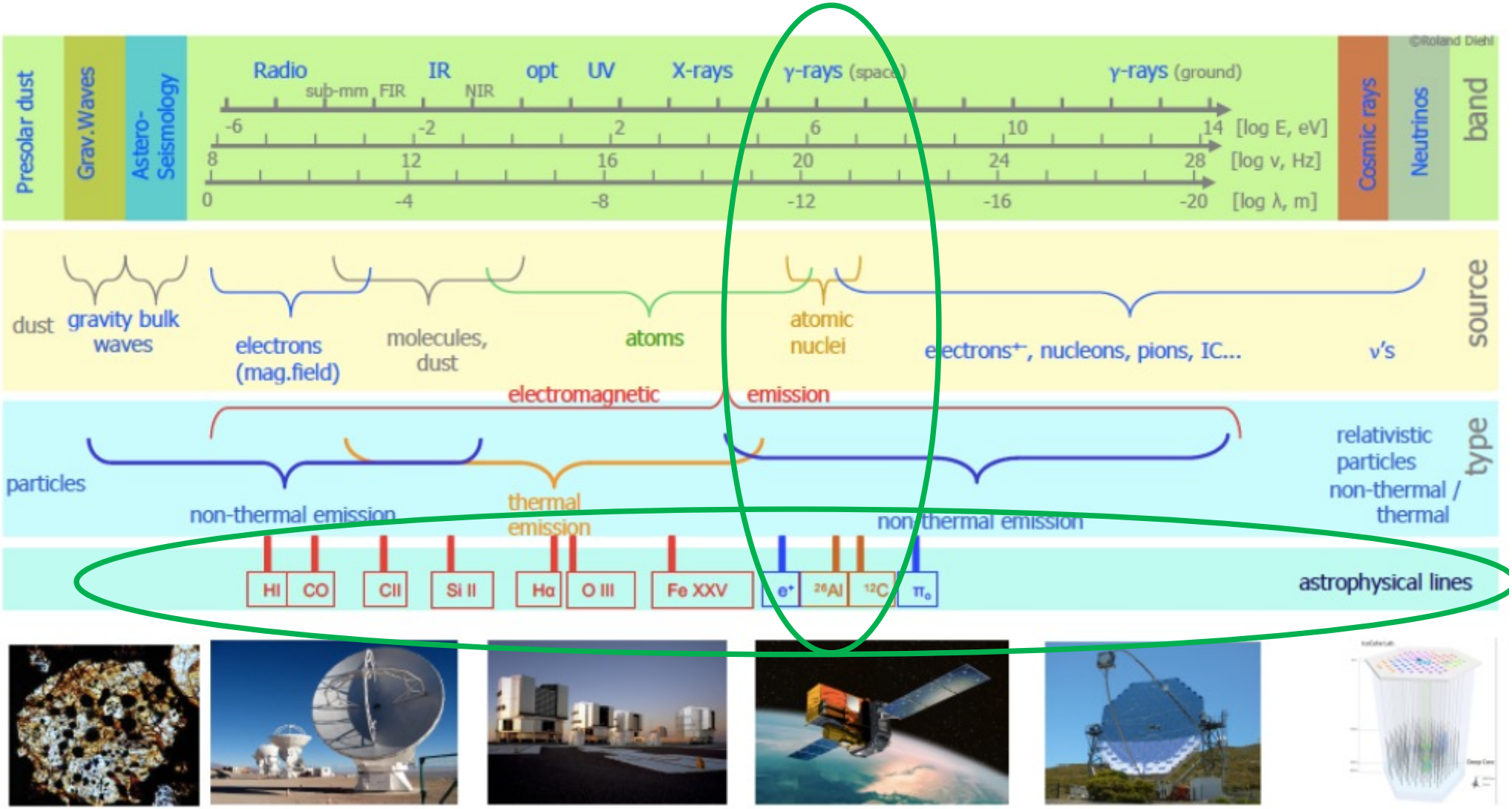
Astronomical Messengers from the Galaxy

The MeV region appears different to other familiar energy windows of astronomy

- Radioactivity gamma rays trace nucleosynthesis ejecta
- Positron annihilation ~traces CR propagation



Varieties of astronomical messengers | Characteristics | ~MeV energies



Relativistic particles: spectral signatures in gamma rays

- continuum science in the MeV region -

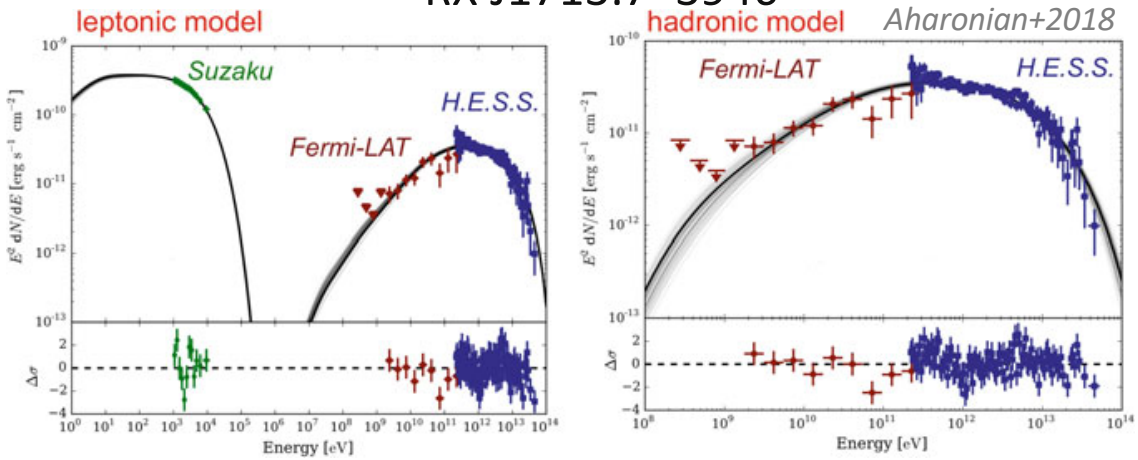
What accelerates cosmic relativistic particles?

☆ leptonic or hadronic emission?

→

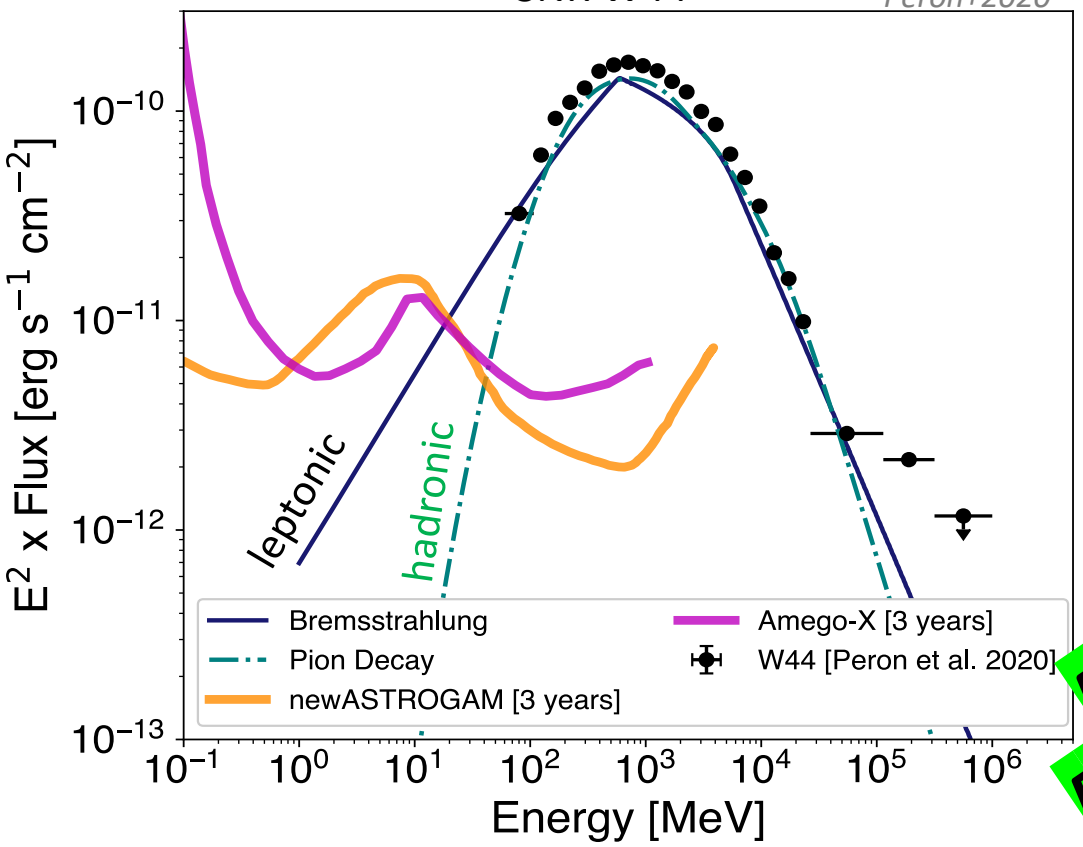
☞ e- and p distinguishable at MeV energies

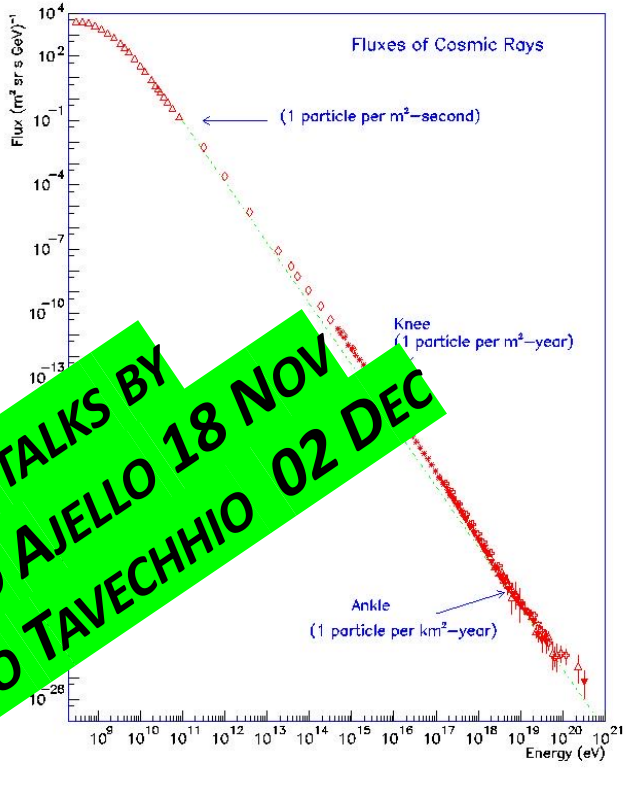
RX J1713.7−3946



SNR W44

Peron+2020

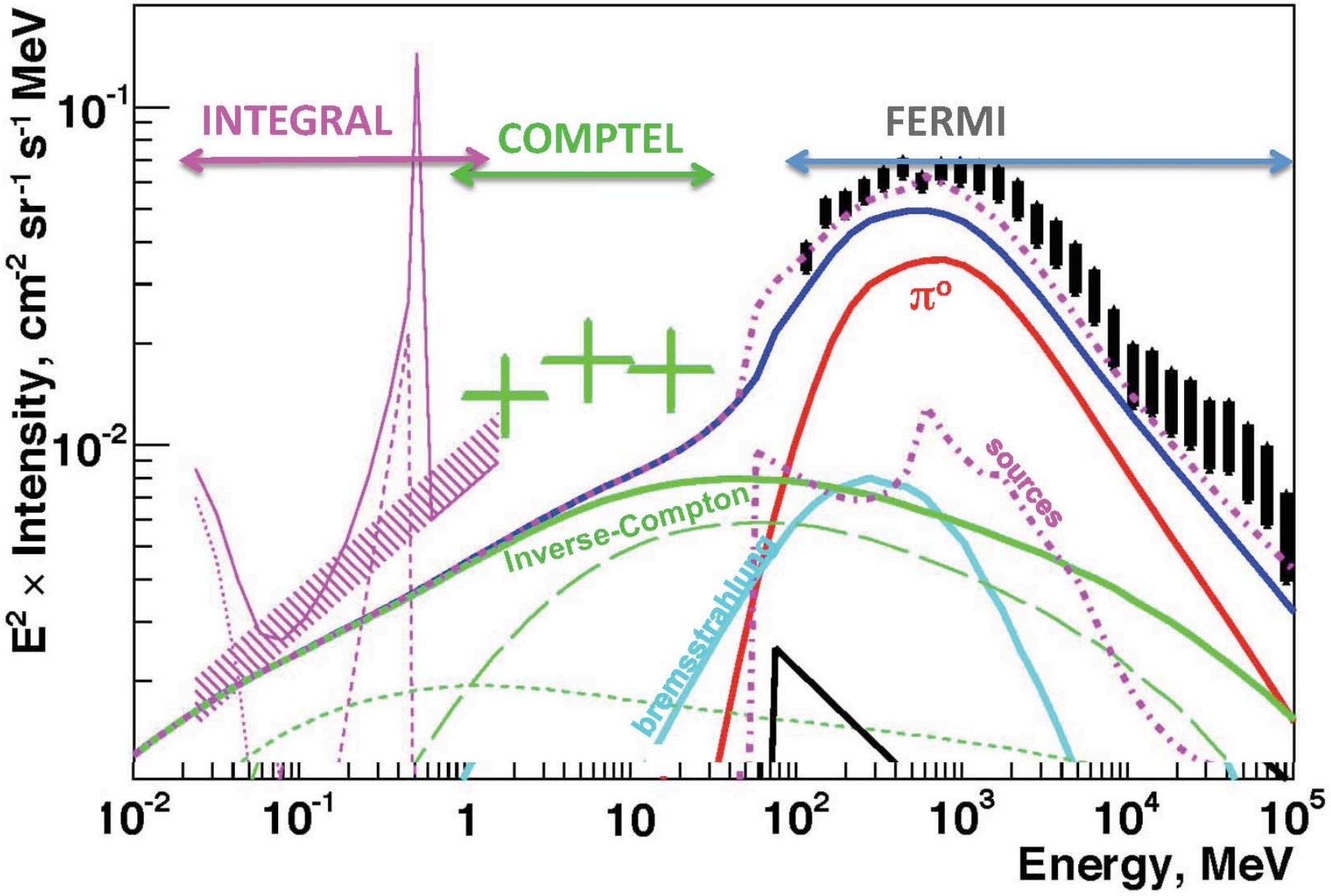




SEE TALKS BY MARCO AJELLO 18 NOV FABRIZIO TAVECHHIO 02 DEC

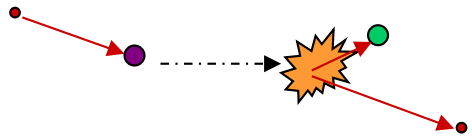
HE γ-ray emission from our Galaxy

- different emission processes from relativistic particles -



Known Positron Production Processes

✓ Cosmic-Ray Nuclear Reactions



☆ e.g. $^{12}C(p,pn)^{11}C(\beta^+)$, or $^{16}O(p,\alpha)^{13}N(\beta^+)$

☆ Pion production in HE collisions

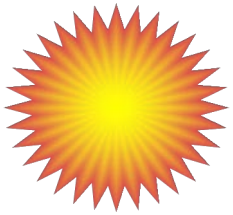
$$p + p \rightarrow \pi^+ + X$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (\tau = 2{,}6 \cdot 10^{-8}\ \mathrm{s})$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (\tau = 2{,}2 \cdot 10^{-6}\ \mathrm{s})$$

✓ Hot-Plasma Pair Production

☆ 'kT>MeV'-Plasma

$$\gamma+\gamma \rightarrow e^+ + e^-$$

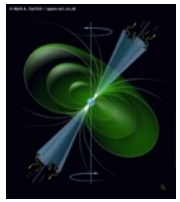


- ☞ Accretion columns & disks
- ☞ Base of relativistic jets

✓ E.M.-Cascade Pair Production

☆ Strong Magnetic Fields

$$\gamma+B \rightarrow e^+ + e^-$$

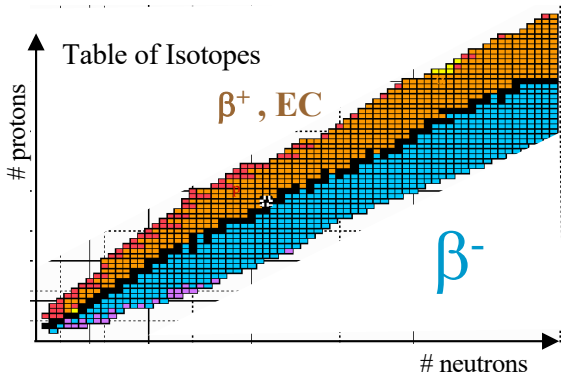


- ☞ Pulsars
- ☞ Jets

✓ Nucleosynthesis

☆ e.g. $^{56}Ni(\beta^+)$, $^{44}Ti(\beta^+)$, $^{26}Al(\beta^+)$, $^{22}Na(\beta^+)$,
$^{13}N(\beta^+)$, $^{14}O(\beta^+)$, $^{15}O(\beta^+)$, $^{18}F(\beta^+)$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \nu_e$$



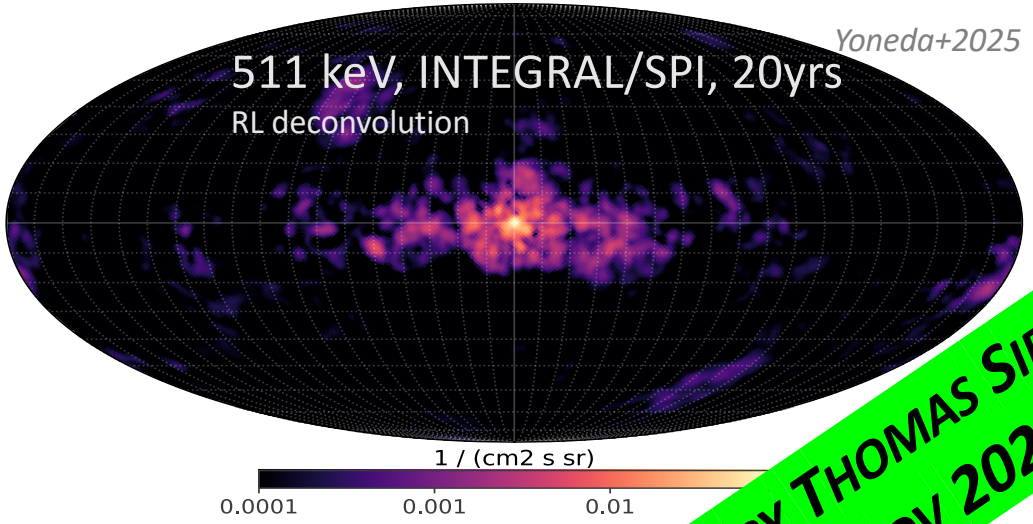
see also Ruffini+2010 for more

Positrons in the Galaxy:

INTEGRAL/SPI results from >20 years

→ (alternative)Image of Annihilation emission

bright extended central emission,
disk extended in latitude width
→ unlike any candidate source map



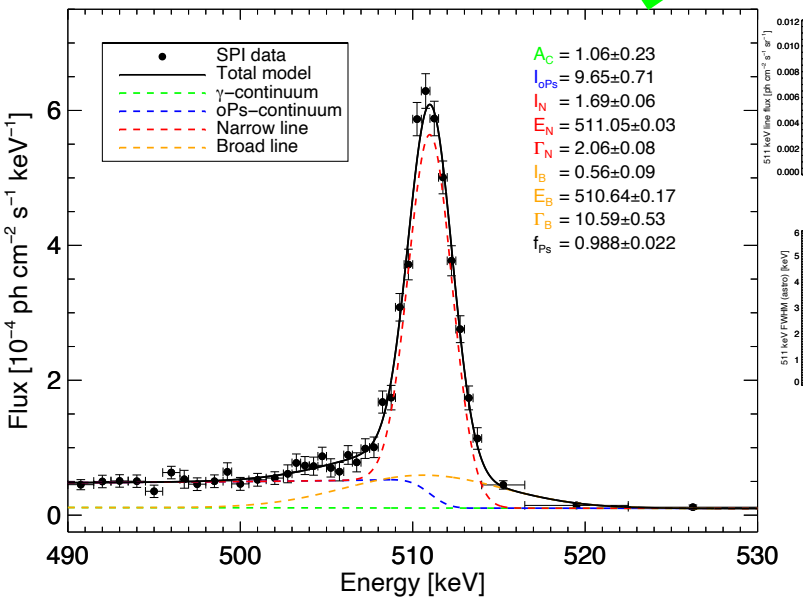
Yoneda+2025

SEE TALK BY THOMAS SIEGERT ON 4 NOV 2026

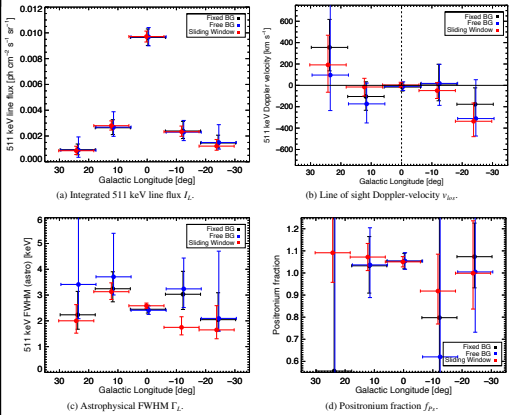
→ Line spectroscopy

and PS continuum emission

slightly-broadened line
significant continuum
→ annihilation medium ~partly ionised"



Siegert+2019

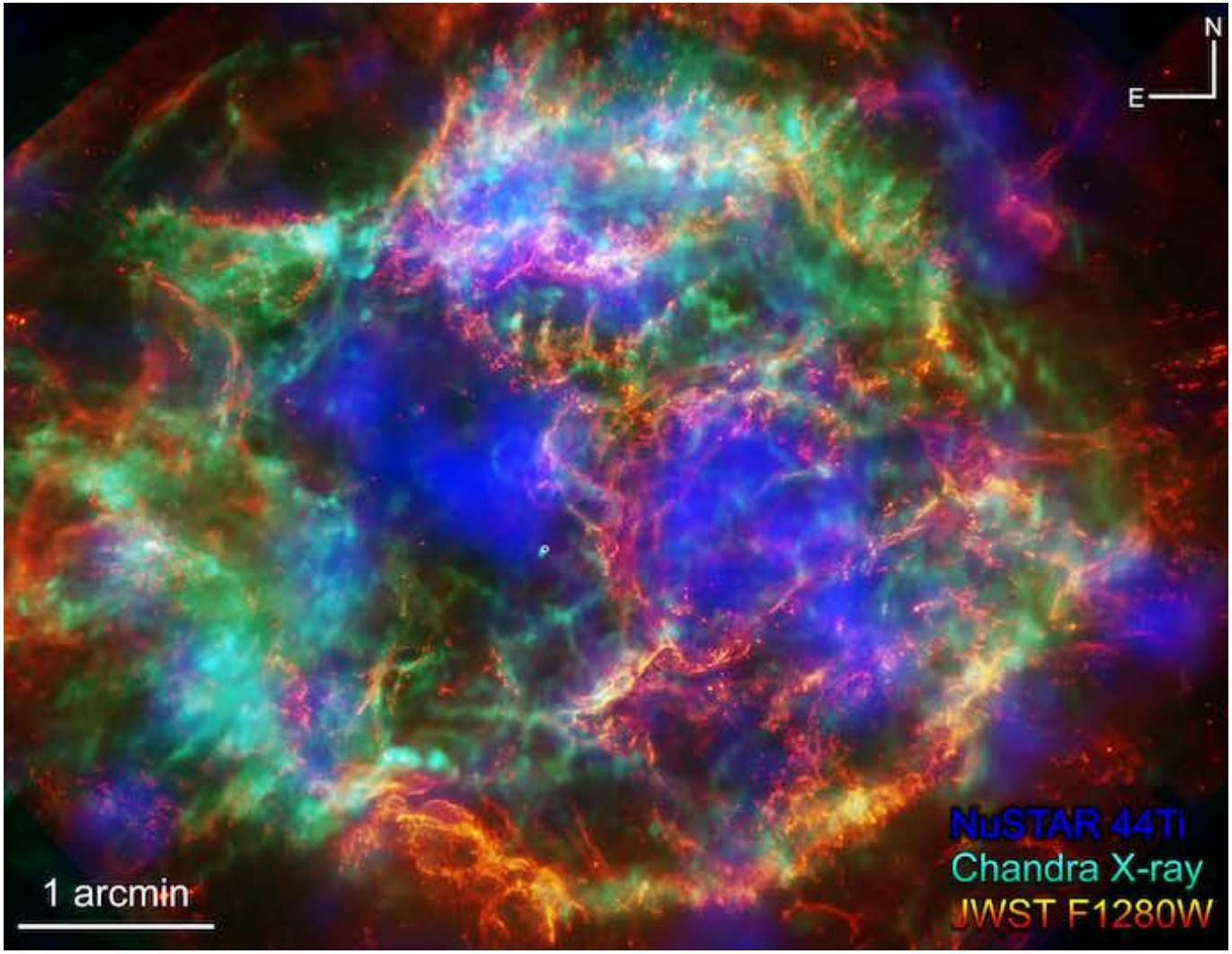


line parameters versus longitude (flux, velocity, width, Ps cont)

The Cas A Supernova Remnant

Combining radiation data from IR through X rays to gamma rays

Milisavljevich+ 2024



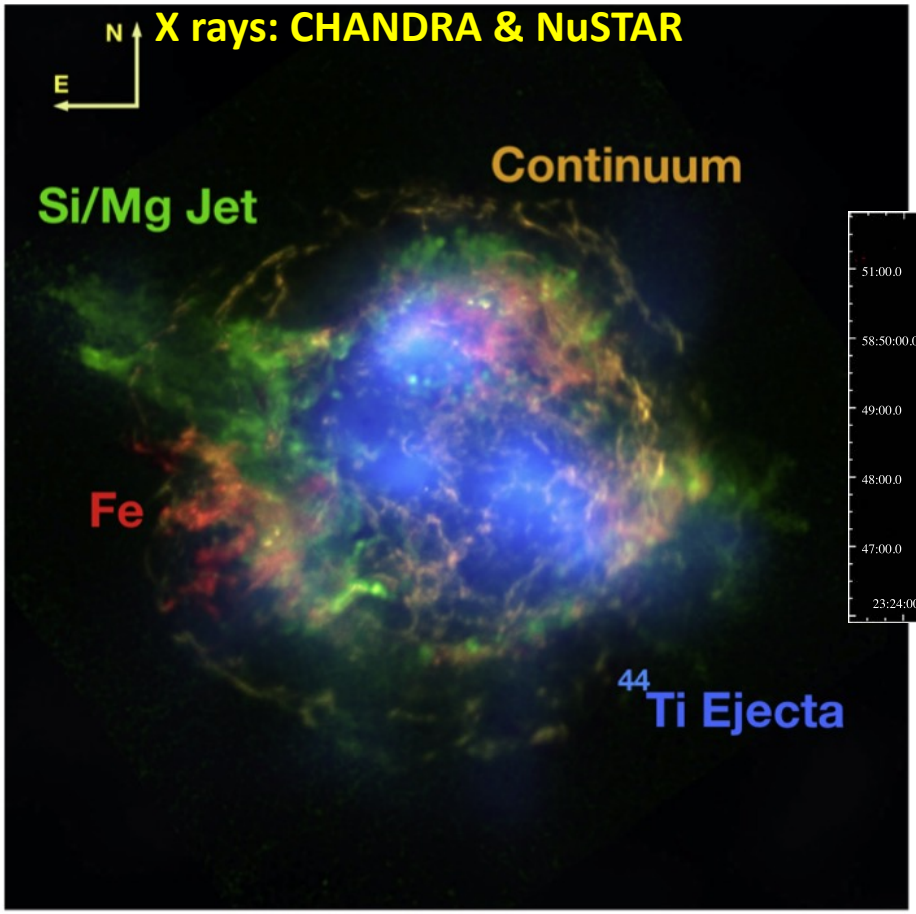
→ what can nuclear γ rays add / provide??

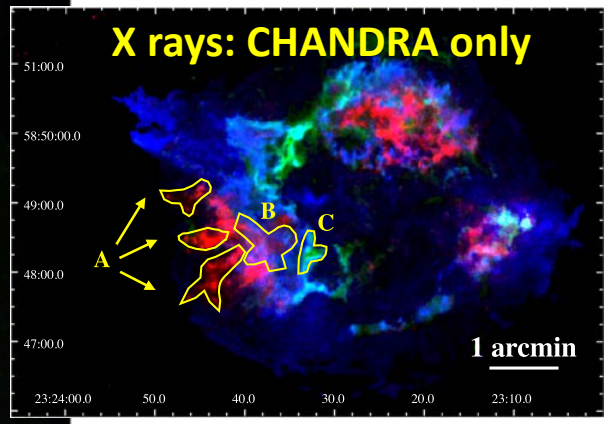
Locating the inner Ejecta in Cas A: Nuclear astronomy

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

☞ first mapping of radioactivity in a young SNR (core origin)

Grefenstette+ 2014; 2017





Tsuchioka+2022


Fig. 1. NuSTAR telescopes in deployed configuration

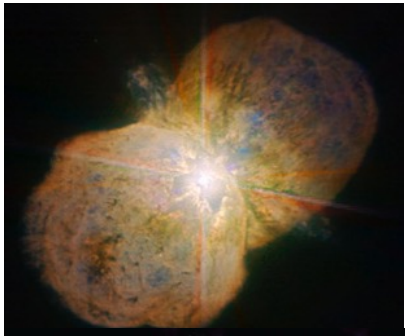
☞ ^{44}Ti radioactive decay → TRUE locations of inner-SN ejecta

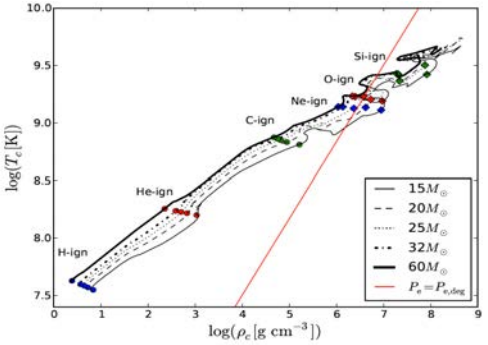
☞ Fe-line X-rays are biased from ionization of plasma by reverse shock (shock did not reach interior yet)

The challenges of cosmic nucleosynthesis sources

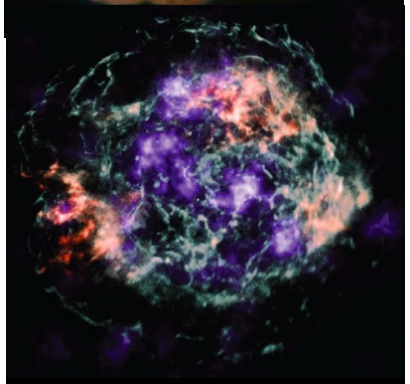
Stellar Explosions: Supernovae (ccSN, SN Ia, NSM)

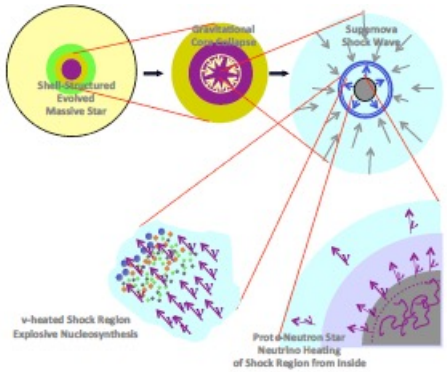
Stars



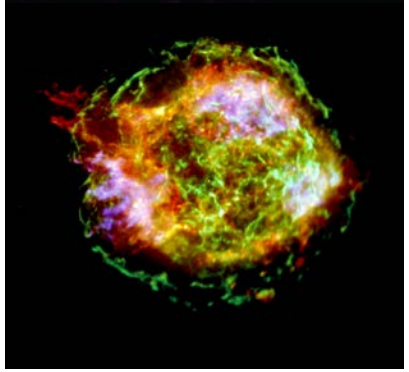


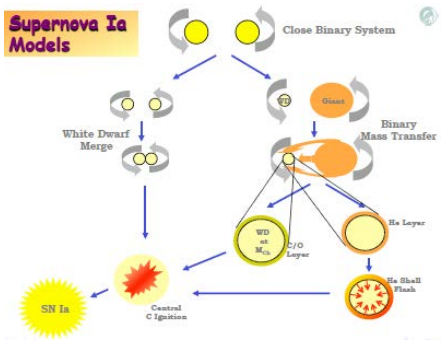
- How much mass is lost in which winds?
- How are fusion fuels & products mixed?
- What is the composition of remnant star?



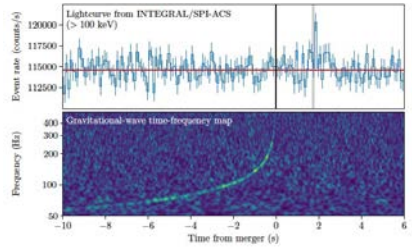


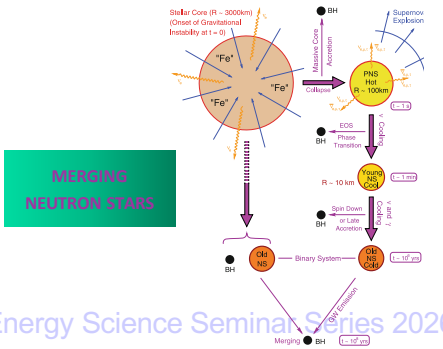
- Which stars explode as a supernova?
- Which parts of collapsing star are ejected?





- Which white dwarfs explode (DD/SD)?
- How is the explosion triggered?
- Which burnings can occur?

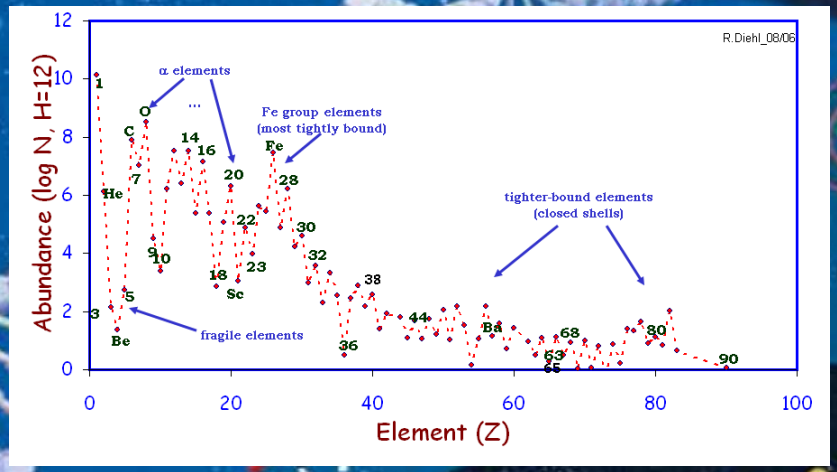


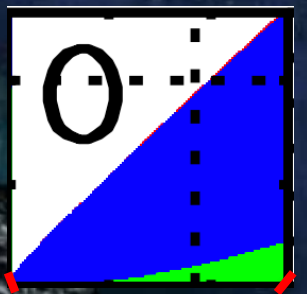


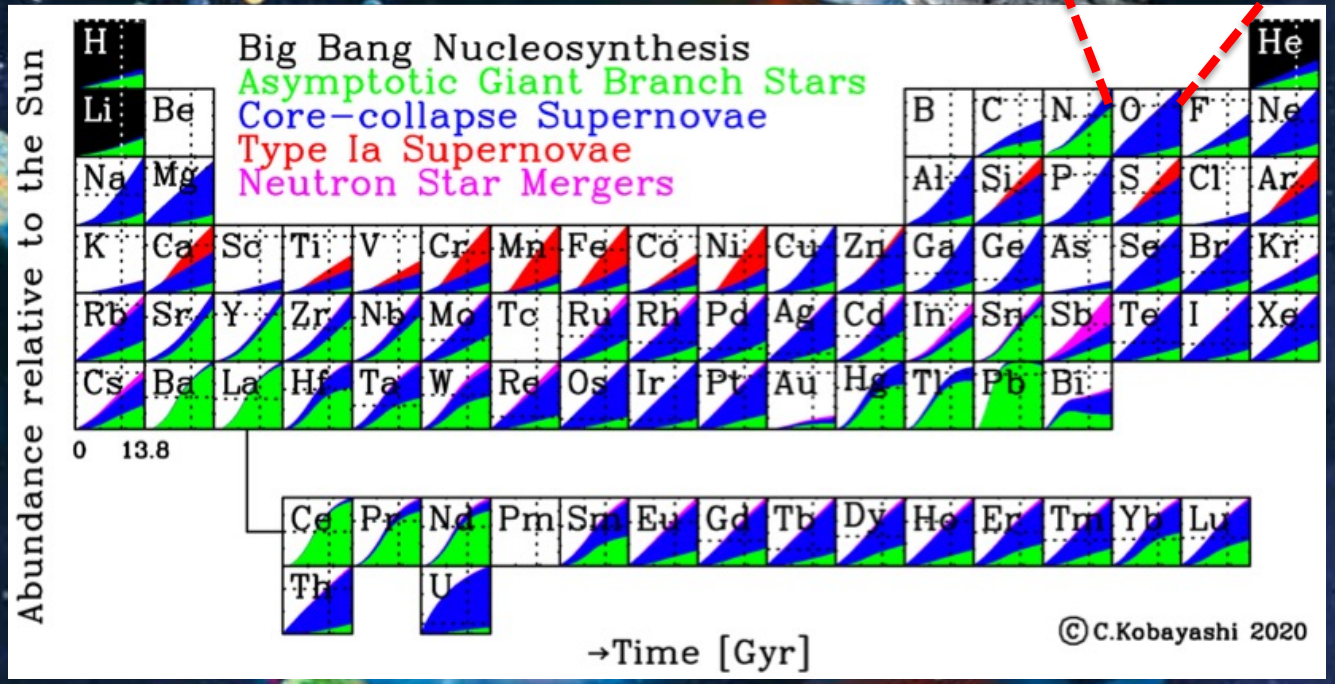
- Which compact stars merge, and when?
- How is the black hole formed?
- Which materials may escape?

Nuclear Astrophysics

what are our origins?

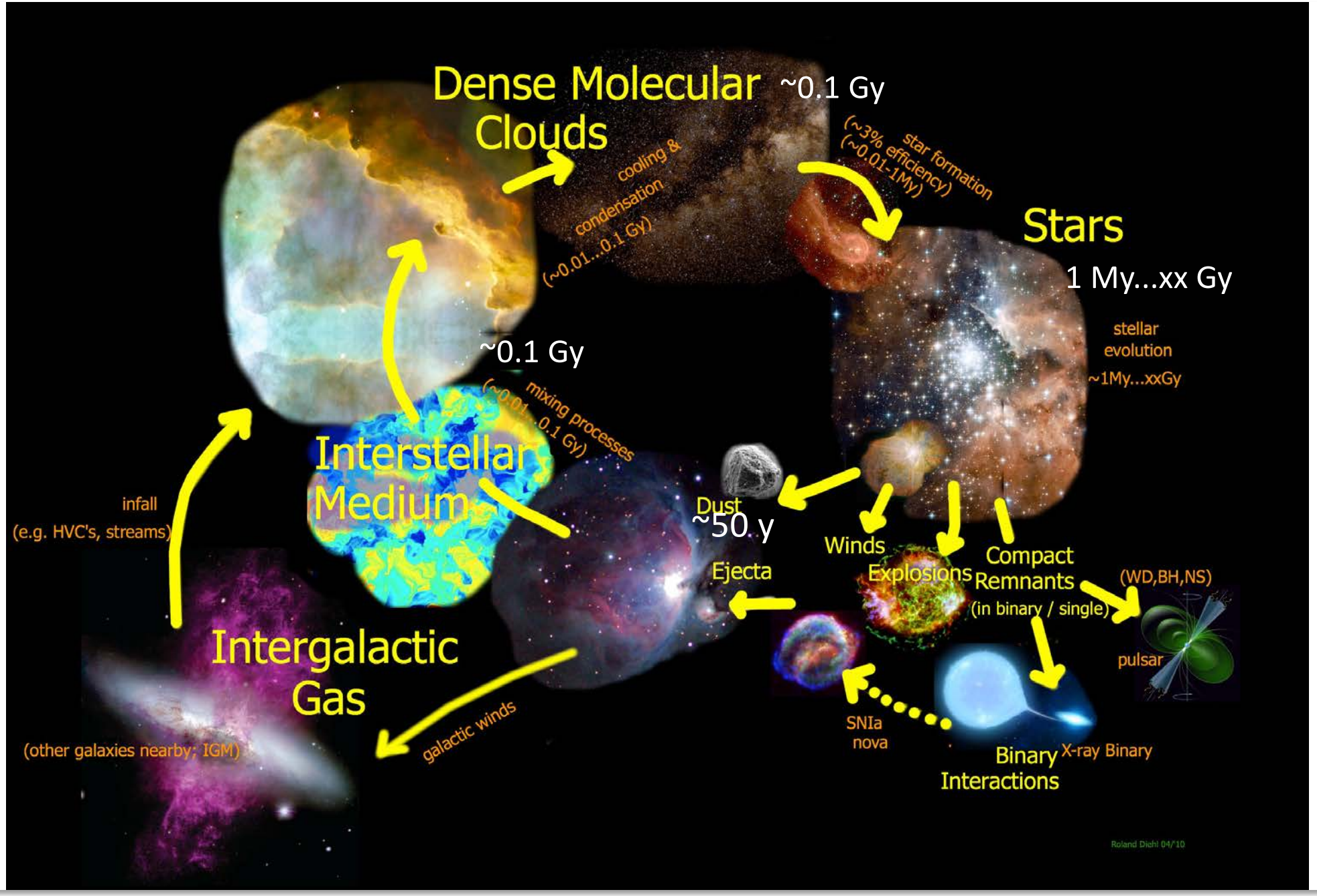




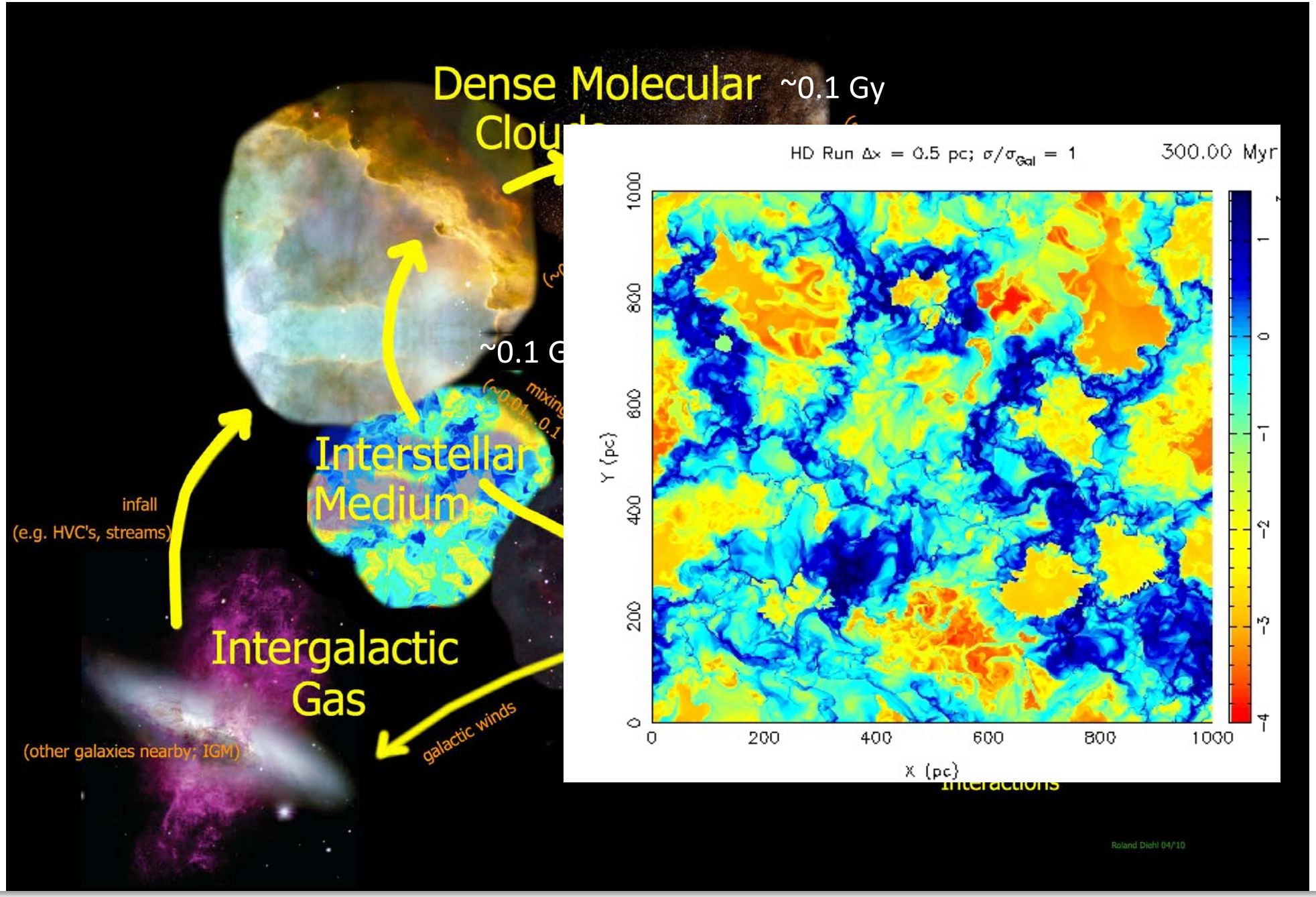


The answers include: models of the sources and the nuclear rates within, and of cosmic evolution including transport and recycling

Iterative enrichments of stellar gas from nucleosynthesis

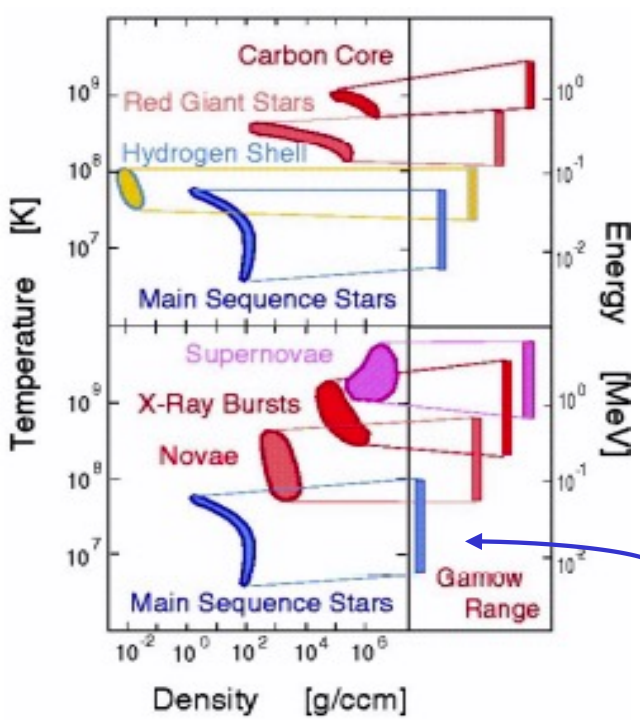


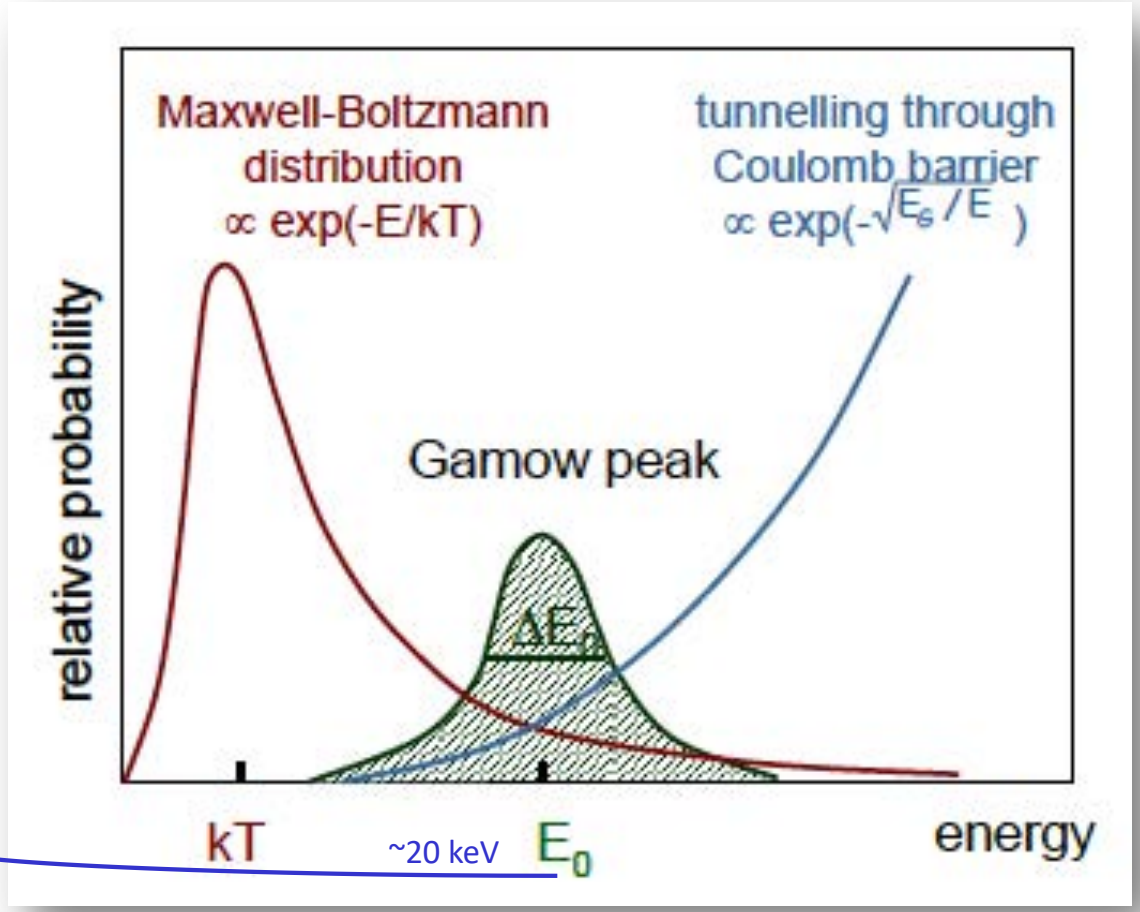
chemical-evolution models: how to capture ejecta in a star...



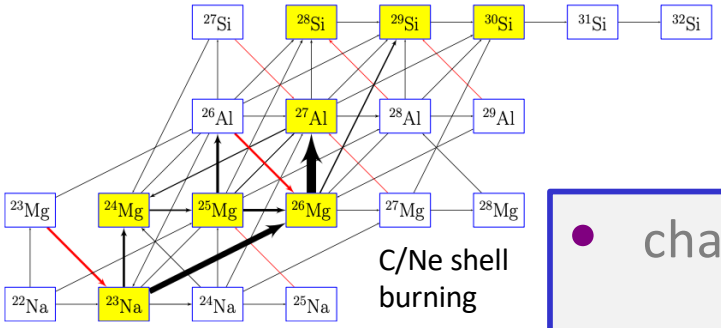
Nuclear reactions in cosmic environments

- ☆ plasma in the Universe is very different from the conditions in terrestrial laboratory experiments
- ☆ quantum tunneling dominates in cosmic-environment reactions



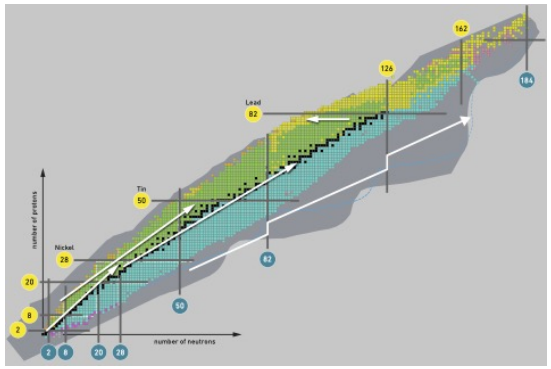


Cosmic Nuclear Reactions

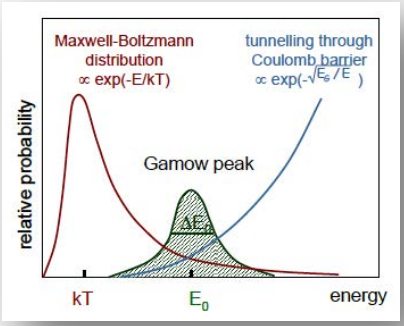


C/Ne shell burning

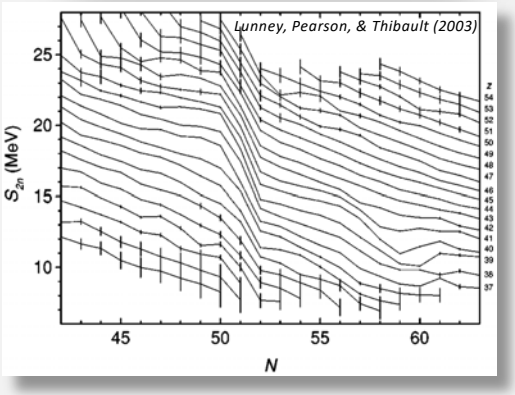
complex nuclear networks are composites of a few reaction types



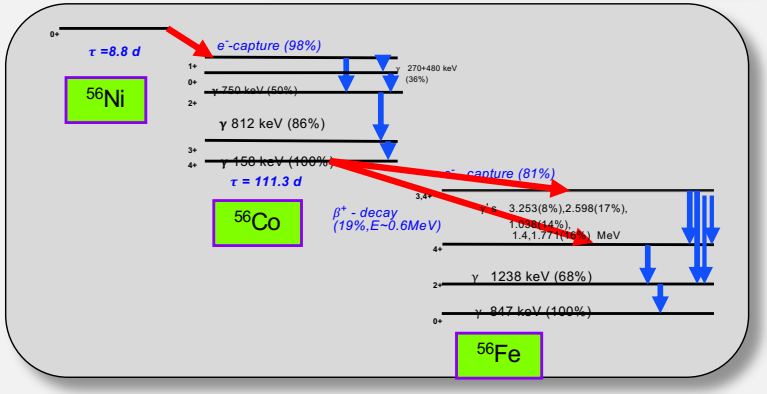
- charged-particle reactions
  - ☞ overcome Coulomb repulsion



- neutron capture reactions
  - ☞ neutron binding by nuclear force



- radioactive decays (&EC)
  - ☞ proton ←→ neutron conversions from weak force

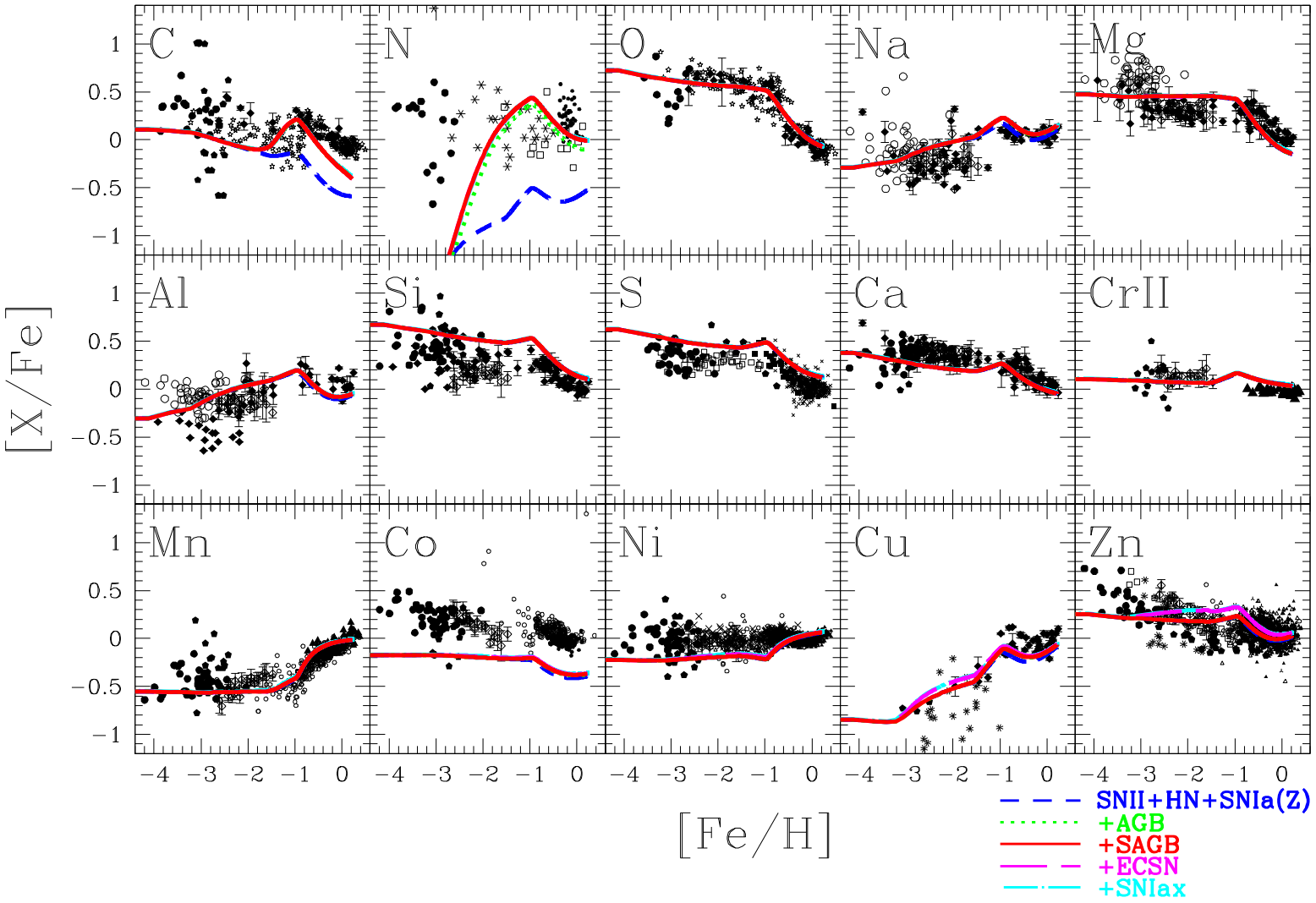


- photon reactions
  - ☞ nuclear levels from nucleon configurations

Stellar abundances versus chemical-evolution models

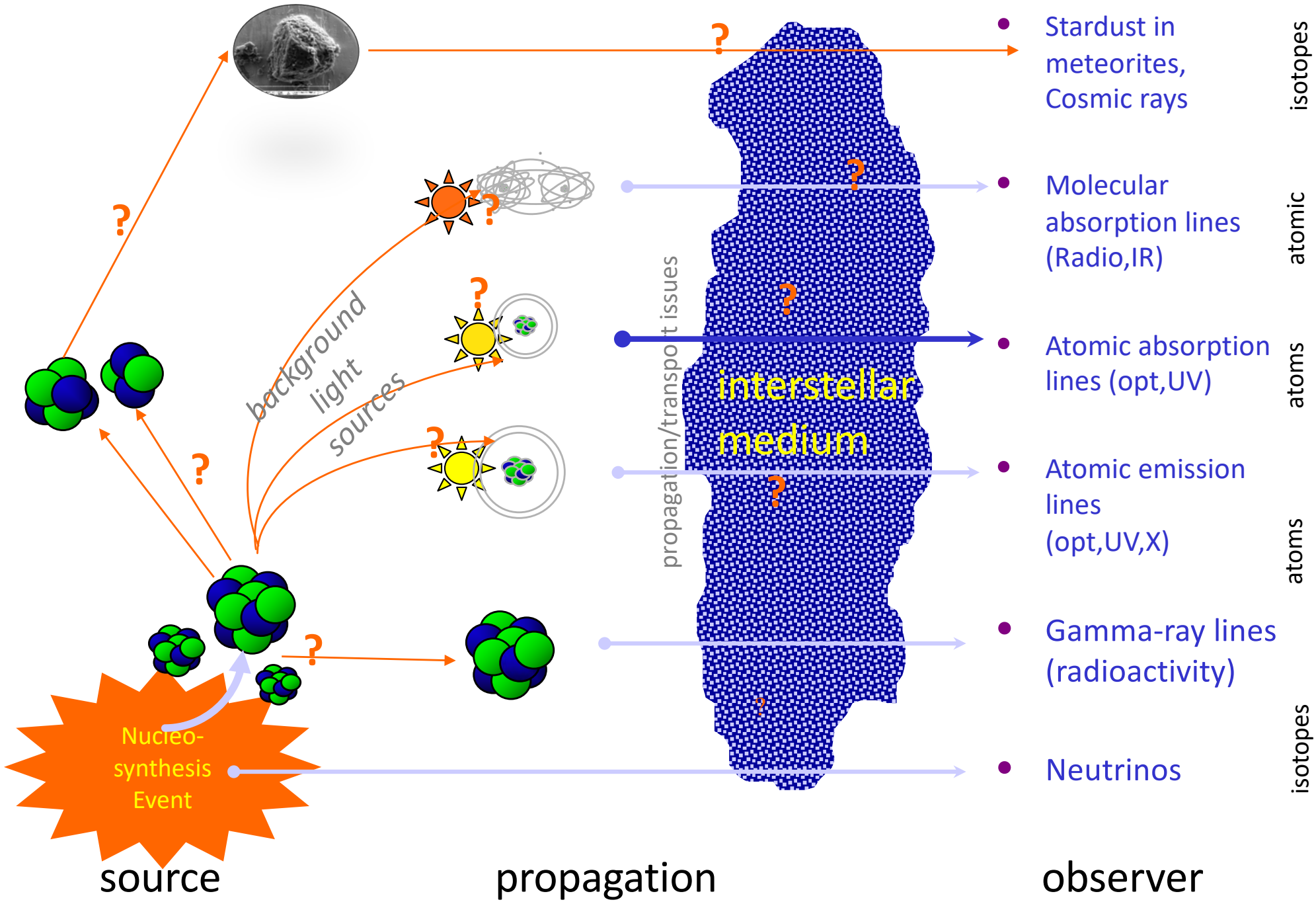
elemental abundances throughout Galaxy

Kobayashi+ 2020



→ agreements for many elements, serious issues for several elements

Observing Nucleosynthesis: Complementing Methods



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}Tl → ^{208}Pb	511, 722, 861, 2615	(none)	NSMs
^{128}Sb	13 h	^{128}Sb → ^{128}Te	75, 404, 482	(none)	White Dwarf AIC, NSMs
^{132}I	4.6 d	^{132}Te→ ^{132}I → ^{132}Xe	506, 523, 630, 668, 773, 1318	(none)	White Dwarf AIC, NSMs
^{89}Sr	50 d	^{89}Sr→^{89}Y	909	(none)	acc: White Dwarf, AGB
^{7}Be	77 d	^{7}Be → ^{7}Li*	478	(none)	Novae
^{56}Ni	8.8 d; 111 d	^{56}Ni → ^{56}Co* →^{56}Fe*+e$^+$	158, 812; 847, 1238	SN2014J; SN1987A, SN1991T(?)	Supernovae
^{57}Ni	390 d	^{57}Co→ ^{57}Fe*	122	SN1987A	Supernovae
^{22}Na	3.8 y	^{22}Na → ^{22}Ne* + e$^+$	1275	(none)	Novae
^{44}Ti	85 y	^{44}Ti→^{44}Sc→ ^{44}Ca*+e$^+$	78; 68; 1157	SNR Cas A	Supernovae
$^{229/230}$Th	~1.0 10^5 y	$^{229/230}$Th →.....→ ^{206}Pb	352... 609…2615	(none)	NSMs, SNe
^{126}Sn	3.3 10^5 y	^{126}Sn →^{126}Sb* →^{126}Te	666; 695; 87; 64	(none)	NSMs, SNe
^{26}Al	1.04 10^6 y	^{26}Al → ^{26}Mg* + e$^+$	1809	Massive-Star Groups Cyg, Ori…	Stars, Novae Supernovae
^{60}Fe	3.5 10^6 y	^{60}Fe → ^{60}Co* → ^{60}Ni*	59, 1173, 1332	Galaxy (?)	Supernovae, Stars
e$^+$	10^5… 10^7 y	e$^+$+e$^-$ → Ps → γγ..	511, <511	Galactic Bulge, Disk	Supernovae, Novae, Pulsars, Microquasars…

radioactive by-products of nuclear reactions provide a new/different observational window on interiors of cosmic nuclear reactors

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

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

plus: nuclear excitation lines (2.2; ^{12}C, ^{16}O, …) (from CRs)

Nuclear Gamma-Ray Line Telescopes / Missions

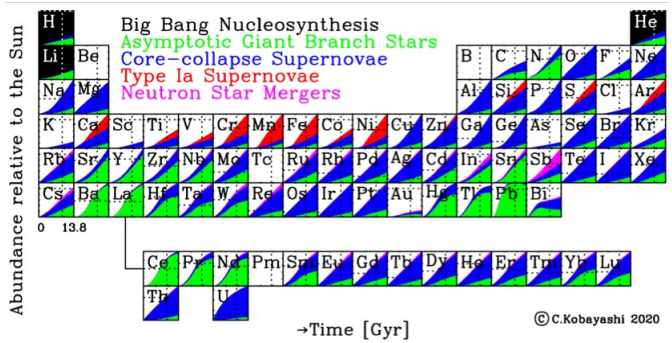
- ☆ Compton Gamma-Ray Observatory
  - 1991-2000
  - NASA



- ☆ INTEGRAL Observatory
  - 2002-2025 (2029)
  - ESA



- ☆ NuSTAR (<80 keV) (2012- today)
- ☆ Earlier Balloone-Borne Experiments
- ☆ SMM; HEAO-C 1978 …



The answers include: models of the sources and the nuclear rates within, and of cosmic evolution including transport and recycling

→ γ-ray lessons for the astrophysical source models

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

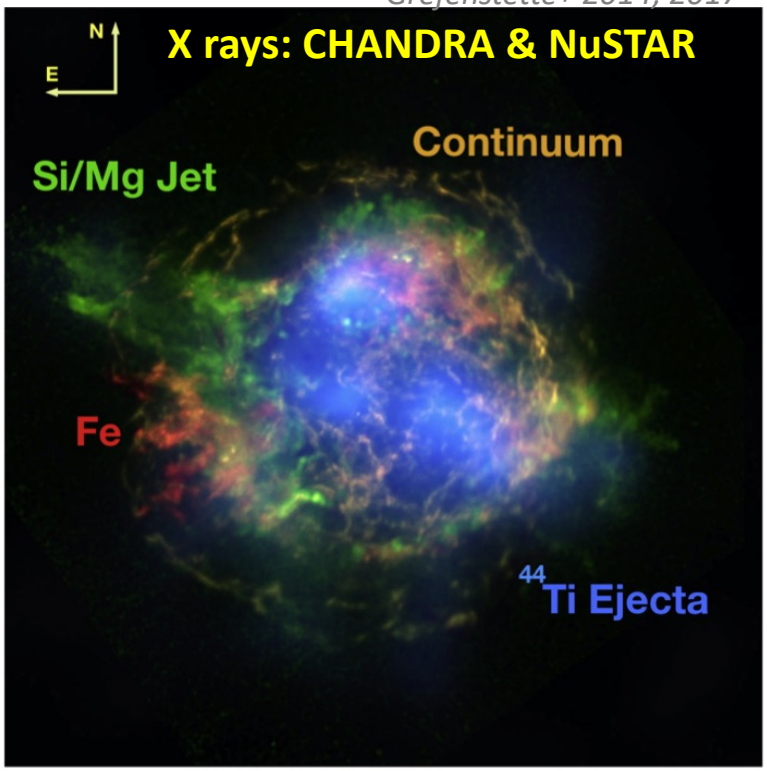
NuSTAR Imaging in hard X-rays (3-79 keV; ^{44}Ti lines at 68,78 keV) →

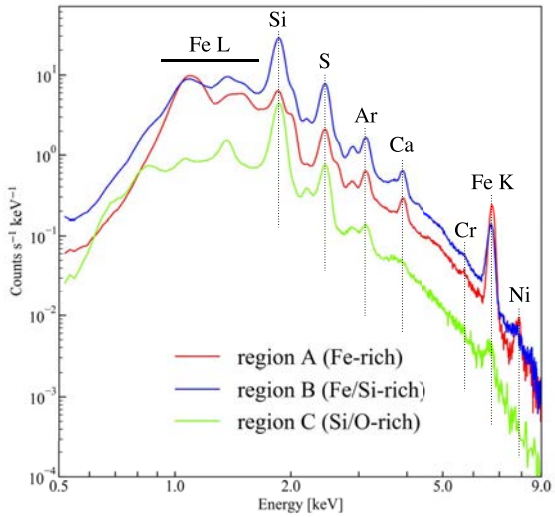
☞ first mapping of radioactivity in a SNR

cmp. X-ray line image

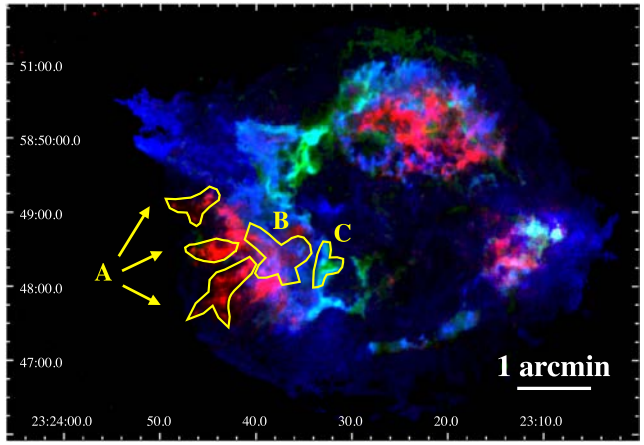
- Both ^{44}Ti lines detected clearly
- redshift ~0.5 keV → 2000 km/s asymmetry
- ^{44}Ti flux consistent with earlier measurements
- Doppler broadening: (5350 ±1610) km s^{-1}
- Image differs from Fe!!

Grefenstette+ 2014; 2017





Tsuchioka+2022



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

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

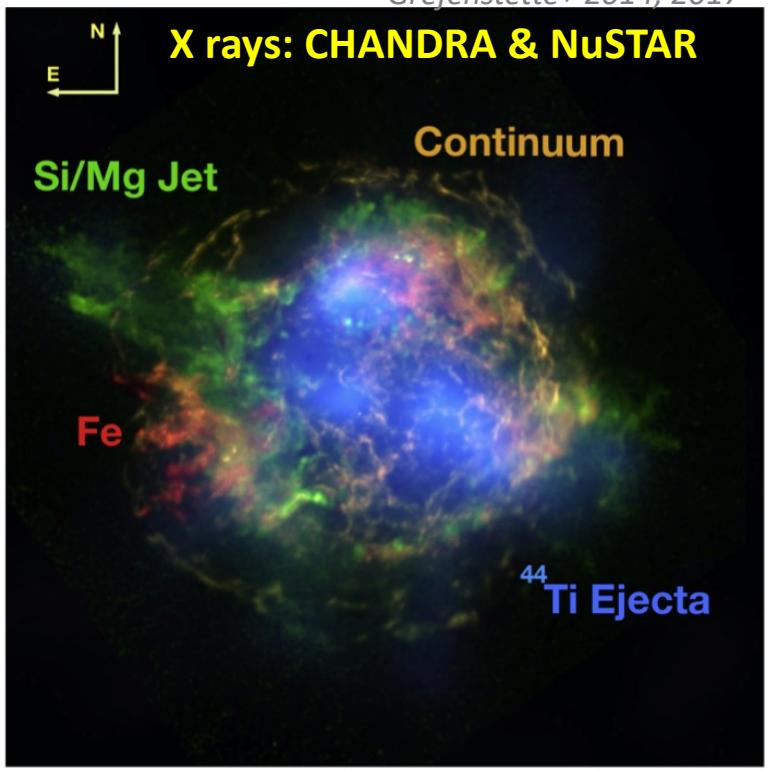
X rays and beyond: Locating the inner Ejecta in Cas A

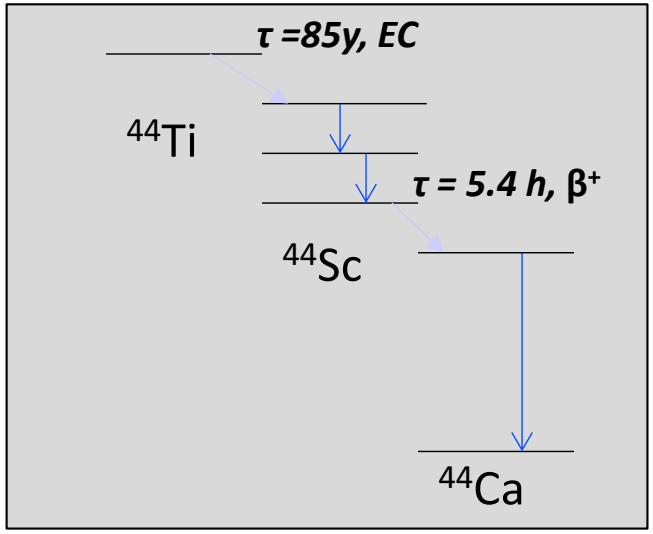
NuSTAR Imaging in hard X-rays (3-79 keV; ^{44}Ti lines at 68,78 keV) →

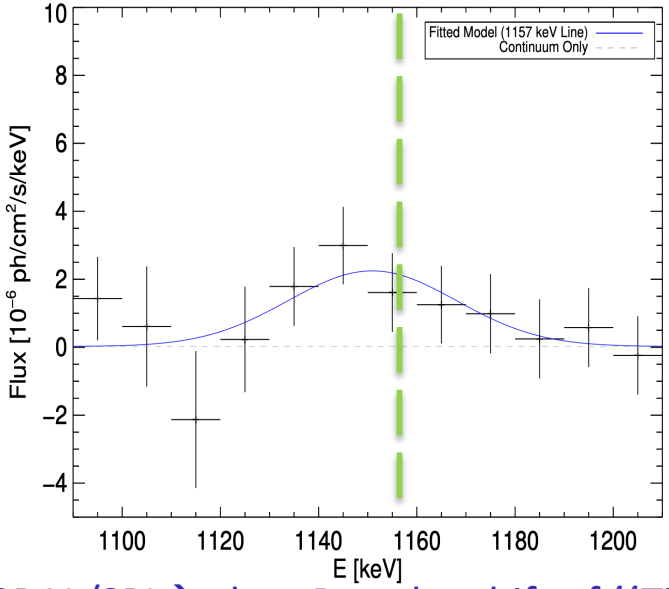
☞ first mapping of radioactivity in a SNR

- 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!!

Grefenstette+ 2014; 2017







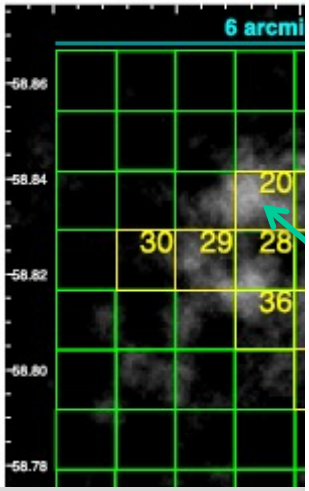
☞ ^{44}Ti→ TRUE locations of inner-SN ejecta

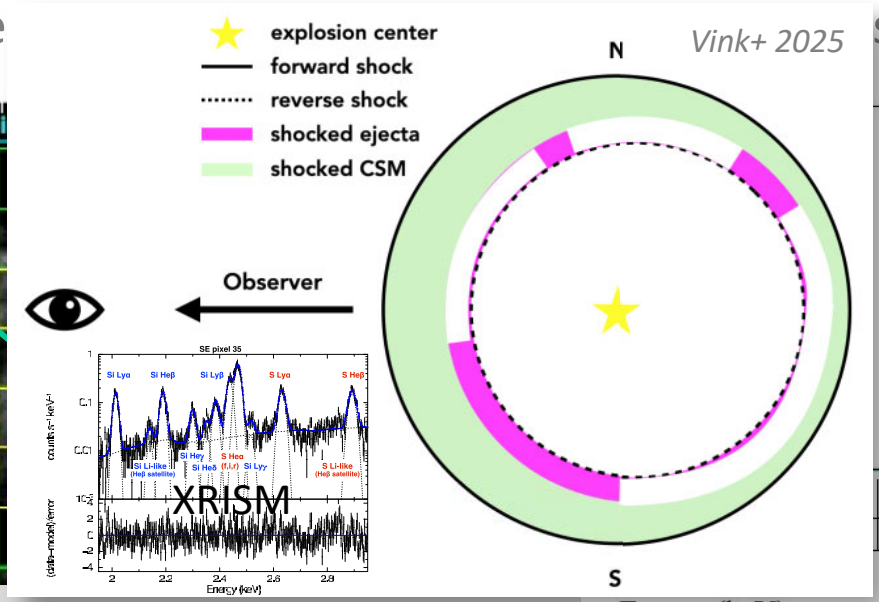
☞ Fe-line X-rays are biased from ionization of plasma by reverse shock

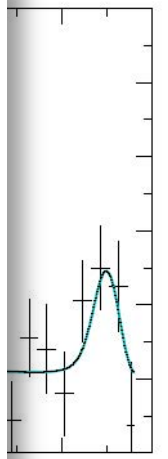
INTEGRAL/SPI→ clear Doppler shift of ^{44}Ti (1800 ±800 km s^{-1} away from observer)

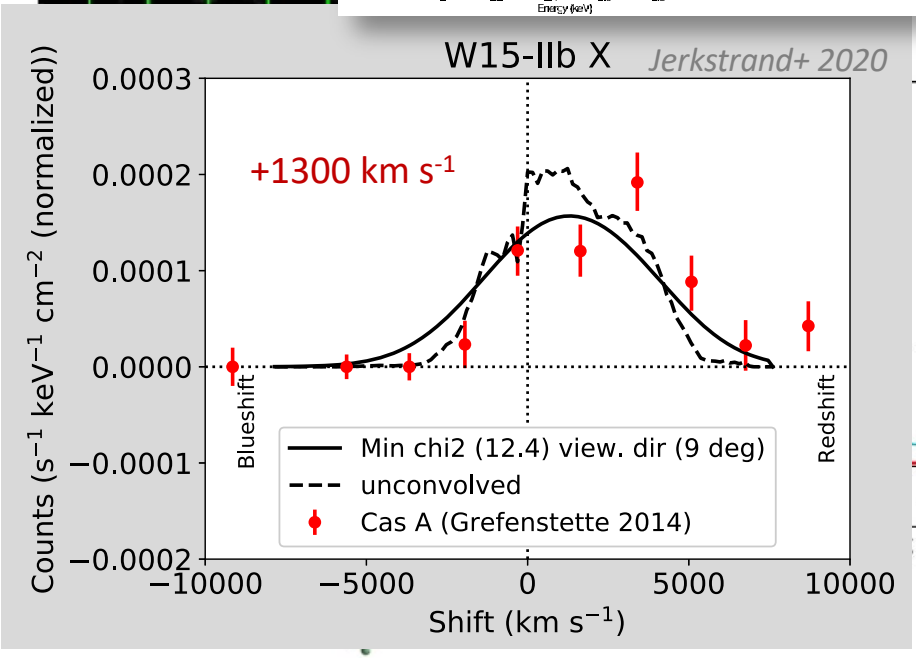
NuSTAR details of ^{44}Ti in Cas A, radiation-transport fitting, XRISM hi-res spectra...

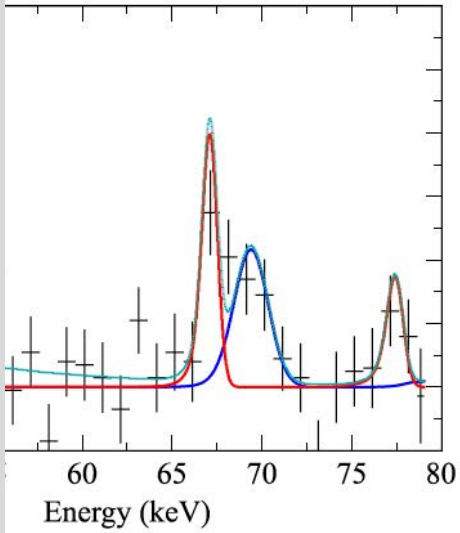
☆ Imaging re s A's ^{44}Ti:



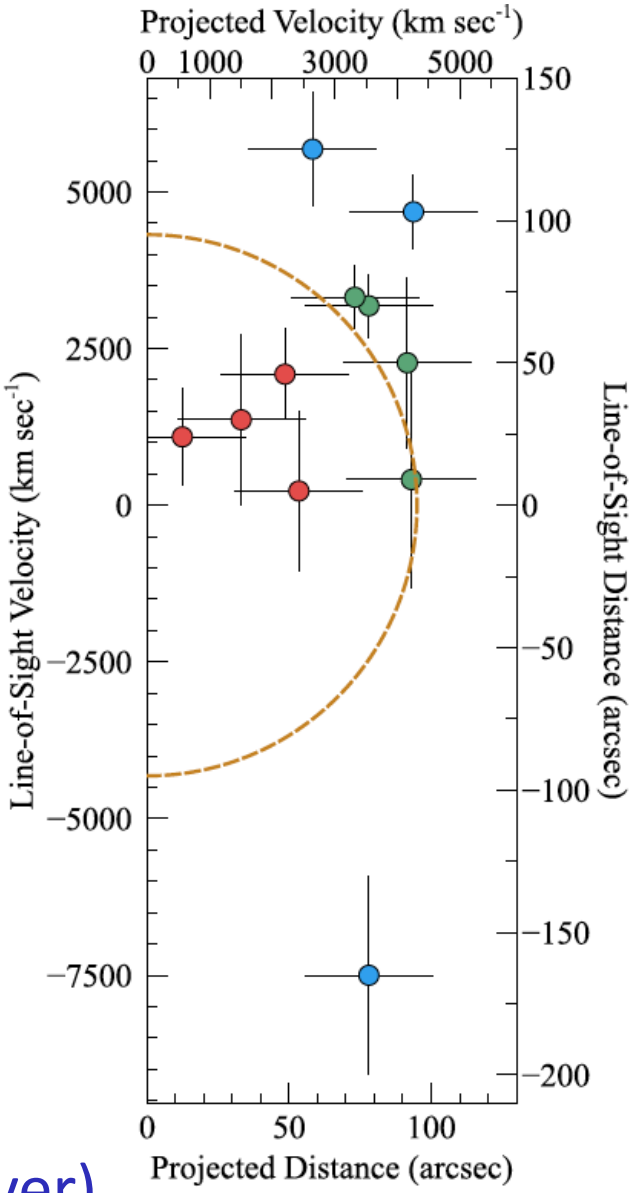








2.4 Msec NuSTAR campaign
Grefenstette et al. 2017

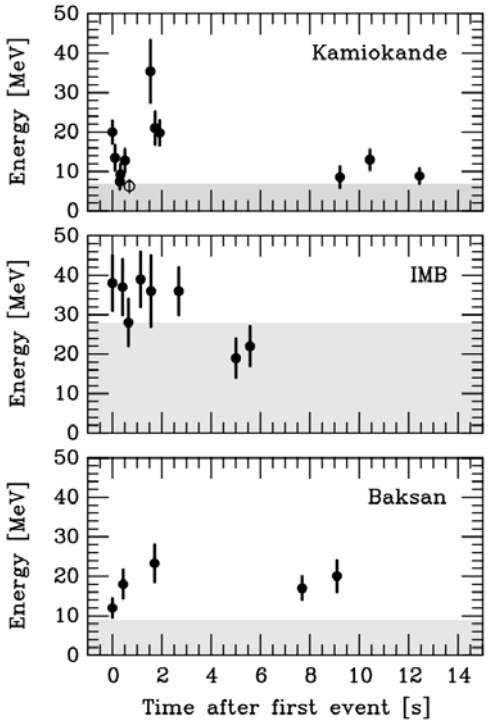


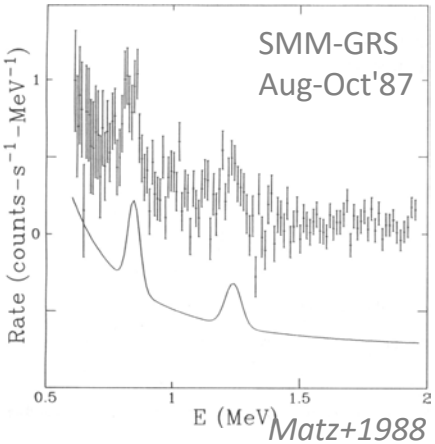
→ bulk red-shifted ^{44}Ti (away from observer)

'Nuclear' Astronomy and SN1987A

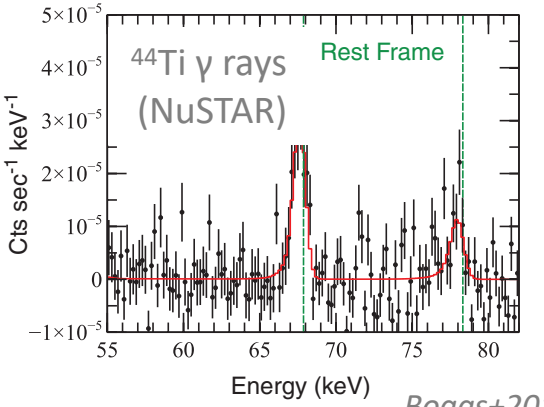
Neutrino burst
from collapsing core

Radioactively-powered
SN afterglow
with nuclear-decay γ rays





Matz+1988



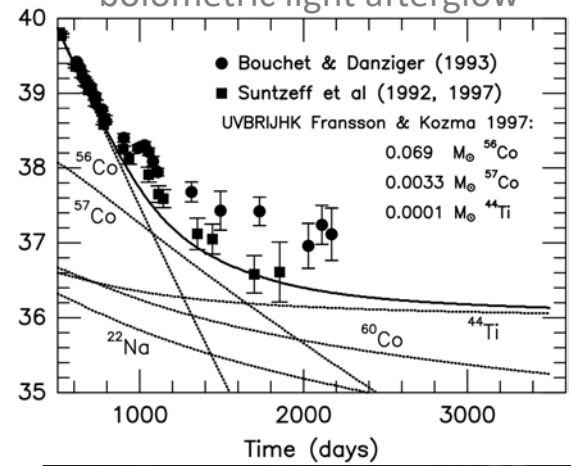
Boggs+2015

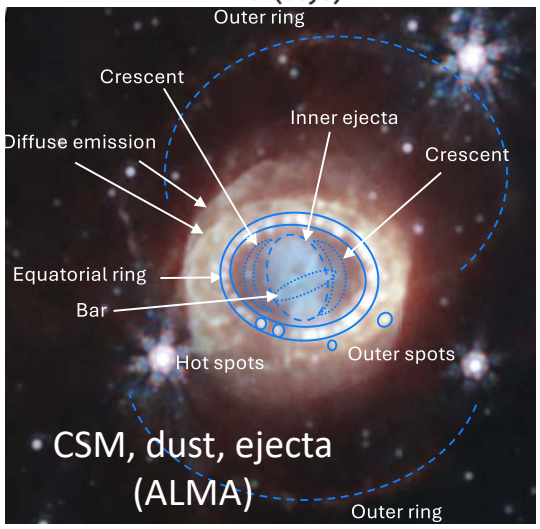
inner region physics

Indirect / bulk



bolometric light afterglow





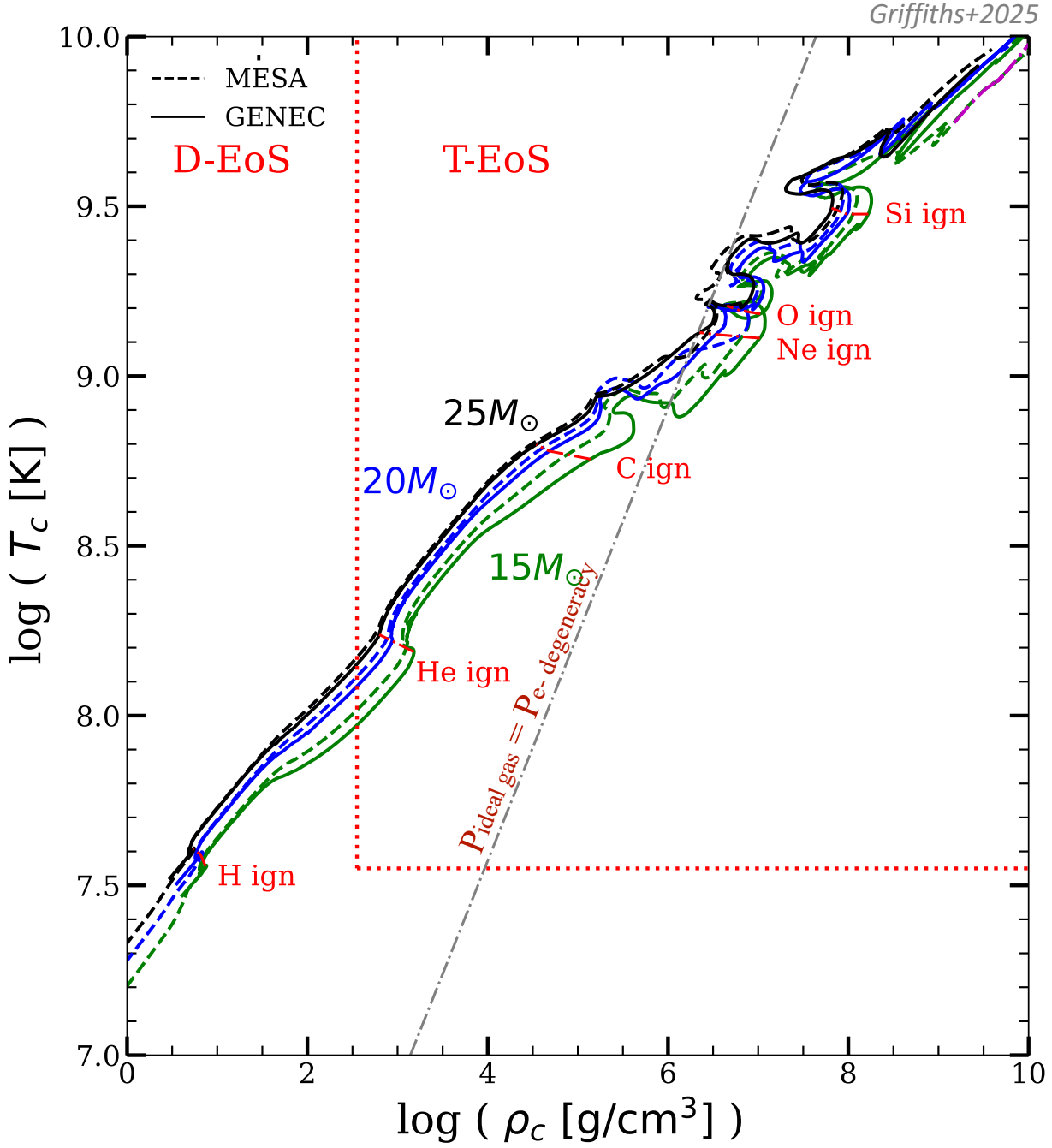
Matsuura+2024

Do we understand the evolution of massive stars?

gravitational contraction

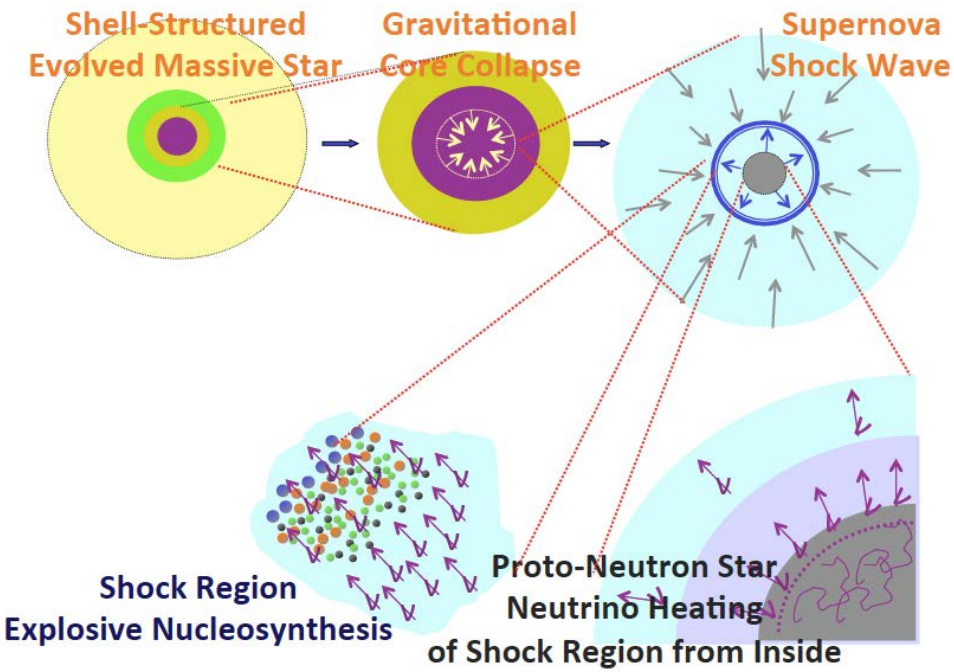
temporarily halted by

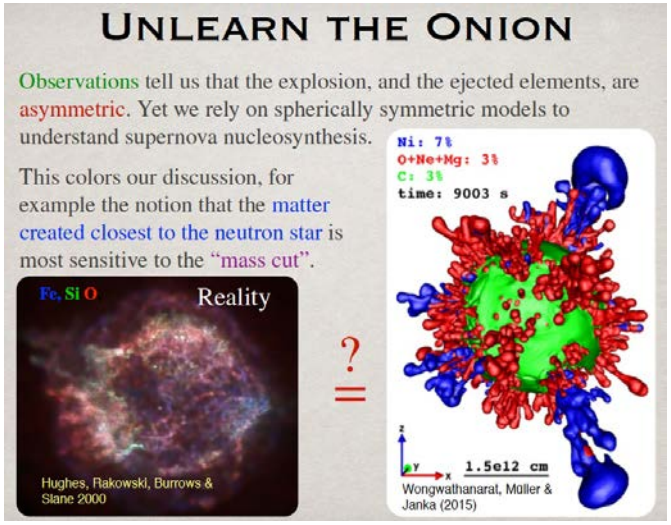
nuclear burning stages



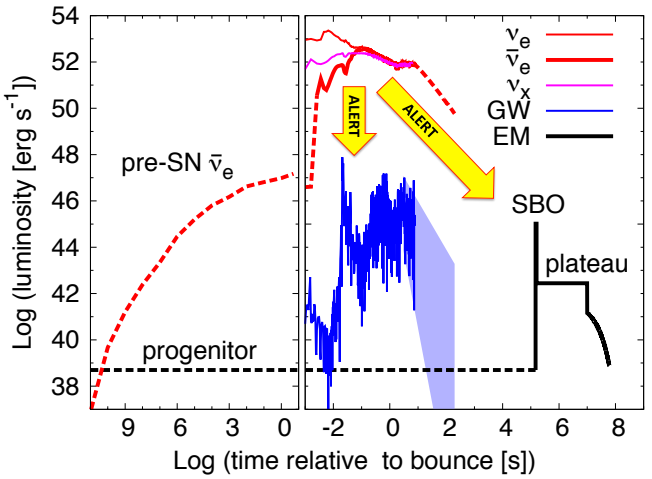
GENEC ___
and
MESA - - - -
for
15/20/25 $M_\odot$

Complexities of Gravitational Collapse and SN

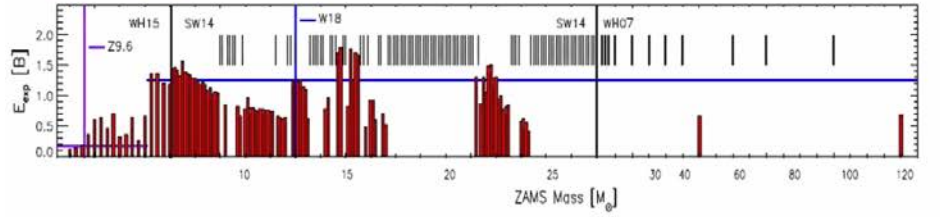




Raph Hix 2016



Kharoussi+ 2020



Ugliano+2012, Sukhbold+ 2016, Couch+2020

- 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

pair instability supernovae

For photon energies (in c.o.m.) > 1.022 MeV → e^+e^- production

→ loss of radiative pressur support → collapse and ...

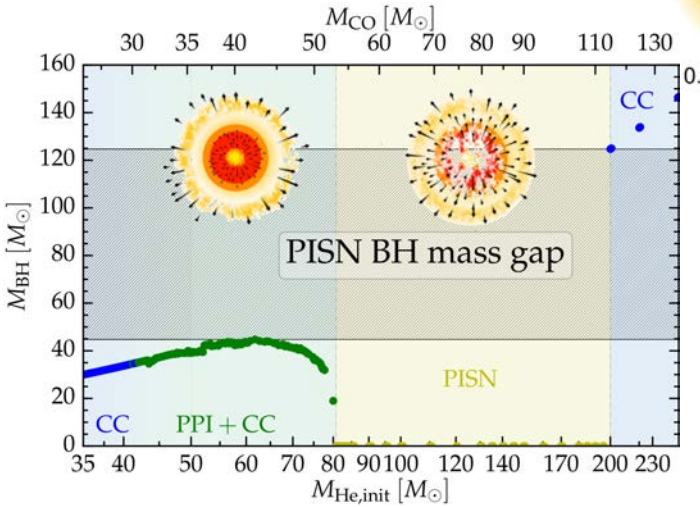
- ☆ explosive O ignition → SN with complete disruption (PISN)

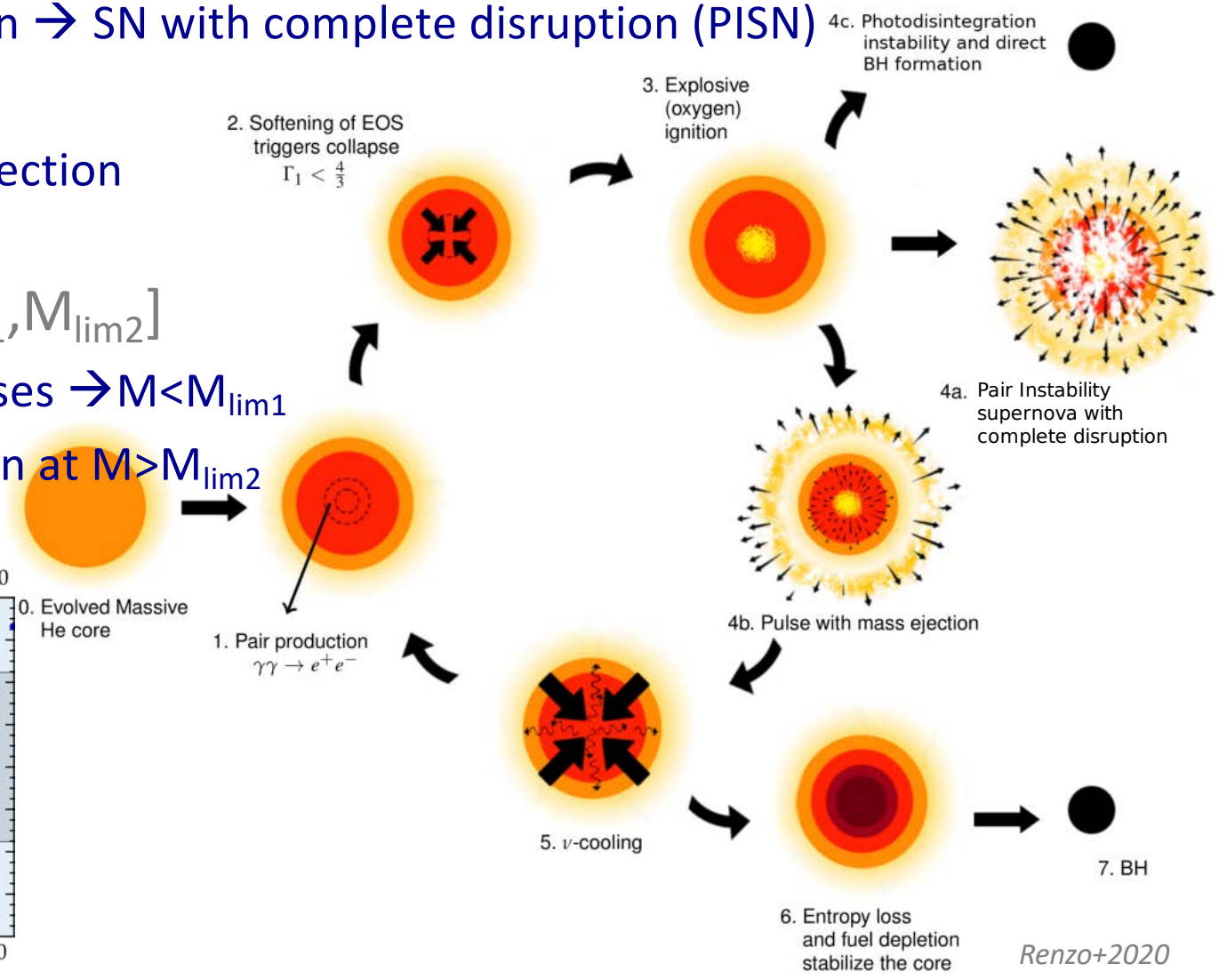
  or

- ☆ pulse with mass ejection → PPISN

BH masses: gap [M_{lim1},M_{lim2}]

- ☆ mass loss with pulses →$M<M_{lim1}$
- ☆ photodisintegration at $M>M_{lim2}$

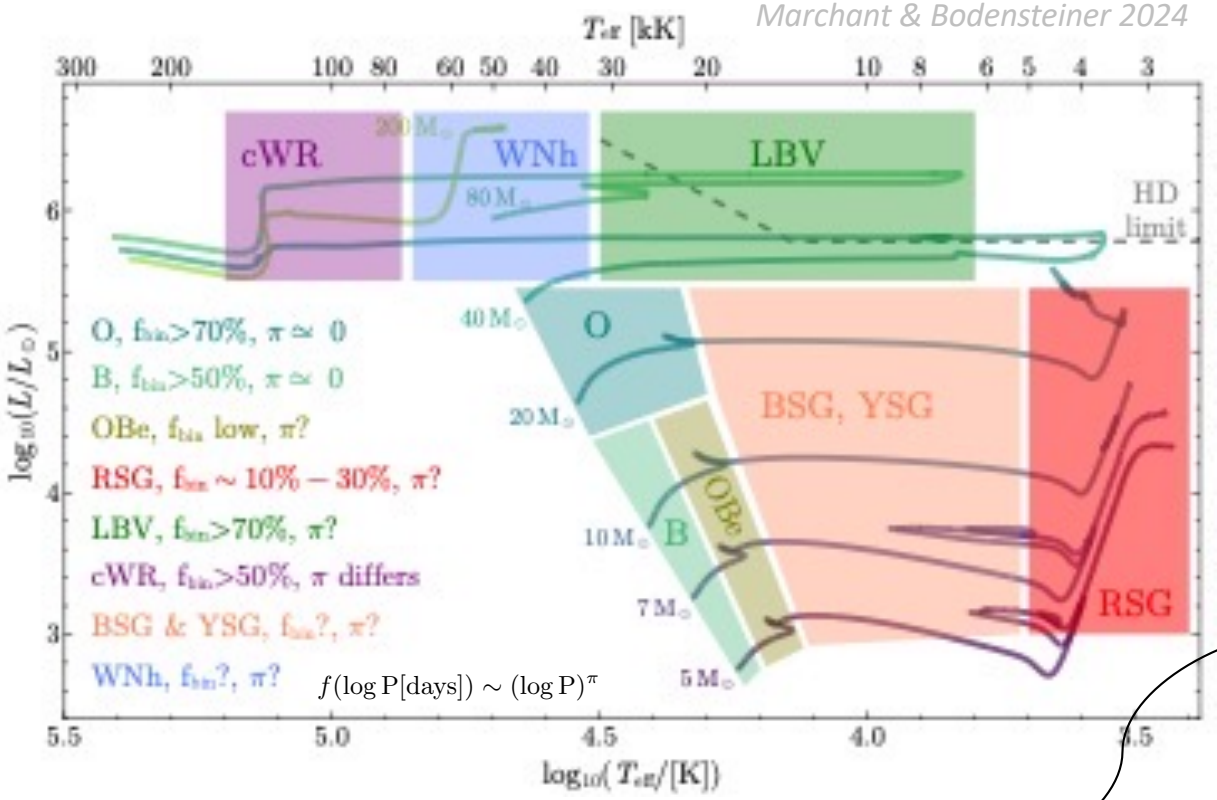




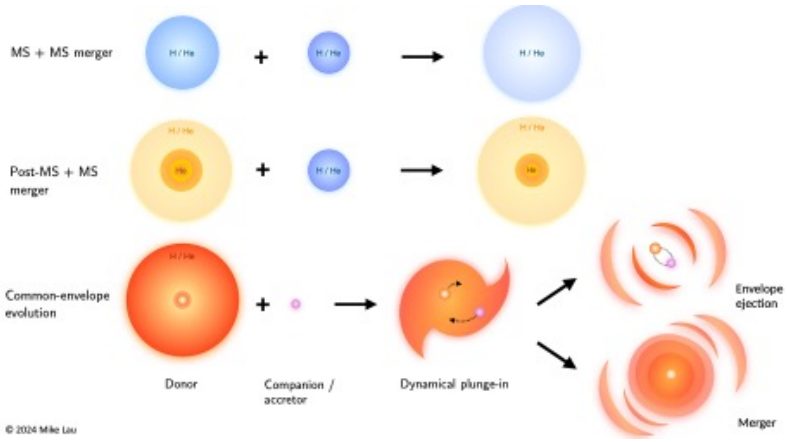
Binary Evolution: the Current Puzzle in Stellar Evolution

A significant fraction of stellar multiples interact → mass transfers+...

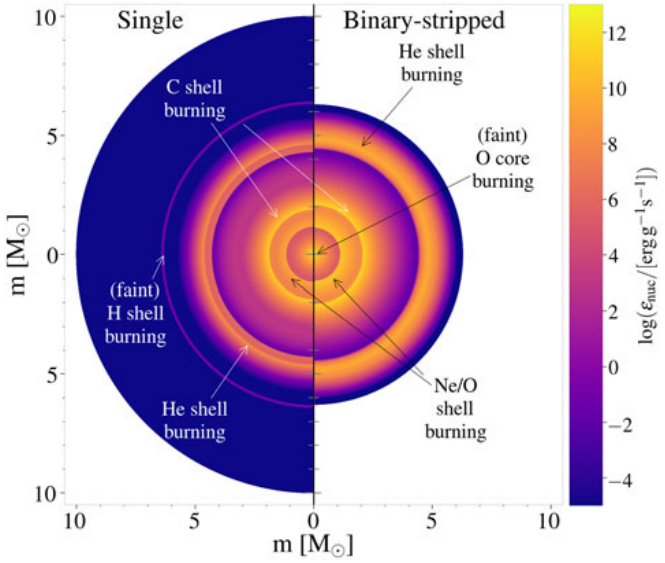
Marchant & Bodensteiner 2024



Schneider+2025



Laplace+2024



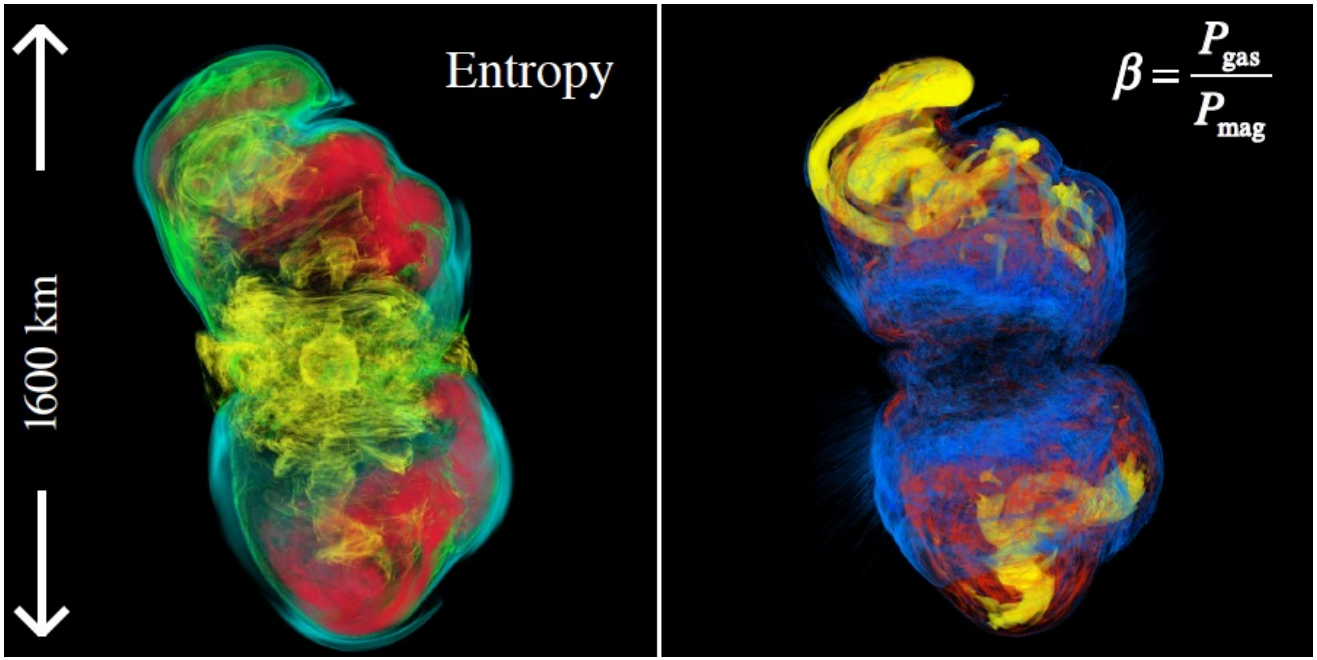
☞ stellar merger variants

☞ different core evolution, SN, BH formation

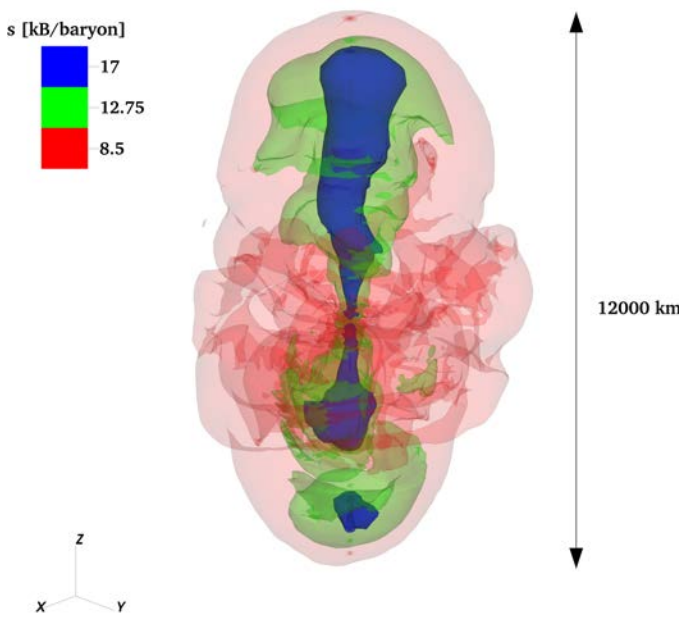
Collapse of a magnetized plasma → jet supernovae

Magnetic-field compression as a significant energy component

Mösta+2014



Bugli+2021



☞ release of magnetic-field torsion launches jet outflow and a supernova explosion

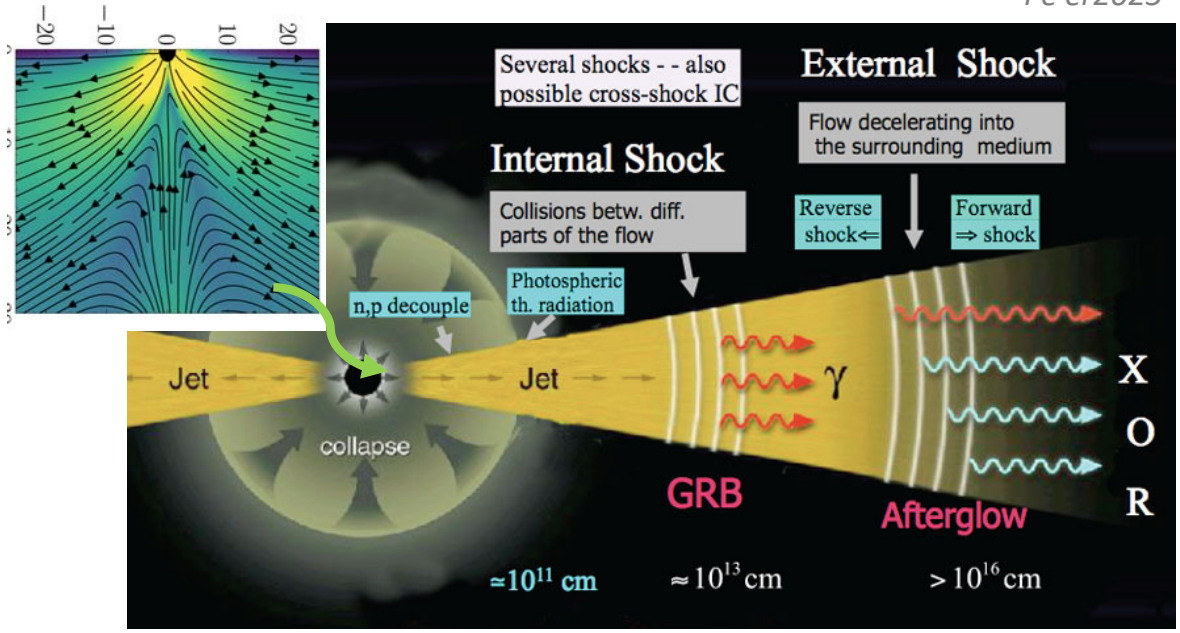
☞ winding up magnetic fields during core collapse → ejection of inner material

Nuclear fusion near a newly-forming BH?

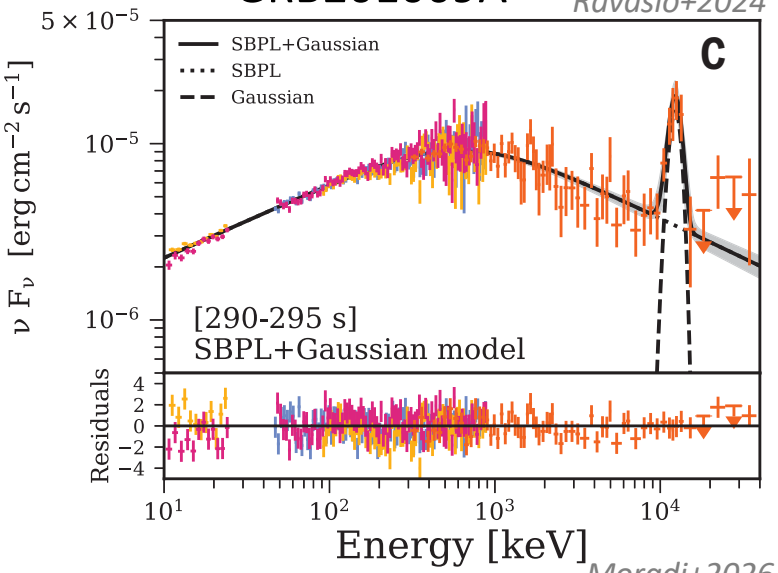
GRB emission model:

- ☆ jet converging shocks particle acceleration
  → broad continuum, reaching high energies
  (GeV... TeV if efficient)

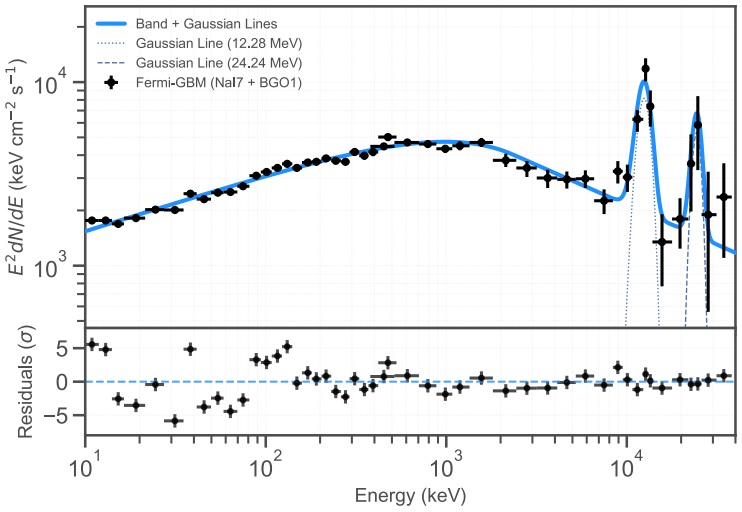
Pe'er2025



GRB201009A *Ravasio+2024*



Moradi+2026



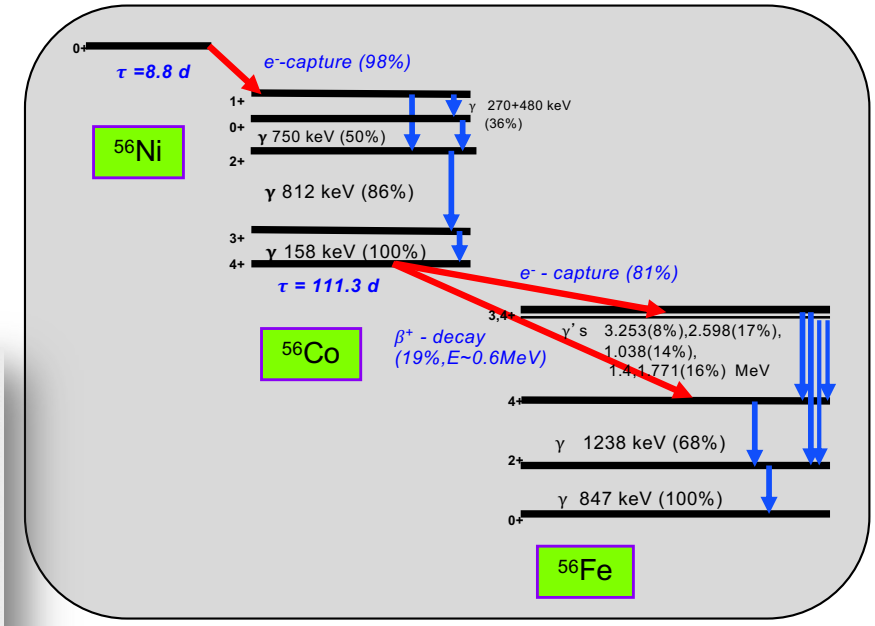
- ☆ pair plasma at jet base → annihilation?
- ☆ nucleosynthesis in BH accretion disk → ^{56}Ni?

each of these may only appear under special aspects,
and requires entrenchment into jet near its base

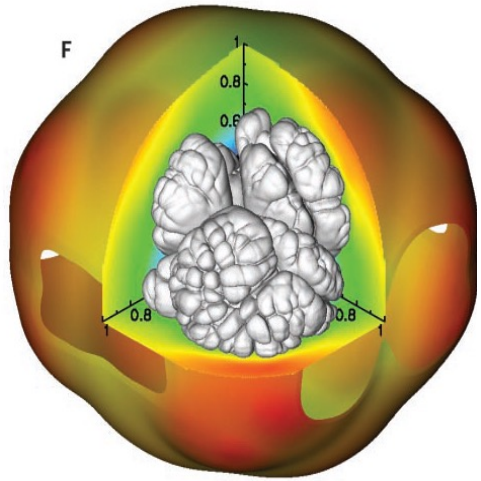
- ☆ jet launched by neutrinos → lepton fireball, or by BH rotation coupling to accretion disk

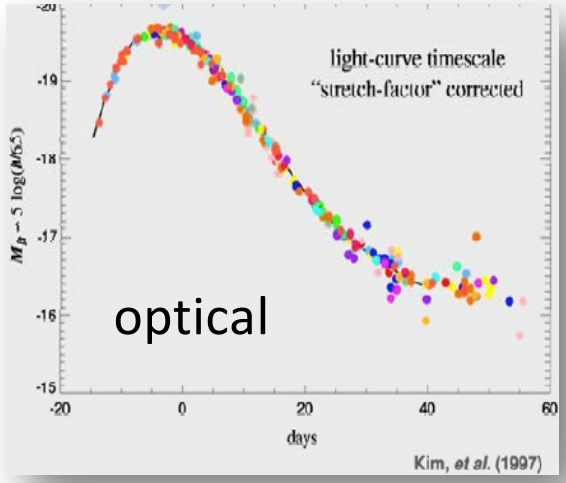
^{56}Ni radioactivity → γ-Rays, e$^+$ → leakage/deposit evolution

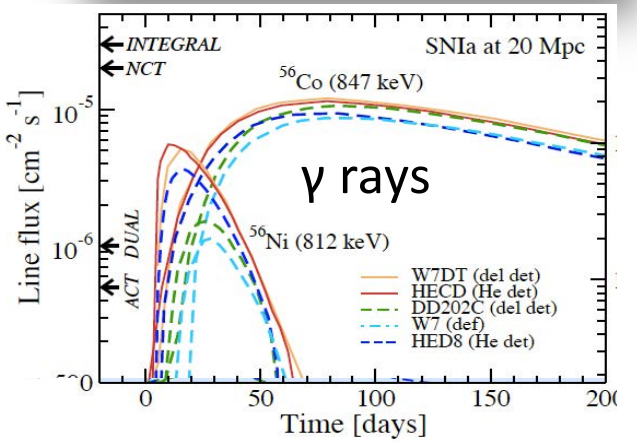
SN Ia →



+







Nuclear BE release from 0.6M$_\odot$ [C,O → ^{56}Ni]

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

Heating of envelope material by absorbed γ,e$^+$

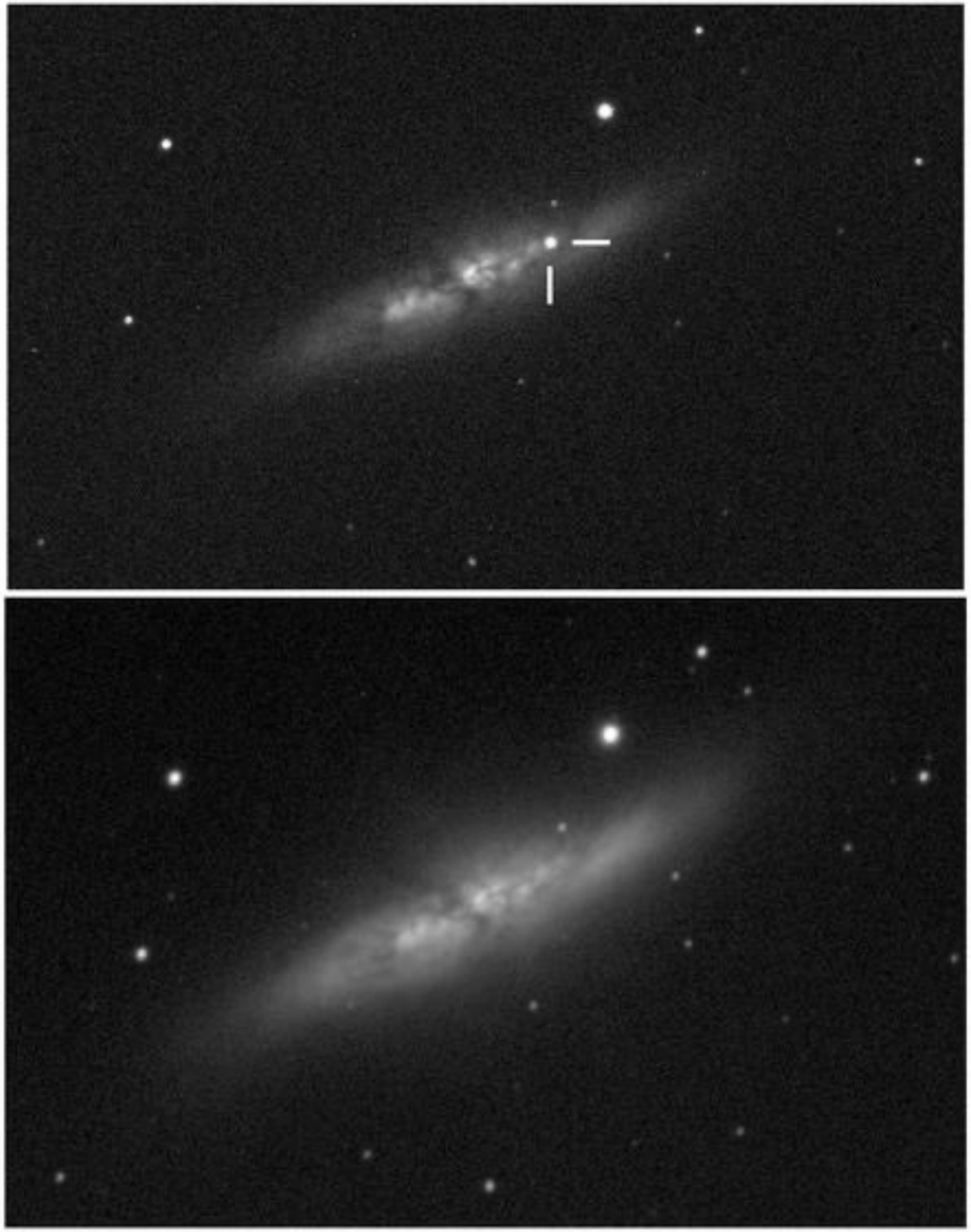
→ Re-radiation of deposited energy in opt...IR radiation

Leakage as envelope expands

→ Escaping γ,e$^+$ lead to γ ray signals

Light curves in optical & γ rays complement each other

SN2014J

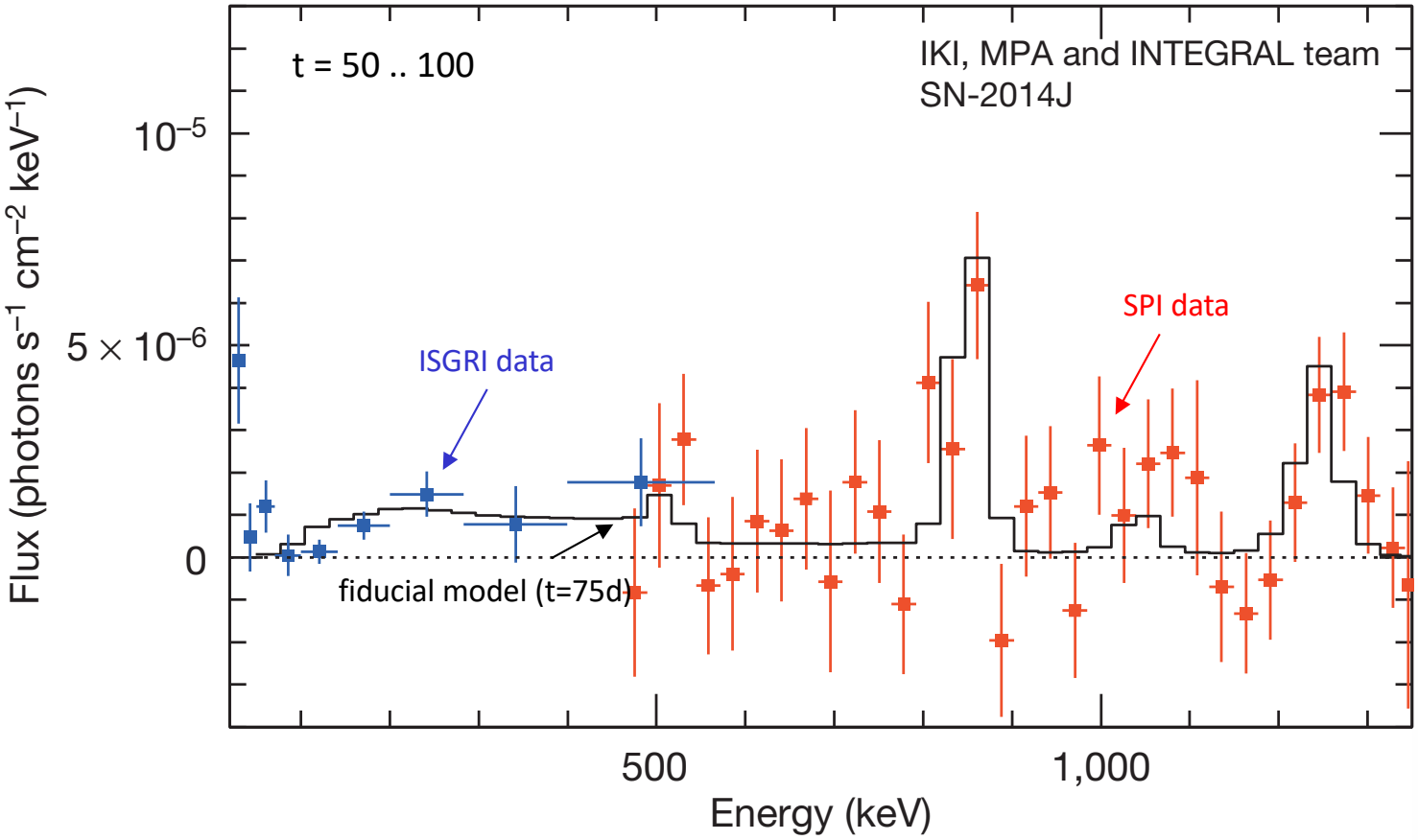


- SN2014J in M82
  (Starburst Galaxy)
  - ☞ Discovered 22 Jan 2014
  - ☞ Likely Explosion Date:
    14 Jan 2014 (14.75 +/-0.3d)
  - ☞ Distance 3.3….3.53 Mpc,
    l=141.41°, b=40.56°
  - ☞ Closest SN Ia in 40 y!

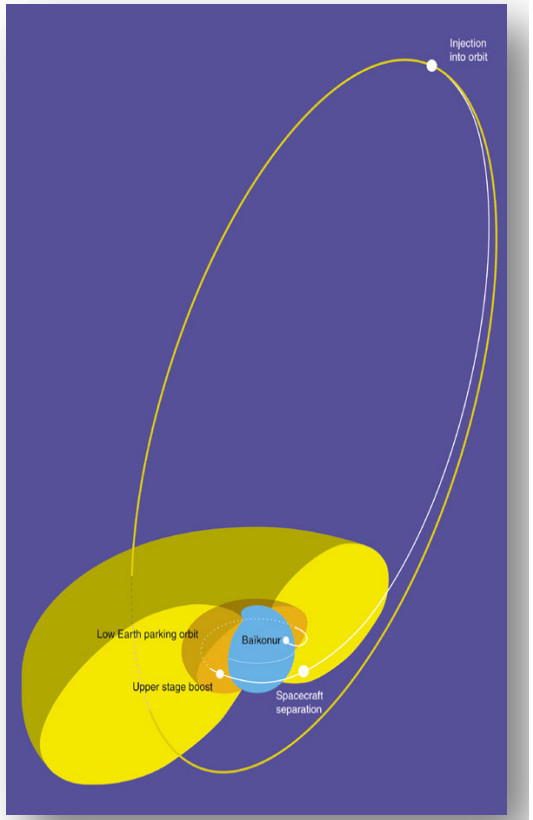
SN2014J: SNIa model verification through ^{56}Ni decay lines

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

Churazov+ 2014







>40 years after its proposal

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

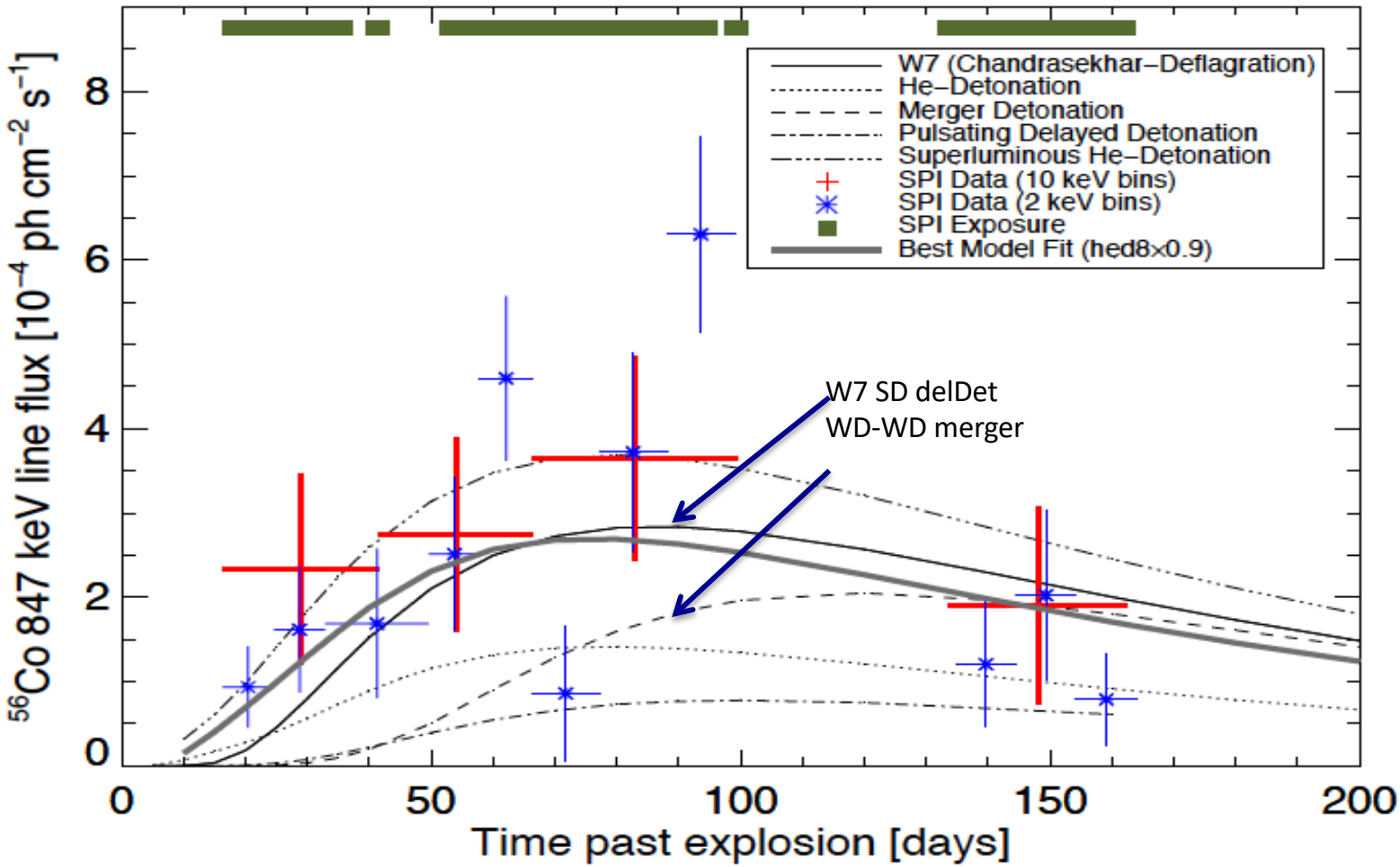
Tracing the light curve of gamma-ray lines →

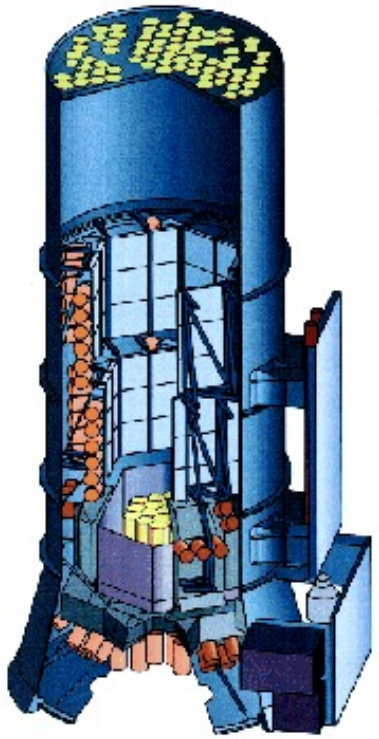
☆ ^{56}Ni mass: 0.49 +/-0.09 $M_\odot$

(cmp from bol. Light → 0.42 +/-0.05 $M_\odot$

from models → 0.5 +/-0.3 $M_\odot$

Diehl+ 2015



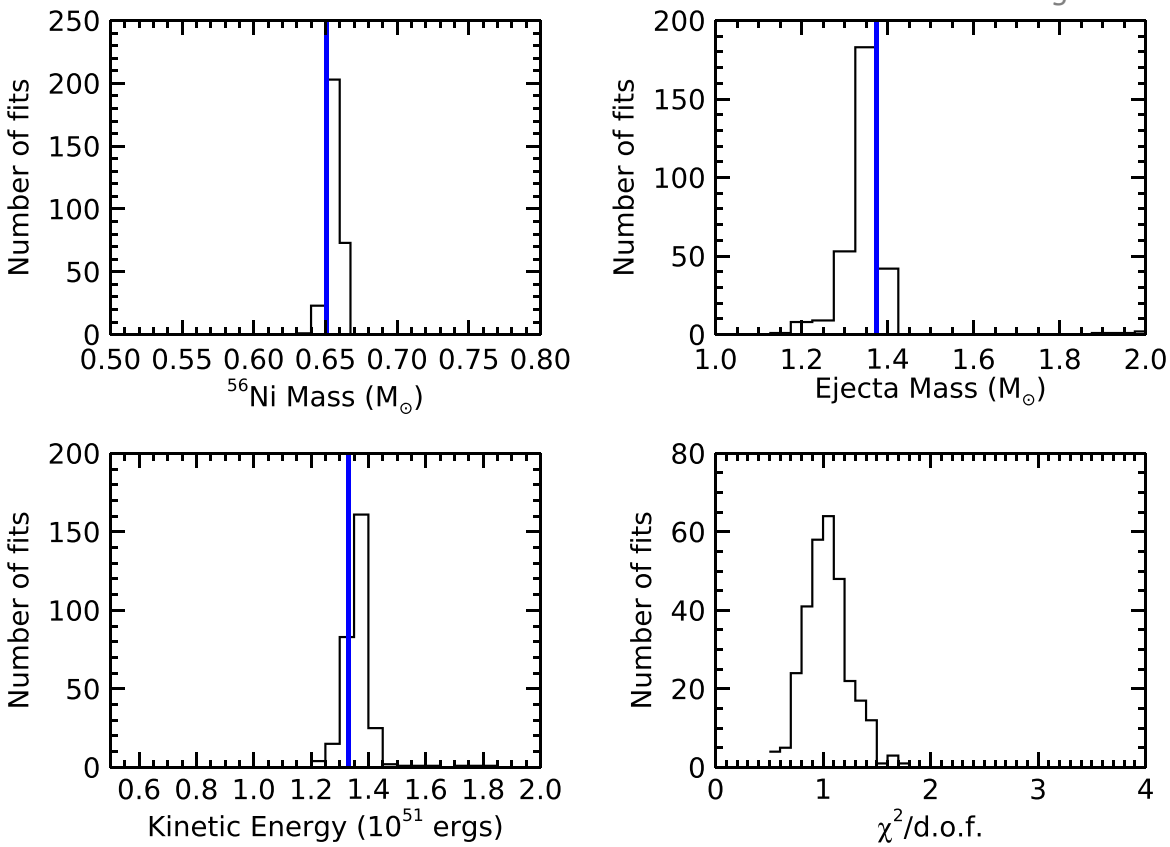


SNIa model verification through ^{56}Ni decay lines

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

- ☞ simulate SNIa 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 though multiple shells of homologous expansion
    → determine also the ejecta mass

Leising 2022



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

- next-generation instrument; several SNe/y

☆ Application to SN2014J:
(with current data)
^{56}Ni mass: 0.4 +/-0.1 $M_\odot$
(cmp 0.49 +/-0.09 $M_\odot$ by *Diehl+2015*)

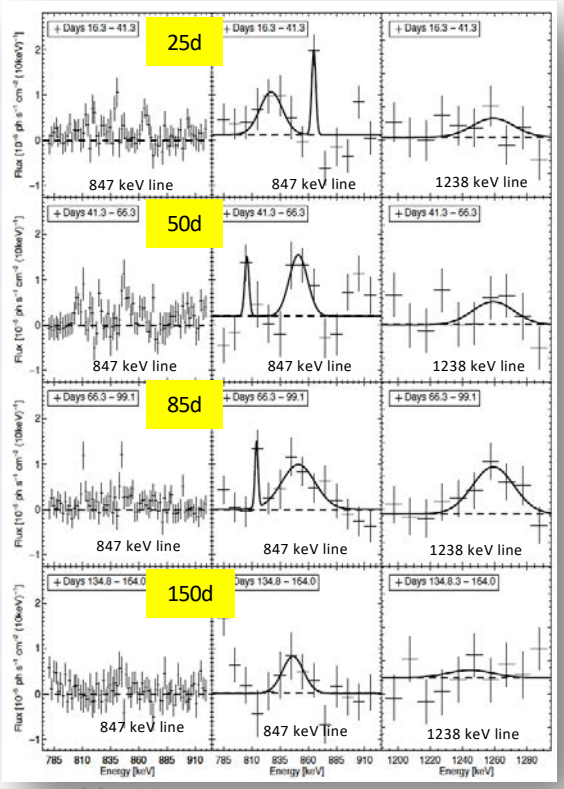
SN2014J: SNIa model verification measuring ^{56}Ni decay lines

☆ ^{56}Ni mass: 0.49 +/-0.09 $M_\odot$

(cmp from bol. Light → 0.42 +/-0.05 $M_\odot$

from models → 0.5 +/-0.3 $M_\odot$

☆ Irregular appearance of ^{56}Co lines

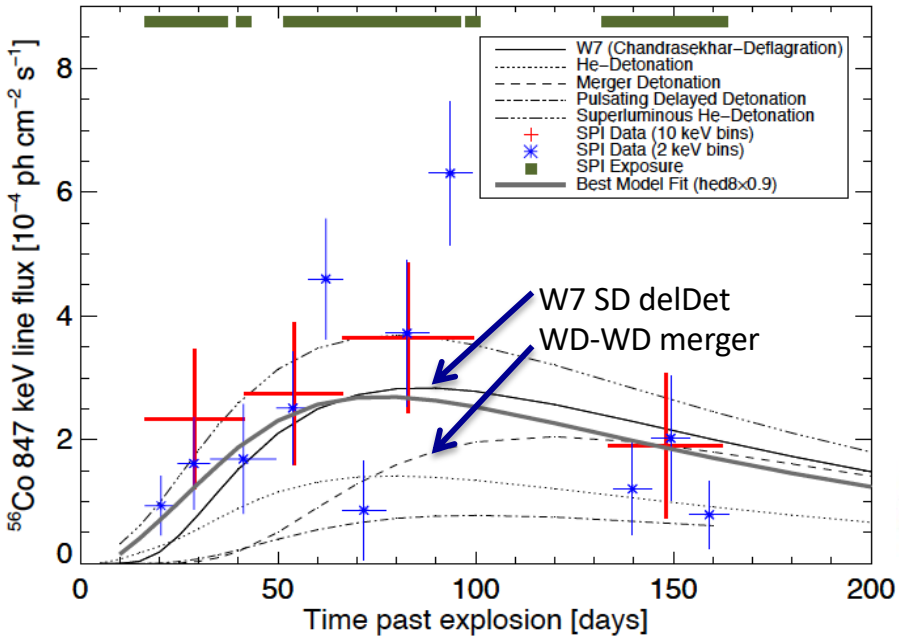


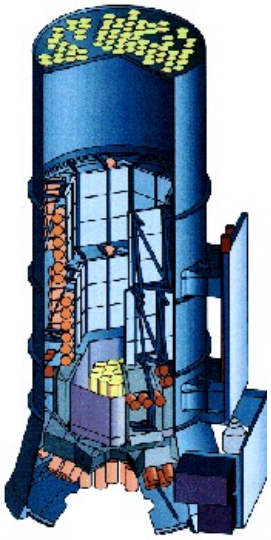
Diehl+ 2015

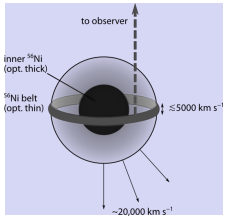
☆ ^{56}Ni lines (τ 9 days) seen at day 20

☞ → 0.06 $M_\odot$ near surface

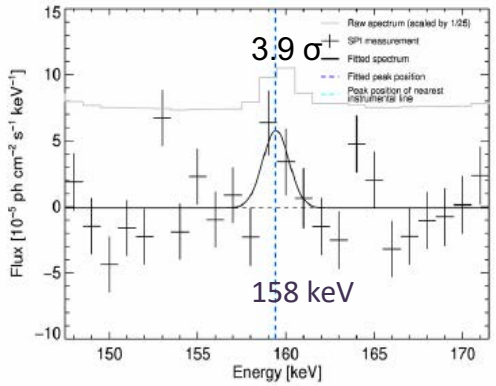
Diehl+ 2015

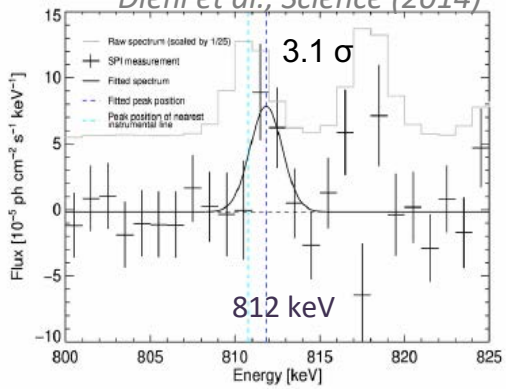






Diehl et al., Science (2014)

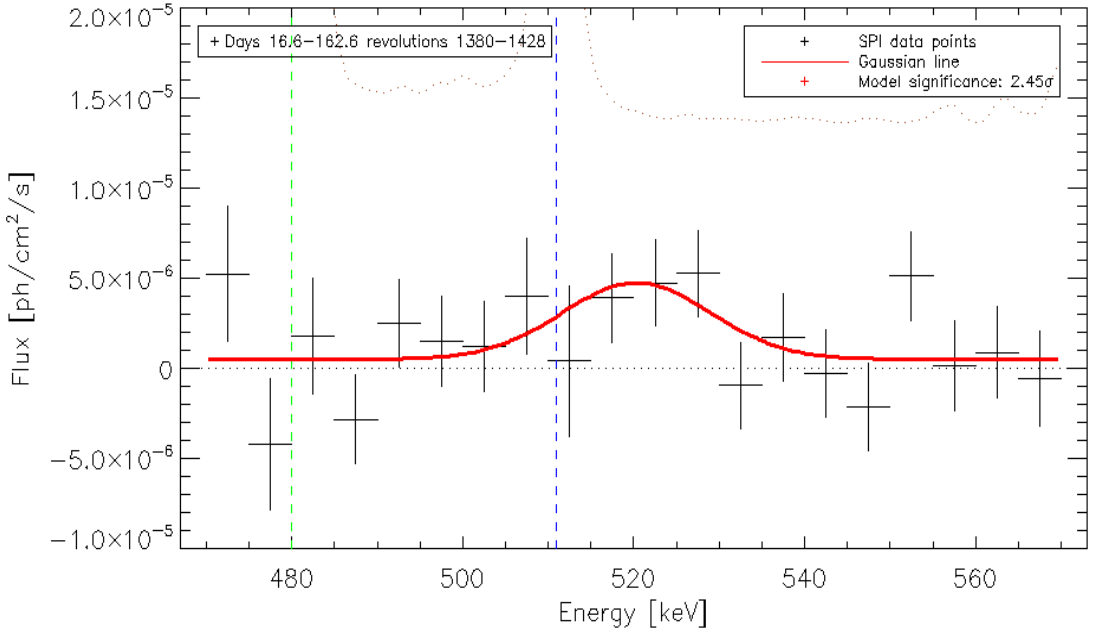


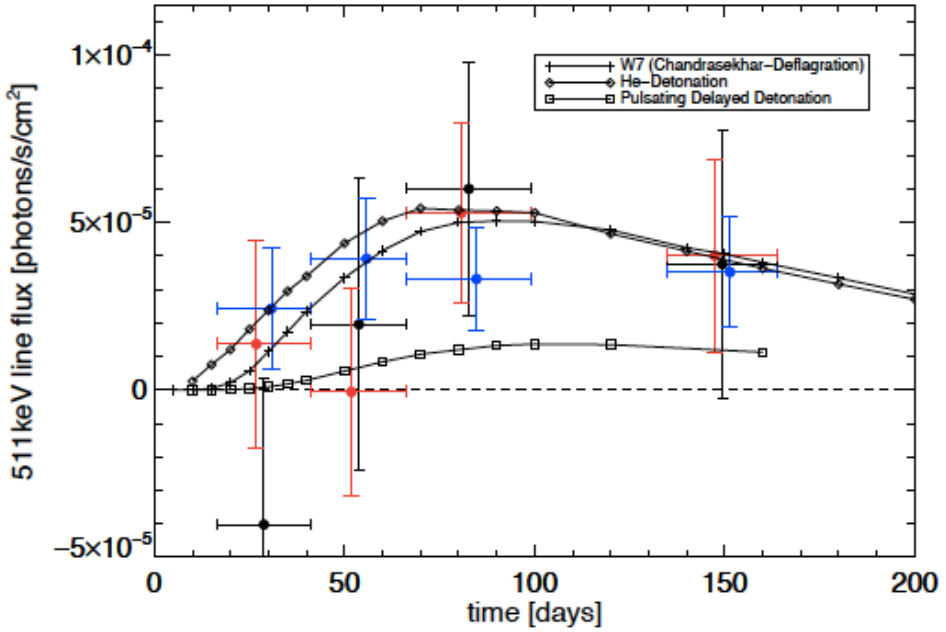


Positron annihilation in SN2014J

- 511 keV line emission suggested (1.7σ)
  - ☆ Flux consistent with ~^{56}Co line fluxes
    → ~all e^+ annihilating
  - ☆ Blue-shifted by 10-15 keV (??)

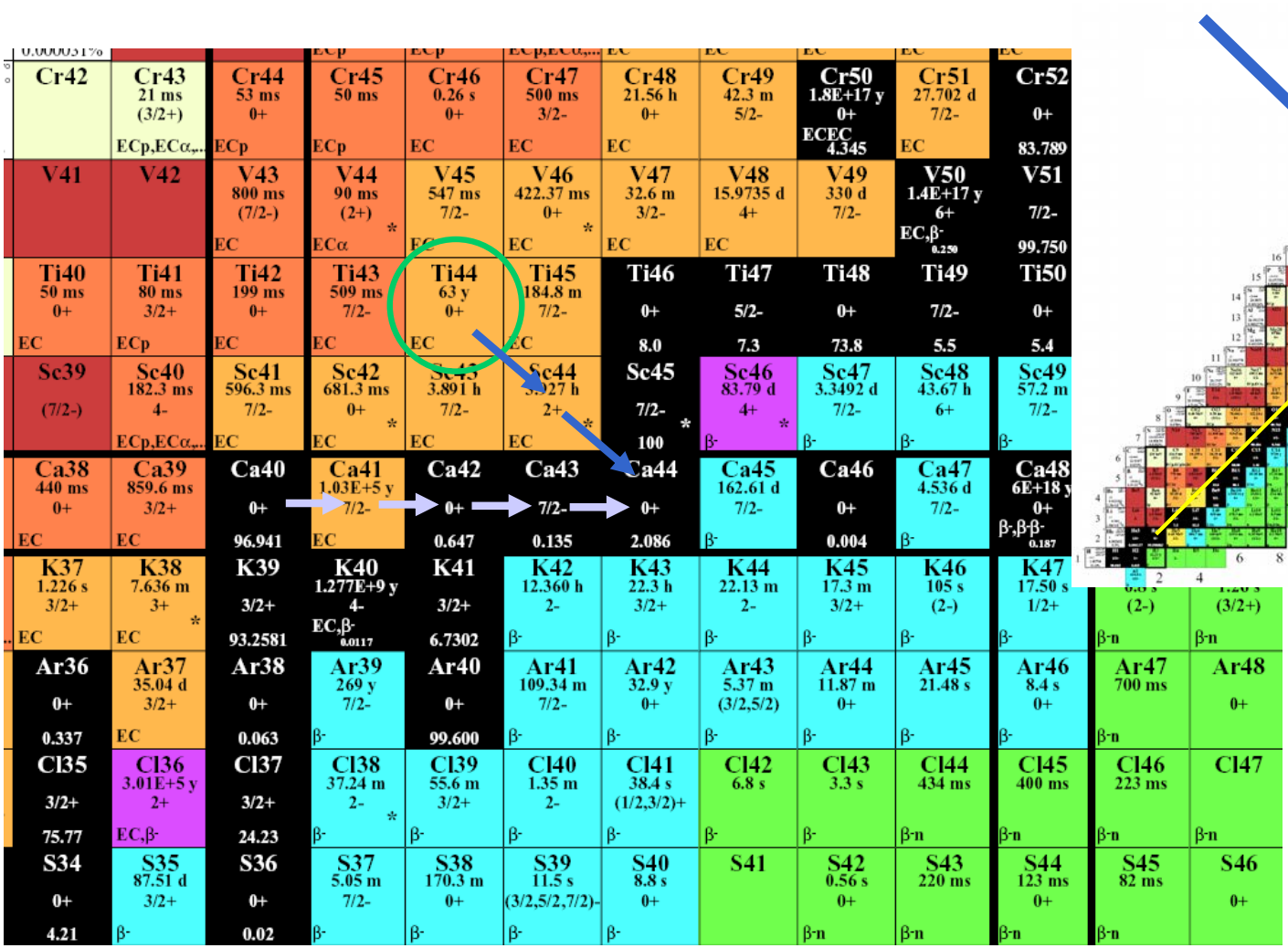
Sonnberger 2019





Nucleosynthesis around ^{44}Ti

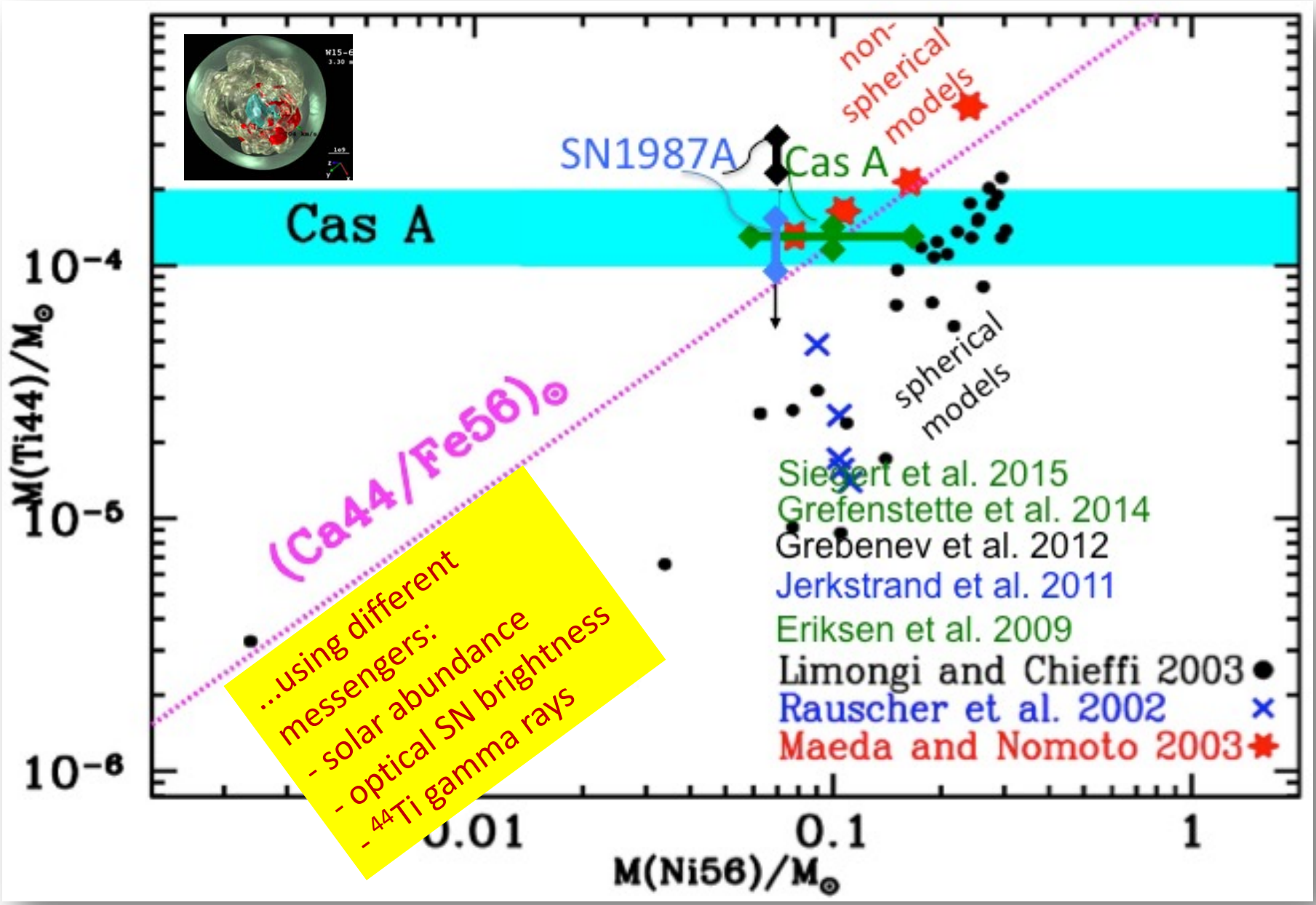
☆ ^{44}Ti is the first unstable nucleus on the "α line"



☆ The ^{44}Ca Isotope is almost-exclusively from ^{44}Ti Decay

☞ some minor admixture from s-process of ^{40}Ca

The case for asymmetries in ccSNe that eject ^{44}Ti

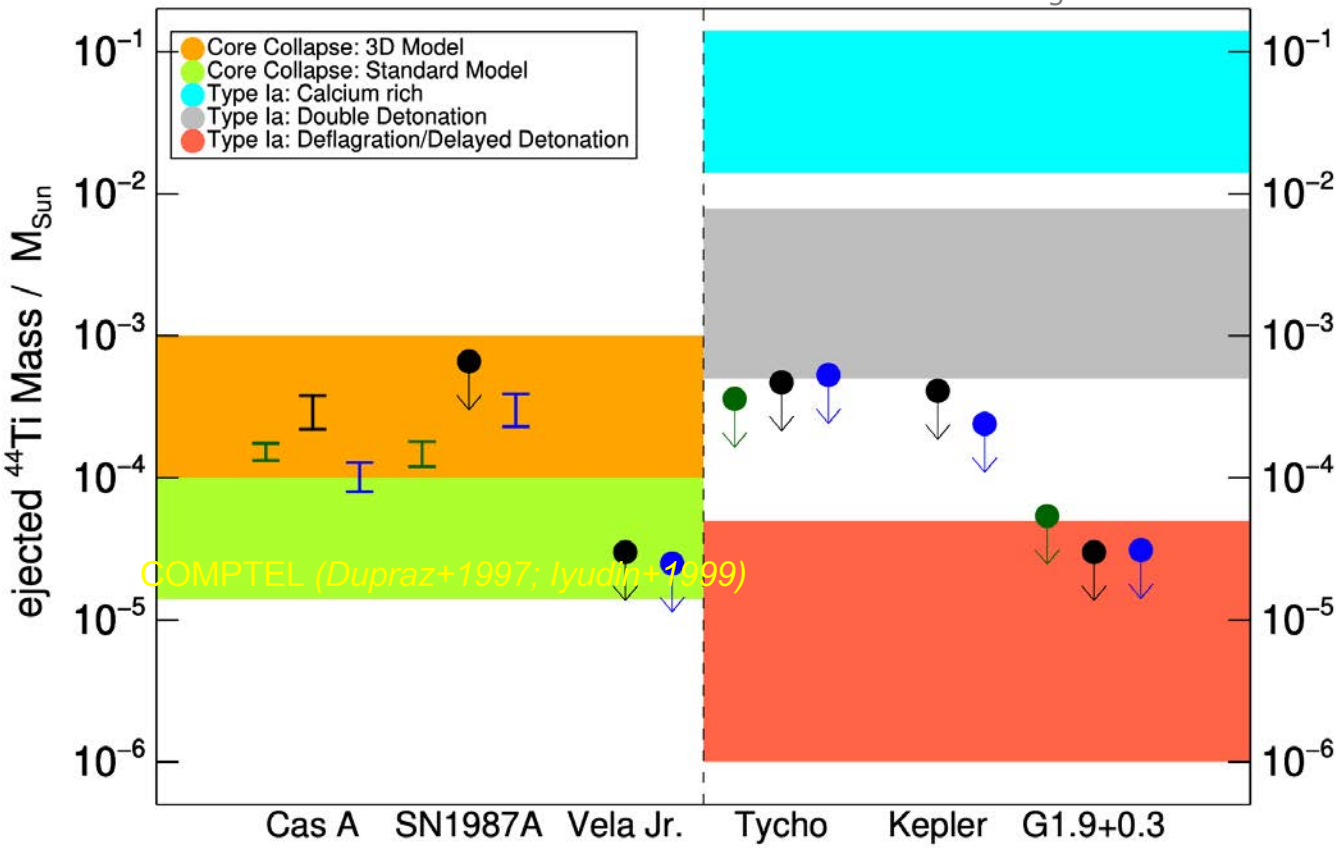


- Only Non-Spherical Models Seem to Reproduce Observed ^{56}Ni/^{44}Ti Ratios
- *The et al. 2006; Dufour&Kaspi 2013*

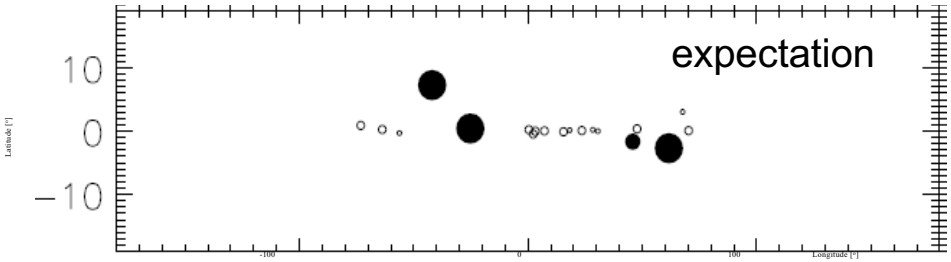
Does ^{44}Ti ejection happen in a supernova?

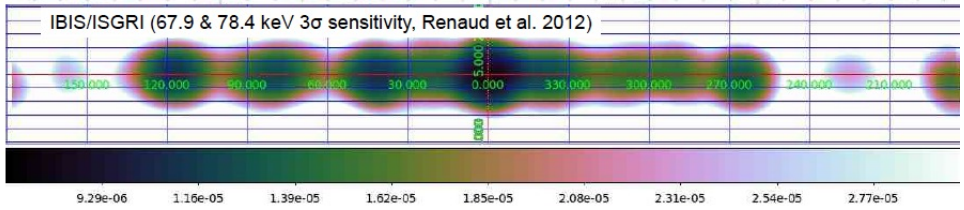
- α capture sequences may occur from
  - ☆ decomposed matter after a core collapse
  - ☆ main matter (He, C, O) in white dwarf stars

Weinberger 2021



☞ How many sources would we expect in our Galaxy?



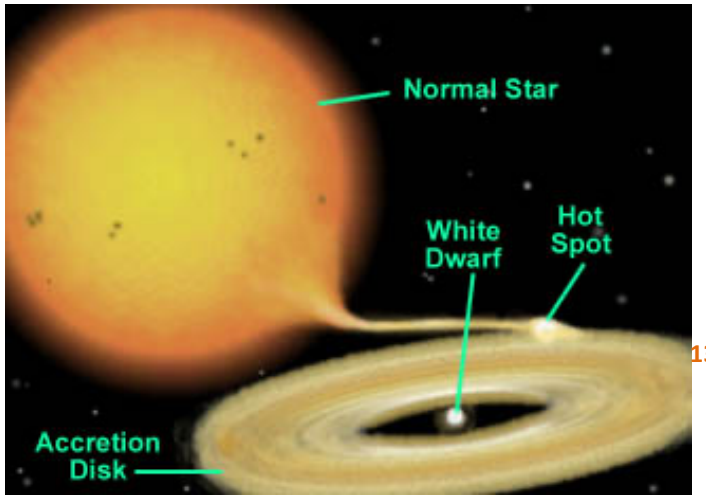


see also Tsygankov+2016

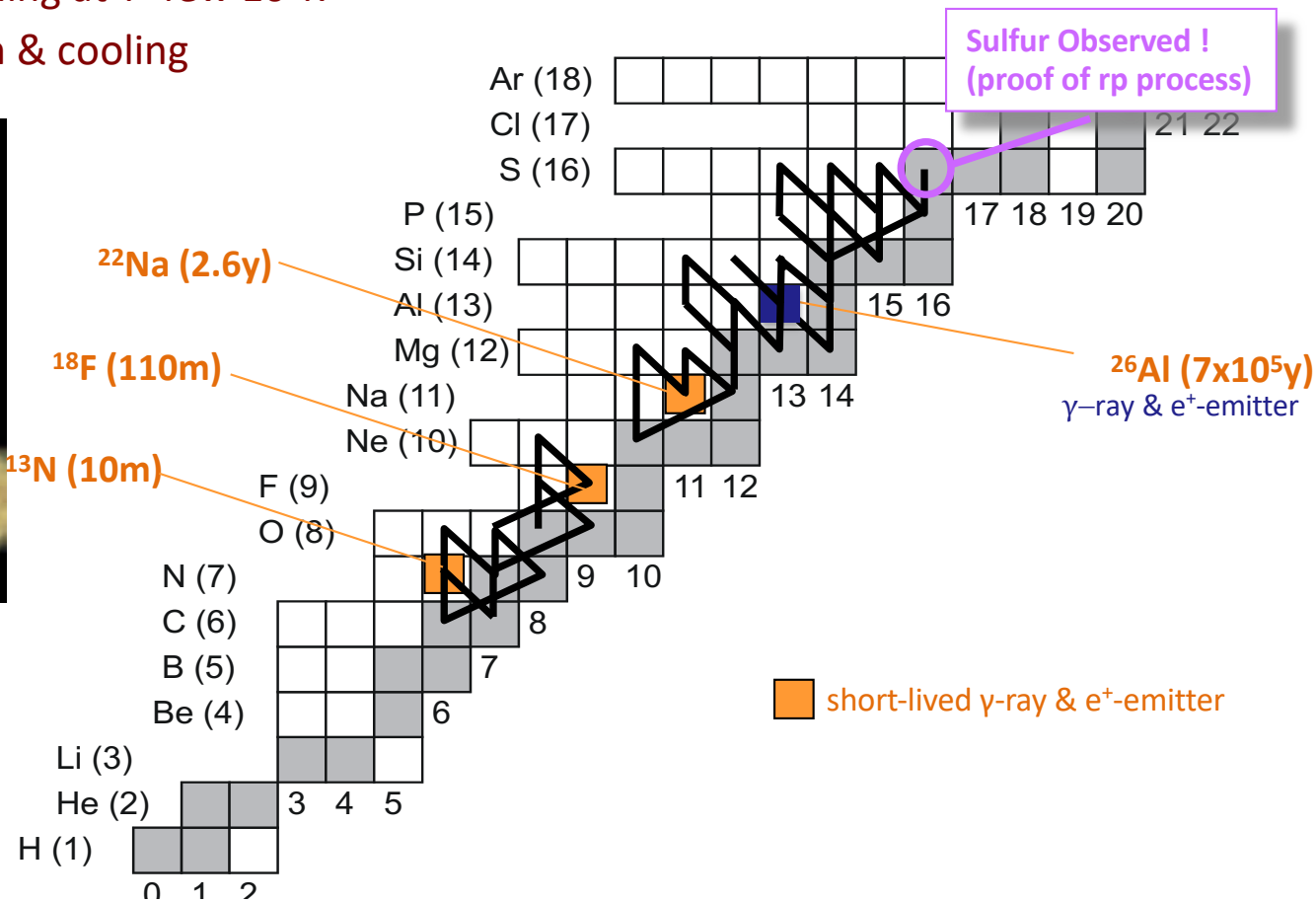
The et al. 2006*; see also Dufour & Kaspi 2013*

Nova explosions: nucleosynthesis on the p-rich side

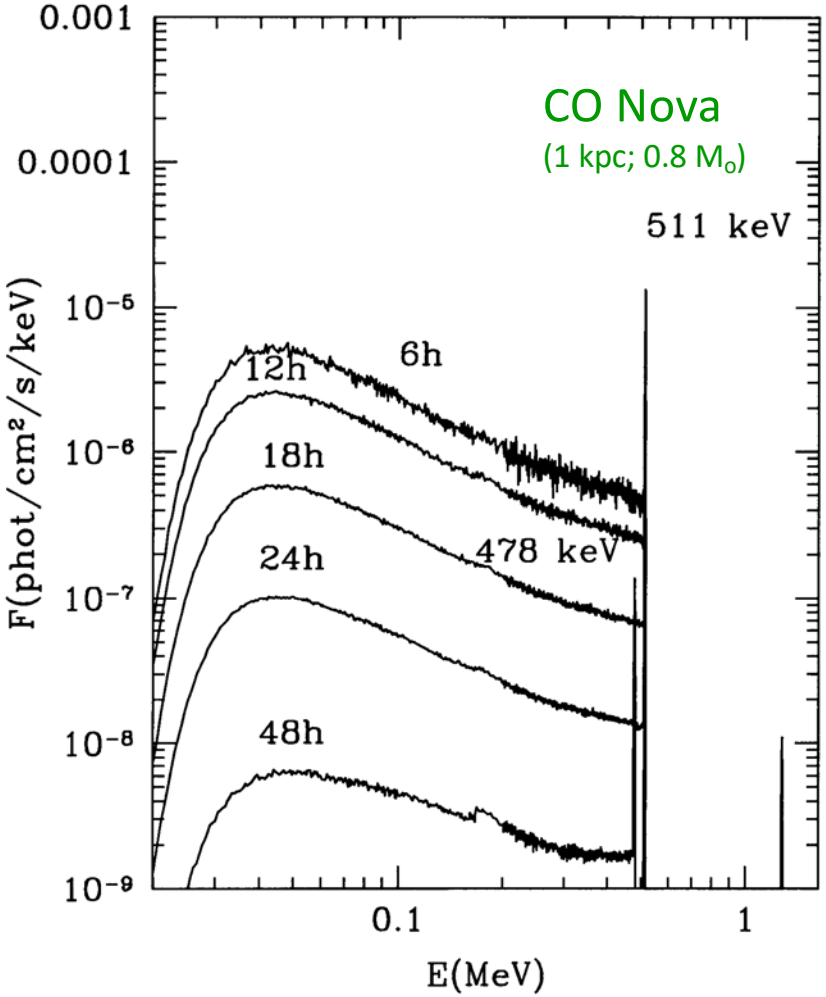
- H-burning in a runaway on WD surface
  - ☞ Accretion of H from companion star
  - ☞ H ignition → H burning at T~few 10^8K
  - ☞ envelope expansion & cooling

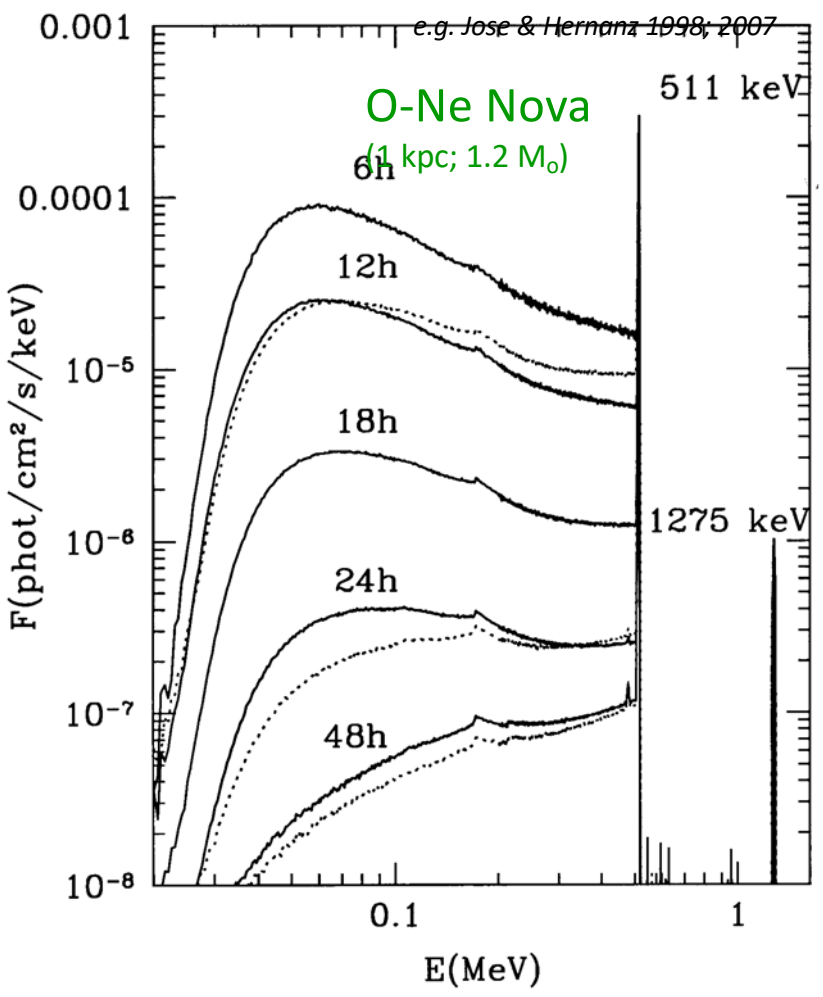


$\dot{M} \sim 10^{-8} M_{\odot} y^{-1}$



Nova Diagnostics Prospect with Nuclear Lines





- ☆ Brief flash due to e^+ annihilations, with 511 keV line and β^+ decay continuum *(before optical nova!)*
- ☆ ^{7}Be radioactivity (CO novae)
- ☆ ^{22}Na radioactivity (O-Ne novae)

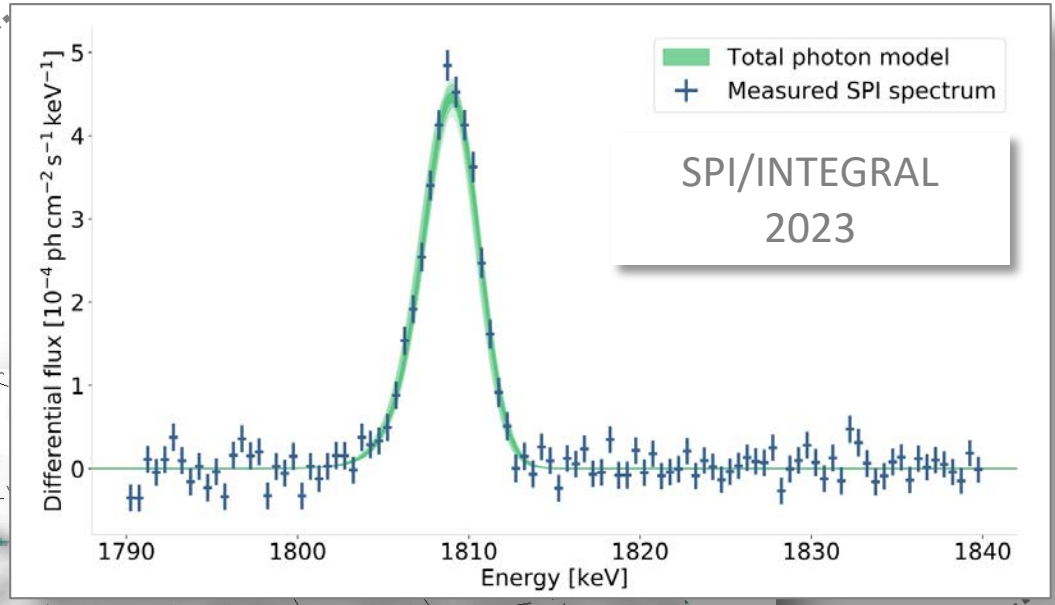
→ not seen (yet?) *Siegert+2018*

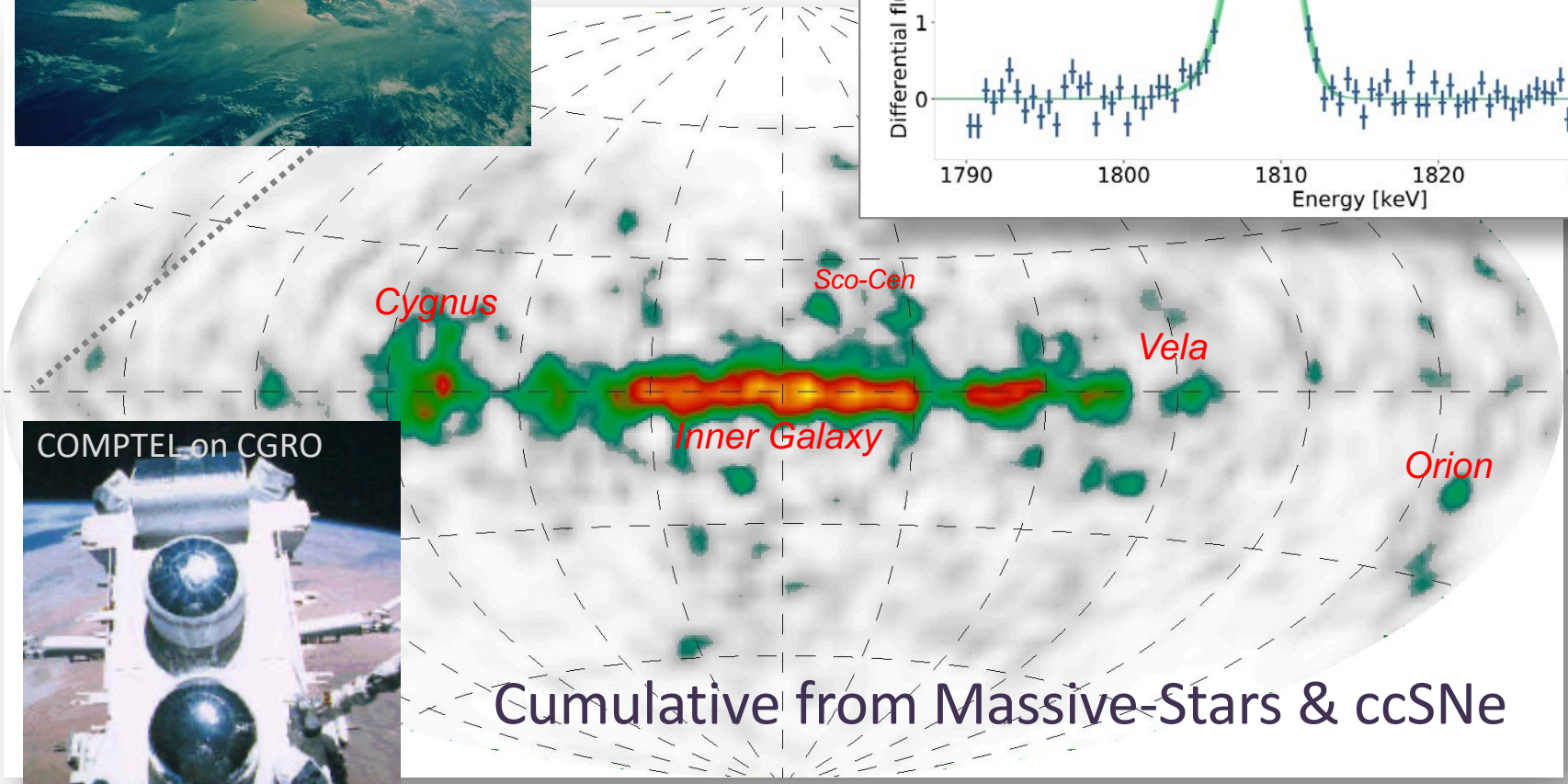
$$M_{3\sigma}^{^{7}\mathrm{Be}} < 4.8\times10^{-9}\left(\frac{d}{\mathrm{kpc}}\right)^2 M_\odot$$

$$M_{3\sigma}^{^{22}\mathrm{Na}} < 2.4\times10^{-8}\left(\frac{d}{\mathrm{kpc}}\right)^2 M_\odot$$

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







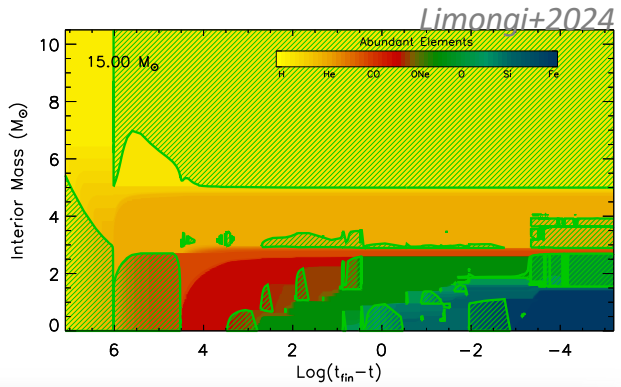
γ-ray flux → cc-SN Rate = 1.3 (± 0.6) per Century

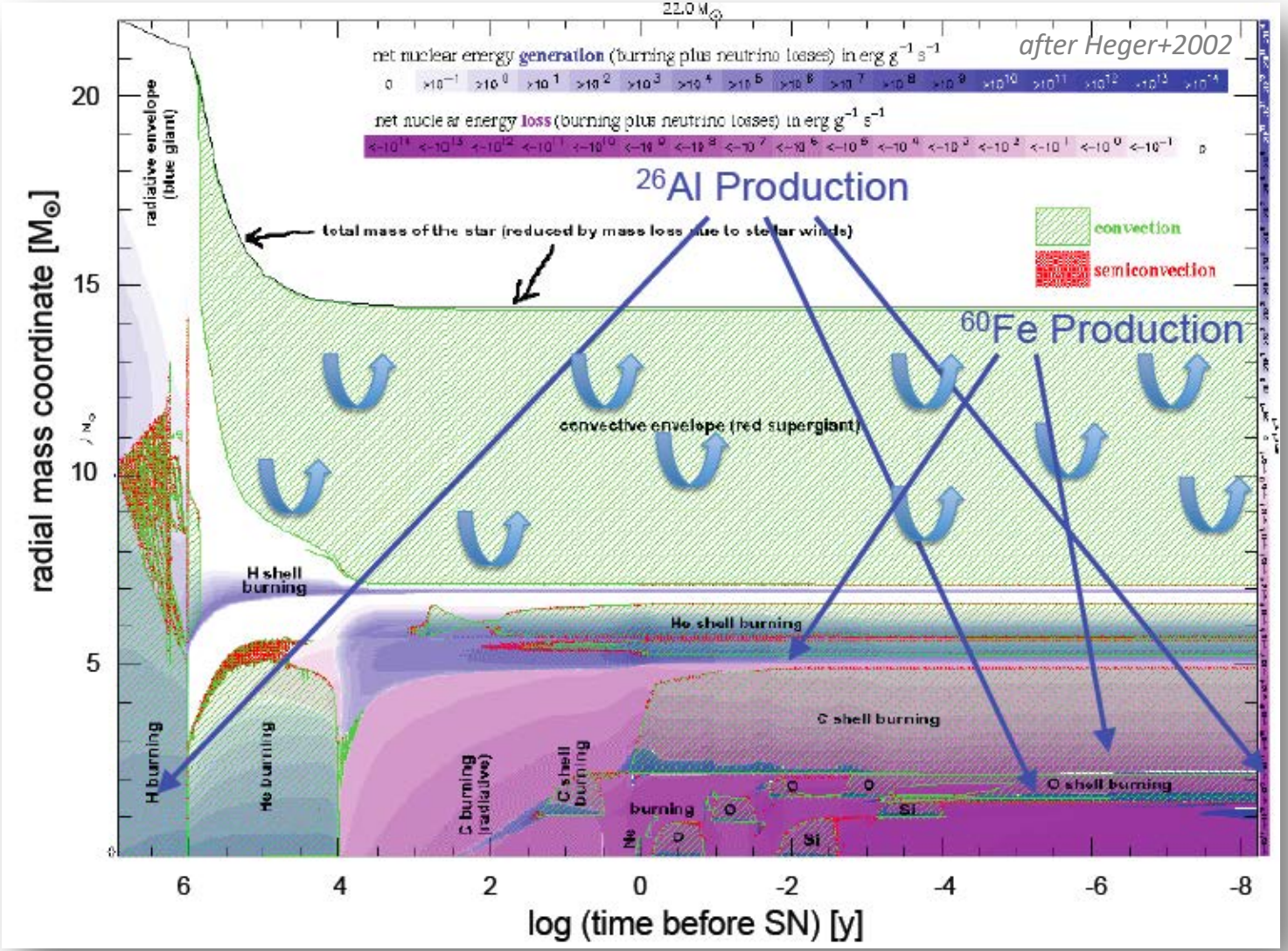
Diehl+2006;2018

Radioactivities from massive stars: ^{60}Fe, ^{26}Al

→ Messengers from Massive-Star Interiors!

…complementing neutrinos and asteroseismology!





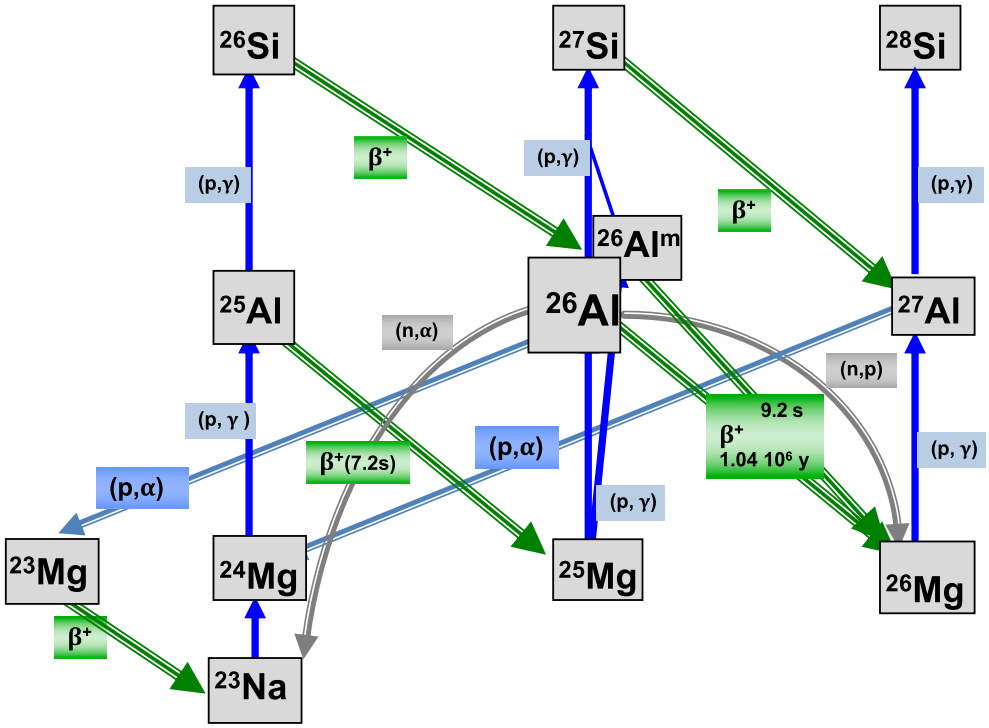
Processes:

- ☆ *Hydrostatic fusion*
- ☆ *WR wind release*
- ☆ *Late Shell burning*
- ☆ *Explosive fusion*
- ☆ *Explosive release*

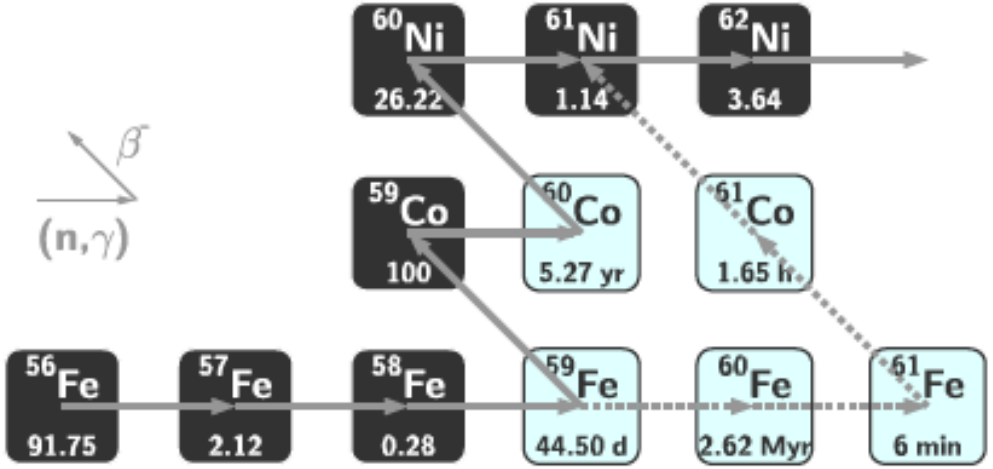
Nuclear reactions to produce ^{26}Al , ^{60}Fe

The Na-Al-Mg cycle: p captures (H burning in stars, +...)

- ☆ production versus destruction reactions...



Neutron capture on Fe in massive-star shells



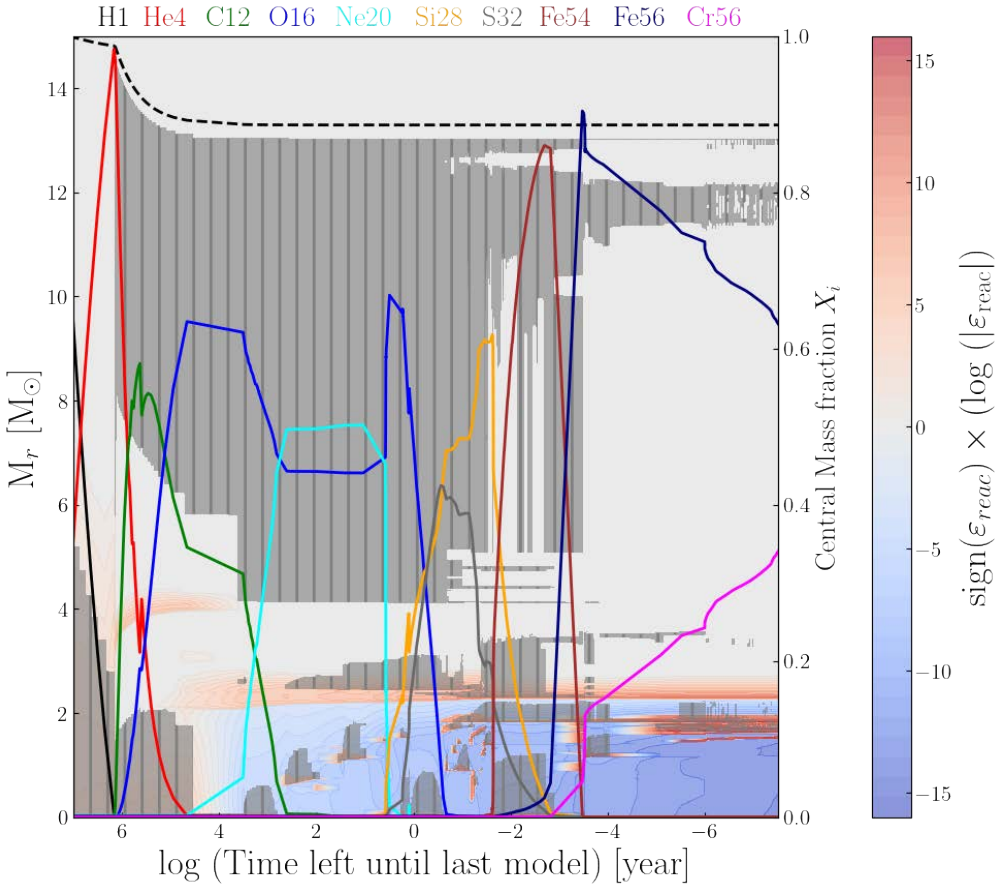
- ☆ What are the n capture rates?
- ☆ What are the β decay lifetimes?

The Evolution of Massive Star Structure

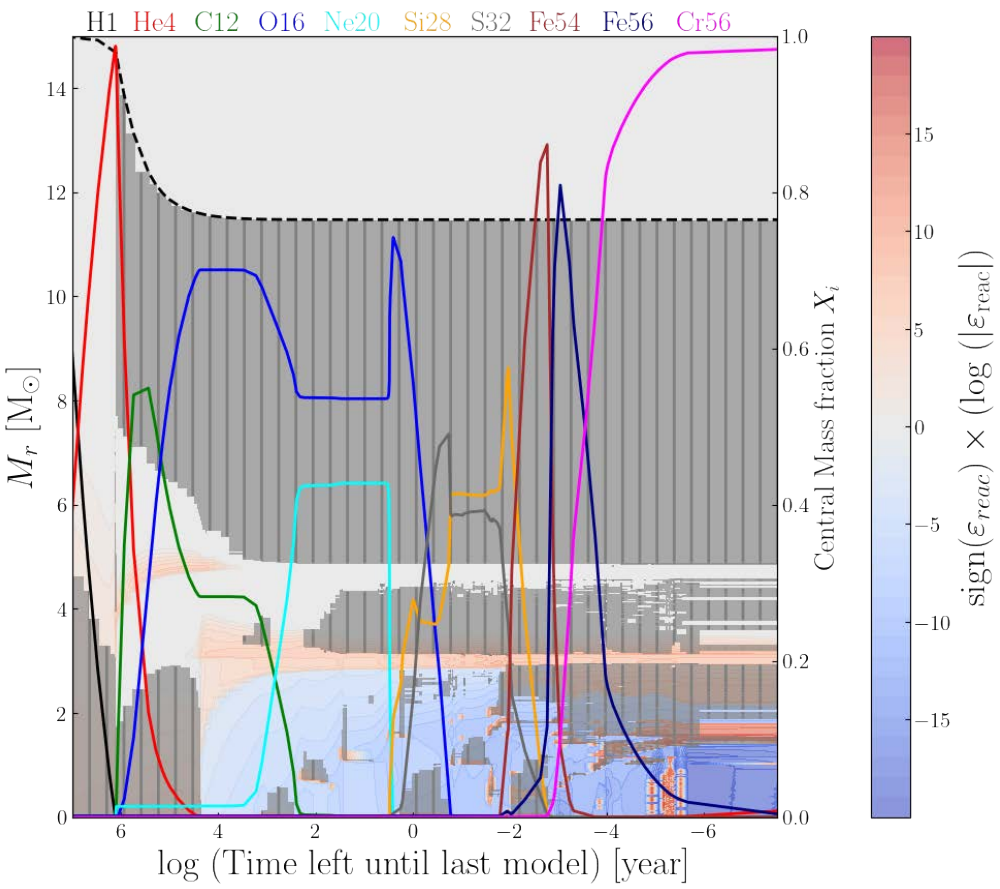
('Kippenhahn' diagrams)

15 $M_\odot$ 2 codes/models (1D)

GENEC



MESA *Griffiths+2025*

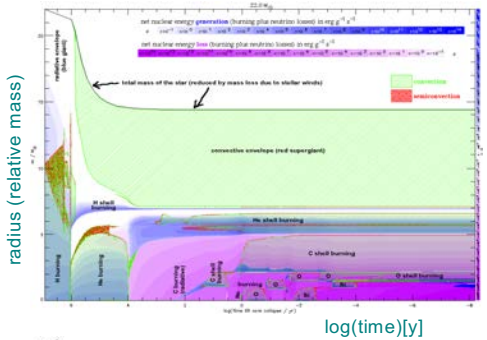


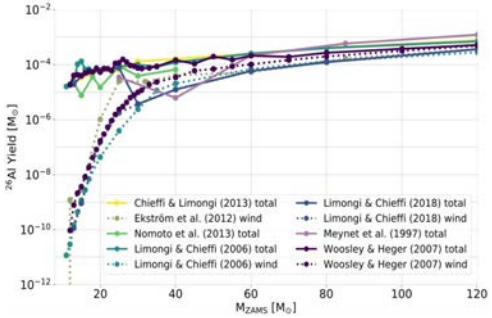
- the challenge of properly treating the 3D nature of mixing, specifically near shell boundaries

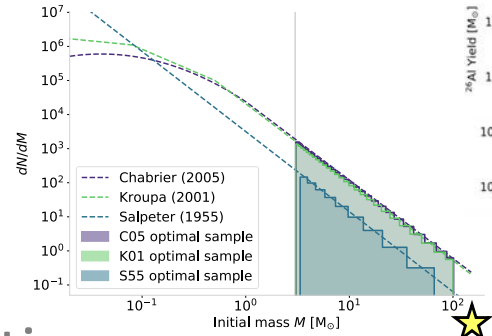
Modelling a Massive-Star Group

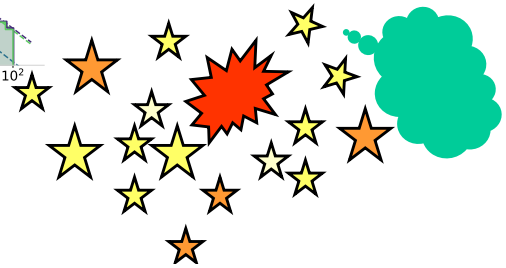
Extract massive-star properties (as a function of their mass)

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







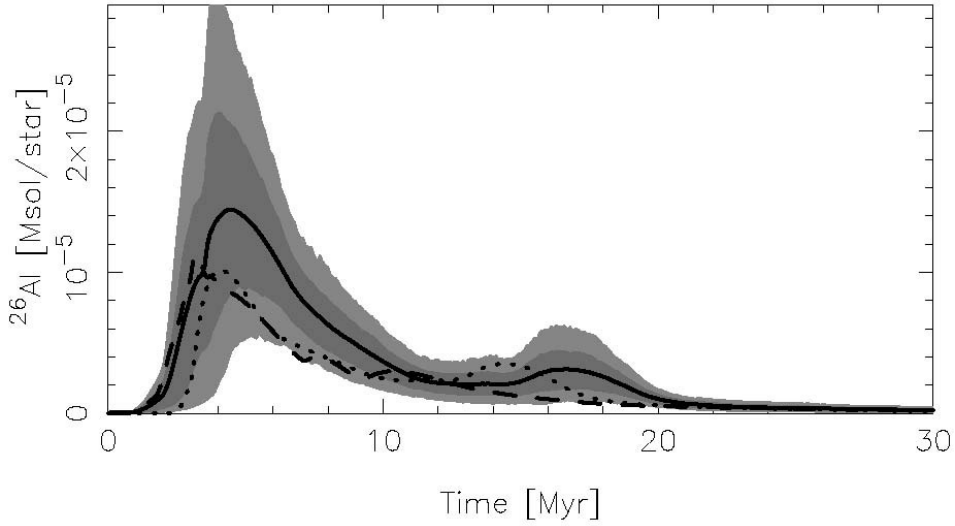


Create a sample for a group of stars

- ☆ 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

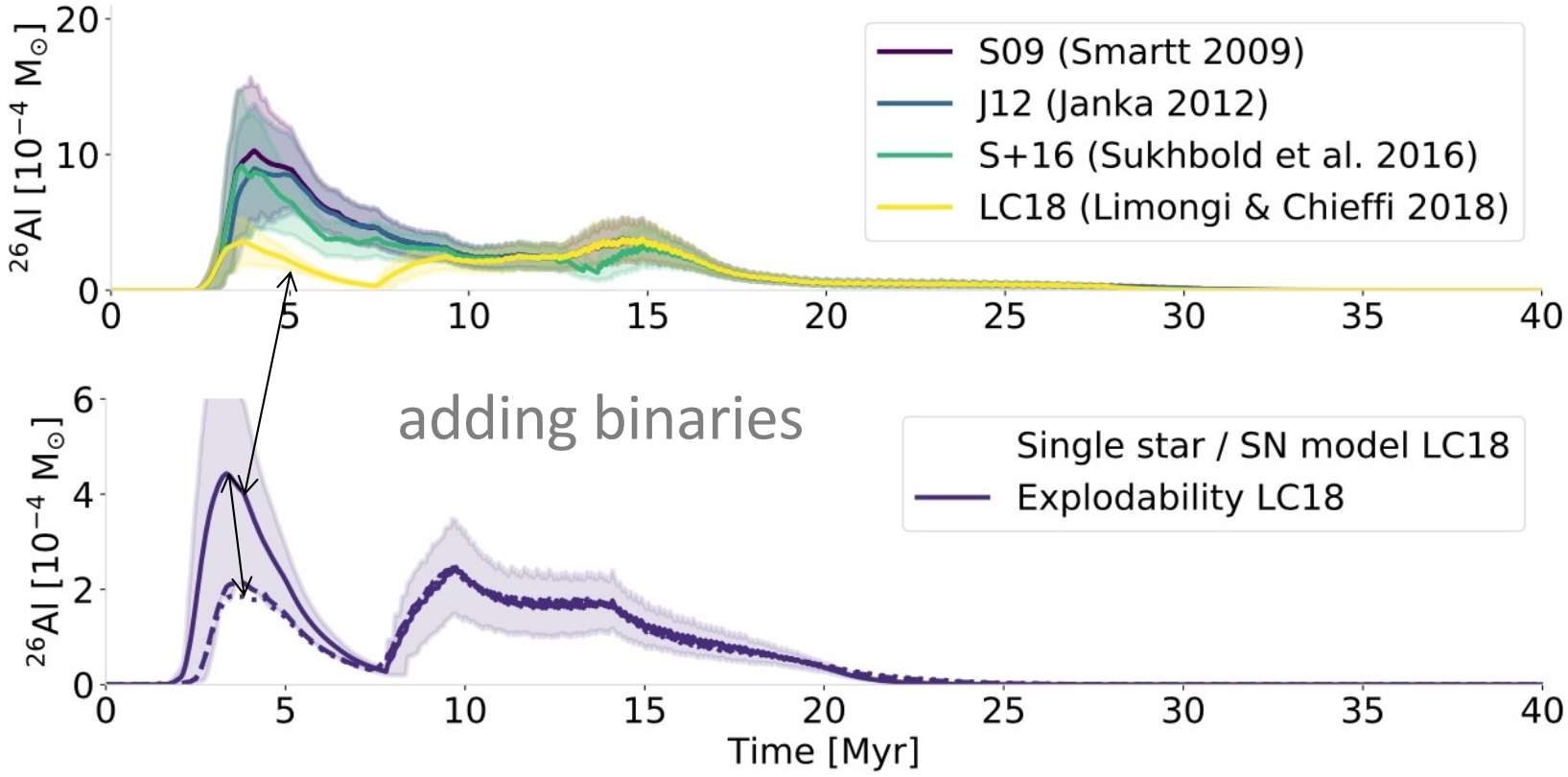
Acronym	Exploding stellar models
S09	$M_* \geq 8$
J12	$8 \leq M_* \leq 100$ and $140 \leq M_* \leq 260$
S+16	Irregular islands and valleys of explodability
LC18	$8 \leq M_* \leq 25$

Pleintinger 2020

variation of explodability

sic yields

& Chieffi 2006



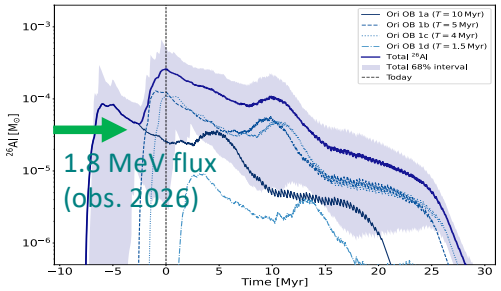
Binary wind yields from Brinkman + 2019

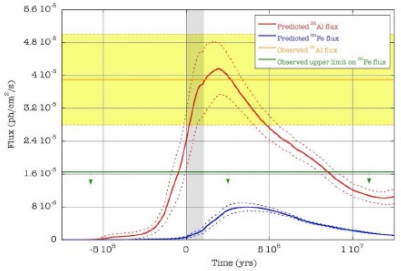
Binary fraction = 0.0

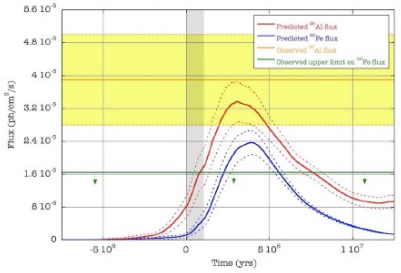
Binary fraction = 0.7

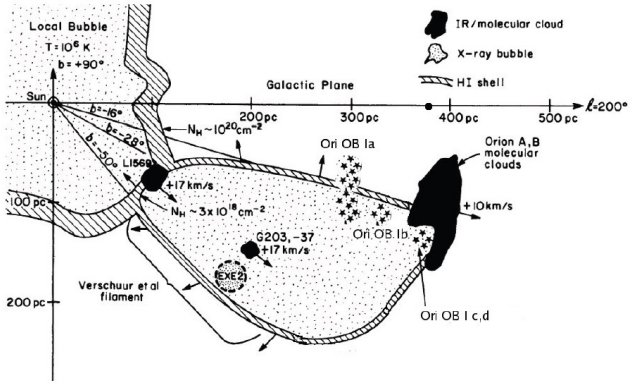
Binary fraction = 0.9

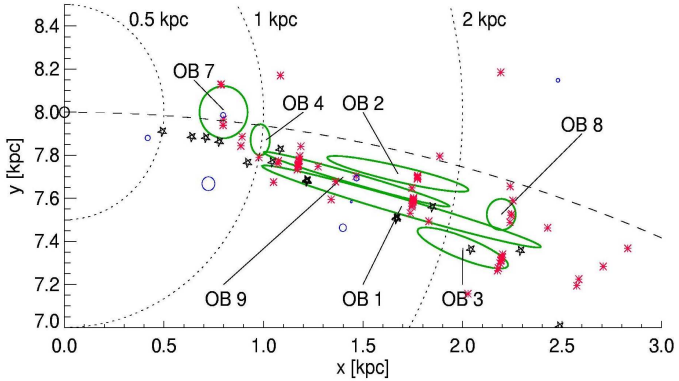
Measurements of ^{26}Al from different massive-star regions

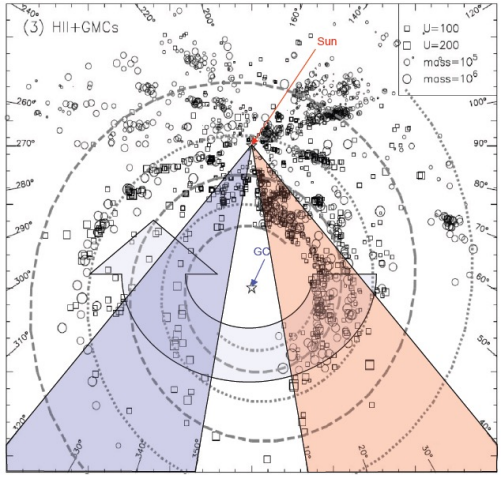




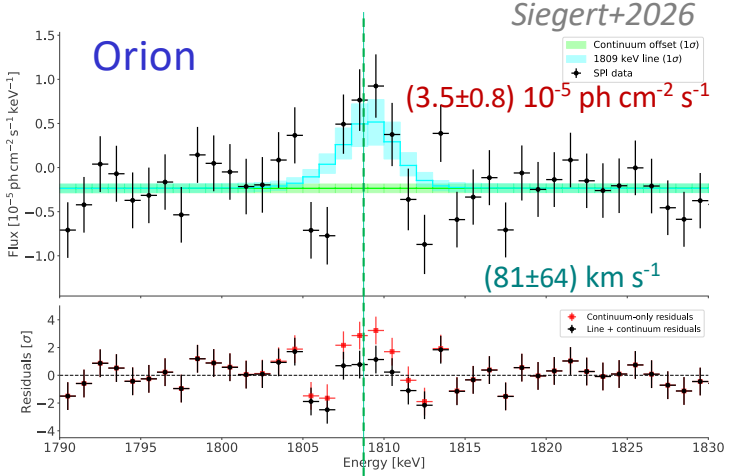


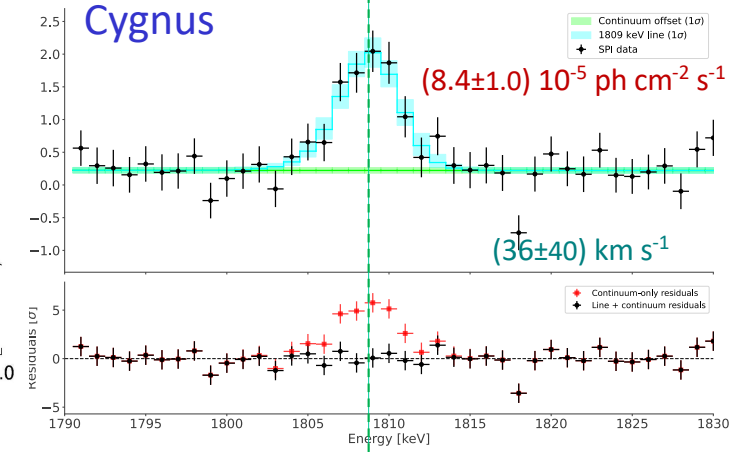


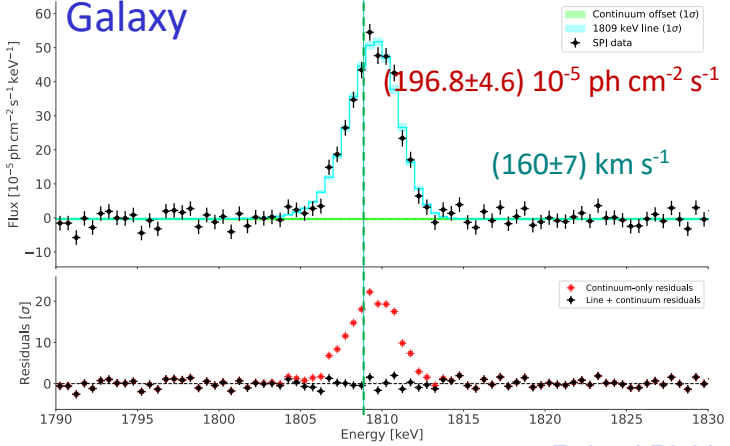




Siegert+2026







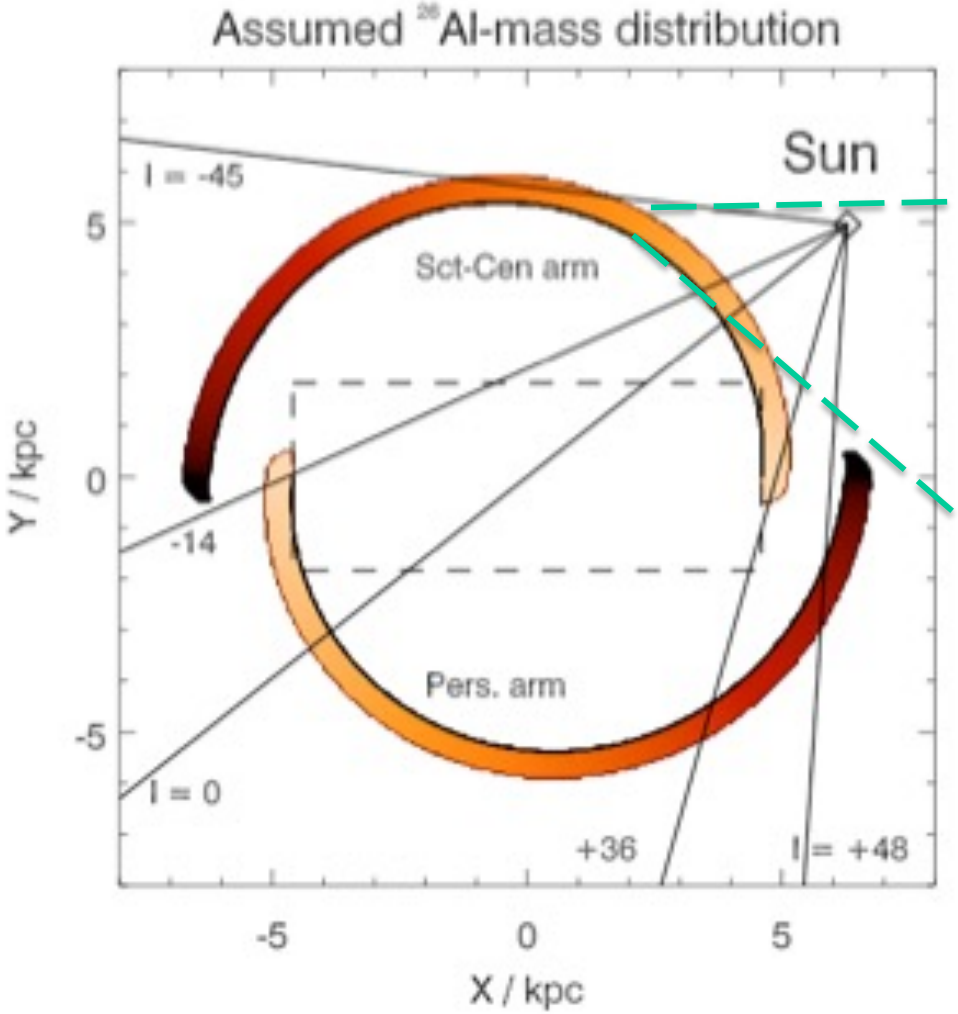
☞ different groups (ages) test the massive-star group evolution model

How radioactive massive-star ejecta trace the spreading…

^{26}Al shows apparently higher galactocentric rotation (?)

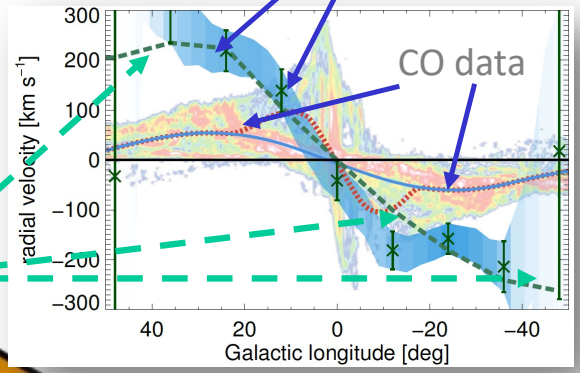
..isotropically blown into cavities that are non-symmetric wrt sources

☞ radioactive decay: more ^{26}Al signal while moving to leading edge

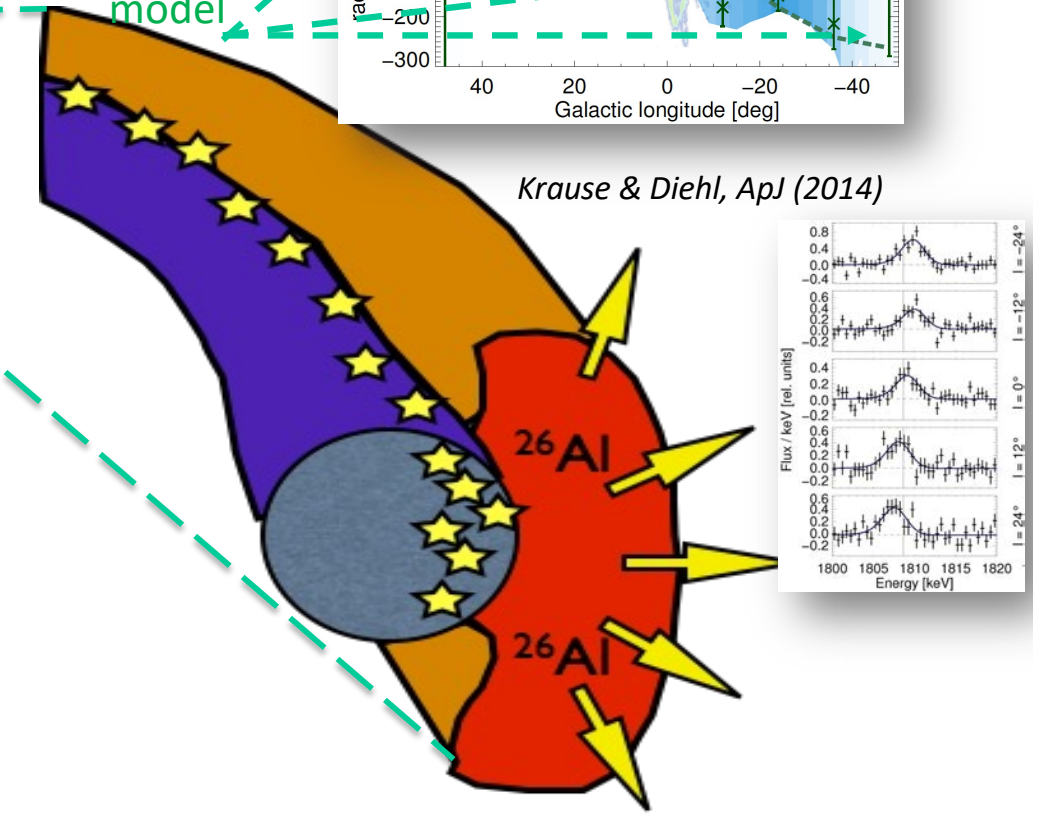


simple geometry model

SPI/INTEGRAL data

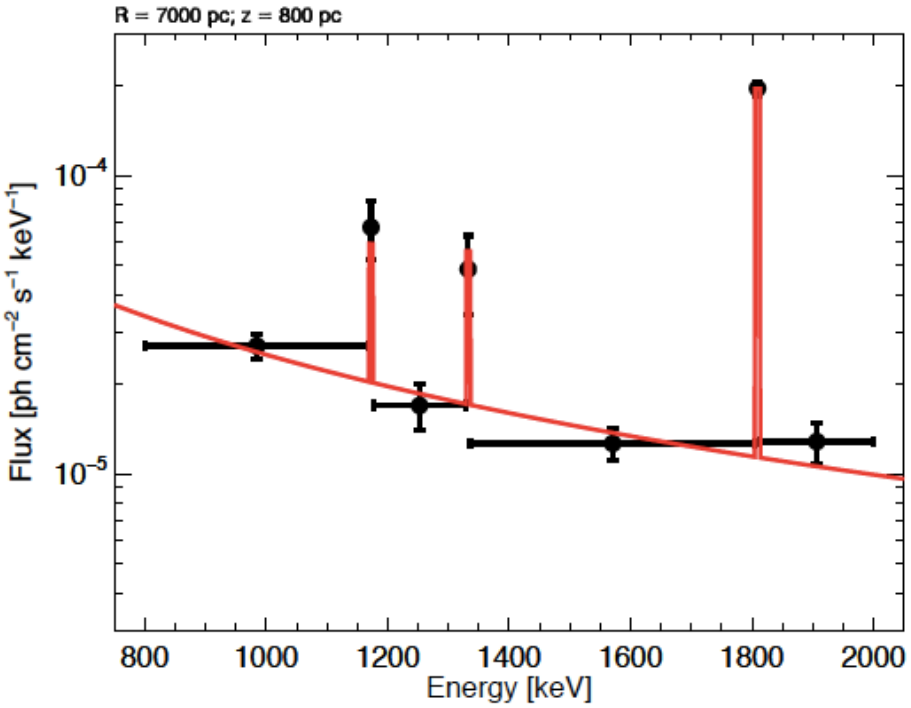


Krause & Diehl, ApJ (2014)



Diffuse gamma-ray emission from ^{60}Fe in the Galaxy

^{26}Al and ^{60}Fe analysis with same INTEGRAL dataset (15+ years) and models



^{60}Fe emission too faint for imaging etc

Variability study on ^{60}Fe/^{26}Al ratio

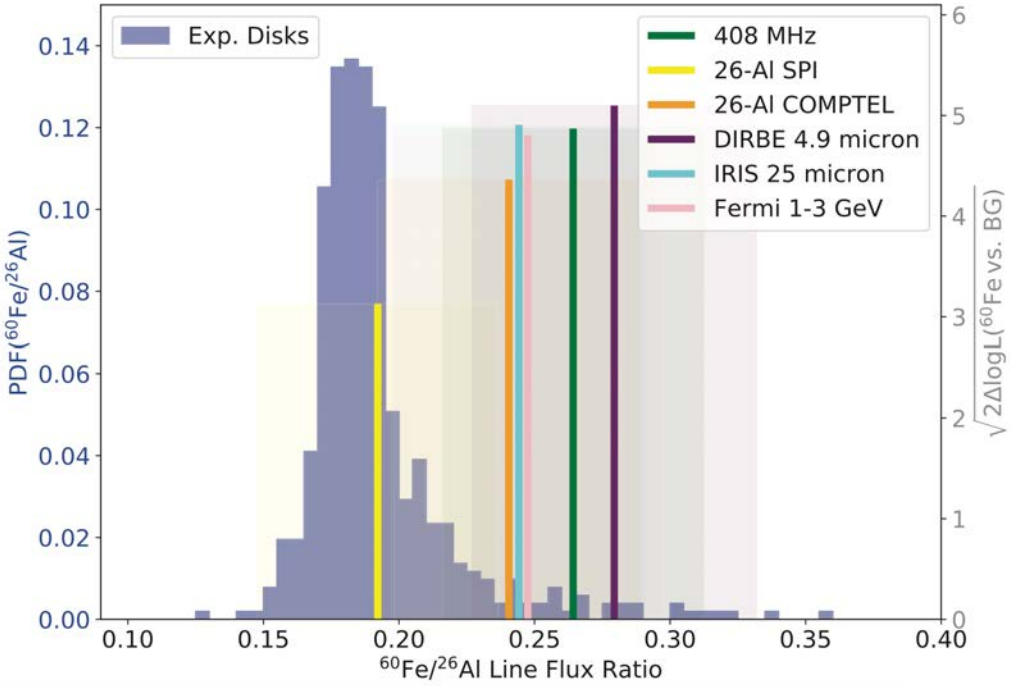
(systematics!)

➔ ^{60}Fe/^{26}Al < 0.4 in Galaxy

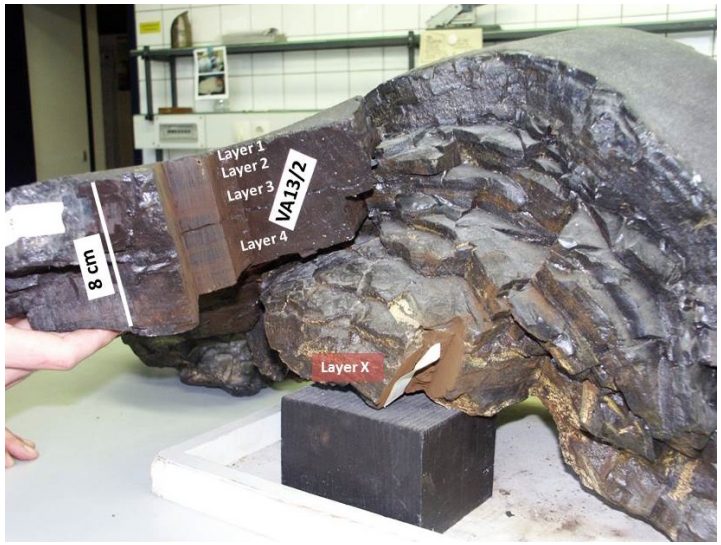
cmp theory: 0.2...1,

and oceancrusts: >0.2

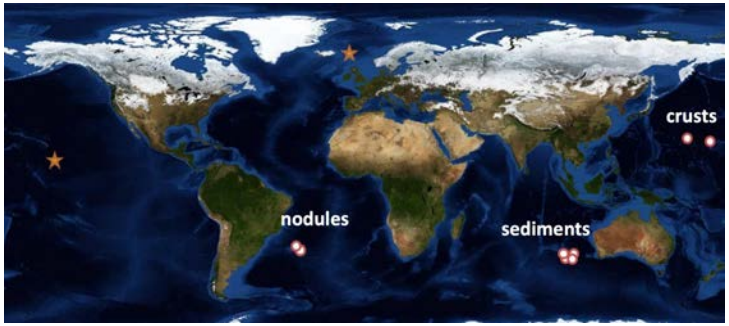
Wang+ 2020



^{60}Fe and ^{244}Pu from nucleosynthesis found on Earth

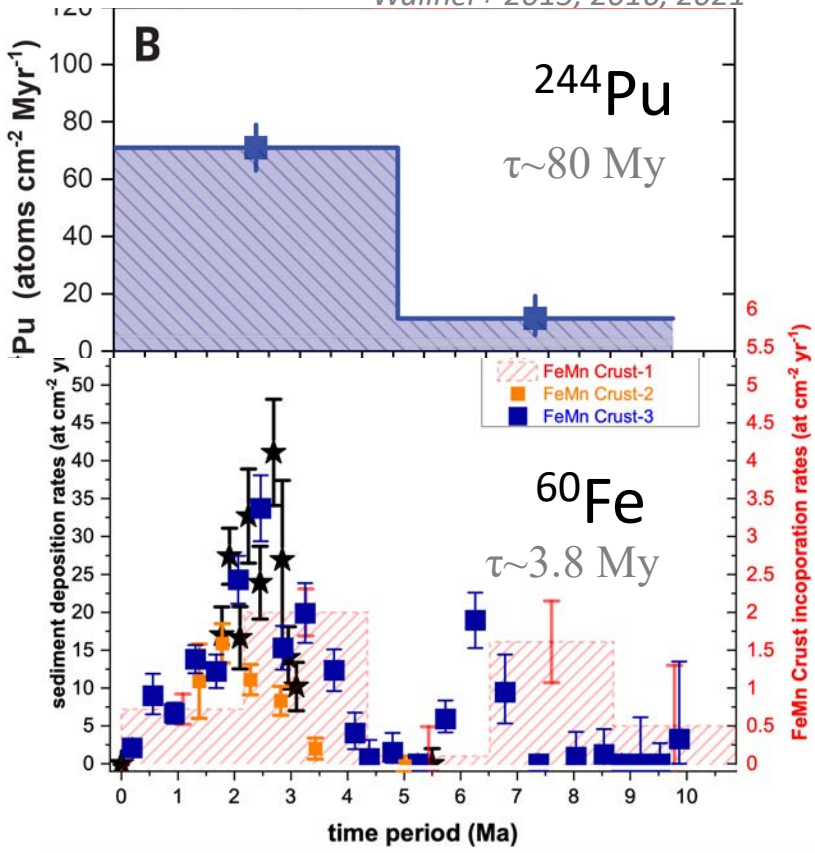


Knie+ 2004, Fimiani+ 2016, Ludwig+ 2016, Koll+ 2019, ...



+ lunar material probes; + antarctic snow

Wallner+ 2015, 2016, 2021



peak of radioactivity influx
≈3 & 6-8 My ago!

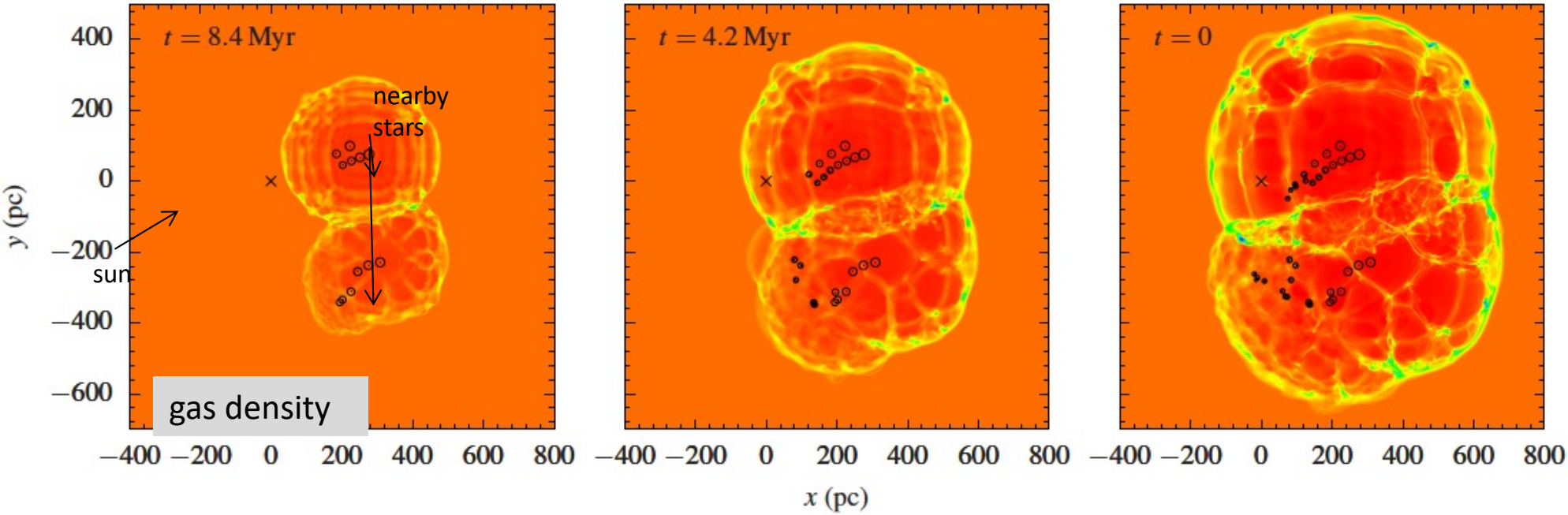
How did these traces of nucleosynthesis get here?

^{60}Fe on Earth from recent nearby supernovae?

The Sun is (now) located inside a hot cavity (the "Local Bubble")

SN explosions within LB → ejecta flows reach the Solar System

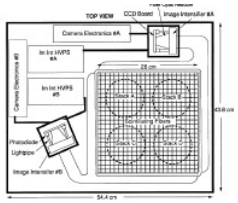
Schulreich+ 2017

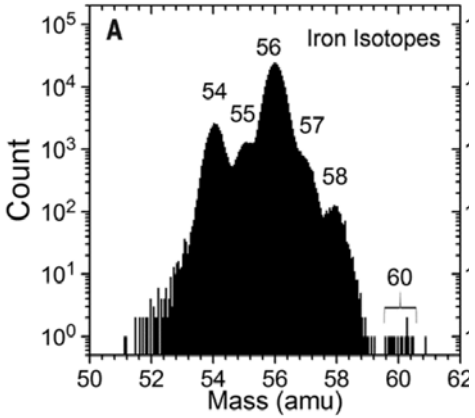


Nearby OB associations and their nucleosynthesis reach the SolarSystem

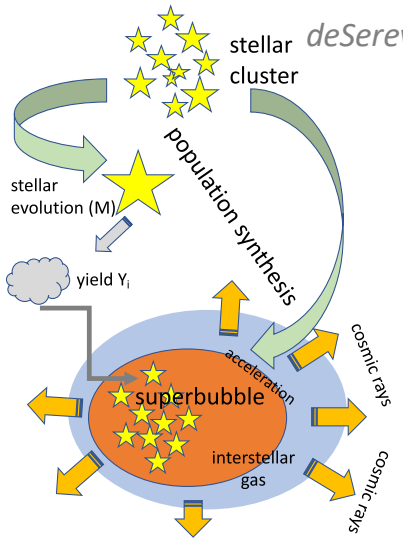
Israel+ 2016; Binns+ 2016

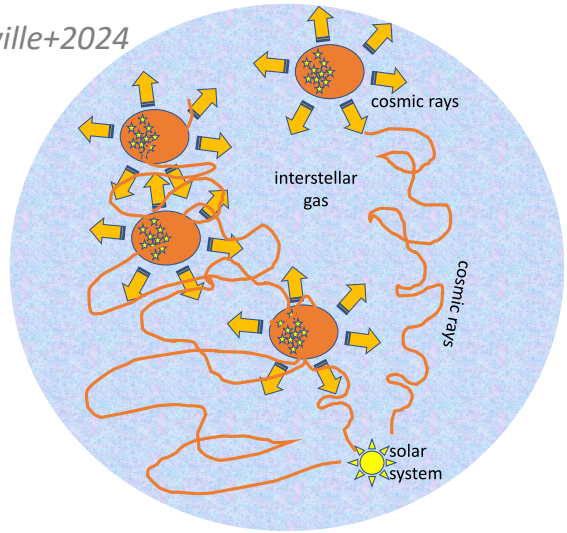






deSereville+2024





Stellar feedback in the nearest massive-star region (Sco-Cen)

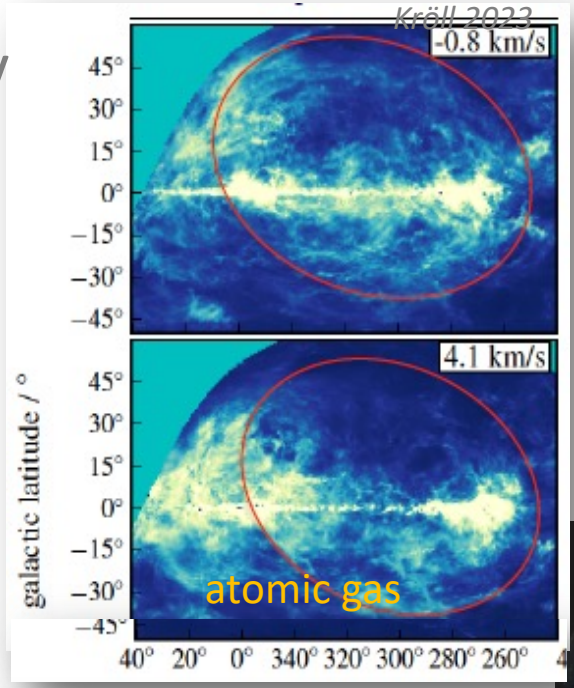
The nearby ISM holds a variety of cavities and shells

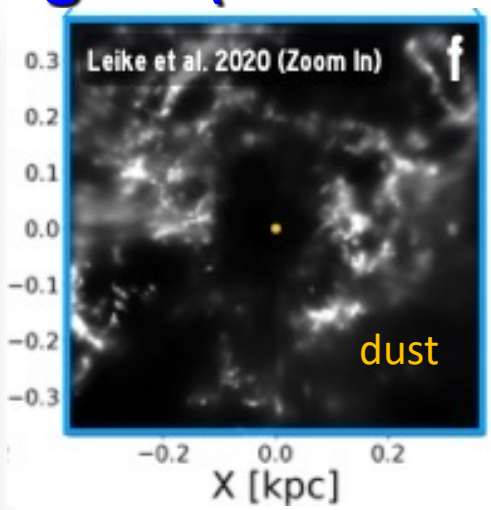
SF in Sco-Cen has been ongoing for ~15+ My; distance~140pc

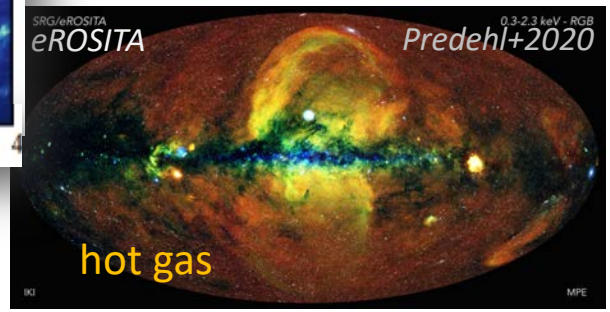
Hot gas and ^{26}Al seen from SF

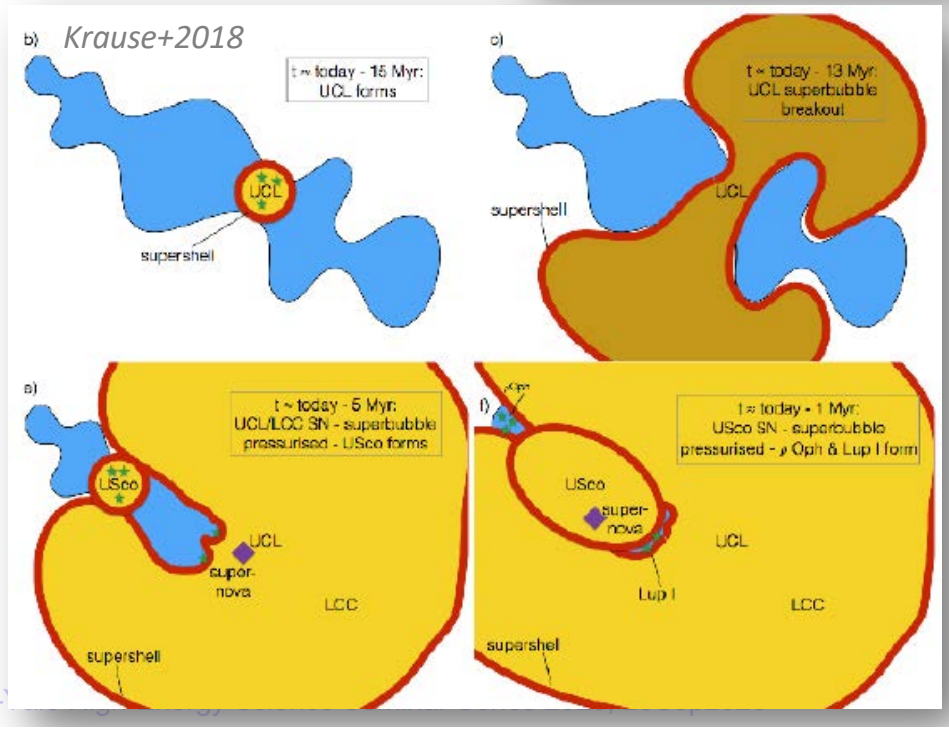
→ *"surround & squish"*

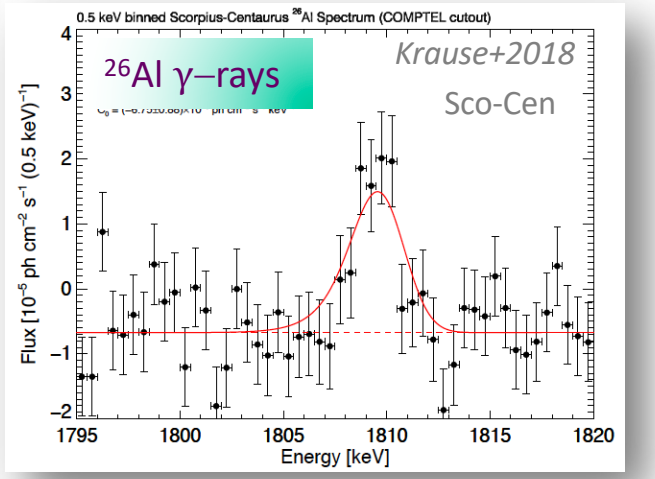
rather than "triggered" star formation





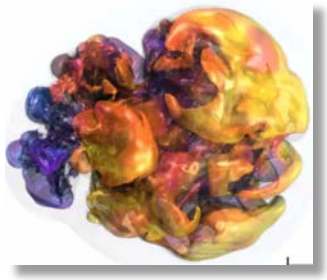


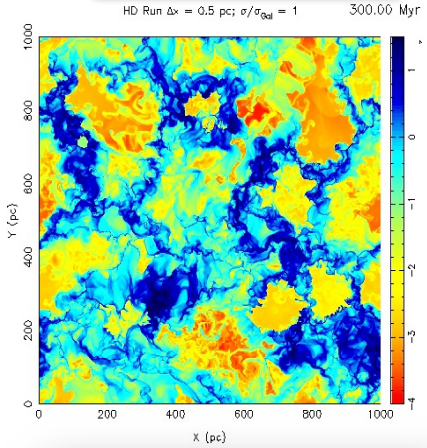


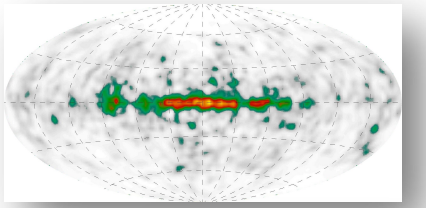


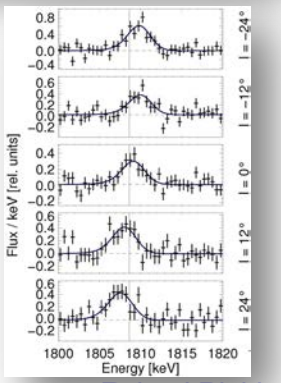
Nuclear Astrophysics with γ-ray lines - Summary

- ☆ Cosmic nuclear-reaction sites are occulted: no direct observations
  - ☞ Stellar photospheric abundances of elements: established, large databases from Gaia and spectrographs led to insights on chemical evolution history of the Galaxy, and anomalies
  - ☞ Stardust, terrestrial deposits, CRs...: isotopic details, but bias
  - ☞ Near-direct messengers (ν's, γ's) are difficult, but unique
- ☆ Gamma ray results have led to major advances
  - ☞ Supernova interiors show new & 3D characteristics in γ rays
  - ☞ Complex radiation transfer is complemented/verified
  - ☞ Current galactic nucleosynthesis is being explored, and tested against massive-star modelings, and feedback theory
  - ☞ Superbubbles have been established as major ejecta locations
- ☆ The next level for deeper γ-ray observations is ready
  - ☞ COSI will provide an important validation and systematics test
  - ☞ Lab experiments are ready to provide a major sensitivity advance
- ☆ The different disciplines of nuclear/astro/astronomy studies all complement each other in the lively field of 'nuclear astrophysics'



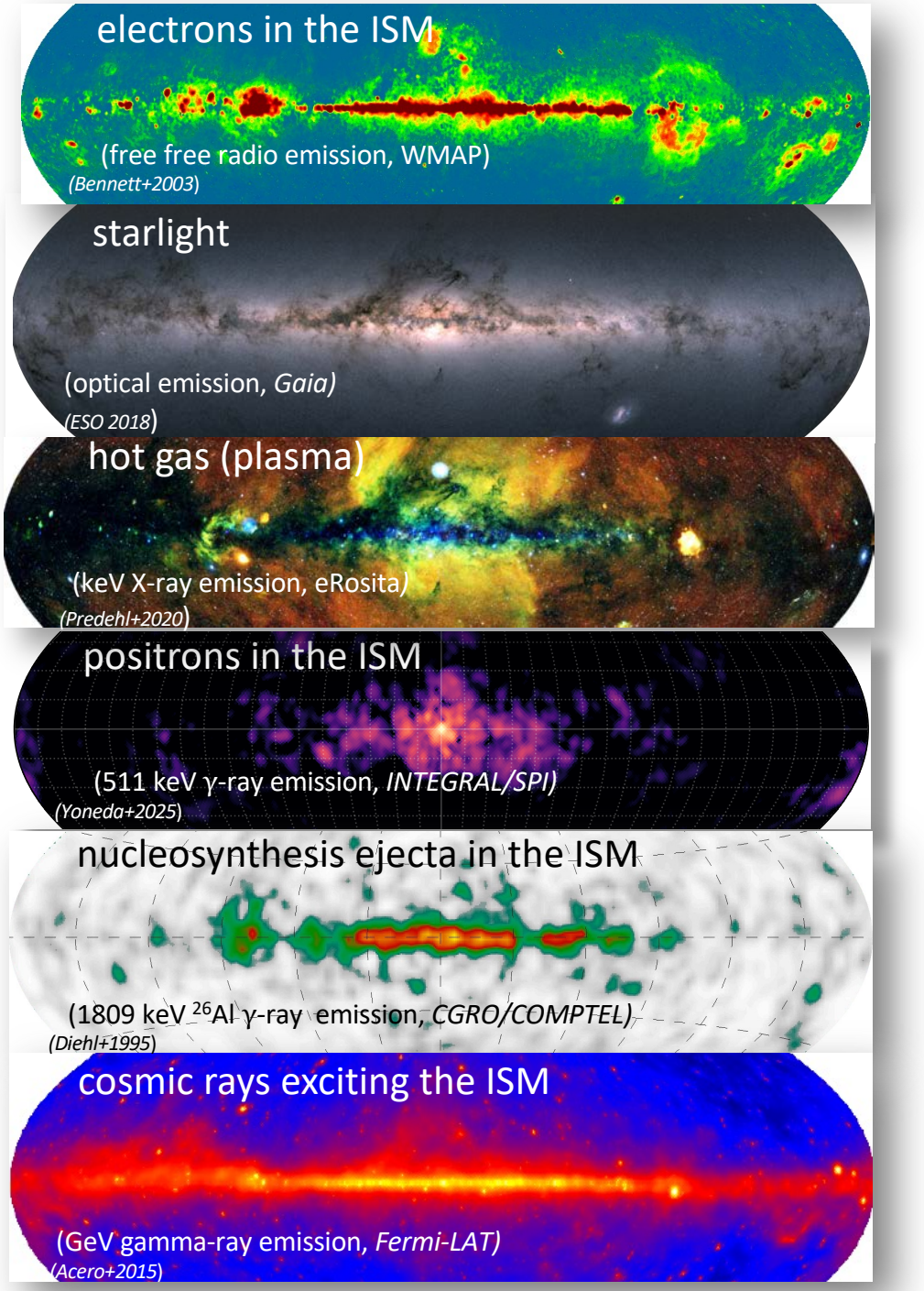




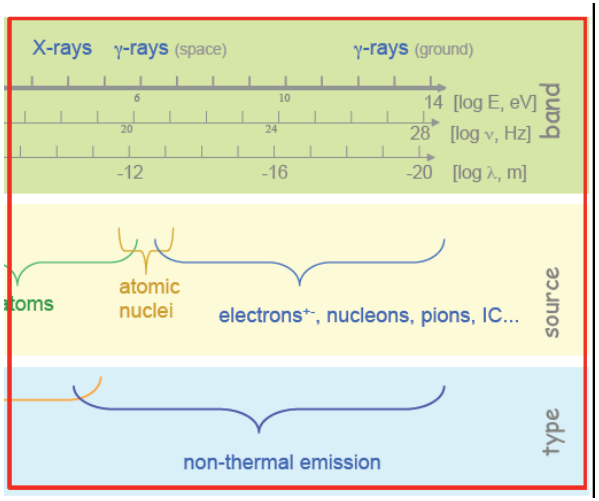


Galactic Messengers

- Radioactivity provides a clock
- ^{26}Al radioactivity gamma rays trace nucleosynthesis ejecta over ~few Myrs
- Radioactive emission is independent of density, ionisation states, …
- Positron annihilation ~traces CR propagation



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



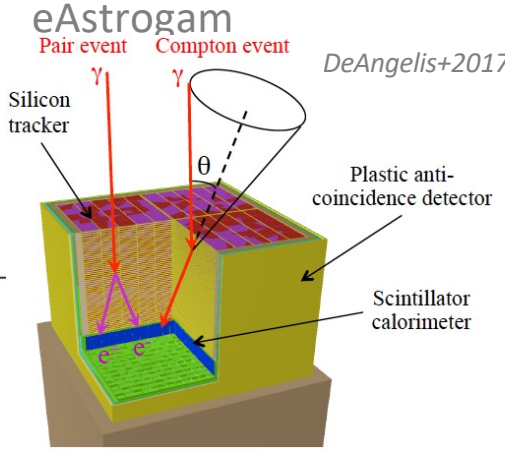
We can build on achievements for bright

(and prospects from theoretical considerations

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

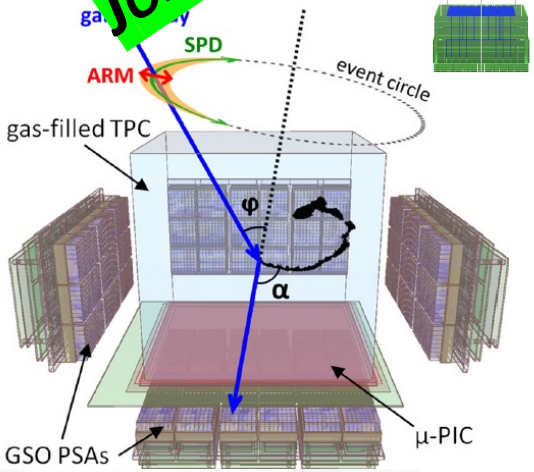
Compton Telescopes+.. are being developed in

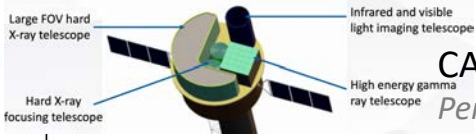
SEE TALKS BY
RUIZHI YANG 07 OCT
HIRO ODAKA 21 OCT
JOHN TOMSICK 16 DEC



DeAngelis+2017, 2018

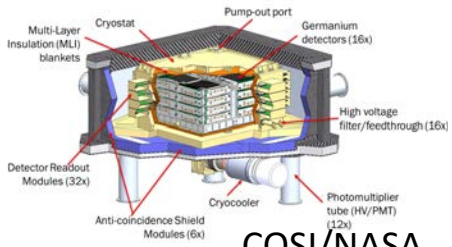
...hori+2015





CAST/CNSA

Peng+2020



COSI/NASA

Tomsick+2021

