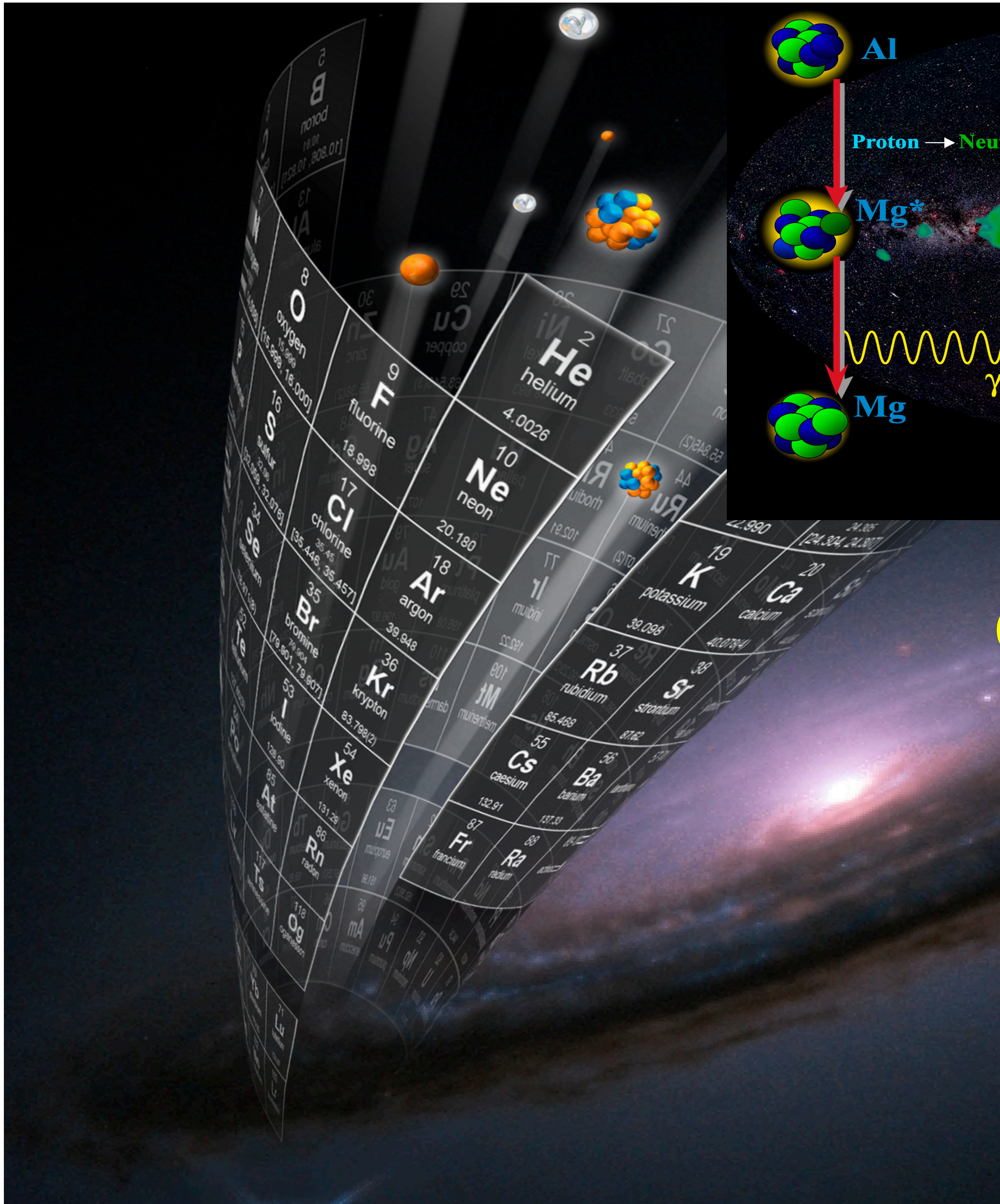
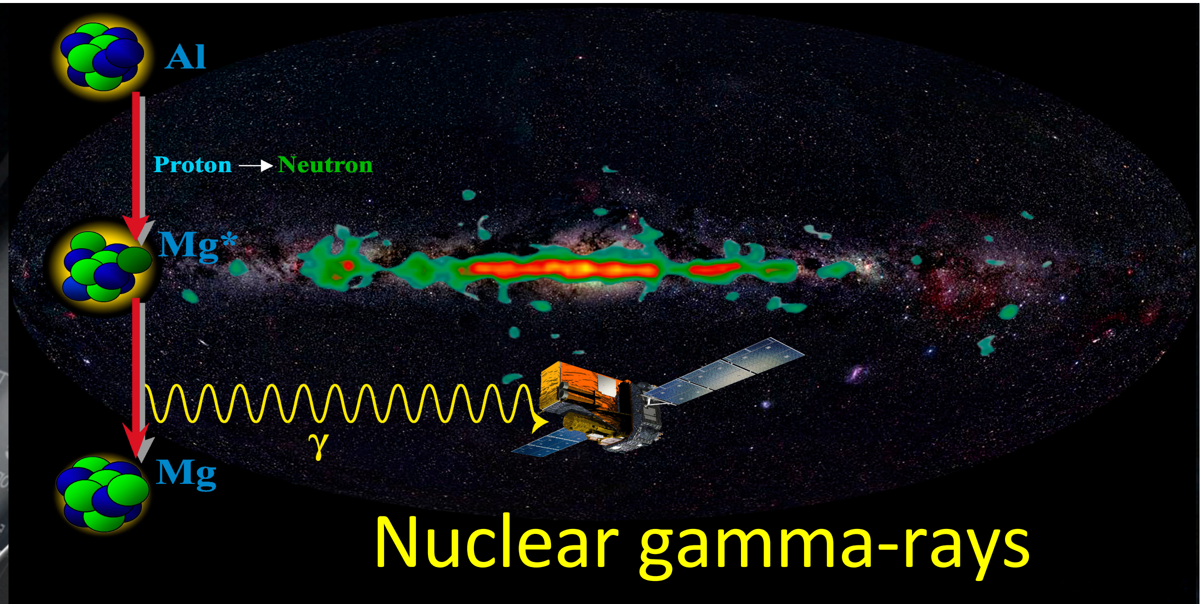




Nuclear gamma-rays and Cosmic Nucleosynthesis

Roland Diehl
Technical University München and
MPE and Origins Cluster emeritus
Garching

Contents:

1. Science goals of γ-ray observations
2. Supernova explosions
3. Galactic-scale nucleosynthesis

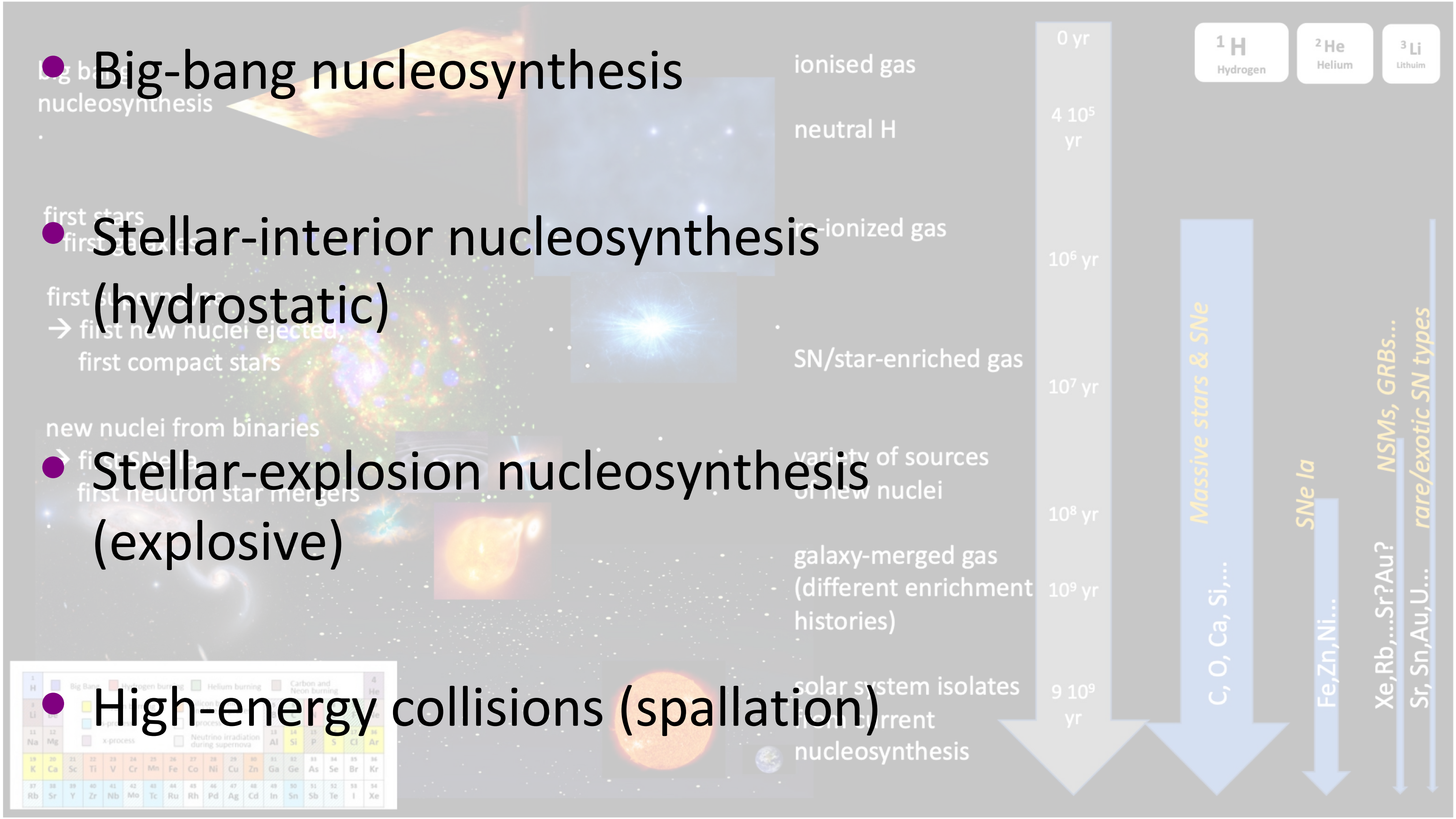
with work from (a.o.)
Martin Krause, Karsten Kretschmer, Moritz Pleintinger,
Thomas Siegert, Rasmus Voss, Wei Wang, Christoph Weinberger

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Figure: ChETEC 2021

Cosmic nucleosynthesis

- Big-bang nucleosynthesis
- Stellar-interior nucleosynthesis (hydrostatic)
- Stellar-explosion nucleosynthesis (explosive)
- High-energy collisions (spallation)



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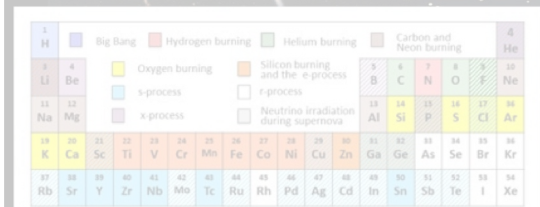
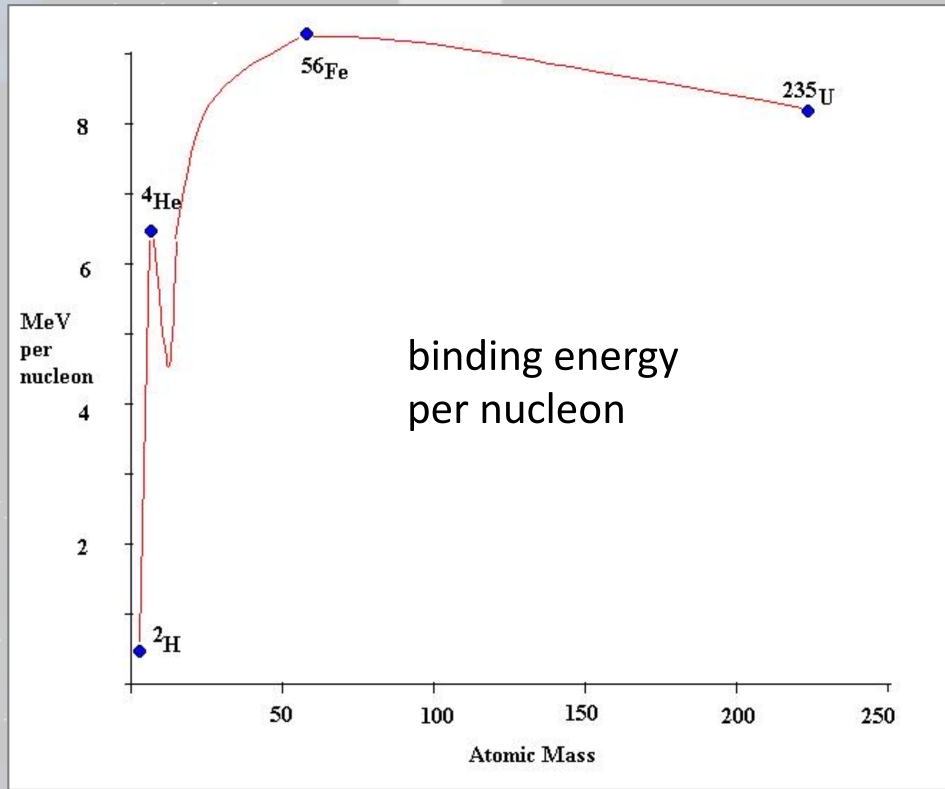


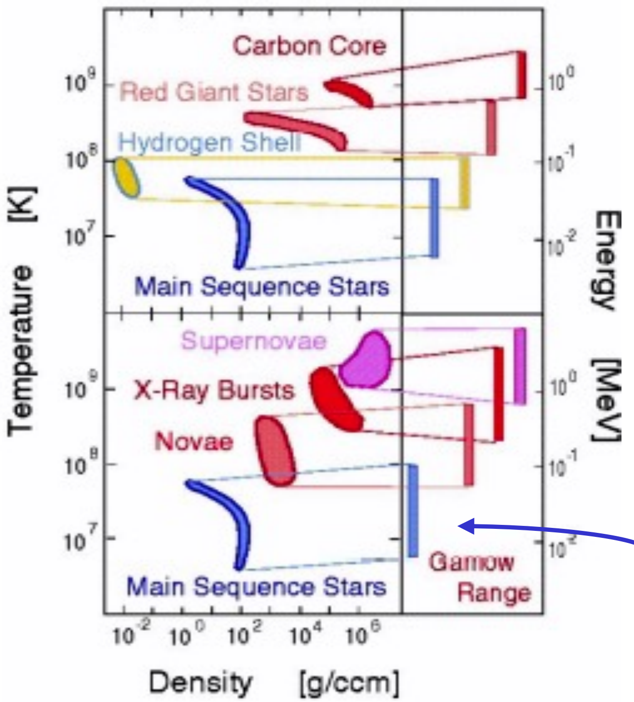


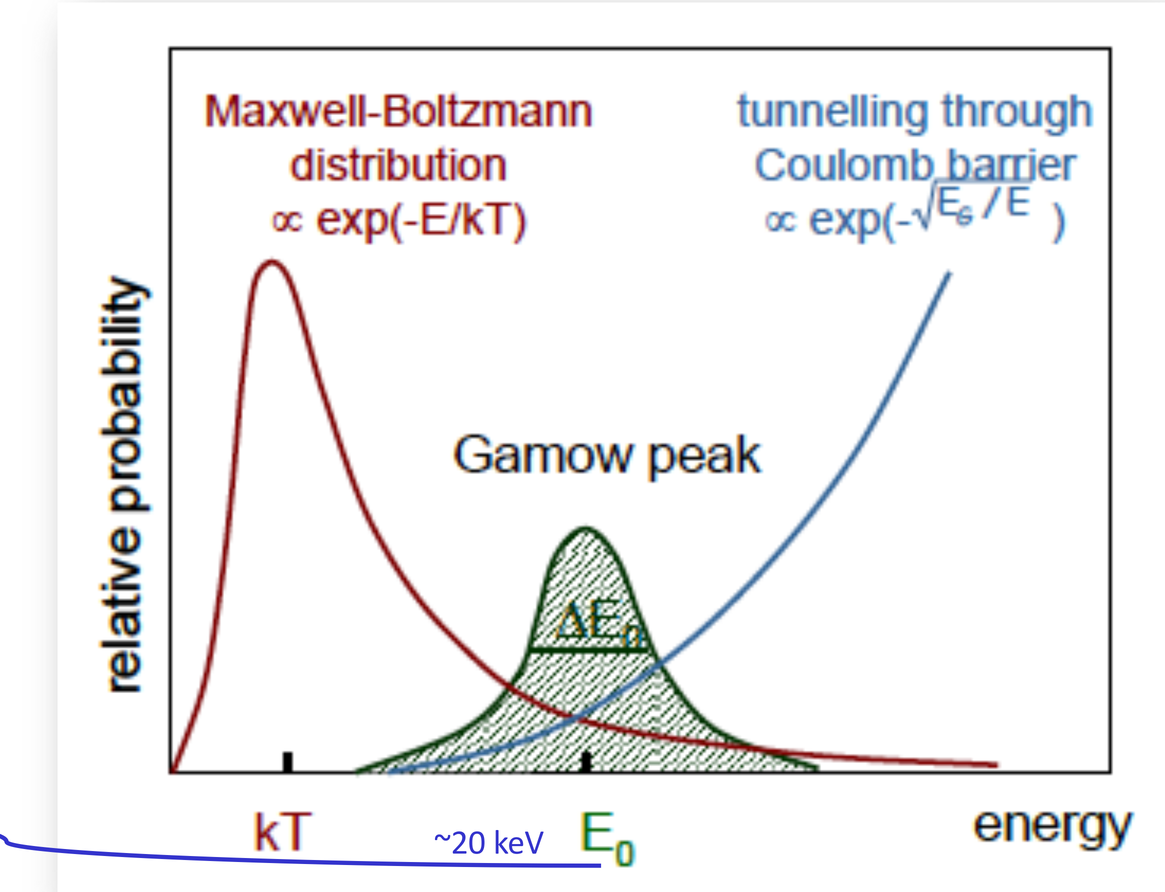
in all cases:
rearrangement of bound nucleons (p,n) in nuclei by nuclear reactions towards tighter binding

Nuclear reactions in cosmic environments

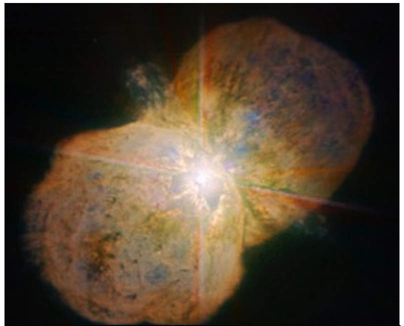
major challenge:

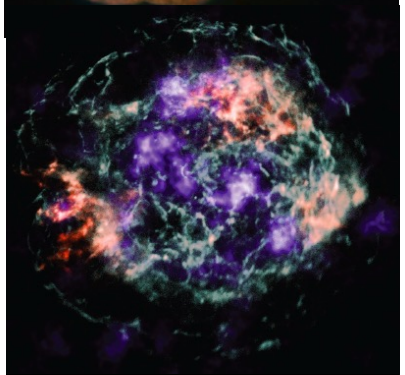
- ☆ plasma in the Universe is very different from the conditions in terrestrial laboratory experiments
- ☆ quantum tunnelling dominates in cosmic-environment reactions

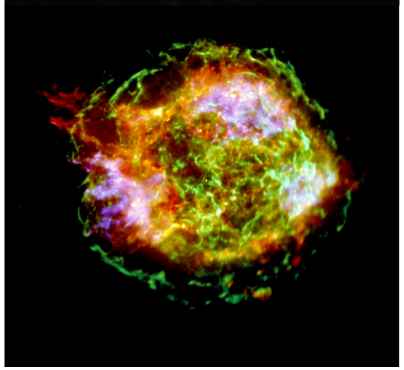


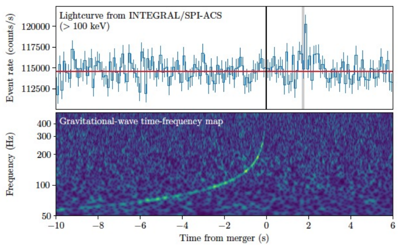


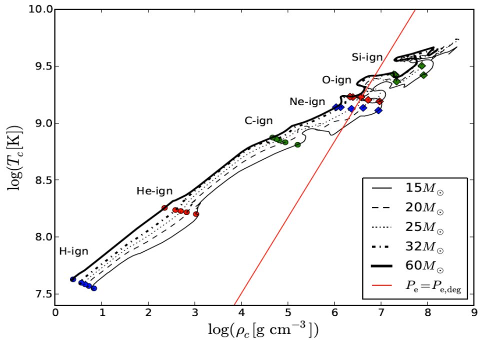
Cosmic nucleosynthesis sources

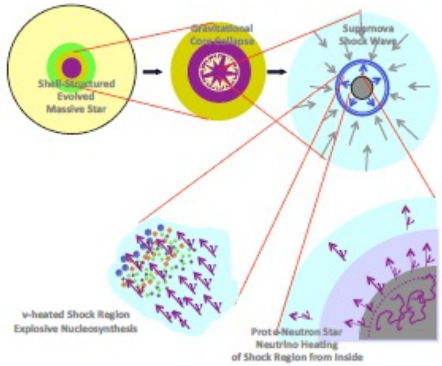


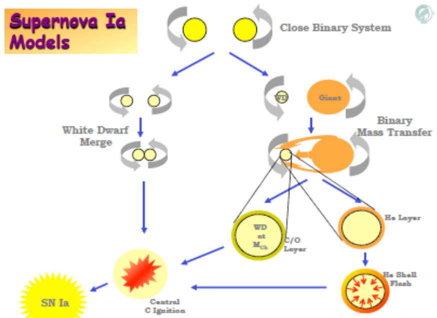


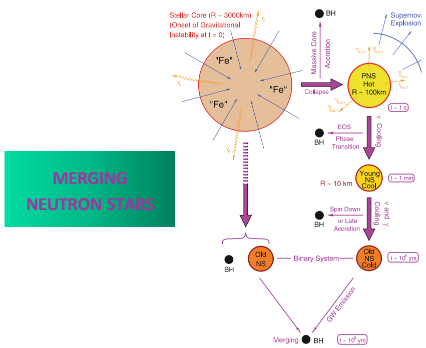








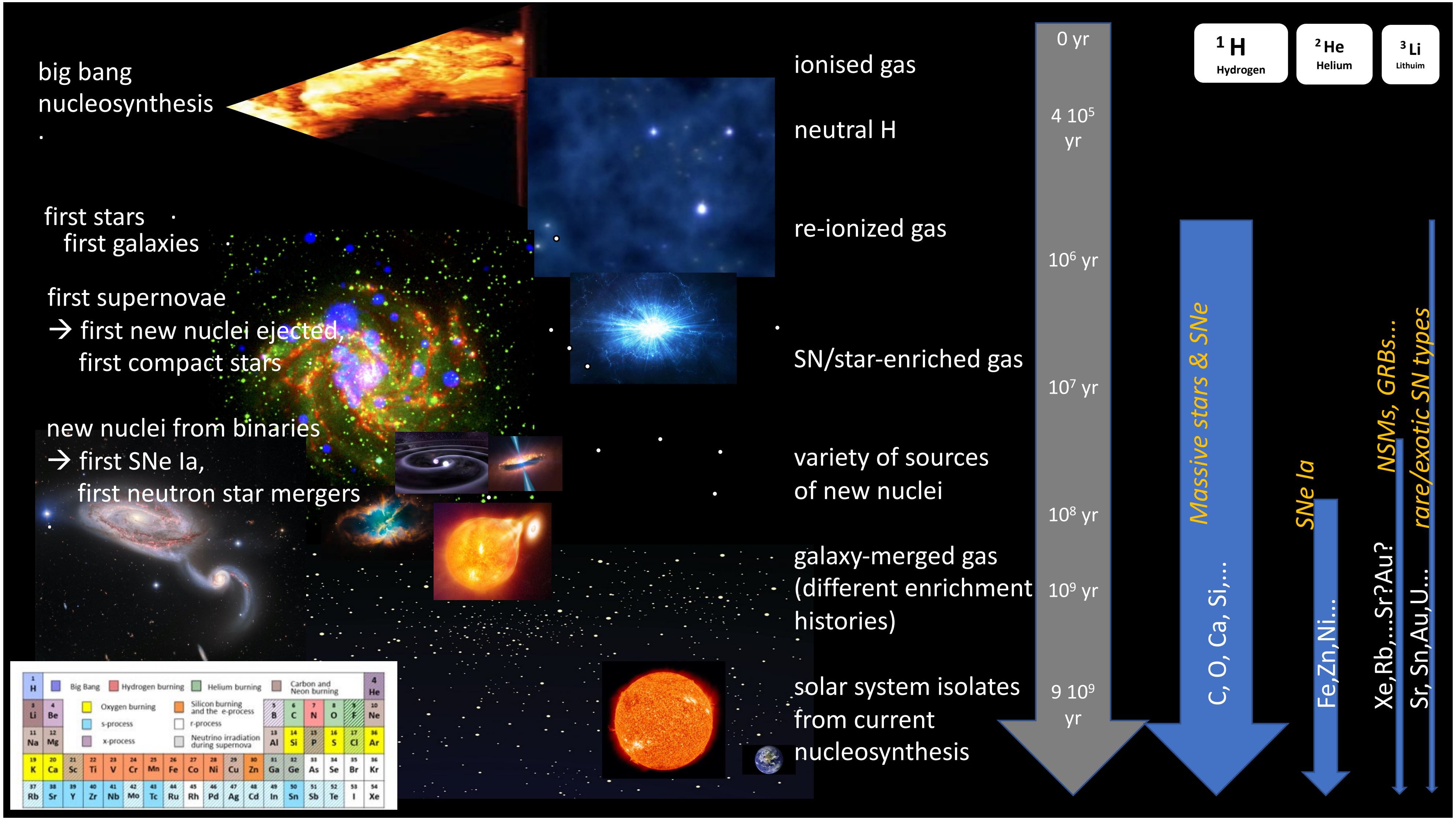




- Nuclear fusion reactions power all stars
- Many stars explode as a supernova at the end of their evolution
- Some binary systems including white dwarf stellar remnants explode as a supernova
- Some binary systems including neutron stars eventually merge to form a black hole

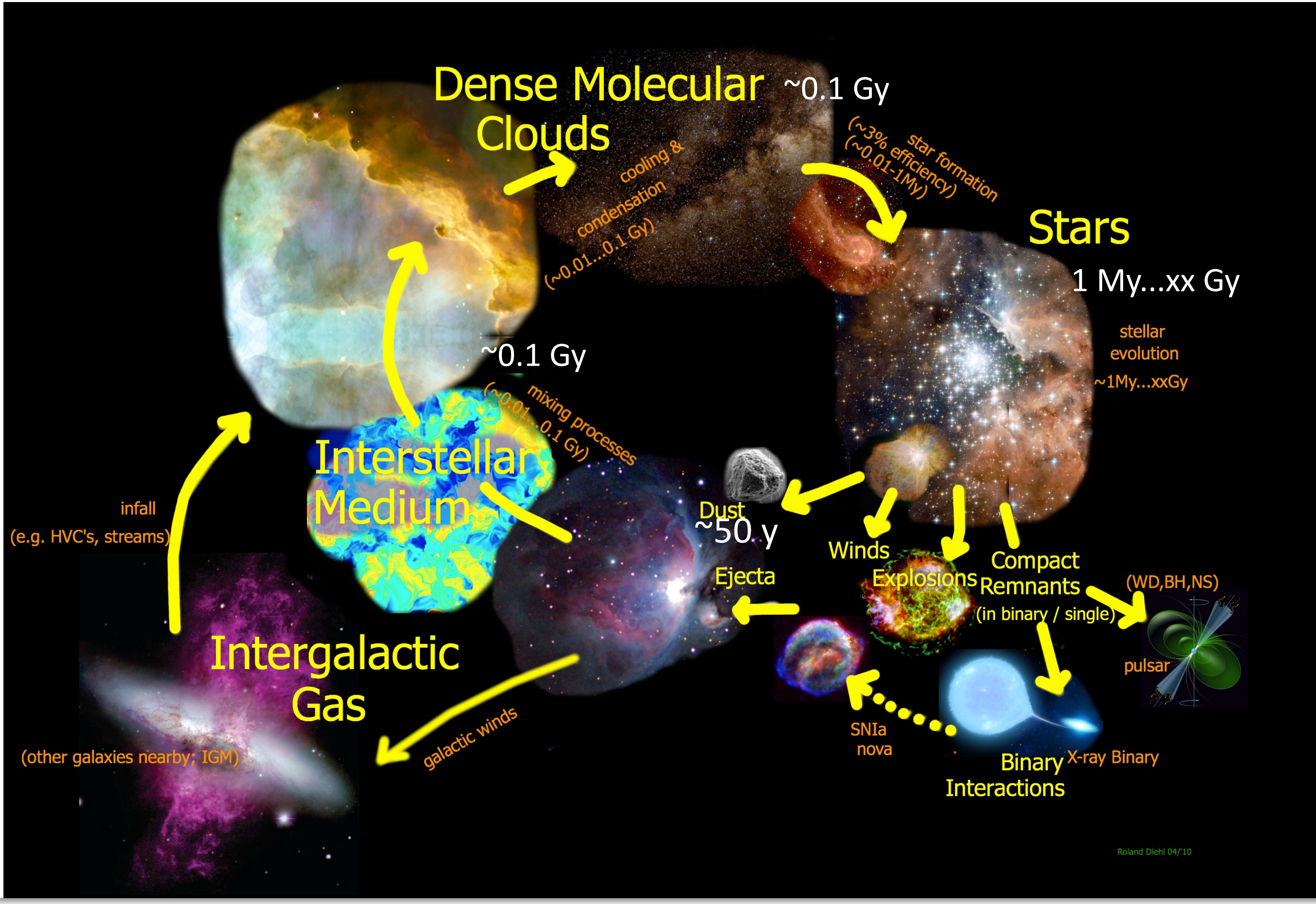
➢ How many new nuclei in ejecta??

The composition of cosmic matter evolves over time

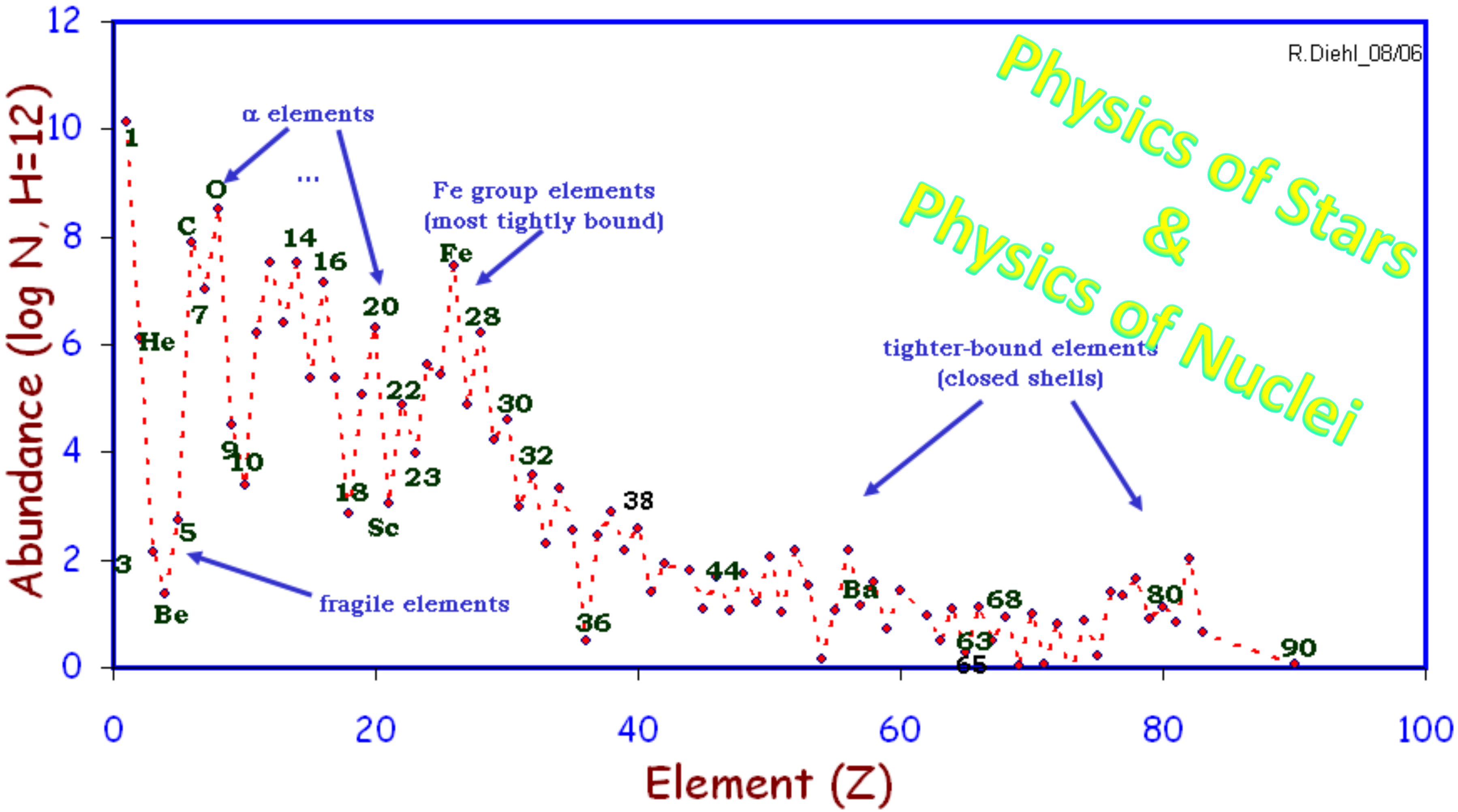


... a coarse picture of cosmic nucleosynthesis.

On-going Enrichments from Nucleosynthesis Sources



The Messages from Cosmic Elemental Abundances



These signatures are a result from the characteristic physical processes within…

… atomic nuclei (which of these can be produced more-easily/more abundantly?)

… cosmic sources (which nuclear-fusion environments occur more often/abundantly?)

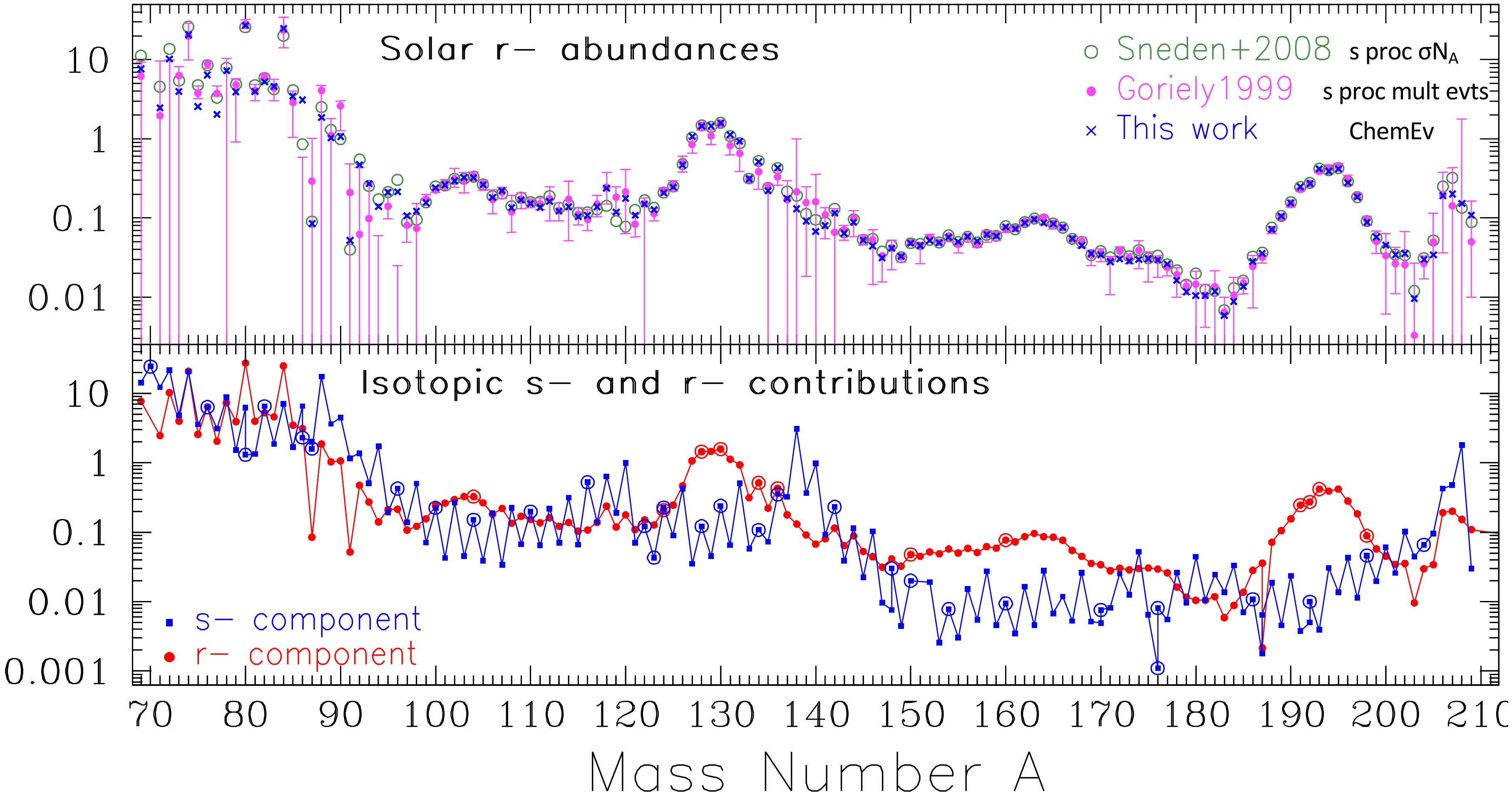
Decomposing abundances towards "processes"

neutron capture physics may be the easier problem: basic physics and cosmic extremes

→ use n capt / β decay & stellar evolution to predict s-process parts

→ subtract from observed abundances to study the r-process parts

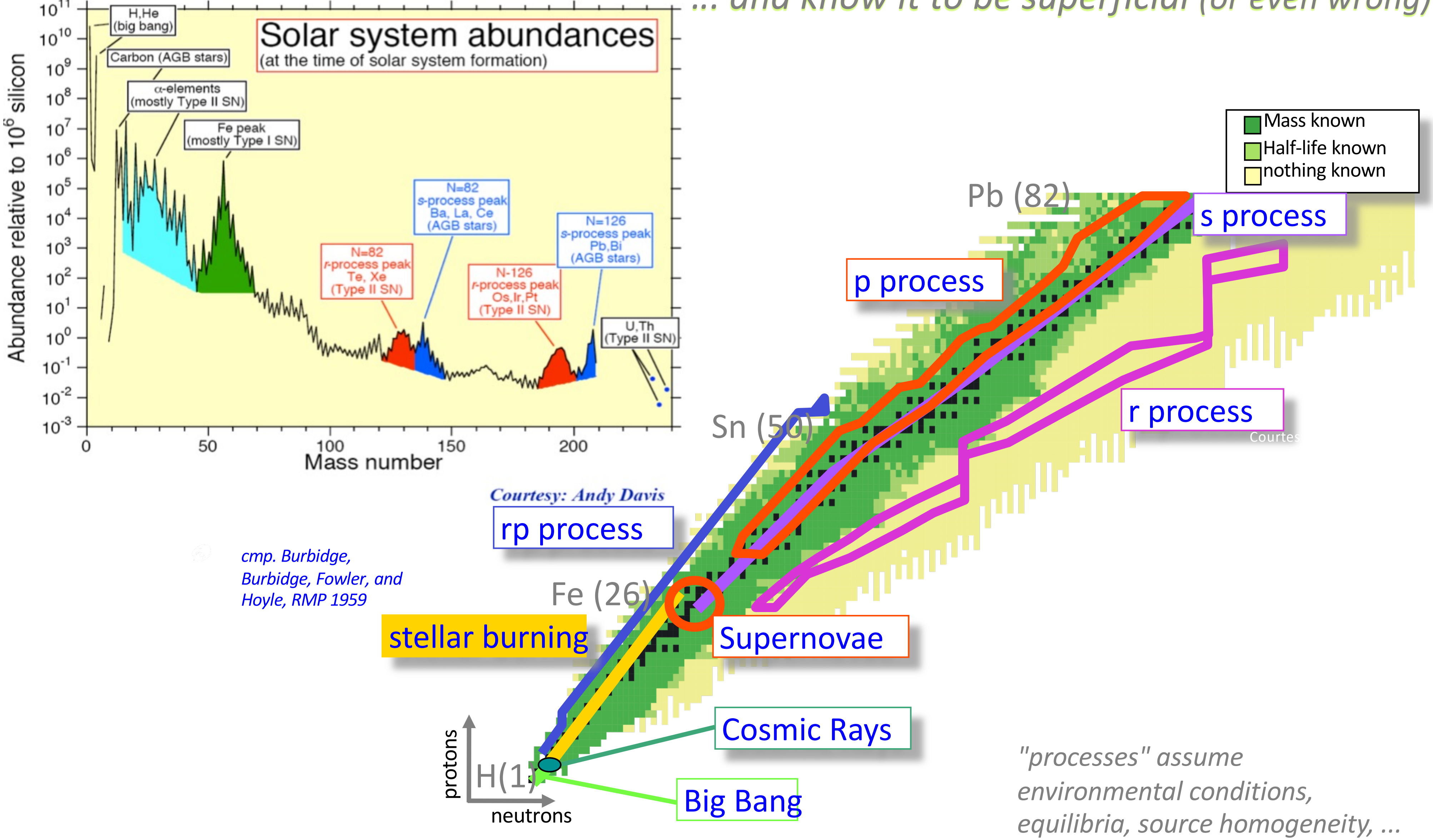
Prantzos+2020



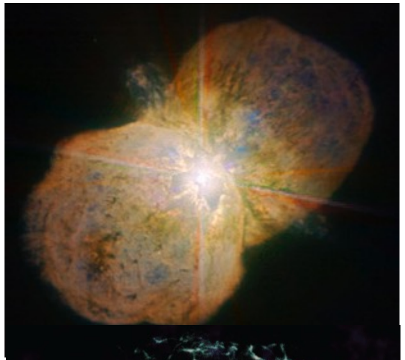
Cosmic origins of the variety of nuclides

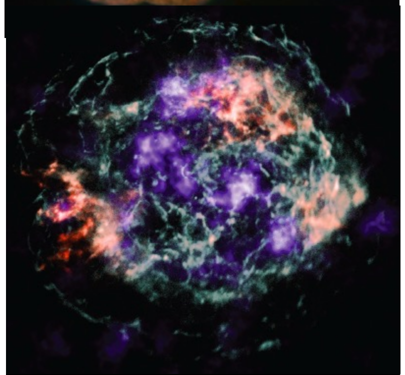
- Associating different "processes" with nuclide groups – *what we teach…*

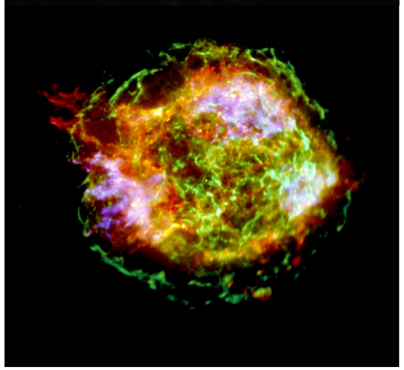
  … and know it to be superficial (or even wrong)

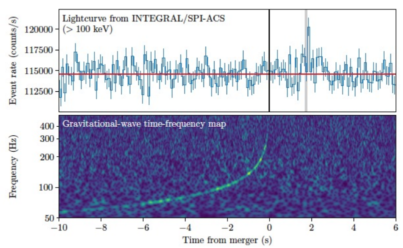


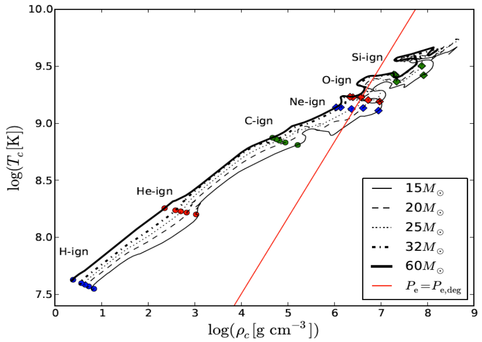
Understanding cosmic nucleosynthesis sources

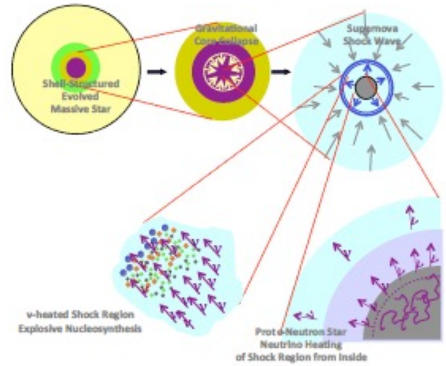


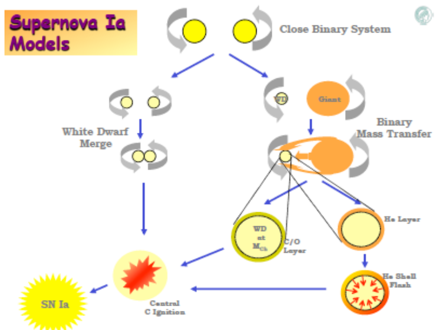


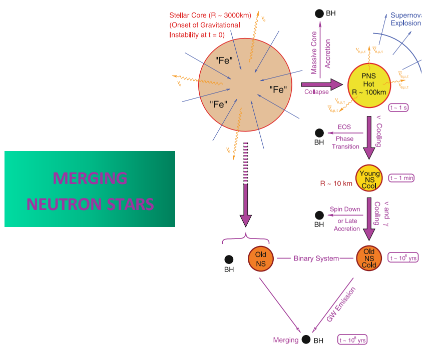












- How much matter is in winds?
- How are fusion products mixed?
- What is the composition of remnant star?

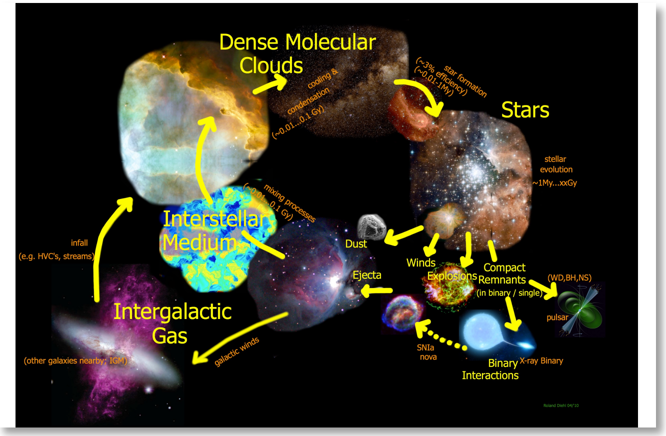
- Which stars explode as a supernova?
- Which parts of collapsing star ejected?

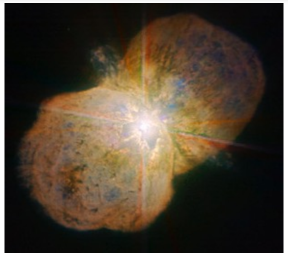
- Which white dwarfs explode?
- How is the explosion triggered?
- Which burnings can occur?

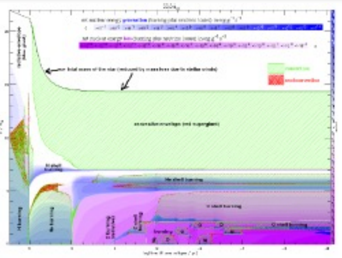
- Which compact stars may merge, when?
- How is the black hole formed?
- Which materials may escape?

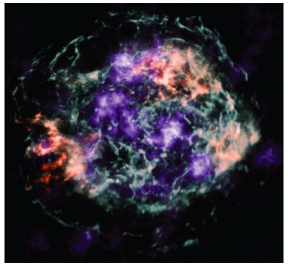
Modeling Compositional Evolution

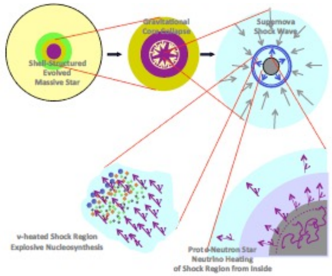
see, e.g., Diehl& Prantzos, NuclPhys.Hndbk 2023

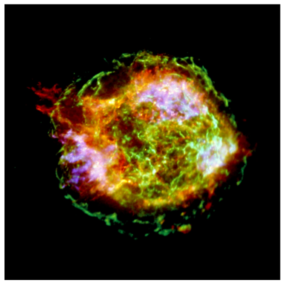


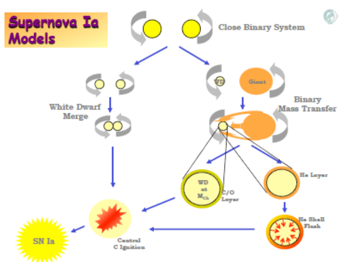












☆ Changes in the forms of cosmic matter:

- stars and gas **flows**:

$$m = m_{\rm gas} + m_{\rm stars} + m_{\rm infall} + m_{\rm outflow}$$

$$\frac{dm_G}{dt} = -\Psi + E + [\, f - o\,]$$

$\Psi(t)$ is the Star Formation Rate (SFR) and $E(t)$ the *Rate of mass ejection*

- gas which is ejected from stars: **when?**

$$E(t) = \int_{M_t}^{M_U} (M - C_M)\, \Psi(t - \tau_M)\, \Phi(M)\, dM$$

- newly-contributed ashes from nucleosynthesis: **what?**

The *mass of element/isotope i* in the gas is $m_i = m_G X_i$

$$\frac{d(m_G X_i)}{dt} = -\Psi X_i + E_i + [\, f X_{i,f} - o X_{i,o}\,]$$

$$E_i(t) = \int_{M_t}^{M_U} Y_i(M)\, \Psi(t - \tau_M)\, \Phi(M)\, dM$$

☆ Ingredients:

- Sources: How fast do they evolve to return (new) gas?

the star of mass M, created at the time $t - \tau_M$, dies at time t

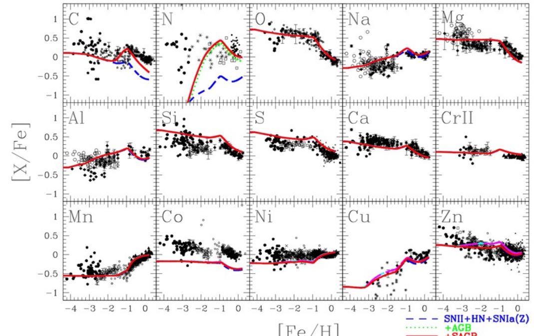
- Sources: How much of species i do they eject (and/or bury)?

$Y_i(M)$ the mass ejected in the form of that element by the star of mass M

- ... (locations and environments of star formation, gas flows, ...)

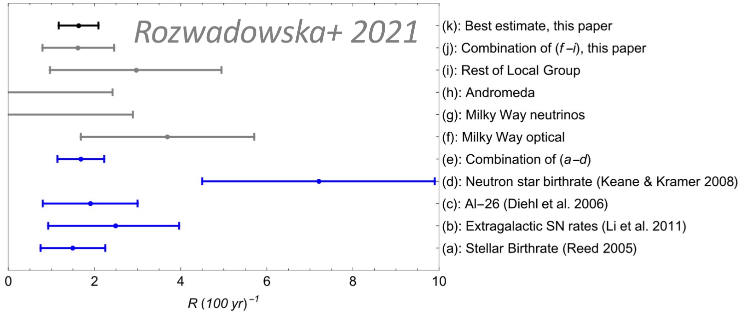
Chemical Evolution: ...there are issues ...

- ☆ model description fails for several elements
  - even for elements from same source type...
  - even using (unrealistic?) models/parameters



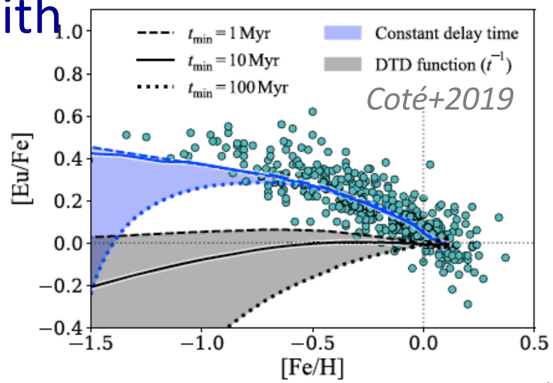
Kobayashi+ 2020

- ☆ inconsistencies with modeled vs observed nucleosynthesis event rates
  - ~350 radio+X SNR (~10000y) vs. ccSN rate 1/70y



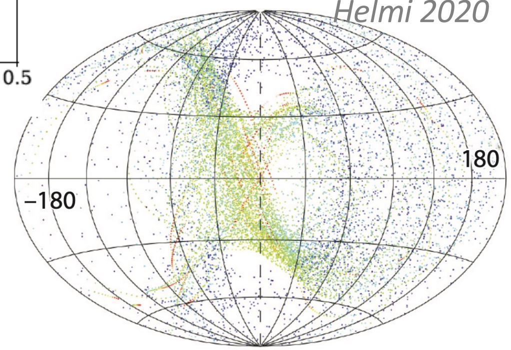
Rozwadowska+ 2021

- ☆ unclear impacts from rare sources with rich specific contributions
  - neutron star mergers?
  - jet supernovae?
  - hypernovae?



Coté+2019

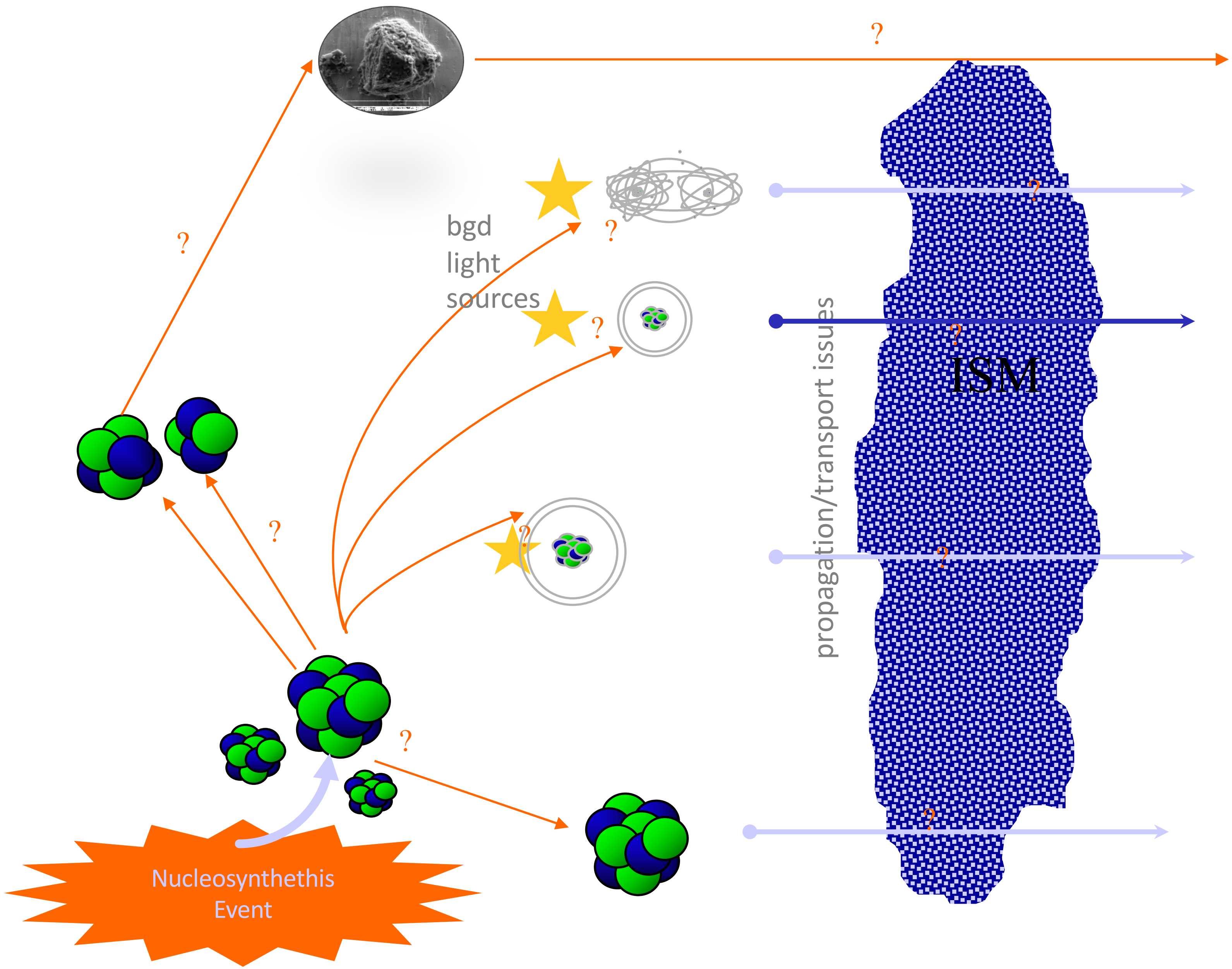
- ☆ mixing with stars & gas from galaxy collisions in the past



Helmi 2020

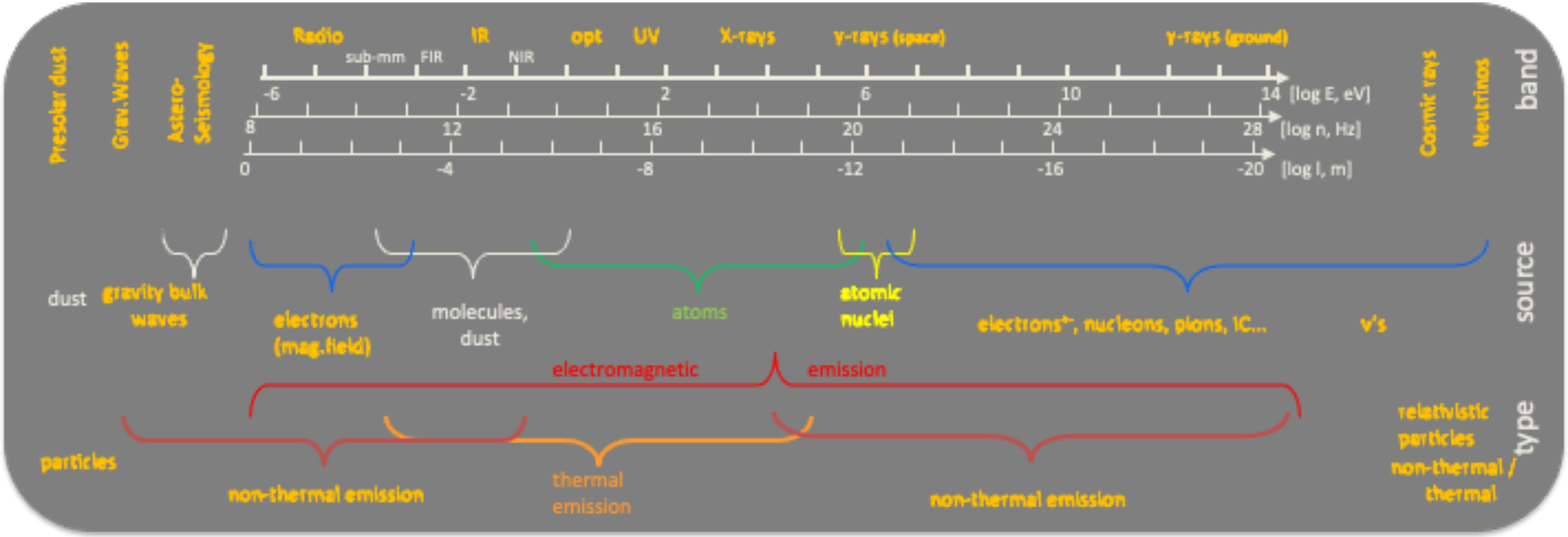
- ☆ early evolution: very massive stars & ccSNe
- ☆ but also something else (binaries!)...

Different Complementing Observing Methods



- Stardust in meteorites, Cosmic rays
- Molecular absorption lines (Radio,IR)
- Atomic absorption lines (opt,UV)
- Atomic emission lines (opt,UV,X)
- Gamma-ray lines from radioactive isotopes

Astronomical Messengers



Gamma-ray lines from cosmic radioactivity

Radioactive trace isotopes are by-products of nucleosynthesis reactions

Released into circum-source ISM, we can observe gamma-ray afterglows:

Isotope	Mean Decay Time	Decay Chain	γ -Ray Energy [keV]	Detected Source	Source Type
^{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)	Neutron Star Mergers, SNe
^{126}Sn	3.3 10^{5} y	^{126}Sn →^{126}Sb*→^{126}Te	666; 695; 87; 64	(none)	Neutron Star Mergers, 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…

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

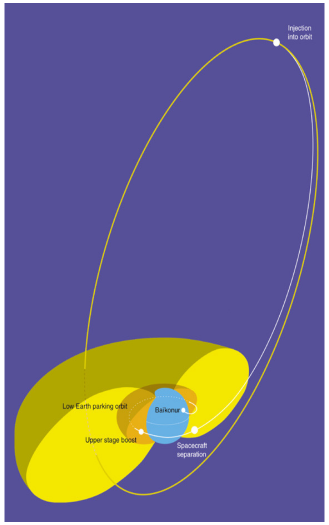
  (abundance; decay time (weeks<τ<10^{8}y) long enough to survive ejection/not too long to be bright)

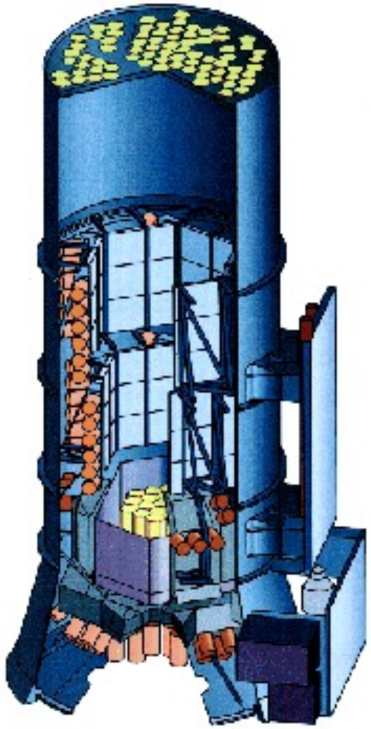
plus:
nuclear excitation lines (^{12}C, ^{16}O, ...) (from CRs)

Current Nuclear Gamma-Ray Line Telescopes

INTEGRAL

- 2002-(2023+..2029)
- ESA
- high E resolution
- Ge detectors
- 15-8000 keV





NuSTAR (only <80 keV!)

- 2012-(2022+) …
- NASA
- hard X ray imaging <80 keV

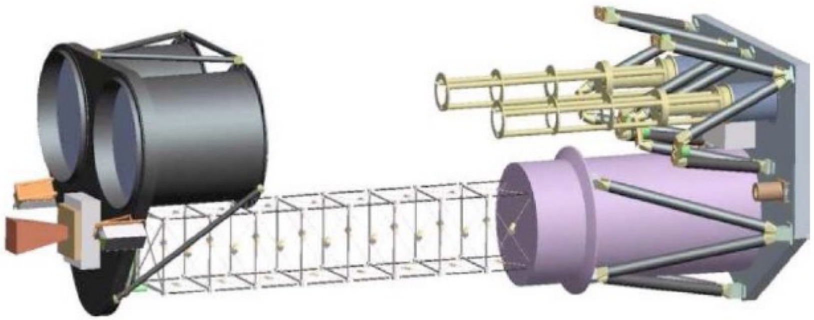
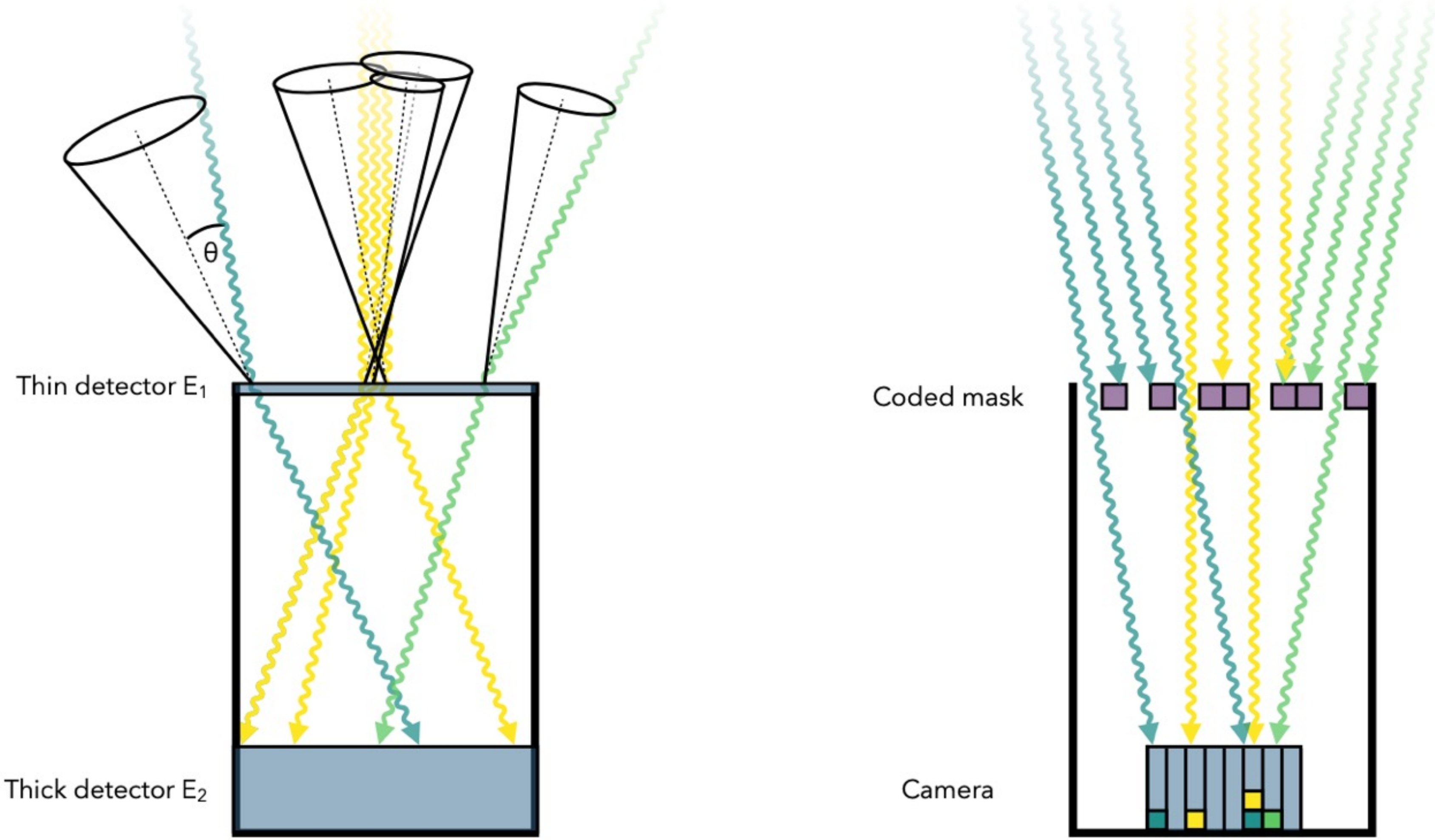


Fig. 1. NuSTAR telescopes in deployed configuration

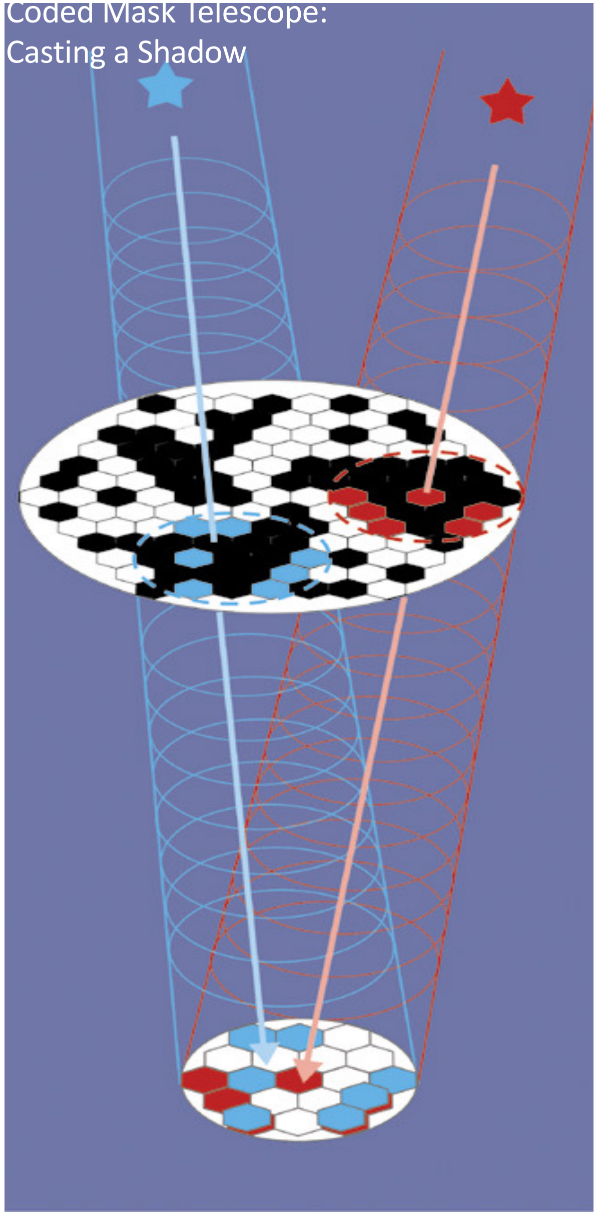
Imaging principles for a MeV-range γ-ray telescope

- **Compton Telescopes and Coded-Mask Telescopes**



Achievable Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution ≥ deg

INTEGRAL Cosmic Photon Measurements: The SPI Ge γ-Spectrometer



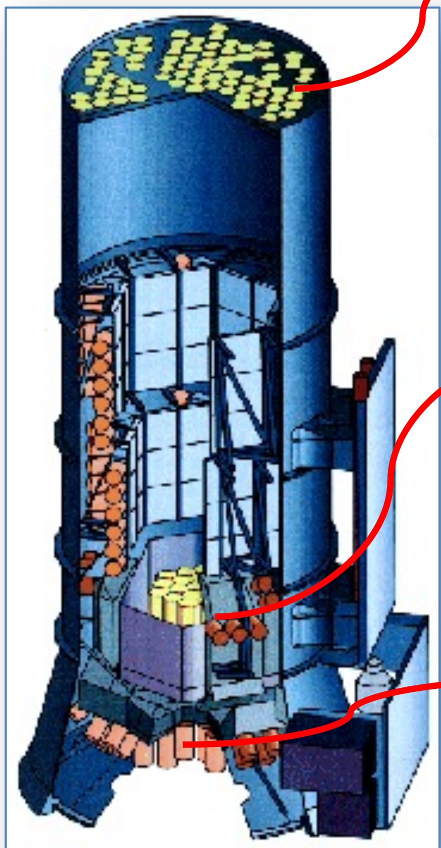
Coded-Mask Telescope

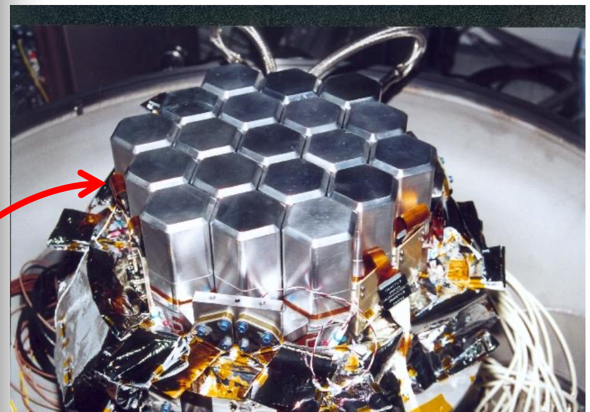
Energy Range 15-8000 keV

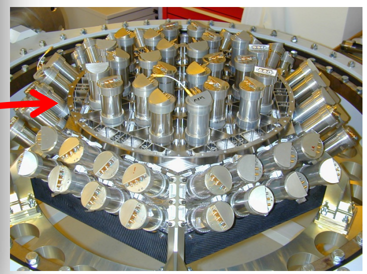
Energy Resolution ~2.2 keV @ 662 keV

Spatial Precision 2.6° / ~2 arcmin

Field-of-View 16x16°

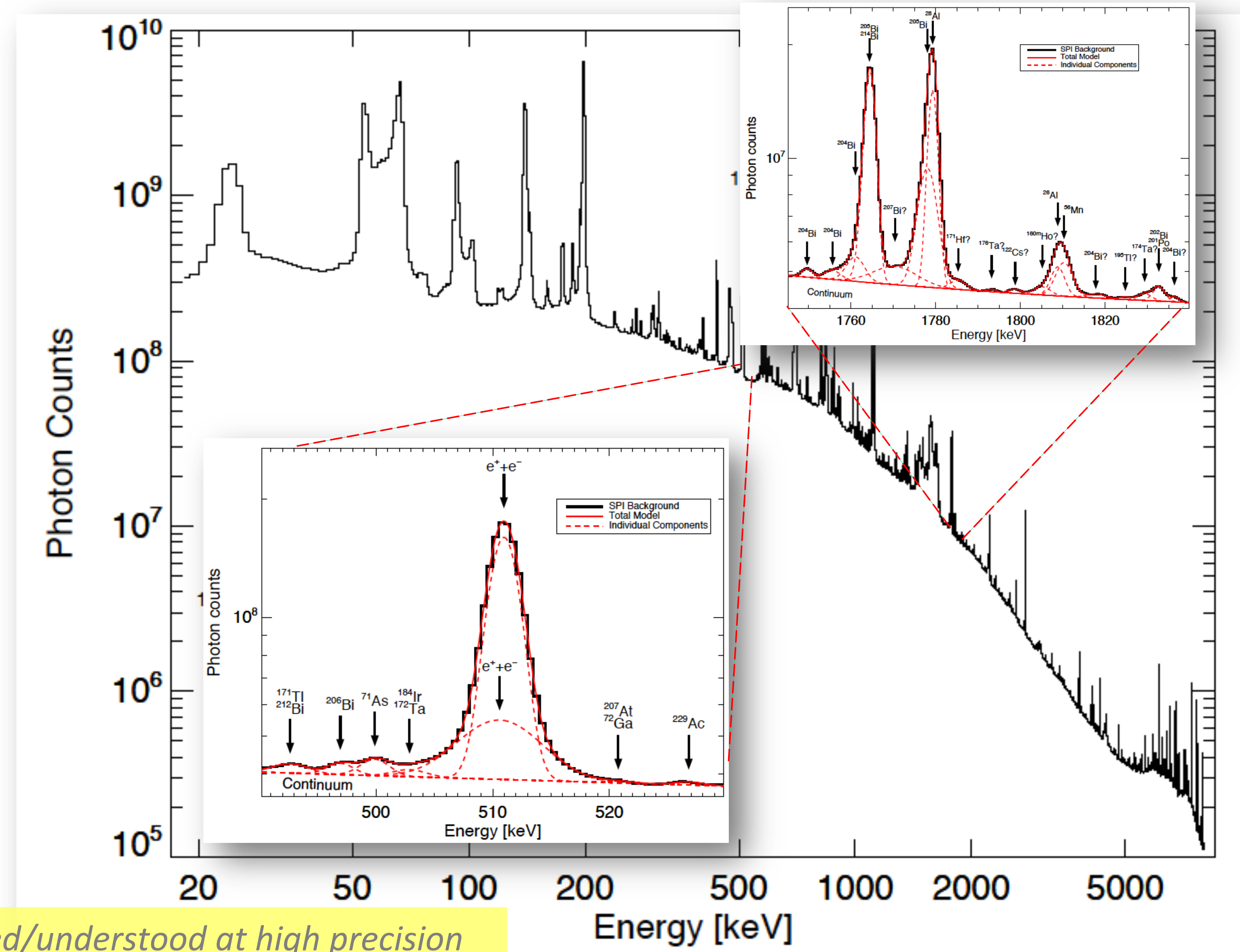






INTEGRAL: Dominance of instrumental background

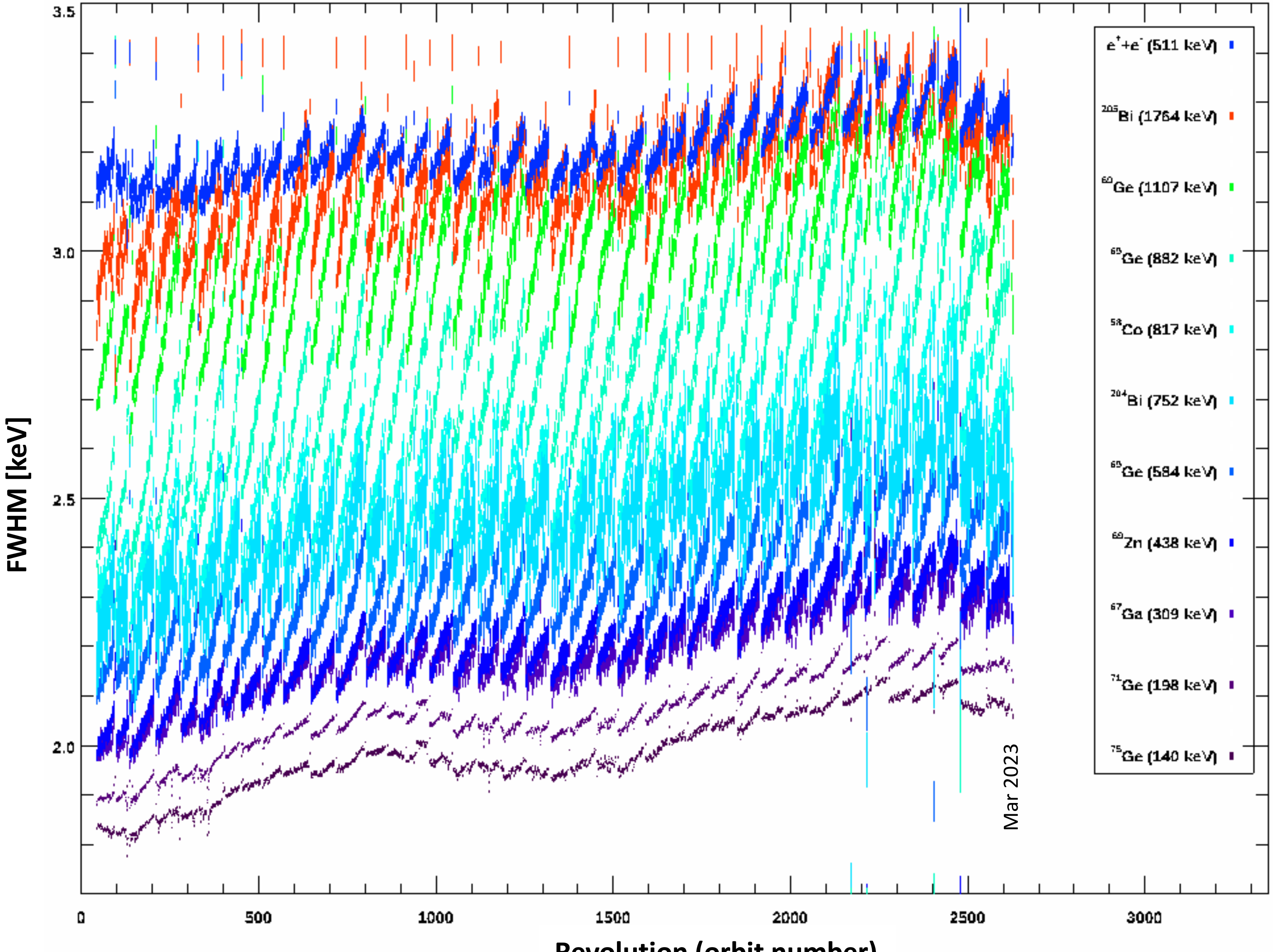
SPI Ge detector spectra



Modelled/understood at high precision

INTEGRAL/SPI Performance Monitoring

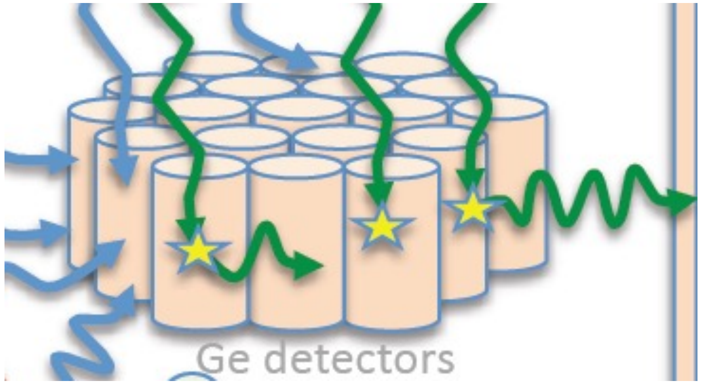
Spectral Resolution in Detail: regular annealings are essential

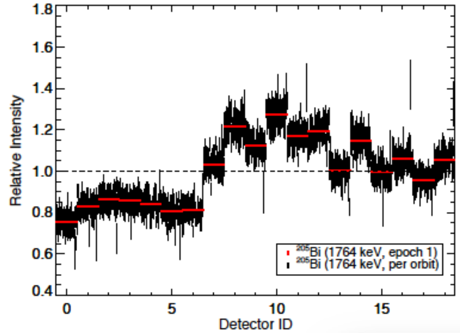


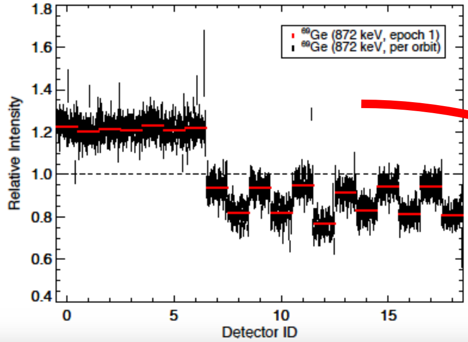
40th annealing just completed (Apr 2023)!

Discriminating Background and Sky Signals in SPI Data

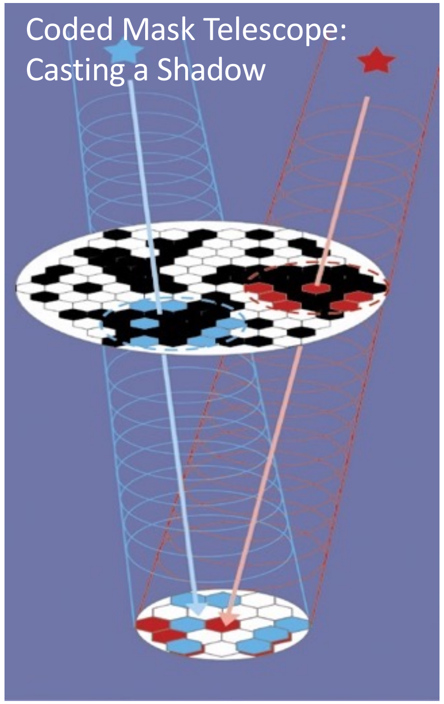
- Tracking the relative count rate ratios among detectors
  - ☞ characteristic signatures from celestial sources withcoded mask, and from background events

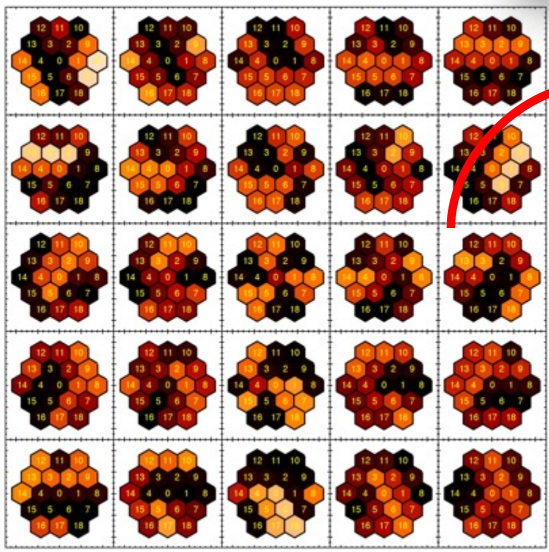


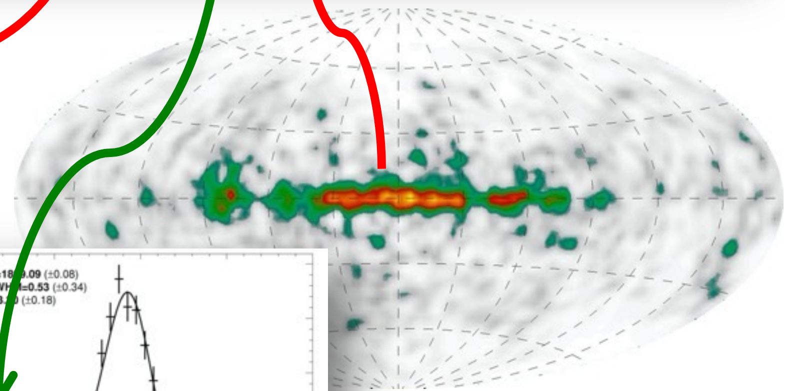


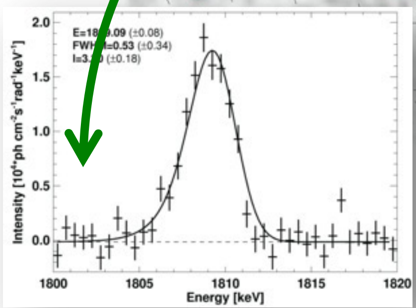


$$d_k = \sum_j R_{jk} \sum_{i=1}^{N_I} \theta_i M_{ij} + \sum_t \sum_{i=N_I+1}^{N_I+N_B} \theta_{i,t} B_{ik}$$









Gamma ray spectroscopy with SPI

...it works! example:

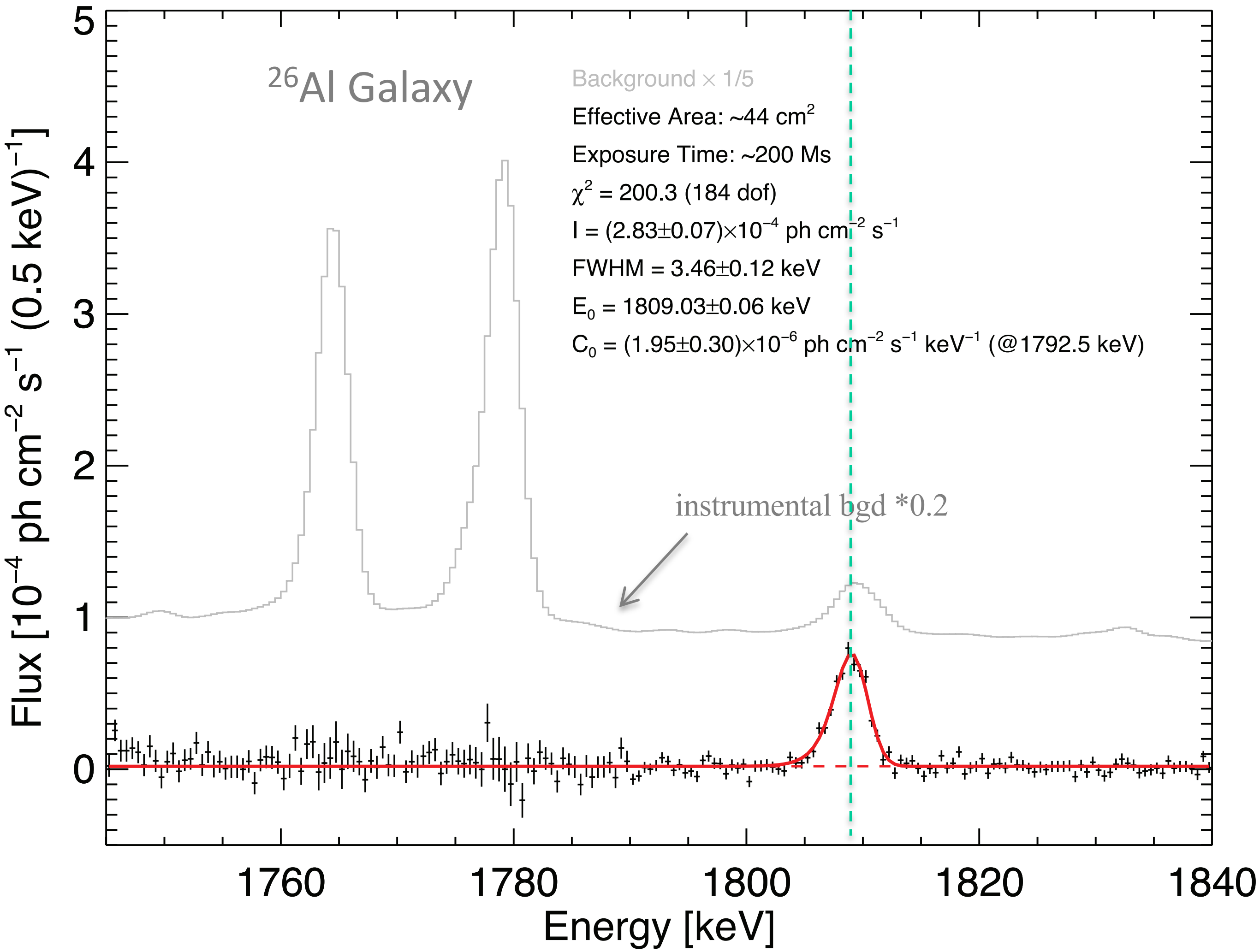
^{26}Al line 1808.6 keV

instrumental lines

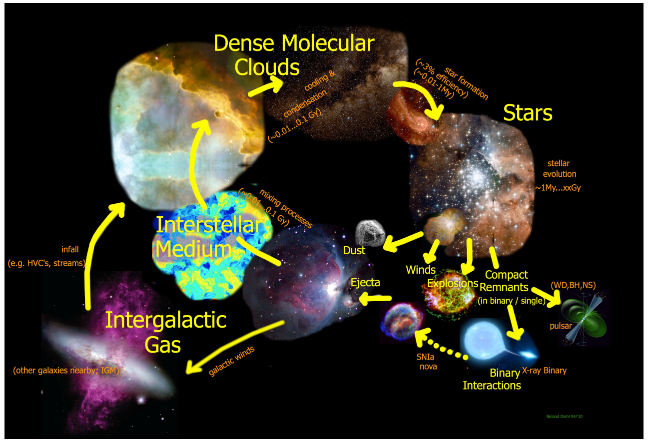
1810 keV

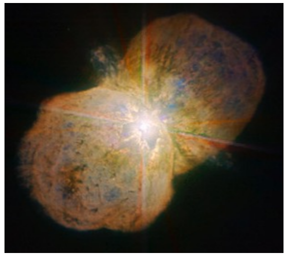
1779 keV

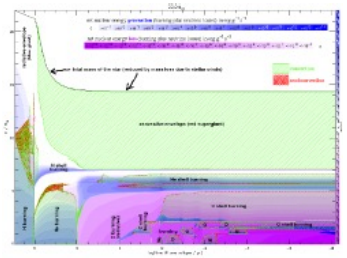
1764 keV

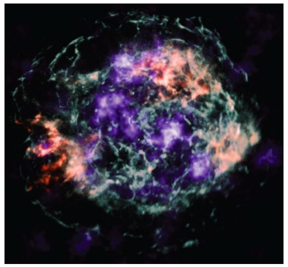


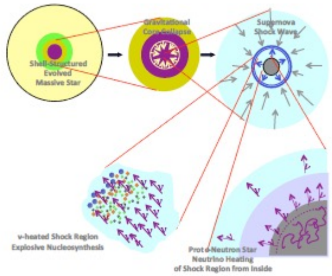
Lessons from radioactive isotopes

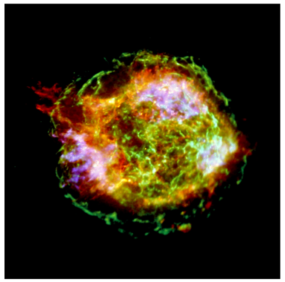


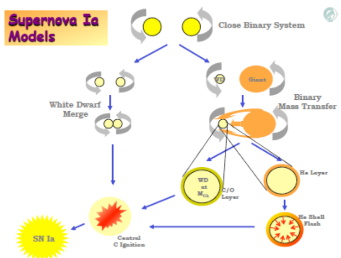










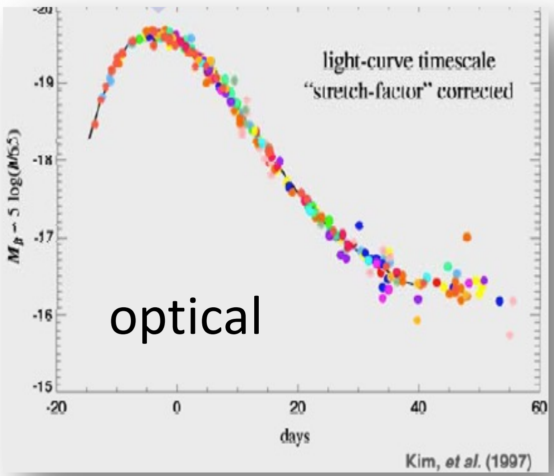


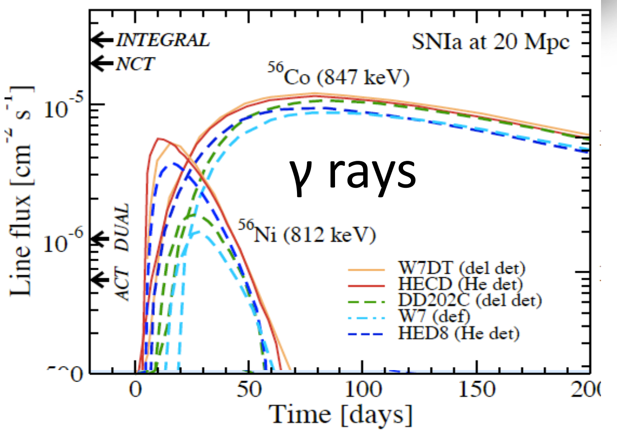
☆Trace the flows of cosmic matter

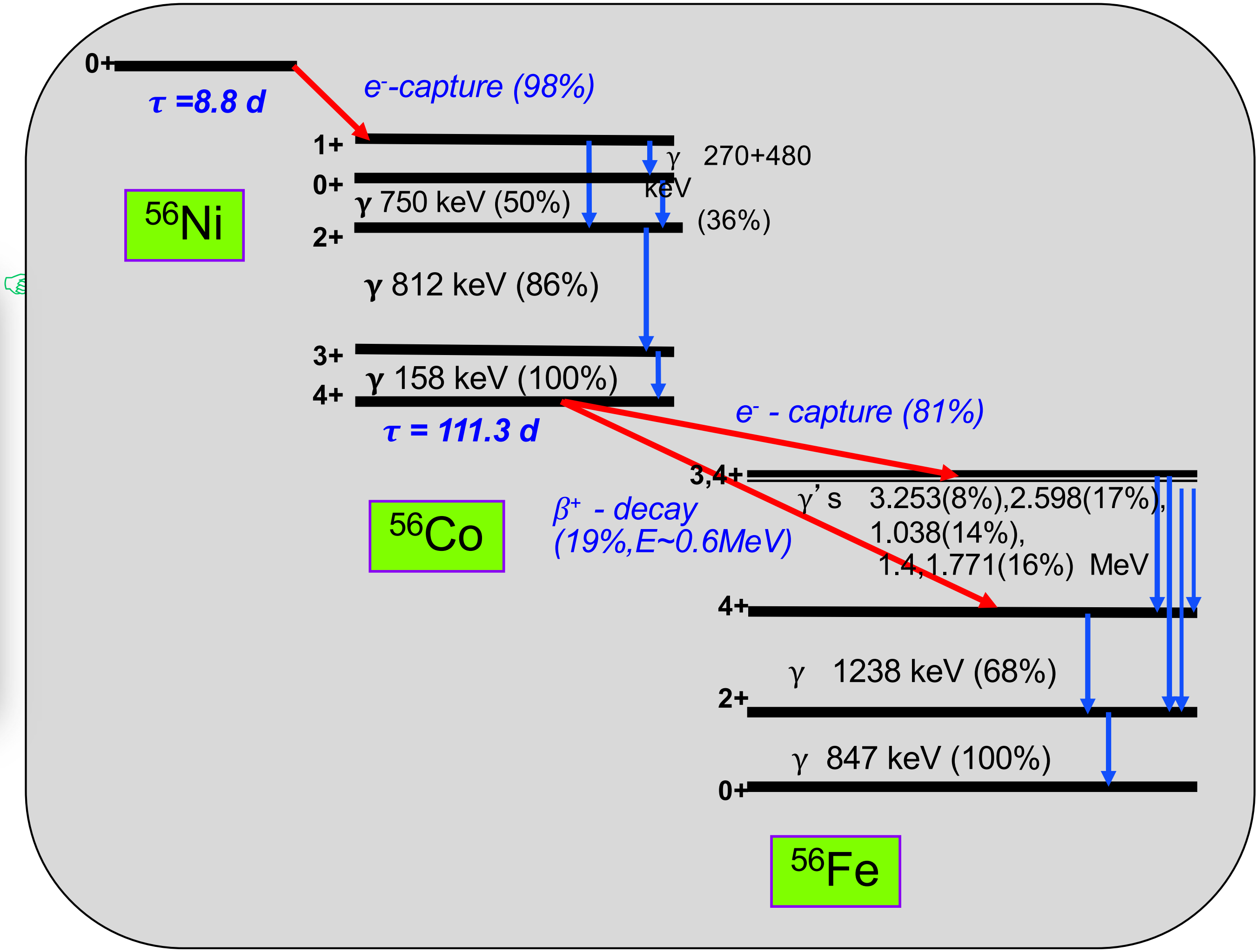
☆Understand the sources of new nuclei

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

SN Ia

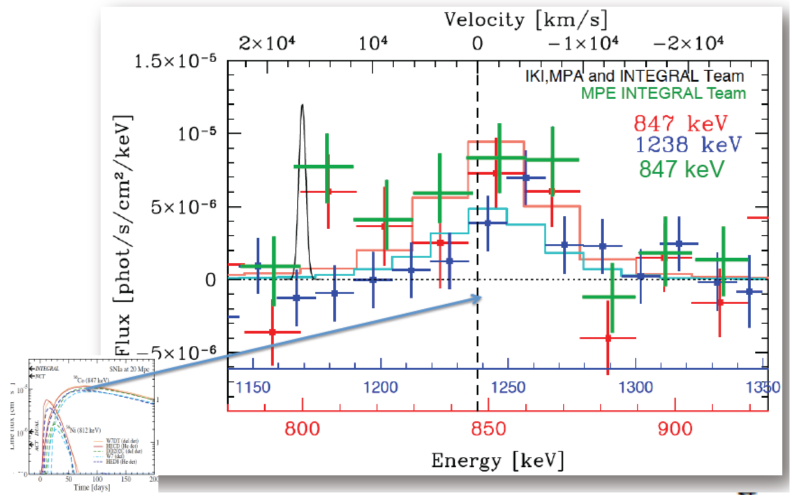




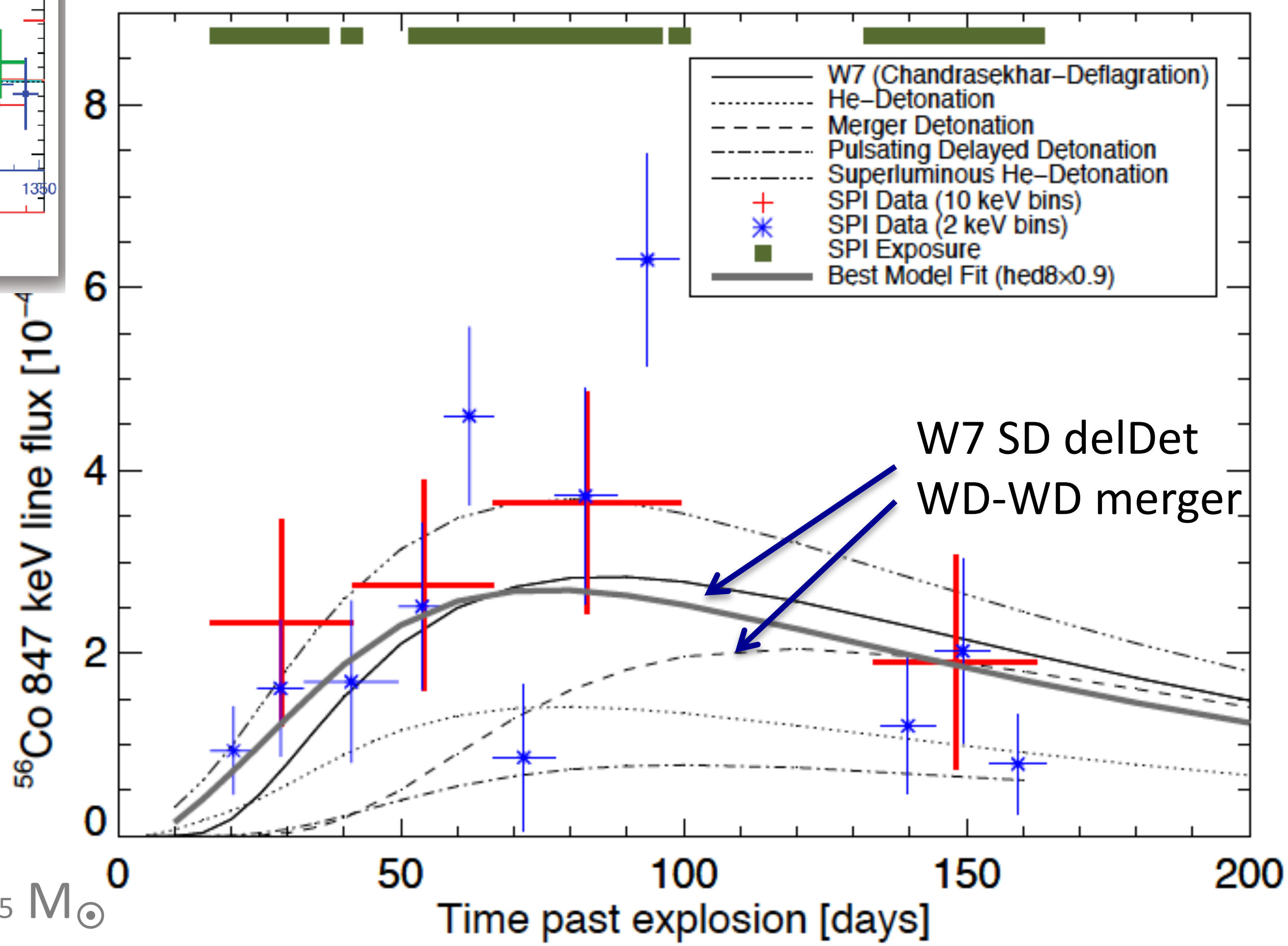


- Nuclear BE release from 0.6M$_{\odot}$ [C,O → ^{56}Ni] = ~1.1 10^{51} erg (>2*BE$_{WD}$)
- Deposit of γ rays and e+ in expanding/diluting envelope
- Re-radiation of deposited energy in low-energy (thermal) radiation

SN2014J light evolution in the 847 keV ^{56}Co line



INTEGRAL/SPI γ ray measurements



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

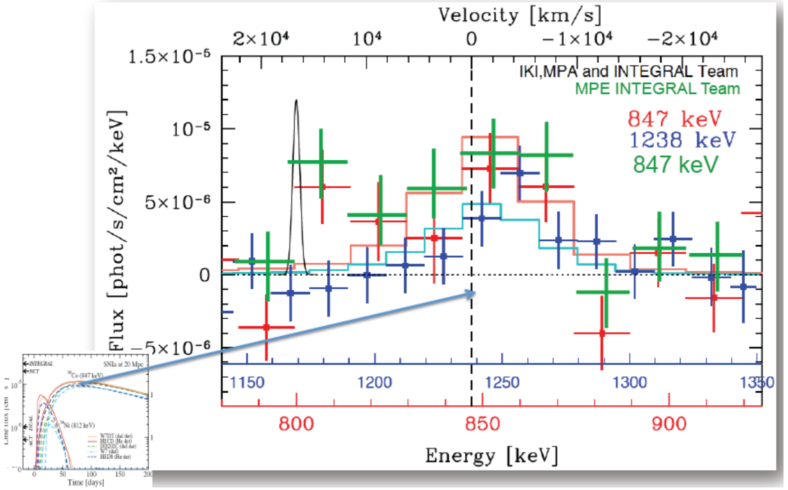
(cmp from bol. Light → 0.42 +/-0.05 $M_\odot$

from models → 0.5 +/-0.3 $M_\odot$

☞ *Diehl et al., A&A 2015*

SN2014J data Jan – Jun 2014: ^{56}Co lines

- ☆ Doppler broadened ✓



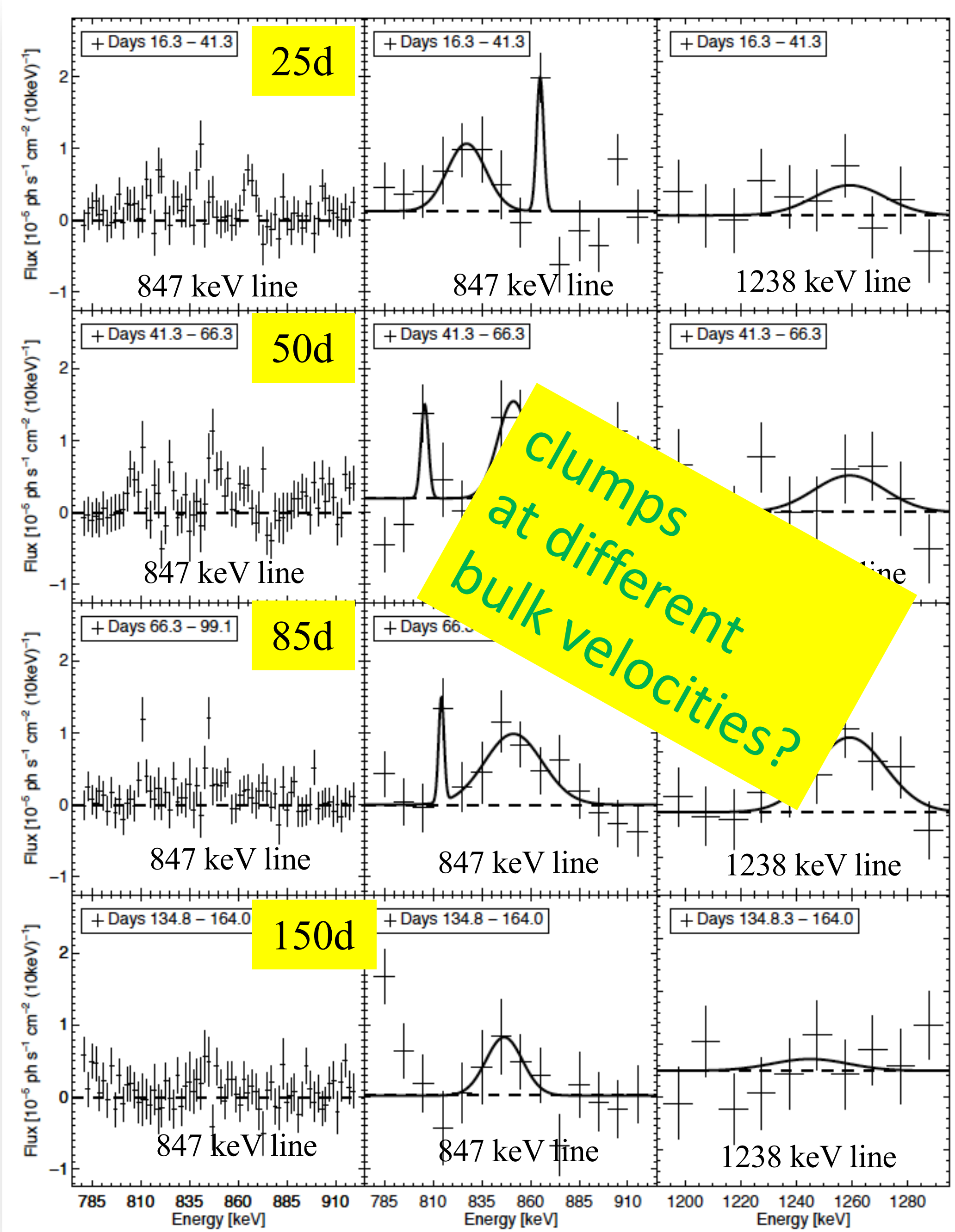
- ☆ Split into 4 time bins
- ☆ Coarse & fine spectral binning

→ Observe a structured and evolving spectrum

– expected: gradual appearance of broadened ^{56}Co lines

☞ *Diehl et al., A&A (2015)*

- ☆ *note: normally, we do not see such fluctuations in 'empty-source' spectra!*

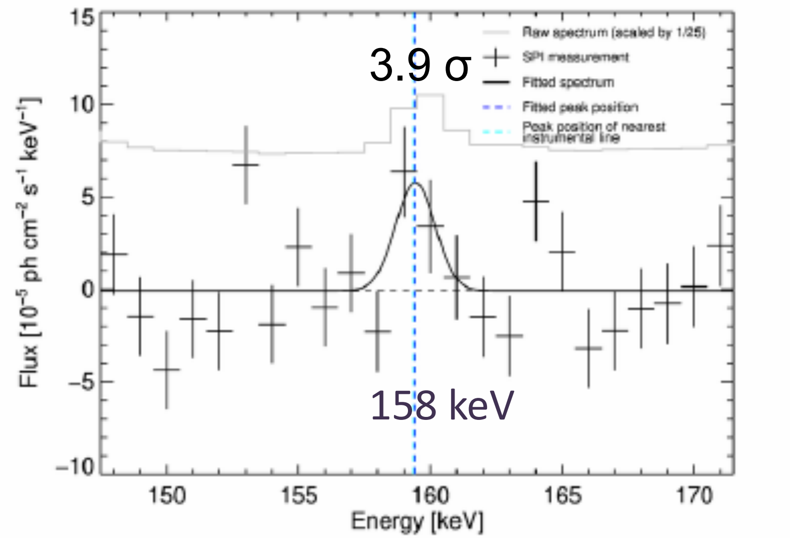


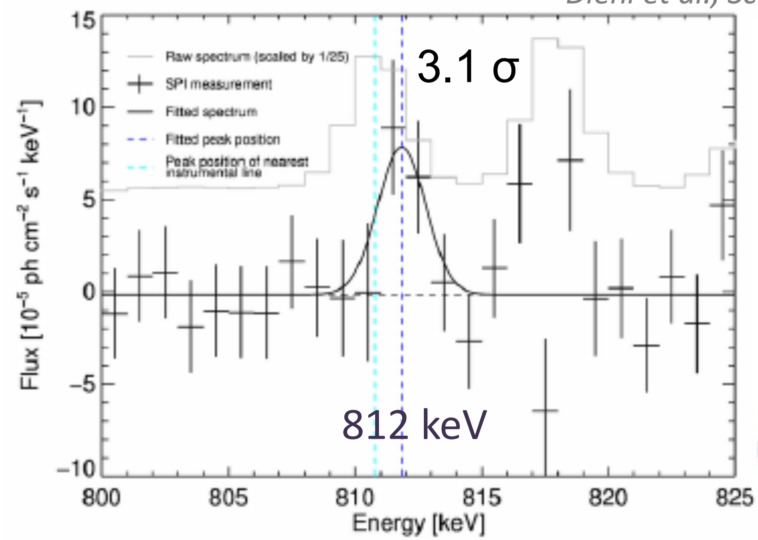
SNIa and SN2014J: Early ^{56}Ni (τ~8.8d)

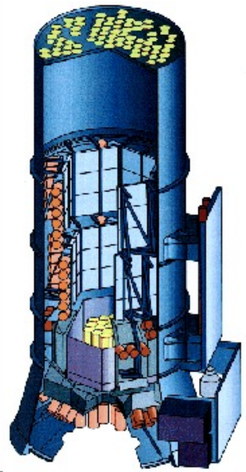
Spectra from the SN at ~20 days after explosion

Clear detections of the two strongest lines expected from ^{56}Ni (should be embedded!)

Diehl et al., Science (2014)

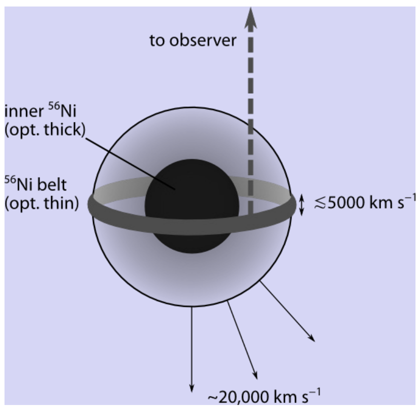






^{56}Ni mass estimate (backscaled to explosion): ~0.06 $M_{\odot}$ (~10%)

i.e.: not the single-degenerate $M_{chandrasekhar}$ model,



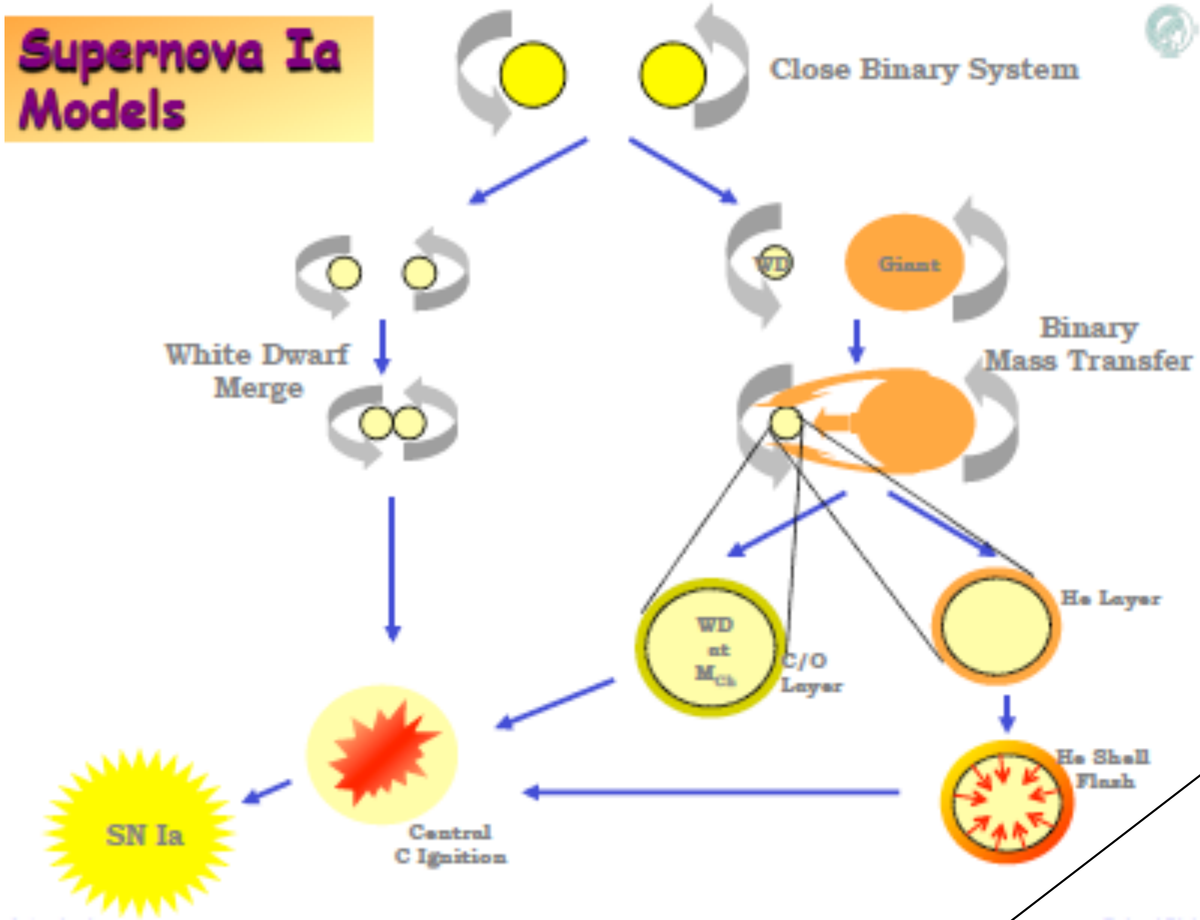
but rather a 'double detonation, i.e.

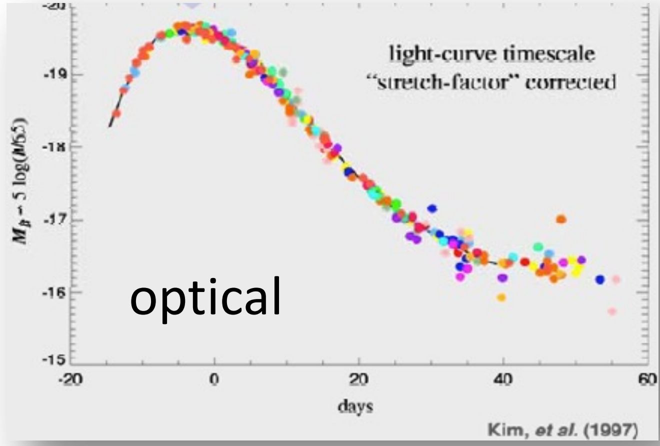
either 2 WDs (double-degenerate)

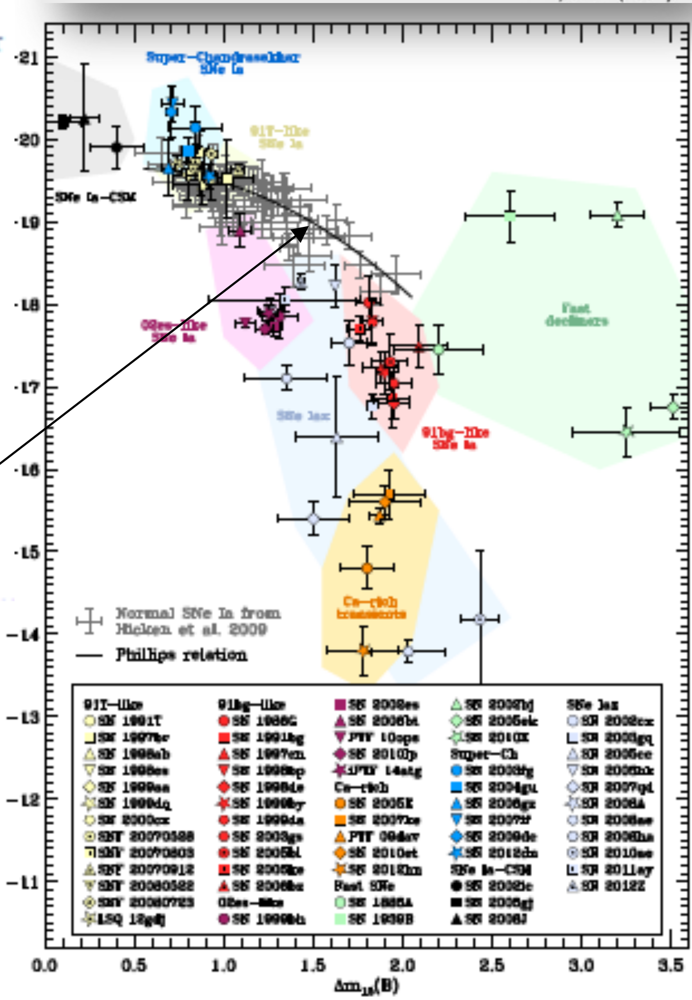
or a He accretor (He star companion)

→ SN Ia are a variety

Supernovae of type Ia







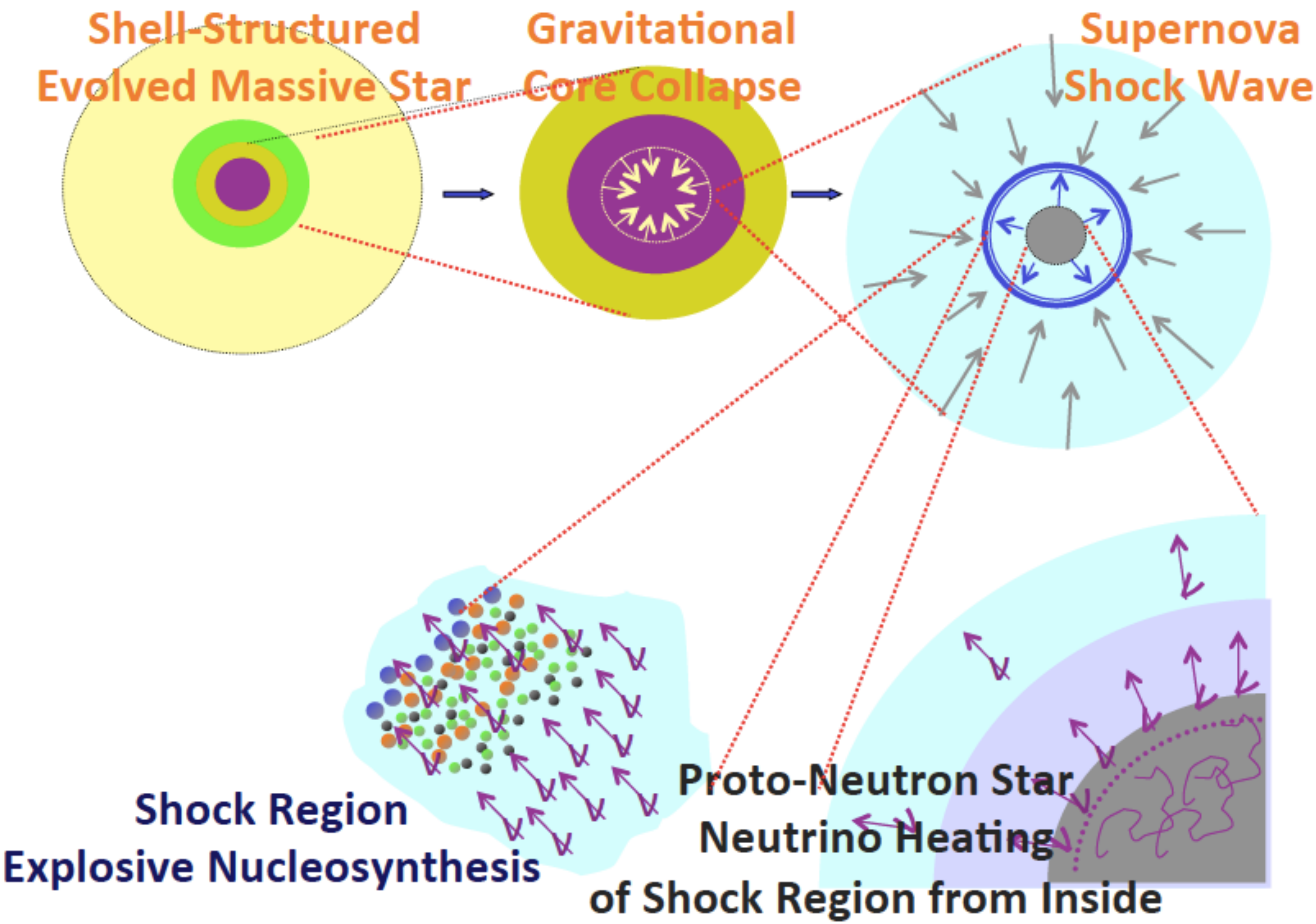
...also from γ-ray observations:

→ SN Ia are a variety

(the "standardizable candles"??)

Taubenberger 2017

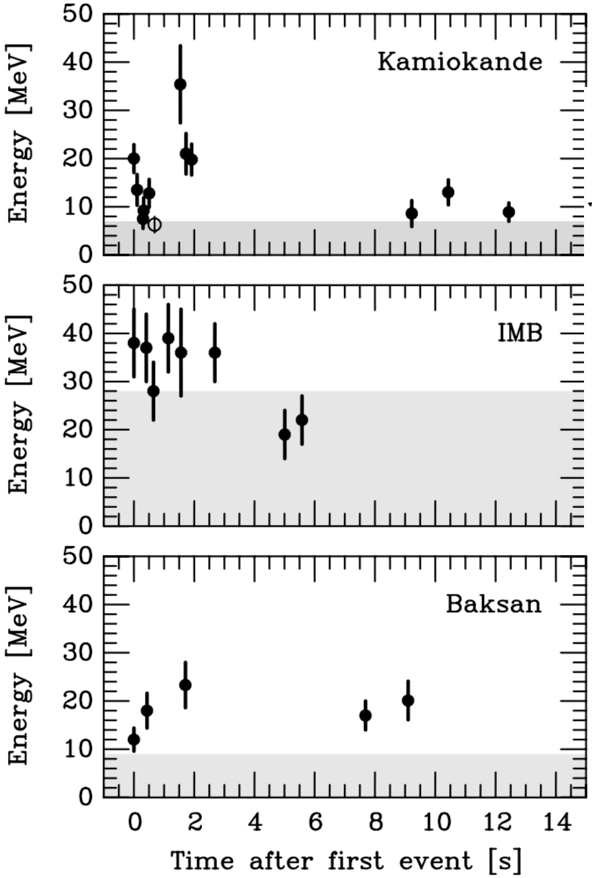
Gravitational Collapse and SN



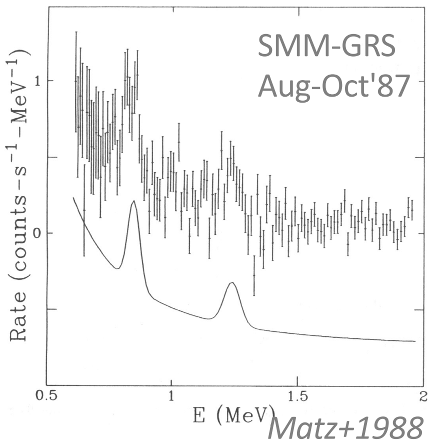
SN1987A

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

- Witness neutrino burst from core collapse

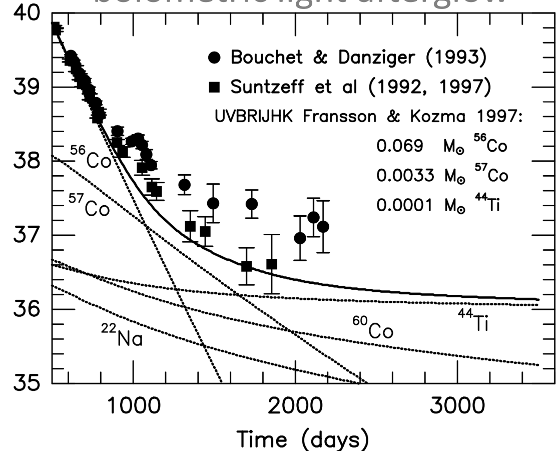


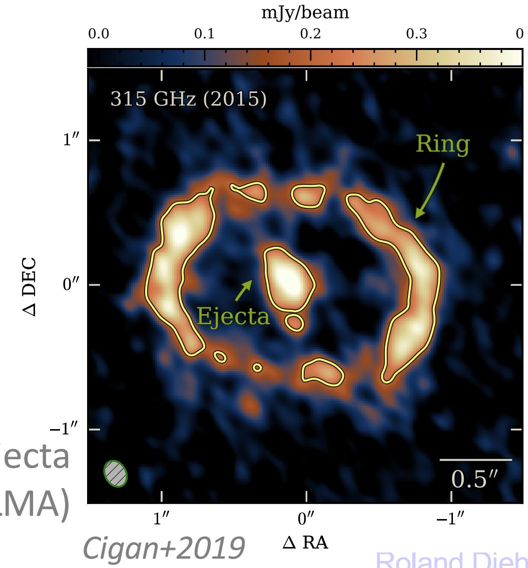
- Witness radioactively-powered SN afterglow and γ rays



Matz+1988

bolometric light afterglow



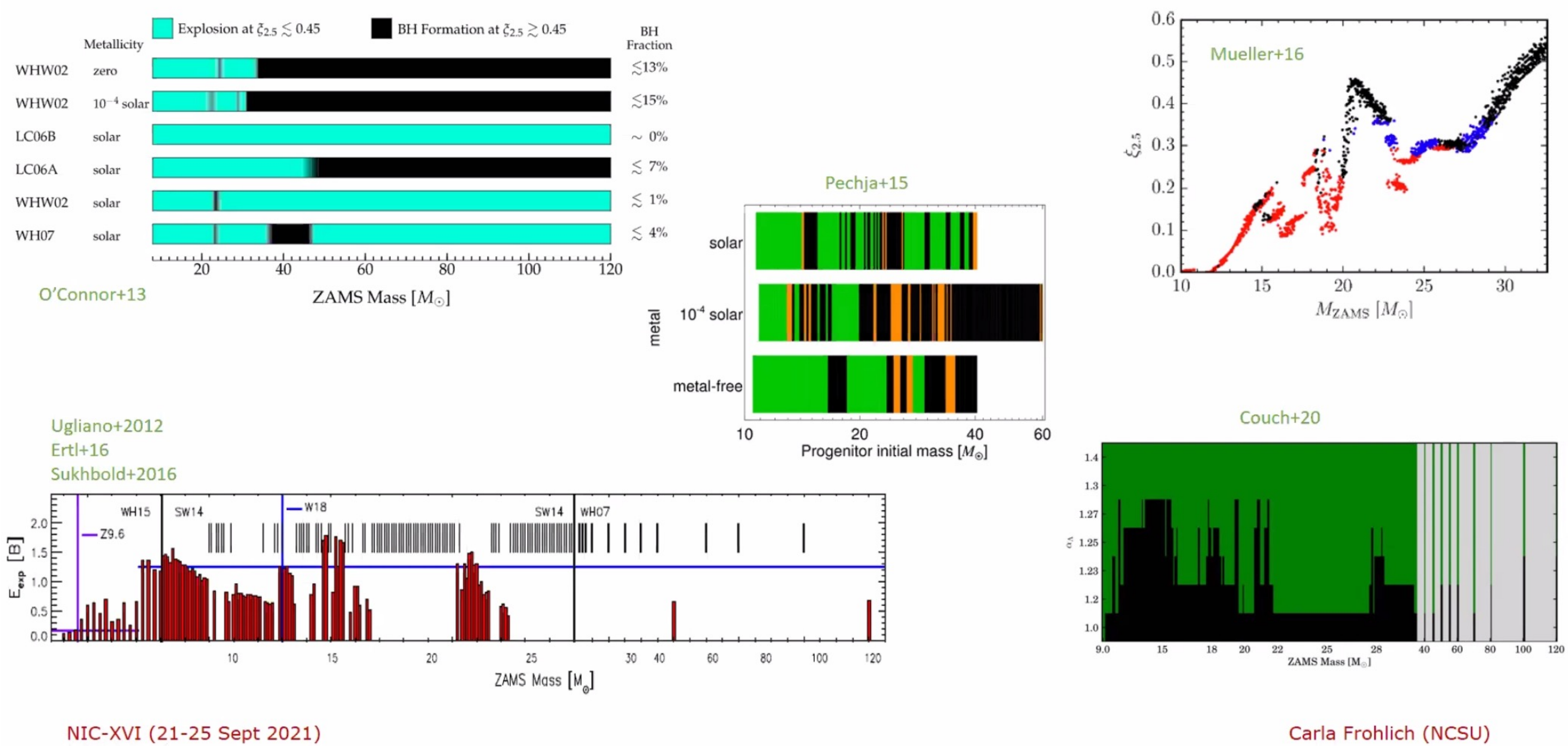


CSM, dust, ejecta (ALMA)

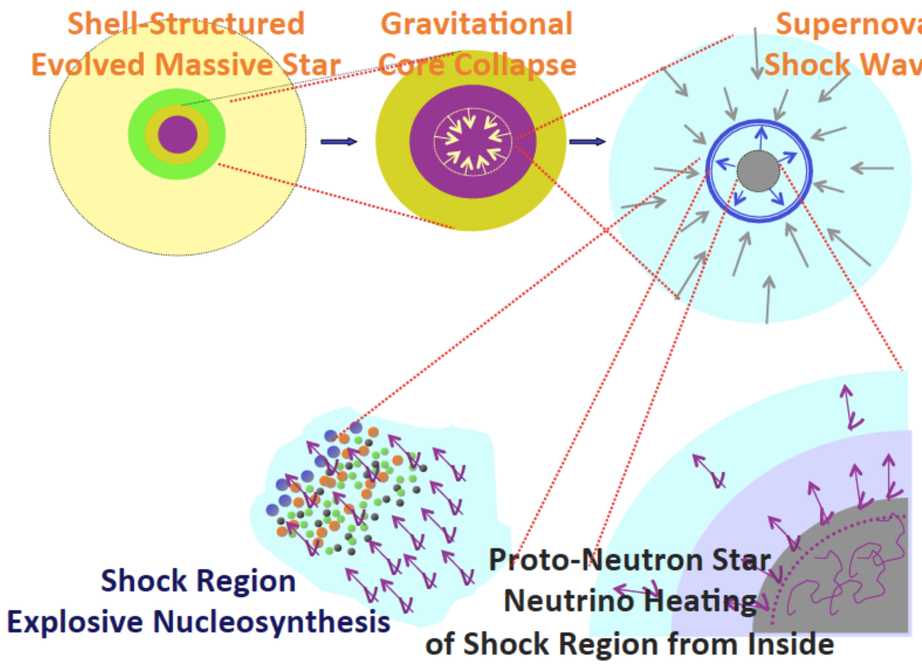
Cigan+2019

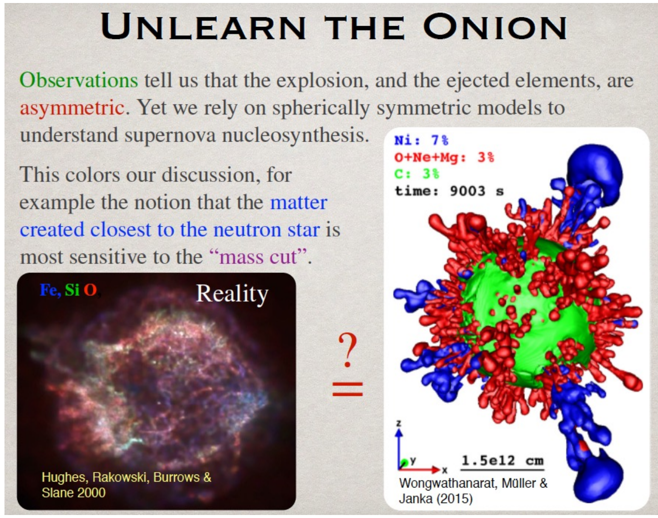
"Explodability" of core collapses

- successful explosion (and mass ejection) depends on subtle balances of internal processes and their kinematic implications
  - ☆ turbulence from gravitational accretion and neutrino energy deposits enhanced by instabilities in flows (Rayleigh-Taylor etc)



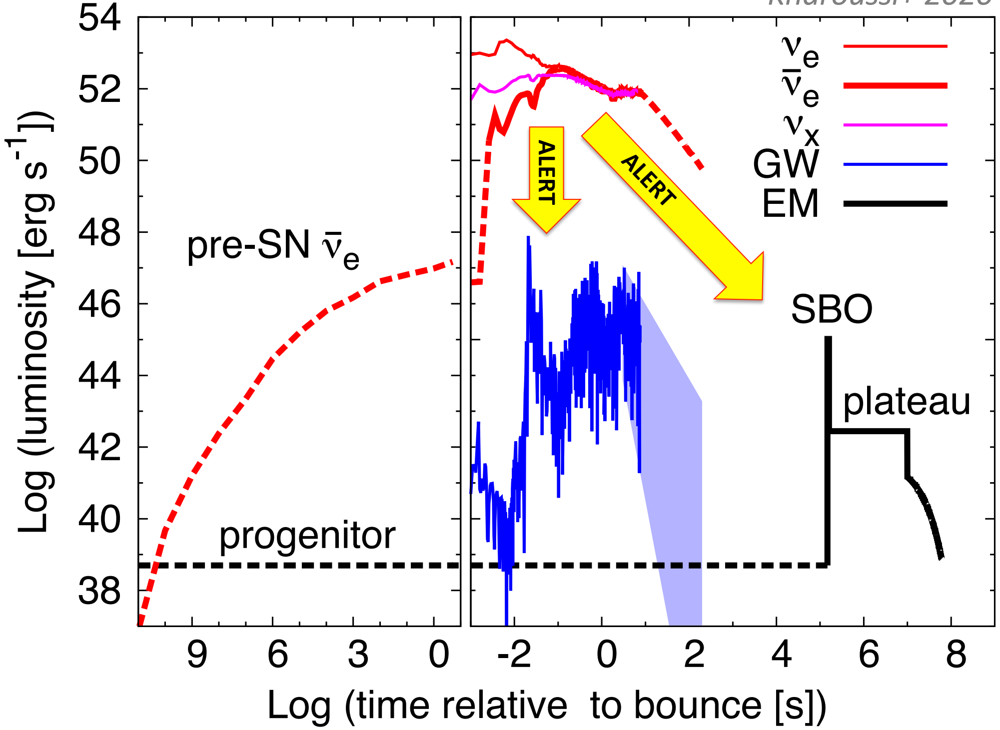
Complexities of Gravitational Collapse and SN





Raph Hix 2016

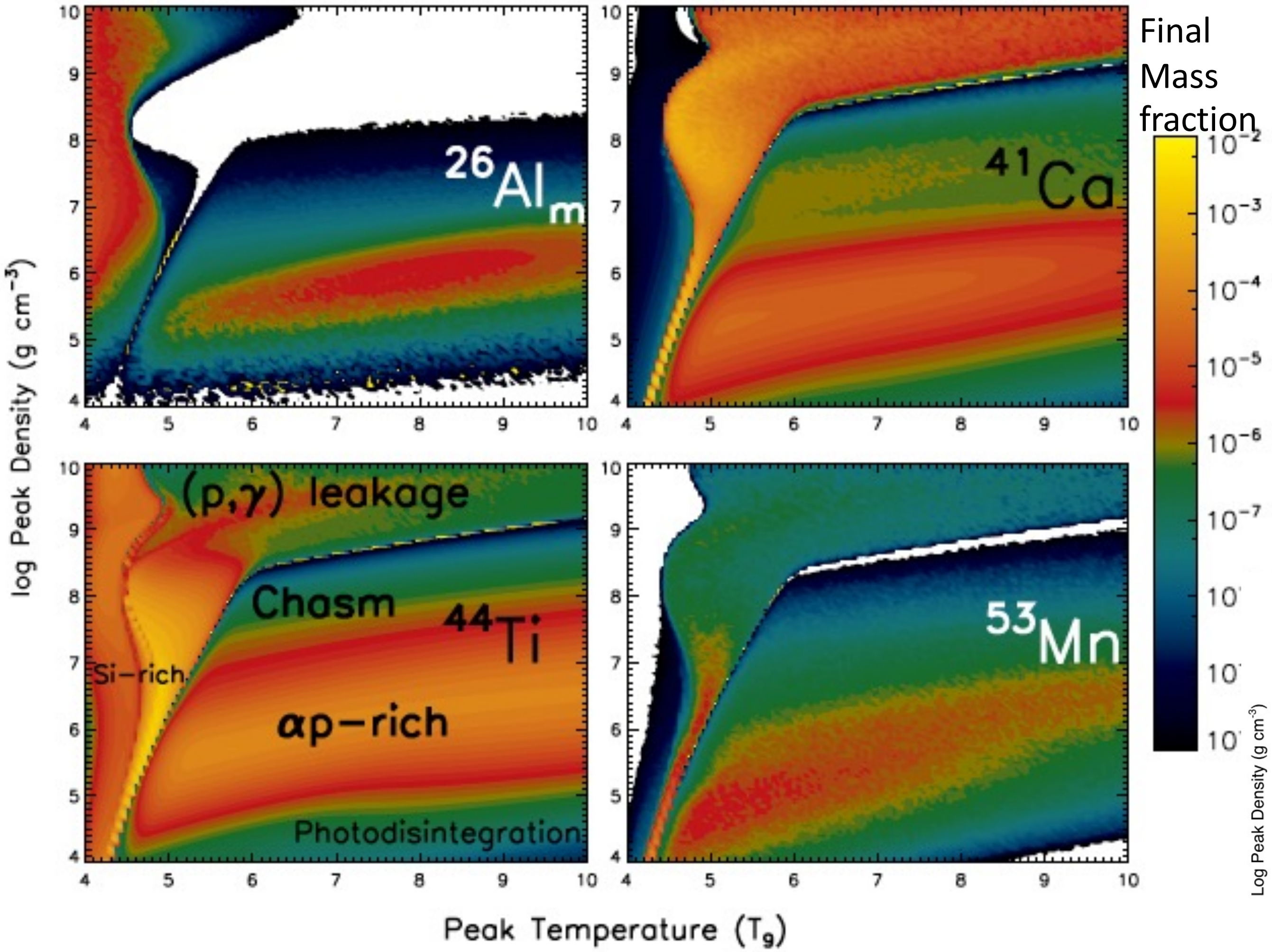
Kharoussi+ 2020



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

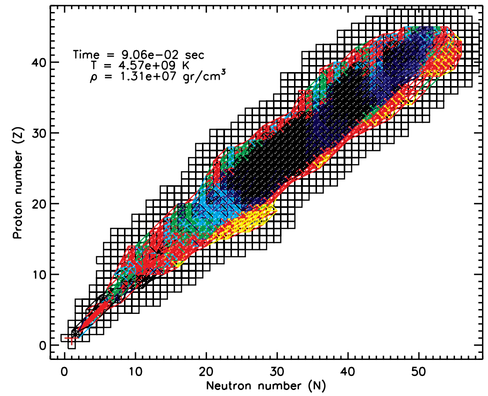
- pre-SN structure is complex
- collapse, ignition, and outflows all occur simultaneously
- collapse and accretion continue long after ignition of nuclear burning
- late accretion and fallback make explosion fail for more massive stars

Nucleosynthesis in cc-SN : Density/Temperature Regimes



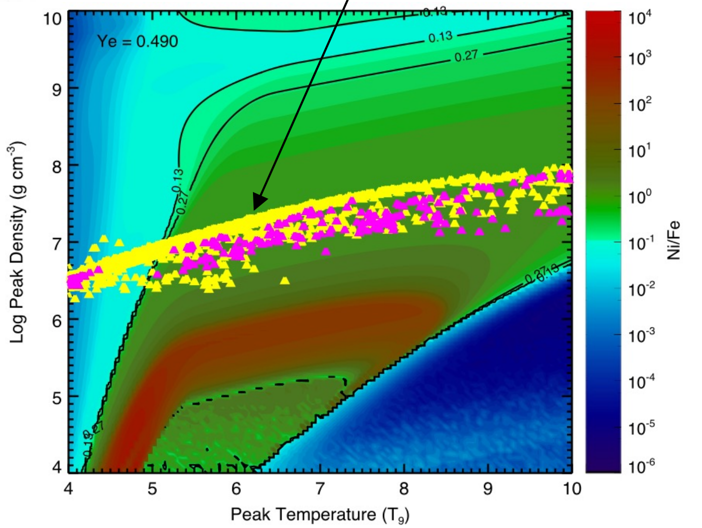
NuGrid collaboration (Magkotsios et al., ApJ 2011)

nuclear reaction network



typical ccSNparameter regions

(Jerkstrand et al., ApJ 2015)

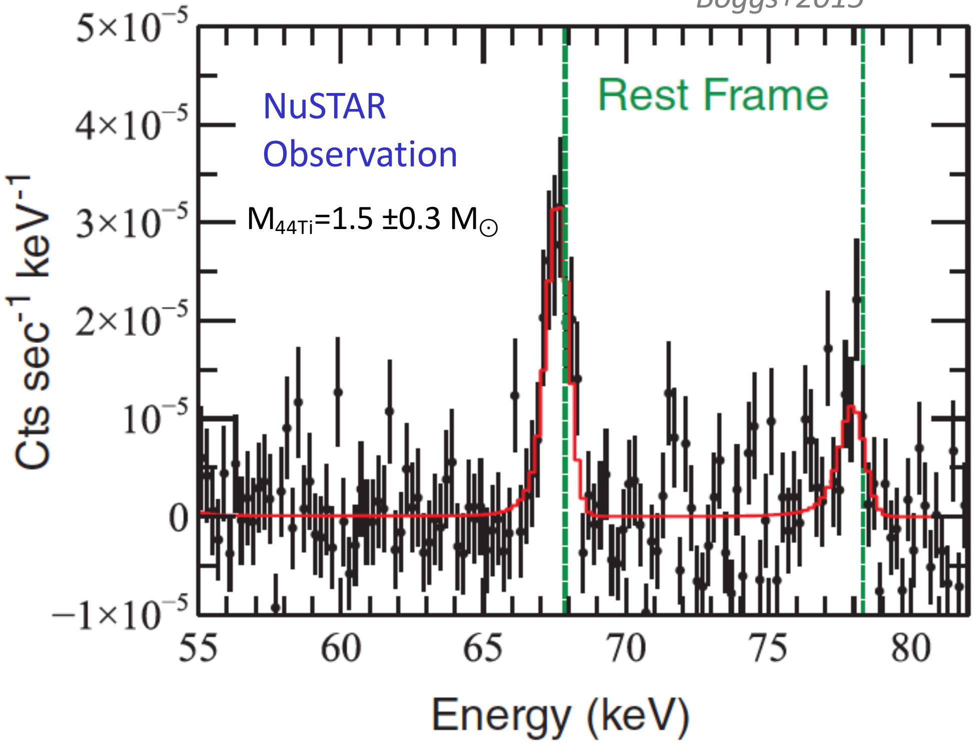


"For each region only certain reactions affect the yields of ^{44}Ti"

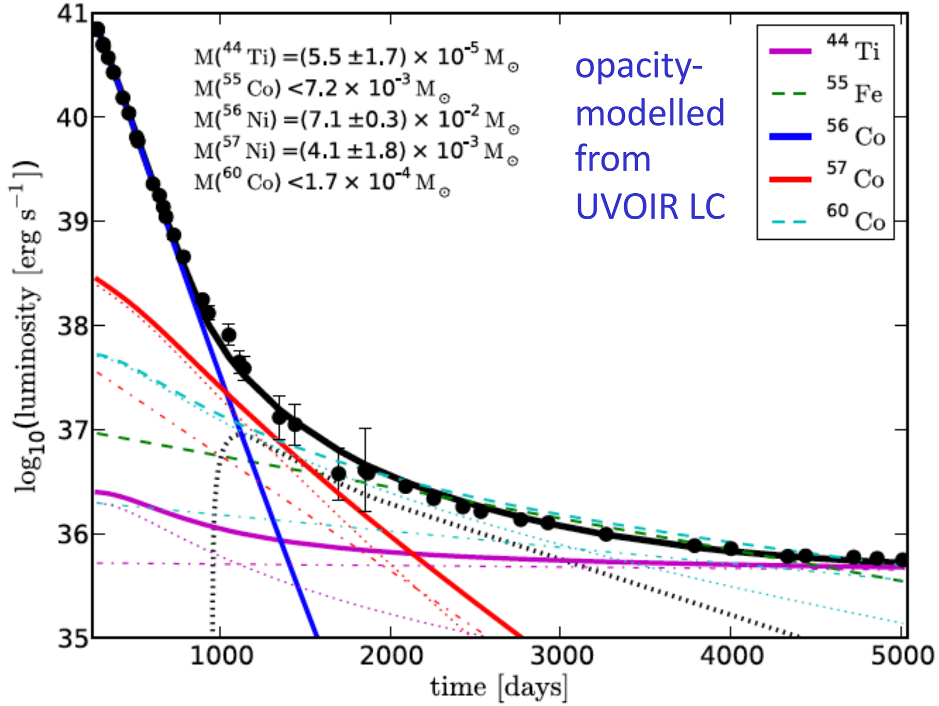
^{44}Ti from SN1987A

- ☆ ab-initio models
  → $M_{44Ti} \approx 0.x\ 10^{-5}\ M_\odot$ (spherical)
  to $0.x\ 10^{-4}\ M_\odot$ (aspherical)
- ☆ UVOIR LC + energy deposition models
  → $M_{44Ti} \approx 0.5...5\ 10^{-4}\ M_\odot$

Boggs+2015



Seitenzahl+2014



- ☆ ^{44}Ti X-ray result NuSTAR
  → $M_{44Ti} \approx 1.5\ _{\pm 0.3}\ 10^{-4}\ M_\odot$
- ☆ ^{44}Ti line measurements INTEGRAL
  → $M_{44Ti} < 3.1\ _{\pm 0.8}\ 10^{-4}\ M_\odot$ (2σ) (IBIS)
- ☆ → $M_{44Ti} < 7.5\ 10^{-4}\ M_\odot$ (2σ) (SPI)

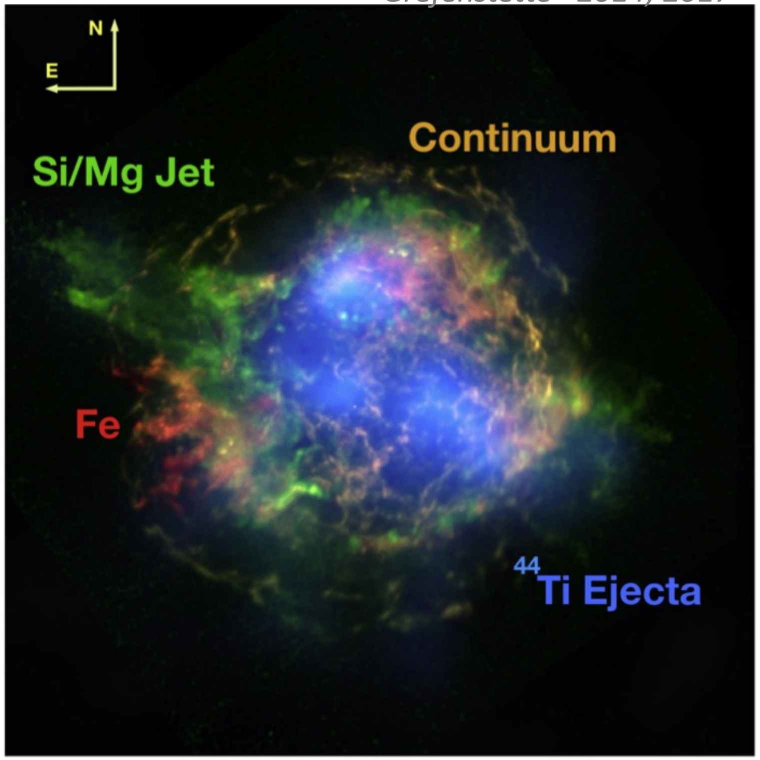
^{44}Ti radioactivity in Cas A: Locating the inner Ejecta

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

☞ first mapping of radioactivity in a SNR

Grefenstette+ 2014; 2017

- 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 ejecta from the inner supernova

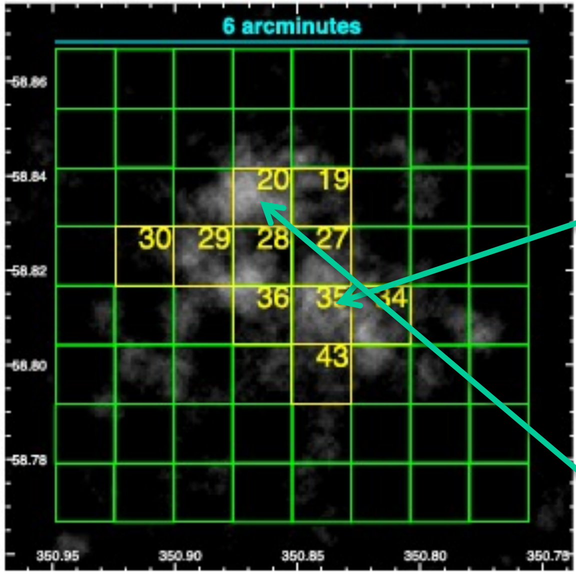
☞ Fe-line X-rays are biased from ionization of shocked plasma

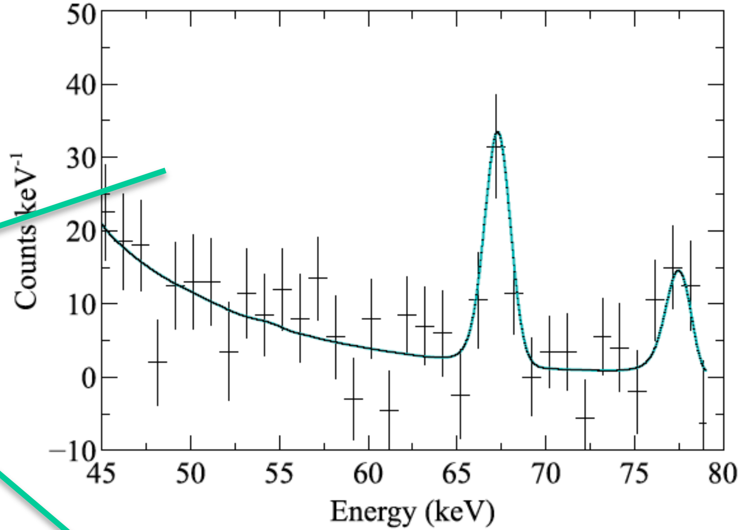
NuSTAR update: ^{44}Ti in Cas A

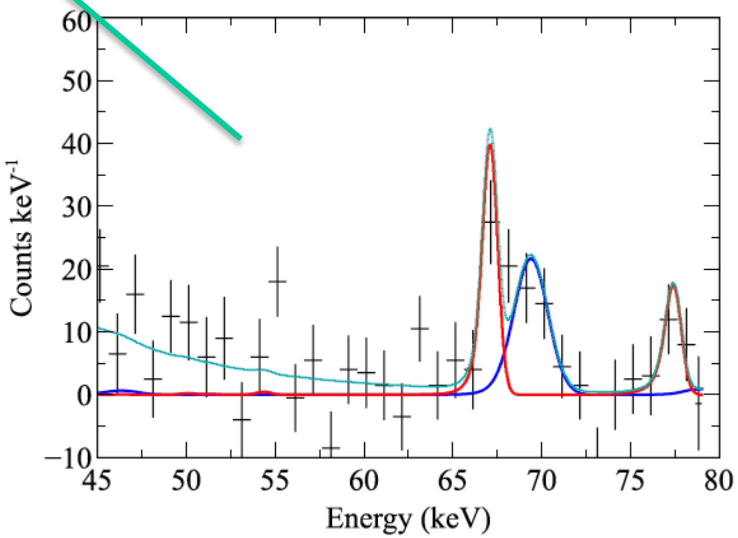
☆ Imaging resolution allows to spatially resolve Cas A's ^{44}Ti:

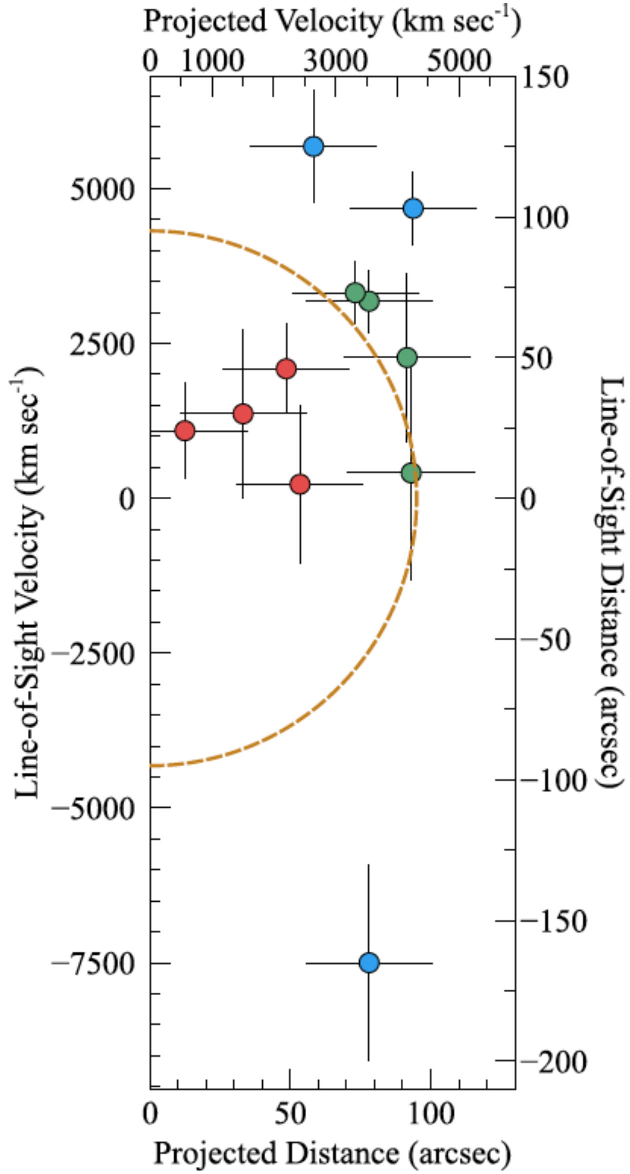
2.4 Msec NuSTAR campaign

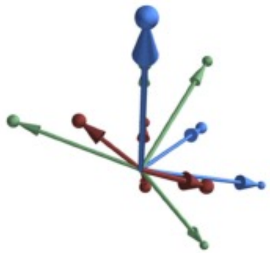
Grefenstette et al. 2017







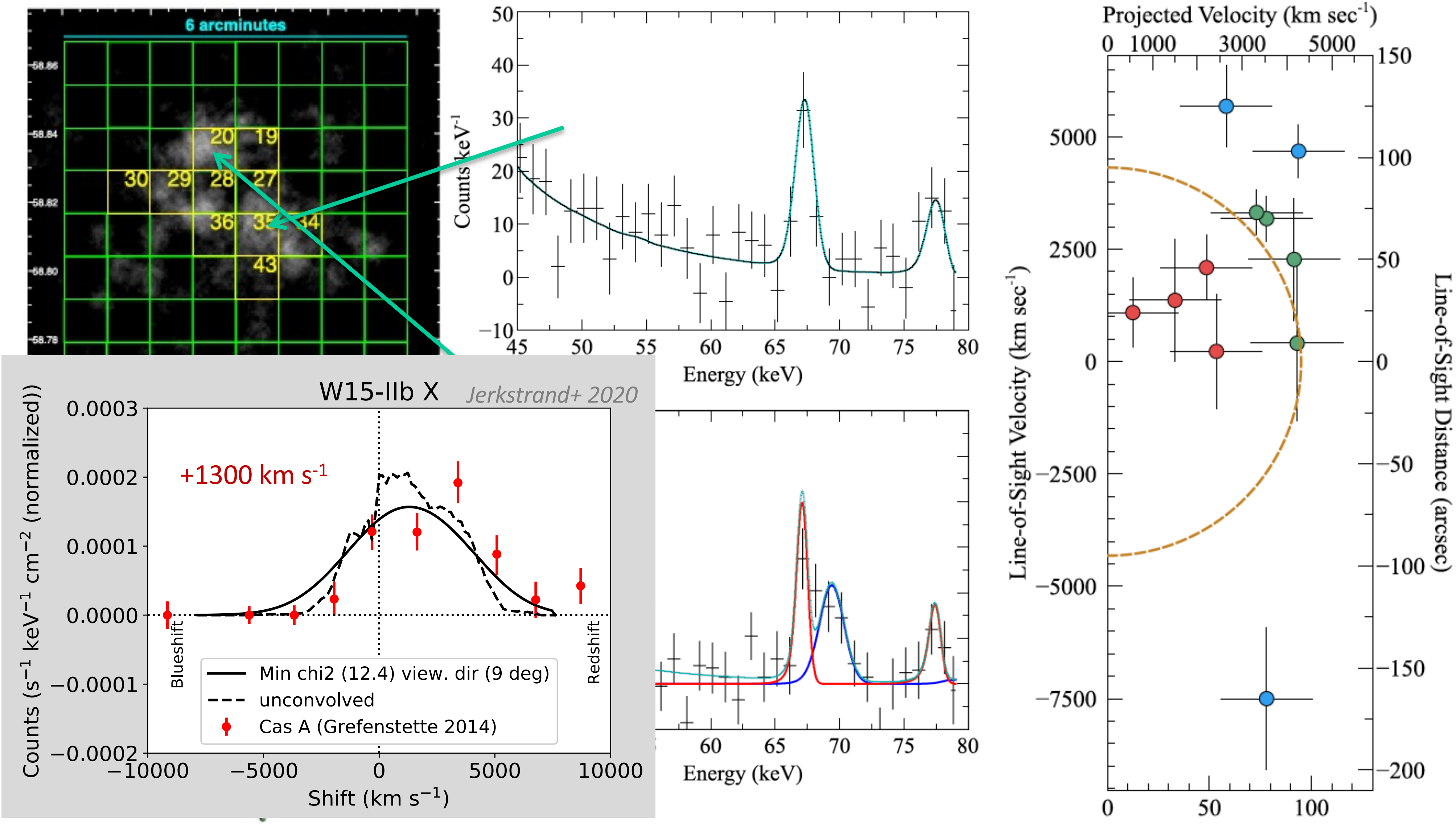




NuSTAR details of ^{44}Ti in Cas A

☆ Imaging resolution allows to spatially resolve Cas A's ^{44}Ti:

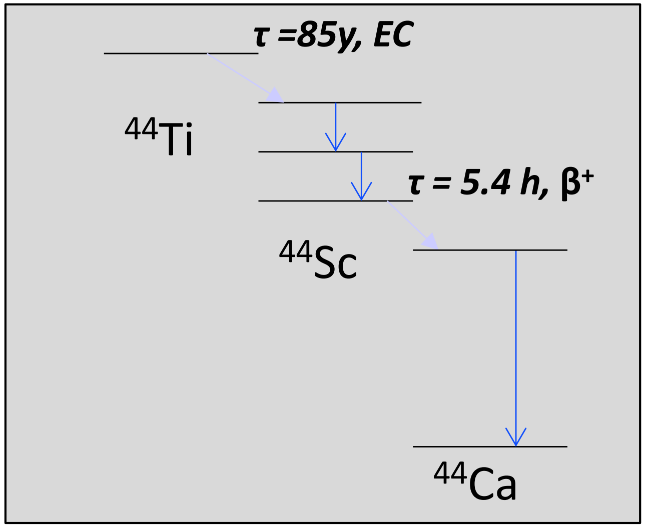
2.4 Msec NuSTAR campaign
Grefenstette et al. 2017



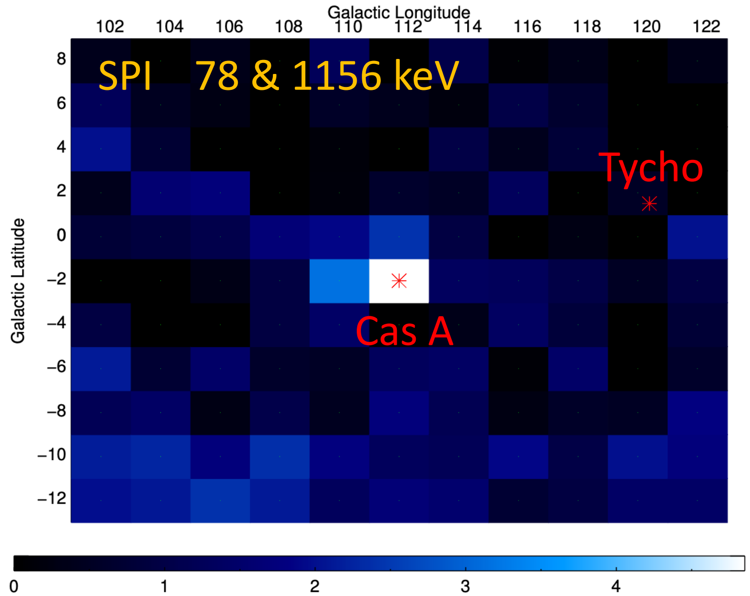
→ bulk red-shifted ^{44}Ti (away from observer)

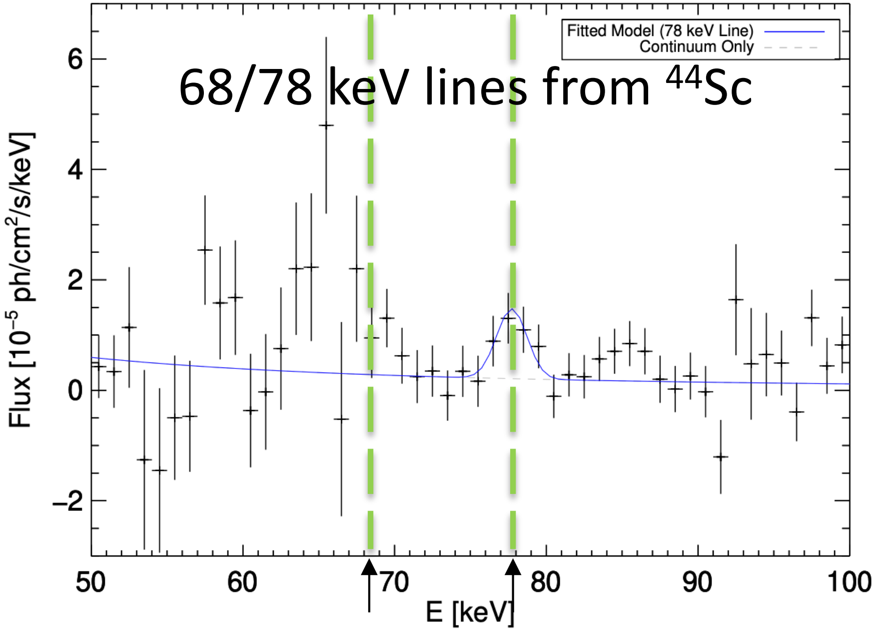
^{44}Ti Cas A: INTEGRAL/SPI confirmations of bulk redshift

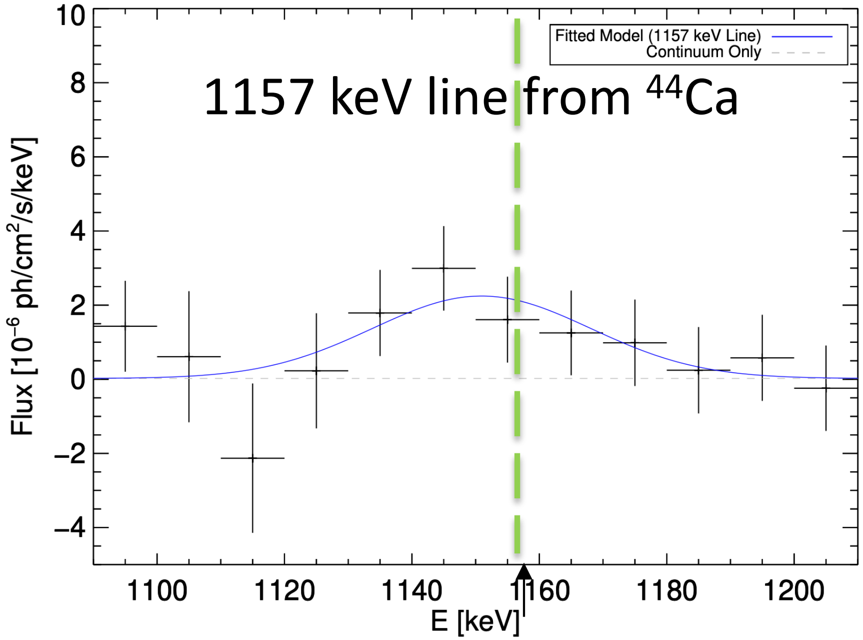
The ^{44}Ti decay chain with INTEGRAL/SPI:



Weinberger+ 2021

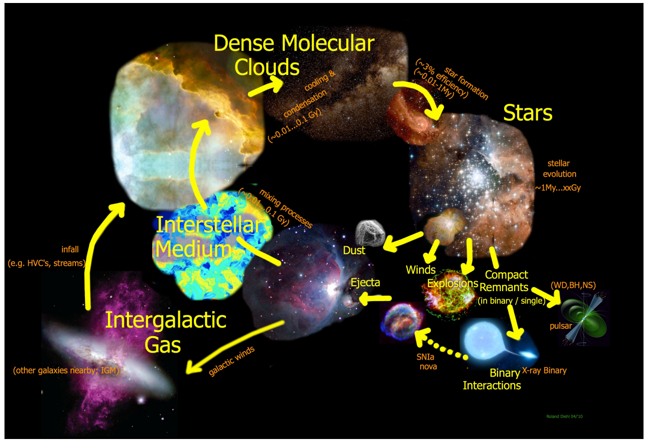


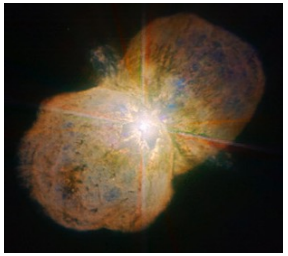


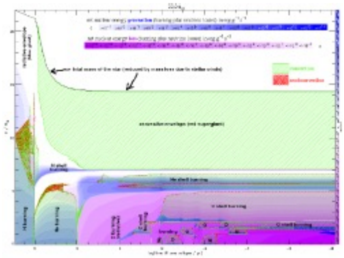


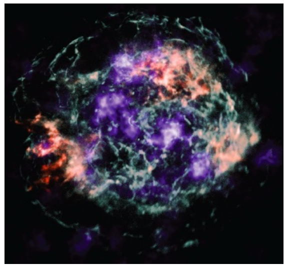
→ clear Doppler shift of ^{44}Ti (1800 ±800 km s^{-1} away from observer)

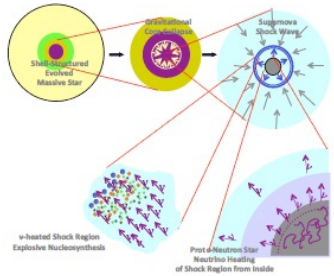
Lessons from radioactive isotopes

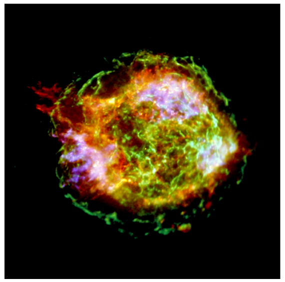


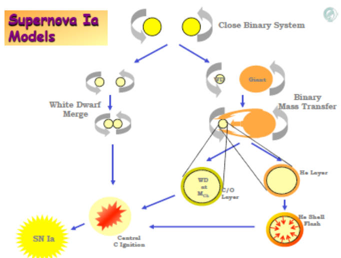








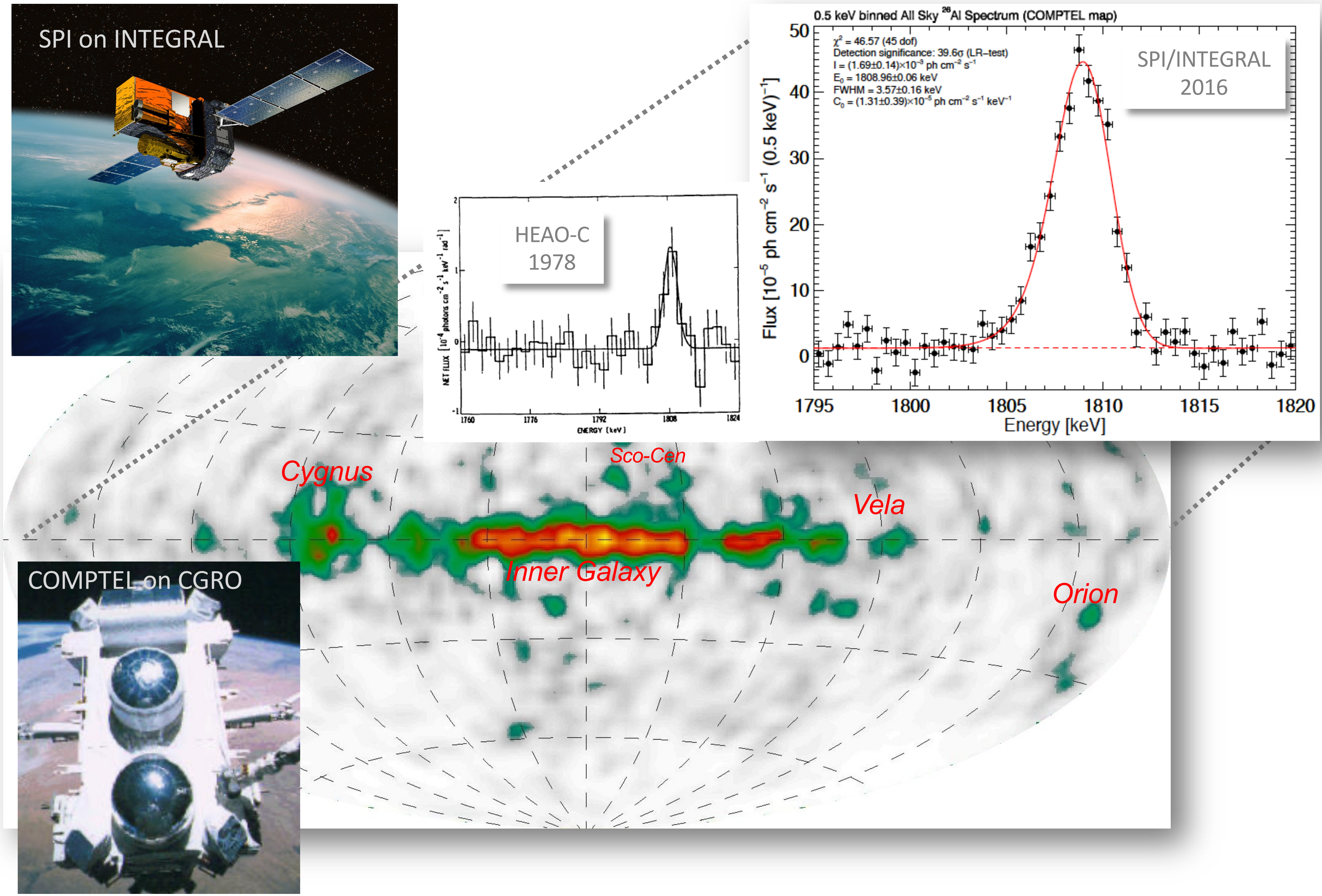




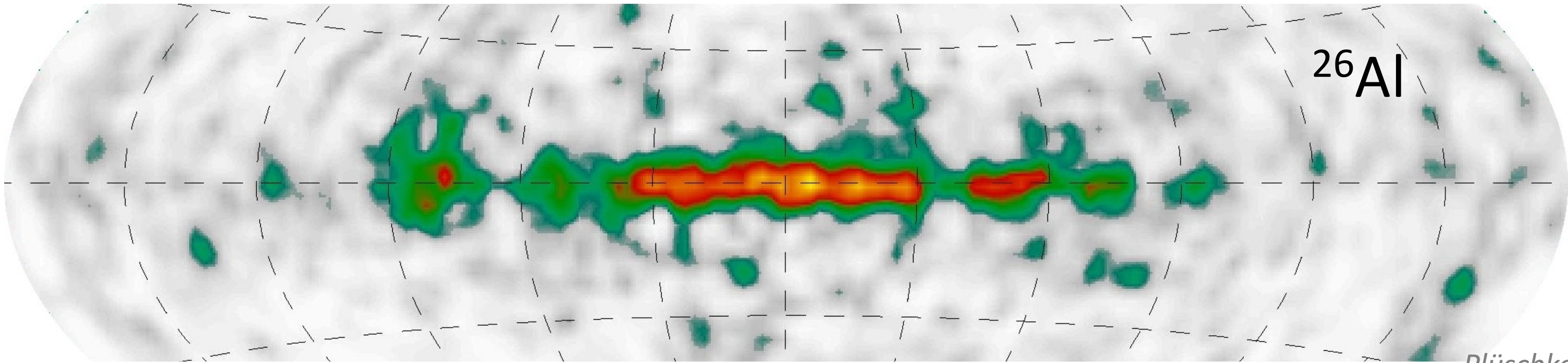
☆Trace the flows of cosmic matter

☆Understand the sources of new nuclei

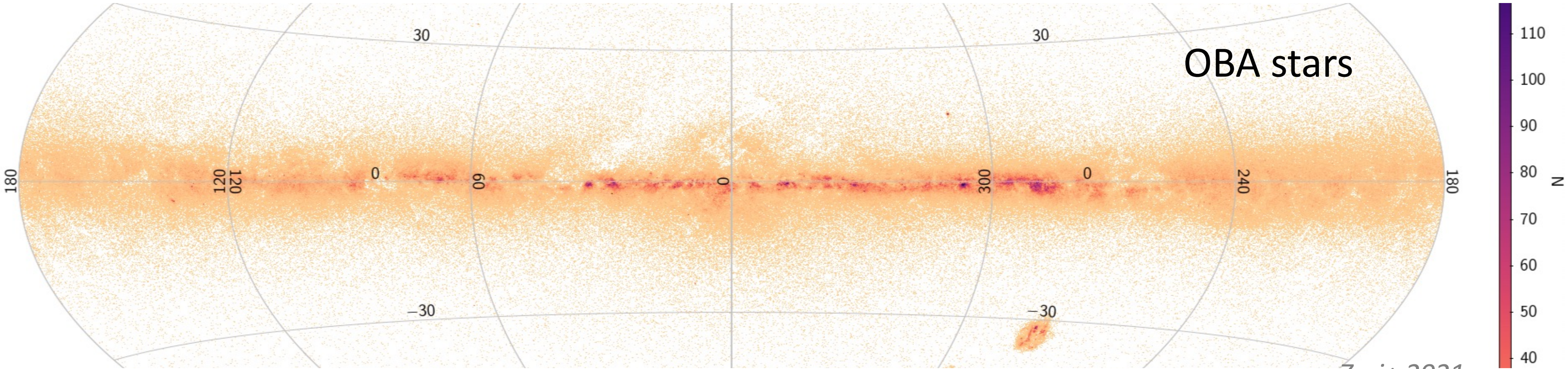
^{26}Al γ-rays from the Galaxy



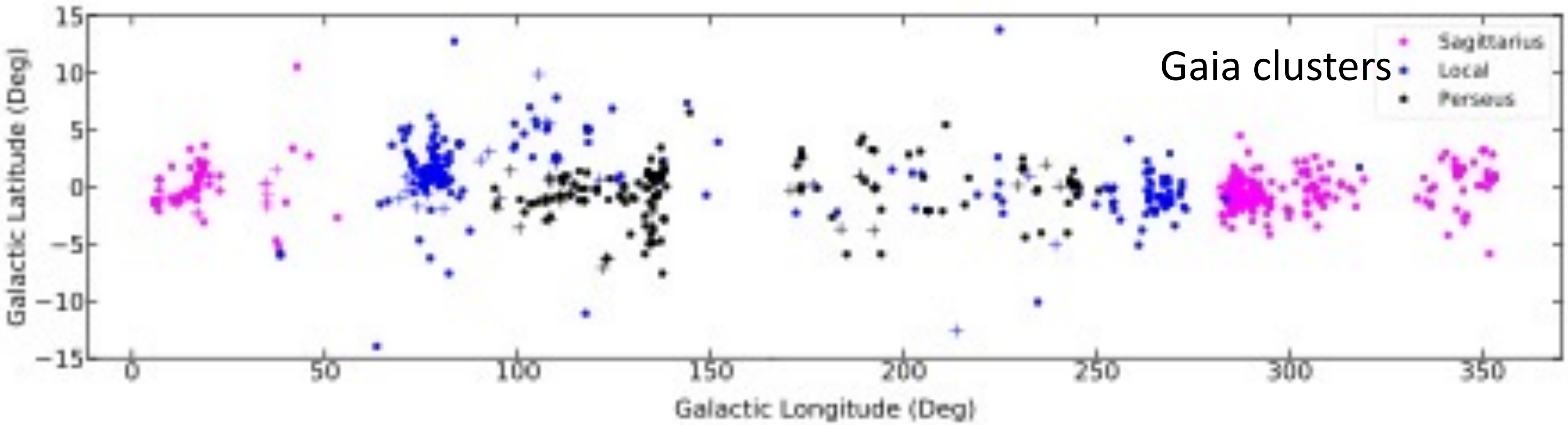
Massive stars and ^{26}Al radioactivity: co-spatial distribution



Plüschke+ 2001



Zari+ 2021

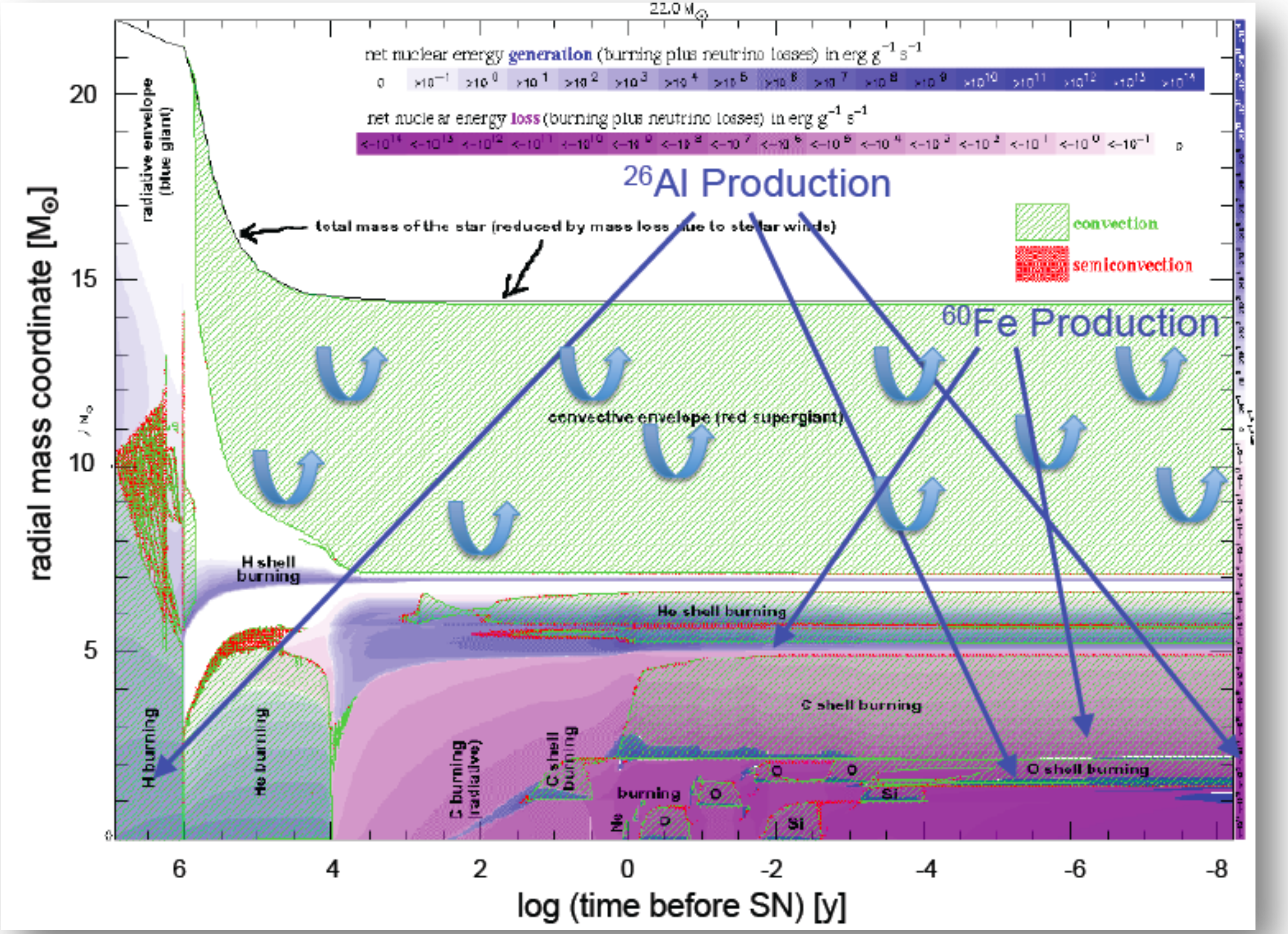


Xu+ 2021

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*

The Al Isotope Ratio $^{26}Al/^{27}Al$

^{27}Al is enriched with Galactic Evolution, i.e. ~time

^{26}Al decays, so from current/recent nucleosynthesis only

Early solar system meteorites measure ESS environment 4.6Gy ago (→ ^{26}Al enriched?)

Pre-solar grains measure nucleosynthesis in dust-producing sources (→ much larger)

'canonical' value for ESS of ~5 10^{-5}

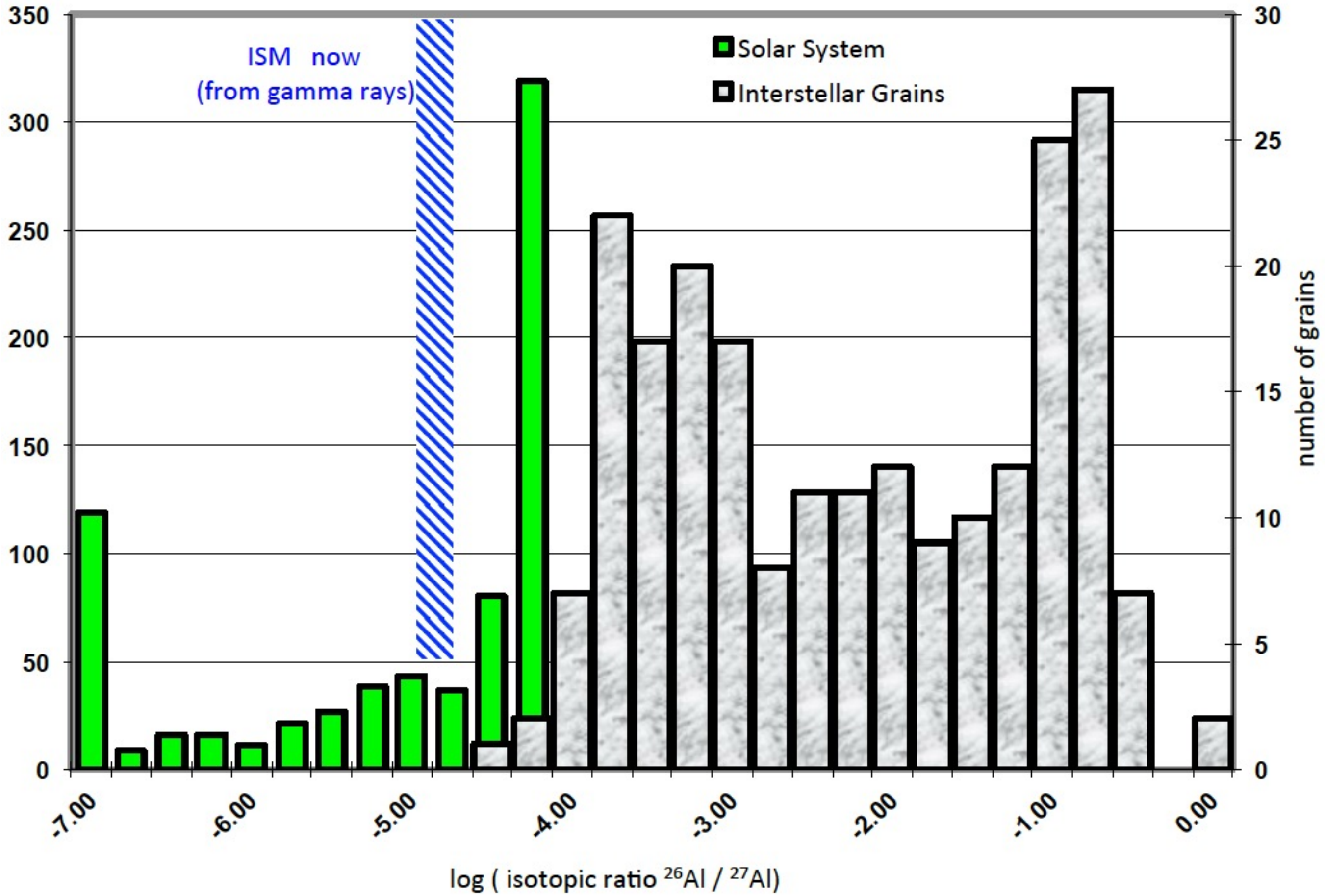
(McPhersson+1995)

'supra-canonical' up to 6.5 10^{-5} ??

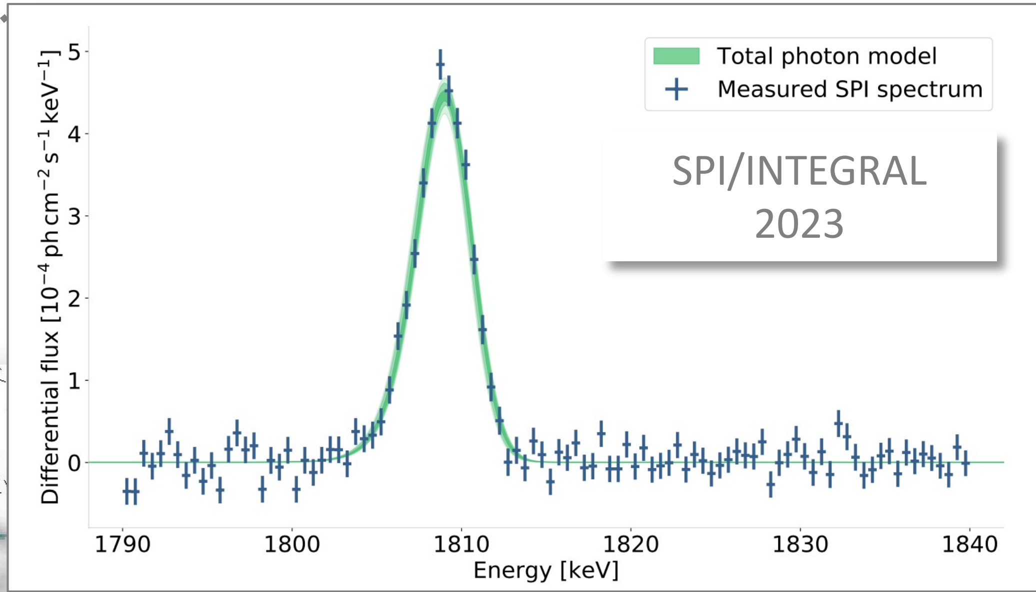
(Krot+2012, Makide+ 2013 ...)

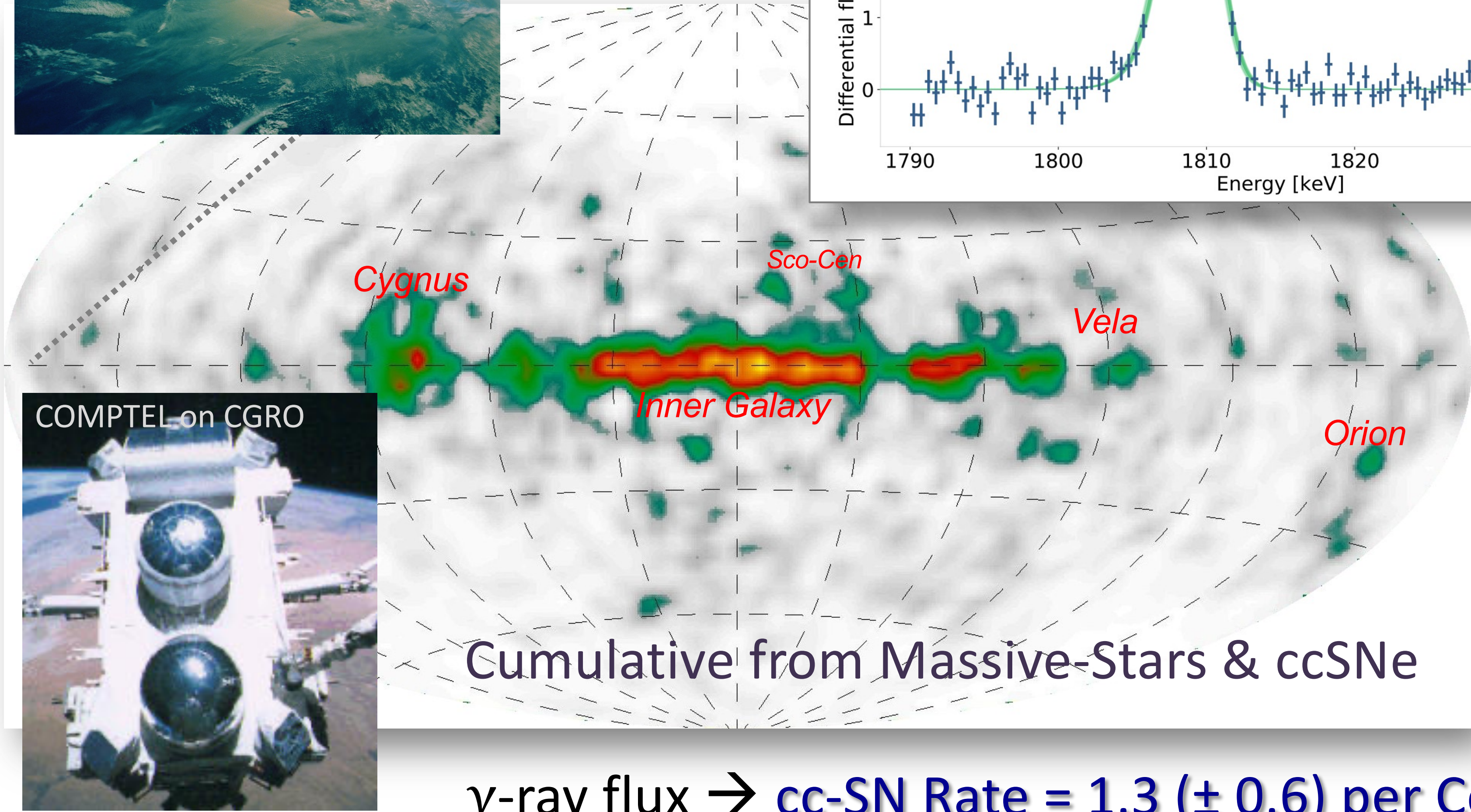
Consolidated ESS $(5.23 \pm 0.13)\ 10^{-5}$

(Jacobsen+2013)



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





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

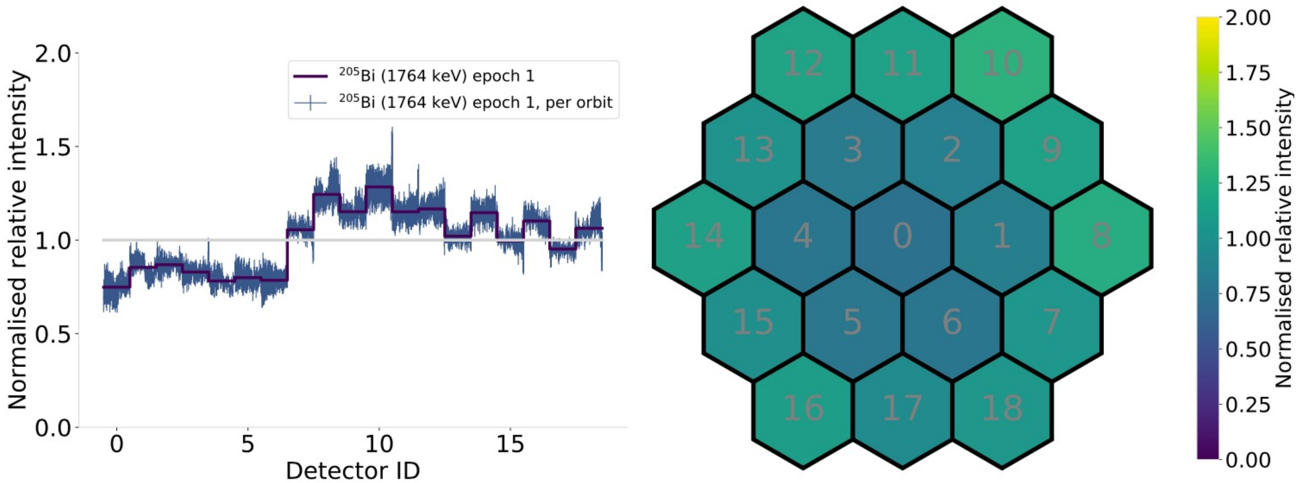
Diehl+2006;2018

Recently: Improved Sensitivity

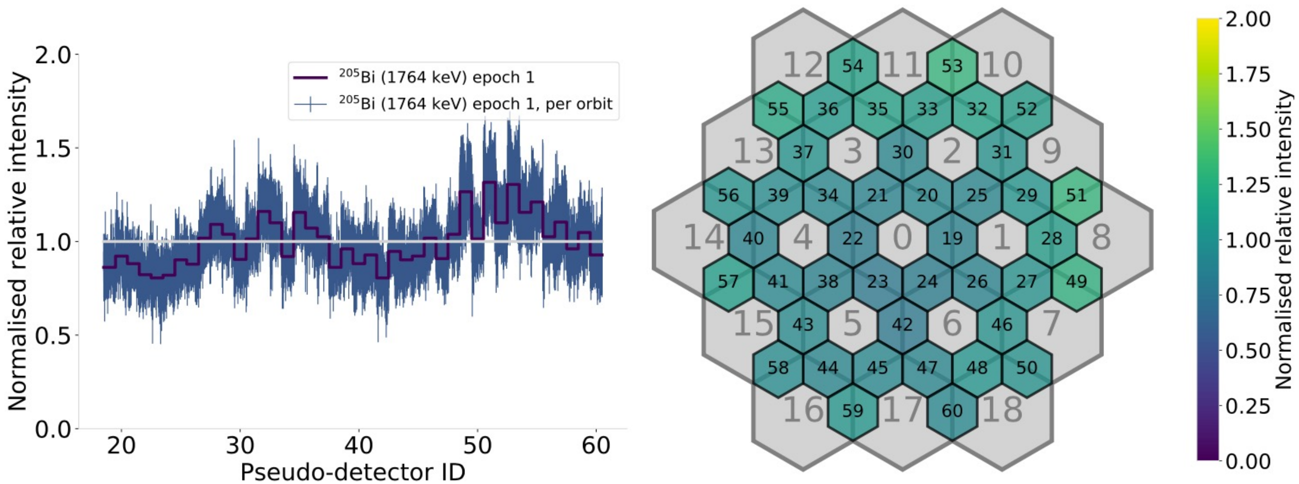
Using also multiple-detector events in SPI

building a model for instrumental background in detail:

Pleintinger+ 2023



single events

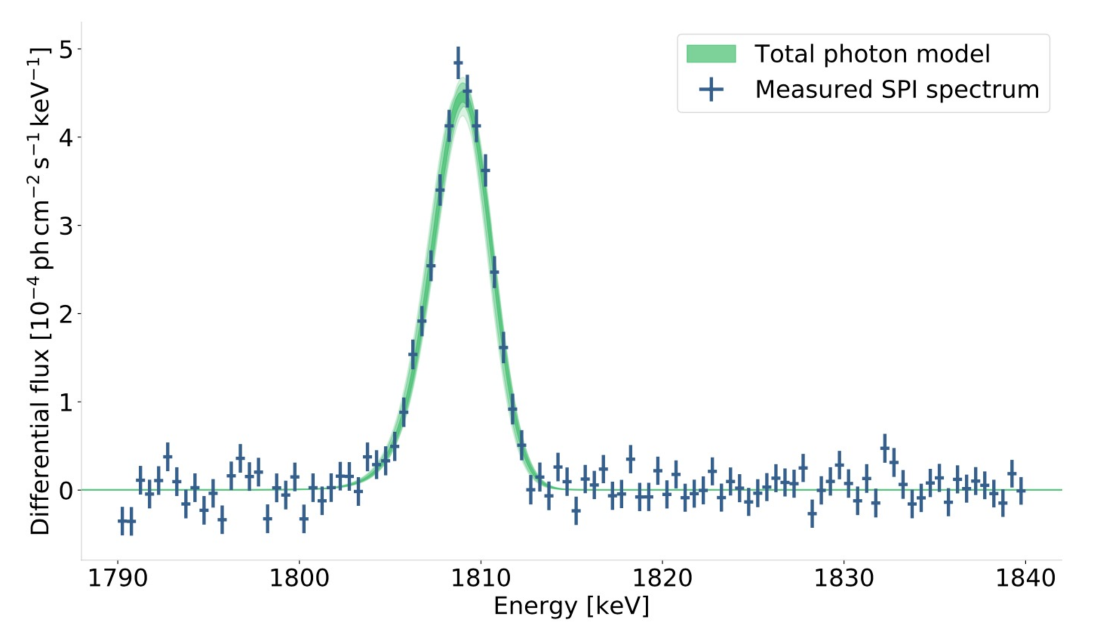


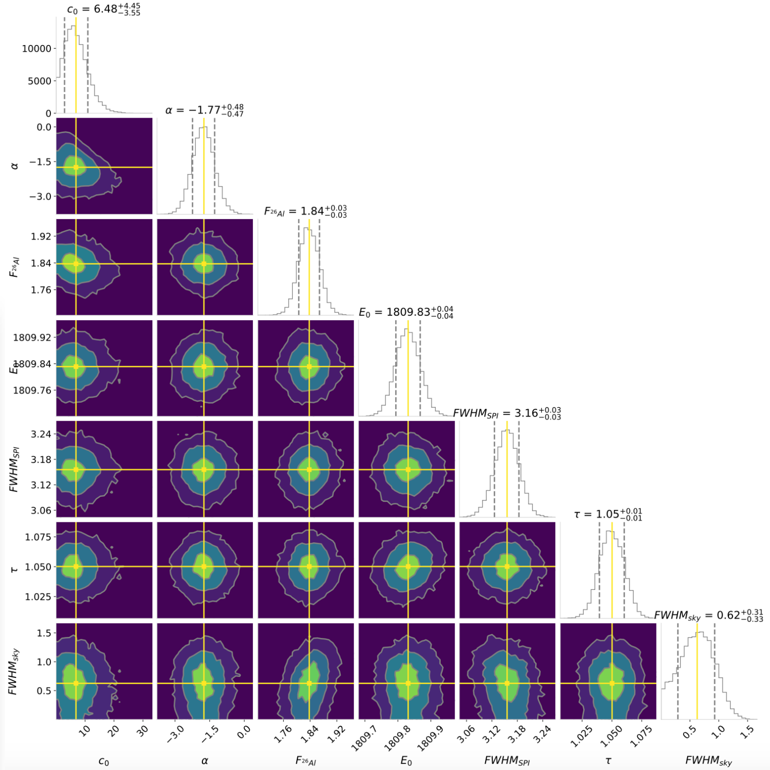
double events

Improved Sensitivity

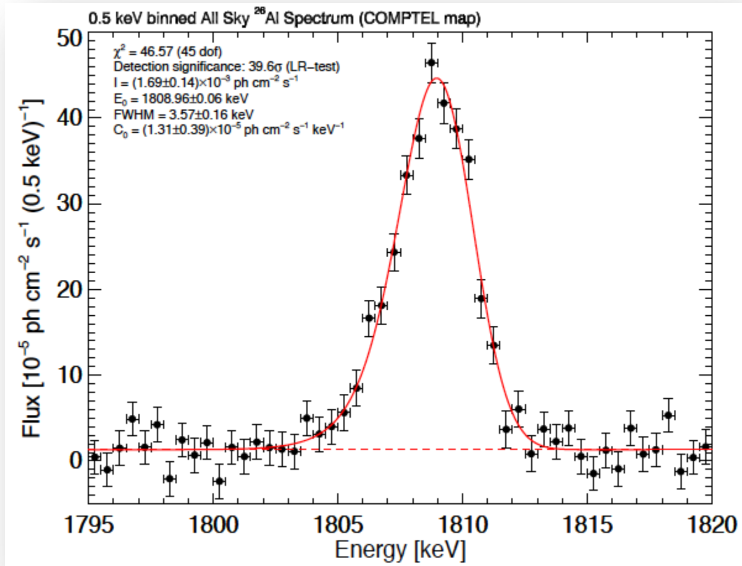
^{26}Al results from SE and DE: >58σ

Pleintinger+ 2023





Siegert 2016



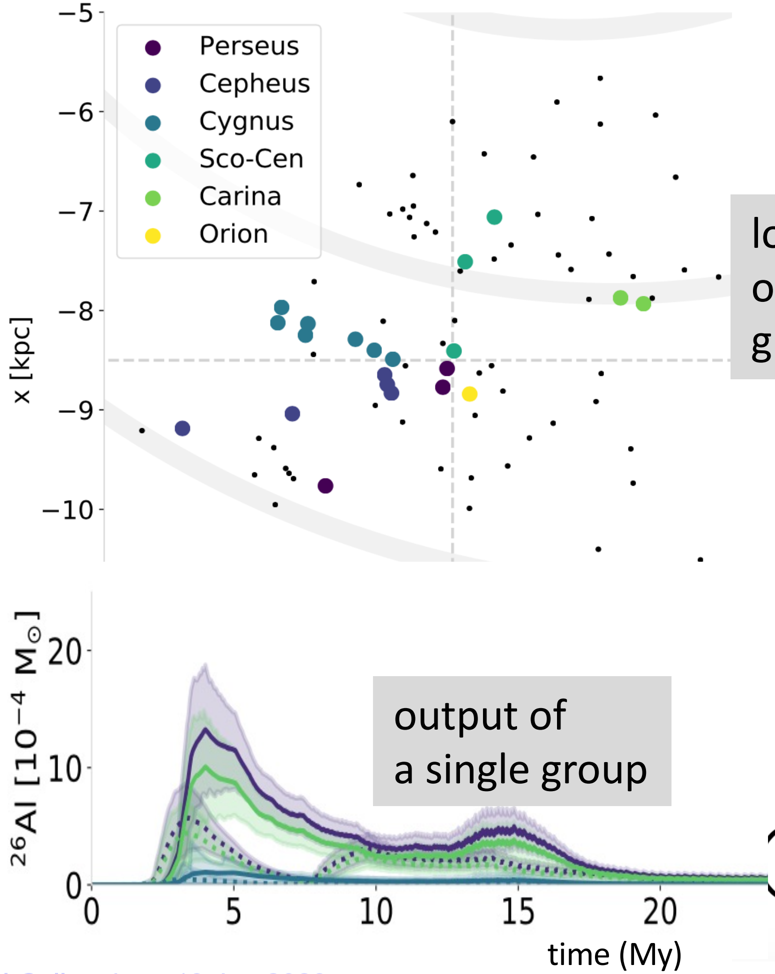
Diffuse radioactivity throughout the Galaxy

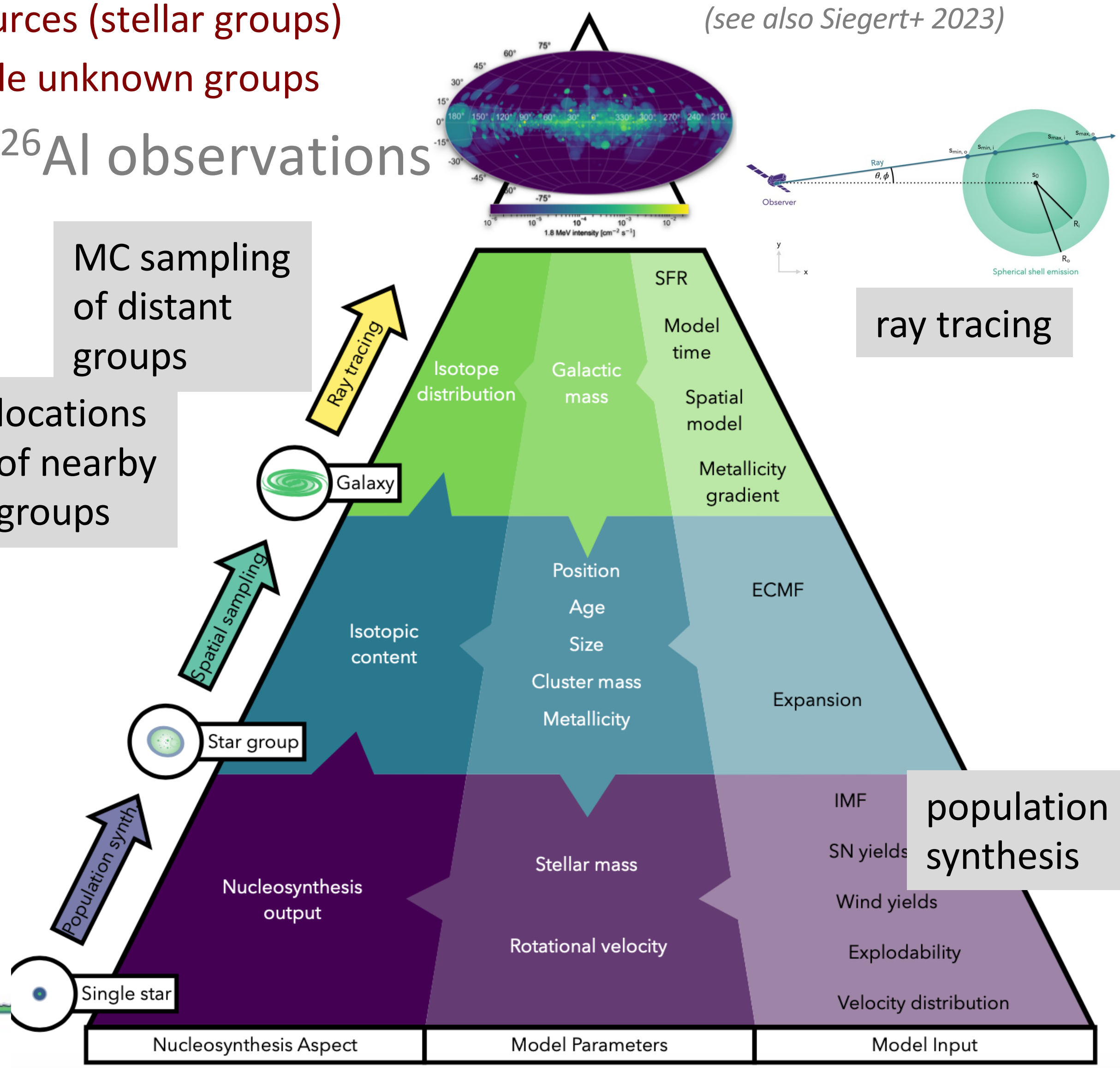
Galactic Population Synthesis Modelling

- Use stellar / SN yields and evolution times
- Include knowledge about sources (stellar groups)
- Include known groups; sample unknown groups

→ bottom-up model for the ^{26}Al observations

Pleintinger PhD thesis 2020 (see also Siegert+ 2023)

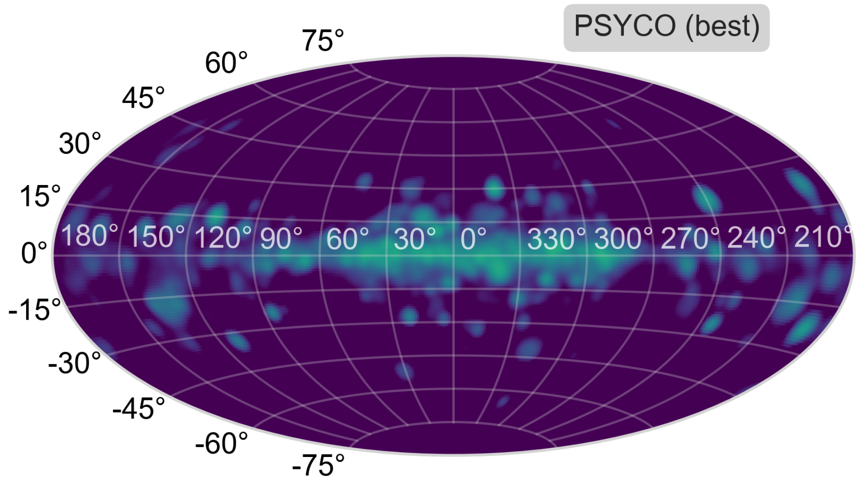


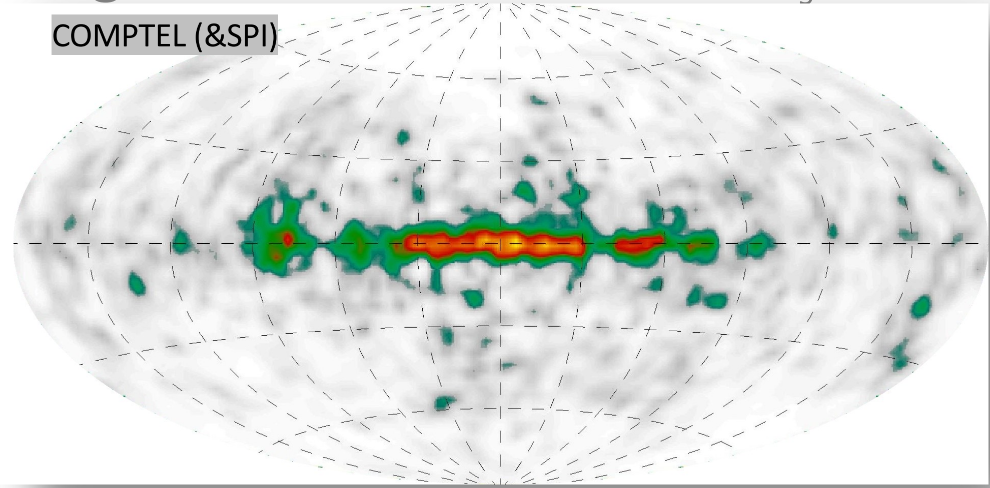


Diffuse radioactivity throughout the Galaxy

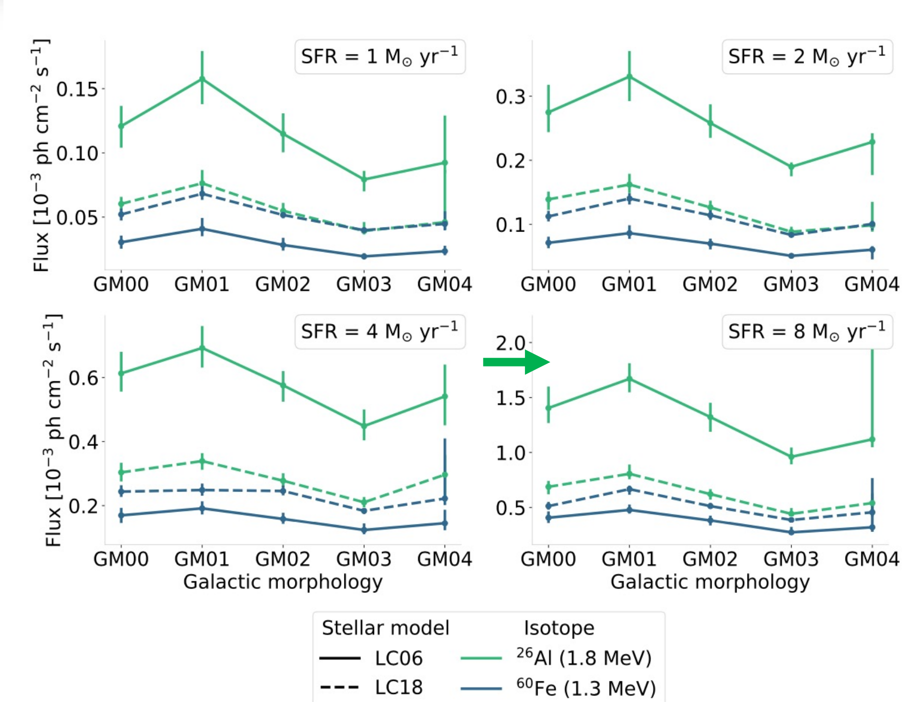
Galactic Population Synthesis Modelling versus observations

Pleintinger 2020
Siegert+ 2023





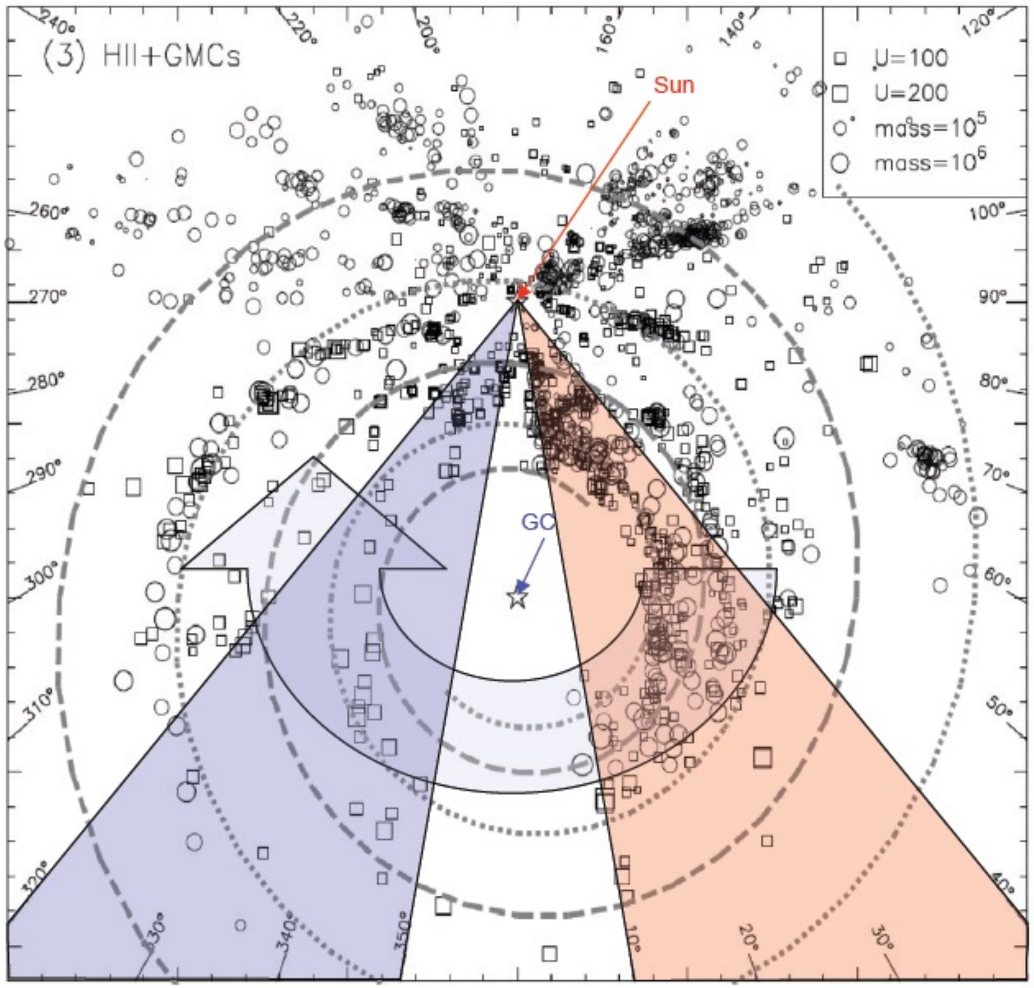
- PSYCO modeling: (30000 sample optimisation)
  → best: 4-arm spiral 700 pc, LC06 yields, SN explosions up to 25 $M_\odot$
- SPI observation: → full sky flux
  $(1.84 \pm 0.03)\ 10^{-3}$ ph cm^{-2} s^{-1}
- flux from model-predicted ^{26}Al:
  → $(0.5..13)\ 10^{-4}$ ph cm^{-2} s^{-1} → too low
- Best-fit details (yield, explodability) depend on superbubble modelling
  (here: sphere only)

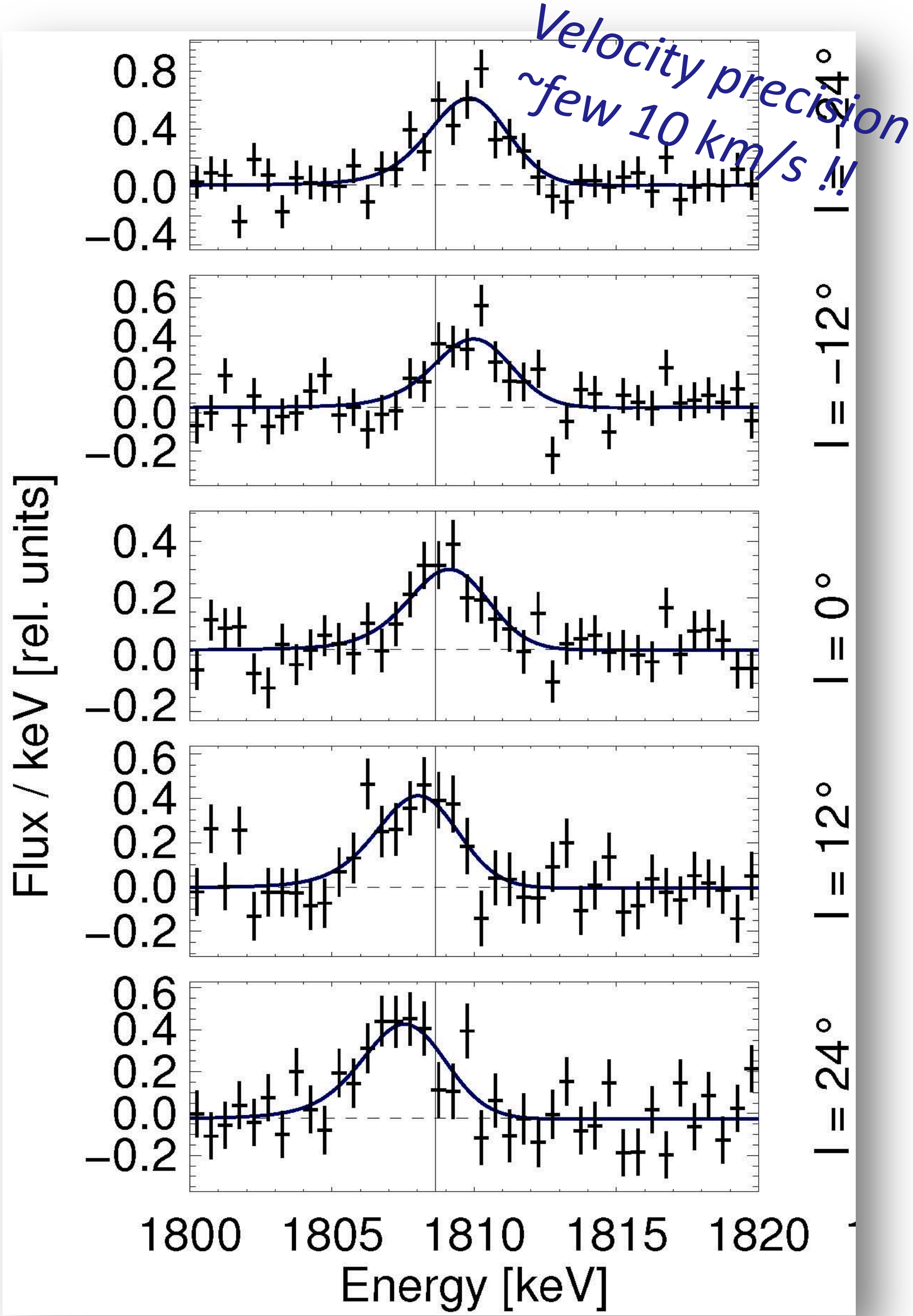


cmp. Gaia/2MASS: ~3.3 $M_\odot$ y^{1} *(Zari+2022)*

Massive Star Groups in our Galaxy: ^{26}Al γ-rays

☞ Large-scale Galactic rotation

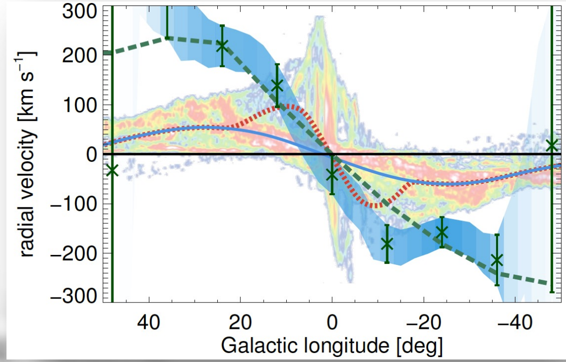


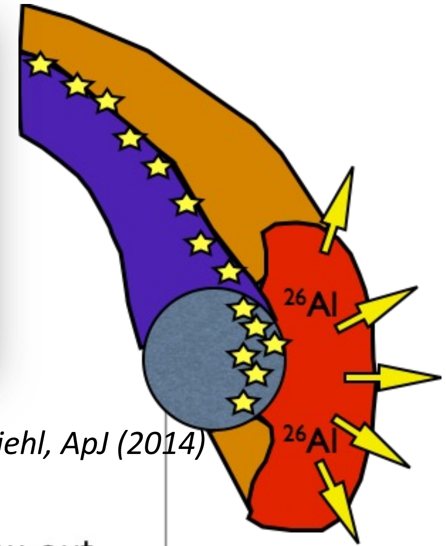


Kretschmer et al., A&A (2013)

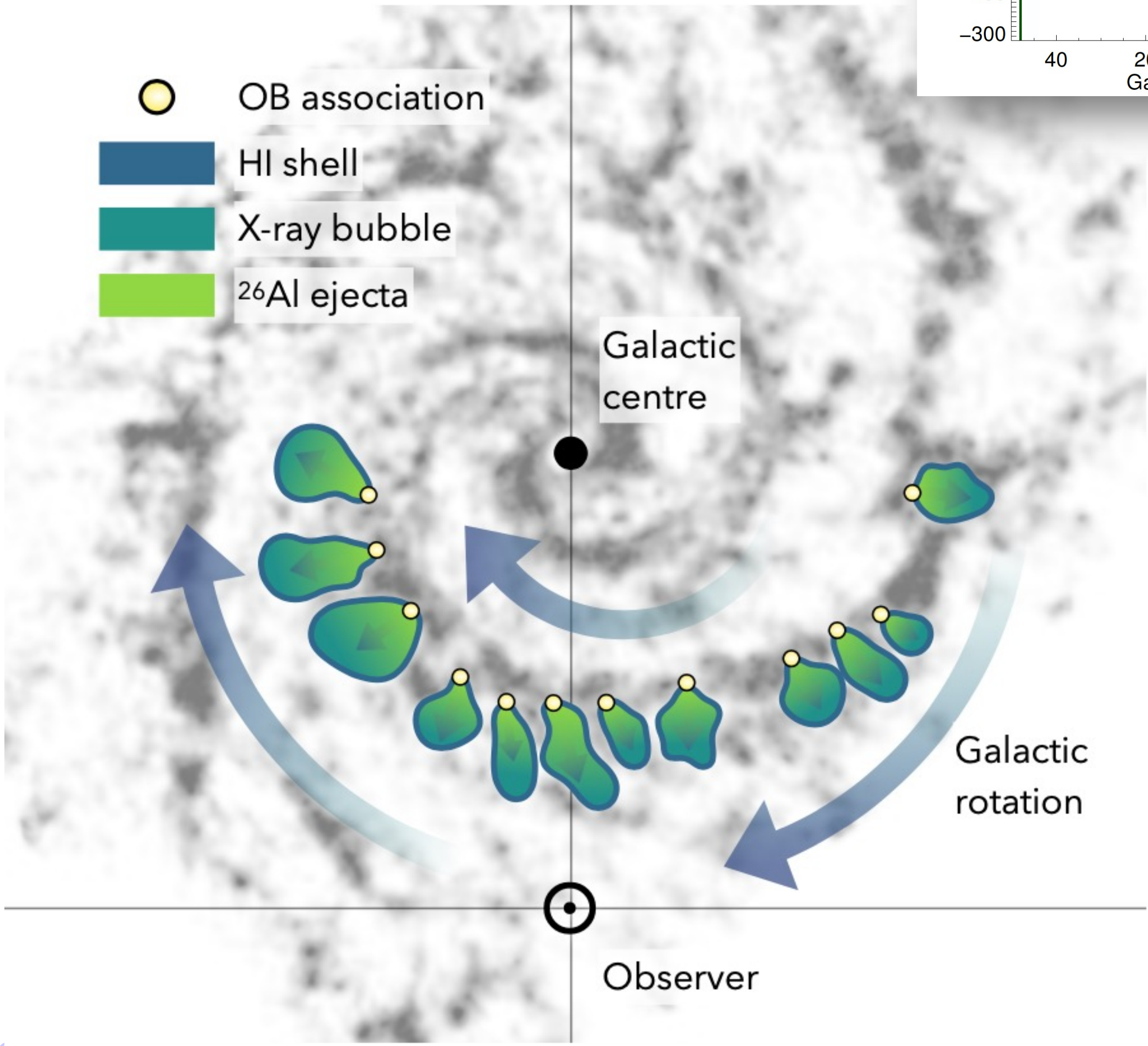
How massive-star ejecta are spread out…

Superbubbles extended away from massive-star groups





Krause & Diehl, ApJ (2014)



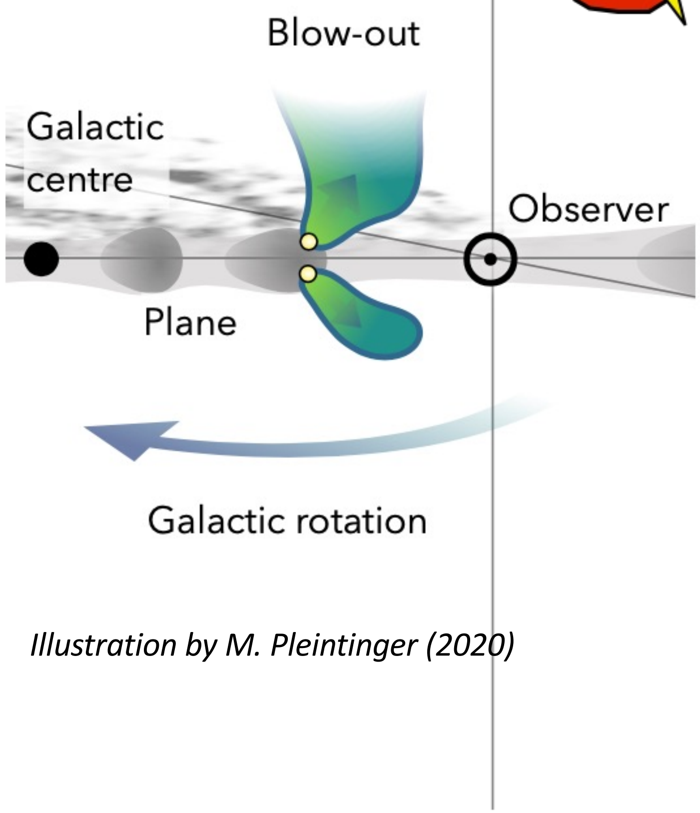
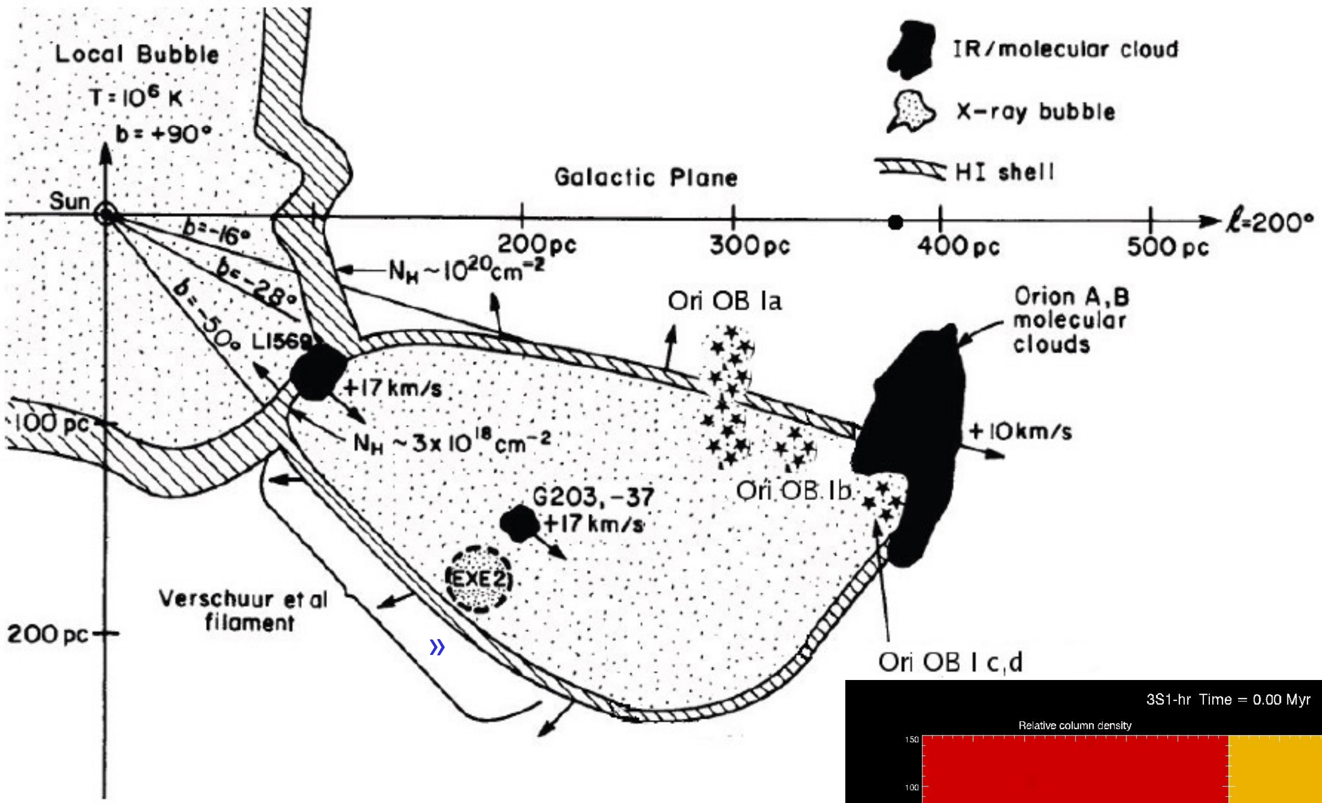
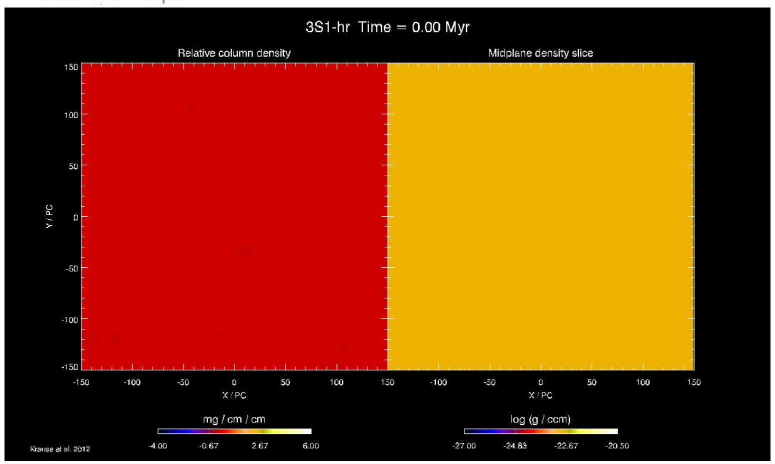


Illustration by M. Pleintinger (2020)

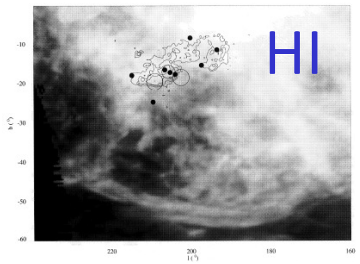
Orion-Eridanus: A superbubble blown by stars & supernovae

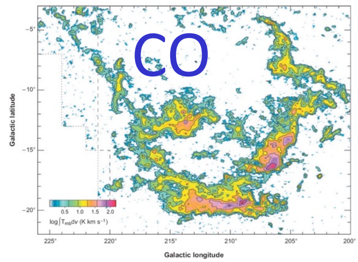
ISM is driven by stars and supernovae → Ejecta commonly in (super-)bubbles

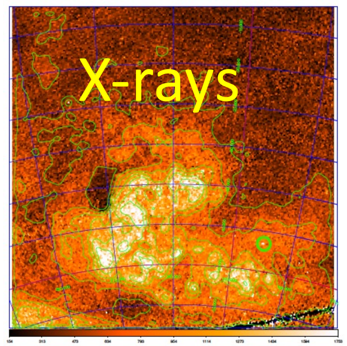


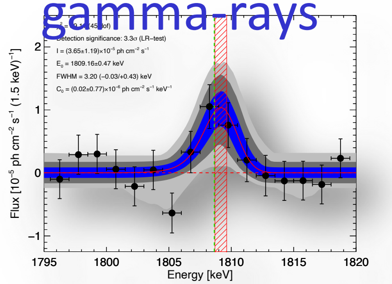


3D MHD sim, 0.1..0.005 pc resolution
Krause+ 2013ff





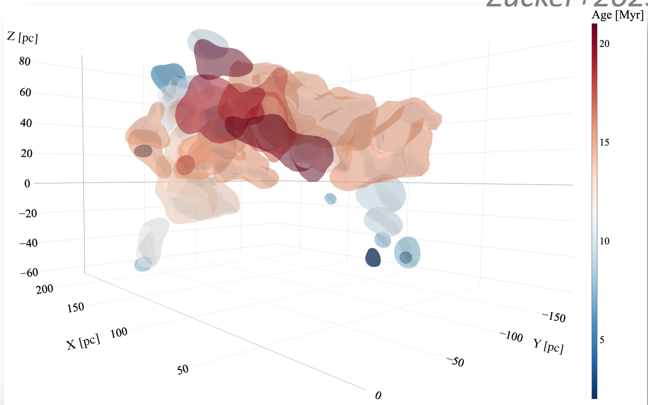




Krause+ 2014, Fierlinger+ 2016,
Voss+ 2010, Diehl+2003

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

Zucker+2023



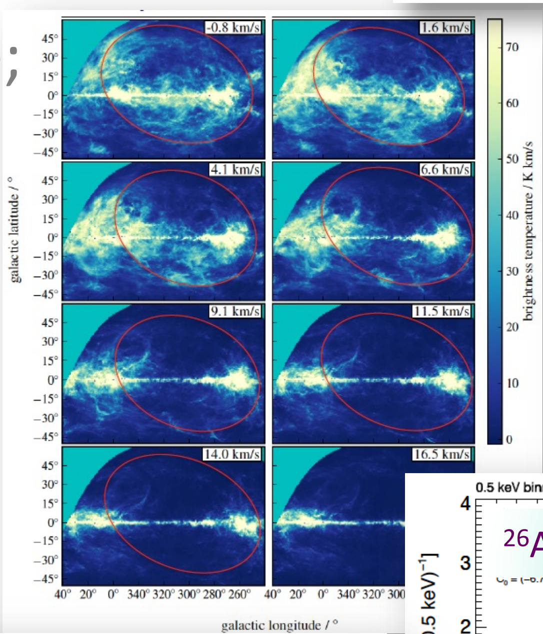
The stellar population covers a wide age range

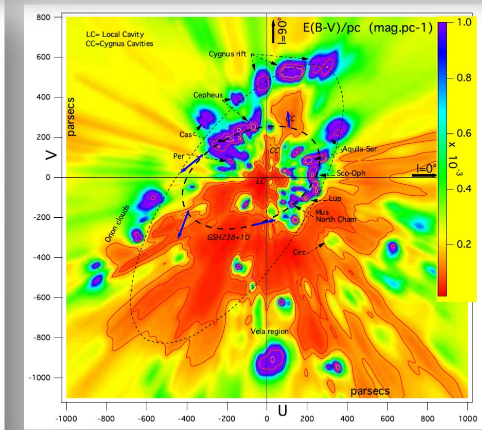
no clear coeval subgroups, SF ongoing for ~15+ My; distance~140pc)

The interstellar medium holds
a network of cavities

ISM dynamics is not easy to unravel

^{26}Al $_{(t\sim1My)}$ covers a large solid angle;
can we measure the flow?

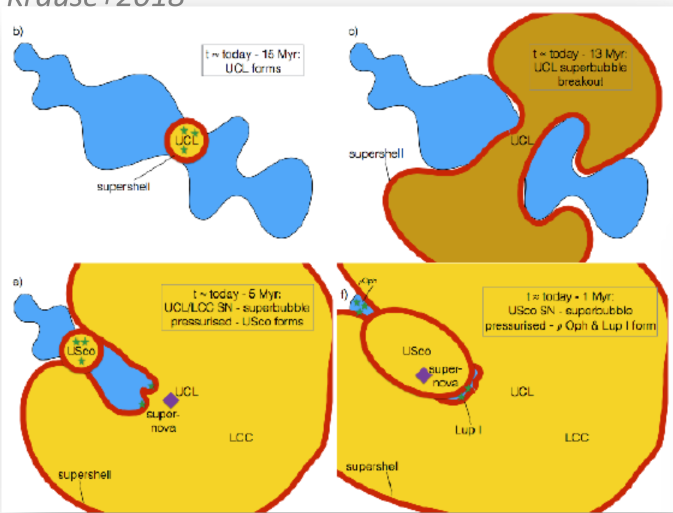


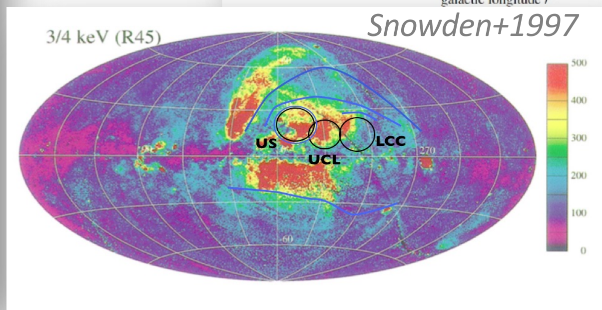


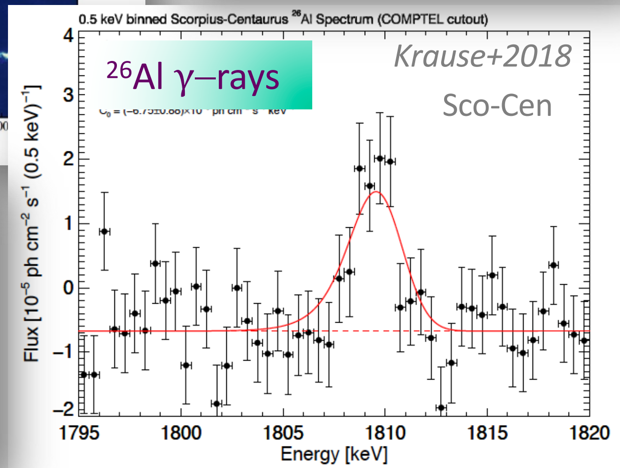
→ *"surround & squish"*

rather than "triggered" star formation

Krause+2018

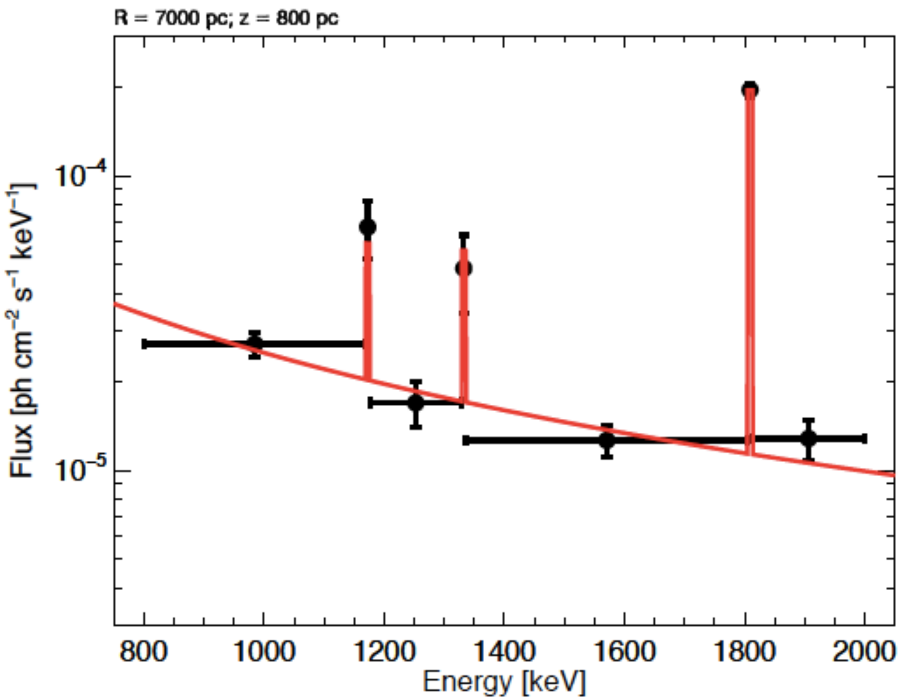






Diffuse gamma-ray emission from ^{60}Fe in the Galaxy

^{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

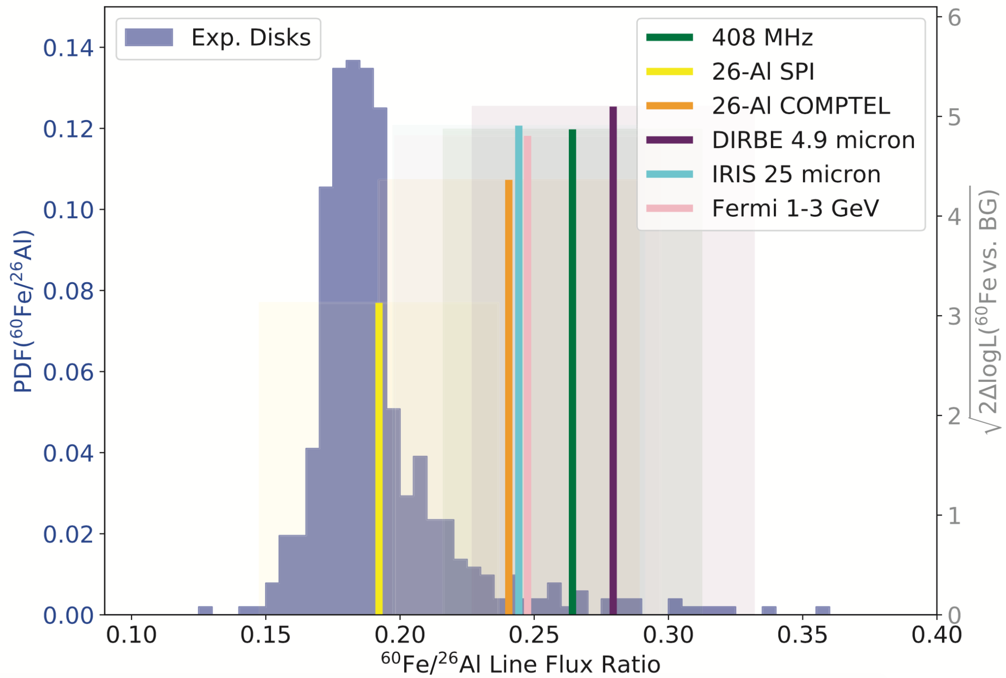
(systematics!)

➔ ^{60}Fe/^{26}Al < 0.4 in Galaxy

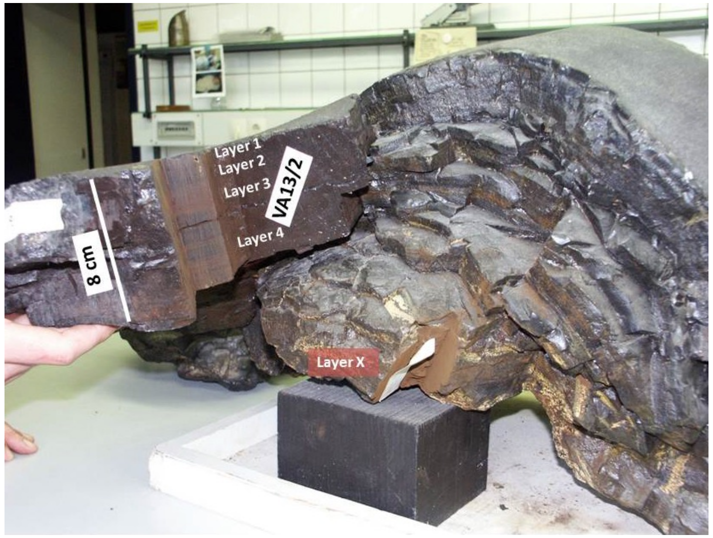
cmp theory: 0.2...1,

and oceancrusts: >0.2

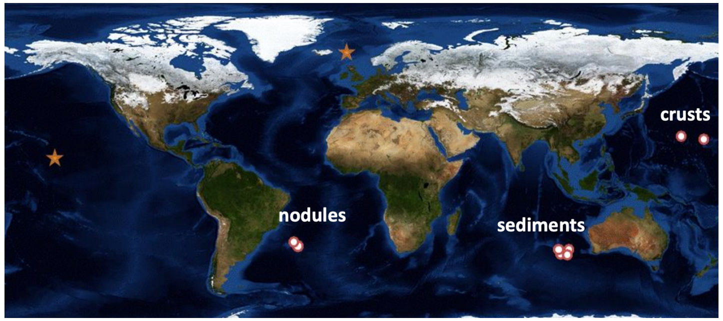
Wang+ 2020



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

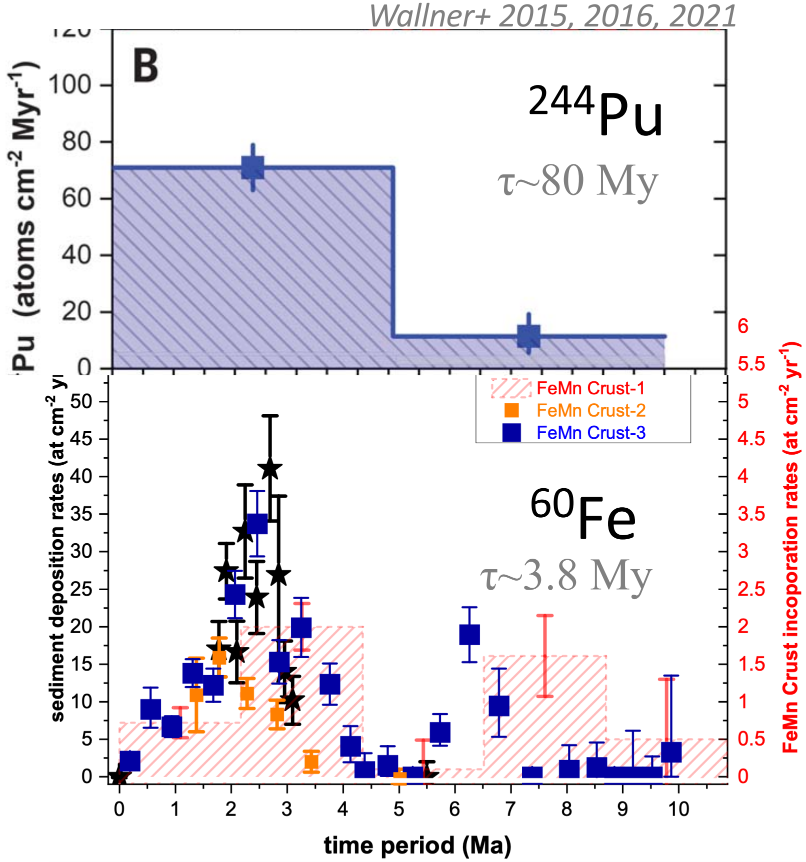


Knie+ 2004, Fimiani+ 2016, Ludwig+ 2016, Koll+ 2019, ….



+ lunar material probes; + antarctic snow

Wallner+ 2015, 2016, 2021



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

What are its sources?

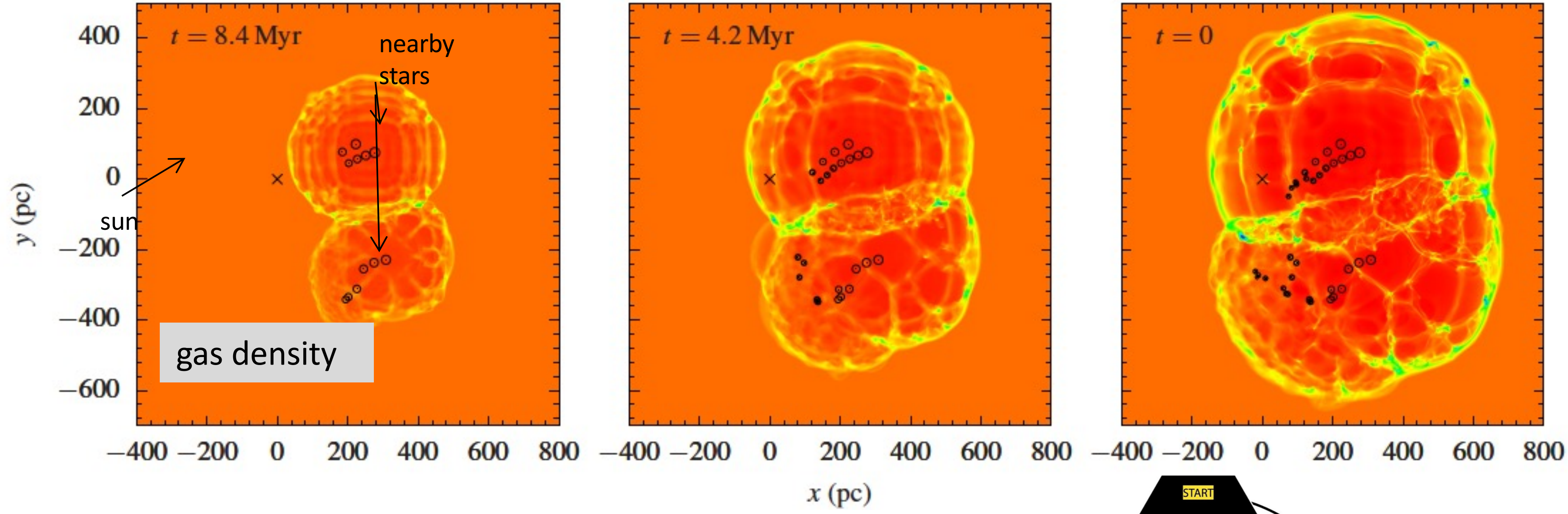
How did these traces of nucleosynthesis get here?

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

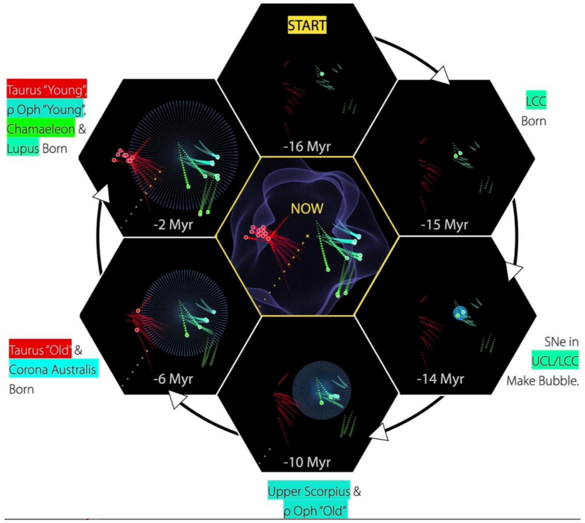
The Sun is (now) located inside a hot cavity (the "Local Bubble")

SN explosions within LB → ejecta flows reach the Solar System

Schulreich+ 2017



see also Zucker+ 2022
for a recent update on the Local Bubble and the Sco-Cen SN activity, confirming this local superbubble interpretation with dust cloud maps and Gaia data

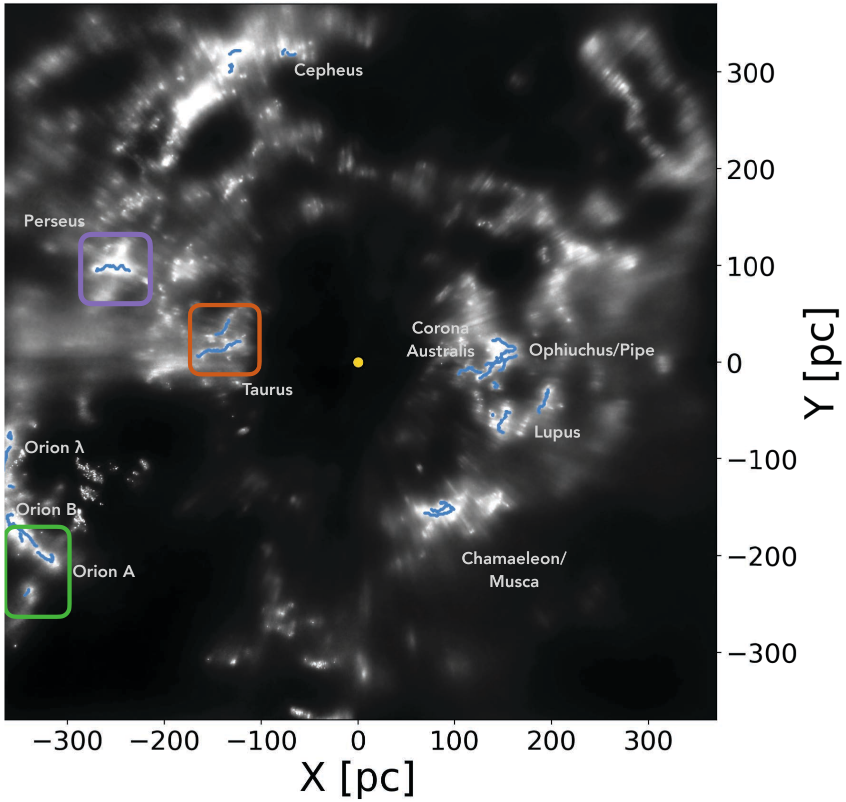


Recent nearby supernovae and the Local Bubble

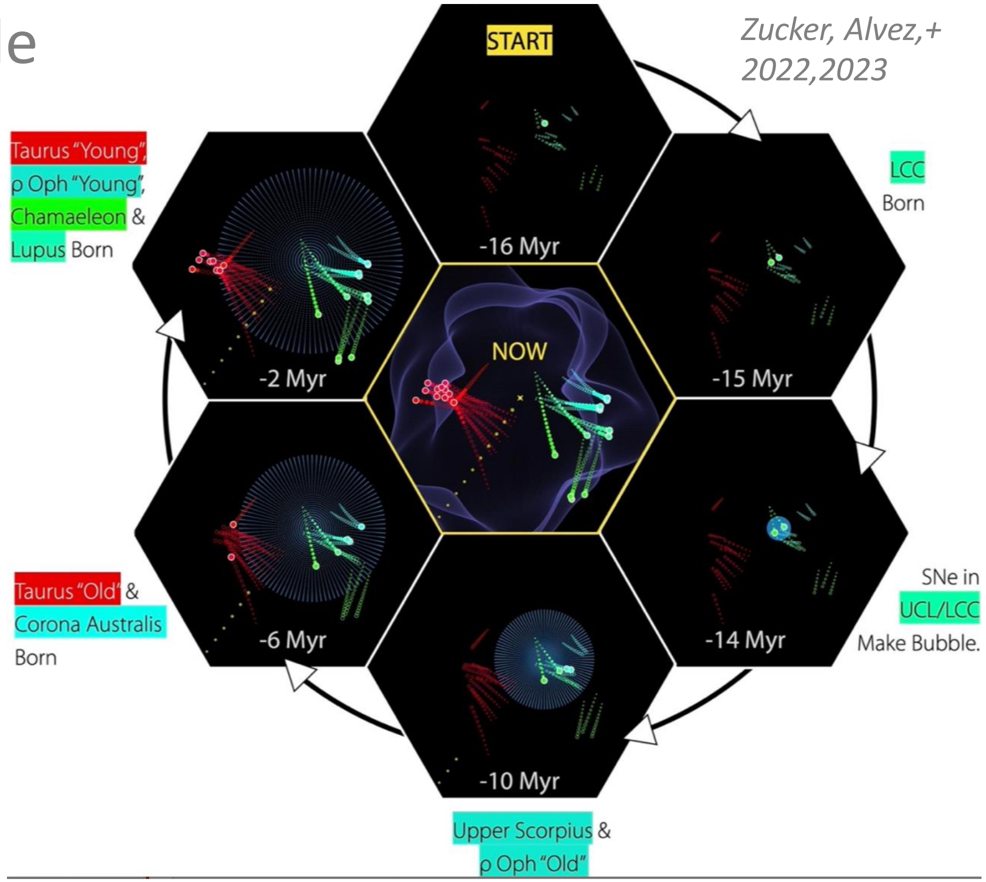
The Sun is (now) located inside a hot cavity (the "Local Bubble")

SN explosions created the Local Bubble

Sun entered Local Bubble ~10 My ago



Zucker, Alvez,+ 2022,2023

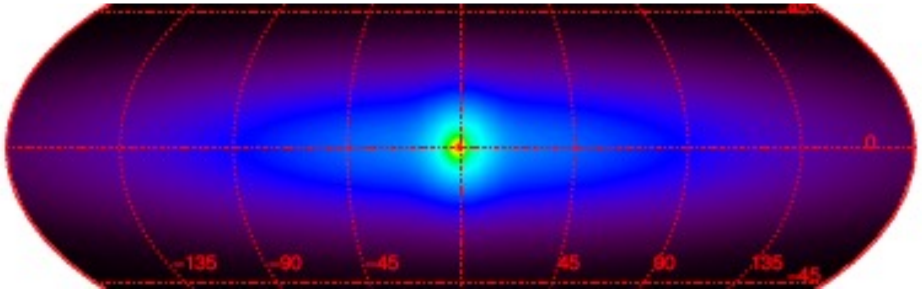


ISM dynamics and trajectory of the Sun lead to wall encounters

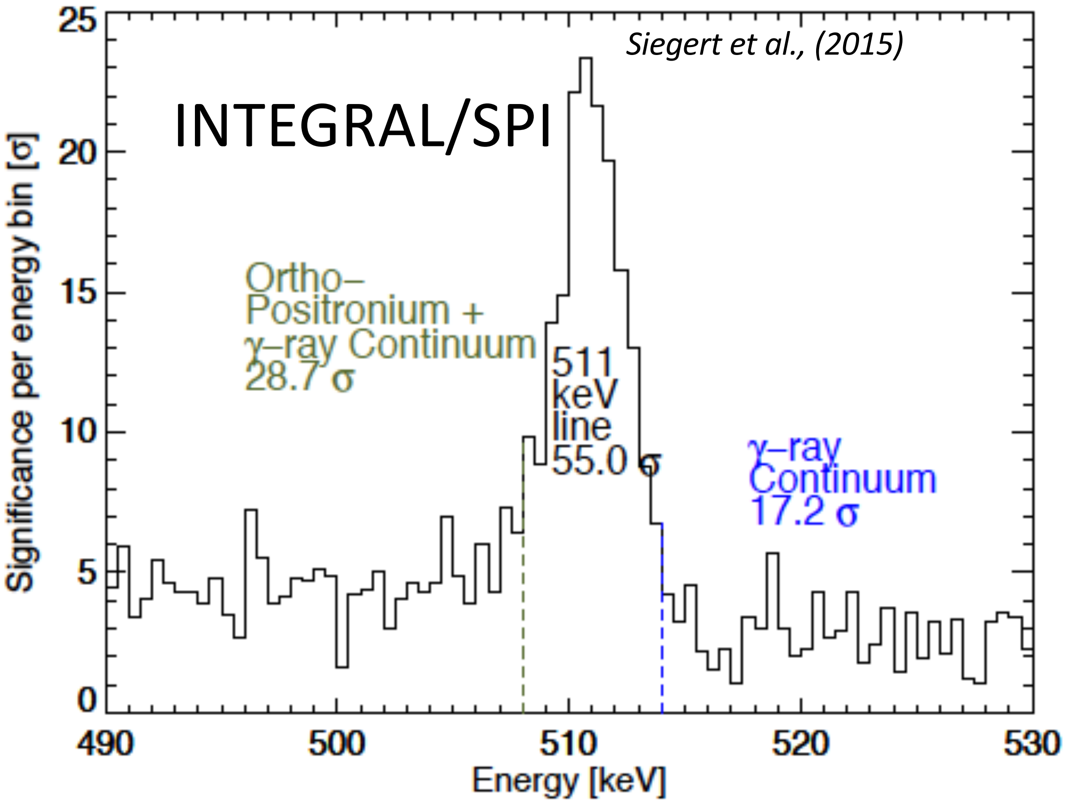
and heliosphere quenching from cloud encounters

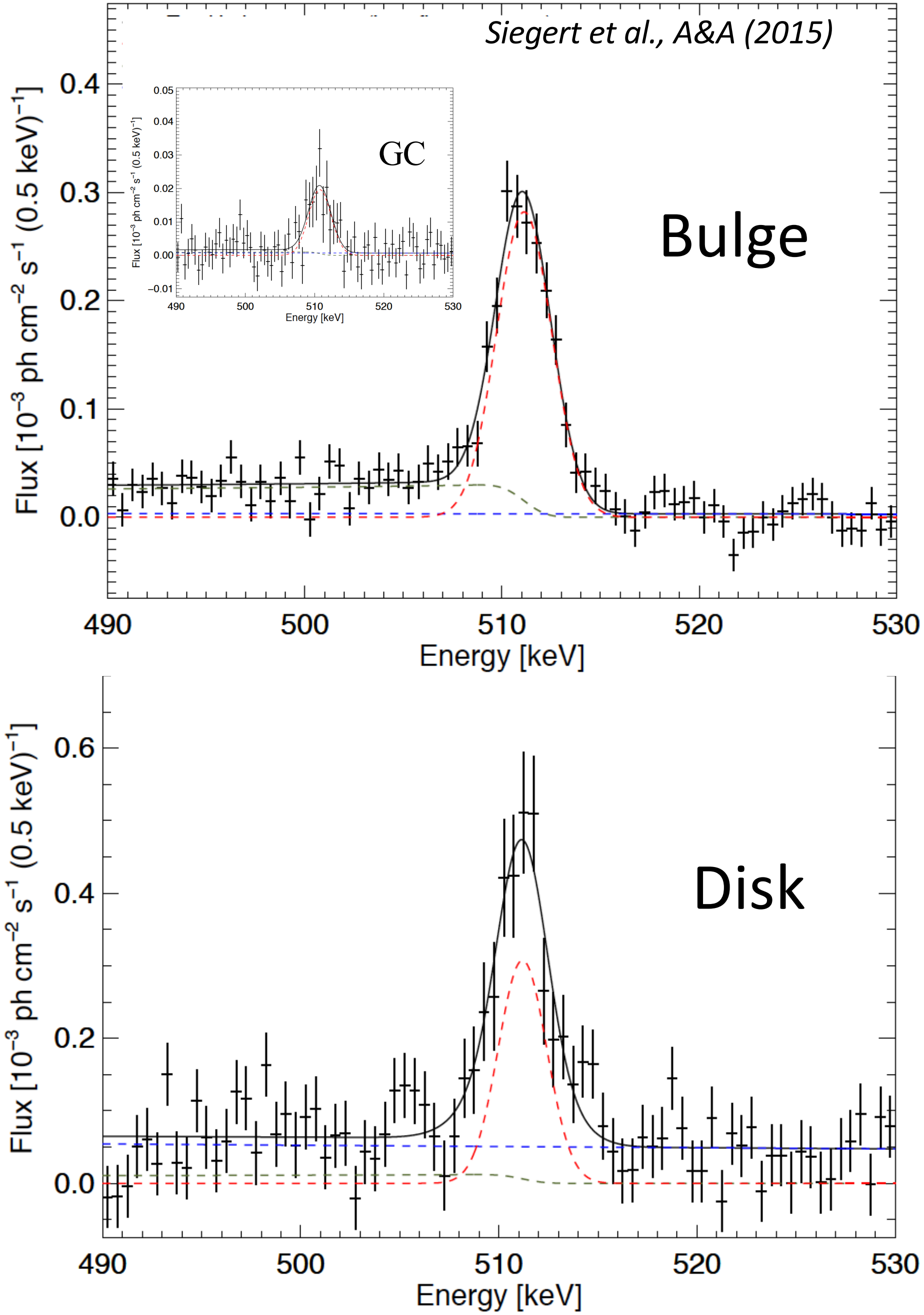
→ nucleosynthesis ejecta flows can reach the Solar System

Spectral details of positron annihilation line



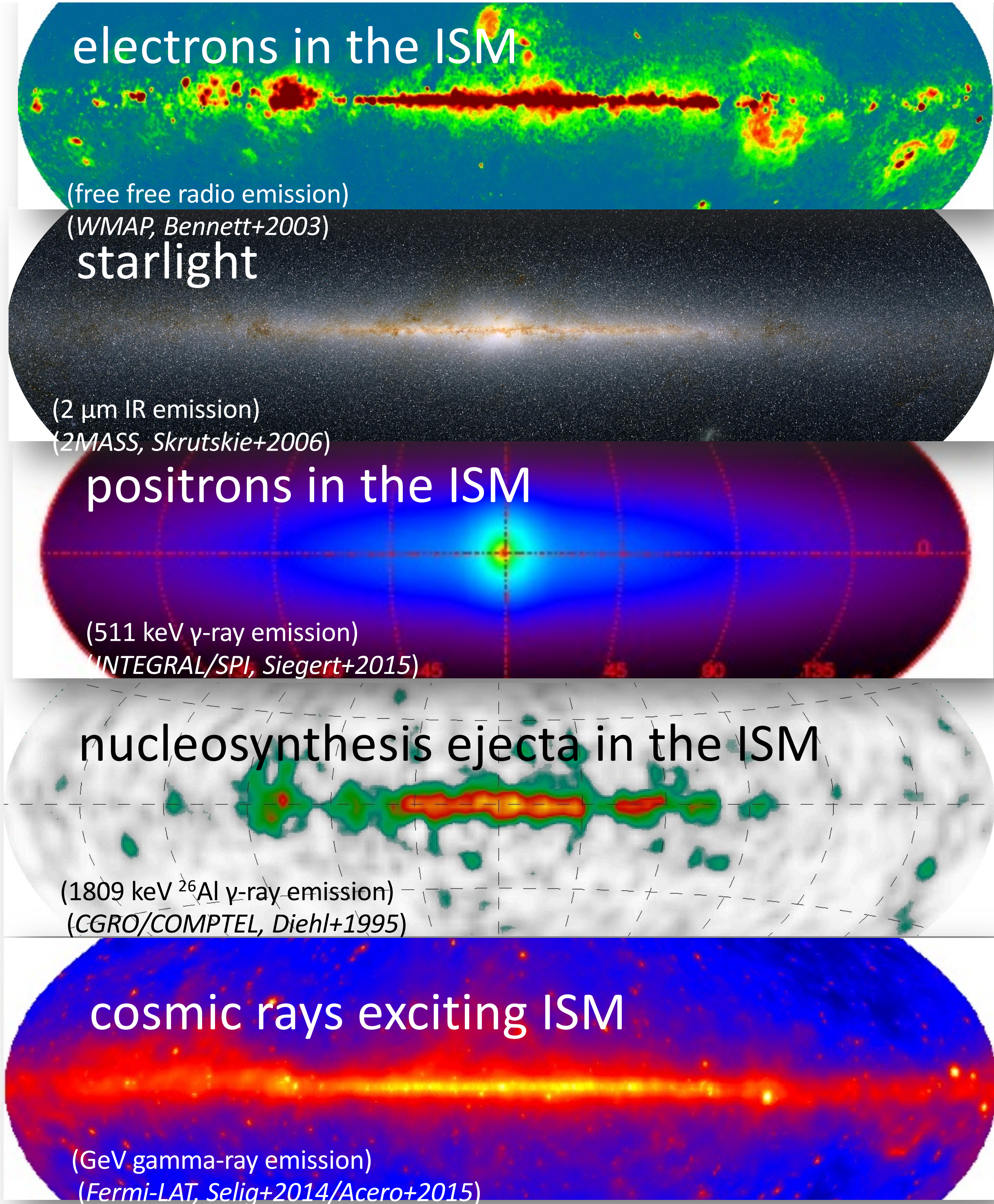
☆ Derive/discriminate spectra from different regions



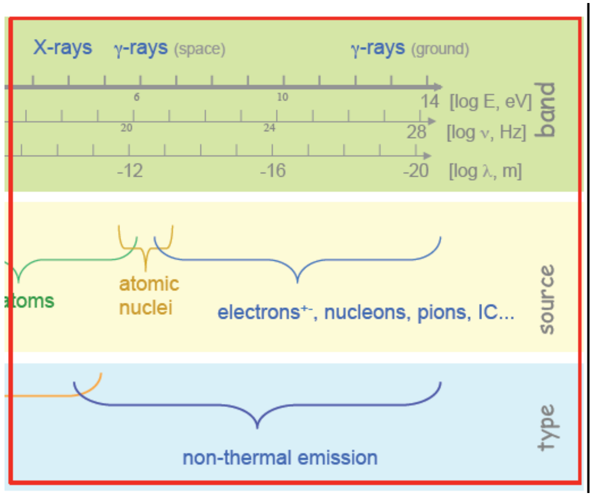


Galactic Messengers

- 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



Perspectives: New/better observations?

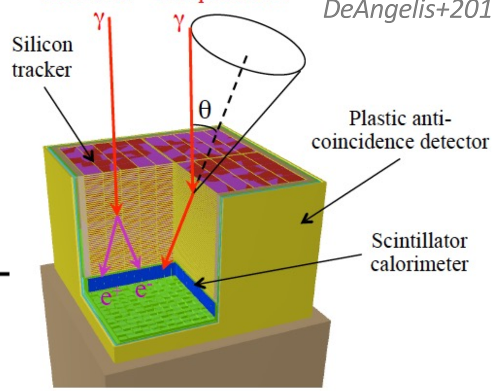


We can do now >one o.o.m. better now

Compton Telescope most promising

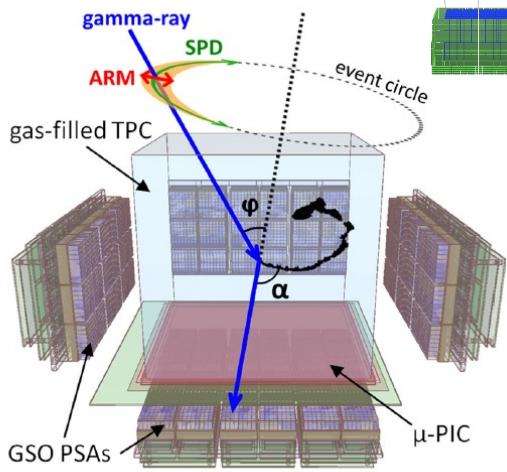
eAstrogam

DeAngelis+2017, 2018

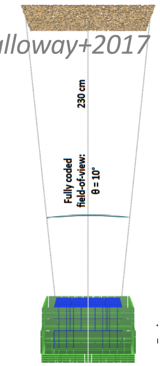


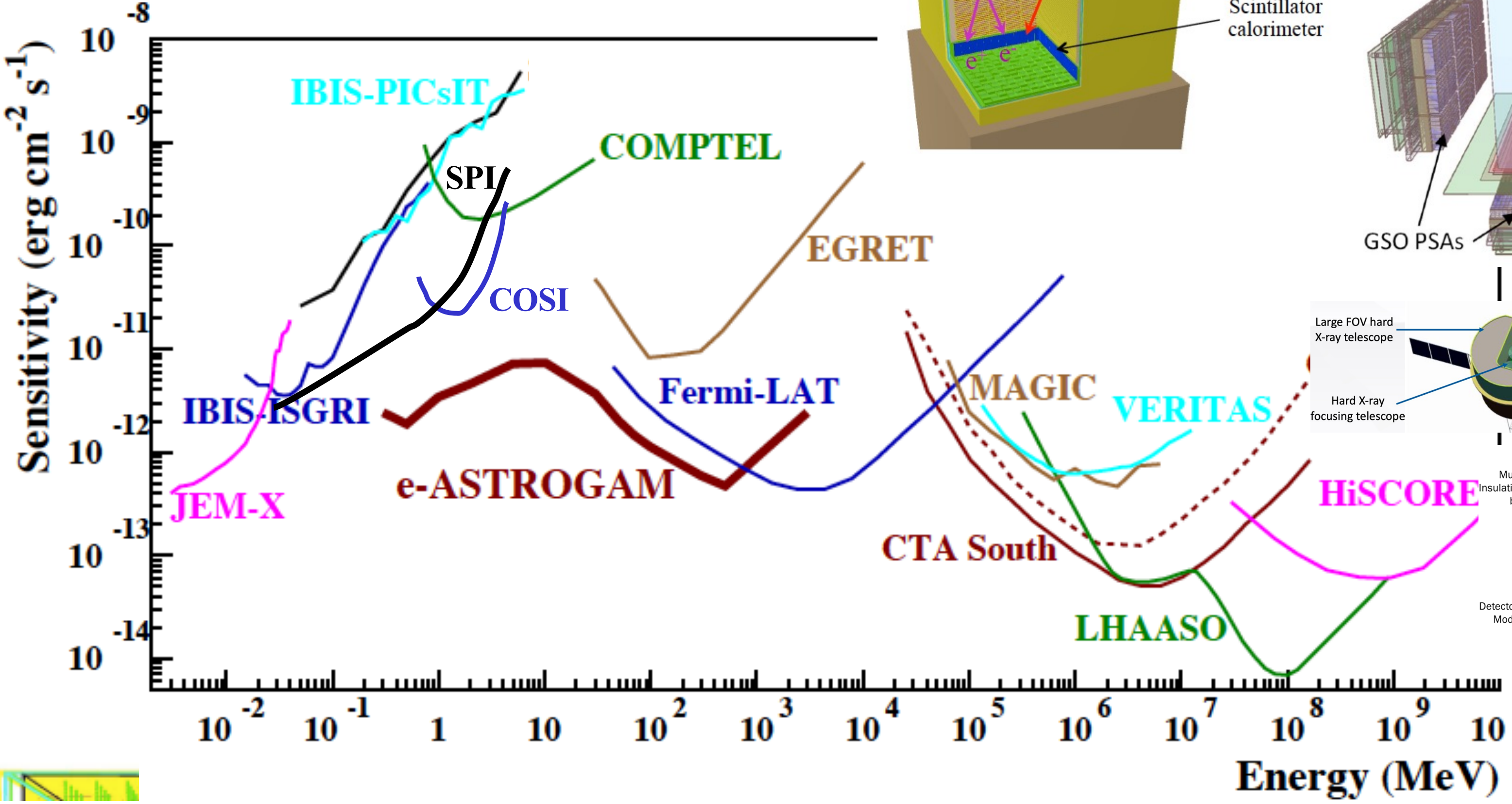
ETCC

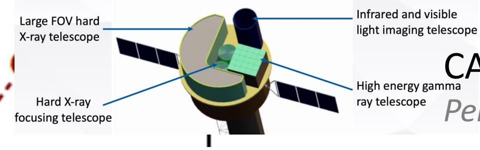
Tanimori+2015



Galloway+2017

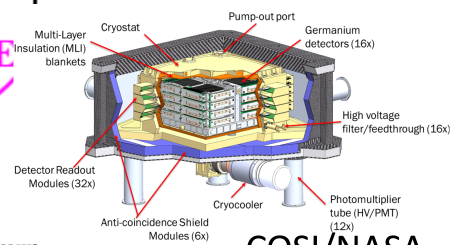






CAST/CNSA

Peng+2020



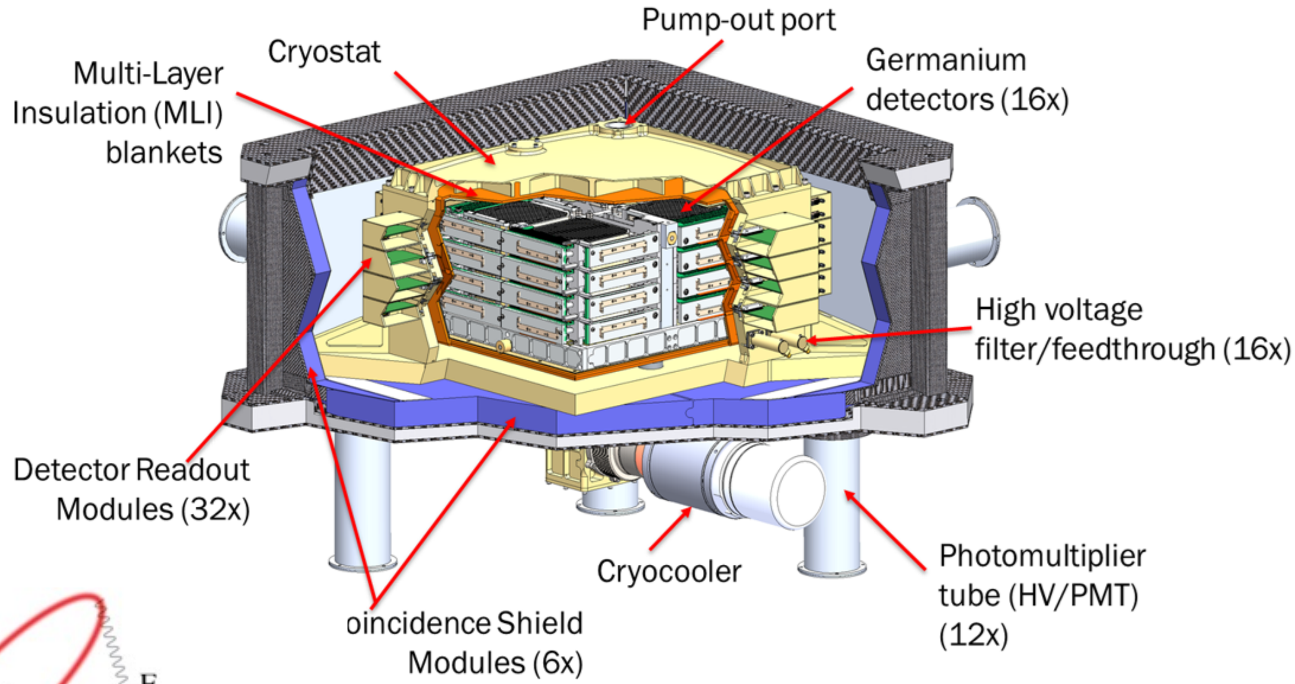
COSI/NASA

Tomsick+2021

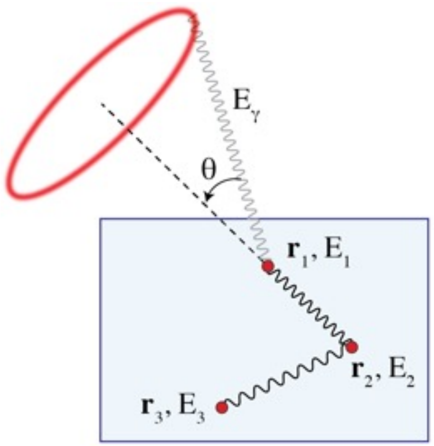
Compton Telescopes:
→ Compton Spectrometer and Imager (*COSI)*

Tomsick+ 2021

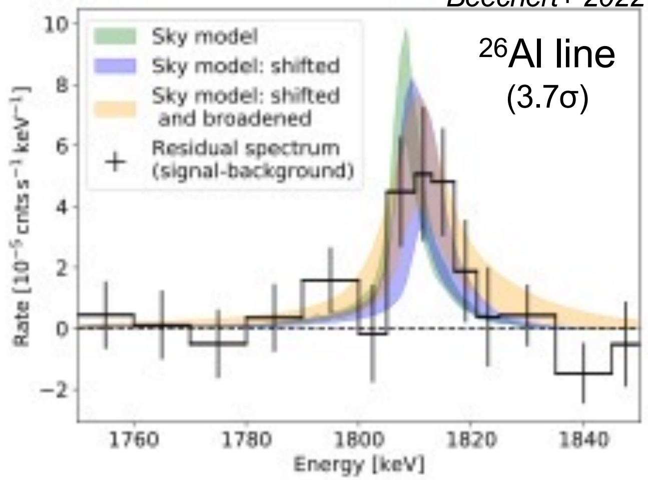
Ge detector based Compton Telescope



- ☆ 18 Ge detectors 8x8x1.5 cm (cross-stripped)
- ☆ BGO anticoincidence shield
- ☆ Measure multiple interactions within Ge detector array

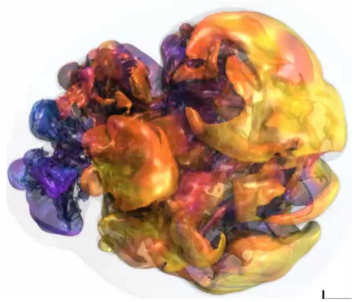


Beechert+ 2022

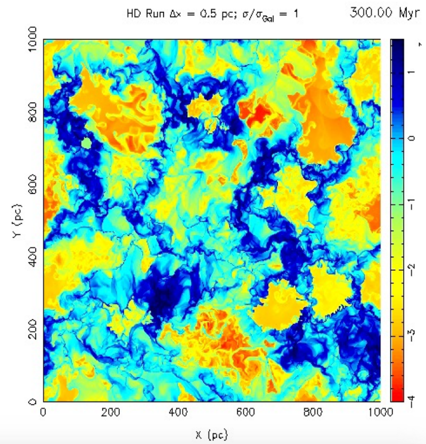


- ☆ COSI-APRA balloon flights 2005, 2009, 2014, 2016
  - ☞ detection of 511 keV and ^{26}Al lines
- ☆ COSI-SMEX Mission scheduled for 2026+
- ☆ Support in Germany by DLR, T. Siegert et al. U Würzburg

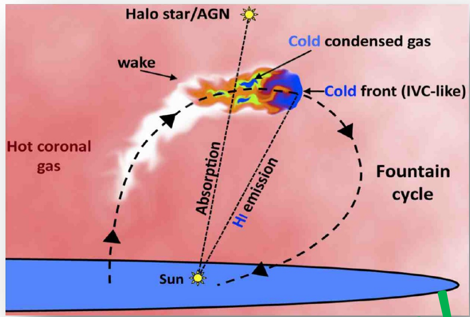
Learning from Gamma-Ray Spectroscopy - Summary



- ☆ Supernova explosions are not entirely spherically symmetric
  - ☞ ^{56}Ni and how it reveals its radiation in SN2014J
    → SN Ia diversity; sub-Chandra models?
  - ☞ ^{44}Ti image and line redshift in CasA; SN87A
    → ccSupernovae are fundamentally 3D/asymmetric



- ☆ Cycling of cosmic gas through sources and ISM is a challenge
  - ☞ ^{26}Al preferentially appears in superbubbles
    → massive-star ingestions rarely due to single WR stars or SNe
  - ☞ the current Galactic SN rate is ~1/70 years
  - ☞ ^{60}Fe is a SN/wind ejecta diagnostic (SBs older than for ^{26}Al)

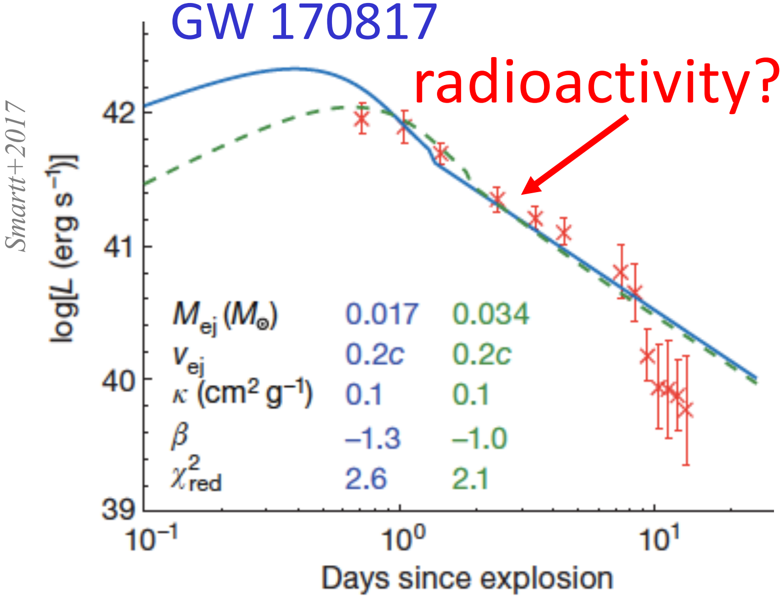


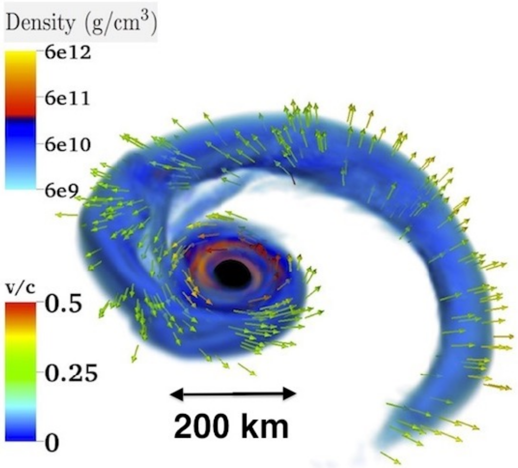
- ☆ Varied messengers complement each other with essential diagnostics
  - ☞ Radioactivity provides a unique and different view on cosmic isotopes (via gamma rays, stardust, CRs, sediments)
  - ☞ A next gamma-ray telescope (light-weight Compton telescope) in 2040+??; INTEGRAL ends 2029; COSI (2027) is a great first step ...

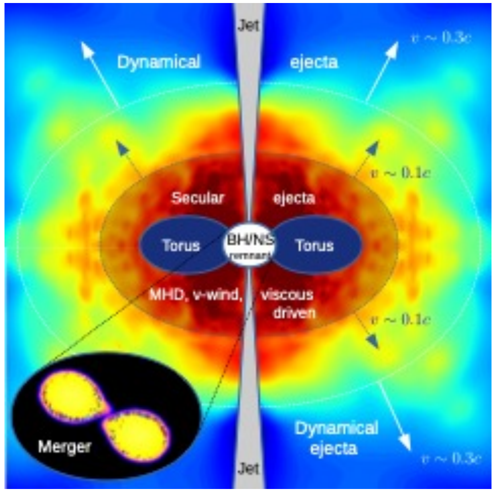
Thank you!

Neutron star collisions: explosive nucleosynthesis

The expected "kilonova" was seen
after a unique gravitational-wave signal
GW 170817

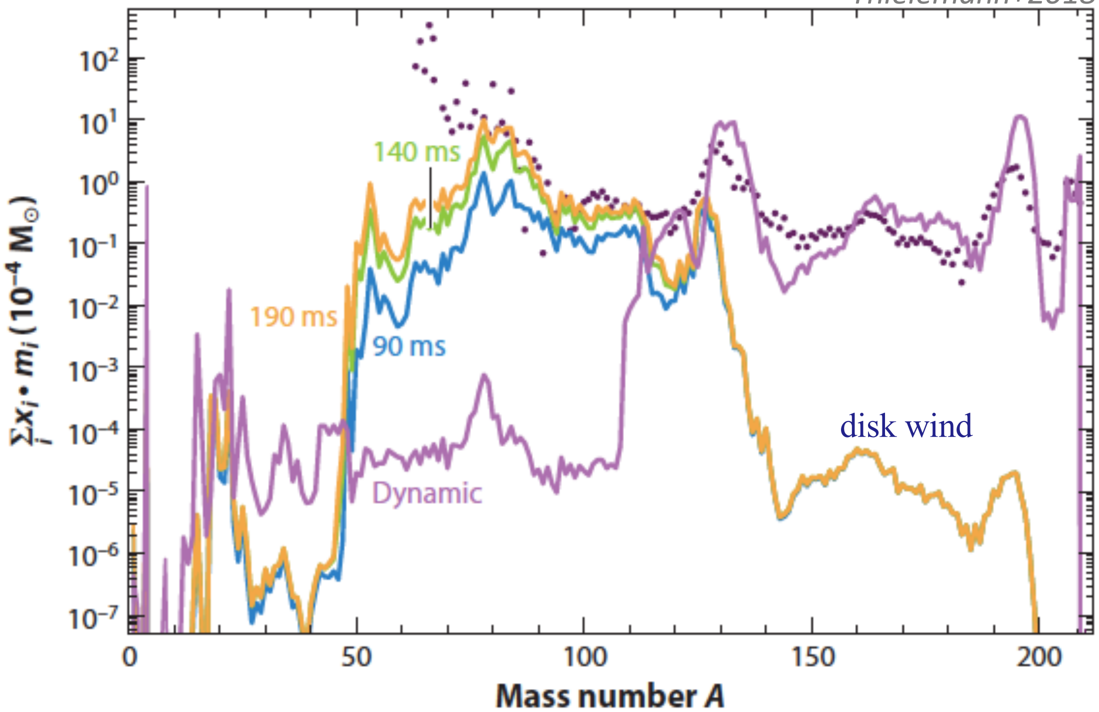






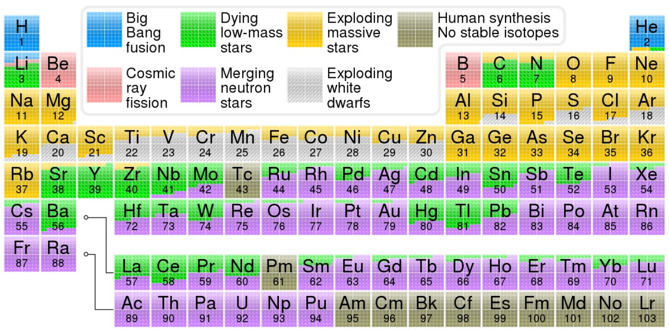
Elemental yields reminiscent of r-process pattern

Thielemann+2018



great enthusiasm...

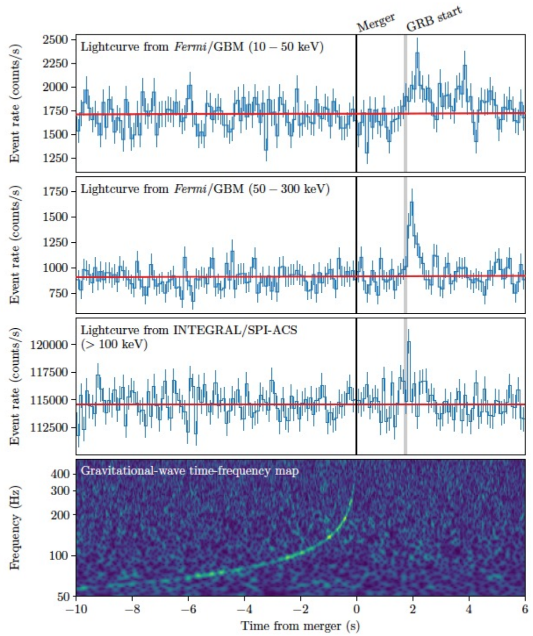
very
rare
events!

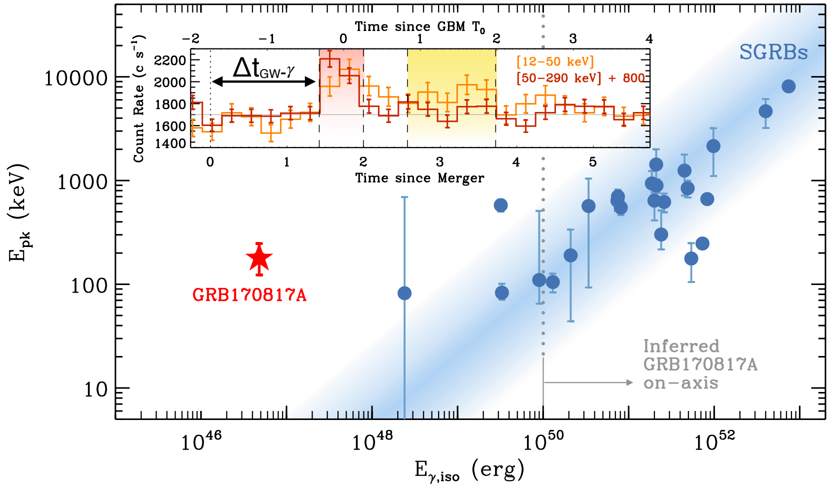


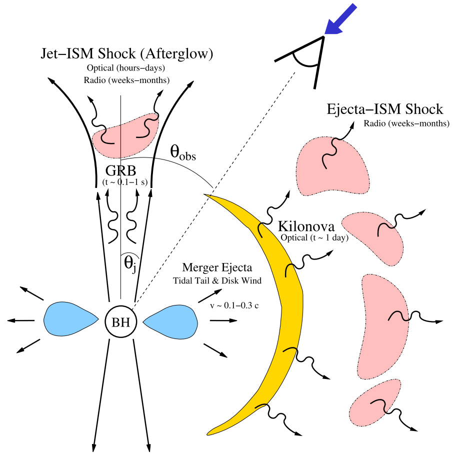
GW170817 / AT2017gfo

gravitational-wave & γ-ray burst triggered multi-band follow-up of NSM

Abbott+2017; Goldstein+2017; Savchenko+2017

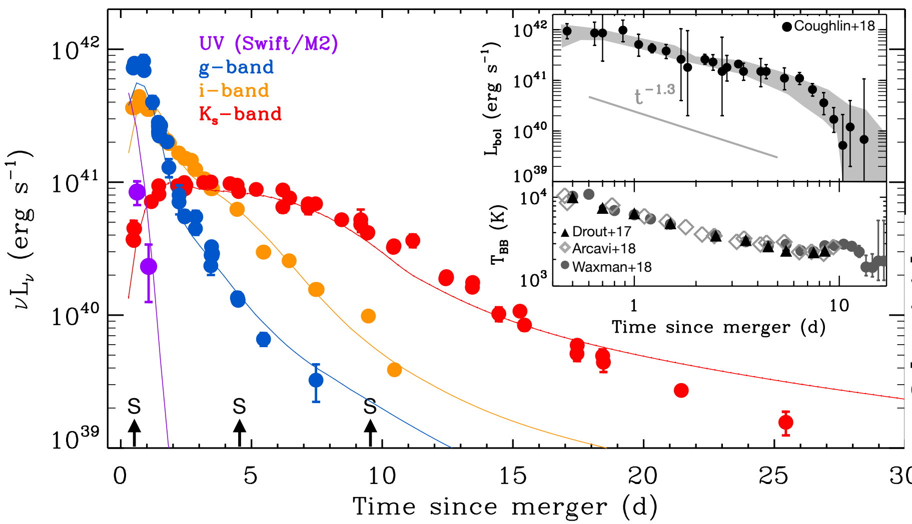






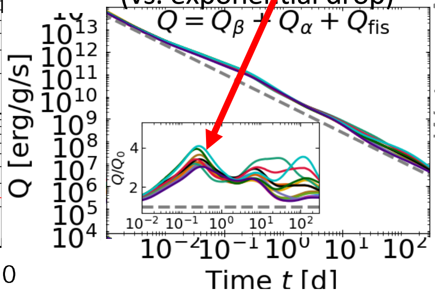
lucky coincidence: seeing a weak sGRB from a large aspect angle

Margutti+2021



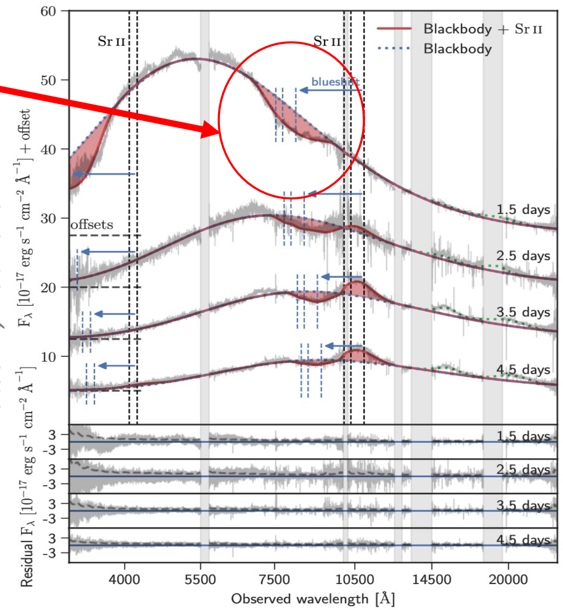
r process synthesis (Sr)?

radioactive heating (vs. exponential drop)



Kullmann+2022

Watson+, Nat 2019

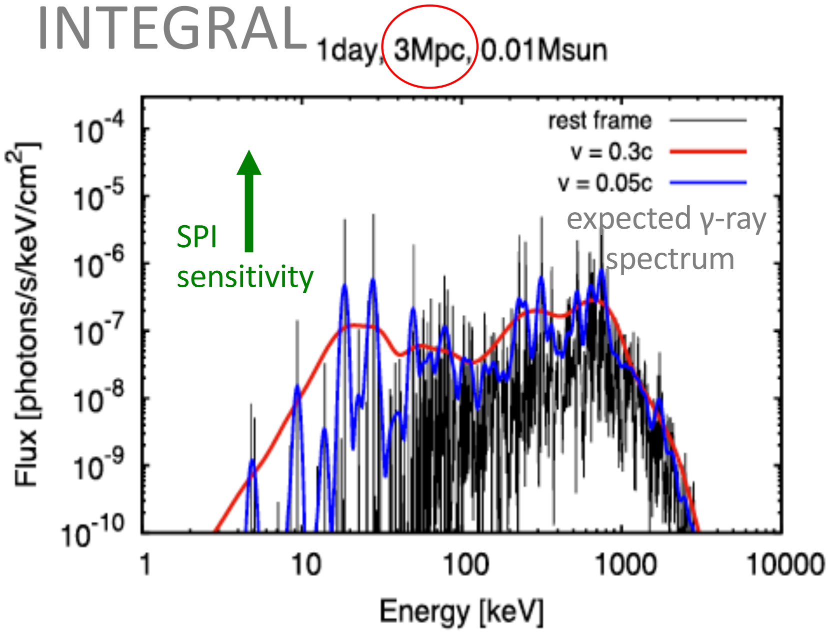


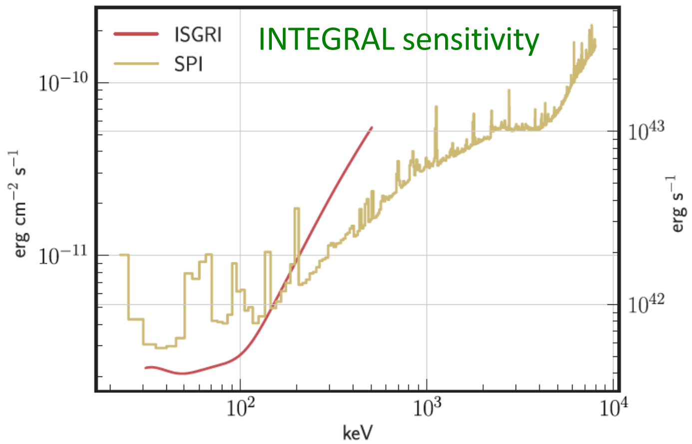
γ-ray line diagnostics of characteristic nuclear lines?

GW170817 was too distant! (other NSMs will be even more...)

Hotokezaka+ 2016

INTEGRAL





Savchenko et al. 2017

other instruments

Li+ 2018