Learning about cosmic nucleosynthesis from gamma-ray observations

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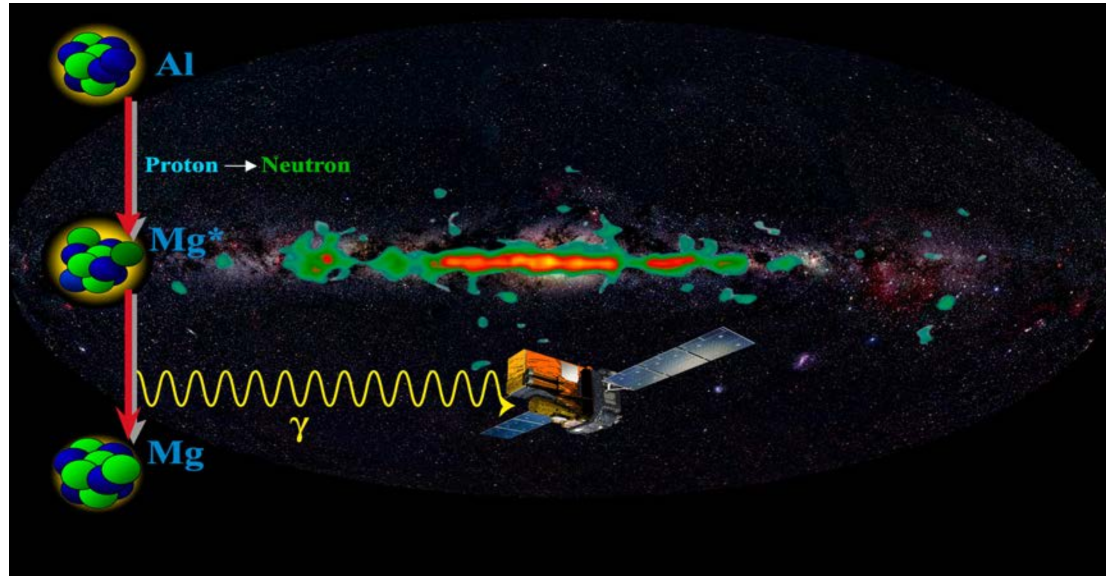
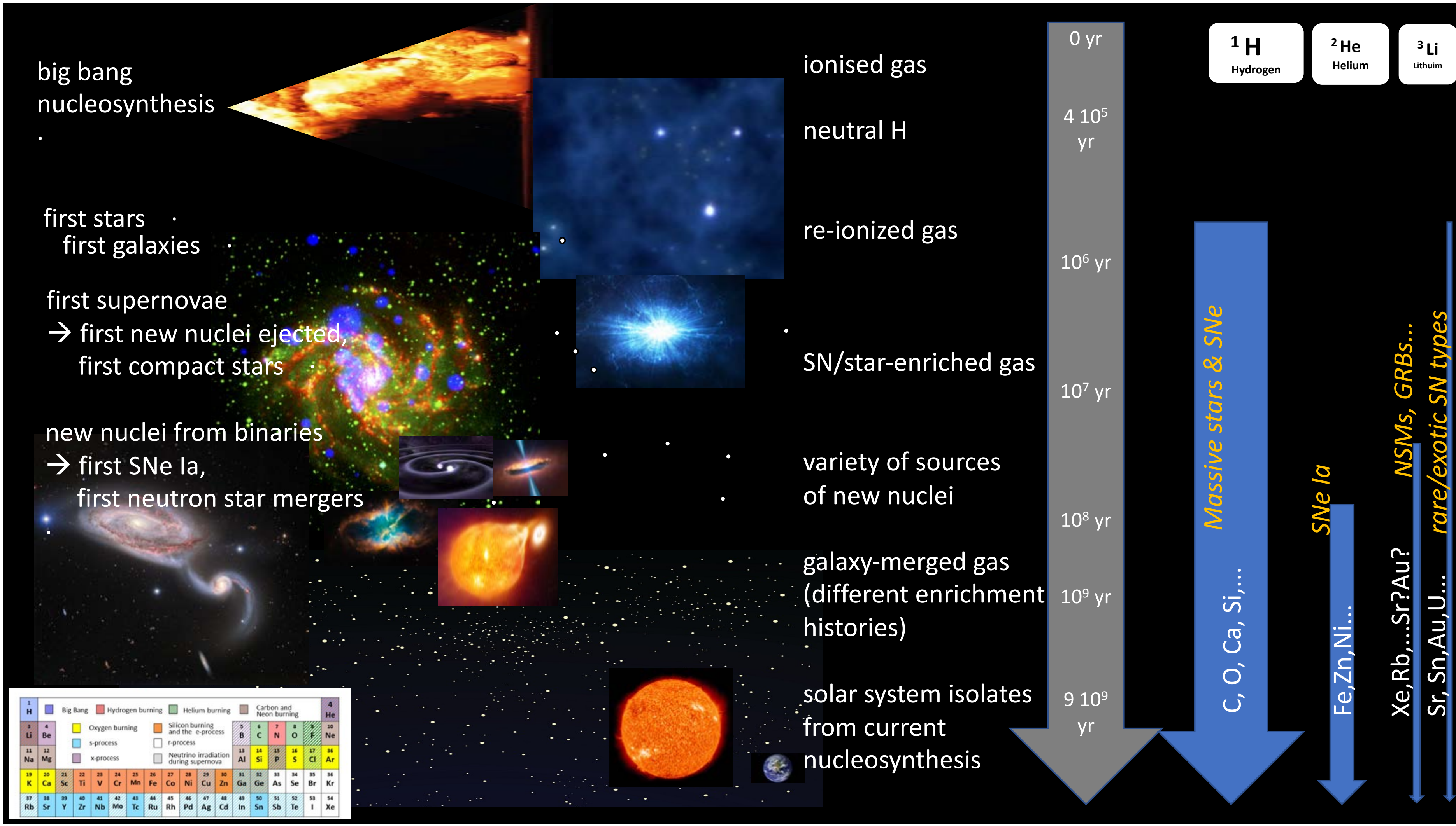
About measurements of cosmic γ-rays and their interpretations



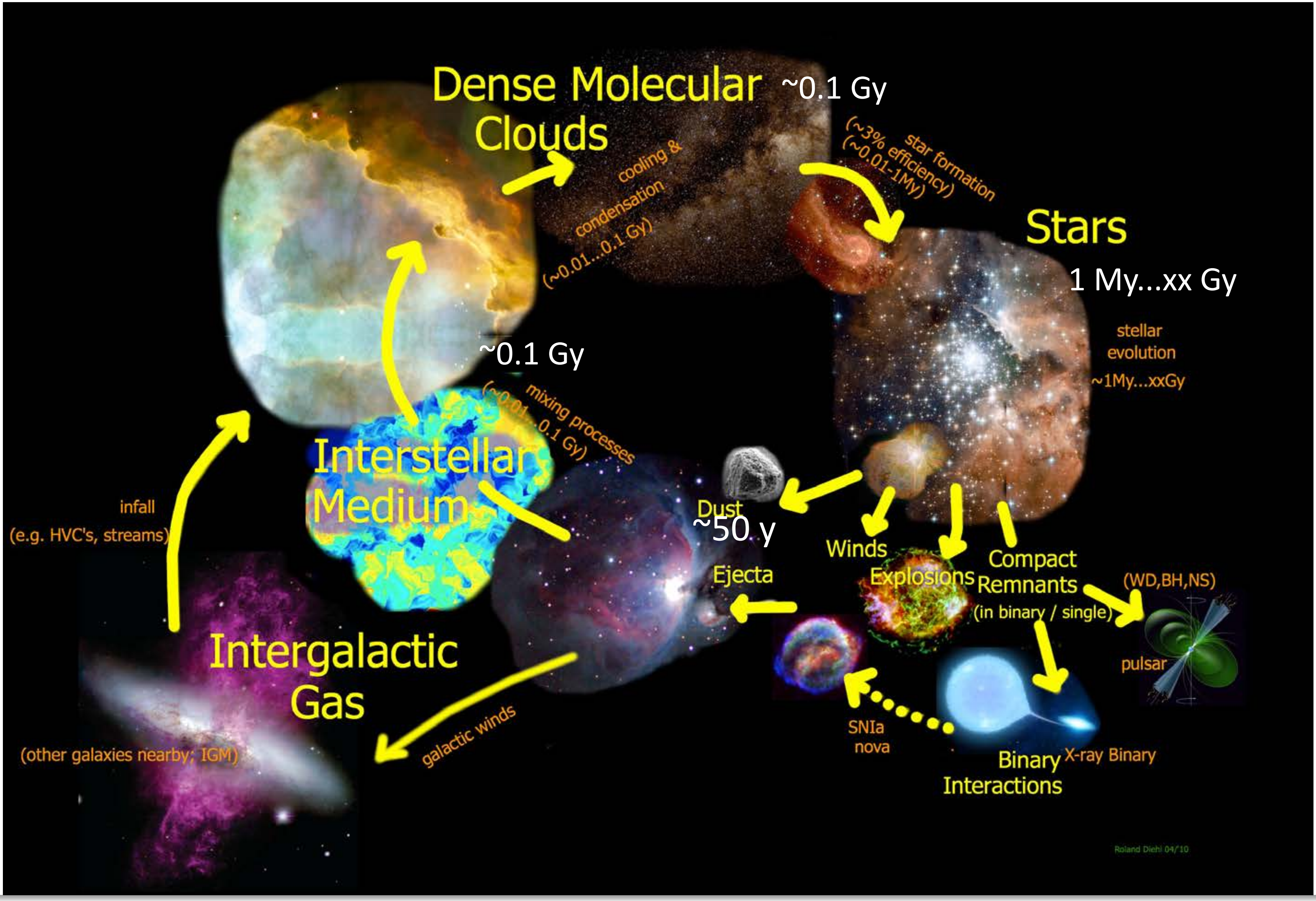
with work from (a.o.)
Martin Krause, Karsten Kretschmer, Moritz Pleintinger, Thomas Siegert, Rasmus Voss, Wei Wang, Christoph Weinberger

Contents:

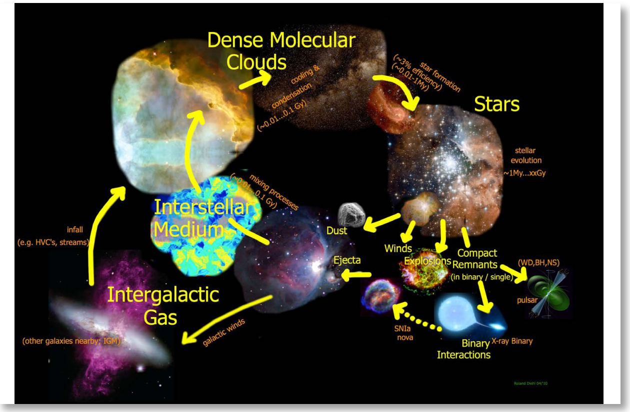
Atomic-nuclei composition evolving over the cosmic history

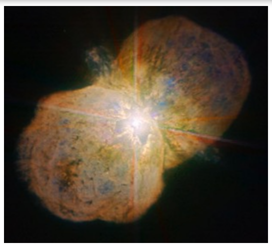


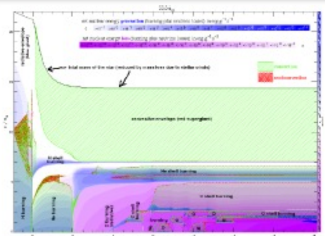
On-going Enrichments from Nucleosynthesis Sources

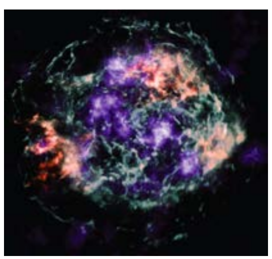


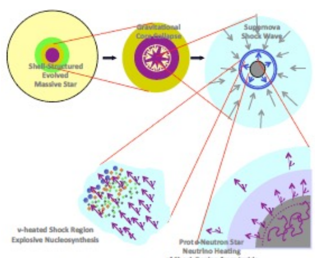
Modeling Compositional Evolution

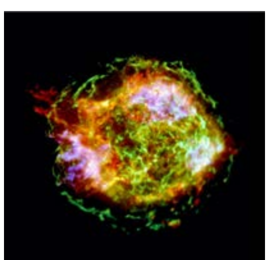


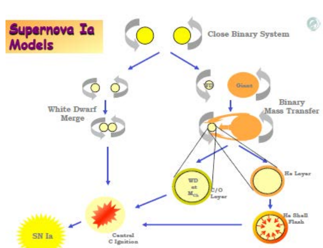












- Changes in the forms of cosmic matter:
  - stars and gas flows:

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

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

    $\Psi(t)$ is the Star Formation Rate (SFR) and $E(t)$ the *Rate of mass ejection*
  - gas which is ejected from stars: when?

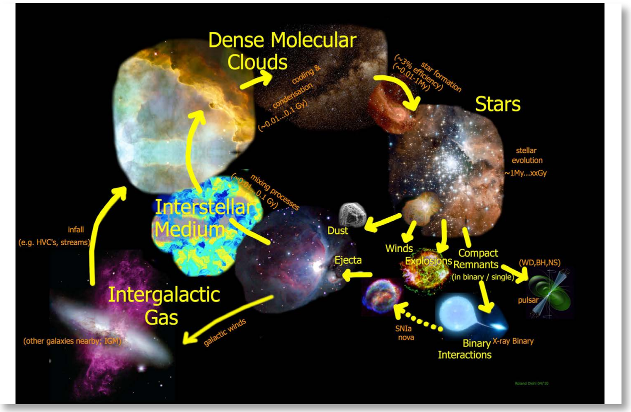
    $$E(t) = \int_{M_t}^{M_U} (M - C_M)\, \Psi(t - \tau_M)\, \Phi(M)\, dM$$
  - newly-contributed ashes from nucleosynthesis: what?

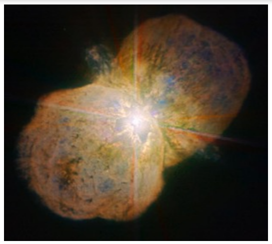
    The *mass of element/isotope* i in the gas is $m_i = m_G X_i$

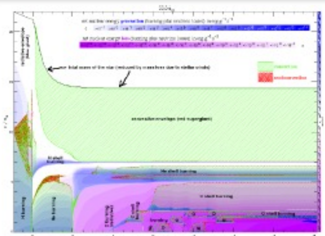
    $$\frac{d(m_G\, X_i)}{dt} = -\Psi X_i + E_i + [\, f X_{i,f} - o X_{i,o} \,]$$

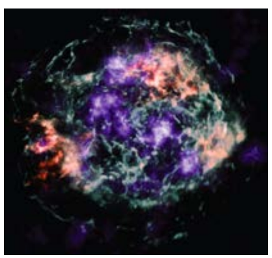
    $$E_i(t) = \int_{M_t}^{M_U} Y_i(M)\, \Psi(t - \tau_M)\, \Phi(M)\, dM$$

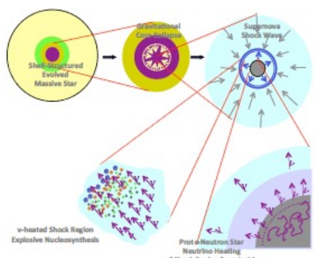
Modeling Compositional Evolution

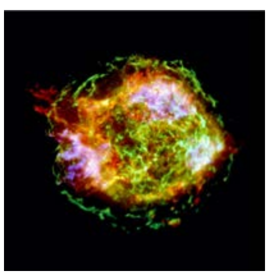


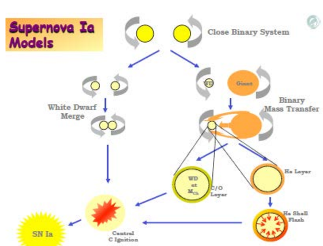












☆ Changes in the forms of cosmic matter:

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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)?

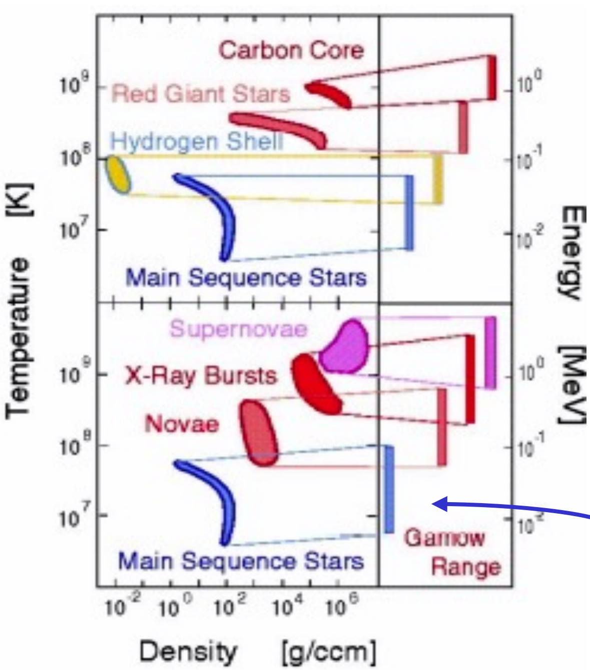
$Y_i(M)$ the mass ejected in the form of that element by the star of mass M

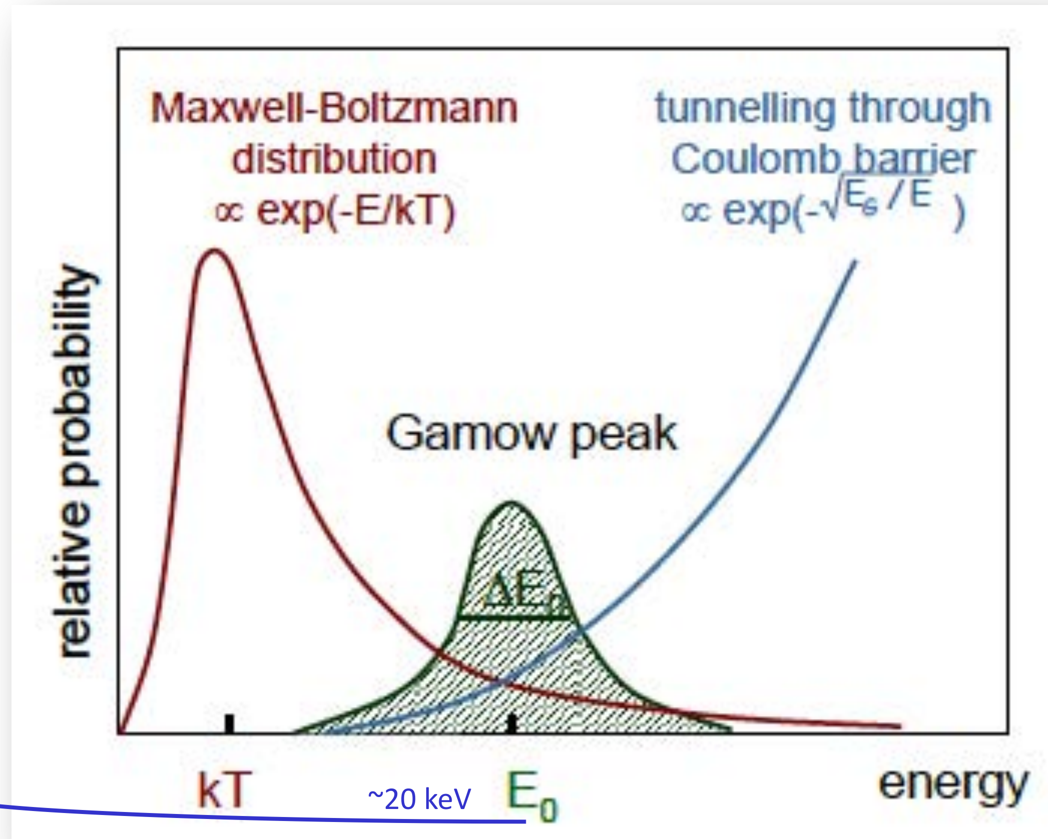
- ... (locations and environments of star formation, gas flows, ...)

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

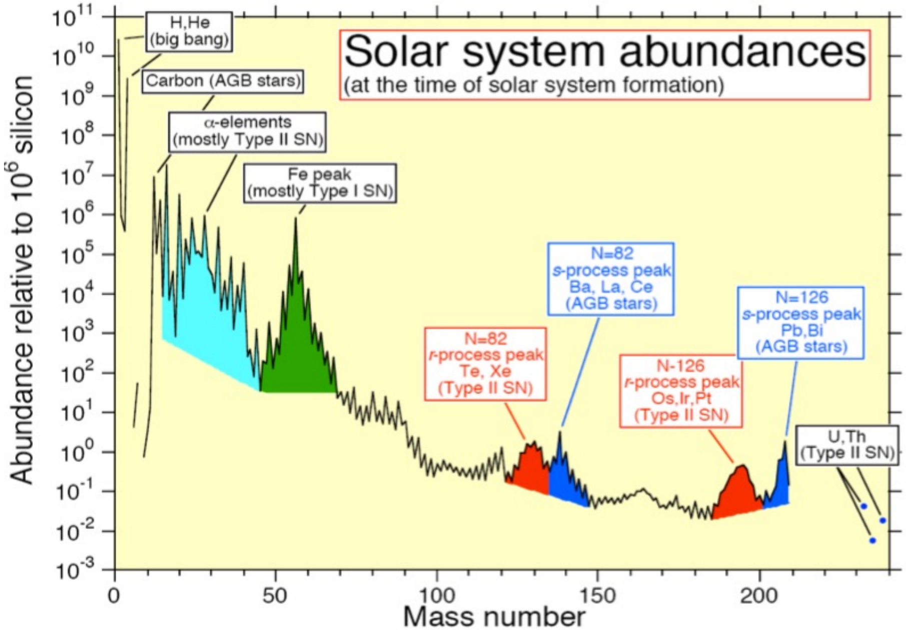




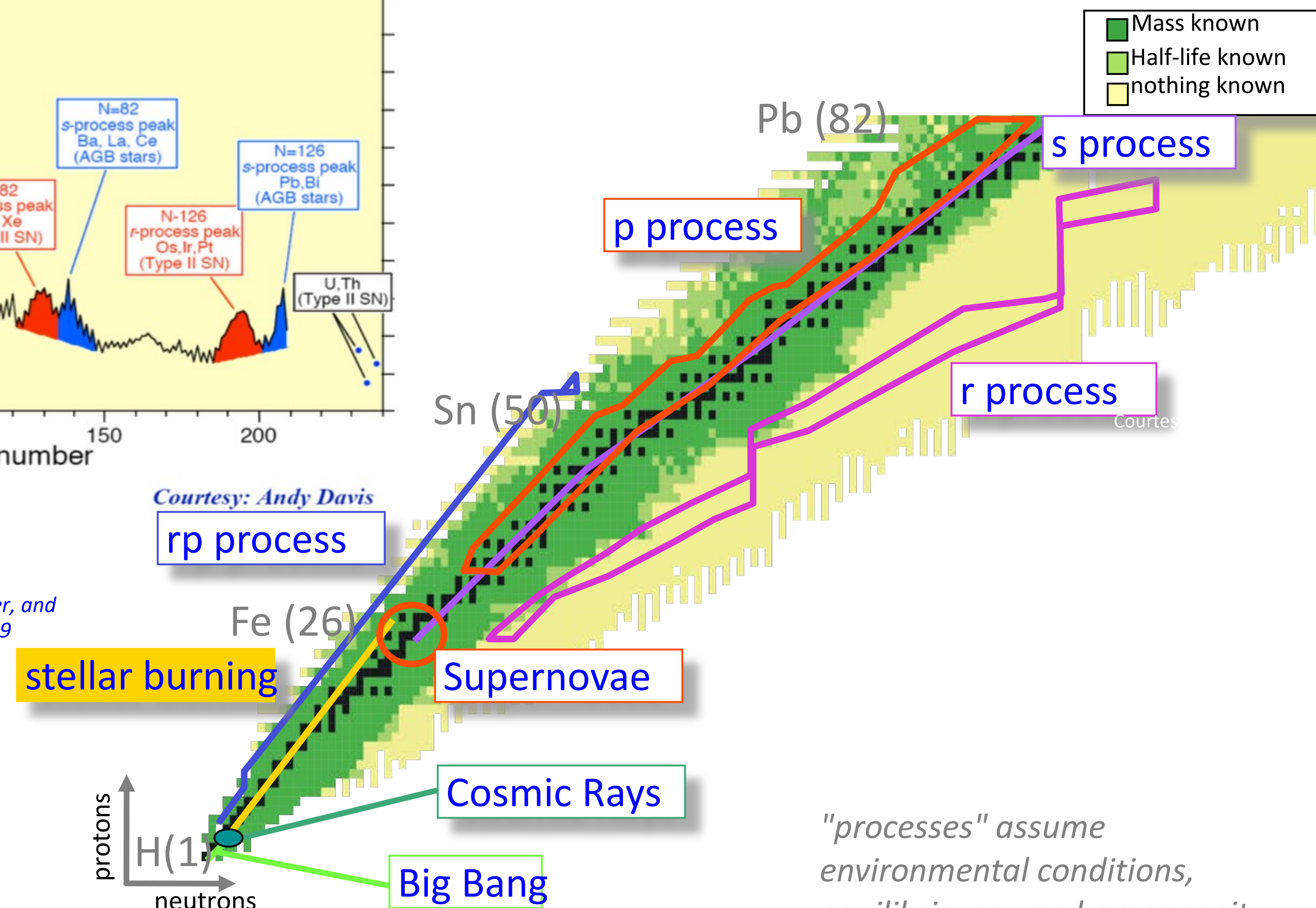
Cosmic origins of the variety of nuclides

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

  … and know is superficial (or even wrong)



Courtesy: Andy Davis

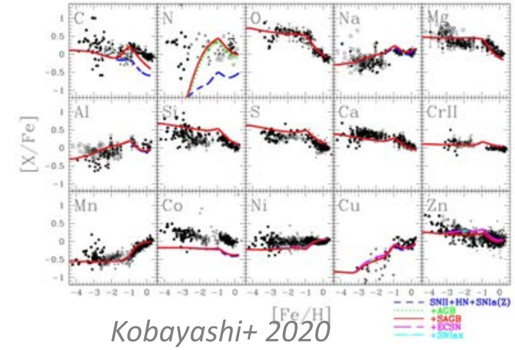


cmp. Burbidge, Burbidge, Fowler, and Hoyle, RMP 1959

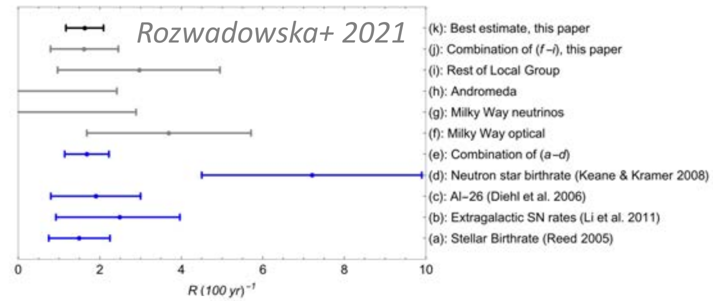
"processes" assume environmental conditions, equilibria, source homogeneity, ...

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

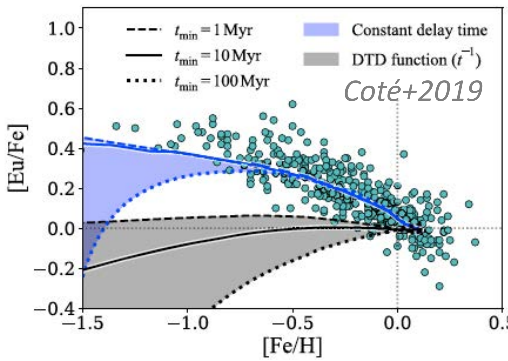
- ☆ model description fails for several elements
  - even for elements from same source type...
- ☆ inconsistencies with modeled vs observed nucleosynthesis event rates
  - ~350 radio+X SNR (~10000y) vs. ccSN rate 1/70y
- ☆ unclear impacts from rare sources with rich specific contributions
  - neutron star mergers?
  - jet supernovae?
  - hypernovae?
- ☆ mixing with stars & gas from galaxy collisions in the past
- ☆ early evolution: very massive stars & ccSNe
- ☆ but also something else (binaries!)...



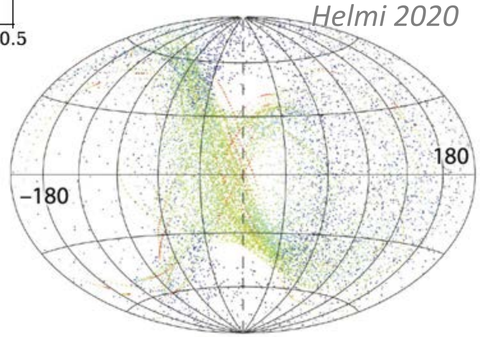
Kobayashi+ 2020



Rozwadowska+ 2021

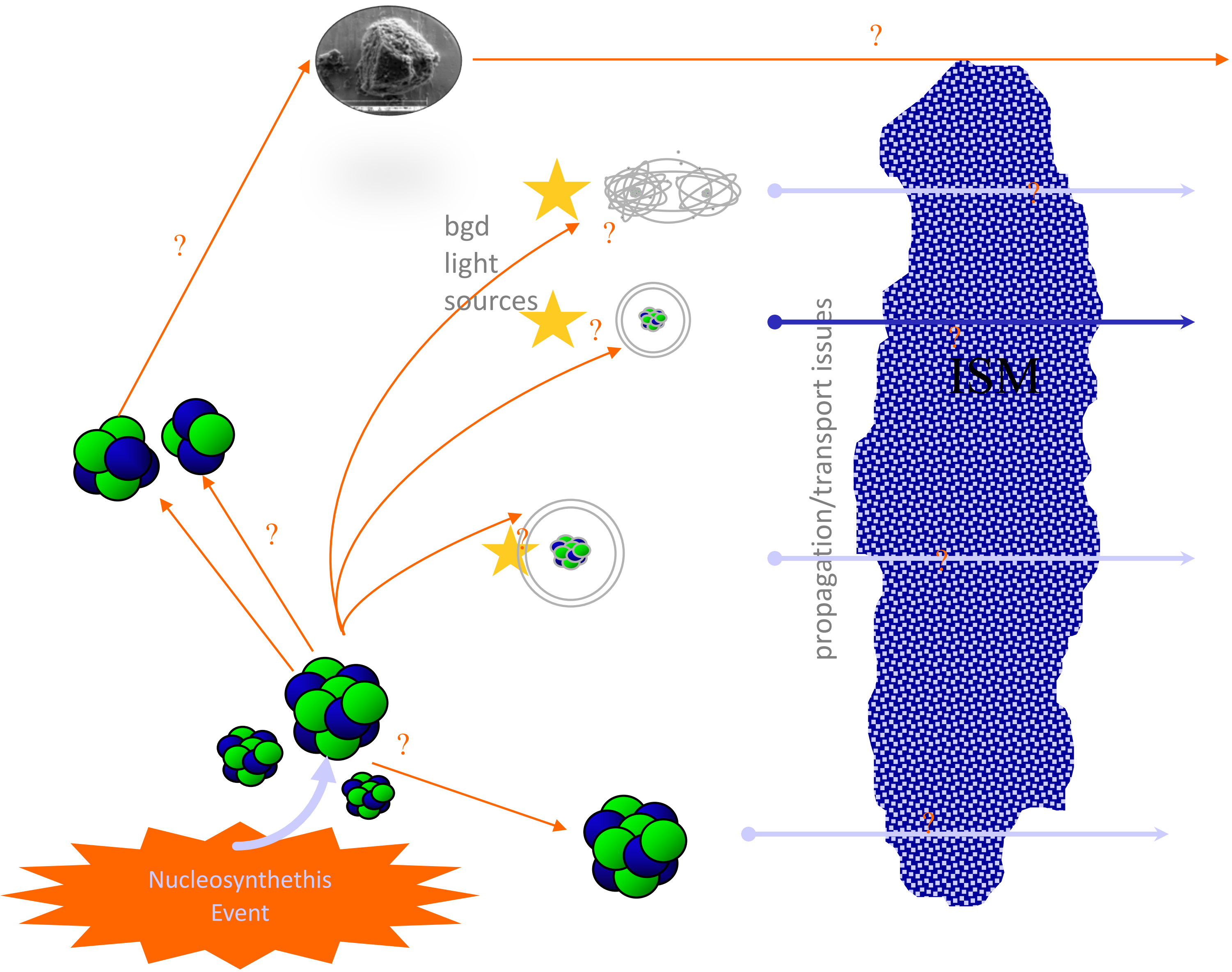


Coté+2019



Helmi 2020

Different Complementing Observing Methods

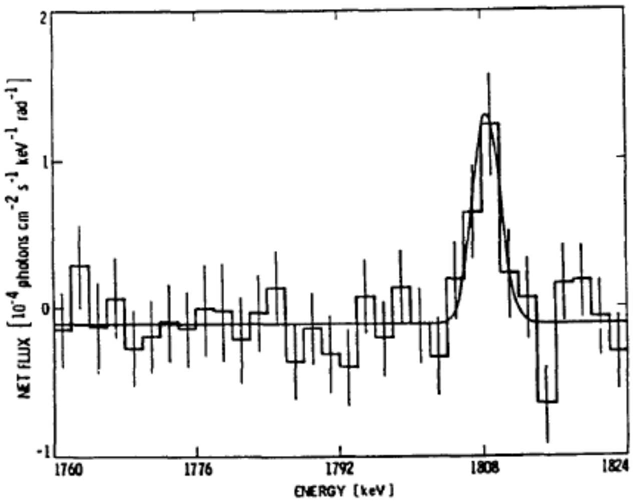


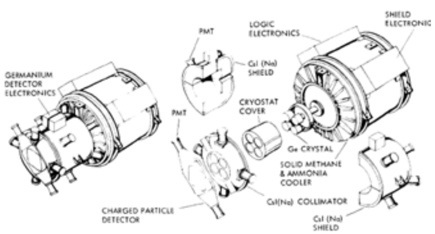
- Stardust in meteorites, Cosmic rays
- Molecular absorption lines (Radio,IR)
- Atomic absorption lines (opt,UV)
- Atomic emission lines (opt,UV,X)
- Gamma-ray lines from radioactive isotopes

Radio-Isotopes with ~My lifetimes: ^{26}Al , ^{60}Fe

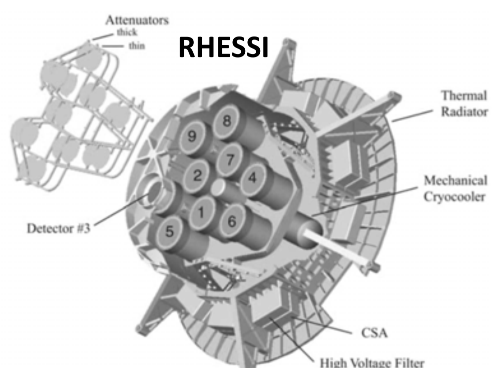
Discoveries

Mahoney+1982

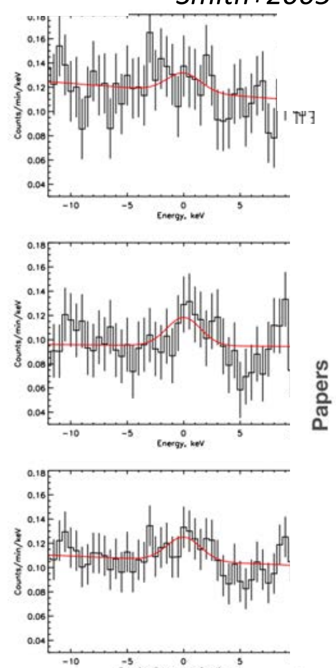




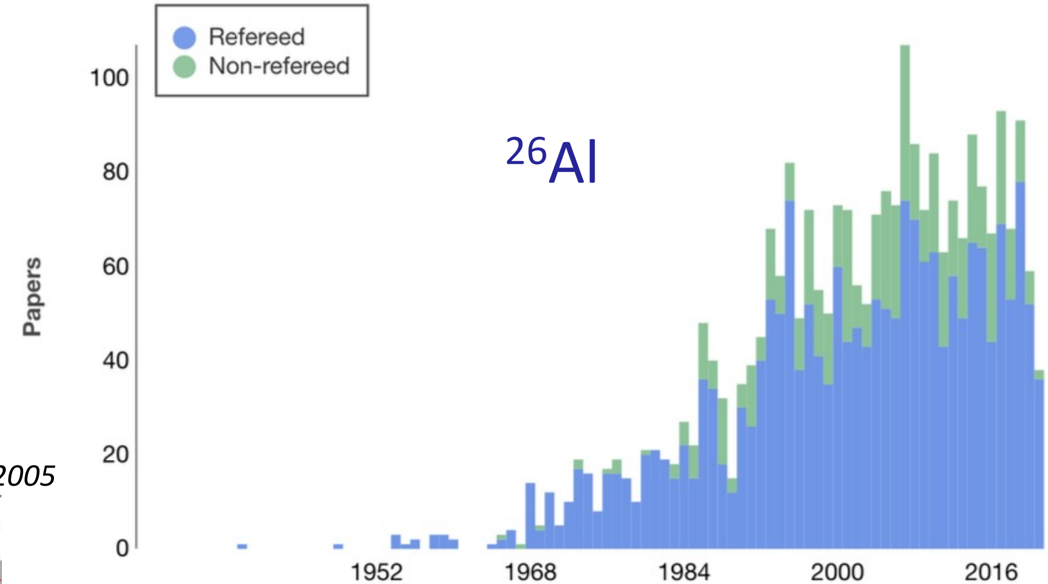
HEAO-C

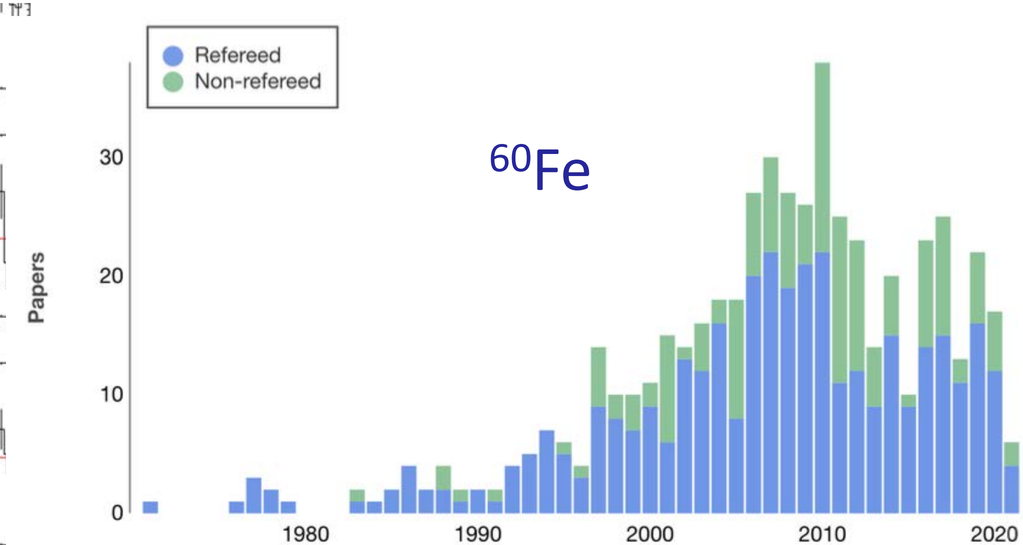


Smith+2005



Temporal evolution of studies





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:

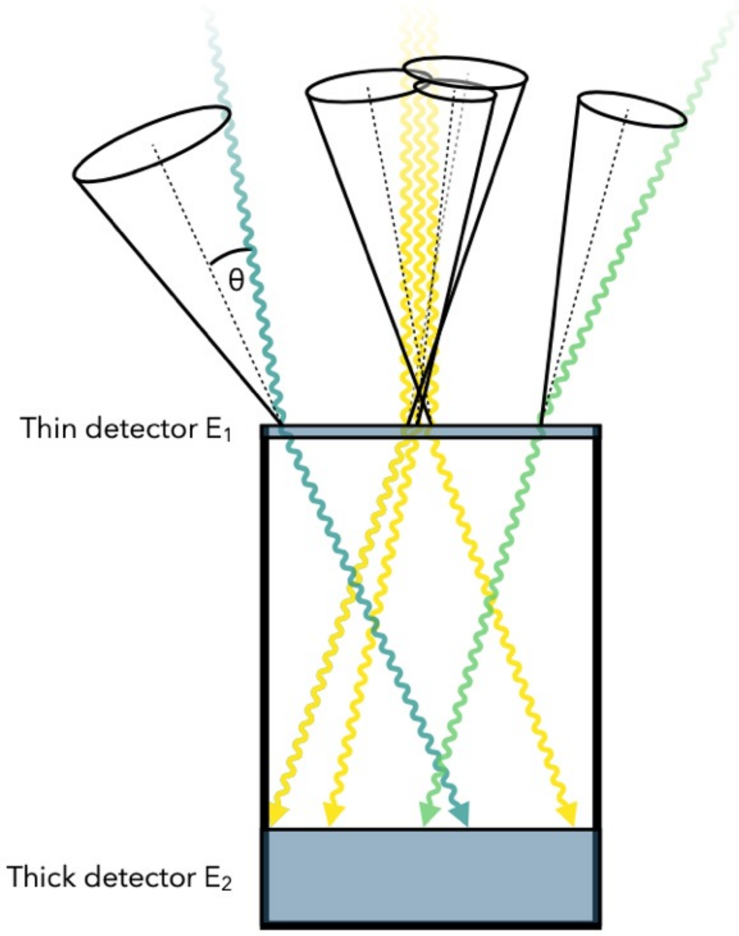
Isotope	Mean Decay Time	Decay Chain	γ -Ray Energy [keV]	Detected Source	Source Type
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^{*}$	478	(none)	Novae
^{56}Ni	8.8 d; 111 d	$^{56}Ni \rightarrow {}^{56}Co^{*} \rightarrow {}^{56}Fe^{*}+e^{+}$	158, 812; 847, 1238	SN2014J; SN1987A, SN1991T(?)	Supernovae
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^{*}$	122	SN1987A	Supernovae
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+}$	1275	(none)	Novae
^{44}Ti	85 y	$^{44}Ti \rightarrow {}^{44}Sc^{*} \rightarrow {}^{44}Ca^{*}+e^{+}$	78, 68; 1157	SNR Cas A	Supernovae
$^{229/230}Th$	~1.0 10^{5} y	$^{229/230}Th \rightarrow \cdots \rightarrow {}^{206}Pb$	352... 609...2615	(none)	Neutron Star Mergers, SNe
^{126}Sn	3.3 10^{5} y	$^{126}Sn \rightarrow {}^{126}Sb^{*} \rightarrow {}^{126}Te$	666; 695; 87; 64	(none)	Neutron Star Mergers, SNe
^{26}Al	1.04 10^{6} y	$^{26}Al \rightarrow {}^{26}Mg^{*} + e^{+}$	1809	Massive-Star Groups Cyg, Ori...	Stars, Novae Supernovae
^{60}Fe	3.5 10^{6} y	$^{60}Fe \rightarrow {}^{60}Co^{*} \rightarrow {}^{60}Ni^{*}$	59, 1173, 1332	Galaxy (?)	Supernovae, Stars
e^{+}	10^{5}... 10^{7} y	$e^{+}+e^{-} \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511	Galactic Bulge, Disk	Supernovae, Novae, Pulsars, Microquasars...

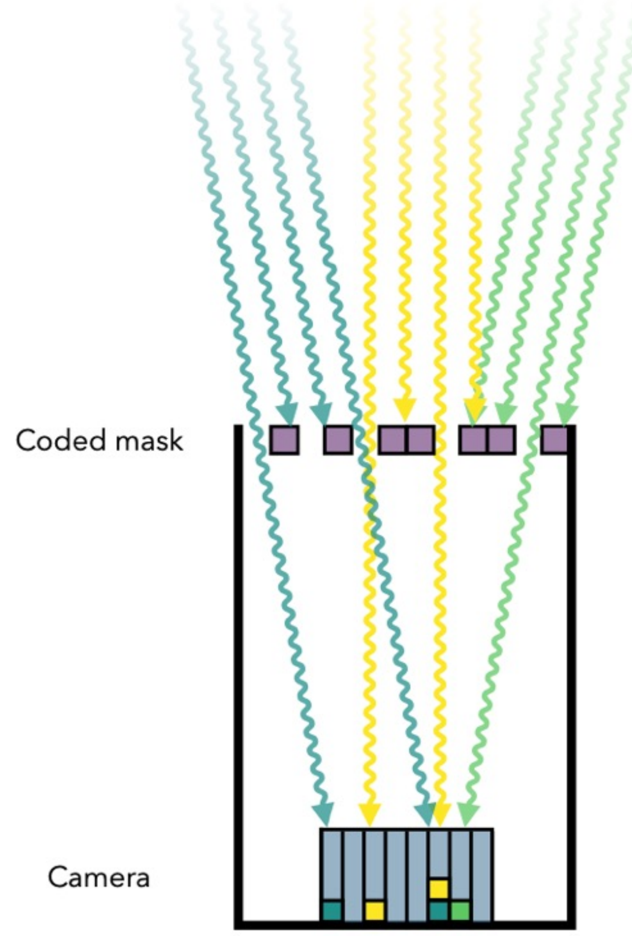
- Only the most-plausible candidates per source type are listed

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

MeV Range Gamma-Ray Telescope Imaging Principles

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



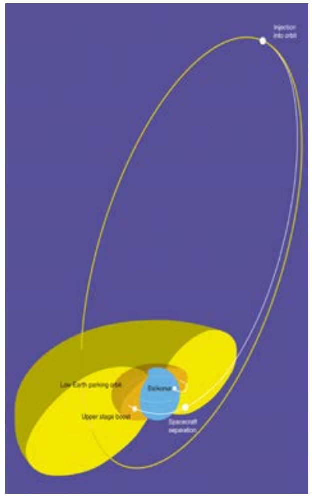


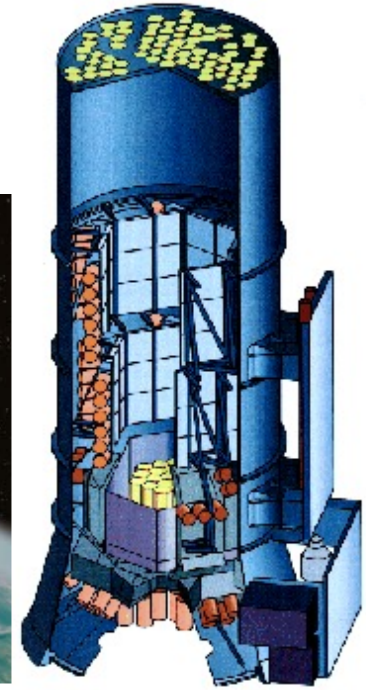
Achievable Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution ≥ deg

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

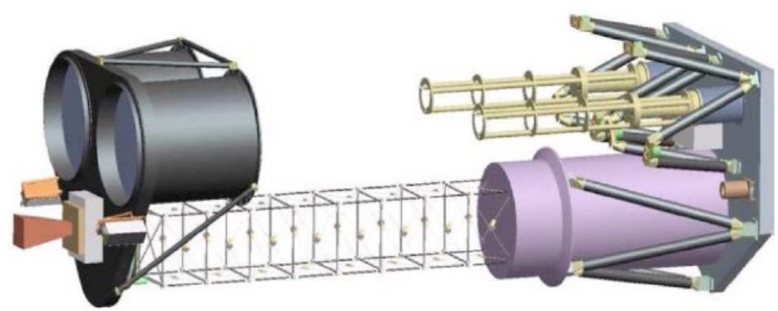
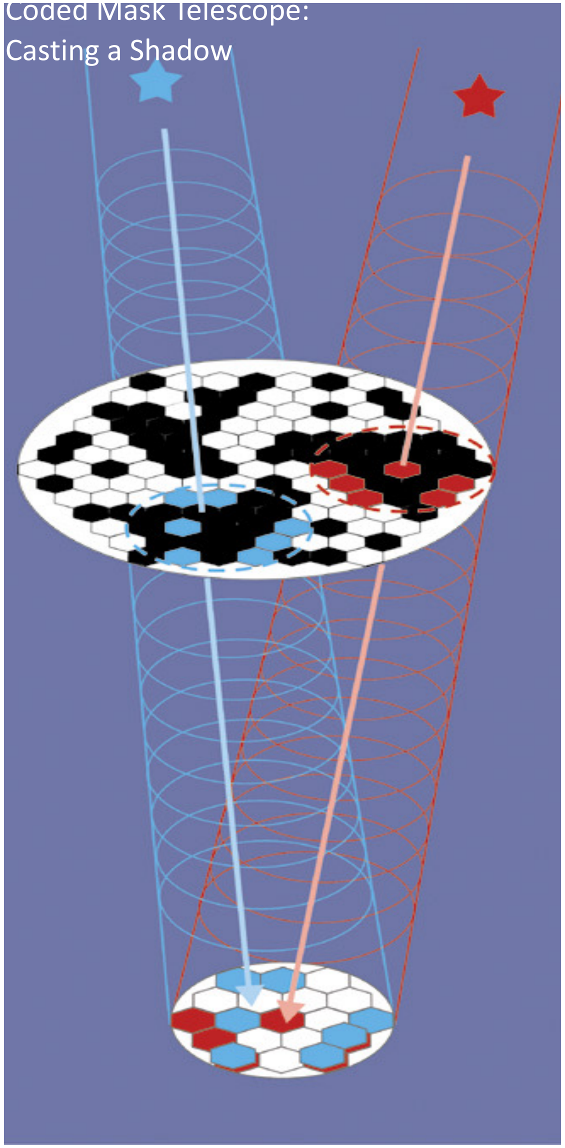


Fig. 1. NuSTAR telescopes in deployed configuration



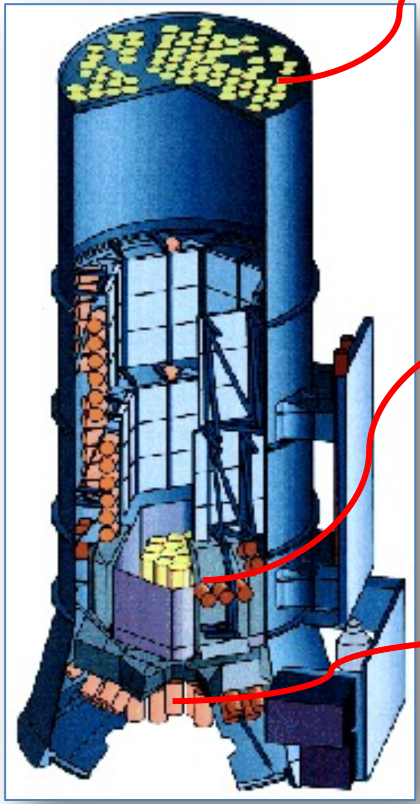
Coded-Mask Telescope

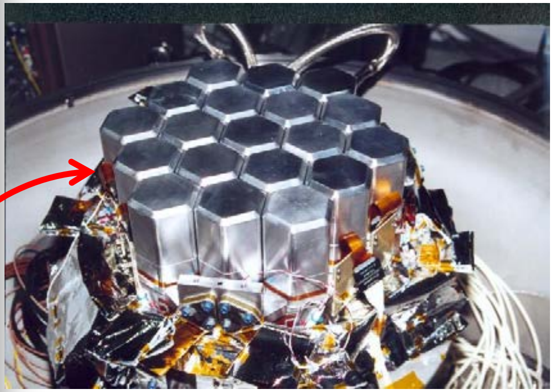
Energy Range 15-8000 keV

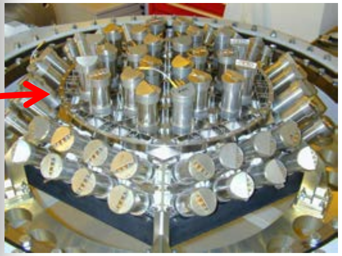
Energy Resolution ~2.2 keV @ 662 keV

Spatial Precision 2.6° / ~2 arcmin

Field-of-View 16x16°

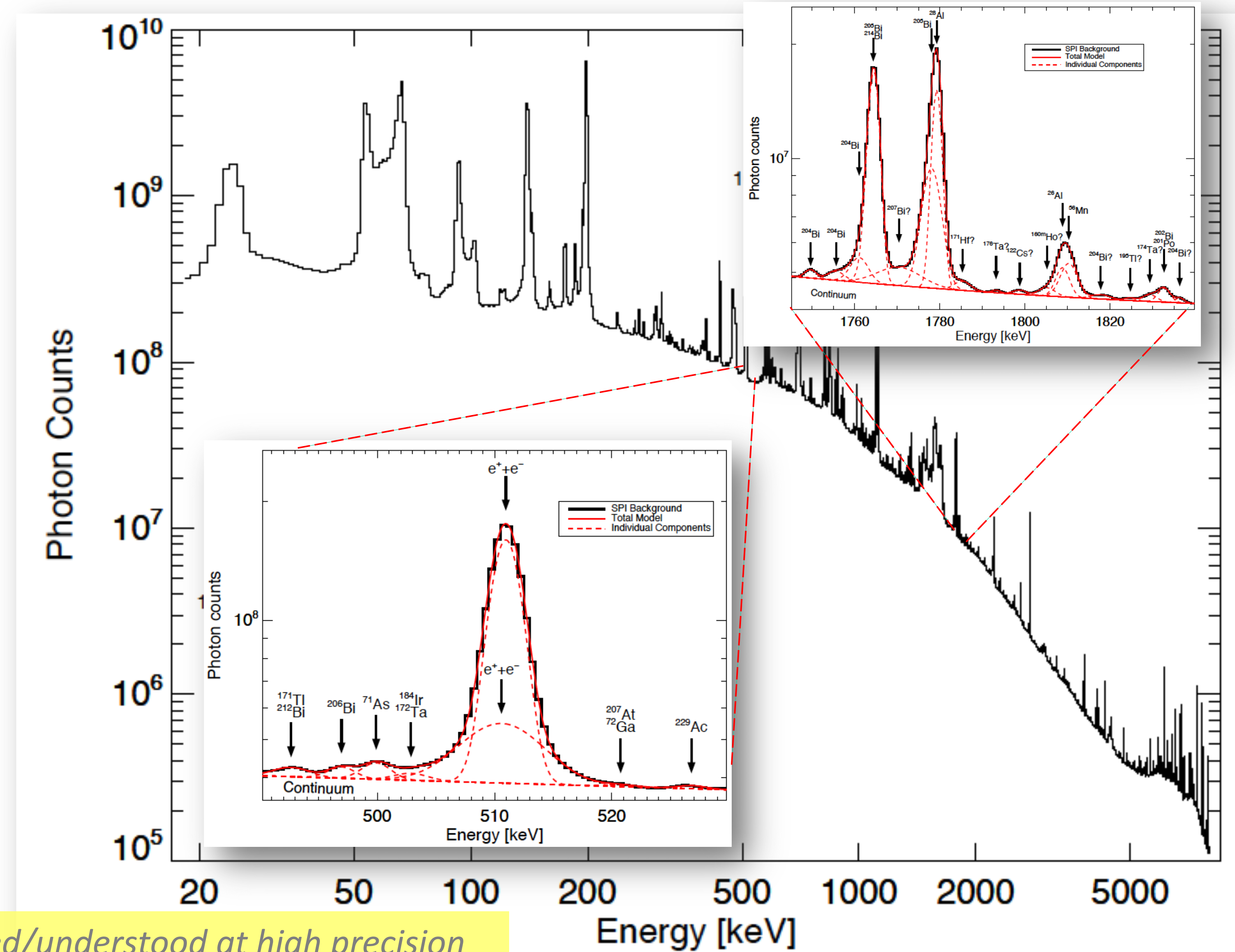






INTEGRAL: Dominance of instrumental background

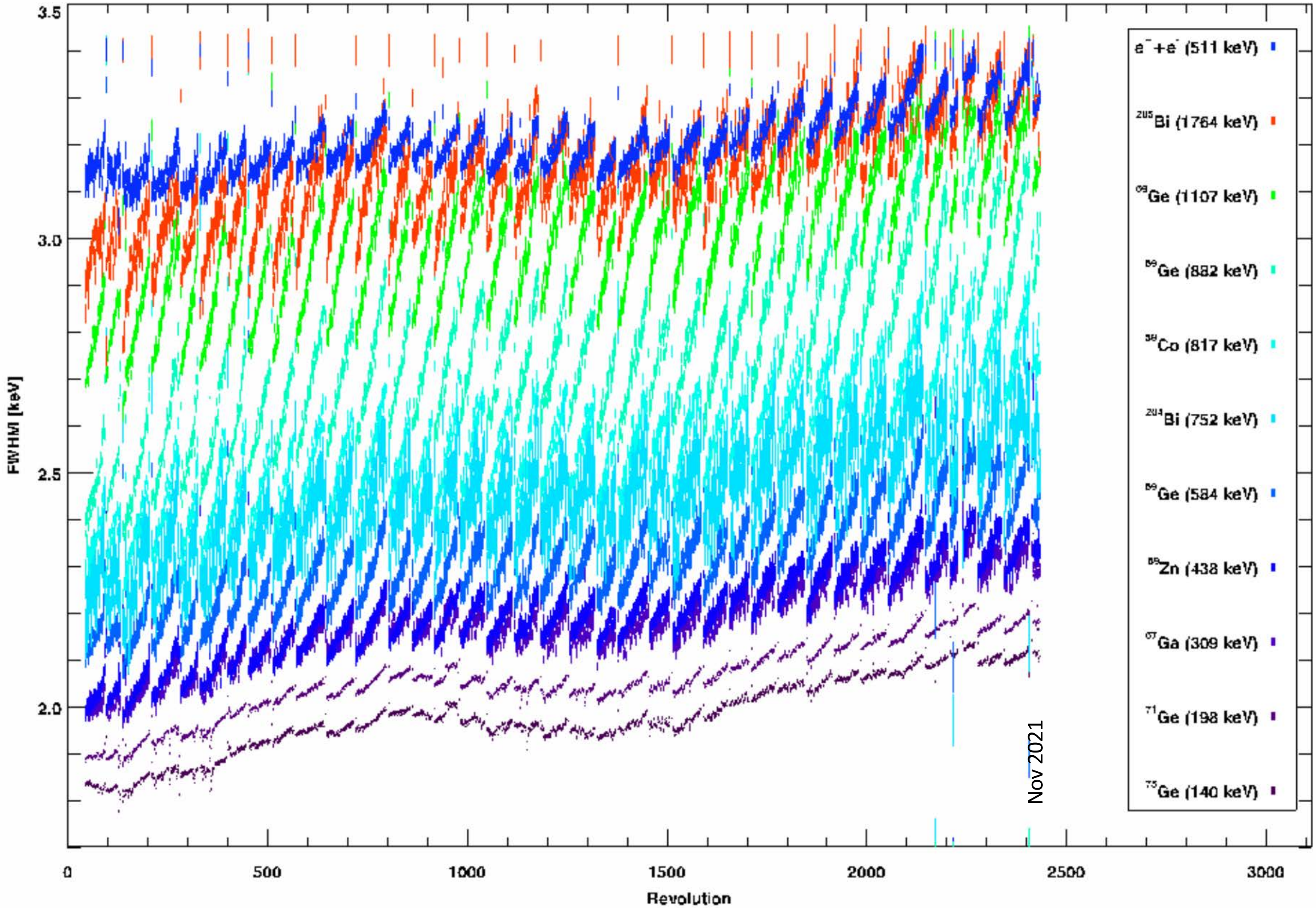
SPI Ge detector spectra



Modelled/understood at high precision

INTEGRAL/SPI Performance Monitoring

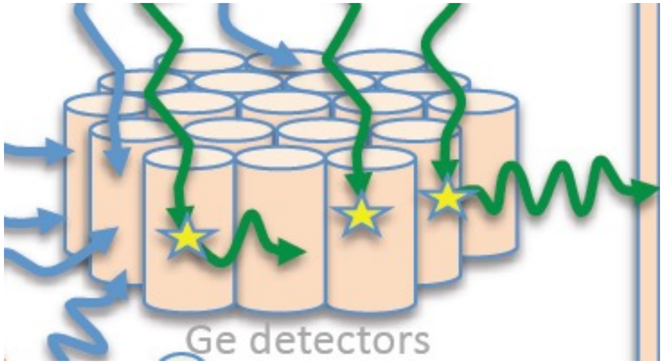
Spectral Resolution in Detail: regular annealings are essential

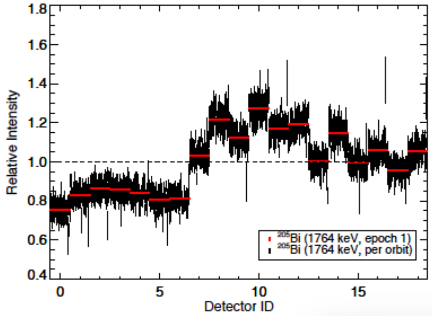


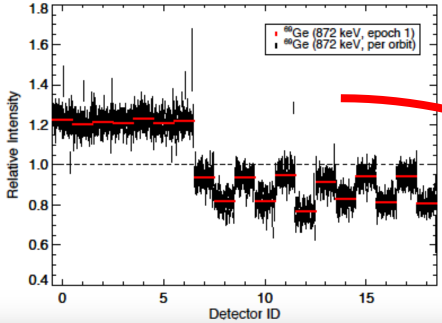
39th annealing just completed (Sep 2022)!

Discriminating Background and Sky Signals in SPI Data

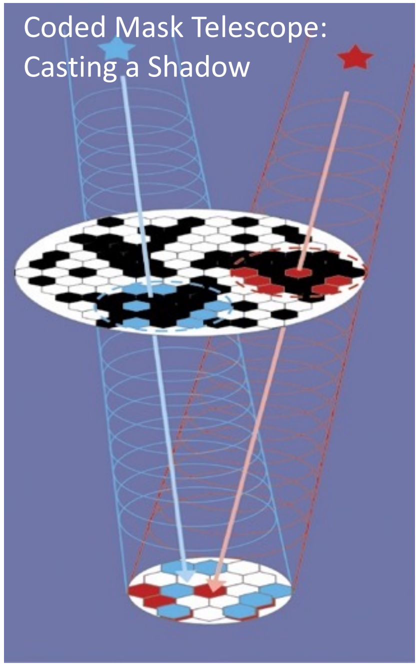
- Tracking the relative count rate ratios among detectors
  - ☞ characteristic signatures from celestial sources withcoded mask, and from background events

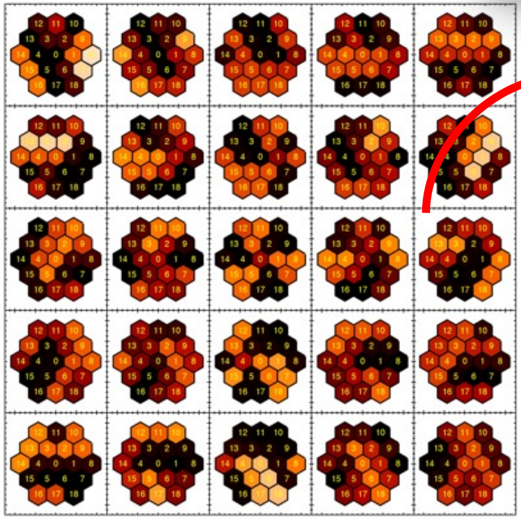


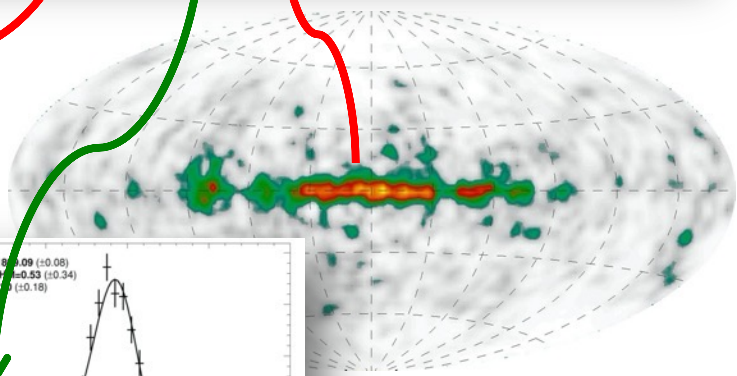


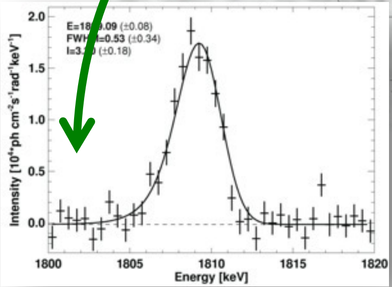


$$d_k = \sum_j R_{jk} \sum_{i=1}^{N_I} \theta_i M_{ij} + \sum_t \sum_{i=N_I+1}^{N_I+N_B} \theta_{i,t} B_{ik}$$









Gamma ray spectroscopy with SPI

...it works! example:

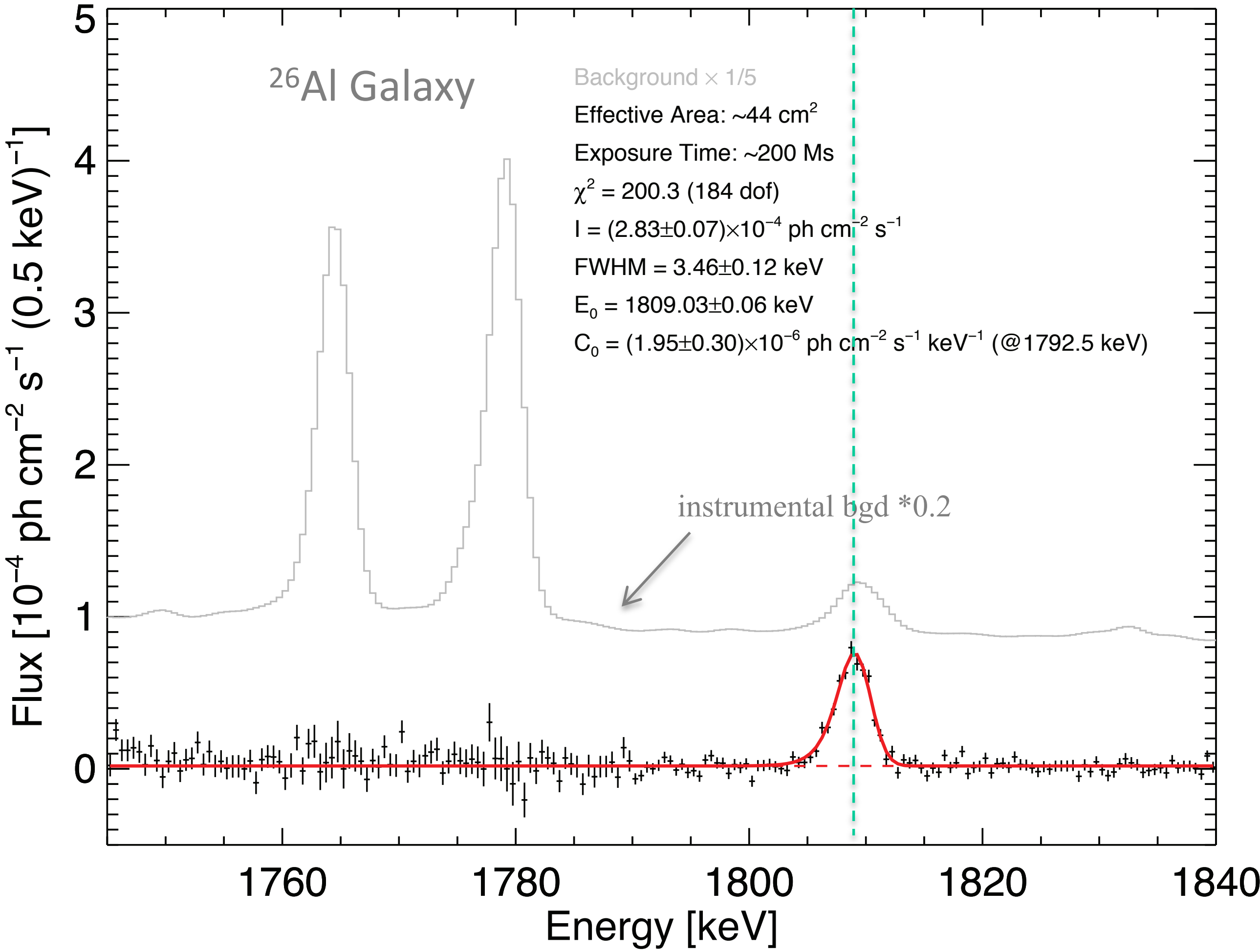
^{26}Al line 1808.6 keV

instrumental lines

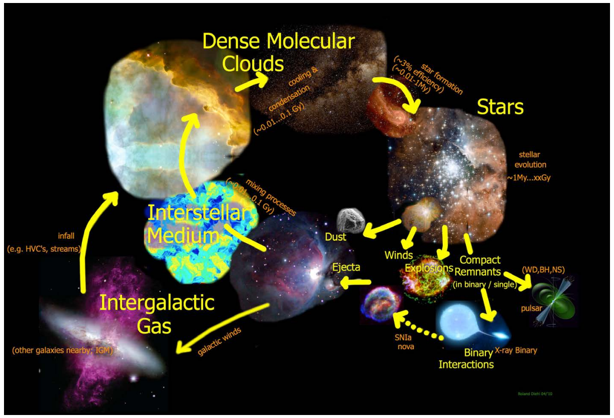
1810 keV

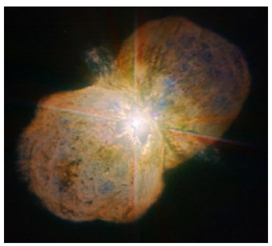
1779 keV

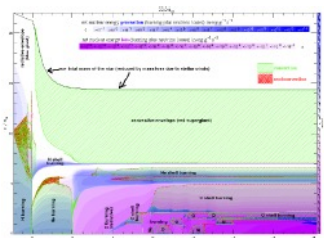
1764 keV

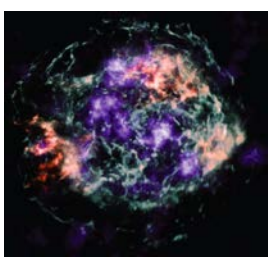


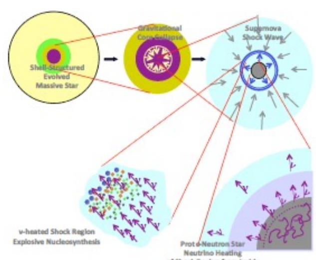
Lessons from radioactive isotopes

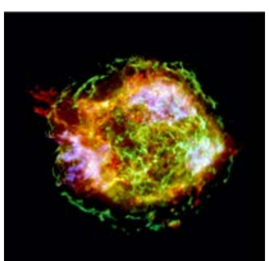


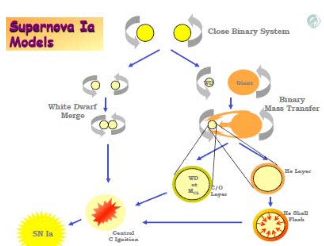










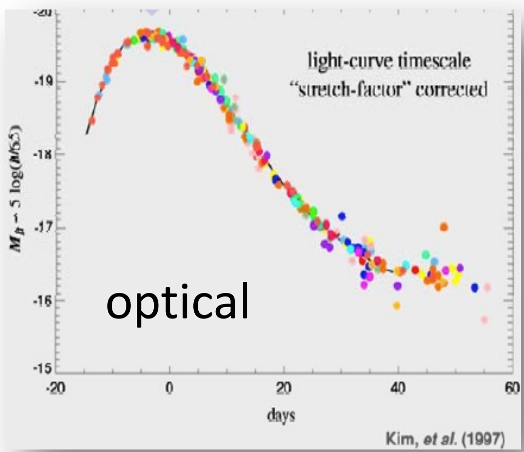


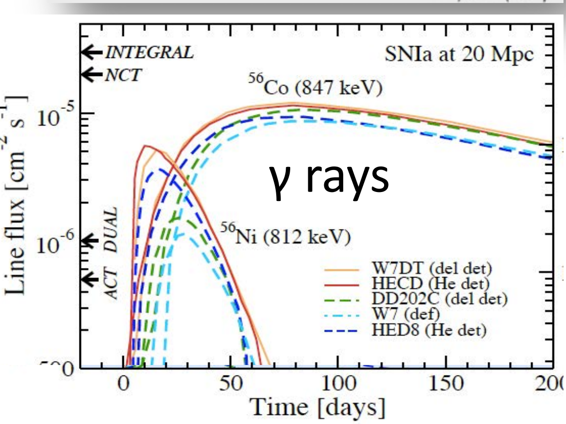
☆Trace the flows of cosmic matter

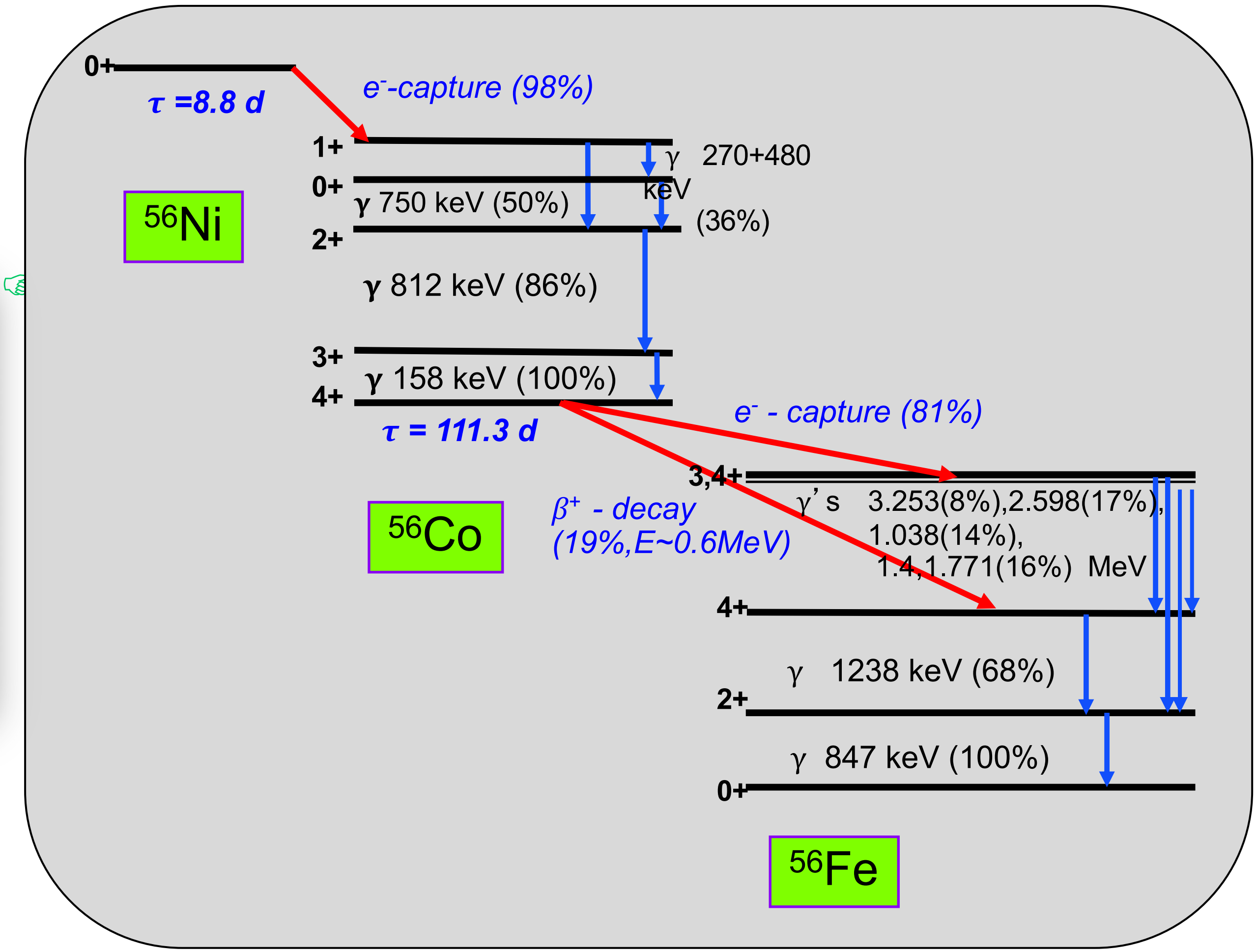
☆Understand the sources of new nuclei

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

SN Ia

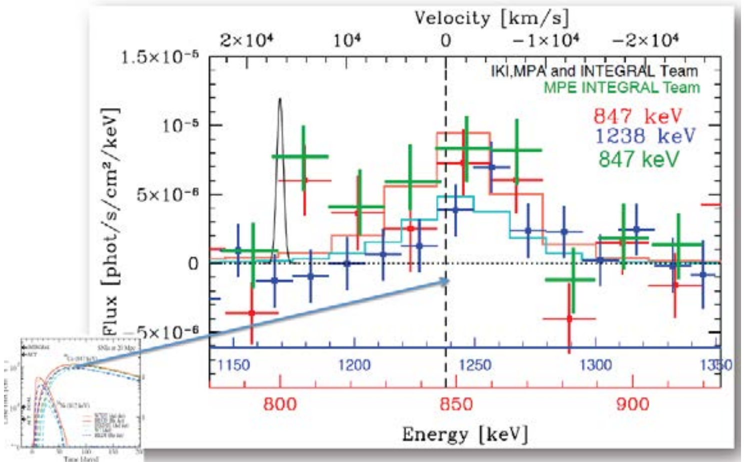




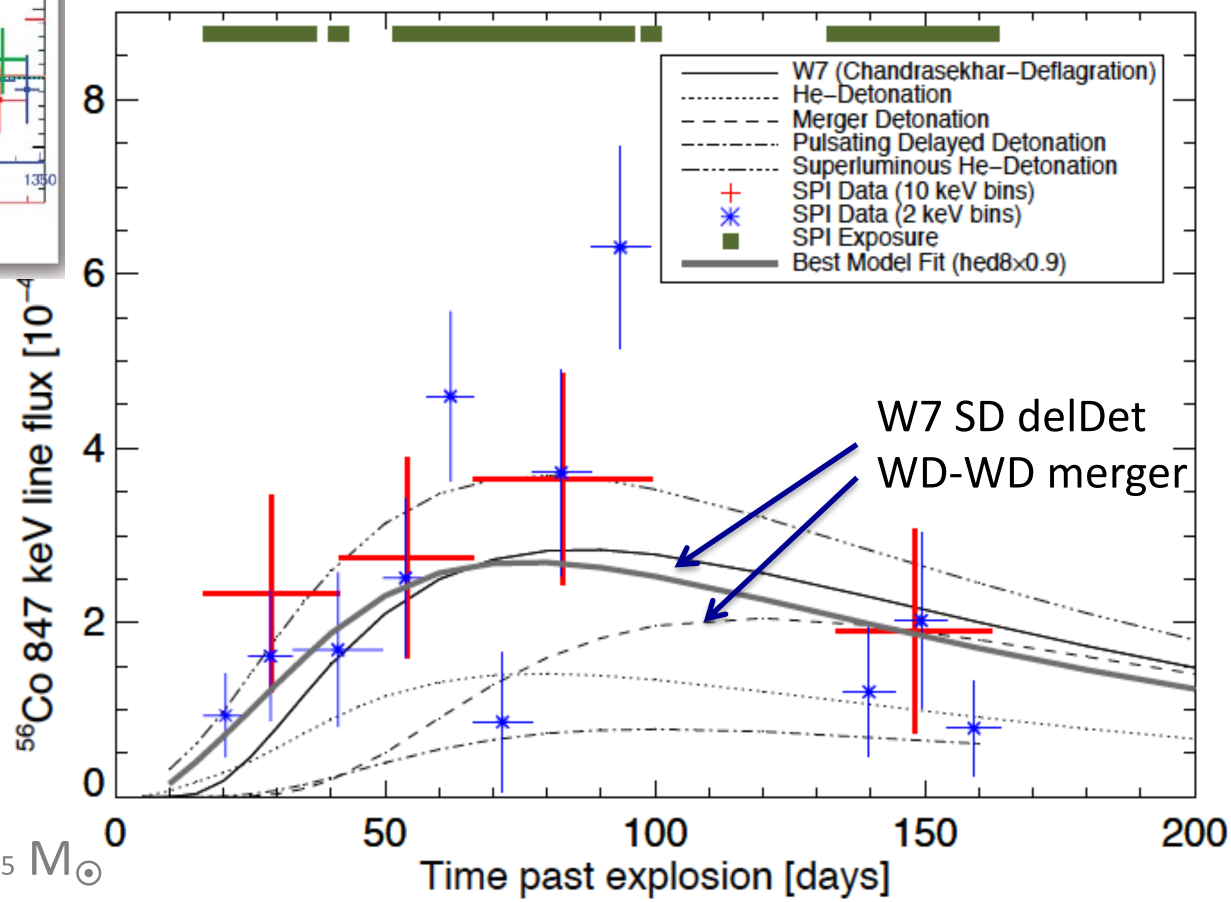


- Nuclear BE release from 0.6M$_{\odot}$ [C,O → ^{56}Ni] = ~1.1 10^{51} erg (>2*BE$_{WD}$)
- Deposit of γ rays and e+ in expanding/diluting envelope
- Re-radiation of deposited energy in low-energy (thermal) radiation

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



INTEGRAL/SPI γ ray measurements



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

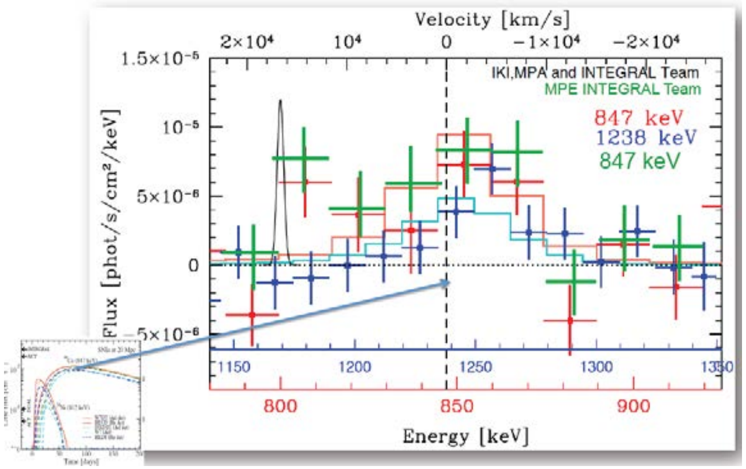
(cmp from bol. Light → 0.42 +/-0.05 $M_\odot$

from models → 0.5 +/-0.3 $M_\odot$

☞ *Diehl et al., A&A 2015*

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

- ☆ Doppler broadened ✓



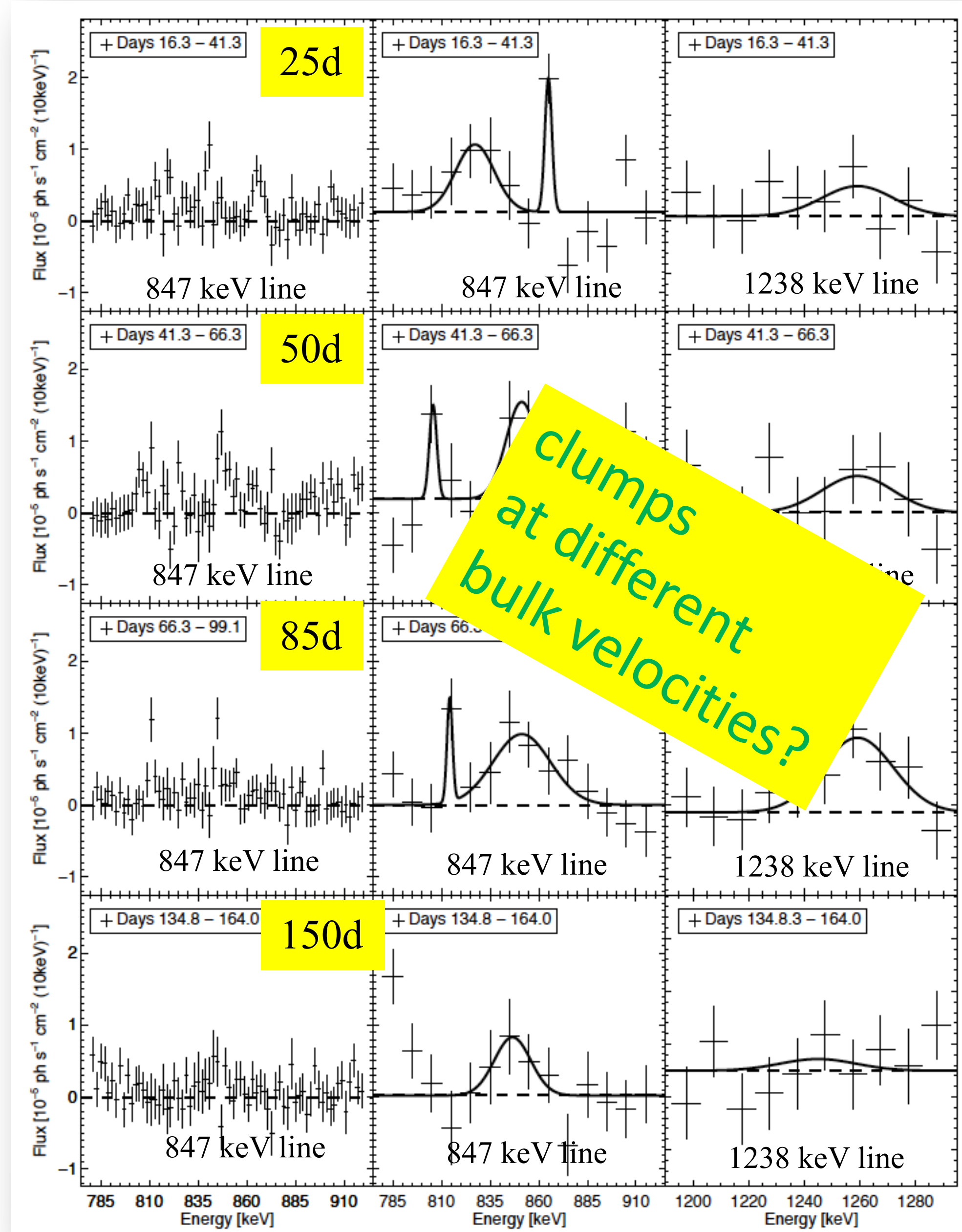
- ☆ Split into 4 time bins
- ☆ Coarse & fine spectral binning

→ 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!*

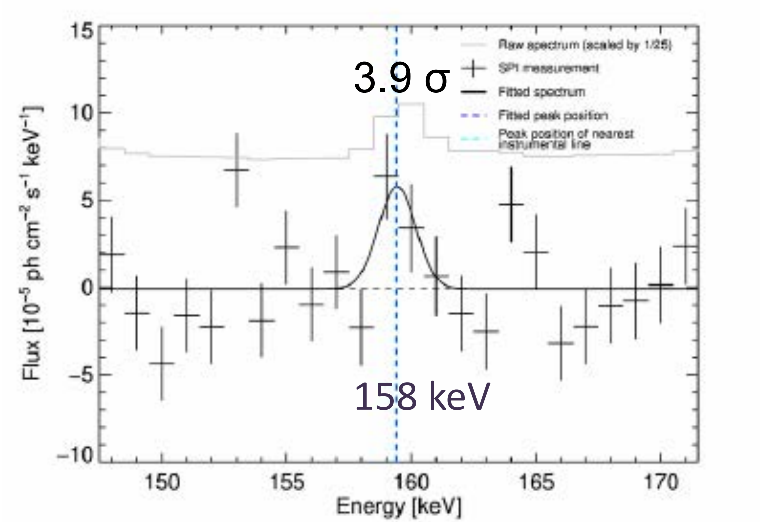


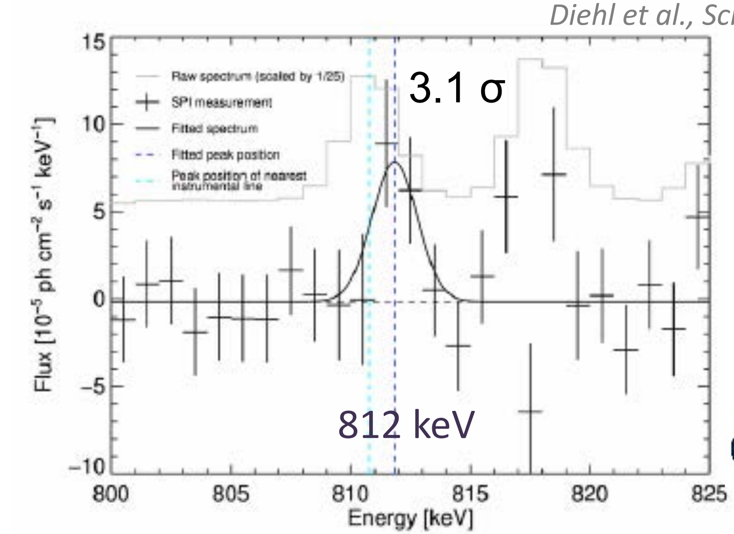
SNIa and SN2014J: Early ^{56}Ni (τ~8.8d)

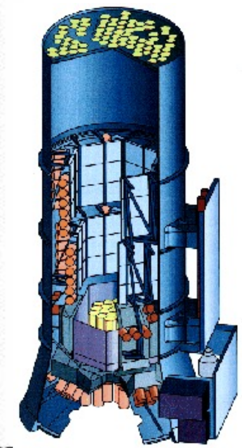
Spectra from the SN at ~20 days after explosion

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

Diehl et al., Science (2014)



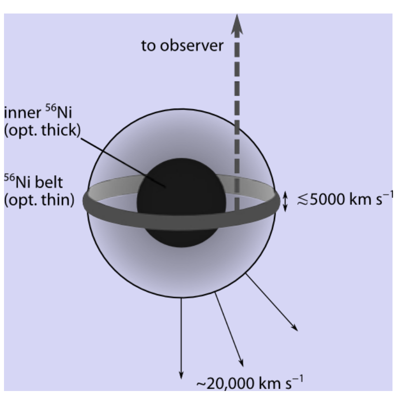




^{56}Ni mass estimate (backscaled to explosion): ~0.06 $M_{\odot}$ (~10%)

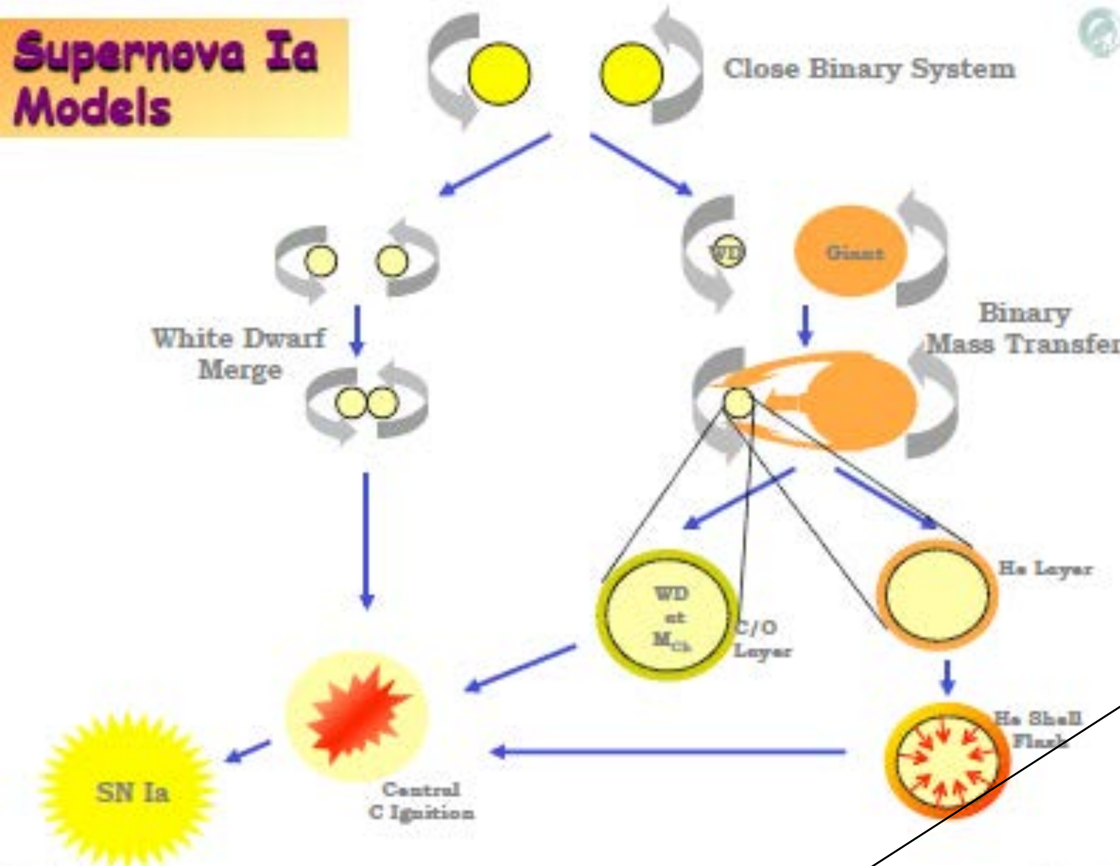
i.e.: not the single-degenerate $M_{chandrasekhar}$ model,

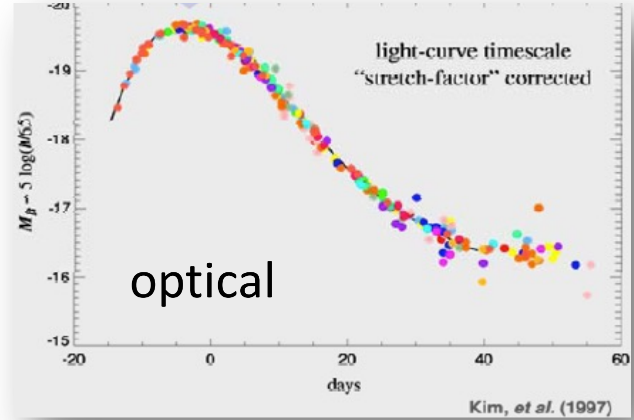
but 2 WDs (double-degenerate)

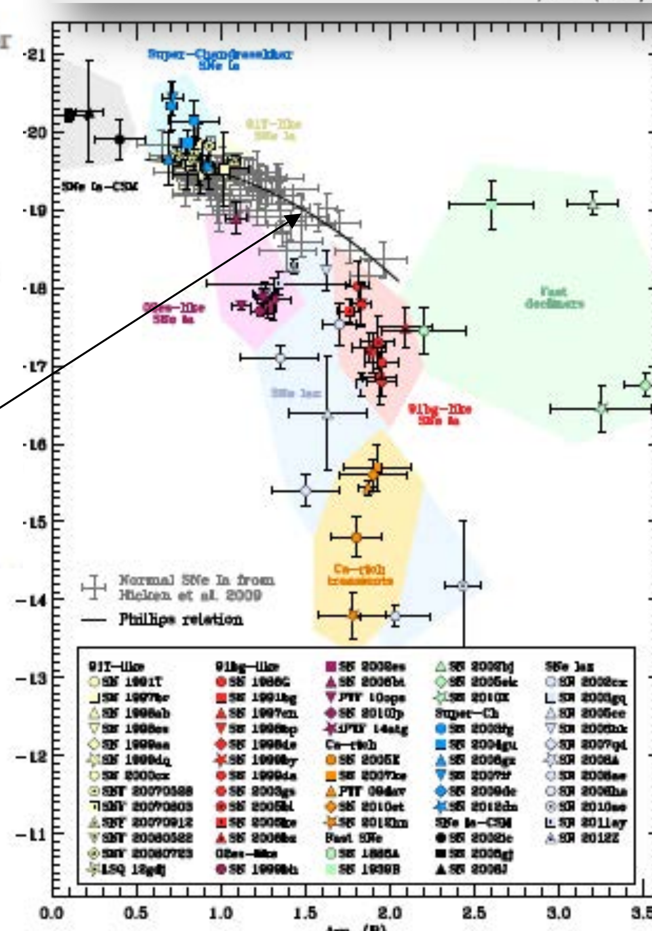


→ SN Ia are a variety

Supernovae of type Ia







→ SN Ia are a variety

"standardizable candles"??

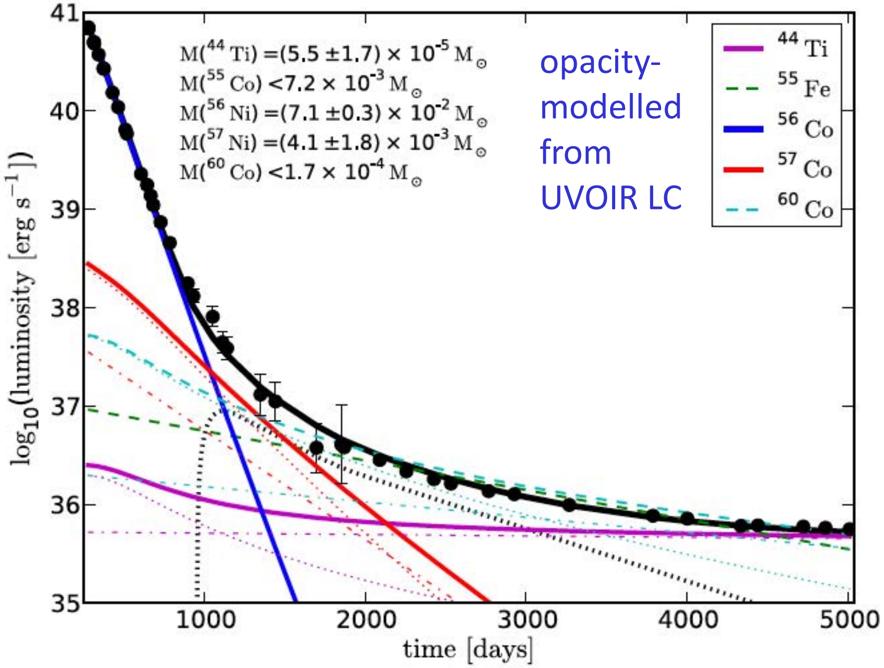
Taubenberger 2017

^{44}Ti from SN1987A

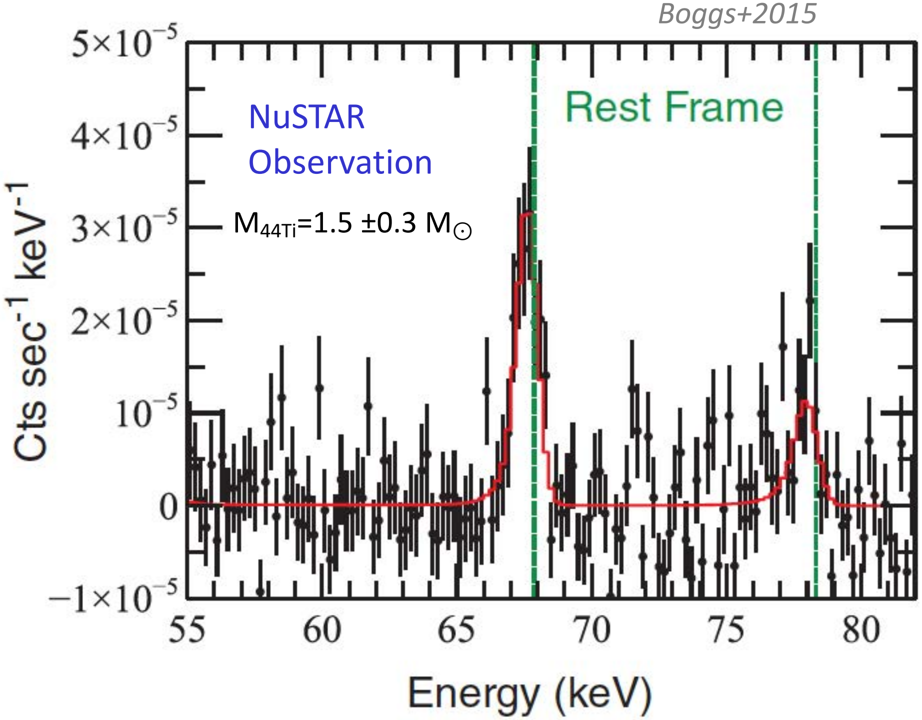
☆ ab-initio models
→ $M_{44Ti} \approx 0.x\ 10^{-5}\ M_\odot$ (spherical)
to $0.x\ 10^{-4}\ M_\odot$ (aspherical)

☆ UVOIR LC + energy deposition models
→ $M_{44Ti} \approx 0.5...5\ 10^{-4}\ M_\odot$

Seitenzahl+2014



Boggs+2015



☆ ^{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)

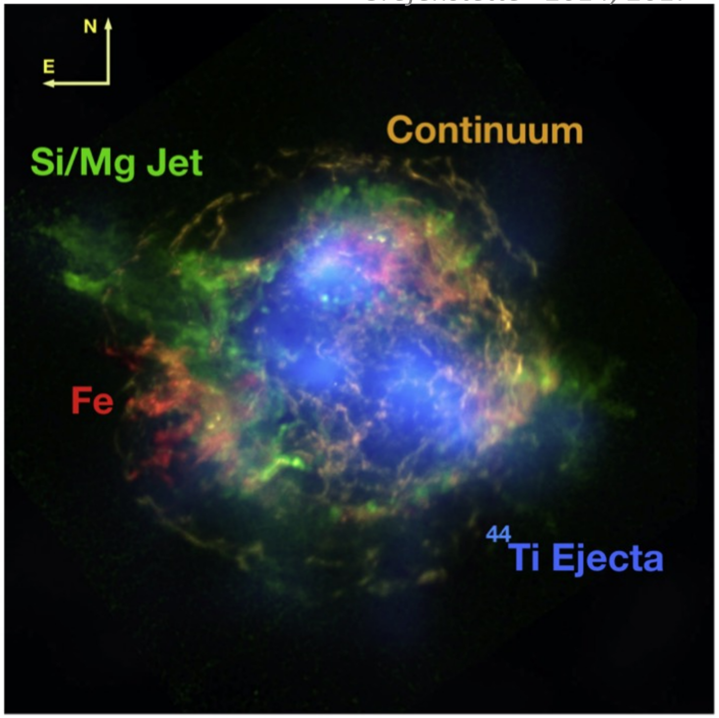
^{44}Ti radioactivity in Cas A: Locating the inner Ejecta

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!!



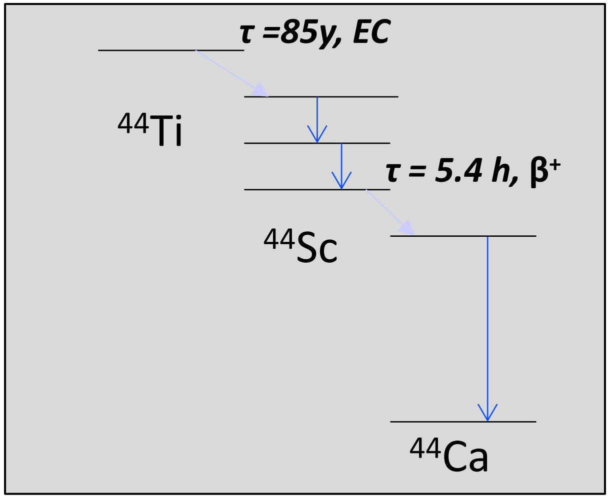
☞ ^{44}Ti→ TRUE locations of ejecta from the inner supernova

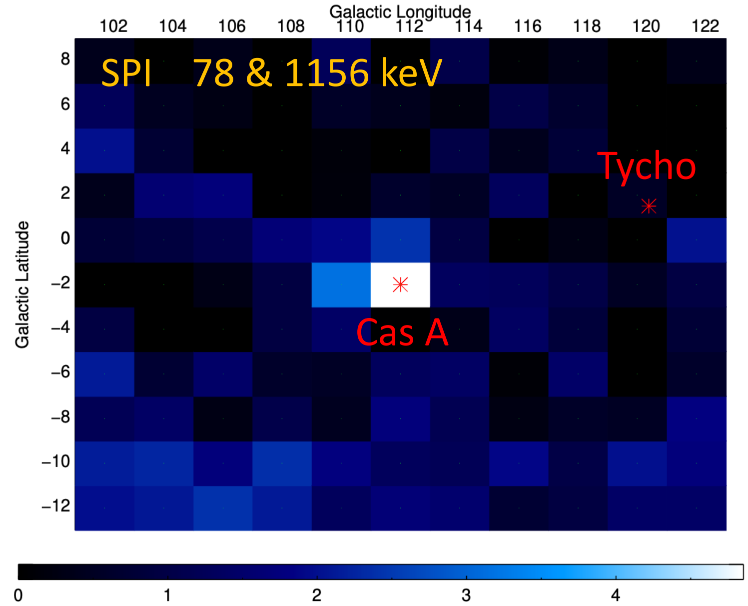
☞ Fe-line X-rays are biased from ionization of shocked plasma

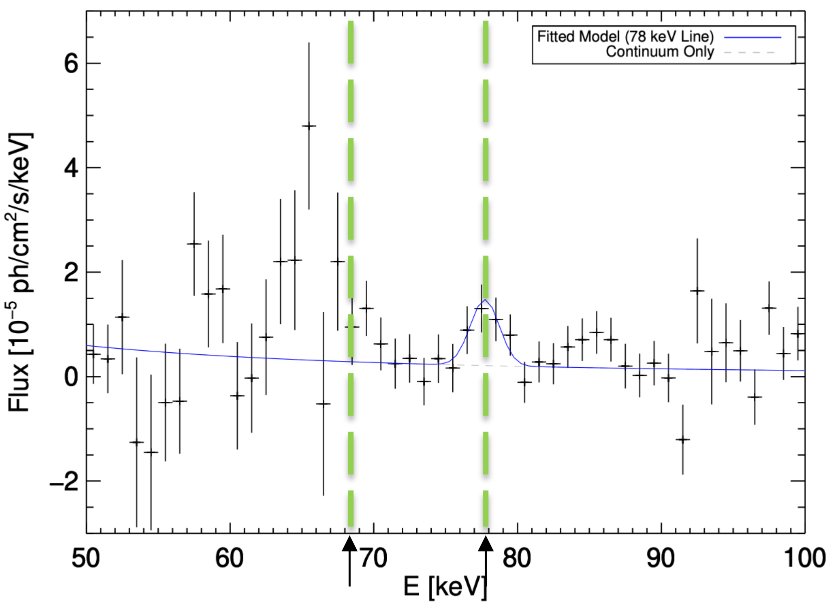
^{44}Ti in Cas A: INTEGRAL/SPI contributions

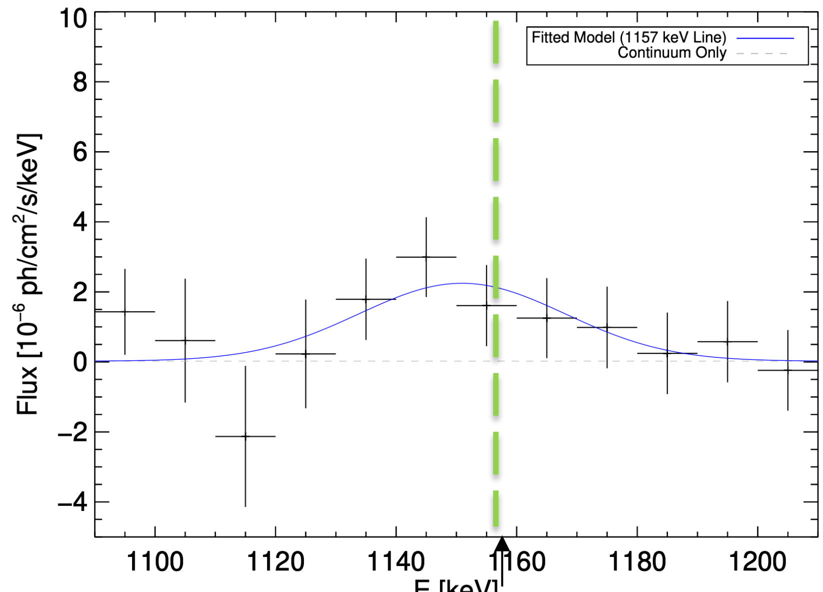
Weinberger+ 2021

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









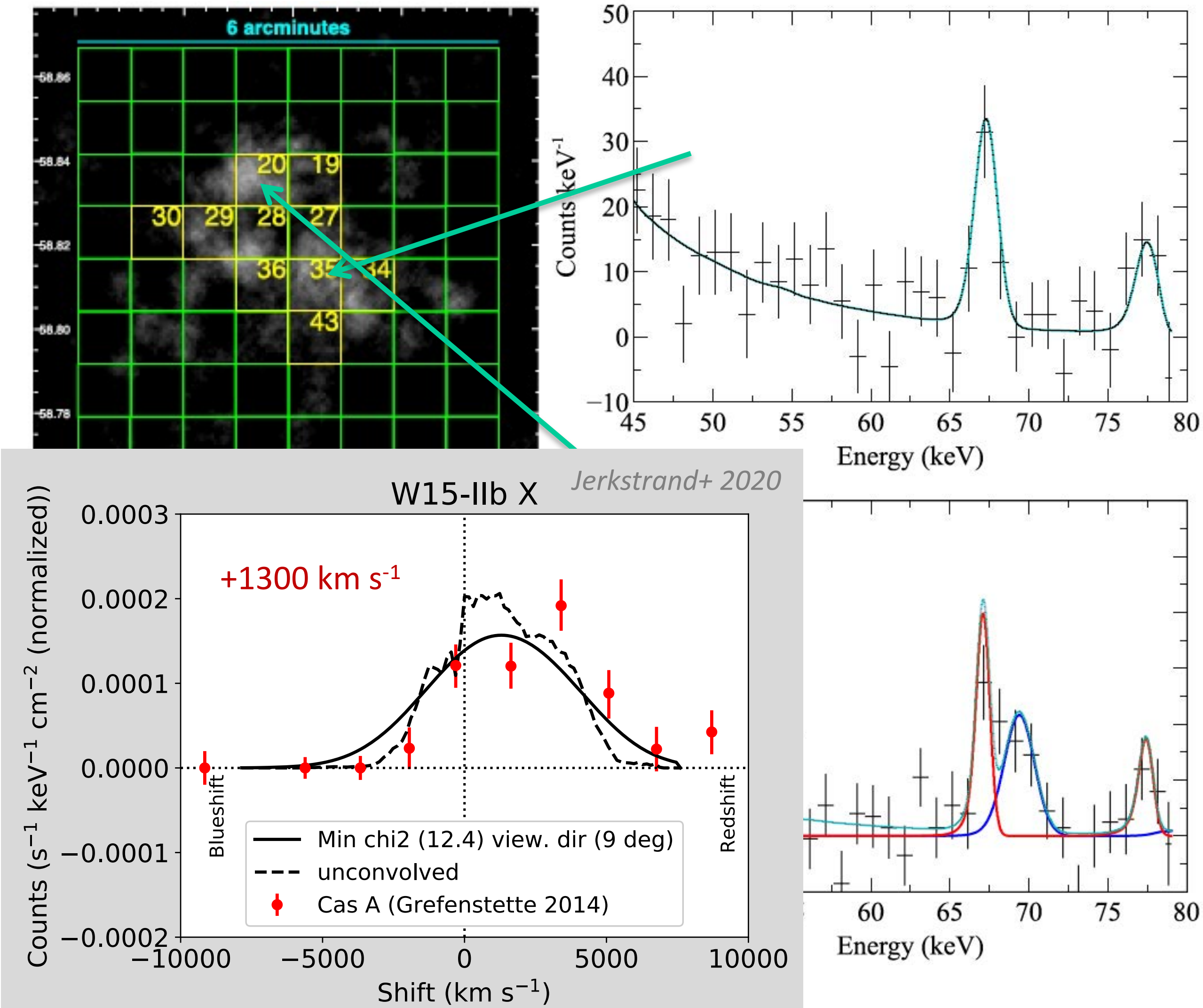
→ bulk red-shifted ^{44}Ti (away from observer)

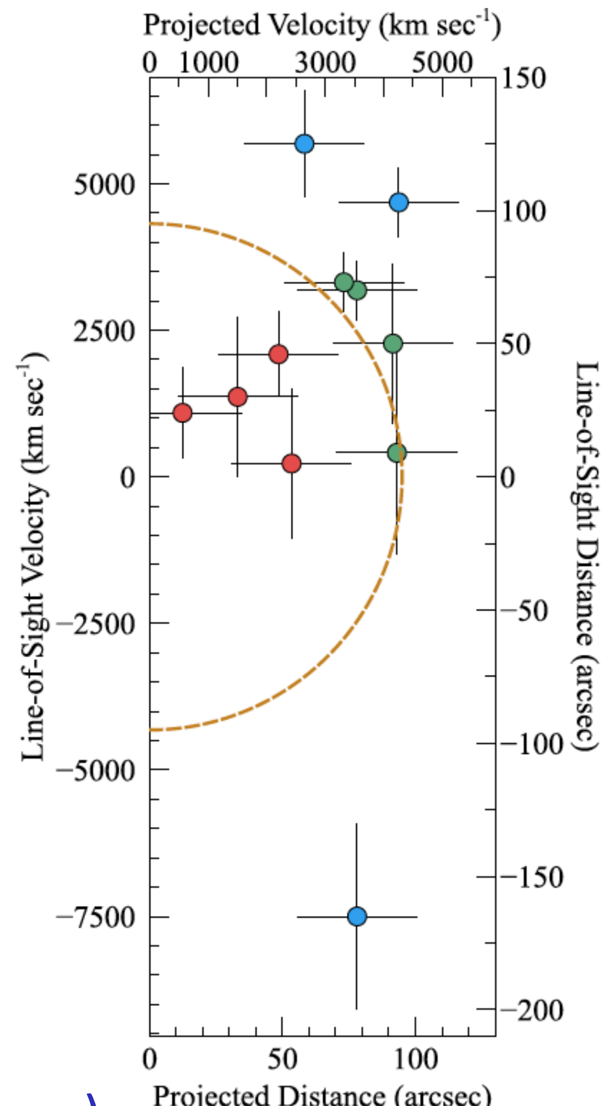
NuSTAR update: ^{44}Ti in Cas A

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

2.4 Msec NuSTAR campaign

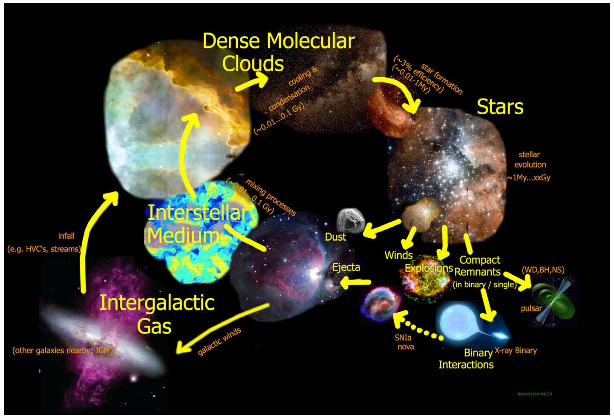
Grefenstette et al. 2017

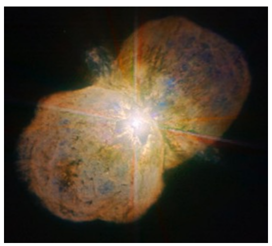


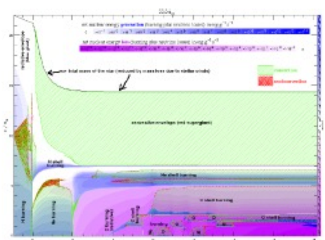


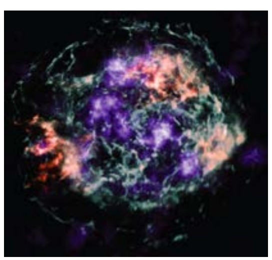
→ bulk red-shifted ^{44}Ti (away from observer)

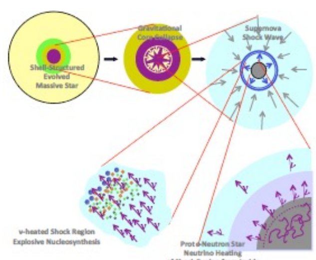
Lessons from radioactive isotopes

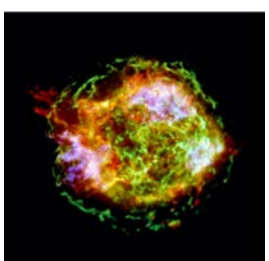


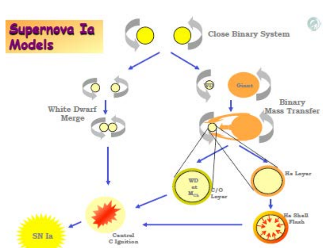








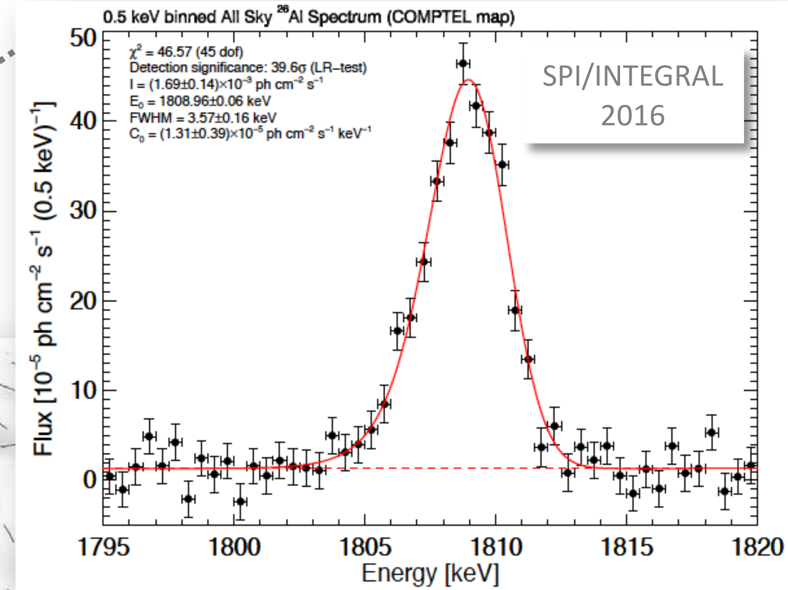


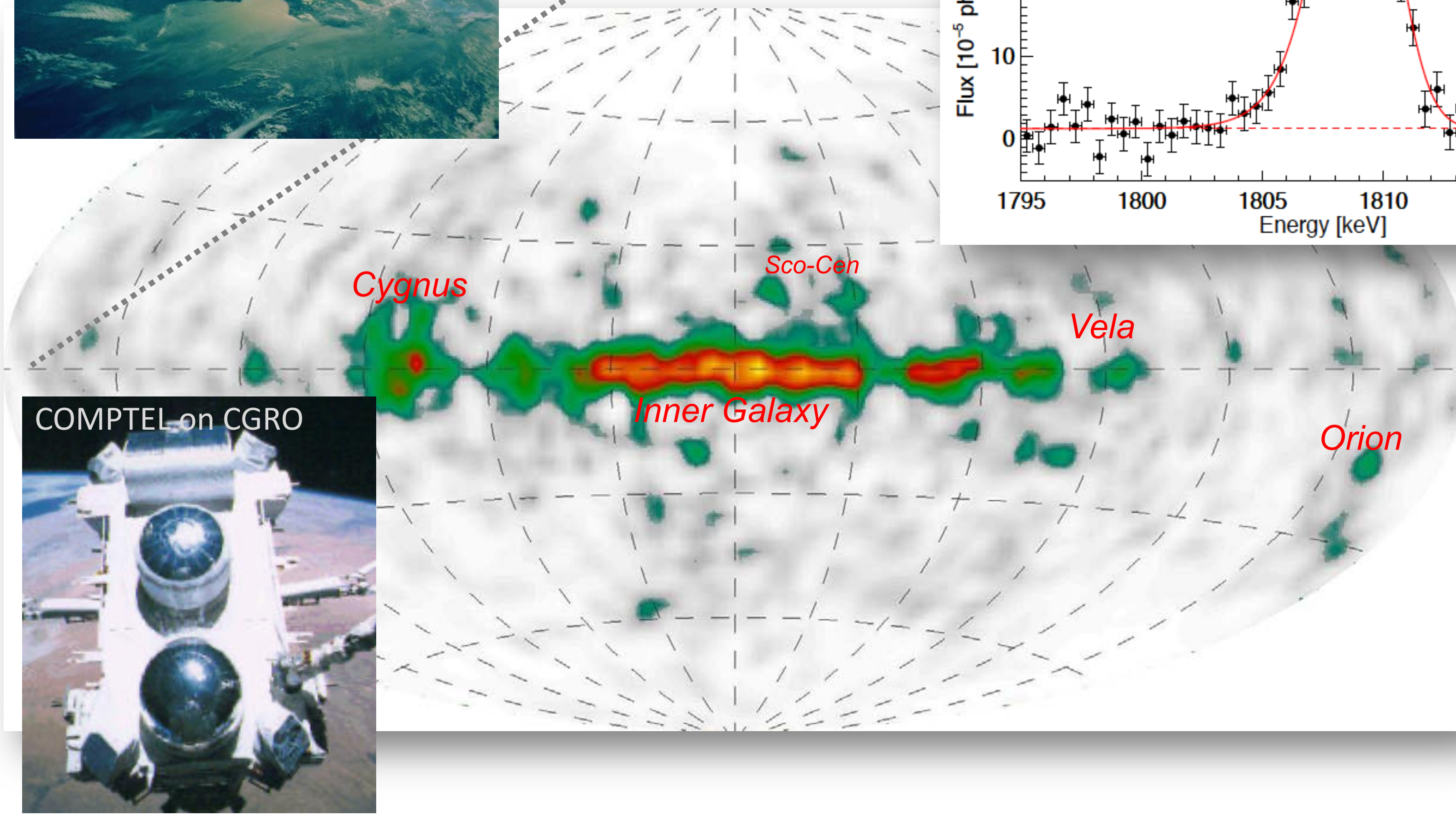


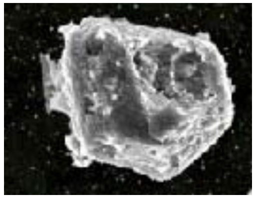
☆Trace the flows of cosmic matter

☆Understand the sources of new nuclei

^{26}Al γ-rays from the Galaxy







← 1 μm →

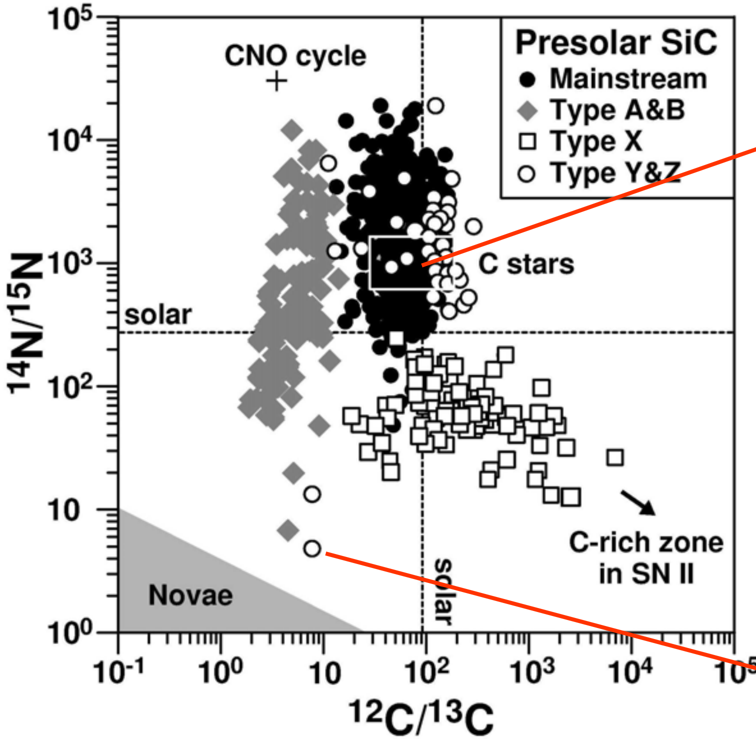
Hints from Presolar Grains

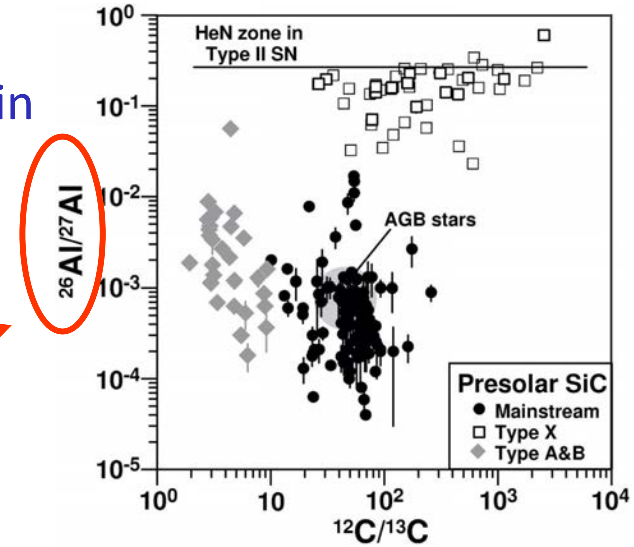
Isotopic Ratios in C,N,Si,...→ Source Type of Presolar Grain

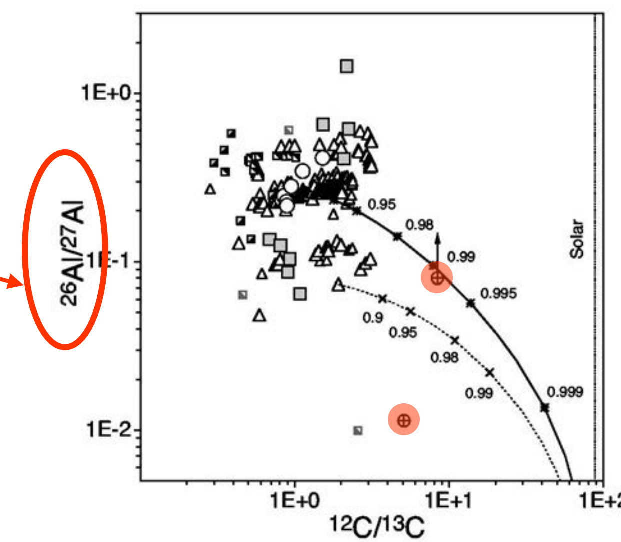
AGB Stars

Supernovae

Novae



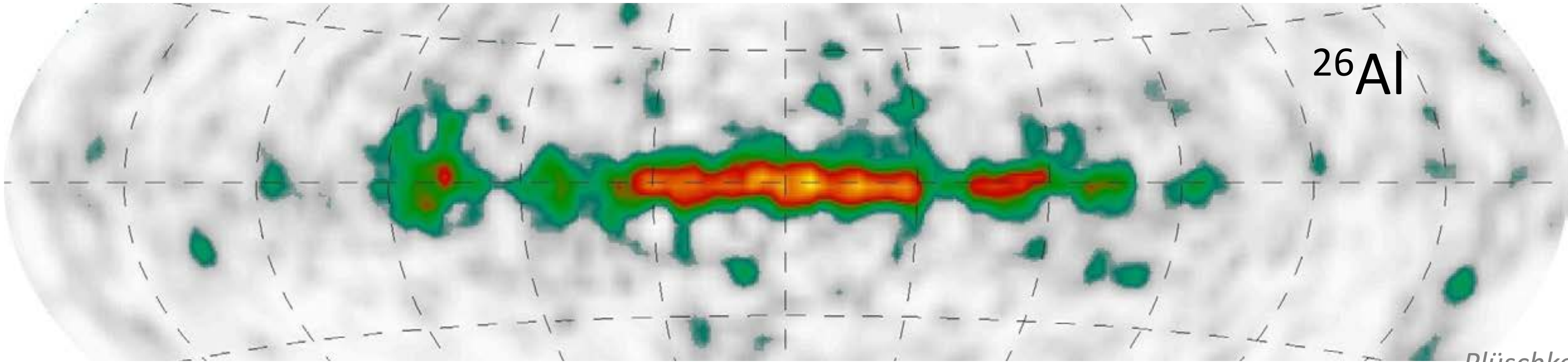




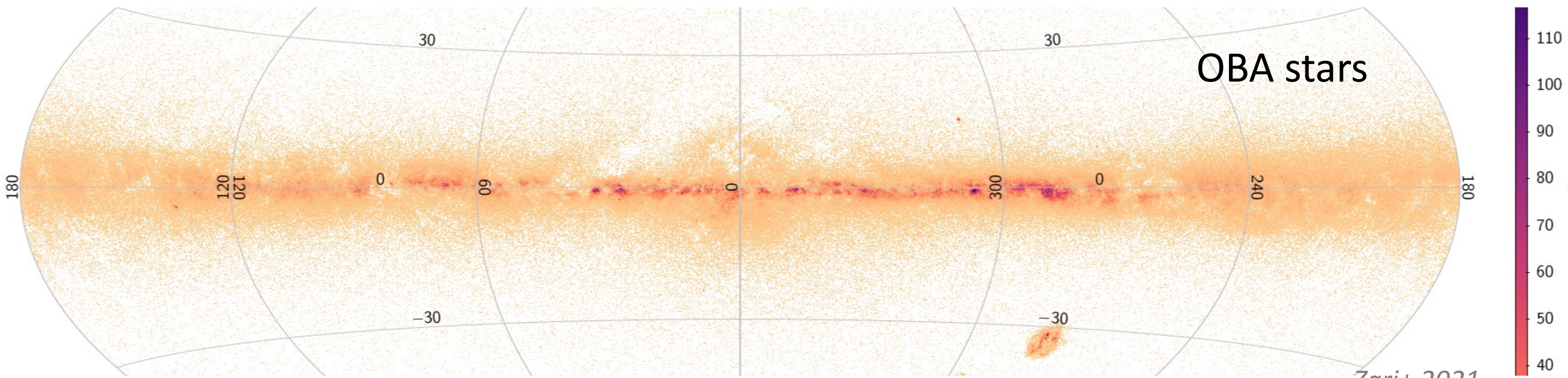
Amari, Nittler, Hoppe, Zinner, ... et al.

^{26}Al Found in ~ALL Candidate Sources

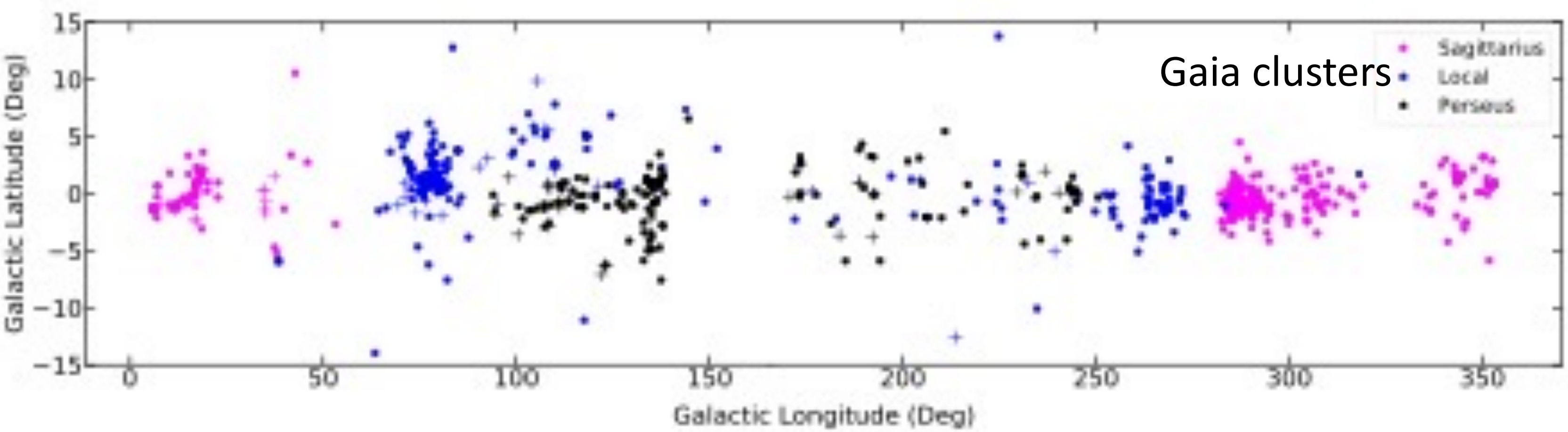
Massive stars and ^{26}Al radioactivity



Plüschke+ 2001



Zari+ 2021



Xu+ 2021

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

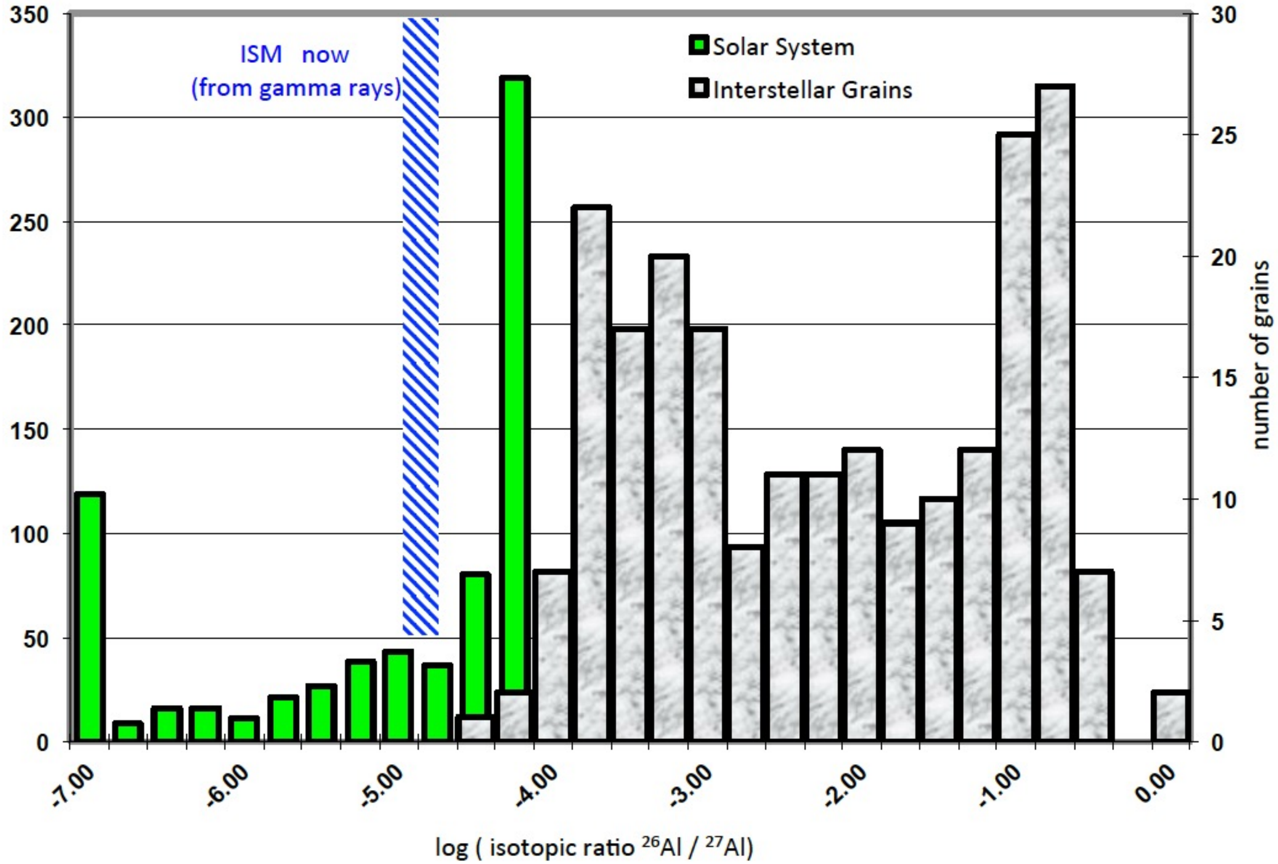
Early solar system meteorites measure ESS environment (→ ^{26}Al enriched?)

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

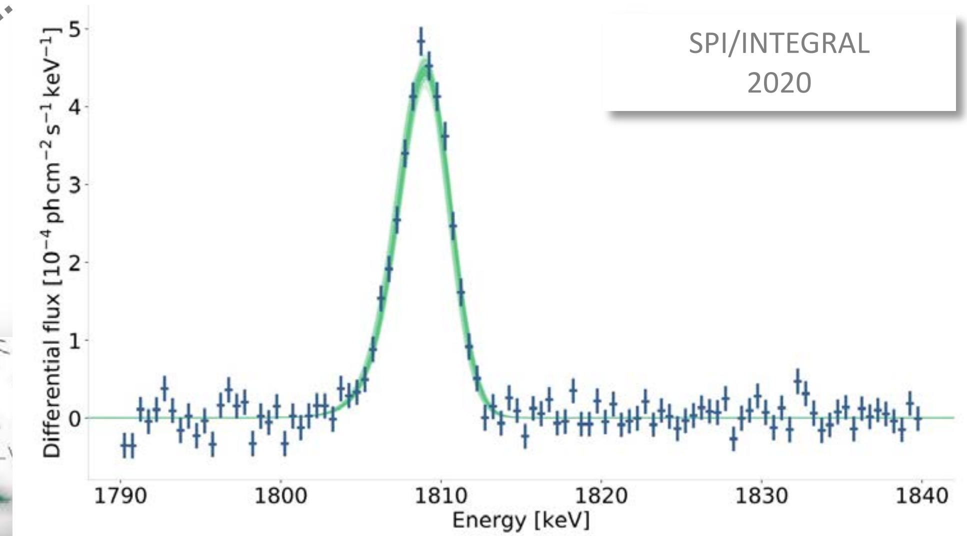
'canonical' value for ESS of ~5 10^{-5}
(McPhersson+1995)

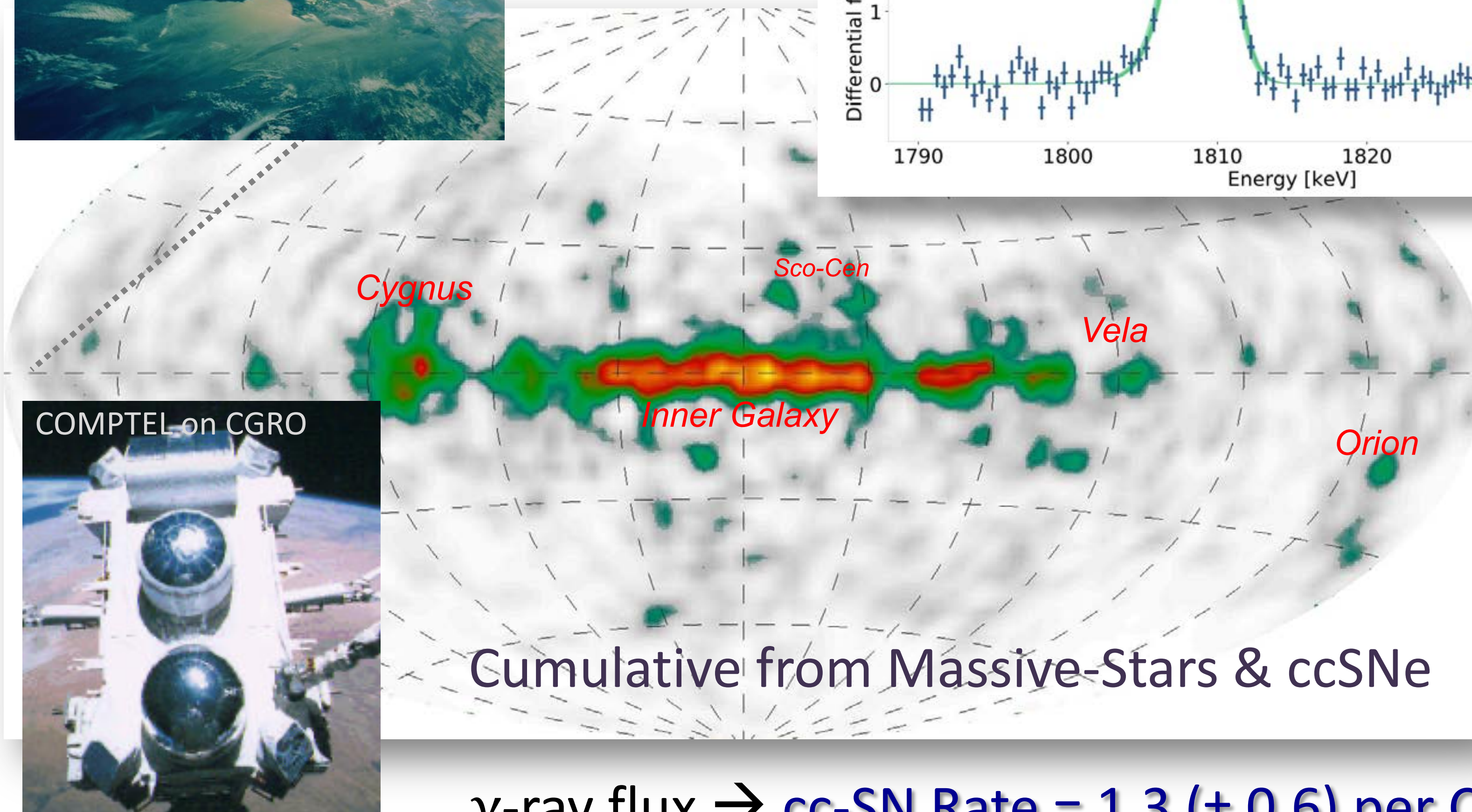
'supra-canonical' up to 6.5 10^{-5} ??
(Krot+2012, Makide+ 2013 ...)

Consolidated ESS $(5.23 \pm 0.13)\ 10^{-5}$
(Jacobsen+2013)



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





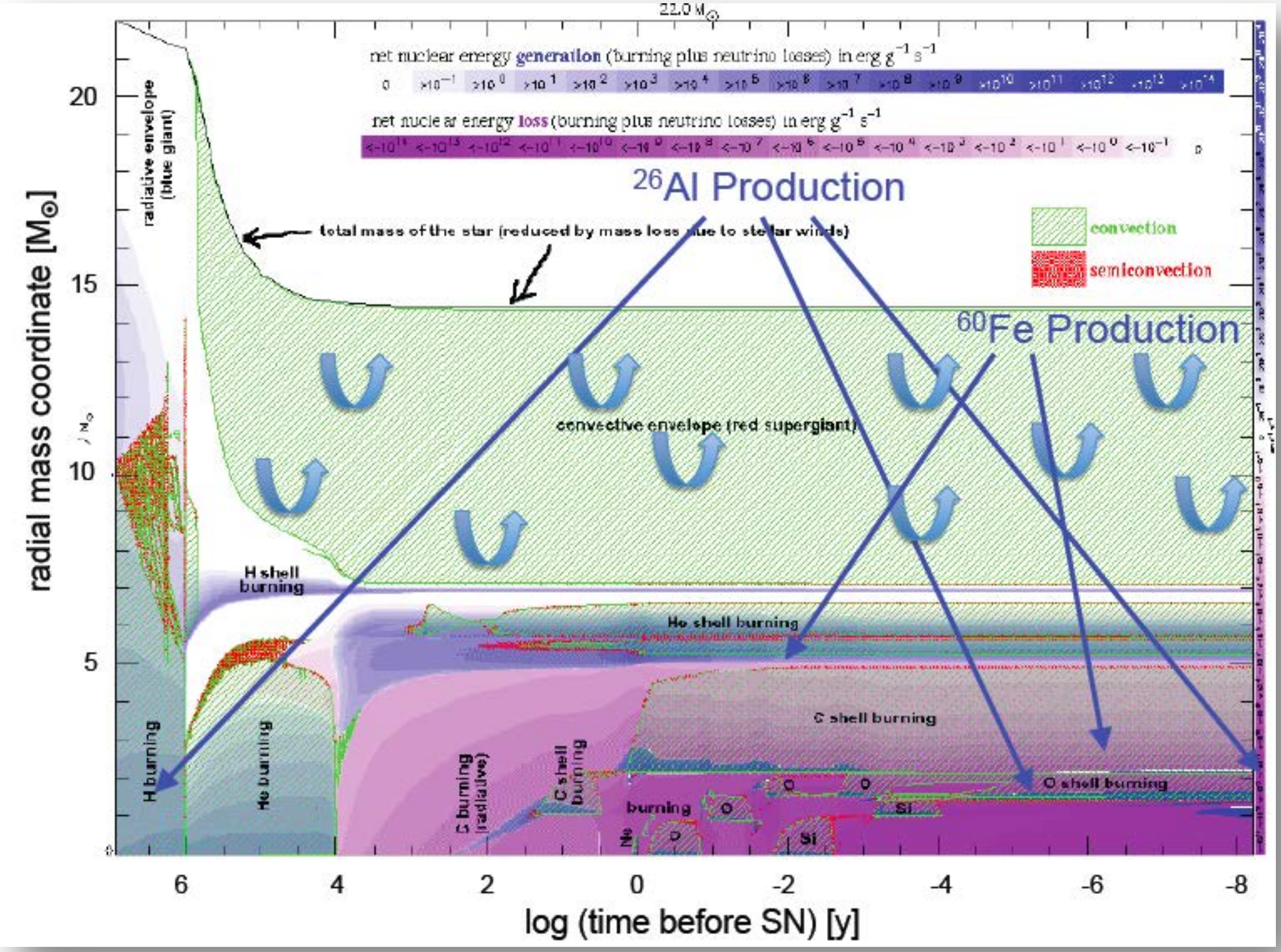
γ-ray flux → **cc-SN Rate = 1.3 (± 0.6) per Century**

Diehl+2006;2018

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

→ Messengers from Massive-Star Interiors!

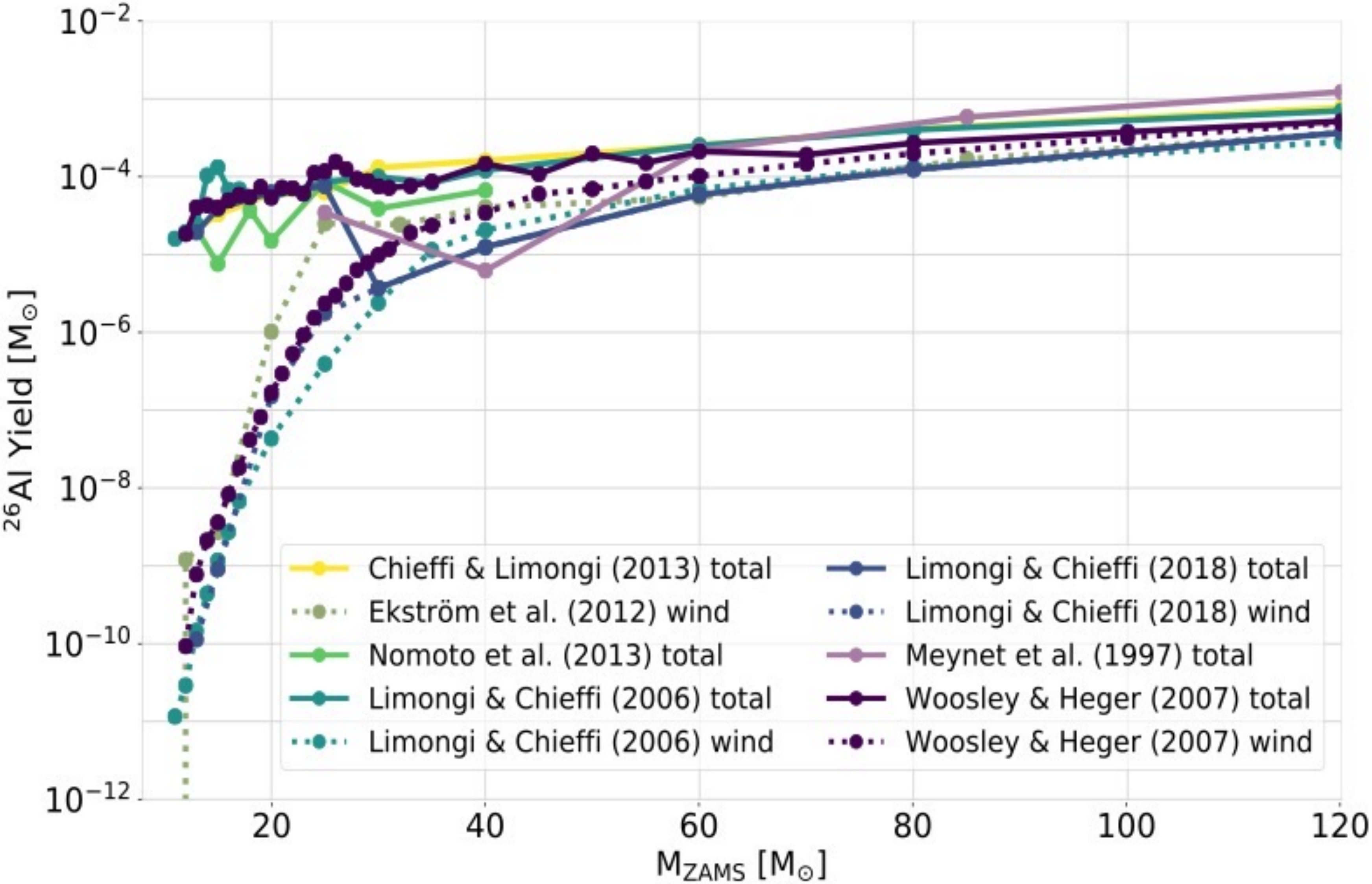
...complementing neutrinos and asteroseismology!



Processes:

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

^{26}Al Yields versus mass, for massive stars and their SNe



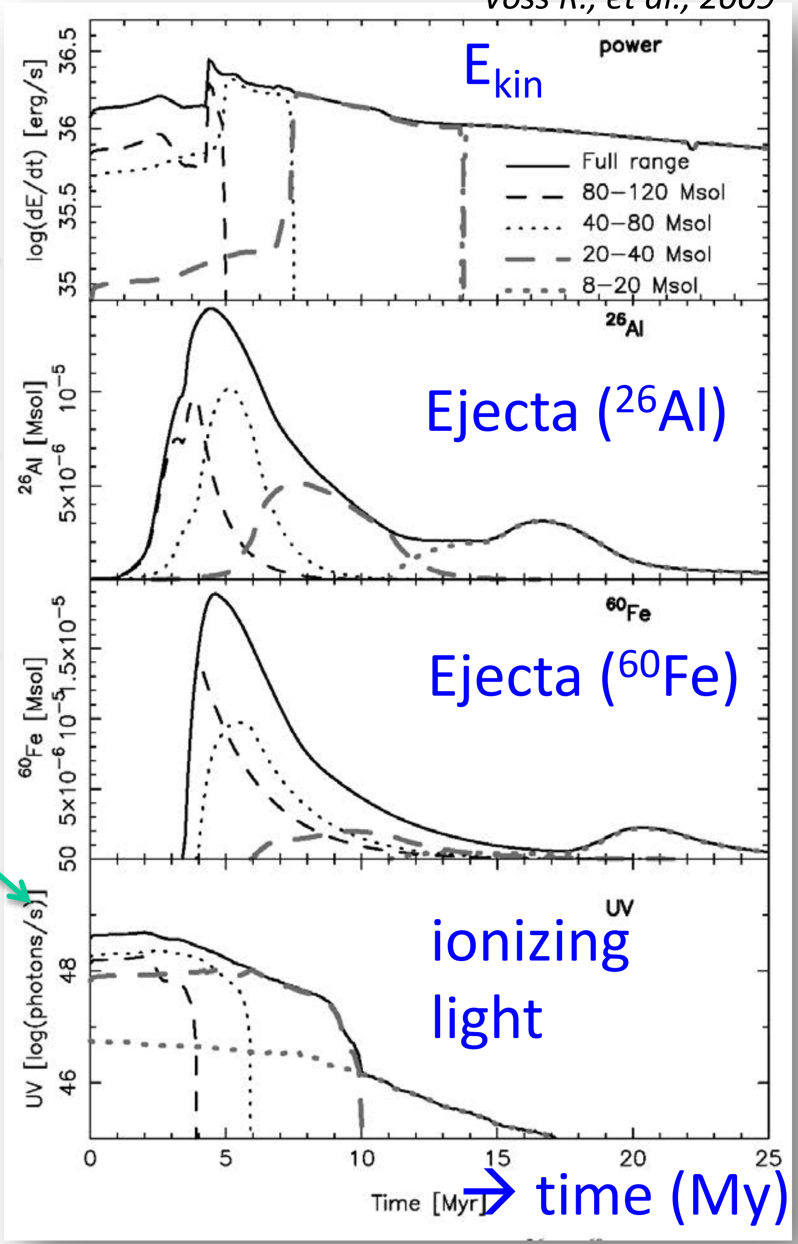
☞ ccSNe dominate for lower-mass range,
winds dominate over explosive ejecta for more-massive stars

Massive-Star Groups: Population Synthesis

- We model the "outputs" of massive stars and their supernovae from theory
  - Winds and Explosions
  - Nucleosynthesis Ejecta
  - Ionizing Radiation

- We get observational constraints from
  - Star Counts
  - ISM Cavities
  - Free-Electron Emission
  - Radioactive Ejecta

Voss R., et al., 2009

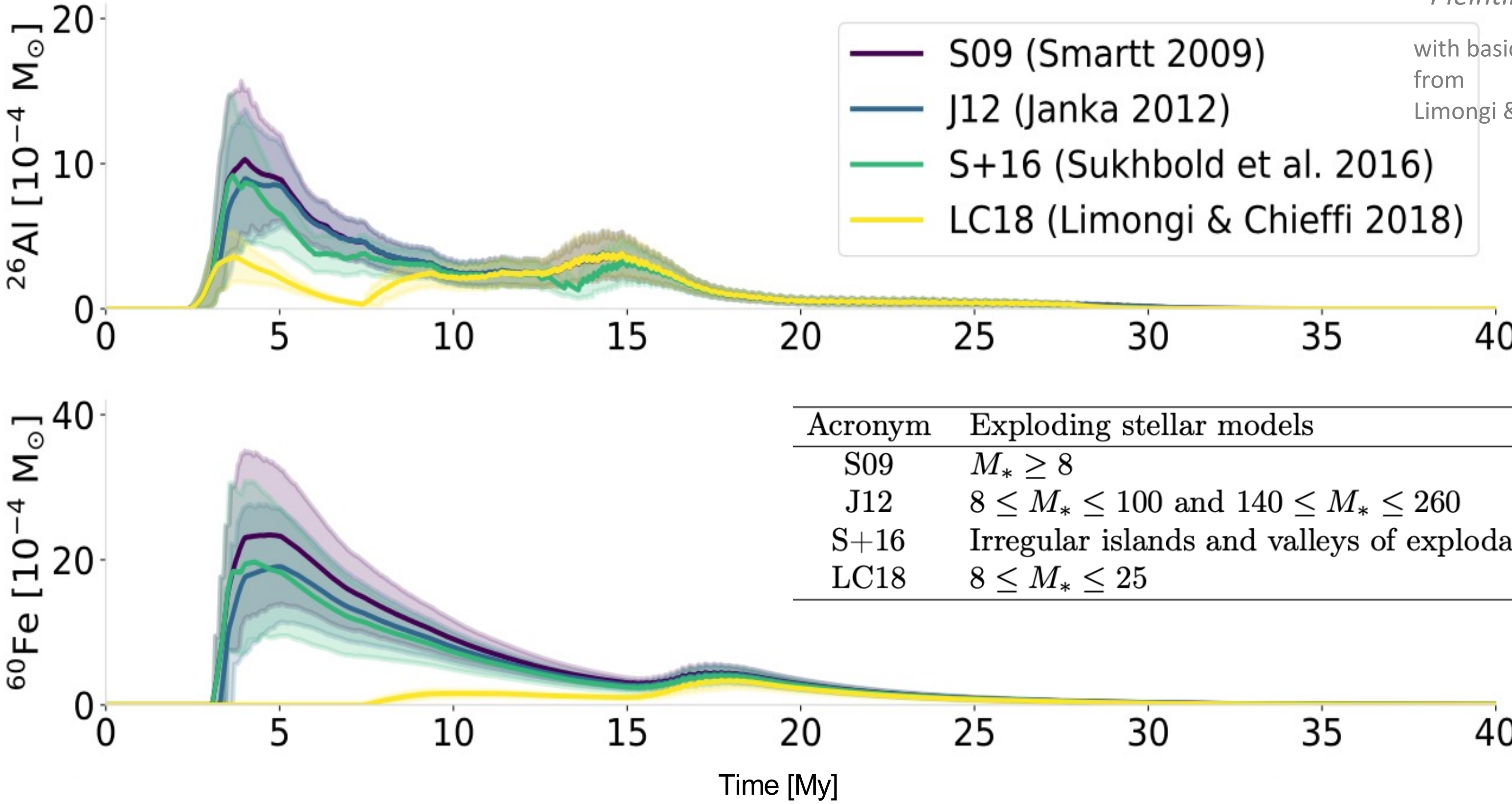


Population synthesis: impact of different inputs on groups

variation of explodability *(i.e.: not all stars of high mass make a SN!)*

Pleintinger 2020

with basic yields from Limongi & Chieffi 2006



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	$8 \leq M_* \leq 25$

☞ contributions from early (i.e. most-massive-stars') SNe eliminated if non-exploding

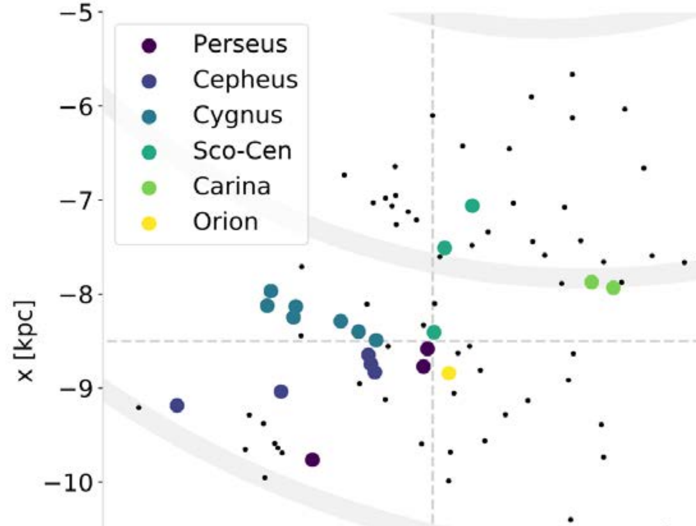
Diffuse radioactivity throughout the Galaxy

Galactic Population Synthesis Modelling

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

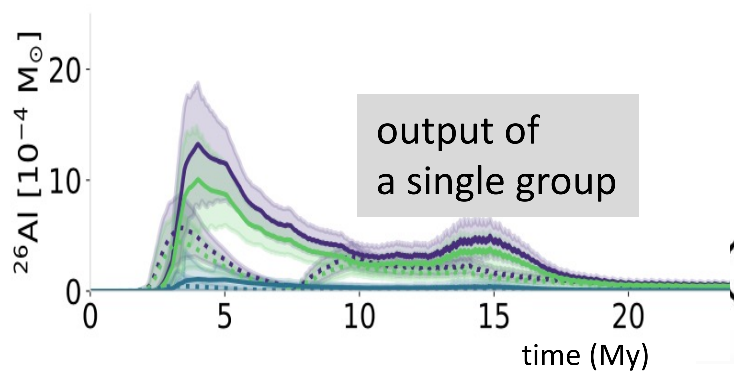
Pleintinger PhD thesis 2020

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

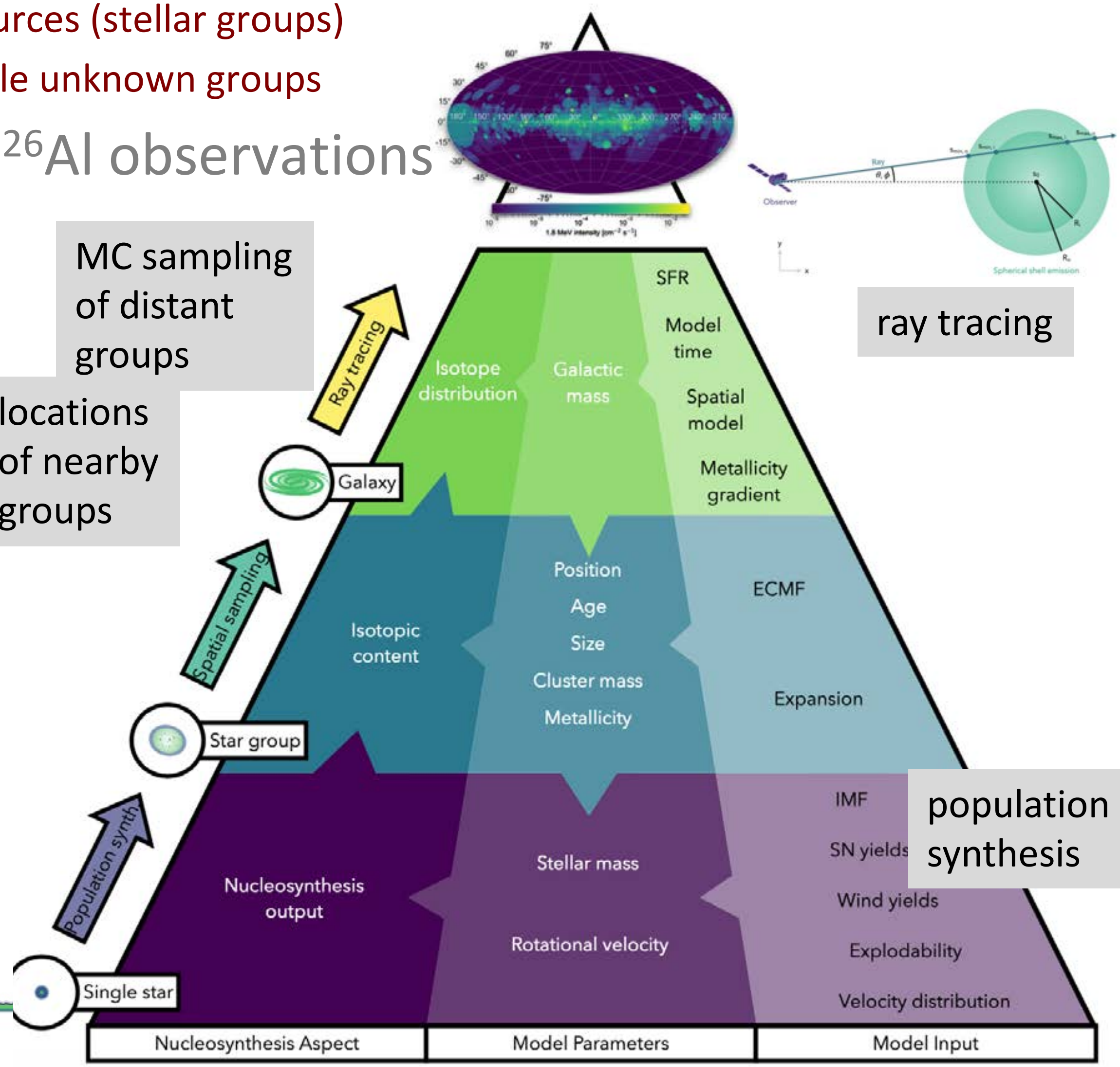


MC sampling of distant groups

locations of nearby groups



output of a single group



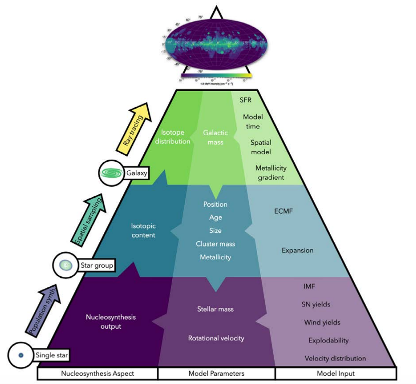
ray tracing

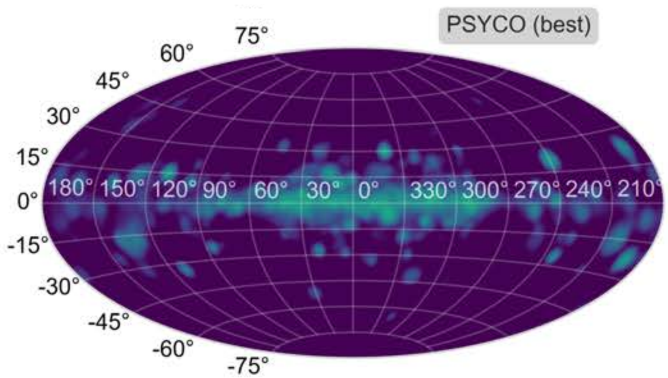
population synthesis

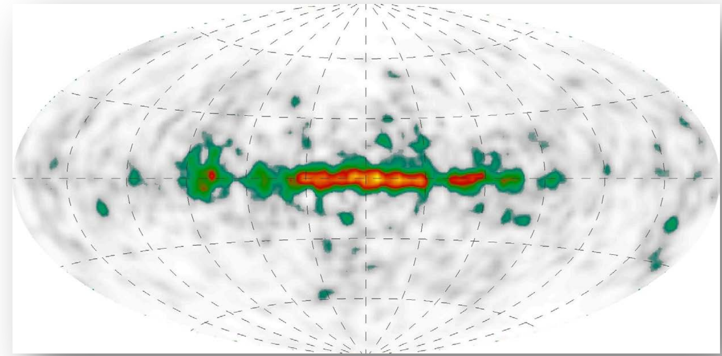
Diffuse radioactivity throughout the Galaxy

Galactic Population Synthesis Modelling versus observations

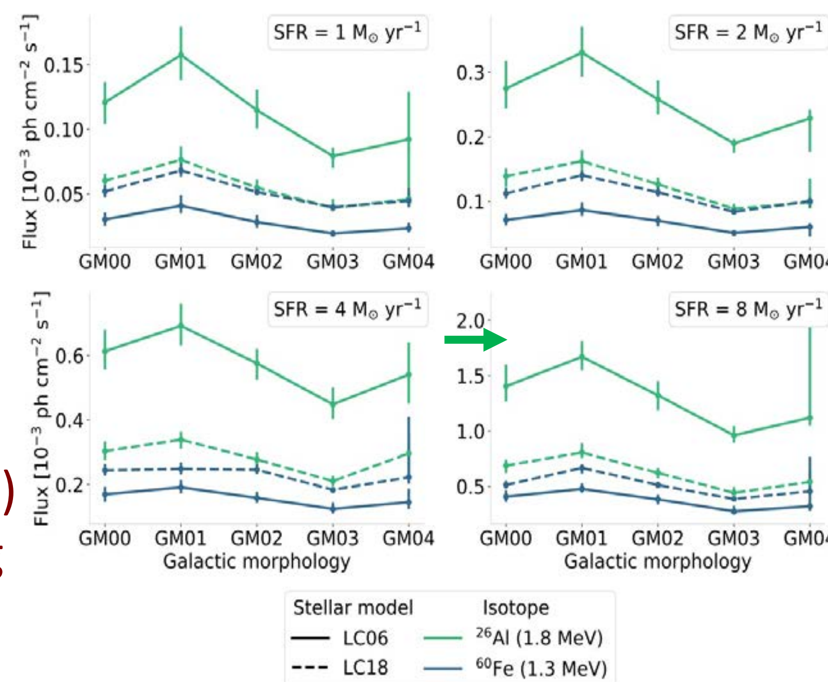
Pleintinger 2020
Siegert+ 2022





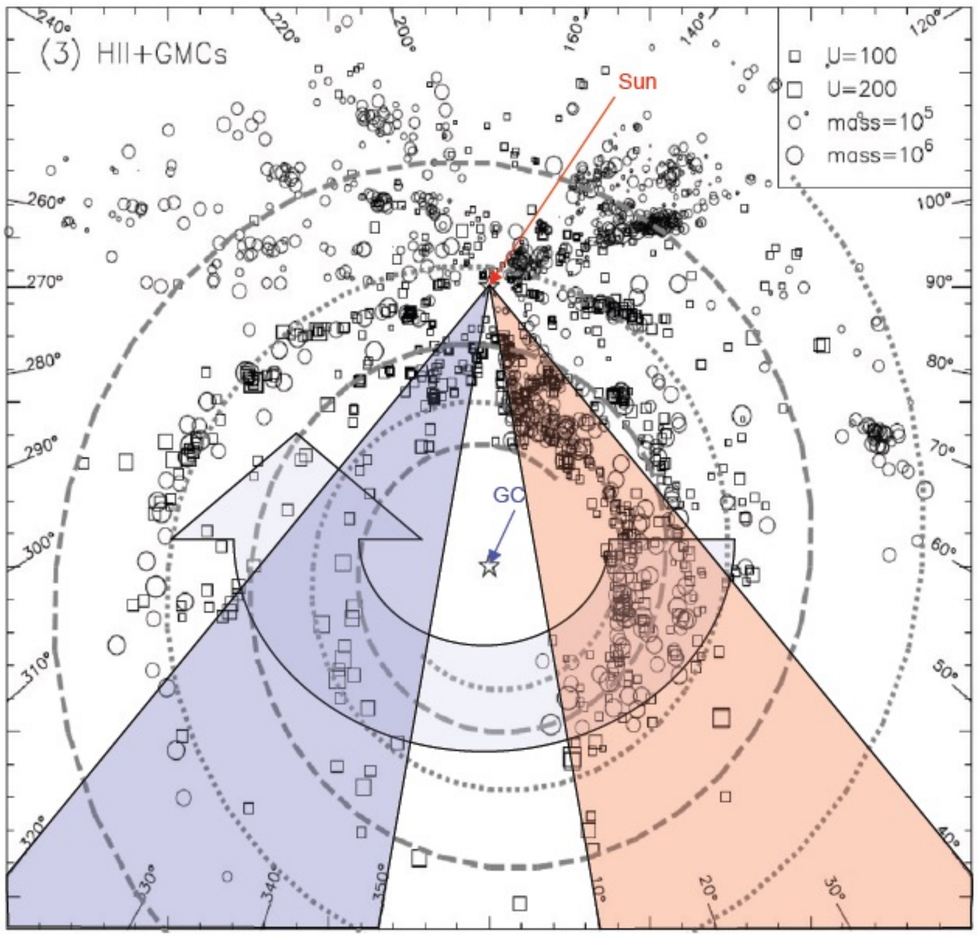


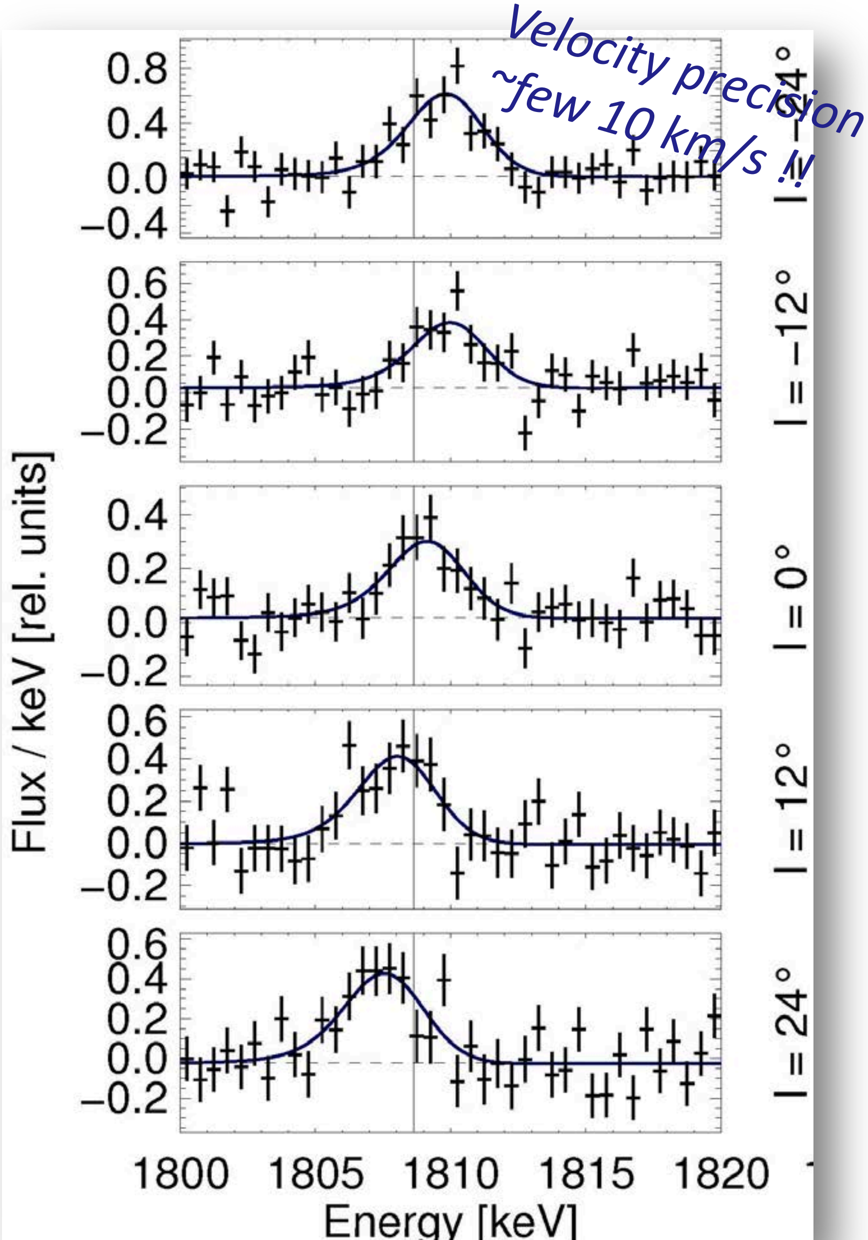
- PSYCO 30000 sample optimisation
  → 4-arm spiral 700 pc, LC06 yields, SN explosions up to 25 $M_\odot$
- observed full sky flux:
  $(1.84 \pm 0.03)\ 10^{-3}$ ph cm^{-2} s^{-1}
- model-predicted ^{26}Al:
  → ≈ x 10^{-4} ph cm^{-2} s^{-1} → too low
- Best-fit details (yield, explodability) depend on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



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

☞ Large-scale Galactic rotation

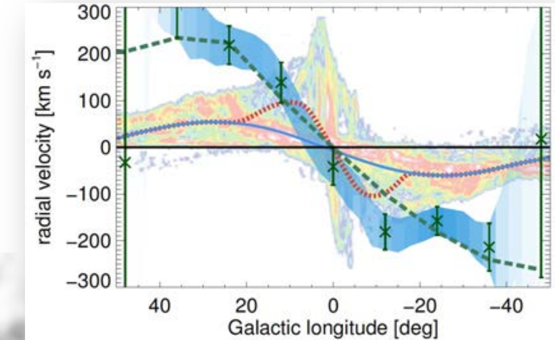


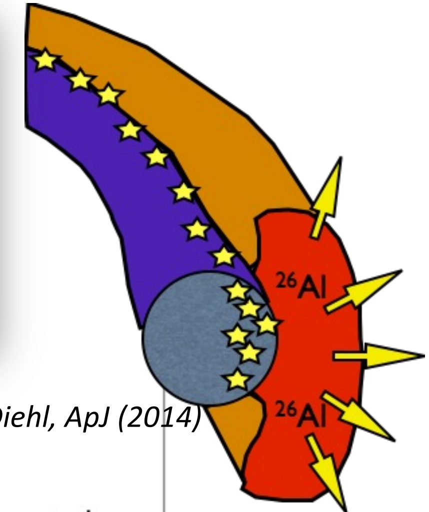


Kretschmer et al., A&A (2013)

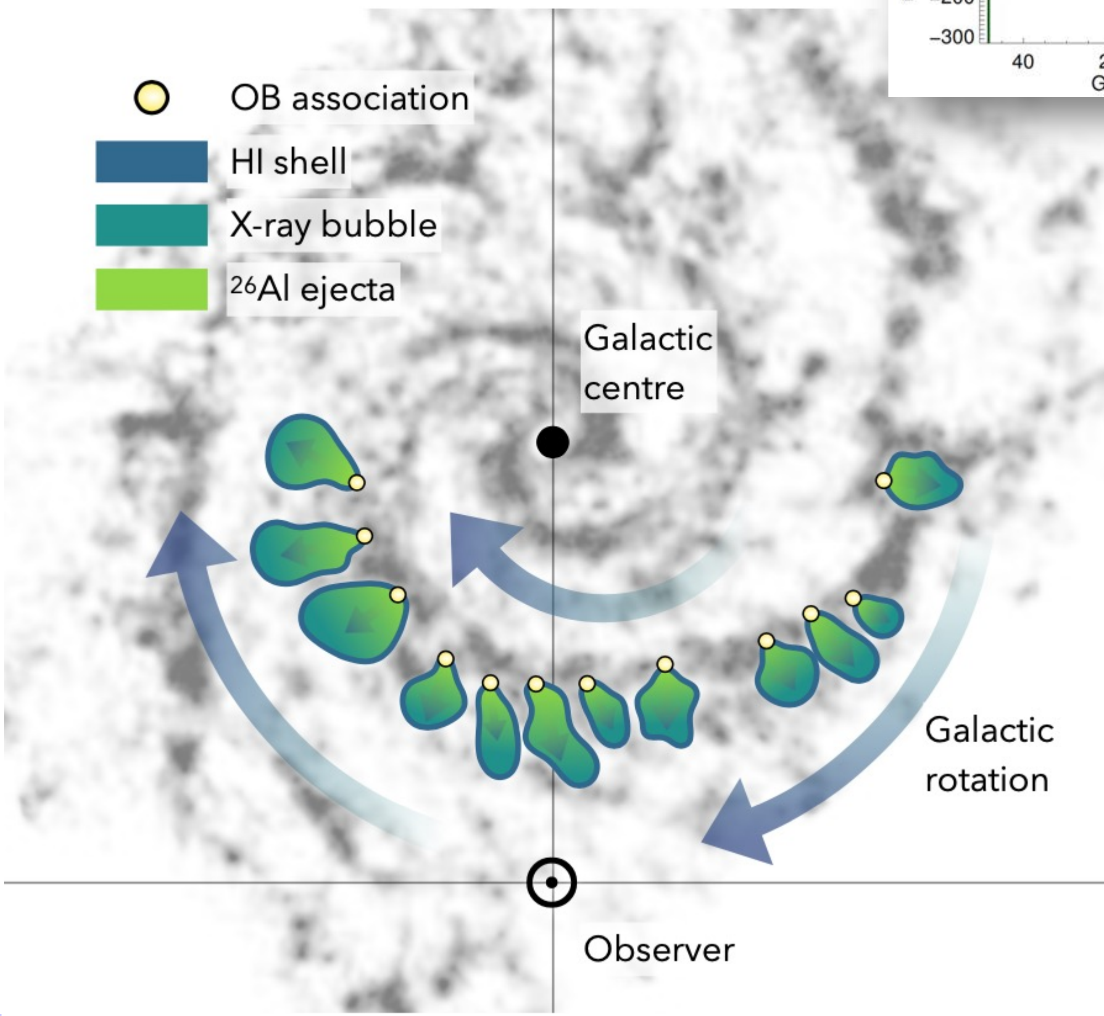
How massive-star ejecta are spread out…

Superbubbles extended away from massive-star groups





Krause & Diehl, ApJ (2014)



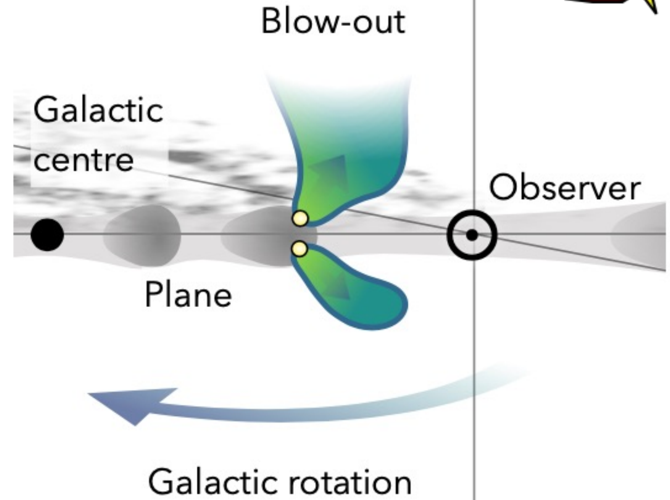
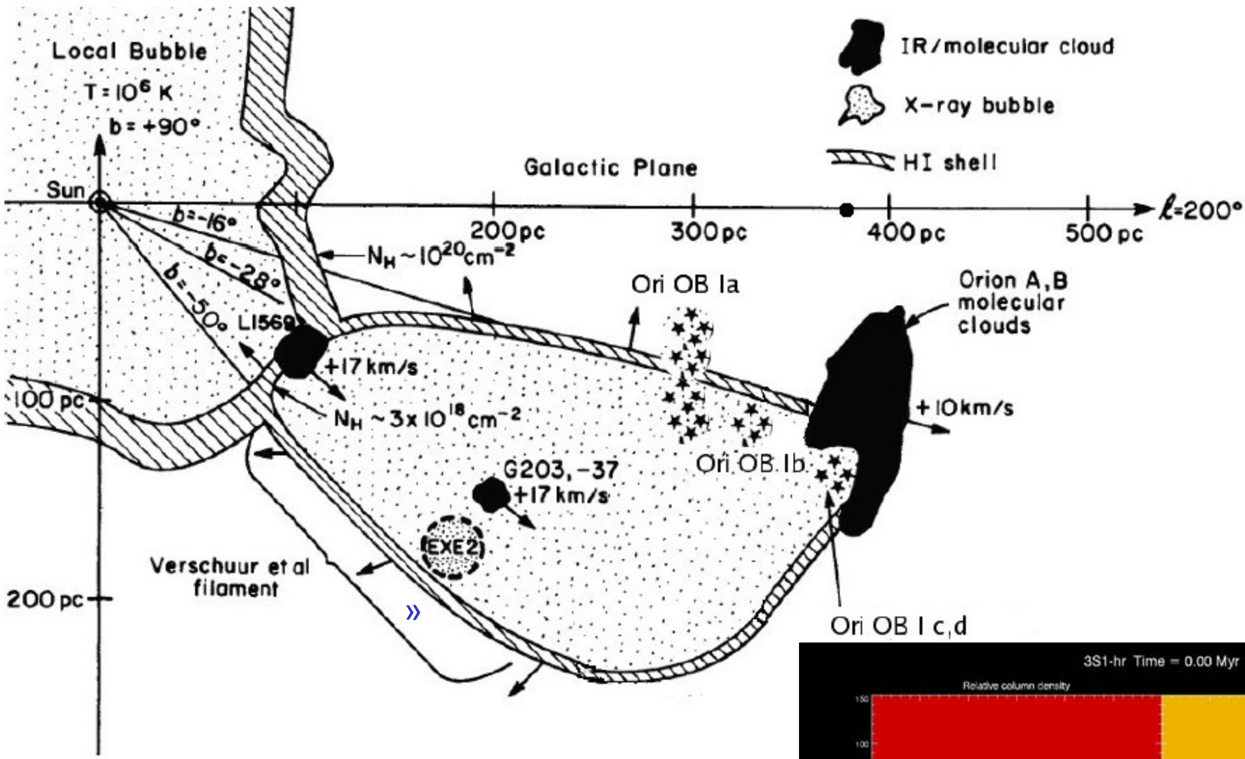
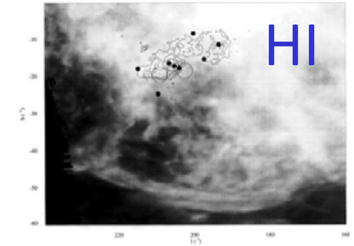


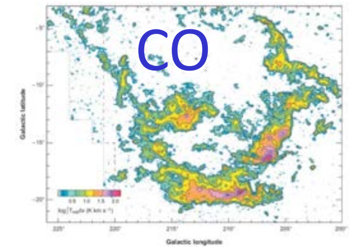
Illustration by M. Pleintinger (2020)

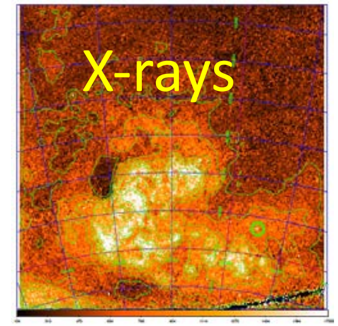
Orion-Eridanus: A superbubble blown by stars & supernovae

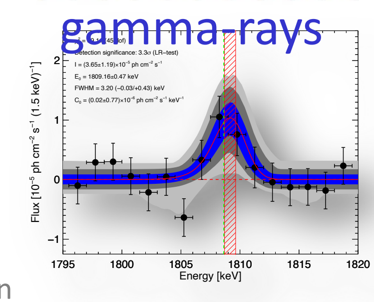
ISM is driven by stars and supernovae → Ejecta commonly in (super-)bubbles



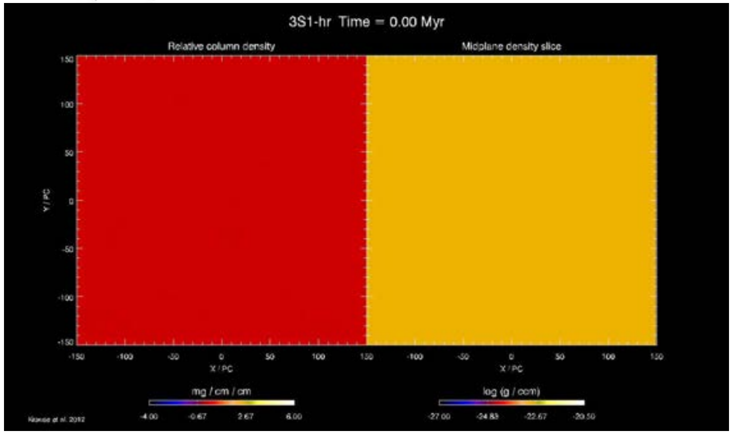








Krause+ 2014, Fierlinger+ 2016,
Voss+ 2010, Diehl+2003

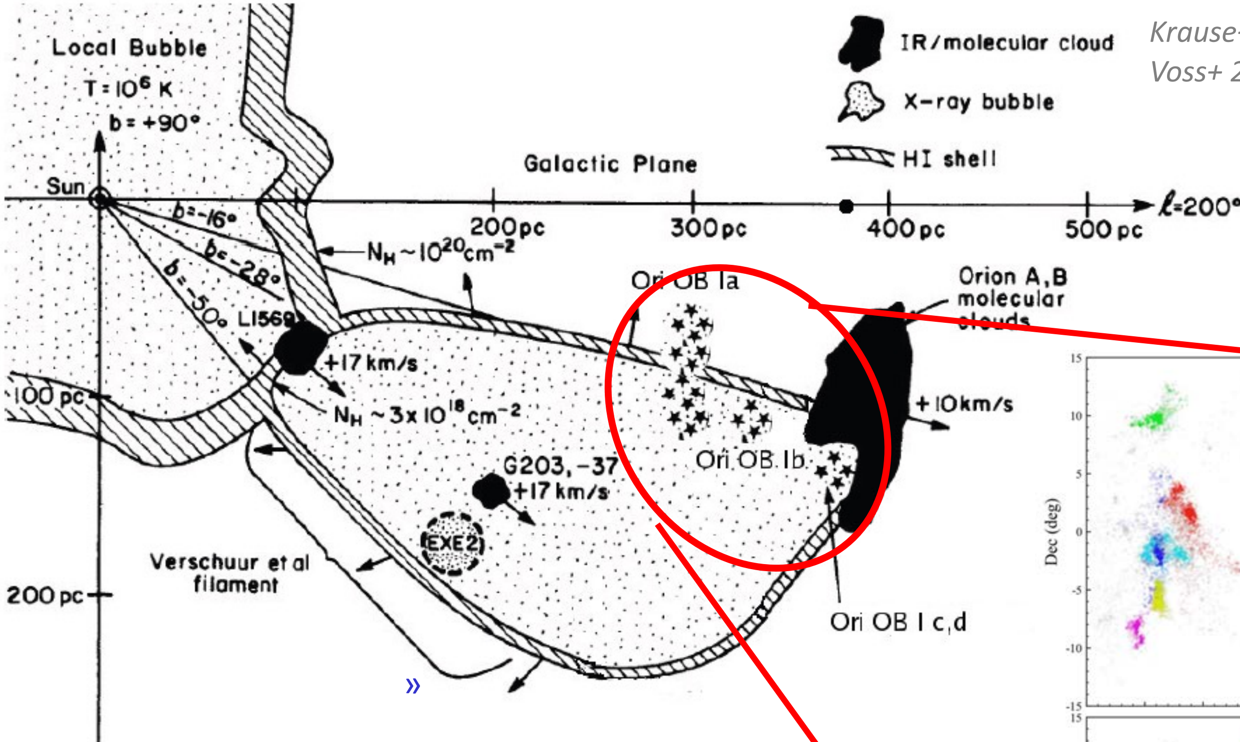


3D MHD sim, 0.1..0.005 pc resolution
Krause+ 2013ff

Stars, structures, & shells

ISM is driven by stars and supernovae

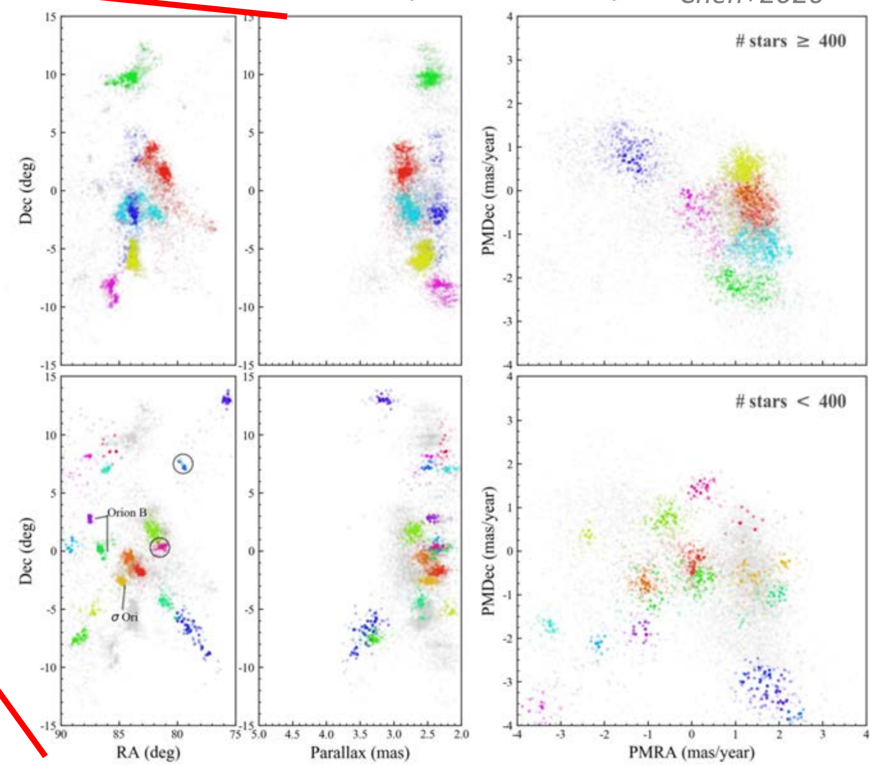
→ Use stellar census for estimation of driving energy & nucleosynthesis (^{26}Al)

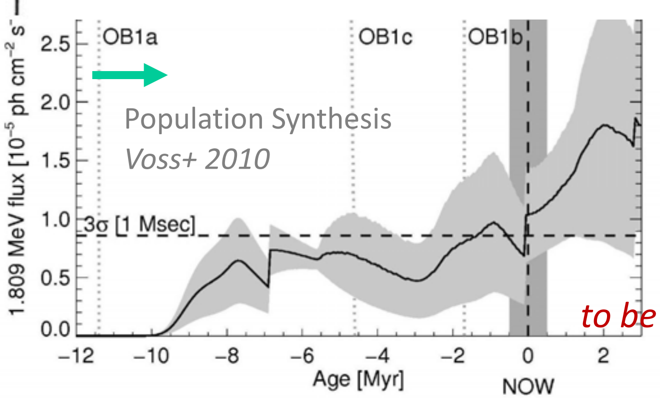


Krause+ 2014, Fierlinger+ 2016, Voss+ 2010, Diehl+2003

Gaia parallax analyses
→ 22 stellar groups
-150pc<MCs<50pc

Chen+2020



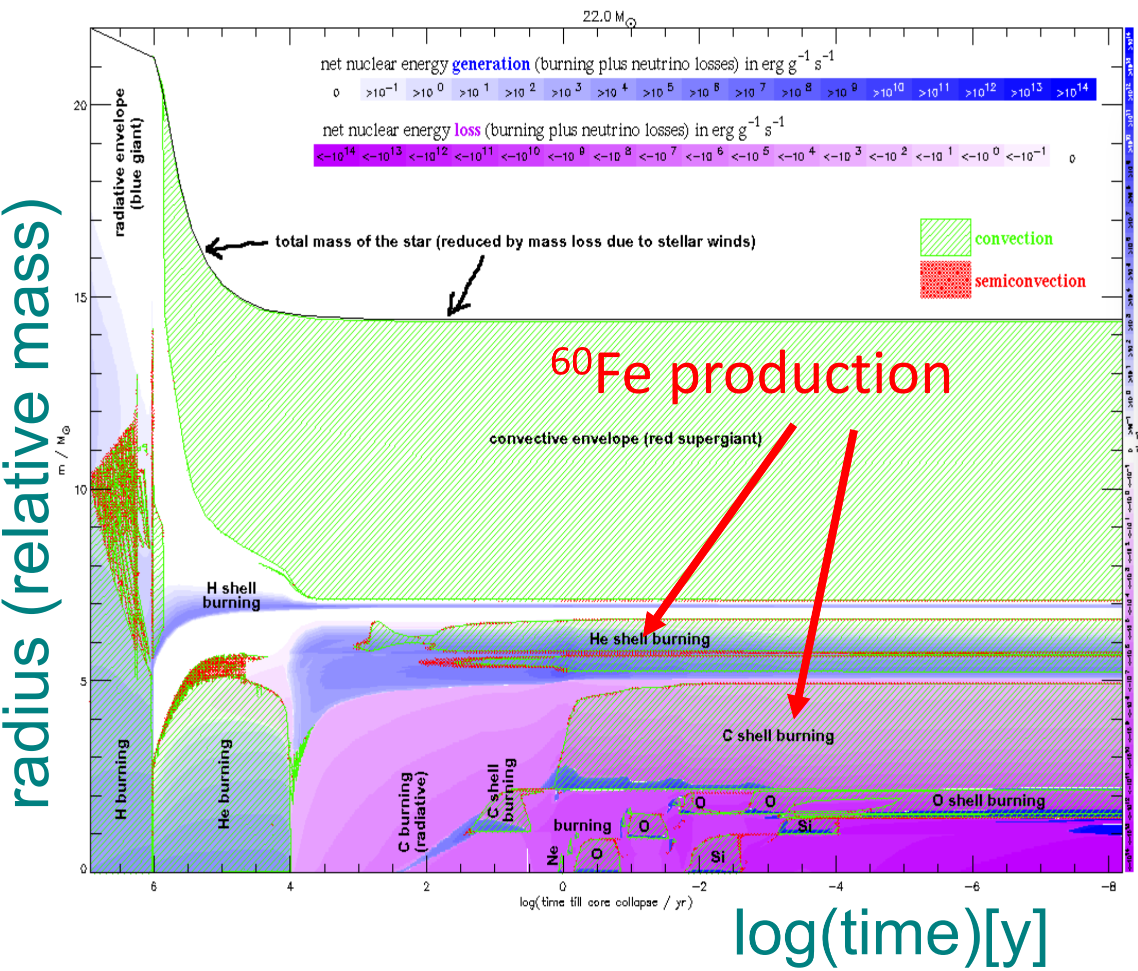


to be renewed...

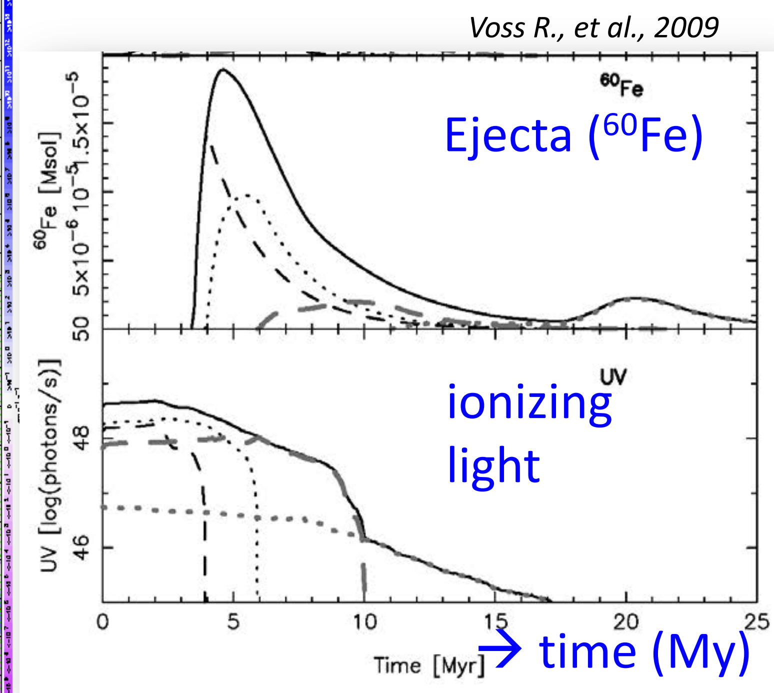
How massive stars stars evolve towards the ccSN

- neutron-releasing reactions only in He and C burning
- ^{60}Fe production only in late evolution → released only with ccSN

Kippenhahn diagramn of stellar evolution

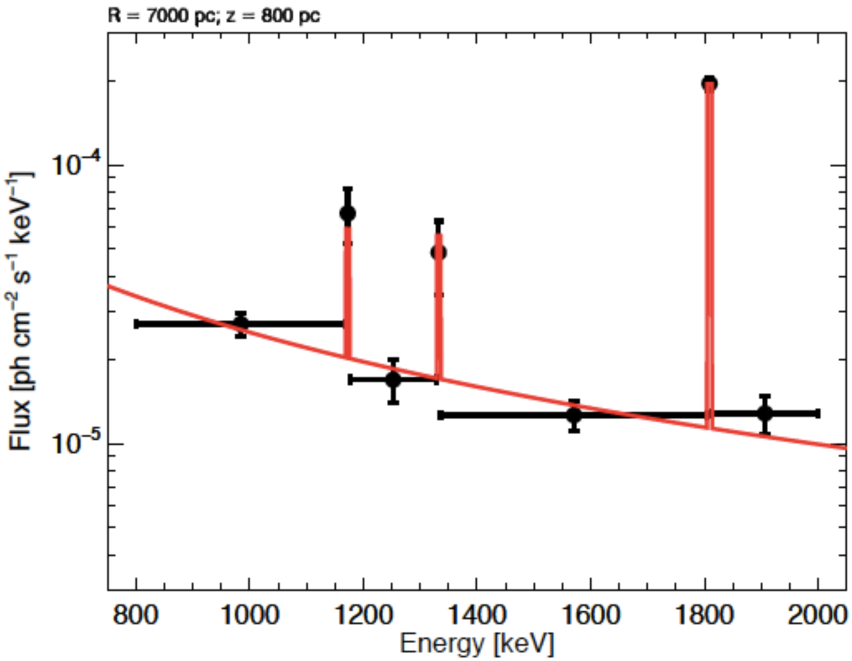


evolution of a group of stars (popSyn)



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

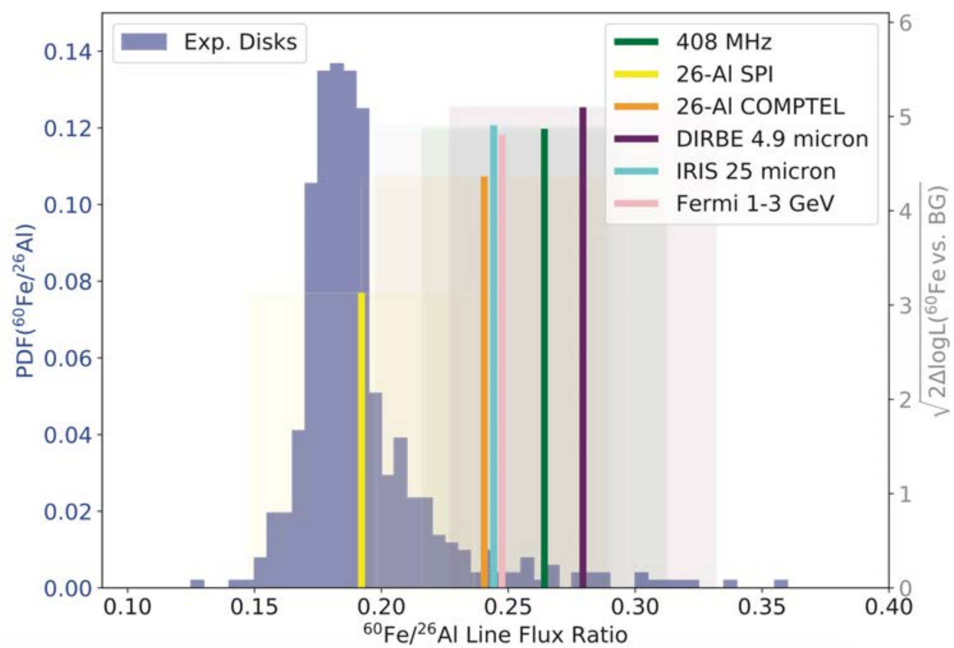
^{26}Al and ^{60}Fe analysis with same INTEGRAL dataset (15+ years) and models



^{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

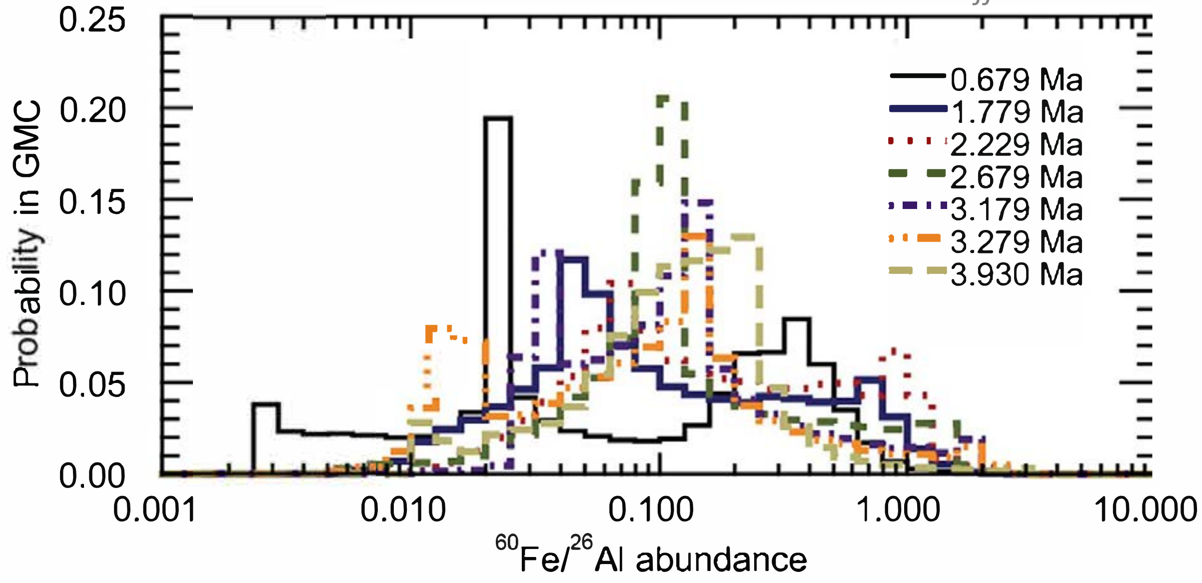
cmp theory: 0.2...1,

and oceancrusts: >0.2

Ejecta in star-forming regions

- The composition will vary locally, near newly-ejected ashes

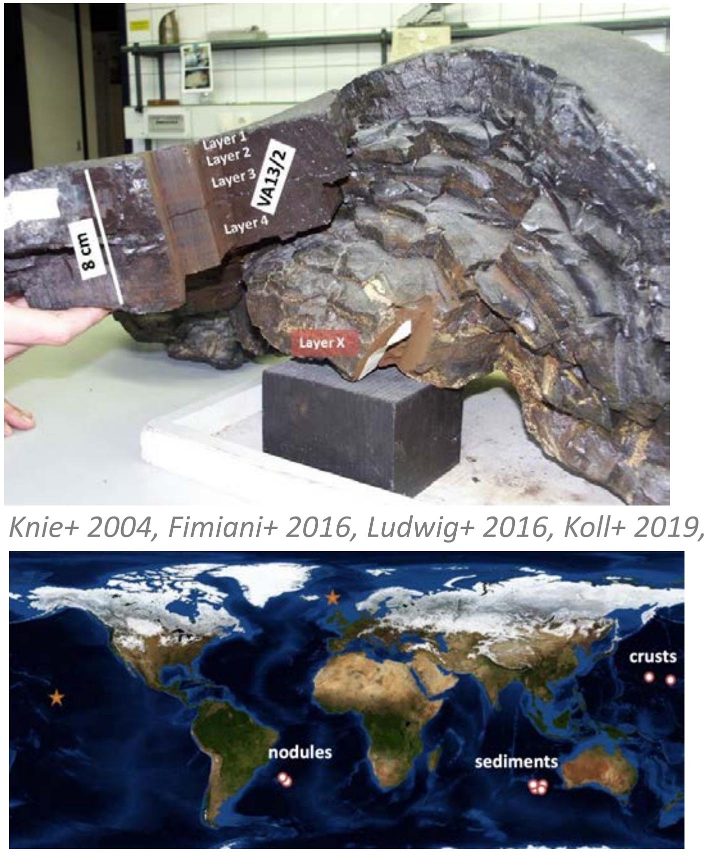
Kuffmeier+2016



☞ major dependencies on assumptions about GMC morphology (→ 'feedback'?!!)

- Newly ejected ashes could be incorporated into 2nd gen stars
- The Galaxy at large has $^{60}Fe/^{26}Al$ ~ 0.5,
  the ESS had ~0.002 – can we get more & different viewpoints?

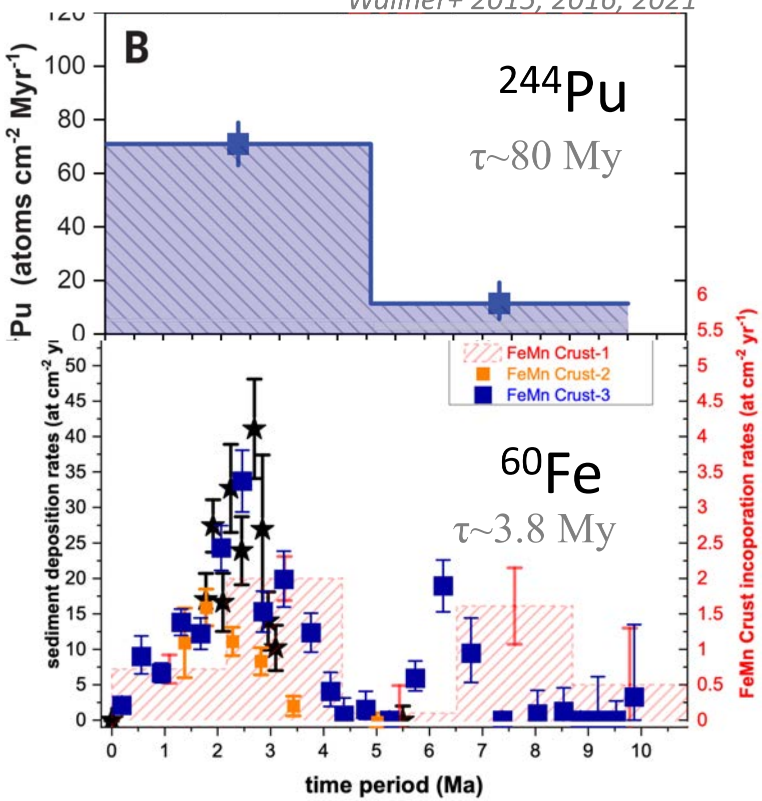
^{60}Fe and ^{244}Pu from nearby nucleosynthesis found on Earth



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?

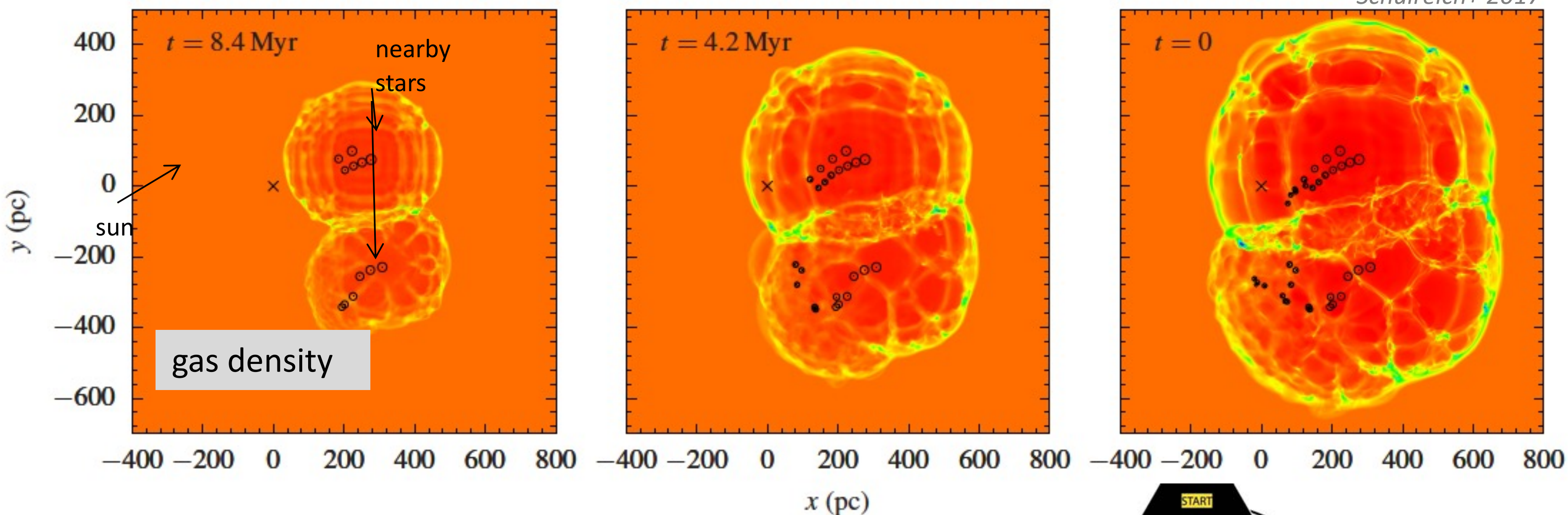
How did these traces of nucleosynthesis get here?

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

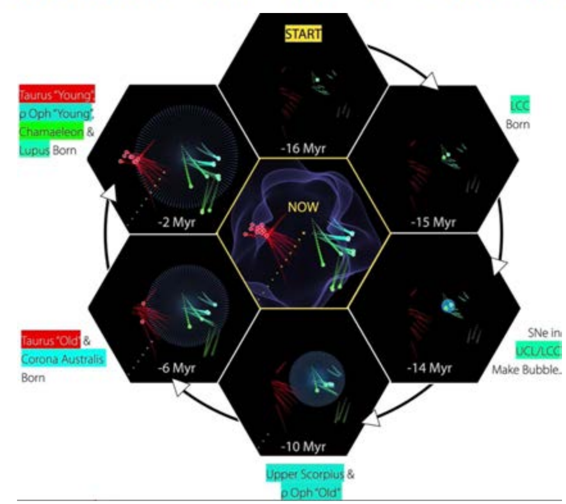
The Sun is located inside a hot cavity (Local Bubble & Loop-1)

SN explosions within LB → ejecta flows reach the Solar System

Schulreich+ 2017

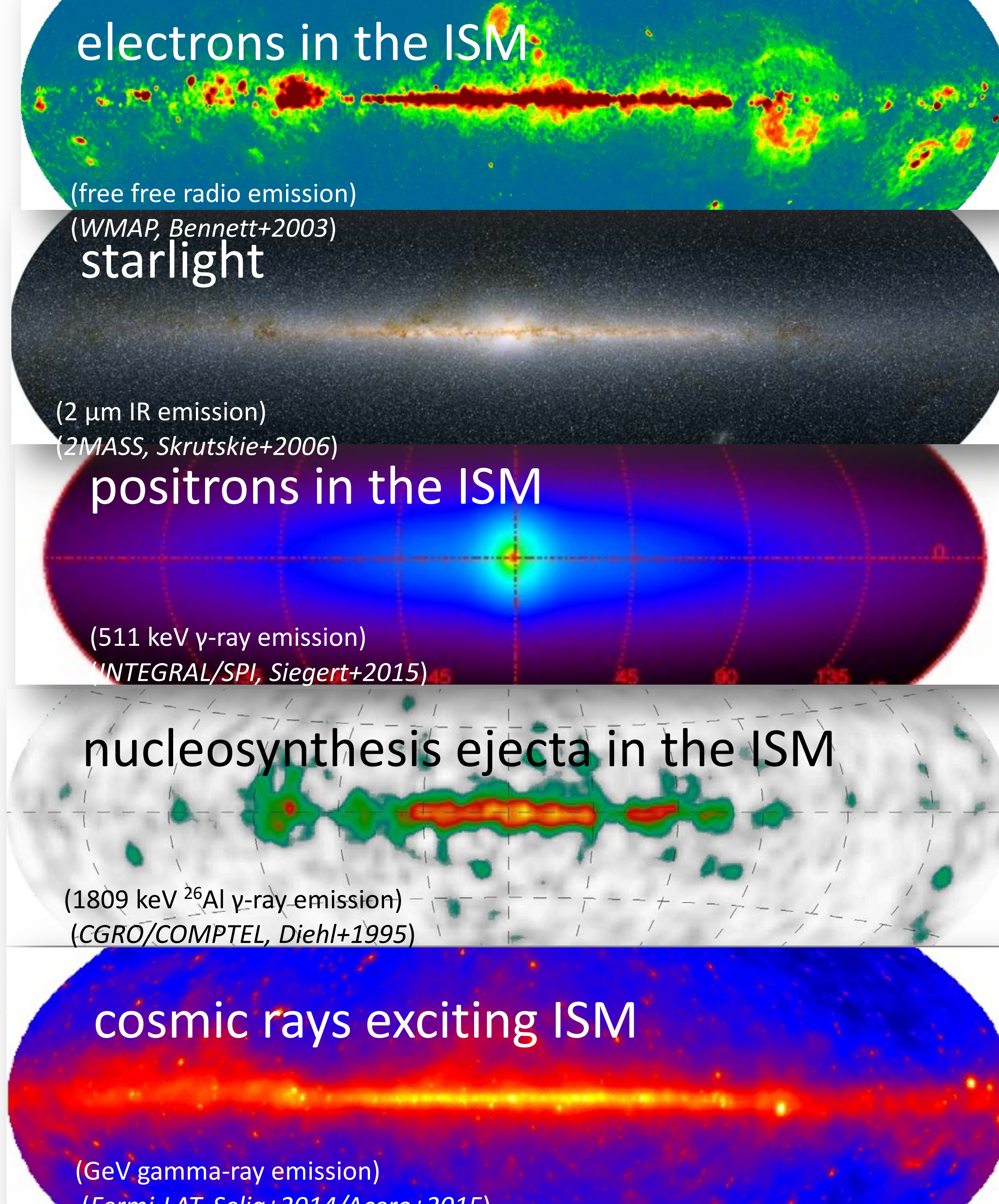


see also Zucker+ 2022 for a recent update on the Sco-Cen SN activity



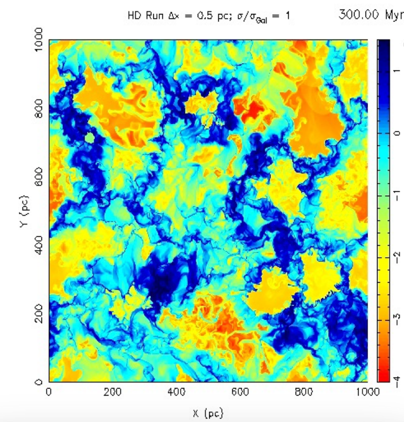
^{26}Al Radioactivity: Special Messengers

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

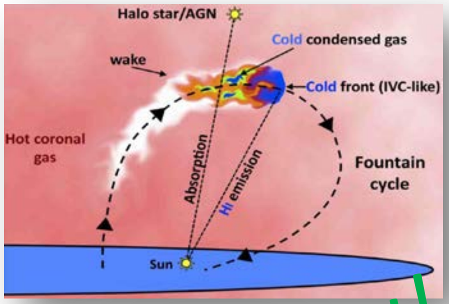


Nucleosynthesis & Gamma-Ray Spectroscopy - Summary

- ☆ 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

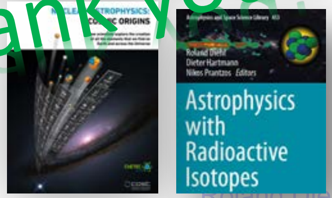


- ☆ Cycling of cosmic gas through sources and ISM is a challenge
  - ^{26}Al preferentially appears in superbubbles
    → massive-star ingestions rarely due to single WR stars or SNe
  - the current Galactic SN rate is ~1/70 years
  - ^{60}Fe is a SN/wind ejecta diagnostic (SBs older than for ^{26}Al)



- ☆ 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)
    is a dream 2040+; INTEGRAL ends 2029; COSI is a step (2027)...

Thank you!



a new brochure on nuclear astrophysics (by ChETEC/COST)

in case you'd like a PDF of this brochure: email rod@mpe.mpg.de