



Proton → Neutron



Nuclear Astrophysics and gamma-ray observations

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Garching

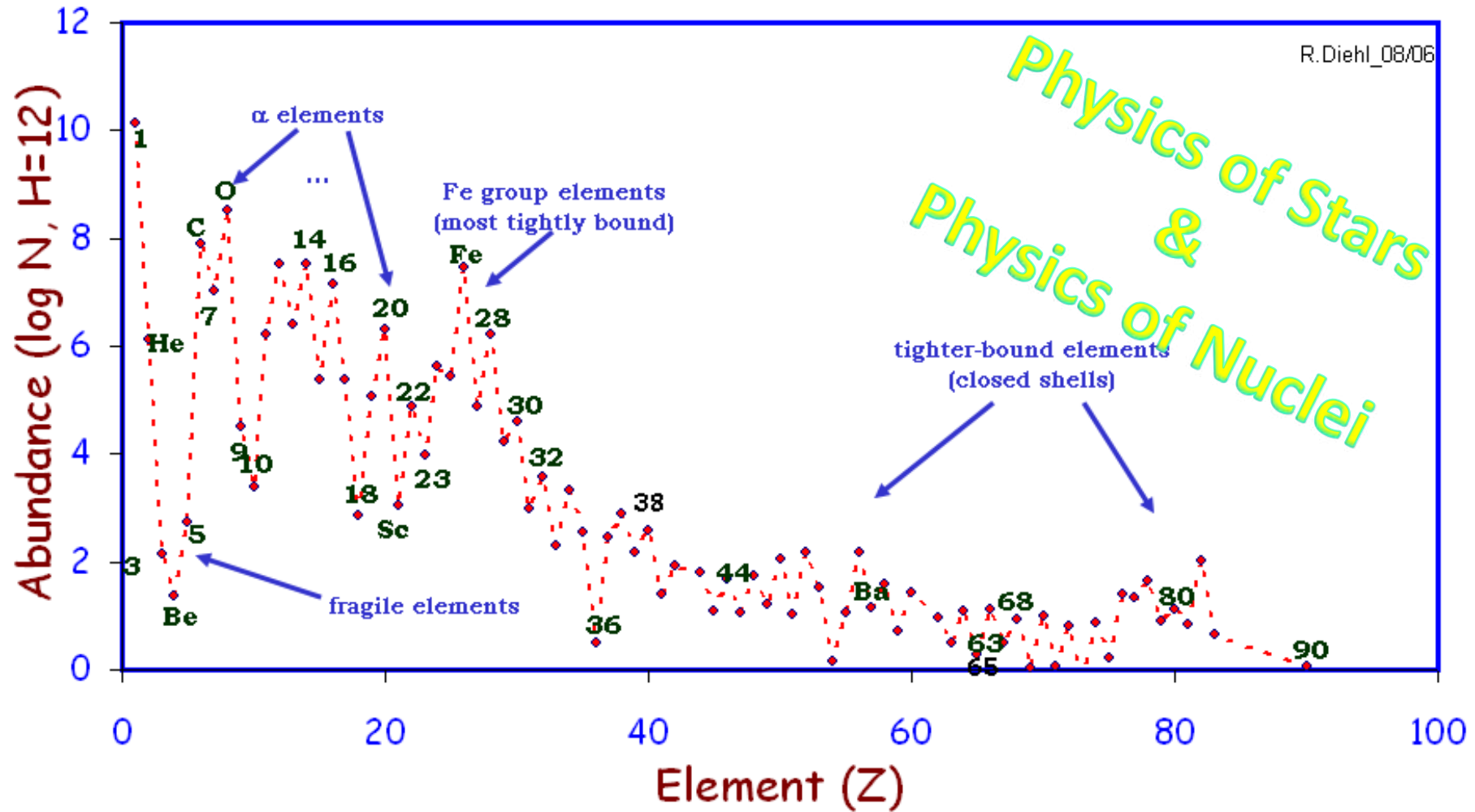
Contents:

1. Challenges in Nuclear Astrophysics
2. Achievements of γ -ray observations
 - supernovae, massive stars
 - ejecta flows
 - ...

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

Figure: ChETEC 2021

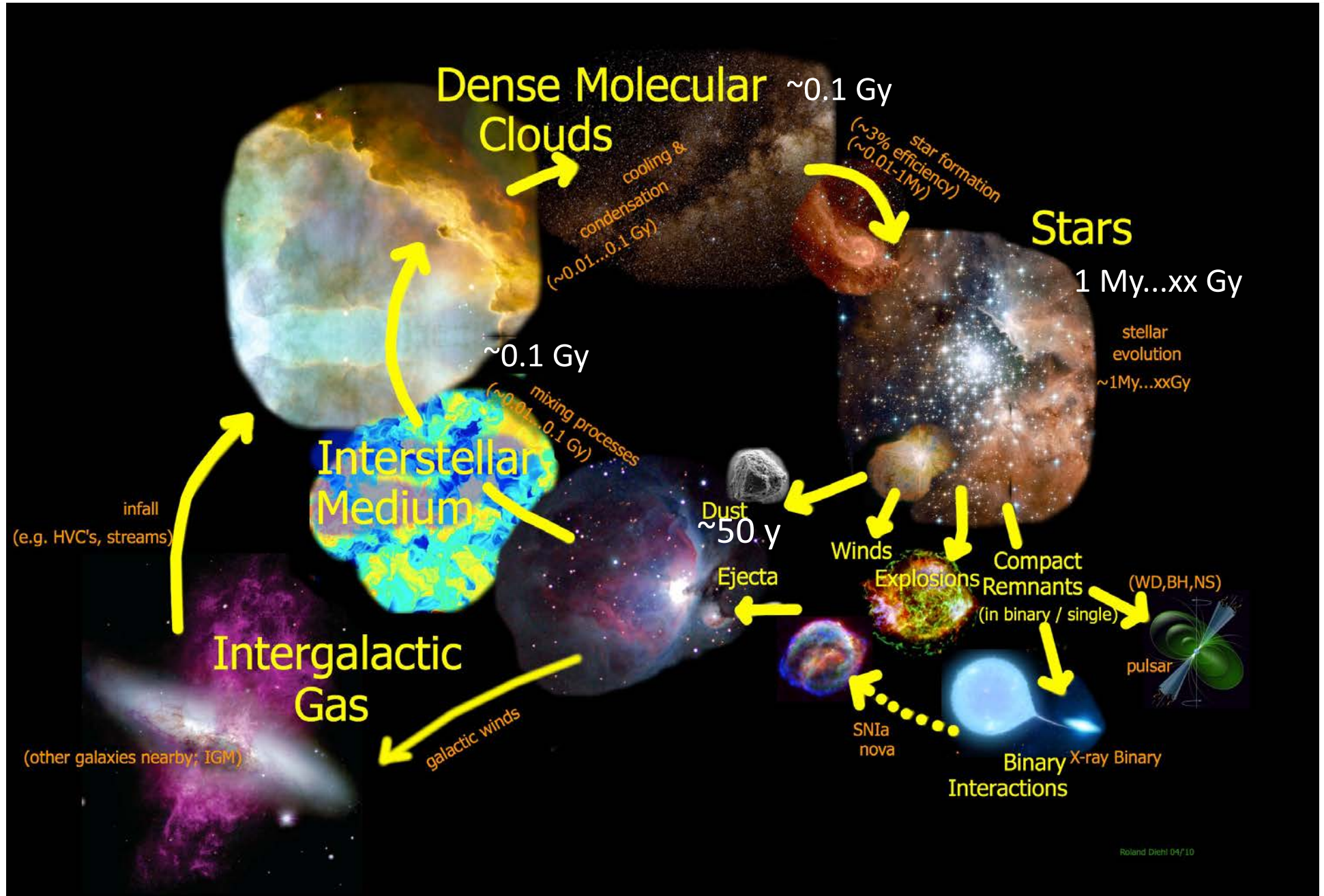
The Messages from Cosmic Elemental Abundances



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?)

On-going Enrichments from Nucleosynthesis Sources

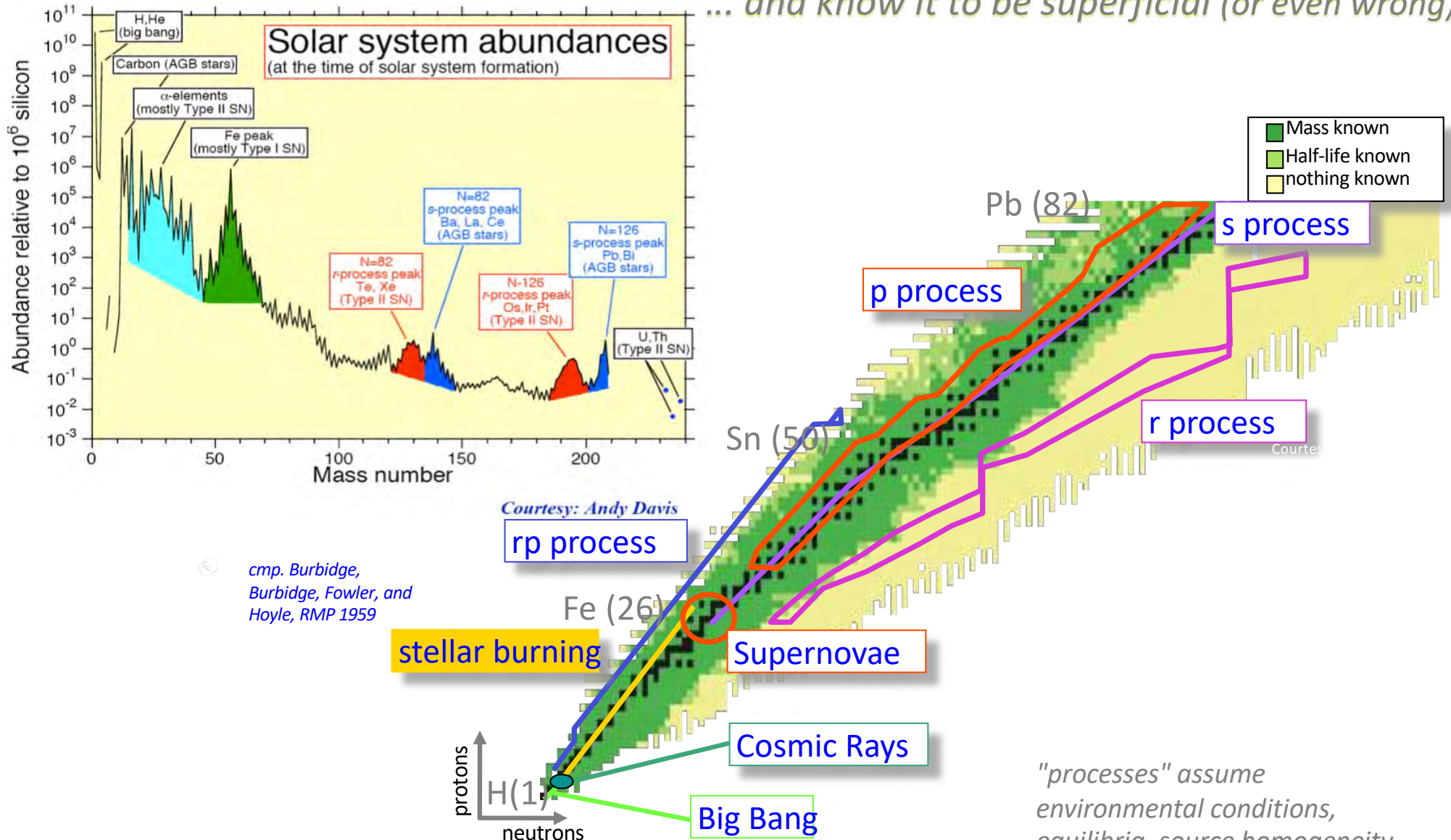


Cosmic origins of the variety of nuclides



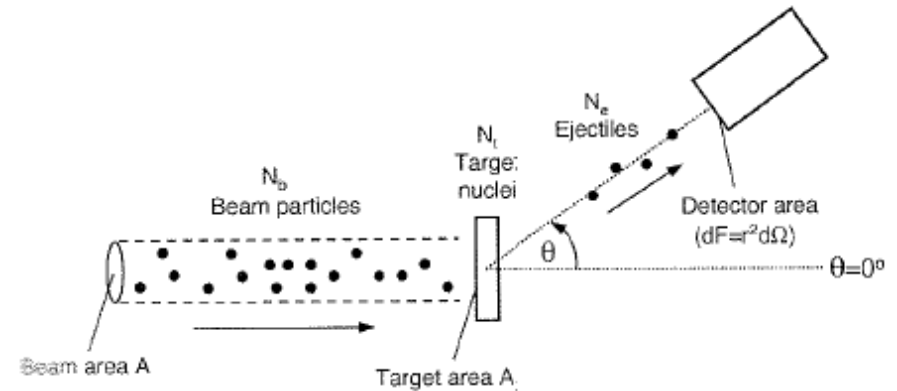
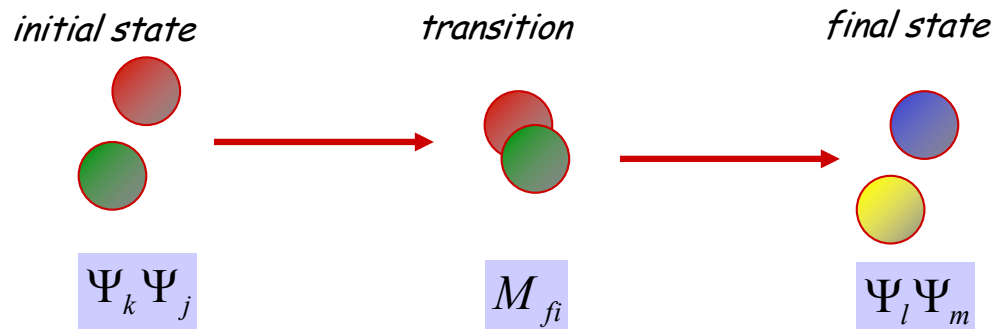
Associating different “processes” with nuclide groups – *what we teach...*

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

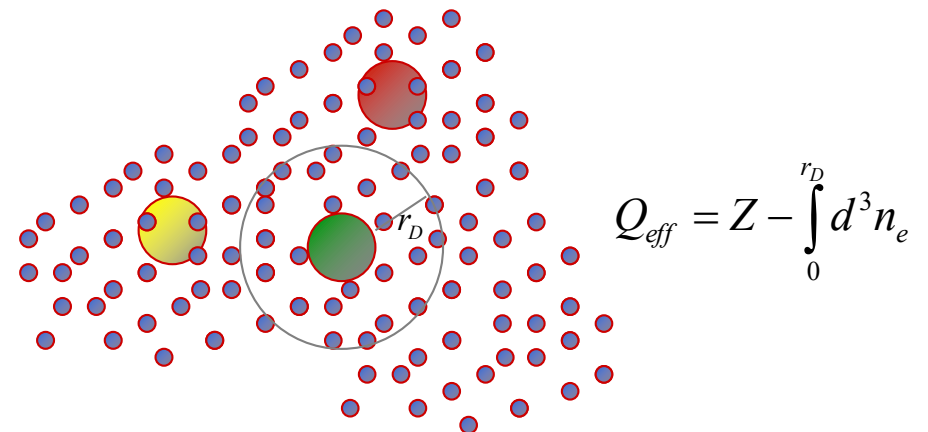
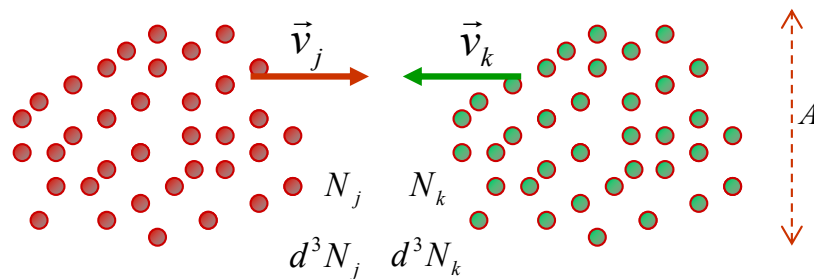


Nuclear Reactions in the laboratory vs. in the cosmos

- Laboratory nuclear physics experiment:
 - ★ Prepare/control conditions, measure products



- Cosmic plasma:
 - ★ different particle populations interact, reduced Coulomb repulsion (screening)
 - wide distributions of particle energies



Experiments: Determining the 'astrophysical S factor'

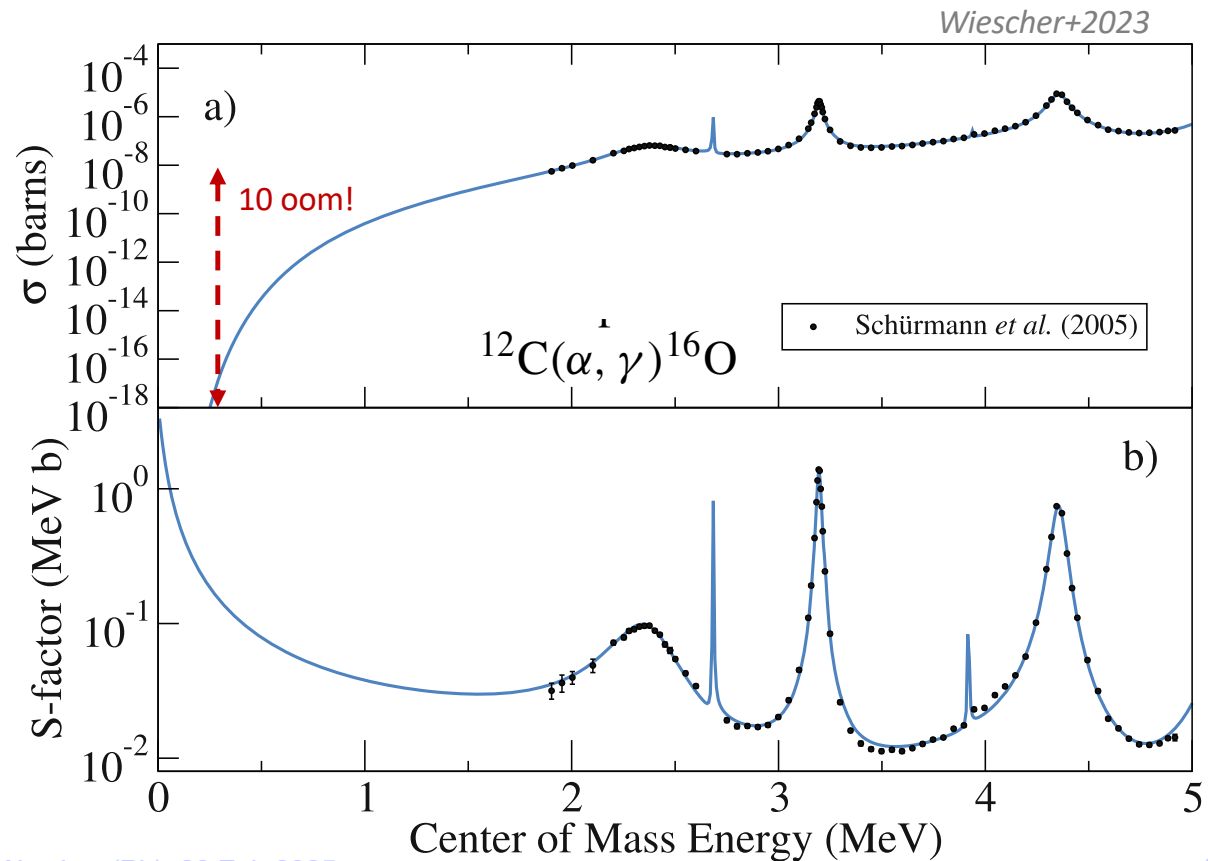
The Reaction Rate Integral: $\langle \sigma \cdot v \rangle = \left(\frac{8}{\pi \cdot \mu} \right)^{1/2} \cdot \left(\frac{1}{kT} \right)^{3/2} \cdot \int_0^{\infty} E \cdot \sigma(E) \cdot e^{-\frac{E}{kT}} \cdot dE$

☆ Separate out geometrical and barrier-tunneling aspects

$$\langle \sigma \cdot v \rangle = \left(\frac{8}{\pi \cdot \mu} \right)^{1/2} \cdot \left(\frac{1}{kT} \right)^{3/2} \cdot \underbrace{\langle S(E) \rangle}_{= \Phi} \int_0^{\infty} e^{-\underbrace{\left(\frac{E}{kT} + \frac{b}{\sqrt{E}} \right)}_{= \Phi}} \cdot dE$$

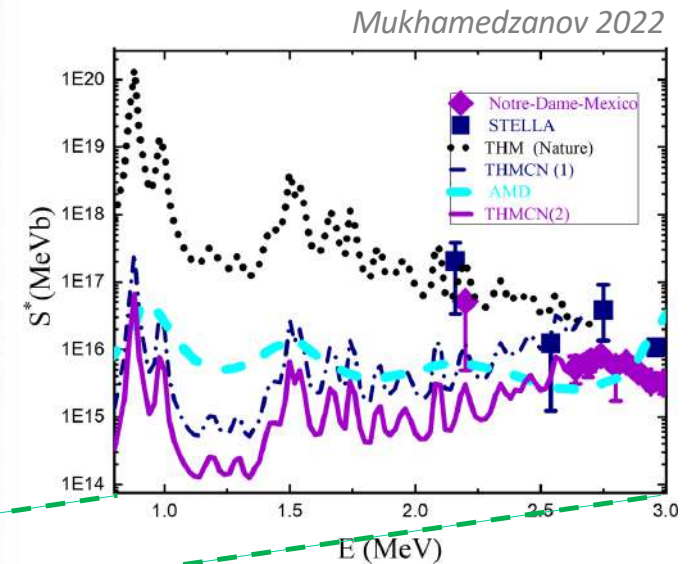
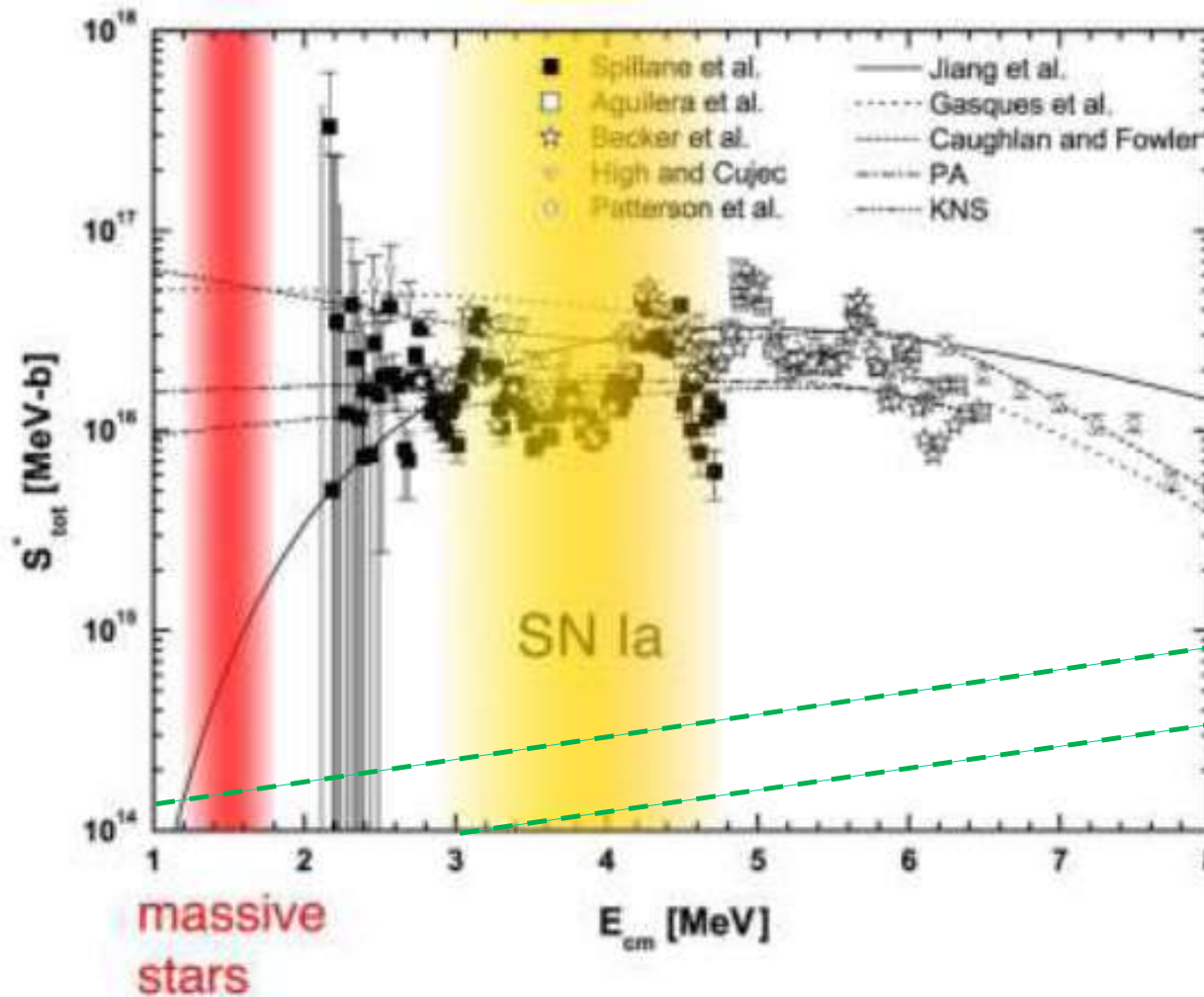
Astrophysical S-factor = Nuclear properties

☆ example: $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$:



Example for a nuclear reaction: Carbon fusion

$^{12}\text{C}+^{12}\text{C}\rightarrow ^{24}\text{Mg} / \text{XX} / \text{XX}\dots$: direct and indirect laboratory experiments:

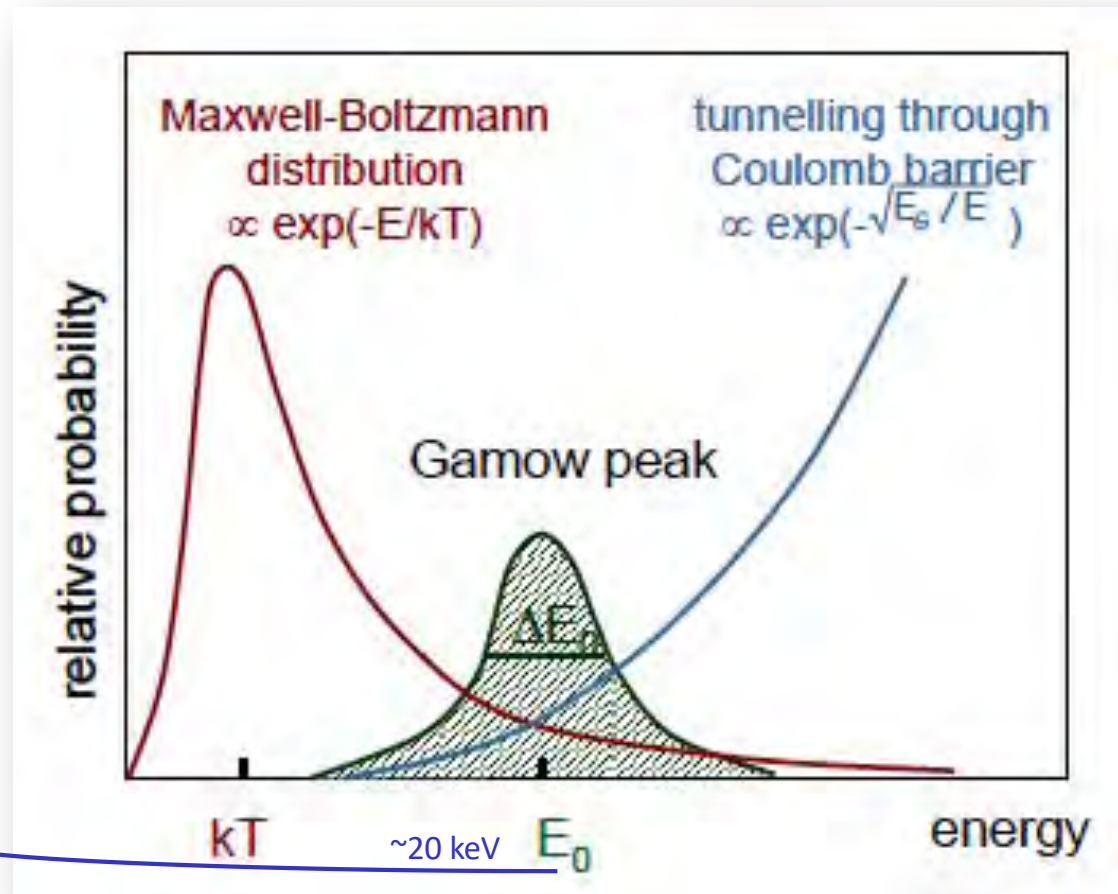
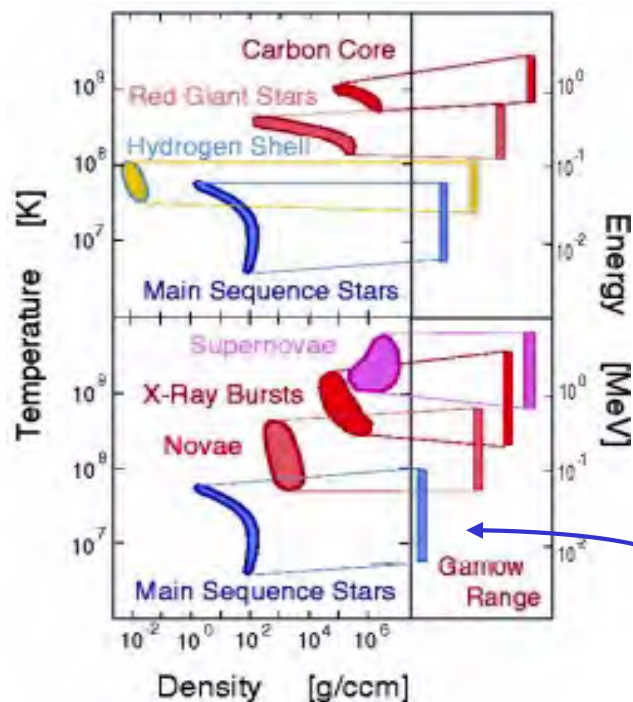


"Hindrance"? ...and sub-threshold resonances
 → Extrapolation to low energy is very uncertain!

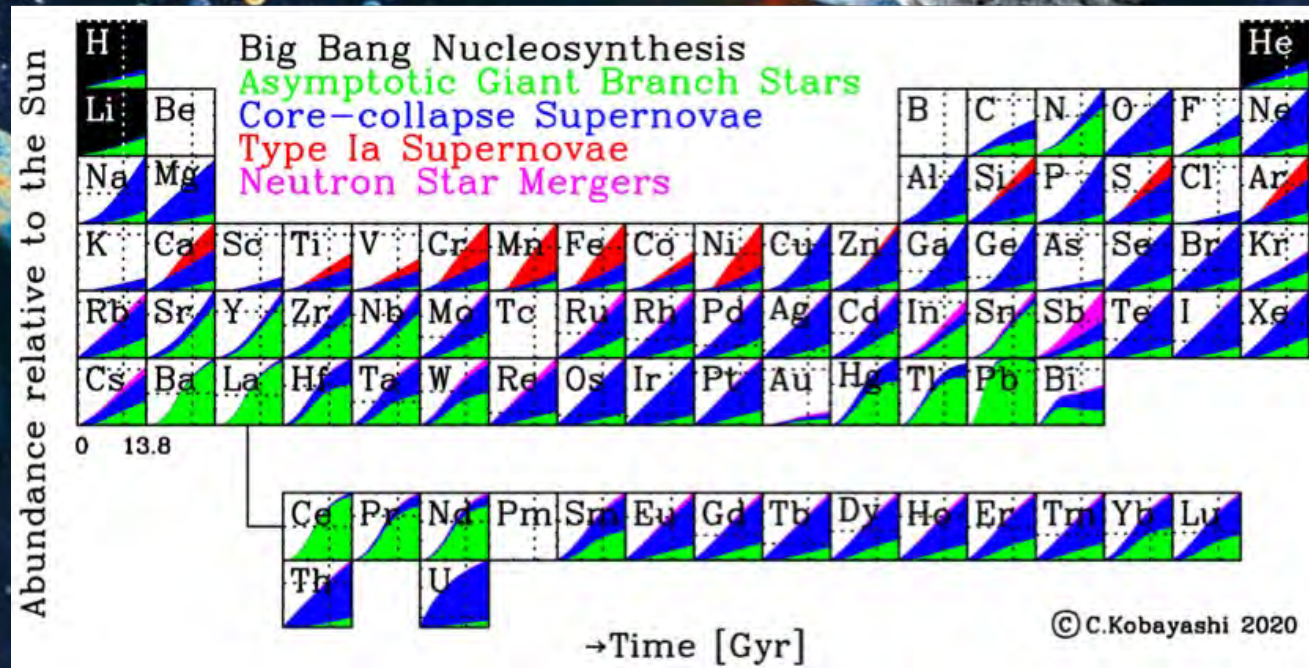
Nuclear reactions in cosmic environments

major challenge:

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

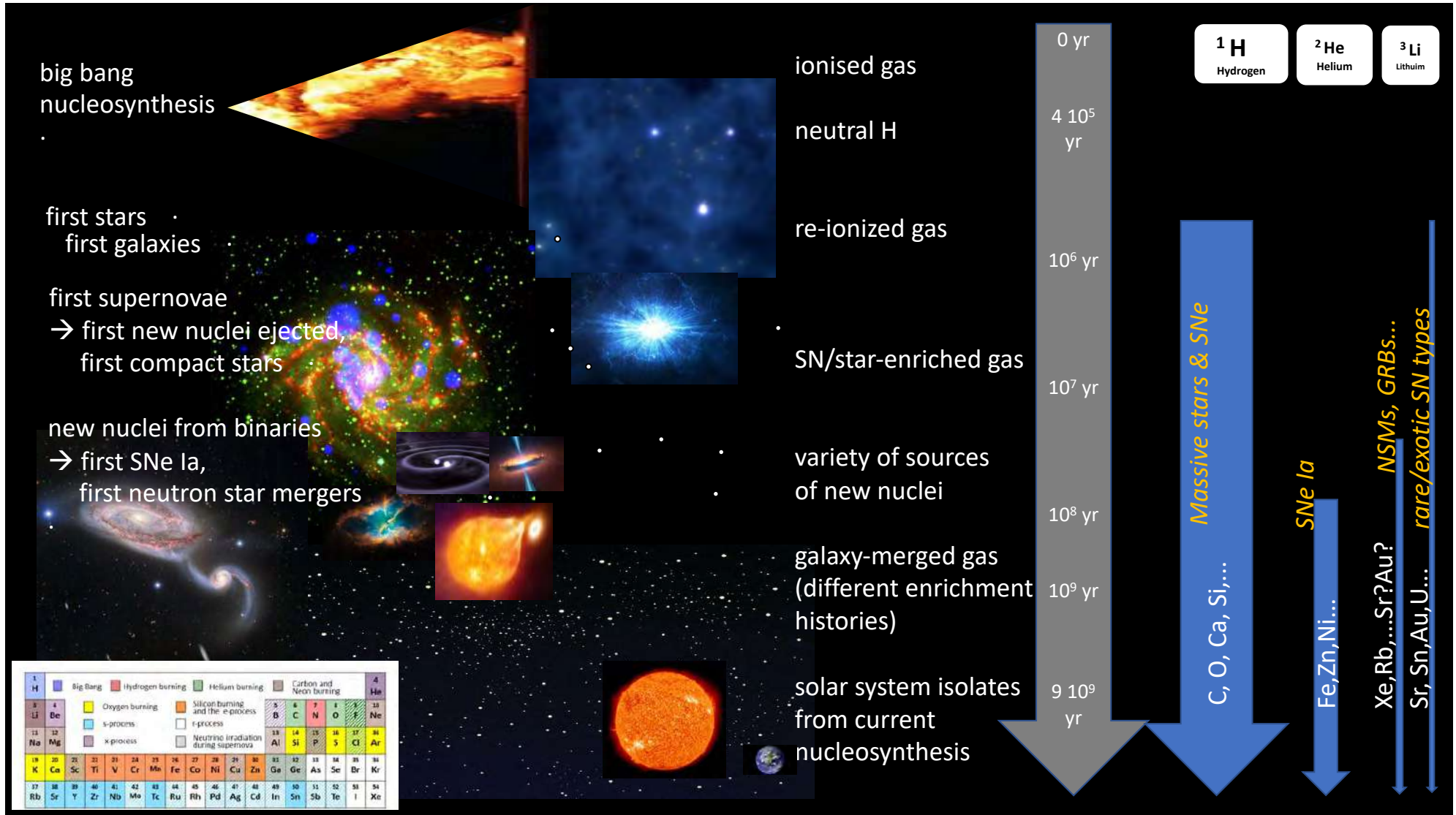


what are our origins?



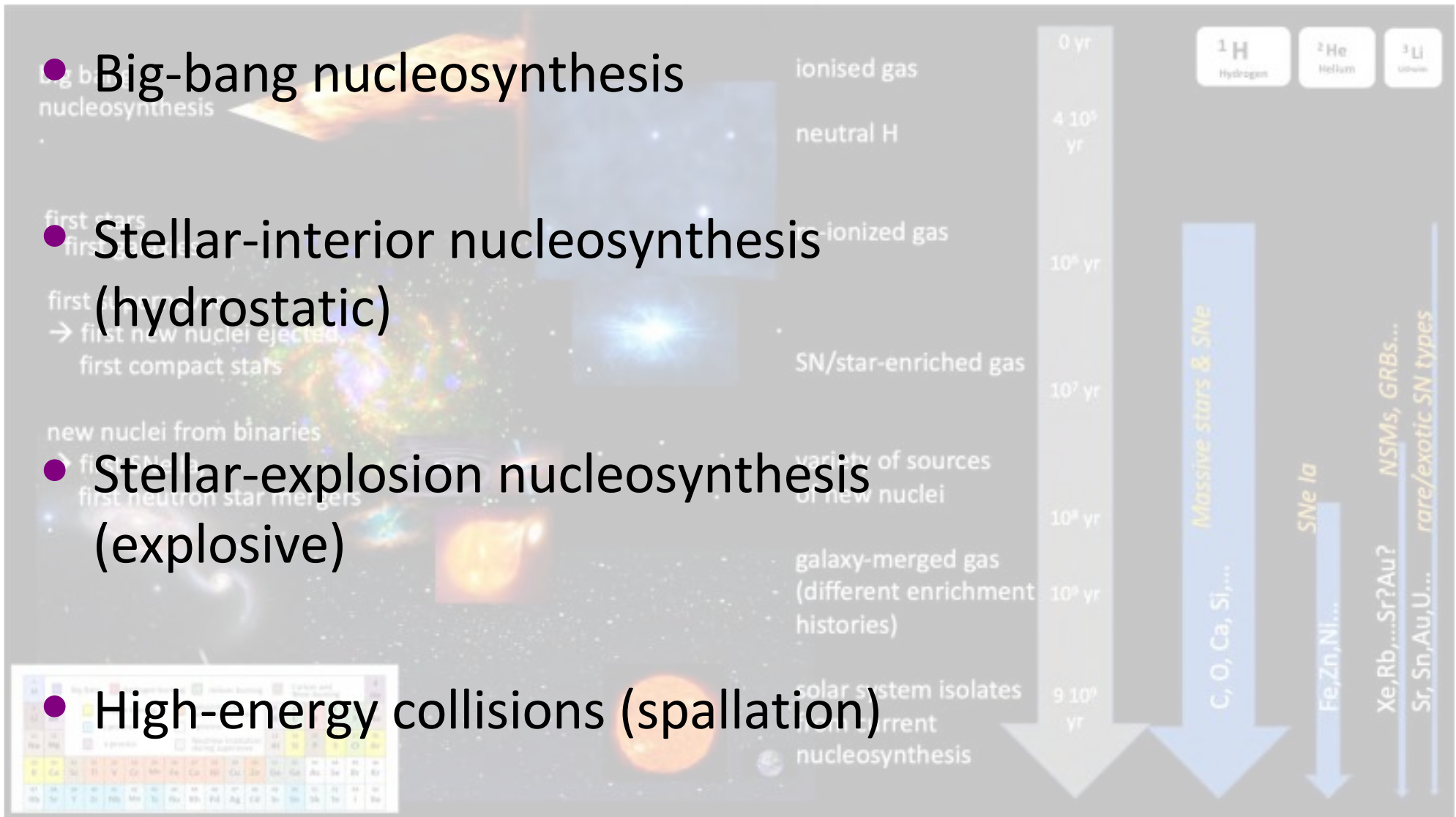
The answers include: models of the sources and the nuclear rates within, and of cosmic evolution including transport and recycling

The broad context: evolving isotopic composition



... the coarse picture of cosmic nucleosynthesis.

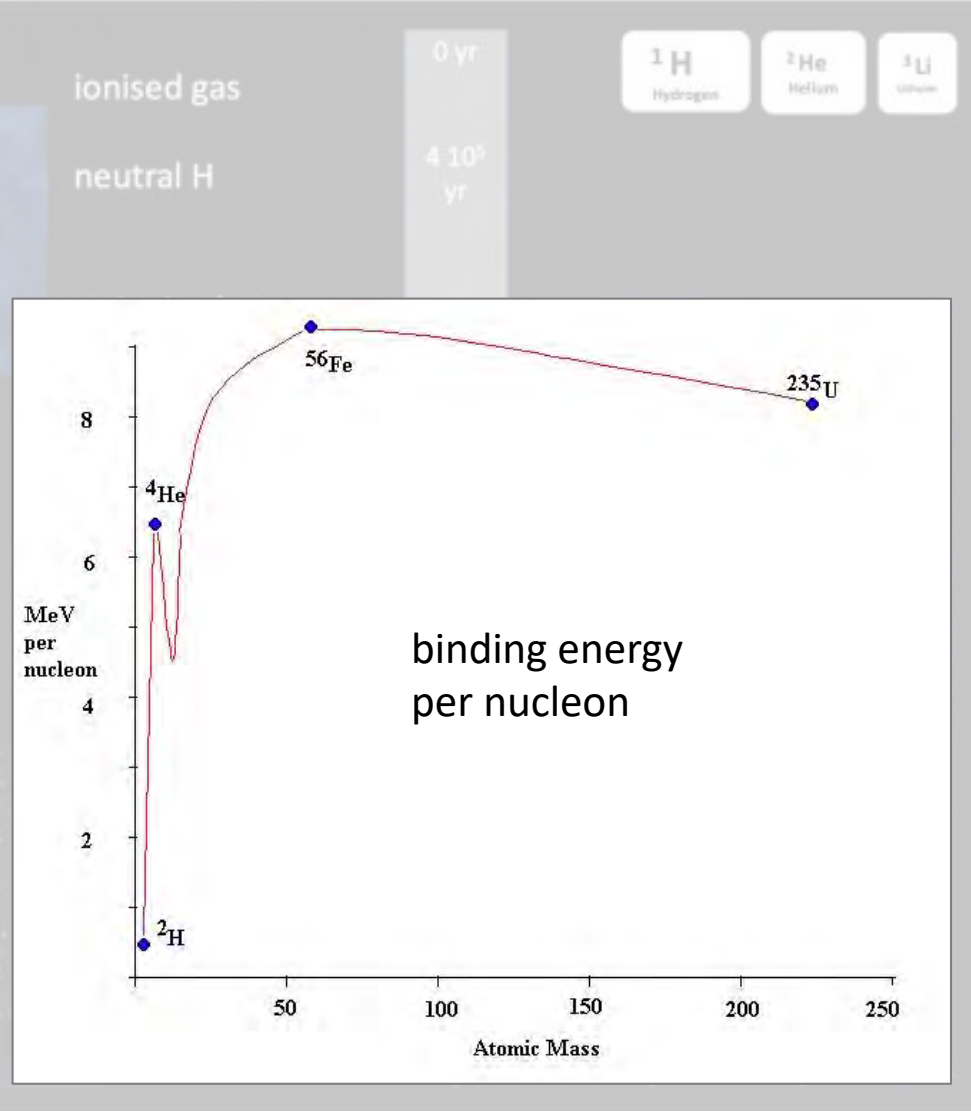
Cosmic nucleosynthesis



Cosmic nucleosynthesis

- Big-bang nucleosynthesis
- Stellar-interior nucleosynthesis (hydrostatic)
 - first galaxies
 - first supernovae
 - first new nuclei ejected
 - first compact stars
- Stellar-explosion nucleosynthesis (explosive)
 - first SNe Ia
 - first neutron star mergers
- High-energy collisions (spallation)

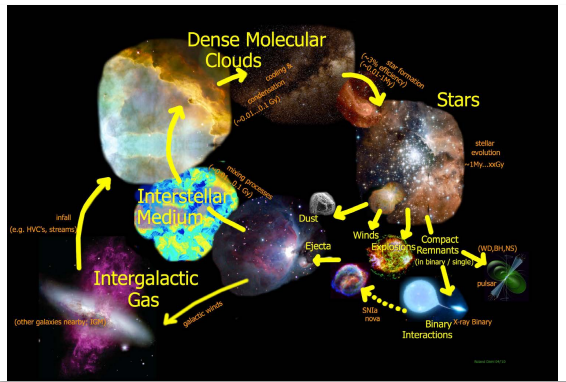
Big Bang		Hydrogen burning		Helium burning		Carbon and Oxygen burning	
1	2	3	4	5	6	7	8
H	He	C	O	Ne	Si	Fe	Ni
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
K	Ca	Ti	V	Cr	Mn	Fe	Ni
Rb	Sr	Zr	Nb	Mo	Tc	Ru	Rh
Cs	Ba	Hf	Ta	W	Re	Os	Ir
Fr	Ra	Th	Pa	U	Np	Pu	Am
Ac	Th	Pa	U	Np	Pu	Am	Cm



in all cases:

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

Describing Compositional Evolution: the Challenges



★ Changes in the forms of cosmic matter:

☞ stars and gas flows:

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

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

$\Psi(t)$ 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:

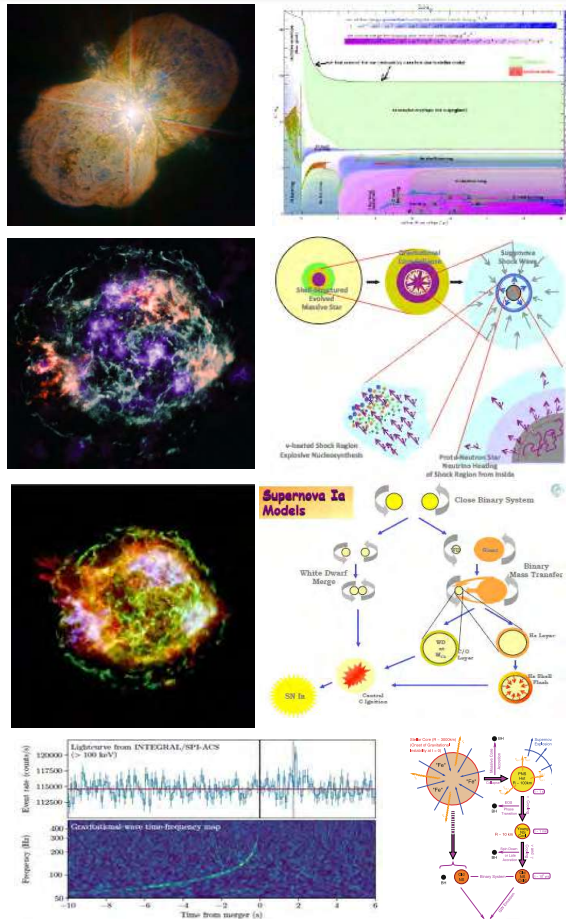
☞ Sources: How fast do they evolve to return (new) gas?

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

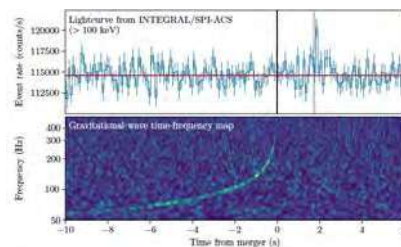
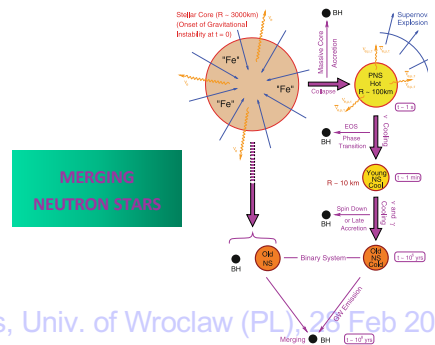
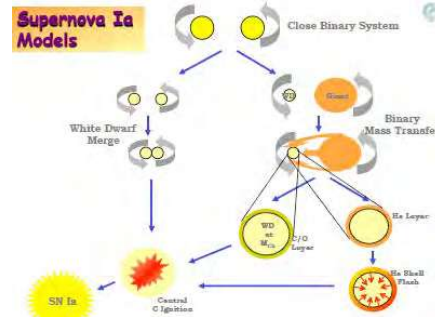
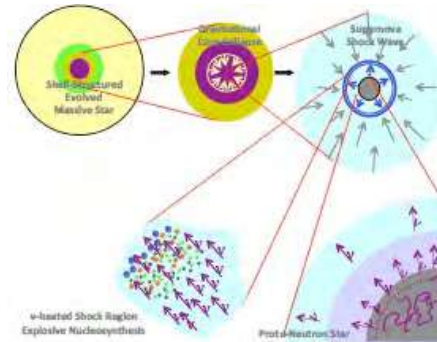
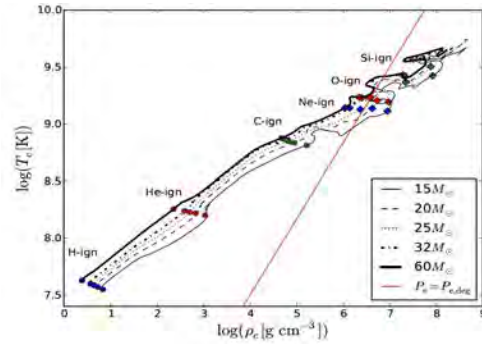
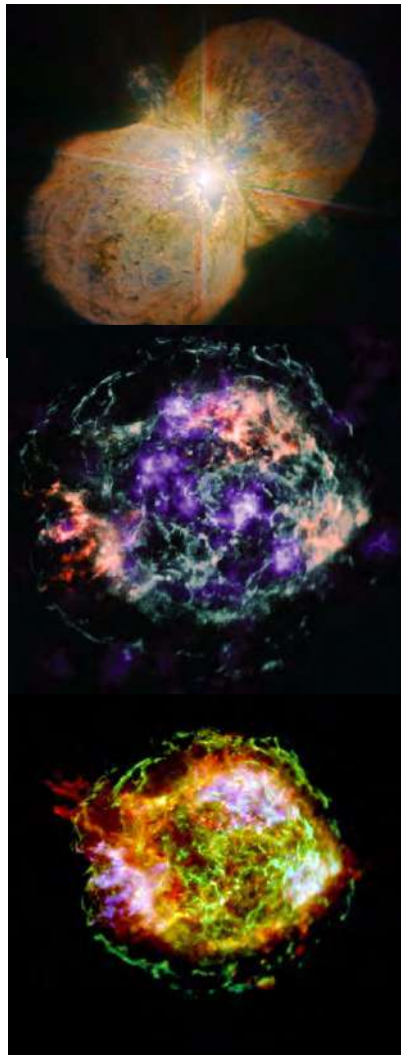
☞ Sources: How much of species i do they eject (and/or bury)?

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

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

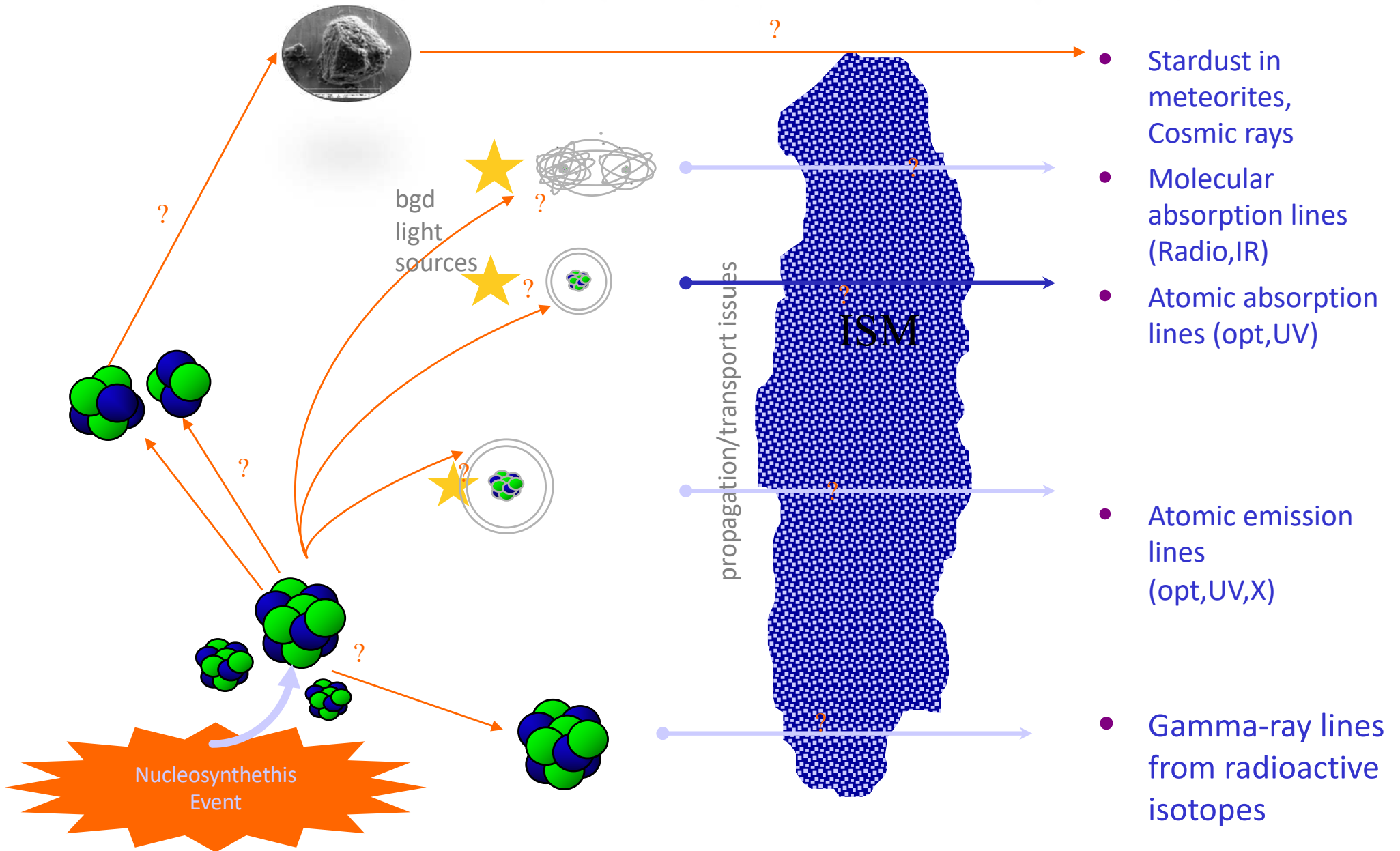


Cosmic nucleosynthesis sources



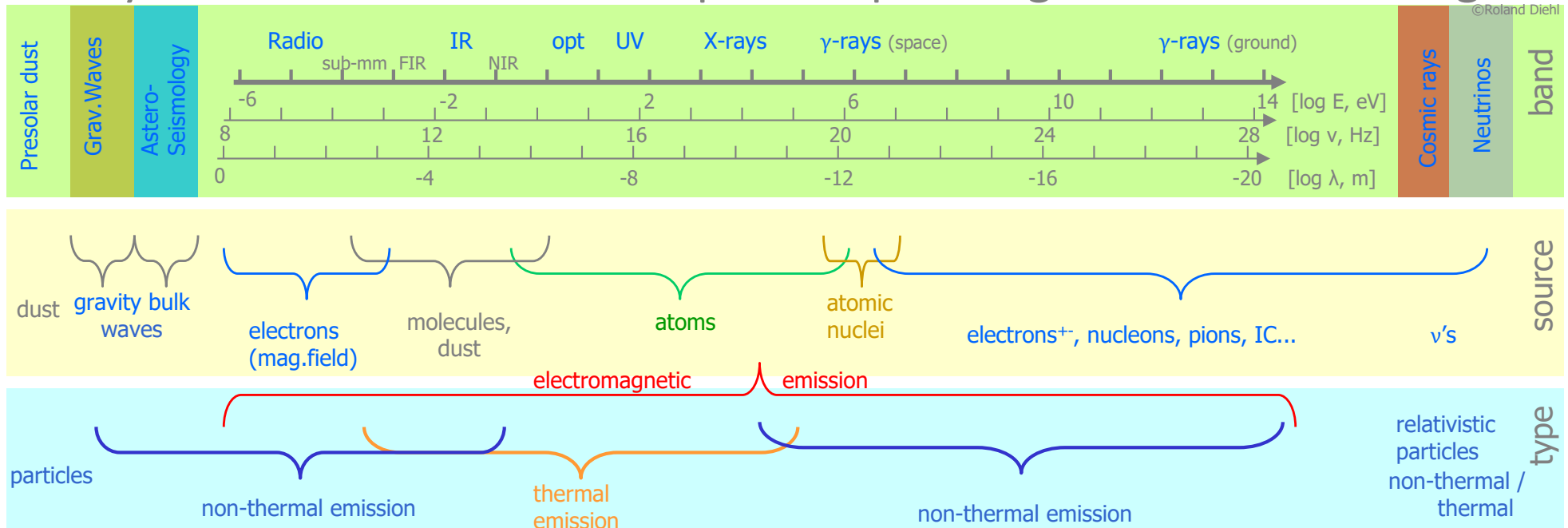
- Nuclear fusion reactions power all stars
- Many stars explode as a supernova at the end of their evolution
- Some binary systems including white dwarf stellar remnants explode as a supernova
- Some binary systems including neutron stars eventually merge to form a black hole
- When do they eject ashes?
- How many new nuclei in ejecta??


Different Complementing Observing Methods

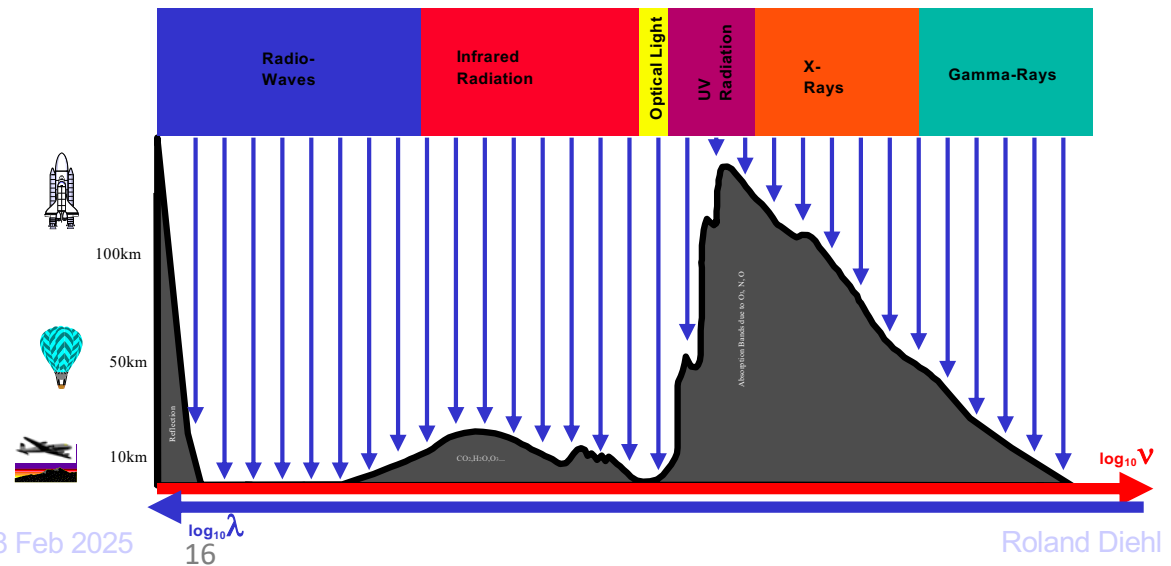


The variety of "astronomies"

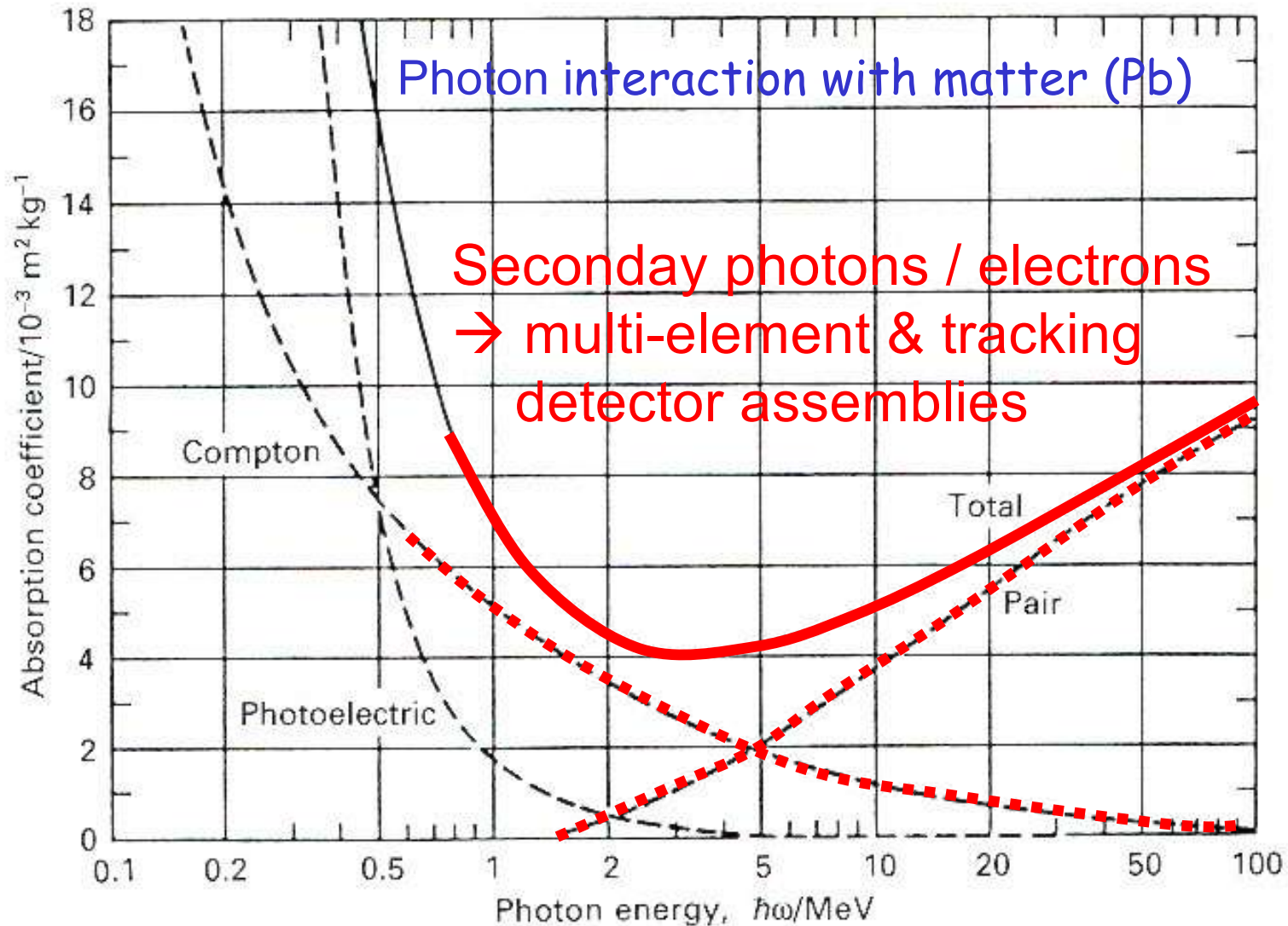
... beyond astronomical telescopes of optical light: cosmic messengers



...  rising above looking at the skies from the surface of our planet



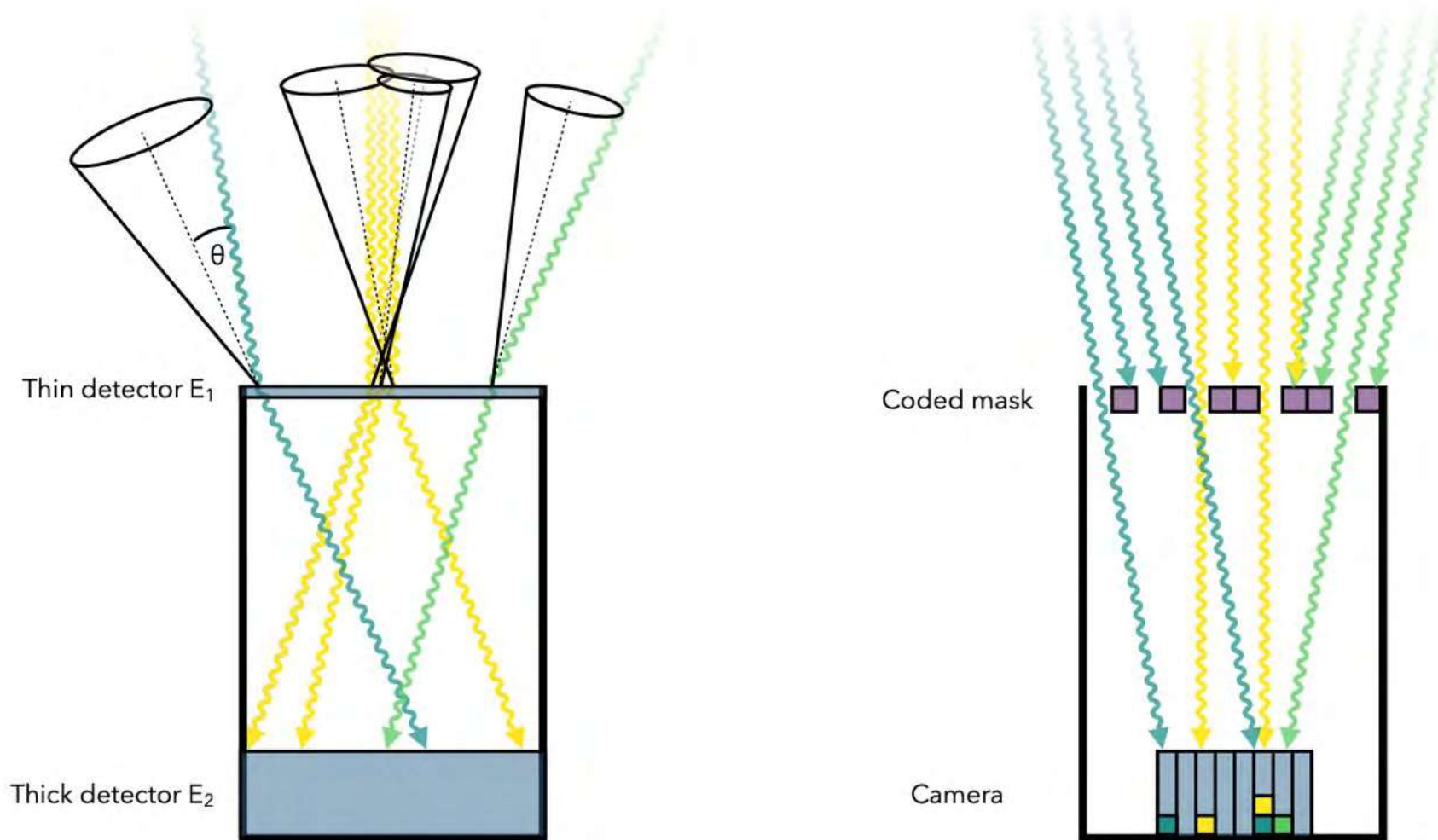
Gamma-Ray Astronomical Telescopes: Interaction of high-energy photons with matter



→ Secondary Particles ... → e.m. cascade

Imaging principles for a MeV-range γ -ray telescope

- Compton Telescopes and Coded-Mask Telescopes



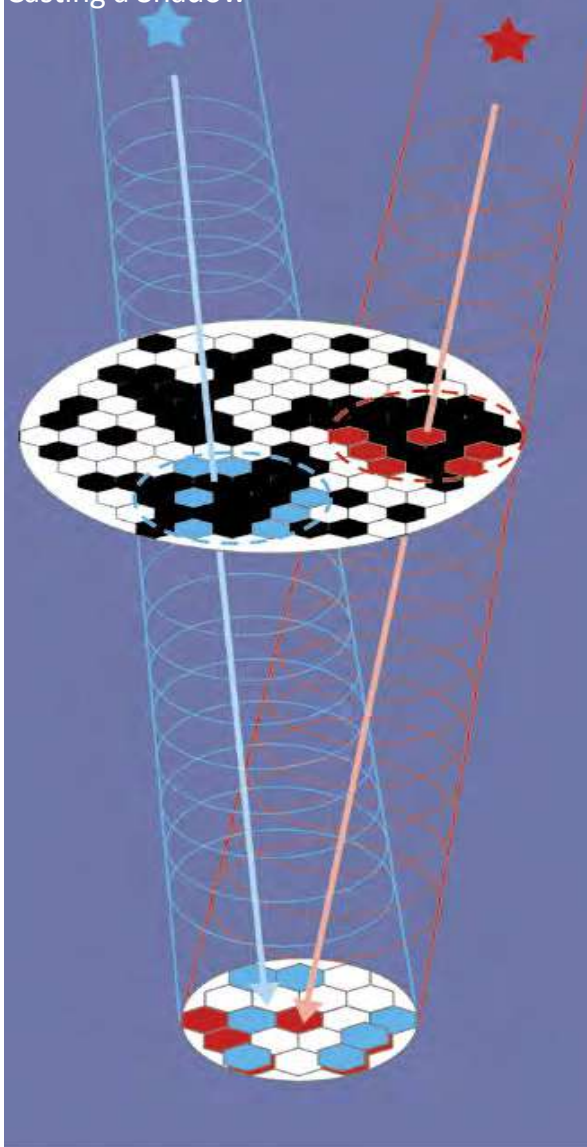
Achievable Sensitivity: $\sim 10^{-5}$ ph cm⁻² s⁻¹, Angular Resolution \geq deg



INTEGRAL Cosmic Photon Measurements: The SPI Ge γ -Spectrometer



Coded Mask Telescope:
Casting a Shadow



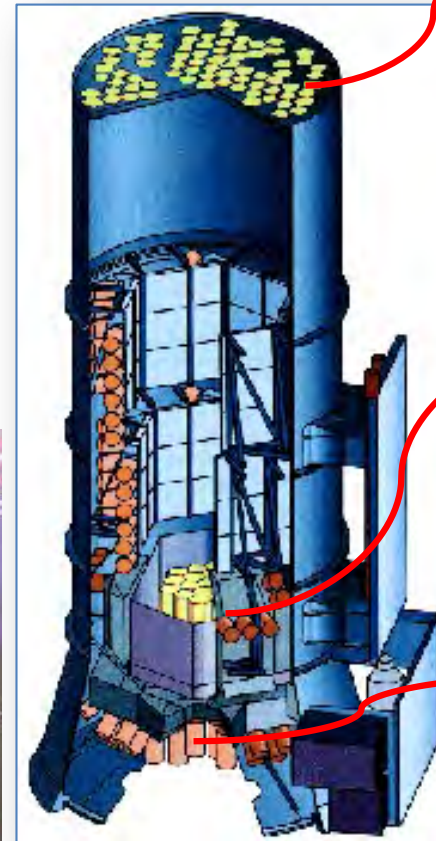
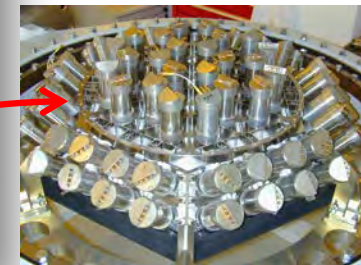
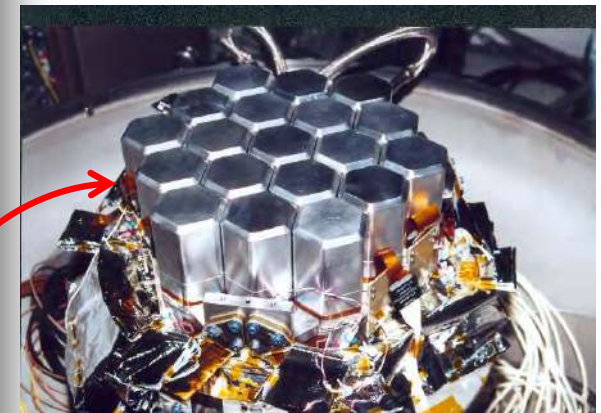
Coded-Mask Telescope

Energy Range 15-8000 keV

Energy Resolution ~ 2.2 keV @ 662 keV

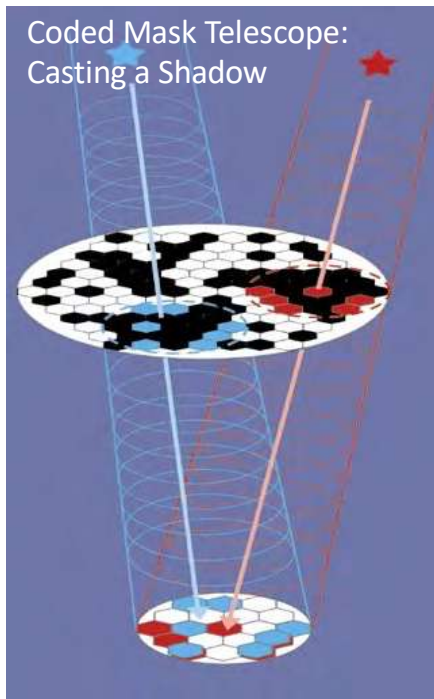
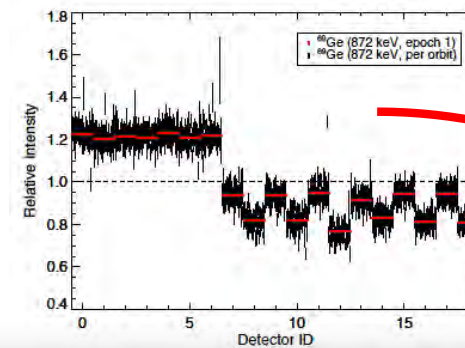
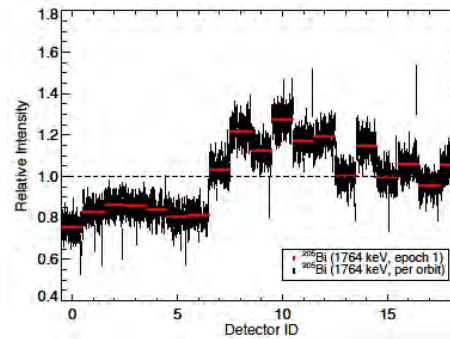
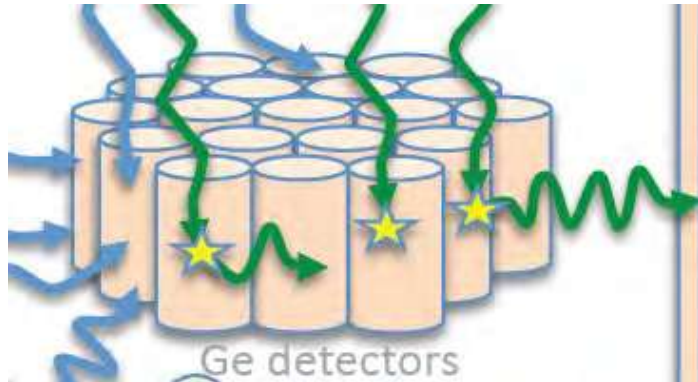
Spatial Precision 2.6° / ~ 2 arcmin

Field-of-View $16 \times 16^\circ$

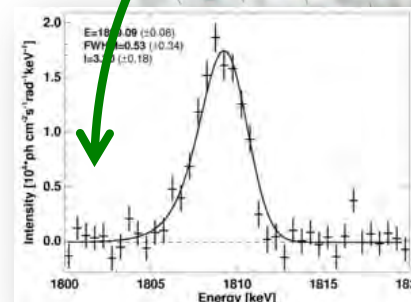
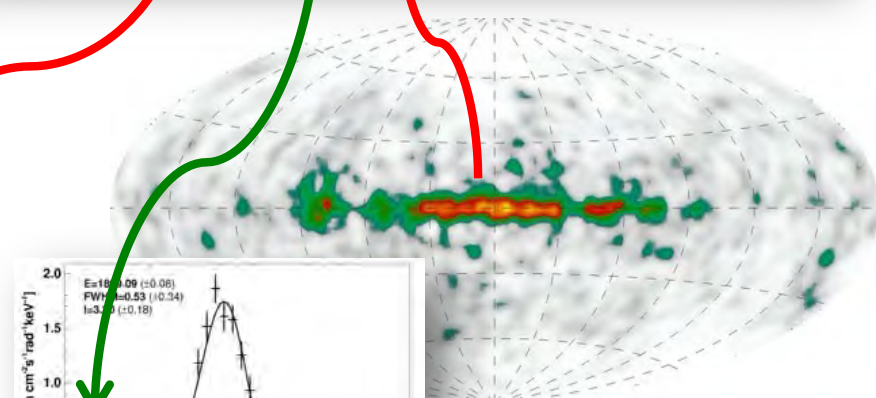
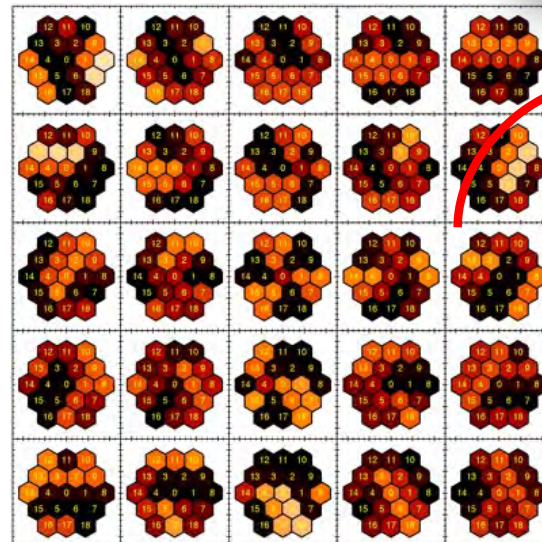


Discriminating Background and Sky Signals in SPI Data

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

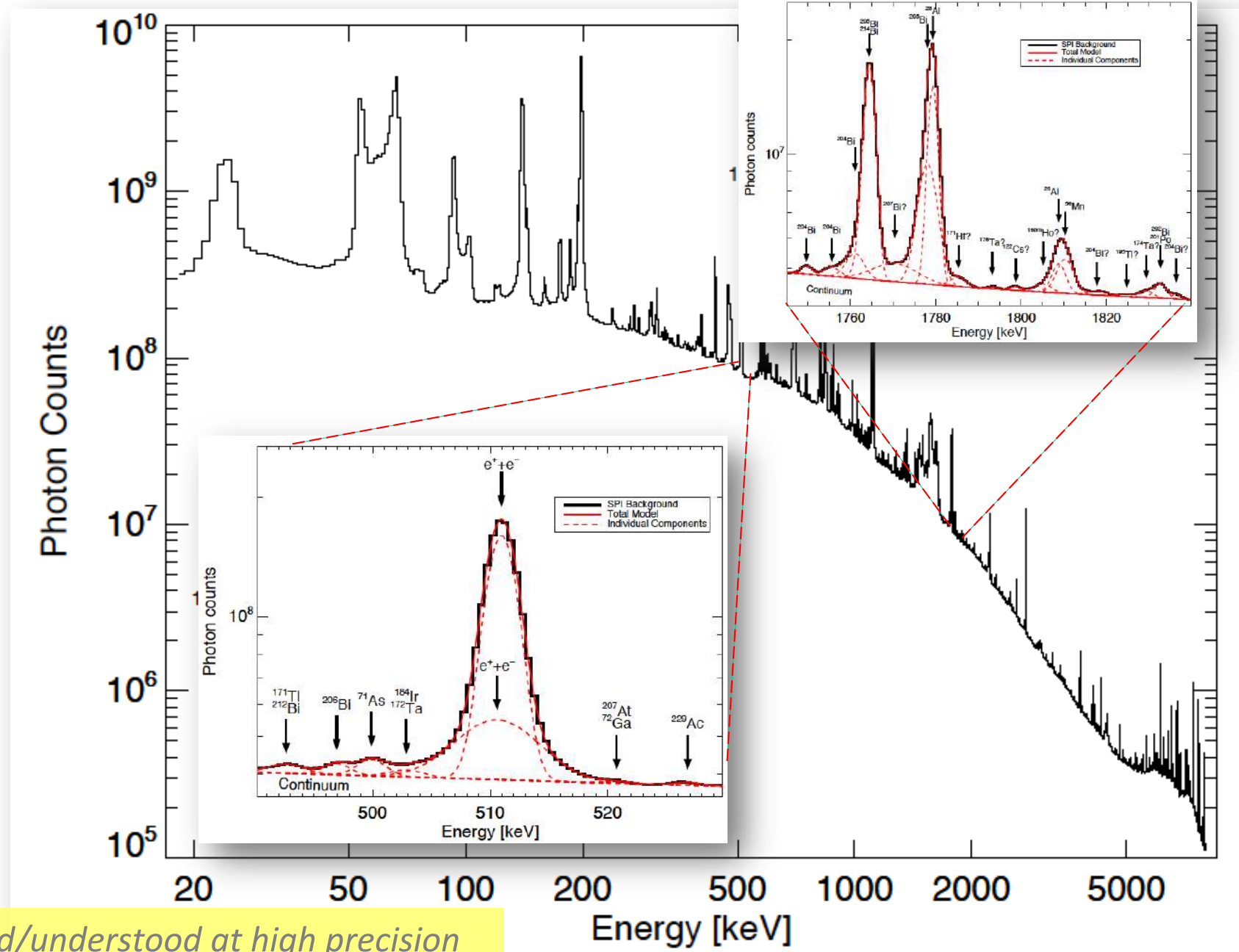


$$d_k = \sum_j R_{jk} \sum_{i=1}^{N_I} \theta_i M_{ij} + \sum_t \sum_{i=N_I+1}^{N_I+N_B} \theta_{i,t} B_{ik}$$



INTEGRAL: Dominance of instrumental background

SPI Ge detector spectra



Modelled/understood at high precision

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

- Only the most-plausible candidates per source type are listed
(abundance; decay time ($\tau < 10^8$ y) long enough to survive ejection/not too long to be bright)

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

Current Nuclear Gamma-Ray Line Telescopes

INTEGRAL

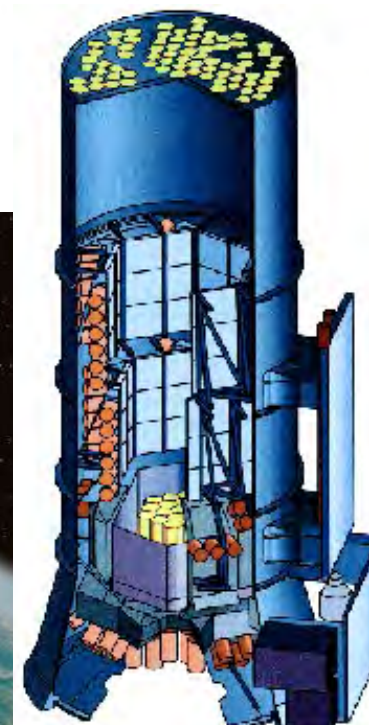
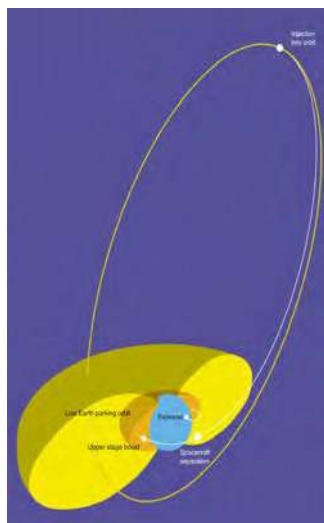
2002-2025 (2029)

ESA

high E resolution

Ge detectors

15-8000 keV



NuSTAR (only <80 keV!)

2012-(2025) ...

NASA

hard X ray

imaging <80 keV

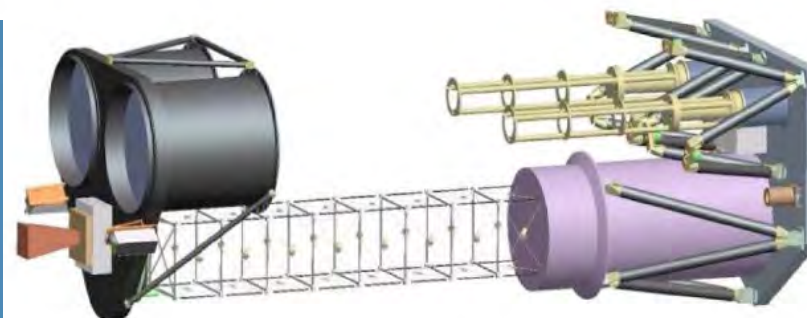
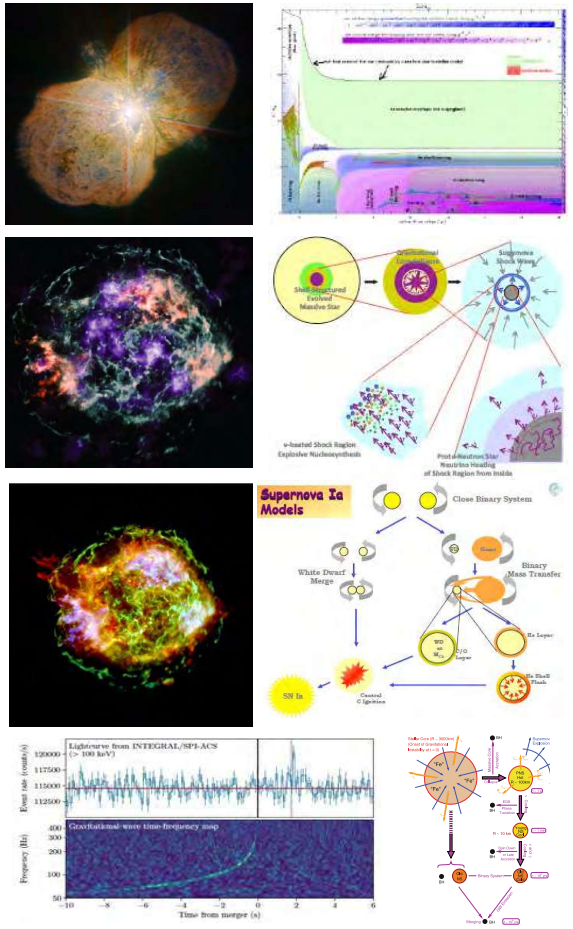


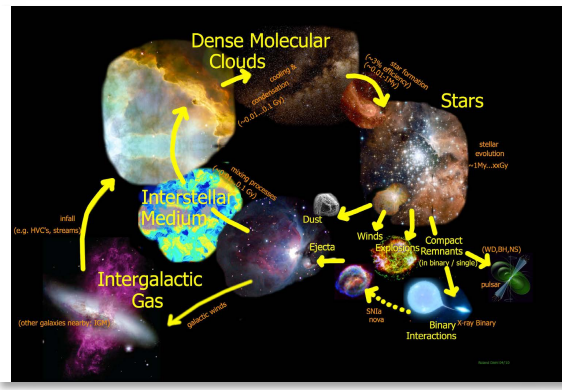
Fig. 1. NuSTAR telescopes in deployed configuration

The Challenges

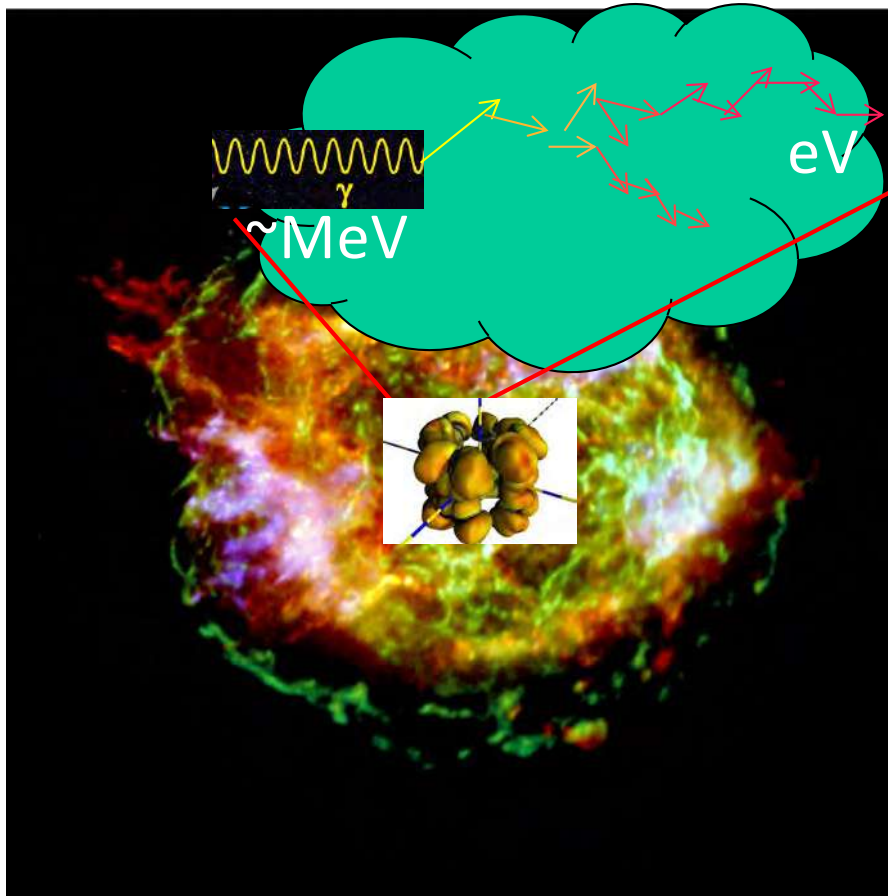


★ Understand the sources of new nuclei

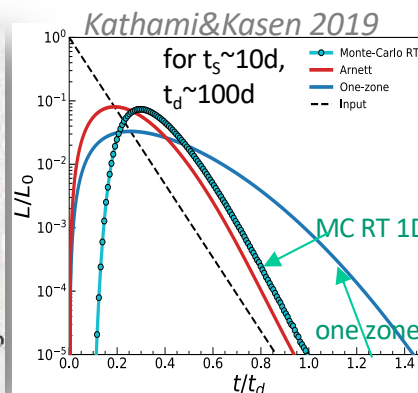
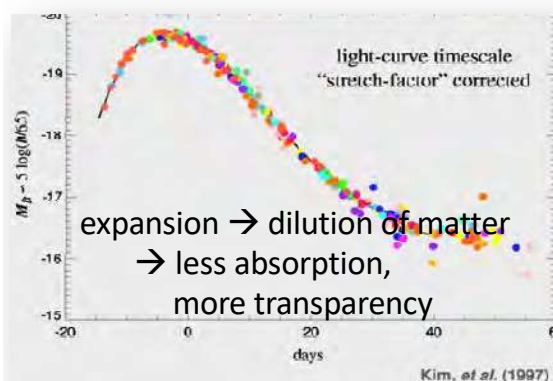
★ Trace the flows of cosmic matter



Radiation Measurements from an Exploding Star

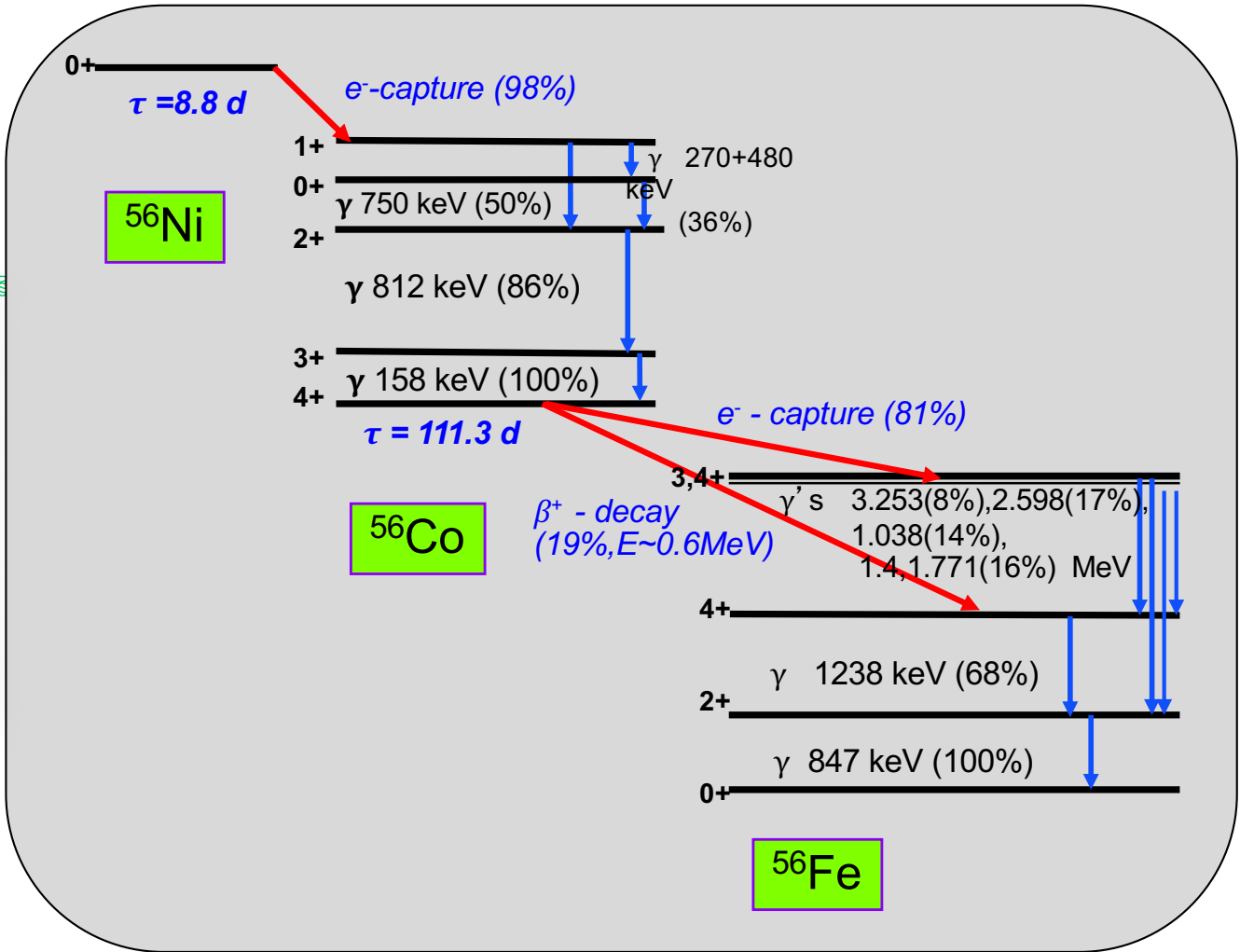
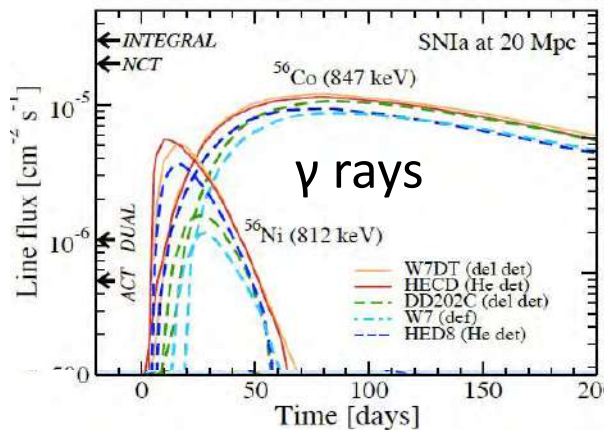
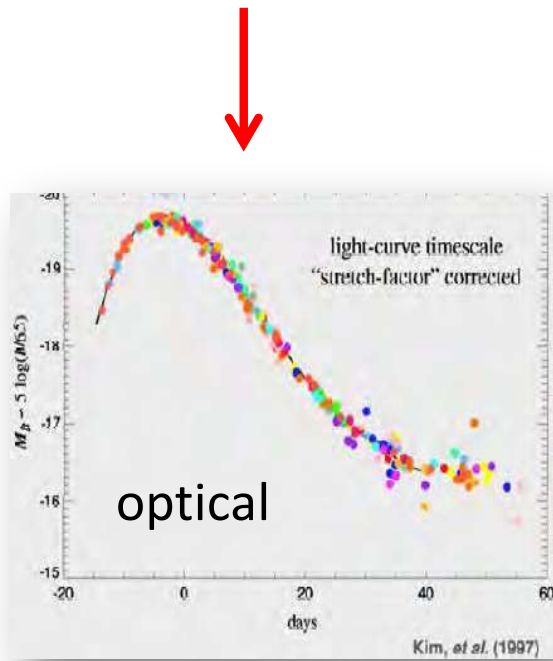


- γ rays: radioactive decay ^{56}Ni , ^{56}Co
- X rays: recombination of highly-ionized atoms; thermal (10^6K)
- UV: recombination of atoms thermal (10^4K)
- opt: thermal (10^3K); atomic and molecular transitions
- IR: thermal gas and dust emission (10^{1-2}K); molecular transitions



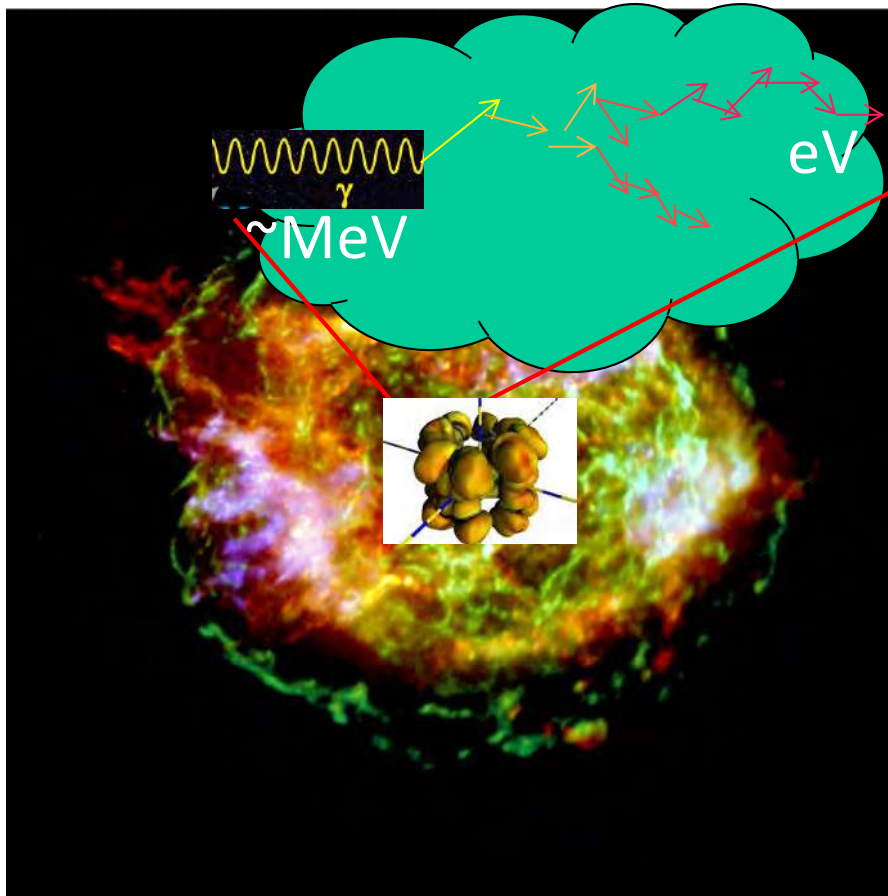
^{56}Ni radioactivity \rightarrow γ -Rays, e^+ \rightarrow leakage/deposit evolution

SN Ia

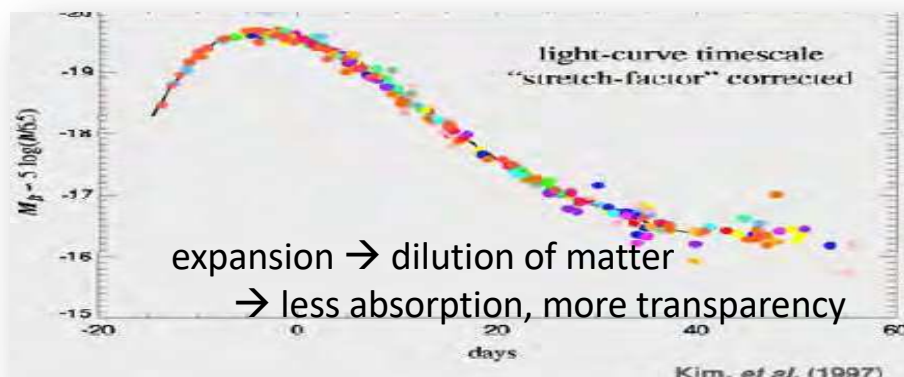


- ☞ Nuclear BE release from $0.6M_{\odot} [\text{C}, \text{O} \rightarrow ^{56}\text{Ni}] = \sim 1.1 \cdot 10^{51}$ erg ($> 2 \cdot \text{BE}_{\text{WD}}$)
- ☞ Deposit of γ rays and e^+ in expanding/diluting envelope
- ☞ Re-radiation of deposited energy in low-energy (thermal) radiation

Radiation Measurements from an Exploding Star

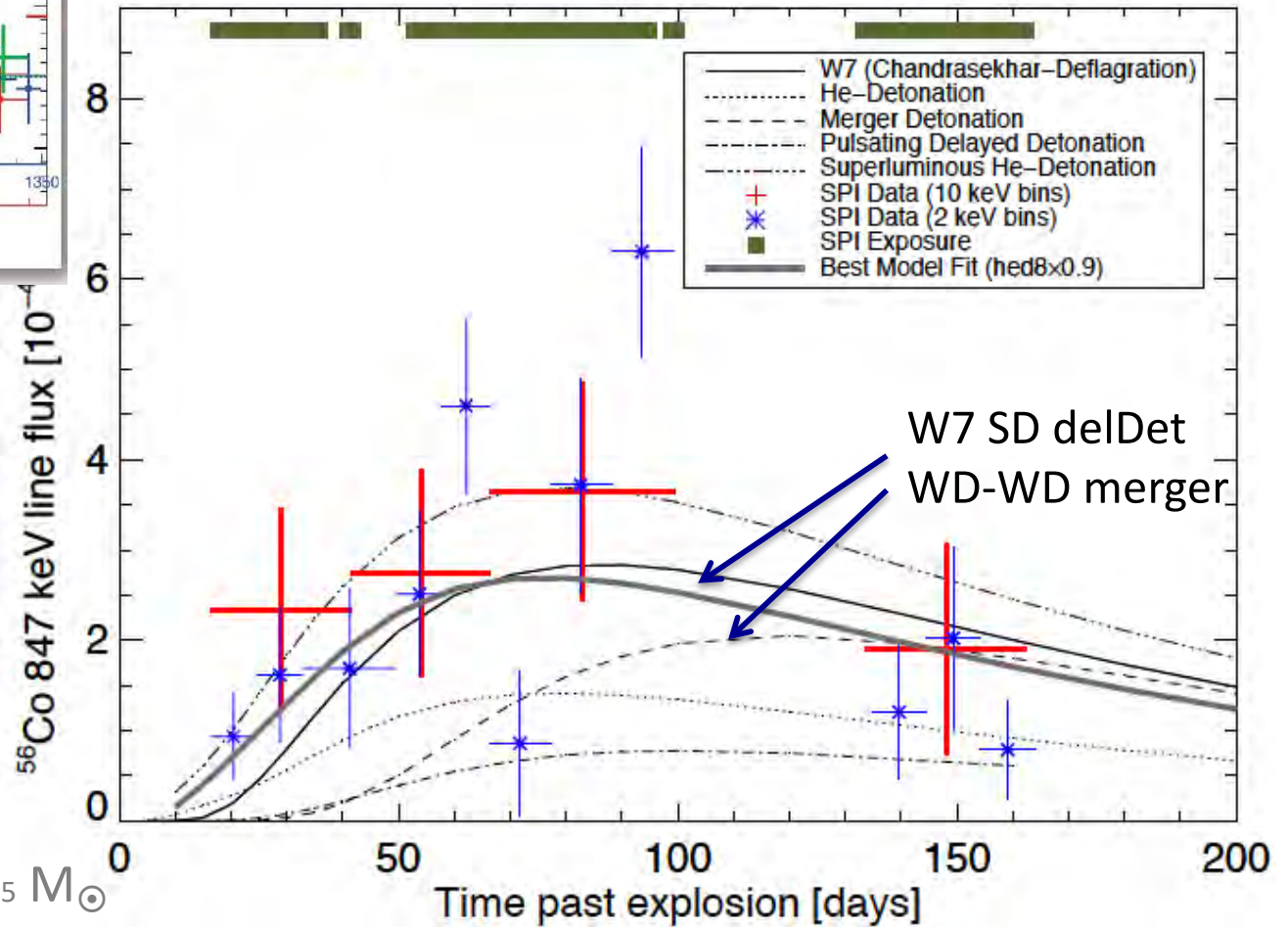
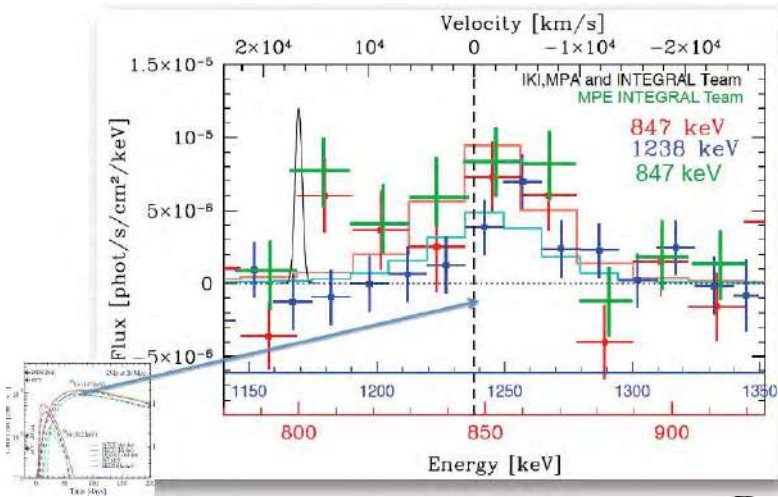


- γ rays: radioactive decay ^{56}Ni , ^{56}Co
where in the envelope is the ^{56}Ni ?
- X rays: recombination of highly-ionized atoms; thermal (10^6K)
what are the states of ionizations?
- UV: recombination of atoms; thermal emission (10^4K)
what are gas temp & ionization?
- opt: thermal (10^3K); atomic and molecular transitions
which transitions are important?
- IR: thermal gas and dust emission (10^{1-2}K); molecular transitions
which transitions? τ gas vs. dust?



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

INTEGRAL/SPI γ ray measurements



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

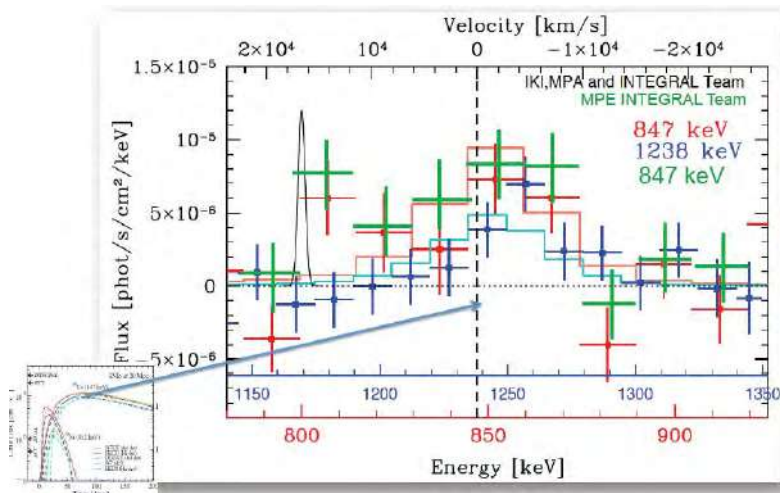
(cmp from bol. Light $\rightarrow 0.42 \pm 0.05 M_{\odot}$)

from models $\rightarrow 0.5 \pm 0.3 M_{\odot}$

👉 *Diehl et al., A&A 2015*

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

★ Doppler broadened ✓



★ Split into 4 time bins

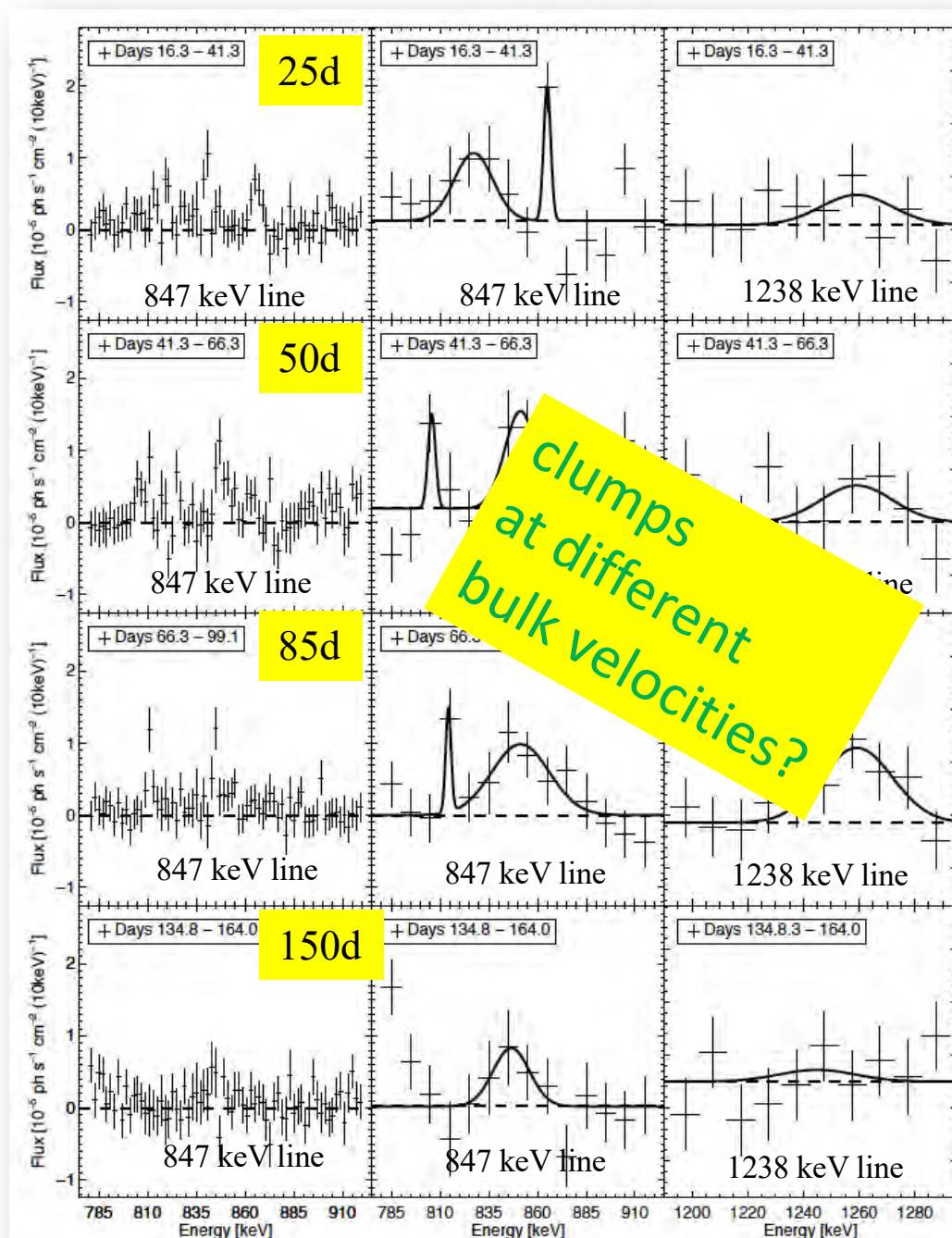
★ Coarse & fine spectral binning

→ 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!

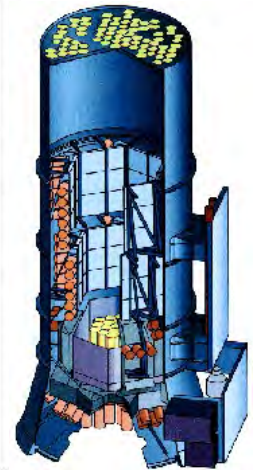
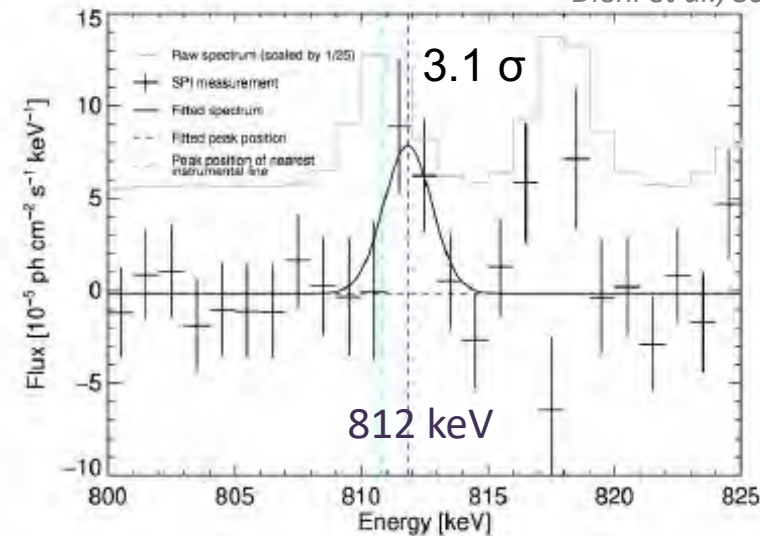
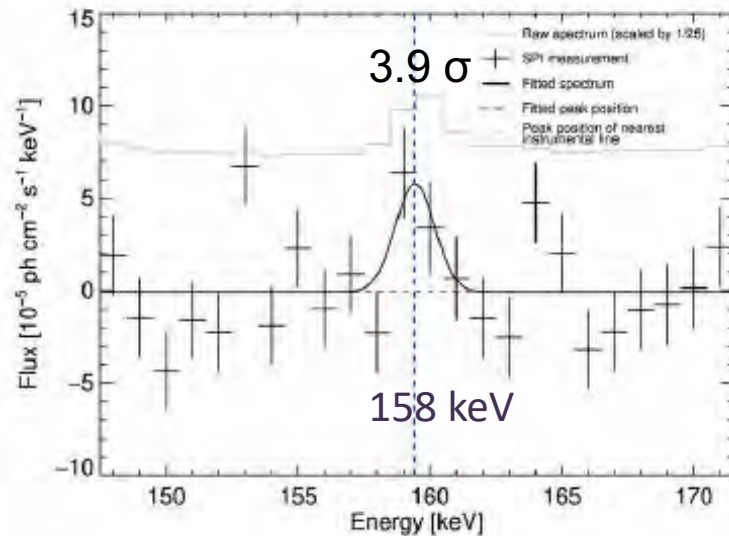


SN Ia and SN2014J: Early ^{56}Ni ($\tau \sim 8.8\text{d}$)

Spectra from the SN at ~ 20 days after explosion

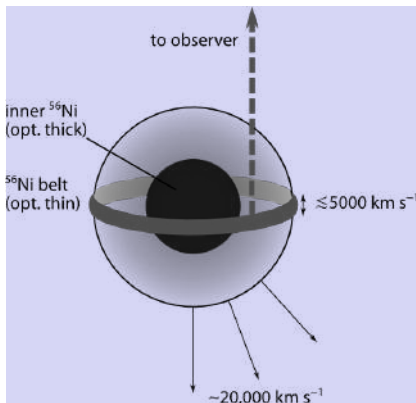
Clear detections of the two strongest lines expected from ^{56}Ni (should be embedded!)

Diehl et al., Science (2014)



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

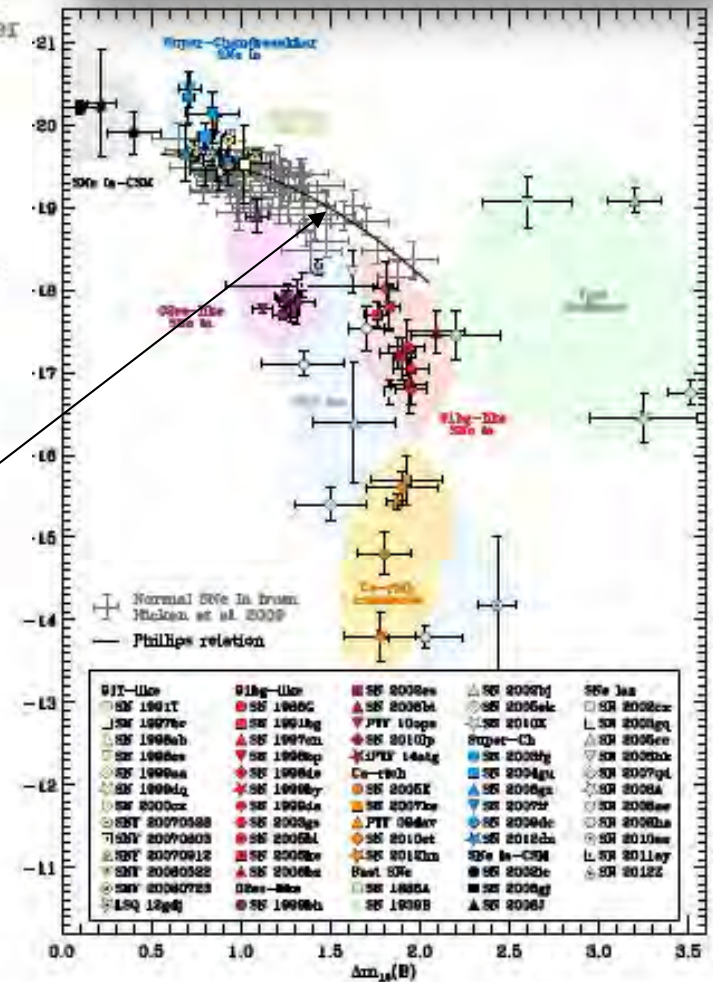
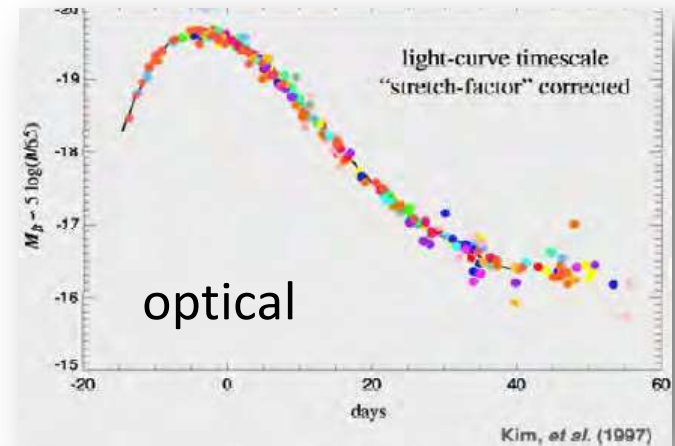
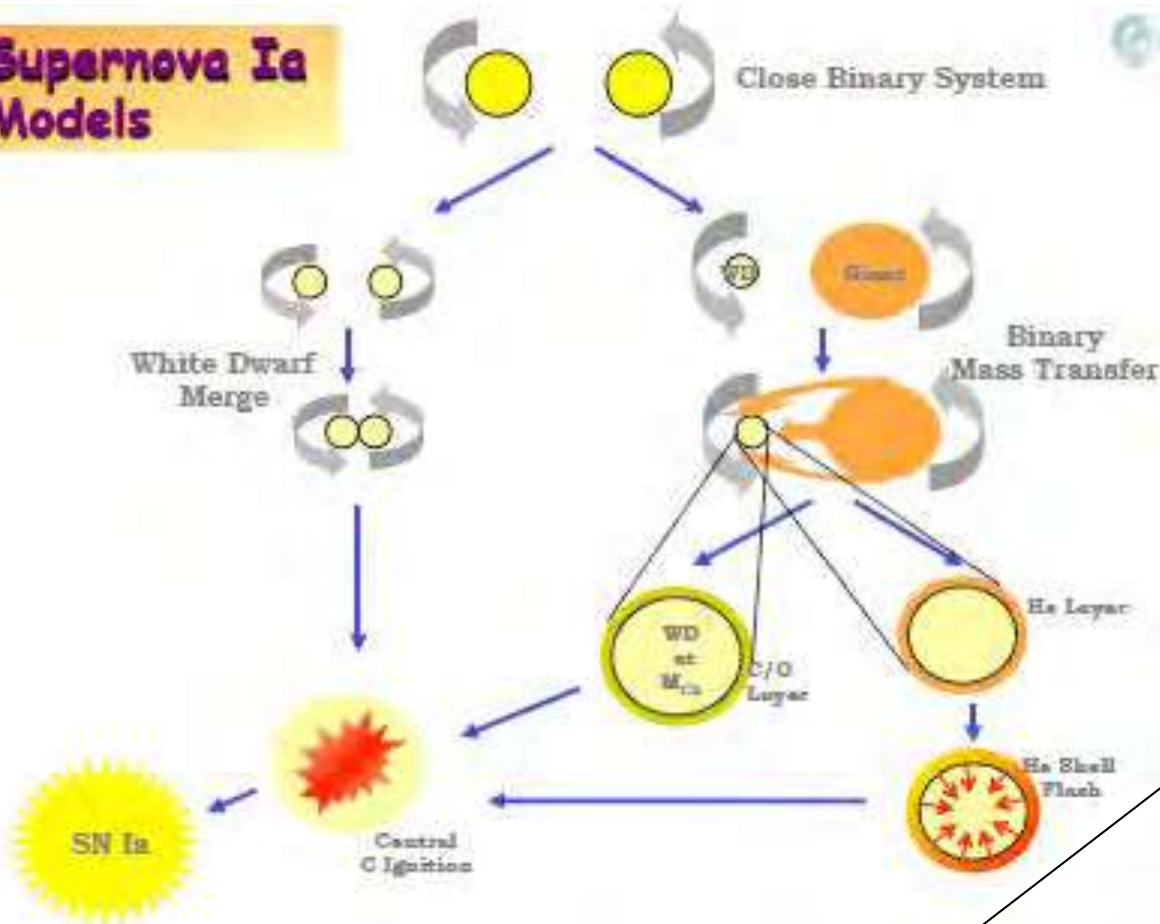
i.e.: not the single-degenerate $M_{\text{chandrasekhar}}$ model,
but rather a 'double detonation', i.e.
either 2 WDs (double-degenerate)
or a He accretor (He star companion)



\rightarrow SN 2014J looks "normal", but is not

Supernovae of type Ia

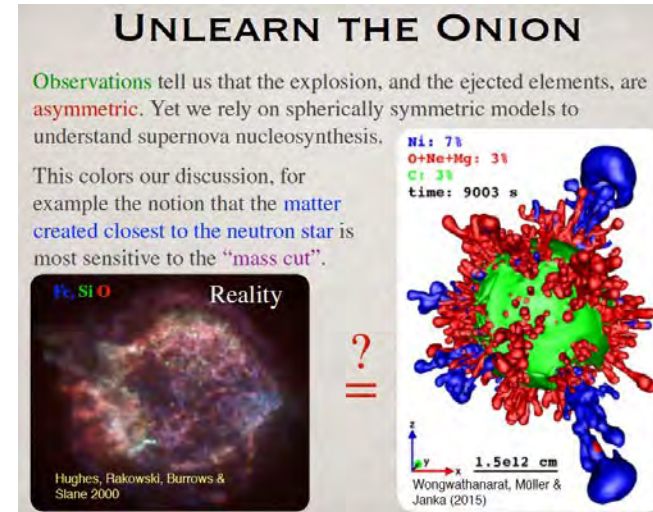
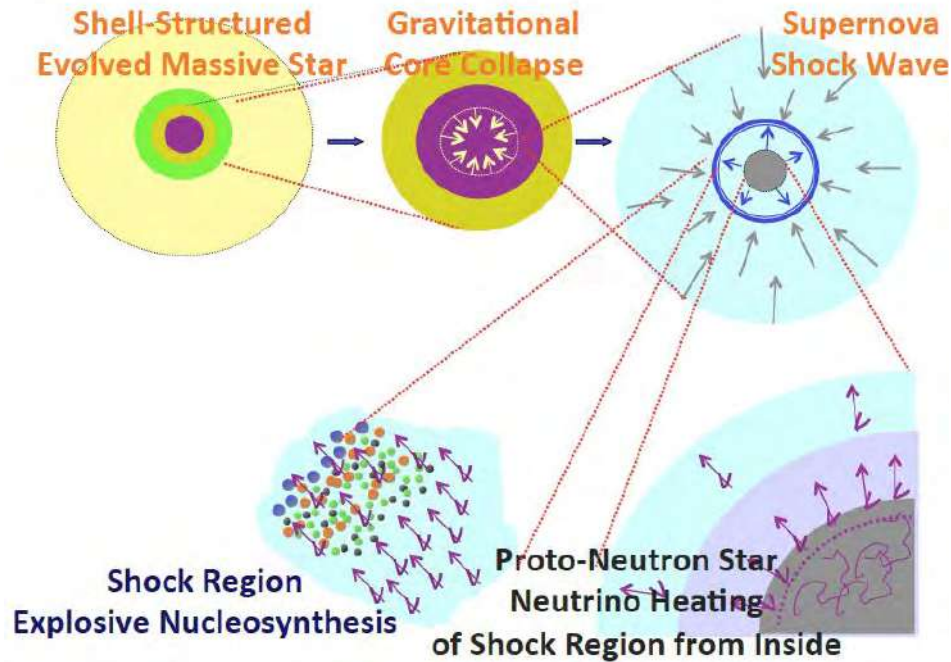
Supernova Ia Models



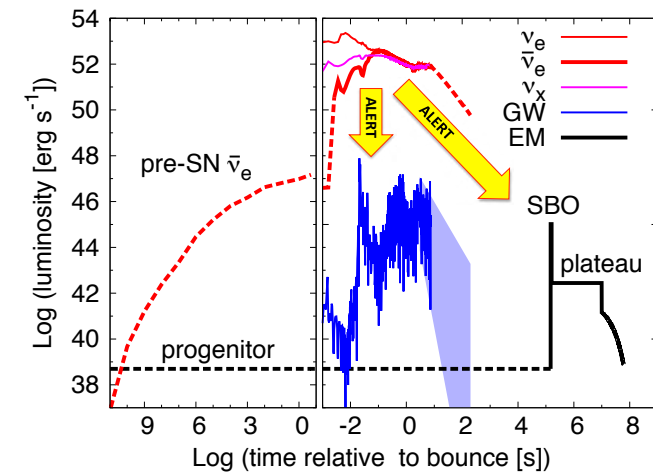
...also from γ -ray observations:
 → SN Ia are a variety
 (the "standardizable candles"??)

Taubenberger 2017

Complexities of Gravitational Collapse and SN



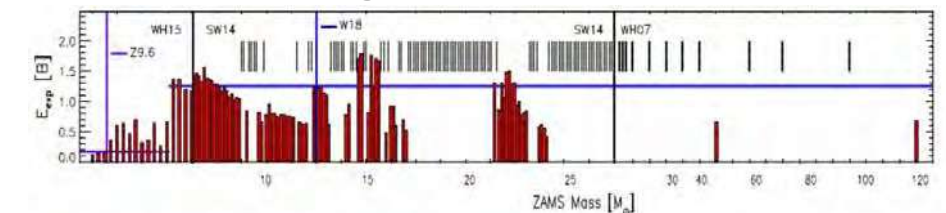
Raph Hix 2016



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

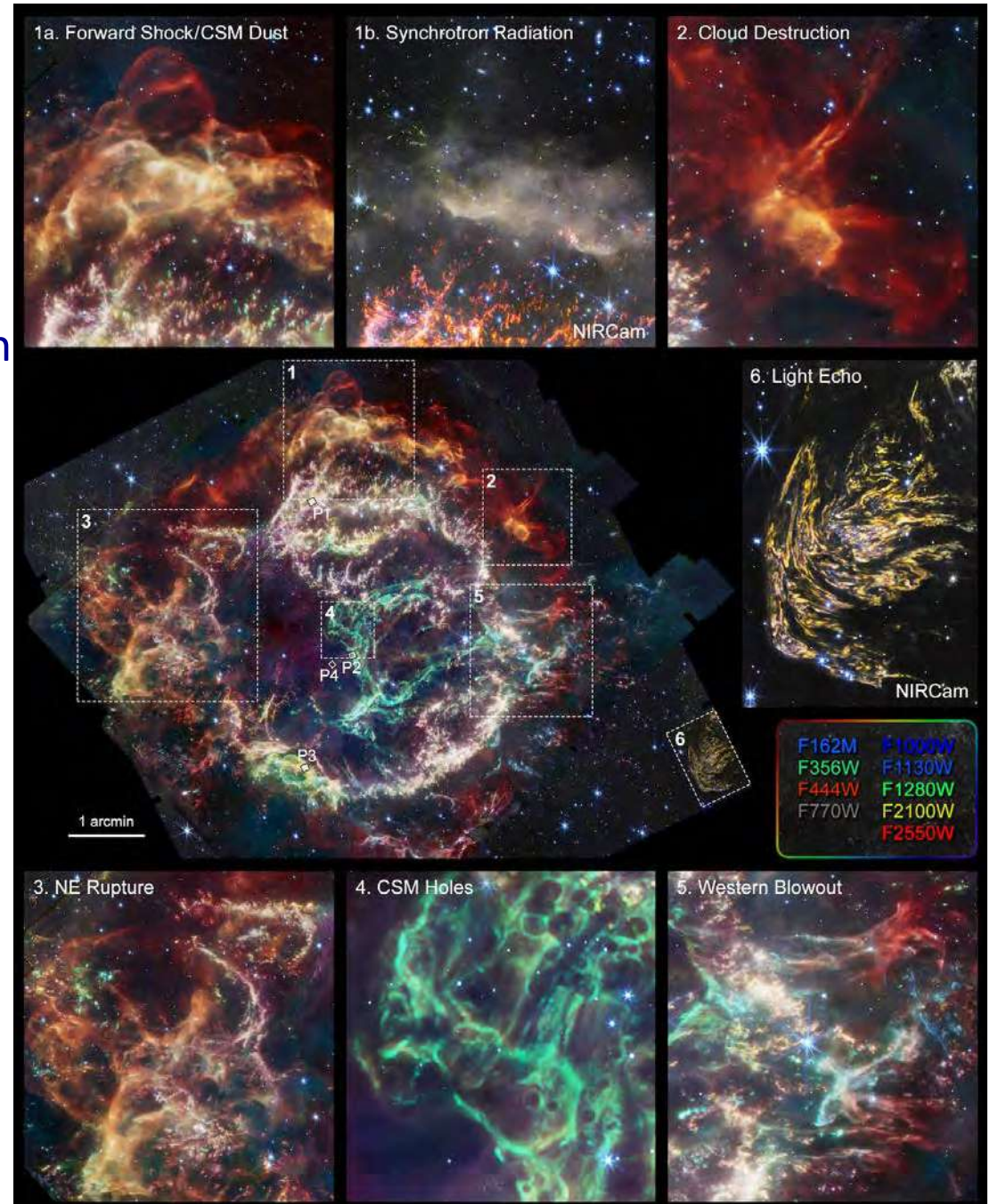
Ugliano+2012, Sukhbold+ 2016, Couch+2020



Cas A with JWST

Milisavljevic+2023

- The Cas A SNR displays a great variety of features that reflect the ccSN explosion history and dynamics
 - ☆ interaction of the SN shock with surrounding CSM
 - 👉 shock and dust
 - 👉 synchrotron emission
 - 👉 destruction of ISM clouds
 - ☆ internal dynamics of the expanding remnant
 - 👉 CSM structure remains
 - 👉 explosion asymmetry remains
 - 👉 RT lobes
 - 👉 jets
 - 👉 reverse-shocked ejecta
 - ☆ light echoes



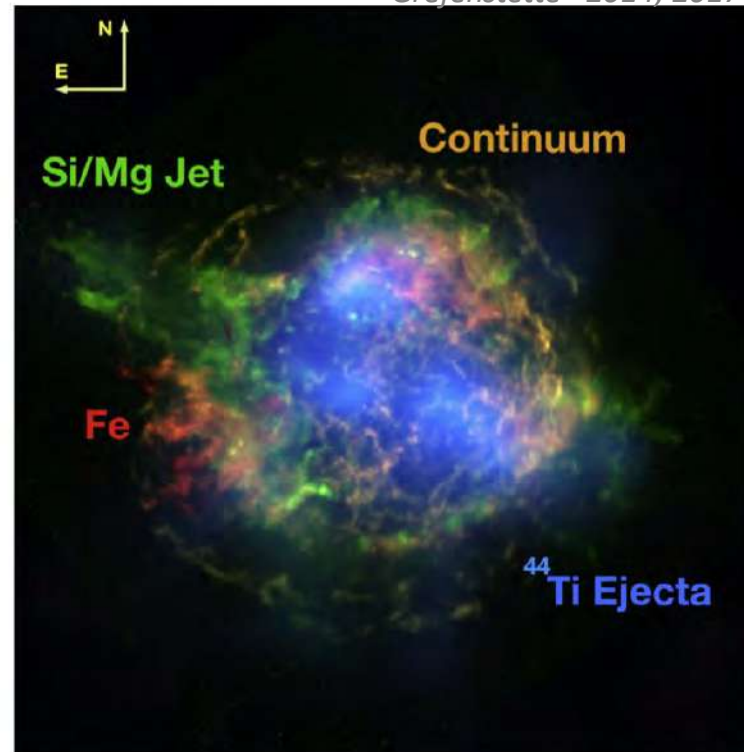
^{44}Ti radioactivity in Cas A: Locating the inner Ejecta

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

👉 first mapping of radioactivity in a SNR

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

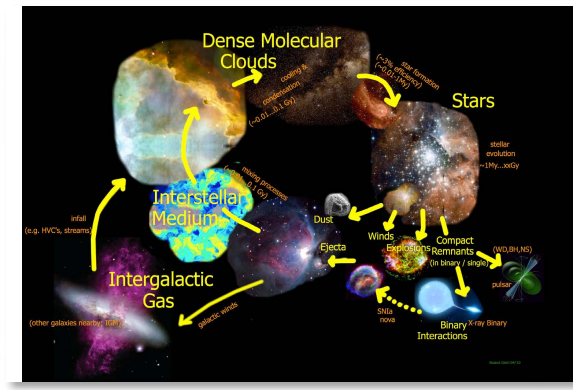
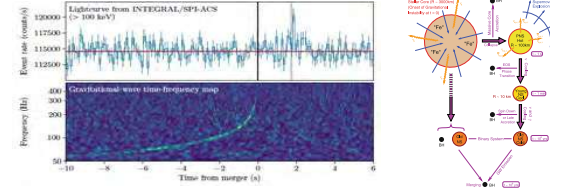
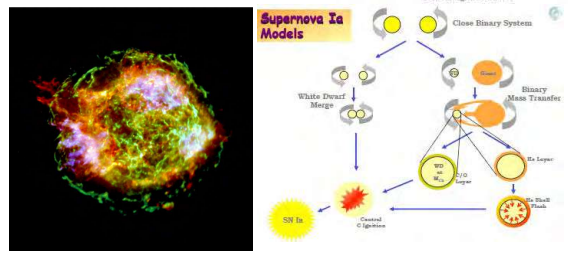
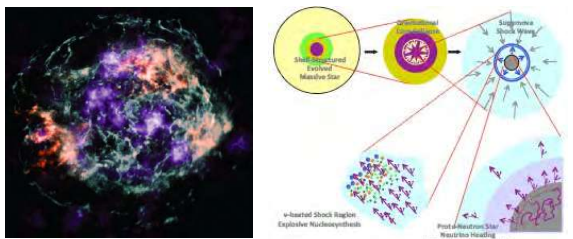
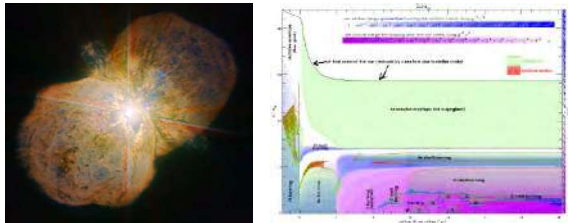
Grefenstette+ 2014; 2017



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

👉 Fe-lines (eg X-rays) are biased from ionization of shocked plasma

The Challenges



★ Understand the sources of new nuclei

★ Trace the flows of cosmic matter

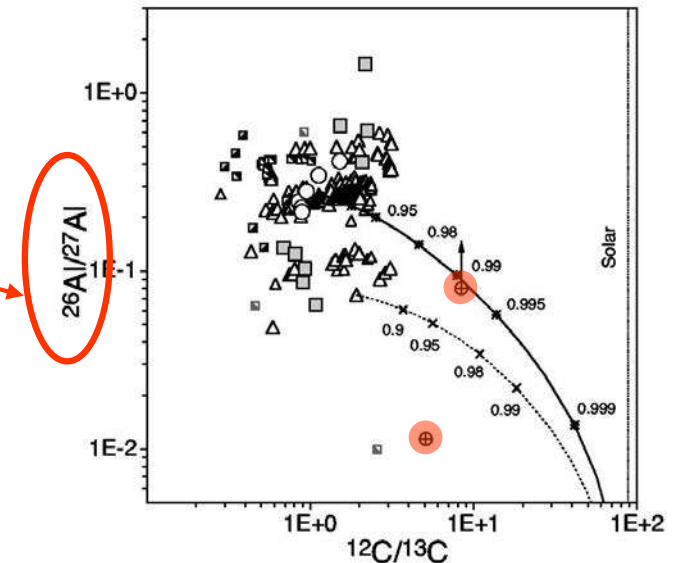
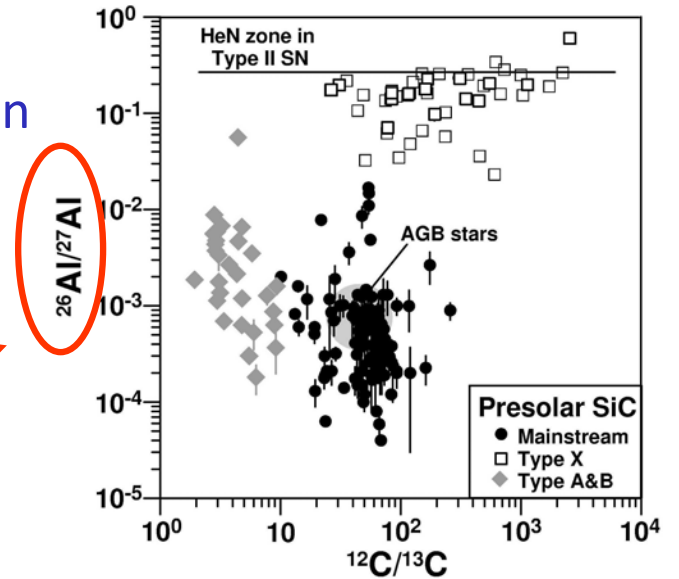
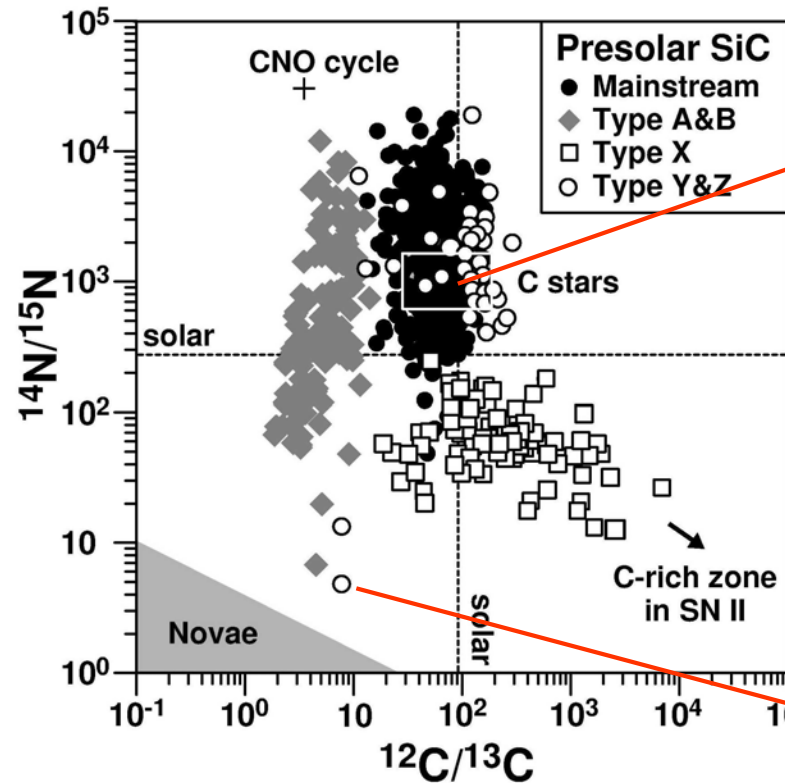


← 1 μm →

Sources of ^{26}Al : Results from Presolar Grains

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

- AGB Stars
- Supernovae
- Novae



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

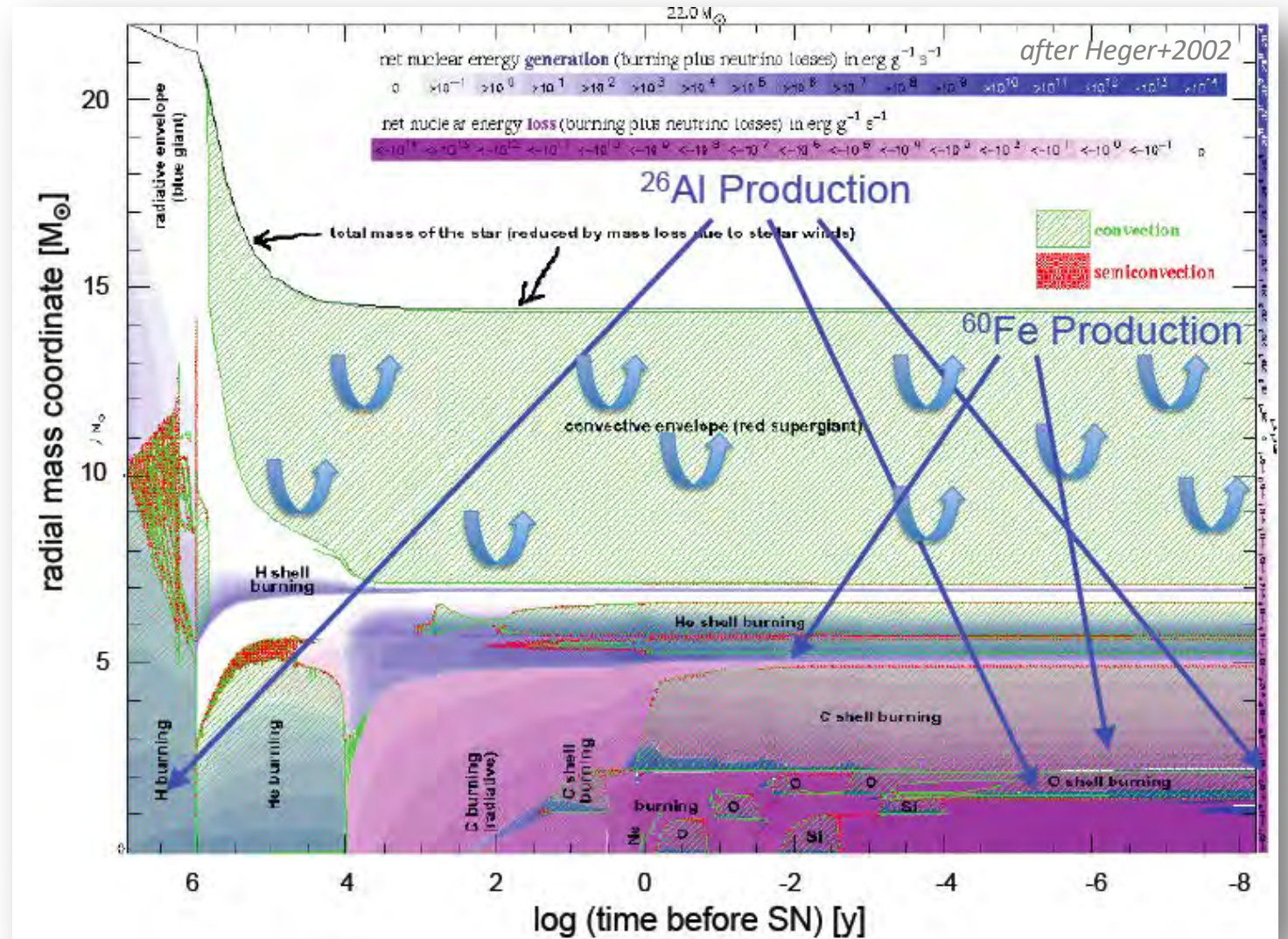
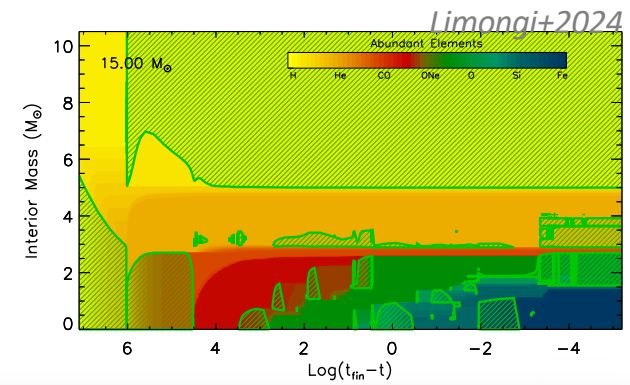
^{26}Al Found
in ~ALL Candidate Sources

Radioactivities from massive stars:

^{60}Fe , ^{26}Al

→ Messengers from Massive-Star Interiors!

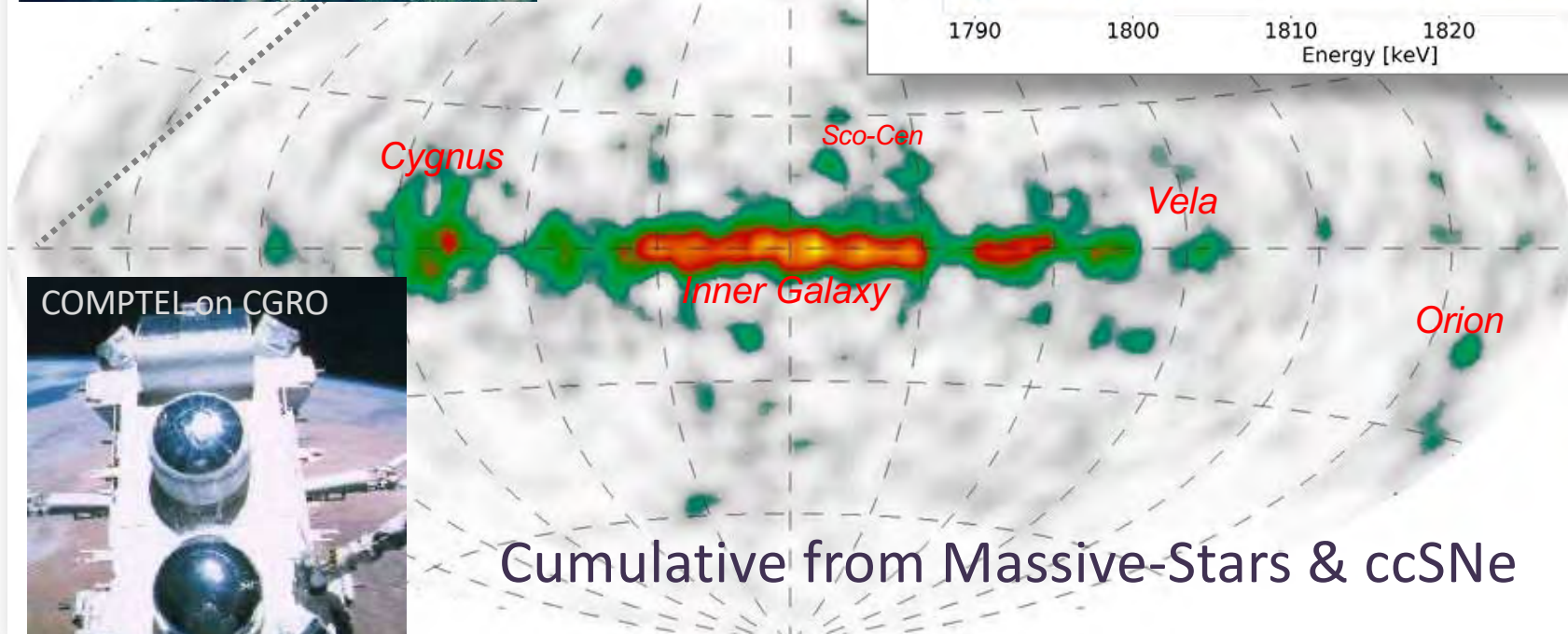
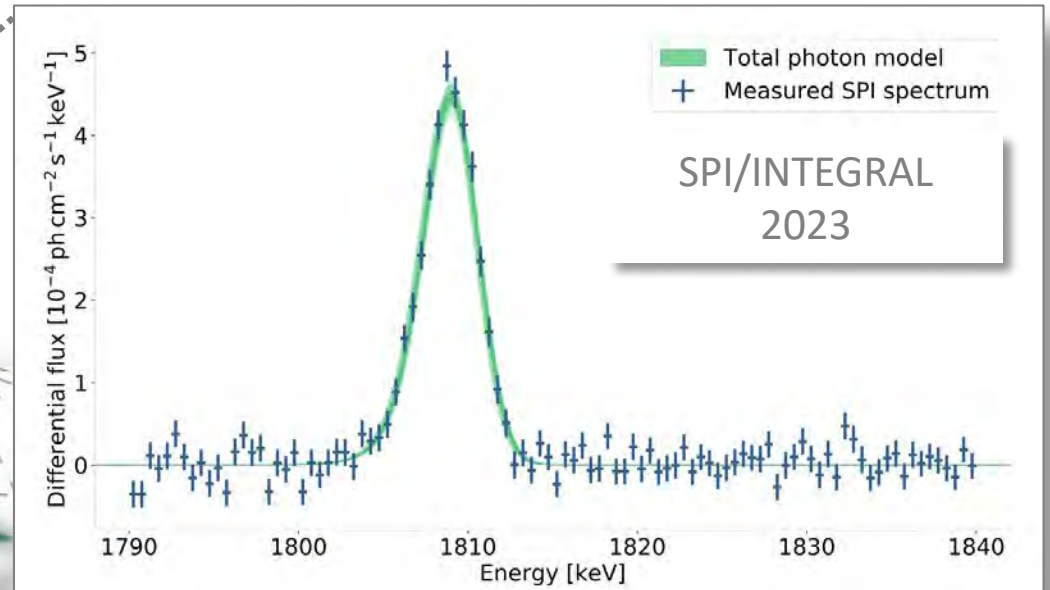
...complementing neutrinos and asteroseismology!



Processes:

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

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

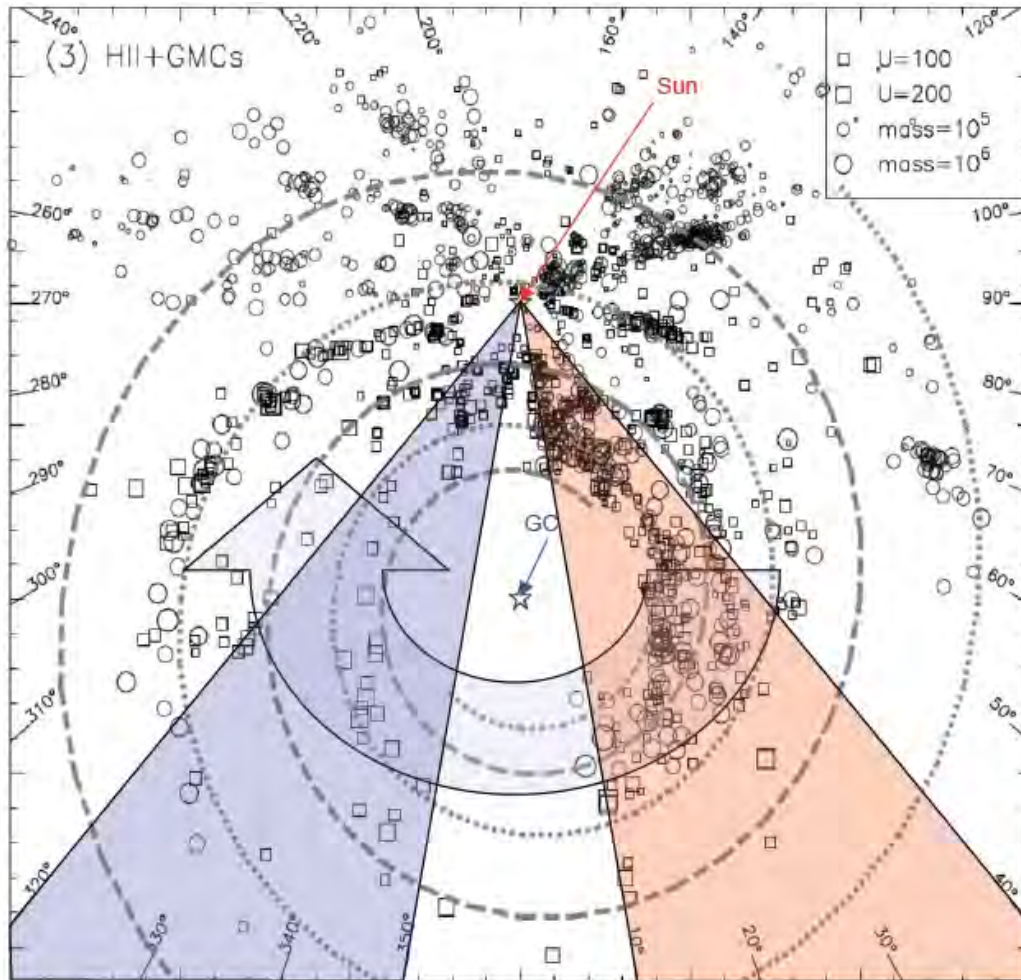


Cumulative from Massive-Stars & ccSNe

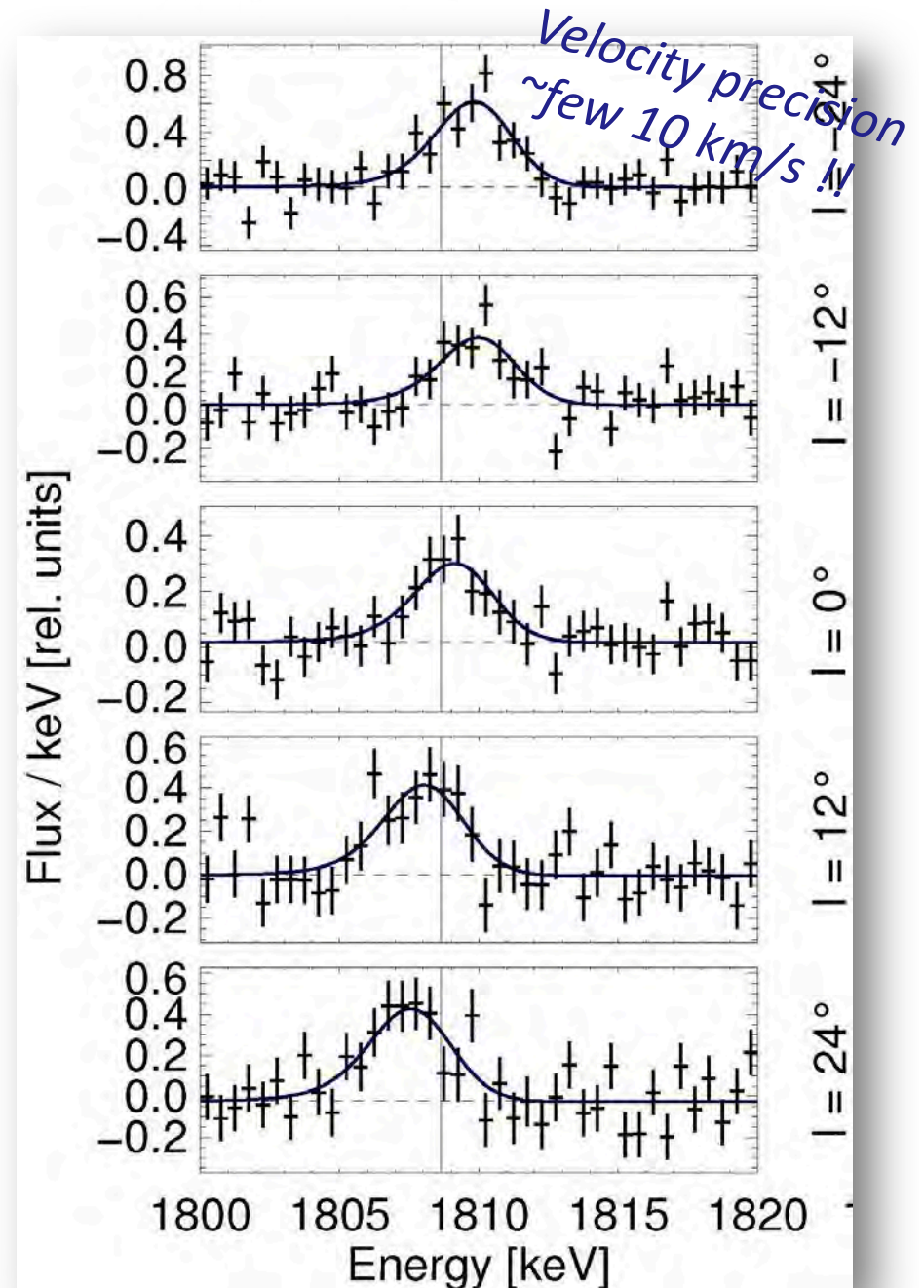
γ -ray flux \rightarrow cc-SN Rate = $1.3 (\pm 0.6)$ per Century

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

👉 Large-scale Galactic rotation

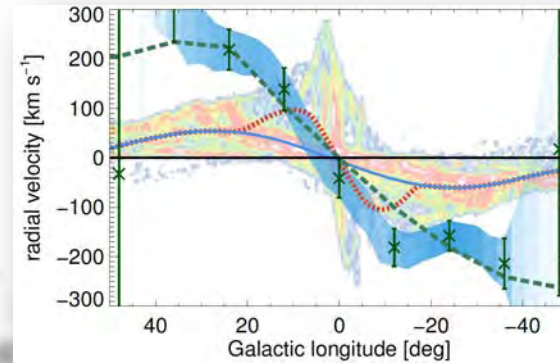


Kretschmer et al., A&A (2013)

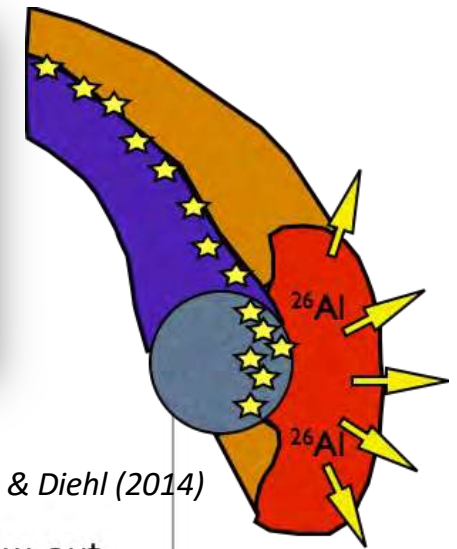


How massive-star ejecta are spread out...

Superbubbles extended away from massive-star groups



Kretschmer+(2013)



Krause & Diehl (2014)

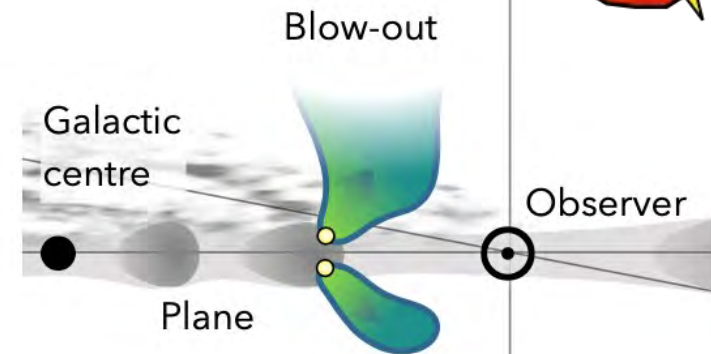
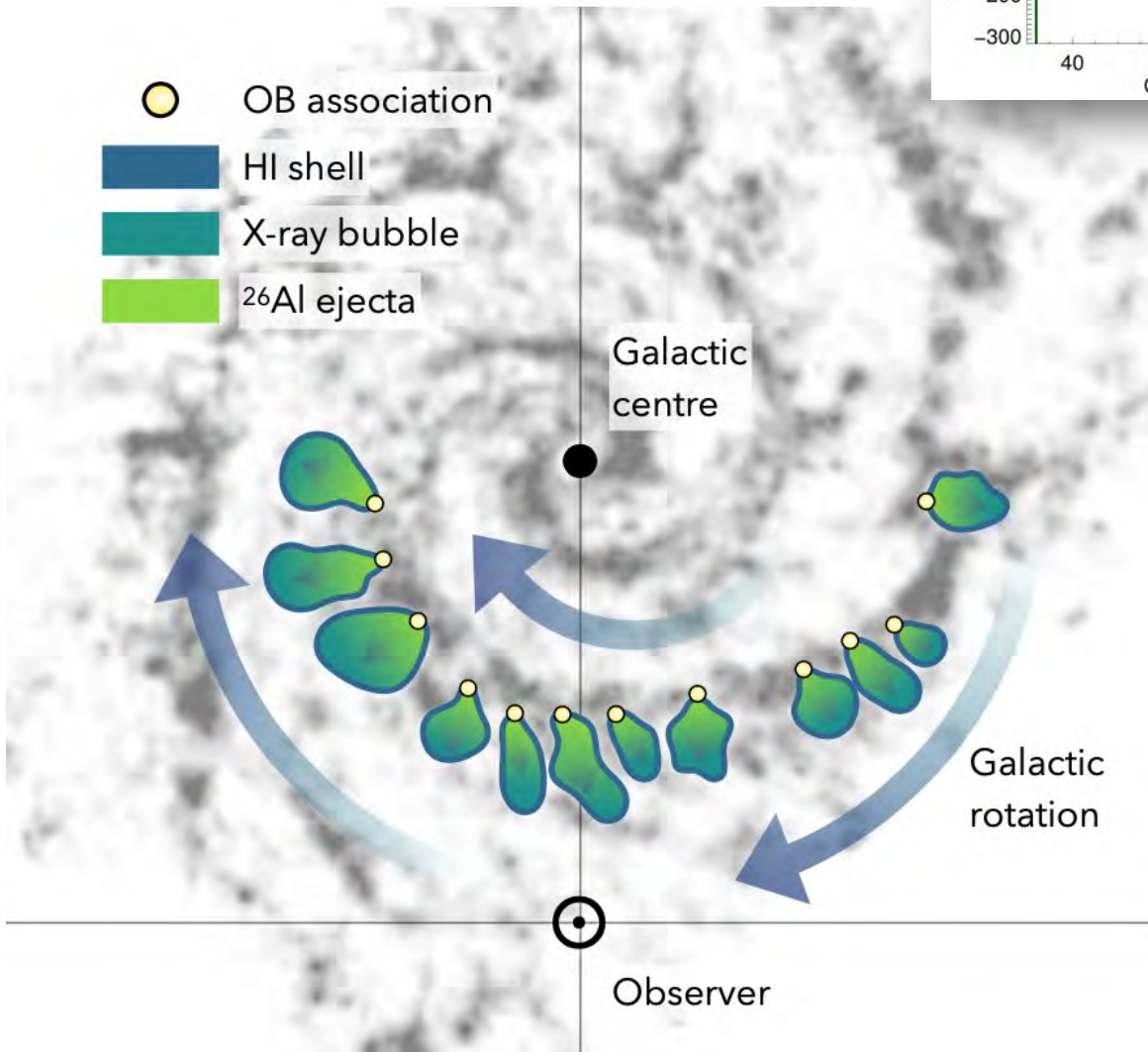
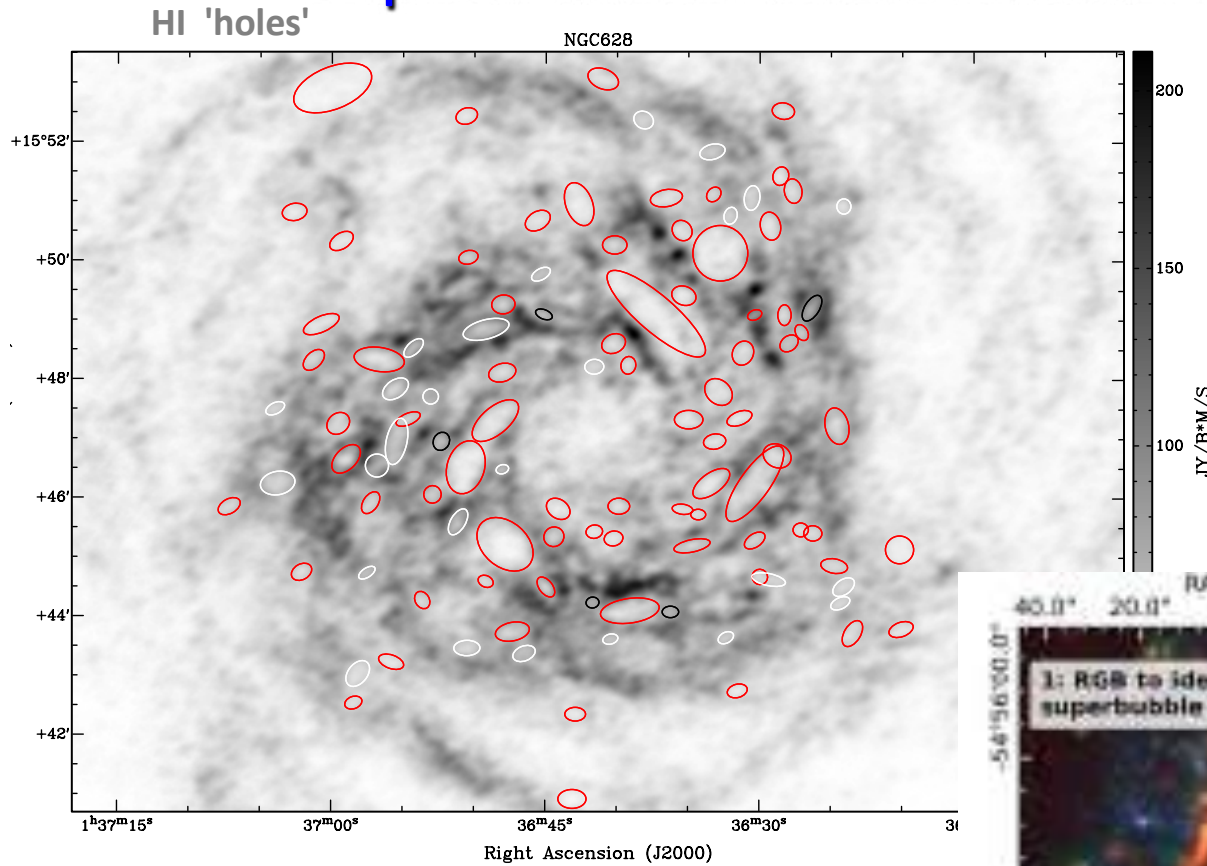
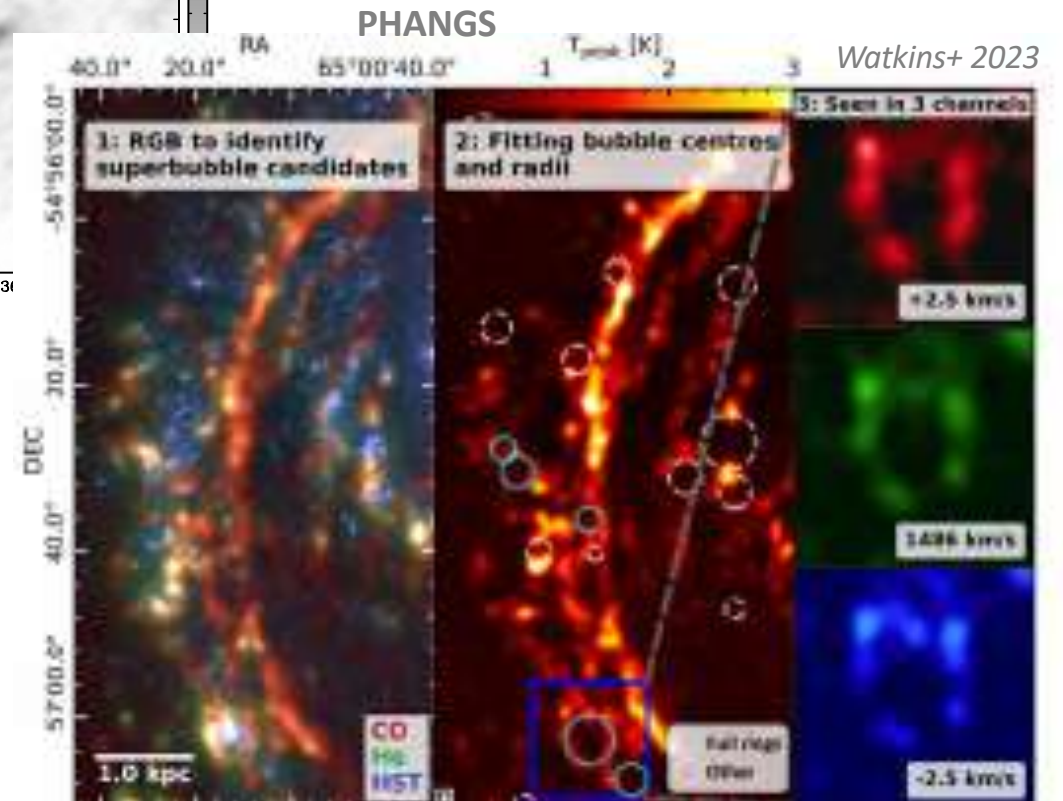


Illustration by M. Pleintinger (2020)

Superbubbles observations in other galaxies



Bagetakos+ 2011

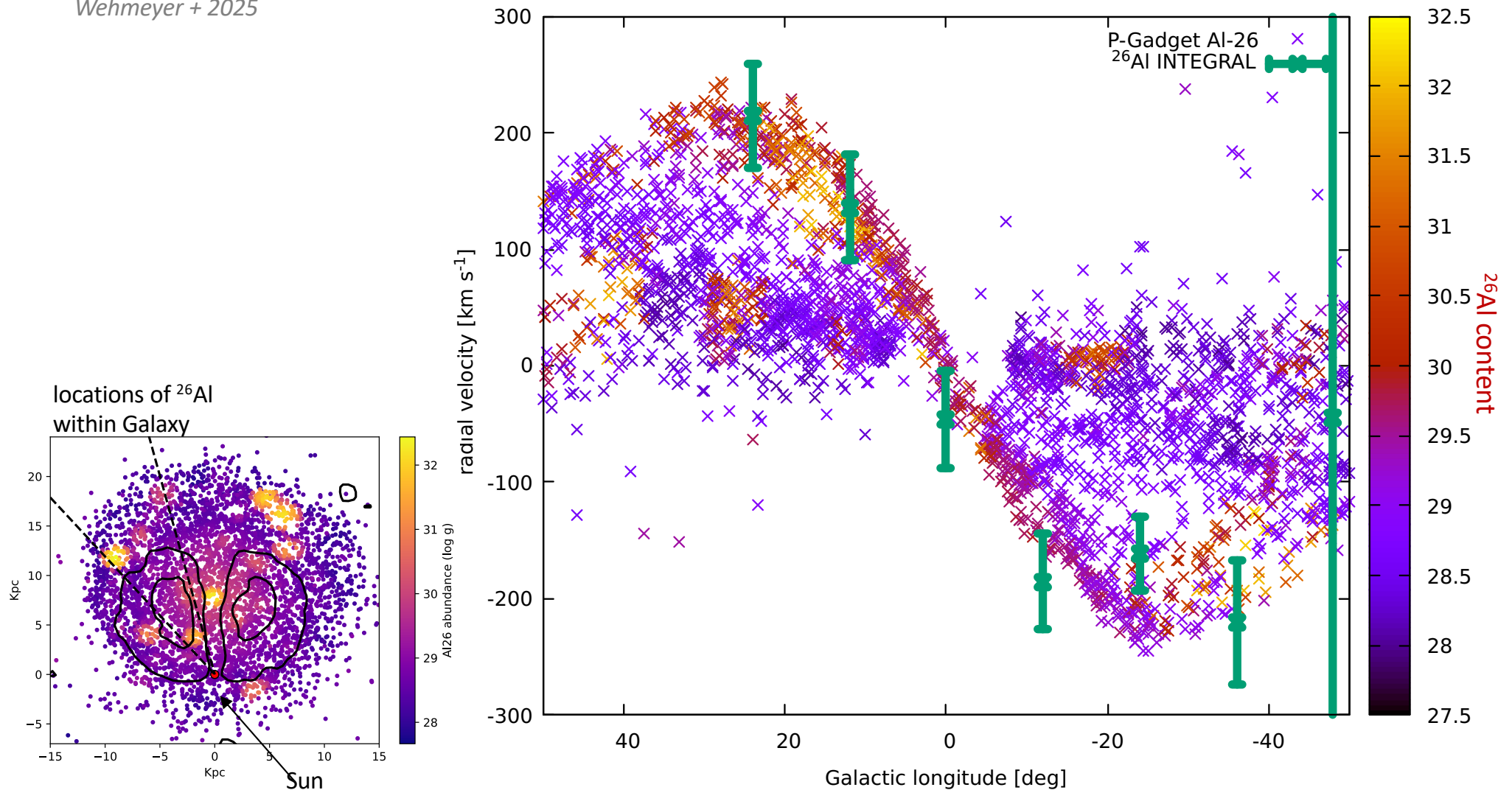


Simulations of (inhomogeneous) galactic evolution

→ ejecta with excess velocities appear naturally within a spiral galaxy

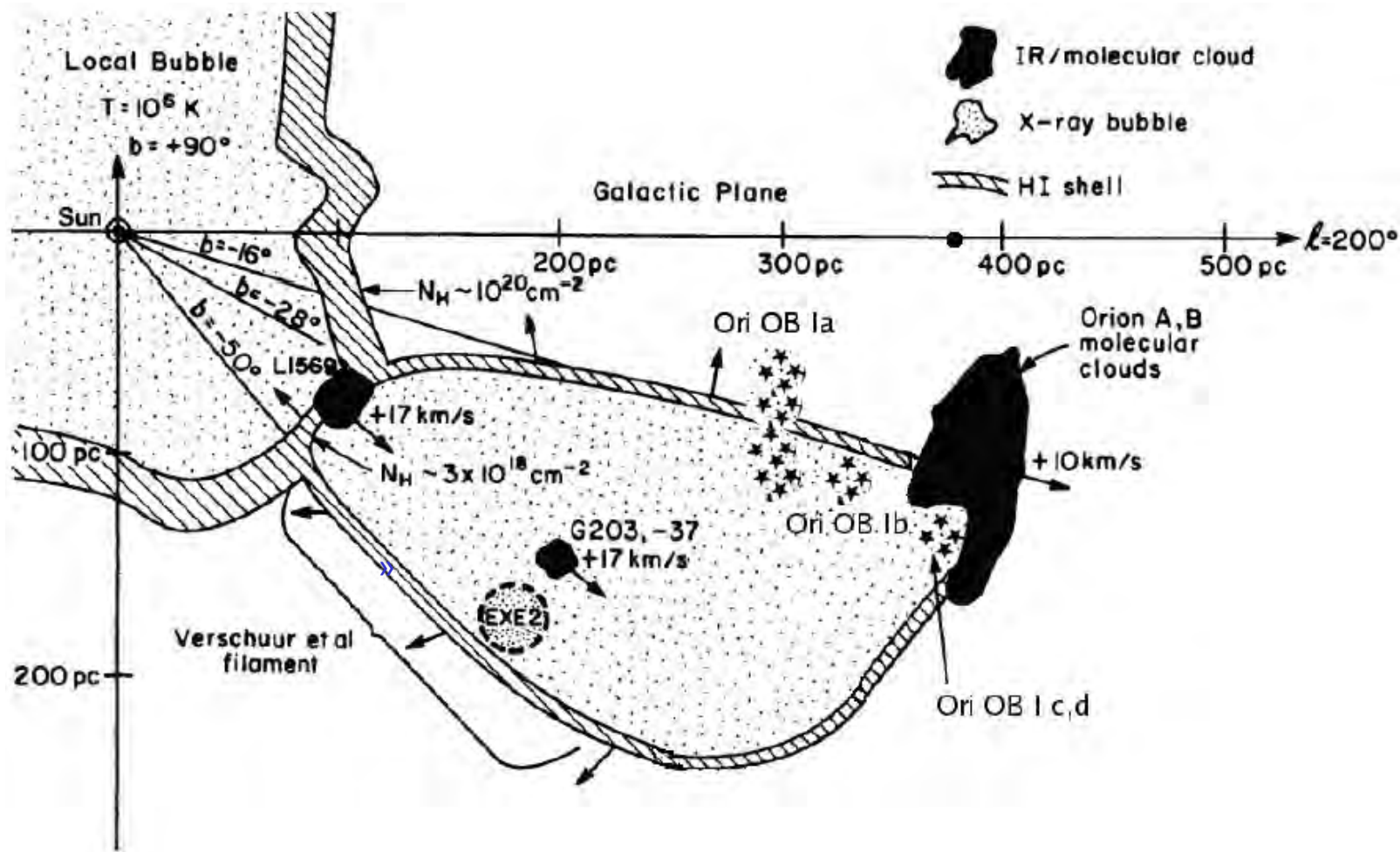
3D SPH simulation: analyze velocities of ^{26}Al -enriched matter from star formation activity

Wehmeyer + 2025

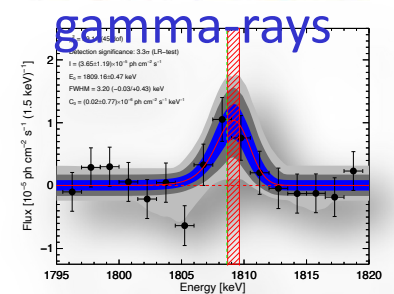
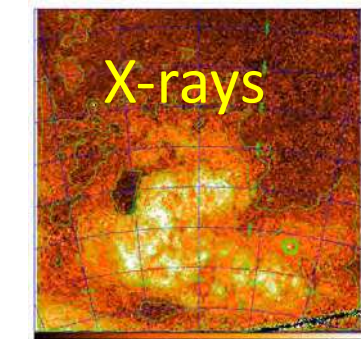
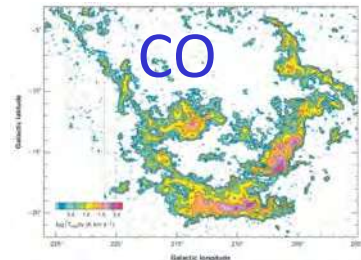
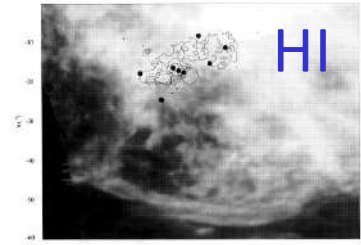


Orion-Eridanus: A superbubble blown by stars & supernovae

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



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

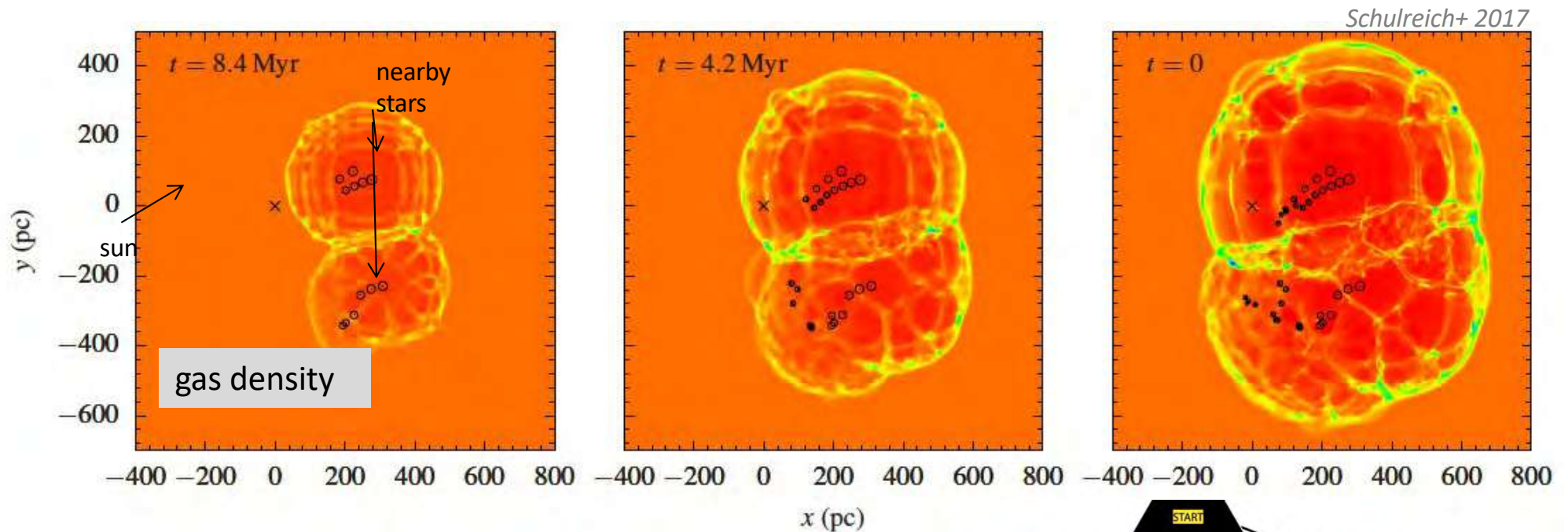


3D MHD sim, 0.1..0.005 pc resolution
Krause+ 2013ff

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

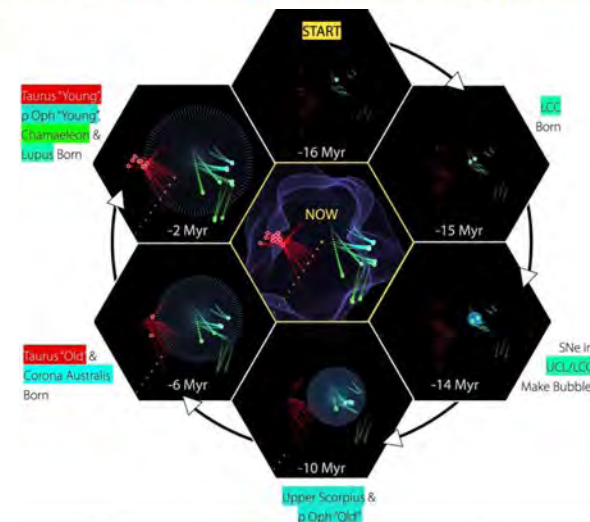
The Sun is (now) located inside a hot cavity (the "Local Bubble")

SN explosions within LB \rightarrow ejecta flows reach the Solar System



see also Zucker+ 2022

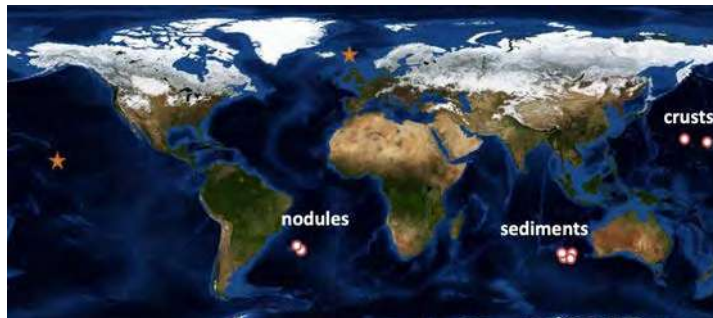
for a recent update on the Local Bubble and the Sco-Cen SN activity, confirming this local superbubble interpretation with dust cloud maps and Gaia data



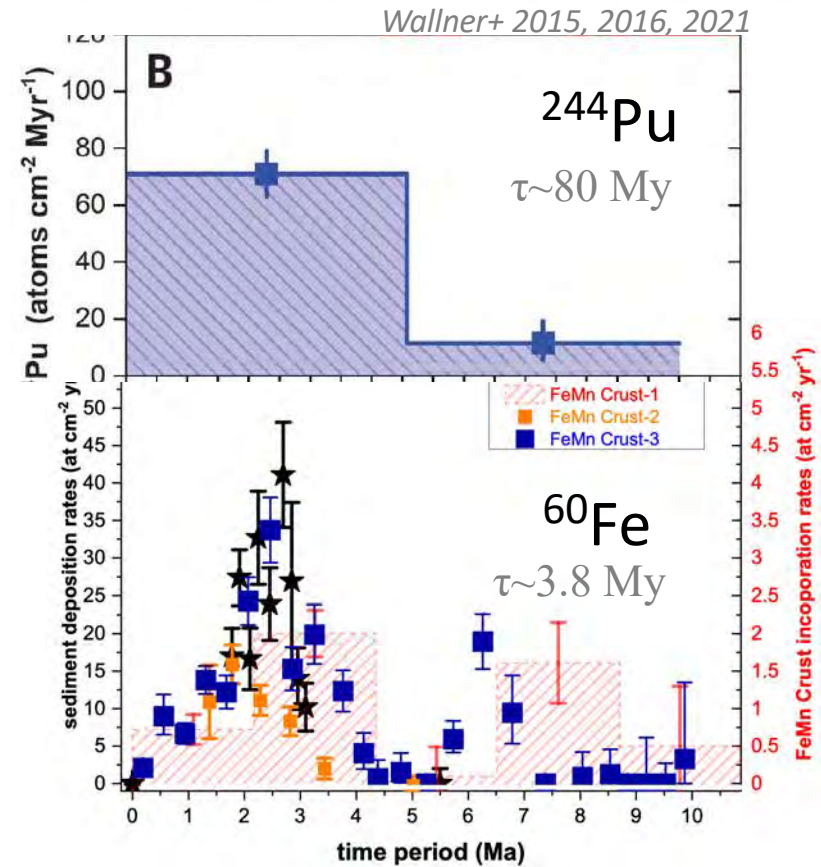
^{60}Fe and ^{244}Pu from nearby nucleosynthesis found on Earth



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



+ lunar material probes; + antarctic snow

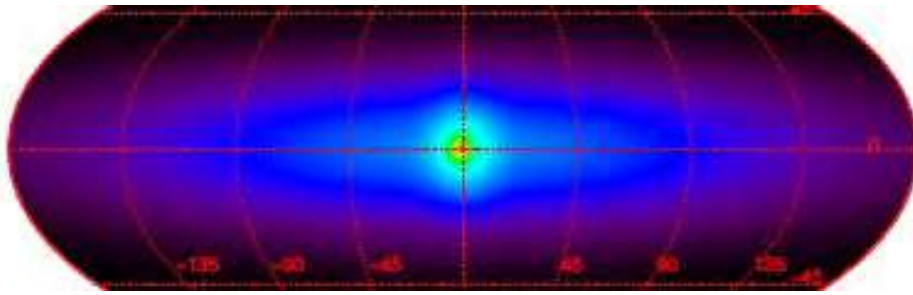


peak of radioactivity influx
 ≈ 3 & 6-8 My ago!

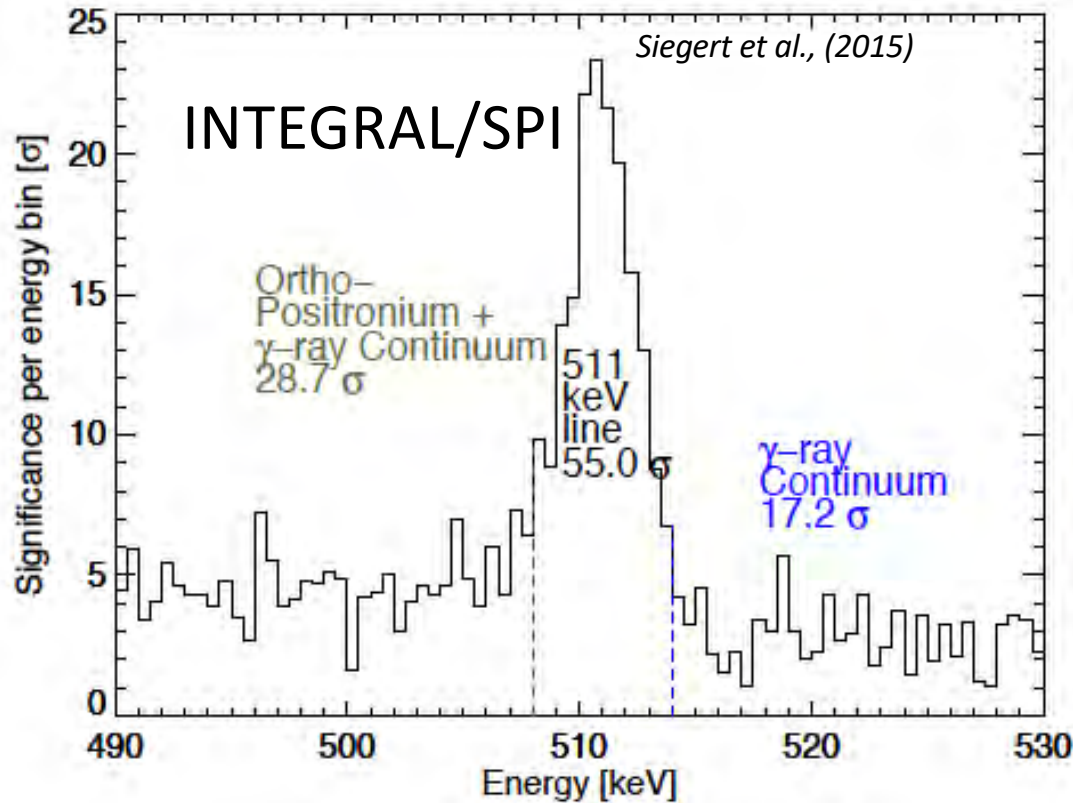
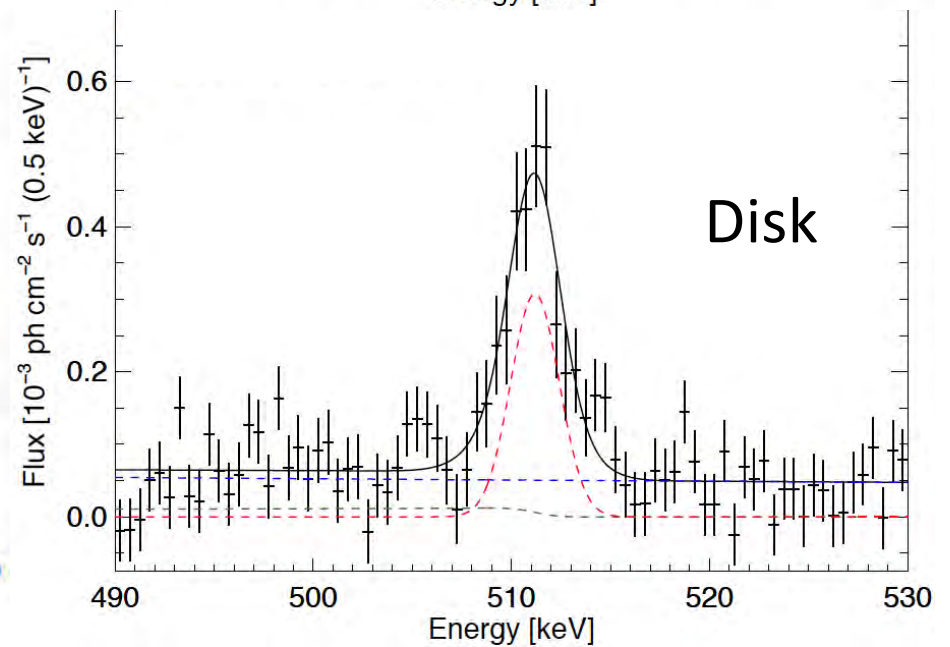
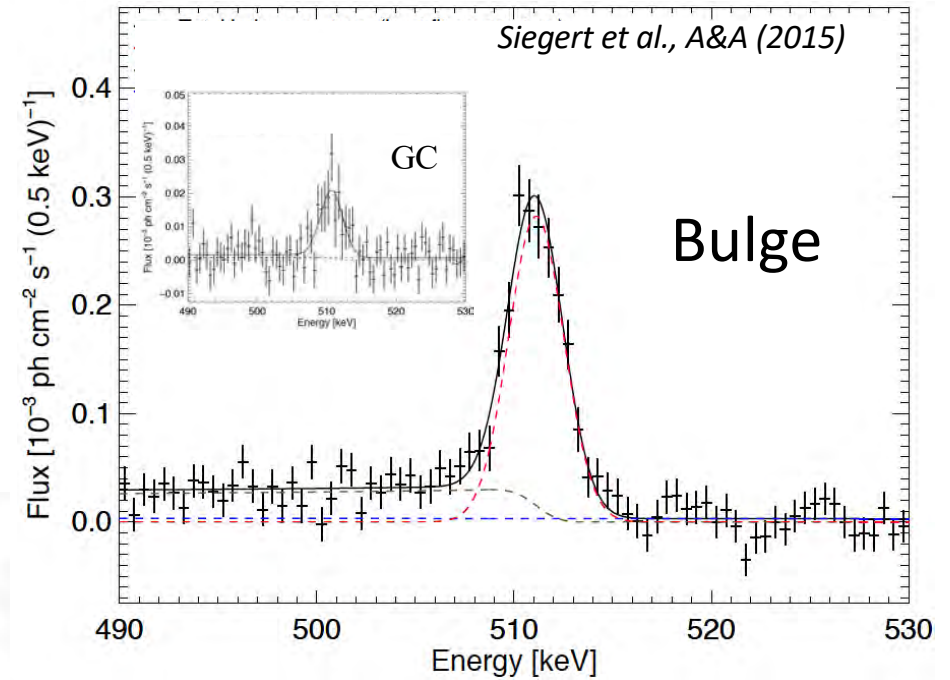
What are its sources?

How did these traces of nucleosynthesis get here?

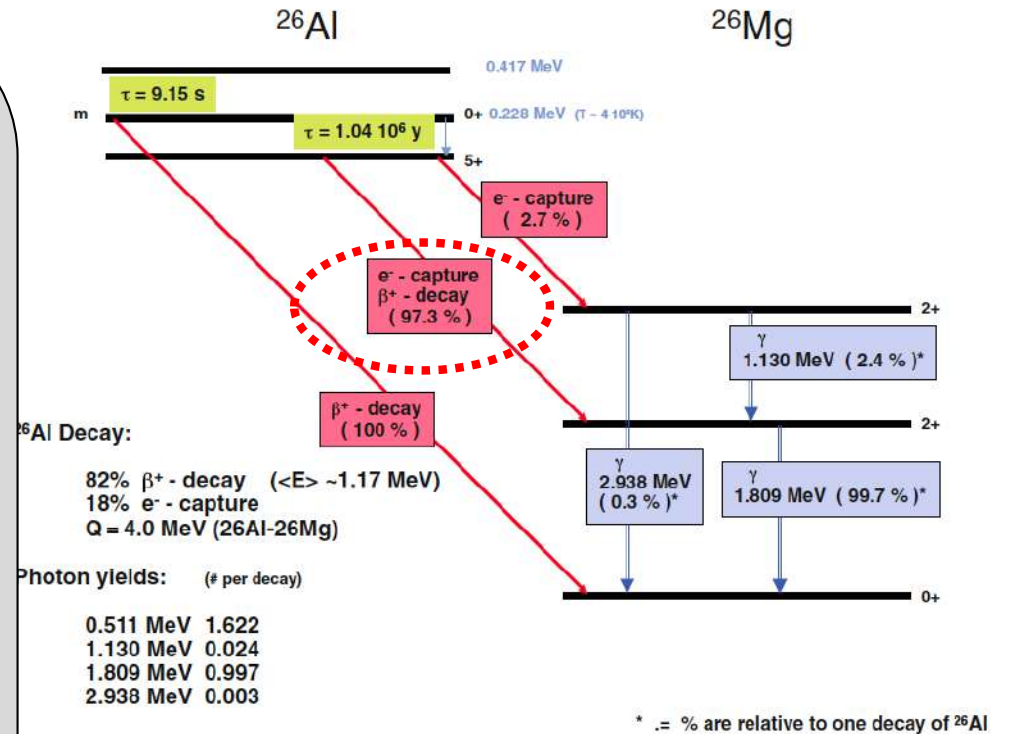
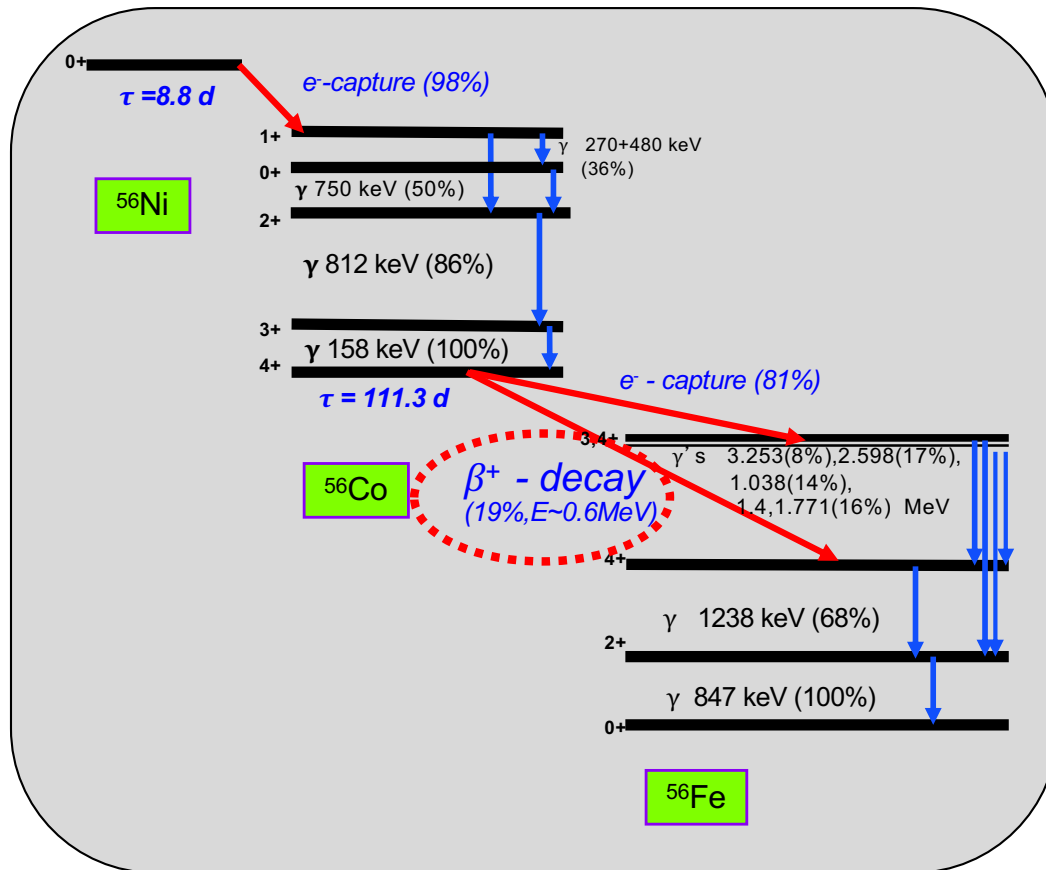
Positron annihilation within our Galaxy



★ Derive/discriminate spectra from different regions



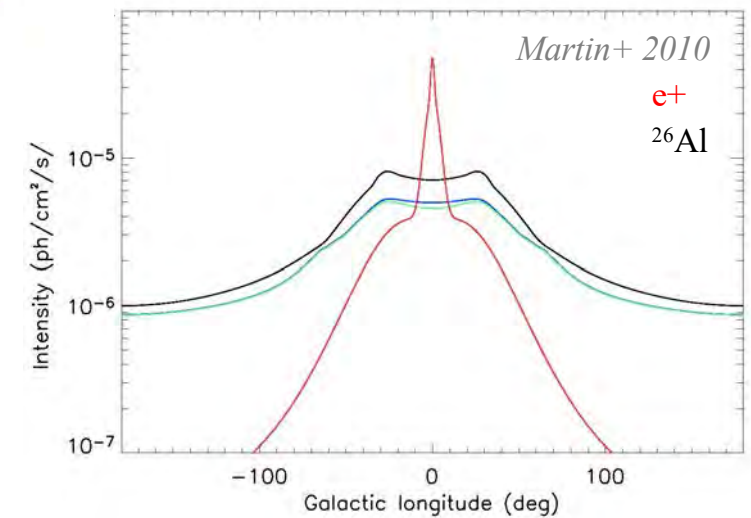
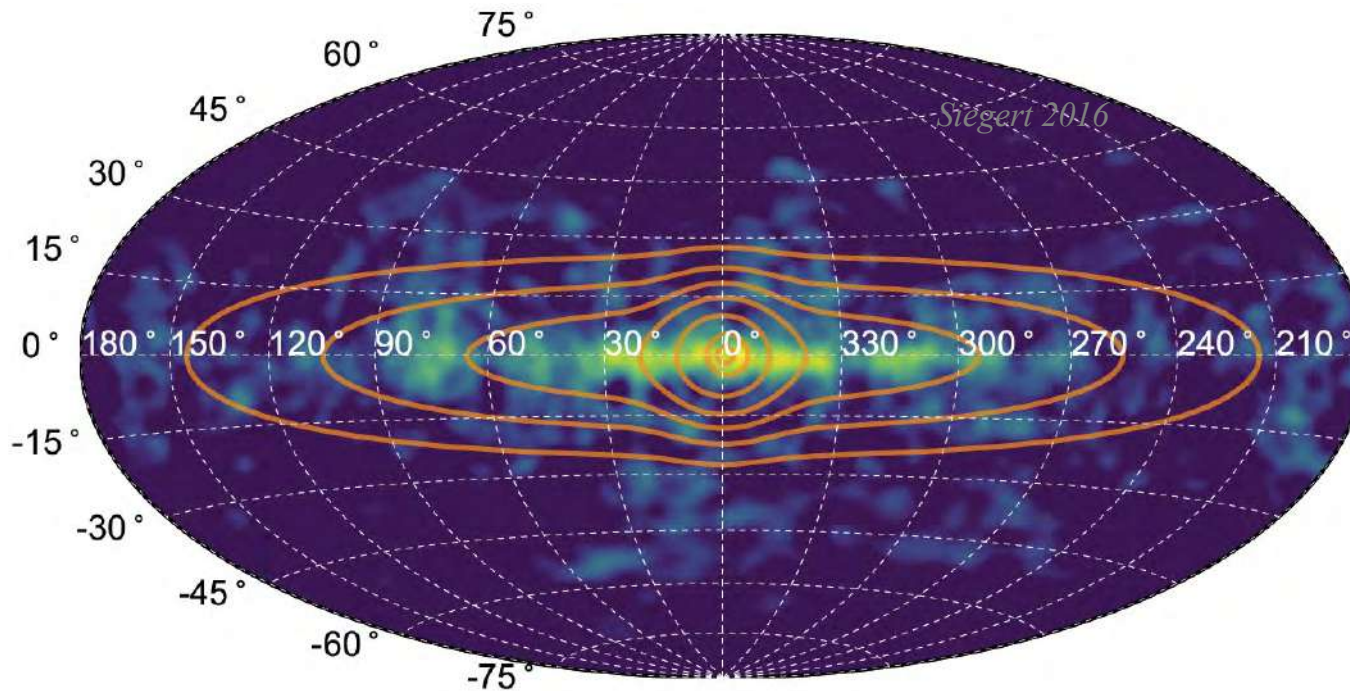
radioactive decay → energy sources = γ rays and positrons



photons and positrons may escape into interstellar medium

The Galactic Positron Annihilation

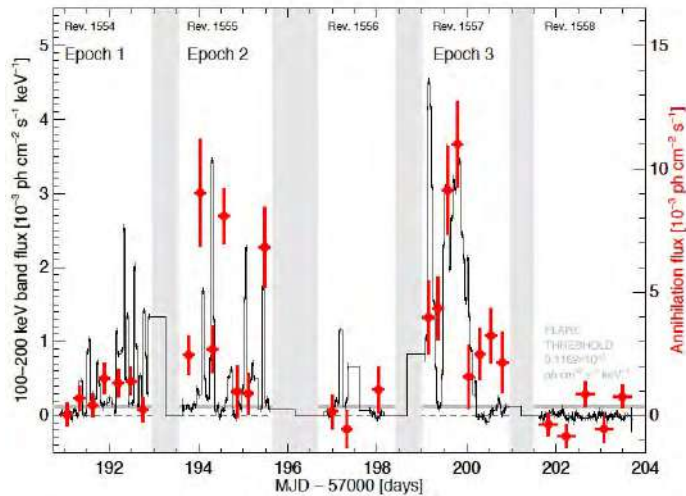
Is it all from ^{26}Al ?



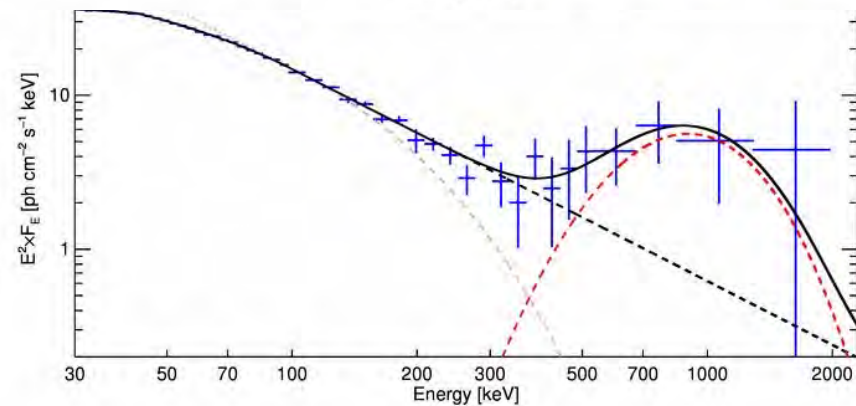
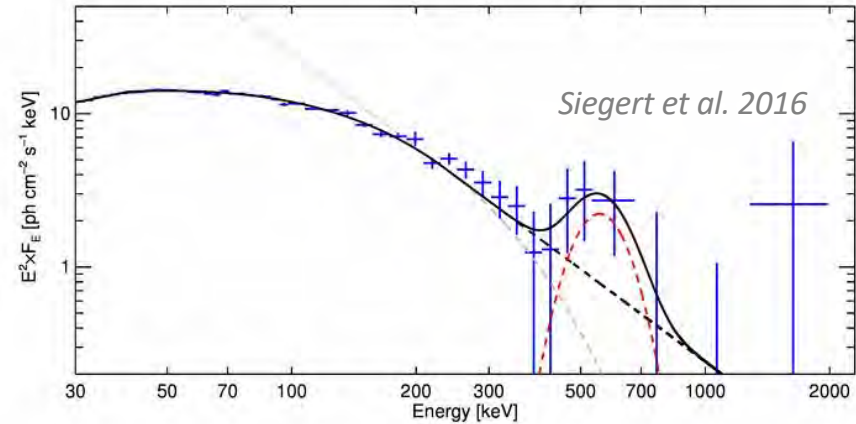
Morphology of emissions is different

→ annihilation astrophysics + other sources

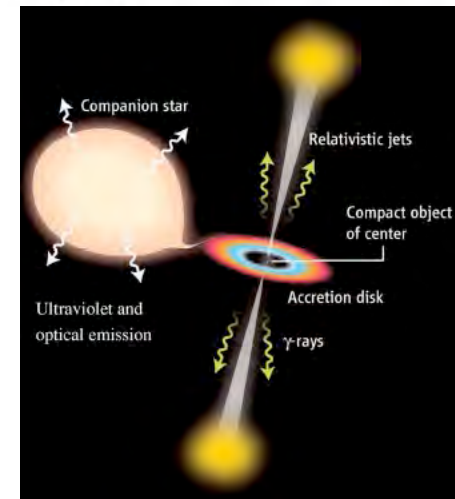
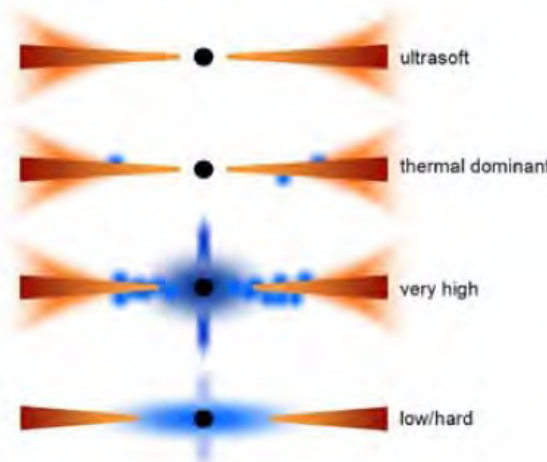
Pair plasma from a black hole in a flaring microquasar



V404Cyg
Jun 2016

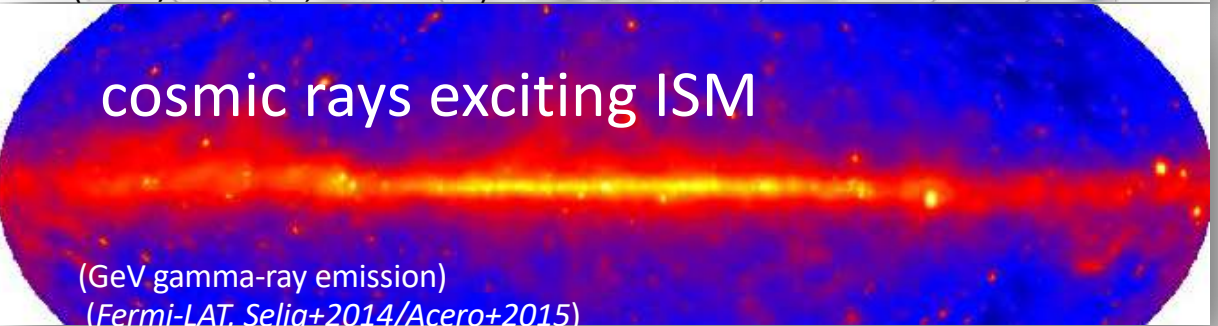
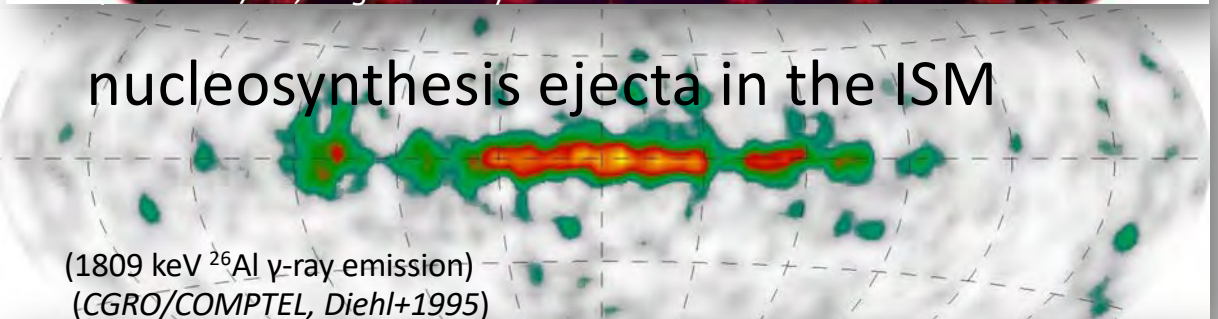
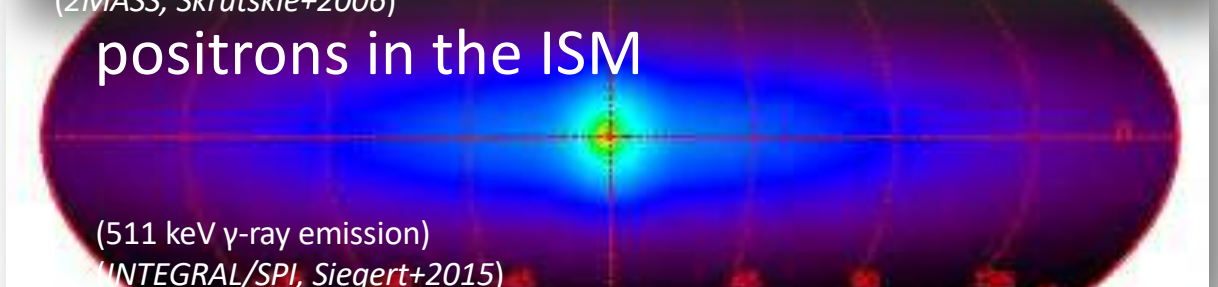
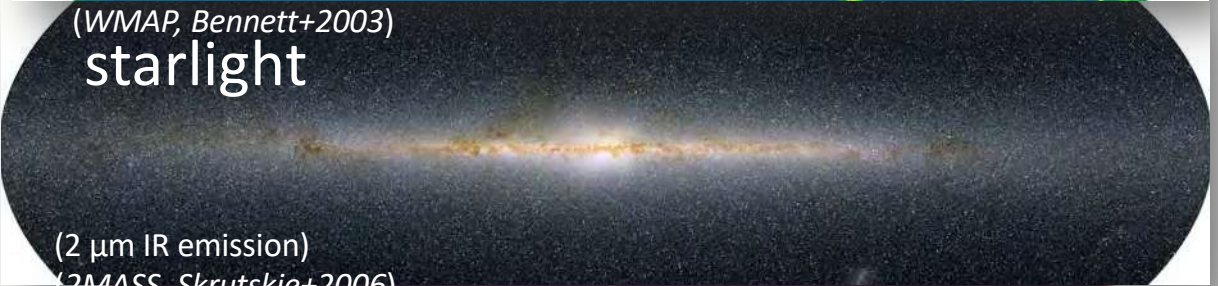
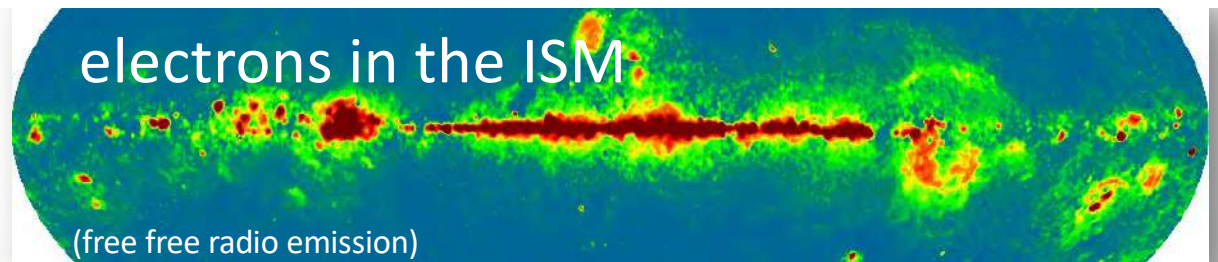


- V404 Cyg flare spectra show e^+ annihilation
- annihilation conditions vary across flaring period
- jet base is the plausible pair production region
- accreting BH binaries may be significant e^+ contributors in the Galaxy



Galactic Messengers

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



Nuclear Astrophysics & Gamma-Ray Spectroscopy - Summary

☆ (even) supernova explosions are not 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 interiors are fundamentally 3D/asymmetric

👉 NSMs/kilonovae are fundamentally asymmetric, & rare



*need more
observed sources*

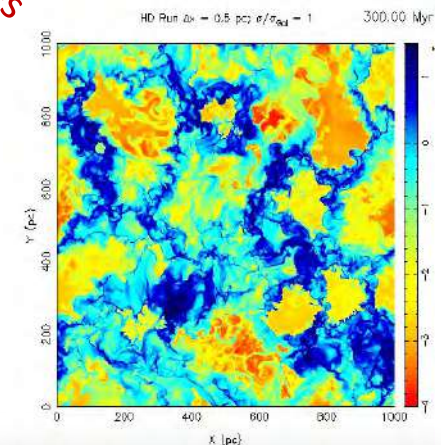
☆ Cycling of cosmic gas through sources and ISM is a challenge

👉 ^{26}Al preferentially appears in superbubbles

→ massive-star ingestions rarely due to single WR stars or SNe

👉 the current Galactic SN rate is $\sim 1/70$ years

👉 ^{60}Fe is a SN/wind ejecta diagnostic, and traces nearby SNe

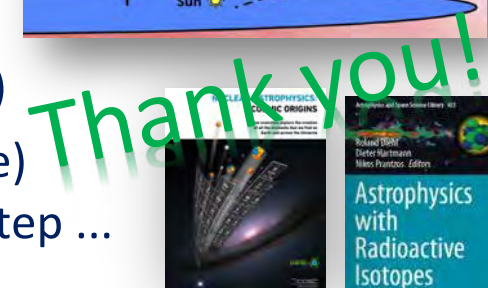
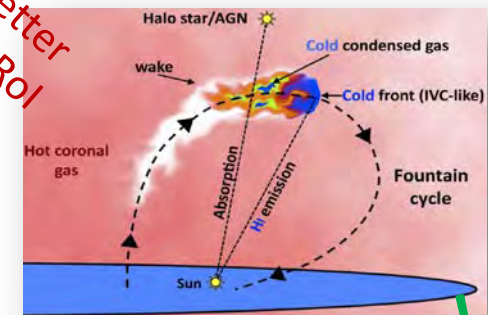


*need better
maps for ROI*

☆ 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!