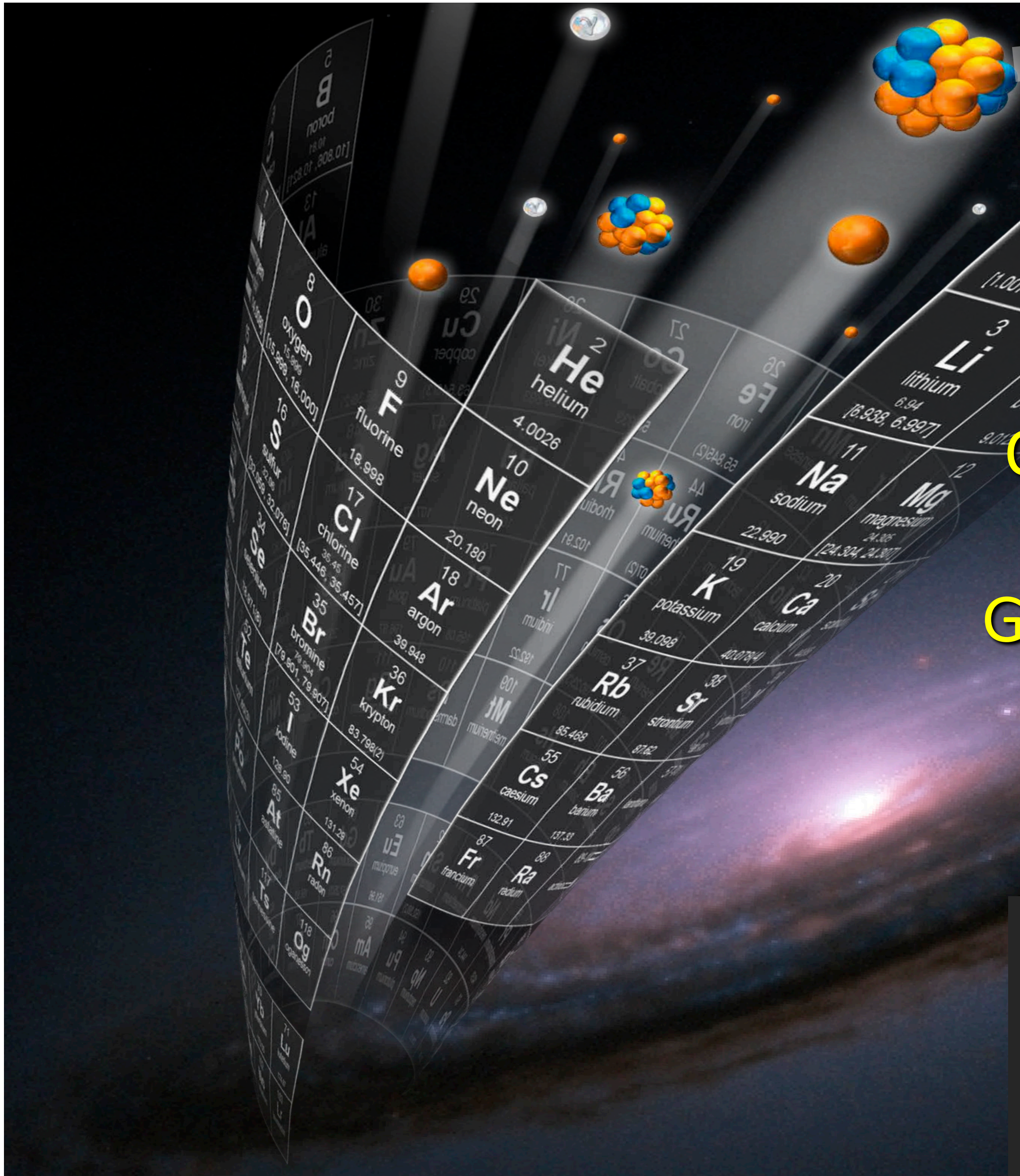
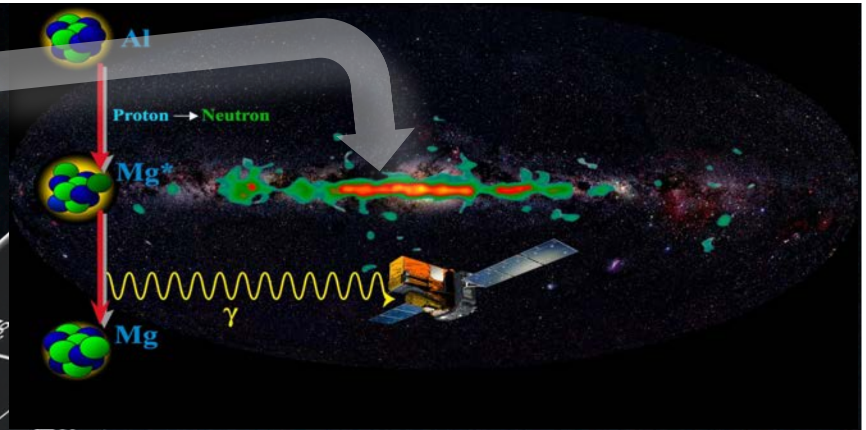




Cosmic Nucleosynthesis: Lessons from Gamma-Ray Spectroscopy

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

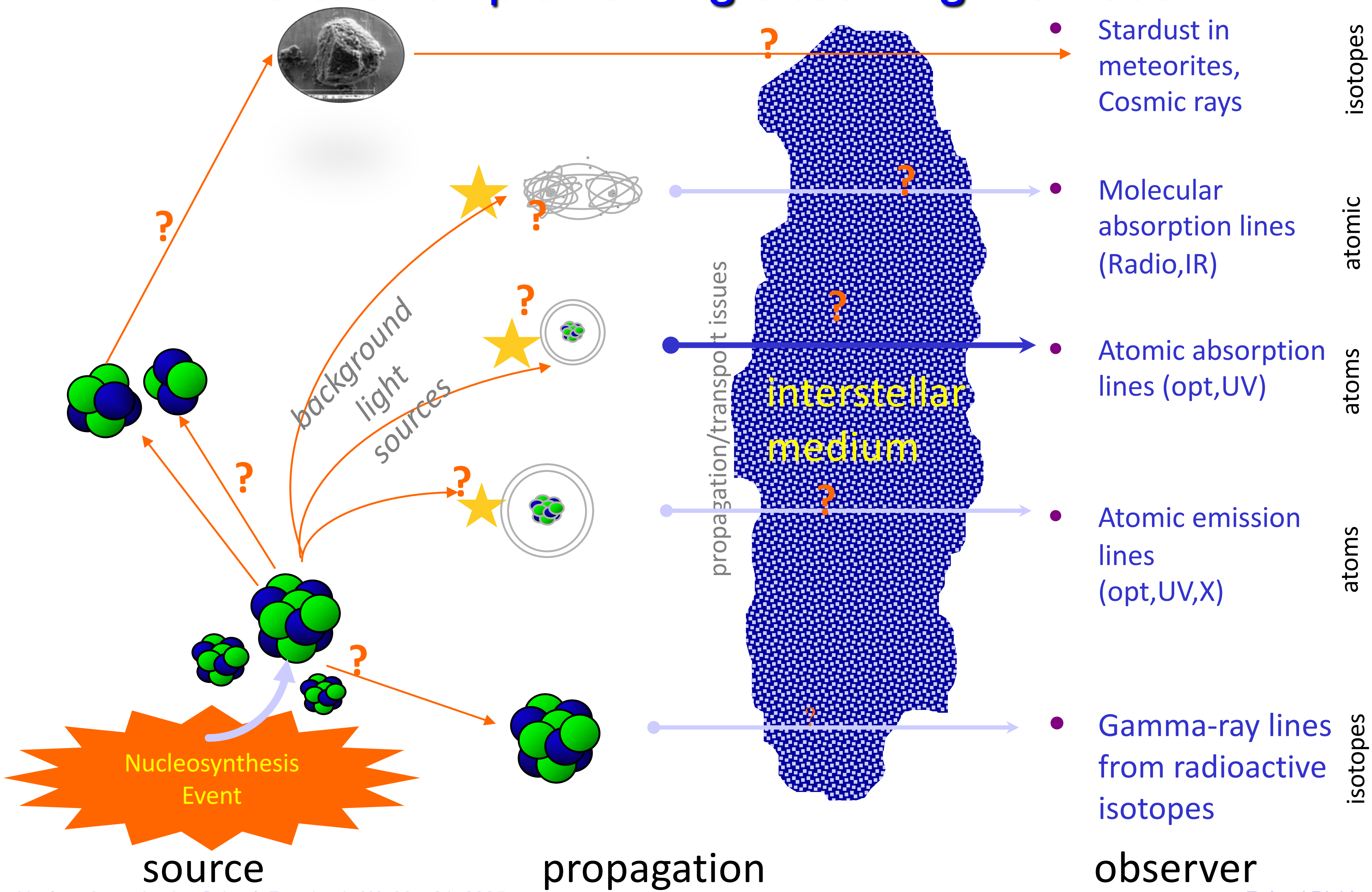
Contents:

1. Nucleosynthesis sources and their Ejecta
2. Learning from γ-ray observations
   - supernova explosions
   - large scale nucleosynthesis
   - star clusters
   - positrons
3. Conclusions and Prospects

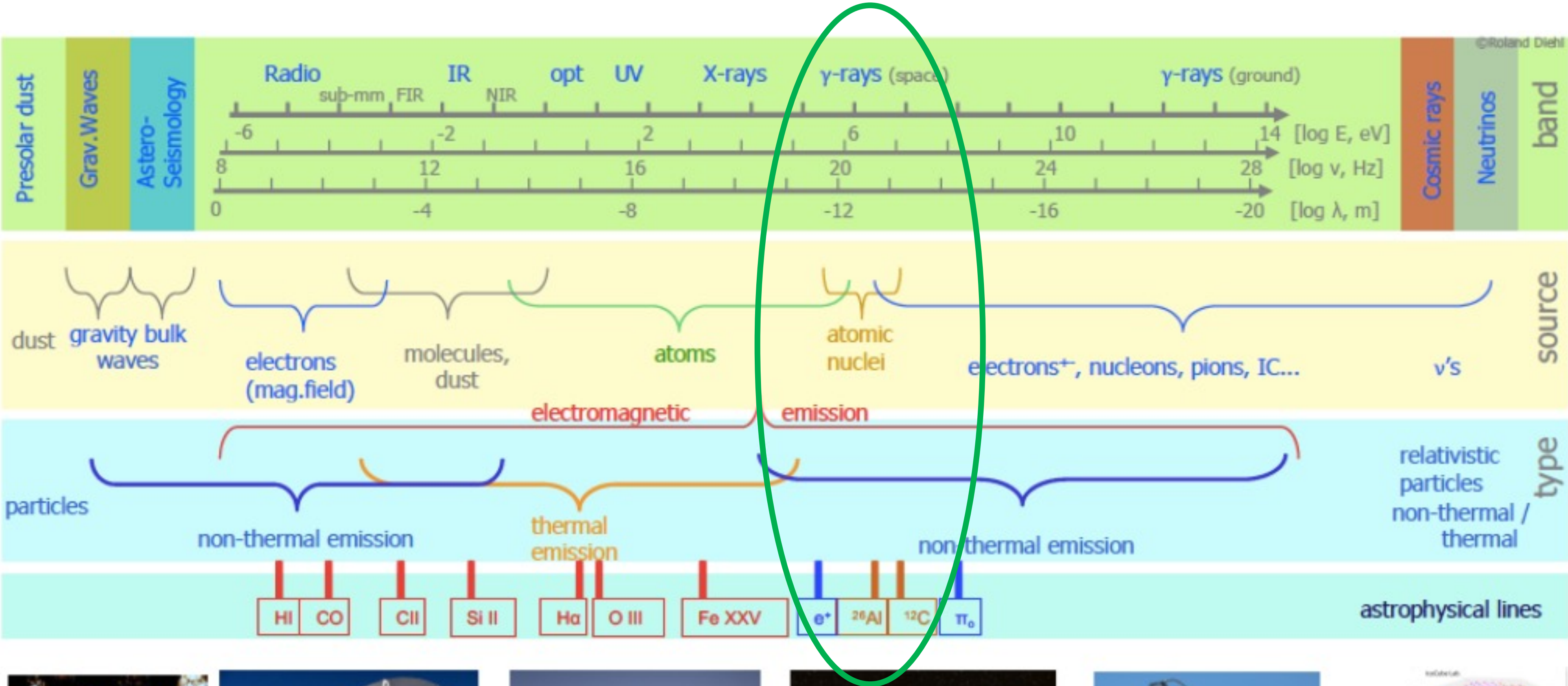
Figure: ChETEC 2021

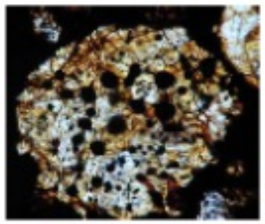
with work from (a.o.)
Martin Krause, Karsten Kretschmer, Moritz Pleintinger,
Thomas Siegert, Rasmus Voss, Wei Wang, Christoph Weinberger

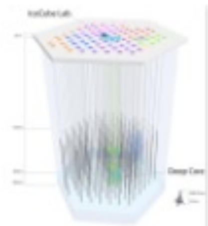
Cosmic Nucleosynthesis: Different Complementing Observing Methods



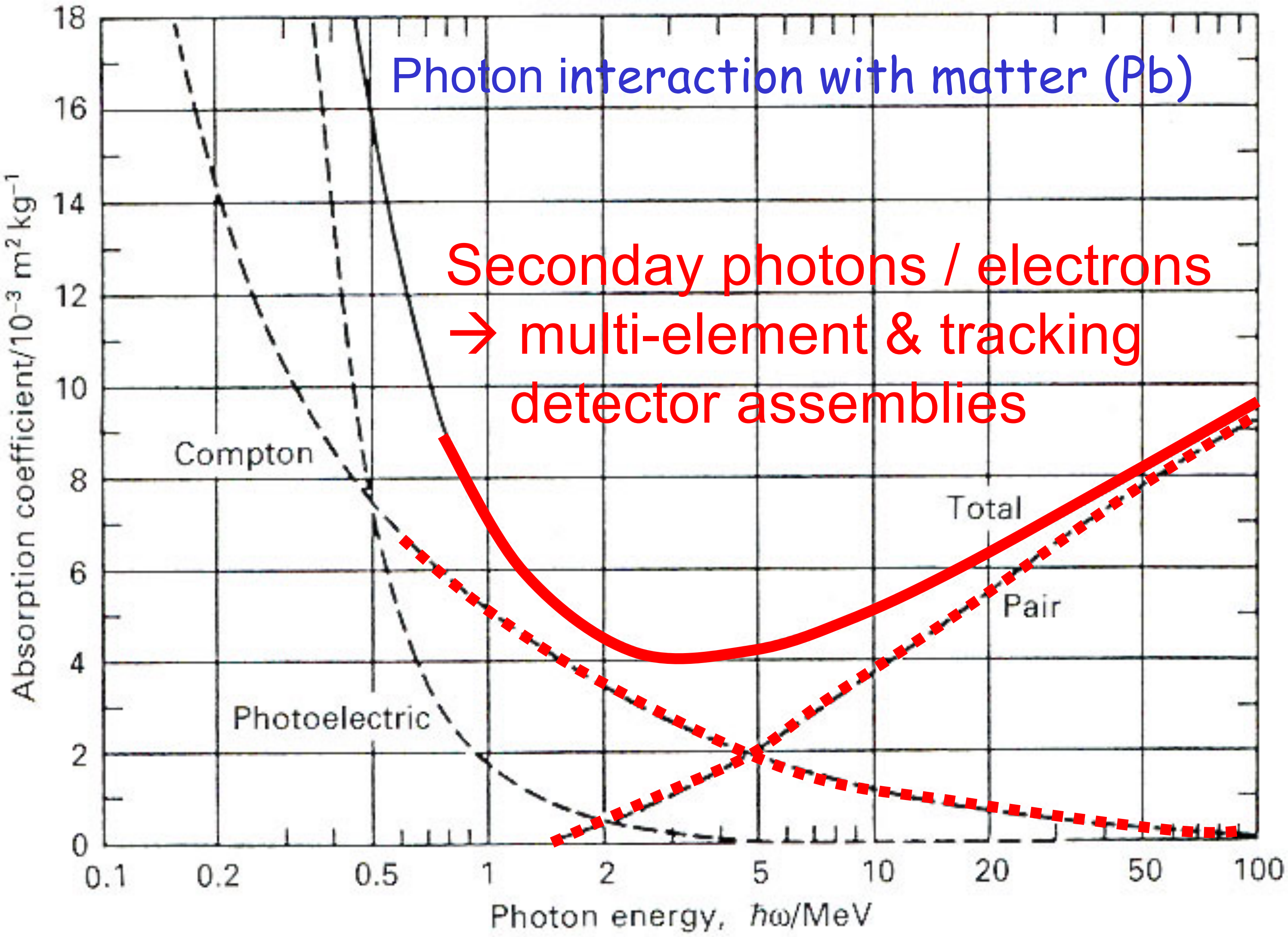
Astronomy of Cosmic Abundances : a Multi-Messenger Enterprise







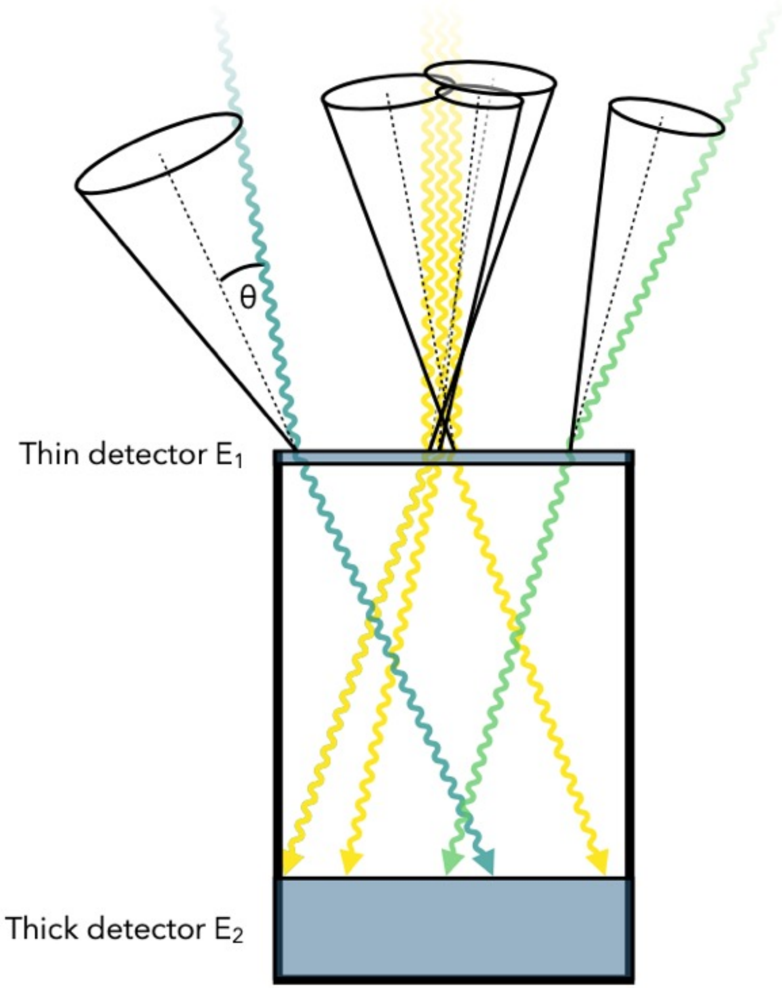
Gamma-Ray Astronomical Telescopes:
Interaction of high-energy photons with matter

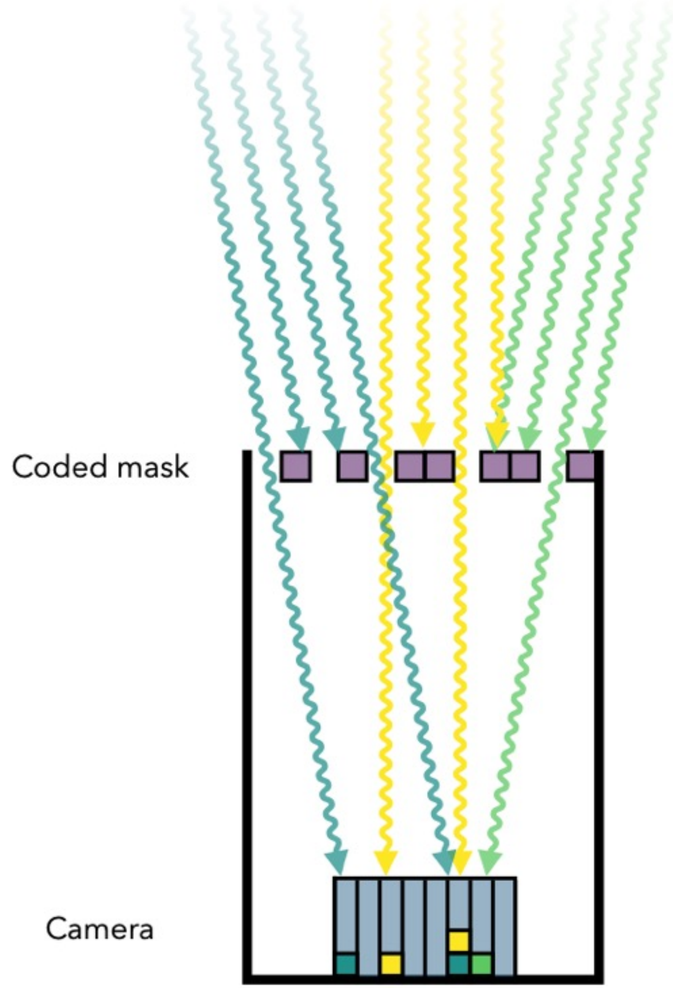


→ Secondary Particles … → e.m. cascade

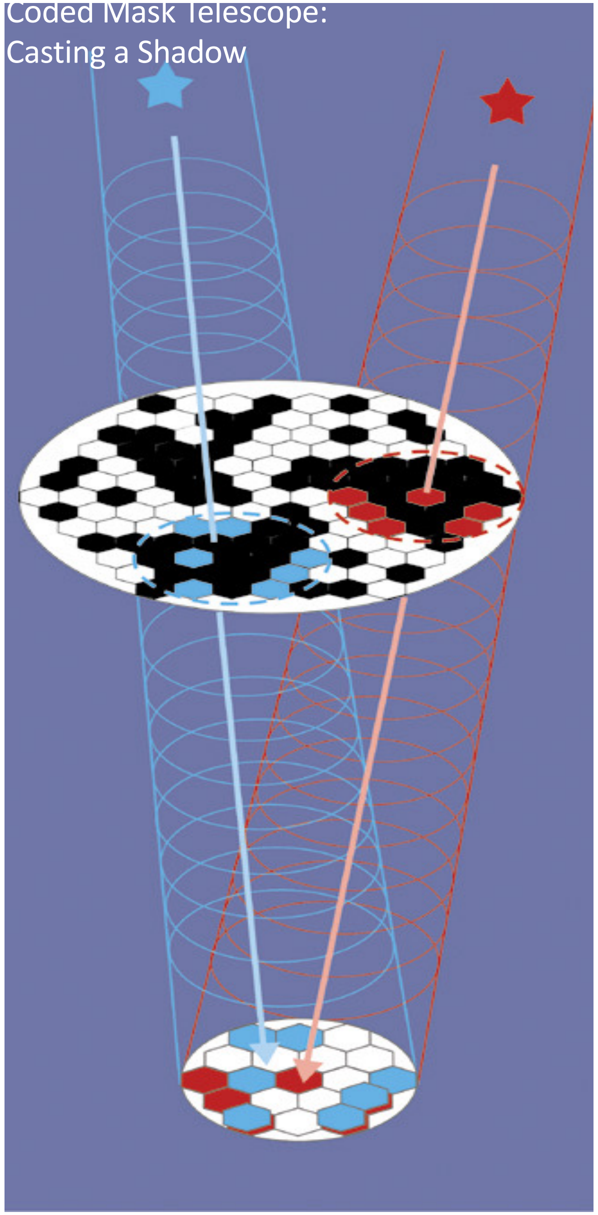
Imaging principles for a MeV-range γ-ray telescope

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





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



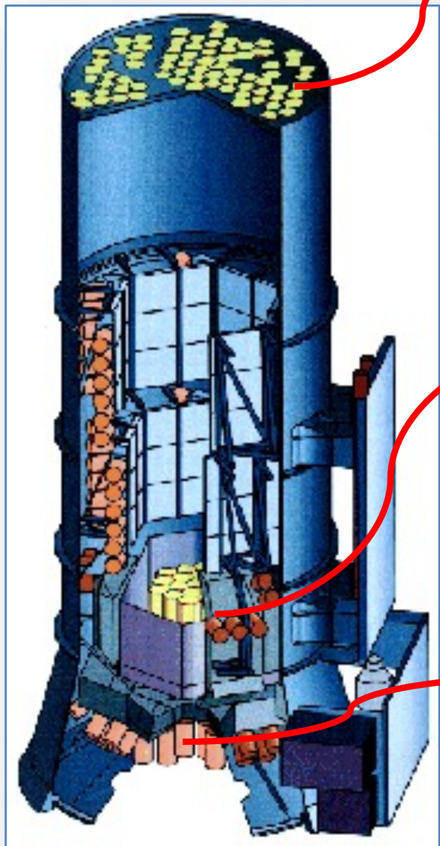
Coded-Mask Telescope

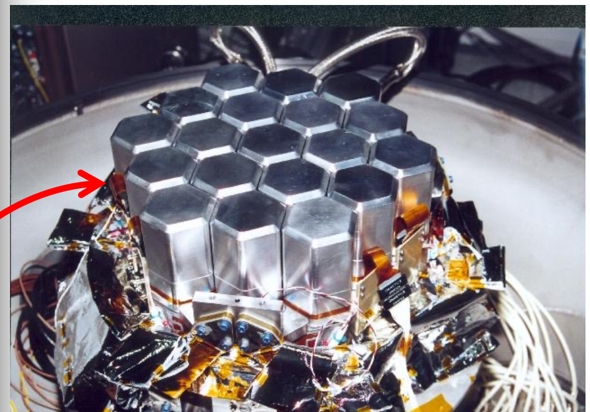
Energy Range 15-8000 keV

Energy Resolution ~2.2 keV @ 662 keV

Spatial Precision 2.6° / ~2 arcmin

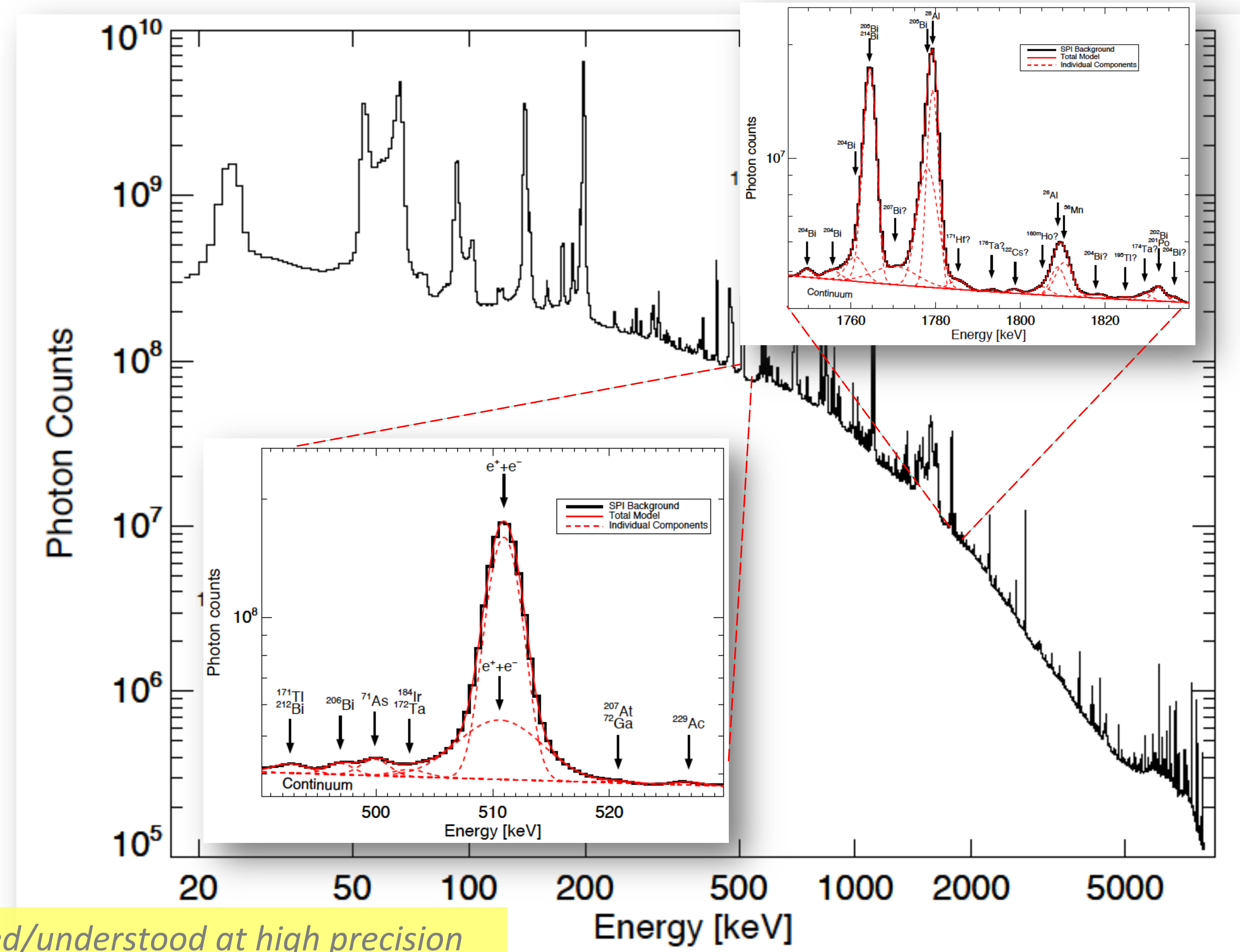
Field-of-View 16x16°





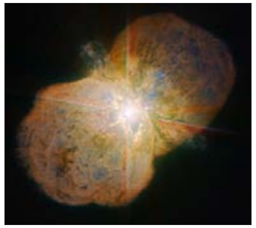
INTEGRAL: Dominance of instrumental background

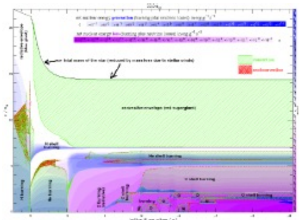
SPI Ge detector spectra

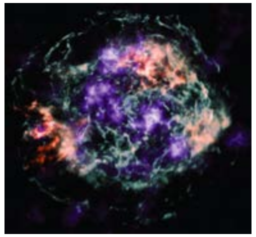


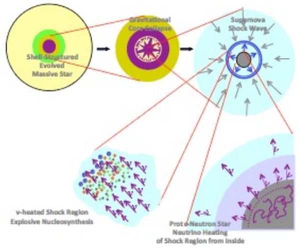
Modelled/understood at high precision

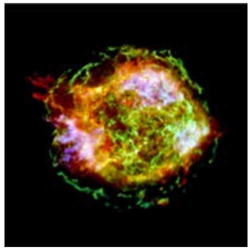
The Challenges

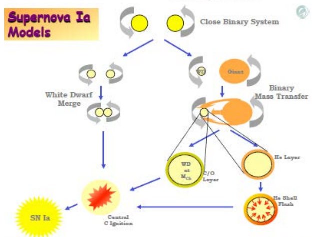


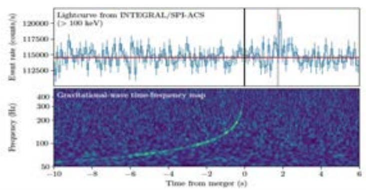


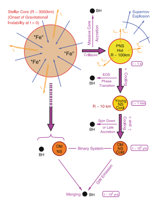




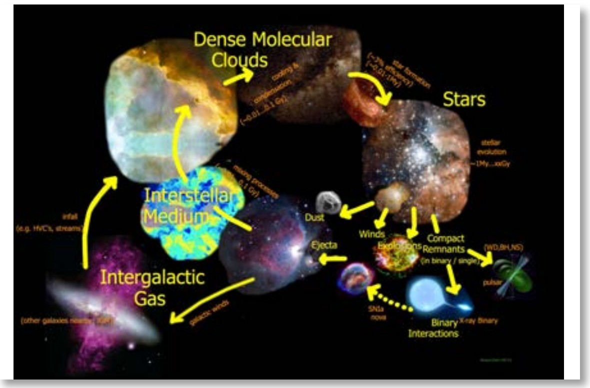






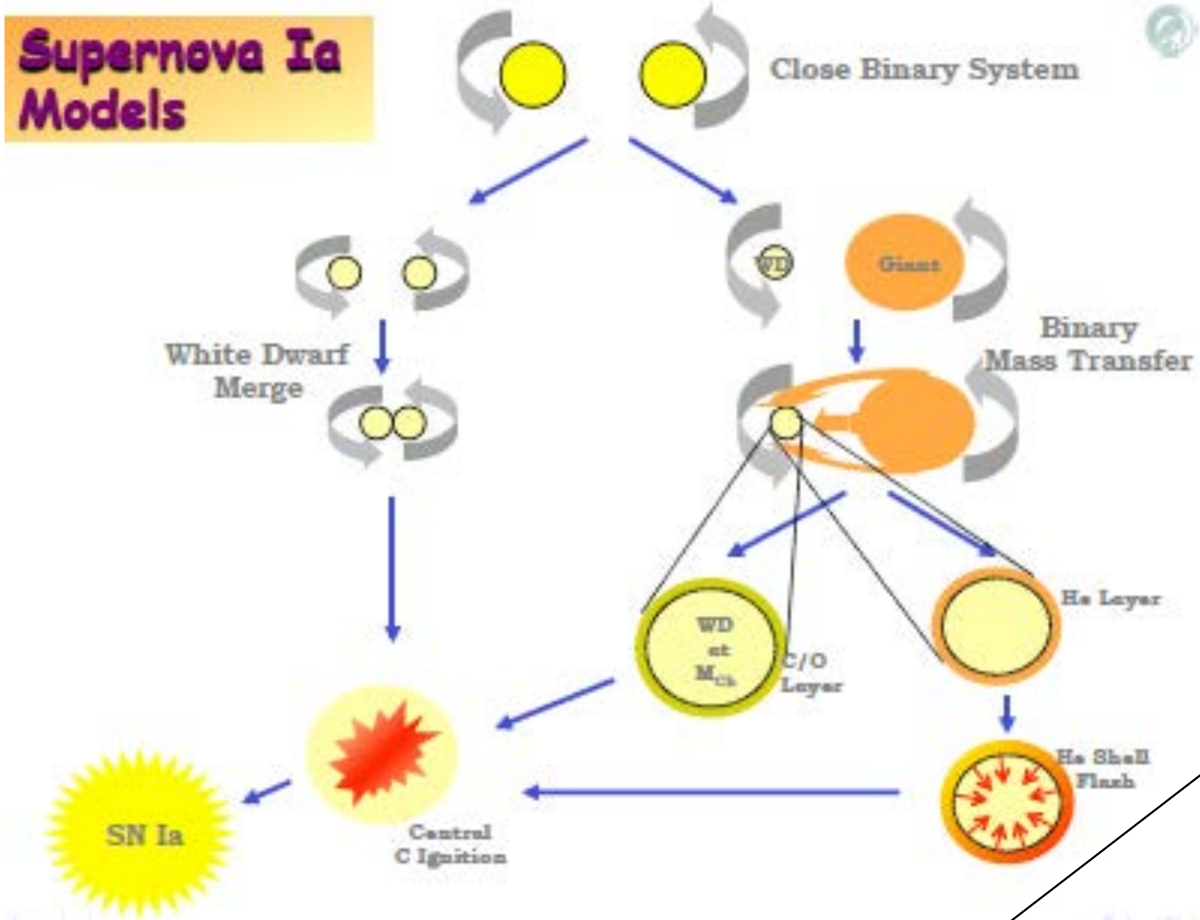


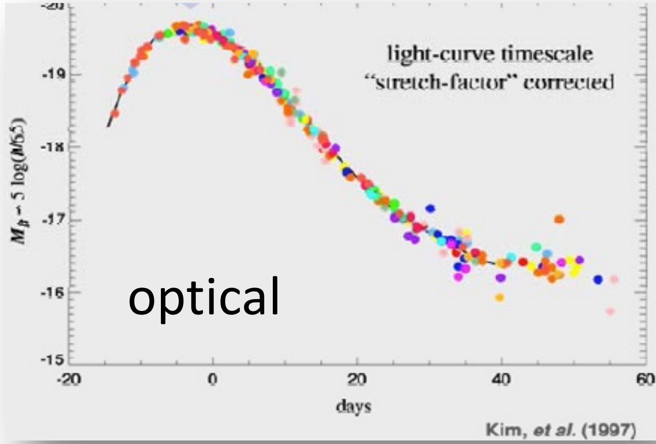
☆Understand the sources of new nuclei

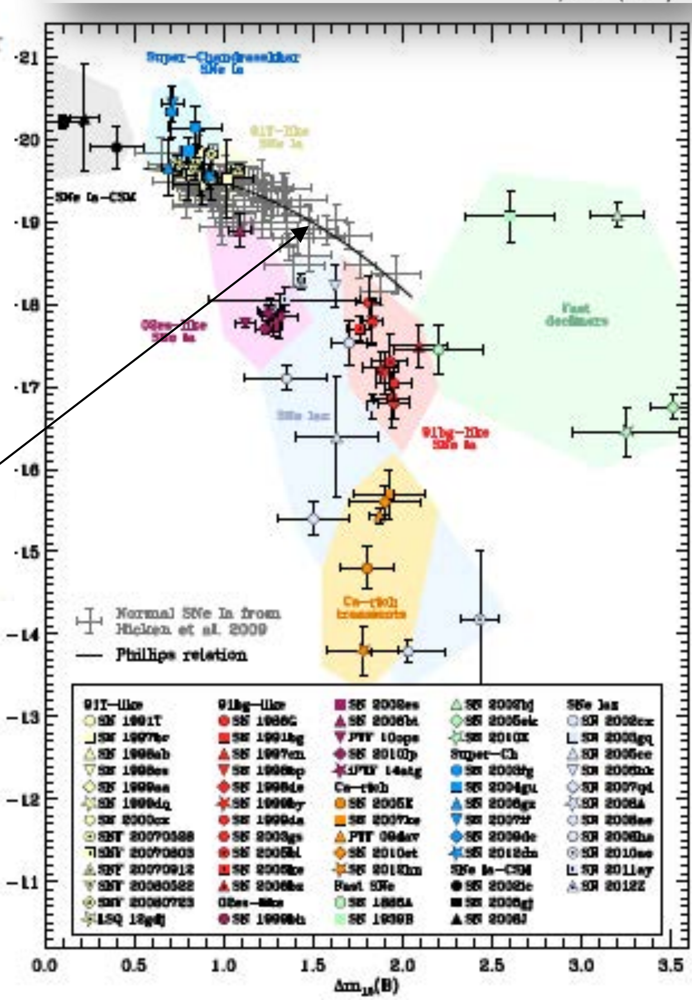


☆Trace the flows of cosmic matter

Supernovae of type Ia







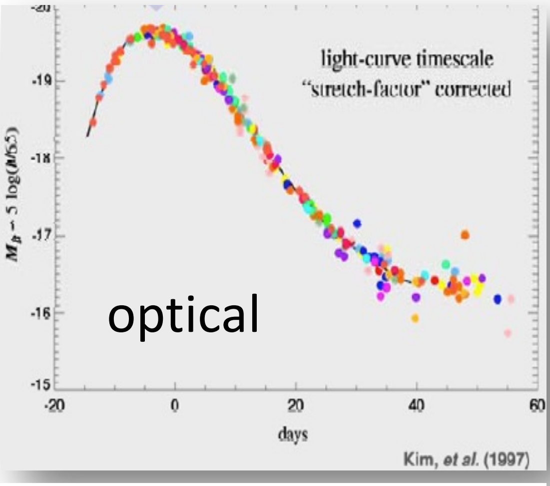
Taubenberger 2017

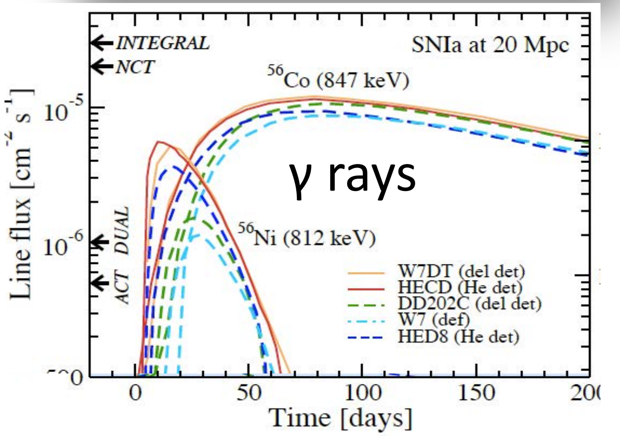
...also from γ-ray observations:
→ SN Ia are a variety

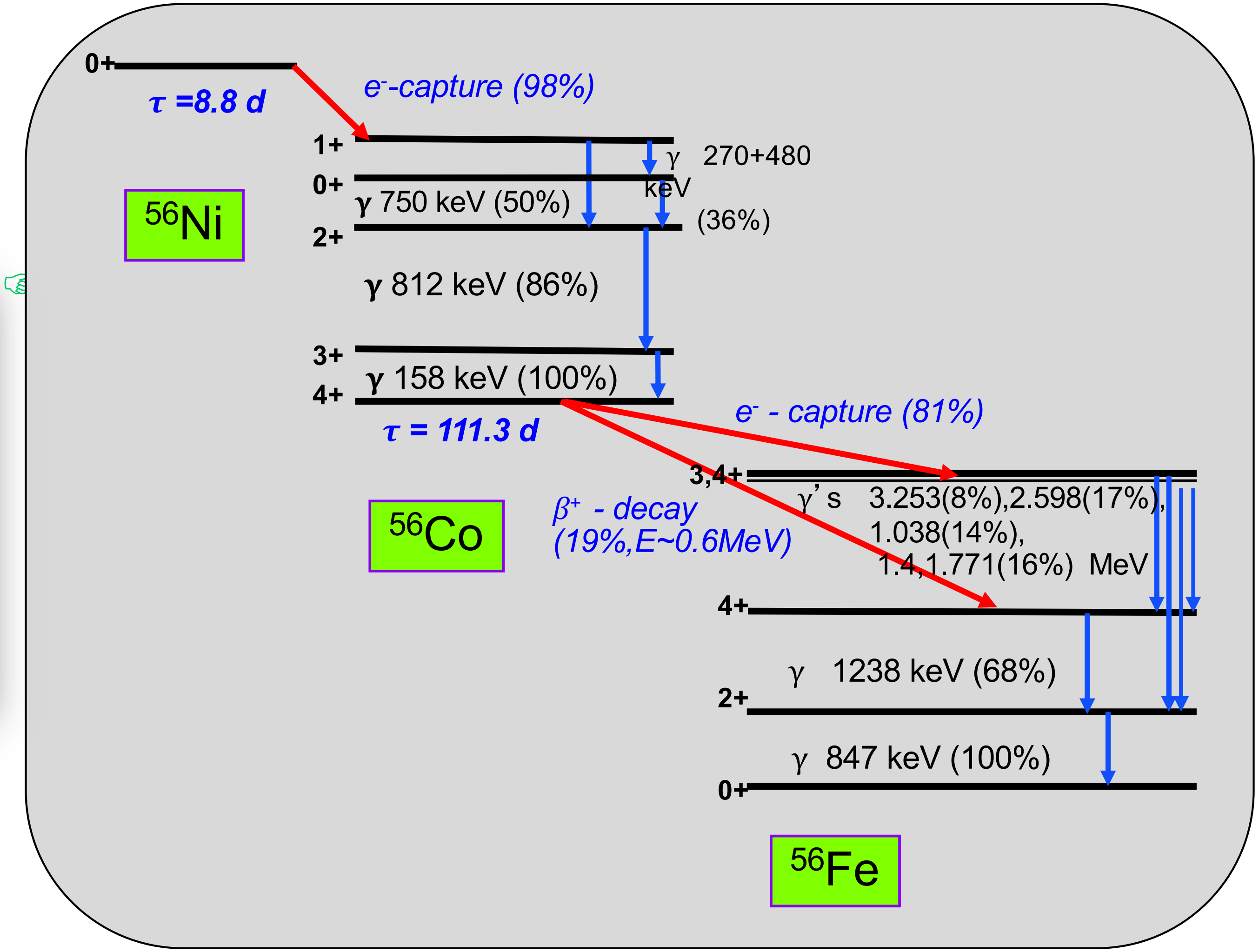
(the "standardizable candles"??)

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

SN Ia







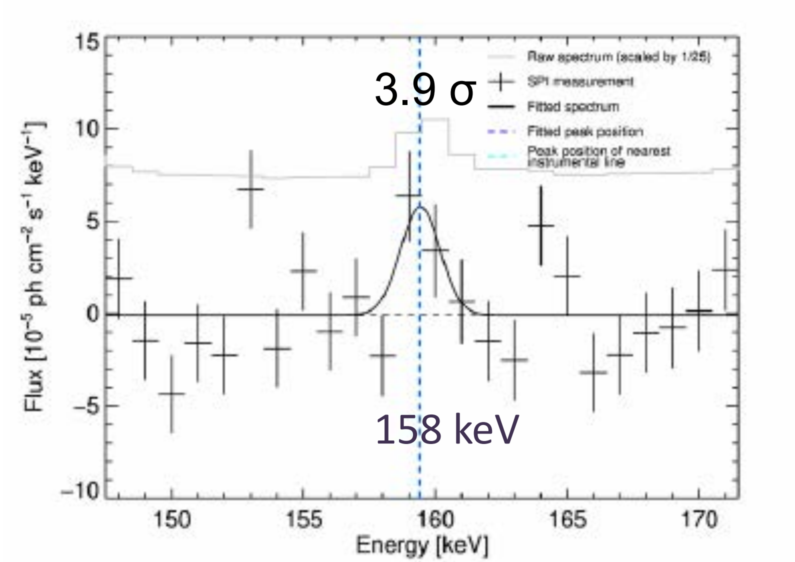
- Nuclear BE release from 0.6M$_{\odot}$ [C,O → ^{56}Ni] = ~1.1 10^{51} erg (>2*BE$_{WD}$)
- Deposit of γ rays and e+ in expanding/diluting envelope
- Re-radiation of deposited energy in low-energy (thermal) radiation

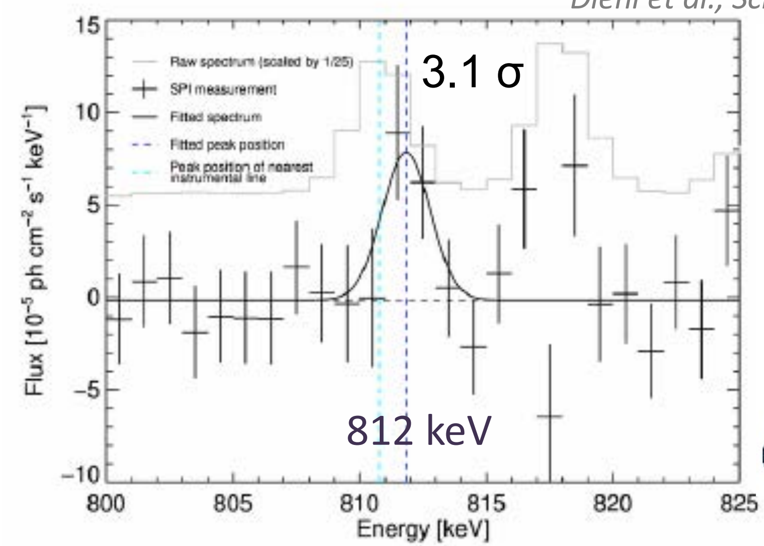
SNIa and SN2014J: Early ^{56}Ni (τ~8.8d)

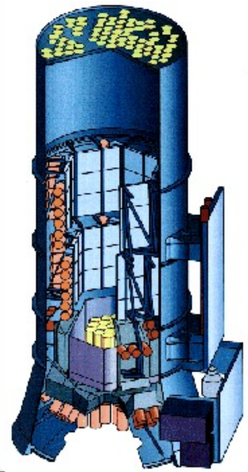
Spectra from the SN at ~20 days after explosion

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

Diehl et al., Science (2014)

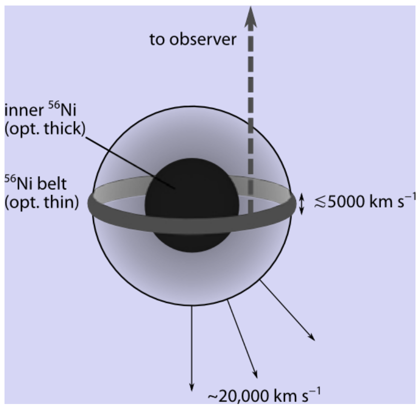






^{56}Ni mass estimate (backscaled to explosion): ~0.06 $M_\odot$ (~10%)

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



but rather a 'double detonation, i.e.

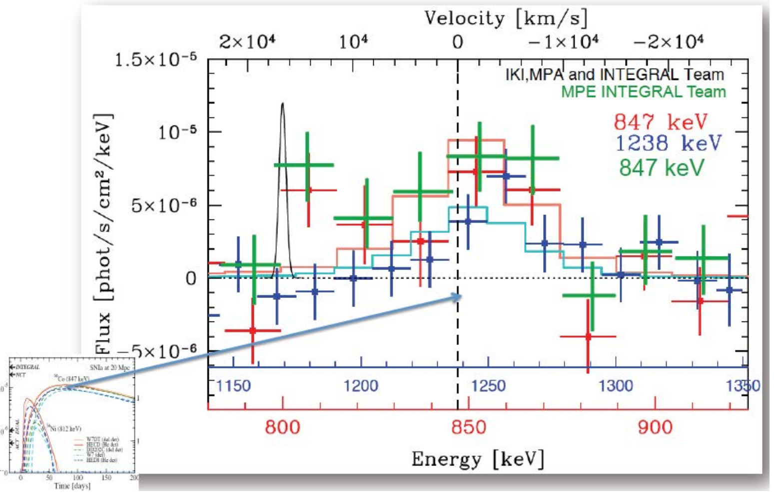
either 2 WDs (double-degenerate)

or a He accretor (He star companion)

→ SN 2014J looks "normal", but is not

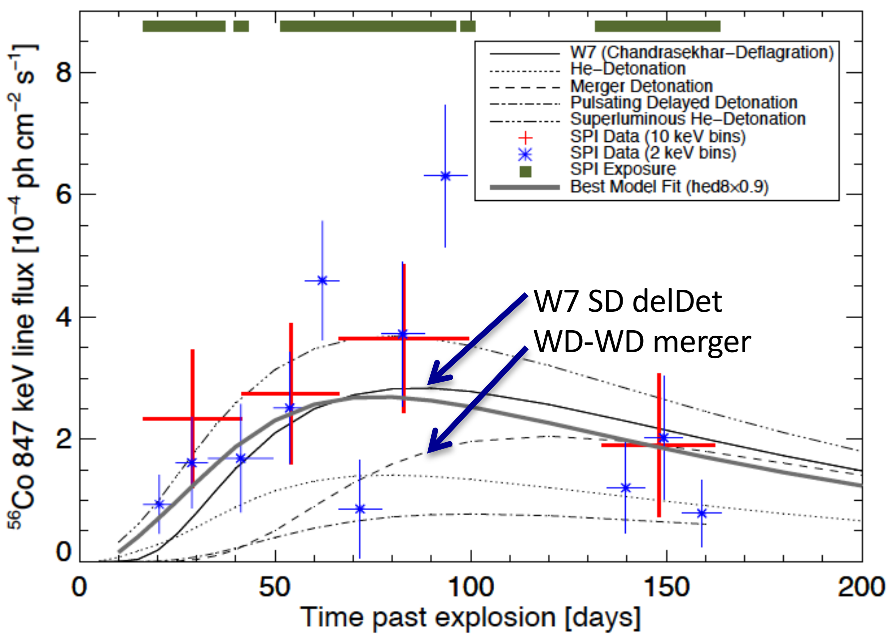
SN2014J data Jan – Jun 2014: ^{56}Co lines

Doppler broadened ✓



Split into 4 time bins

Diehl+ 2015



☆ ^{56}Ni mass:

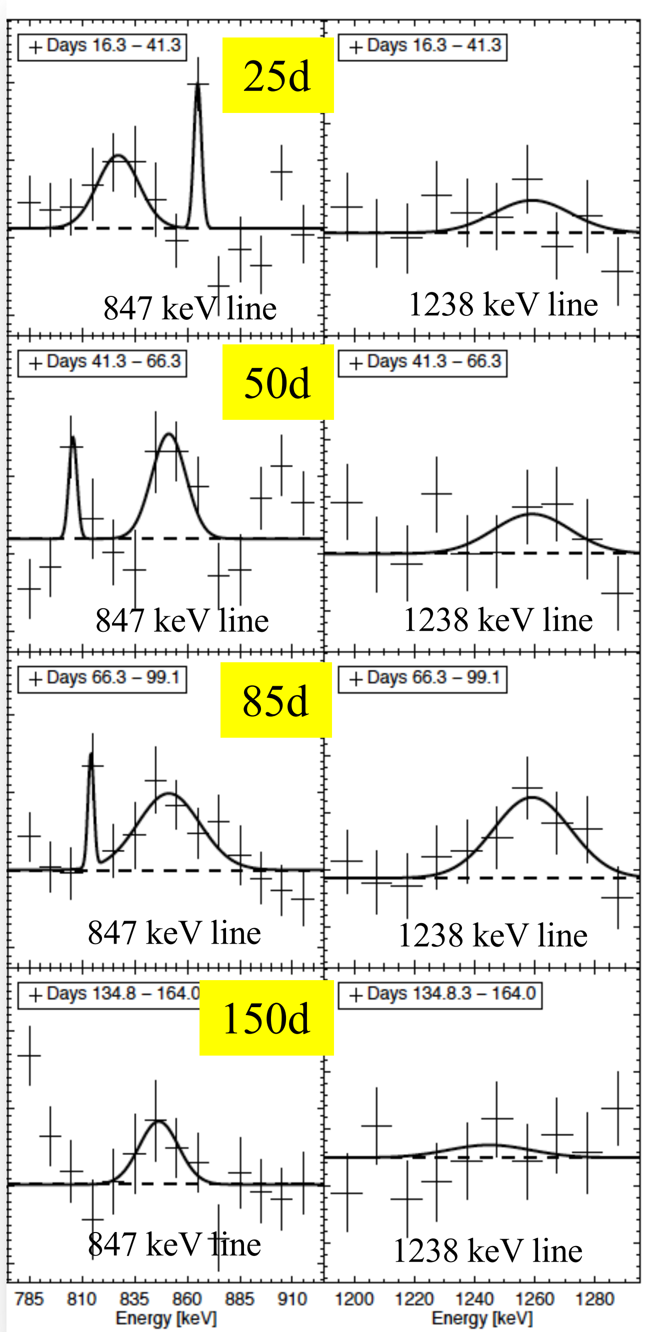
0.49 +/-0.09 M$_\odot$

(cmp from bol. Light

0.42 +/-0.05 M$_\odot$

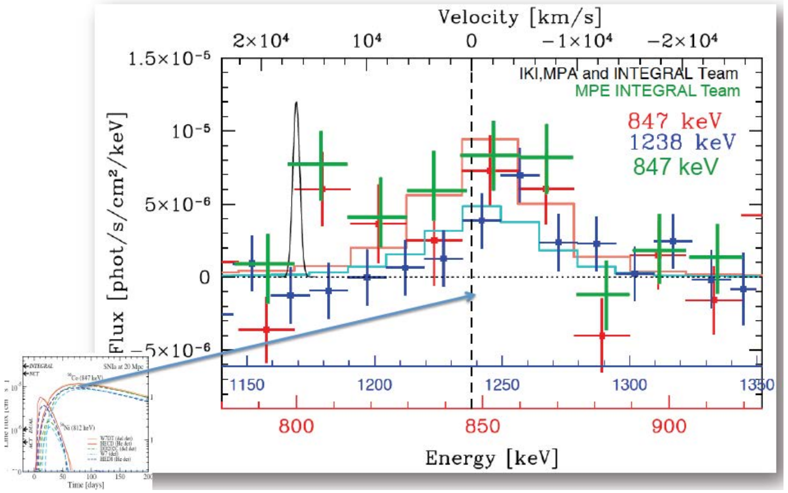
from models

0.5 +/-0.3 M$_\odot$



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

- ☆ Doppler broadened ✓



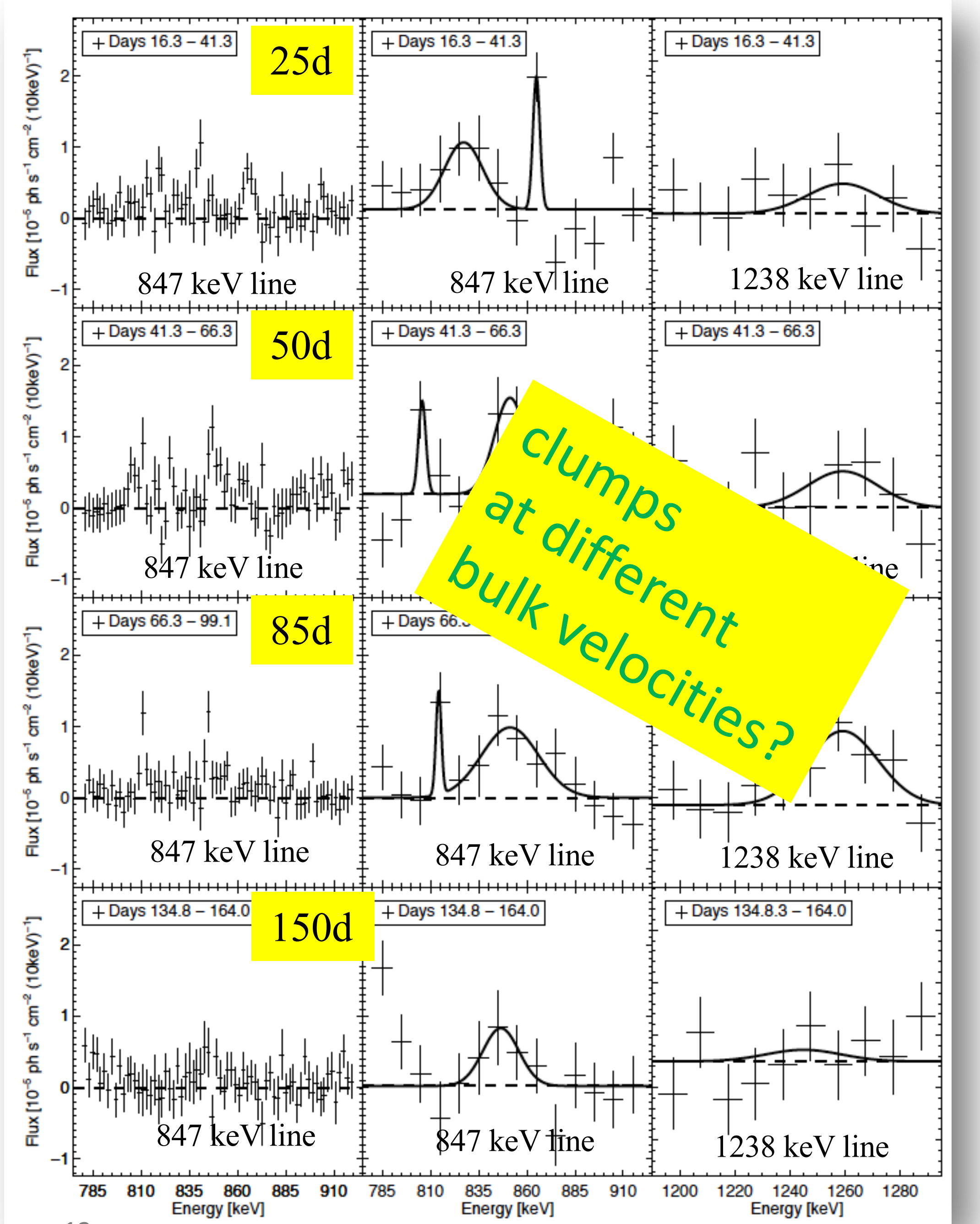
- ☆ Split into 4 time bins
- ☆ Coarse & fine spectral binning

→ Observe a structured and evolving spectrum

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

☞ *Diehl et al., A&A (2015)*

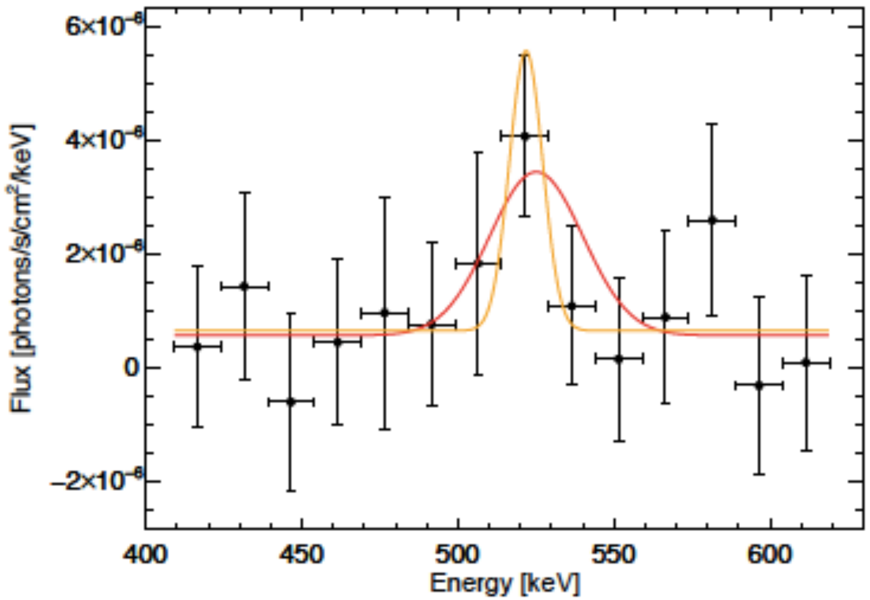
- ☆ *note: normally, we do not see such fluctuations in 'empty-source' spectra!*

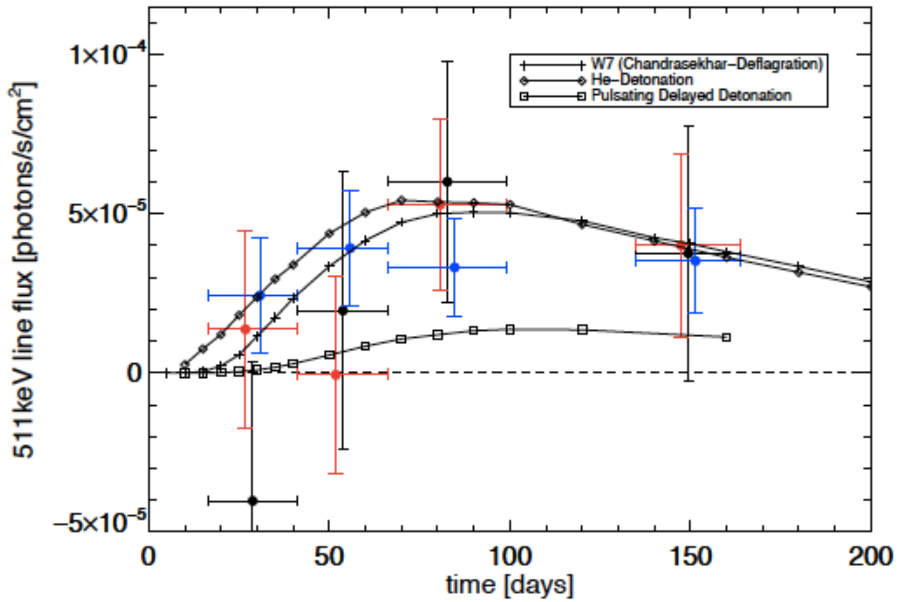


Positron annihilation in SN2014J

- The 511 keV line is marginally detected
  - ☆ Red-shifted by 10-15 keV
  - ☆ Flux consistent with ~^{56}Co line fluxes → ~all e^+ annihilating

Sonnberger+, in prep.



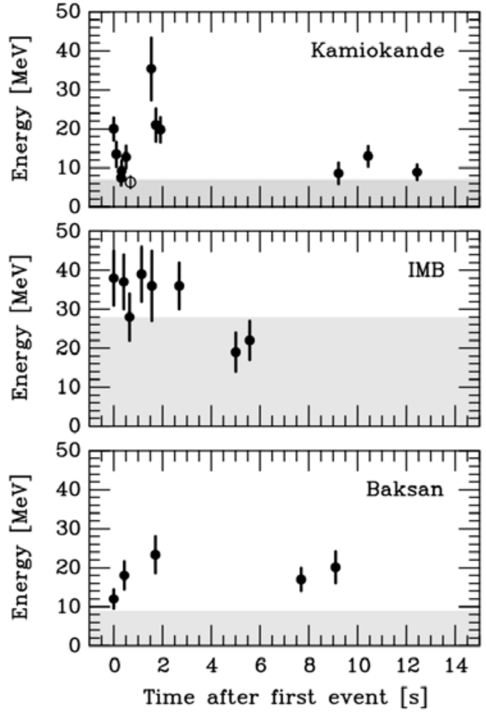


- Model study *Brahe, Hoeflich, & Diehl 2022*
  - ☞ positron escape is ~%

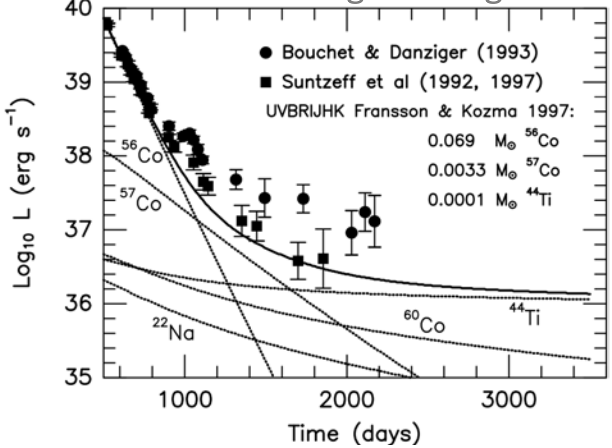
SN1987A

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

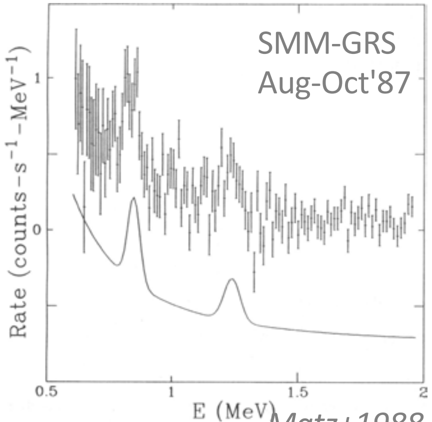
- Witness neutrino burst from core collapse



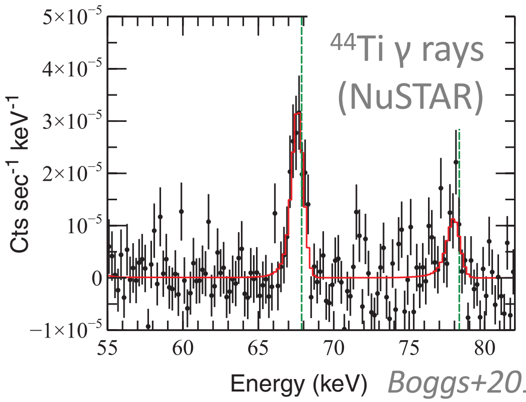
bolometric light afterglow



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

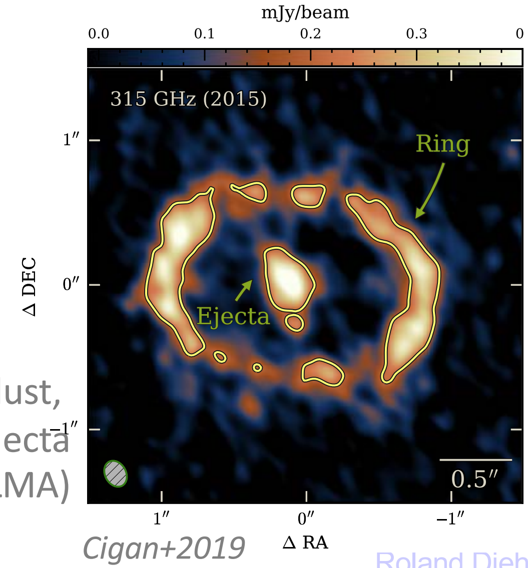


Matz+1988



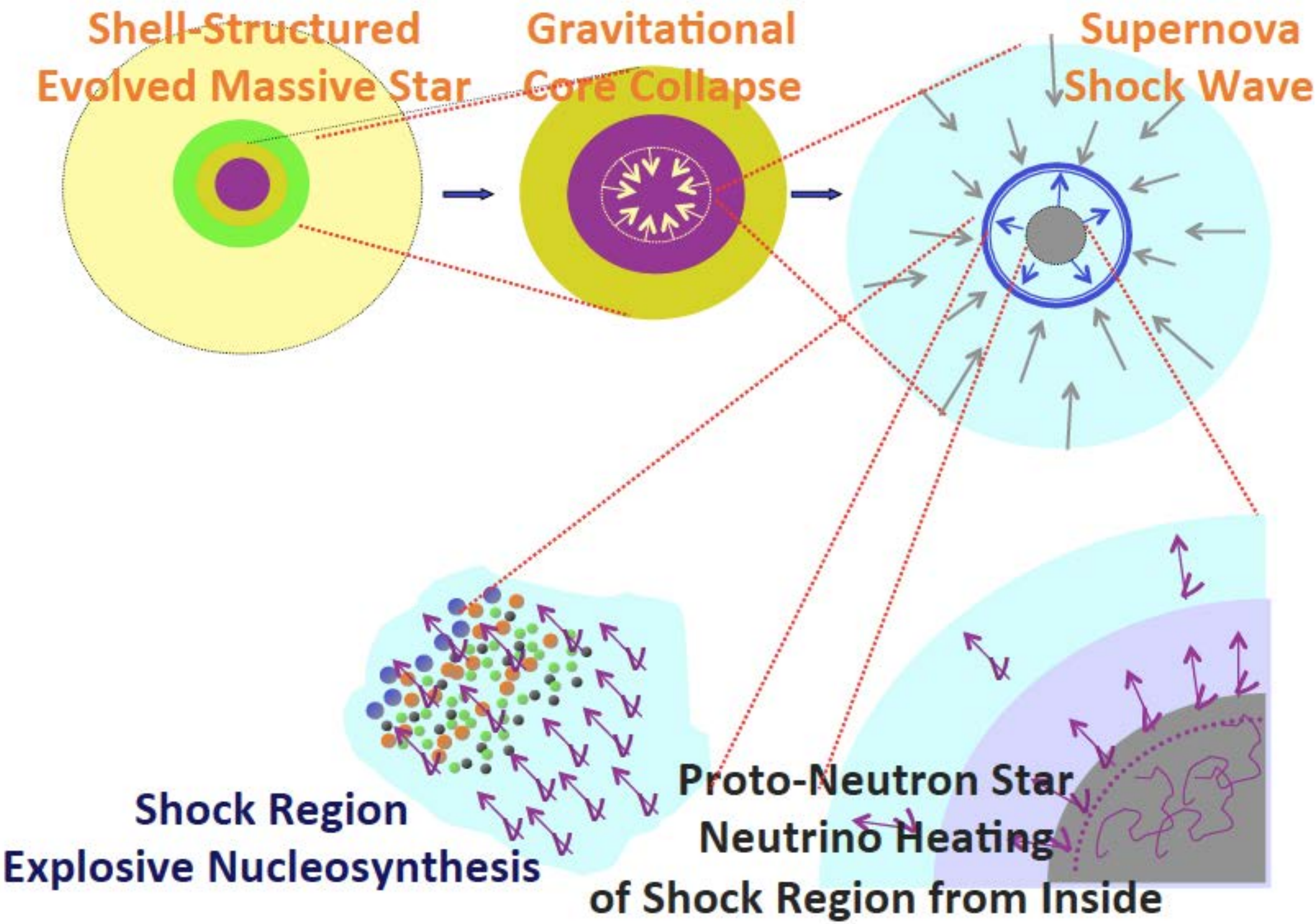
Boggs+2015

CSM, dust, ejecta (ALMA)



Cigan+2019

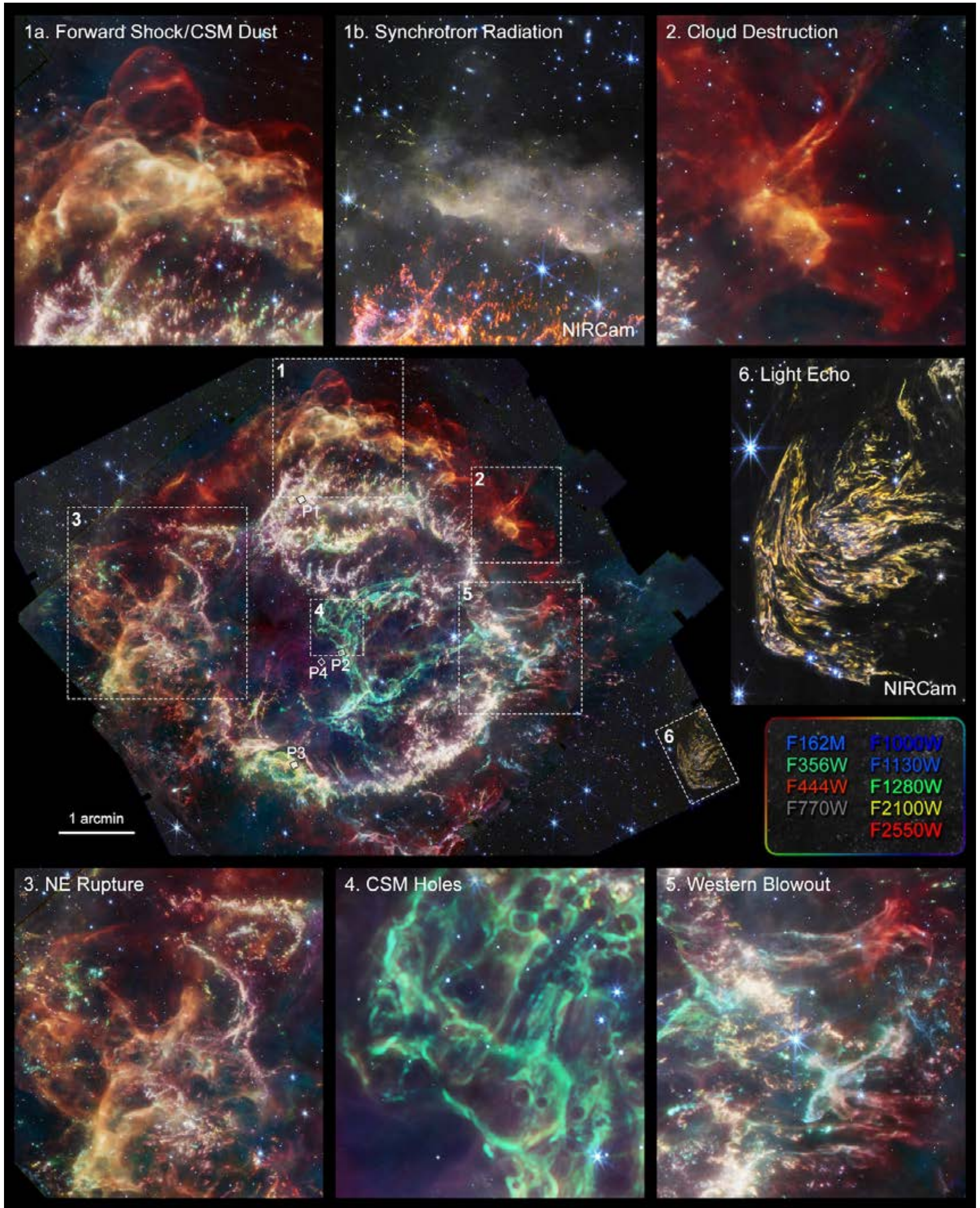
Gravitational Collapse and SN



Cas A with JWST

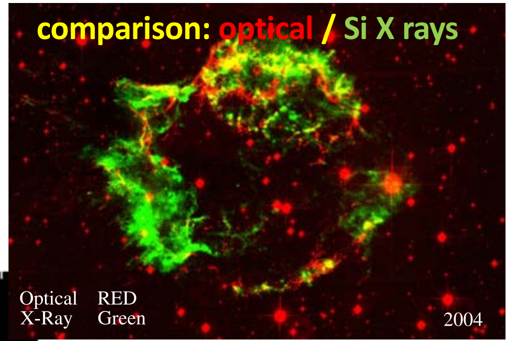
Milisavljevic+2023

- 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



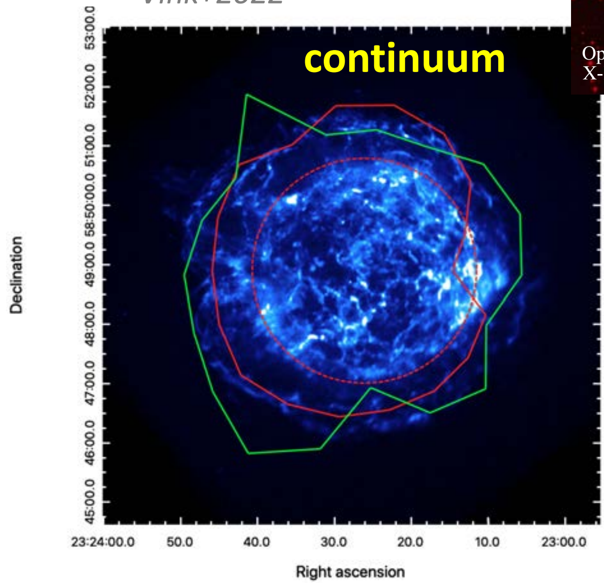
Cas A in X rays

- Cas A SNR composition and dynamics is reflected in X rays
  - ☆ interaction of the SN shock with surrounding CSM
    - ☞ shock acceleration (e^-)
    - ☞ synchrotron emission, non-thermal Bremsstrahlung
  - ☆ composition of remnant
    - ☞ reverse-shocked ejecta
    - ☞ characteristic lines from highly-ionised species



Patnaude&Fesen2014

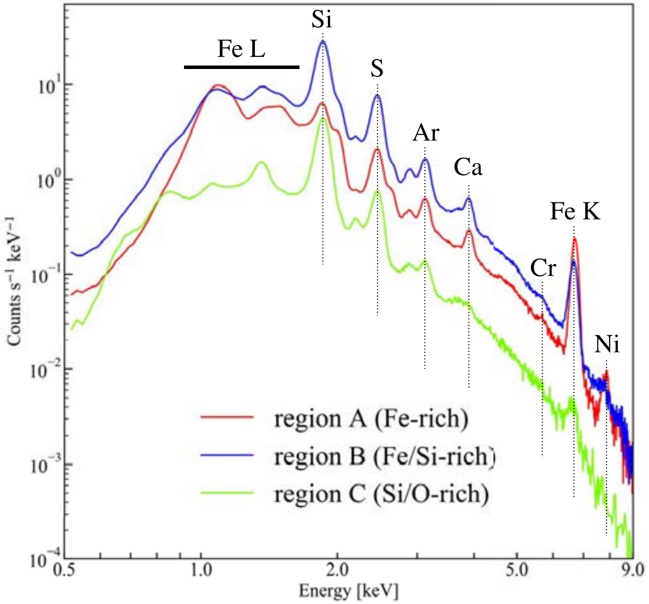
Vink+2022



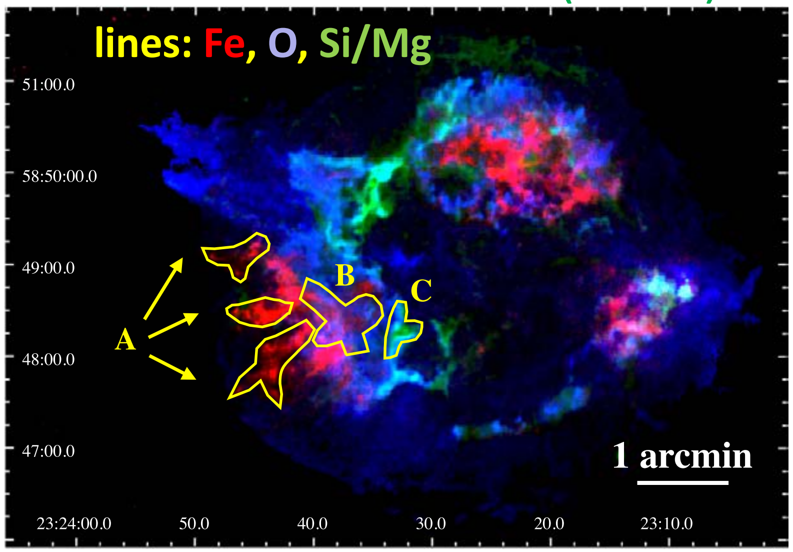
➔ complex shock dynamics

➔ overturn of ejecta material (shells)?

0.9- 9 keV, Chandra



Tsuchioka+2022



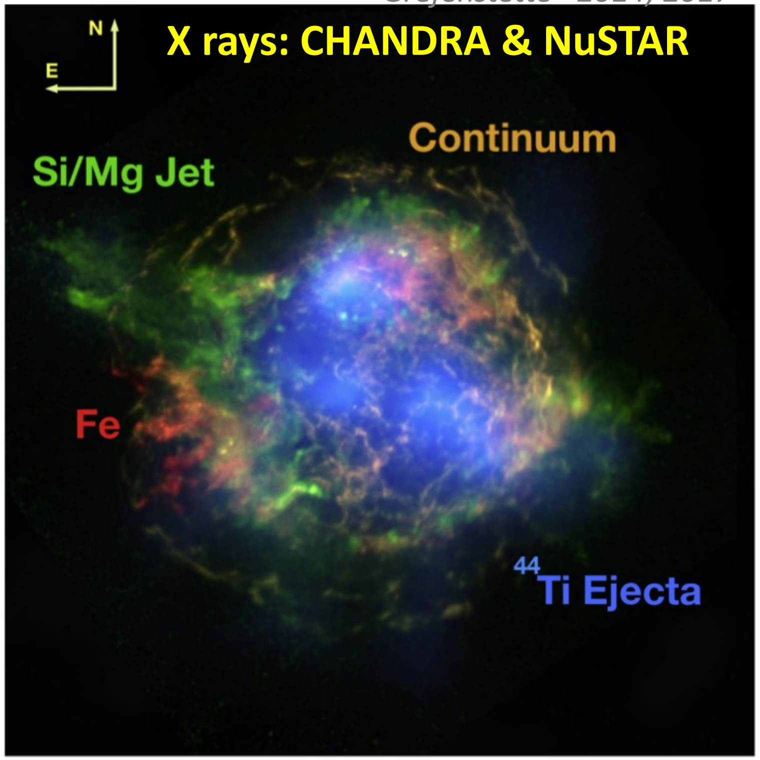
Beyond X rays: Locating the inner Ejecta in Cas A

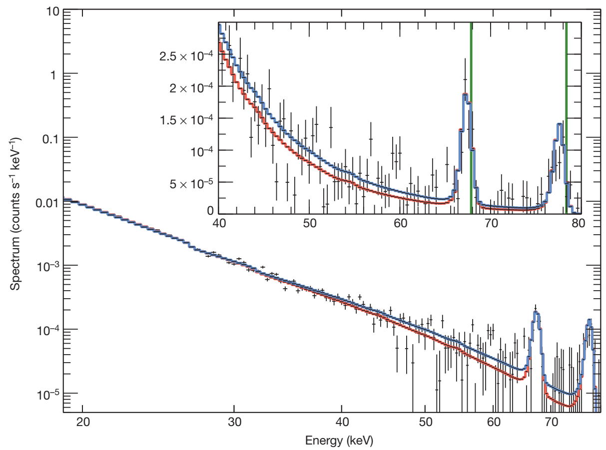
NuSTAR Imaging in hard X-rays (3-79 keV; ^{44}Ti lines at 68,78 keV) →

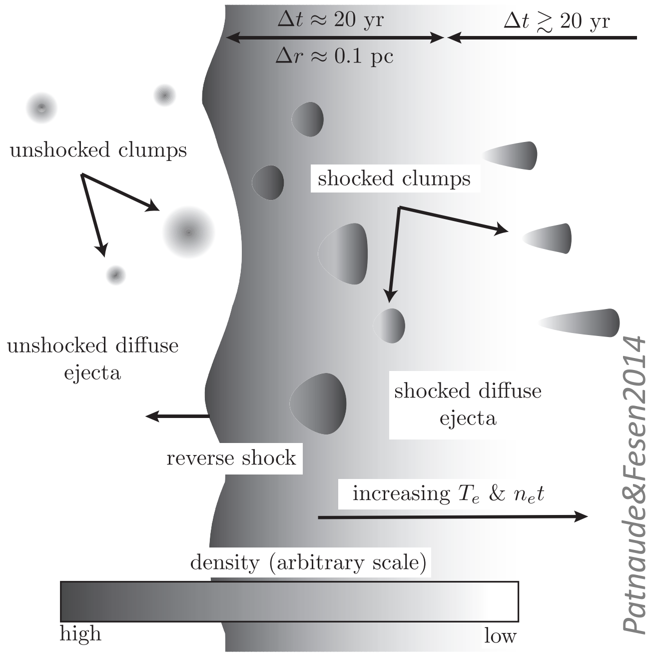
☞ first mapping of radioactivity in a SNR

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

Grefenstette+ 2014; 2017







Patnaude&Fesen2014

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

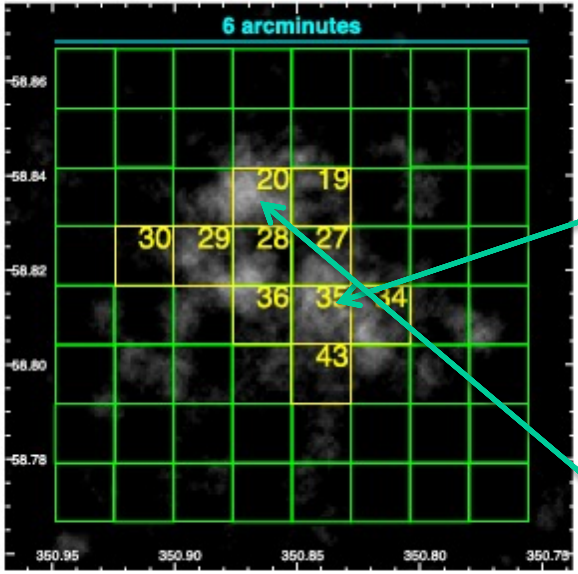
☞ Fe-line X-rays are biased from ionization of plasma by reverse shock

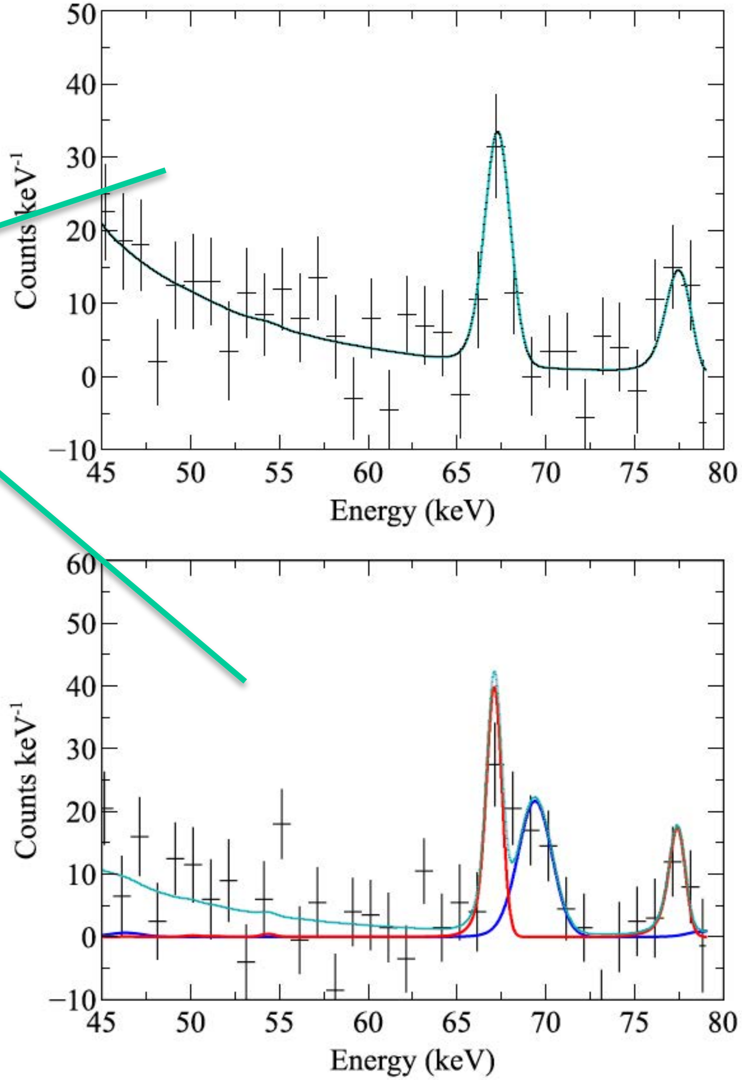
NuSTAR update: ^{44}Ti in Cas A

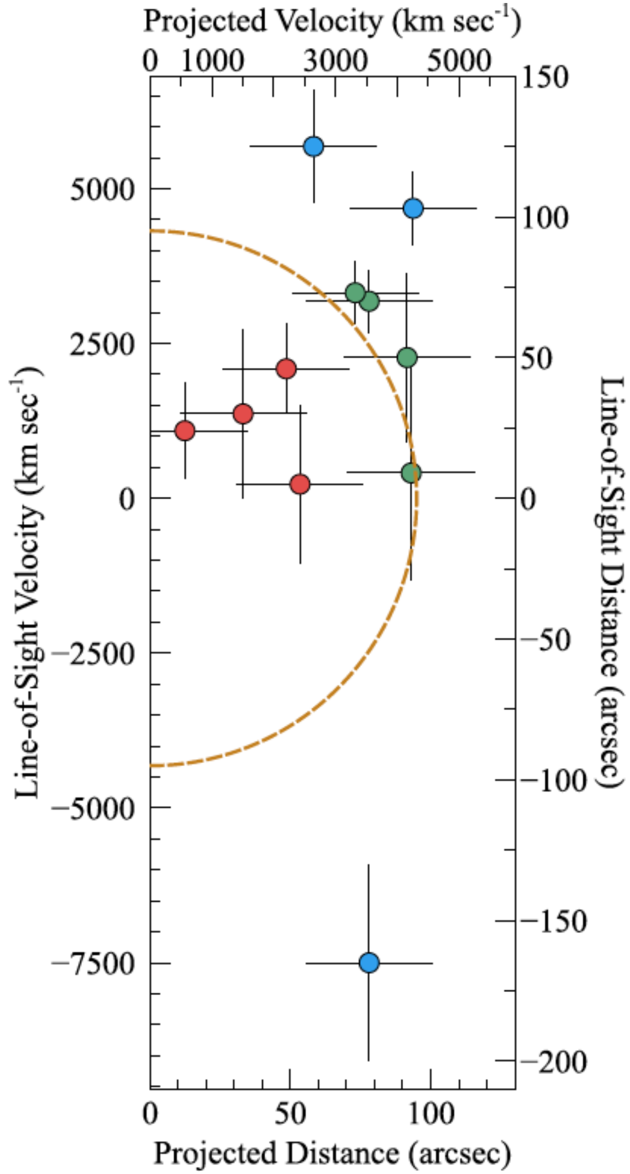
☆ Imaging resolution allows to spatially resolve Cas A's ^{44}Ti:

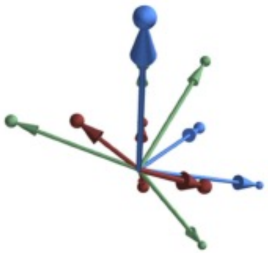
2.4 Msec NuSTAR campaign

Grefenstette et al. 2017





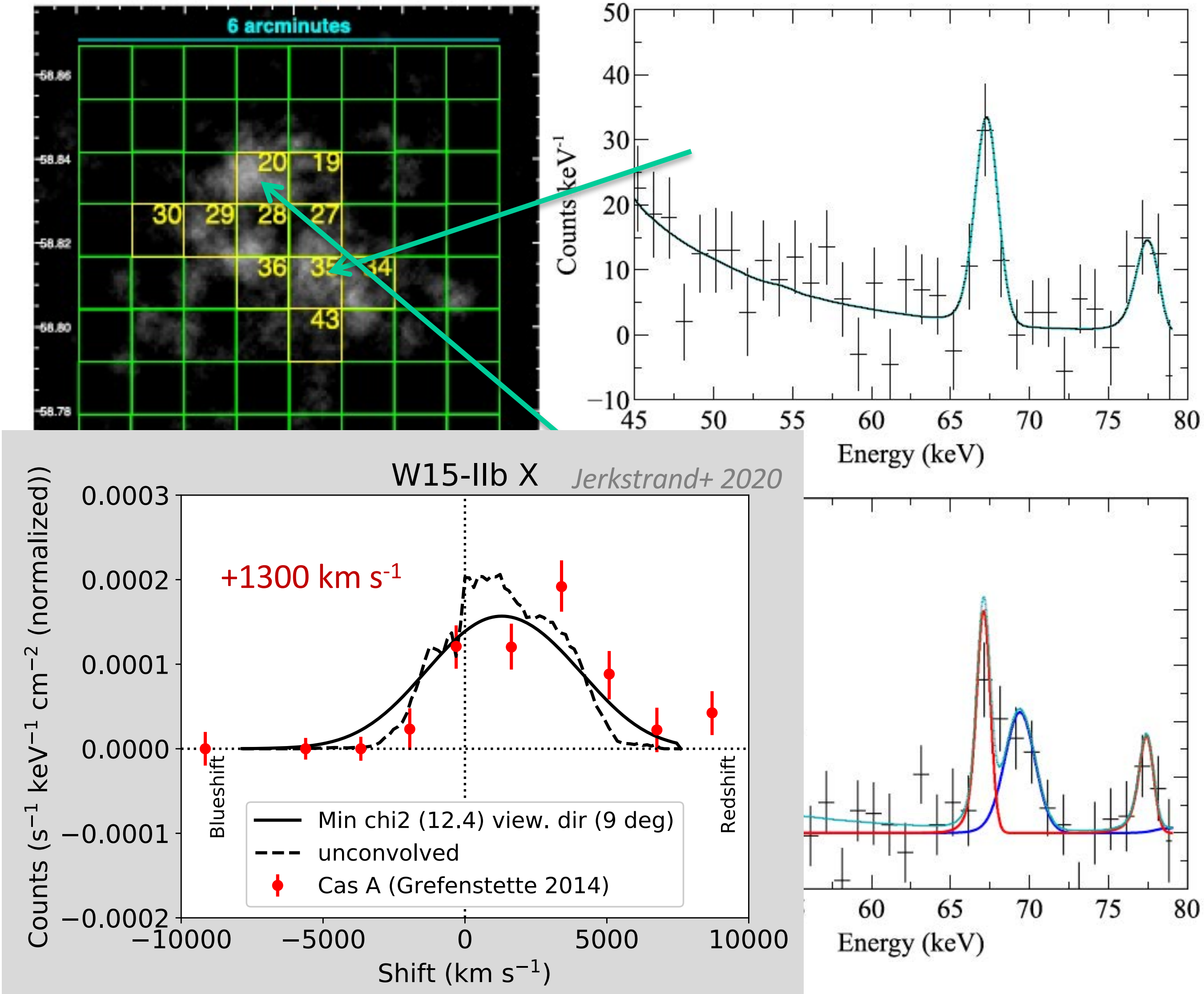


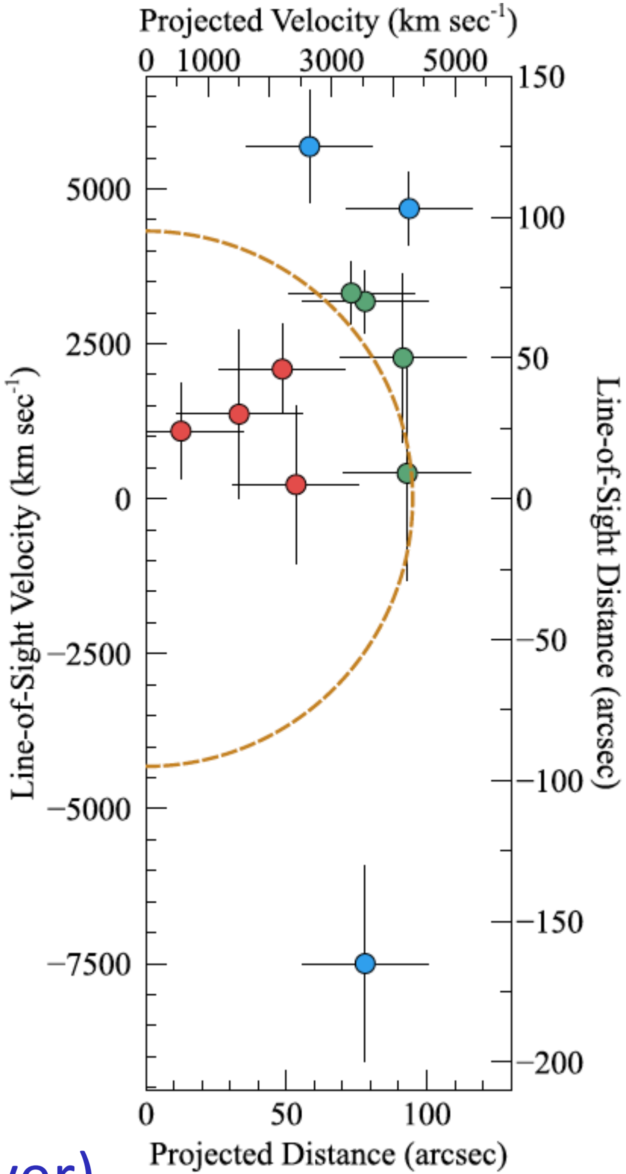


NuSTAR details of ^{44}Ti in Cas A

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

2.4 Msec NuSTAR campaign
Grefenstette et al. 2017

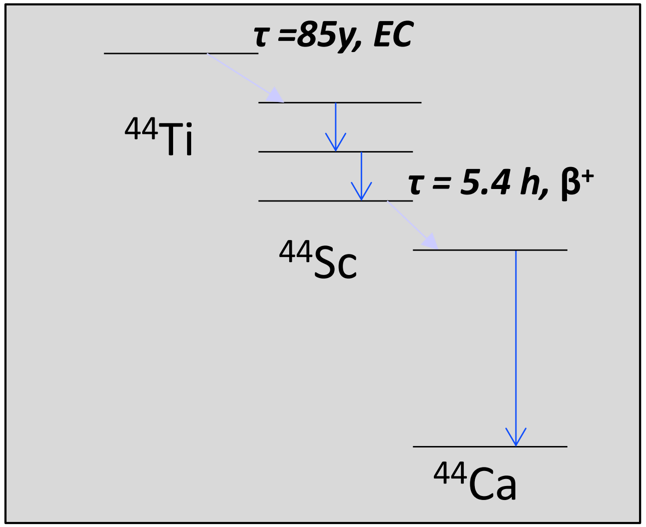




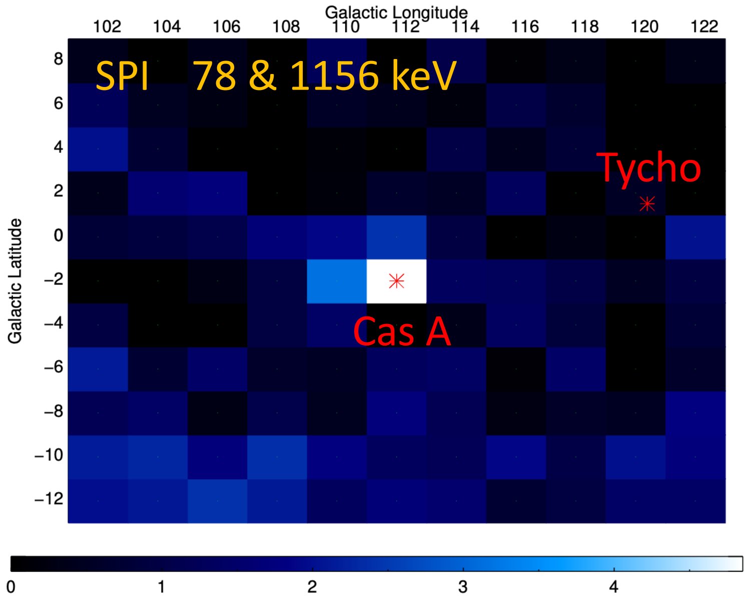
→ bulk red-shifted ^{44}Ti (away from observer)

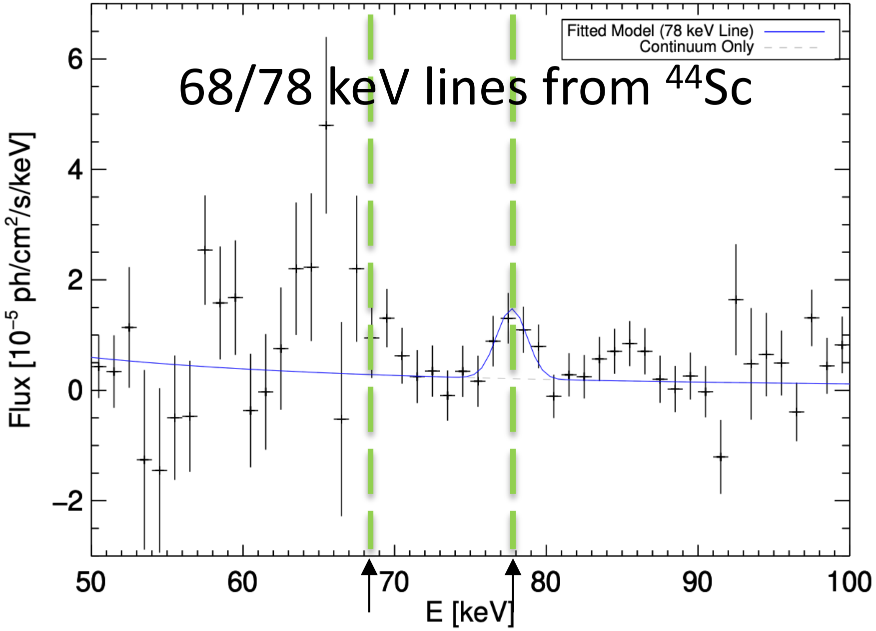
^{44}Ti Cas A: INTEGRAL/SPI confirmations of bulk redshift

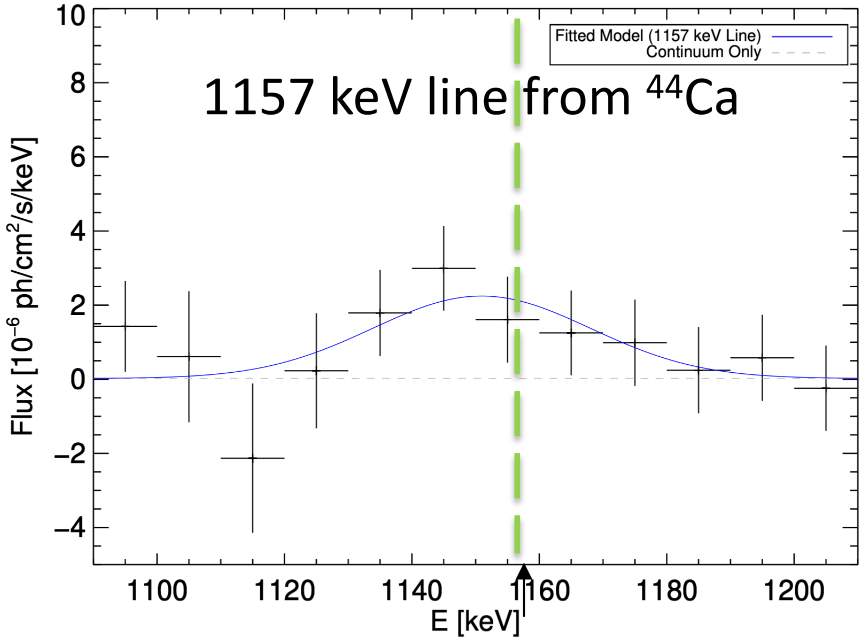
The ^{44}Ti decay chain with INTEGRAL/SPI:



Weinberger+ 2021





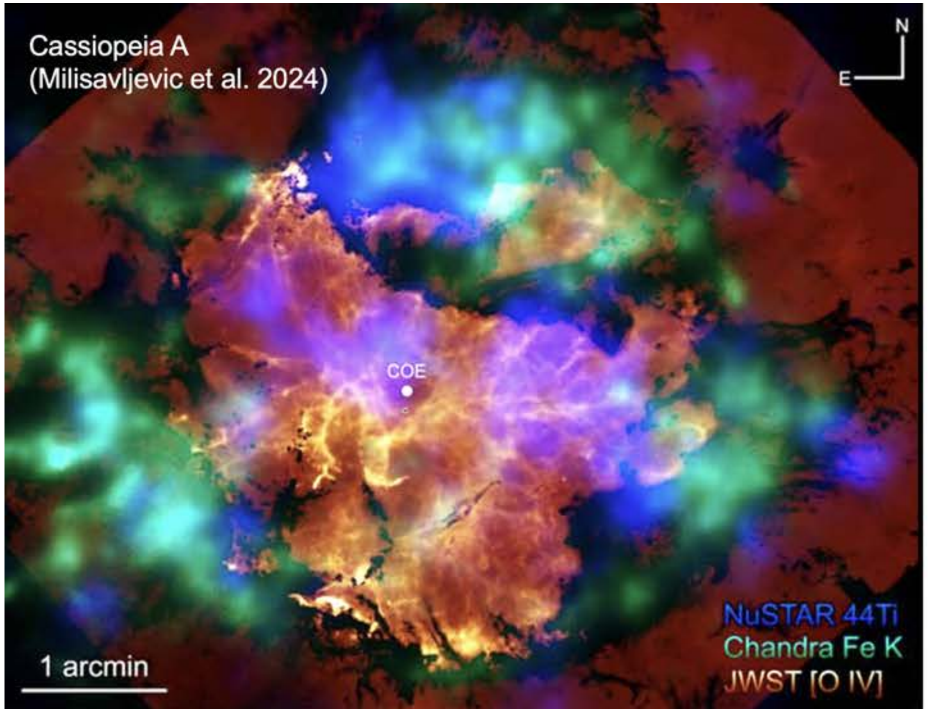


→ clear Doppler shift of ^{44}Ti (1800 ±800 km s^{-1} away from observer)

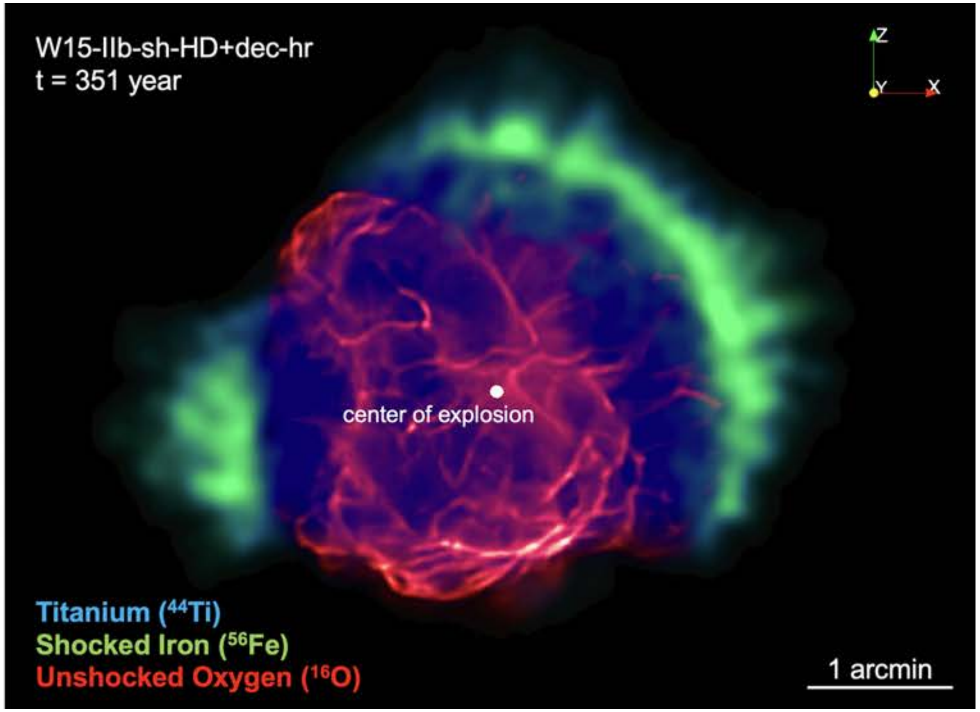
Understanding the filamentary detail of JWST image

SN explosion seeds a bubble structure that evolves into filaments

JWST image detail



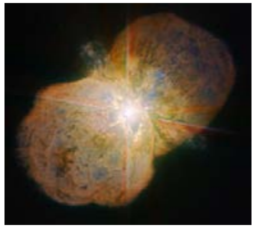
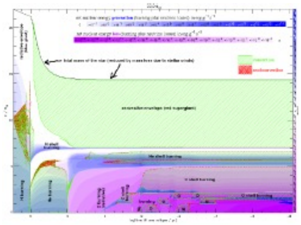
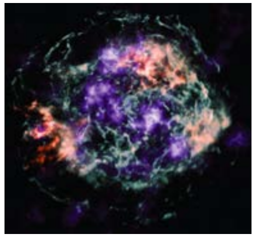
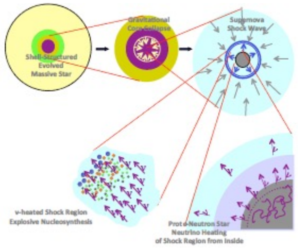
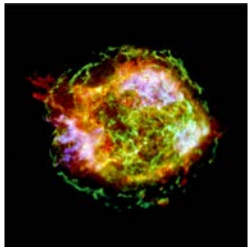
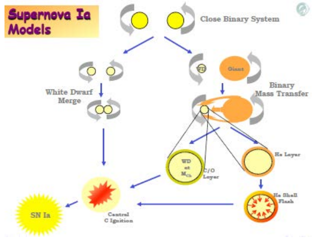
SN simulation

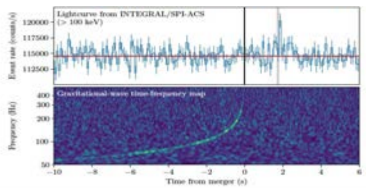


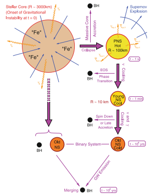
Orlando+2025

→ *"forget about the "onion shell" (Raph Hix)*

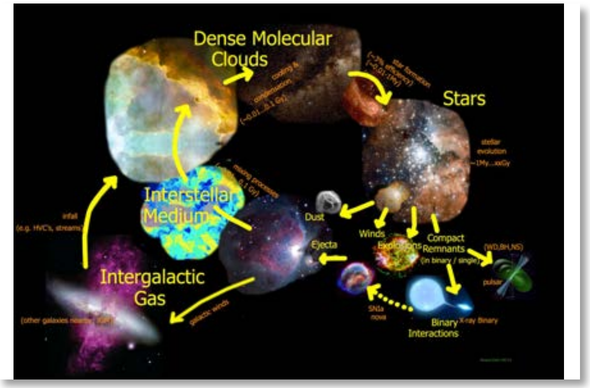
The Challenges



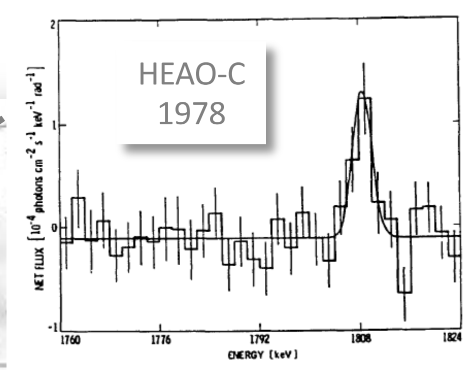


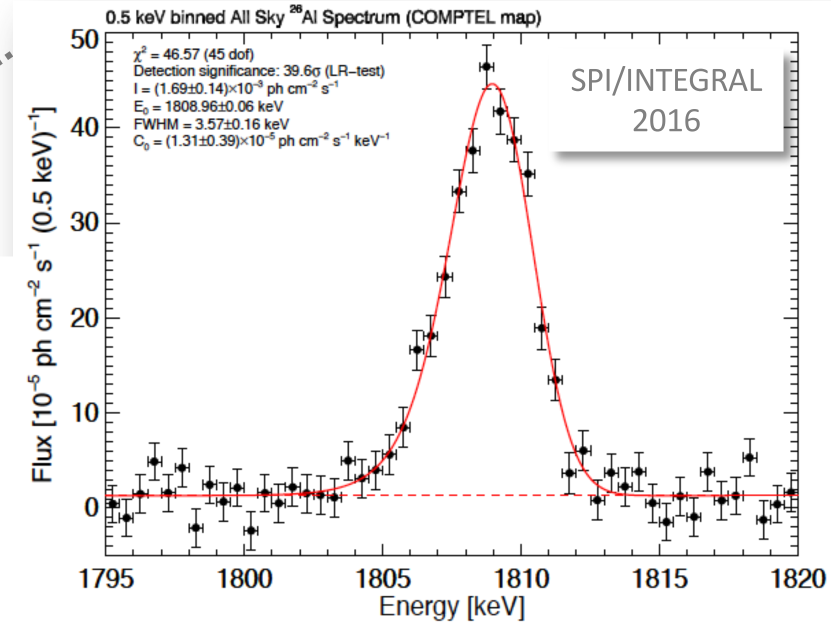
☆Understand the sources of new nuclei

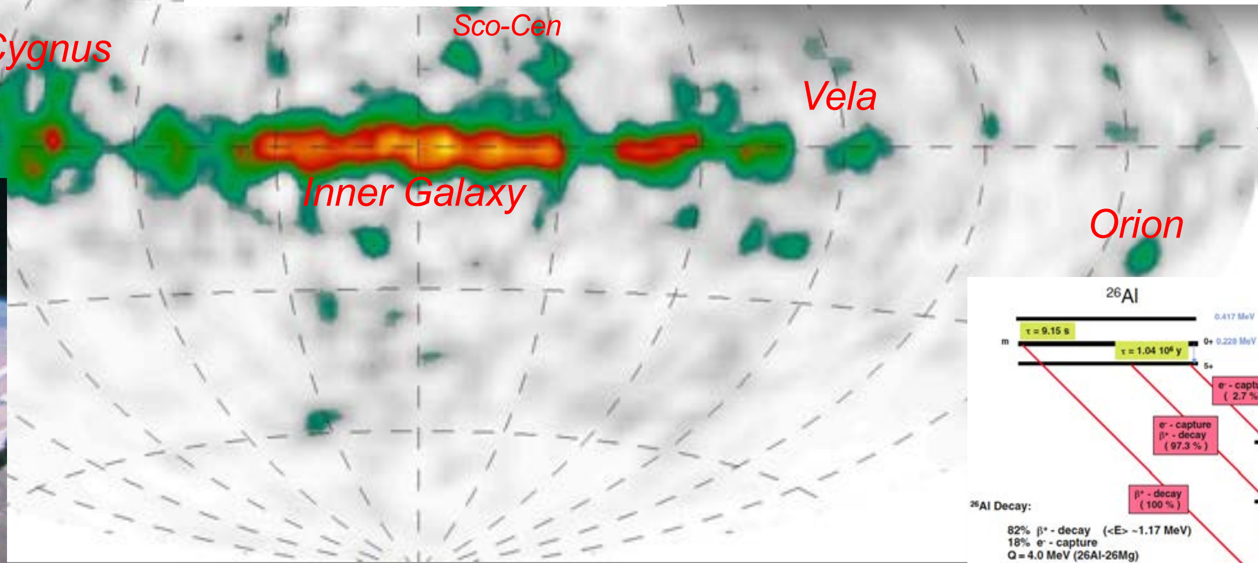


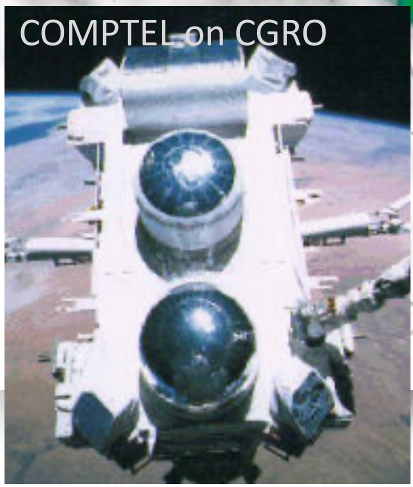
☆Trace the flows of cosmic matter

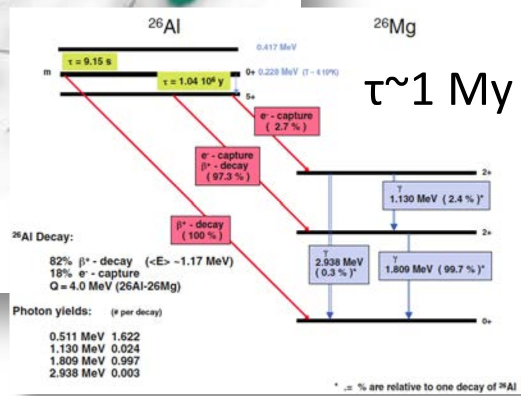
^{26}Al γ-rays from the Galaxy



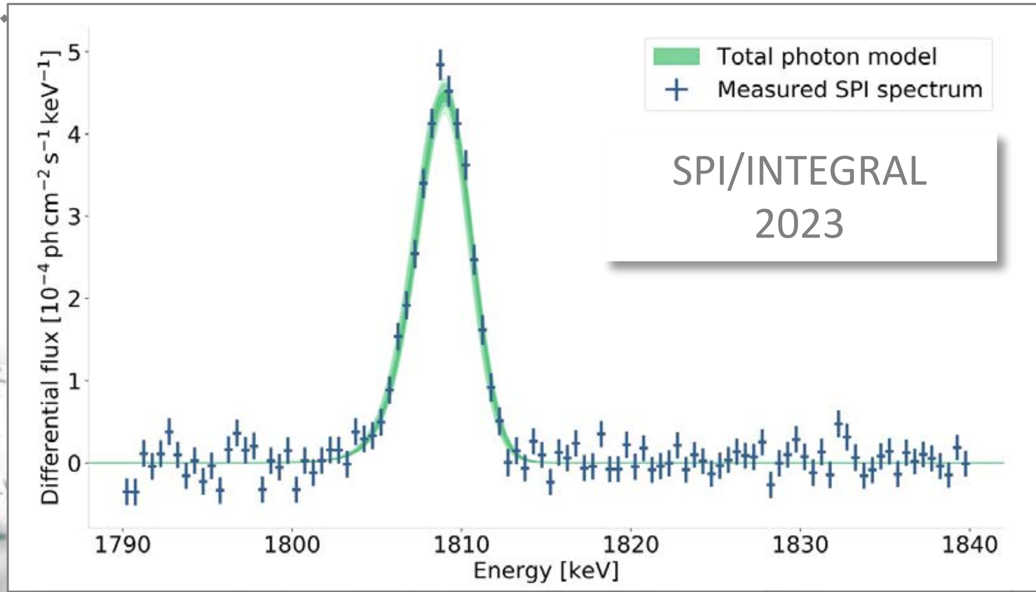


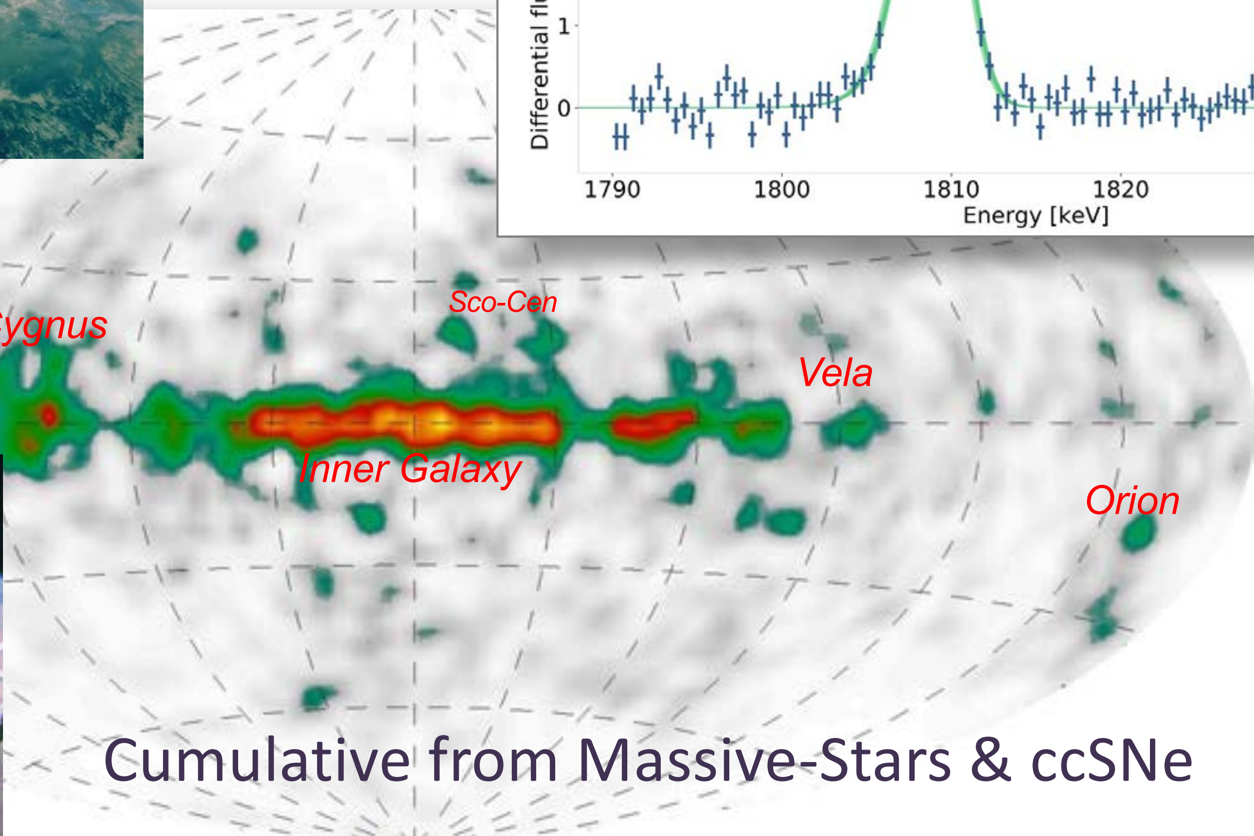


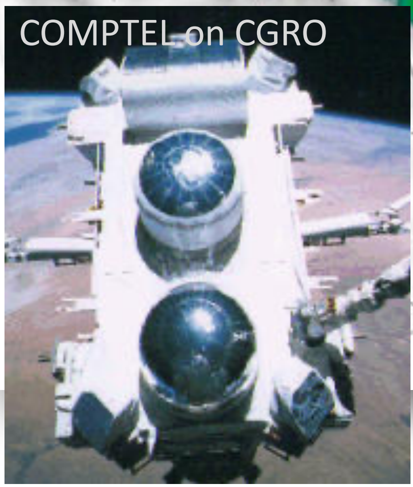




^{26}Al γ-rays and the galaxy-wide massive star census







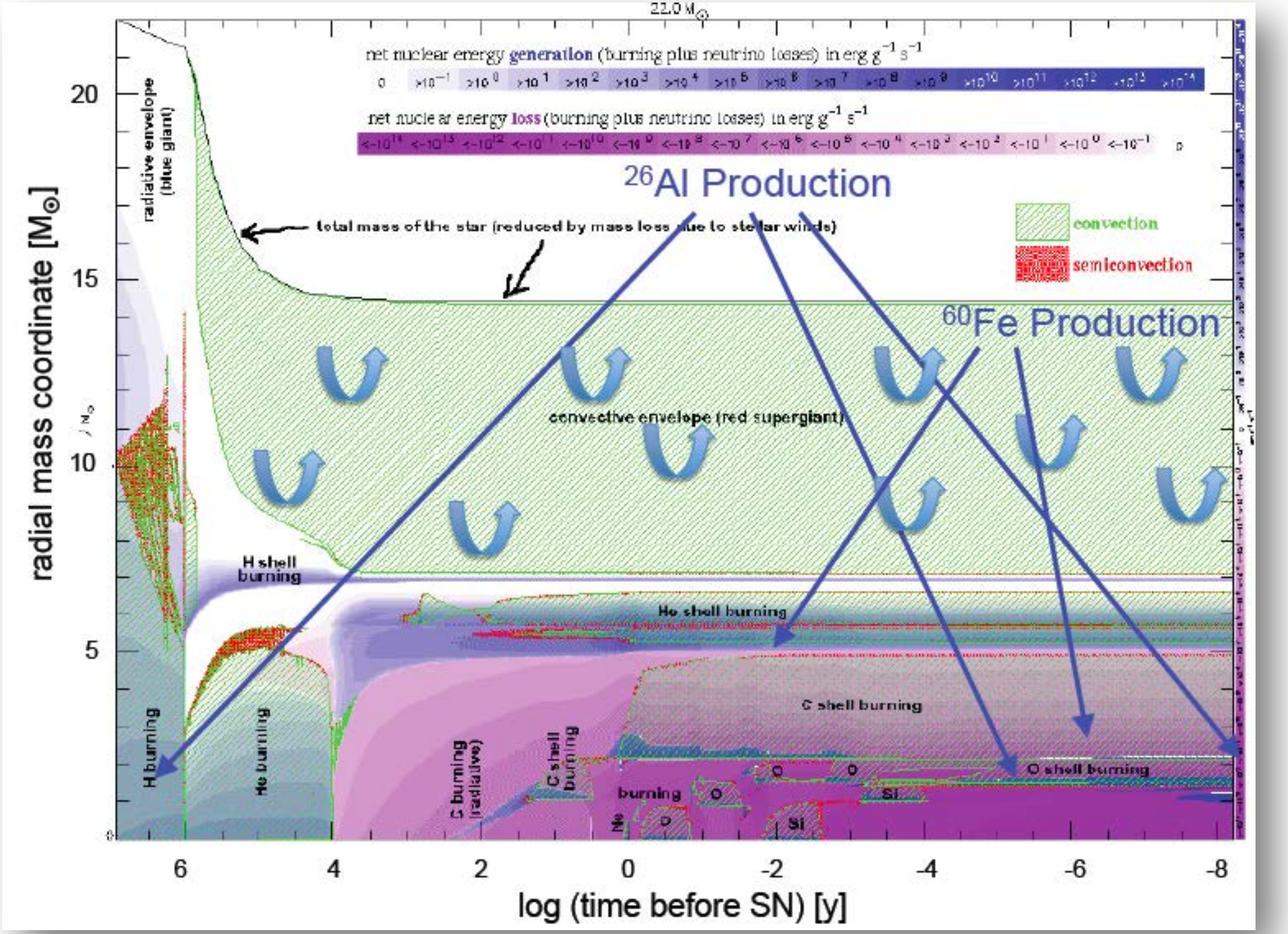
γ-ray flux → **cc-SN Rate = 1.3 (± 0.6) per Century**

Diehl+2006;2018

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

→ Messengers from Massive-Star Interiors!

...complementing neutrinos and asteroseismology!



Processes:

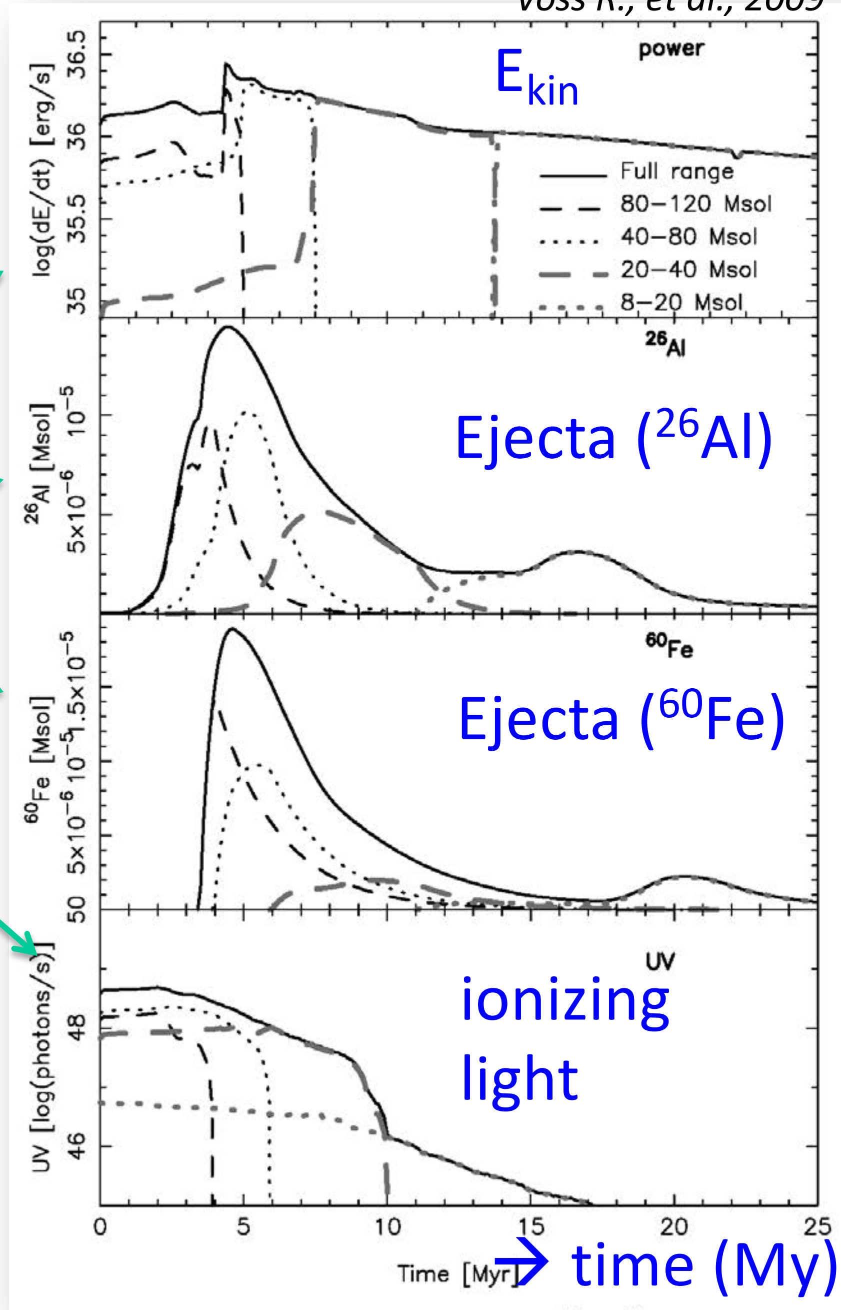
- ☆ *Hydrostatic fusion*
- ☆ *WR wind release*
- ☆ *Late Shell burning*
- ☆ *Explosive fusion*
- ☆ *Explosive release*

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



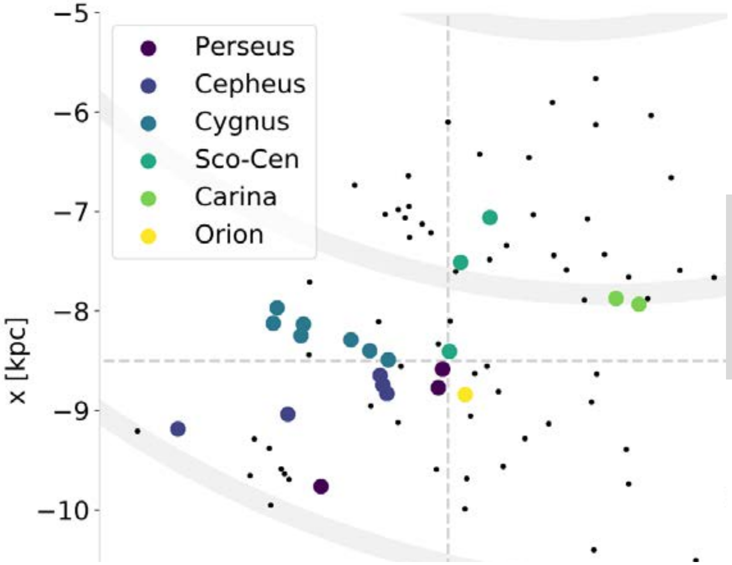
Diffuse radioactivity throughout the Galaxy

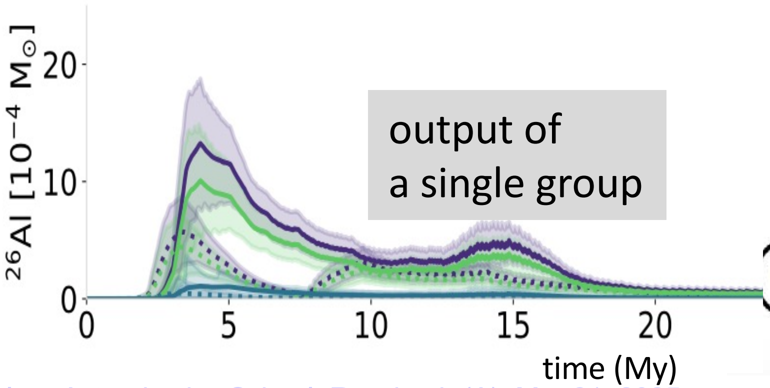
Galactic Population Synthesis Modelling

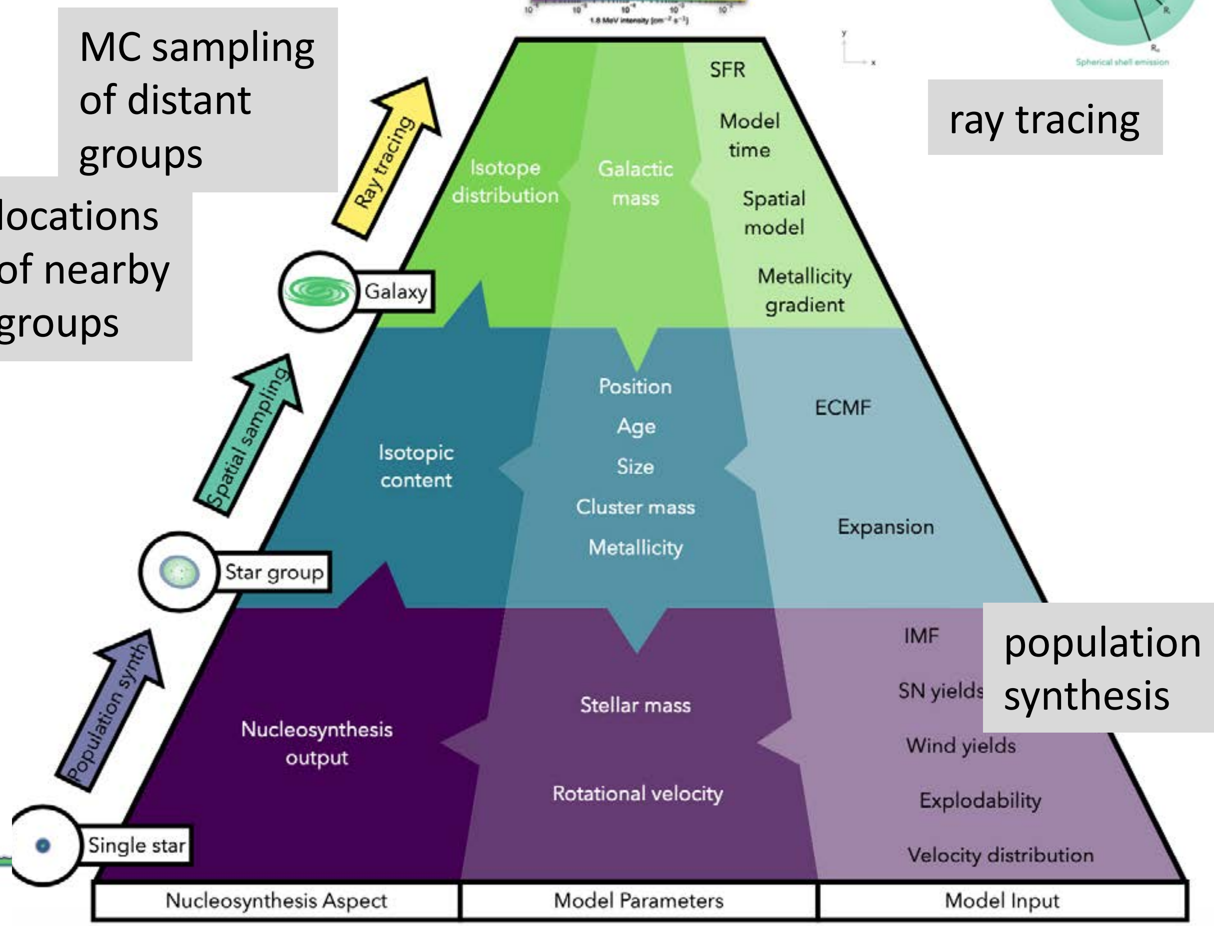
- Use stellar / SN yields and evolution times
- Include knowledge about sources (stellar groups)
- Include known groups; sample unknown groups

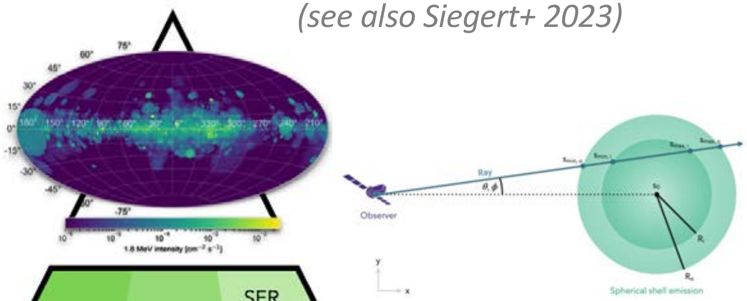
Pleintinger PhD thesis 2020
(see also Siegert+ 2023)

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





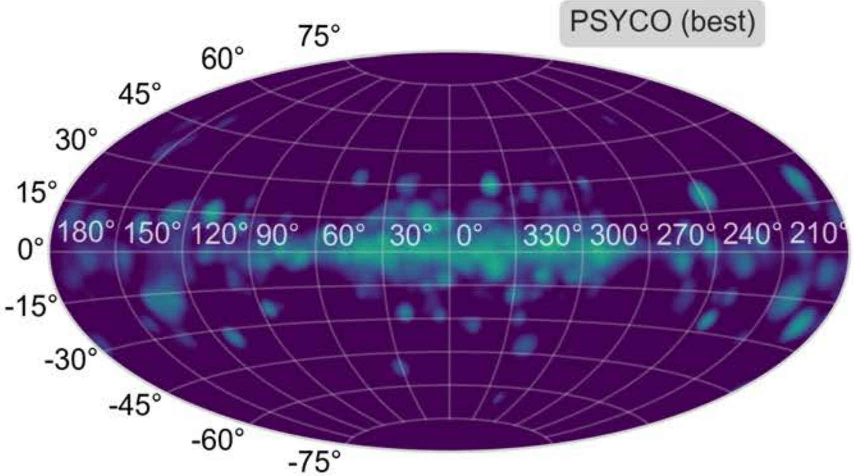


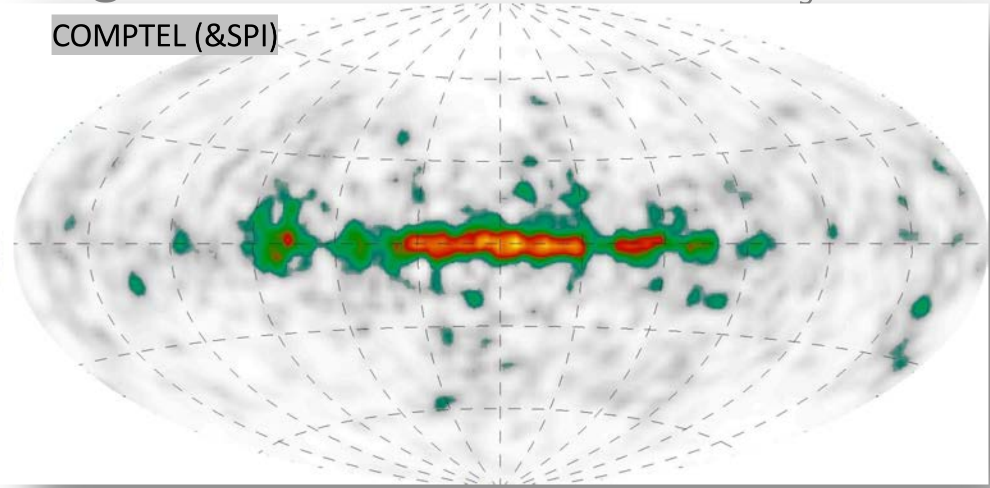


Diffuse radioactivity throughout the Galaxy

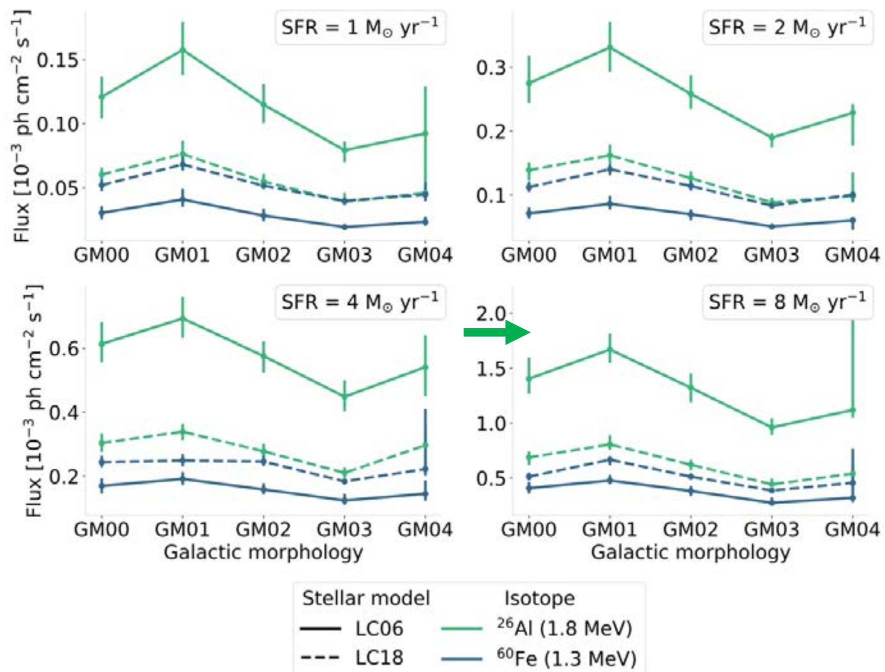
Galactic Population Synthesis Modelling versus observations

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)

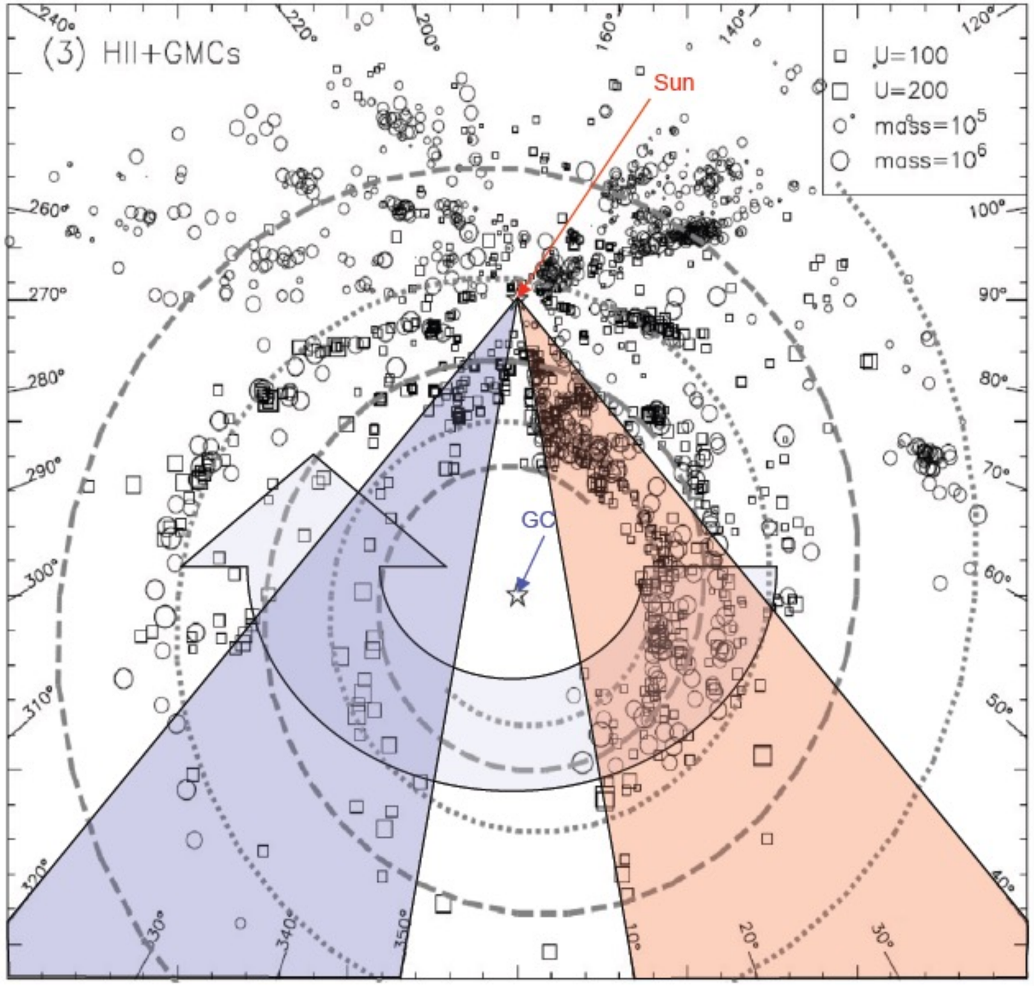


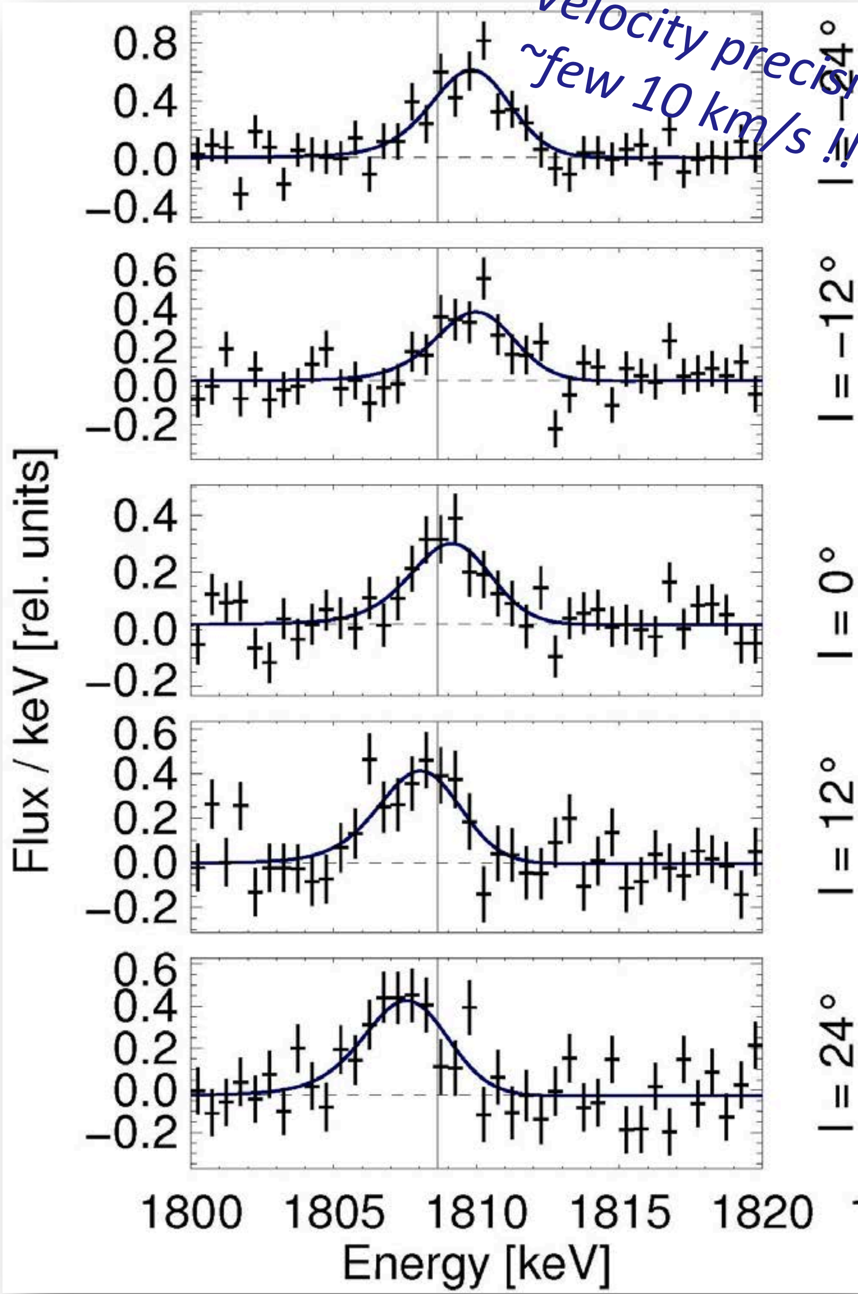
cmp. Gaia/2MASS: ~3.3 $M_\odot$ y^{-1} *(Zari+2022)*

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

☞ Large-scale Galactic rotation

Velocity precision ~few 10 km/s !!



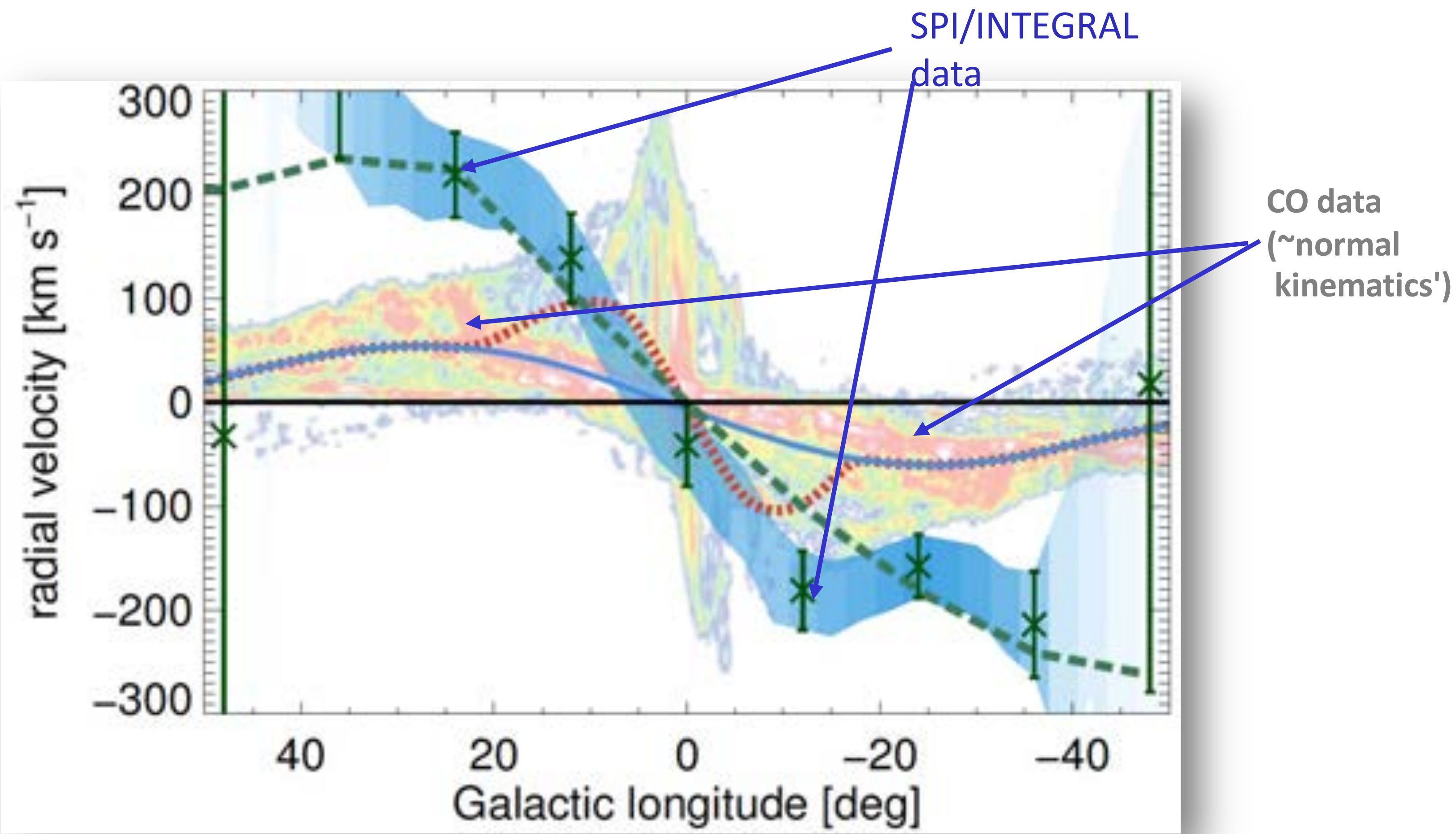


Kretschmer et al., A&A (2013)

How massive-star ejecta are spreading…

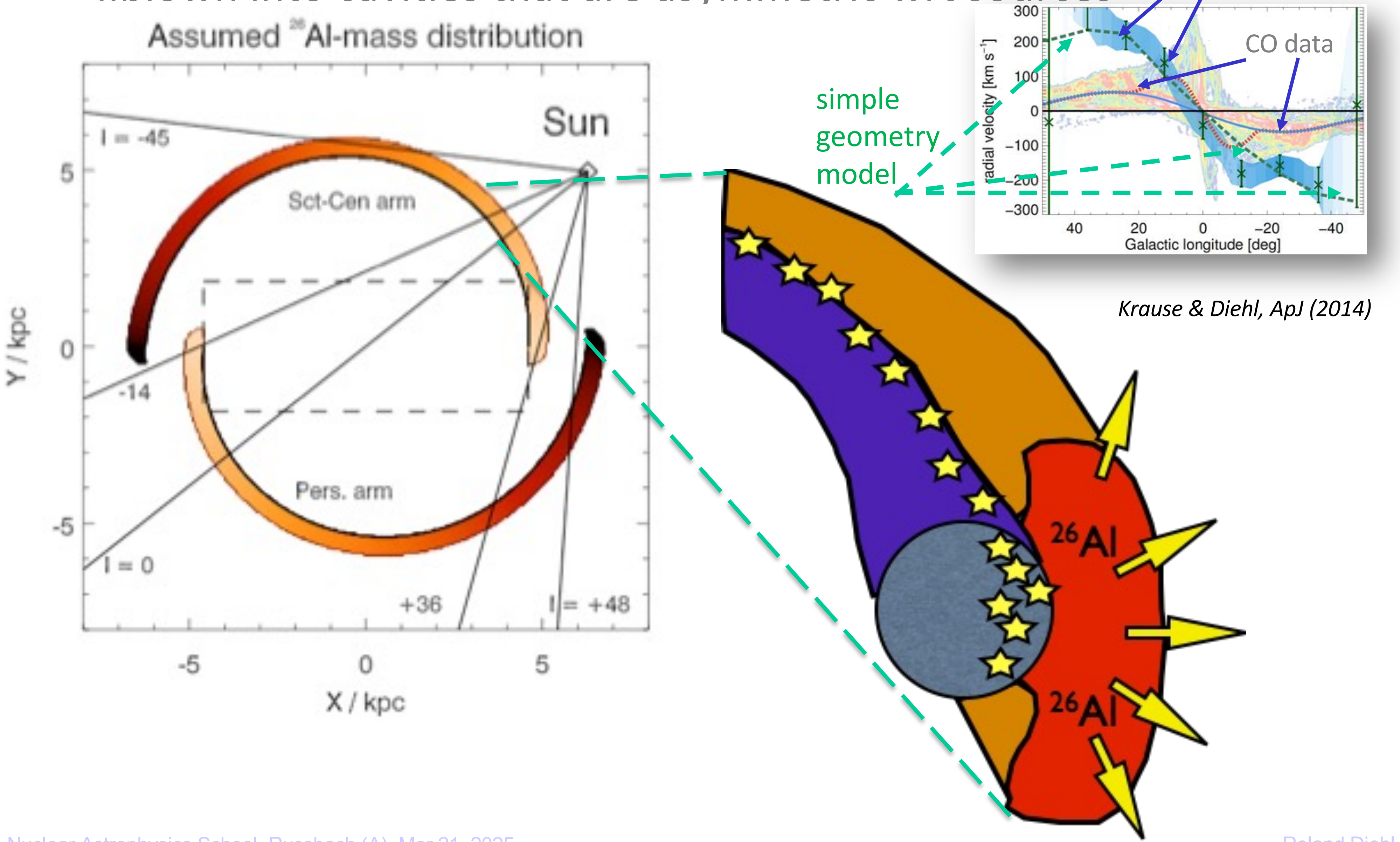
- ^{26}Al shows apparently higher galactocentric rotation (?)

Kretschmer+(2013)



How massive-star ejecta are spreading…

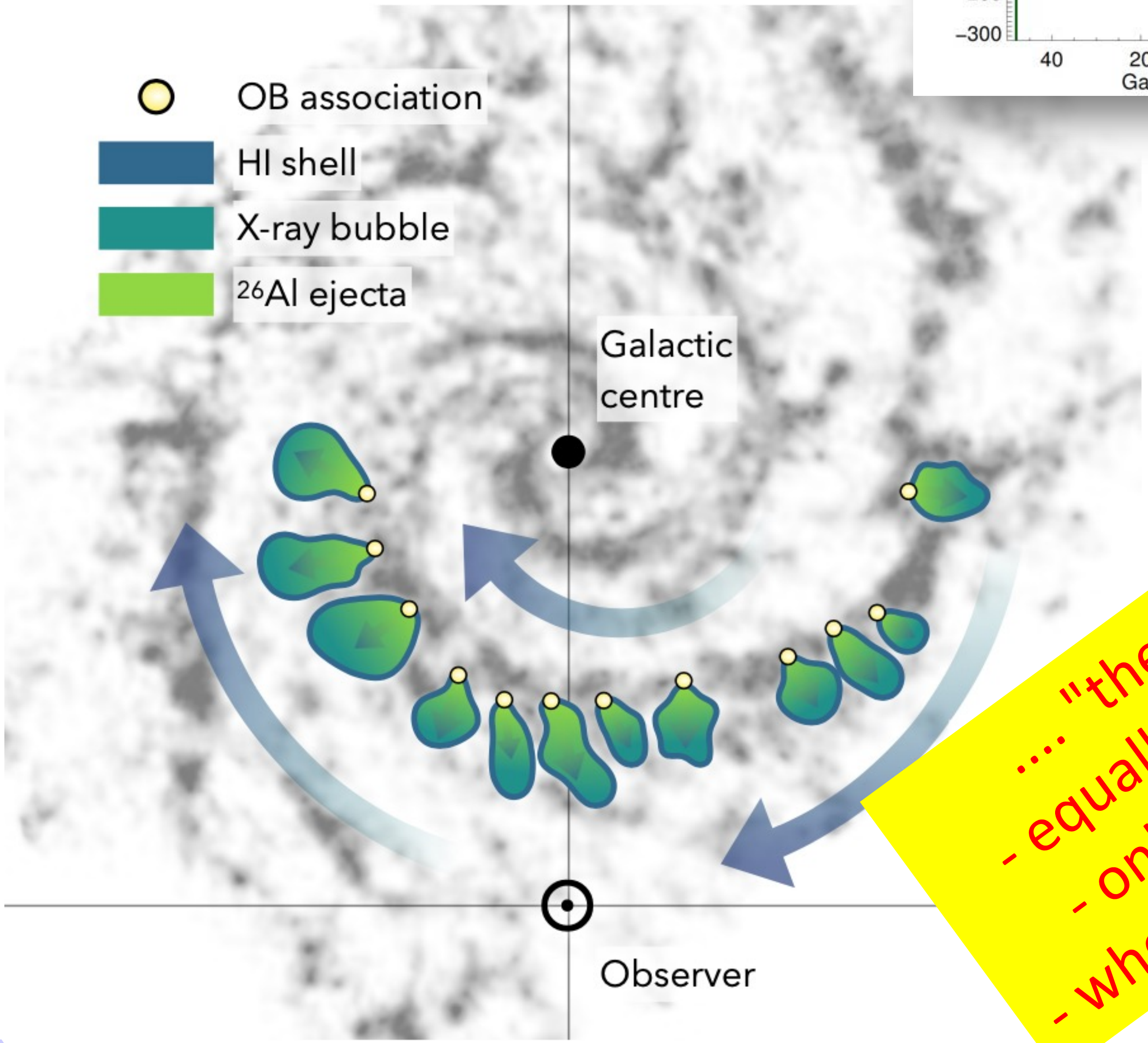
- ^{26}Al shows apparently higher galactocentric rotation (?)
- ..blown into cavities that are asymmetric wrt sources

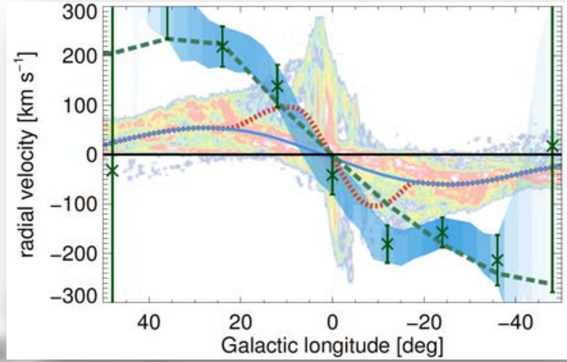


Krause & Diehl, ApJ (2014)

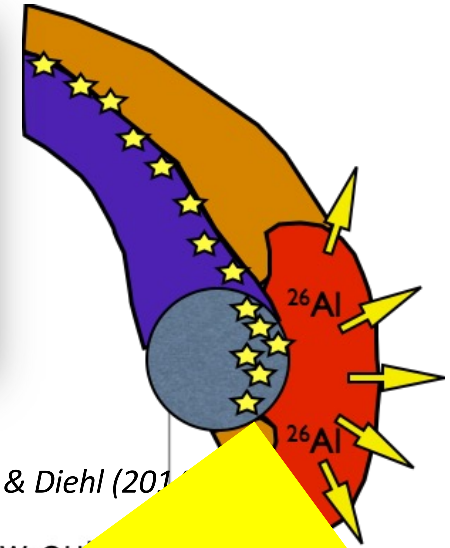
How massive-star ejecta are spread out…

Superbubbles extended away from massive-star groups





Kretschmer+(2013)



Krause & Diehl (201

Blow-ou

Galactic centre

otation

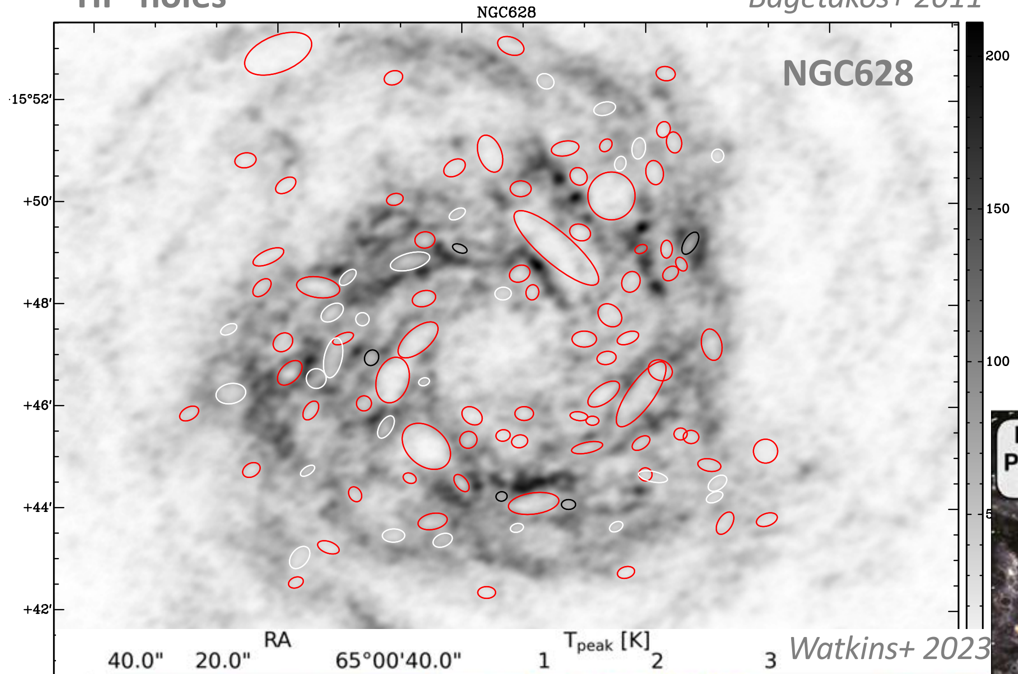
on by M. Pleintinger (2020)

…. "the ISM is well-mixed" ---
- equally for all types of sources???
- only within the disk of Galaxy??
- where does the chimney material go?

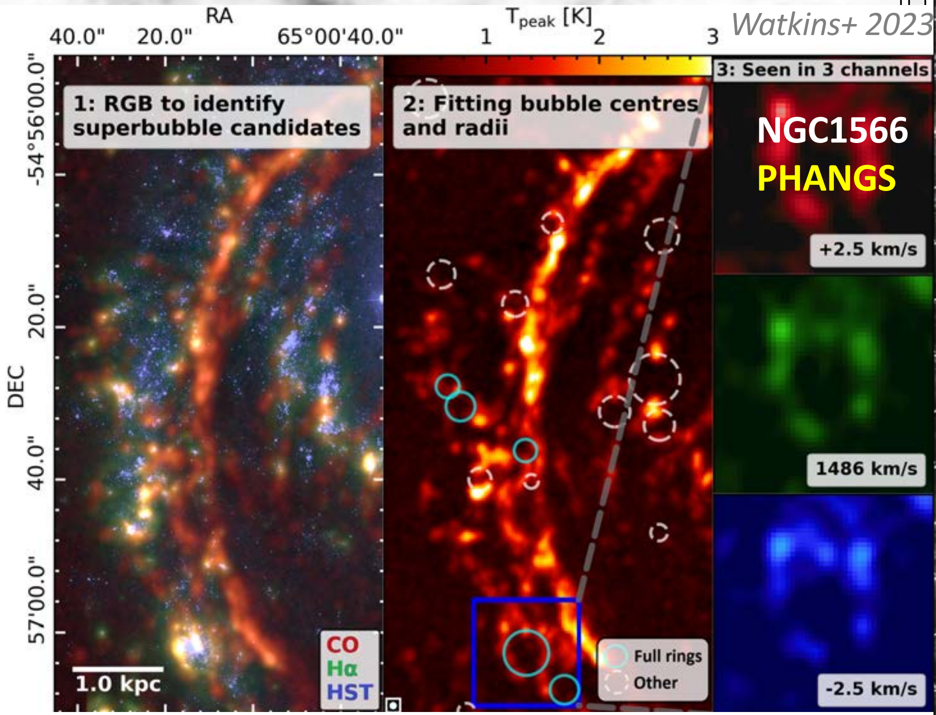
Superbubbles observations in other galaxies

HI 'holes'

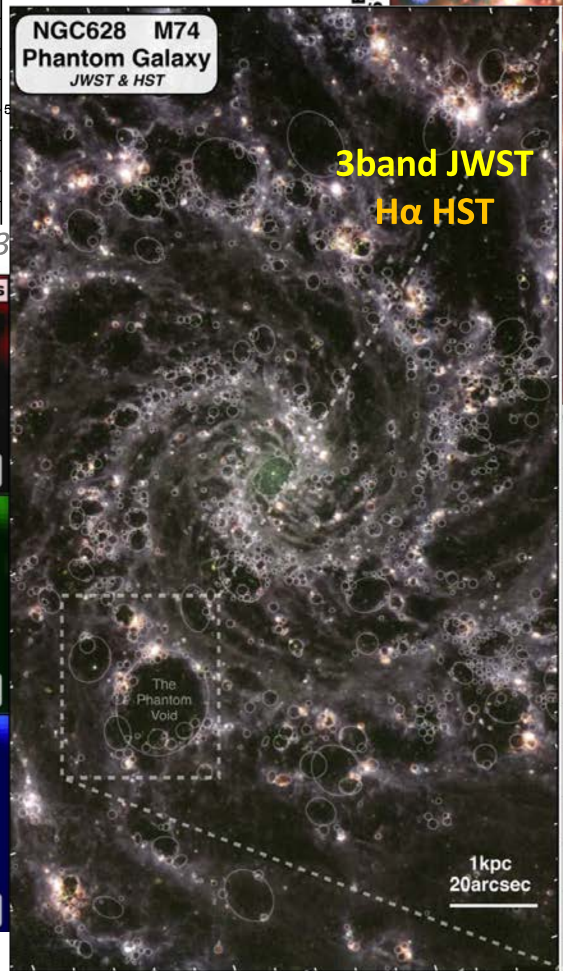
Bagetakos+ 2011



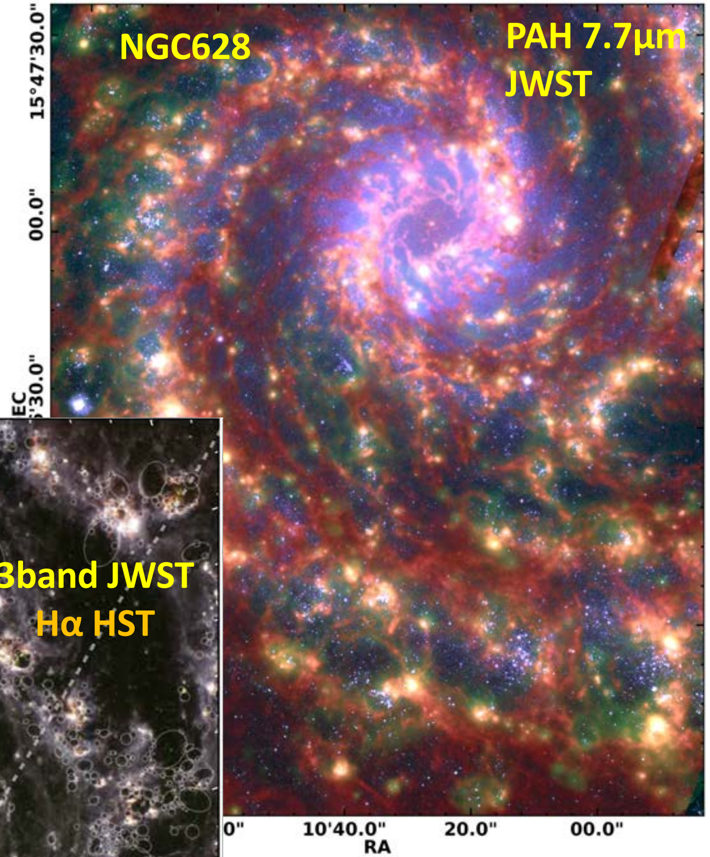
Watkins+ 2023



Barnes+2023



Schinnerer&Leroy2024



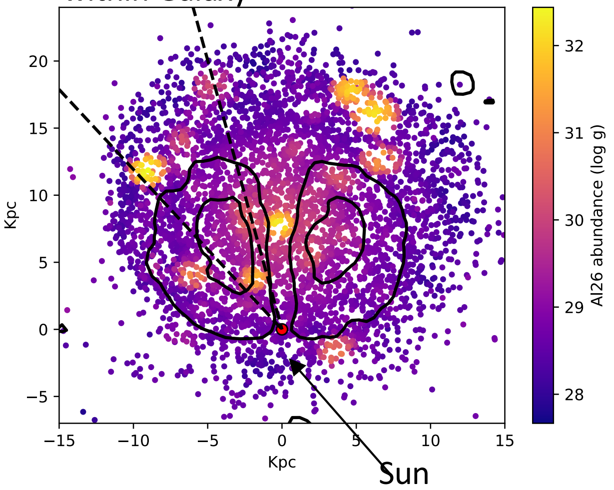
Simulations of (inhomogeneous) galactic evolution

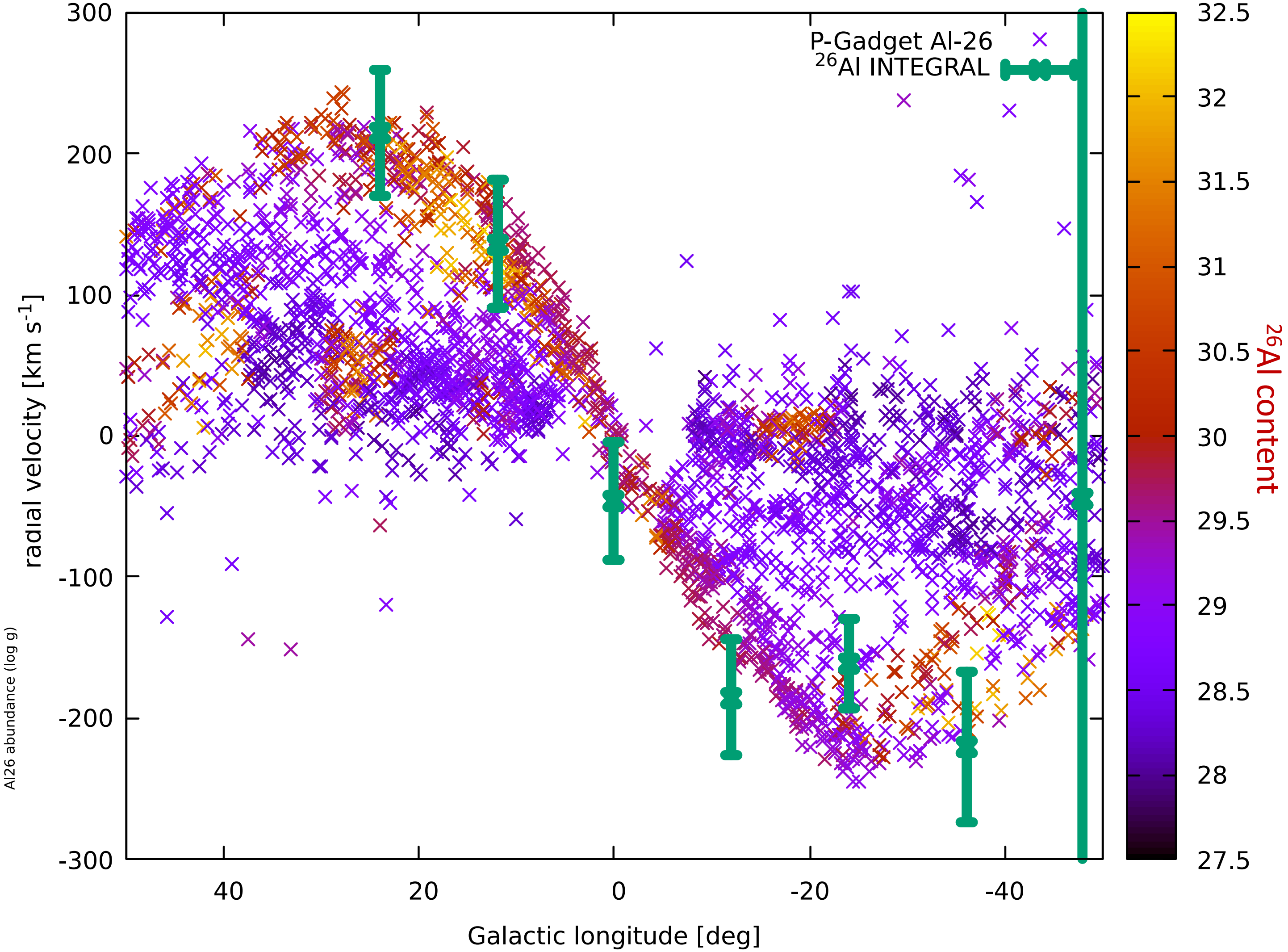
→ ejecta with excess velocities appear naturally within a spiral galaxy

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

Wehmeyer + 2025

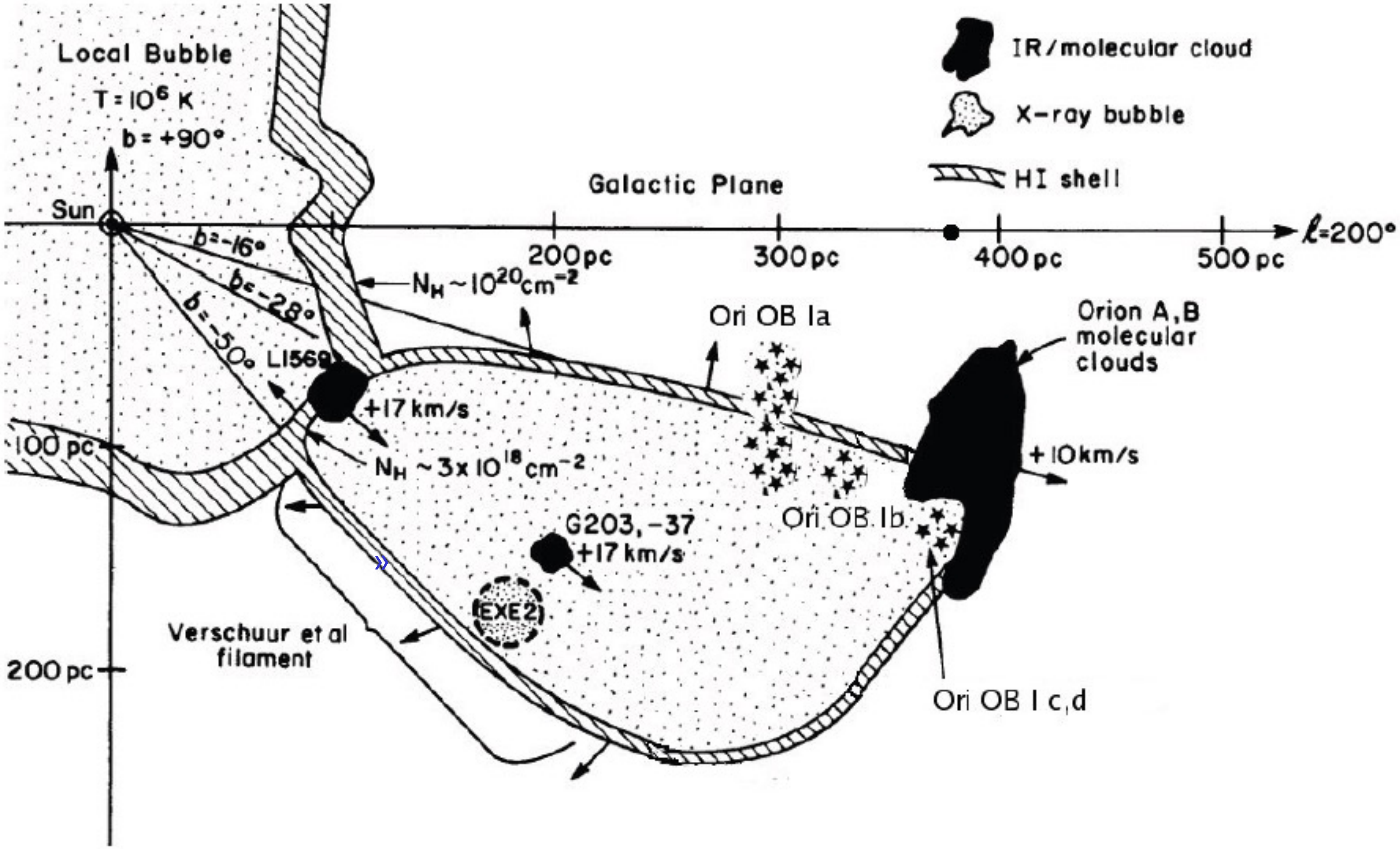
locations of ^{26}Al within Galaxy



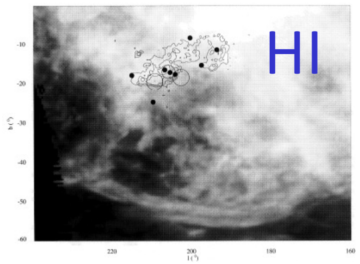


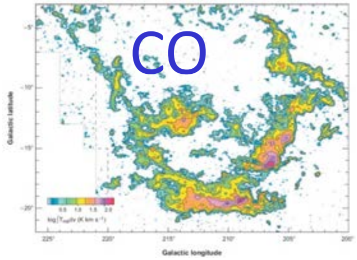
Orion-Eridanus: A superbubble blown by stars & supernovae

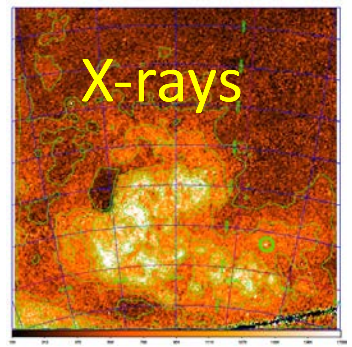
ISM is driven by stars and supernovae → Ejecta commonly in (super-)bubbles

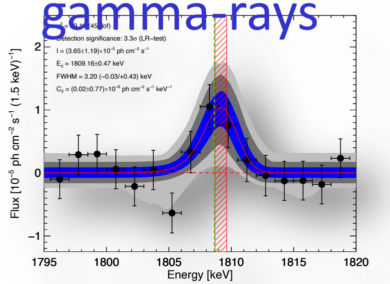


Krause+ 2014, Fierlinger+ 2016,
Voss+ 2010, Diehl+2003, Siegert 2016









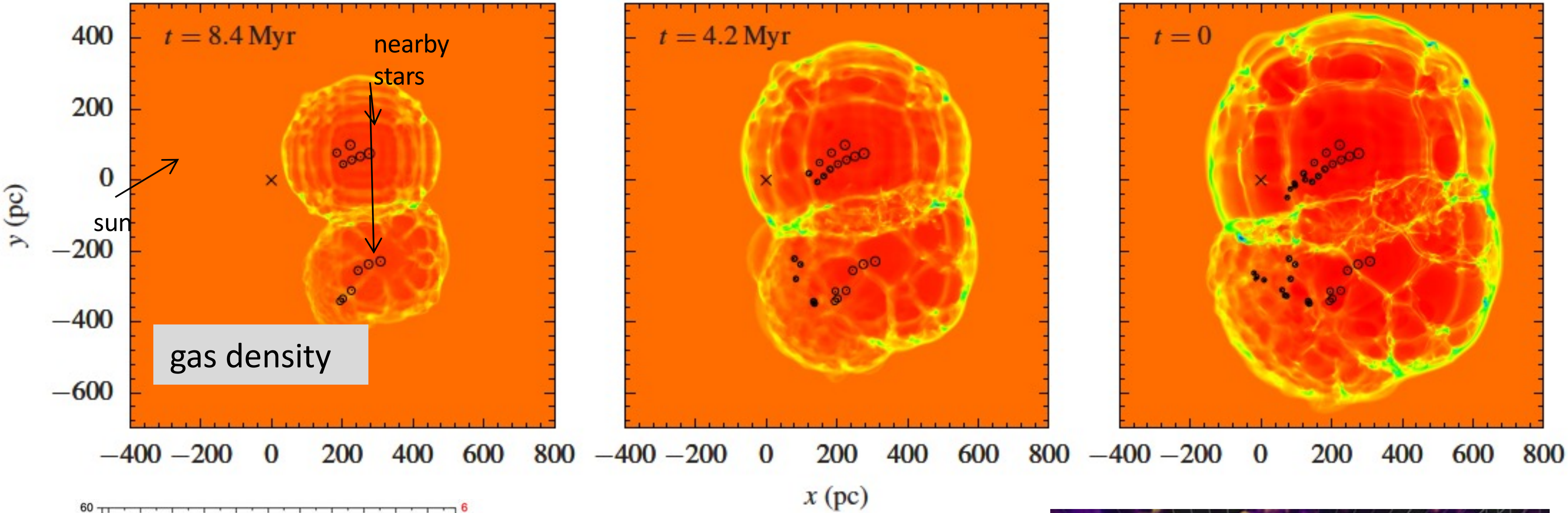
3D MHD sim, 0.1..0.005 pc resolution
Krause+ 2013ff

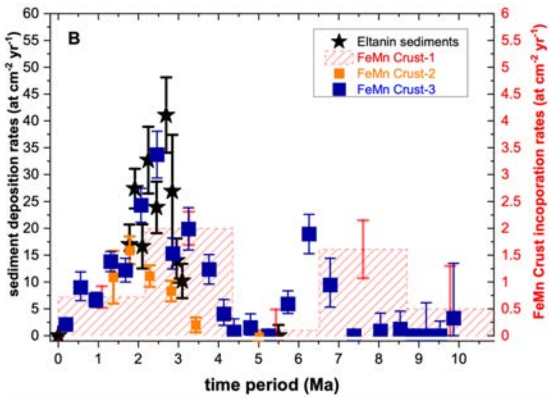
^{60}Fe on Earth from recent nearby supernovae?

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

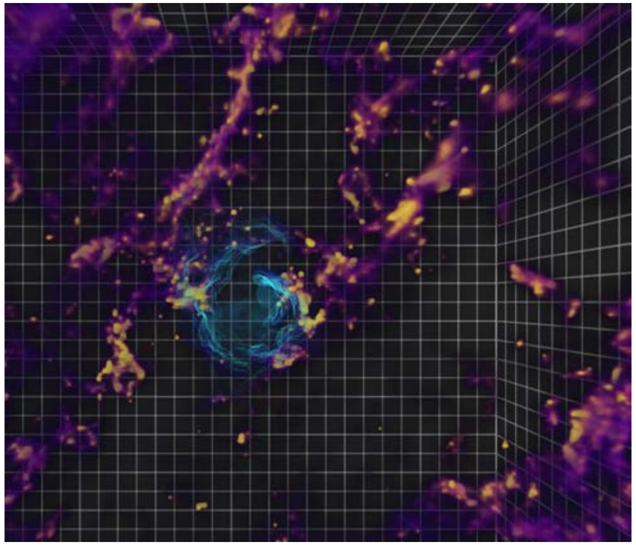
created by SN explosions, recent ones adding ejecta flows

Schulreich+ 2017





ocean crusts show
^{60}Fe deposition history
(Wallner+ 2015,2016,2021)



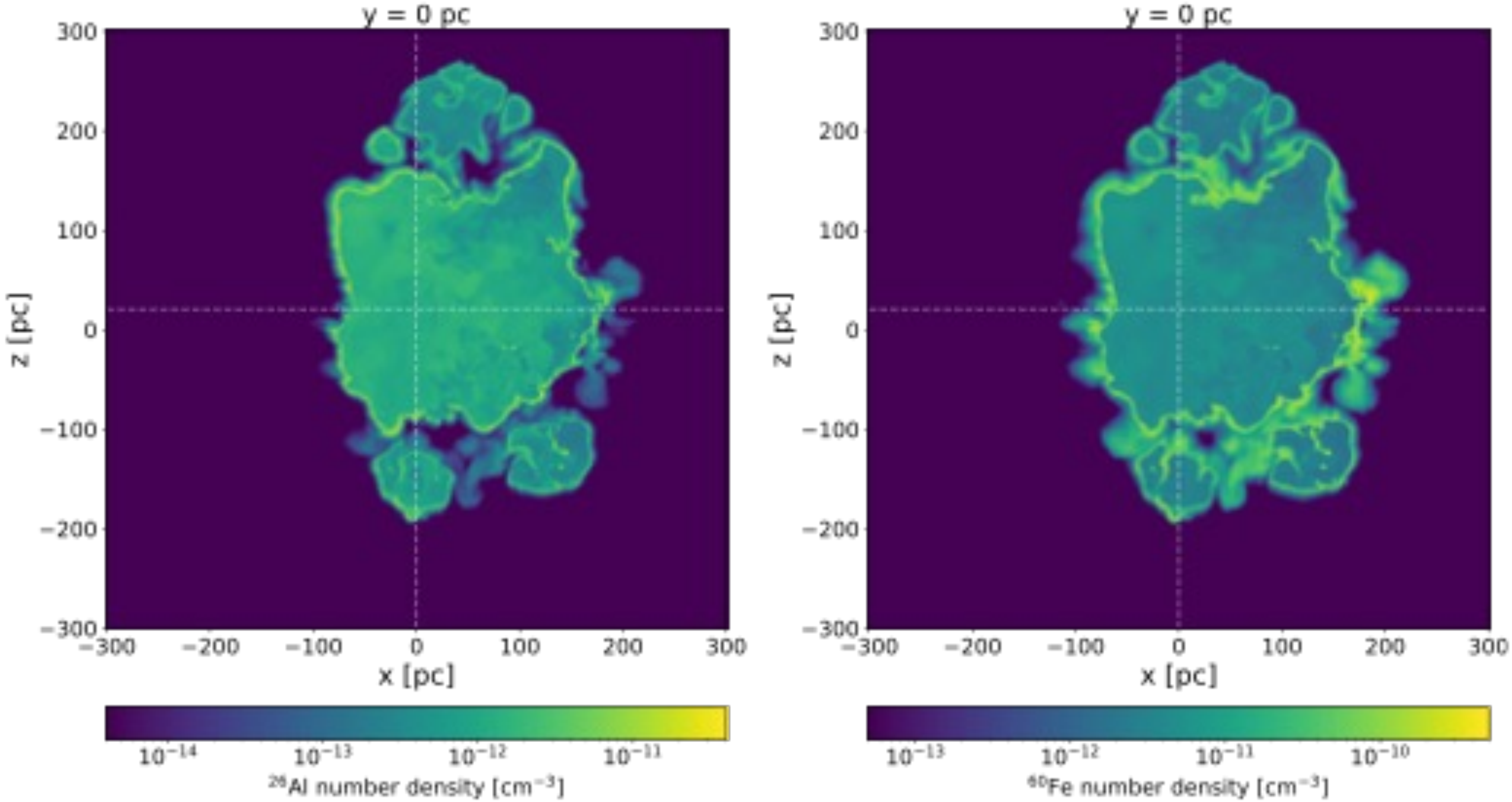
see also *Zucker+ 2022 and O'Neill+2024*
for updates on the solar vicinity
with superbubbles, clusters, molecular gas...

^{26}Al and ^{60}Fe in the Local Bubble

3D hydro simulations of Local Bubble evolution

^{26}Al predominantly in hot bubble interiors, ^{60}Fe deposition at bubble walls

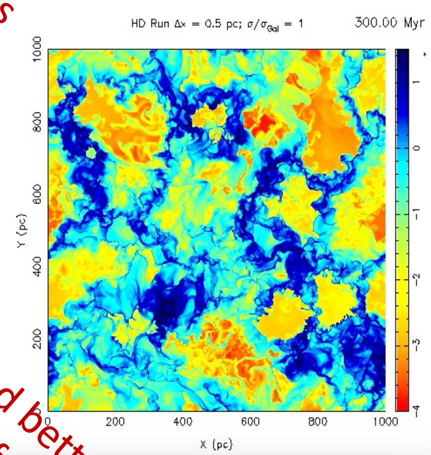
Siegert, Schulreich+,2024



Nuclear Astrophysics & Gamma-Ray Spectroscopy - Summary

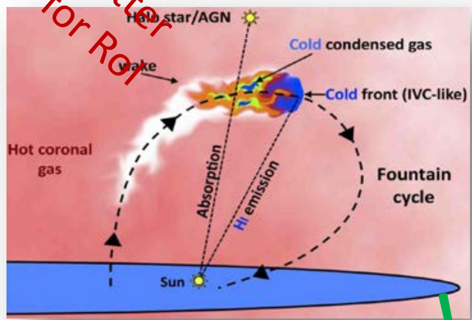
- ☆ (even) supernova explosions are not spherically symmetric
  - ^{56}Ni and how it reveals its radiation in SN2014J
    → SN Ia diversity; sub-Chandra models?
  - ^{44}Ti image and line redshift in CasA; SN87A
    → ccSupernovae interiors are fundamentally 3D/asymmetric
  - NSMs/kilonovae are fundamentally very asymmetric, & rare
  - Novae are good candidates, no gamma rays seen yet

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
  - What is the role of SNe & superbubbles in mixing of ISM??
  - How are gas flows in and above/below the disk linked?

need better maps for RoI



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

Thank you!