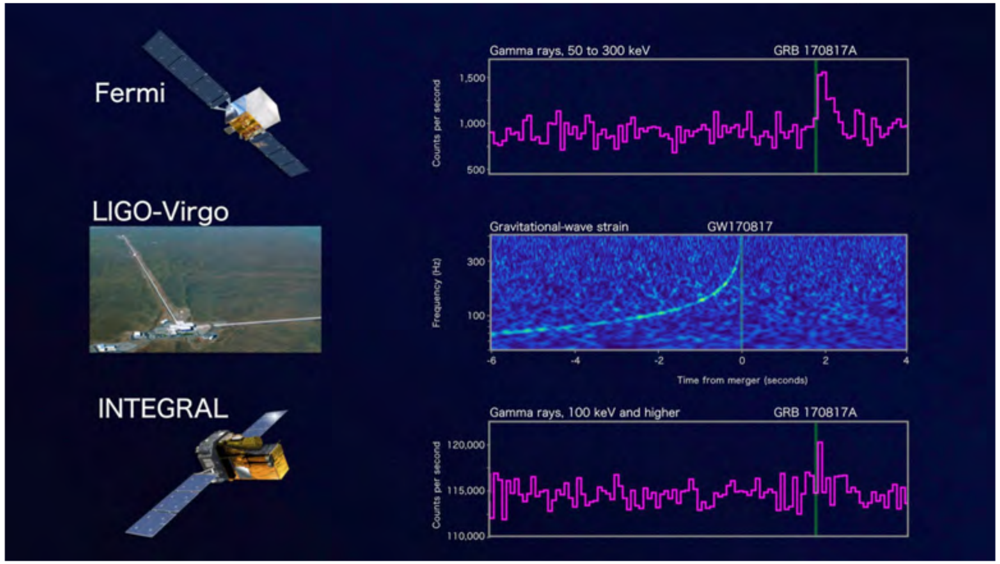
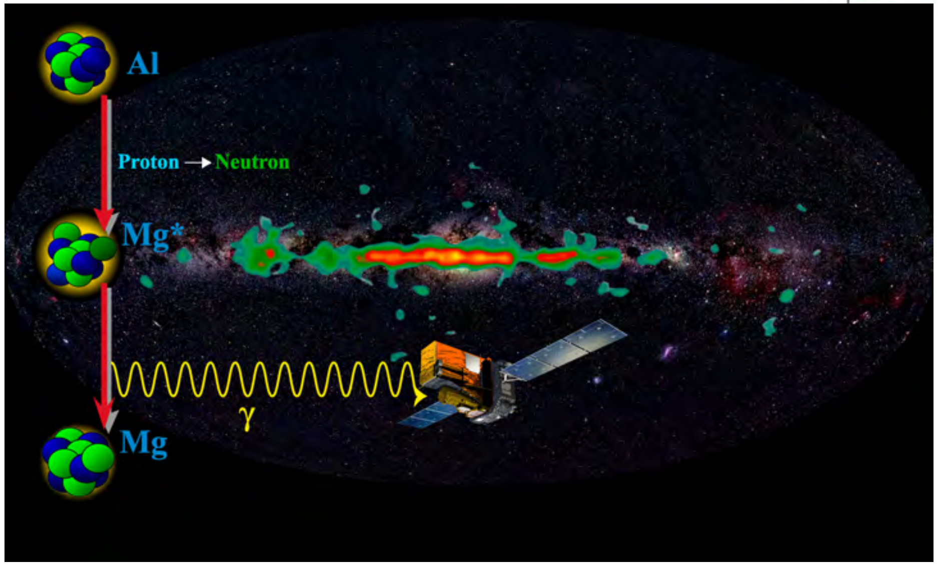
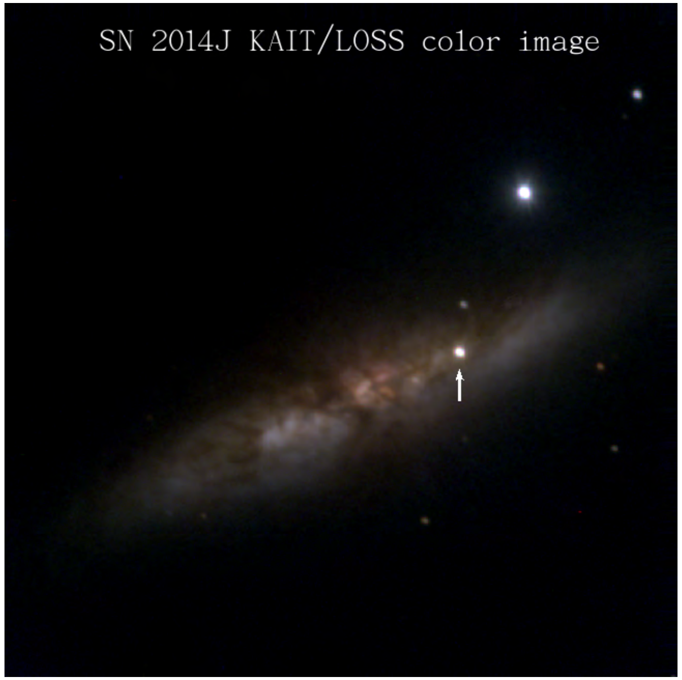
Gamma-ray astronomy and spectroscopy from cosmic nuclei

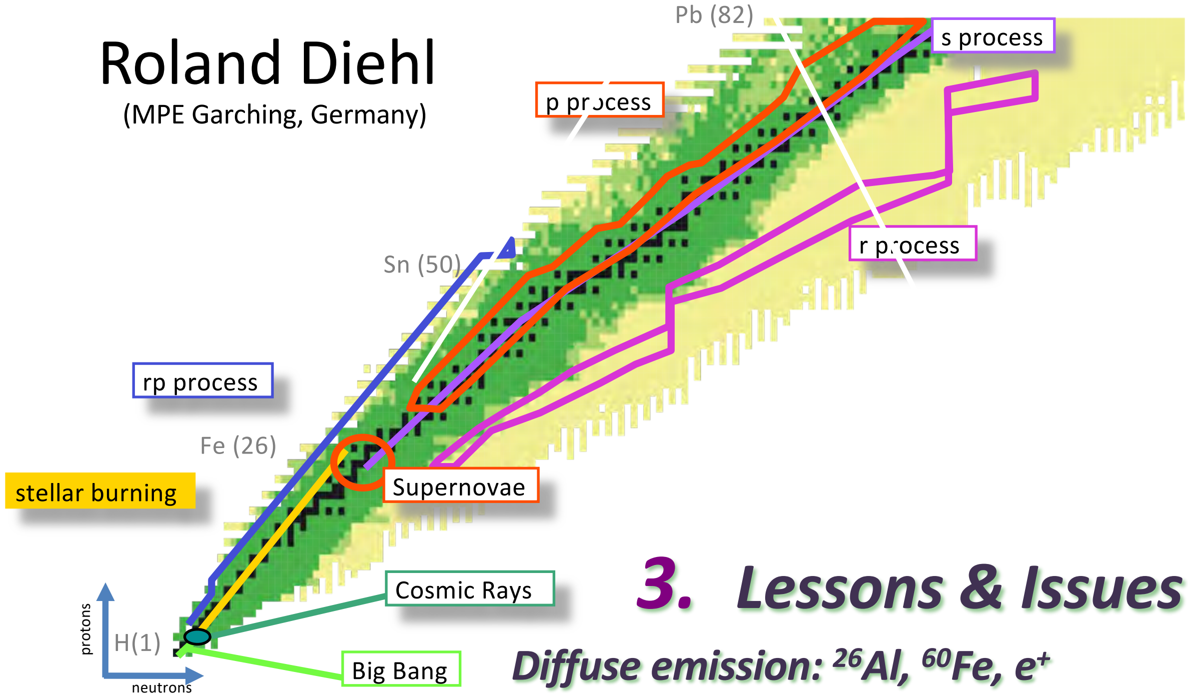






Roland Diehl

(MPE Garching, Germany)



3. *Lessons & Issues*

Diffuse emission: ^{26}Al, ^{60}Fe, e^{+}

Specific sources: Supernovae Ia, CC

Nuclear Gamma-Ray Lines

Isotope	*Mean Lifetime*	*Decay Chain*	*γ-Ray Energy (keV)*
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^{*}$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^{*} \rightarrow {}^{56}Fe^{*}+e^{+}$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^{*}$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+}$	1275
^{44}Ti	85 y	$^{44}Ti \rightarrow {}^{44}Sc^{*} \rightarrow {}^{44}Ca^{*}+e^{+}$	78, 68; 1157
^{26}Al	$1.04\ 10^{6}$y	$^{26}Al \rightarrow {}^{26}Mg^{*} + e^{+}$	1809
^{60}Fe	$3.8\ 10^{6}$y	$^{60}Fe \rightarrow {}^{60}Co^{*} \rightarrow {}^{60}Ni^{*}$	59, 1173, 1332
e^{+}	…. 10^{5}y	$e^{+}+e^{-} \rightarrow Ps \rightarrow \gamma\gamma..$	511, <511

individual object/event (^{7}Be to ^{44}Ti)

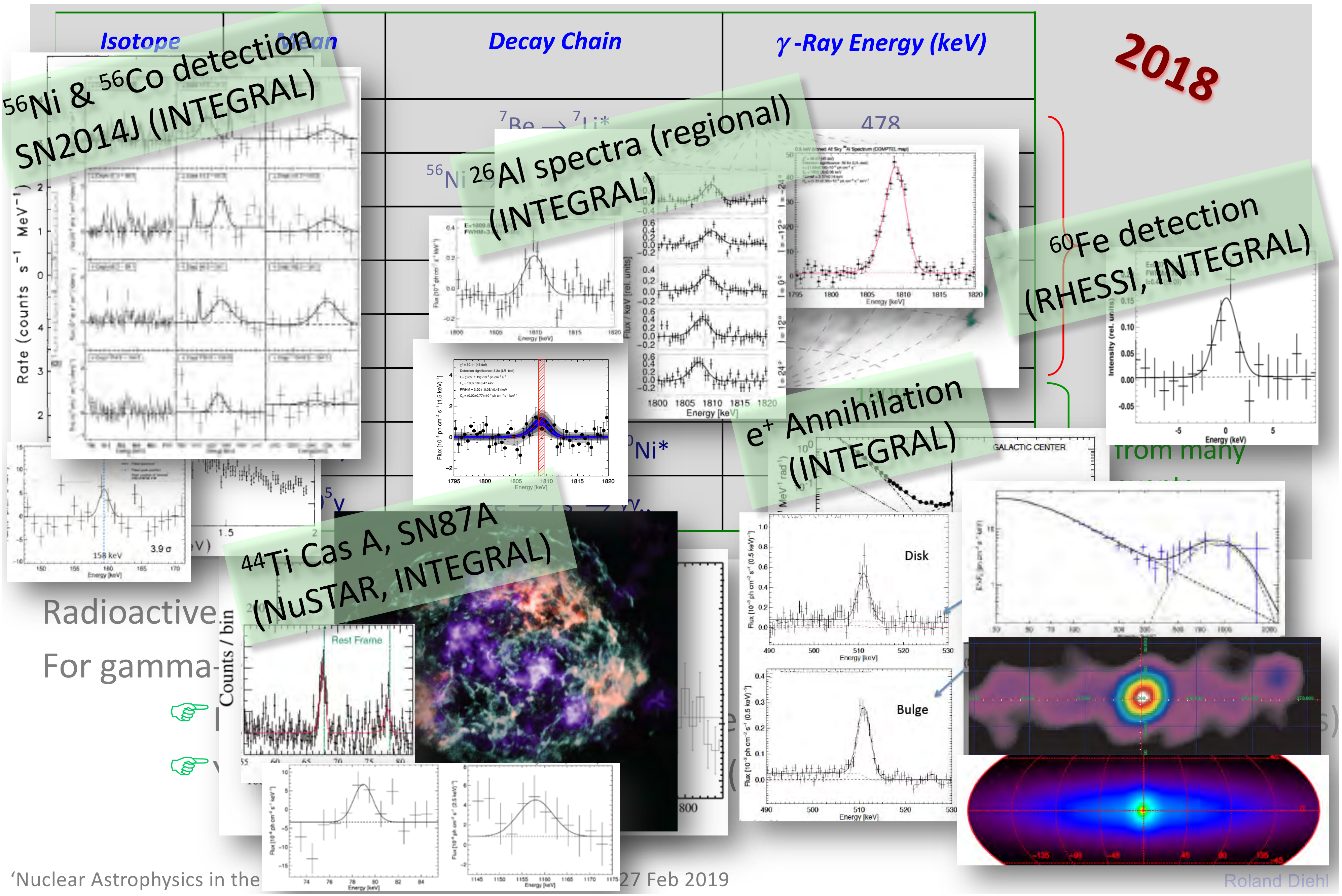
cumulative from many events (^{26}Al, ^{60}Fe, e^{+})

Radioactive trace isotopes are by-products of nucleosynthesis

For gamma-ray detections we need:

- ☞ Decay Time > Source Dilution Time (~weeks) (→ no < days lifetimes)
- ☞ Yields > Instrumental Sensitivities (10^{-5} ph cm^{-2} s^{-1}) (→ no elements > Fe)

Nuclear Gamma-Ray Lines

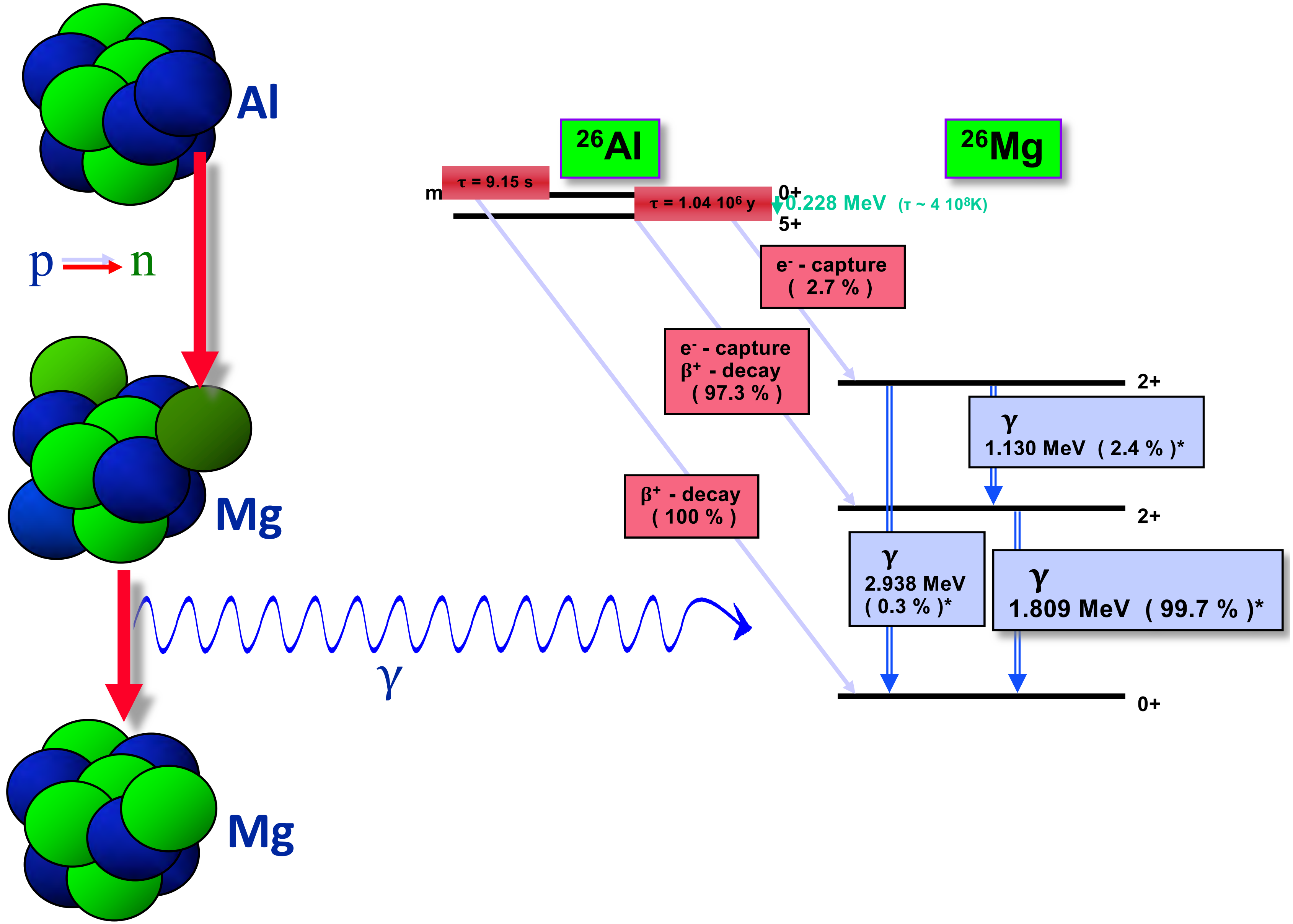


Radioactive Tracer of Nucleosynthesis

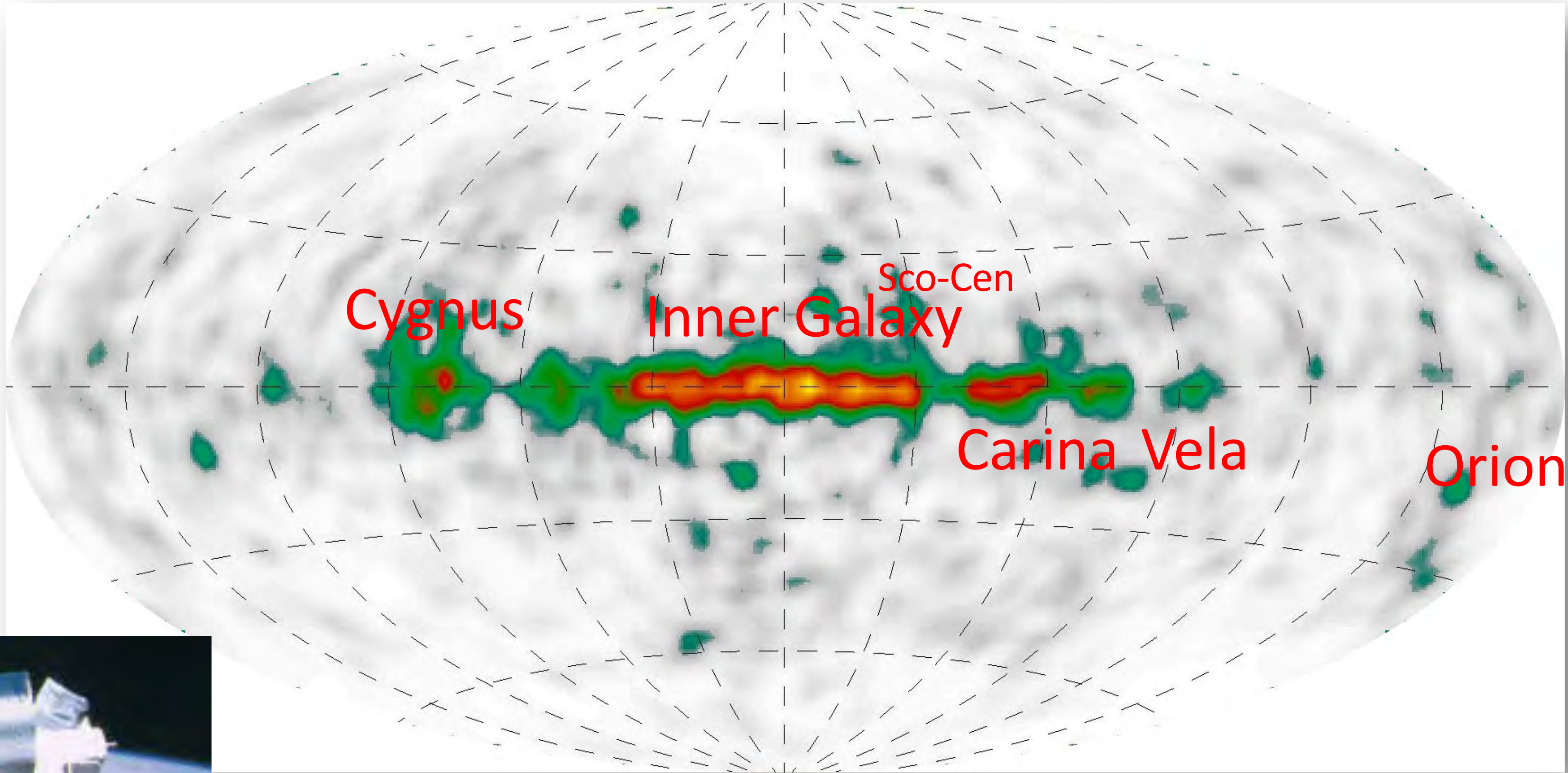
Cosmic Nucleosynthesis Source

Weak Decay

De-Excitation

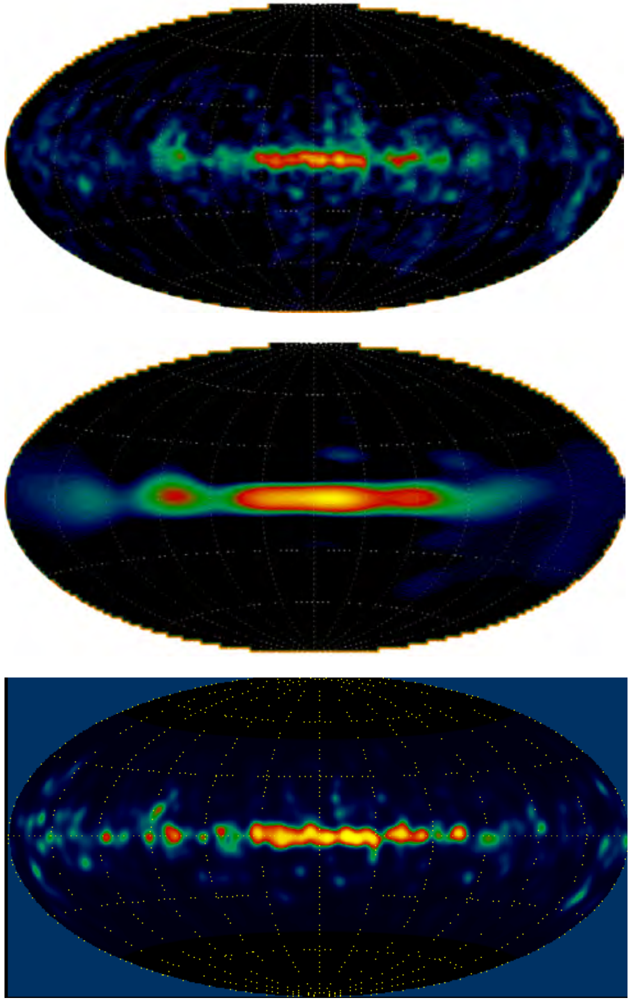


^{26}Al in our Galaxy: γ-ray Image

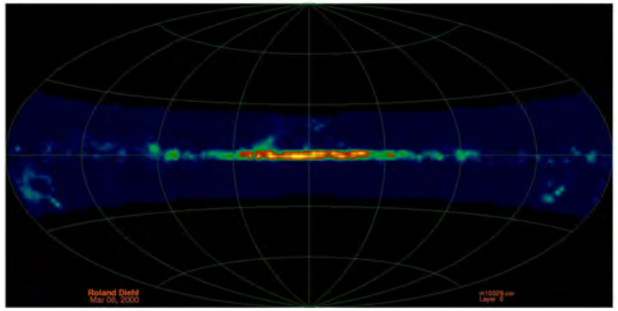


Massive-Star Nucleosynthesis
in the Current Galaxy:
Current Enrichment (~My) from ^{26}Al γ-rays

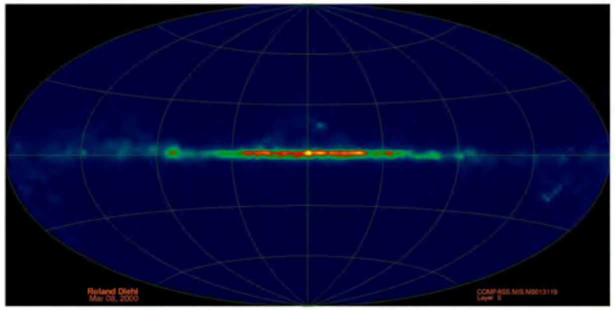
COMPTEL 1.809 MeV Maps and Possible Source Counterparts



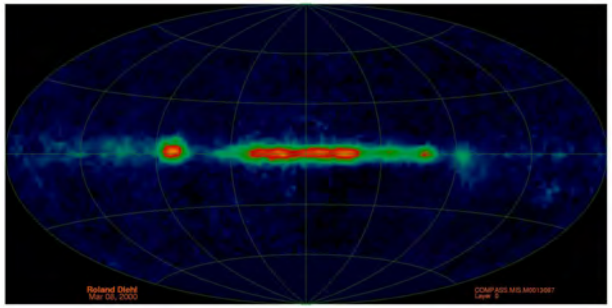
Different Imaging Methods
(ME, MREM, MLik)



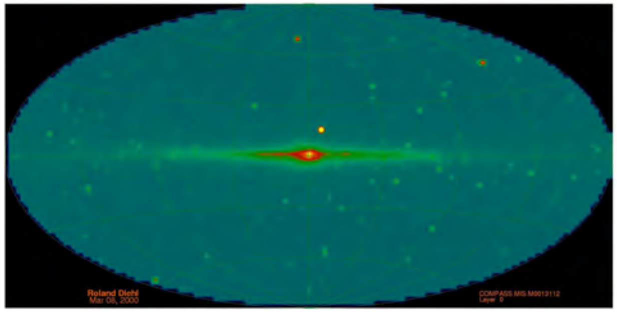
CO map of molecular gas



IR map at 240 μm, dust

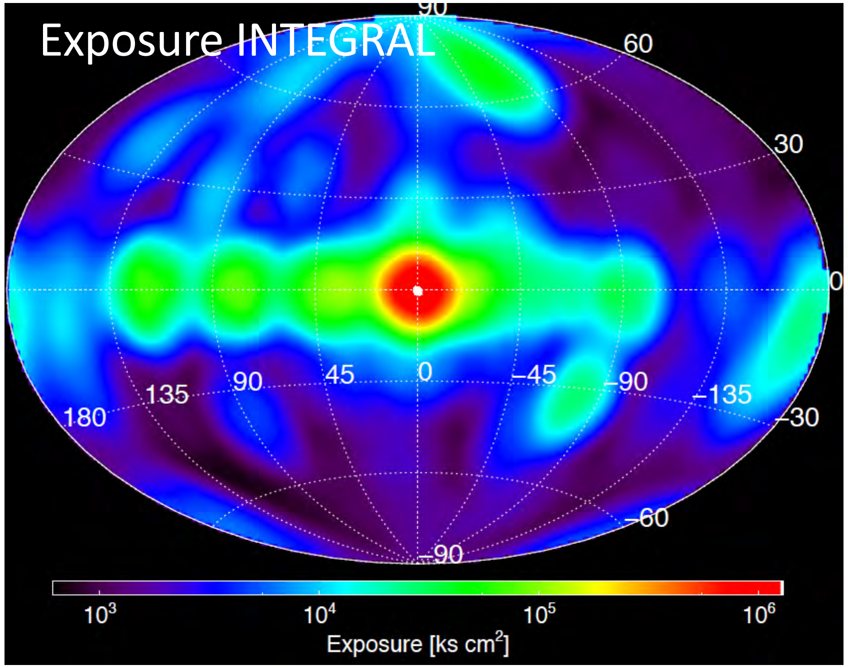


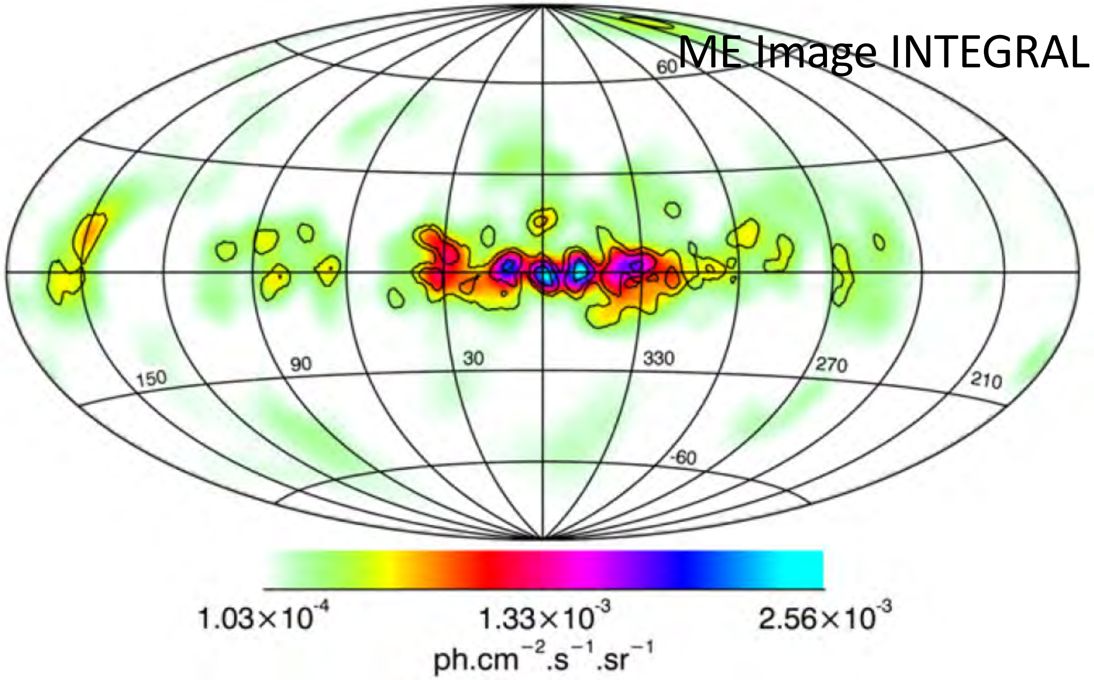
Radio map at 53 GHz, free electrons



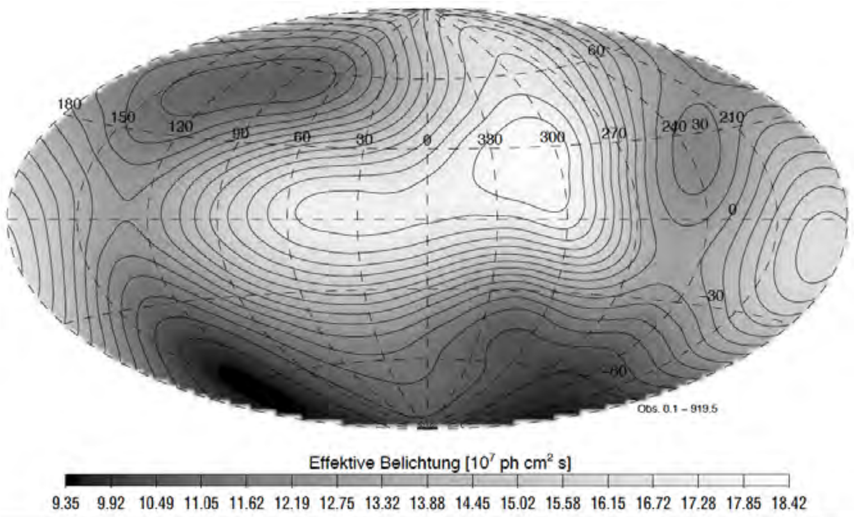
IR map at 3.5 μm, starlight

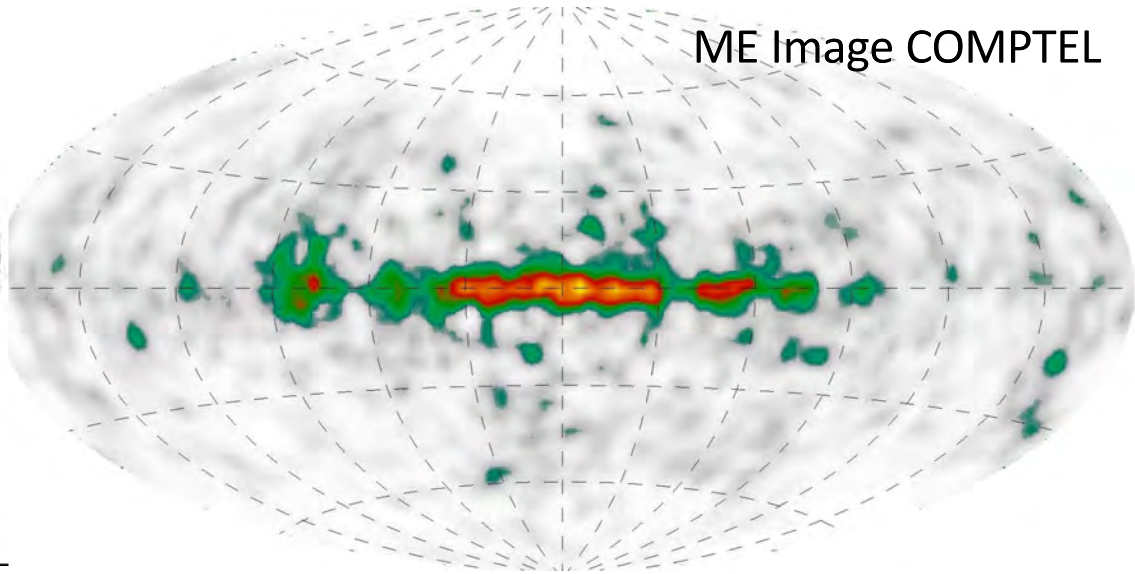
Imaging Galactic ^{26}Al with COMPTEL & SPI



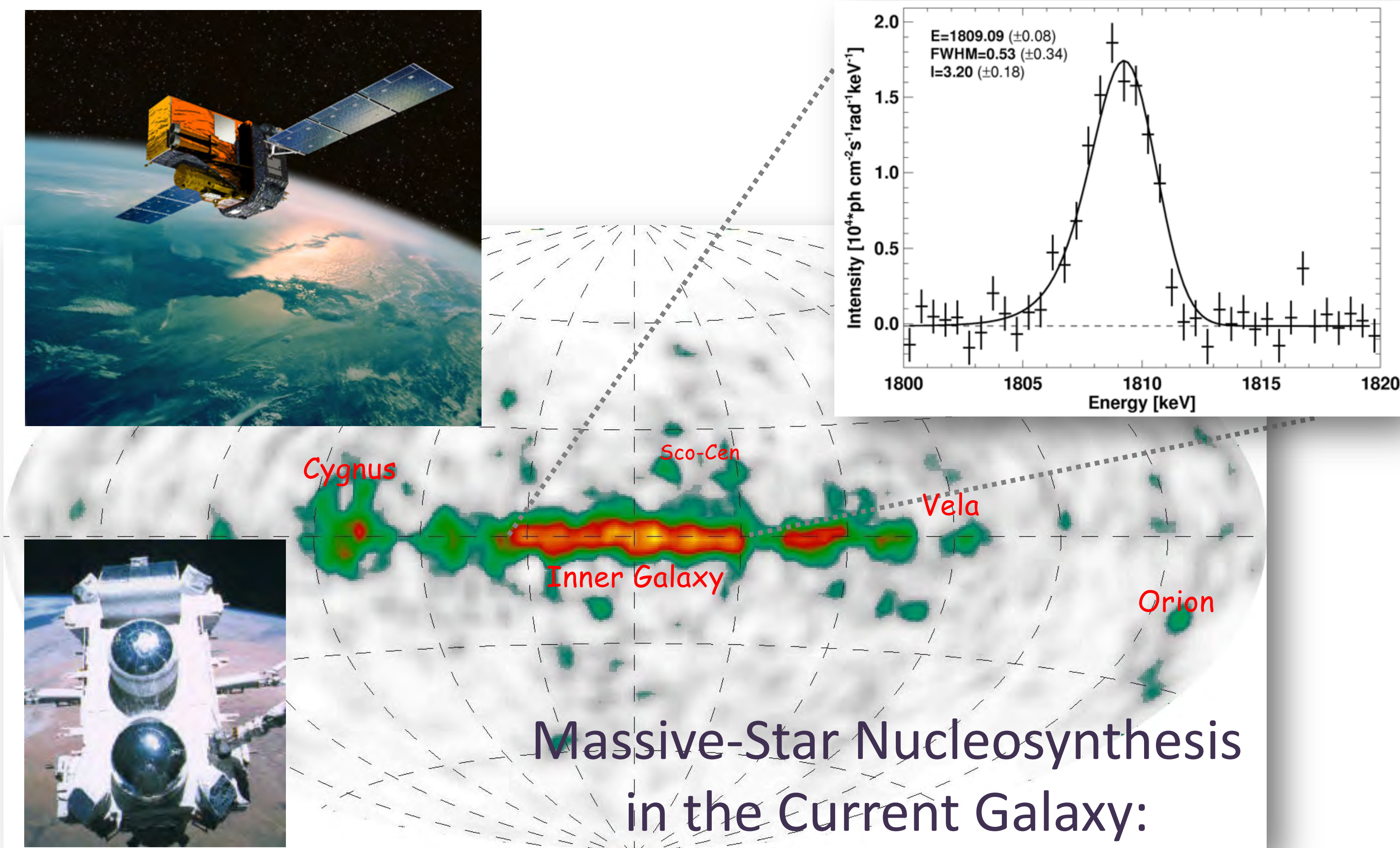


Exposure COMPTEL





^{26}Al in our Galaxy: γ-ray Image and Spectrum



Massive-Star Nucleosynthesis
in the Current Galaxy:
Current Enrichment (~My) from ^{26}Al γ-rays

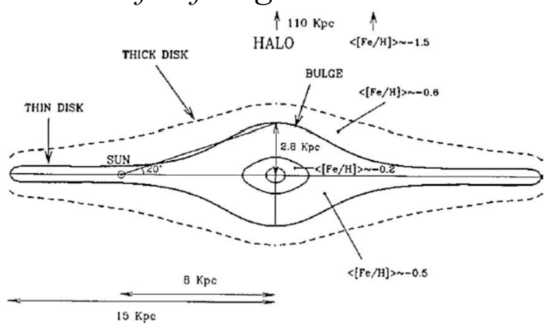
Using the ^{26}Al Line to Characterize the Galaxy's SN Activity

→ Diehl et al., Nature 2006
*→ Diehl et al., A&A 2010**
*→ Diehl et al., in prep. (2019)**

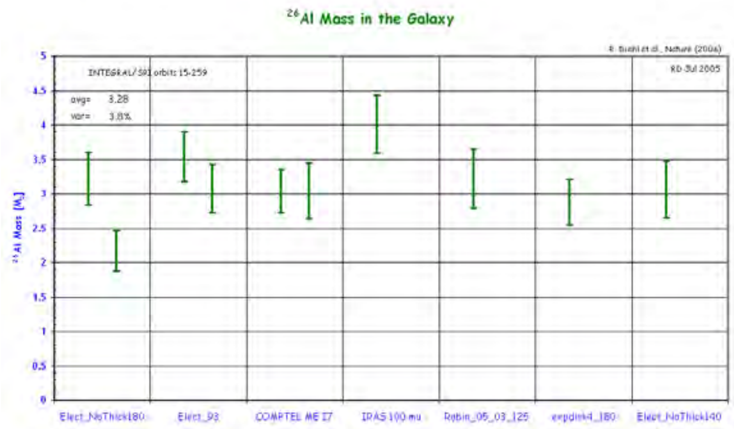
Measured Gamma-Ray Flux*

Galaxy Geometry

**) better account for foreground emission*

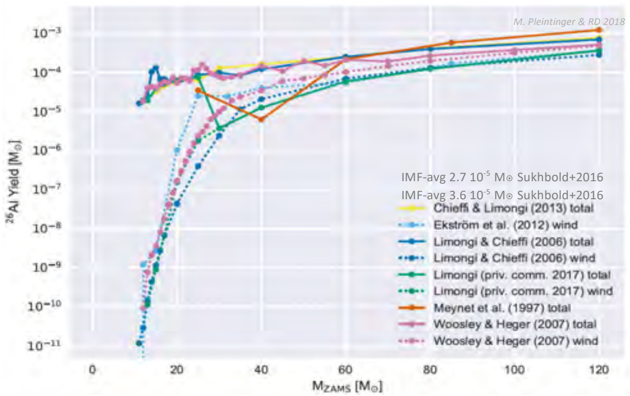


➢ ^{26}Al Mass in Galaxy = 2.0 (±0.3) $M_\odot$

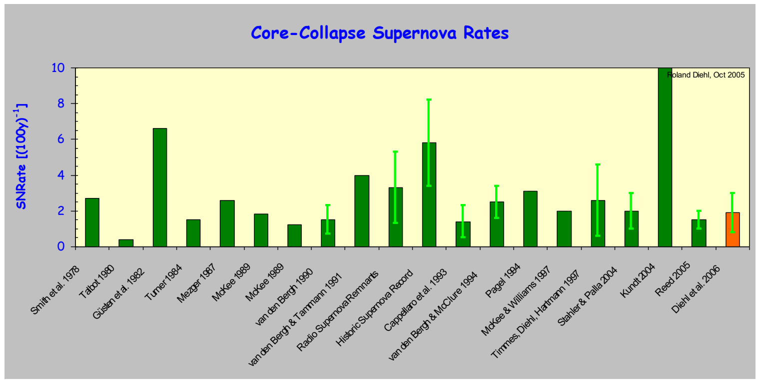


^{26}Al Yields per Star

Stellar Mass Distribution



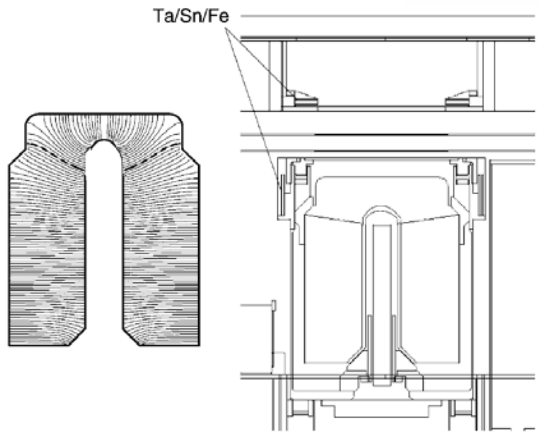
✓ cc-SN Rate = 1.3 (± 0.6) per Century

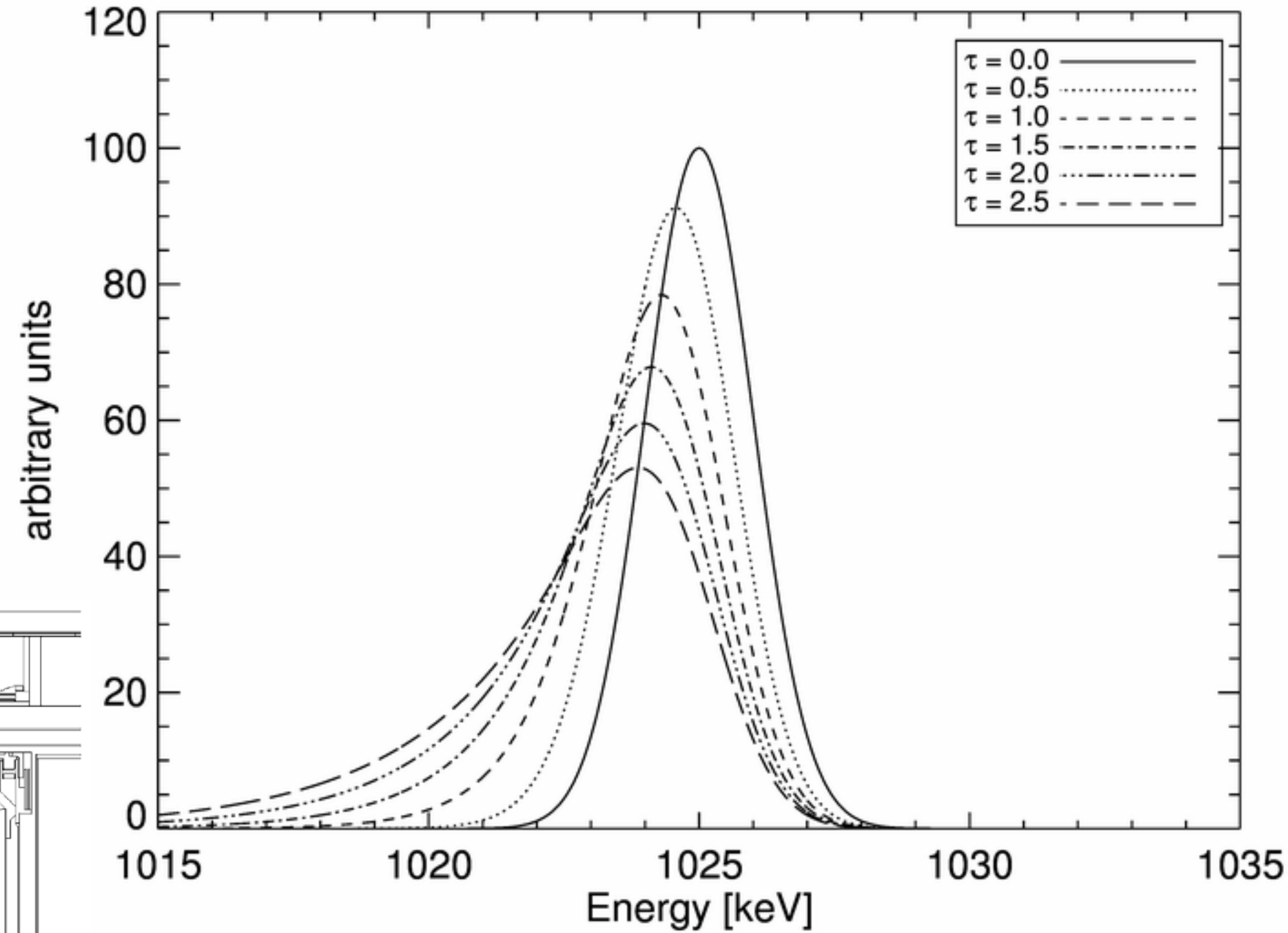


✓ Star Formation Rate = 2.8 $M_\odot$/yr

Detector degradation and annealings

- The instrumental lines are Gaussian in ideal cases
- Degraded charge collection leads to a one-sided bias





Detector degradation and annealings

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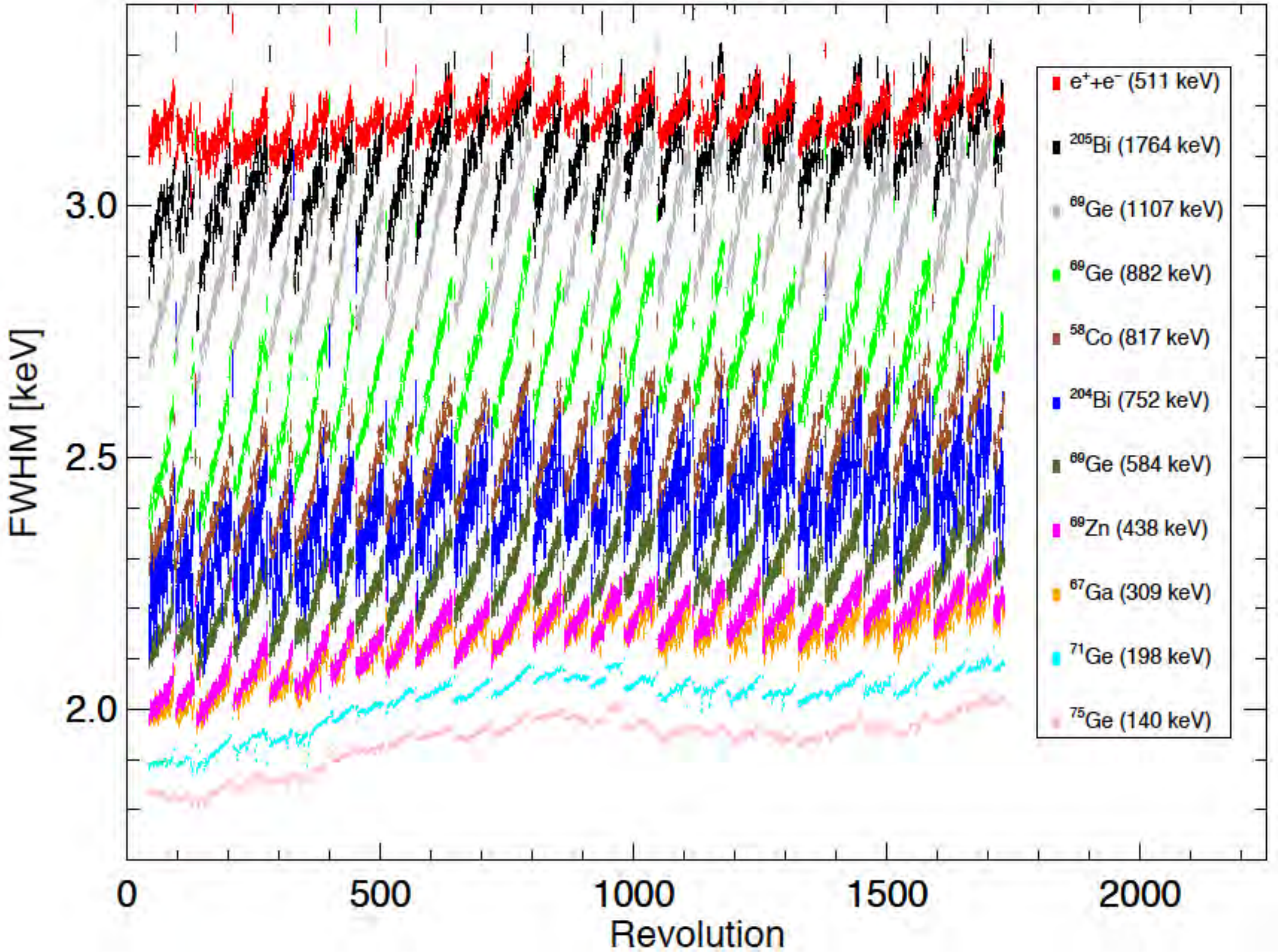
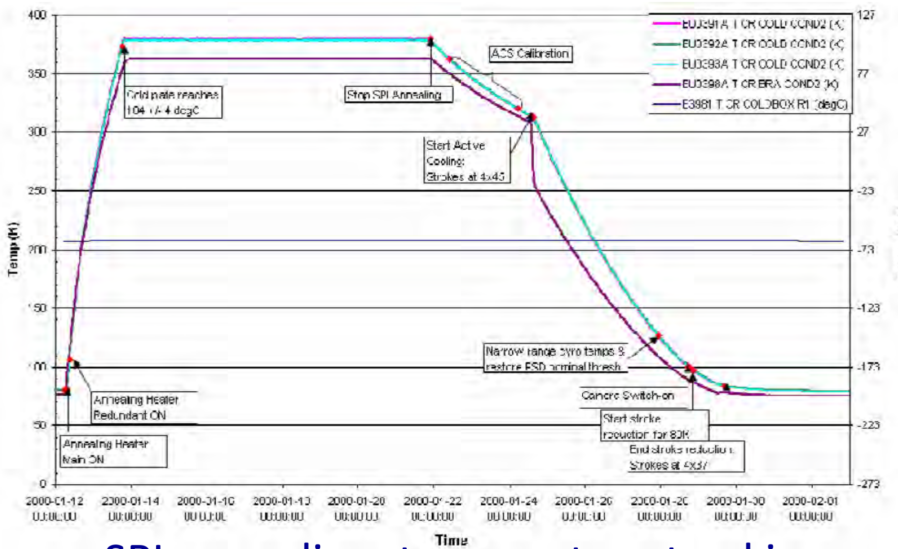
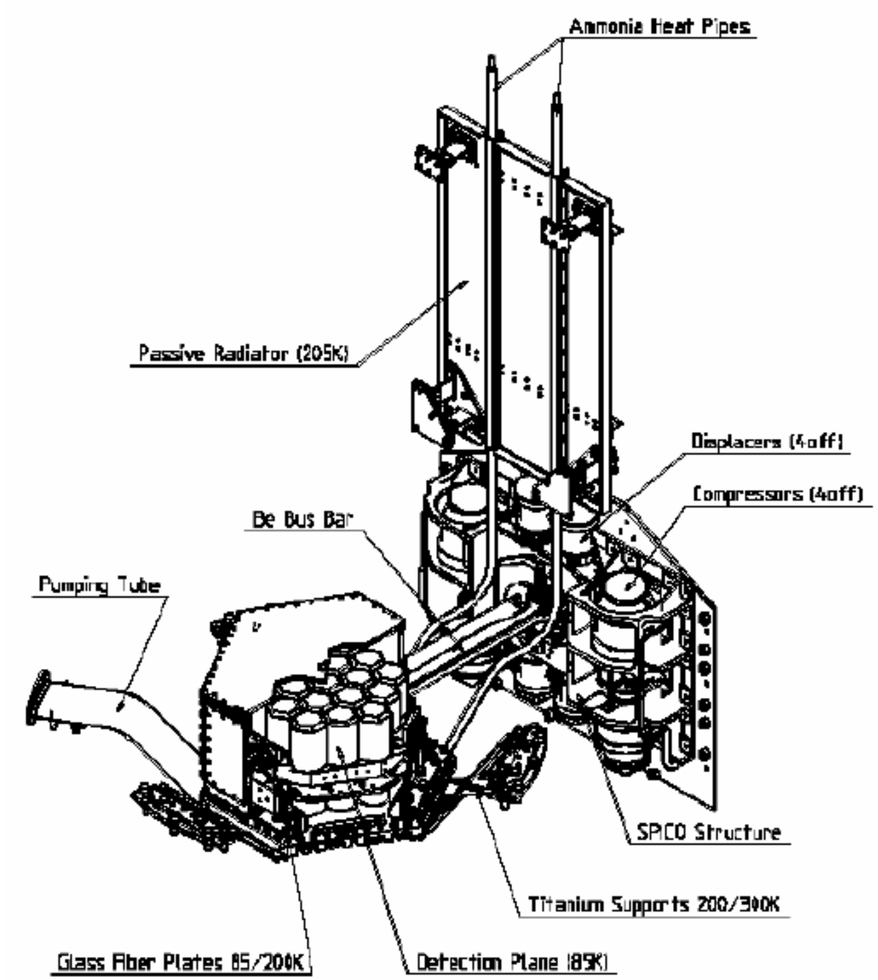


Ge detector annealing in space

- Stirling coolers are turned off, HV off
- Heaters are turned on
- ~100-200 hours at 100º C
- Heaters off, Coolers on
- → 80K operation temperature
- ~2 weeks total duration



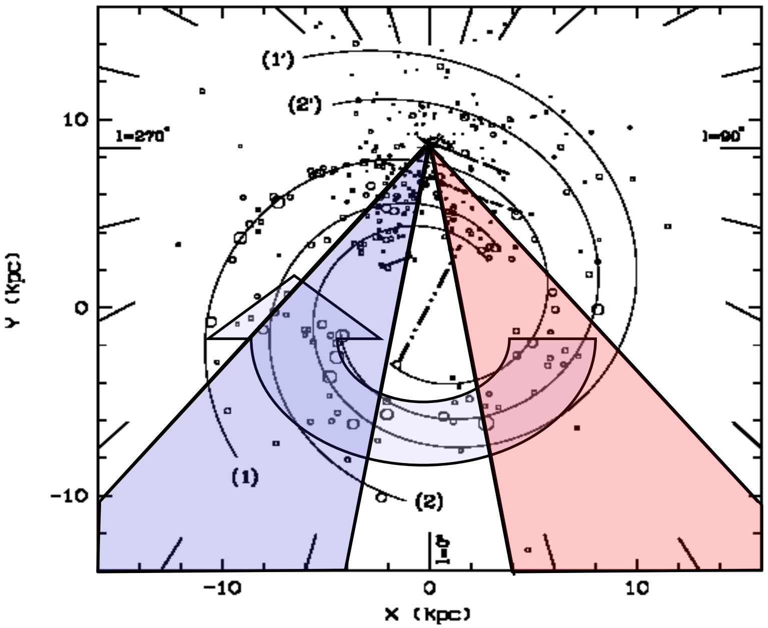
SPI annealing: temperature tracking

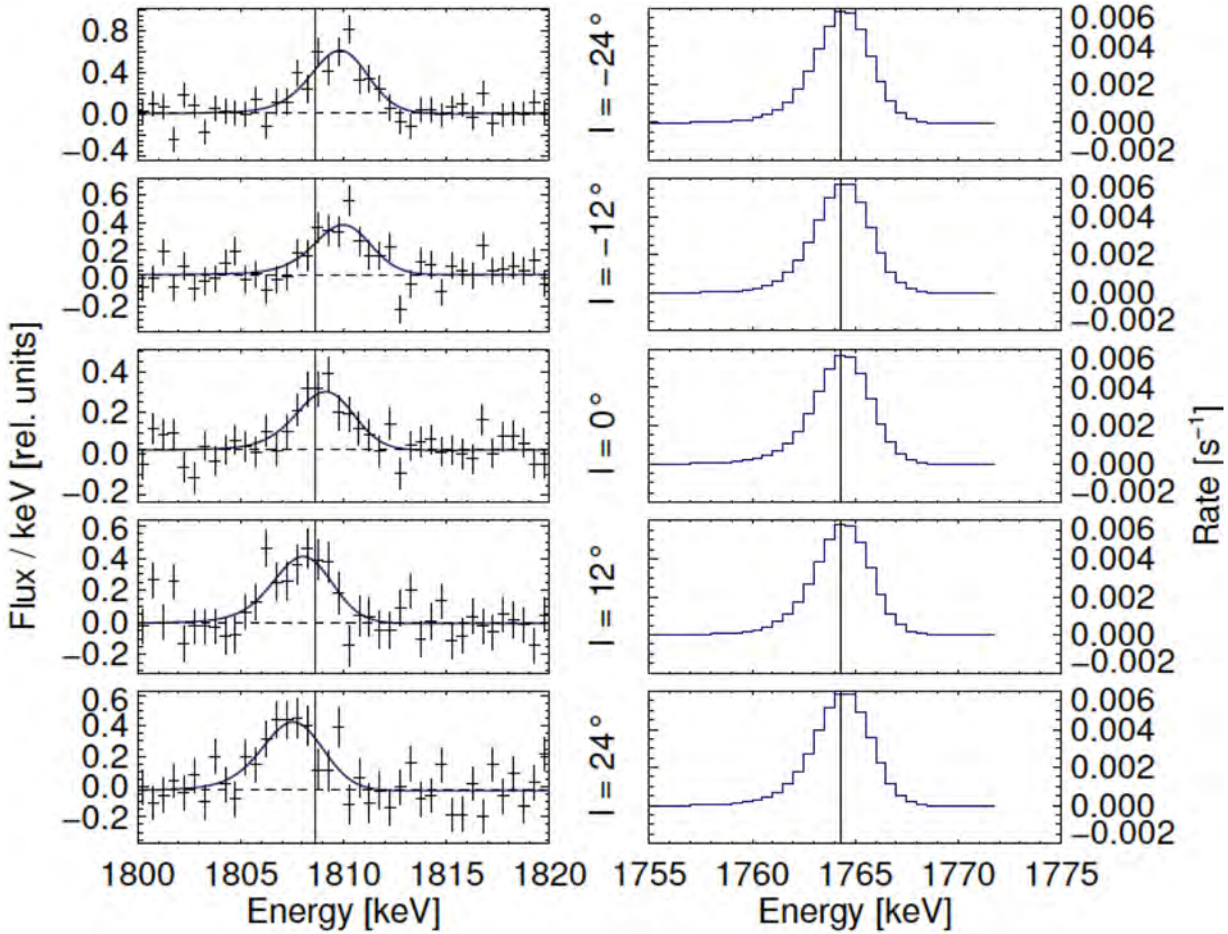


SPI Cooling System

Spatially-Resolved Spectroscopy

- Analyze Line Shape and Position for Different Directions
  - ☆ Galactic Rotation

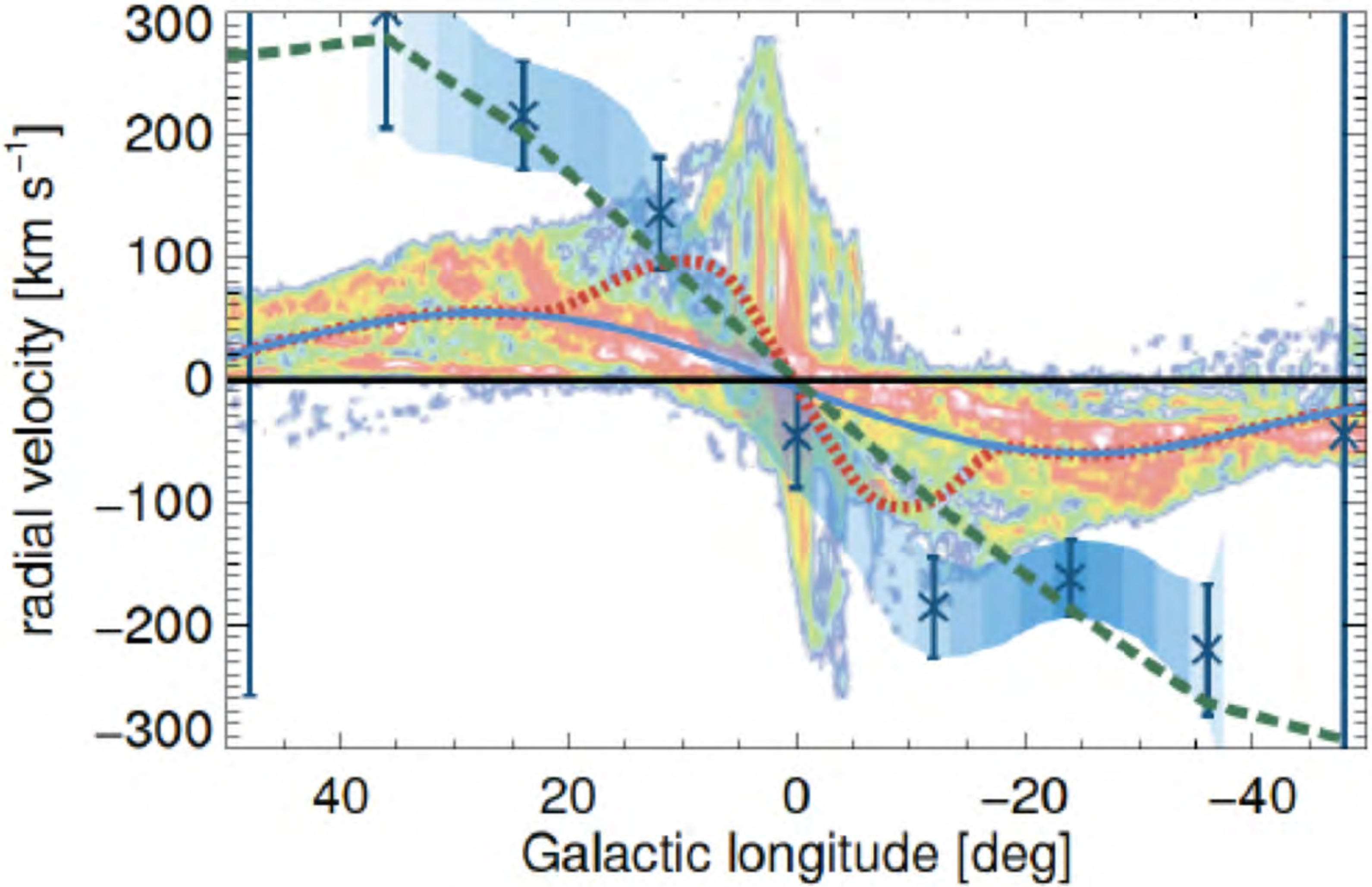




^{26}Al in the Inner Galaxy: Excess Gas Velocities Seen in ^{26}Al

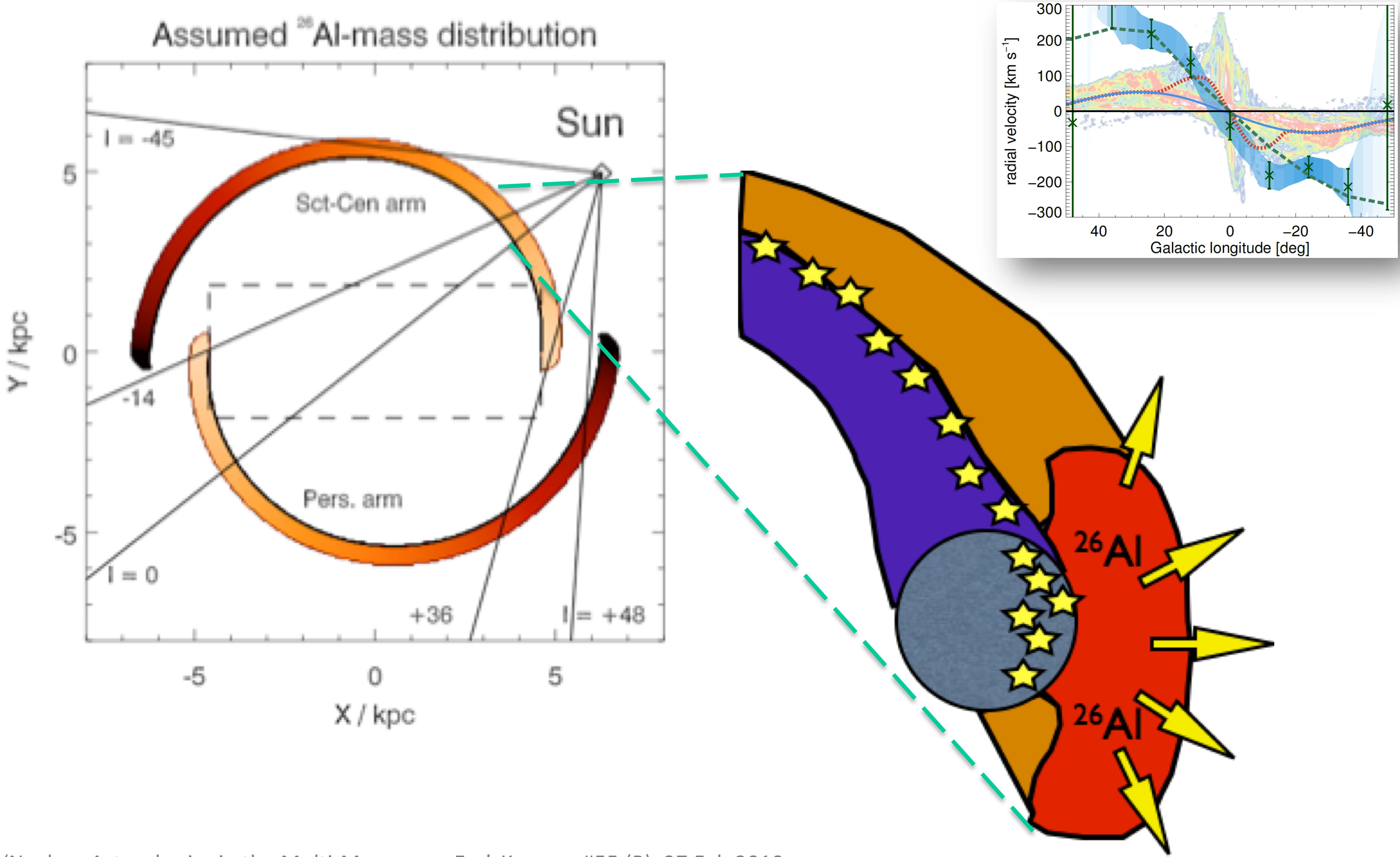
☞ Comparison of ^{26}Al velocities to others, e.g. CO

- solid blue: expected if ^{26}Al follows CO densities, and a standard rotation curve is adopted
- dotted red: same but fraction of ^{26}Al placed in a Galactic Bar
- green dashed: two-spiral arm distribution of ^{26}Al sources, with enhanced densities towards inner arm ends



How massive-star ejecta are spread out…

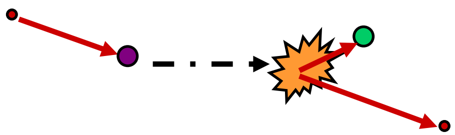
- Superbubbles in inter-arm regions are filled with new nuclei !!



Roland Diehl

Positron Production Processes

✓ Cosmic-Ray Nuclear Reactions



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

- ☆ Pion Production in HE Collisions

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

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

✓ Hot-Plasma Pair Production

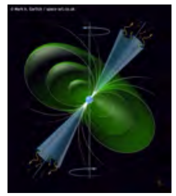
- ☆ 'kT>MeV'-Plasma
  - ☞ Accretion Columns & Disks
  - ☞ Jet Bases

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

✓ E.M.-Cascade Pair Production

- ☆ Strong Magnetic Fields
  - ☞ Pulsars
  - ☞ Jets

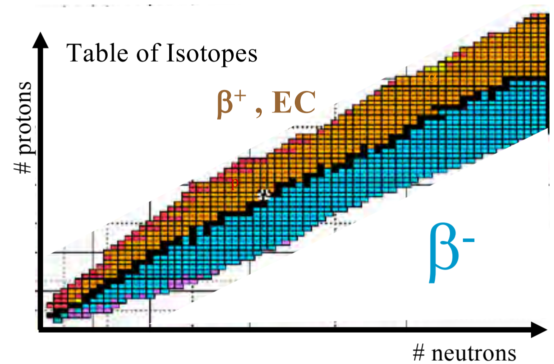
$$\gamma + B \rightarrow e^+ + e^-$$



✓ Nucleosynthesis

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

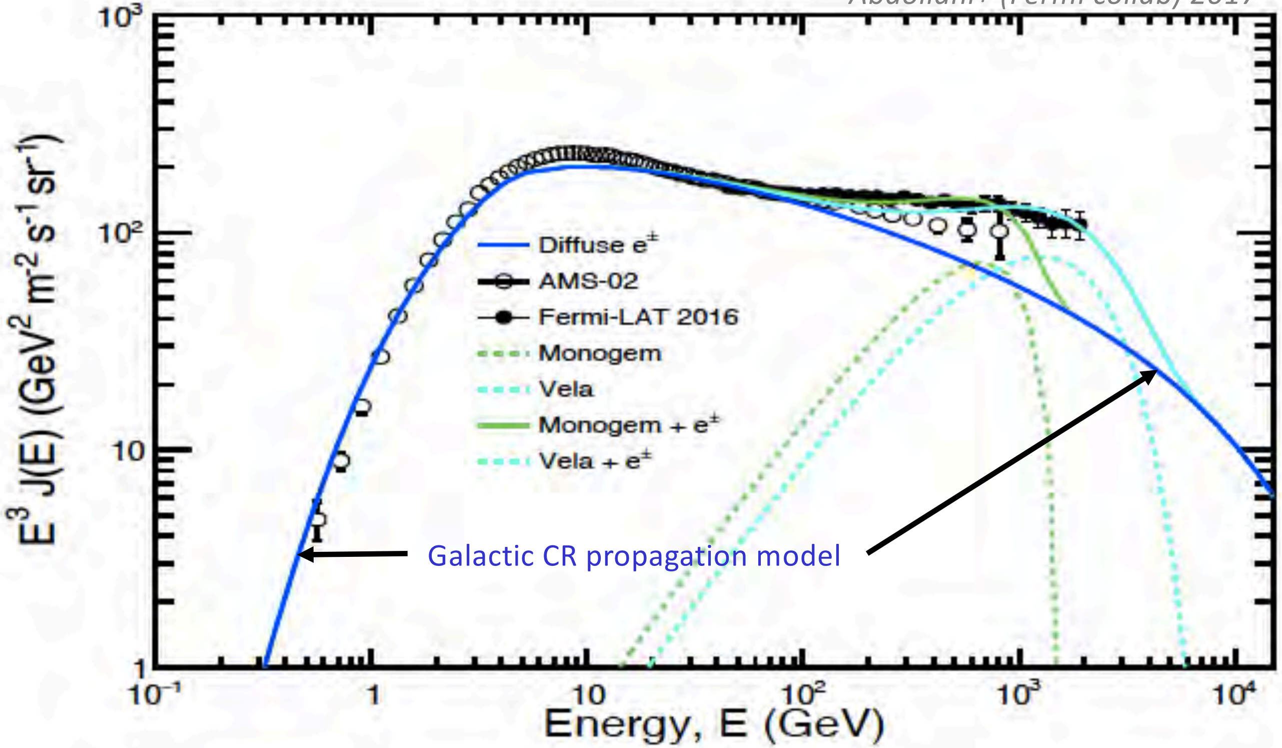
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \nu_e$$



Direct positron measurements

- Cosmic-ray measurements within solar system
  - ☆ AMS on space sation
  - ☆ PAMELA balloon flight
  - ☆ Fermi particle tracking chamber
  - → Excess of positrons at high energies >100 GeV

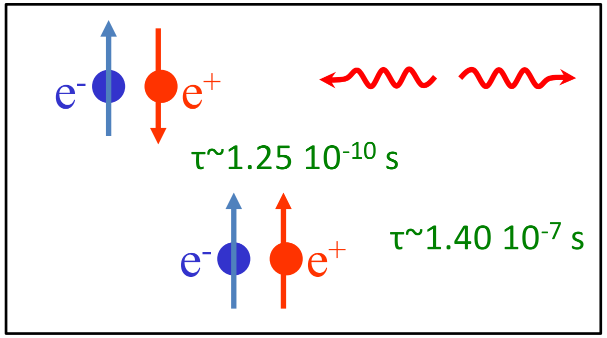
Abdollahi+ (Fermi collab) 2017



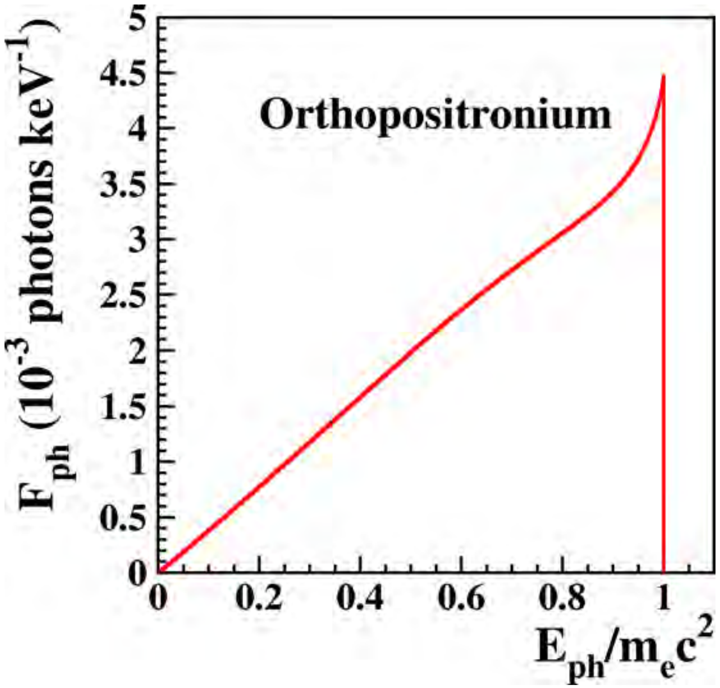
- Positrons advected from nearby pulsars (pair cascades)?

Positronium – the intermediate step of e⁺ annihilation

- "Atom" with e^- and e^+
- Relative Spin Orientations →
  - ☆ Singlet State $^1S_0$/ Para-Positronium
  - ☆ Triplet State $^3S_1$/ Ortho-Positronium

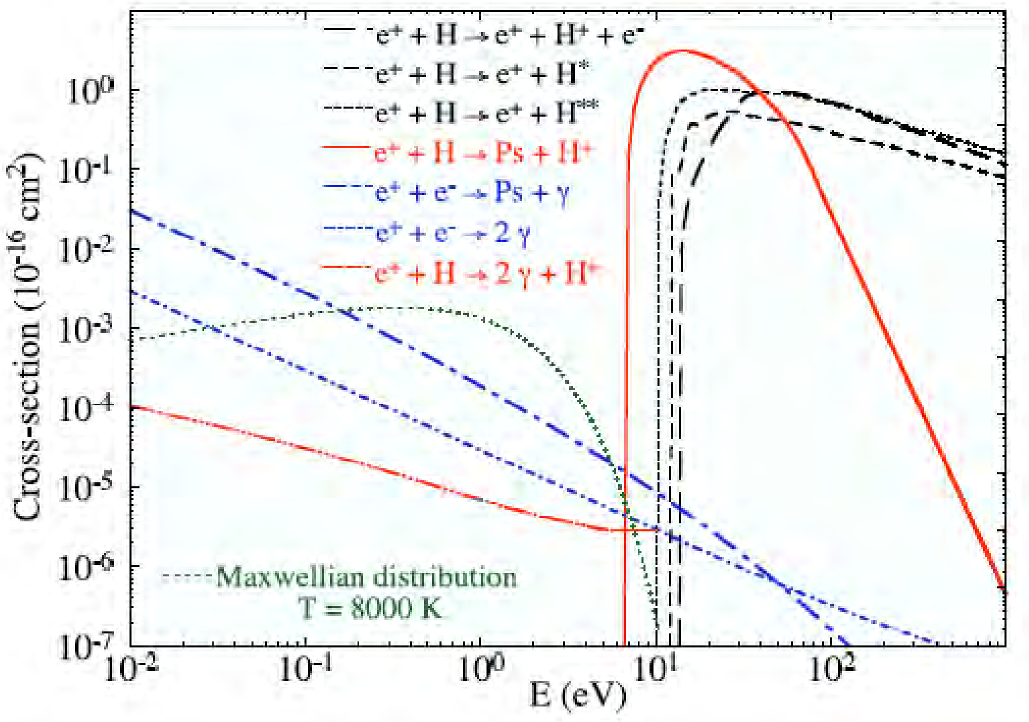


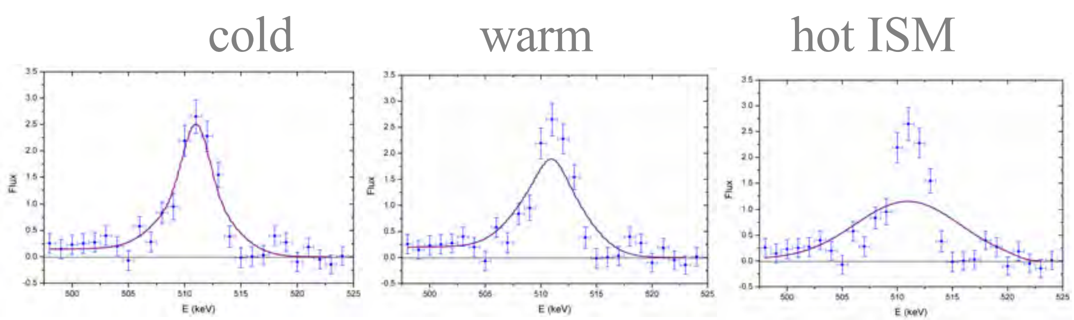
- Annihilation Spectrum
  - ☆ 2-Photon Annihilation Only for Para-Ps:
  - ☆ 3-Photon Annihilation from Ortho-Ps



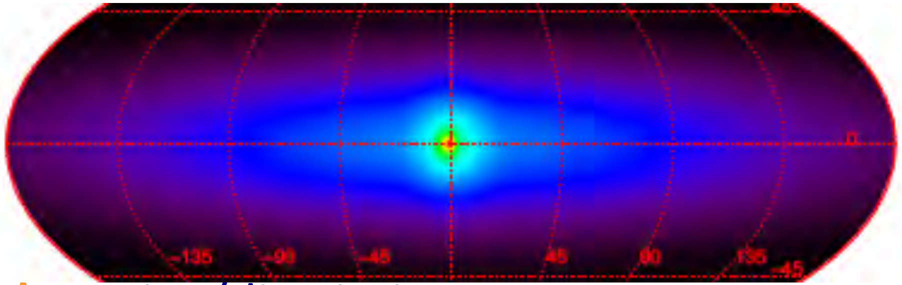
γ-Ray Spectrum Diagnostics

- ☆ Annihilation occurs around ~10-100 eV
  - ☞ Original energies >> MeV, relativistic
- ☆ 3-photon Continuum / Line Ratio Reflects Ps versus Radiative-Capture Annihilation Branches
  - ☞ 'Ps Fraction' $$f_{Ps} = \frac{8 \times \frac{I_{3\gamma}}{I_{2\gamma}}}{9 + 6 \times \frac{I_{3\gamma}}{I_{2\gamma}}}$$
  - ☞ INTEGRAL/SPI: → $f_{Ps} \sim 100$ %
  - ☞ Neutral-Media f_{Ps}~80-95% (from laboratory data)
- ☆ 511 keV Line Width Reflects Kinematics of e+

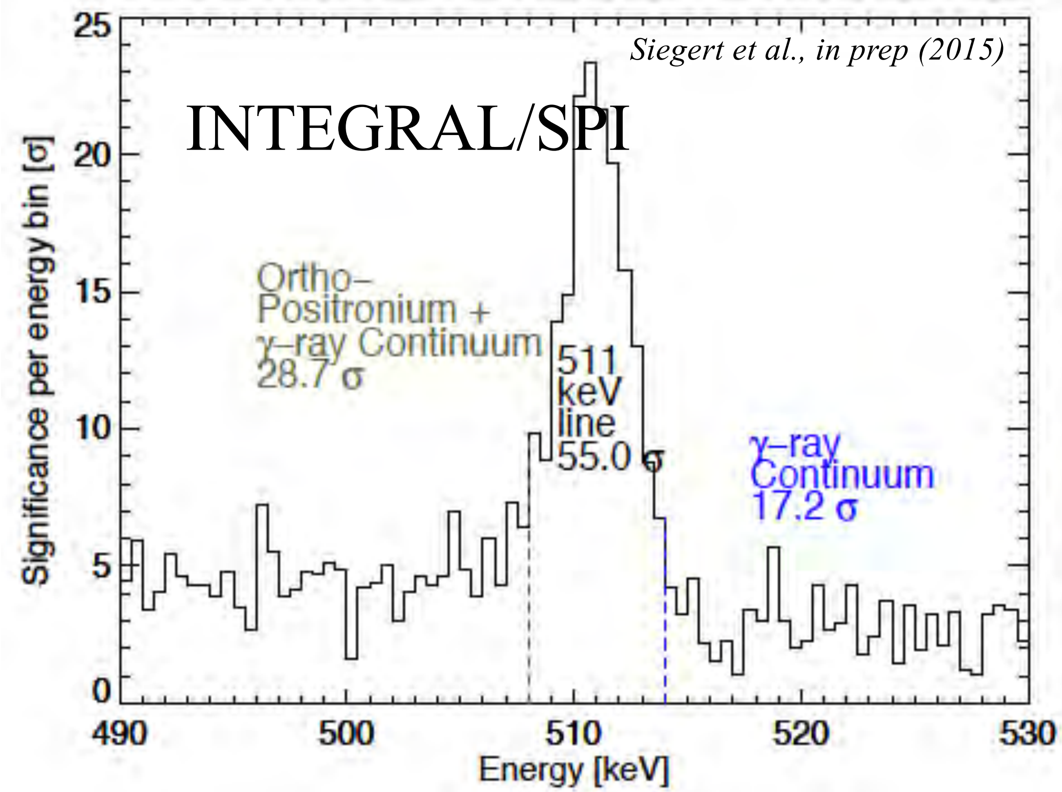


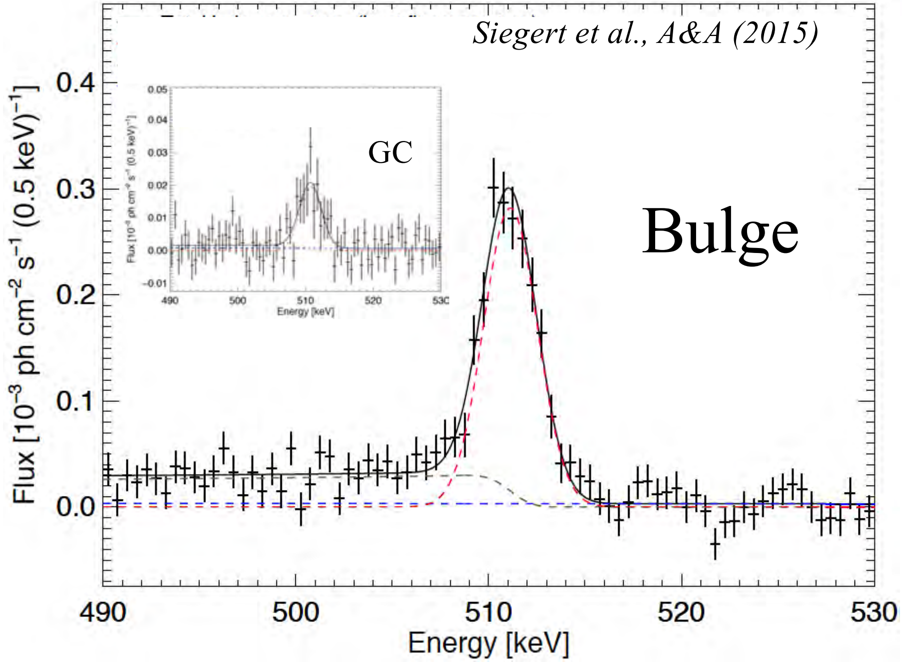


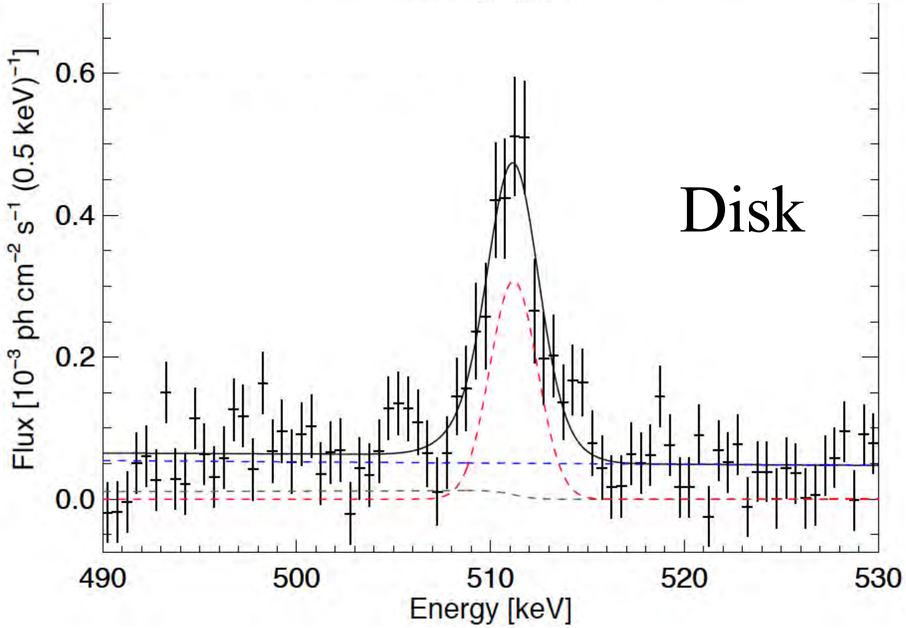
Insights from spectral details?



☆ Derive/discriminate spectra from different regions

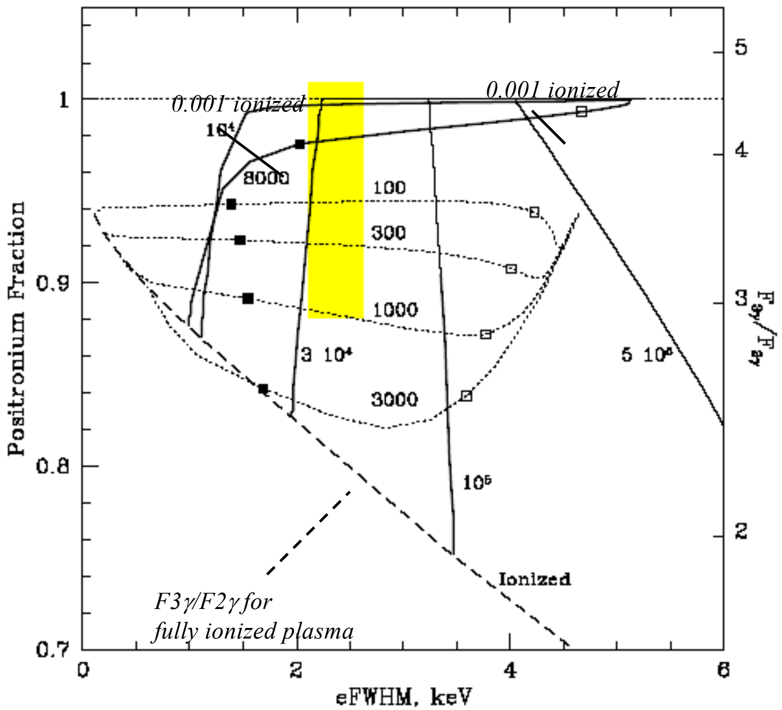


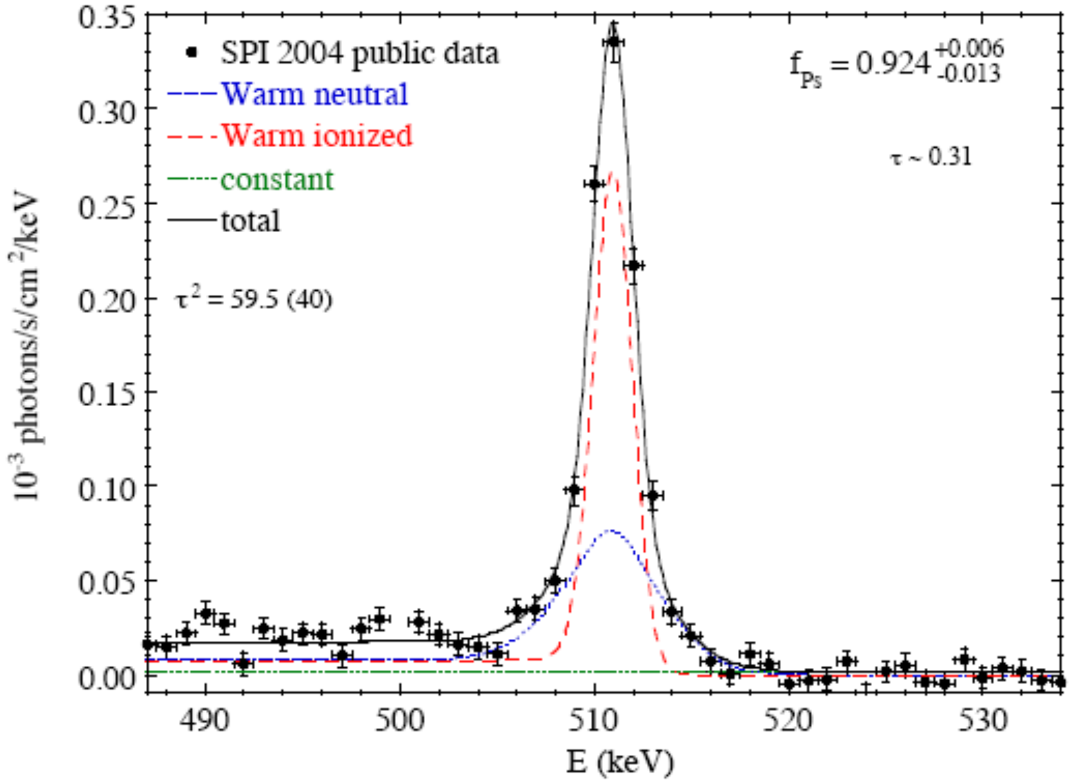




Annihilation Conditions: Which ISM Phase?

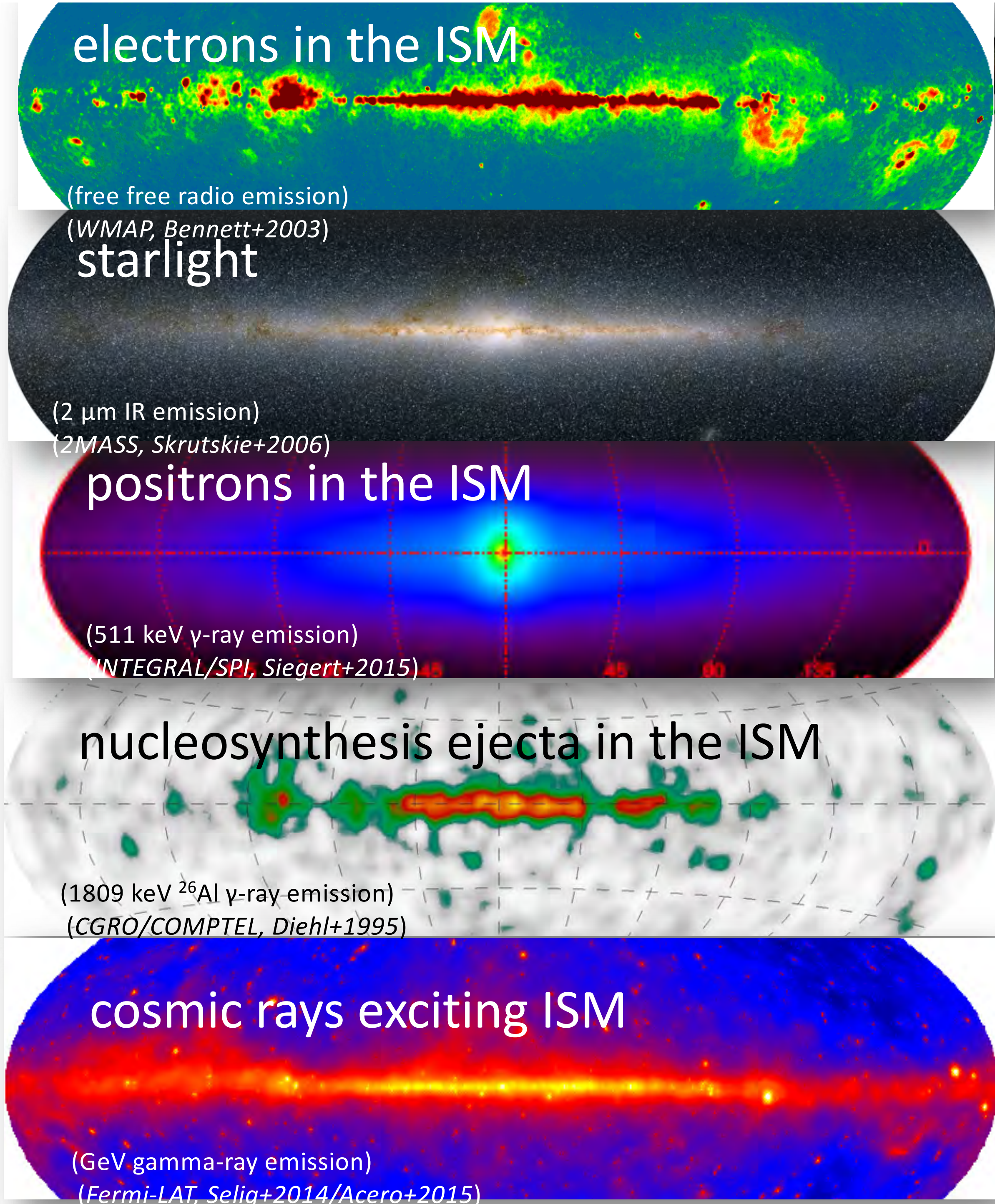
- ☆ Warm Ionized ISM is Dominating Annihilation Environment
- ☆ No ISM Grain "Narrowing" Needed
  - ☞ *Jean et al. 2005, 2006*
    - – Fitting Different Phases with their Characteristic Spectral Shapes
  - ☞ *Churazov et al. 2004*
    - – Determining the best-matching Temperature and Ionization Fraction





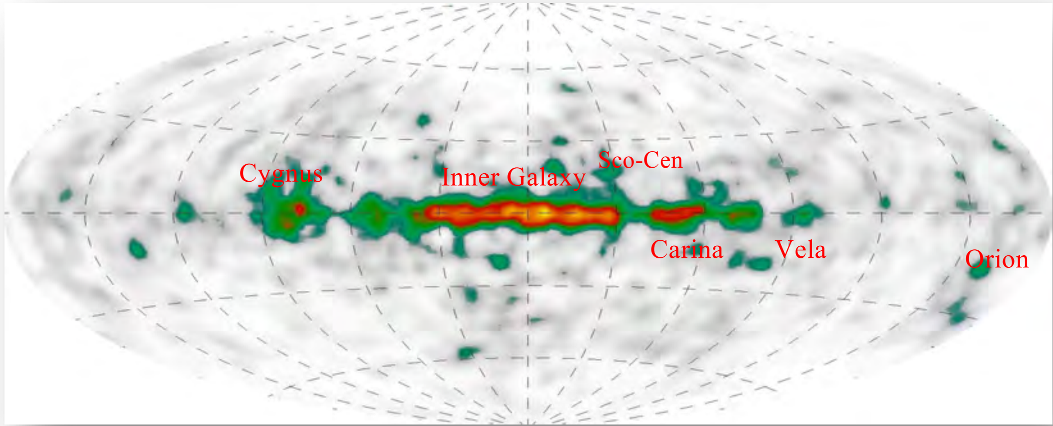
^{26}Al Radioactivity: Special Messengers

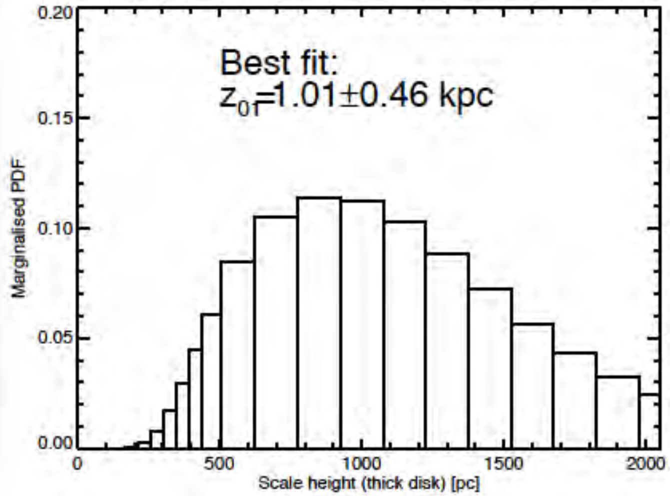
- Radioactivity provides a clock
- ^{26}Al radioactivity gamma rays trace nucleosynthesis ejecta over ~few Myrs
- Radioactive emission is independent of density, ionisation states, …



Imaging the Galaxy in γ-Ray Lines: Scale Height?

- ^{26}Al, e^{+}: The hot & diffuse ISM (?)





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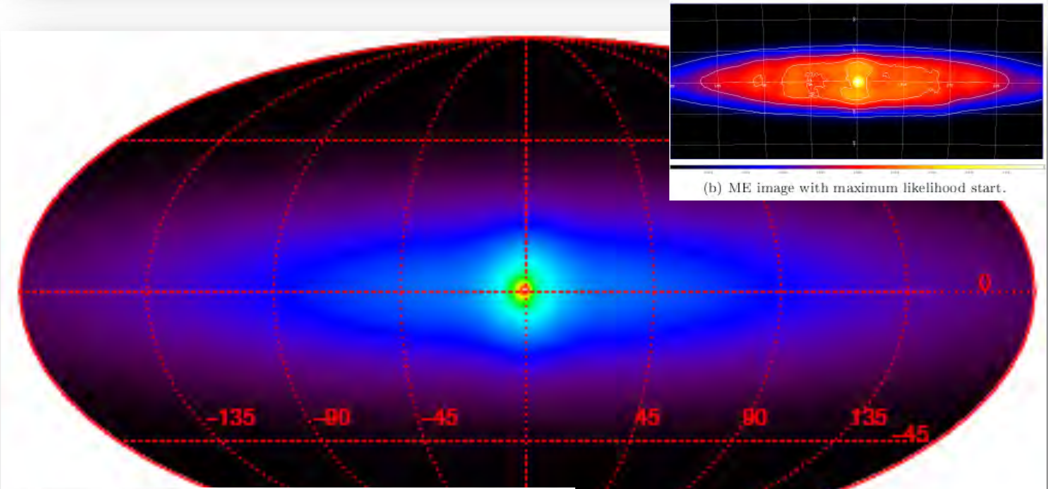
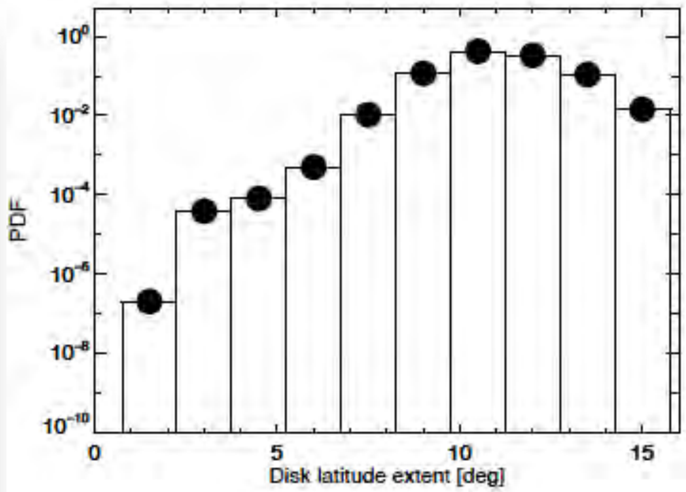


Component	l_0 [deg]	b_0 [deg]	σ_l^{Γ} [deg]	σ_b^{Γ} [deg]
NB	−1.25	−0.25	5.75	5.75
BB	0.00	0.00	20.55	20.55
Disk	0.00	0.00	141.29	24.73



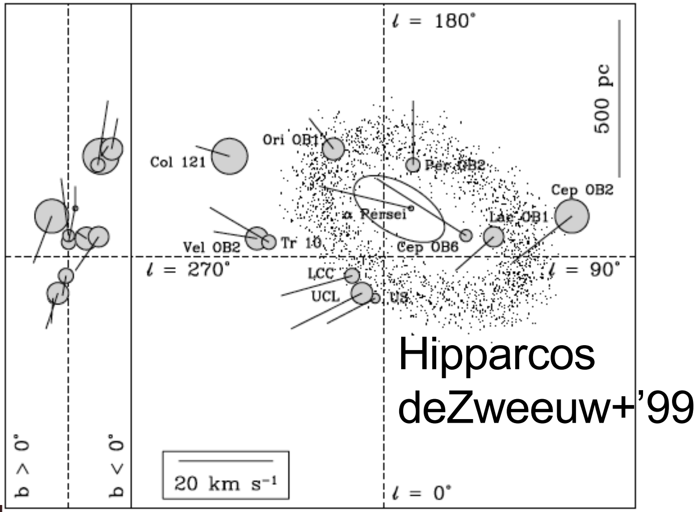
Resolving ^{26}Al Emission from Specific Groups of Stars

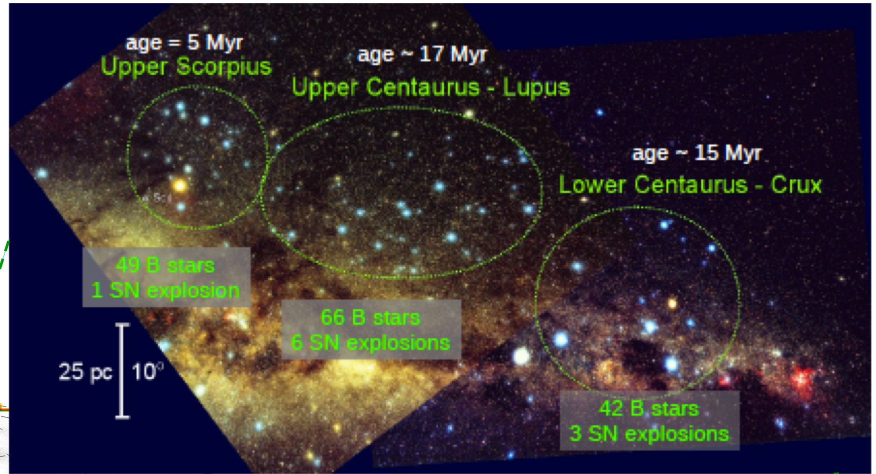
Groups of Stars:

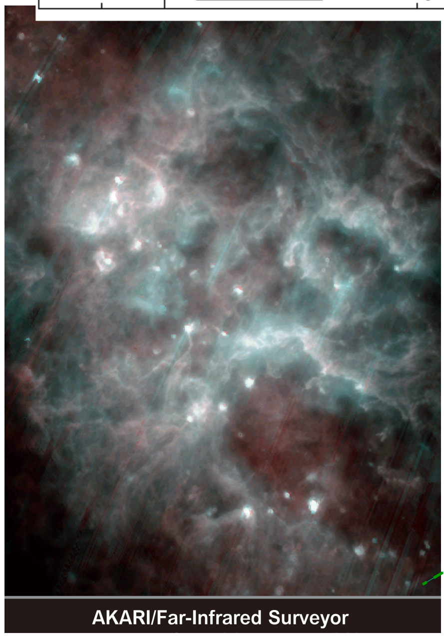
Test our Models for Consistency

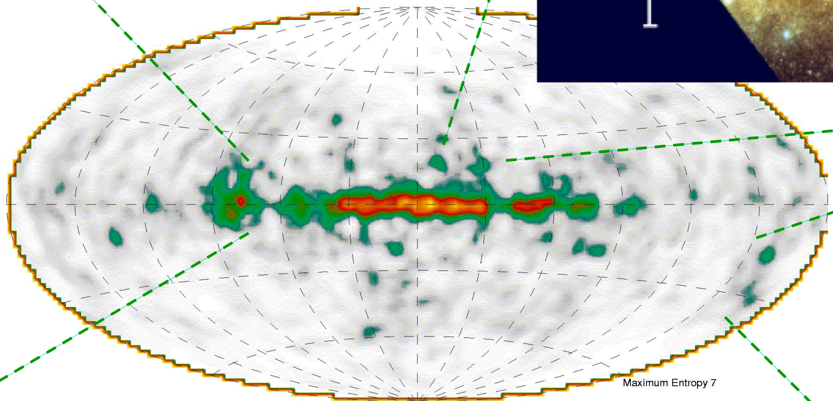
Separate WR-Wind from SN yields

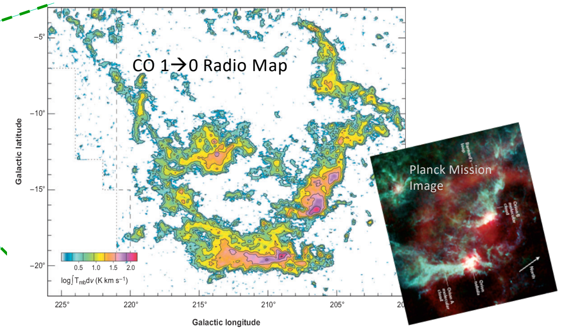
Measure ejecta kinematics









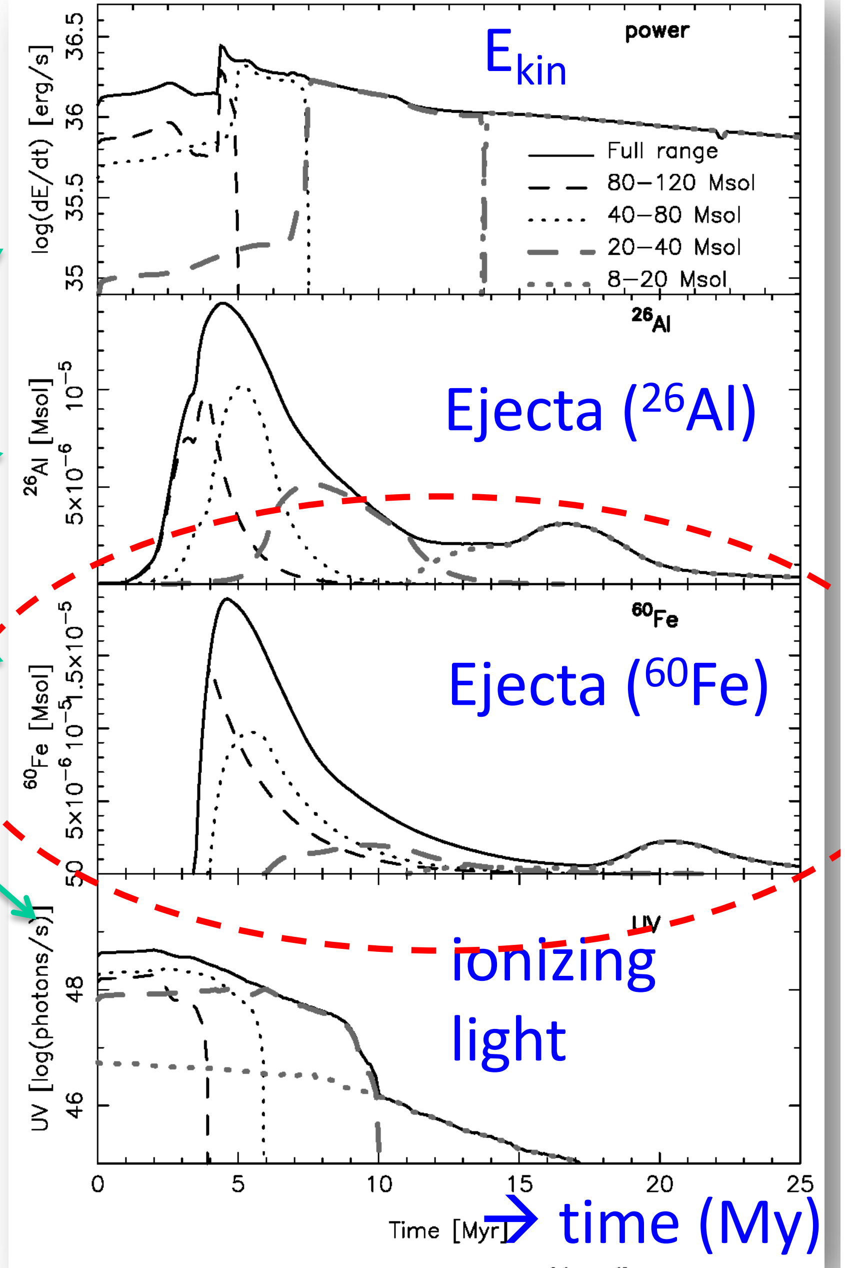


Massive-Star Groups

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

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

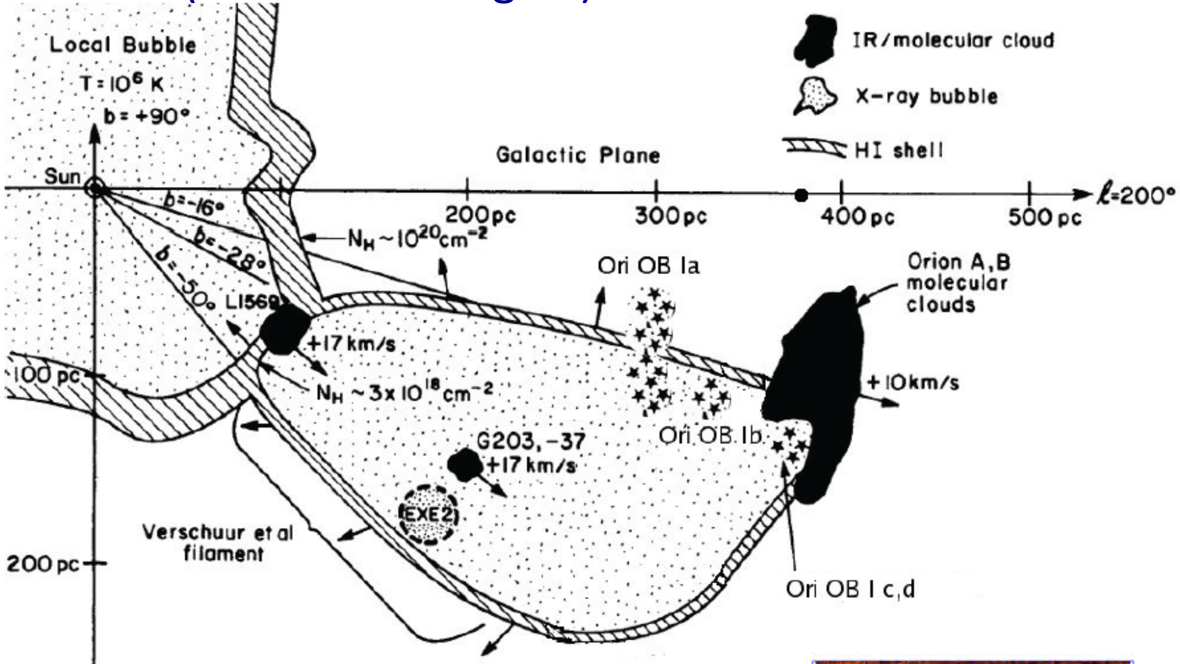
Voss R., et al., 2009

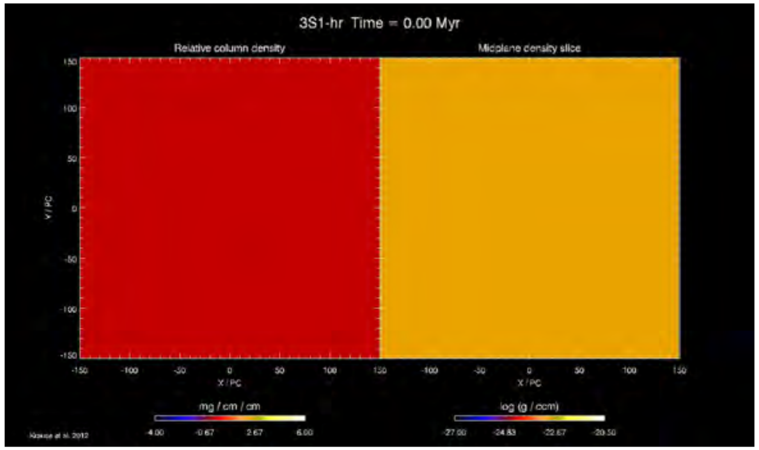


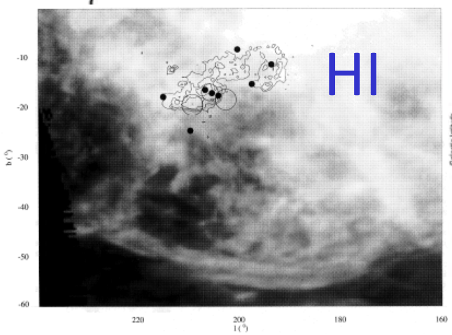
Roland Diehl

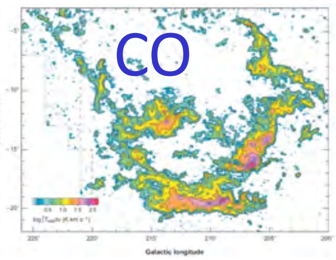
Example in Nuclear Astrophysics:
Nucleosynthesis Ejecta and the Dynamic Interstellar Medium

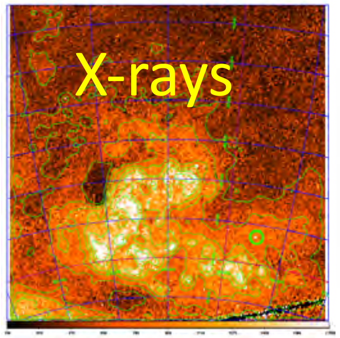
- ISM is Driven by Stars and Supernovae → Ejecta in (Super-)Bubbles
  - ☆ Study Multi-Messenger Observations, also through Simulations (here: Orion Region)

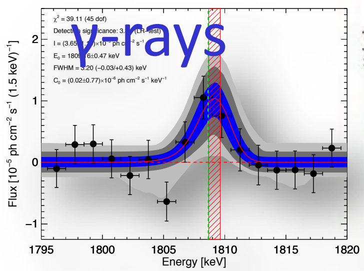


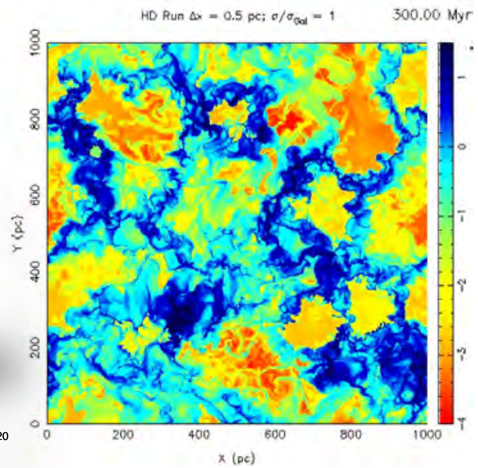












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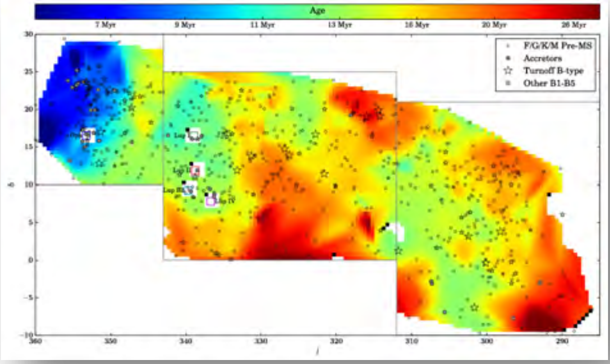
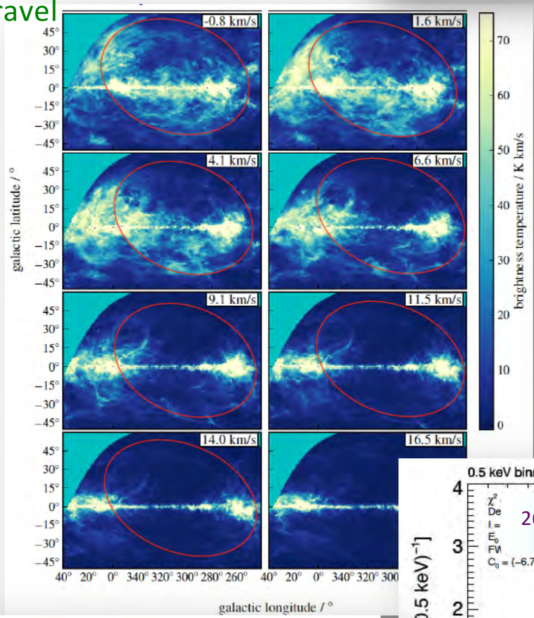
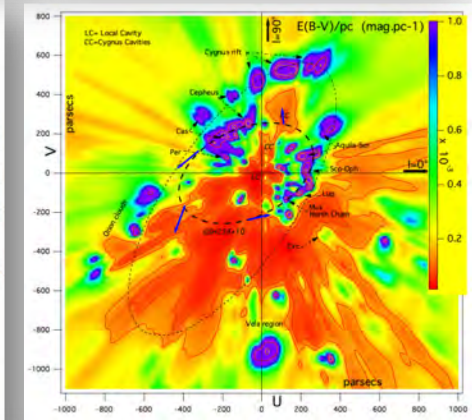
Stellar feedback in the Sco-Cen region (d~140 pc)

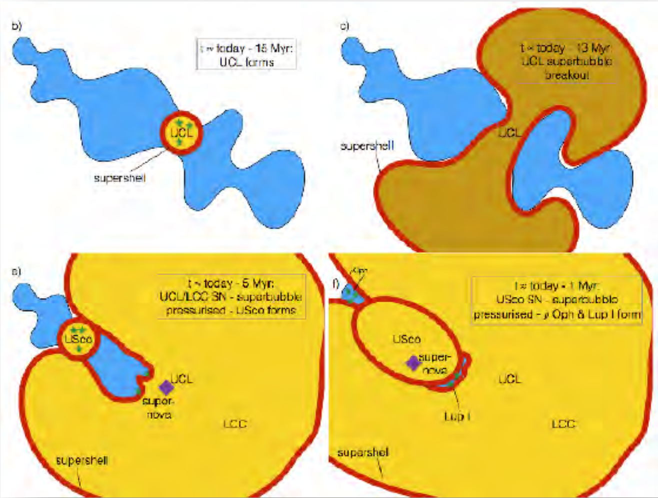
- The stellar population covers a wide age range
  - » no clear coeval subgroups, rather SF ongoing for ~15+ My
- The interstellar medium holds a network of cavities
  - » the ISM dynamics is not easy to unravel
- Newly-produced atomic nuclei add a diagnostic
  - » ^{26}Al (t~1My) seems widely spread; can we measure the flow?

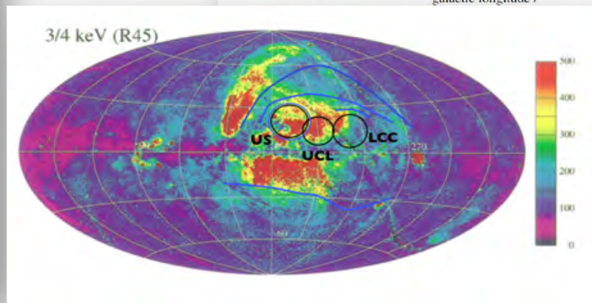
→ *"surround & squish"* *by M. Krause et al.*

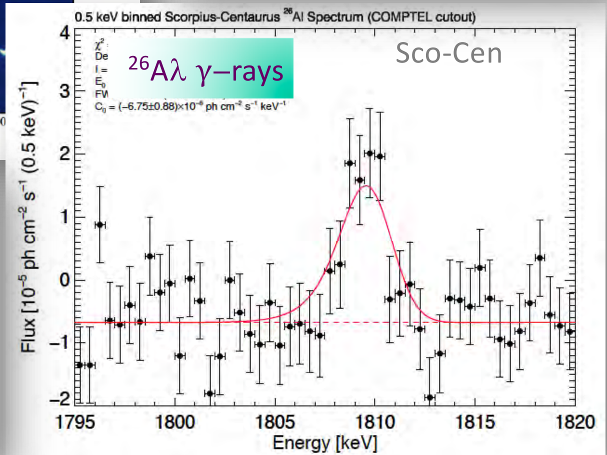








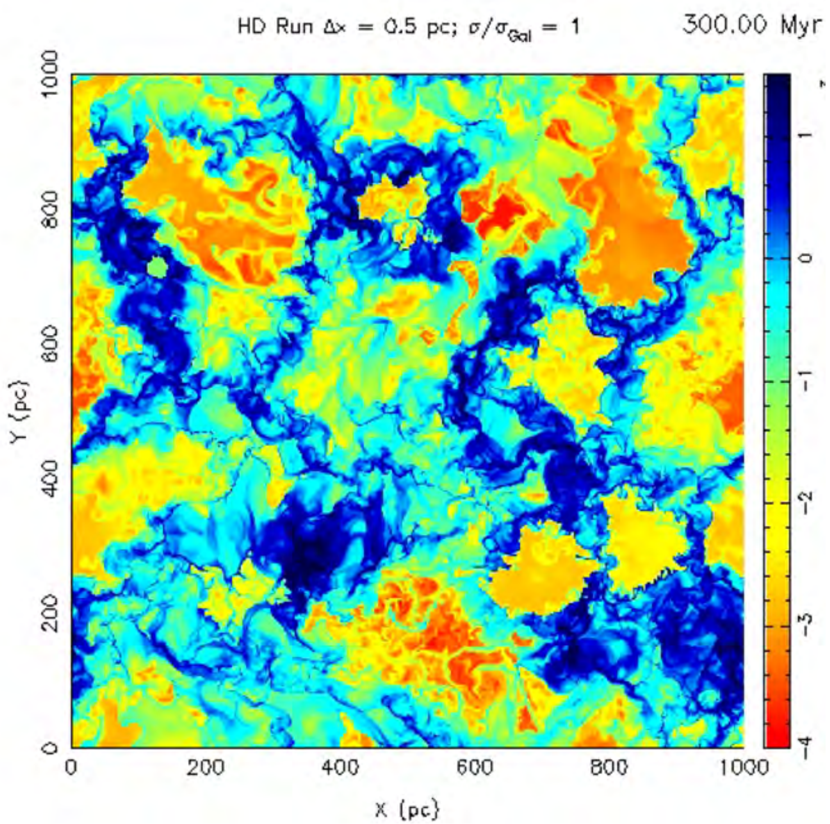




What if...

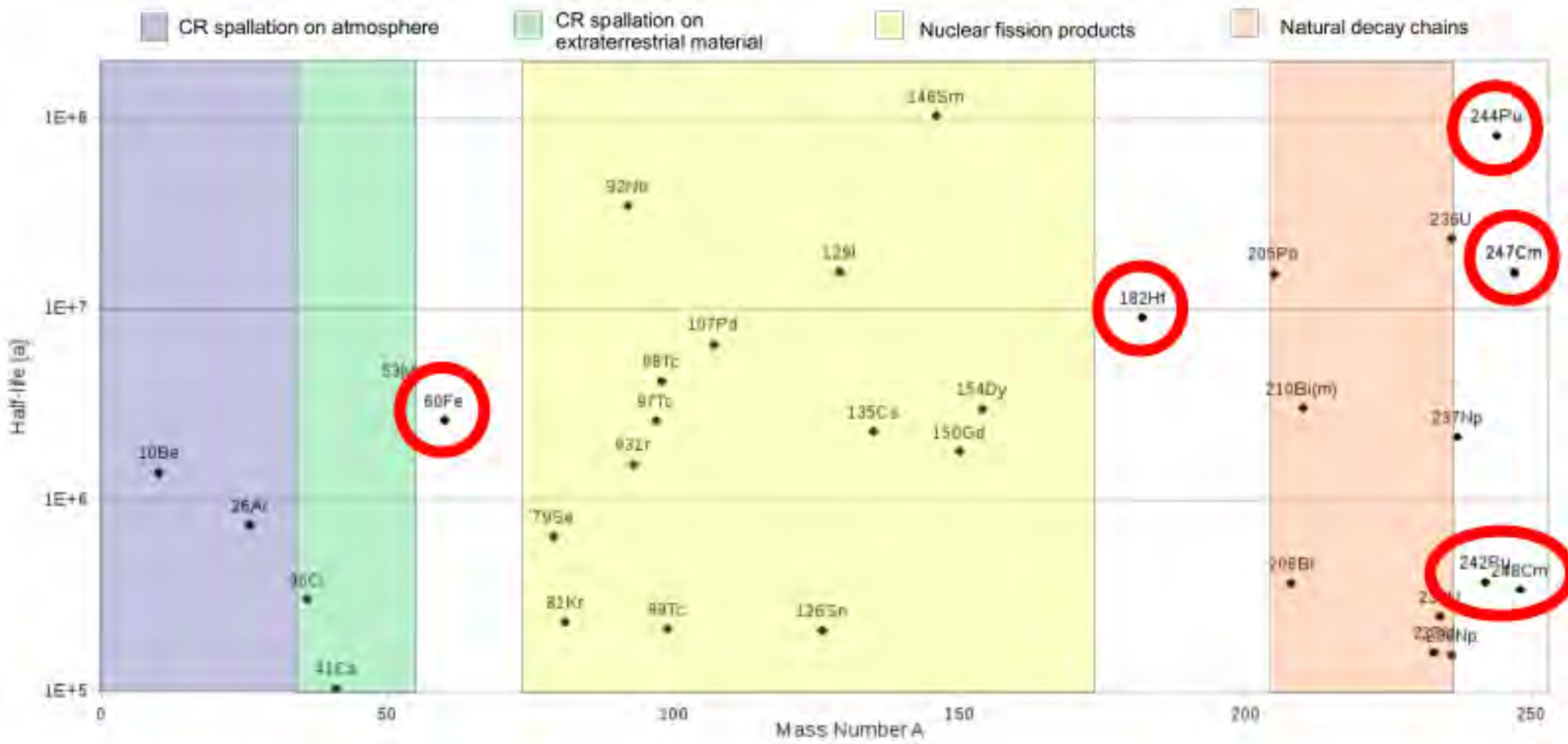
... we place ourselves within such a wind- and supernova-driven and thus highly dynamic interstellar medium

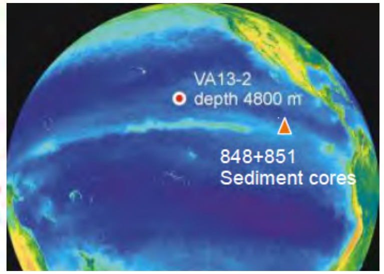
- ☆ Onto a newly-forming star
  (→ capturing nucleosynthesis for stellar astronomy)
- ☆ Within our solar system
  (→ which nucleosynthesis can we feel here?)



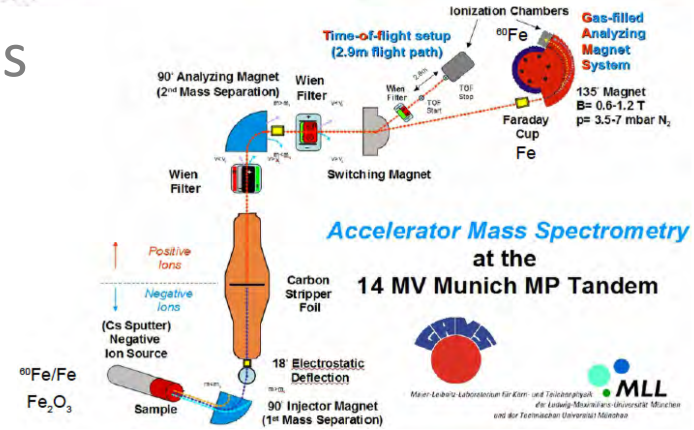
SN ejecta on Earth and Moon

Candidate isotopes for supernova searches on Earth





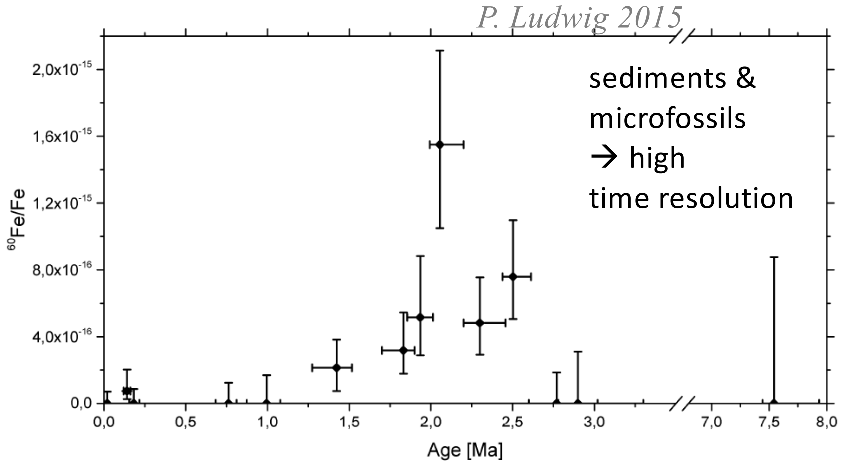
- Search for ^{60}Fe and ^{53}Mn atoms in sediments and on moon
  - ☞ Recent (2...10 My) influx of supernova material!

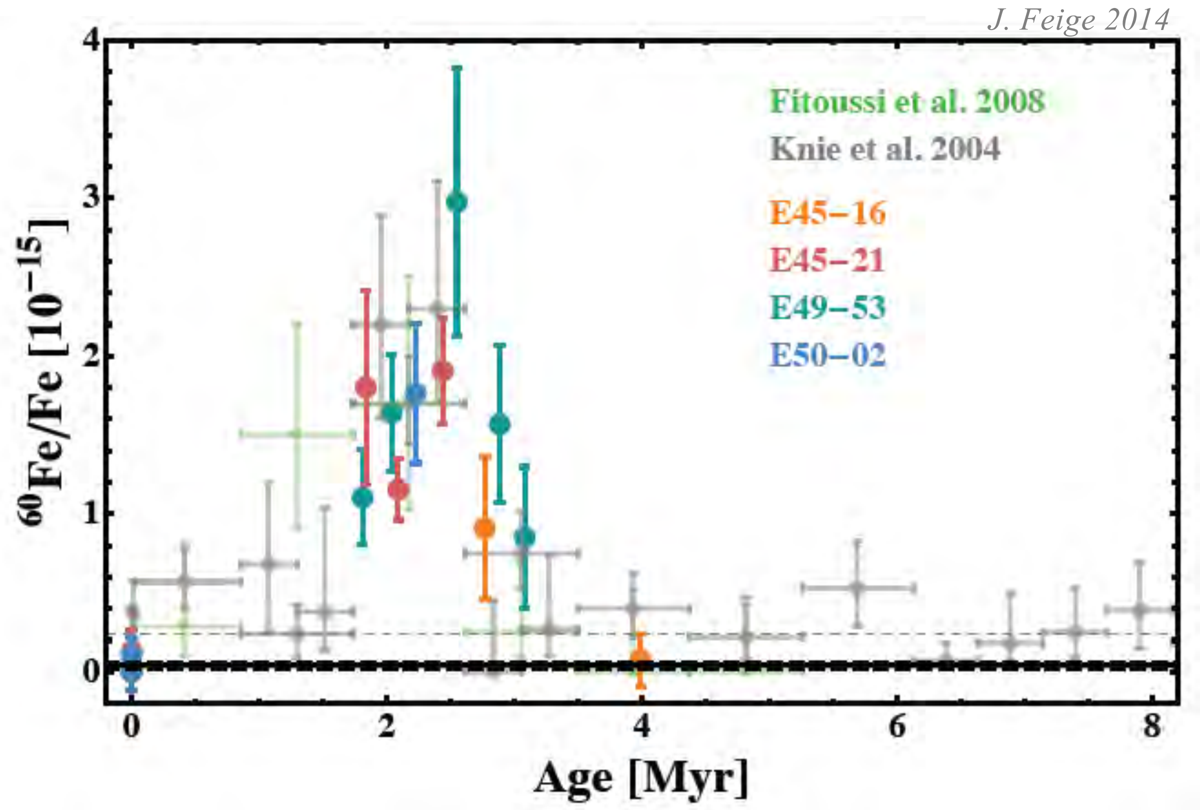


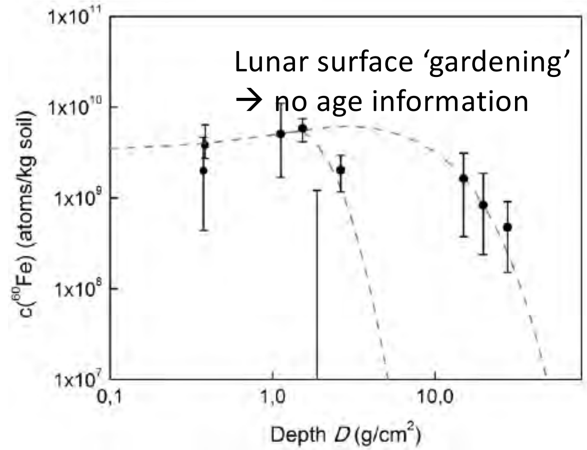
SN Ejecta Nearby: Deposits on Solar-System Bodies

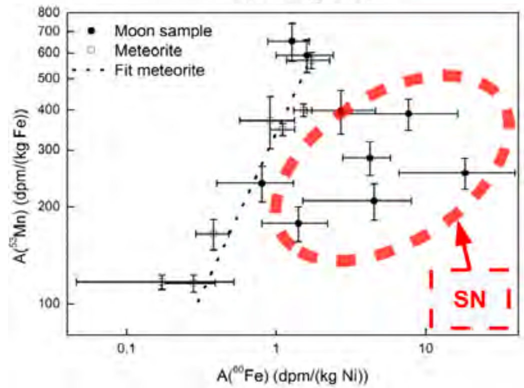
- ^{60}Fe Clearly Seen on Earth & Moon
  - ☆ In complementing samples
  - ☆ in Lunar Samples *(Fimiani et al. 2014)*
  - ☆ in Sediments *(Bishop et al. 2014)*

sediments → high time resolution



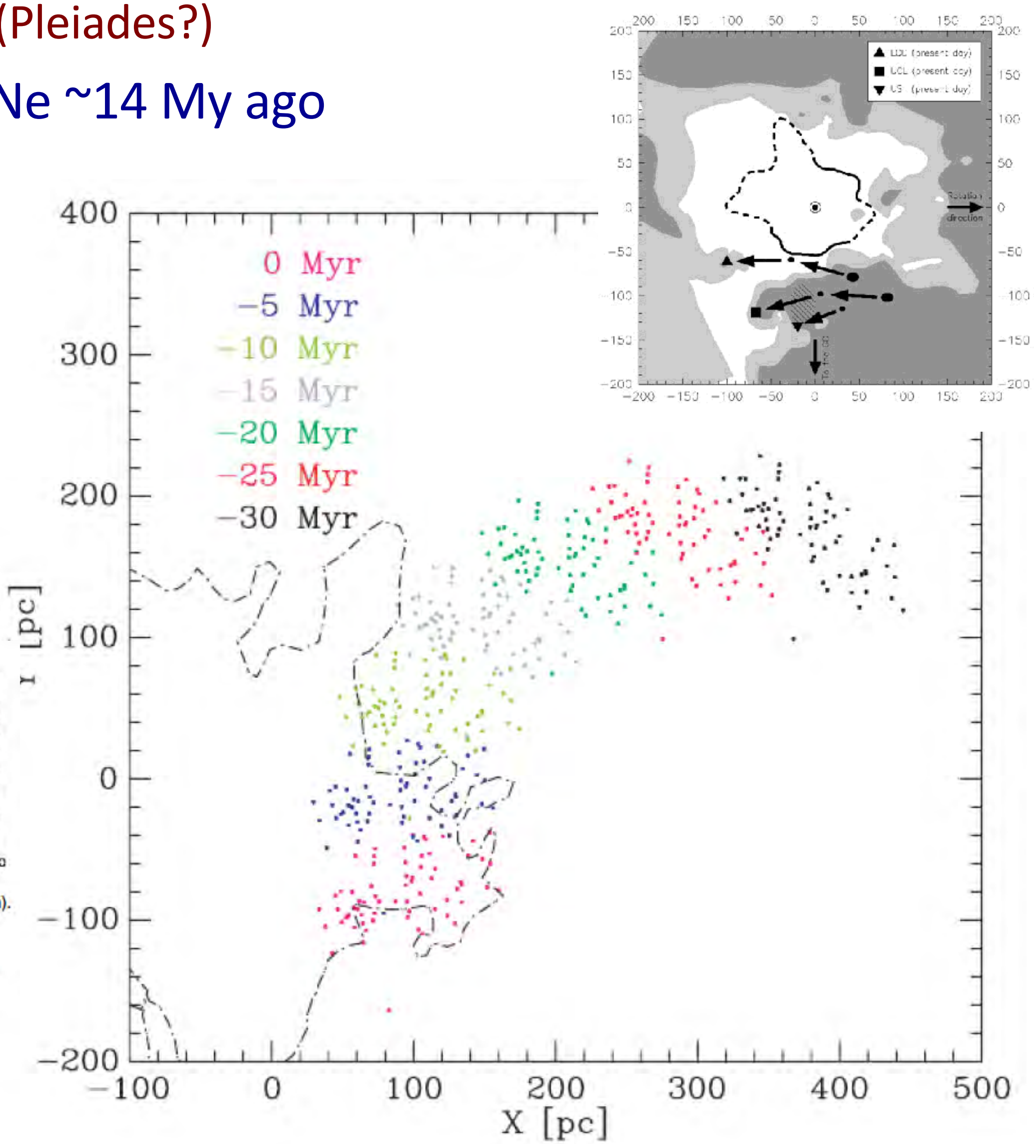


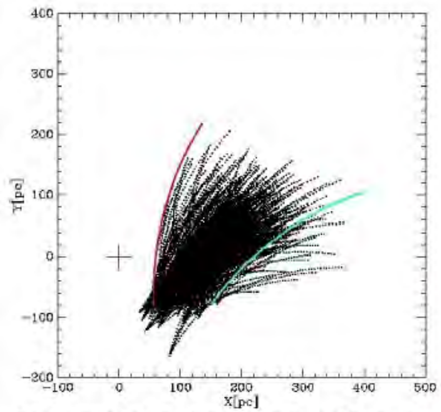




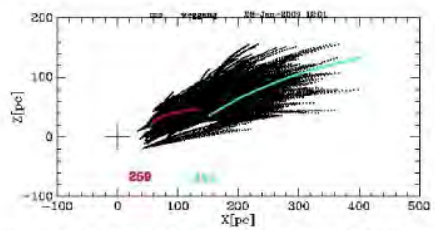
^{60}Fe on Earth: Origins?

- Back-Propagate Relative Motions of Sun and Nearby Stars
  - Scorpius-Centaurus Subgroups; (Pleiades?)
- Local Bubble formed by ~15-20 SNe ~14 My ago
- Relative Proximities:
  - UCL and LCC Subgroups closest at ~65 pc ~2.2 My ago
  - *J. Feige et al. 2010;2012+*





The trajectories in the X-Y plane (Courtesy of C. Dettbarn).



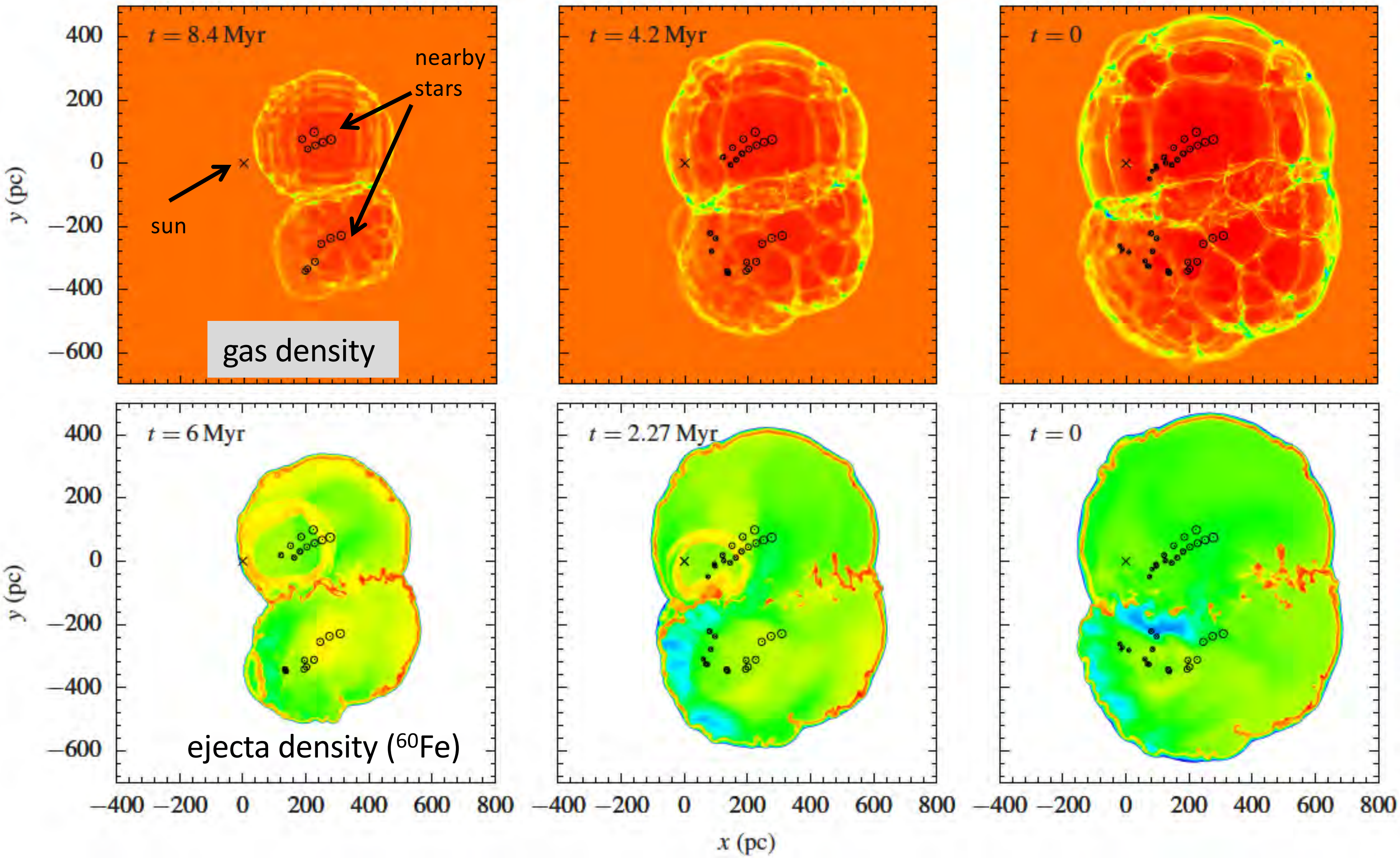
The trajectories in the X-Z plane (Courtesy of C. Dettbarn).

- Red: the closest trajectory
  - closest point: 2.2 Myr ago, ~65 pc
- Blue: the most distant trajectory

How ^{60}Fe came onto Earth

- Two local ISM cavities merge (Local Bubble & Loop-1)
- SN explosions within LB → ejecta flows reach the Sun

Schulreich+ 2017



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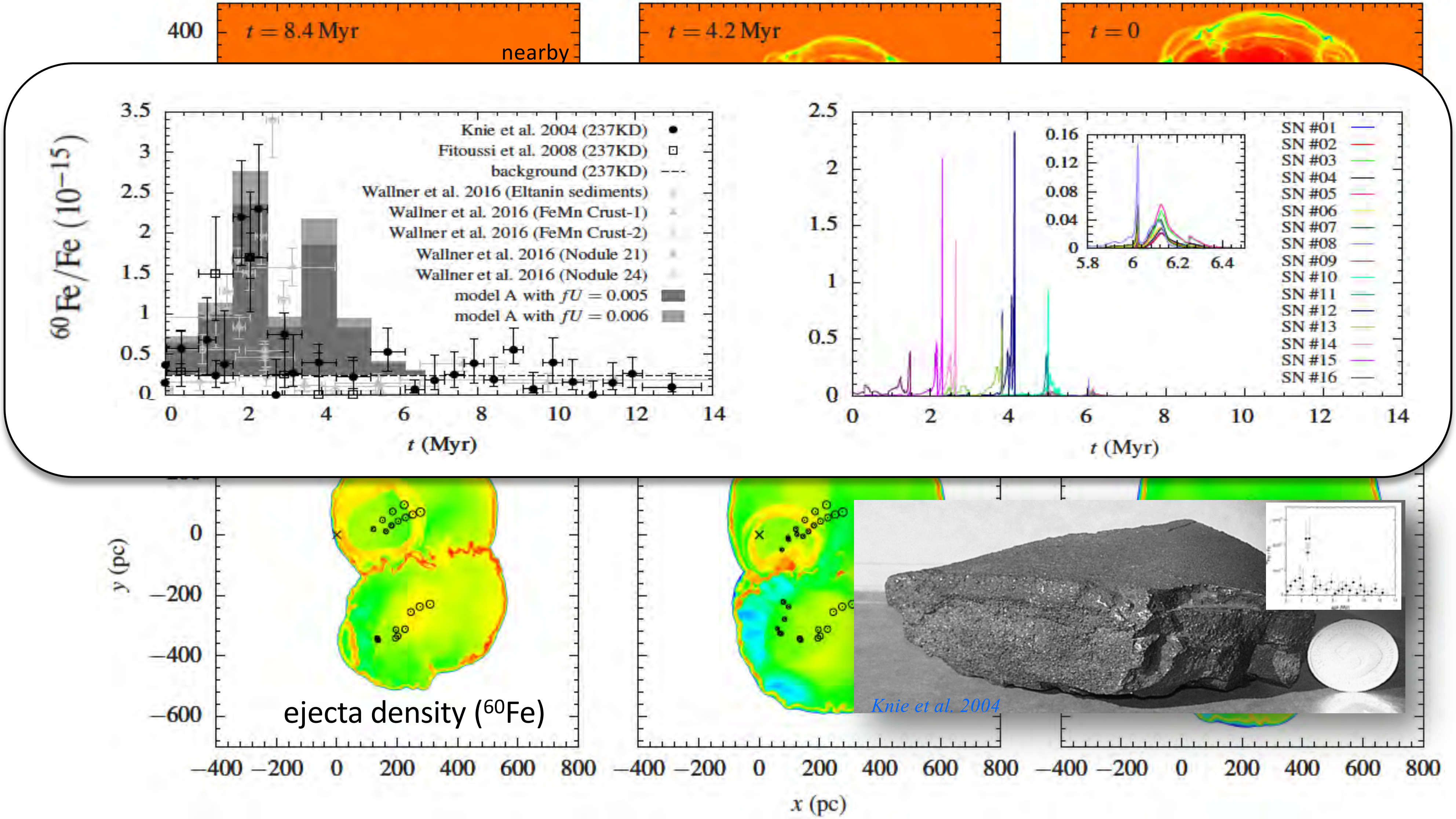
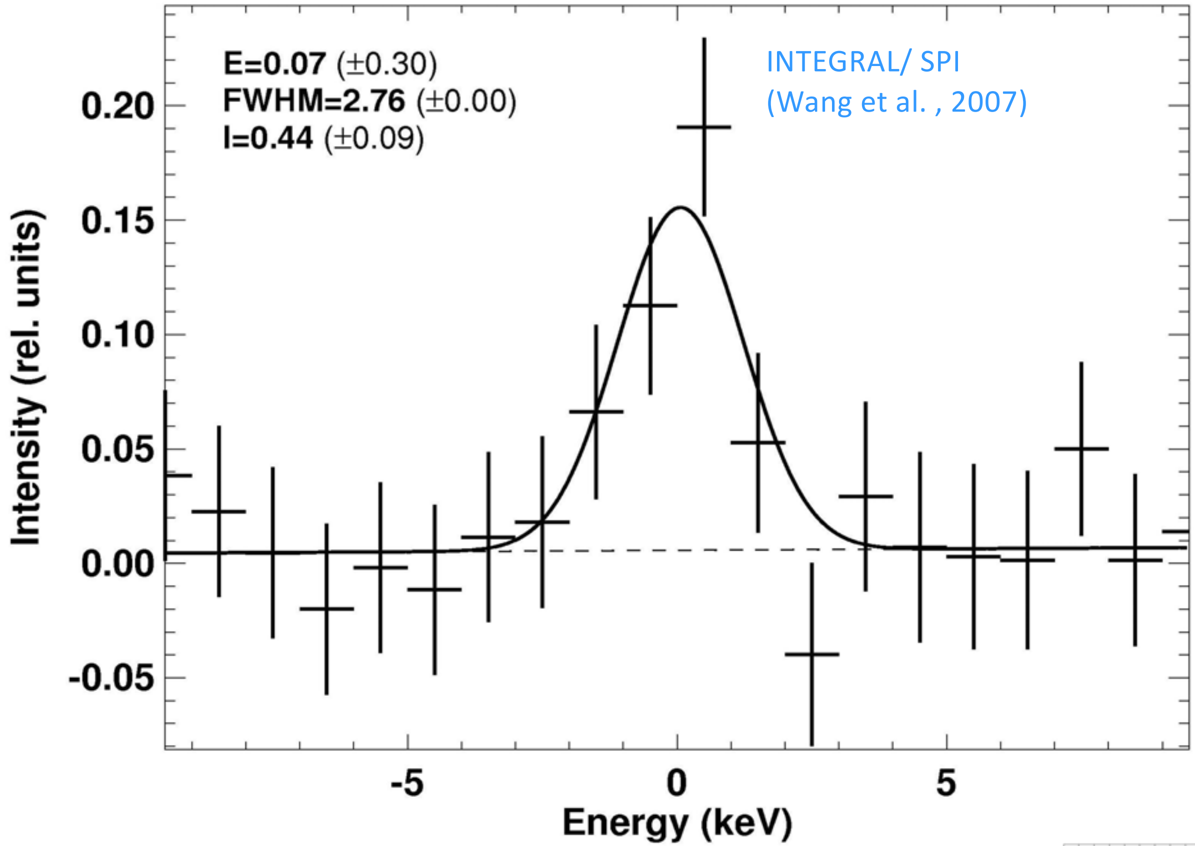
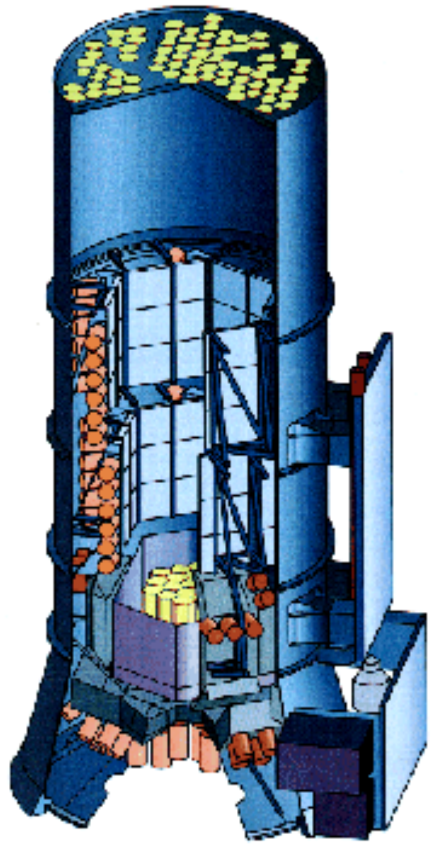
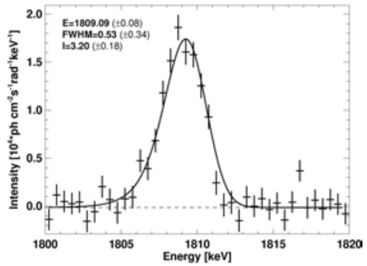


Diffuse ^{60}Fe emission is seen from the Galaxy



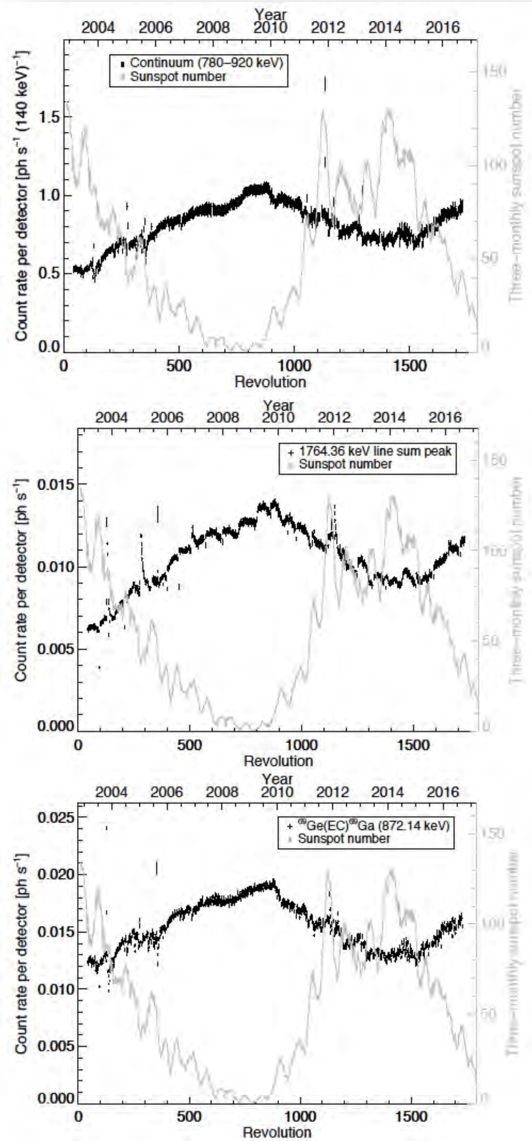




- ☆ Clear but faint gamma-ray signal (5σ)
- ☆ ^{60}Fe/^{26}Al emission ratio ~15%

Instrumental background in space orbits

Prompt, delayed, and built-up backgrounds

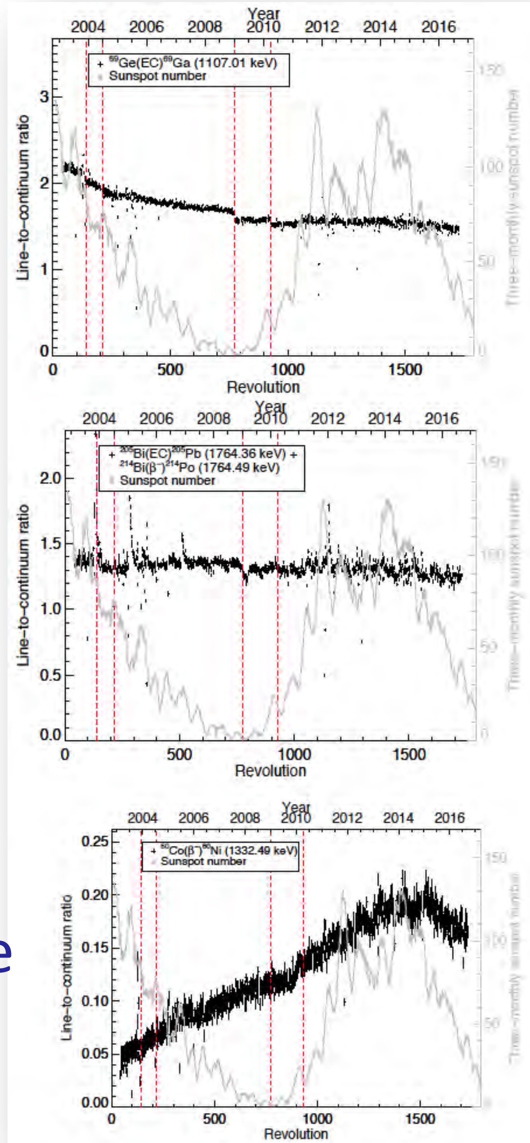


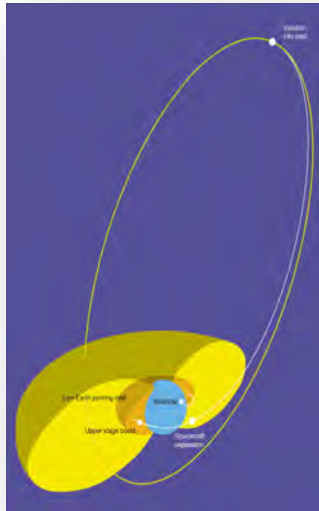
linked to
solar activity

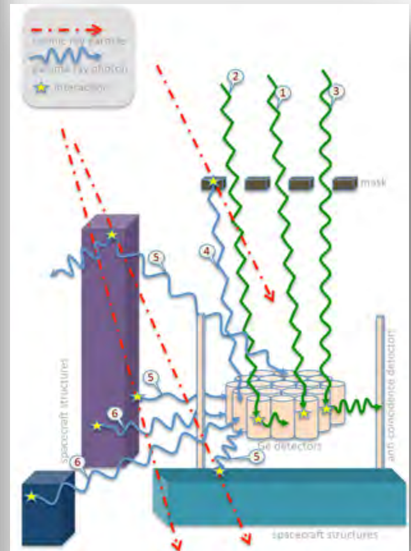
normalise with continuum

→

specific isotope characteristics



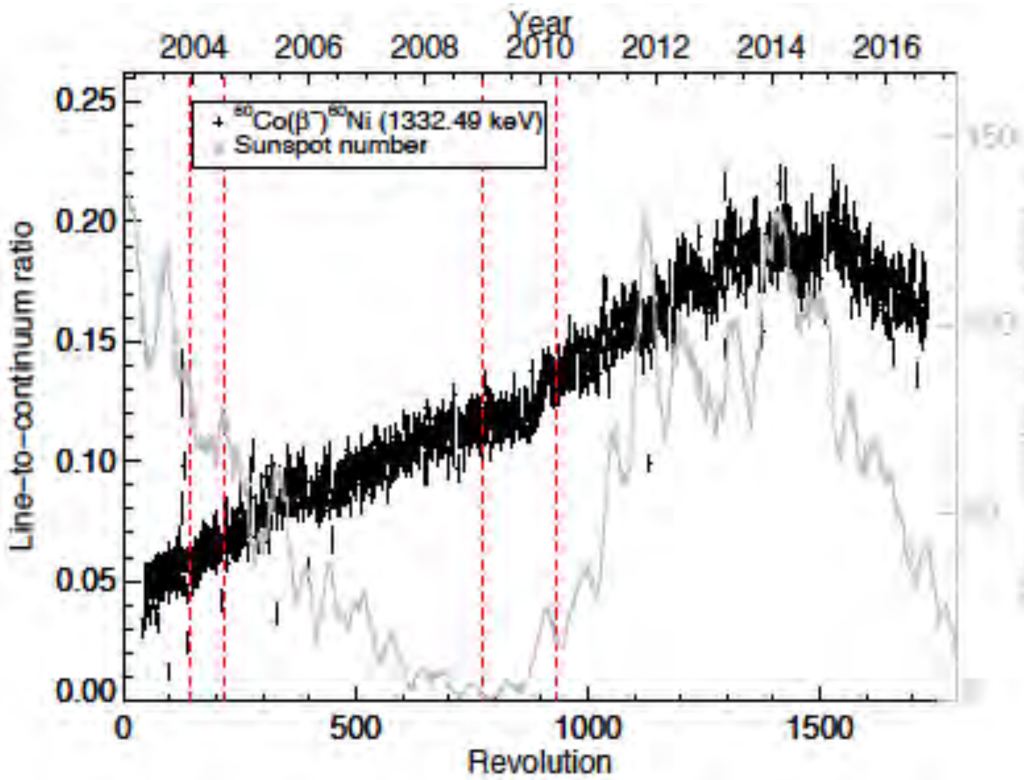


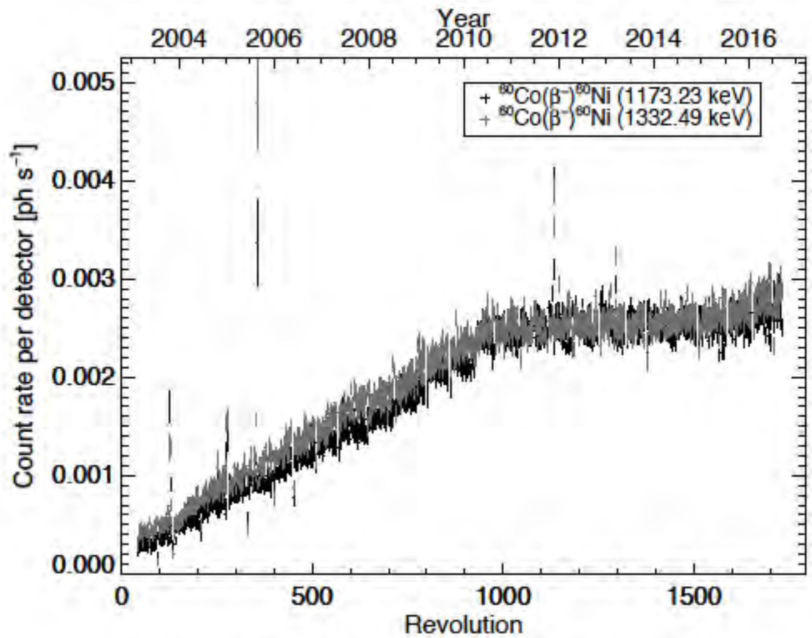


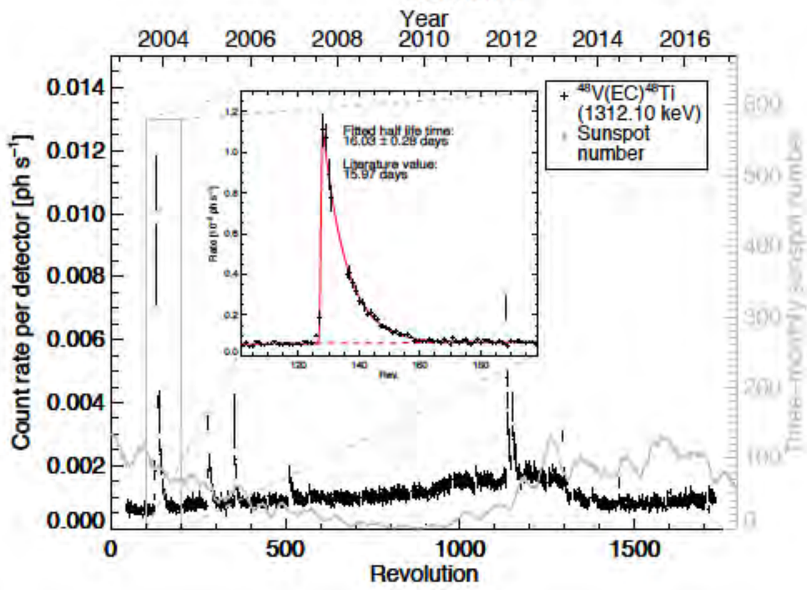
Diehl+, A&A (2018)

Background Variations: Radioactivity Build-Up

- Activation of materials happens: ^{60}Co, ^{48}V

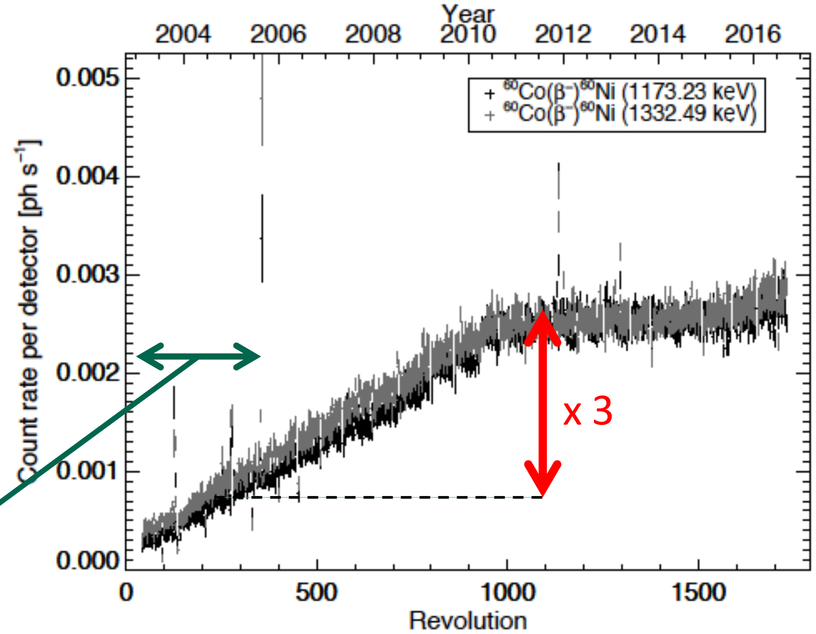


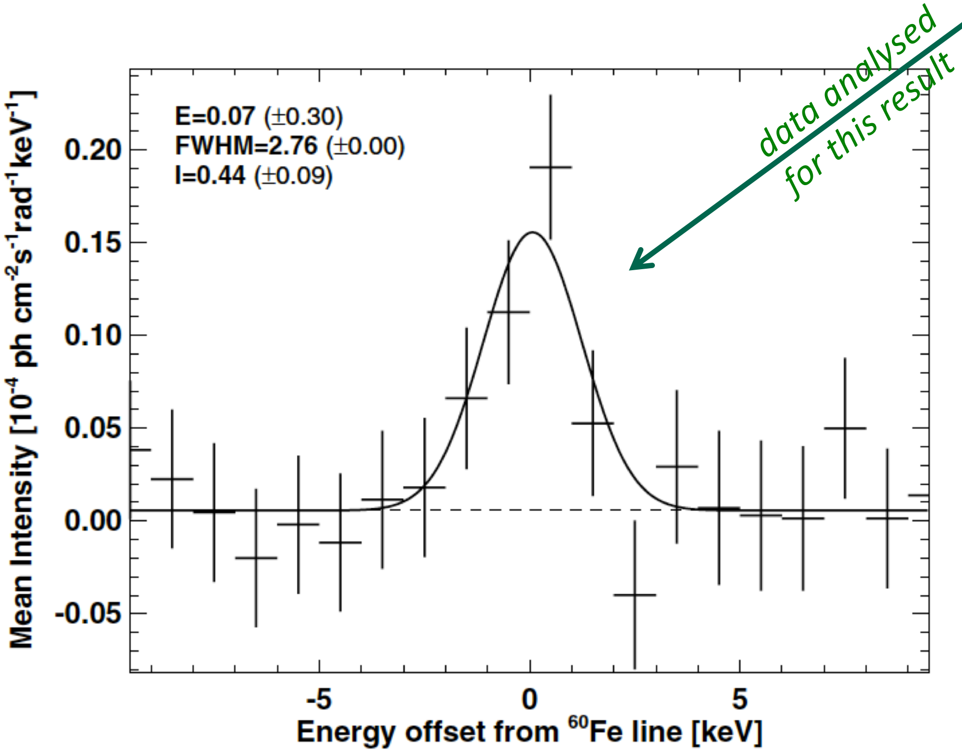


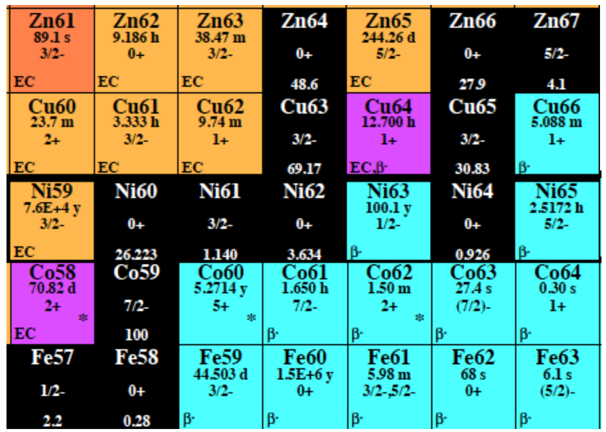


^{60}Fe Analysis SPI

Activation of materials: ^{60}Co



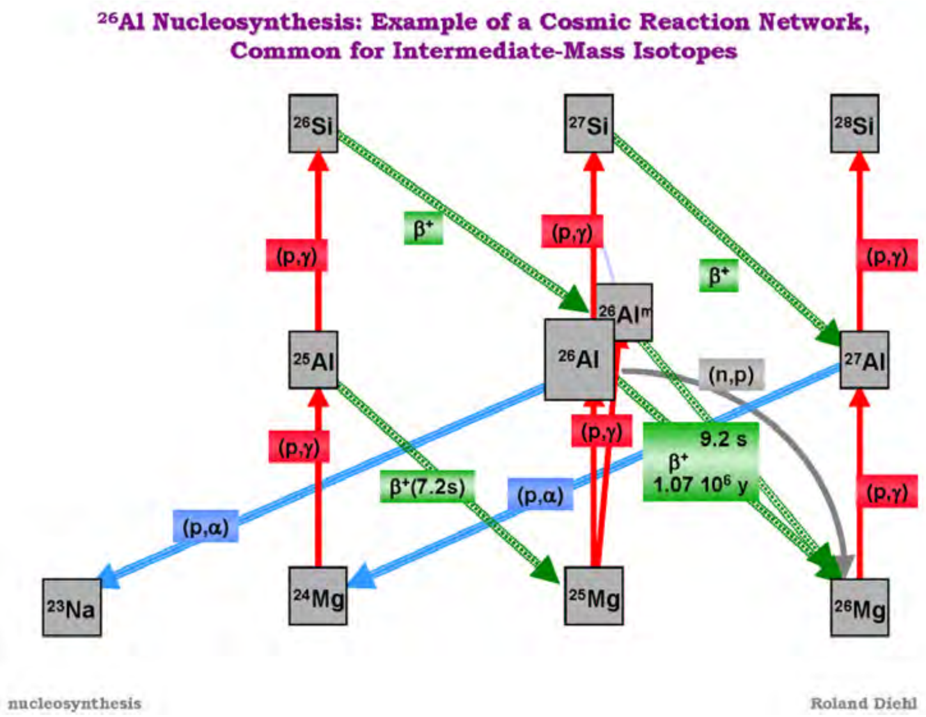




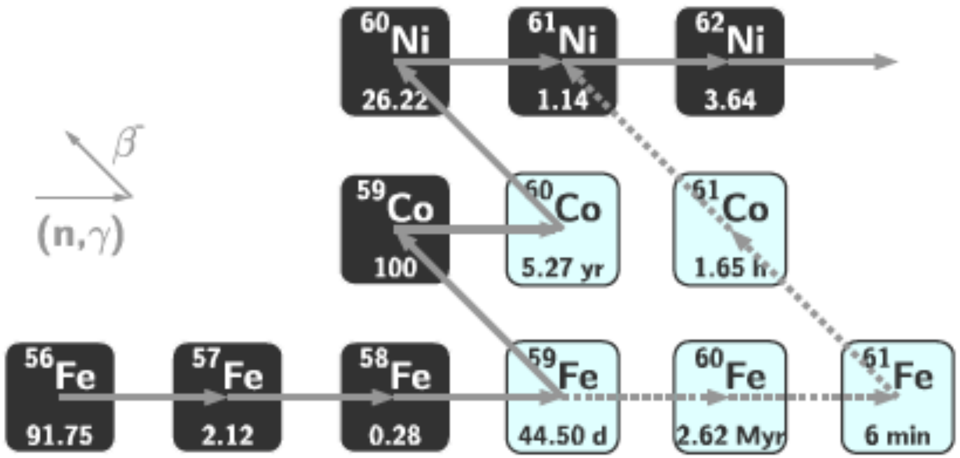
^{60}Fe is a very unfortunate coincidence:
Spallation reactions on Ni, Cu, Zn

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

- The Na-Al-Mg cycle: p captures (H burning, +…)



- Neutron capture on Fe in massive-star shells

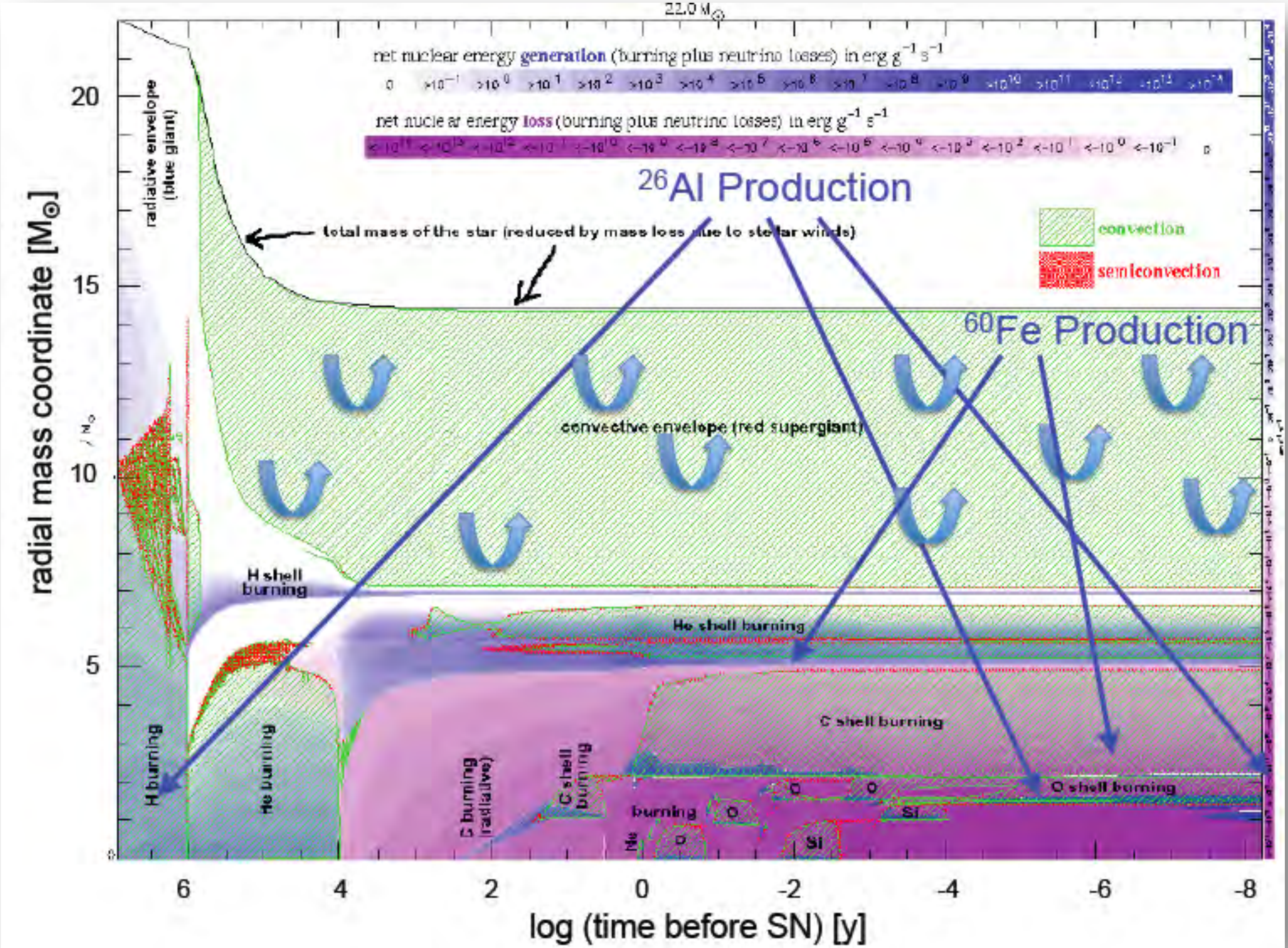


Radioactivities from massive stars: ^{60}Fe, ^{26}Al

Massive-Star Interiors

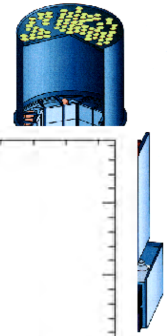
(adapted from Heger)

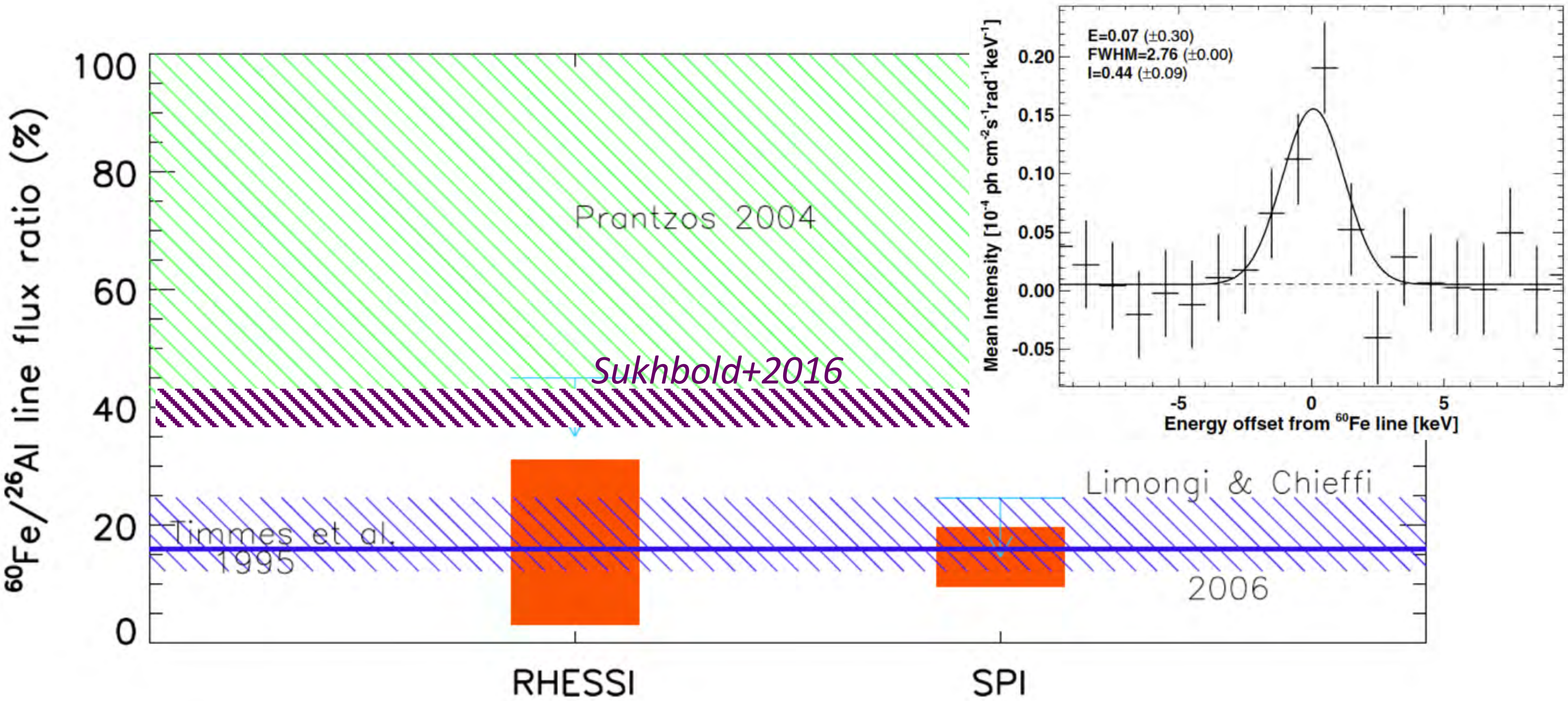
- ☆ *Hydrostatic fusion*
- ☆ *WR wind release*
- ☆ *Late Shell burning*
- ☆ *Explosive fusion*
- ☆ *Explosive release*



^{60}Fe in the Current Galaxy's ISM

- Observed ^{60}Fe/^{26}Al Intensity Ratio ~15% (±4%)

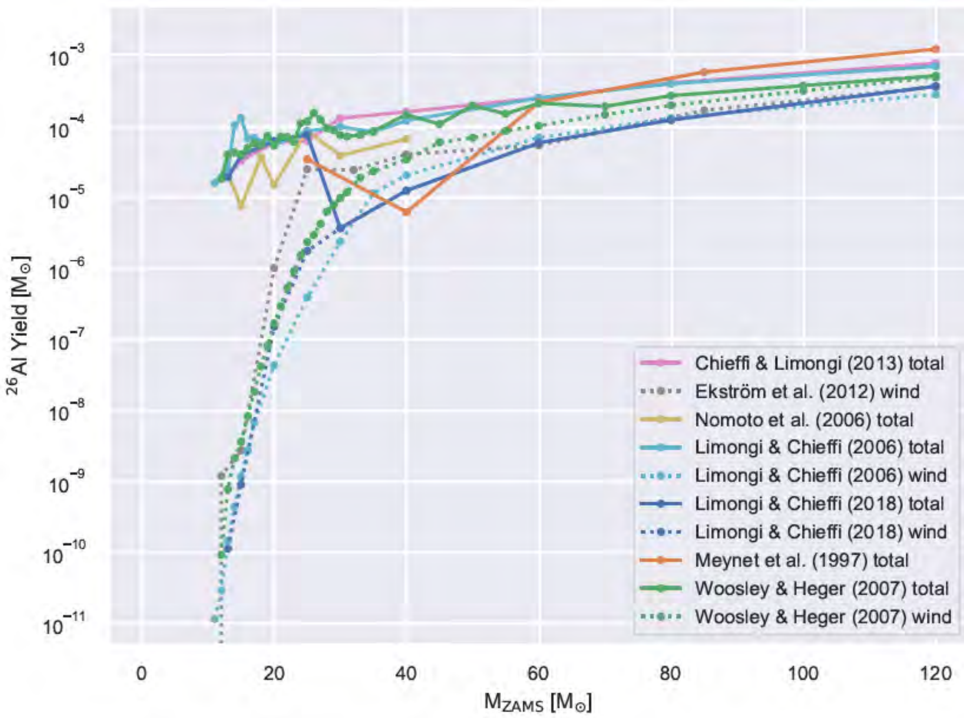




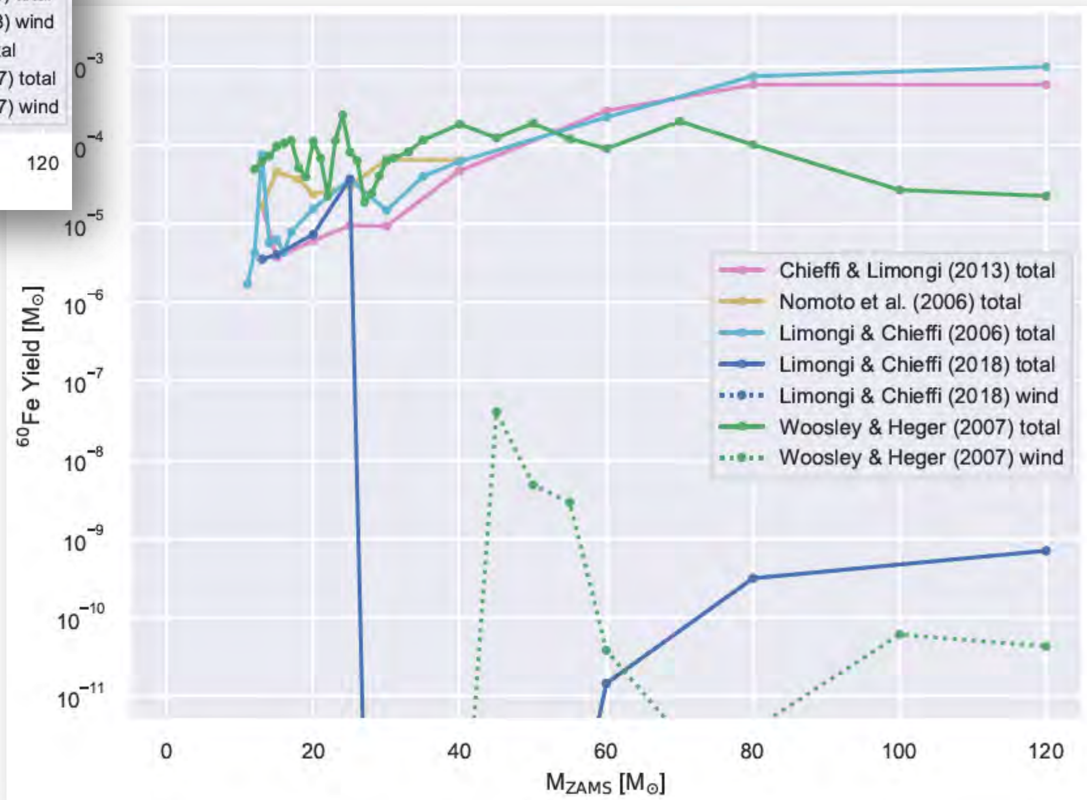
☞ ^{60}Fe/^{56}Fe isotope ratio in current ISM = 1.5 10^{-7} (model: 7 10^{-4} *Sukhbold+2016*)

– using M_{ISM}=4.95 10^9 $M_\odot$ and SAD 7.5 and M_{26Al}=2.25 $M_\odot$ → M_{60Fe}~1.2 $M_\odot$

Theoretical Yields of ^{26}Al and ^{60}Fe Sources



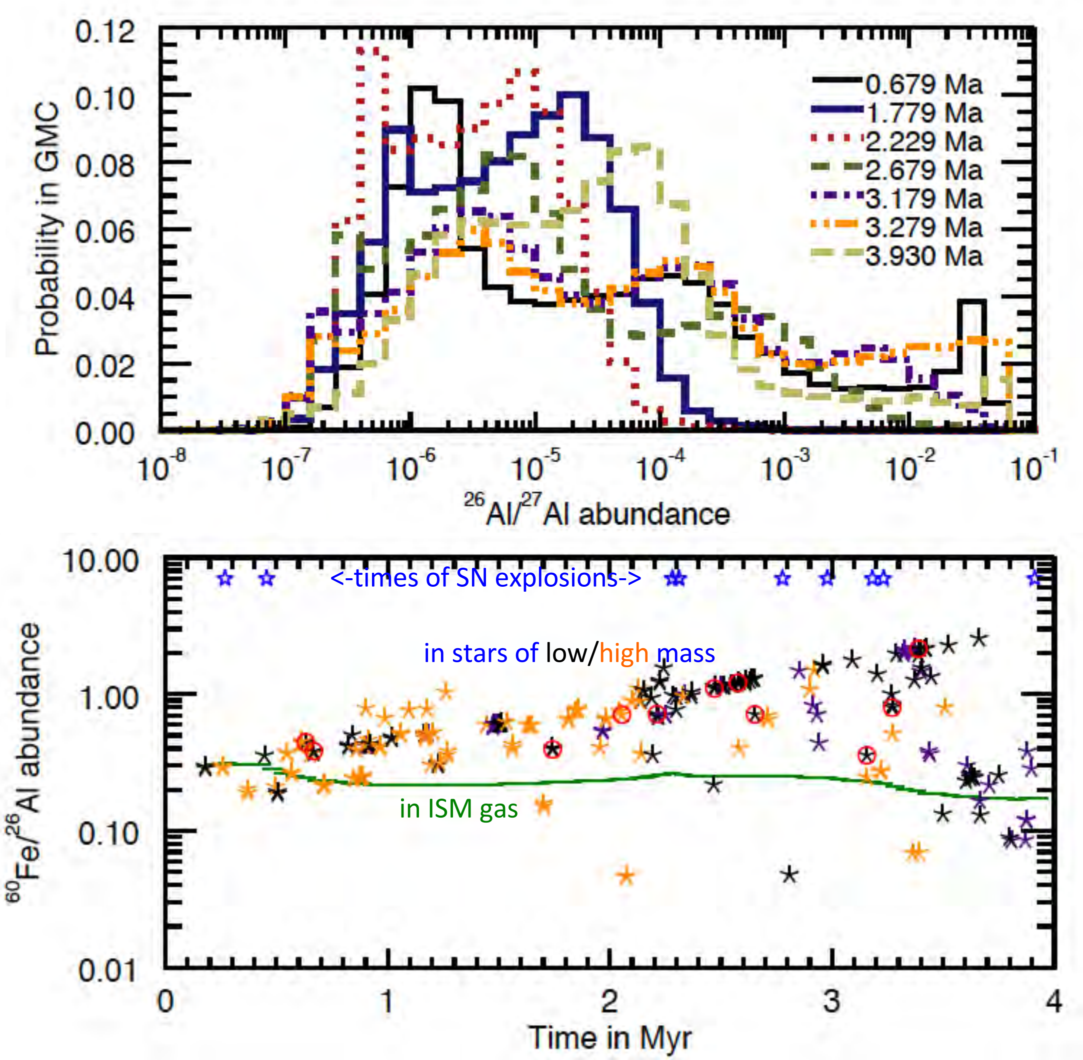
- ☆ Models for massive-star & SN nucleosynthesis
  - ☞ Wind ejection
  - ☞ Explosive nucleosynthesis addition and SN ejection
    - *Assembled by M. Pleintinger 2018*

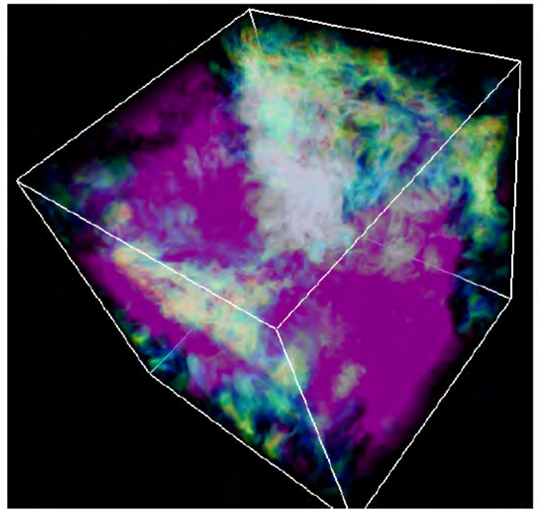


Enrichment of star forming gas

Kuffmeier et al. 2016

- Simulating how supernovae affect the enrichment of nearby gas in a giant molecular cloud (→ ESS!?!)





^{26}Al distribution (low/high) in GMC after ~4 My

The Al Isotope Ratio

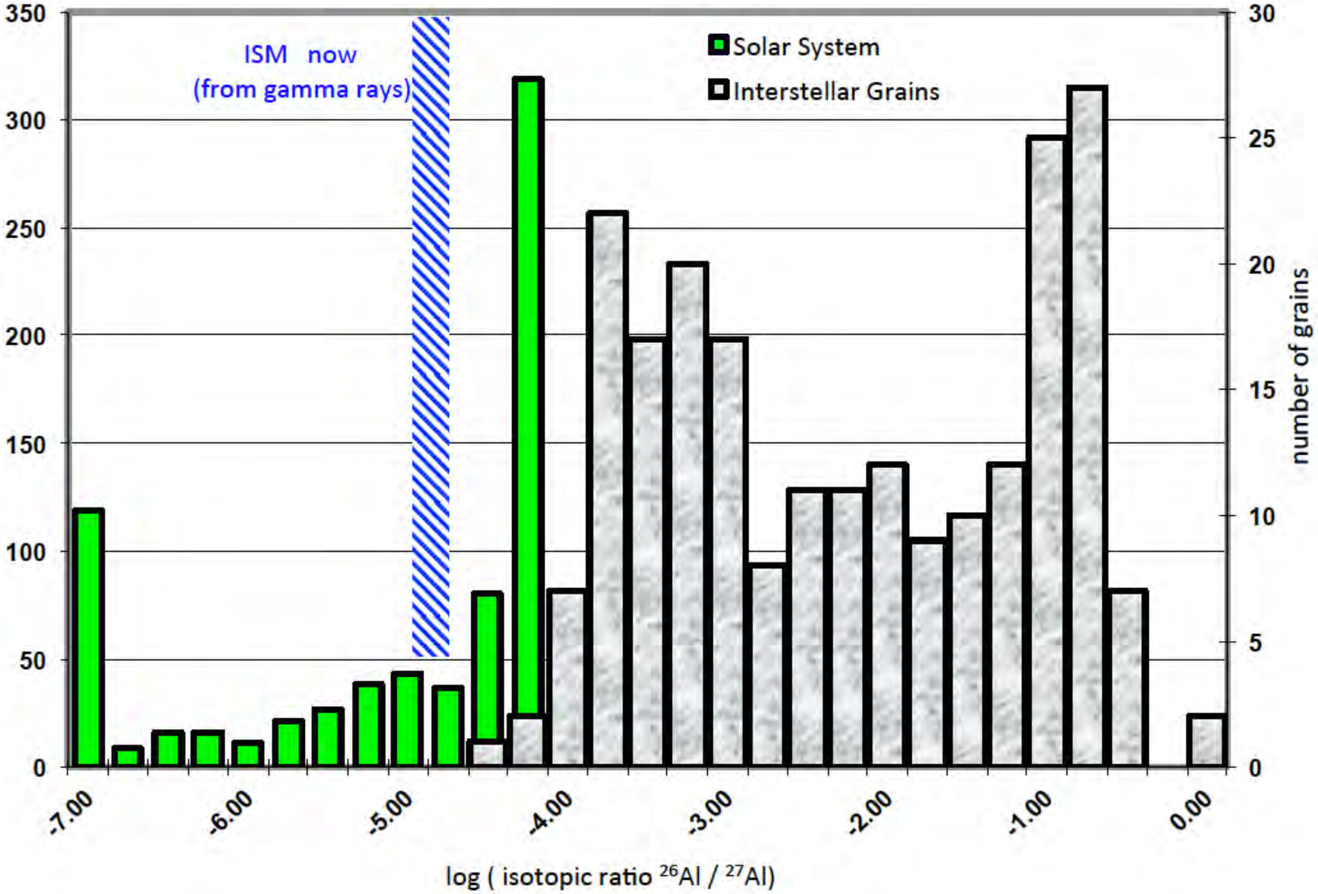
- ^{27}Al is enriched with Galactic Evolution
- ^{26}Al decays, so from current nucleosynthesis
- Early solar system meteorites measure ESS environment
- Pre-solar grains measure nucleosynthesis in dust-producing sources

☆ '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±0.13) 10^{-5} *(Jacobsen+2013)*

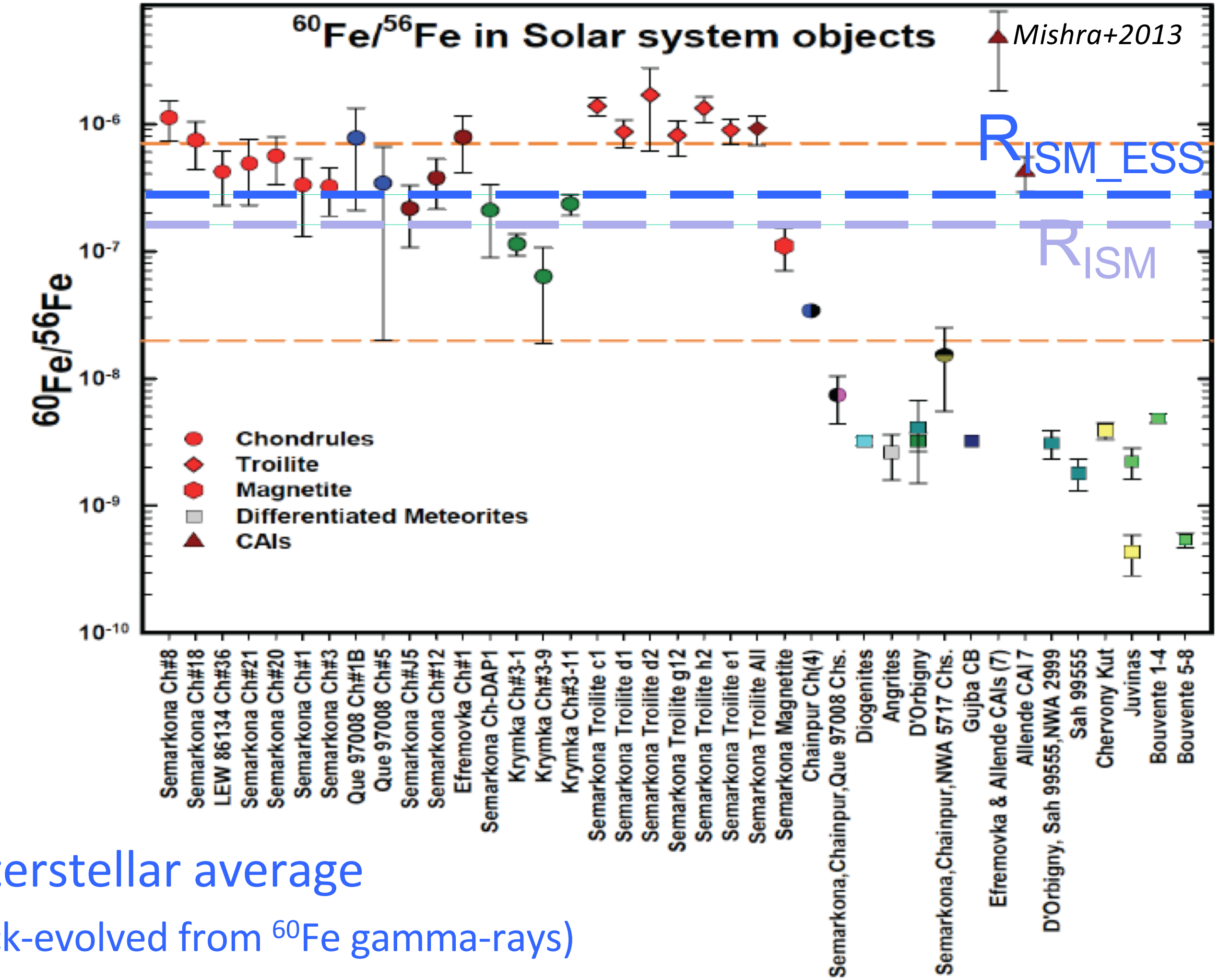


^{60}Fe in the Early Solar System

☆ Measurements from Early-Condensated Bodies:

☞ Initial $^{60}Fe/^{56}Fe$ ratios uncertain between few 10^{-7} and $<10^{-8}$

– *see also Tang & Dauphas 2012; re-inforced by Reto Trappitsch NIC 2018:* 10^{-8}



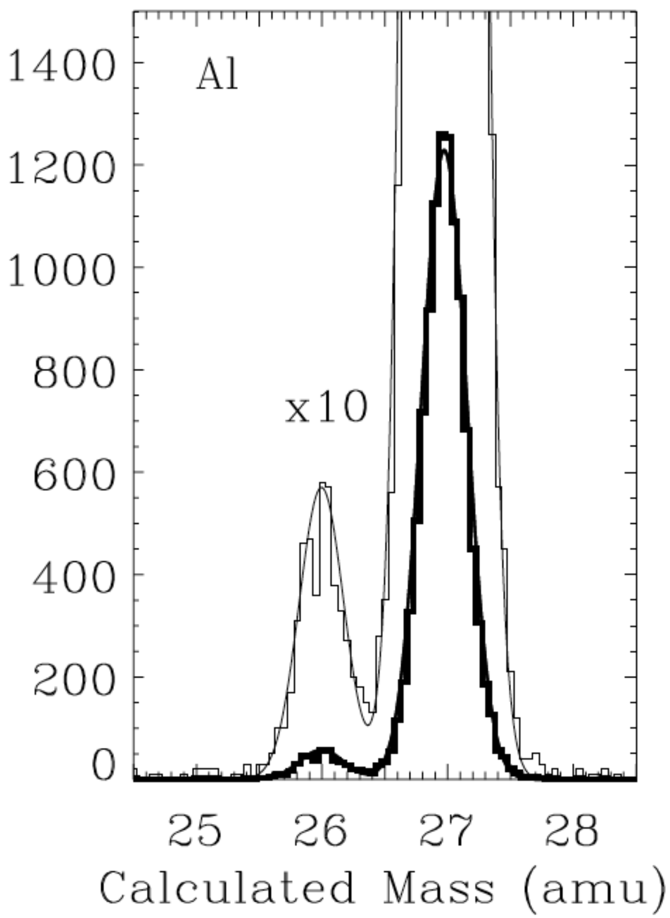
☆ Could be ~ interstellar average

(R_ISM_ESS, back-evolved from ^{60}Fe gamma-rays)

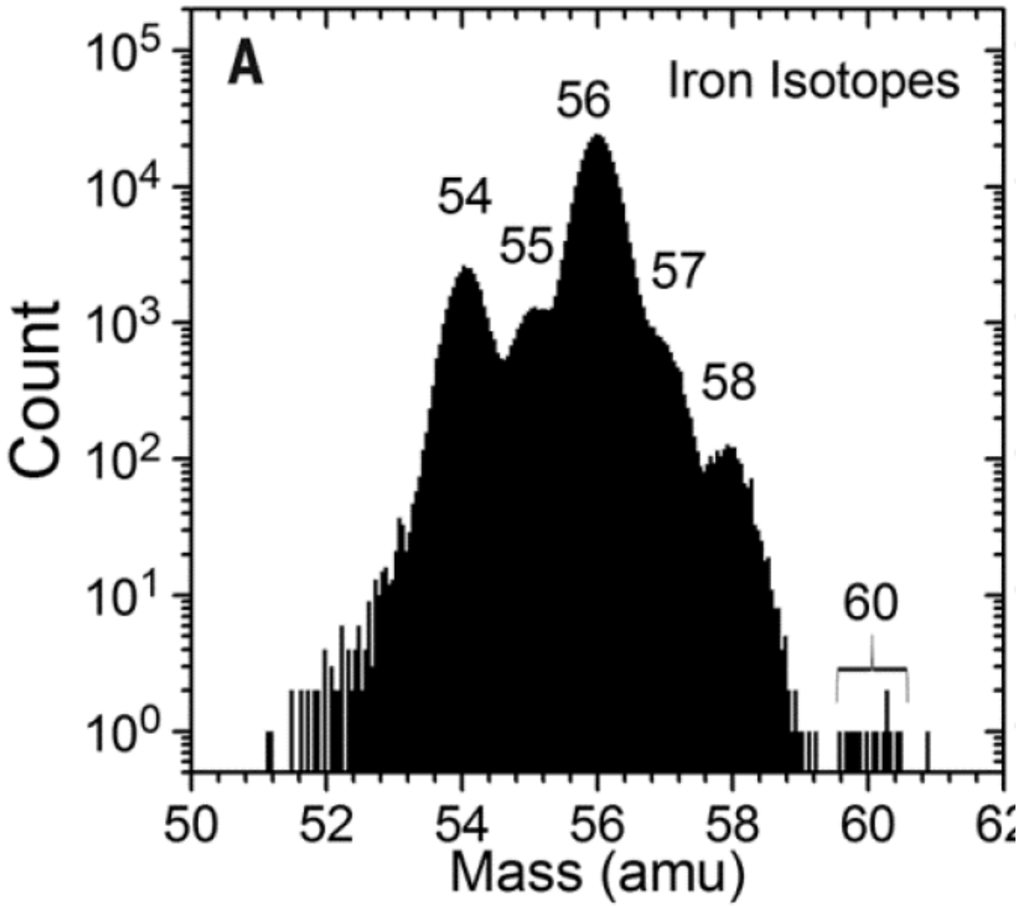
^{26}Al and ^{60}Fe in Cosmic Rays

- Direct measurement in solar system with ACE

Yanasak et al. 2001

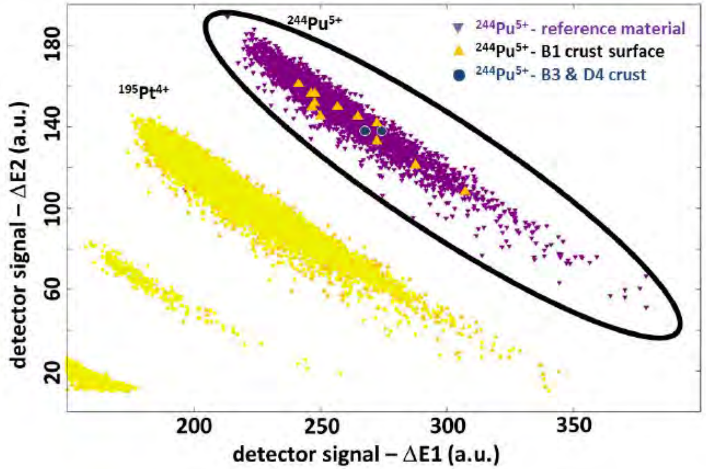


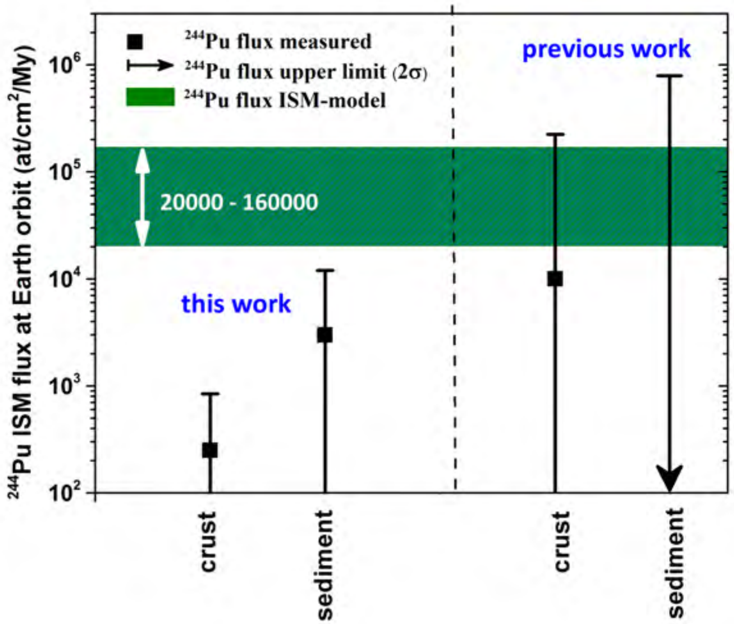
Binns et al. 2016



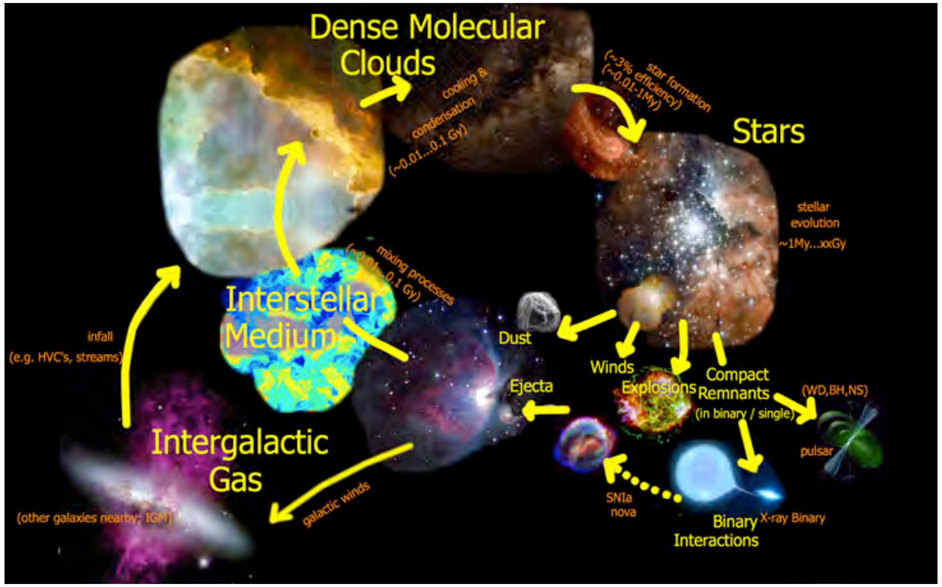
r process ejecta on Earth?

- ($T_{1/2}$(^{244}Pu)=81 My) → If r process occurs nowadays:
  → interstellar material should bring this to Earth
  - ☆ search for typical r-process isotopes in sediments with AMS
    - – *A. Wallner+ (Nat. 2015)*
    - ☞ *Lower than expected*
      - – *1 atom in 2 of 9 crust samples; bomb testing signal ~16 atoms*

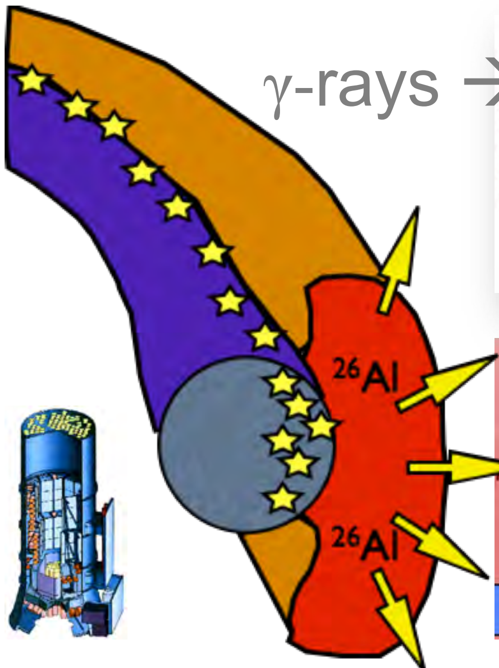


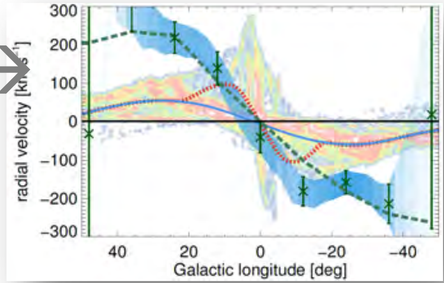


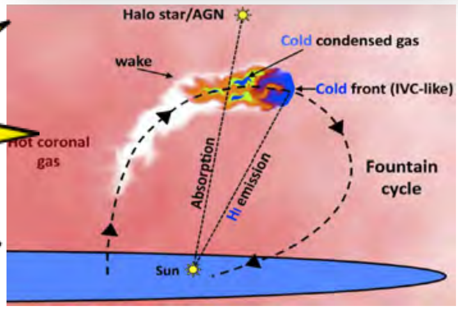
How gas is recycled…

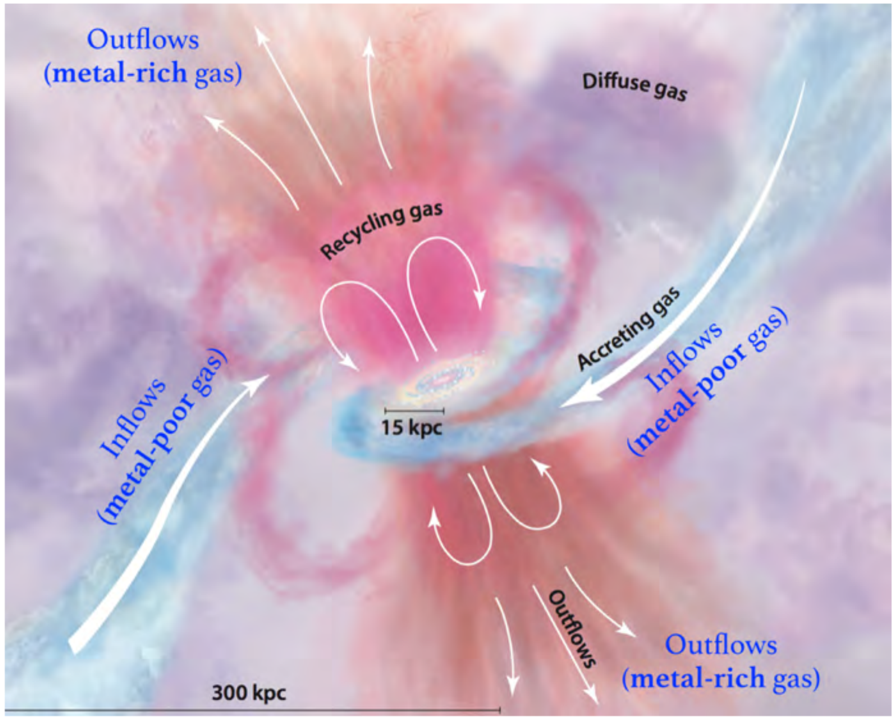


- New nuclei are in hot plasma
- Stars form from cold gas
- Cooling/mixing may depend on source (delay, efficiency)









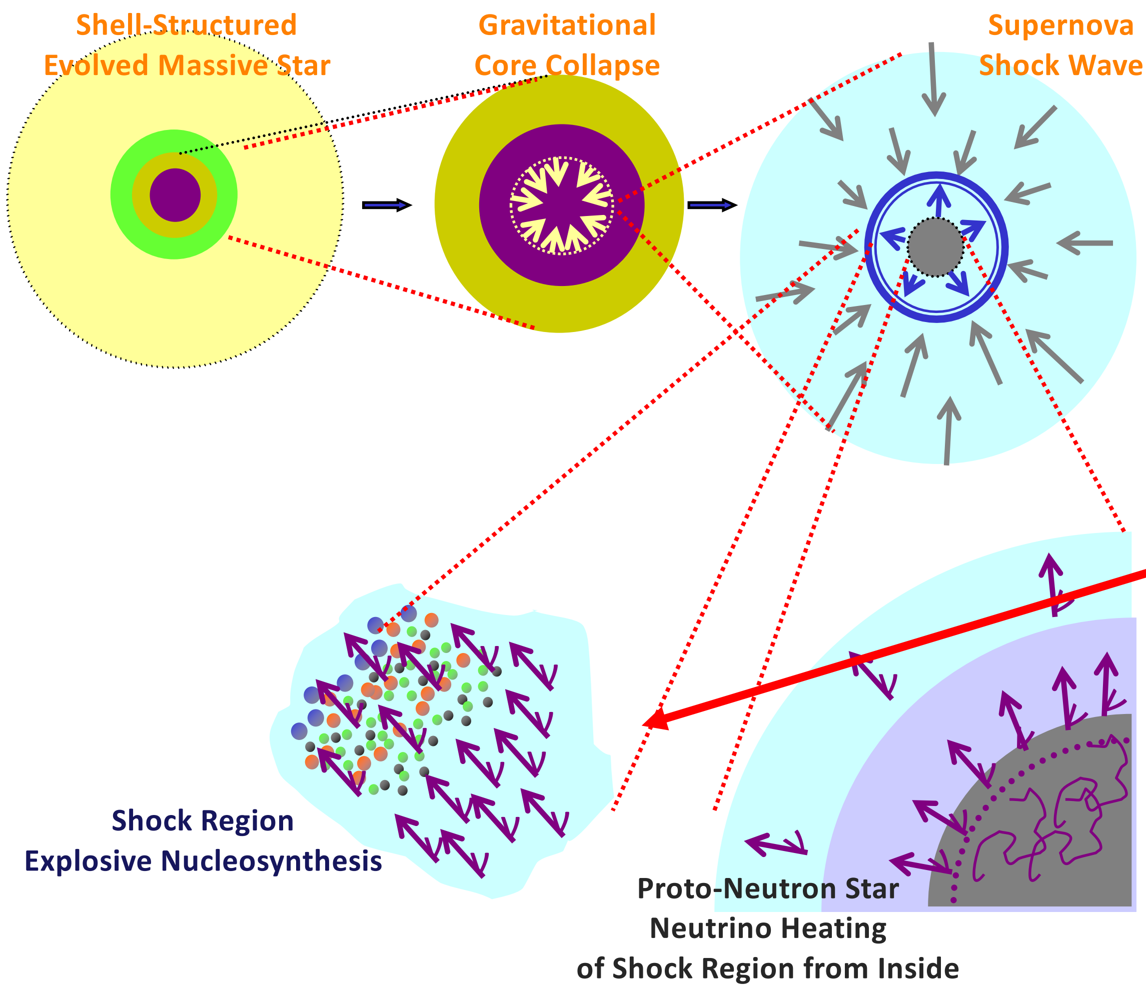
Roland Diehl

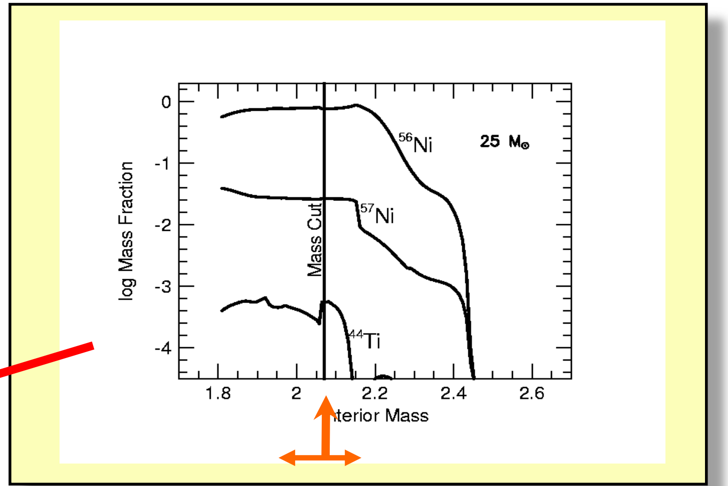
- Diagnostics of stellar explosions
  (A POINT SOURCE)

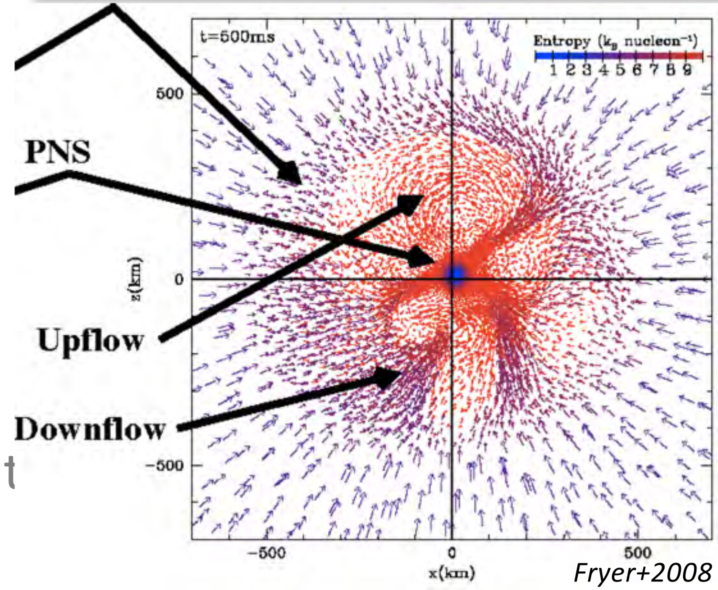
  - ☆ Novae

  - ☆ Supernovae
    - ☞ SN2014J, SN2011fe
    - ☞ Cas A, SN1987A

Nucleosynthesis in CC-Supernova Models and ^{44}Ti







Fryer+2008

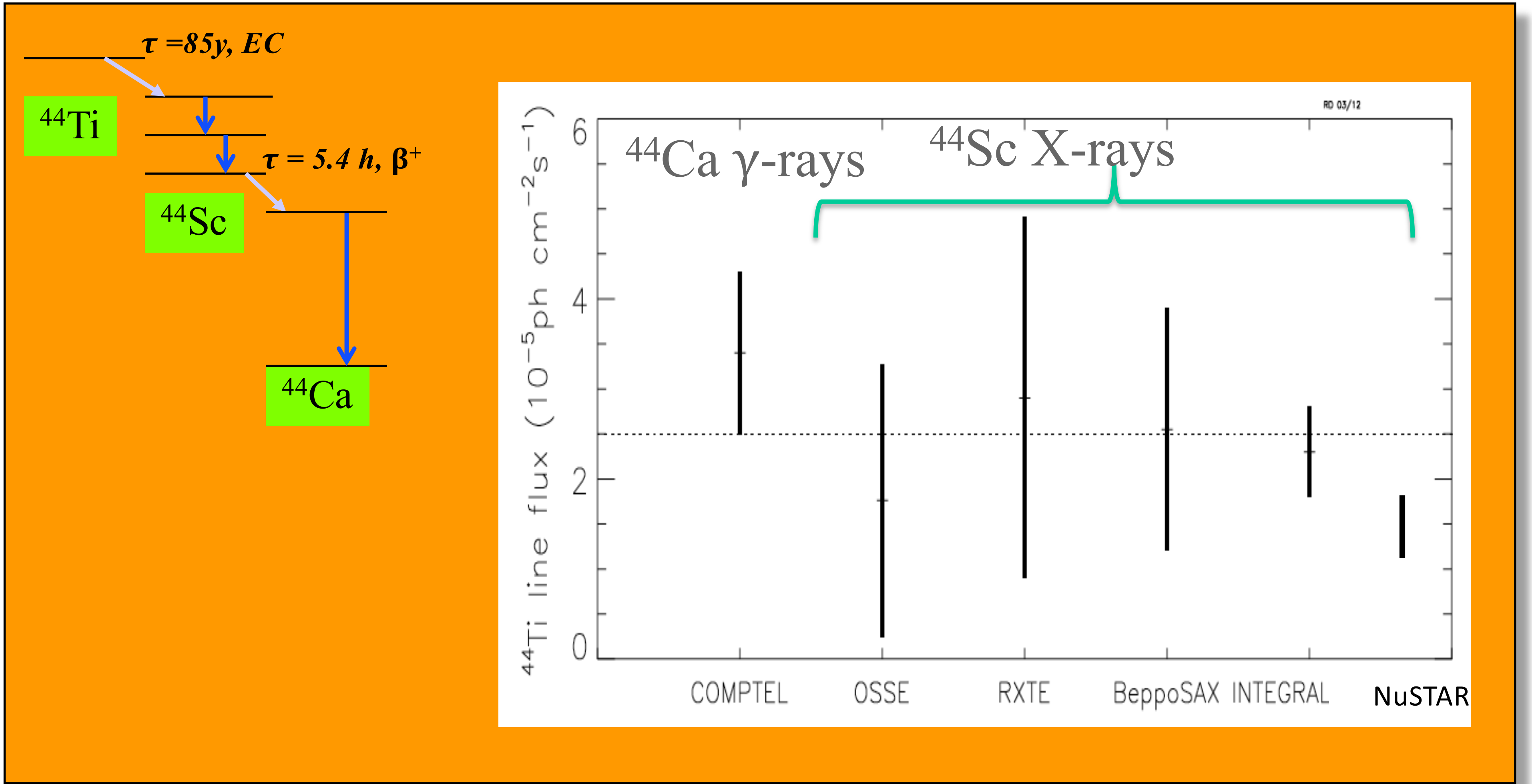
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out

  => Unique Probe (+Ni Isotopes)

^{44}Ti γ-rays from Cas A

τ=85y (Ahmad et al. 2006)

89 y	$^{44}Ti \rightarrow ^{44}Sc^* \rightarrow ^{44}Ca^* + e^+$	78, 68; 1157



↳ ^{44}Ti Ejected Mass ~1.23 ±0.25 10^{-4} $M_\odot$

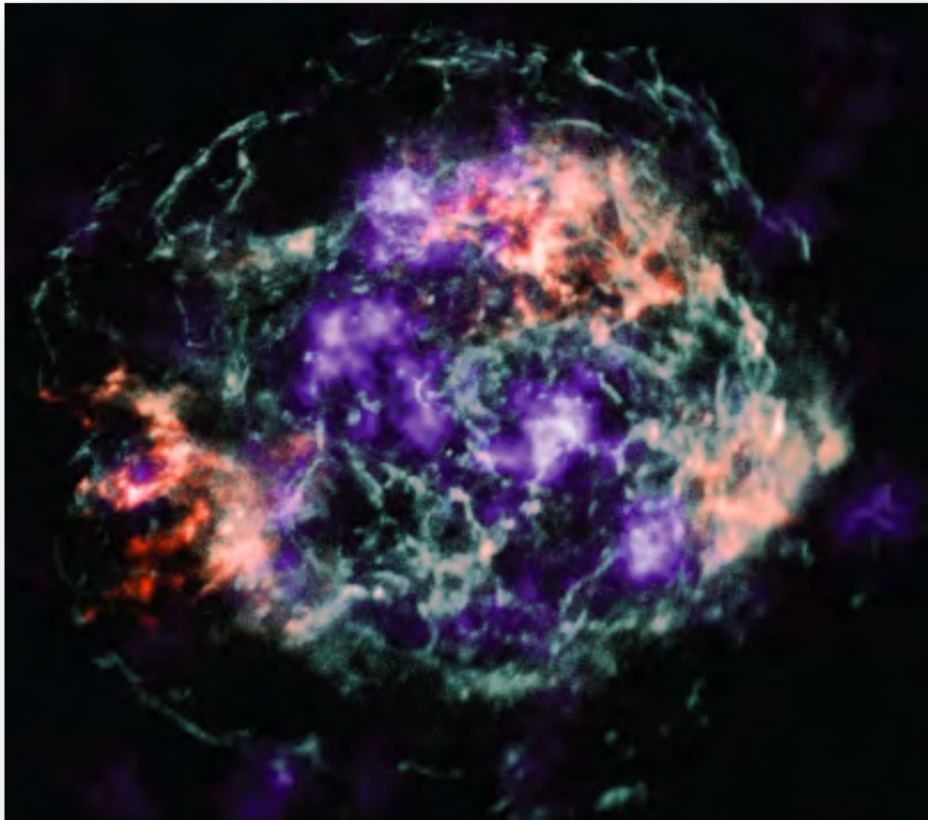
Roland Diehl 16th Carpathian School of Physics

NuSTAR measurement of ^{44}Ti in Cas A

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

☞ Cas A: first mapping of radioactivity in a SNR

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

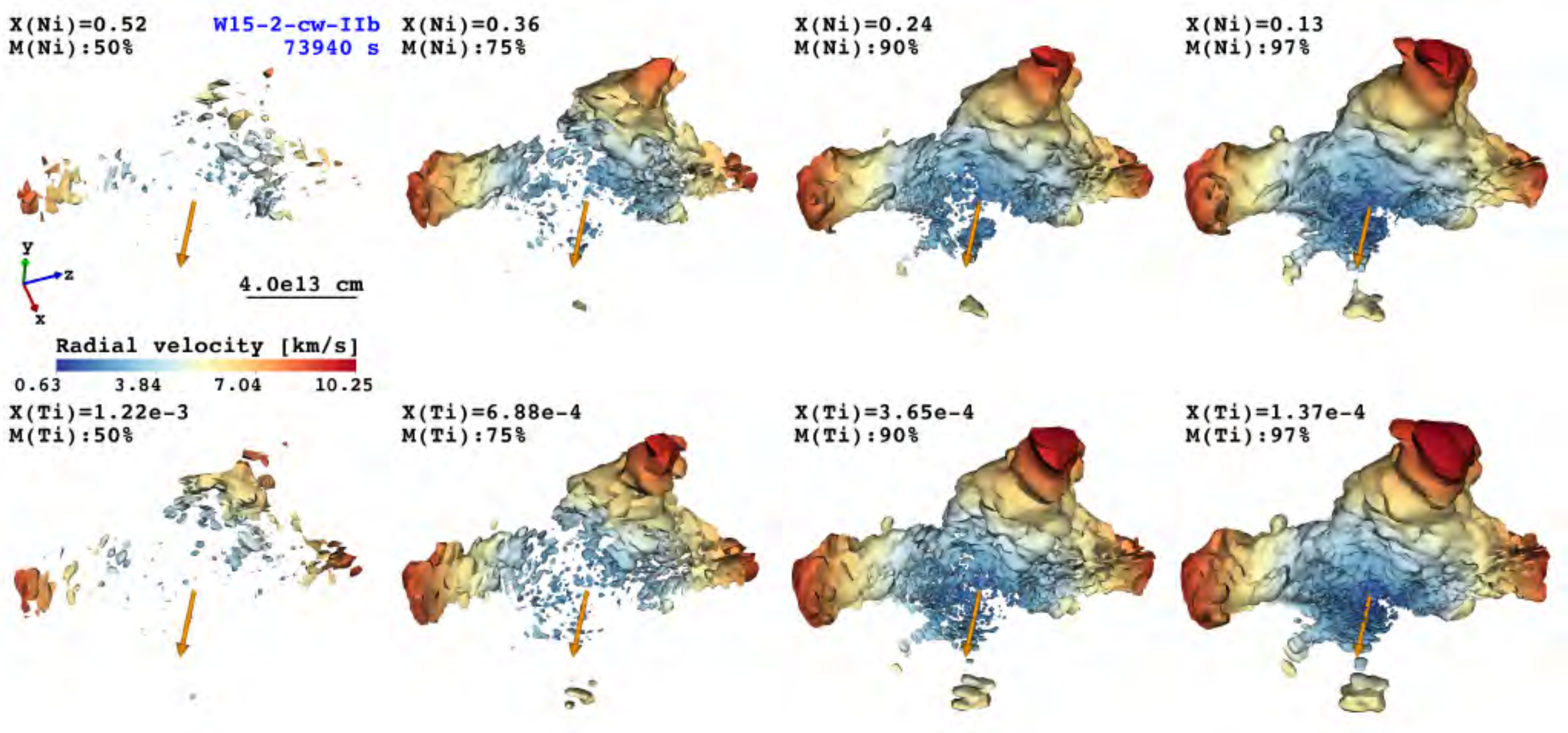


Chandra (Fe) vs NuSTAR (^{44}Ti)

Grefenstette et al. 2014

Observations versus Models

- Cas A ^{44}Ti ejecta morphology resembles simulation outcomes!
  ☞Wongwatharanat+2017

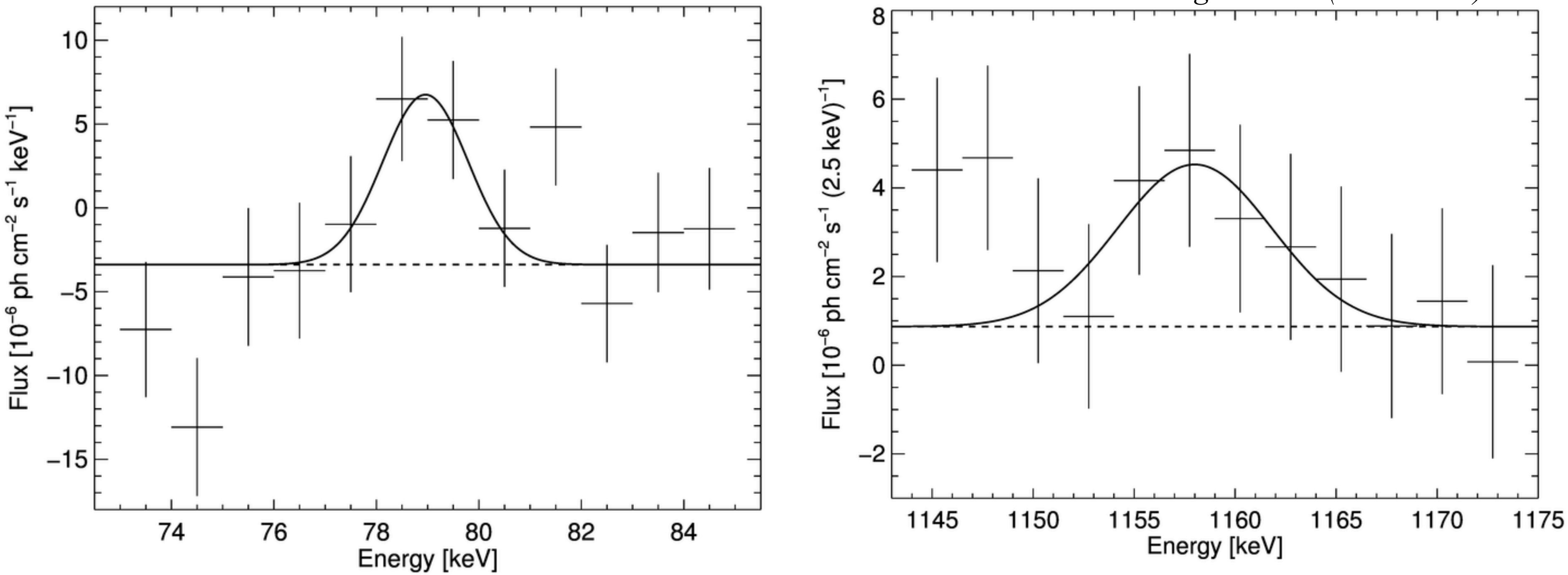


INTEGRAL/SPI Re-Analysis of Cas A for ^{44}Ti

Using cumulative data from >12 years,
and a new instrumental-background treatment

78 keV and 1157 keV line, seen with same instrument

Siegert et al. (A&A 2015)

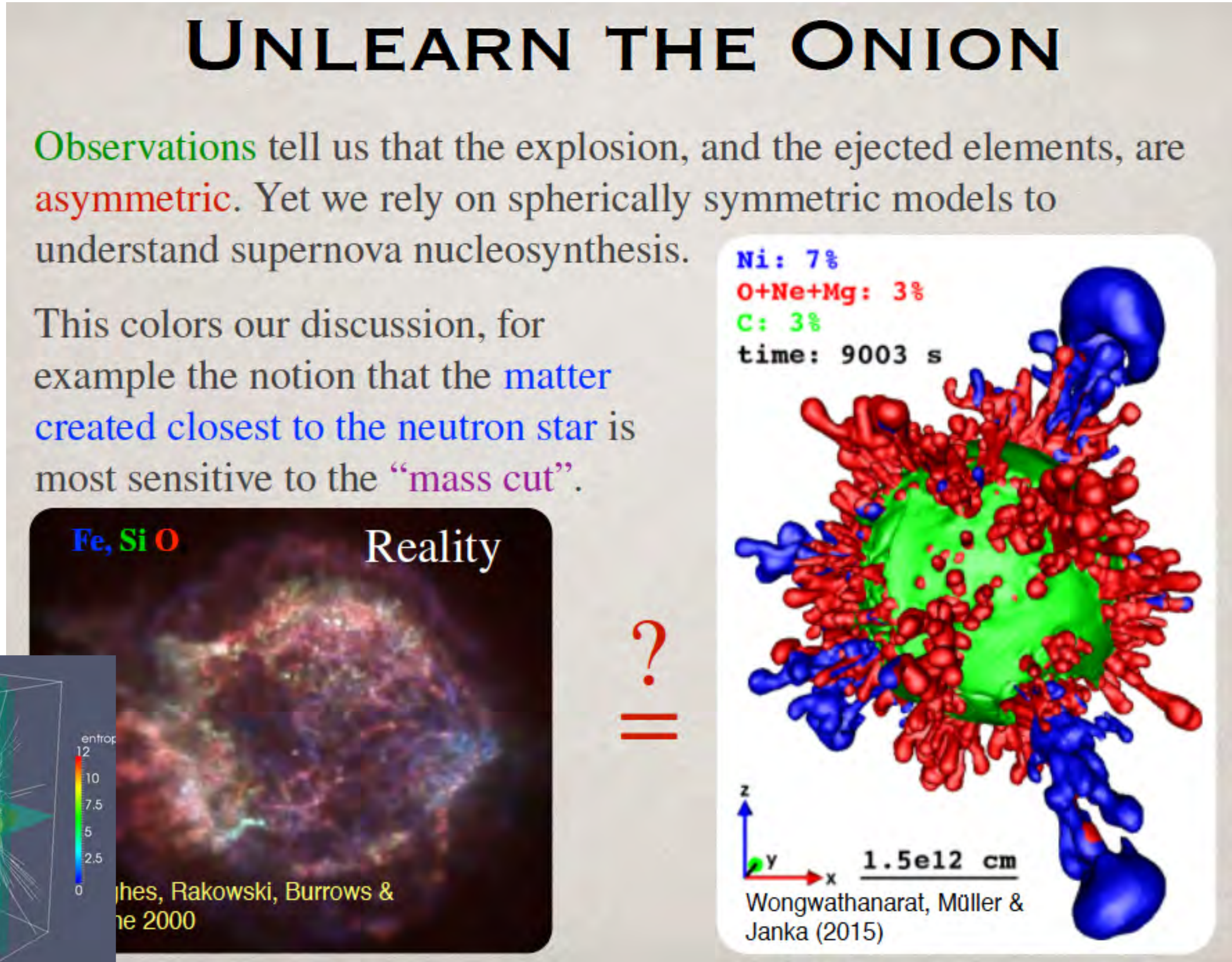


- ☆ Doppler broadening: 4300±1600 / 2200±1600 km s^{-1} (78, 1157 keV)
- ☆ ^{44}Ti mass = (1.29 ± 0.15) 10^{-4} $M_{\odot}$ (78 keV line only)
- ☆ ^{44}Ti mass = (2.72 ± 0.43) 10^{-4} $M_{\odot}$ (1.157 MeV line only)
- ☆

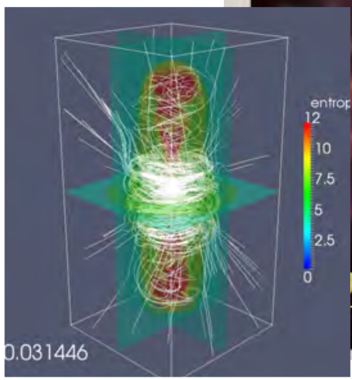
Core Collapse Supernovae

- 3D effects are crucial (← ^{44}Ti X/gamma rays!)

NIC 2018



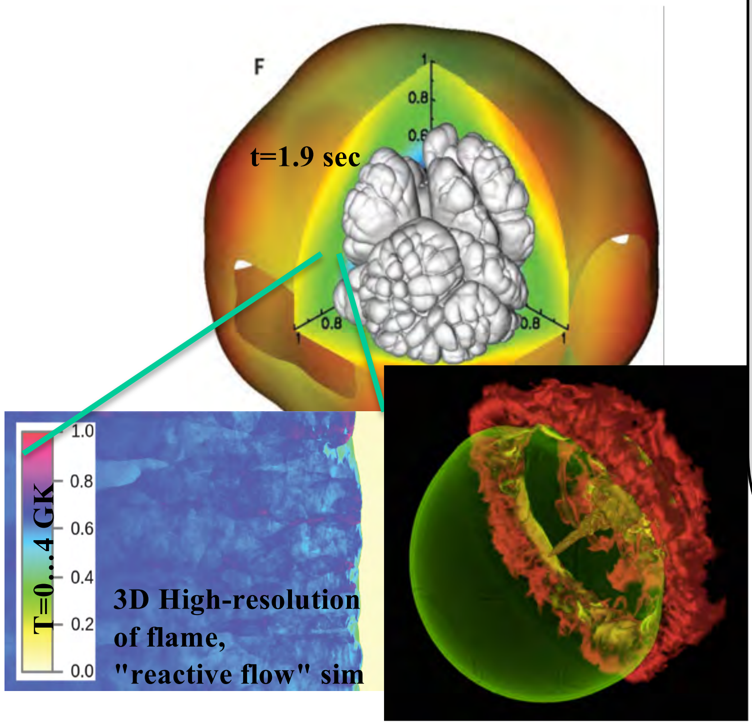
- + rare variants!

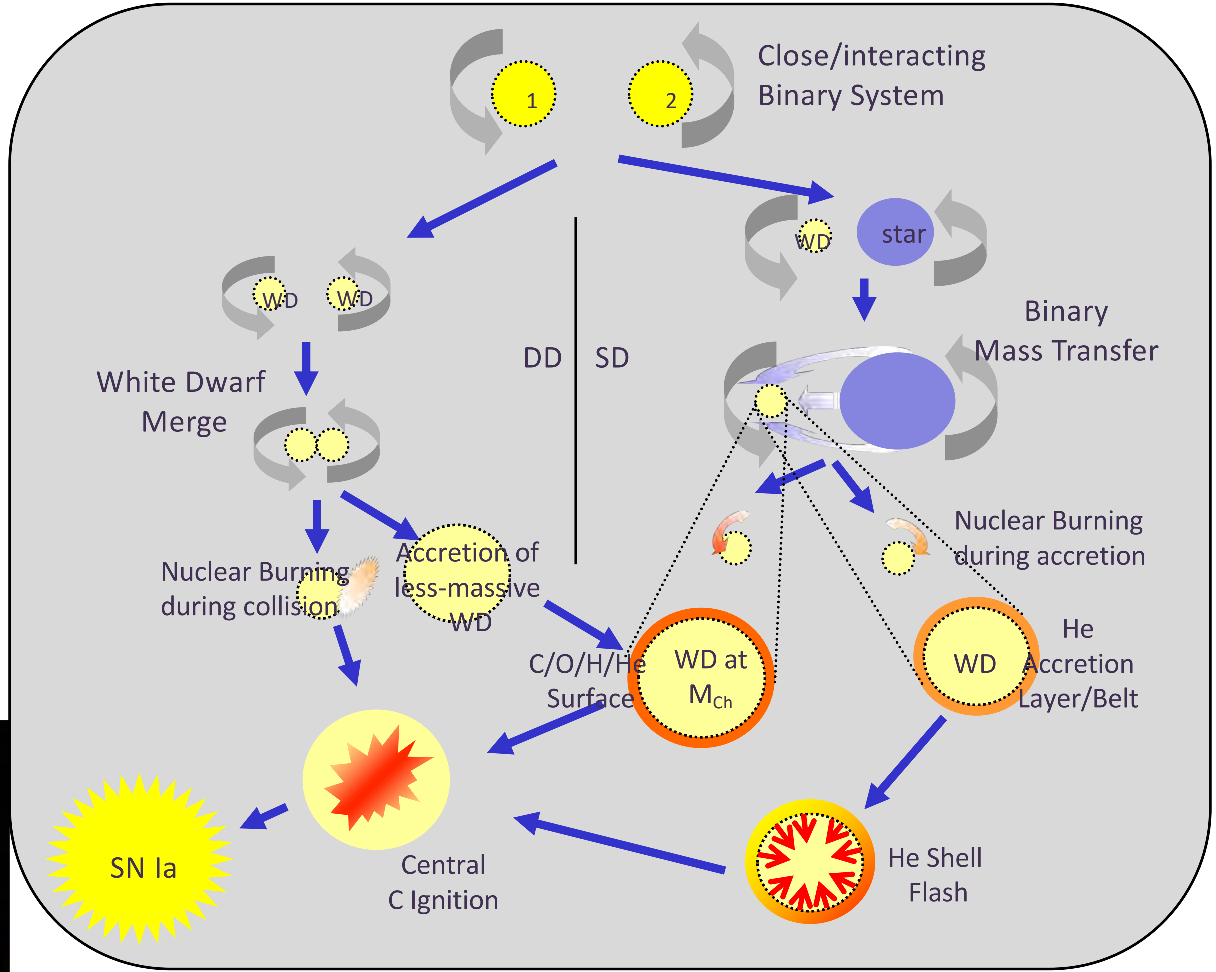


How we understand supernovae of type Ia

☆ Consensus:
Explosion of a CO WD (C fusion)

☆ Issues:
- Ignition
- Flame propagation

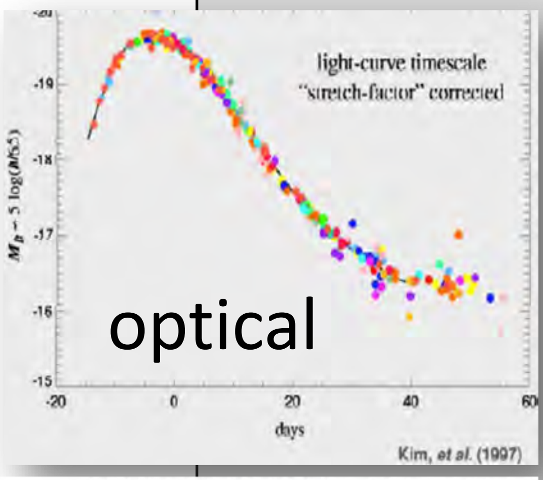


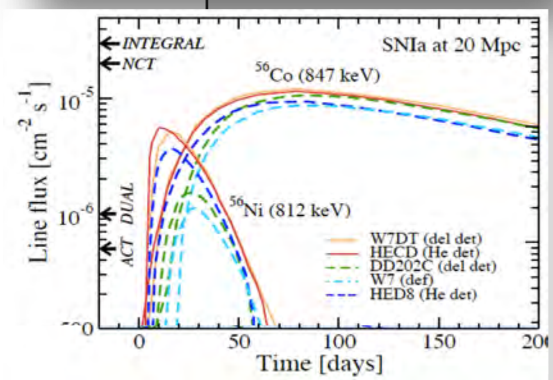


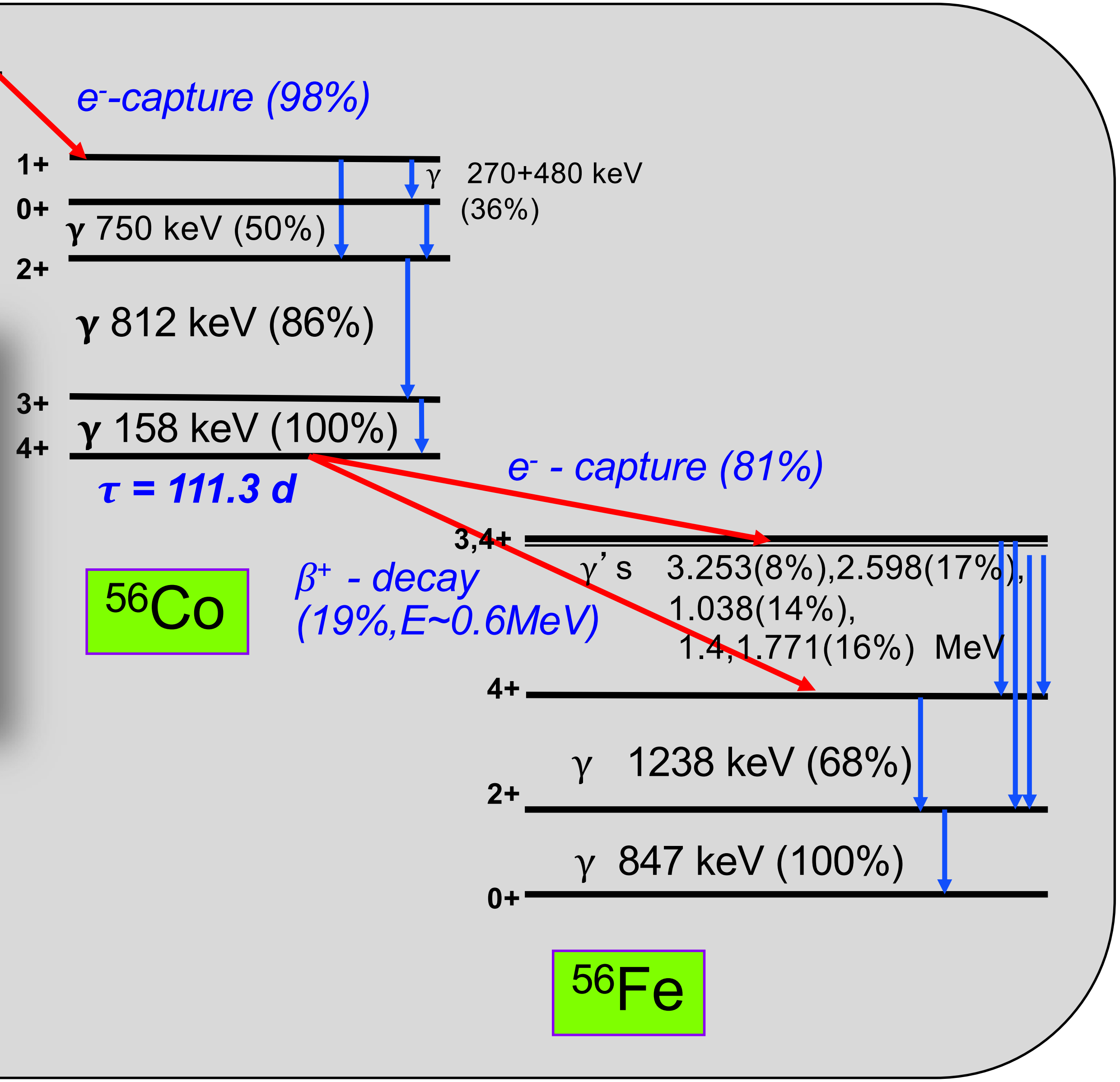
☞ ??

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

SN Ia



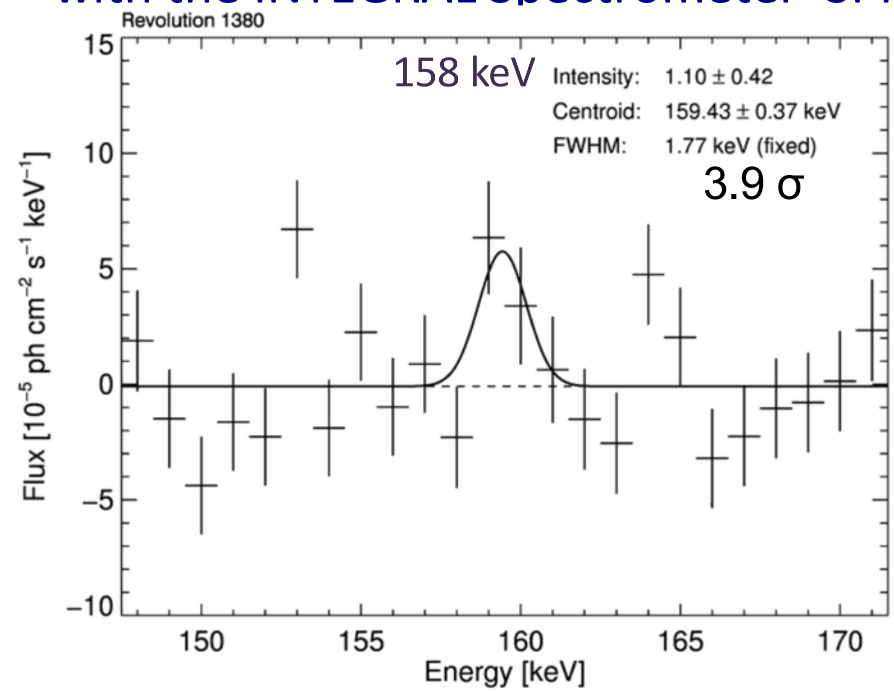


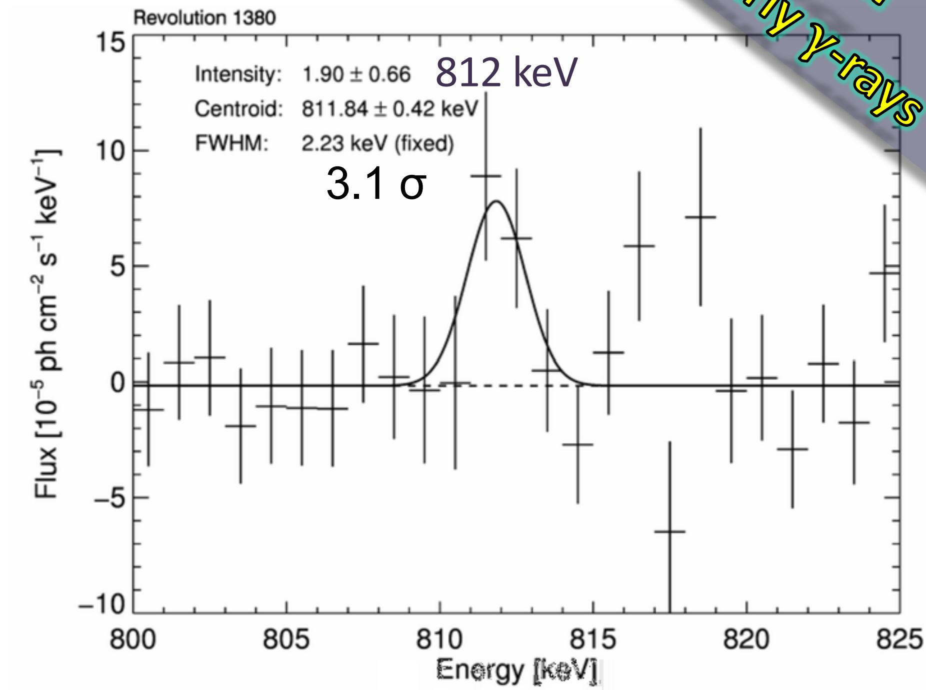


SN2014J: Early ^{56}Ni

Unexpected
SN should absorb early γ-rays

- Spectra from the SN position
  - ☆ Clear detections of the two strongest lines expected from ^{56}Ni with the INTEGRAL Spectrometer 'SPI'





  - ☆ Intensities:

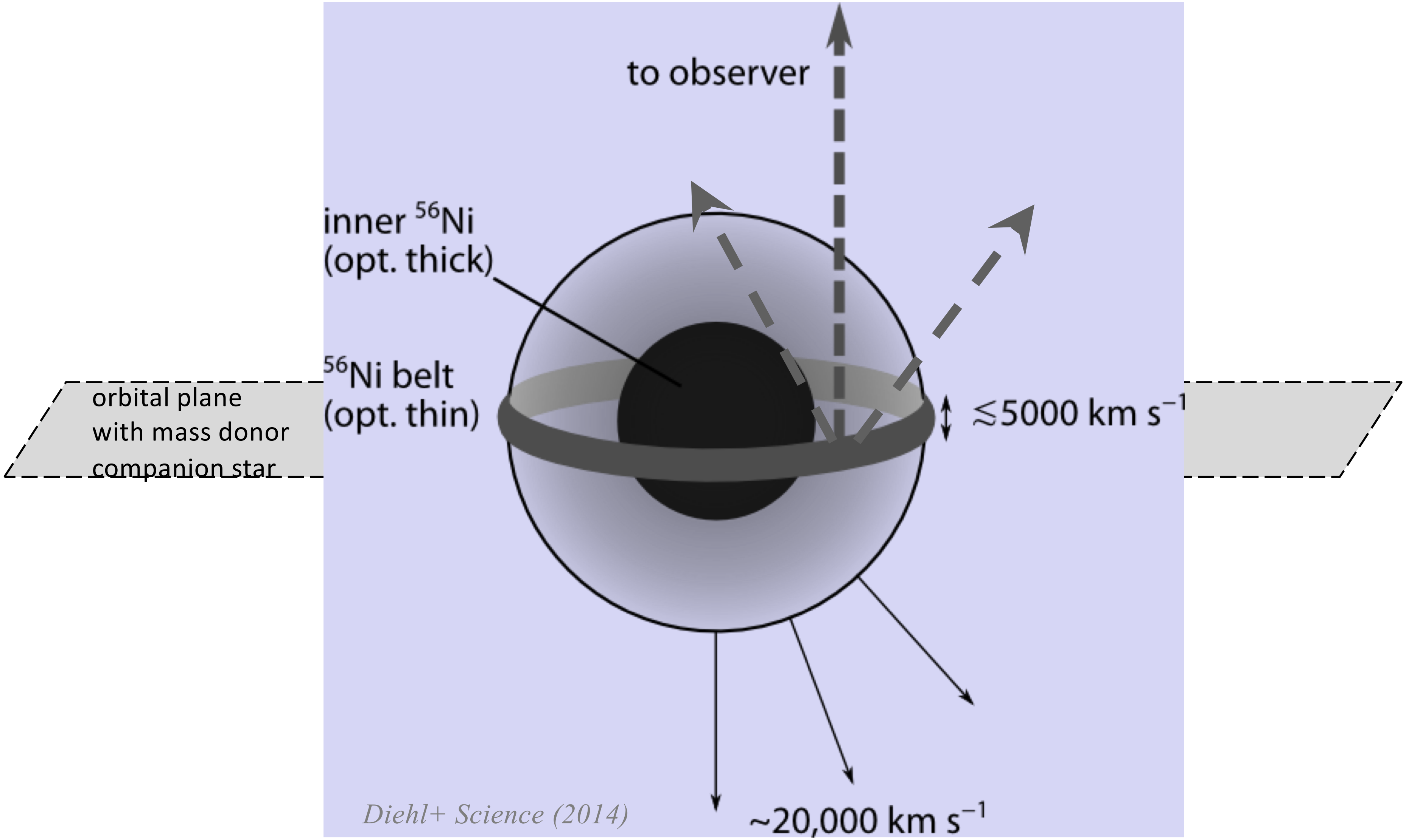
    $(1.14 \pm 0.43)\ 10^{-4}$ ph cm^{-2} s^{-1} (158 keV line)

    and $(1.91 \pm 0.67)\ 10^{-4}$ ph cm^{-2} s^{-1} (812 keV line)
  - ☆ ^{56}Ni mass estimate (backscaled to explosion): ~0.06 $M_{\odot}$

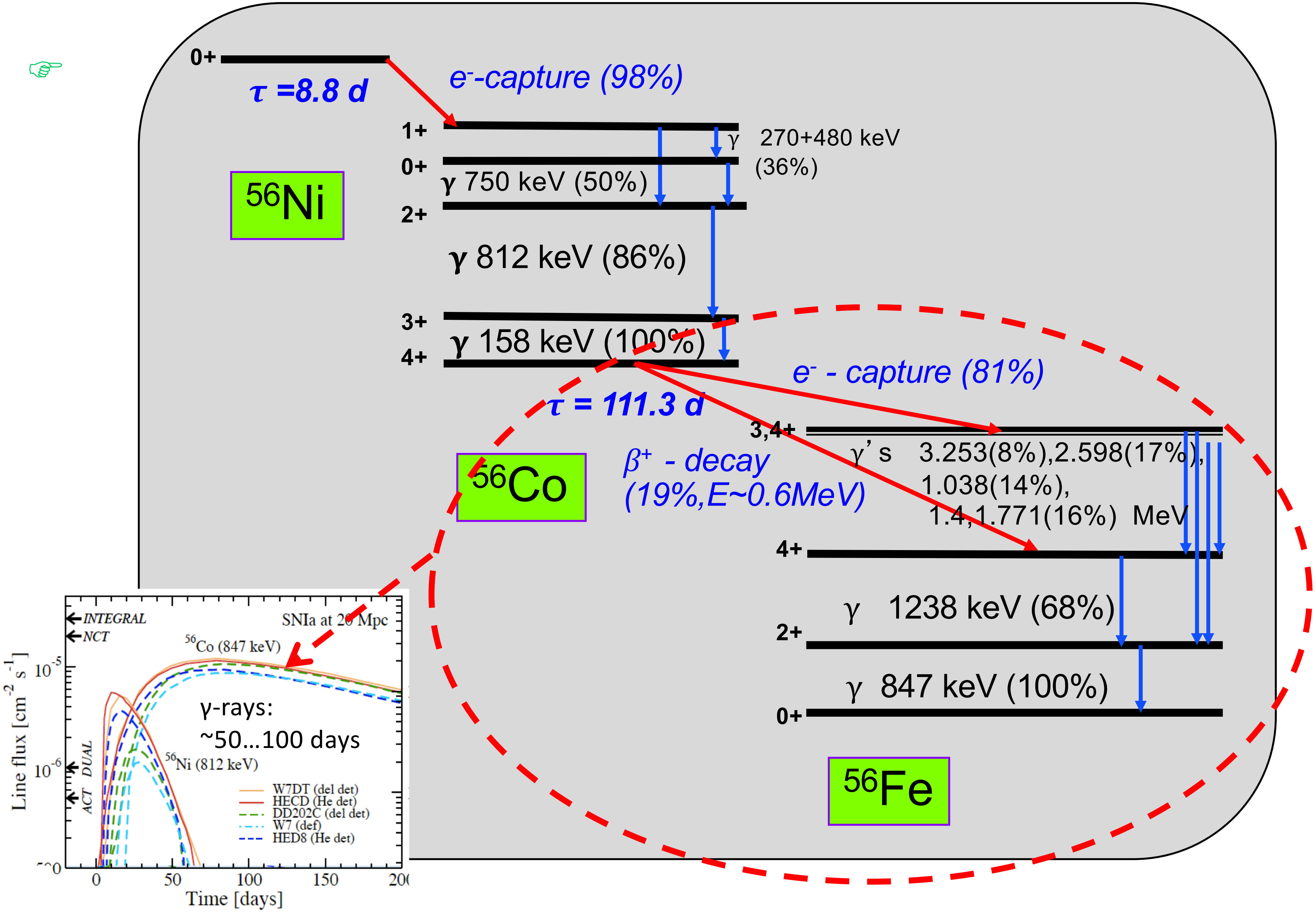
SN2014J: An unusual (triggered) explosion?

Possible scenario:

A belt of He accreted from the companion star → initial He explosion, triggering the SNIa explosion of the CO white dwarf ($M<M_{ch}$)



^{56}Ni Radioactivity: Decay Chain and Gamma-Rays



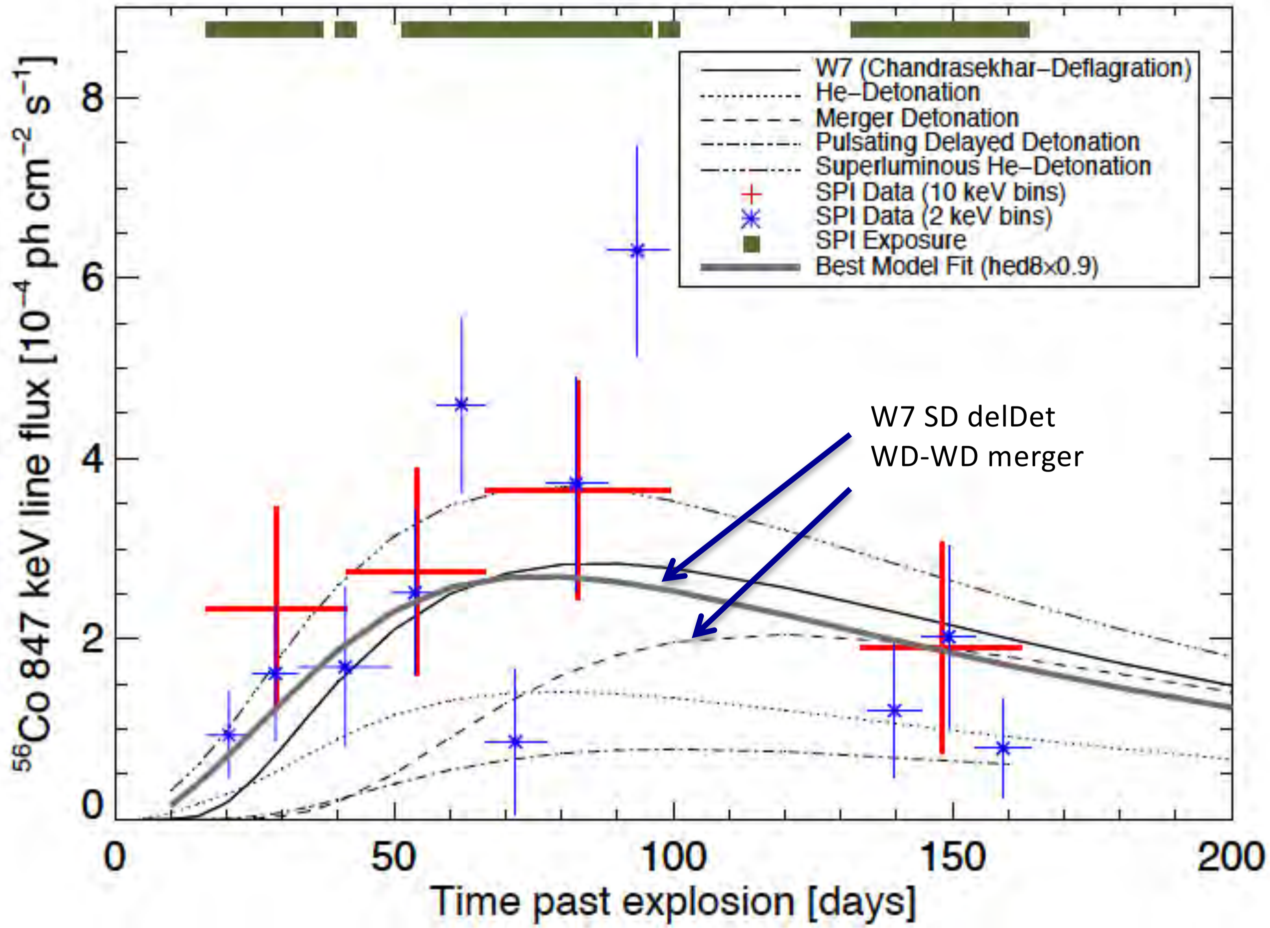
SN2014J data Jan – Jun 2014: 847 keV ^{56}Co line

☆ Track emergence of gamma rays i.e. fading energy deposit

Saul Perlmutter Brian Schmidt Adam Riess

Nobel Prize 2011

→ Calibration of optical emission against ^{56}Ni amount!



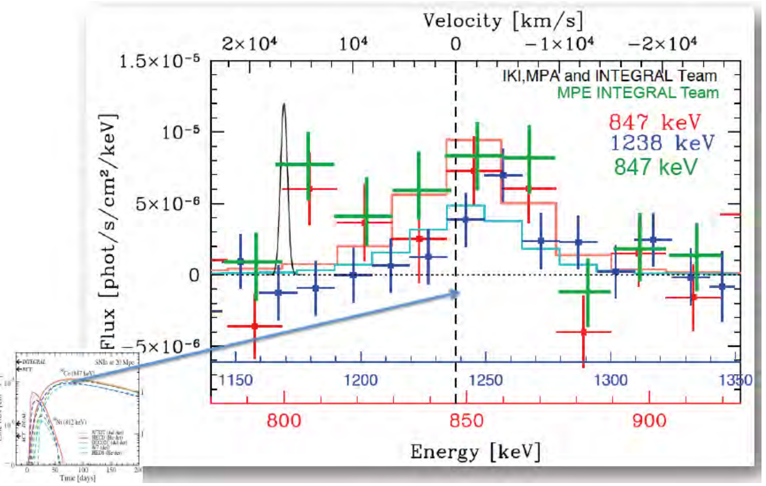
☆ ^{56}Ni mass (fitted): 0.49 +/-0.09 $M_\odot$

(cmp from empirical law) → 0.42 +/-0.05 $M_\odot$

(from models) → 0.5 +/-0.3 $M_\odot$

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

☆ Doppler broadened ✓



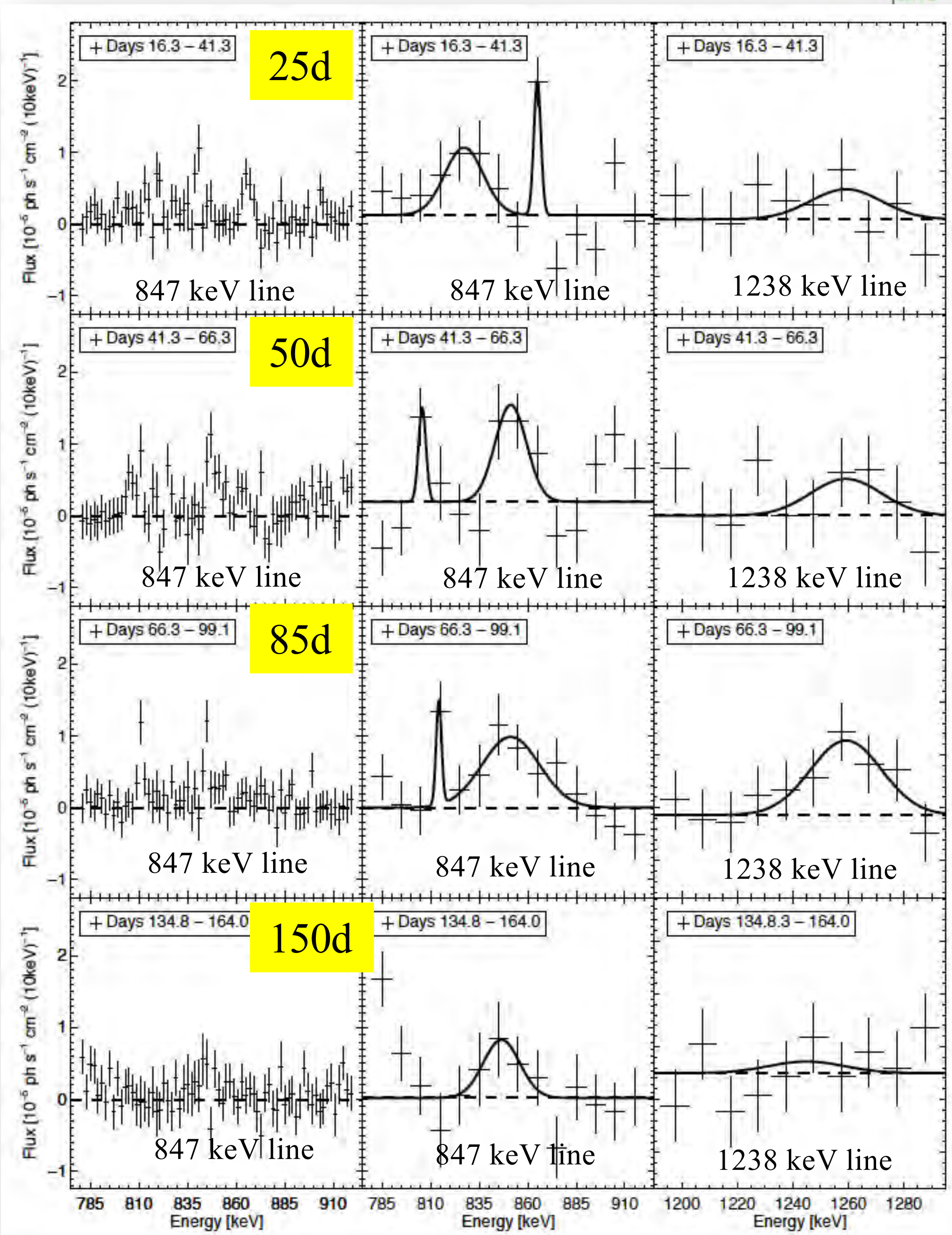
☆ Coarse & fine spectral binning

→ Observe a structured and evolving spectrum

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

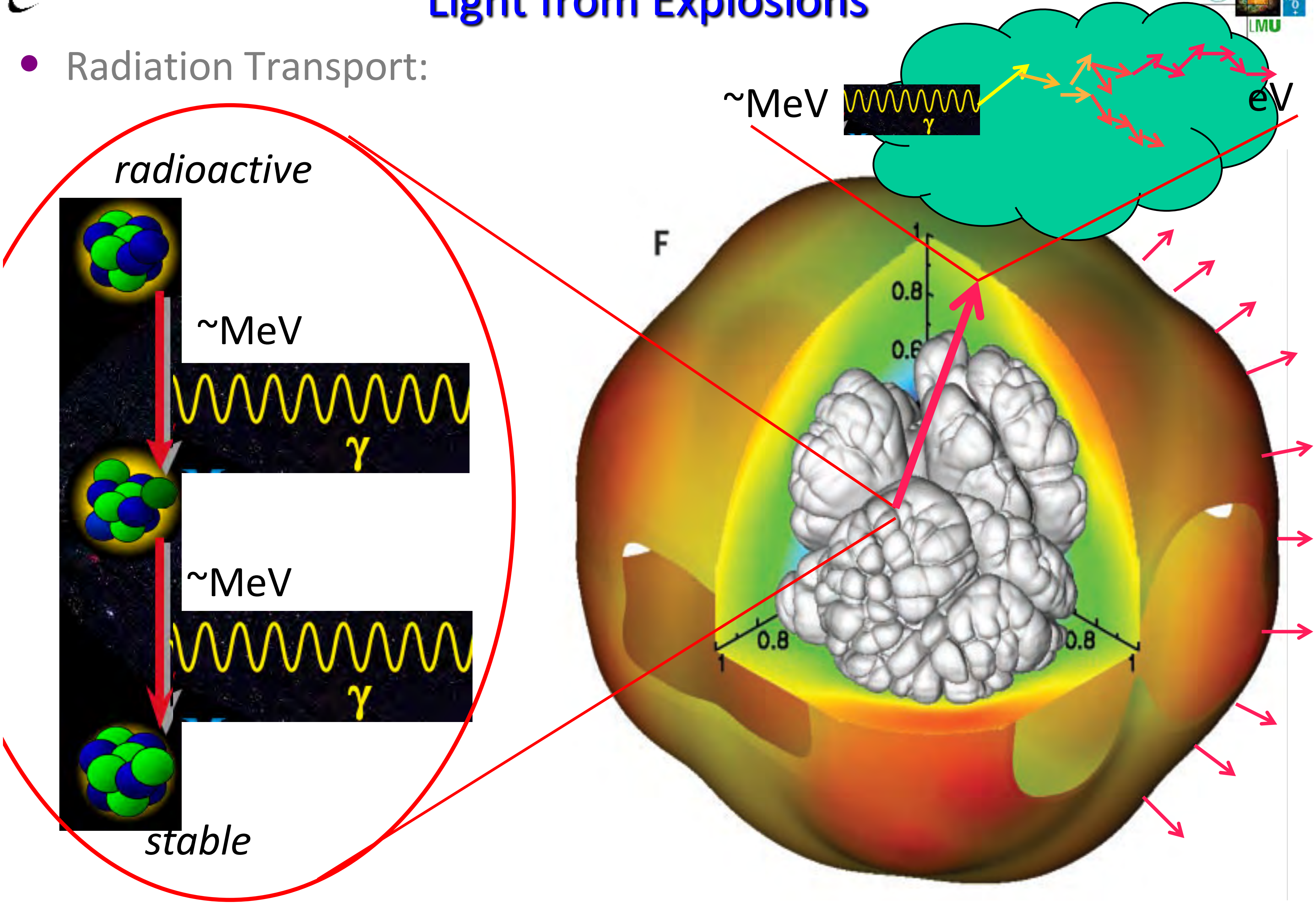
☞ *Diehl et al., A&A (2015)*

☆ ***How an envelope becomes transparent after an explosion***

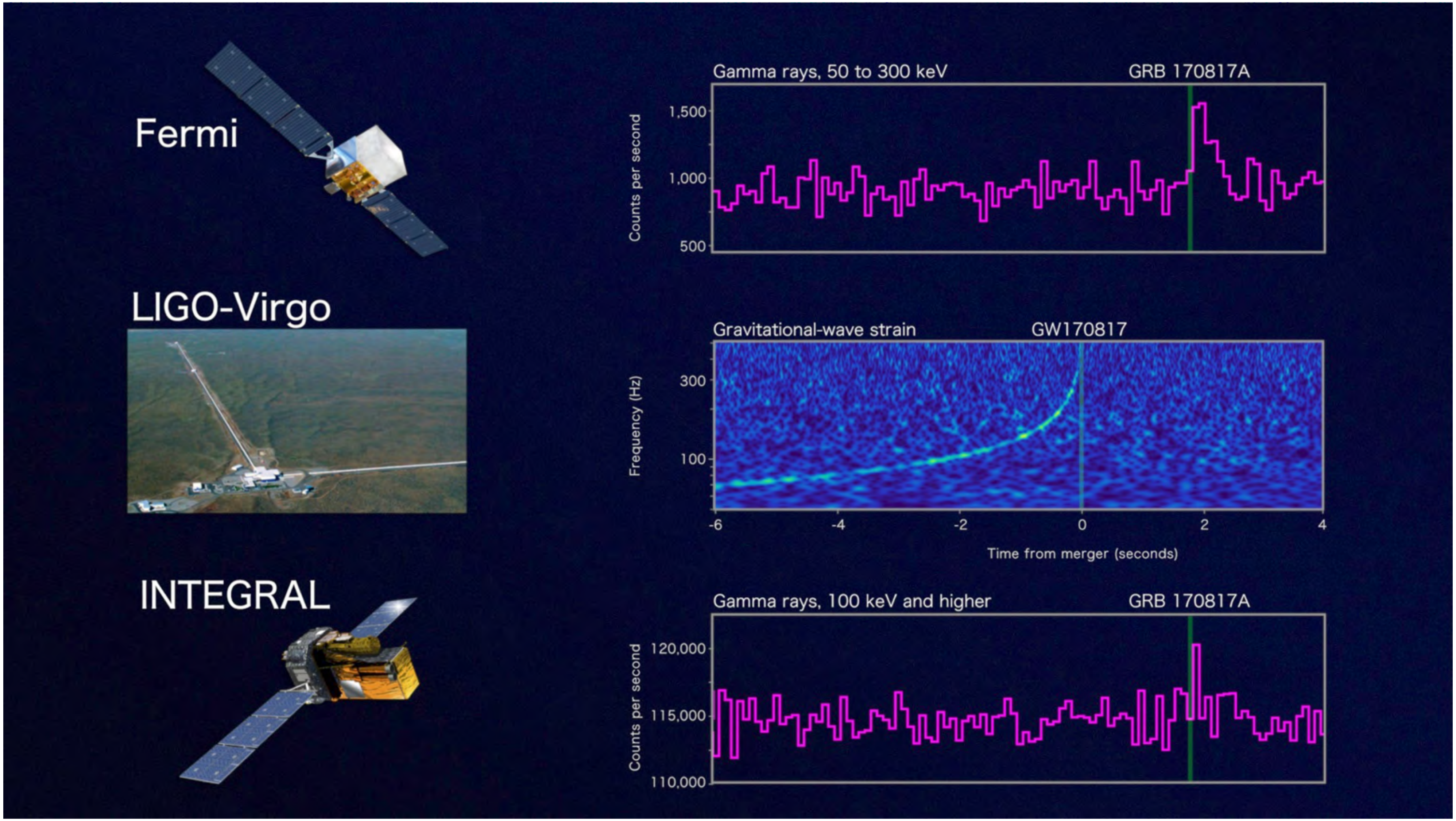


Light from Explosions

- Radiation Transport:



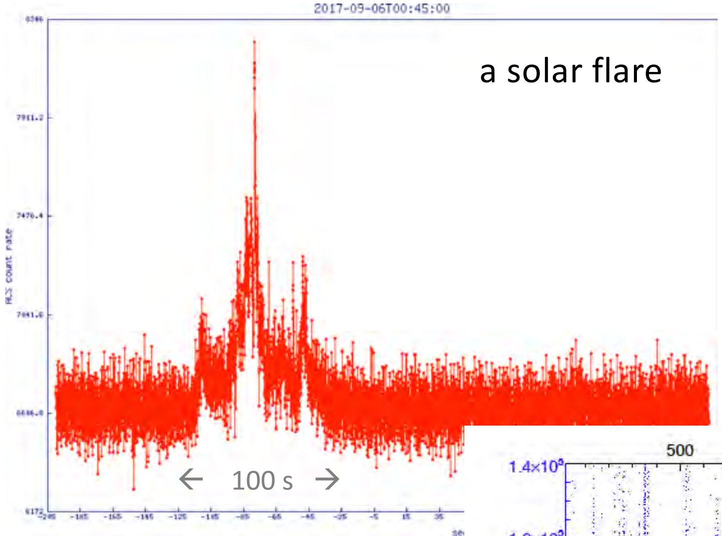
A short GRB from Colliding Neutron Stars!

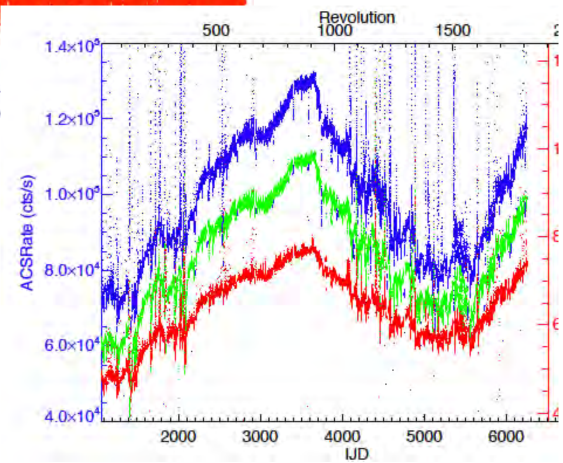


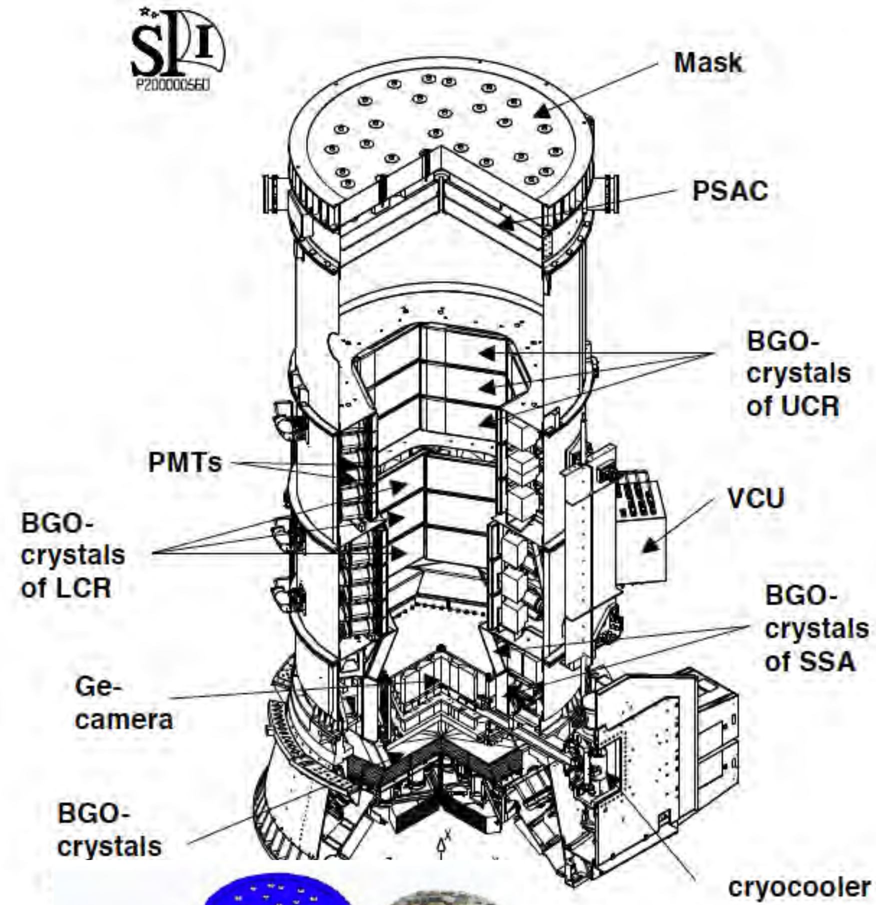
INTEGRAL's most-sensitive GW γ-ray Instrument

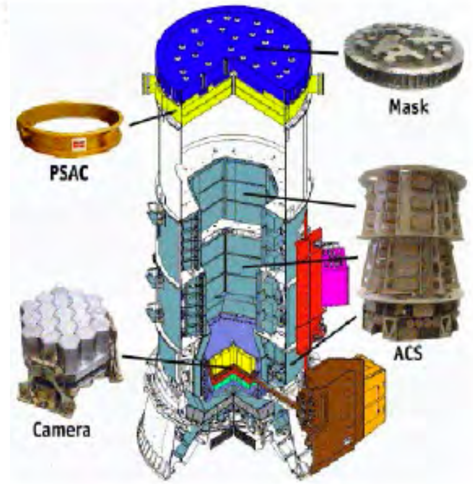
The SPI-AntiCoincidenceSystem (ACS)

- 500 kg (world-largest) BGO scintillation detector, 91 modules
- rate sampling at 50 ms intervals
- used for CR bgd event suppression









Models for prompt gamma-ray emission

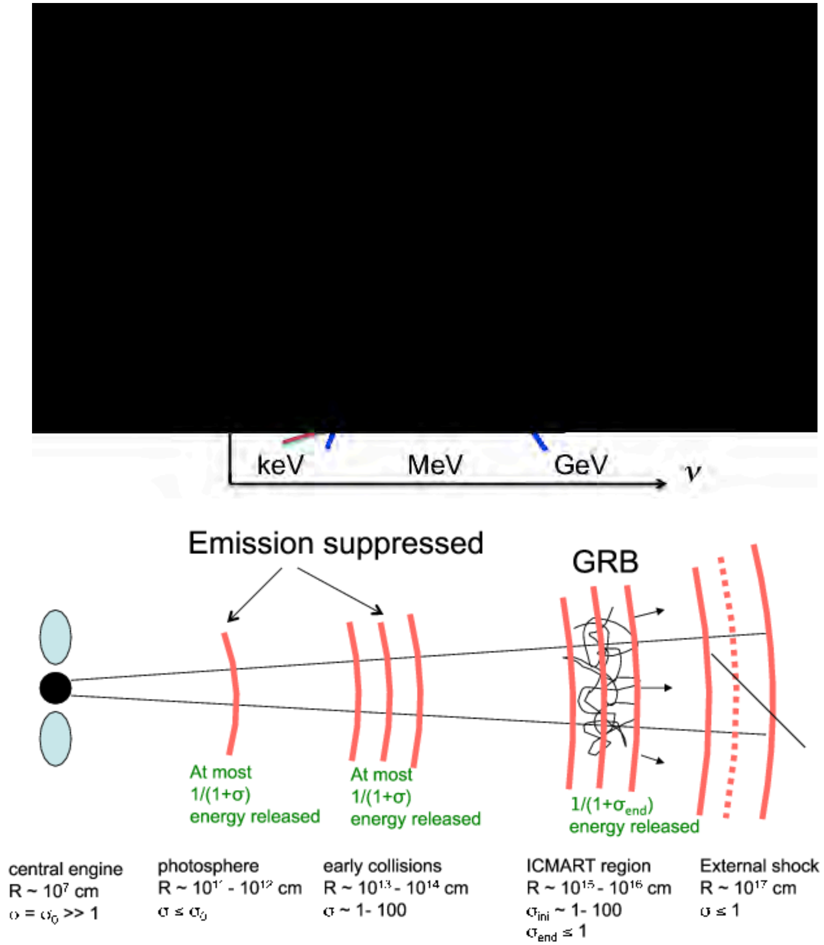
Standard model:

Synchrotron emission from the electrons that were Fermi-accelerated in these internal shocks

(but not undisputed: main problem is the necessary high efficiency)

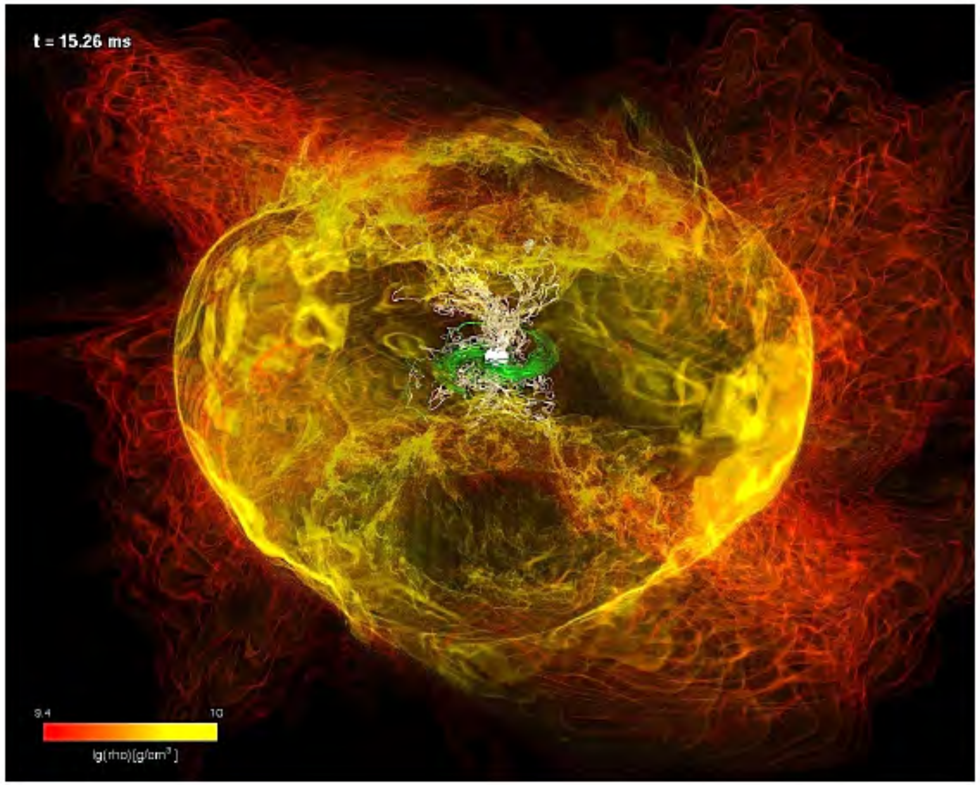
Alternative models

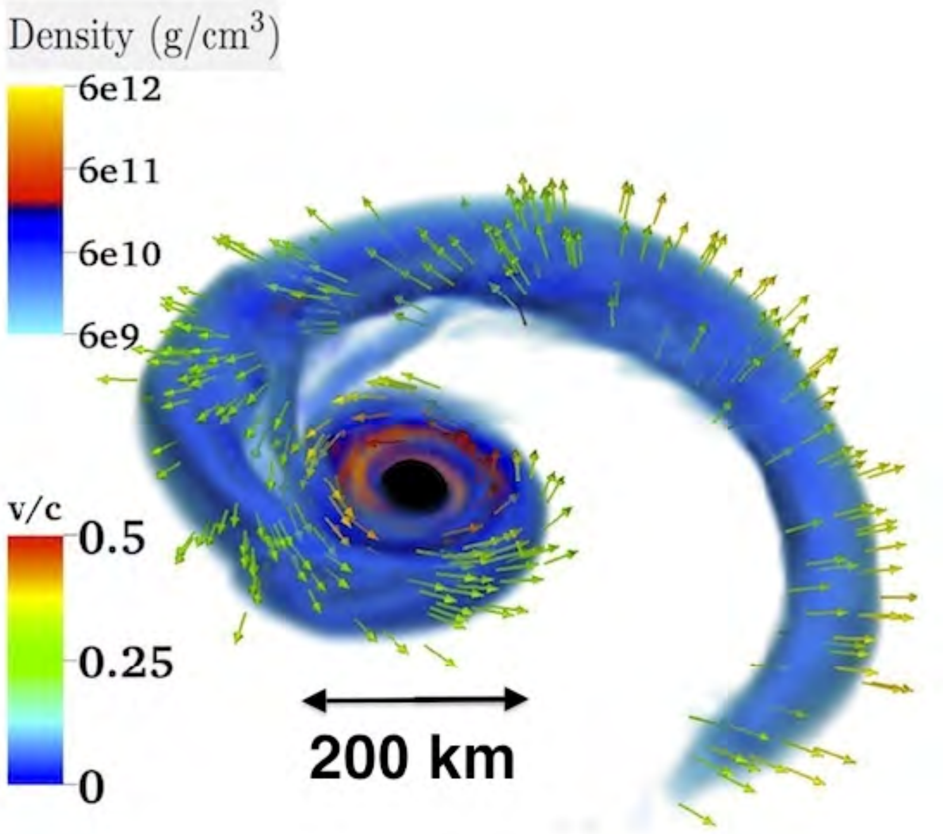
- Photospheric emission:
  sub-photospheric heating leads to broadening of Planck spectrum
- Magnetically dominated jet:
  magnetic reconnection leads to broad-band spectrum



Post-merger dynamics

disruption of less-massive neutron star → ejection, nuclear reactions



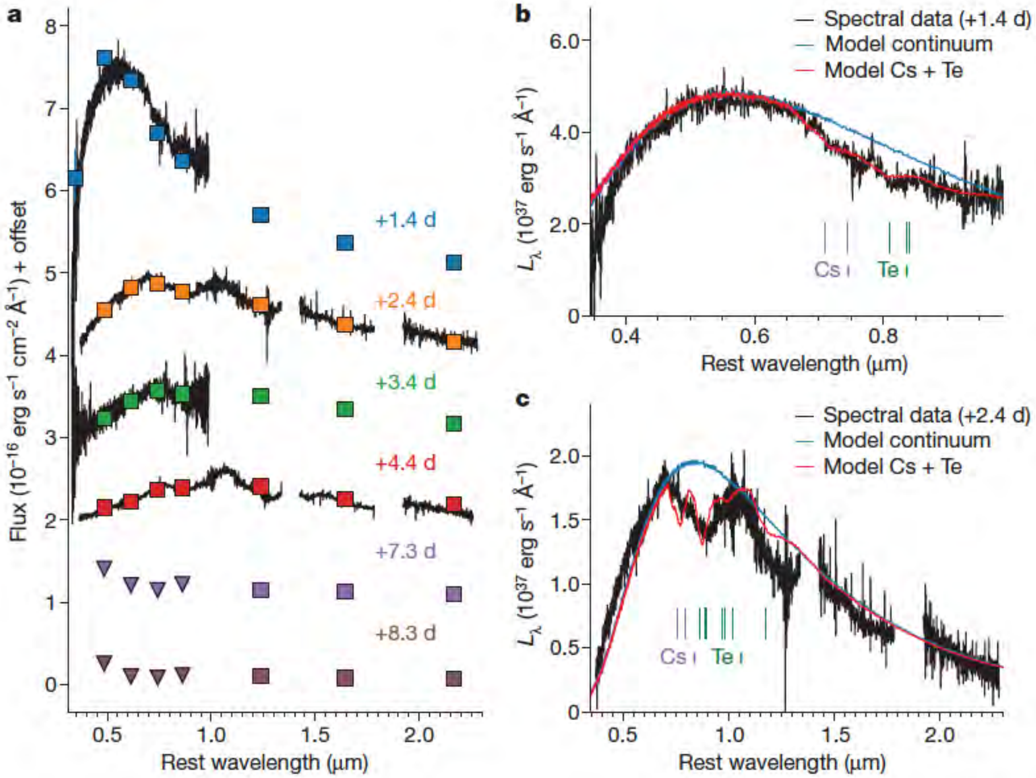


Fernández & Metzger 2016 from Rezolla+ 2011, and Fouchart+ 2014

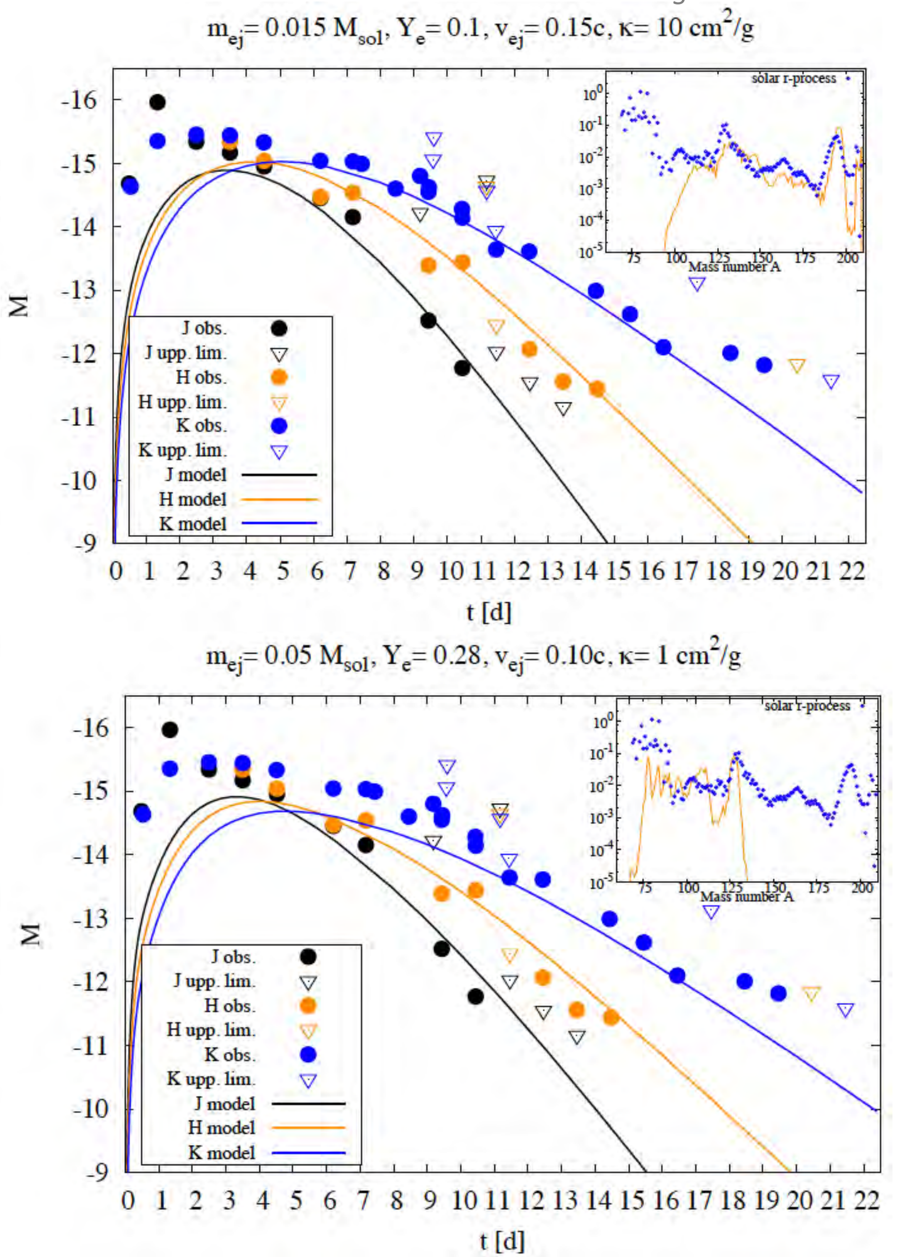
Nucleosynthesis from a NSM

radioactivity from r-process isotopes !

Smartt+2017



Rosswog+2018



☆ which isotopes?

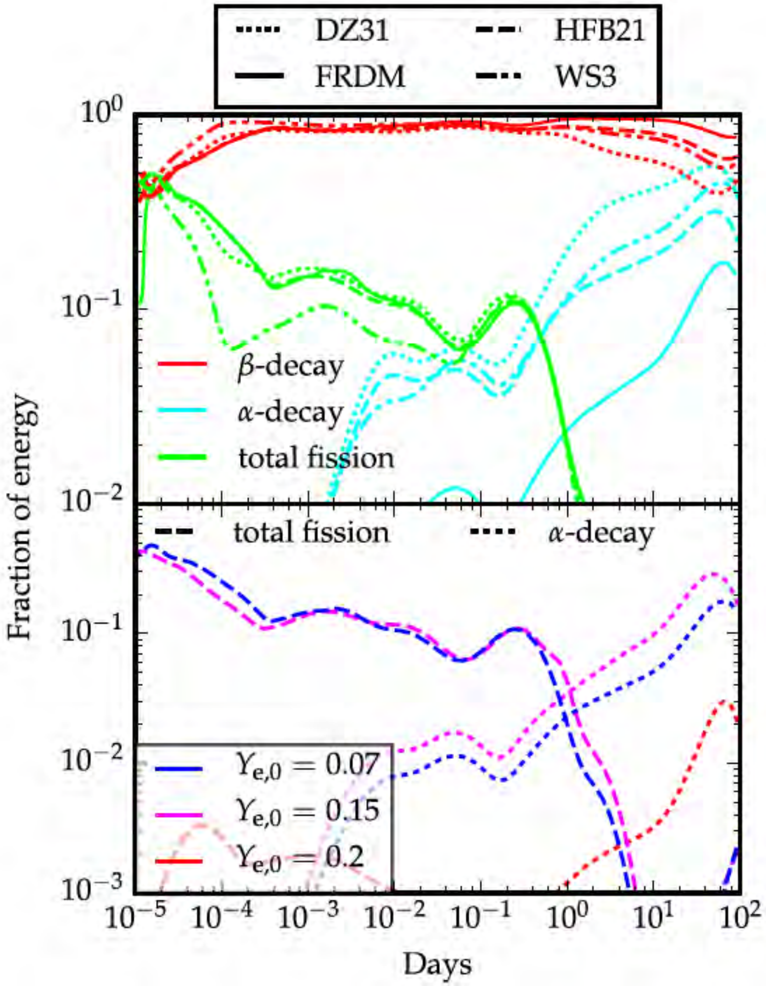
- ☞heavy (up to A~195) ??
- ☞lighter (A<130) ??

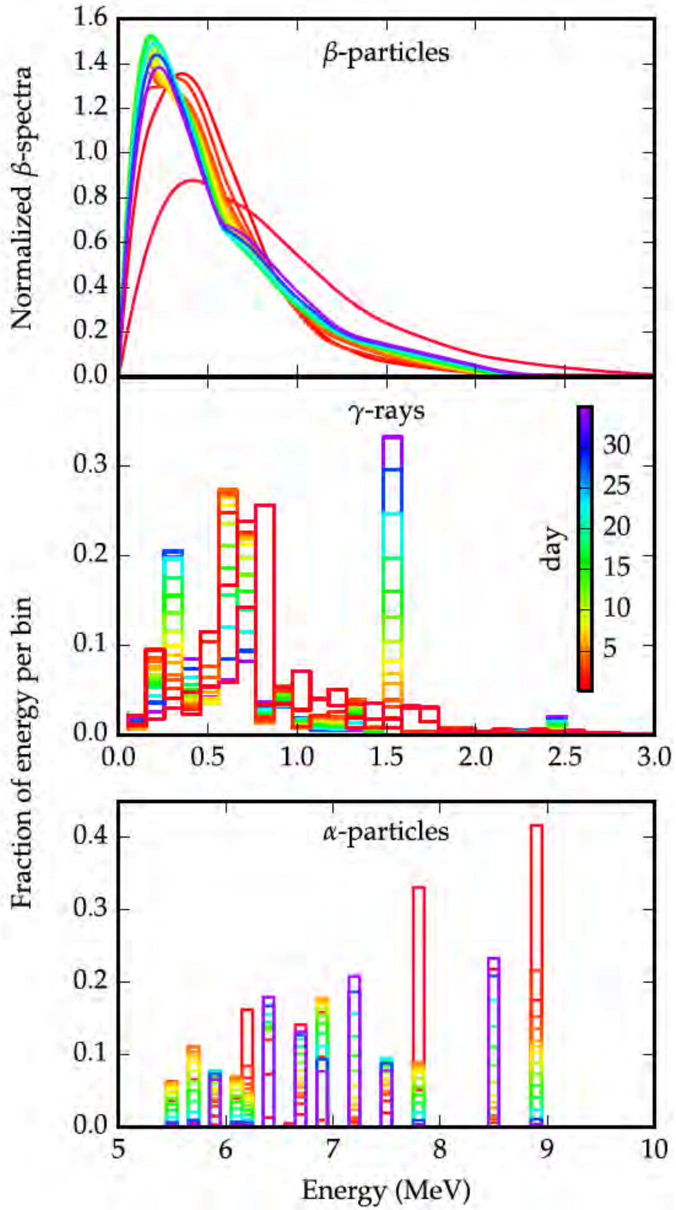
(both provide acceptable fits!)

Radiation Transfer from Radioactivity

Barnes et al. 2016

Radioactive decay:



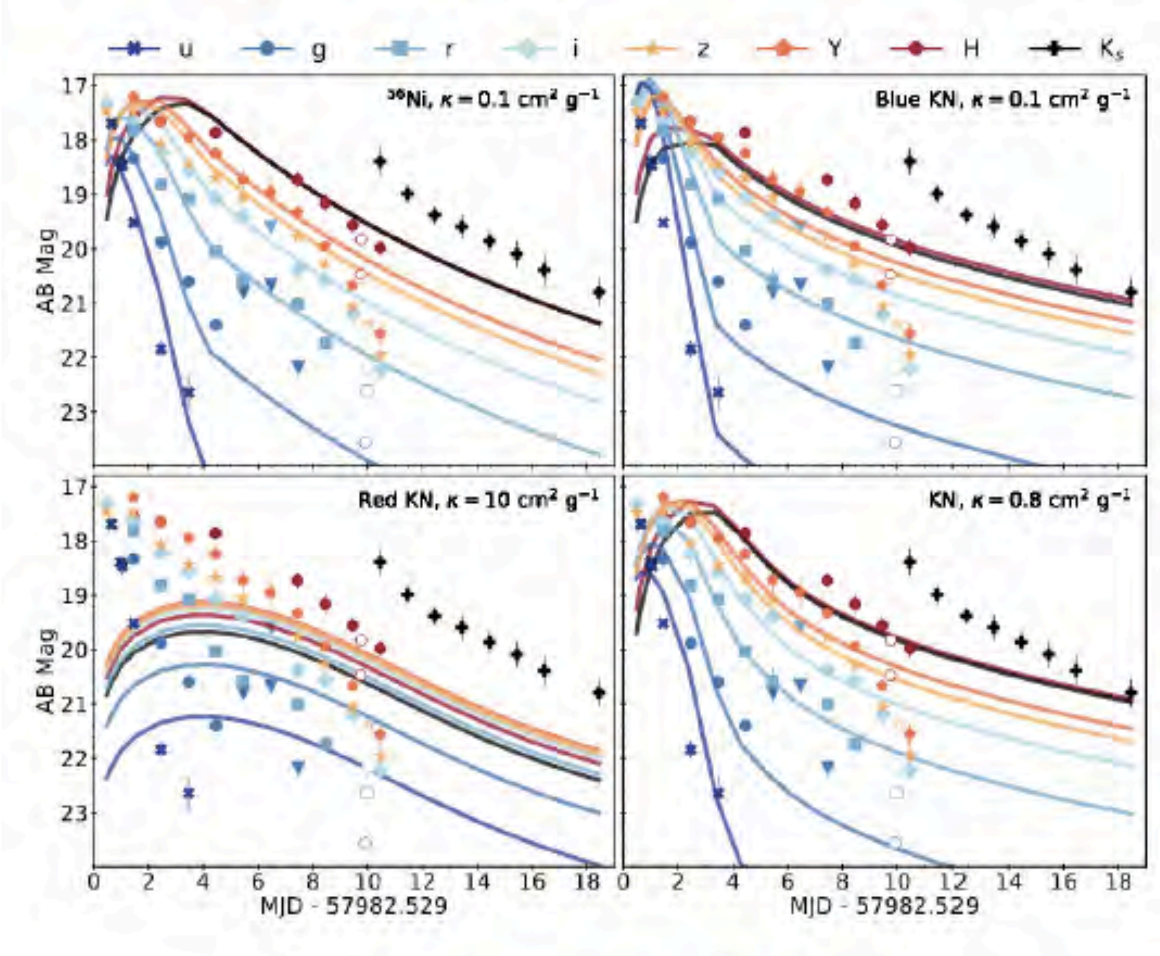


→ Inputs ~ as in SNe,
but with late α particle E deposits

Understanding Radiation Transfer in Kilonovae

- Single-Component Models Cannot Fit Multi-Color Light Curves:

☞from A. Perego



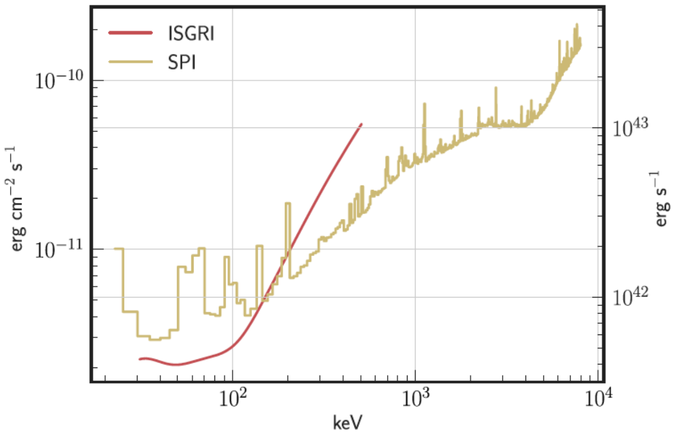
Cowperthwaite+ 2017, ApJL

- Need Multiple Components (→ multiple model parameters)

INTEGRAL γ-ray line measurements of GW170817?

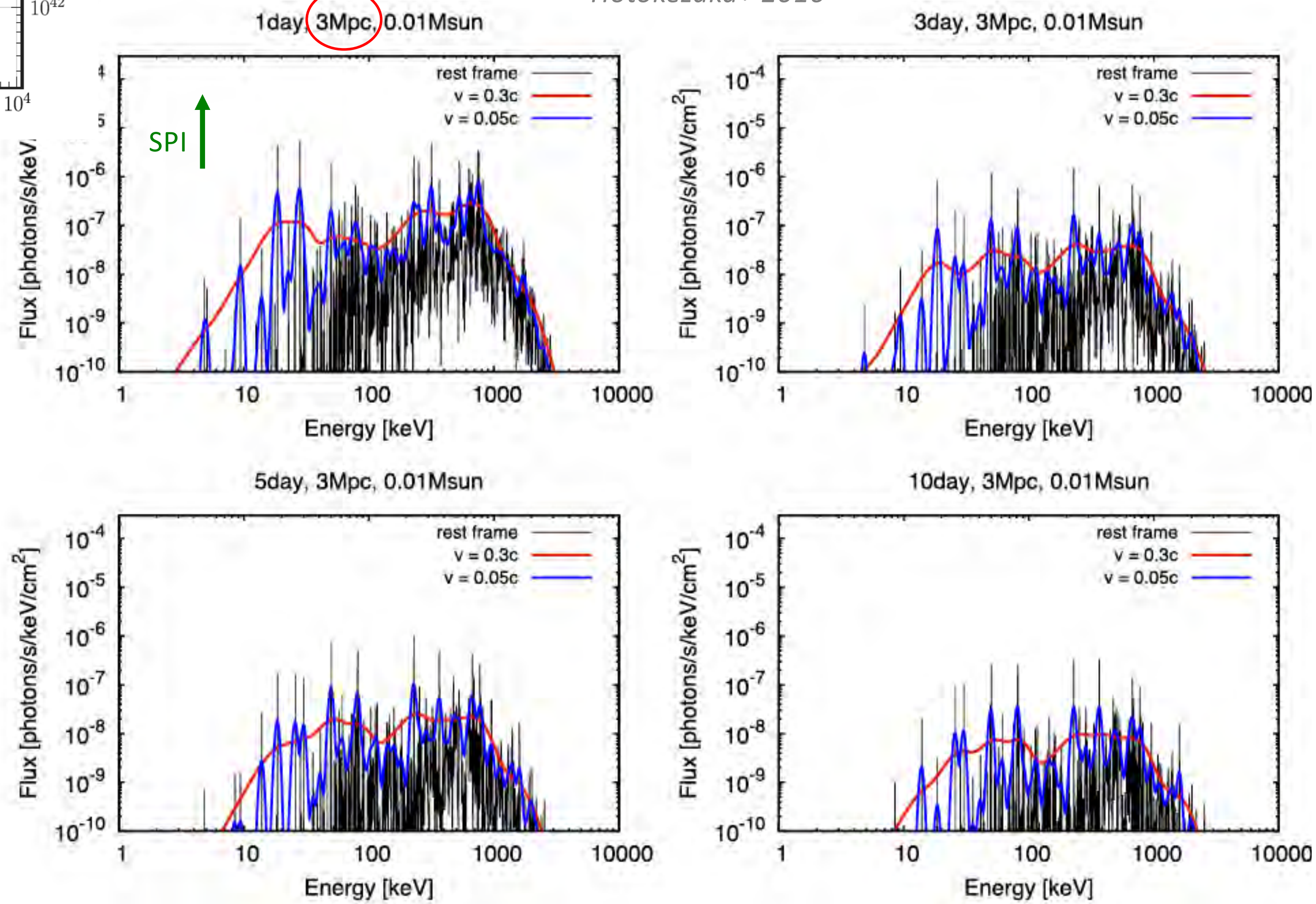
Help from characteristic gamma rays (radioactivities):

GW170817 is too distant!



Savchenko et al. 2017

Hotokezaka+ 2016



Cosmic Radioactivities **Summary**

- ☆ Radioactivity γ-rays provide a unique / different view
  - ☞ Yield constraints for SNe and Novae, Independent of complexity from unfolding of the explosion
  - ☞ Radioactivity traces diluted ejecta at late phases
- ☆ SNIa ^{56}Ni and how the explosion generates SN light
  - ☞ SN2014J reveals its ^{56}Ni,^{56}Co irregularly → 3D effects?
- ☆ ccSupernova ^{44}Ti demonstrates SN asymmetries
  - ☞ Only Some SN Eject ^{44}Ti, but then much, and clumpy
- ☆ Massive-star shell structure & evolution tests: ^{26}Al, ^{60}Fe
  - ☞ ^{26}Al as a tool: understand groups of massive stars (Mys)
  - ☞ How much ^{60}Fe from n captures in C and He shells?
- ☆ ISM in the Galaxy: Role of superbubbles; e$^+$ sources
  - ☞ ^{26}Al spreads into large (super)bubbles
  - ☞ e$^+$ sources are a variety & puzzle; incl μQSOs