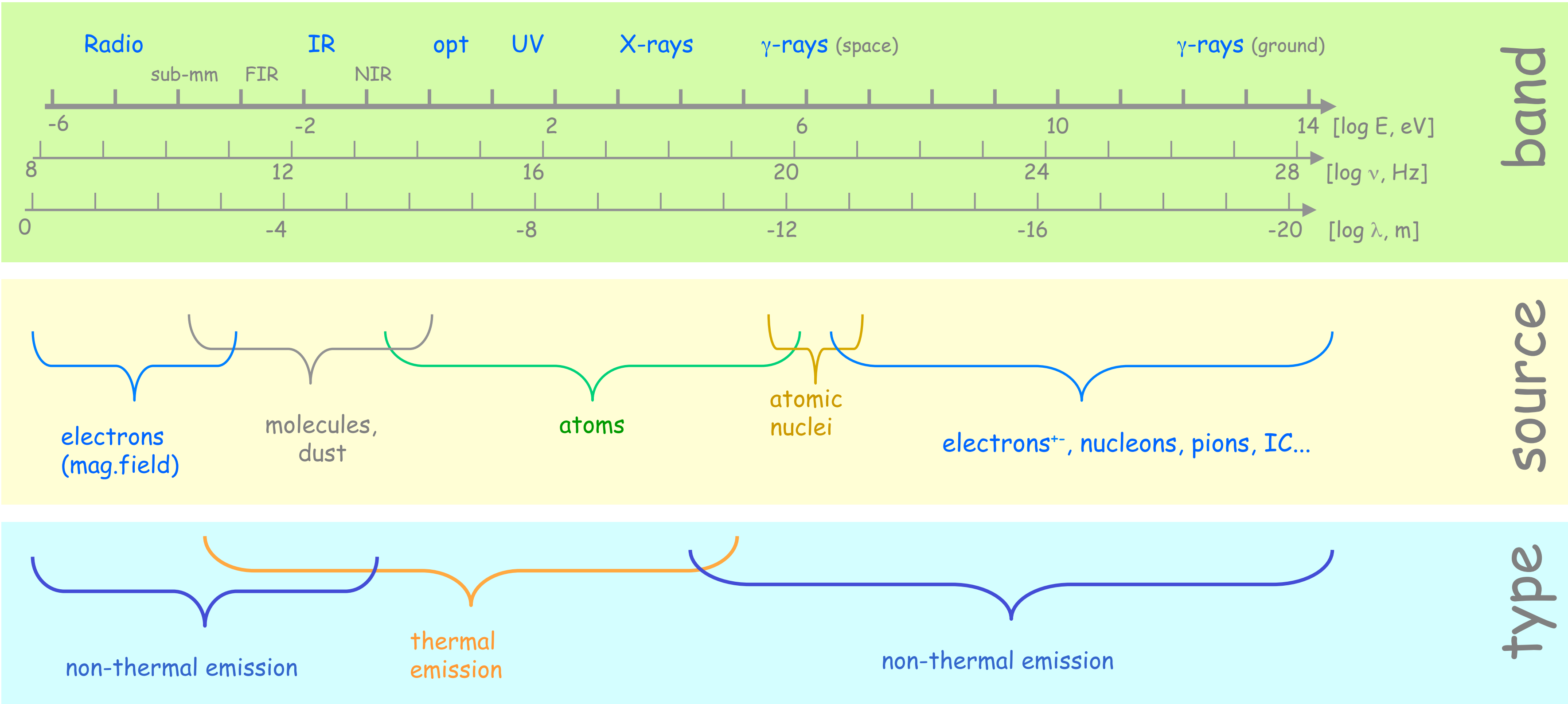
Cosmic Radioactivity

Radioactivity in Astrophysics

Understanding Cosmic Sources

Roland Diehl

Astronomy across the Electromagnetic Spectrum



☆ **"Nuclear" Astronomy:**

- **Diagnostics of high-energy processes MeV...100 MeV; Non-Thermal Emission**
- **Radiation Characteristics for Astronomy:**
  - **Intensity not dependent on ionization states, temperature**
  - **No attenuation/occultation issues**

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Astronomy with Radioactivities

☆ A Clock

$I(t-t_0) \sim \exp(-(t-t_0)/\tau)$

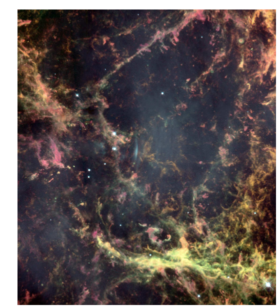
☞ **Dating event times or durations**

^{26}Al ... ^{59}Ni ...

- **cosmic-ray acceleration delay after nucleosynthesis**
- **interstellar-gas mixing time**
- **....**

☆ Emission due to Weak Interaction

$I(t)$ independent of $\rho(t)$, $T(t)$,..



☞ **Resolve uncertainties in thermodynamic state**

- **ionization state & gas temperature**
- **absorbing gas**
- **...**

Applications of Astronomy with Radioactivities

- ☆ **Supernova Explosions**
  - ☞ SNIa and ^{56}Ni Decay
  - ☞ Core-collapse Supernovae: ^{56}Ni and ^{44}Ti Yields
- ☆ **Nova Explosions**
  - ☞ Positrons from β^+ Radioactivities; Explosive H Burning and ^{22}Na Production
- ☆ **Stellar Interiors**
  - ☞ Massive Stars and ^{26}Al Production in Core and Shells
  - ☞ Massive Star Shells and s-Process Conditions (^{60}Fe)
  - ☞ Neutron-Star Crust Conditions of Thermonuclear Flashes (Type-I XRBs)
- ☆ **The Early Solar System**
  - ☞ ESS Radioactivities and Late-Nearby Nucleosynthesis
  - ☞ Formation of Solid Bodies in ESS
- ☆ **The Interstellar Medium**
  - ☞ Dating Nucleosynthesis Events, Nucleocosmochronology
  - ☞ Propagation and Mixing of Nucleosynthesis/SN Ejecta
  - ☞ Propagation and Annihilation of Positrons from β^+ Radioactivities
- ☆ **Cosmic Ray Origins and Propagation**
  - ☞ Spallation Production of Radio-Isotopes
  - ☞ Delay between Nucleosynthesis and CR Acceleration

Applications of Astronomy with Radioactivities

- ☆ **Supernova Explosions**
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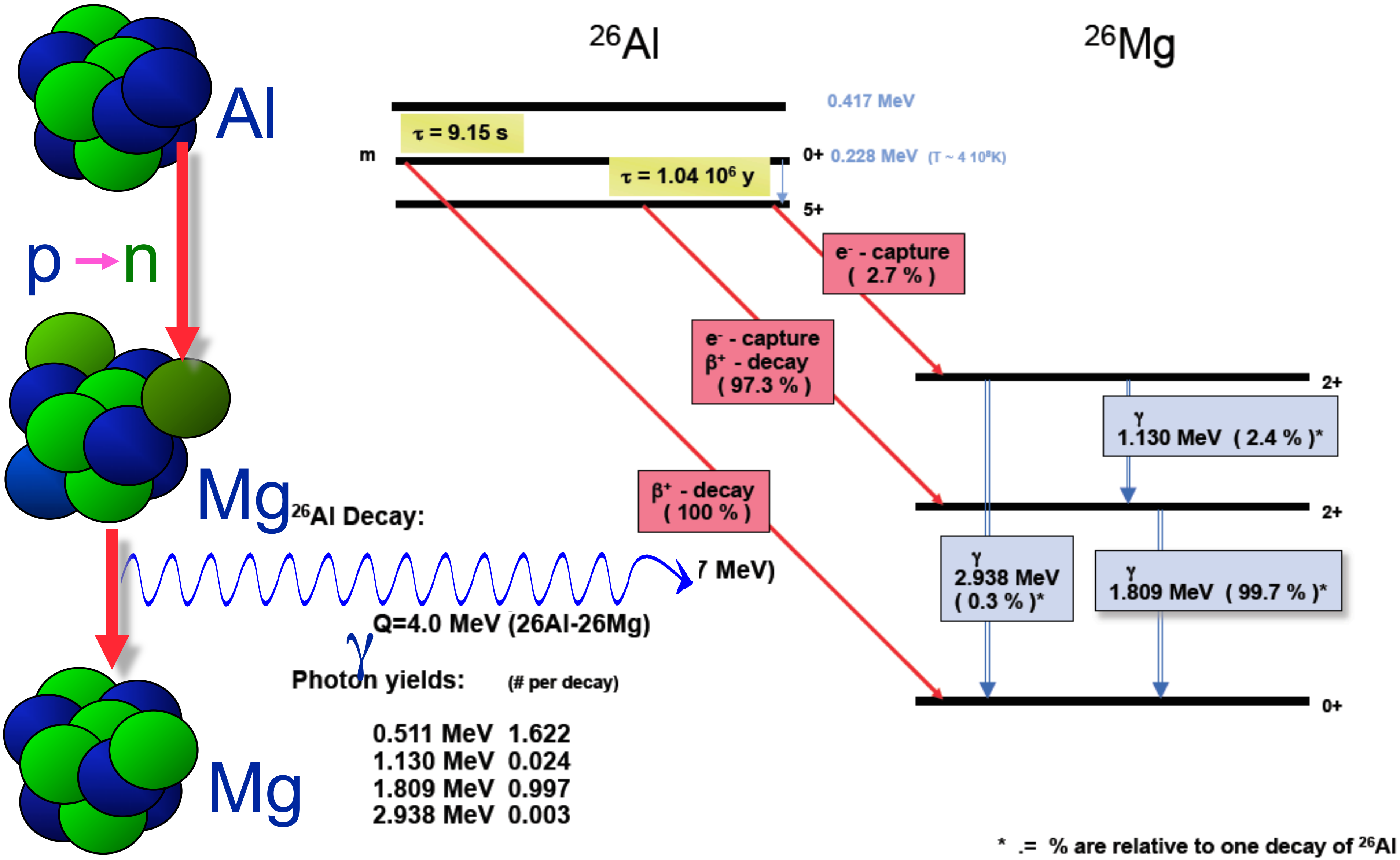
Radioactivity in Astrophysics – an Example



Radioisotope Gamma-Ray Lines and their Messages

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	^{7}Be → ^{7}Li*	478
^{56}Ni	111 d	^{56}Ni → ^{56}Co* → ^{56}Fe*+e^{+}	158, 812; 847, 1238
^{57}Ni	390 d	^{57}Co→ ^{57}Fe*	122
^{22}Na	3.8 y	^{22}Na → ^{22}Ne* + e^{+}	1275
^{44}Ti	89 y	^{44}Ti→ ^{44}Sc*→ ^{44}Ca*+e^{+}	78, 68; 1157
^{26}Al	1.04 10^{6}y	^{26}Al → ^{26}Mg* + e^{+}	1809
^{60}Fe	3.8 10^{6}y	^{60}Fe → ^{60}Co* → ^{60}Ni*	59, 1173, 1332
e^{+}	…. 10^{5}y	e^{+}+e^{-} → Ps → $\gamma\gamma$..	511, <511

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

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

Nuclear Gamma-Ray Line Telescopes / Missions

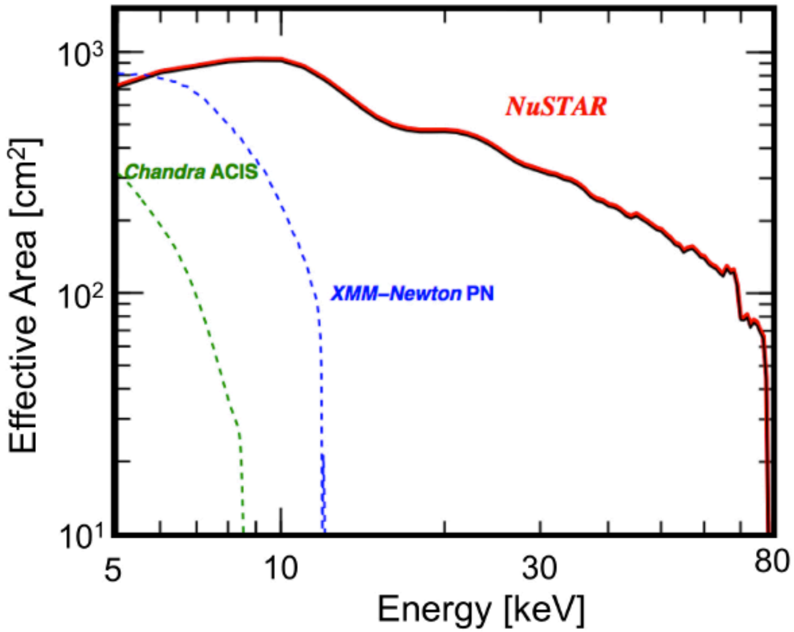
- ☆ **Compton Gamma-Ray Observatory**
  1991-2000
  NASA

- ☆ **INTEGRAL Observatory**
  2002-(2014+)
  ESA

- ☆ Earlier Balloone-Borne Experiments
- ☆ HEAO-C
  1978

NuSTAR

- **An X-Ray Telescope extended towards ^{44}Ti Lines (80 keV)**



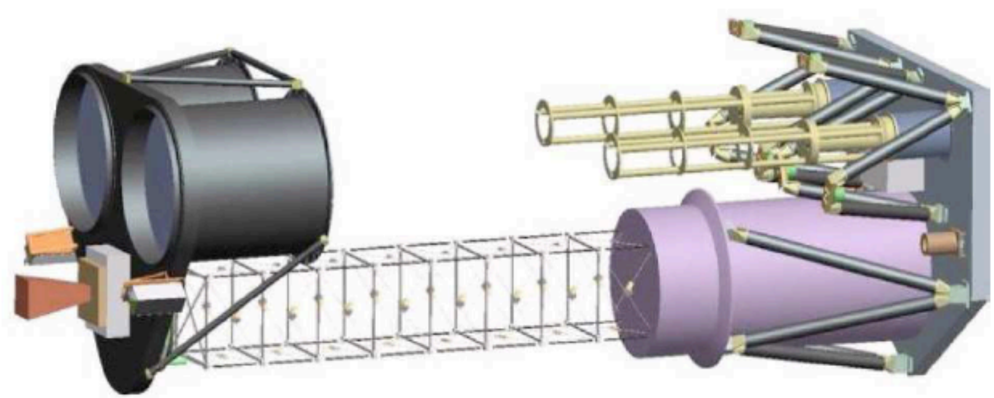
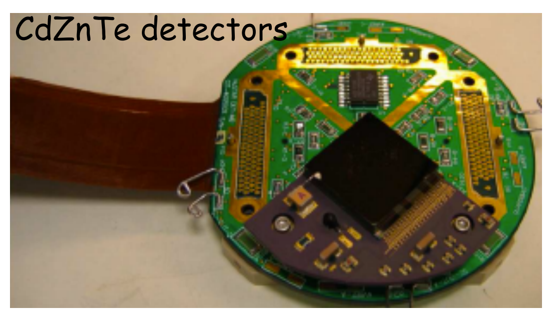
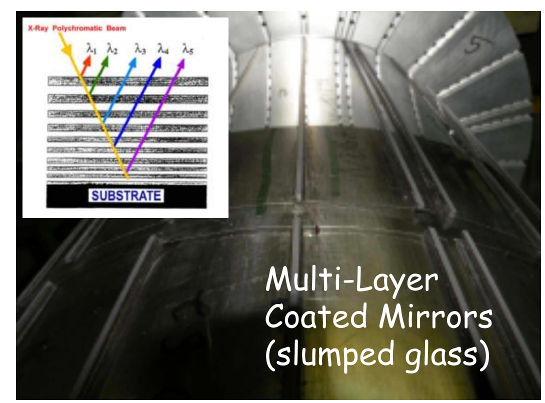


Fig. 1. NuSTAR telescopes in deployed configuration

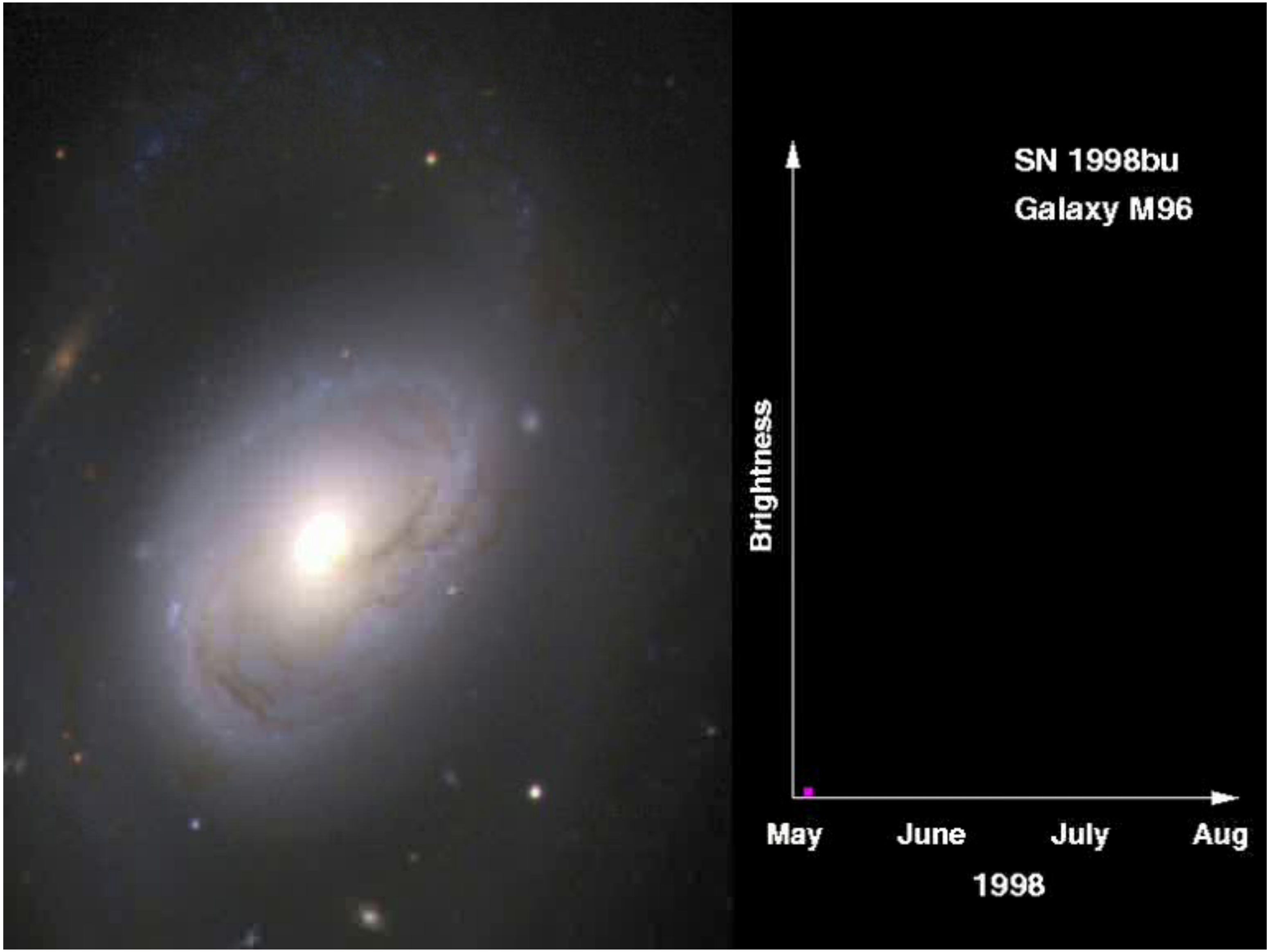
Launch scheduled for March 2012





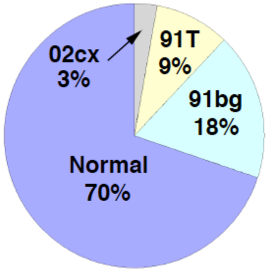
- **Understanding Cosmic Sources**
  - ☆ **SNIa**
  - ☆ **cc-SNe**
  - ☆ **Massive Stars**

Appearance of a Supernova



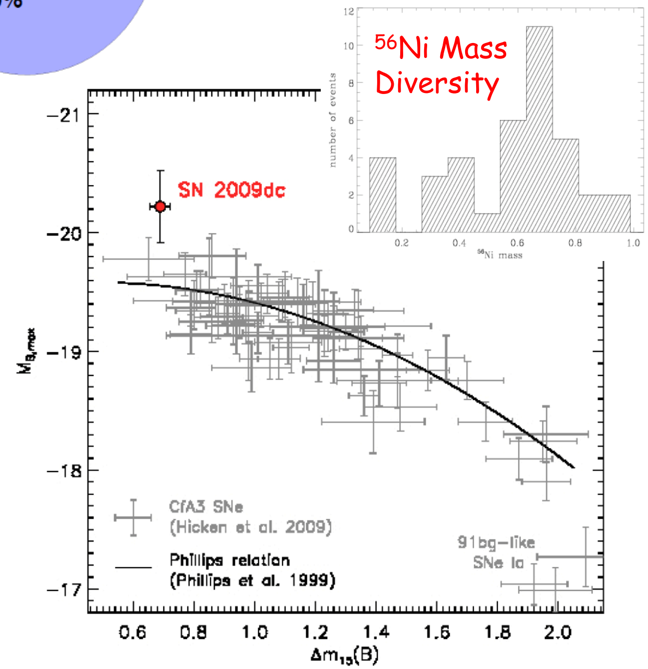
What are Supernovae Type Ia?

☆ **Only ~1/3 of SNIa are Selectable for Cosmological Studies**



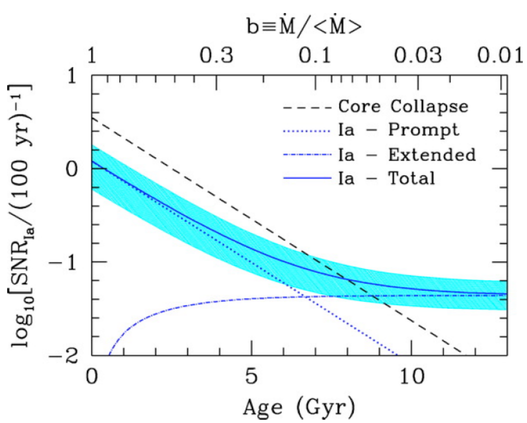
☆ **SNIa Diversity becomes Clearer, and is not Understood**

- ☞ **Faint Extremes**
- ☞ **Bright Extremes**
- ☞ **Asymmetries of Ignition, and obs. Aspect**
- ☞ **Mergers / sub-Ch / Ch Models?**
- ☞ **The Standard-Picture (M_{Ch}WD) Erodes**



- ☞ **Sub-Chandrasekhar / Chandrasekhar-Models and WD-WD Mergers all seem ~plausible**

☆ **The Dominating Underlying Source Process may Evolve with z**



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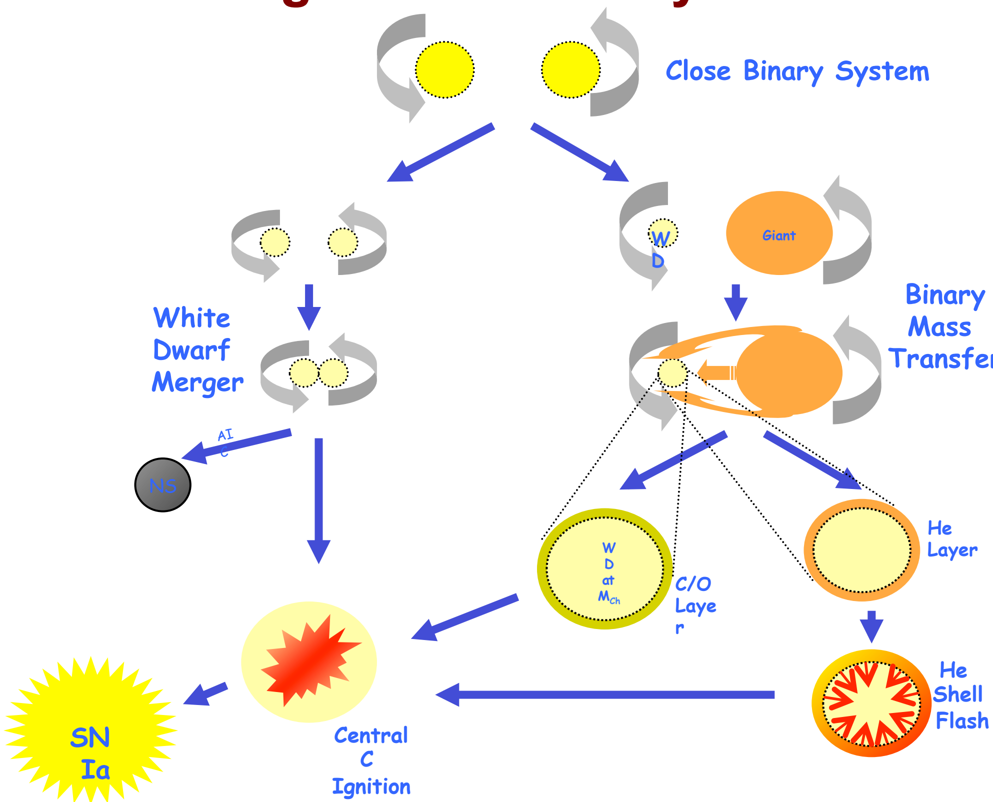
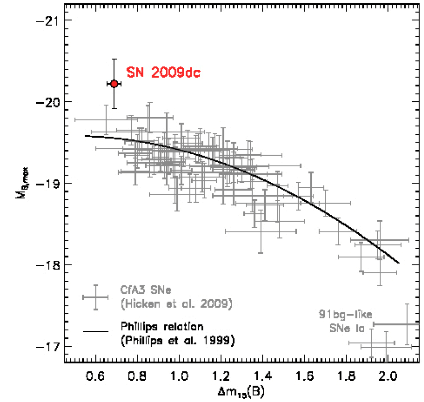
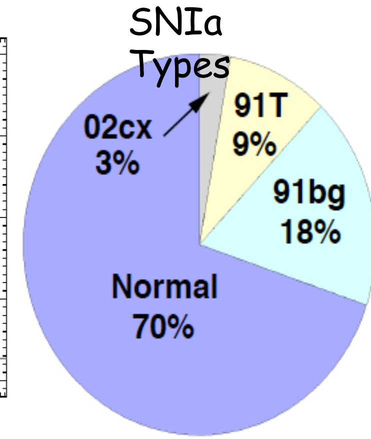
SNIa

- **SNIa Diversity**

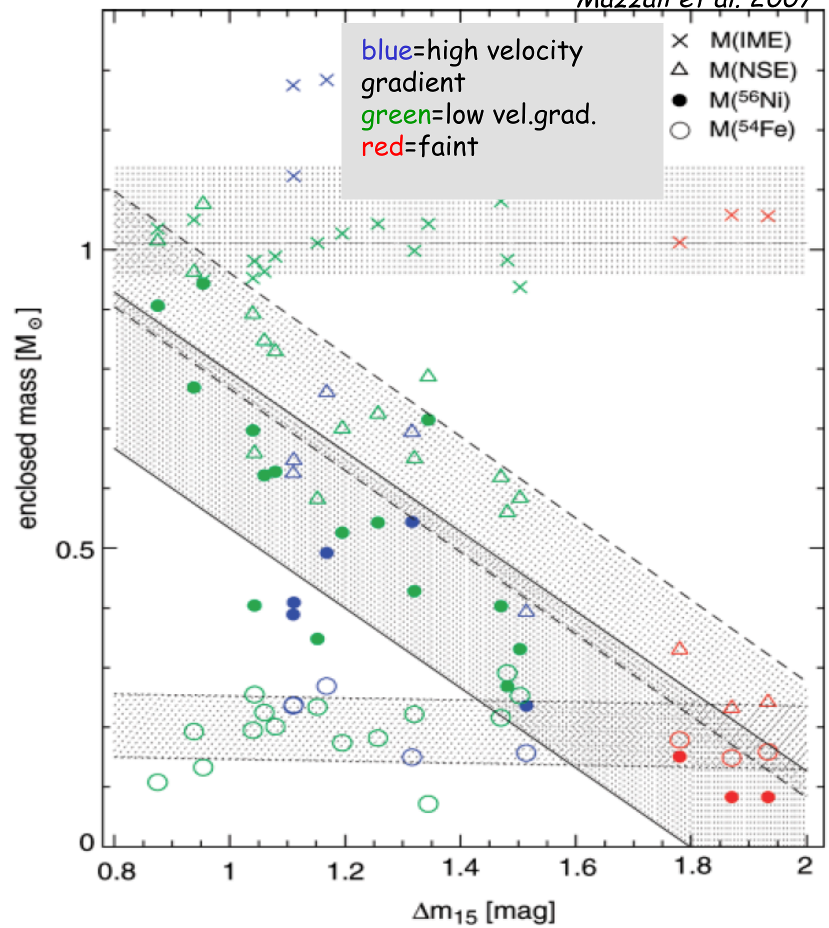
☞ **Progenitor Diversity?**



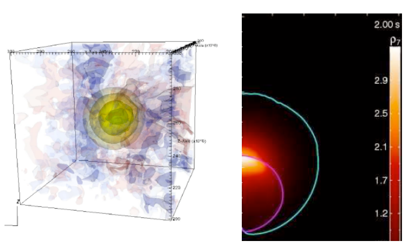




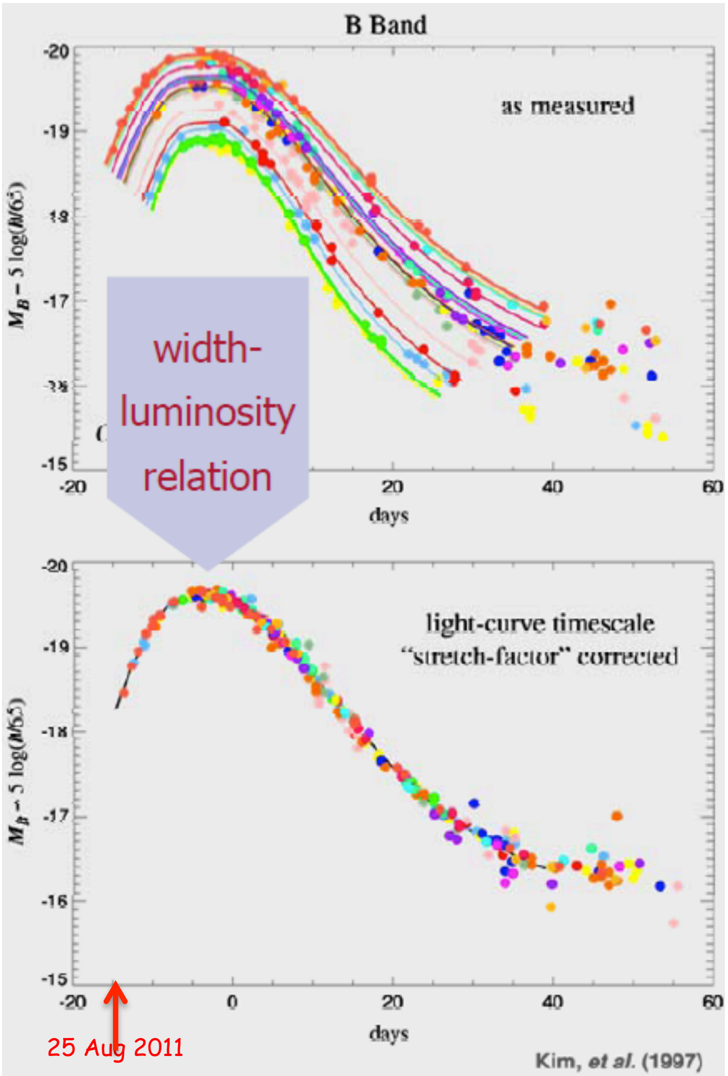
Mazzali et al. 2007

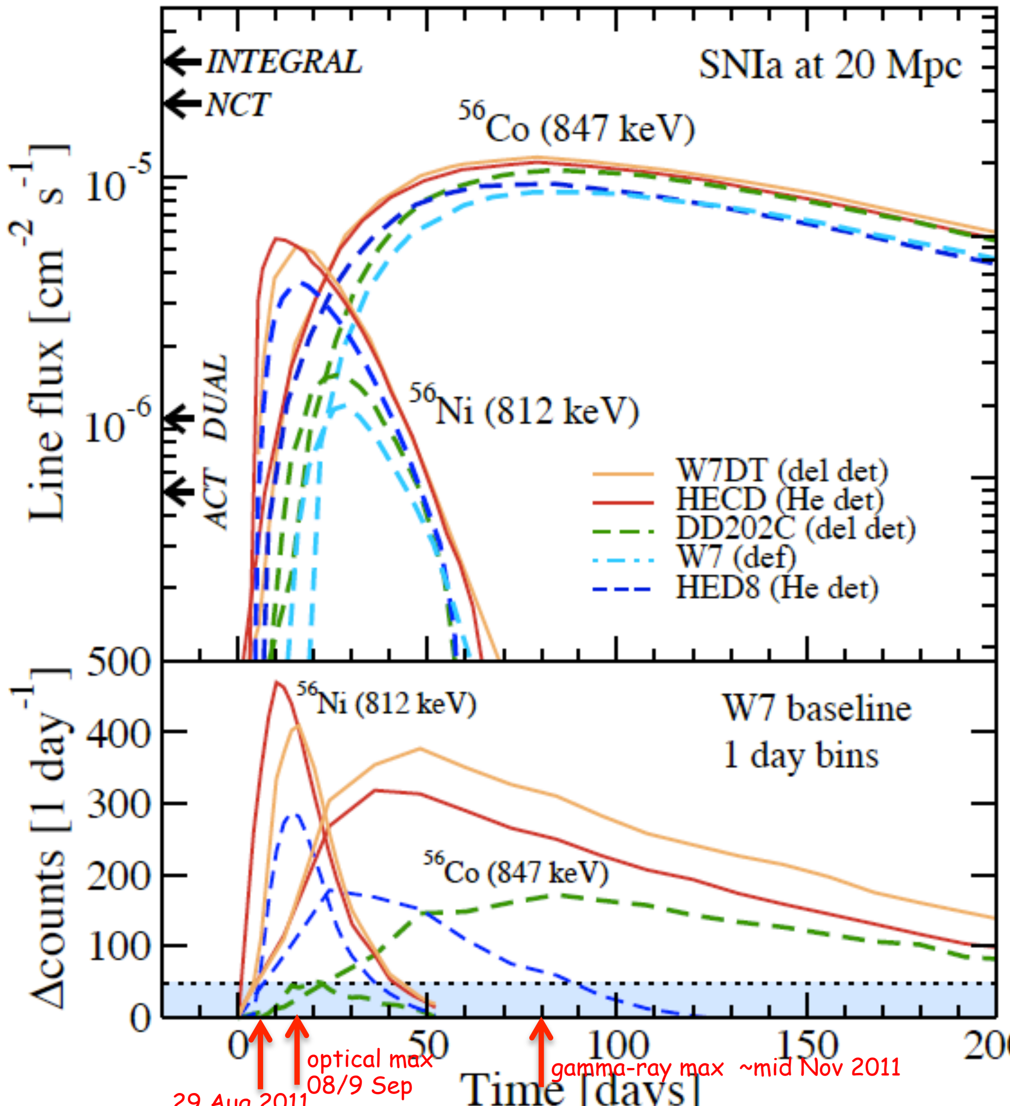


☆ **Ignition Physics?**



SNIa Models and Radioacivity Gamma-Rays

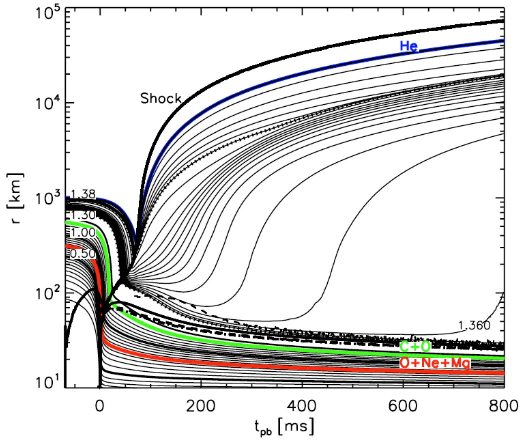


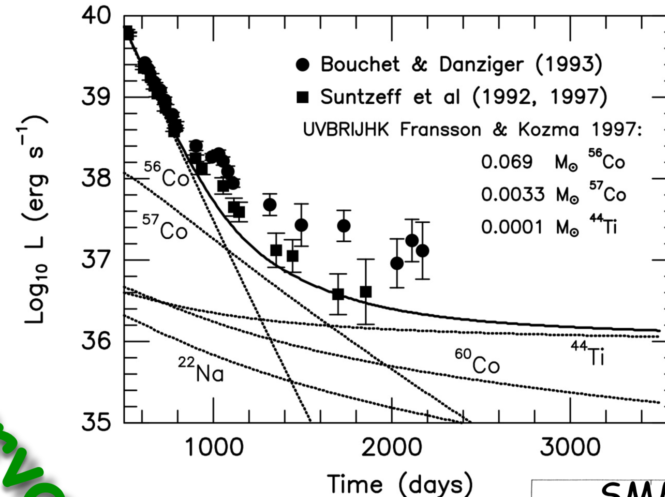


- **SN 2011fe in M101 is a Chance to Gamma-Calibrate SNIa Models** (d~6.4 Mpc)
  - ☆ **Phillips Relation, Light Transport Codes from Gamma to X/UV/OPT/IR**

Aspects of a Core-Collapse Supernova

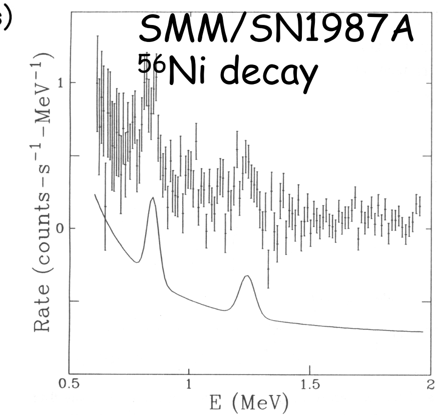
- **Nuclear Energy Conversions +...**
  - ☆ **Dynamics of Explosions**
  - ☆ **Structure of Stars**

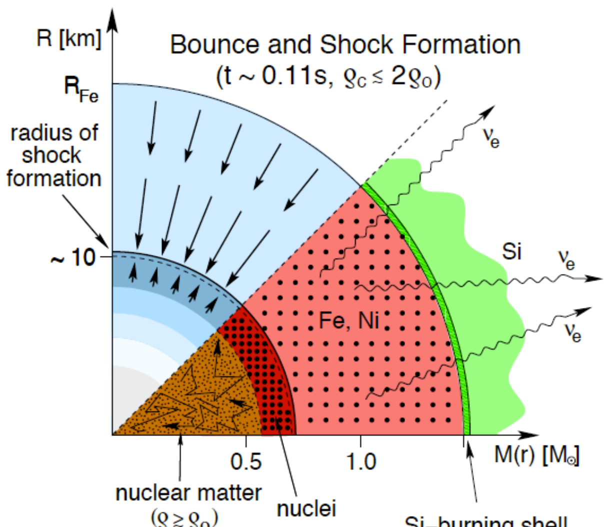


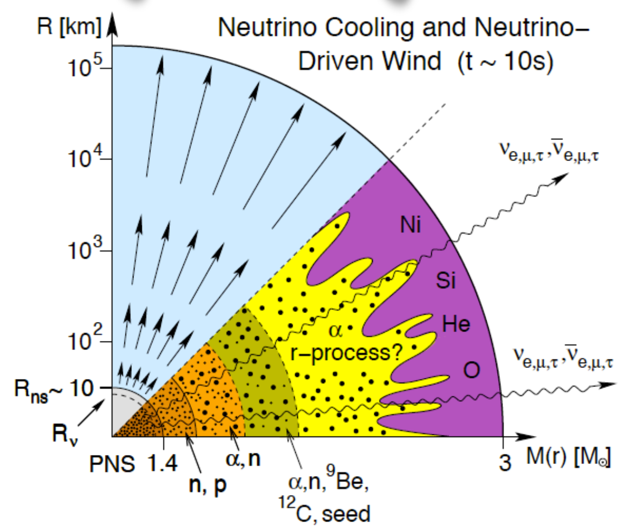


Observations

Models







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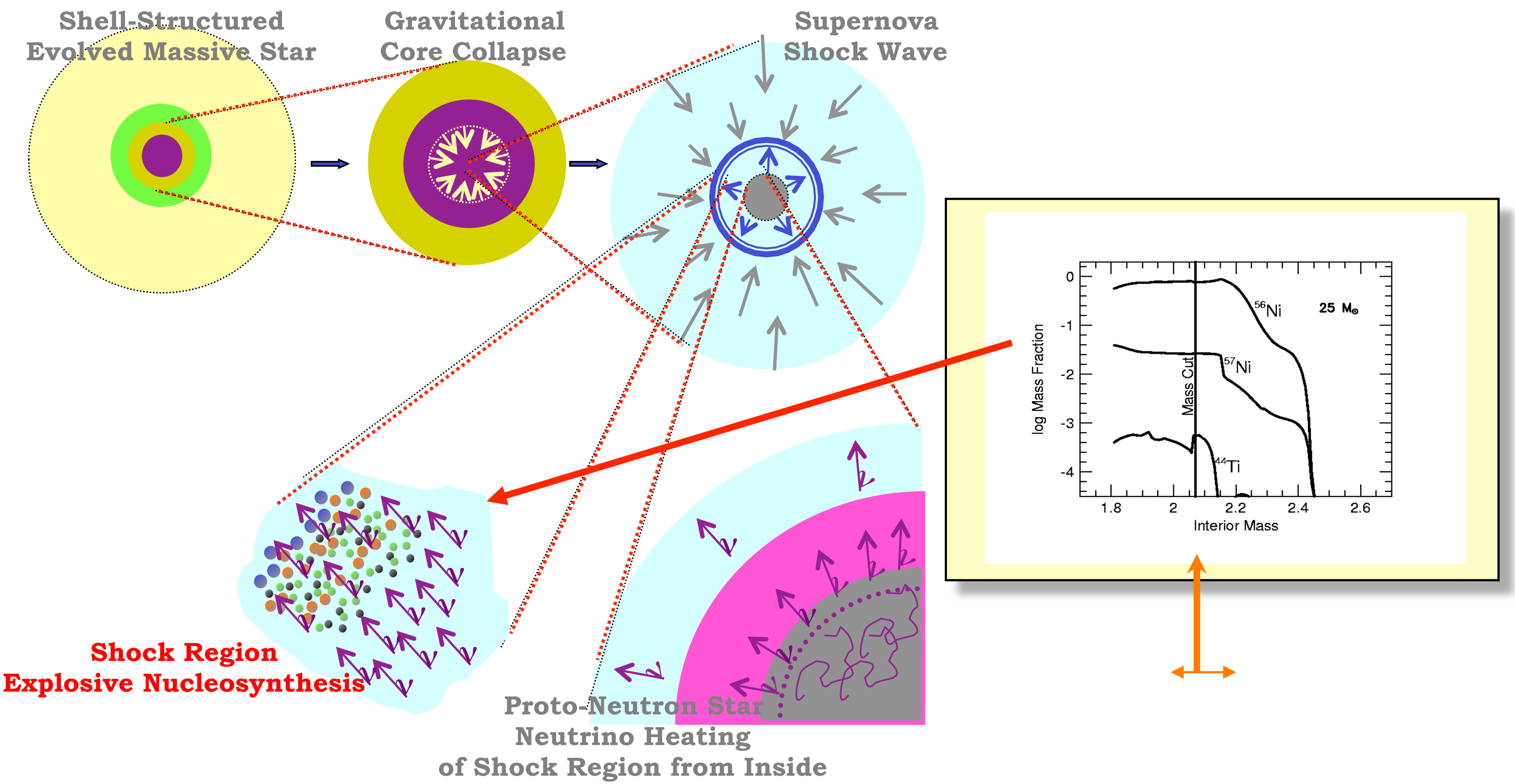
Nucleosynthesis in CC-Supernova Models and ^{44}Ti



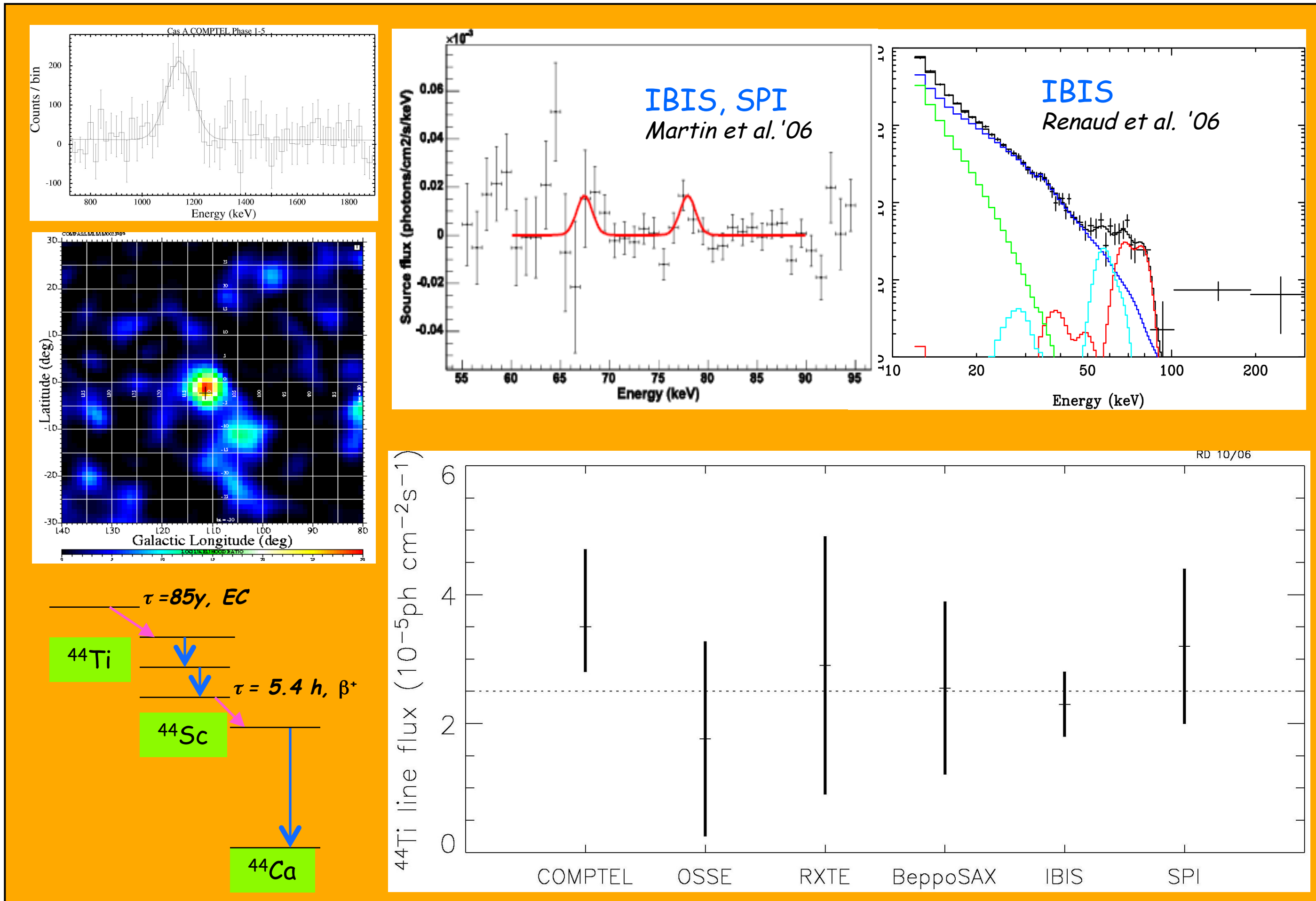
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out,

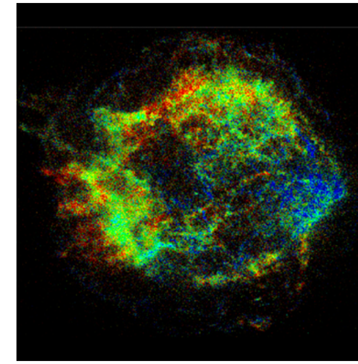
  => Unique Probe (+Ni Isotopes)

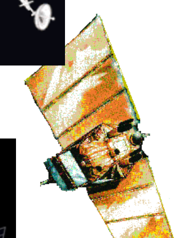
^{44}Ti γ-rays from Cas A

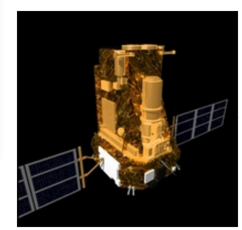
τ=85y (Ahmad et al. 2006)

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





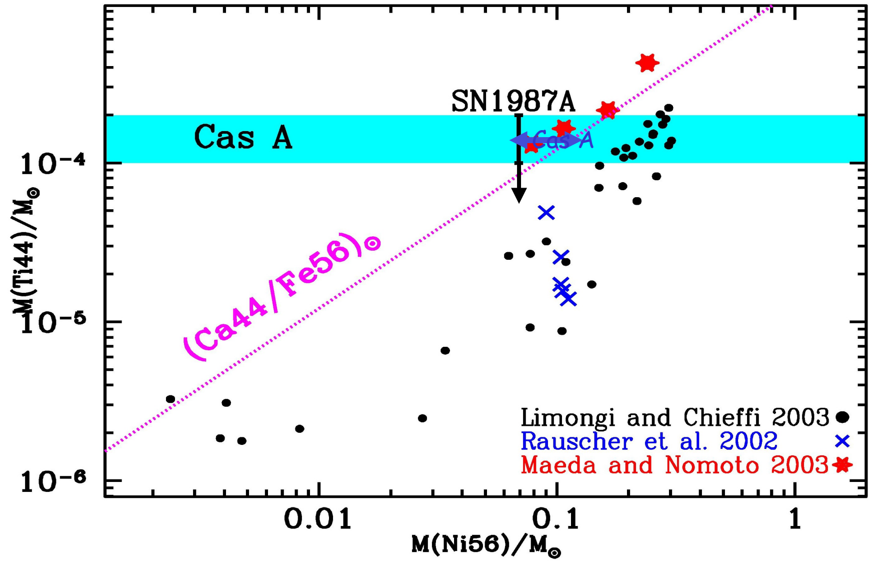




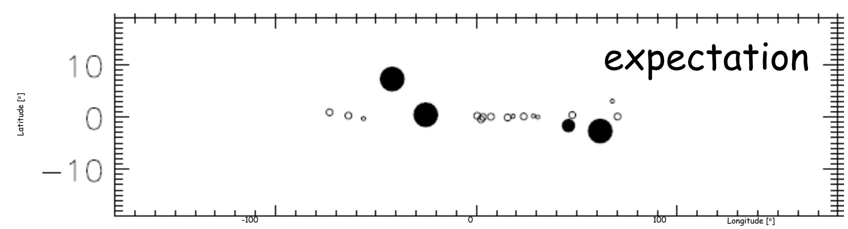
^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} $M_{\odot}$

"Abnormal" Core Collapse Supernovae as ^{44}Ca (=^{44}Ti) Sources?

- ☆ ^{44}Ti vs. ^{56}Ni: Models compared to
  - ➢ Solar ^{44}Ca/^{56}Fe
  - ➢ SN1987A & Cas A
  - ⇨ Only Non-Spherical Models Seem to Reproduce Observed ^{56}Ni/^{44}Ti Ratios

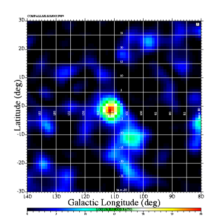


- ☆ Sky Regions with Most Massive Stars are ^{44}Ti Source-Free (COMPTEL, INTEGRAL)



- ☆ ***^{44}Ti is from Rare Events??***

- ⇨ *The et al. 2006*

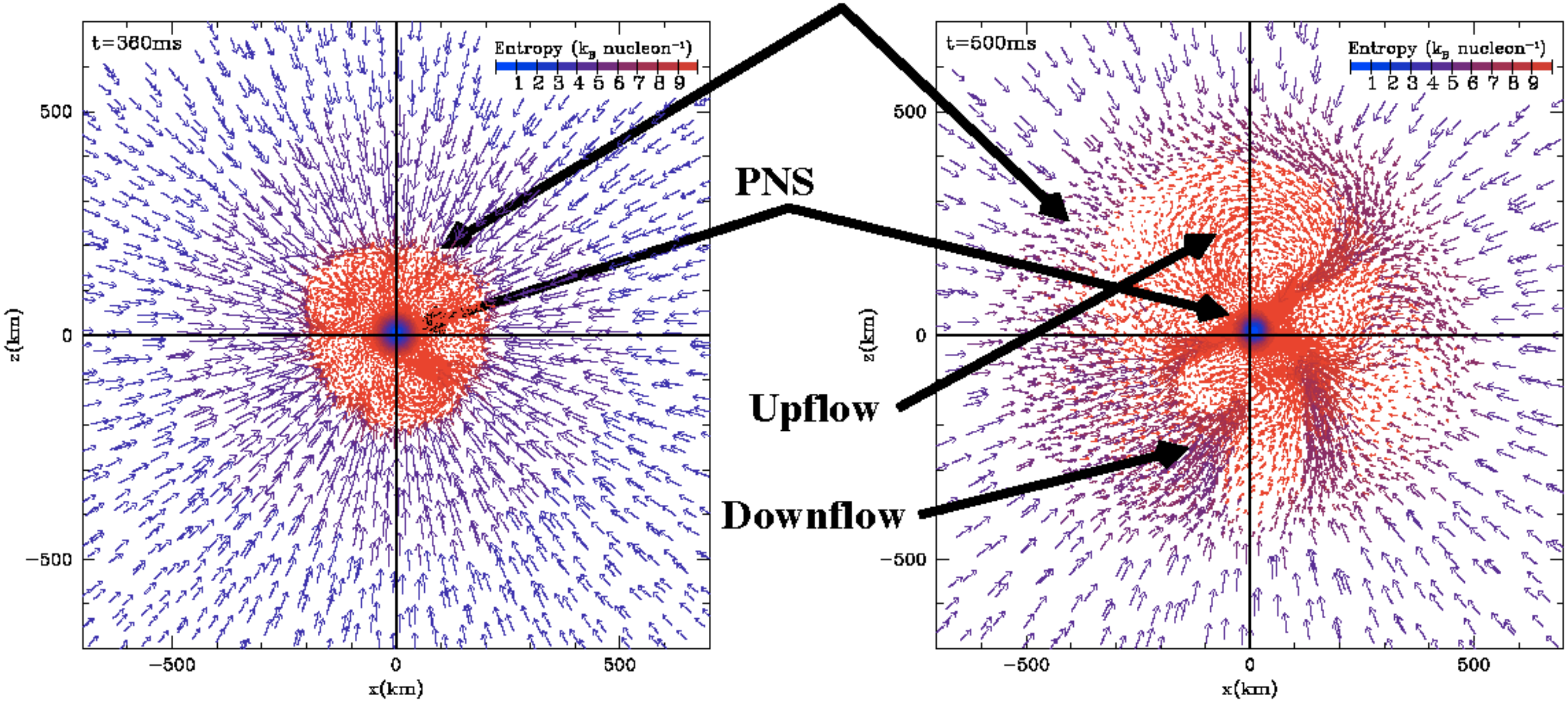


Cas A is the ONLY Source Seen in our Galaxy

(Iyudin et al 1994)

Inner ccSN

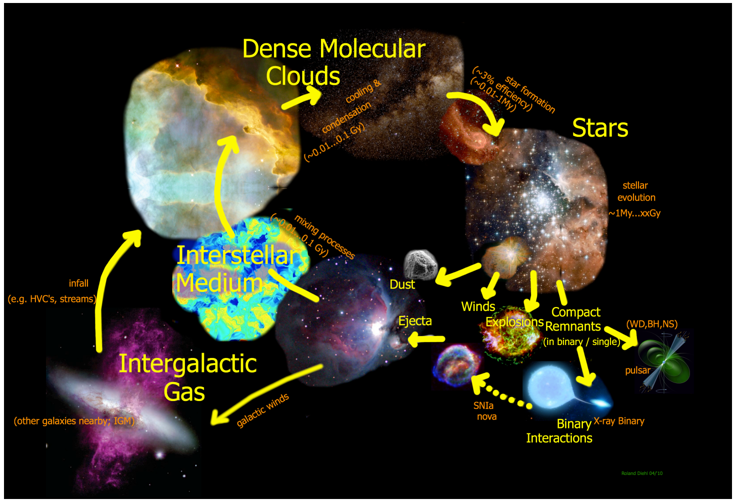
- **Complex Inward & Outward Gas Flows**



Massive-Star Interiors

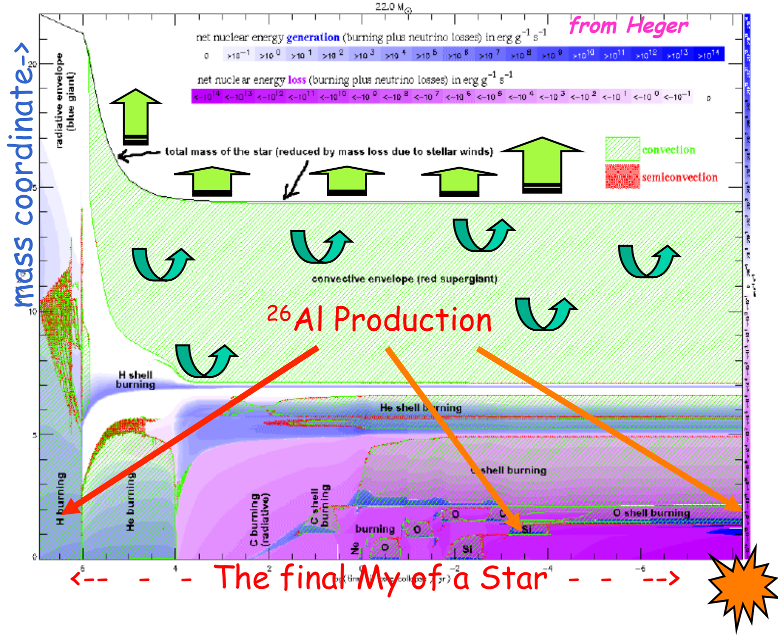
☆ **Massive Stars are:**

- ☞ **Key Producers of Cosmic 'Metals'**
- ☞ **Key Agents for Cosmic Evolution in Galaxies**



☆ **How does the Interior Structure Evolve in Late Stages?**

- ☞ **Which "Shells" are Active?**
- ☞ **Which Nuclei are Produced? (ejected?)**
- ☞ **What are the Time Scales?**
- ☞ **How does all this Depend on Rotation?**
- ☞ **How does all this Depend on Metallicity?**



Main Sources of ^{44}Ti, ^{26}Al, ^{60}Fe

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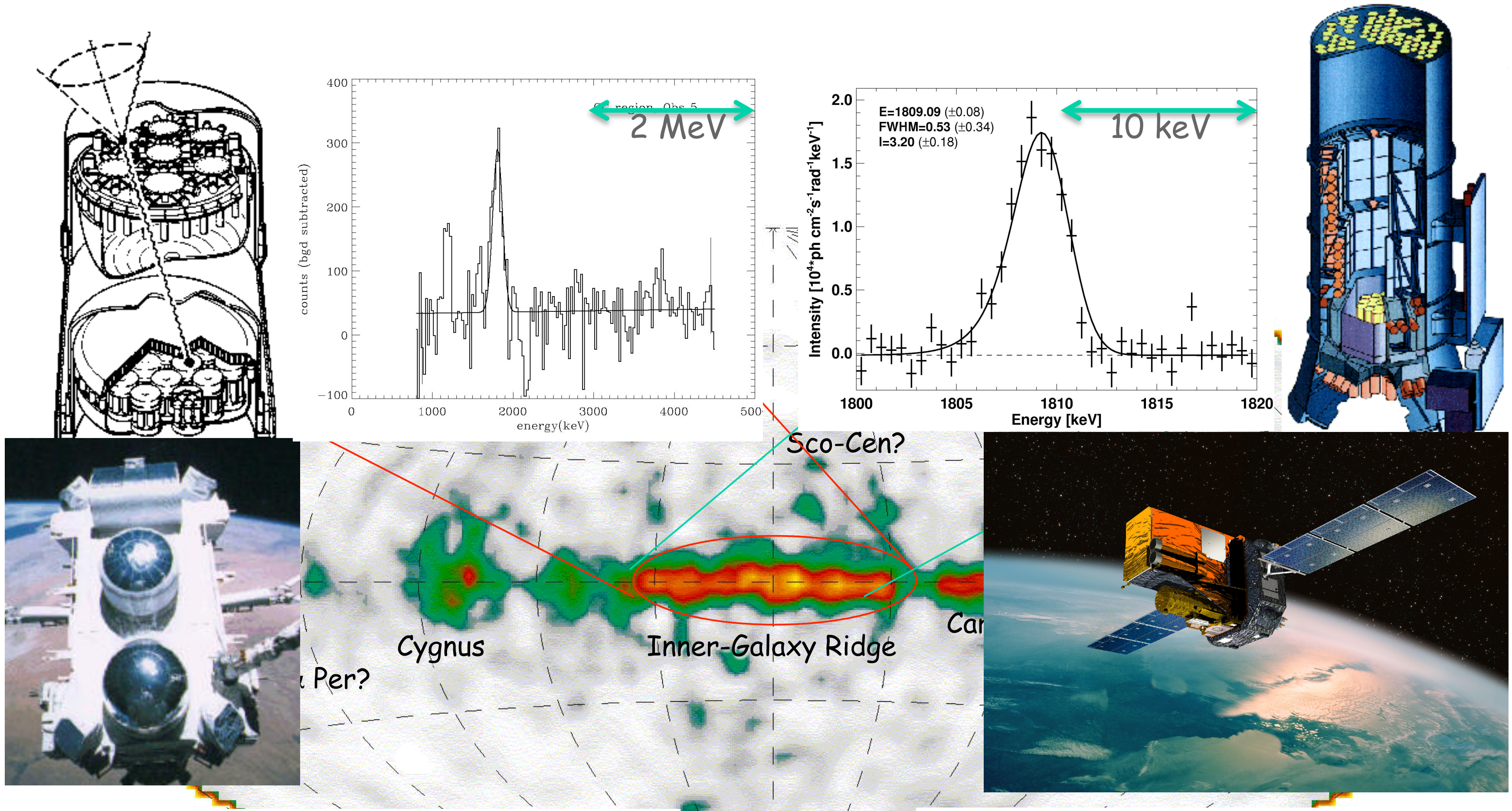
CGRO (<2000) / INTEGRAL (>2002) Spectroscopy



COMPTEL's δE~200 keV
(-> $v_{Doppler}$>25000km/s needed ☹)

INTEGRAL's δE~3 keV
(-> $v_{Doppler}$>100km/s needed ☺)

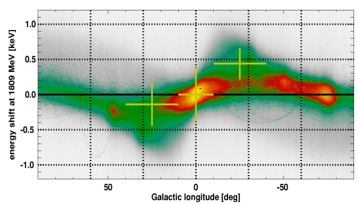
Using the ^{26}Al Line to Characterize the Galaxy

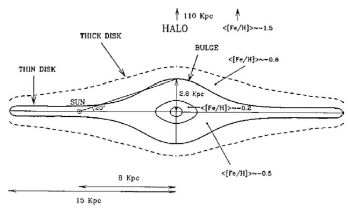
-> Diehl et al., Nature 2006

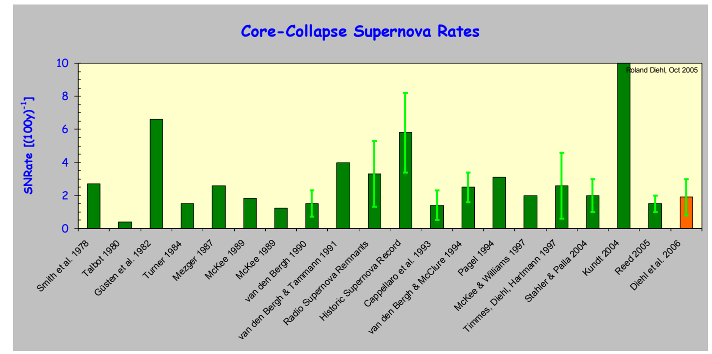
☆ **Measured Gamma-Ray Flux**

☆ **Galaxy Geometry**

➢ ^{26}Al Mass in Galaxy = 2.8 (±0.8) $M_\odot$





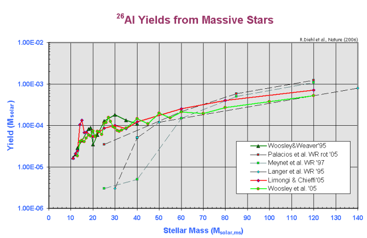


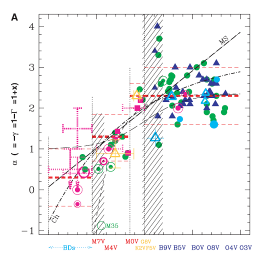
☆ **^{26}Al Yields per Star**

☆ **Stellar Mass Distribution**

✓ cc-SN Rate = 1.9 (± 1.1) per Century

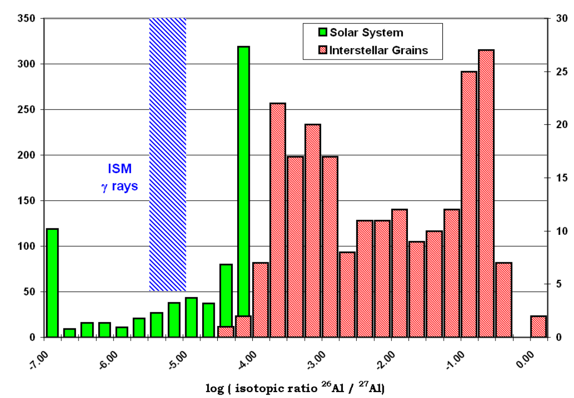
✓ SFR = 3.8 $M_\odot$/yr





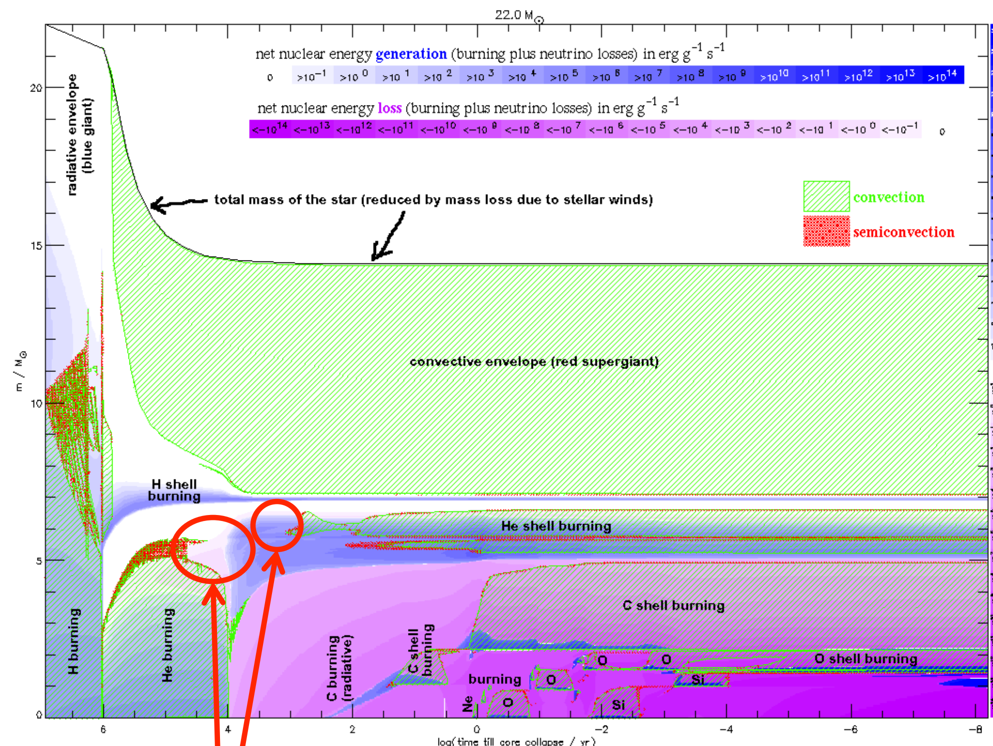
☆ **Gas Mass in Galaxy**

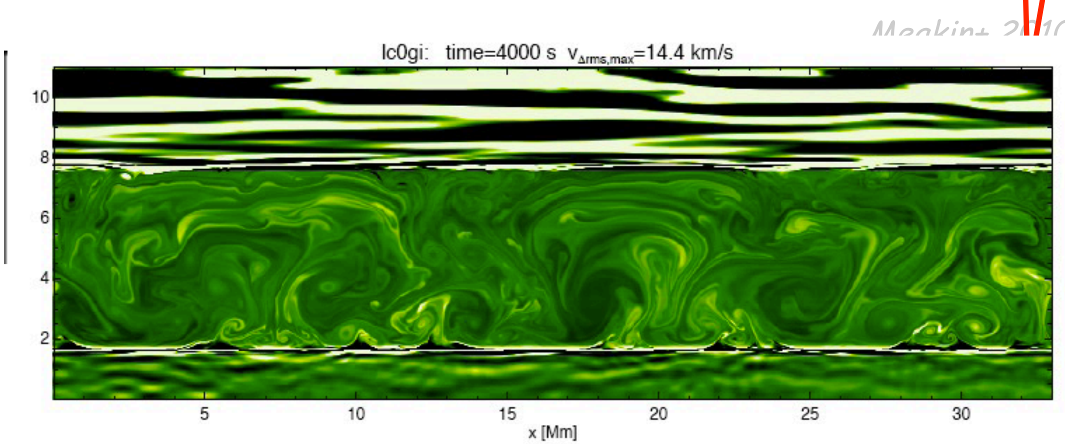
✓ Al Isotopic Ratio = 8.4 10^{-6}

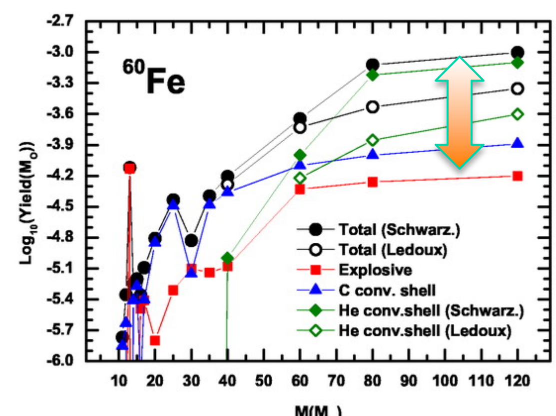


Massive-Star Structure: Convection Issues

- ☆ **How Does Convective Zone Transit into Stable (radiative) Zone?**
- ☆ **3D Simulations Illustrate**
  - ☞ The Inadequacy of "Mixing-Length" Modeling
  - ☞ Details of "Semiconvection", "Overshooting" and other Empirical Corrections
  - ☞ How e.g. Stellar Rotation Leads to 3D Mixing Processes



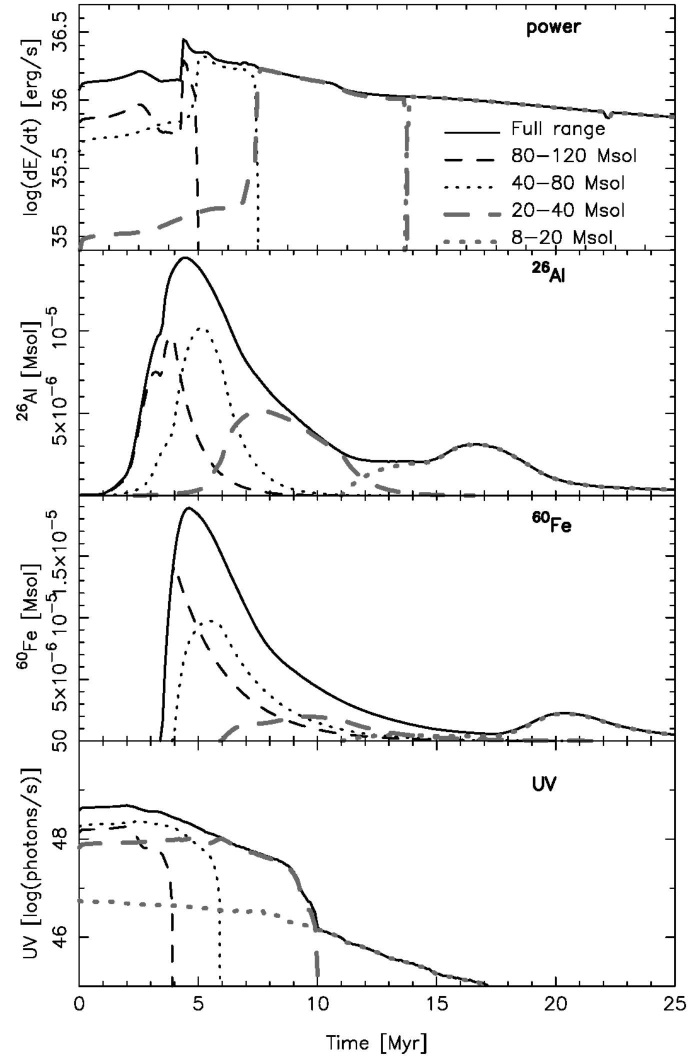




☞ Affects Isotopic Yields (e.g. ^{60}Fe)

Massive-Star Actions

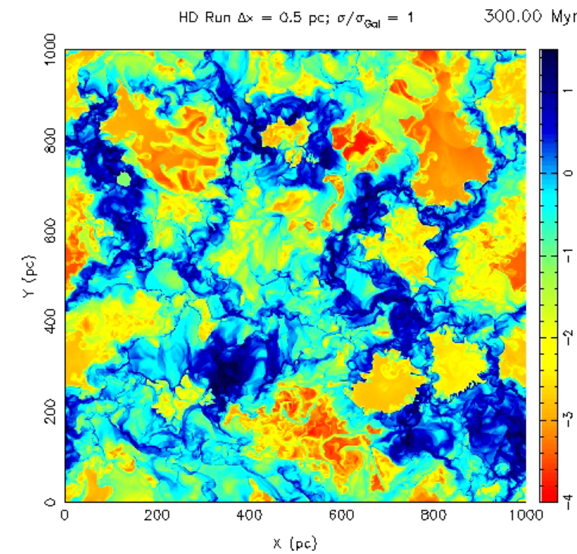
- ☆ **We study the impacts of massive stars on their surroundings:**
  - ☞ **Winds and explosions**
  - ☞ **Nucleosynthesis ejecta**
  - ☞ **Ionizing light**

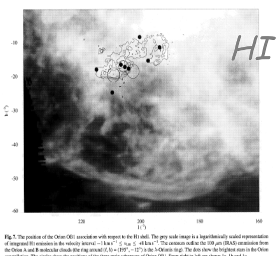


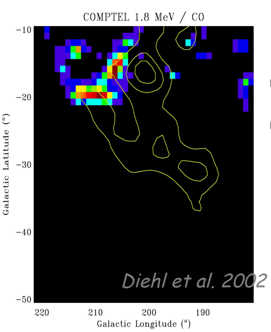
- ☆ **Multiple astronomical messengers:**
  - – **ISM cavities**
  - – **Radioactivity gamma-rays**
  - – **Free-free emission**
  - – **Star counts**

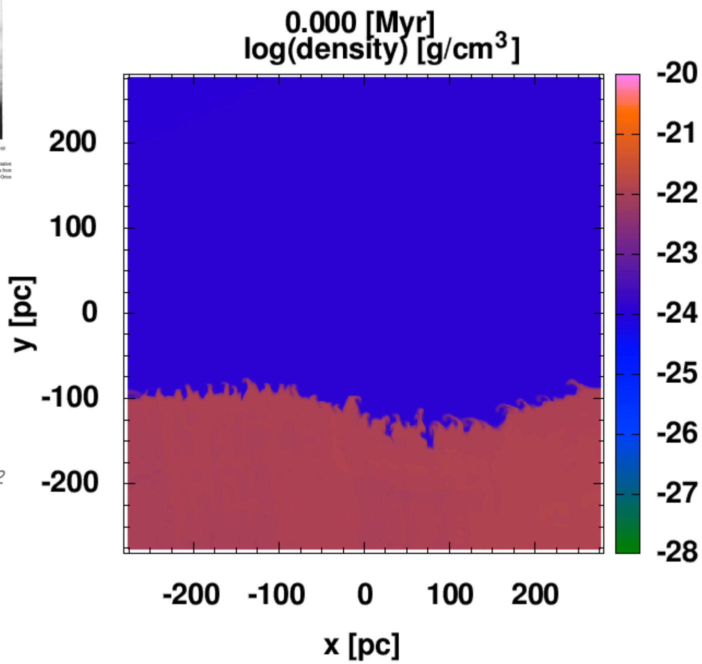
Dynamics of the Interstellar Medium

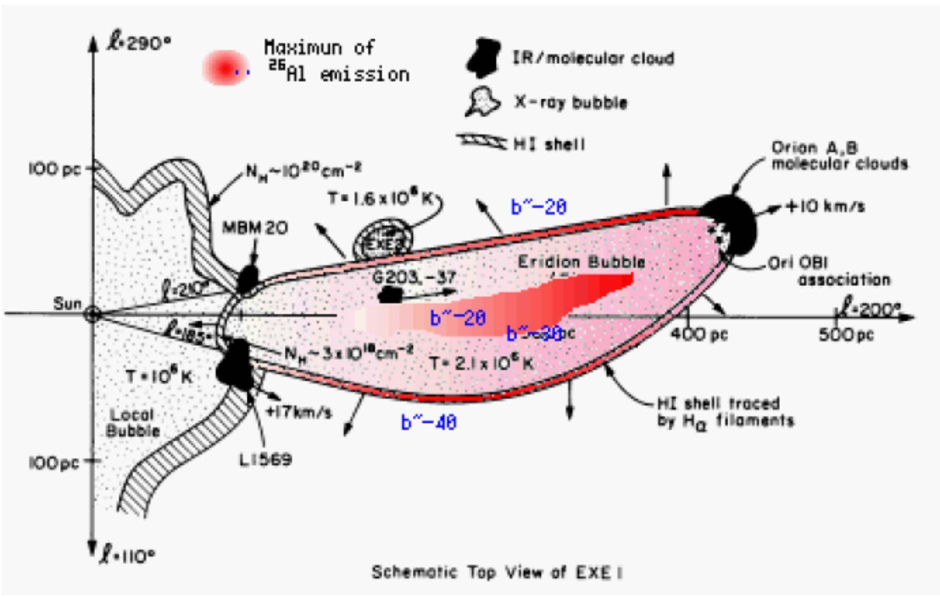
- **The Orion Region as Test Case (Laboratory)**
  - ☆ **Mixing of SN Ejecta into Multi-Phase ISM?**
- **Simulations:**
  - ☆ **Trace Evolution of Massive-Star Activity in Parental Cloud**





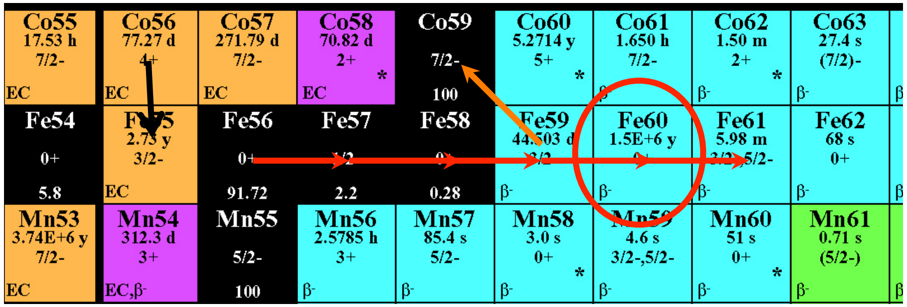


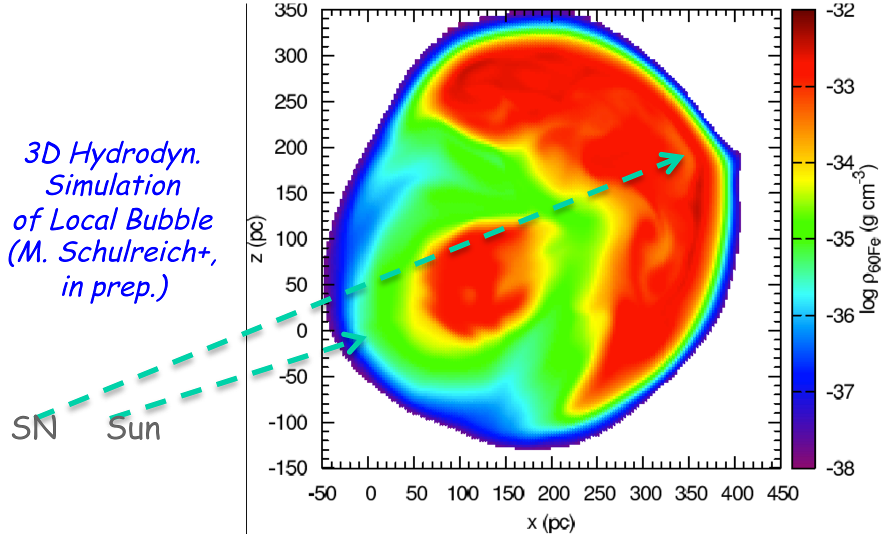


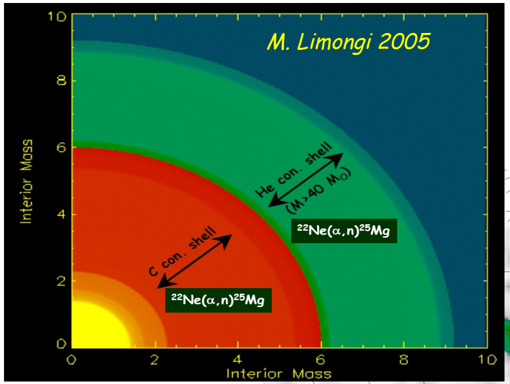


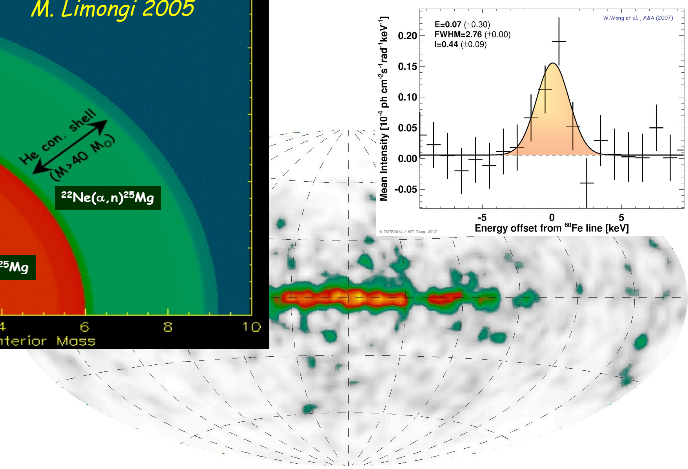
Understanding Measurements of SN Ejecta

- ^{60}Fe
  - ☆ Clearly Seen in Oceanfloor Sample (and Galaxy-wide)
  - ☆ Nuclear Physics?? (β decay, n capture)
  - ☆ Massive-Star Envelope Models?? (Shell Burning & Mixing)
  - ☆ SN Ejecta Transport at ~10pc Scale??



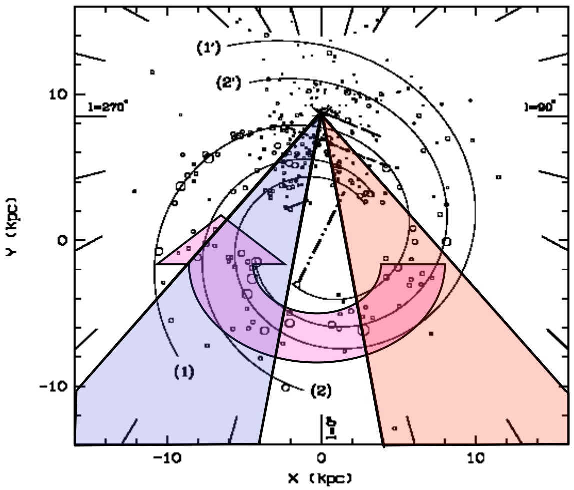


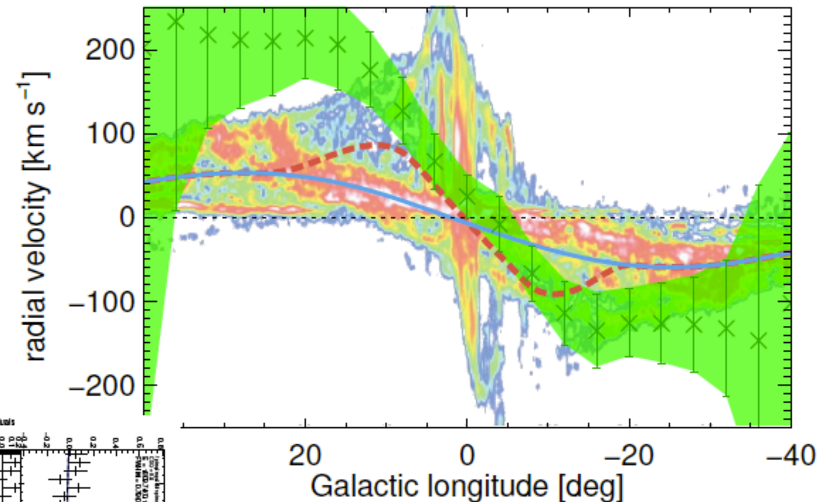


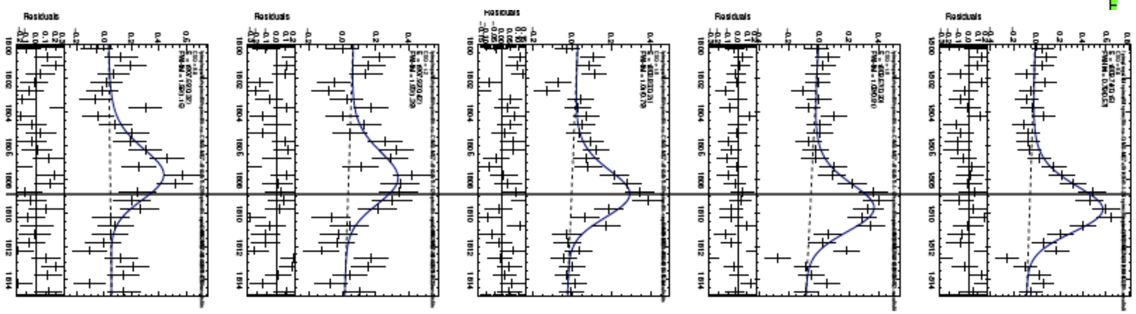


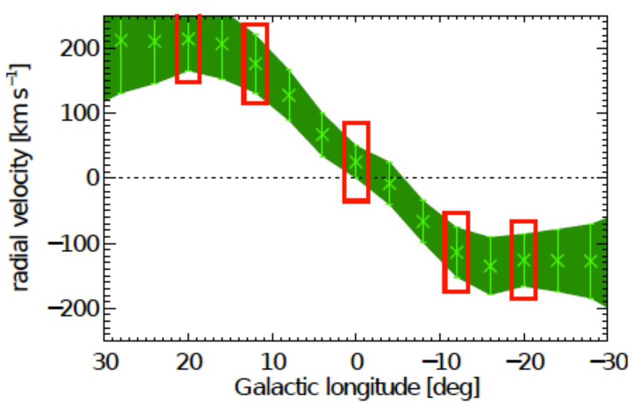
The Inner Galaxy and ^{26}Al Line Shifts

☞ ***Does Hot Gas Rotate at Higher Velocities?***

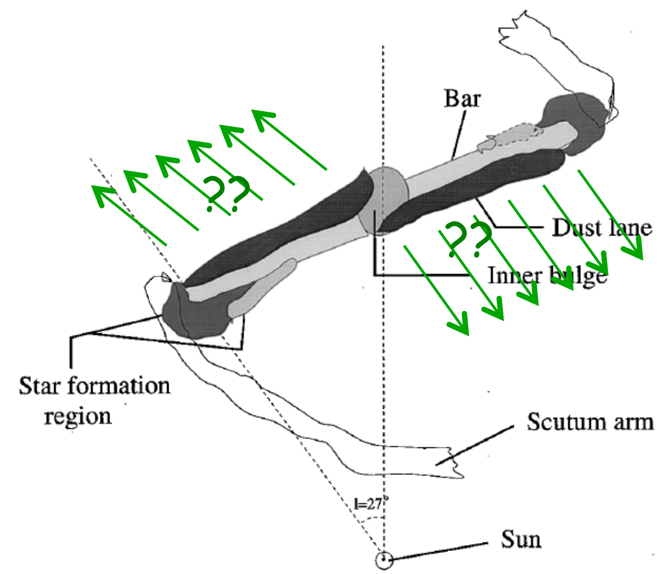




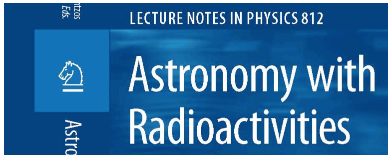




- fit sky maps to INTEGRAL data → spectrum
- spectral fit → line centroid
- scan region of interest along Galactic plane

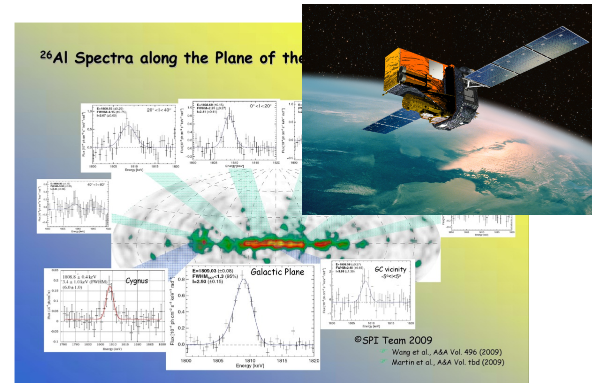


Roland Diehl

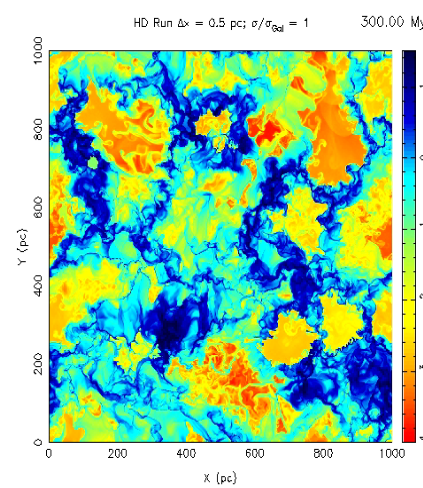


Cosmic Radioactivities Summary

- ☆ **Radioactivity provides a unique / different astronomical tool**
  - ☞ **Intensity change only due to radioactive decay**
  - ☞ **Thermodynamic gas state unimportant**



- ☆ **Supernova interiors can be explored**
  - ☞ **SNIa brightness evolution and ^{56}Ni yield calibration**
  - ☞ **Core collapse evolution into an explosion with ^{56}Ni and ^{44}Ti production**
- ☆ **Massive-star shell structure and evolution can be explored**
  - ☞ **^{26}Al production in core H burning and late shell burning**
  - ☞ **^{60}Fe production in C and He shells**



- ☆ **Chemical evolution uncertainties can be explored**
  - ☞ **ISM state and dynamics around massive-star regions**
  - ☞ **Nucleosynthesis ejecta recycling times**